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FORMAL REPORT

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High pT Physics at RHIC

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are three Fellows and seven Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program had increased to include ten theorists and one experimentalist in academic year, 2001-2002. With five fellows having already graduated, the program presently has ten theorists and three experimentalists. Five of the ten RHIC Physics Fellows have been awarded/offered tenured positions, and this will be their final year in the program.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by RBRC Researchers. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC also has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are fifty-six proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998. A 10 teraflops QCDOC computer in under development and expected to be completed in JFY 2004.

N. P. Samios, Director
January 2004

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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"High $p_\perp$ Physics at RHIC"

— Introduction and Overview —

The *AuAu*, *dAu*, and *pp* collision modes of the RHIC collider at BNL have led to the publication of exciting high $p_\perp$ particle production data. There have also been two physics runs with polarized protons, and preliminary results on the double-spin asymmetry for pion production had been presented very recently. The ontological questions behind these measurements are fascinating: Did RHIC collisions create a *Quark-Gluon-Plasma* phase and did they verify the *Color Glass Condensate* as the high energy limit of QCD? Will the *Spin Crisis* finally be resolved in terms of gluon polarization and what new surprises are we yet to meet for *Transverse Spin*? Phenomena related to sub-microscopic questions as important as these call for interpretations that are footed in solid theory.

At large $p_\perp$, perturbative concepts are legitimately expected to provide useful approaches. The corresponding hard parton dynamics are, in several ways, key to unraveling the initial or final state and collisional phase of hard scattering events in vacuum as well as in hot or cold nuclear matter. Before the advent of RHIC data, a RIKEN-BNL workshop[1] had been held at BNL in March 1999 on "Hard Parton Physics in High Energy Nuclear Collisions". The 2003 workshop on "High $p_\perp$ Physics at RHIC" was a logical continuation of this previous workshop. It gave the opportunity to revisit the 1999 expectations in the light of what has been found in the meantime and, at the same time, to critically discuss the underlying theoretical concepts.

We brought together theorists who have done seminal work on the foundations of parton phenomenology in field theory, with theorists and experimentalists who are presently working on RHIC phenomenology. The participants were both from a high-energy physics and nuclear physics background and it remains only to be said here that this chemistry worked perfectly and the workshop was a great success.

We hope to have raised the reader's appetite and that he will enjoy browsing through the contributions for answers to the above questions — there have been far too numerous excellent talks that we wanted to pick out particular ones here or even attempt to summarize[2]. We thank all speakers and participants for coming to the Center and making it the successful meeting it has been. Many have encouraged us early on or sent positive feed-

[1] BNL-52574, RBRC vol. 17

[2] Most talks can also be assessed in full on the workshop program page: http://thy.phy.bnl.gov/ kretzer/workshop/highpt_program.html

back later – we want to particularly acknowledge Drs. L. McLerran and T. Kirk here. The level of support provided by the RIKEN-BNL Research Center through Prof. T.D. Lee and Dr. N. Samios and by the BNL Physics Department through Dr. S. Aronson has been magnificent and we are very grateful. Many thanks go to T. Heinz and M. Chaloupka for their outstanding organizational skills which helped take the administrative burden off our shoulders and made the conference an enjoyable experience for all.

Stefan Kretzer, Dave Morrison, Raju Venugopalan and Werner Vogelsang

RBRC, December 2003

Opening Talk

A. Mueller, Columbia University

for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

1. Introduction

In central unit of rapidity in central Au-Au collision dense gluonic system is produced at time $\lesssim \frac{1}{2}$ Fm. This system appears to equilibrate rapidly forming a quark gluon plasma much denser than cold nuclear matter.

Hard probes are good probes of the density of the matter. Comparing A-A, Deuterium-A and p-p reactions using a hard probe allows one to separate properties of the initial wavefunctions (light-cone gauge) from those of the final state evolving matter.

p-p, d-Au, Au-Au at $y=0$: Suppression of high momentum particles due to (final state) energy loss in Au-Au

p-p, d-Au at large y: Strong shadowing observed. Good evidence for Color Glass Condensate (Saturation).

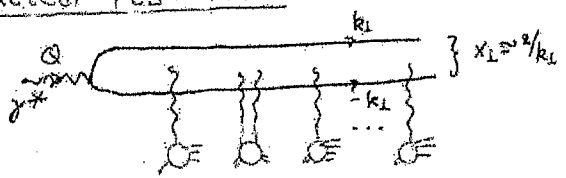
2. Saturation (Color Glass Condensate)

Saturation (CGC) is property of light cone wavefunction. Easiest to view by DIS probe.

A. McLerran–Venugopalan model

Alternative pictures in different frames

Nuclear rest frame



$$F_2 = \frac{Q^2}{8\pi^2\alpha_{em}} \int d^2b \int_0^1 dz \int d^2x_\perp \, |\Psi_T(x_\perp, z, Q)|^2 \, 2\Big(1 - \underbrace{e^{-x_\perp^2 \bar{Q}_s^2/4}}_{S(x_\perp, b)}\Big)$$

is Glauber-type formula.

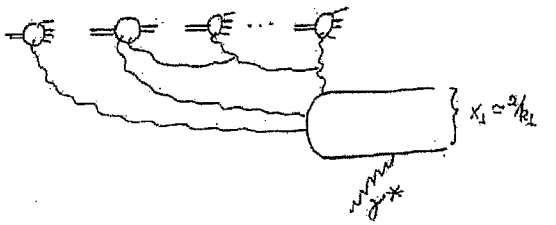
$$\frac{1}{4} x_\perp^2 \bar{Q}_s^2 = \frac{1}{2} \sigma_{q\bar{q}}(x_\perp) \, 2\sqrt{R^2 - b^2}\, \rho$$ nuclear density

$$Q_s^2 = \frac{4\pi^2 \alpha N_c}{N_c^2 - 1} \, 2\sqrt{R^2 - b^2}\, \rho \times G_p \quad ; \quad \bar{Q}_s^2 = \frac{C_F}{N_c} Q_s^2$$

$\bar{Q}_s$ sets scale where S goes from 1 (weak interaction) to 0 (unitarity limit).

$Q_s \simeq 1\,\text{GeV}$ for large

Bjorken Frame (P_z large for nucleus)

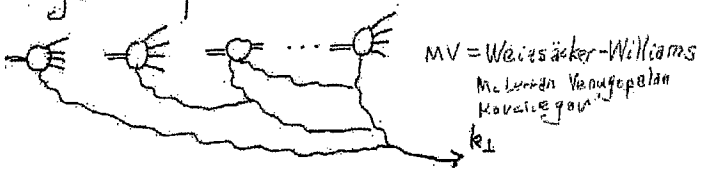


Now describe quark sea in large nucleus by

$$f_q(k_\perp, b) \simeq \frac{d\,x(q_F + \bar{q}_F)}{d^2k_\perp d^2b} \frac{(2\pi)^3}{\underbrace{2}_{\text{spins}} \cdot \underbrace{2}_{\text{particle-antiparticle}} \cdot N_c}$$

$$S \simeq 0 \overset{k_\perp < \bar{Q}_s}{\Longleftrightarrow} f_q \simeq \frac{1}{\pi}$$ — Saturation, Color Glass Condensate

For gluons picture is



$$f_g = \frac{1}{\alpha N_c} \int \frac{d^2x_\perp}{\pi x_\perp^2} e^{-ik_\perp \cdot x_\perp} \left(1 - e^{-x_\perp^2 Q_s^2/4}\right) \simeq \frac{1}{\alpha N_c} \int^\infty \frac{dt}{t} e^{-t k_\perp^2/Q_s^2}$$

$$f_g \simeq \frac{1}{\alpha N_c}$$

Color Glass Condensate

Unitarity limit (Nuclear rest frame) ⟷ Saturation (Bjorken Frame)

In M-V model

Gluons classical

no shadowing, just rearrangement of gluons in nuclear wavefunction.

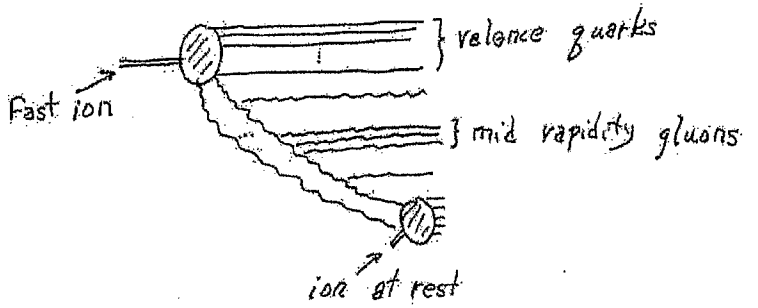
Quarks quantum (one loop)

quark distribution is shadowed, but there is no leading twist shadowing

Probably a reasonable starting point for $y \simeq 0$ in RHIC central collisions.

3. Heavy Ion Collision (Semiclassical Picture)

Take one ion at rest



Picture: Gluons in the Fast ion having $k_\perp \lesssim Q_s$ are Freed in the collision. Gluons having $k_\perp \gtrsim Q_s$ are not.

Numerical simulations by Krasnitz, Nara and Venugopalan confirm this picture with about ½ the gluons being Freed. Collision increases $\langle k_\perp \rangle$ by $\approx 50\%$. KNV Lappi

Phenomenology by Kharzeev, Levin, Nardi ...; Baier et al.

Wave Function relevant to DIS comes in directly in initial condition after a heavy ion collision.

4. BFKL evolution and anomalous scaling

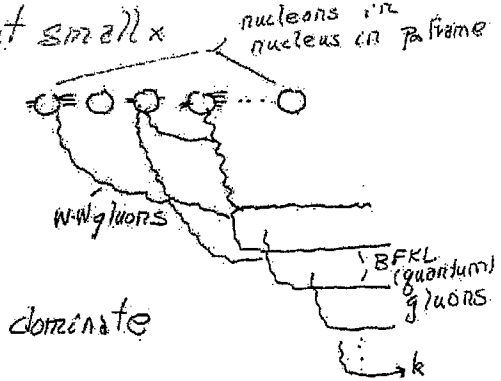
Saturation momentum can be large ($\gg \Lambda_{QCD}$) for two reasons:

(i) Large nucleus, at high momentum, has large number of Weizsäcker-Williams gluons.

$$Q_s^2(b) \sim 2\sqrt{R^2-b^2}\,\rho \sim A^{1/3}$$

(ii) BFKL evolution, at small x, gives large number of gluons.

Combines big nucleus at small x



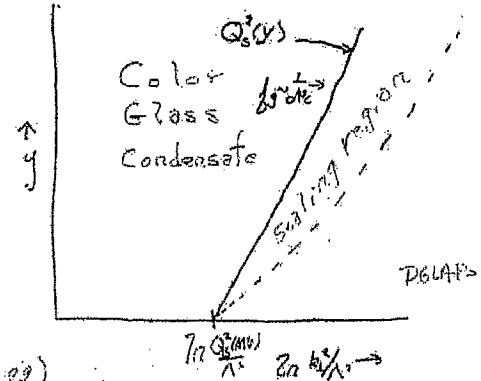
$$\frac{dN_g(b,y)}{dy} \sim \underbrace{\alpha N_g(b,y)}_{\text{random}} \text{ charges dominate}$$

$$N_g(b,y) \simeq \underbrace{N_g(b,0)}_{\text{W-W}}\ \underbrace{e^{\alpha y}}_{\text{BFKL enhancement}}$$

In scaling region

(i) $\rho g \ll \frac{1}{\alpha N_c}$

(ii) leading twist (BFKL) dynamics



In scaling region (From Kovchegov eq.)

$$\frac{k_\perp^2\, dN_g(k_\perp,b,y)}{d^2b\, d^2k_\perp\, dy} \simeq C_1 \frac{k_\perp^2}{\alpha}\left(Q_s^2(y)/k_\perp^2\right)^{1-\lambda_0}\left[\ln \frac{k_\perp^2}{Q_s^2} + C_2\right]$$

$$Q_s^2(y) = Q_s^2(MV)\,\frac{e^{\frac{2\alpha N_c}{\pi}\frac{\chi(\lambda_0)}{1-\lambda_0}y}}{[\alpha y]^{\frac{3}{2(1-\lambda_0)}}} \times C_3$$

A.M. & D. Antonyuk T. S. Munier & R. Peschanski
M. Lublinsky, Kharzeev & Levin
Khoze, Kovchegov, Tuchin
⋮

Nice numerical calculations by Albacete, Armesto, Kovner, Salgado, Wiedemann and by Weigert & Rummukainen, and Kowalski, Stasto et al.

Comments:

(i) A-dependence of unintegrated gluon distribution is $A^{1/3(1-\lambda_0)}$ rather than $A^{1/3}$. $1-\lambda_0 \simeq 0.63$. Suppression of gluon density in scaling region is shadowing due to closeness to saturation. This is leading twist shadowing. Note genuine DGLAP evolution has $\lambda = 0$ and does not give shadowing. In BRAMS region $Q_s^2(y) \simeq 2 \cdot Q_s^2(MV)$.

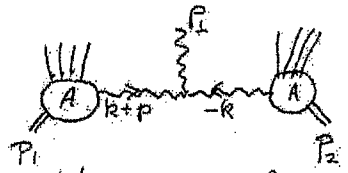
(ii) Size of scaling region determined by amount of BFKL evolution. Numerical studies, Albacete et al. KKT, Baier et al. et al., KKT, suggest rapid turn-on of BFKL effects.

(iii) Details of prefactors still to be understood. Question: Is Kovchegov equation adequate for prefactors in Q_s^2 and in $k_\perp^2 \frac{dN_g}{dy\, d^2k_\perp d^2b}$?

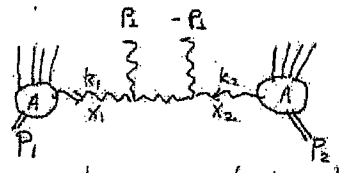
(iv) Chance to do exciting small-x physics in forward region at RHIC. Better understand high occupancy gluon systems. Better understand start of thermalization.

5. Hard Scattering at RHIC

A. High-$p_\perp$ jets (particles) at central rapidity



vs



When $p_\perp$ in scaling region
Unintegrated gluon distributions

When $p_\perp$ outside scaling region; Normal gluon distrib.
Hard Scattering Formalism

Hard Scattering Formalism can be used also in scaling region, but then a resummation of higher order terms in the hard part must be done. Scaling region is leading twist.

B. Kinematics (central rapidity)

Use hard scattering picture; take $p_\perp = 5\,\mathrm{GeV}$ and $x_1 = x_2$.

$$x_1 x_2 s = x^2 \cdot 4\times10^4\,\mathrm{GeV}^2 = 4p_\perp^2 \Rightarrow x = 0.05$$

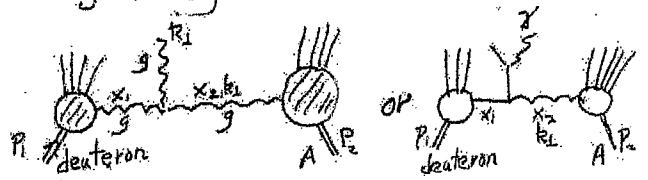
$$k_{1z} \simeq 5\,\mathrm{GeV} \Rightarrow (\Delta z)_k \simeq \frac{1}{25}\,\mathrm{Fm}$$

$$(\Delta z)_A \simeq 10\,\mathrm{Fm}\cdot\frac{1}{100} \simeq \frac{1}{10}\,\mathrm{Fm}$$

Coherence marginal!

Hard to get much evolution!

B. Large-x region



$x_1 x_2 s \simeq k_\perp^2$ $\qquad$ $x_1 x_2 s = k_\perp^2 + M^2$

$x_2 \to x_2 e^{-y}$ if one goes away from $y=0$

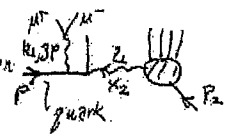
$y \simeq 3$ decreases x_2 by factor of 20

get to $x \simeq 0.001$ region where

anomalous scaling (shadowing) can be expected to be important.

C. μ-pair production

Jalilian-Marian, Gelis, Kopeliovich, Raufeisen, Tarasov, Johnson, Baier, Shiff, A.M.



$$\frac{d\sigma}{d^2b\, d^2k_\perp\, dh_q} = \frac{\alpha_{em}^2 \alpha_s}{3\pi^2 N_c}\left[1+(1-y)^2\right]\int \frac{d^2 l_\perp}{l_\perp^2}\, \phi(l_\perp, x_2, b)\left\{\frac{y^2 l_\perp^2}{k_\perp^2+\eta^2}\,\frac{1}{(k_\perp - y l_\perp)^2+\eta^2} - \eta^2\left[\frac{1}{k_\perp^2+\eta^2} - \frac{1}{(k_\perp - y l_\perp)^2+\eta^2}\right]^2\right\}$$

$$\eta^2 = M_{\mu^+\mu^-}^2 - (1-y)$$

$$\phi(l_\perp, x_2, b) = C_1 \left(Q_s^2(x_2)/l_\perp^2\right)^{1-\lambda_0}\left[\ln \frac{l_\perp^2}{Q_s^2(x_2)} + C_2\right]$$

A-dependence $A^1 A^{-\lambda_0/3}$ related to $k_\perp$-dependence

$\uparrow$ shadowing

Summary

M-V or Semiclassical Saturation

Probably dominates central region in Au-Au collisions at RHIC

Gluons $k_\perp \lesssim Q_s$ in condensate $f_g \sim 1/\alpha$

Gluons <u>not</u> shadowed. Gluons are classical.

Quarks are quantum and shadowed. No leading twist shadowing.

M-V + BFKL

BRAMS data suggests BFKL evolution important at forward rapidity regions

Now leading twist gluon (and quark) shadowing in scaling region, intimately related to saturation.

High p_T experimental results @ RHIC:

Au+Au, d+Au, p+p collisions at $\sqrt{s}$ = 200 GeV

RIKEN/BNL Research Center Workshop
"High p_T physics at RHIC"

Brookhaven National Lab, NY, Dec. 2, 2003

David d'Enterria
Nevis Labs, Columbia University, NY

Overview

1. Introduction:
   - Study of QCD media (QGP, CGC) via hard scattering processes.
2. High p_T results (Au+Au vs. p+p):
   - dN/dp_T (light quarks u,d,s):
     - Suppression of hadron spectra: p_T, $\sqrt{s}$, centrality, & rapidity dependence.
     - "Anomalous" hadron composition (p_T = 2 – 4 GeV/c): baryon enhancement.
   - dN/dp_T (heavy quark: c): Unsuppressed open charm spectra.
   - $dN_{pair}/d\varphi$ azimuthal anisotropies:
     - Strong collective behaviour: large elliptic flow.
     - Disappearance of jet signals: reduced away-side dijet correlations.
4. High p_T results in d+Au ("control" experiment):
   - dN/dp_T:
     - "Cronin-like" enhancement at y = 0, and suppression at y ≈ 3.
     - p_T, centrality, and particle species dependence.
   - $dN_{pair}/d\varphi$: jet-like azimuthal anisotropies.
5. Data vs. theory.
6. Summary

... plus my (personal) list of selected exp./phenom. "issues"

Hard scattering in A+A collisions

Initial-state effects:

p_T broadening:
("Cronin enhancement")
Soft & semi-hard extra k_T

[Experimental handle: p,d+A]

Leading-twist shadowing
(modified nuclear PDF)
OR
Gluon saturation in the
highly non-linear regime
of small-x

[Experimental handle: e+A, p,d+A]

Final-state effects:

medium-induced
parton energy loss:

gluon bremsstrahlung
("jet quenching")

[Experimental handle: A+A]

possible hadronic
rescattering
(after/before
hadronization ?)

- Study mods. of high p_T hadroproduction in A+A with respect to p+A and p+p (incl. spectra, azim. correlat., partic. composition) to learn about QCD many-body dynamics:
  - "Quark Gluon Plasma" (A+A final-state) and
  - "Color Glass Condensate" (A initial-state).

Summary (I)

- Vast amount of high p_T data: dN/dp_T, $dN/d\varphi$ for many different species ($h^{\pm}, \pi^0, K^0_s, \bar{p}, p, \bar{\Lambda}, \Lambda, e^{\pm}$ ...) and diff. centrality classes, in Au+Au, d+Au, and p+p collisions @ $\sqrt{s}$ = 200 GeV

- Central Au+Au collisions :

  - ★ Strong suppression (factor ~ 4-5) of all u,d,s hadrons (with respect to N_{coll} scaling) above p_T~ 5 GeV/c.
  - ★ Flat and universal (pid-wise) p_T dependence of suppression >5 GeV/c.
  - ★ Very different behaviour than at lower $\sqrt{s}$ ("Cronin" enhancement).
  - ★ Smooth centrality dependence of suppression (weak N_{part} scaling).
  - ★ "Anomalous" particle composition at intermediate p_T~2-5 GeV/c: baryon/meson ≈ 0.8 ratio >> baryon/meson ≈ 0.2 in p+p and e^+e^-.
  - ★ Same suppression at y ≈ 0 and y ≈ 2.
  - ★ No suppression of charm mesons observed (within exp. uncertainties).
  - ★ Strong elliptic flow signal (early collective rescattering).
  - ★ Jet-like signal in near-side azimuthal correlations.
  - ★ Disappearance of jet away-side azimuthal correlations.

Summary (II)

- **Peripheral Au+Au collisions:**
  - ★ Within errors, behave effectively as p+p collisions plus N_{coll} scaling (expected pQCD behaviour) for all species and for all observables.
- **d+Au collisions:**
  - ★ No suppression observed (min.bias, central d+Au, "p"+Au) at y = 0.
  - ★ Cronin-like enhancement for π^0 (small) and $h^{\pm}$ (larger) at y = 0.
  - ★ Opposite behaviour of the centrality dependence of high p_T production compared to Au+Au (y=0).
  - ★ No dissapearance of away-side dijet correlations.
  - ★ Factor ~2 suppression observed at forward rapidities $y \approx 3$.
- **Data vs. theory:**
  - ★ pQCD-based final-state parton energy loss ("QGP") models are clearly consistent with Au+Au, d+Au data at y=0 (though non-perturbative effects, e.g. quark recombination, are needed at intermediate p_T).
  - ★ Gluon saturation ("CGC") effects may start to show up clearly at forward rapidities in d+Au (first insight of pQCD factorization breakdown at small-x ?)

The wealth of (high quality) high p_T data at RHIC is at the root of the most significant advances in the knowledge of Quantum Chromo Dynamics in years !

Spin Physics

Marco Stratmann

Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

We review how RHIC is expected to deepen our understanding of the spin structure of longitudinally and transversely polarized nucleons. After briefly outlining the current status of spin-dependent parton densities and pointing out open questions, we focus on theoretical calculations and predictions relevant for the near-term goal of the RHIC spin program: a first determination of Δg from single-inclusive hadron and jet production. Results from PHENIX and STAR for the unpolarized transverse momentum spectrum of neutral pions for central and forward rapidities, respectively, turn out to be in excellent agreement with perturbative QCD. This is of outmost importance for upcoming polarized measurements. First preliminary results from PHENIX, which may point towards a negative double spin asymmetry for π^0 production at moderately large transverse momenta, will be discussed in some detail.
Finally, we turn to the spin physics program with transverse polarization. Here, in particular measurements of sizable single transverse spin asymmetries A_N, also for the first time at a $\sqrt{S}$ of 200 GeV by the STAR Collaboration, have sparked a lot of theoretical activities recently, which will be further discussed in other talks during this workshop.

II. Spin Physics at RHIC

starting point: universality of parton densities

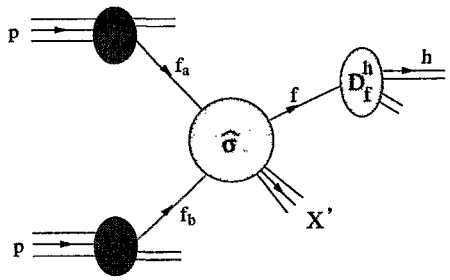
· foundation of predictive power of perturbative QCD

· makes notion of "nucleon structure" meaningful

factorization @ work: high-p_T processes

Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.; ...

e.g., high-p_T single-inclusive hadron production



long-distance

from exp.; μ-dep.: $d\sigma/d\mu = 0$ (pQCD)

$$\frac{d\sigma^{pp\to\pi X}}{d\mathcal{P}} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, f_a(x_a,\mu_f)\, f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu_{f'}) \times \frac{d\hat{\sigma}^{ab\to cX'}}{d\mathcal{P}}(x_aP_a, x_bP_b, P^{\pi}/z_c, \mu_f, \mu_{f'}, \mu_r) + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

short-distance

calculable in pQCD: power series in α_s

power corr.

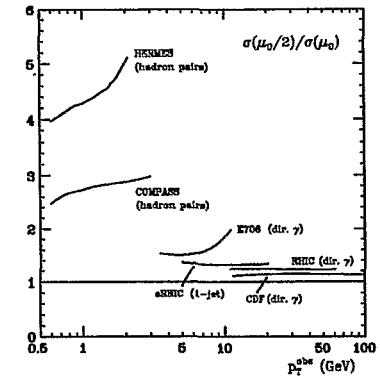
neglected

· $\mathcal{P}$: appropriate set of kin. variables $(p_T, y, \ldots)$

· arbitrary scales $\mu_{f,f',r}$: separate long- and short-dist. physics

QCD in a collider environment: many advantages ...

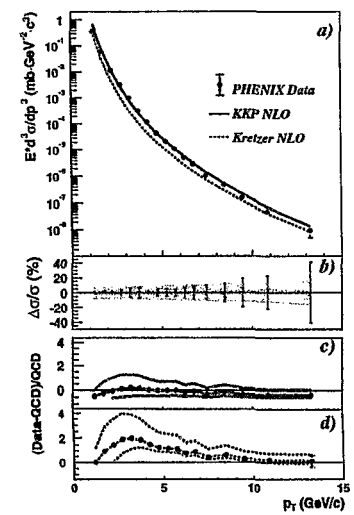
- large c.m.s. energy → high p_T accessible
  - · domain of perturbative QCD: $\alpha_s(\mu_r \simeq p_T) \ll 1$
  - · scale dependence ↔ reliability of pQCD calc.:



ratios of "x-secs" for two choices of μ_f

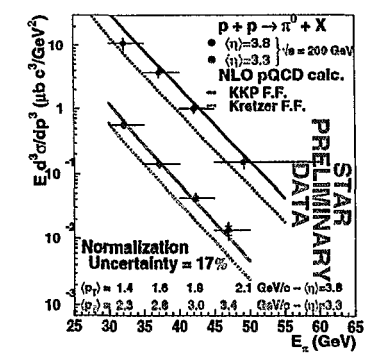
← should be $\simeq 1$

- a success story in describing *unpolarized* collisions



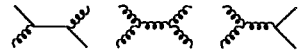
1st examples from RHIC:

high p_T pion production



agrees well with NLO pQCD

Processes one-by-one

- **high-p_T hadrons:** 

NLO: Jäger, MS, Schäfer, Vogelsang; de Florian

recall: · unpol. measurements agree well with pQCD

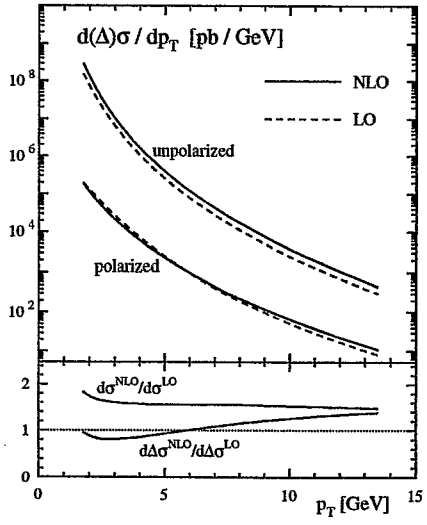
· $D^\pi(z)$ set of Kniehl, Kramer, Pötter favored

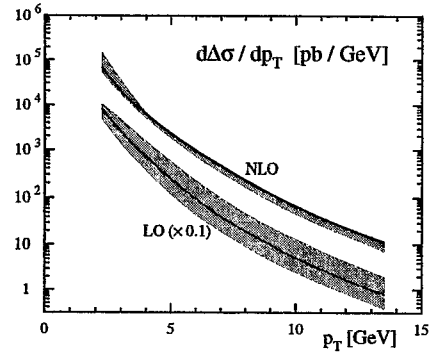
→ exciting prospects for polarized measurement

results: · $d(\Delta)\sigma^{NLO}/d(\Delta)\sigma^{LO}$ reasonably small

· theor. uncertainties much reduced in NLO

π^0-production, $\sqrt{S} = 200$ GeV, $|\eta| \leq 0.38$

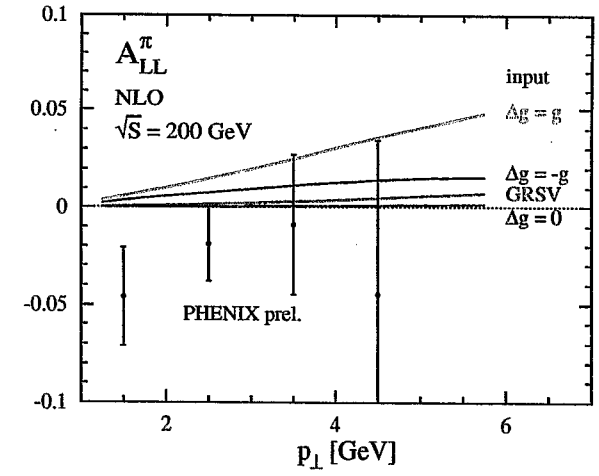




[figs. taken from Jäger et al.]

exciting development: first prel. results by PHENIX

[pol. scaling error (~ 30%) not included]



⟵ expectations for Δg inputs allowed by $|\Delta g| \leq g$

naive analysis:

partonic spin asymmetries:

$$gg \to gg \quad \hat{a}_{LL} > 0$$
$$gg \to q\bar{q} \quad \hat{a}_{LL} - 1$$
$$gq \to gq \quad \hat{a}_{LL} > 0$$

$\langle z \rangle = 0.3 \div 0.4$ where $D_q^\pi > D_g^\pi$

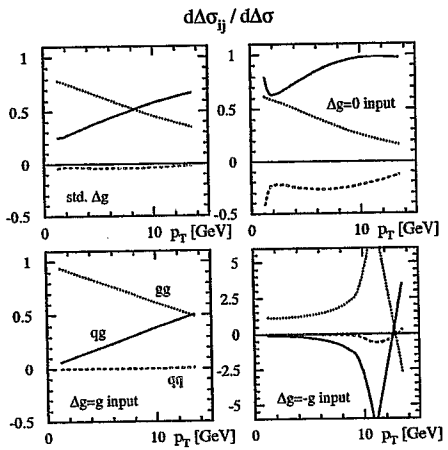
→ conclude: $gg \to q\bar{q}$ resp. for neg. A_{LL}^π

but

$\Delta\hat{\sigma}_{gg\to gg} \simeq 160\, \Delta\hat{\sigma}_{gg\to q\bar{q}}$!! (for $\eta \simeq 0$)

a closer look: can A_{LL}^{π} be negative?

Jäger, Kretzer, MS, Vogelsang



subprocess contrib.:

gg process dominates for $p_T \lesssim 10$ GeV

qg process takes over for $p_T \gtrsim 10$ GeV

qq channel always small

take $x_T^2 \equiv 4p_T^2/S$ moments of η-integrated $d\Delta\sigma$:

$$\Delta\sigma^{\pi}(N) = \left(\Delta g^{N+1}\right)^2 \underset{gg}{\mathcal{A}^N} + 2\Delta g^{N+1} \underset{qg}{\mathcal{B}^N} + \underset{qq}{\mathcal{C}^N}$$

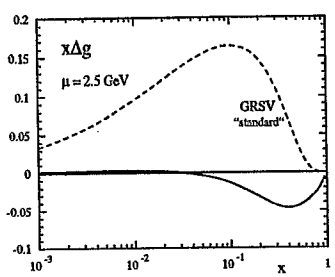
$$\text{minimize}: \quad \Delta\sigma^{\pi}(N)\Big|_{\text{min}} = -\frac{\left(\mathcal{B}^N\right)^2}{\mathcal{A}^N} + \mathcal{C}^N$$

$\rightarrow$ negative, but tiny lower bound $A_{LL}^{\pi}\big|_{\text{min}} \simeq \mathcal{O}(-10^{-3})$

resulting Δg:

node! $\rightarrow \Delta g(x_a)\Delta g(x_b) < 0$

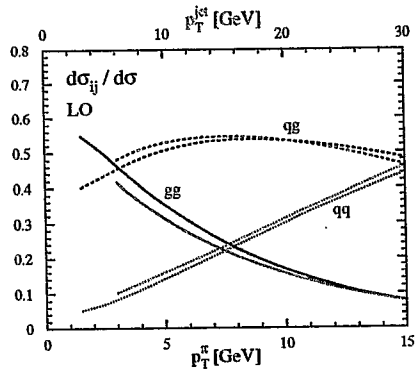
confirmed by full "global analysis"



• high-p_T jets:

NLO: de Florian, Frixione, Signer, Vogelsang; Jäger, MS, Vogelsang

proceeds through the same subprocesses as π-production



π's have roughly $\langle z \rangle \simeq 0.5$:

π with $p_T \simeq$ jet with $2p_T$

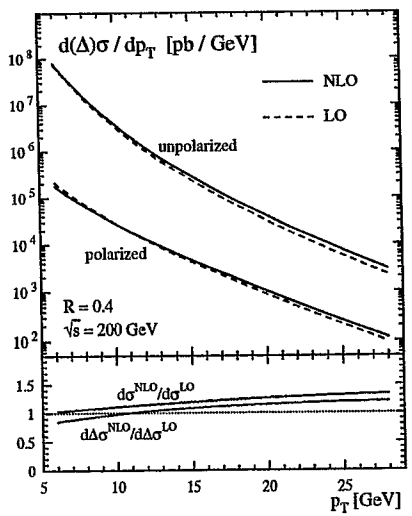
$\rightarrow$ jet and π results similar

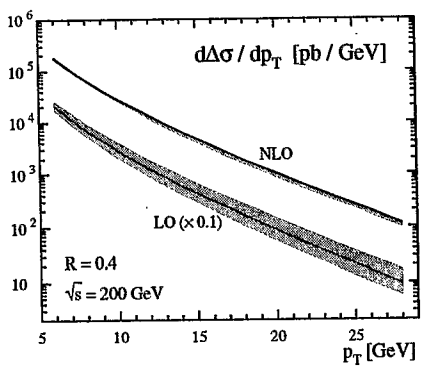
advantages of jets:

- much higher rates
- no uncertainties from $D(z)$

results: theor. uncertainties even smaller than for hadrons

$$\sqrt{S} = 200\text{ GeV},\ R_{\text{cone}} = 0.4\ (\text{SCA}),\ |\eta| \leq 1$$

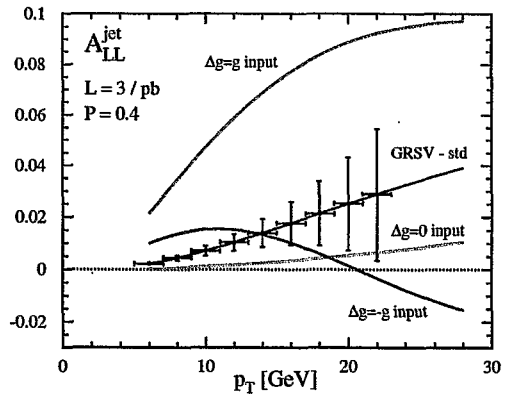




[figs. taken from Jäger, MS, Vogelsang]

expectations for STAR :

$\sqrt{S} = 200$ GeV, $R_{\text{cone}} = 0.4$ (SCA), $0 \leq \eta \leq 1$



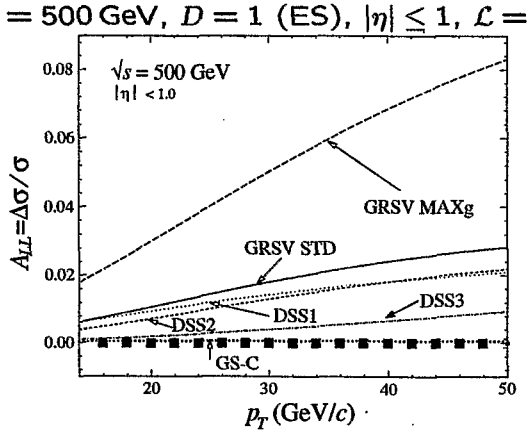
[fig. taken from Jäger, MS, Vogelsang]

estimate of statistical errors: $\delta A \simeq \frac{1}{P_1 P_2} \times \frac{1}{\sqrt{\mathcal{L}\sigma_{\text{bin}}}}$

[with $P_1 = P_2 = 0.4$ (beam pol.) and $\mathcal{L} = 3$ pb^{-1}]

and in the long run:

$\sqrt{S} = 500$ GeV, $D = 1$ (ES), $|\eta| \leq 1$, $\mathcal{L} = 800$ pb^{-1}



[fig. taken from de Florian, Frixione, Signer, Vogelsang]

summary on inclusive jets and hadrons:

- excellent near-term prospects for a first determination of Δg
- important: unpolarized "benchmark x-secs" so far in perfect agreement with pQCD [even down to unexpectedly small p_T]
- first exciting results from PHENIX

  if large & negative A_{LL} persists: new spin surprise; effect due to intr. k_T or ?

  important to collect more data soon

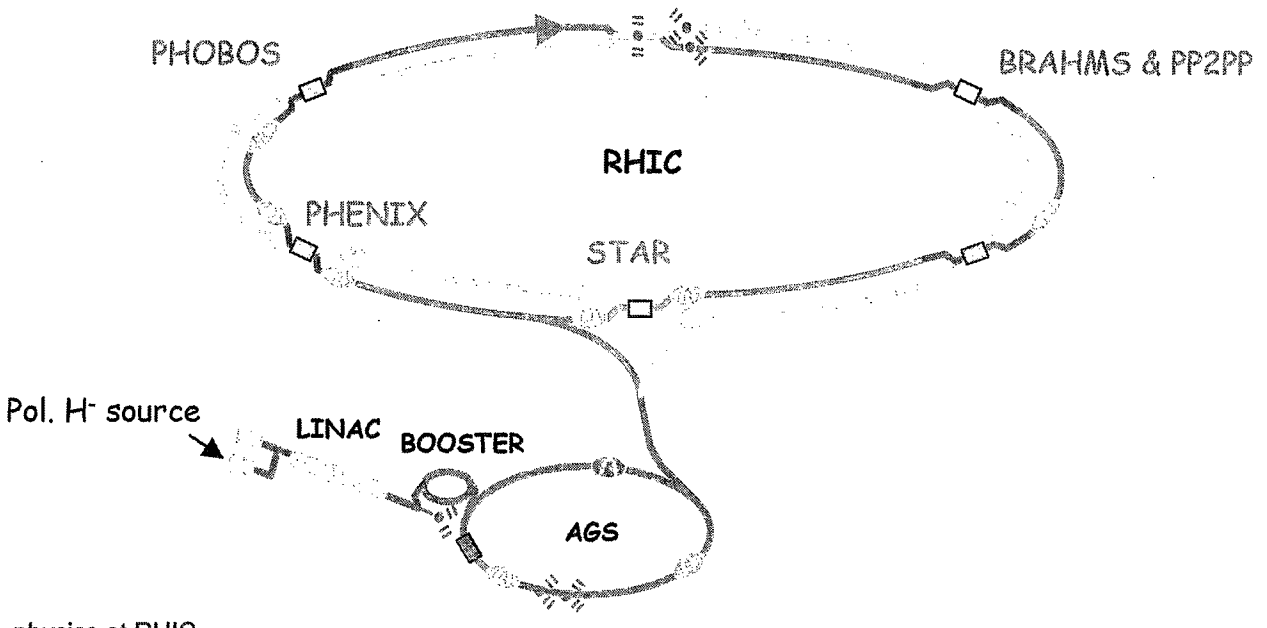
long-term goals:

need much higher luminosities and/or $\sqrt{S} = 500$ GeV

- prompt photons: cross-check of Δg results
- heavy flavors: extend Δg to smaller x
- $W^{\pm}$ bosons: further information on $\Delta q, \Delta\bar{q}$

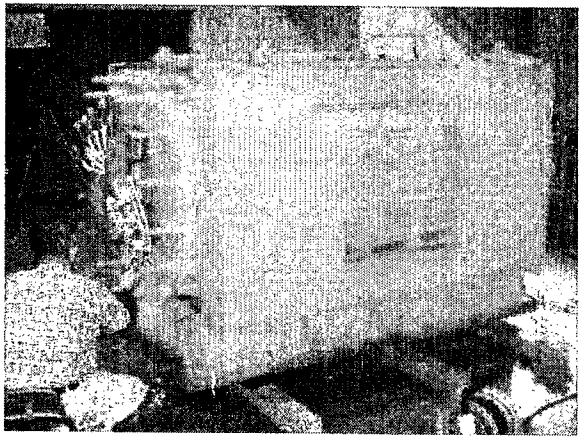
Experimental aspects of the RHIC spin program

Bernd Surrow
BNL



Polarized proton collider

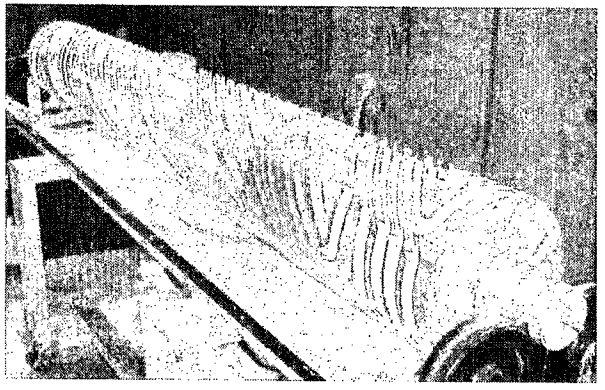
- Overview of commissioning status
  - Commissioning status:
  - ☑ Siberian snake and spin rotator magnets successfully commissioned
  - ☑ Fast polarimeters in AGS/RHIC demonstrated to work
  - ☑ Spin transfer AGS to RHIC demonstrated to work
  - ☐ Installation and commissioning of AGS partial snake magnets
  - ☐ Commissioning of polarized gas jet target (⇨ Absolute polarization measurement!)
  - ☐ Commissioning of 250GeV ramp
  - ☐ Adequate time for commissioning and luminosity development...!



⇨ 5 % helical snake build at Tokana Industries funded by RIKEN (Just arrived at BNL!). Installation: Jan. 2004!

RHIC SPIN effort is in the beginning of its multi-year program!

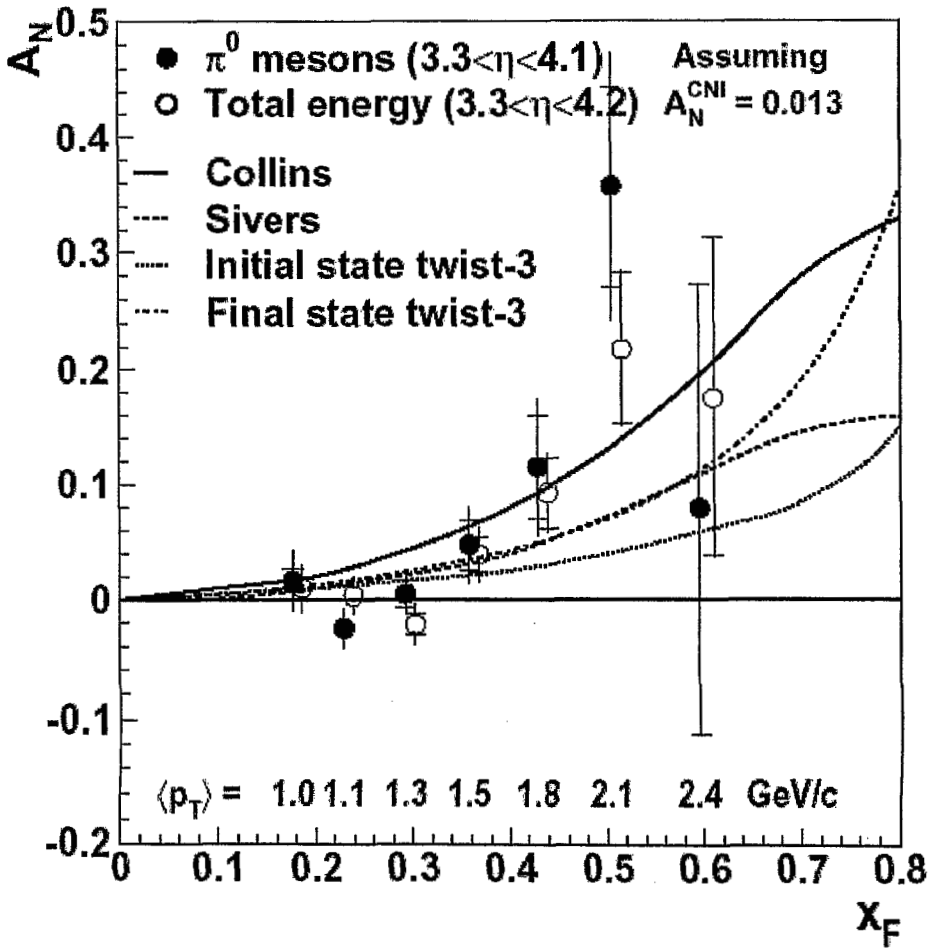
- Warm snake avoids polarization mismatch at AGS injection and extraction
- Cold strong snake eliminates all depolarizing resonances in AGS



⇨ 30% s.c. helical snake build at SMD (AIP)
Installation: Oct. 2004!

First results (STAR)

- First measurement of A_N for forward π^0 production at RHIC



- A_N is found to increase with energy similar to E704 result ($\sqrt{s}$ = 20 GeV (10 X smaller than at RHIC), 0.5 < p_T < 2.0 GeV)
- This behavior is also seen by several models which predict non-zero A_N values
- Several approaches beyond the basic "naive QCD calculations" yield non-zero A_N values at RHIC energies:
  - ⇨ Sivers: include intrinsic transverse component, $k_\perp$, in initial state (orbital momentum) (before scattering takes place)
  - ⇨ Collins: include intrinsic transverse component, $k_\perp$, in final state (transversity) (after scattering took place)
  - ⇨ Qiu and Sterman (Initial-state twist-3)/Koike (final-state twist-3): more "complicated QCD calculations" (higher-twist, multi-parton correlations)

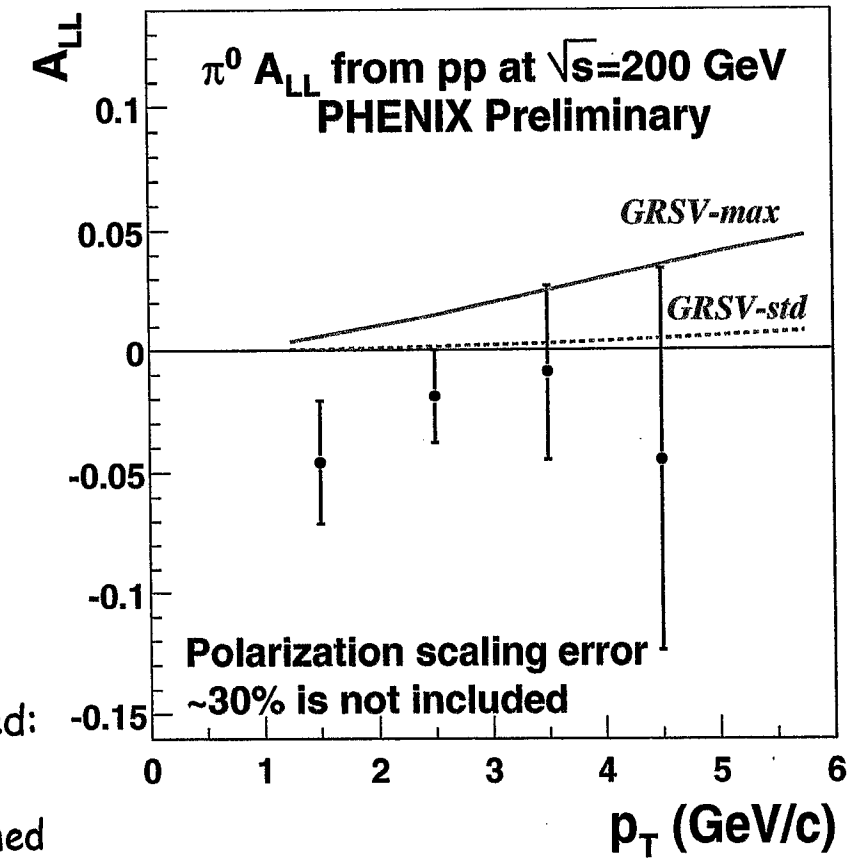
STAR collaboration, hep-ex/0310058, submitted to Phys. Rev. Lett.

First results (PHENIX)

- First measurement of A_{LL} at RHIC for inclusive π^0 production

p_T GeV/c	$A_{LL}^{\pi 0+bck}$ (r_{bck})	A_{LL}^{bck}	$A_{LL}^{\pi 0}$ (Background subtracted)
1-2	-0.028±0.012 (45%)	-0.006±0.014	-0.046±0.025
2-3	-0.022±0.015 (17%)	-0.035±0.027	-0.019±0.019
3-4	-0.002±0.033 (7%)	0.094±0.092	-0.009±0.036
4-5	-0.023±0.074 (5%)	0.38±0.24	-0.045±0.079

Luminosity: 0.215 pb^{-1}, Average polarization: 26%

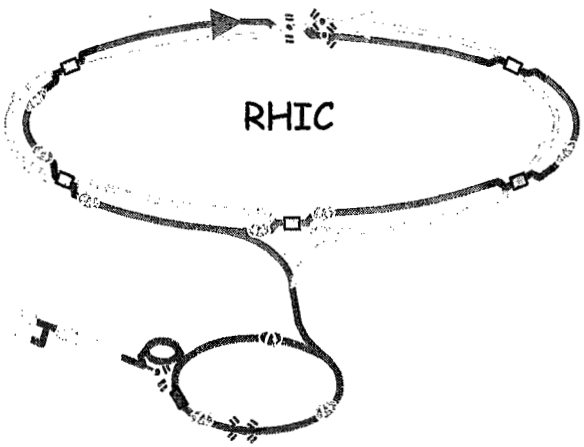


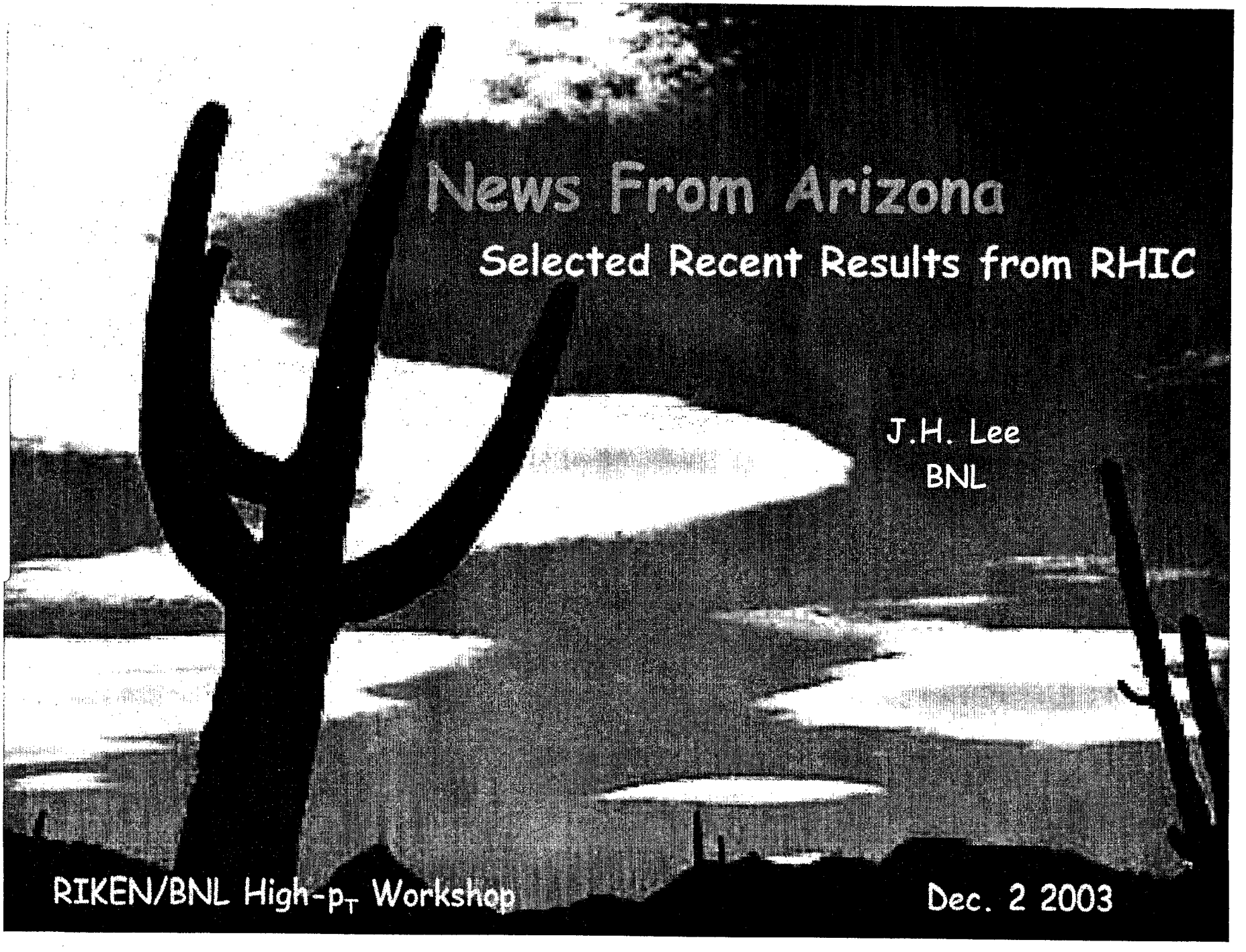
- Polarization scaling error $\delta P/P$ ~30% is not included:
  - Enters A_{LL} in quadrature
  - Analyzing power A_N(100 GeV) = A_N(22GeV) is assumed
  - $\delta P/P$ ~ 30%: combined stat. and sys. error for A_N(22GeV) (AGS E950)
- Relative luminosity contribution to π^0 A_{LL} error is < 0.2%
- p_T smearing correction is not included

More data needed!

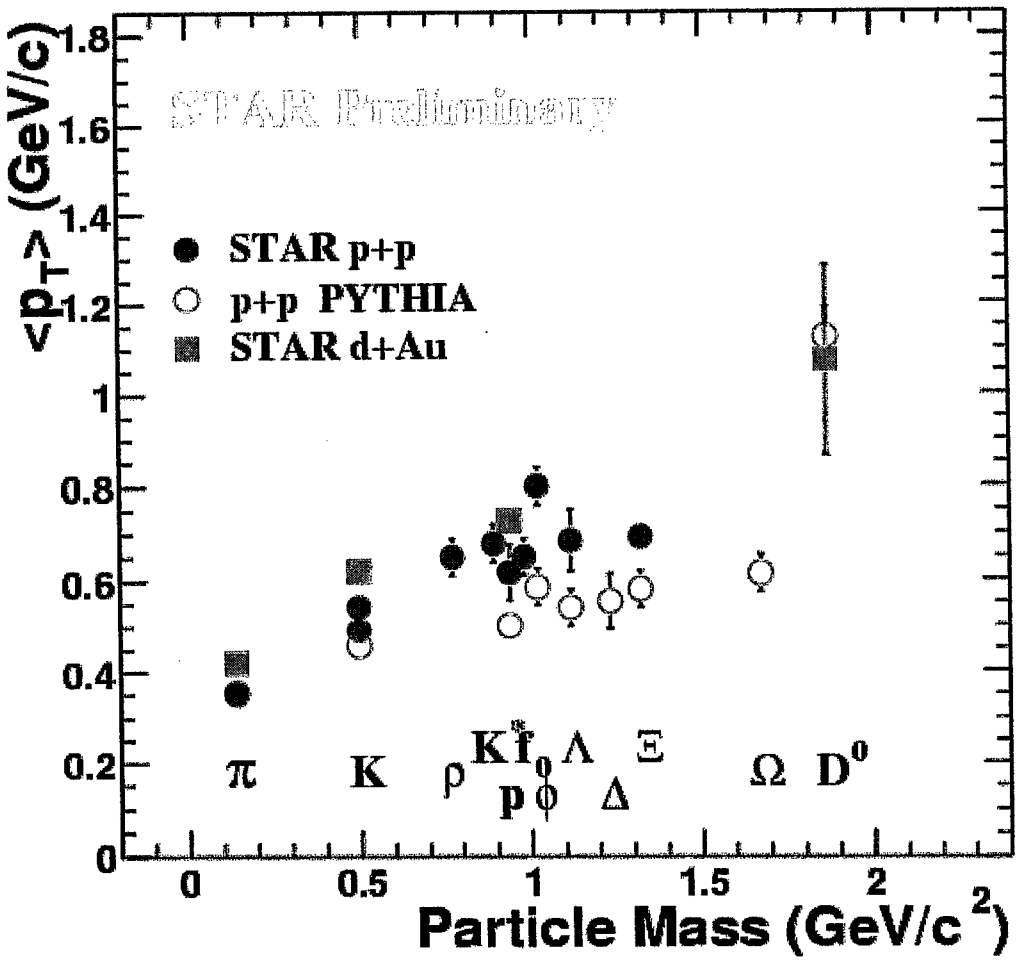
Summary and Outlook

- RHIC Spin program at BNL
  - First successful polarized proton collisions ever at RHIC (transverse and longitudinal)
  - Successful upgrade and commissioning of various new STAR/PHENIX components for the first polarized proton run at RHIC
  - First measurement of A_N for forward π^0 production at STAR and A_N for forward neutron production at PHENIX (and PHENIX-IP12)
  - First measurement of A_{LL} (Inclusive pion production - PHENIX) and STAR analysis for inclusive jets in preparation
  - Unique opportunity to explore the spin structure and dynamics of the proton in a new unexplored regime at RHIC over the next years:
    - Transverse spin dynamics and transversity
    - Gluon polarization
      - Short-term: PHENIX (Pion production) and STAR (Inclusive jet production)
      - Long-term: Prompt photons and heavy quark production
    - Flavor decomposition (W production)
  - This requires various accelerator, polarimeter and detector components to be completed and upgraded! (High polarization and luminosity ⇨ Frequent pp running and development crucial!)




News From Arizona
Selected Recent Results from RHIC
J.H. Lee
BNL
RIKEN/BNL High-p_T Workshop
Dec. 2 2003

D^0 Mean Transverse Momentum



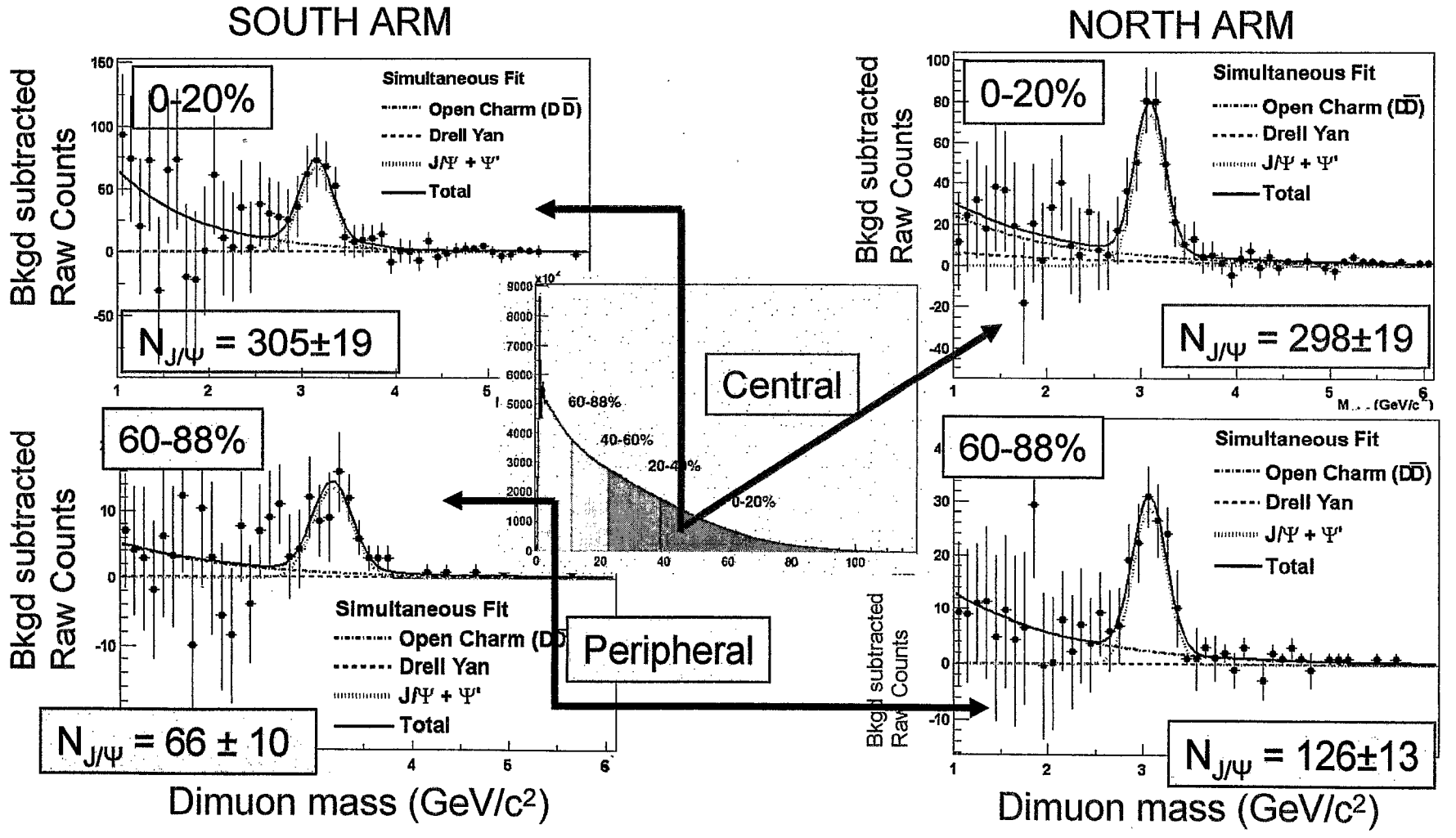
- $\langle p_T \rangle$ = 1.073 ± 0.170 (stat.) ± 0.121 (sys.) GeV/c
- Relatively large mean p_T for D^0 in both p+p pythia calculations and d+Au measurements
- D^0 might be produced from gluon fusion

J/Ψ->μ+μ- in d+Au Collisions

- PHENIX Centrality selected raw dimuon mass distributions

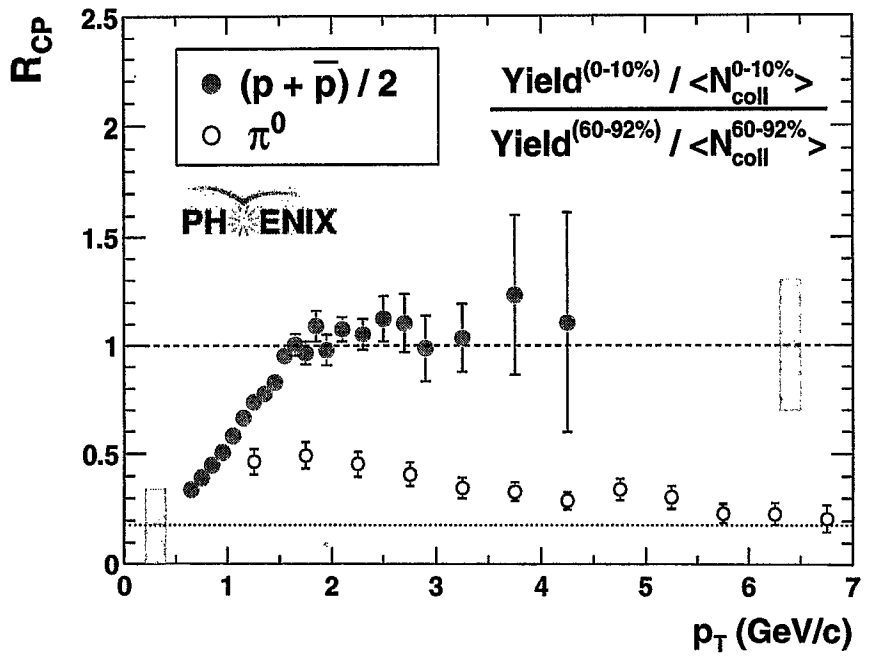
Signal to background and fitting of all contributions are currently under study

Not corrected for efficiency and acceptance

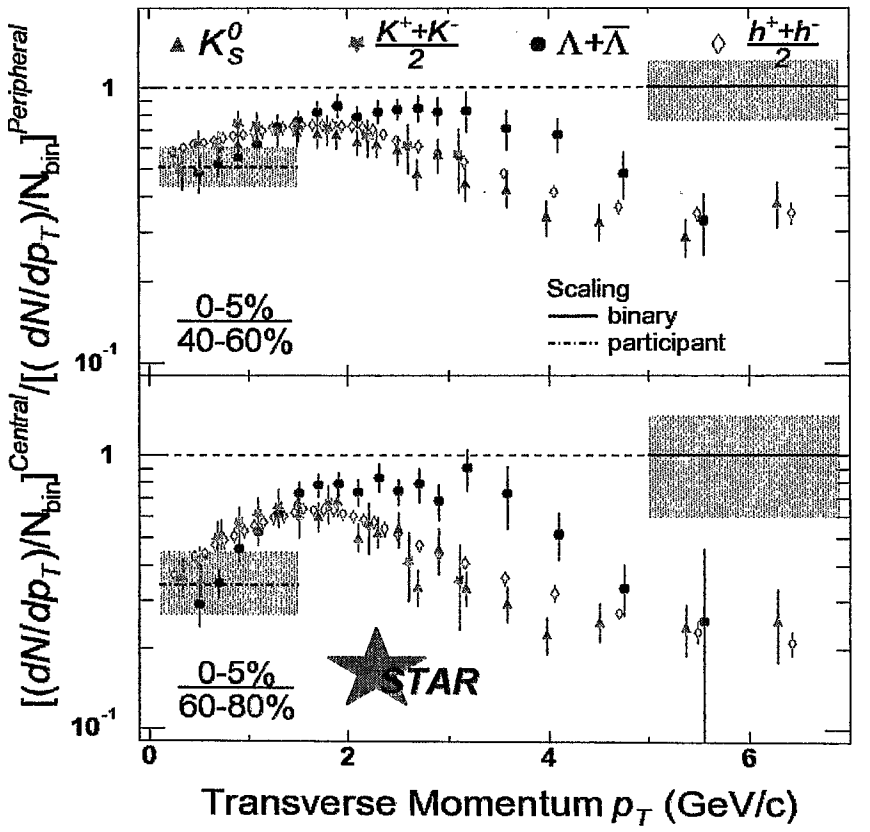


Baryons vs. mesons

PHENIX: PRL 91, 172301

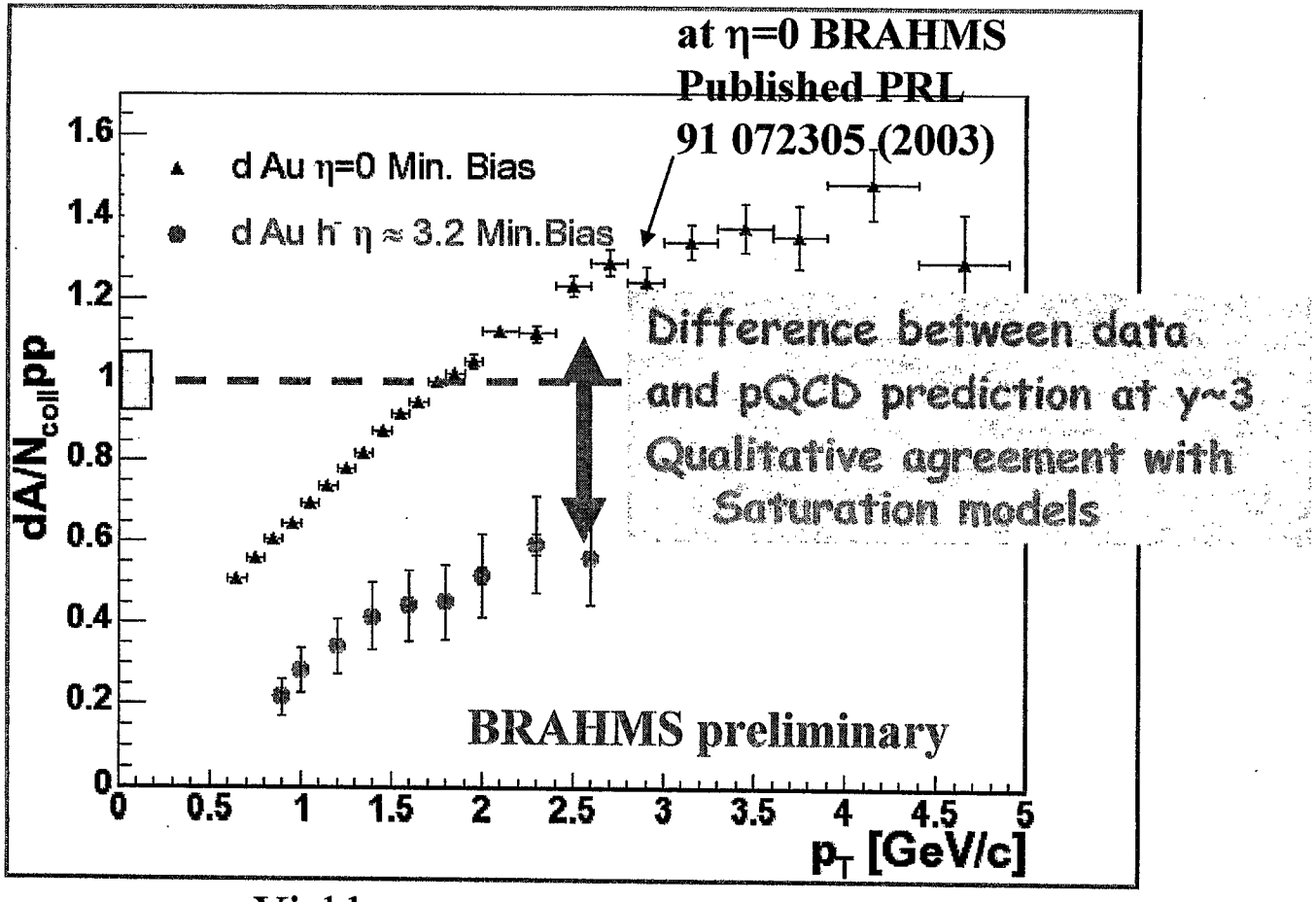


STAR: nucl-ex/0306007



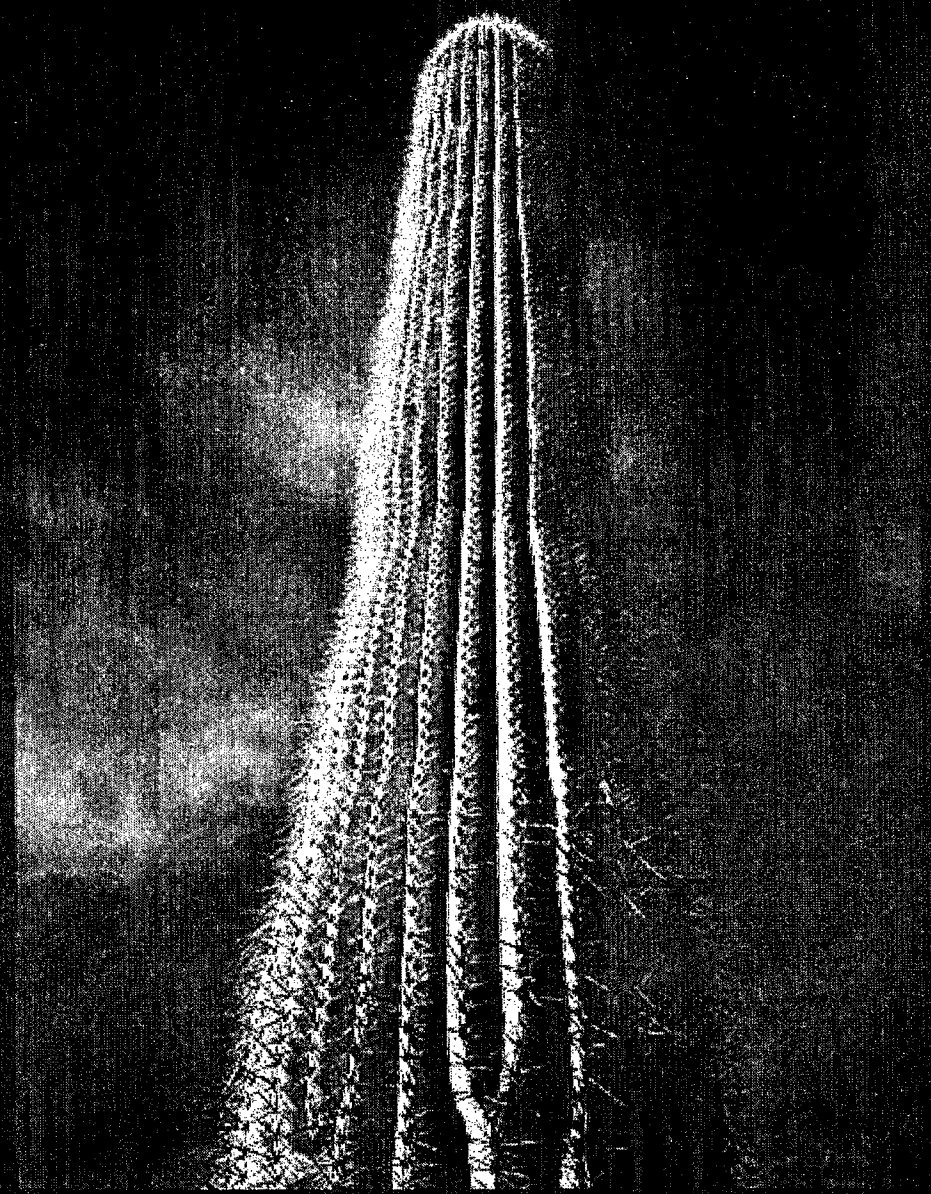
Significant proton-pion and lambda-kaon differences, but the "baryon enhancement" ends by $p_T \sim 5$-6 GeV/c

d-Au Nuclear Modification factor at η ~3.2 h^- for minimum-bias events



$$R_{dAu} = \frac{\text{Yield}_{dAu}}{\langle N_{coll} \rangle_{dAu} \text{Yield}_{pp}}$$

$\langle N_{coll} \rangle_{dAu}$ calculated for BRAHMS min-bias : 7.2



Summary

- Selected Latest results from RHIC
- Rich structure and data in p_T and y
- More data shown on high-p_T suppression due to final state effect at y~0
- Universal attenuation at higher-p_T (>~6GeV/c)?
- Is the initial state effects enhanced and seen at forward?
- Exciting rare probe physic to come

Lattice Gauge Theory and Heavy Ion Collisions

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SUMMARY

We discuss lattice results on the QCD transition from hadronic matter to the quark gluon plasma and point out where lattice calculations can provide input to the interpretation of heavy ion collisions.

In particular, we discuss the role of resonances for the occurrence of the transition to the quark-gluon plasma in hot and dense matter. Properties of a hadronic resonance gas are compared to lattice results on the equation of state at zero as well as non-zero baryon chemical potential. We also show that the quark mass dependence of the transition temperature can be understood in terms of lines of constant energy density in a resonance gas.

Furthermore, we discuss recent advances in calculating thermal properties of light and heavy quark bound states. In particular, we discuss the dissolution of heavy quark bound states in the plasma phase and stress the existing discrepancies between lattice and HTL calculations of the thermal dilepton rate.

Finally we discuss prospects for performing lattice calculations with a realistic quark mass spectrum on the next generation of special purpose computer designed for lattice QCD calculations in Europe (apeNEXT) and the US (QCDOC).

Lattice Gauge Theory and Heavy Ion Collisions

– exploring the properties of hot and dense matter

– testing QCD in extreme conditions

Quark gluon plasma

What are the properties of this new form of matter?

(equation of state, screening)

Critical behavior in dense matter

What are the critical parameter of the transition to the QGP?

$$(T_c(\mu), \epsilon_c)$$

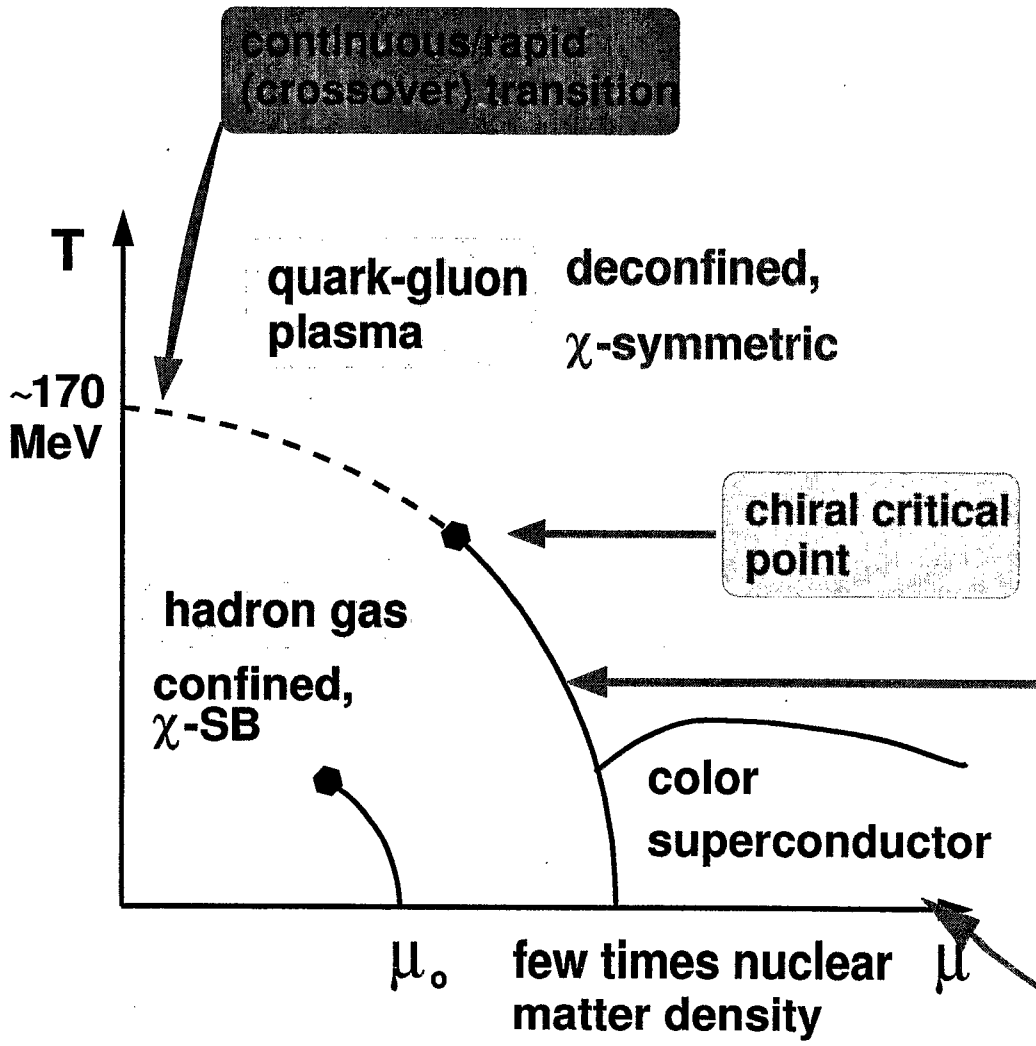
Dense hadron gas

What happens to resonances in a dense hadronic gas?

$$(m_H(T,\mu), \Gamma(T,\mu))$$

decreasing temperature and/or density

Critical behavior in hot and dense matter: phase diagram



continuous transition for small chemical potential and small quark masses at

$$T_c \simeq 170\, MeV$$
$$\epsilon_c \simeq 0.7\, GeV/fm^3$$

2nd order phase transition; Ising universality class

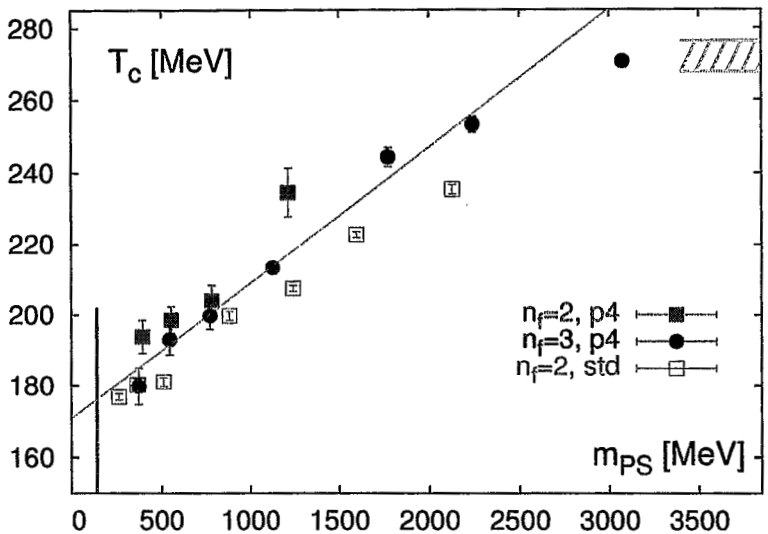
$T_c(\mu)$ under investigation

1st order phase transition ???

expected - however, so far no direct evidence from lattice QCD

attractive 1–gluon exchange => qq–condensates

Critical temperature, equation of state and the resonance gas



$$n_f = 2: \quad \epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$
$$n_f = 0: \quad \epsilon_c \simeq (0.5 - 1)\, T_c^4$$
$$\simeq (0.3 - 0.7)\, GeV/fm^3$$

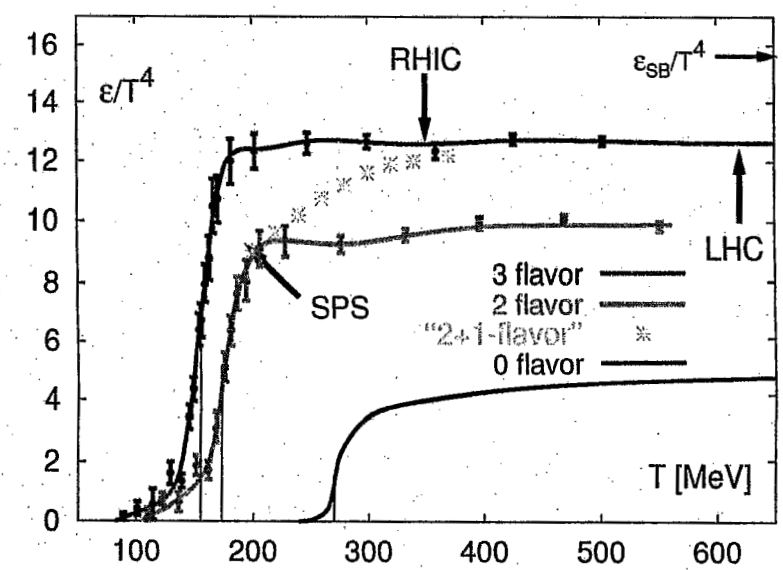
change in ϵ_c/T_c^4 compensated by shift in T_c
transition sets in at similar energy densities
$\Rightarrow$ percolation

$\Leftarrow$ understood in terms of an exponentially rising energy spectrum for string fluctuations:

$$\frac{T_c}{\sqrt{\sigma}} \simeq \sqrt{\frac{3}{(d-2)\pi}}$$

$\Rightarrow$ resonance gas

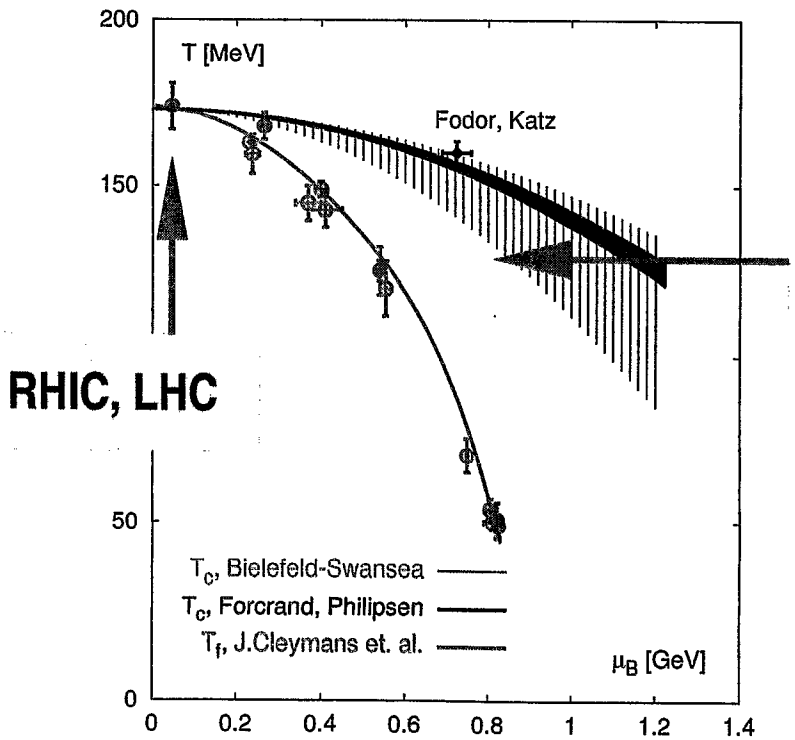
energy density for 0, 2 and 3-flavor QCD



Extending the phase diagram to non-vanishing chemical potential

non-zero baryon number density: $\mu > 0$

$$Z(V,T,\mu) = \int \mathcal{D}\mathcal{A}\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{e}^{-S_E(V,T,\mu)}$$
$$= \int \mathcal{D}\mathcal{A}\mathcal{D}\ det\ M(\mu)\ \mathrm{e}^{-S_E(V,T)}$$



$\frac{T_c(\mu)}{T_c(0)}$: $1 - 0.0056(4)(\mu_B/T)^2$

deForcrand, Philipsen (imag. μ)

GSI future $1 - 0.0078(38)(\mu_B/T)^2$

Bielefeld-Swansea

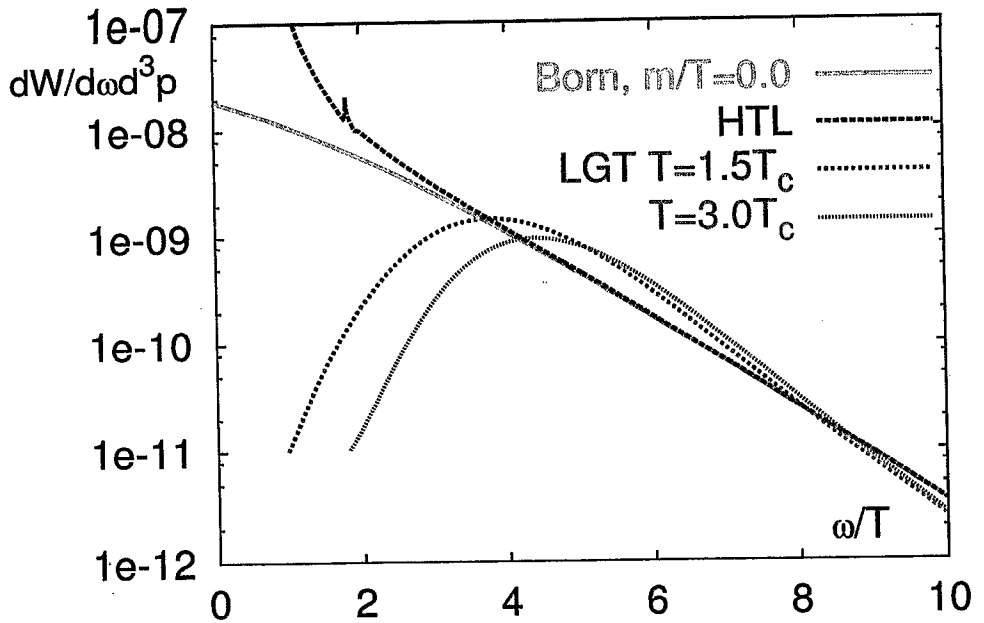
($\mathcal{O}(\mu^2)$ reweighting)

chiral critical point

$(T_c, \mu_c) \simeq (160(4)\ MeV, 725(35)\ MeV)$

Fodor, Katz (exact determinants $\Rightarrow$ small lattices)

Dilepton rate: HTL and lattice calculations



thermal dilepton rate

$$\frac{dW}{d\omega d^3p} = \frac{5\alpha^2}{27\pi^2}\frac{\sigma_V(\omega,\vec{p},T)}{\omega^2(e^{\omega/T}-1)}$$

HTL and lattice disagree for: $\omega/T \lesssim (3-4)$

- infra-red sensitivity of HTL-calculations $\Leftrightarrow$ "massless gluon" cut in HTL-propagator
- infra-red sensitivity of lattice calculations $\Leftrightarrow$ thermodynamic limit, $V \to \infty$
- $VT^3 = (N_\sigma/N_\tau)^3 < \infty \quad \Rightarrow \quad$ momentum cut-off: $p/T > 2\pi N_\tau/N_\sigma$

$\Rightarrow$ need large lattices to analyze infra-red regime

$\Rightarrow$ in future also thermal photon rates

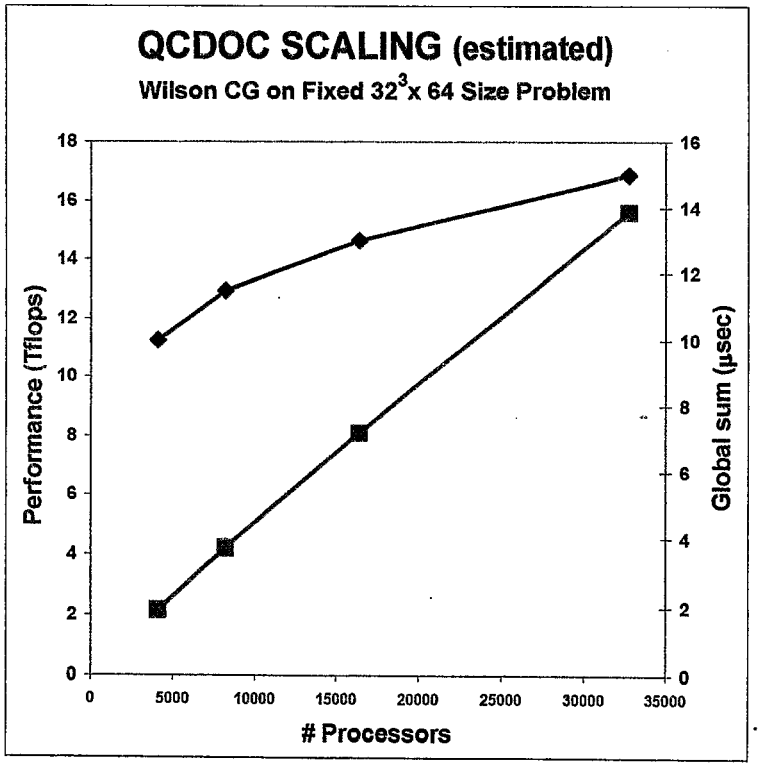
Outlook: Next generation lattice calculations

- Thermodynamics of pure gauge theory has been "solved" on (1-10)GFlops computers (1996)
- Thermodynamics of QCD with "still too heavy" quarks has been studied on (10-100) GFlops computers
- Analysis of "continuum and thermodynamic limit" of QCD thermodynamics with light quarks, requires computers with $\sim$10 TFlops peak speed.(LatFor, 2003)

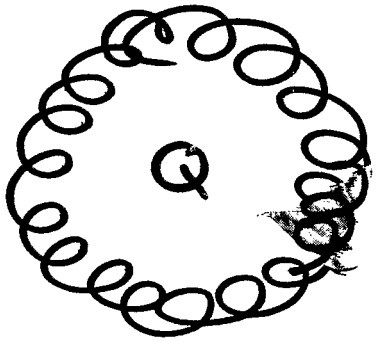
QCDOC and apeNEXT:

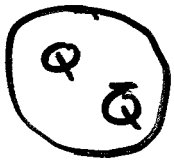
scaling to 10's of Teraflops

with $1/MFlops Cost/performance



Production of Heavy Hadrons and Quarkonium





Eric Braaten

Ohio State University

1. New discoveries in Spectroscopy
2. Inclusive production of Quarkonium
3. Inclusive production of Charm Hadrons

New Discoveries in Spectroscopy

Charm mesons

$c\bar{s}$	2317, 2460 MeV	BABAR, CLEO, BELLE

Charmonium

$\eta_c(2S)$	3628 MeV	BELLE, BABAR
X	3870	BELLE, CDF

Bottomonium

$\Upsilon(1D)$	10162 MeV	CLEO

Doubly-charmed Baryons

ccu	3460, 3541, 3780 MeV	SELEX
ccd	3443, 3520	

Inclusive Production of Quarkonium

NRQCD Factorization Formula

Models for Long-distance factors

- Color-singlet
- Color-evaporation
- NRQCD truncated at v^4

Challenges for NRQCD

- hadron colliders
  - polarization at large p_T
  - cross section at low p_T
- e^+e^- colliders
  - momentum distribution
  - double $c\bar{c}$ fraction

Inclusive Production of Charm Hadrons

Factorization "Theorems"

Fragmentation Model

Charm Asymmetries

Previous Models
- Valon recombination
- Intrinsic charm
- String fragmentation (PYTHIA)
- Quark-gluon string
- ⋮

Heavy-quark Recombination

- charm mesons
- charm baryons

Summary

1. New discoveries in Spectroscopy

strange charm mesons
charmonium
bottomonium
doubly-charmed baryons

} new challenges
new opportunities

2. Inclusive production of Quarkonium

C.S.M. RIP

C.E.M. RIP

NRQCD polarization?
double $c\bar{c}$?

3. Inclusive production of Charm Hadrons

Fragmentation Model
cannot explain charm asymmetries

Heavy-quark recombination?

PERTURBATIVE QCD FOR HIGH PT REACTIONS

George Sterman
YITP, Stony Brook

Many of the predictions of perturbative QCD follow from the factorization of long- and short-distance dynamics. The latter may be computed perturbatively, employing the asymptotic freedom of the theory. Such short-distance quantities are said to be infrared safe. Factorization implies the introduction of a momentum scale to separate the long- and short-distance regimes. Other, rapidity-like scales can separate the dynamics of particles mutually receding at light-like velocities. This is the origin of independent jet evolution.

The independence of the cross section from the exact choice of scale implies evolution equations, and the solutions to these equations give resummations of large ratios in physical observables. For example, Sudakov resummations are related to factorizations of short and long distances and of sets of light-like collinear particles.

The limit of narrow jets relates annihilation and inelastic scattering processes with Sudakov resummation. Resummed cross sections can be used to infer the structure of nonperturbative corrections. The application of these ideas to single-particle inclusive hadron production can help explain why higher-order and nonperturbative effects are important at fixed-target energies, yet relatively small at RHIC energies, as observed by the Phenix and STAR Collaborations. The talk presented preliminary work on this issue in collaboration with Werner Vogelsang.

- **Self-consistent recoil in Joint Resummation**

Laenen, GS, Vogelsang

- **Double inverse transform and approximation:**

$$p_T^3 \frac{d\sigma_{ab}}{dp_T} \sim \int_{-i\infty}^{i\infty} dN \int_{-\infty}^{\infty} d^2b\, d^2Q_T\, \mathrm{e}^{i\vec{Q}_T\cdot\vec{b}}$$

$$\times\ \tilde{\sigma}_{ab}^{(0)}(N)\, \mathrm{e}^{E(N,b,p_T)}$$

$$\times \underbrace{\left(\frac{S}{4(\vec{p}_T - \frac{1}{2}\vec{Q}_T)^2}\right)^{N+1}}_{=\left(x_T^2\right)^{-N-1}\, \mathrm{e}^{N\vec{Q}_T\cdot\vec{p}_T/p_T^2}\left(1+\mathcal{O}(1/N,Q_T^2/p_T^2)\right)}$$

- Q_T, b **integrals** (N **imaginary**) $\Rightarrow$

$$p_T^3 \frac{d\sigma_{ab}}{dp_T} \sim \int_{-i\infty}^{i\infty} dN\, \tilde{\sigma}_{ab}^{(0)}(N)\, \left(x_T^2\right)^{-N-1}$$

$$\mathrm{e}^{E\mathrm{thr}(N,p_T)}\ \mathrm{e}^{\delta\, E\mathrm{recoil}(N,p_T)}$$

$$\delta\, E_{\mathrm{recoil(N,p_T)}} = \pi \int_0^{Q^2} \frac{dk_T^2}{k_T^2} \sum_{i=a,b} A_i\left(\alpha_s(k_T^2)\right)$$

$$\left[\left(I_0\left(\frac{Nk_T}{p_T}\right) - 1\right) K_0\left(\frac{Nk_T}{p_T}\right)\right]$$

- **Isolate perturbative recoil; NLL in N:**

$$\delta\, E_{\rm recoil}(N, p_T) = \delta E_{\rm PT} + \delta\, E_{\rm np}$$
$$\delta E_{\rm PT} \propto \frac{\alpha_s(p_T^2/N^2)}{\pi}\,\frac{\zeta(2)}{2}$$

- **isolate low scales $\leftrightarrow$ strong coupling**

$$\delta\, E_{\rm recoil} \;=\; {\rm PT} \;+\; \lambda_{\rm ab}\,\frac{{\rm N}^2}{{\rm p}_{\rm T}^2}\,\ln\frac{{\rm p}_{\rm T}}{\rm N}$$

$$\lambda_{ab} \sim\; 2g_{\rm EW} \;\propto \int dk_T^2\,\alpha_s(k_T^2)$$

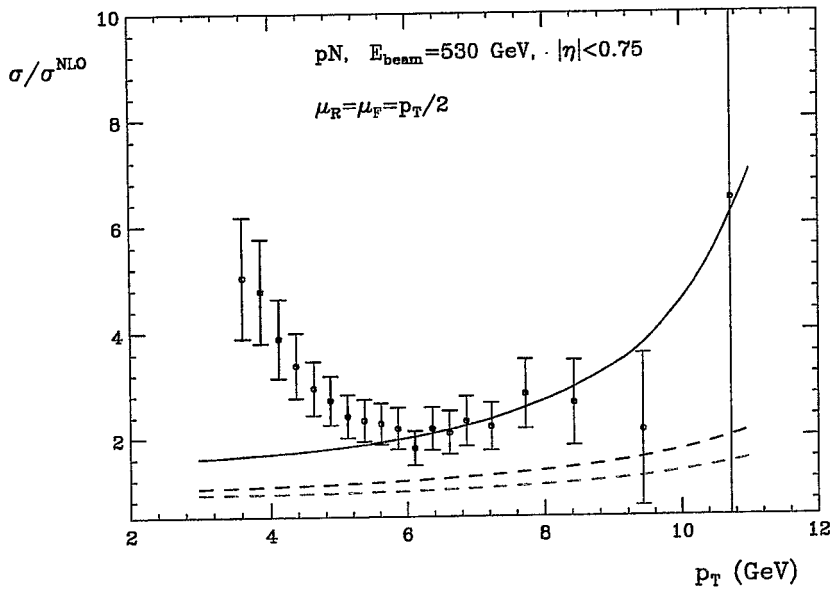
$$N \;\leftrightarrow\; \frac{1}{\ln x_T^2}$$

$$\delta\, E_{\rm recoil} \;=\; {\rm PT} \;+\; \lambda_{\rm ab}\,\frac{1}{{\rm p}_{\rm T}^2\ln^2\left(\frac{4{\rm p}_{\rm T}^2}{\rm S}\right)}\,\ln\left({\rm p}_{\rm T}\ln\left(\frac{4{\rm p}_{\rm T}^2}{\rm S}\right)\right)$$

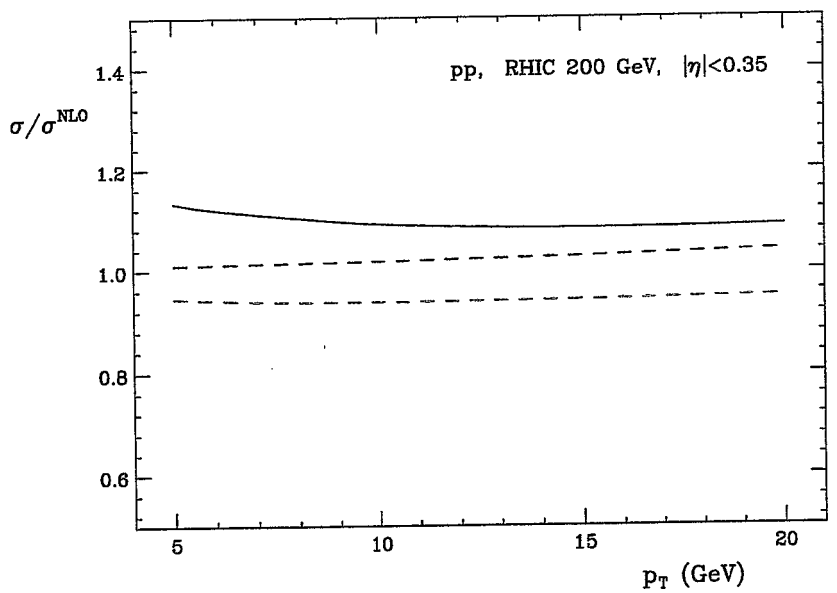
- **power suppressed in p_T**
- **decreases with S at fixed p_T**
- **match to large- and small-N behavior of Bessel functions $\rightarrow$ sample 'shape function' of N/p_T only:**

$$\delta E_{\rm np} = \frac{N^2}{p_T^2}\,\frac{ln\left(1+\frac{2p_T}{N}\right)}{\left(1+\frac{p_T}{N}\right)^2}$$

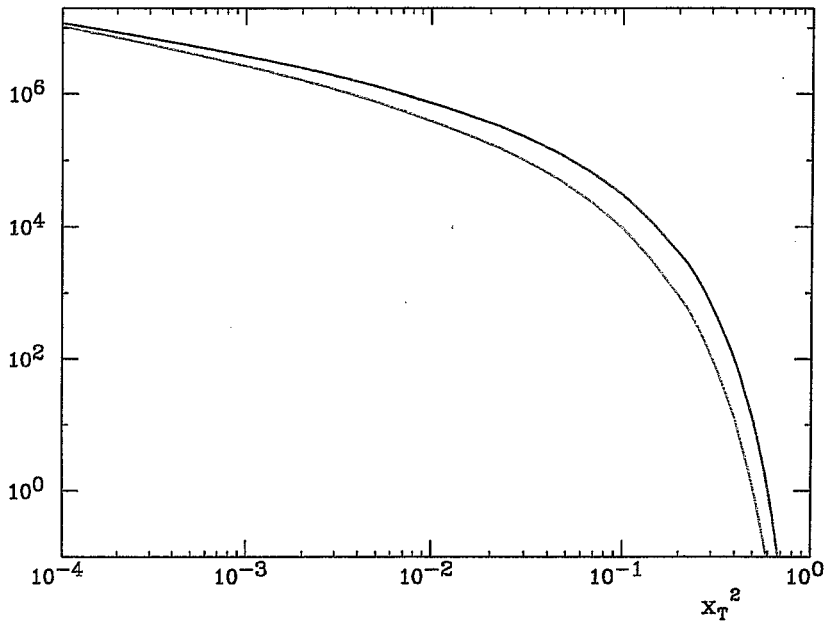
(p_T in GeV)



Including E_{recoil} for direct photons at E706



Including E_{recoil} for RHIC



The NLO cross section $p_T^3 d\sigma_\gamma/dp_T$ *vs.* x_T^2**.**

Origin of high-p_T **enhancement:**

$\exp CN^2/p_T^2$ **on** $p_T^3 d\sigma_\gamma/dp_T \sim (x_T^2)^{-\lambda} \Rightarrow (x_T^2)^{-\lambda} \times \mathrm{e}^{C\lambda^2/p_T^2}$

QCD Hard Scattering and Massive Hadron Pair Production

J.F. Owens
Florida State University

Summary

Single particle inclusive processes have been a mainstay in testing QCD in hadron-hadron scattering. Yet, some problems remain in the comparison of next-to-leading order calculations with data for the production of particles, jets, or photons in some kinematic regions. The production of massive hadron pairs offers another testing ground for hard scattering which differs from the single particle case in that two hadrons are produced on opposite sides of the event and with roughly balancing transverse momenta. A next-to-leading order calculation of such processes is described and compared to the data. The agreement with each experiment is generally quite good, although it is observed that different scale choices are required to match data sets which use different sets of cuts on the hadronic variables. This is traced to the fact that the calculation of the distribution in the azimuthal angle between the two hadrons is too narrow and a resummation calculation will be required in order to achieve agreement with the data. Future experiments measuring dihadron production should avoid tight cuts which require the hadrons to be back to back, as they then make the observables sensitive to soft gluon effects.

QCD Hard Scattering and Massive Hadron Pair Production

J.F. Owens
Florida State University

1. Introduction
2. QCD hard scattering
   - Basic formalism
   - Problems and some proposed solutions
3. Next-to-leading-order Monte Carlo calculations
4. Comparison to hadron pair production data
5. Conclusions

Introduction

- Single particle inclusive cross section
  - early test of QCD
  - preceded tests with jet production
  - early evidence for the role of gluons
- Collider Era
  - emphasis shifted to jet production
  - no serious problems noted initially
- However, with increased experimental precision problems appeared in ...
  - B production
  - γ and π^0 production
  - jet production

Some suggested solutions

- Enhance gluon distribution at high-p_T (helps jet problems)
- Uncertainties in fragmentation functions (helps B and π^0 problems)
- Improved theoretical treatment via resummation techniques

Underlying QCD formalism not questioned. But, could there be another hard scattering hadron-hadron process where QCD could be studied?

Hard Scattering in QCD

Basic form for producing some final state from collisions of hadrons A and B

$$\sigma \sim \sum_{ab} \int dx_a\, dx_b\, G_{a/A}(x_a, \mu_f^2) G_{b/B}(x_b, \mu_f^2) \sigma_{ab}(x_a, x_b, \mu_f^2, s, \theta, \ldots)$$

where

$$\sigma_{ab} = \alpha_s^n \sigma_0 + \alpha_s^{n+1} \sigma_1 + \ldots$$

- Parton distribution functions from global fits - usually to next-to-leading-logarithm accuracy
- Hard scattering cross section calculated through next-to-leading-order
- For a specific final state hadron, one also needs parton fragmentation functions

Many questions

- Is the hard scattering formalism basically correct?
- Are there large corrections to fragmentation processes?
- Are there large initial state radiation corrections?
- How good is our knowledge of fragmentation functions?

Massive Hadron Pair Production

Process such as $pp \to h_1 + h_2 + X$

$$\sigma \sim \sum_{abcd} \int dx_a\, dx_b\, dz_1\, dz_2\, G_{a/A}(x_a, \mu_f^2) G_{b/B}(x_b, \mu_f^2)$$
$$D_{h_1/c}(z_1, M_f^2) D_{h_2/d}(z_2, M_f^2) \sigma_{ab\to cd}(x_a, x_b, \mu_f^2, s, \theta, \ldots)$$

- High mass $\Rightarrow h_1, h_2$ come from fragmenting partons on opposite sides of the event
- Involves two fragmentation functions, both with high momentum fraction
- Symmetric - no advantage provided by an initial state k_T kick
- Sensitive to same region of fragmentation functions as single particle cross section
- Can test if fragmentation functions are adequate and if large corrections are needed
- Can test underlying hard scattering picture

Next-to-Leading-Order Calculations

- Ingredients
  - $2 \to 2$ $\mathcal{O}(\alpha_s^2)$ subprocesses, e.g. $qq \to qq, qg \to qg$, and $gg \to gg$
  - $\mathcal{O}(\alpha_s^3)$ one-loop corrections to $2 \to 2$ subprocesses
  - $2 \to 3$ subprocesses such as $qq \to qqg$, etc
- $\mathcal{O}(\alpha_s^3)$ terms have singular regions corresponding to soft gluons and/or collinear partons
- Need a method to handle such singularities
- Observables involve many kinematic variables since there are now two hadrons
- Jacobians from parton variables to hadron variables are complex
- Suggests using a Monte Carlo approach, but one which allows the singularities to be properly treated

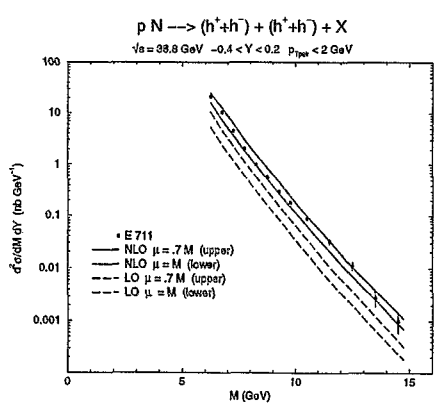
Phase Space Slicing Monte Carlo

- See B. Harris and J.F. Owens hep-ph/0102128
- Work in n=4-2ϵ dimensions using dimensional regularization
- Notation:
  - At the parton level: $p_1 + p_2 \to p_3 + p_4 + p_5$
  - Let $s_{ij} = (p_i + p_j)^2$ and $t_{ij} = (p_i - p_j)^2$
- Partition $2 \to 3$ phase space into three regions
  1. Soft: gluon energy $E_g < \delta_s \sqrt{s_{12}}/2$
  2. Collinear: s_{ij} or $|t_{ij}| < \delta_c s_{12}$
  3. Finite: everything else

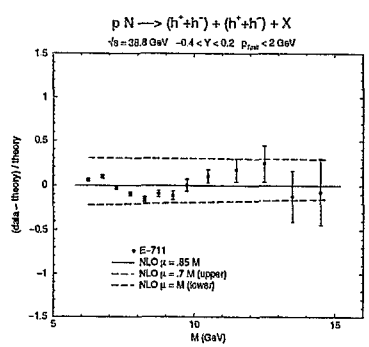
- In soft region use the soft gluon approximation to generate a simple expression for the squared matrix element which can be integrated by hand
- In the collinear region use the leading pole approximation to generate a simple expression which can be integrated by hand.
- Resulting expressions have explicit poles from soft and collinear singularities
- Factorize initial and final state mass singularities and absorb into the fragmentation and distribution functions
- Add soft and collinear integrated results to the $2 \to 2$ contributions – singularities cancel
- generate finite region contributions in 4 dimensions using usual Monte Carlo techniques
- End results is a set of two-body weights and a set of three-body weights.
- Both are finite and both depend on the cutoffs δ_s and δ_c
- Cutoff dependence cancels for sufficiently small cutoffs when the two sets of weights are added at the histogramming stage

Hadron Pair Production

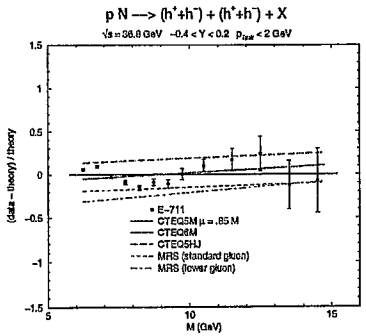
- Kinematic variables for the dihadron system
  - Mass of the dihadron system M
  - Rapidity of the hadron pair Y
  - Cosine of the scattering angle in the parton-parton system $\cos\theta^*$
  - Transverse momentum of the dihadron system $p_{T_{pair}}$
  - Event sample may also involve cuts being placed on the transverse momenta and rapidities of the individual hadrons
- High statistics, large acceptance experiments
  1. NA-24: $pp \to \pi^0\pi^0 + X, \sqrt{s} = 23.7$ GeV
  2. E-706: $pN \to \pi^0\pi^0 + X, \sqrt{s} = 31.6, 38.8$ GeV
  3. CCOR: $pp \to \pi^0\pi^0 + X, \sqrt{s} = 44.8, 62.4$ GeV
  4. E-711: $pN \to (h^+ + h^-)(h^+ + h^-) + X, \sqrt{s} = 38.8$ GeV
- Use CTEQ5M parton distributions as standard
- Two sets of parton fragmentation functions fit to high statistics LEP data
  - Kniehl, Kramer, and Pötter (use as standard)
  - Bourhis, Fontannaz, Guillet, and Werlen



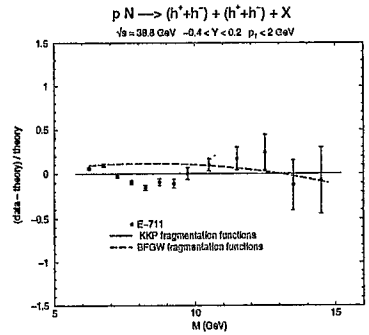
- NLO results significantly higher than LO results
- Still have significant scale dependence
  - Two scale dependent fragmentation function
  - Two scale dependent distribution functions
  - Two powers of α_s at lowest order



Expanded linear scale shown in (data-theory)/theory format



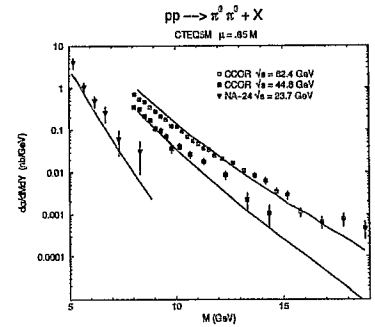
- Variations in parton distributions comparable to variations due to changes of scale
- Can not decide between CTEQ5HJ and other data sets
- Good news is that no large variations in scale are needed in order to describe data



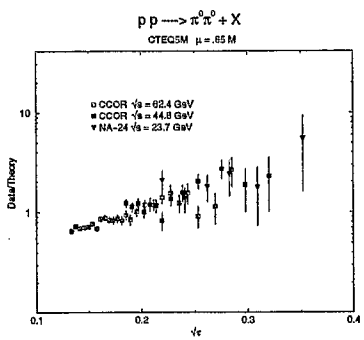
Variations due to fragmentation functions are within about 10 %

$pp \to \pi^0\pi^0 + X$

- NA-24 and CCOR experiments used the same sets of cuts to analyze their data
- $|Y| < 0.35$, $p_{T pair} < 1$ GeV, and $|\cos\theta^*| < 0.4$

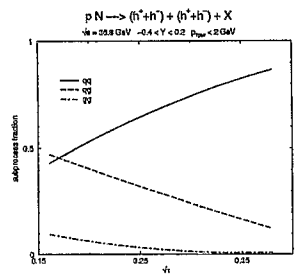


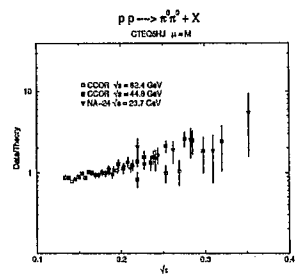
Plot same data in a data/theory format versus $\sqrt{\tau} = M/\sqrt{s}$



Upward slope suggests that CTEQ5HJ might improve the agreement with the data

Need to examine what subprocesses contribute to the data at different masses

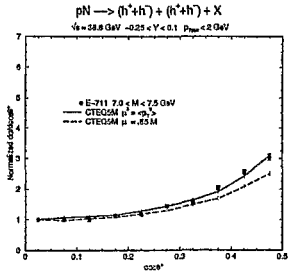


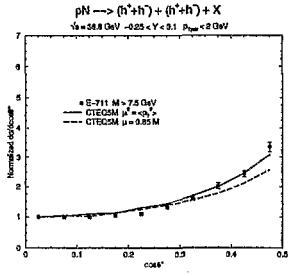


Some effect, but not enough...

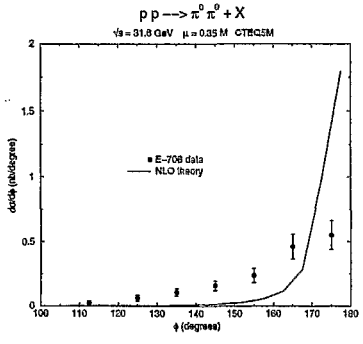
Angular distributions

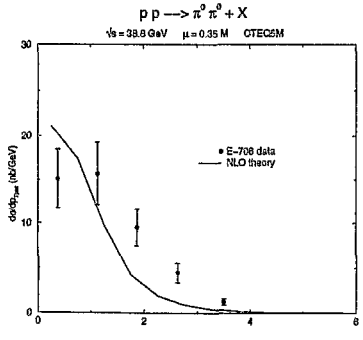
- Boost to frame where the two hadron system has zero longitudinal momentum
- Calculate cosine of the angle between each hadron and the beam direction
- Won't be the same since the two hadrons aren't exactly back to back (transverse momenta need not be the same in this frame because of fragmentation effects, for example)
- Use average of the two values
- Scale choice: for $d\sigma/dM$ only have one variable with the dimension of mass to use for the scale - M
- For $d\sigma/d\cos\theta^*$ at fixed M, one could choose M again or something like $M\sin\theta^*$ which is proportional to the transverse momentum of the individual hadrons
- Use two choices: M and the average of the two squared p_T values



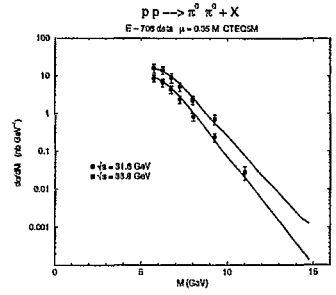


Choice of $< p_T^2 >$ gives a steeper curve, in better agreement with the data. At fixed M larger $\cos\theta^*$ gives a smaller scale which increases the cross section.





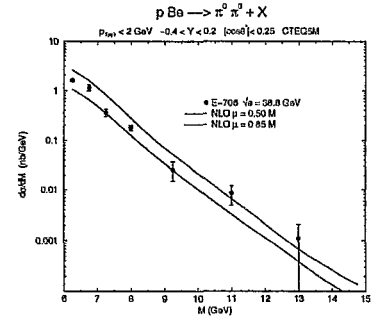
E-706 Data



- Agreement is good, but the scale is much smaller than in the previous cases
- Cuts used are much different than the other experiments, but they can be duplicated in the calculation
- Require each pion to satisfy $p_T > 2.5$ GeV and $-.8 < y < .8 (-1.05 < y < .55)$ for $\sqrt{s} = 31.6(38.8)$ GeV
- No cuts on $p_{T pair}$, wider acceptance in the azimuthal angle between the two pions ($\Delta\phi$)
- So what is causing the difference?

- E-706 has wider acceptance in $p_{T pair}$ and $\Delta\phi$
- Opening up the acceptance region increases the experimental results, but doesn't increase the theoretical result nearly as much
- Results in an apparent normalization shift requiring that the theory be increased (use smaller scale)
- *Not* an experimental problem!
- Both distributions are δ-functions at lowest order
- Correct description requires the use of the appropriate resummation formalism
- Will get misleading results if cuts are placed on a distribution which is not well described by the theory
- Better to integrate over the variable in question if the acceptance of the experiment allows it

- E706 also analyzed data using the same cuts as for E-711



- Agreement is much better with nearly the same scale choice
- Answer to the question lies in the $p_{T pair}$ and $\Delta\phi$ distributions

Summary and Conclusions

- NLO calculation provides a good description of the mass and angular distributions for the production of high mass hadron pairs
- Distributions which are δ-functions at lowest order are not well described
  - Distributions diverge at the edge of the physical region at this order
  - Resummation techniques required in order to properly treat soft gluon effects
- No apparent problems associated with existing fragmentation functions
- Encouraging evidence that the underlying hard scattering process is correctly described by QCD
- Problems with single photon and single hadron cross sections may be ascribed to a combination of effects due to an incomplete application of the theory and possible inconsistencies amongst data sets

Parton Distribution Functions and QCD Global Fitting*

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I. INTRODUCTION

High energy hadrons interact through their quark and gluon constituents. The interactions become weak at short distances thanks to the asymptotic freedom property of QCD, which allows perturbation theory to be applied to a rich variety of experiments. The nonperturbative nature of the proton for single hard interactions is thus characterized by Parton Distribution Functions (PDFs) $f_a(Q,x)$ of momentum scale Q and light-cone momentum fraction x. The evolution in Q is determined perturbatively by QCD renormalization group equations, so the nonperturbative physics can be characterized by functions of x alone at a fixed small Q_0. The ongoing project to extract those functions from experiment, and to estimate their uncertainties, is the subject of this talk. The applicability of single nucleon PDFs to hard scatterings between heavy nuclei is a key question to be addressed in the workshop.

The global QCD analysis to extract the parton distributions from experiment rests on three pillars:

- **Factorization** $\Rightarrow$ Short distance and long distance are separable (see Fig. 1);
- **Asymptotic Freedom** $\Rightarrow$ Hard scattering processes are perturbatively calculable;
- **DGLAP Evolution** $\Rightarrow$ PDFs are characterized by functions of x at a fixed small Q_0, with the PDFs at all higher Q being determined from these by renormalization group evolution.

$$F_A^\lambda(x,\frac{m}{Q},\frac{M}{Q}) = \sum_a f_A^a(x,\frac{m}{\mu}) \otimes \hat{F}_a^\lambda(x,\frac{Q}{\mu},\frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$

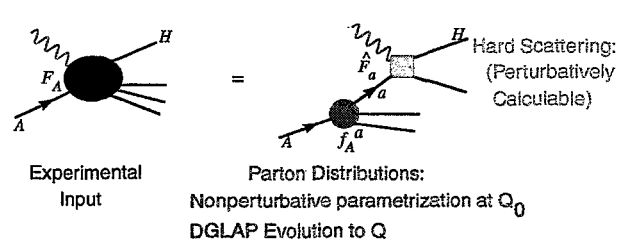

FIG. 1: The factorization theorem

* Presented at the Riken/BNL Workshop "High p_T physics at RHIC," Brookhaven, 3 December 2003

The kinematic range of available data, after cuts to suppress effects at low Q and low W, are shown in Fig. 2. The data cover a wide range of scales. They are tied together by DGLAP evolution and by the fact that the PDFs are universal. Consistency or inconsistency between different processes, and between different data points for the same process can be observed only by applying QCD to tie them together in a global fit. Future data from HERA, Tevatron run II (W, Z production), HERA II, and LHC will dramatically extend the range and accuracy of this global fit.

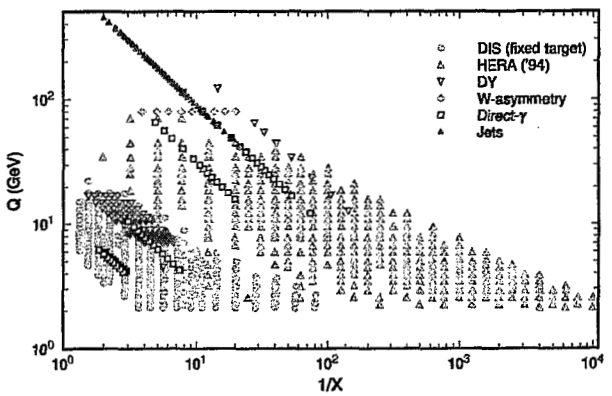

FIG. 2: Kinematic region covered by data

II. SOME DETAILS OF THE CTEQ GLOBAL ANALYSIS

Input from Experiment: ~ 2000 data points with $Q > 2\,\mathrm{GeV}$, $W > 3.5\,\mathrm{GeV}$ from e, μ, ν DIS; lepton pair production (DY); lepton asymmetry in W production; high p_T inclusive jets; $\alpha_s(M_Z)$ from LEP.

Input from Theory: NLO QCD evolution and hard scattering.

Parametrization at Q_0: Use the form $A_0\, x^{A_1}\,(1-x)^{A_2}\, e^{A_3 x}(1+A_4 x)^{A_5}$ for $u_v = u - \bar{u}$, $d_v = d - \bar{d}$, $\bar{u} + \bar{d}$, and g.

Assumptions based on lack of information: $s = \bar{s} = 0.4\,(\bar{u} + \bar{d})/2$ at Q_0; no intrinsic b or c.

Procedure: Construct effective $\chi^2_{\mathrm{global}} = \sum_{\mathrm{expts}} \chi^2_n$, including published systematic error correlations. Minimize χ^2_{global} to obtain "Best Fit" PDFs.

Uncertainty estimates: Use the variation of χ^2_{global} in neighborhood of the minimum to estimate uncertainty limits as the region of parameter space where $\chi^2 < \chi^2(\mathrm{BestFit}) + T^2$ with $T \approx 10$. This "Tolerance Factor" $T \sim 10$ is quite different from the traditional value 1 from Gaussian statistics, because of unknown systematic errors in theory and experiments. It can be estimated from the apparent inconsistencies between experiments when they are combined in the global fit.

To measure a set of continuous PDF functions at Q_0 on the basis of a finite set of data points would appear to be an ill-posed mathematical problem. However, this difficulty is not so severe as might be expected since the actual predictions of interest that are based on the

PDFs are discrete quantities. In particular, fine-scale structure in x in the PDFs at Q_0 tend to be smoothed out by evolution in Q. They correspond to flat directions in χ^2 space, so they are not accurately measured; but they have little effect on the applications of interest.

Some representative Best Fit parton distributions from the analysis are shown in Figs 3, 4. Ones sees that valence quarks dominate for $x \to 1$, and the gluon dominates for $x \to 0$, especially at large Q.

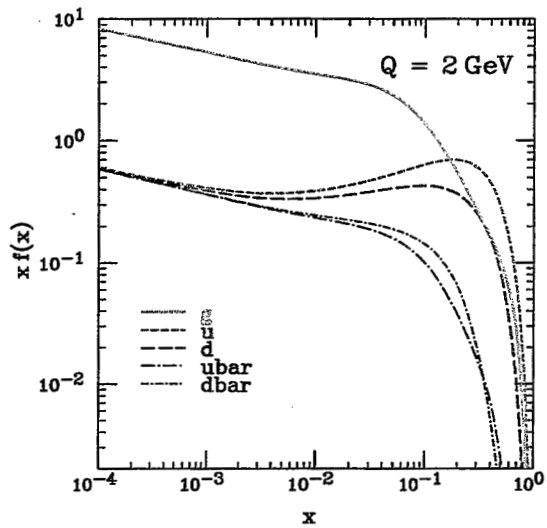

FIG. 3: Parton distributions at $Q = 2$ GeV

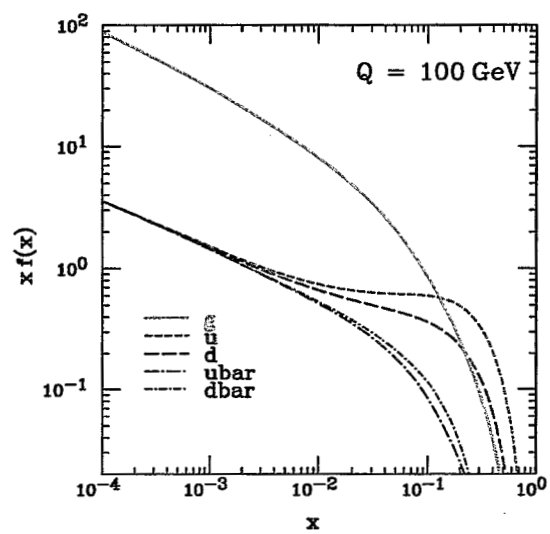

FIG. 4: Parton distributions at $Q = 100$ GeV

III. UNCERTAINTIES IN PDFS

There are several **Sources of uncertainty:**

- Experimental errors included in χ^2
- Unknown experimental errors
- Parametrization dependence
- Higher-order corrections & Large Logarithms
- Power Law corrections ("higher twist")

There are some **Fundamental difficulties:**

- Good experiments run until systematic errors dominate, so the magnitude of remaining systematic errors involves guesswork.
- Systematic errors of the theory and their correlations are even harder to guess.
- Quasi–ill-posed problem: we must determine continuous functions from a discrete data set. (Because of the smoothing effect of DGLAP evolution, this is not as impossible as it sounds.)
- Some combinations of variables are unconstrained, e.g., $s - \bar{s}$ before NuTeV data.

There are several **Approachs to estimating the uncertainty.** In all of the uncertainty methods, we continue to use χ^2 as a measure of the quality of the fit; but vary weights assigned to the experiments to estimate the range of acceptable fits, rather that relying on the classical $\Delta\chi^2 = 1$.

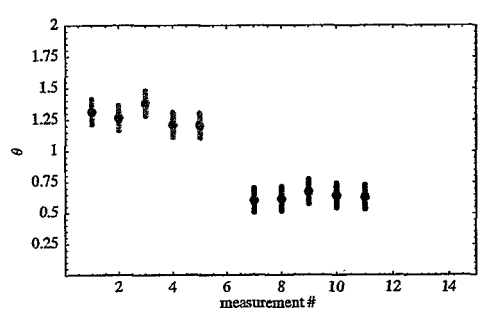

FIG. 5: Hypothetical measurements of hypothetical parameter θ.

The essence of the Uncertainty Problem can be seen in the Fig. 5, which shows some hypothetical measurements of a single parameter θ. Suppose the quantity θ has been measured by two different experiments, or extracted using two different approximations to the True Theory. What would you quote as the Best Fit and the Uncertainty? The disagreements are of course not so obvious in the many-parameter global fit. However, the disagreements can be probed in one dimension by, for example, studying the variations of the Best Fit that result from assigning different weights to different experiments, or to different kinematic regions etc. Much of this is discussed in our papers; and more is work in progress.

IV. OUTLOOK

Parton Distribution Functions are a necessary infrastructure for precision Standard Model studies and New Physics searches at hadron colliders and at experiments using hadron targets. Some issues that were discussed, but not necessarily included in this writeup due to space limitations:

- PDFs of the proton are increasingly well measured.
- Useful tools are in place to estimate the uncertainty of PDFs and to propagate those uncertainties to physical predictions. There is adequate agreement between various methods for estimating the uncertainty:
  - "Hessian Method" based on the eigenvectors of the error matrix
  - "Lagrange Multiplier Method" based on finding the uncertainty on a predicted quantity by studying the variation of χ^2 as a function of that quantity
  - systematic reweighting of experiments (work in progress with John Collins)
  - random reweighting of experiments: a variant of the "well known" statistical bootstrap method
- The "Les Houches Accord" interface makes it easy to handle the large number of PDF solutions that are needed to characterize uncertainties. [hep-ph/0204316]
- Improvements in the treatment of heavy quark effects are in progress, and together with neutrino experiments they will allow improved flavor differentiation.
- Since PDFs summarize some fundamental nonperturbative physics of the proton, they should be considered a challenge to be computed! (Low moments of meson PDFs have indeed been calculated in lattice gauge theory.)
- Other nonperturbative methods, e.g. for $s(x) - \bar{s}(x)$, may be helpful.
- HERA and Fermilab run II data will provide the next major experimental steps forward, followed by LHC.
- Theoretical improvements such as resummation to use direct photon and W transverse momentum data will be useful.
- In view of possible isospin breaking, and the importance of nuclear shadowing & anti-shadowing effects, HERA measurements on deuterons would be highly welcome.

I thank the organizers for an excellent workshop, and my collaborators on this work, D. Stump, W.K. Tung, J. Huston, P. Nadolsky, F. Olness, S. Kuhlmann, J. Owens; S. Kretzer, and J. Collins for many valuable discussions.

Low mass dilepton production at high p_T as a probe of gluon density

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In order to understand the overwhelming data from the Relativistic Heavy Ion Collider (RHIC) and make predictions for the future Electron Ion Collider (EIC) and Large Hadron Collider (LHC) in terms of the successful perturbative QCD factorization approach we need precise information of the nuclear parton distribution functions (nPDFs), in particular, the gluon distribution at small $x(< 0.1)$ [1].

Recently, it was argued that for physical processes where the effective x is very small and the typical momentum exchange of the collision Q is not large the number of soft partons in a nucleus may saturate to form the color glass condensate (CGC) [2]. Since nPDFs are not direct physical observables, it requires some kind of factorization to connect physical observables to the desired nPDFs. By identifying the characteristic scale of power corrections in conventional perturbative QCD approach to all physical process, we could estimate when the conventional factorization approach fails and where is the boundary of this novel regime.

In terms of the QCD factorization approach, we calculate and resum a perturbative expansion of nuclear enhanced power corrections in the quantity $(\xi^2/Q^2)(A^{1/3} - 1)$ to the structure functions (SFs) measured in lepton-nucleus deeply inelastic scattering (DIS) [3] Our results for the Bjorken x-, Q^2- and A-dependence of nuclear shadowing in SFs are consistent with existing data for a characteristic scale $\xi^2 = 0.09 - 0.12$ GeV^2 for quark initiated DIS processes. We find that the same scale ξ^2 provides a consistent description of the features observed in neutrino-nucleus DIS.

We also discuss the potential of low mass Drell-Yan dilepton production as a probe of gluon density. We found [4,5] that gluon initiated subprocesses contribute more than 70% (or 80% in the forward region) of Drell-Yan cross section when $Q_T > Q/2$ at RHIC energy. Unfortunately, the process suffers a low production rate at RHIC. A better production rate could be achieved at RHIC while preserving the gluon dominance if we are able to identify Drell-Yan dilepton pairs with invariant mass $Q \ll 1$ GeV at $Q_T \sim$ a few GeV, which seems to be possible experimentally [6].

[1] A. Accardi *et al.*, hep-ph/0308248, and references therein.

[2] E. Iancu, A. Leonidov and L. McLerran, arXiv:hep-ph/0202270.

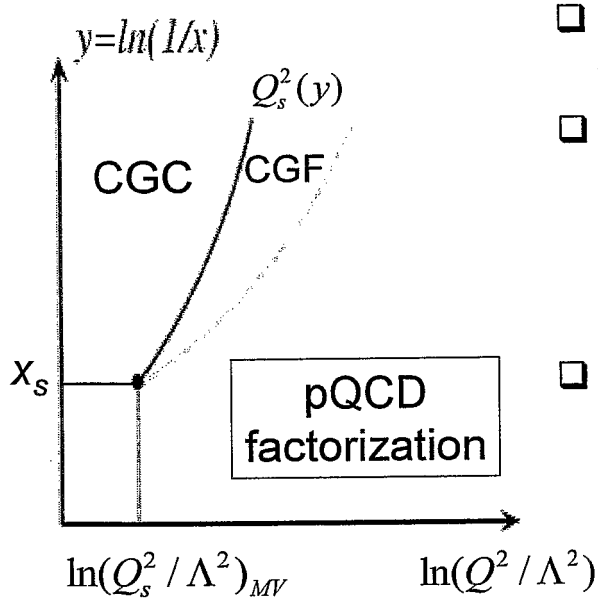
[3] J. W. Qiu and I. Vitev, arXiv:hep-ph/0309094.

[4] G. Fai, J. W. Qiu and X. F. Zhang, Phys. Lett. B **567**, 243 (2003).

[5] E. L. Berger, J. W. Qiu and X. F. Zhang, Phys. Rev. D **65**, 034006 (2002).

[6] M. Tannenbaun, comments at the workshop.

Phase diagram of parton densities



- Experiments measure cross sections, not PDFs
- PDFs are extracted based on
  - factorization
  - truncation of perturbative expansion
- How to probe the boundary between different regions?

Look for where pQCD factorization approach fails

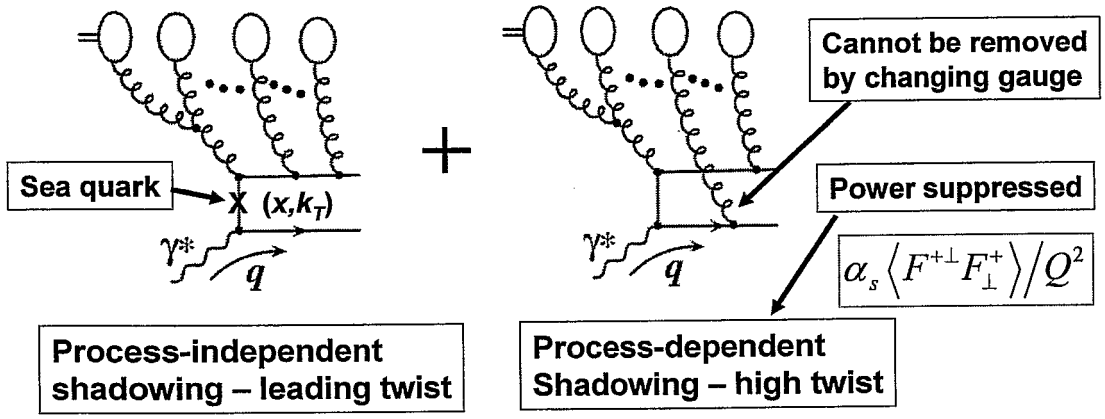
DIS structure functions at low x_B

- **Virtual photon of (x_B,Q^2) probes:**

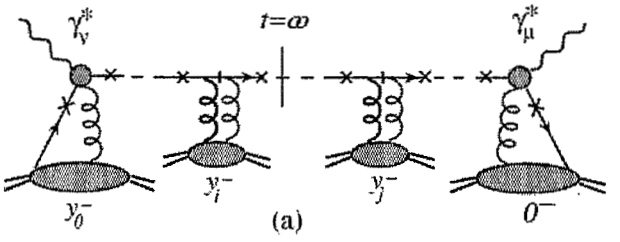
  Transverse area $A_\perp \sim \frac{1}{Q^2}$ **Longitudinal uncertainty** $\Delta Z^- \sim \frac{1}{x_B p^+}$

- **Interact coherently with more than one nucleon**

  if $\Delta Z^- > 2r_0 \frac{m}{p^+}$ or $x_B < \frac{1}{2mr_0} \sim 0.1$



Resummed power corrections to SFs



- resum all powers in $(A^{1/3}-1)\xi^2/Q^2$
- evaluate the ξ^2 to leading power in α_s

$$\xi^2 = \left(\frac{3\pi\alpha_s(Q^2)}{8r_{0\perp}^2}\right)\left\langle p\left|\hat{F}^2(\lambda_i)\right|p\right\rangle \Longrightarrow \frac{1}{2}\lim_{x\to 0} xG(x,Q^2)$$

$$F_T^A(x,Q^2)=\sum_{n=0}^{N}\frac{A}{n!}\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n\frac{d^nF_T^{(LT)}(x,Q^2)}{d^nx}\approx A\,F_T^{(LT)}\left(x+\frac{x\xi^2(A^{1/3}-1)}{Q^2},Q^2\right)$$

Vitev's talk on Thursday (Qiu and Vitev, hep-ph/0309094)

Estimate the saturation scale

- Maximum characteristic scale of power corrections from DIS shadowing:

$$\xi^2 \sim 0.9-0.12\ \text{GeV}^2 \quad\Longrightarrow\quad \xi^2(A^{1/3}-1)\le 0.6\ \text{GeV}^2$$

- Saturation scale for gluonic matter:

$$Q_s^2 < \frac{C_A}{C_F}\xi^2(A^{1/3}-1)\le 1.35\ \text{GeV}^2$$

- Separation between the process-dependent power corrections and the universal nuclear effect in the leading twist nPDFs
  - **Precise data on Q^2-dependence of the structure functions**
  - **QCD sum rules – Gross-Llewellyn Smith sum rule**
    - **nuclear effect in leading twist PDFs does not change valence qurak numbers**

The Gross-Llewellyn Smith Sum Rules

$$S_{\rm GLS} = \int_0^1 dx\ \frac{1}{2x}\left(xF_3^{\nu N}(x,Q^2) + xF_3^{\bar{\nu} N}(x,Q^2)\right)$$

$$\approx \#U + \#D = 3$$

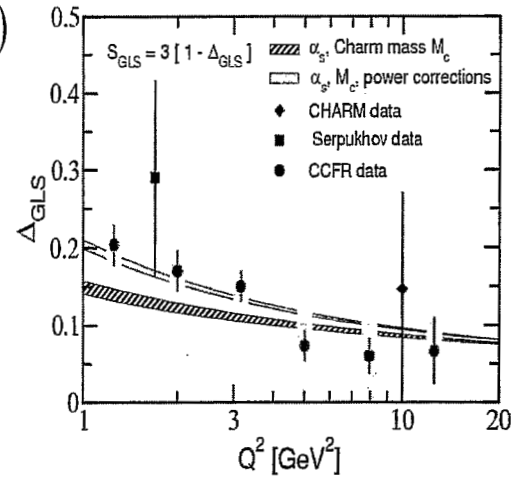
D.J.Gross and C.H Llewellyn Smith , Nucl.Phys. B 14 (1969)

$$\Delta_{\rm GLS} \equiv \frac{1}{3}(3 - S_{\rm GLS}) = \frac{\alpha_s(Q)}{\pi} + \frac{\kappa}{Q^2} + O\left(\frac{1}{Q^4}\right)$$

Fully coherent final-state power corrections to the sum rule almost cancel due to the unitarity:

$$\int_{-\infty}^{+\infty} dx\ \varphi(x+\Delta x) = \int_{-\infty}^{+\infty} dx\ \varphi(x)$$

But, nuclear enhanced power corrections only for a limited values of $x \in (0, 0.1)$



Qiu and Vitev, to appear on hep-ph

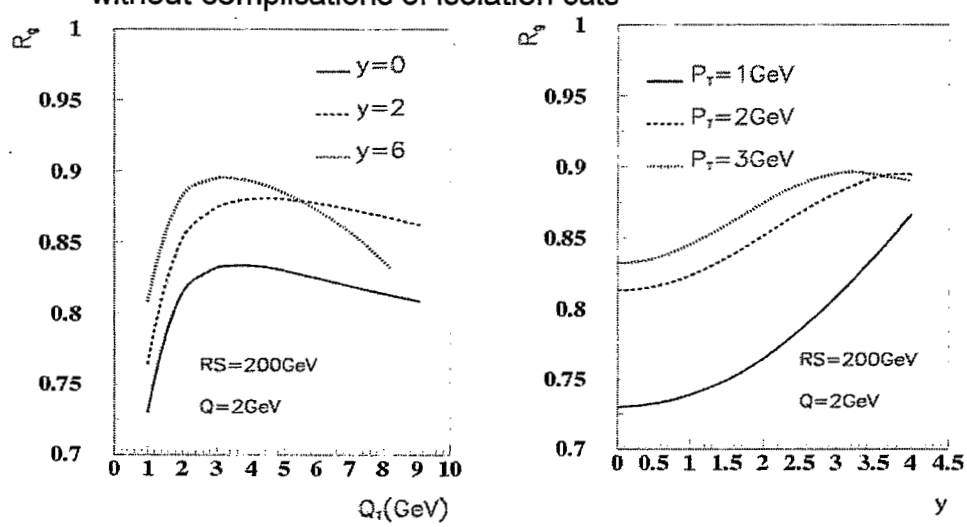
Prediction is compatible with the trend in the current data

Process-dependent power corrections are important!

Low mass Drell-Yan in forward region

- Like direct photon production, gluon Compton dominates the production rate for $p_T > Q/2$,

  without complications of isolation cuts



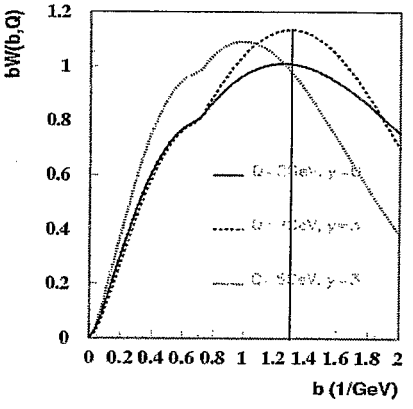
- Forward region to probe the small-x gluon distribution

Large nonperturbative effect at low p_T

- resummation of large Sudakov logarithms

$$\frac{d\sigma_{AB\to\gamma^*(Q)}}{dQ^2 dy dQ_T^2} \propto \frac{\alpha_s}{Q_T^2}\left(a + b\ln(Q^2/Q_T^2)\right) \Rightarrow \infty \quad \text{as } Q_T^2 \to 0$$

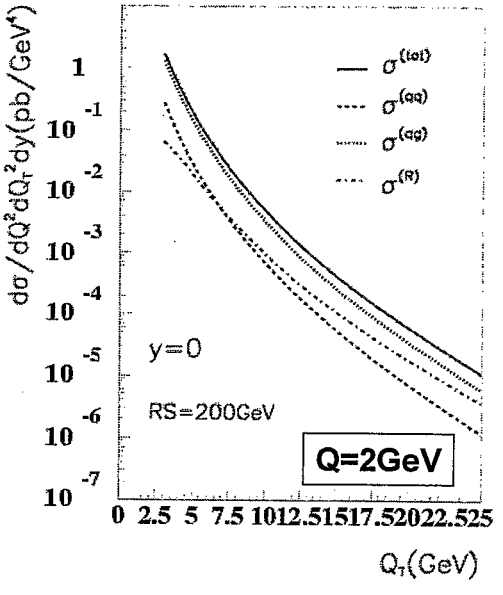
$$\Longrightarrow \quad \frac{d\sigma_{AB\to\ell^+\ell^-(Q)}}{dQ^2 dy dQ_T^2} \propto \int db J_0(Q_T b) b W(b, Q^2)$$

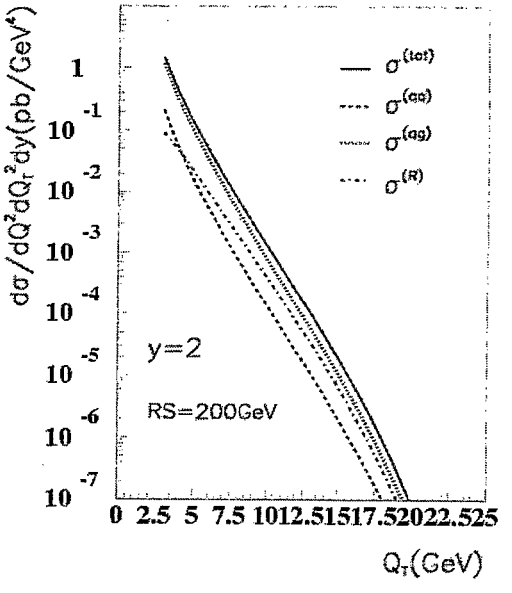


- **predictive power relies on the convergence of large-b region**

- **low mass Drell-Yan get a lot of nonperturbative contribution!**

Also suffers low production rate at RHIC





Include resummation of final-state fragmentation logs

Only perturbative contributions

Berger, Qiu, Zhang, PRD65, 2002

Multijet production as a centrality trigger for pp collisions at LHC

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The talk reports results of two recent studies addressing proximity to the black body limit in DIS off protons and nuclei [1] a the relevance of the black body limit for the central pp collisions at LHC which are the main sourse of the production of new particles [2]

In the first paper we use information about DIS and J/ψ production on hydrogen to model the t-dependence of the $\gamma^* N$ scattering amplitude. We investigate the profile function for elastic scattering of hadronic components of the virtual photon off both a nucleon and heavy nuclear target, and we estimate the value of the impact parameter where the black body limit is reached. We also estimate the fraction of the cross section that is due to hadronic configurations in the virtual photon wave function that approach the unitarity limit. We extract, from these considerations, approximate lower limits on the values of x where the leading twist approximation in DIS is violated. We observe that the black body limit may be approached within HERA kinematics with Q^2 equal to a few GeV^2 and $x \sim 10^{-4}$. Comparisons are made with earlier predictions by Munier *et al.*, and the longitudinal structure function is compared with preliminary HERA data. The principle advantage of our method is that we do not rely solely on the t-dependence of ρ-meson production data. This allows us to extend our analysis down to very small impact parameters and dipole sizes. Finally, we perform a similar calculation with a ^{208}Pb target, and we demonstrate that the black body limit is already approached at $Q^2 \sim 20$ GeV^2 and $x \sim 10^{-4}$.

In the second paper we demonstrate that a trigger on hard dijet production at small rapidities allows to establish a quantitative distinction between central and peripheral collisions in $\bar{p}p$ and pp collisions at Tevatron and LHC energies. Such a trigger strongly reduces the effective impact parameters as compared to minimum bias events. This happens because the transverse spatial distribution of hard partons ($x \gtrsim 10^{-2}$) in the proton is considerably narrower than that of soft partons, whose collisions dominate the total cross section. In the central collisions selected by the trigger, most of the partons with $x \gtrsim 10^{-2}$ interact with a gluon field whose strength rapidly increases with energy. At LHC (and to some extent already at Tevatron) energies the strength of this interaction approaches the unitarity ("black-body") limit. This leads to specific modifications of the final state, such as a higher probability of multijet events at small rapidities, a strong increase of the transverse momenta and depletion of the longitudinal momenta at large rapidities, and the appearance of long-range correlations in rapidity between the forward/backward fragmentation regions. The same pattern is expected for events with production of new heavy particles (Higgs, SUSY). Studies of these phenomena would be feasible with the CMS–TOTEM detector setup, and would have considerable impact on the exploration of the physics of strong gluon fields in QCD, as well as the search for new particles at LHC.

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[1] T. Rogers, V. Guzey, M. Strikman and X. Zu, "Determining the proximity of $\gamma^* N$ scattering to the black body limit using DIS and J/psi production," arXiv:hep-ph/0309099.

[2] L. Frankfurt, M. Strikman and C. Weiss, "Dijet production as a centrality trigger for p p collisions at LHC," arXiv:hep-ph/0311231.

HERA data confirm the increase of the cross sections of the small dipoles predicted in pQCD

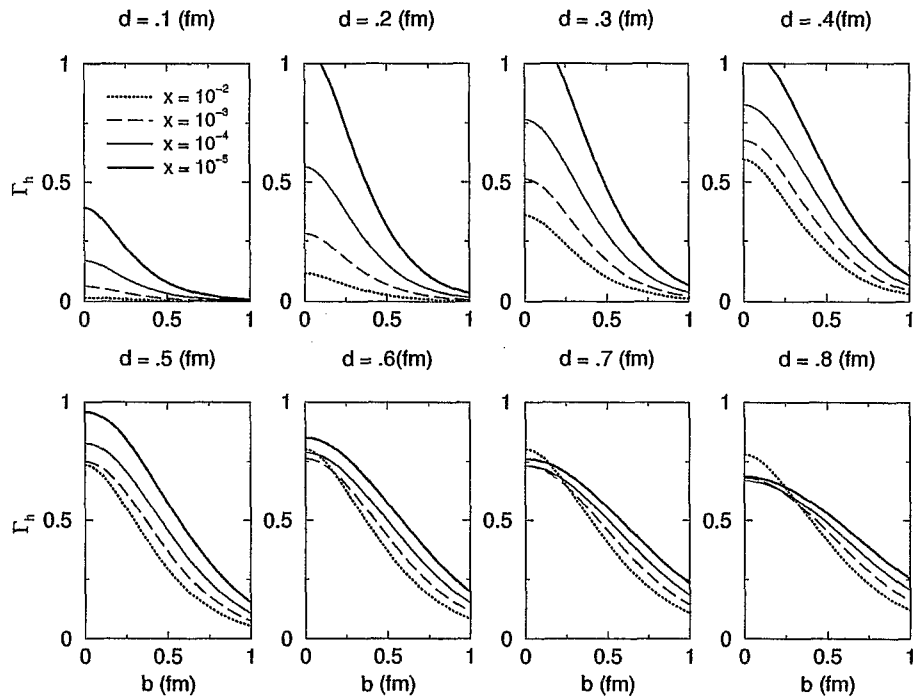
Can the rapid increase of σ continue forever?

Knowing information about the t-dependence of the elastic dipole-nucleon scattering we can test how far are the partial waves of elastic scattering from the S-channel unitarity limit:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t)$$

$\Gamma(b) = 1$ corresponds to the black body limit (BBL) $\sigma_{inel} = \sigma_{el}$.

For small 88 dipole -hadron scattering where pQCD is applicable $\Gamma(b)$ is 9/4 times larger).



The hadronic configuration-nucleon profile function for different x values. The large $\Gamma_h(b)$ region ($\Gamma_h \geq 1/2$) is reached for intermediate hadronic sizes. T.Rogers, et al

Final state properties for central pp collisions

In the central (dijet triggered) pp collisions all leading partons will end up with large (few GeV/c) transverse momenta - similar to central pA collisions at RHIC.

Qualitative predictions for properties of the final states with dijet trigger

- The leading particle spectrum will be strongly suppressed compared to minimal bias events. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons.

- The average transverse momenta of the leading particles $\geq 1\,GeV/c$.
- A large fraction of the events will have no particles with $z \geq 0.02 - 0.05$. This suppression will occur simultaneously in both fragmentation regions, corresponding to the emergence of long–range rapidity correlations between the fragmentation regions.

- In the forward production of dimuons or dijets one expects a broadening of the distribution over transverse momenta Gelis,Jalilian-Marian 2002, as well as a weaker dependence of the dimuon production cross section on the dimuon mass for masses $\leq$ few GeV Frankfurt, MS2002.
- The background for heavy particle or high–$p_\perp$ jet production should contain a significant fraction of hadrons with transverse momenta $p_\perp \sim p_{\perp,BBL}$, originating from fragmentation of partons affected by the strong gluon field. The direction of the transverse momenta of these hadrons should be unrelated to the transverse momenta of the jets. This phenomenon will make it difficult to establish the direction of jets unless $p_\perp\ (jet) \gg p_{\perp,BBL}$.
- Forward cone of the primary proton - air interaction near ZGK cutoff will often resemble iron-air interactions.

Recombination and Fragmentation of Hadrons from a Dense Parton Phase

Rainer J. Fries

University of Minnesota

Talk at the RIKEN Workshop on High-P_T Physics at RHIC, December 3, 2003

Experiments at RHIC show a large suppression of high-P_T particles in central Au+Au collisions. This jet quenching results from a strong energy loss of fast partons traveling through the hot medium created in these collisions. Particle creation at high P_T (i.e. P_T>2 GeV) is usually described by perturbative QCD (pQCD). The strong energy loss, however, suppresses this hard particle production and enables soft particle production mechanisms to dominate even at intermediate transverse momentum. At RHIC energies this intermediate region can extend as far as 4...6 GeV in transverse momentum.
A suitable description of hadron production in this region is possible by assuming a recombination mechanism of constituent quarks at the phase transition. A quark-antiquark pair can form a meson, three quarks can form a baryon. If P_T is larger than the mass of the hadron, the calculation becomes independent of the shape of the hadronic wave function for an exponential parton spectrum, making this a quite universal description. One can show that recombination is more effective for exponential spectra, while power-law spectra favor (pQCD) fragmentation. Calculations using a combination of recombination from a thermal parton phase and pQCD fragmentation yield excellent agreement with experimental data on hadron production for P_T > 2 GeV. In particular, the anomalously large baryon/meson ratio, and the particle dependence of nuclear suppression can be explained.
Recombination predicts a simple scaling law for elliptic flow, $v_2(P_T) = n\, v_2^{part}(P_T/n)$, where n is the number of valence partons in the hadron, n=2 for mesons, n=3 for baryons, n=6 for deuterons. v_2^{part} is the elliptic flow in the parton phase before hadronization. Experimental data from STAR and PHENIX impressively confirm this scaling law, therefore supporting the hypothesis of a universal elliptic flow in the parton phase.

- R.J. Fries, C. Nonaka, B. Müller & S.A. Bass, PRL 90, 202303 (2003); PRC 68, 044902 (2003)
- C. Nonaka, R.J. Fries & S.A. Bass, nucl-th/0308051, PLB in print.

Recombination formalism

$$\frac{dN_M}{d^3P} = \sum_{a,b} \int \frac{d^3R}{(2\pi)^3} \int \frac{d^3q d^3r}{(2\pi)^3} W_{ab}(R - \frac{r}{2}, \frac{P}{2} - q; R + \frac{r}{2}, \frac{P}{2} + q) \Phi_M(r,q)$$

- choose a hypersurface Σ for hadronization
- use local light cone coordinates (hadron defining the + axis)
- $w_a(r,p)$: single particle distribution functions for quarks at hadronization
- Φ_M & Φ_B: light-cone wave-functions for the meson & baryon respectively
- x, x' & $(1-x)$: momentum fractions carried by the quarks
- integrating out transverse degrees of freedom yields:

$$E\frac{dN_M}{d^3P} = \int_\Sigma d\sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta} \int dx\, w_\alpha(R, xP^+)\, \bar{w}_\beta(R, (1-x)P^+) \left|\bar{\phi}_M(x)\right|^2$$

$$E\frac{dN_B}{d^3p} = \int_\Sigma d\sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta,\gamma} \int dx\, dx'\, w_\alpha(R, xP^+)\, w_\beta(R, x'P^+)\, w_\gamma(R, (1-x-x')P^+) \left|\bar{\phi}_B(x,x')\right|^2$$

Input and Parameters

Input for the model is the momentum distributions of a thermal phase of constituent quarks at the time of hadronization

- the quark distribution is assumed to have a low p_t thermal component and a high p_t pQCD mini-jet component
- the thermal component is parameterized as:

$$w_a(\sigma, p) = g_a e^{-p\cdot v(\sigma)/T}\, e^{-\eta^2/2\Delta^2} f(\rho, \phi)$$

with a flavor dependent fugacity g_a, temperature T, rapidity width Δ and transverse distribution $f(\rho,\phi)$.

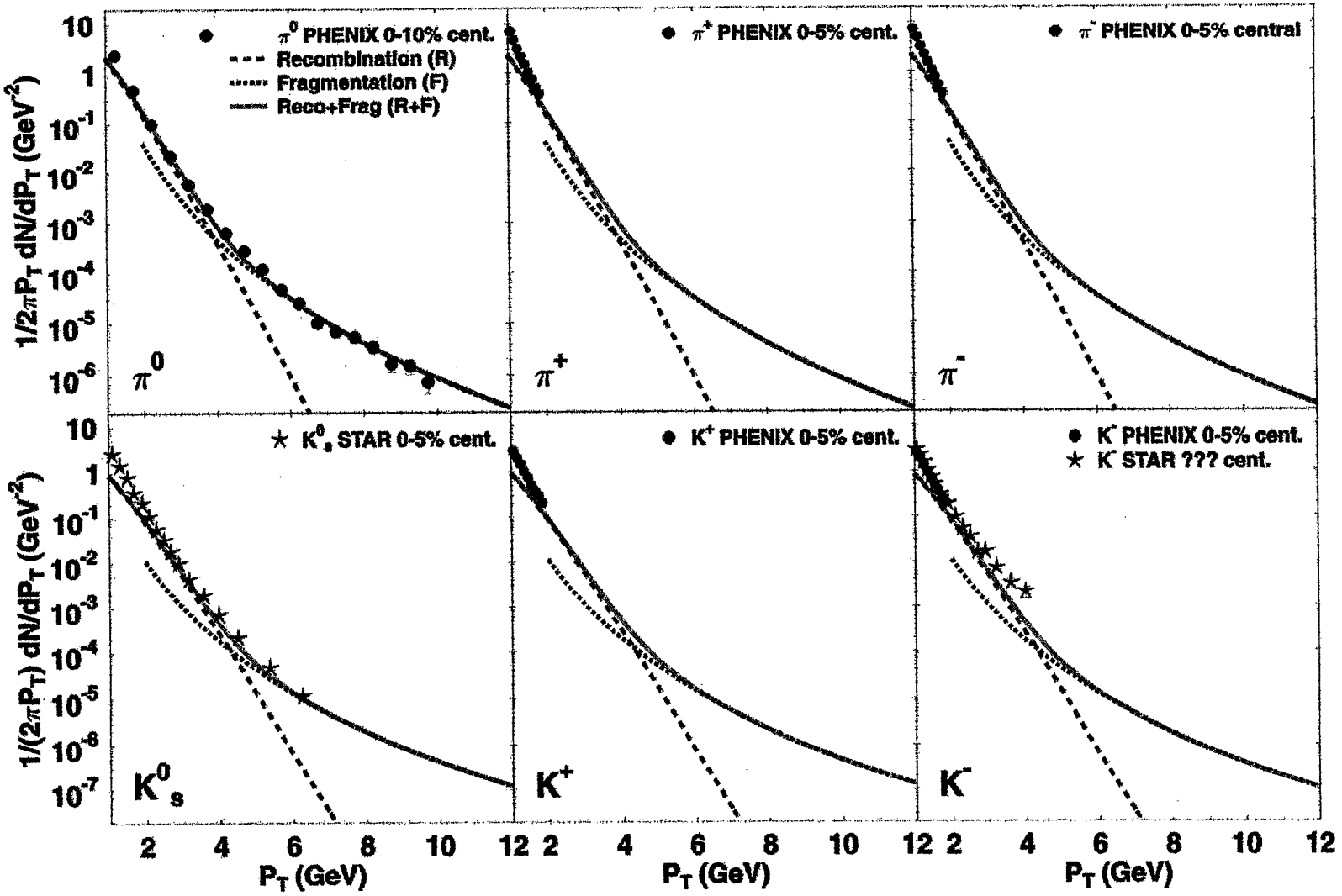
- Perturbative calculation using KKP fragmentation functions and energy loss

- Use hypersurface Σ with $t^2-z^2=\tau^2$;
- τ = 5 fm/c.
- Fix T=175 MeV

Parameters:

- Radial flow β=0.55 c
- Emission volume
- Energy loss parameter
- Fugacities

Hadron Spectra I

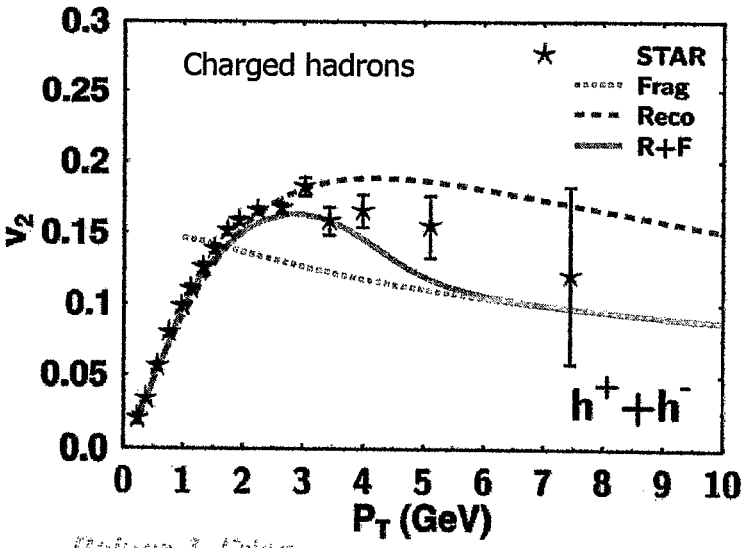


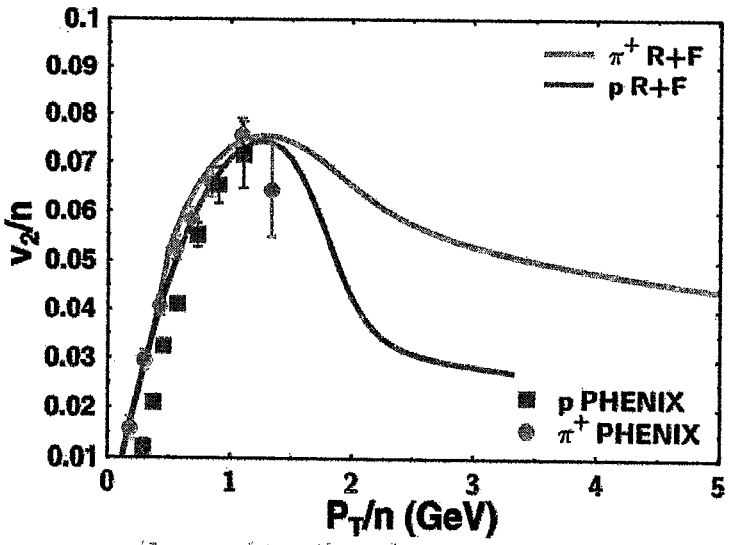
Parton Number Scaling of Elliptic Flow

•in the recombination regime, meson and baryon v_2 can be obtained from the parton v_2 in the following way:

➢neglecting quadratic and cubic terms, one finds a simple scaling law:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$





The dihadron fragmentation function and its evolution

A. Majumder[1] and X. N. Wang[1]

[1] *Nuclear Science Division, Lawrence Berkeley National Laboratory, 1 Cyclotron road, Berkeley, CA 94720*

Experiments are now underway at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory to study nuclear collisions at very high energies. The aim is to create energy densities high enough for the production of a state of essentially deconfined quarks and gluons: the quark gluon plasma (QGP). The QGP is rather short lived and soon hadronizes into a plethora of mesons and baryons. Hence, the existence of such a state in the history of a given collision must likely be surmised through a variety of indirect probes. One of the most promising signatures has been that of high p_T particles emanating from such collisions and the energy loss encountered by these as they cut a path through the dense medium. Various models exist attempting to explain the single inclusive measurements as listed on page 2.

A recent effort has measured the two particle correlation between two high p_T hadrons with a variety of angles between them [1]. While it may be argued that for large enough angles the process essentially consists of independent partons traversing the medium, escaping and eventually fragmenting (hence these can be explained by a simple extension of the energy loss models); the case at very small angles (also called the same-side correlation) is the result of two hadrons fragmenting from the same parton. This will require us to introduce a dihadron fragmentation function $D^{h_1h_2}(z_1, z_2, Q^2)$ (see pages 2 and 3 for explanations of the variables). The complete calculation of same side correlation will require the inclusion of medium effects leading to energy loss of the high p_T parton preceding its fragmentation. In this effort we will concentrate on the definition of the double fragmentation function and derive the equations that describe the DGLAP evolution with the energy scale of the fragmenting parton.

In the interest of an accurate definition and to prove factorization of $D(z_1, z_2)$ in a simple environment we chose to define the quantity in e^+e^- annihilations. In this case one may factor out the strong and electromagnetic sectors as an inner product of a leptonic tensor $\mathcal{L}_{\mu\nu}$ and a hadronic tensor (or current-current correlator) $W^{\mu\nu}$. One essentially begins with the operator expression for the current current correlator $W^{\mu\nu}$ and expands it order by order in perturbation theory. At leading order one deals with the imaginary part of the quark self-energy of the virtual photon as shown on page 3. To obtain the dihadron fragmentation function one replaces the outgoing quark or antiquark basis states with a sum over all possible hadronic states of which two have been identified. In the limit of very high energies one has two back-to-back quarks of very high energy which then fragment into collinear jets of hadrons. At such energies, one can make use of the collinear kinematics, where all transverse and backward light-cone momenta may be neglected in comparison with the forward light-cone momenta. The forward direction is defined in the direction of the sum of the two leading hadron momenta. In this limit we may factorize the cross section in to a familiar hard piece and a soft piece which encodes the information of how partons fragment into hadrons. These results are presented in the cut vertex formalism of Mueller on page 3.

To ensure the consistency of the definition and to calculate the evolution of this quantity with the scale of the process we calculate the NLO contribution to this process. We focus solely on the leading log contribution at NLO as these give $O(1)$ corrections to the fragmentation functions. In light-cone gauge the leading log contribution emanates solely from the diagrams where one of the quark lines of page 3 have been modified to include a self-energy due to a single gluon. Both the real and imaginary parts of this diagram have to be considered to ensure the cancellation of infrared divergences. Collinear divergences will remain and will have to be factored off into a redefinition of the fragmentation function. This is similar to the case of single inclusive fragmentation. The main difference emanates from the possibility that in replacing the partonic basis with a sum over all states of hadrons with two hadrons identified, one may identify both hadrons as emanating from the quark, the gluon or one hadron emanating from each. This last piece includes a modification of the dihadron fragmentation function from two independent single fragmentation functions. All three cases have been oulined in pictures on page 4.

In this preliminary study we focus on the non-singlet fragmentation function, $D_{NS}^{h_1h_2} = D_q^{h_1h_2} - D_{\bar{q}}^{h_1h_2}$. The evolution equations for this quantity do not contain the contribution from gluon fragmentation (last line on page 4). We present results for the ratio of the double fragmentation function to that of the single fragmentation function of the leading particle. As a starting ansatz we set $D^{h_1h_2}(Q^2 = 2\text{GeV}^2) = D^{h_1}D^{h_2}(Q^2 = 2\text{GeV}^2)$. Two cases are displayed that for $z_1 = z_2$ and $z_1 = 2z_2$. As will be noted the ratios show very little change as one evolves from $Q^2 = 2$ to $Q^2 = 100\text{GeV}^2$. The results are also sensitive to the ratio of z_1 to z_2. This stability with respect to a change of Q^2 already indicates as to why the same side correlation in [1] shows no change from pp to $AuAu$ collisions. Calculation of the inmedium modifications is currently in progress

REFERENCES

[1] C. Adler et al. Phys. Rev. Lett. **90**, 082302 (2003).

* PARTONIC ENERGY LOSS MODELS CAN EXPLAIN (BDMPS, GLV, GW...)

a) SINGLE INCLUSIVE

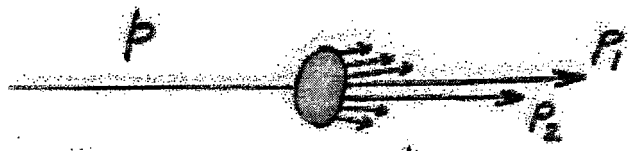
b) TWO HADRONS (BACK-TO-BACK) (X. N. WANG)

* REQUIRE HIGH DENSITY OF SCATTERERS

* HIGH DENSITY ⇒ QGP!

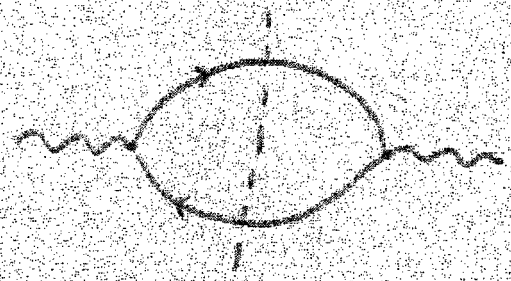
* WHAT ABOUT SAME SIDE?

REQUIRES $\mathcal{D}_q^{h_1 h_2}(z_1, z_2)$!

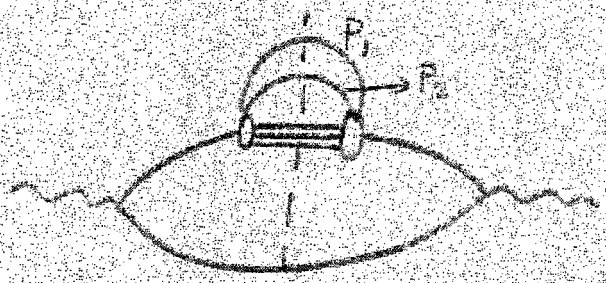


$$z_1 = \frac{p_1}{p}, \quad z_2 = \frac{p_2}{p}$$

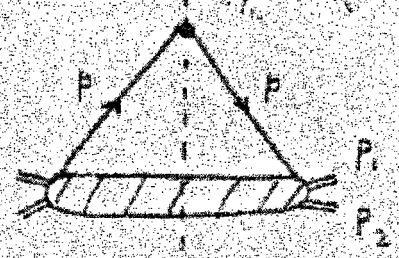
IN DIAGRAMS:



CHANGE BASIS ON ONE QUARK LINE



$$= \quad \frac{P_{2\perp}}{z} \quad \otimes \quad \frac{z^+}{2k_1^+}\,\delta\left(z_1+z_2-\frac{k_2^+}{P^+}\right)$$



$\widehat{T}_q(k, P_1, P_2)$

LIGHT VERTEX.

$$C_q(z_1, z_2) = \int \frac{d^2 \frac{z_\perp}{2}\, \frac{z_\perp}{2}}{(2\pi)^2}\, \frac{z}{2z_1 z_2} \cdot \frac{z^3}{2} \cdot$$

$$= \int \frac{d^2 \frac{z_\perp}{2}\, \frac{z_\perp}{2}}{(2\pi)^2}\, \frac{z}{2z_1 z_2}\, \frac{z^3}{2} \int \frac{d^4 k}{(2\pi)^4}\, \mathrm{Tr}\left[\frac{\gamma^+}{2k^+}\, \widehat{T}_q(k, k_1, k_2)\right] \delta\left(z - \frac{P_1^+ + P_2^+}{P^+}\right)$$

IN SIMPLE PICTURES:

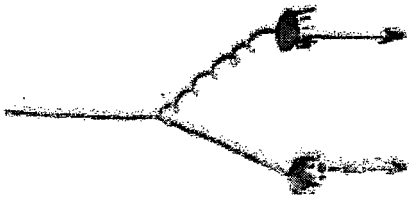
LO

$$\mathcal{D}(z_1, z_2, \mu^2)$$

NLO

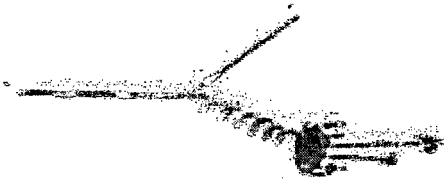
$$\frac{\alpha_s}{2\pi}\int_{\mu^2}^{Q^2}\frac{dp_\perp^2}{p_\perp^2}\int_{z_1+z_2}^{1}\frac{dy}{y^2}\,P_{q\to qg}(y)\,\times$$

$$\mathcal{D}_q\left(\frac{z_1}{y}, \frac{z_2}{y}, \mu^2\right)$$

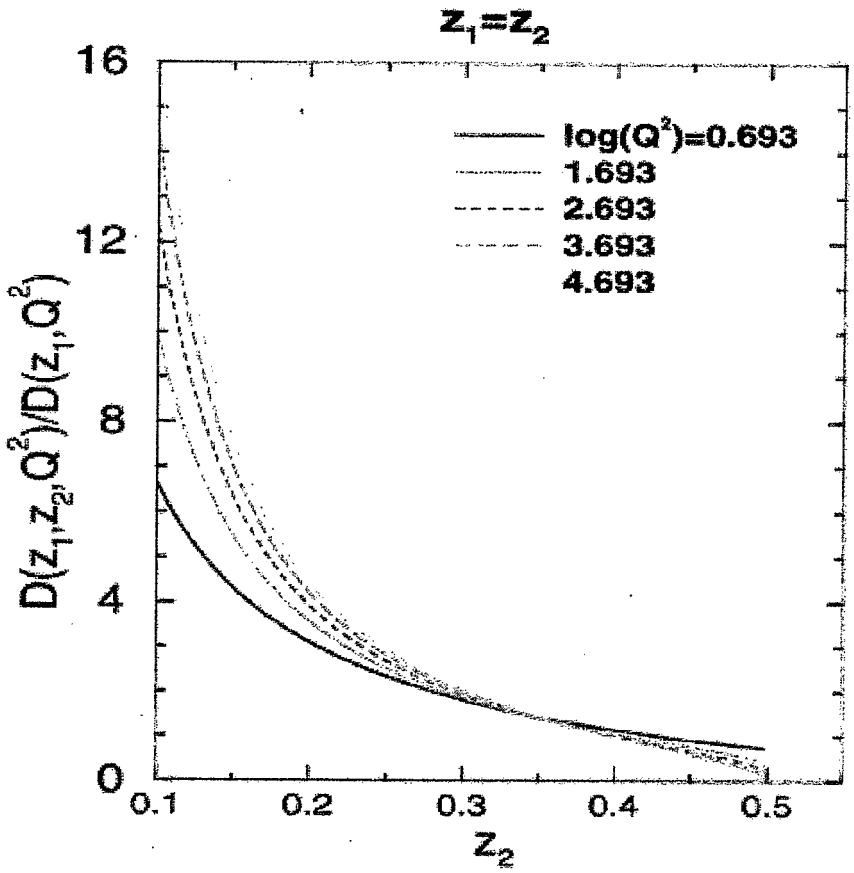
+ 

$$\frac{\alpha_s}{2\pi}\int_{\mu^2}^{Q^2}\frac{dq_\perp^2}{q_\perp^2}\int_{z_1}^{1-z_2}\frac{dy}{y(1-y)}$$

$$\hat{P}_{q\to qg}(y)\,\mathcal{D}_q\left(\frac{z_1}{y}, \mu^2\right)\mathcal{D}_g\left(\frac{z_2}{1-y}, \mu^2\right)$$

+ 

$$\frac{\alpha_s}{2\pi}\int_{\mu^2}^{Q^2}\frac{dp_\perp^2}{p_\perp^2}\,P_{q\to gq}\otimes\mathcal{D}_g\left(\frac{z_1}{y}, \frac{z_2}{y}, \mu^2\right)$$

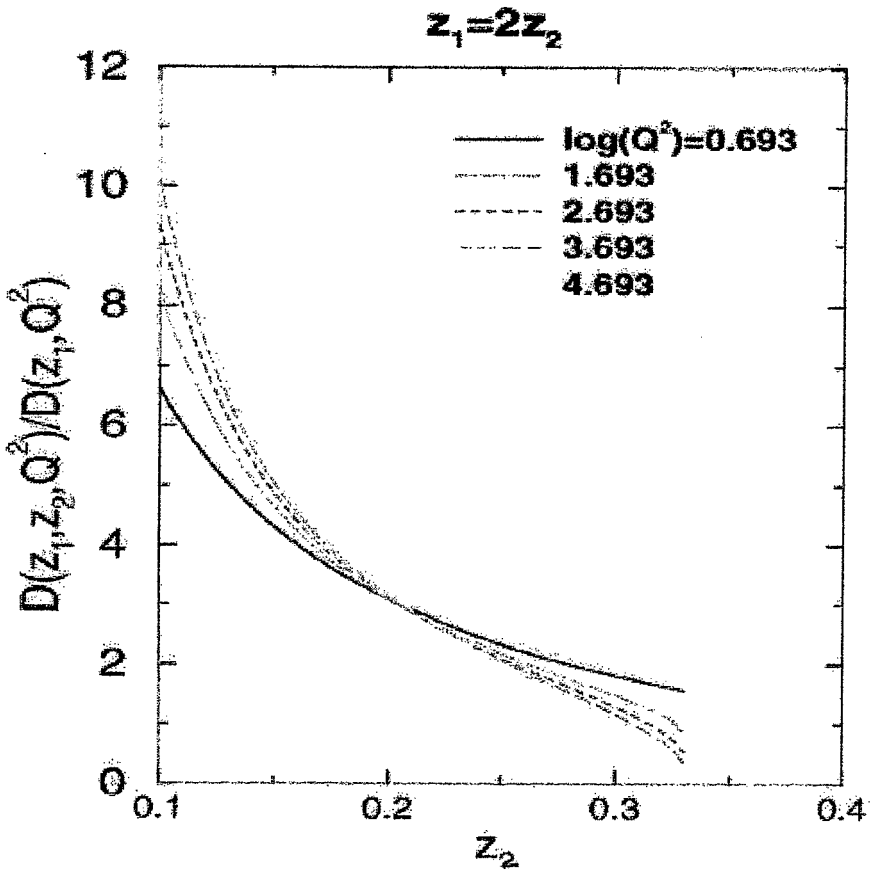


START WITH ANSATZ

$D(z_1, z_2) =$

$\mathcal{D}(z_1)\,\mathcal{D}(z_2)$

AT $Q^2 = 2\ \mathrm{GeV}^2$



VERY LITTLE CHANGE AT z_1, z_2 LARGE

Nuclear PDFs @ NLO†

Daniel de Florian
Universidad de Buenos Aires
Argentina

We perform a next to leading order QCD global analysis of nuclear deep inelastic scattering and Drell-Yan data using the convolution approach to parameterize nuclear parton densities. We find both a significant improvement in the agreement with data compared to previous extractions, and substantial differences in the scale dependence of nuclear effects compared to leading order analyses.

With the obtained nPDFs we have studied the production of neutral pions in d-Au collisions at NLO, finding a small nuclear effect for the yield R_{dAU}. To quantify the effect of nuclear shadowing in the gluon distribution on hadron production at RHIC we have computed the same observable using an alternative NLO set of nPDF with a larger shadowing in the gluon distribution at small x_N. It is found a reduction in the d-Au cross section at small p_T for the set with larger gluon shadowing, however it seems unlikely to obtain a value of $R_{dAU} < 0.8$ at $p_T \sim 2$ GeV with realistic nPDF. Similar conclusions, with a slightly bigger reduction at small p_T, are reached if the same observable is computed for neutral pion production in the forward region ($\eta \sim 3$). Any experimental finding on a stronger reduction of R_{dAU} might certainly be considered as an evidence of a new phenomena, at least beyond pQCD.

†D.de F., R.Sassot, hep-ph/0311227

nPDFs @ NLO

- NLO nPDFs needed to have a consistent pQCD calculation

- Since nuclear effects are moderate, customary to relate proton and nuclear PDFs

$$f_i^A(x_N, Q^2) = R_i(x_N, Q^2, A, Z)\, f_i(x_N, Q^2),$$

  where $f_i^A(x_N, Q^2)$ parton distribution of a *proton* bound in the nucleus

- Advantage: Easy to use $\Rightarrow$combine R_i with any set of free-proton PDFs (CTEQ, GRV, MRST)

- Problem: strictly speaking $0 \leq x_N \leq A$, but R_i and f_i only defined for $x_N \leq 1$ $\Rightarrow$problems might arise in data fit procedure: momentum conservation and NLO structure functions

- More natural $\Rightarrow$use convolution relation at initial scale Q_0

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^{A} \frac{dy}{y} W_i(y, A, Z)\; f_i(\frac{x_N}{y}, Q_0^2)$$

- Nuclear effects parametrized by weight function $W_i(y, A, Z)$ $\sim$ effective density of nucleons within the nucleus carrying momentum fraction $y \leq A$ $\Rightarrow$without nuclear effects $W_i(y, A, Z) = A\,\delta(1-y)$

- Convolution becomes a product in Mellin $\widehat{g}(N) \equiv \int_0^1 dx\, x^{N-1} g(A\,x)$ space

$$\widehat{f}_i^A(N, Q_0^2) = \widehat{W}_i(N, A, Z)\, \widehat{f}_i(N, Q_0^2)$$

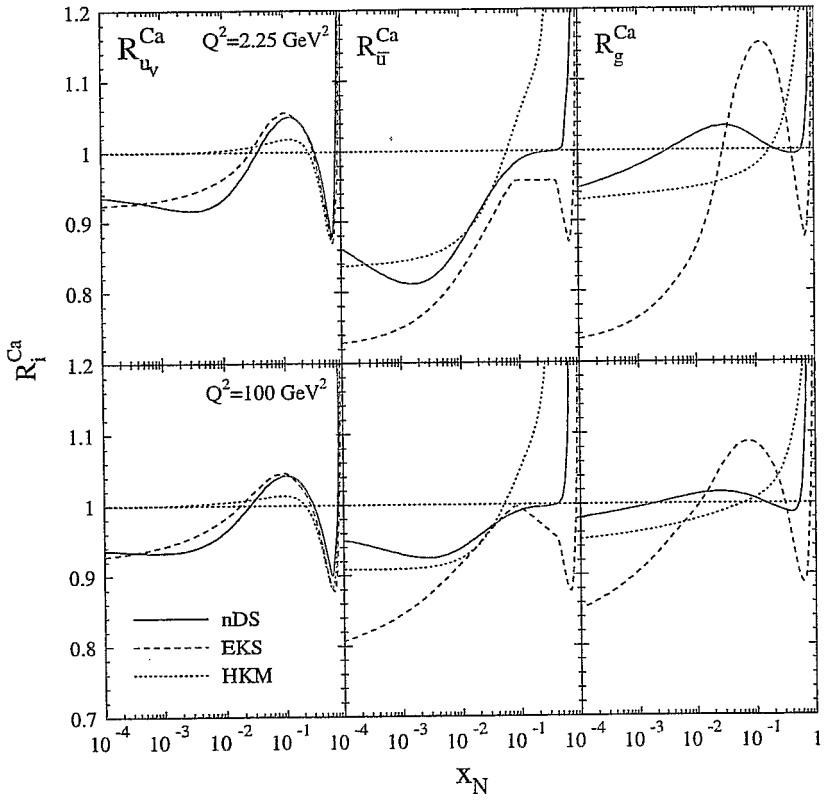
nPDFs @ NLO

- Simple procedure
  - Parametrize W functions at initial scale
  - Evolve nuclear structure function to x, Q^2 experimental value (fast Mellin inversion)
  - Compute $\chi^2 \equiv \sum_i \frac{(\sigma_i^{ex} - \sigma_i^{th})^2}{\Delta_i^2}$
  - Selecting $Q \geq 1$GeV + Drell-Yan $\Rightarrow$420 data points
  - Iterate until minimize χ^2
- Parametrization should be flexible enough $\Rightarrow$more parameters needed for valence distributions, sea and gluon important at small x
- W_i combinations of $\delta(1-\epsilon-y)$ and $(y/A)^\alpha(1-y/A)^\beta$ with smooth A dependence of the parameters to cover $4 \leq A \leq 208$ $\Rightarrow\sim$ 25 parameters
- Neglect nuclear effect in Deuterium
- Analysis performed at LO and NLO $\Rightarrow$couple of hours in P4 machine
- $\chi^2 = 300$ @ NLO and $\chi^2 = 316$ @ LO (393 d.o.f., syst. and stat. errors)

Comparison to other LO distributions

- EKS: no χ^2 analysis but comparison to almost same set of data
  K.J. Eskola, V.J. Kolhinen and C.A. Salgado (1999)
  K.J. Eskola, V.J. Kolhinen and P.V. Ruuskanen (1998)

- HKM: no Drell-Yan and Q^2 dependent Sn data
  M. Hirai, S. Kumano, and M. Miyama (2001)



- $\chi^2 \sim 630$ for EKS (large contribution from Q^2 dependent Sn data) and larger for HKM if full data set included

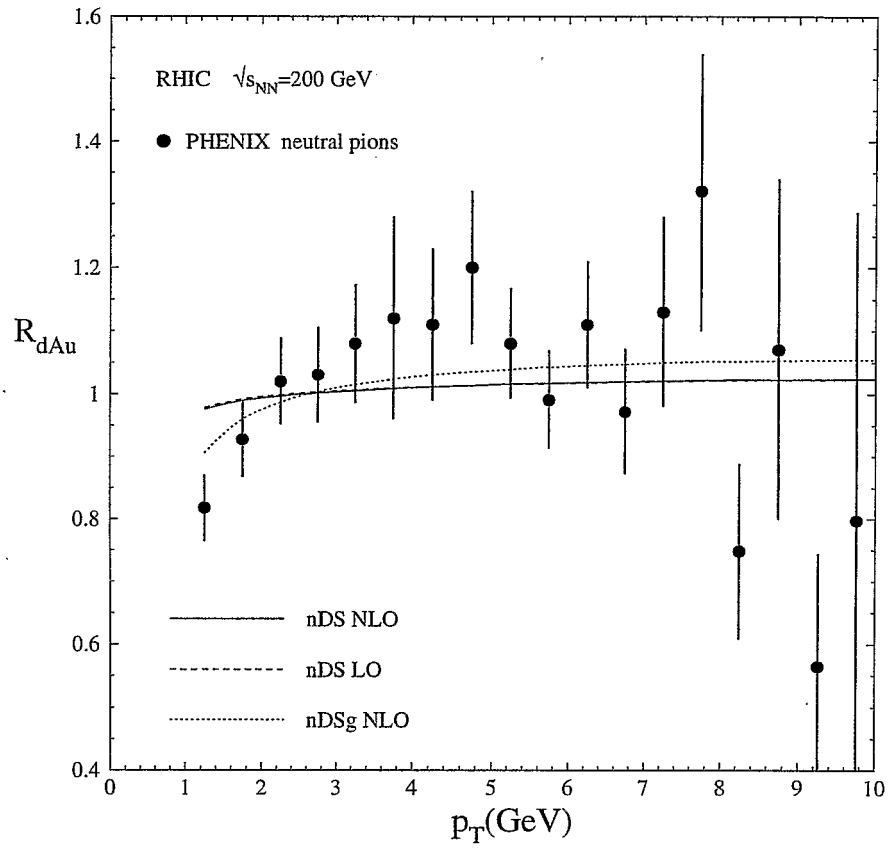
- Differences between sets $\Rightarrow$large for gluon and sea quark distributions

- Differences between LO and NLO ratios not negligible $\Rightarrow$not convenient to use LO ratios to compute NLO observables!

Pion production at RHIC

- 'high-p_T' π^0 production at PHENIX with $\sqrt{s_{NN}} = 200$ GeV and central rapidity

- Ratio $R_{dAu} = \sigma_{dAu}/\sigma_{pp}$ using frag.fnct. Kretzer (2000)



- NLO corrections almost 'cancel' in the ratio (but not in the cross-section!) $\Rightarrow$Perturbative stability of sets

- Result shows dependence on (Au) gluon density $\Rightarrow$see R_{dAu} computed using nDSg set

- Still data not precise enough to draw any conclusion or include in a global fit

- Similar results for larger rapidity: more shadowing at $p_T < 2$ GeV but never $R_{dAu} < 0.8$

High-p_T data at RHIC

Boris Kopeliovich

- Gribov's inelastic shadowing corrections and the normalization of high-p_T data
- BRAHMS data: the usual Glauber suppression ($\sim A^{-\frac{1}{3}}$) for valence quark production
- Inside-outside hadronization.

Read in: J. Nemchik, E. Predazzi, A. Hayashigaki & B.K. hep-ph/0311220

- **What is needed:** the cross section of high-p_T hadron production $\frac{d\sigma^{dA}}{d^2p_T}$ (with absolute normalization)

- **What is measured:** only the shape of the p_T-distribution

$$\underbrace{\frac{dN^{dA}}{d^2p_T}}_{\text{measured}} = \underbrace{\frac{1}{\sigma_{in}^{dA}}}_{\text{calculated}} \underbrace{\frac{d\sigma^{dA}}{d^2p_T}}_{\text{needed}}$$

The normalization factor σ_{in}^{dA} is predicted theoretically within the Glauber model (!).

How reliable and model-independent are these calculations?

S.K.
PRC 68 (2003)
044906

These calculations may be challenged in two respects

- Glauber model results are subject to Gribov's inelastic corrections which make σ_{in}^{dA} smaller.

- The Glauber model itself should be applied properly.
  σ_{in}^{dA} may be calculated differently, dependent on which inelastic channels are included.

Nuclear cross section

$$\sigma_{tot}^{hA} = 2\int d^2b \sum_i |\psi_i|^2 \left[1 - e^{-\frac{1}{2}\sigma_i^{hN} T_A(b)}\right]$$

$$= 2\int d^2b \left[1 - \left\langle e^{-\frac{1}{2}\sigma_i^{hN} T_A(b)}\right\rangle\right]$$

Glauber approximation

$$\sigma_{tot}^{hA}\Big|_{Gl} = 2\int d^2b \left[1 - e^{-\frac{1}{2}\langle\sigma_i^{hN}\rangle T_A(b)}\right]$$

Nuclear medium is more transparent

$$\left\langle e^{-\frac{1}{2}\sigma_i^{hN} T_A}\right\rangle \geq e^{-\frac{1}{2}\langle\sigma_i^{hN}\rangle T_A}$$

(Some of the fluctuations are more penetrating than others)

The difference is the Gribov's inelastic shadowing correction.

The multiplicity of radiated gluons which is proportional to $A^{1/3}$ explains $\propto A$ dependence at $\eta = 0$.

However, the number of valence quarks is fixed and independent of A.

Therefore, at $\eta = 3.2$

$$\int d^2p_T \left.\frac{d\sigma(dA \to hX)}{d^2p_T\, d\eta}\right|_{\eta=3.2} \propto A^{2/3}$$

Therefore it is suppressed by factor $\sim \frac{1}{6}$ compared to $\eta = 0$ at least at small p_T.

This is a higher twist effect enhanced by factor $A^{1/3}$

Conclusions for Gribov's corrections

- The normalization of the high-p_T cross section is calculated and overestimated, since misses the Gribov's corrections.

- The main uncertainty comes from the energy dependent part of the Gribov's corrections related to gluon shadowing. Current models predict corrections ranging from 10% to 30%

- To fix the normalization one should either directly measure the cross sections, or study the Gribov's corrections experimentally, e.g. with spectator nucleons.

B. Cole, Columbia University / BNL

Contribution unavailable at time of print.

for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

Application of the Monte Carlo Glauber Model in d+Au Collisions

M. Miller, Yale University

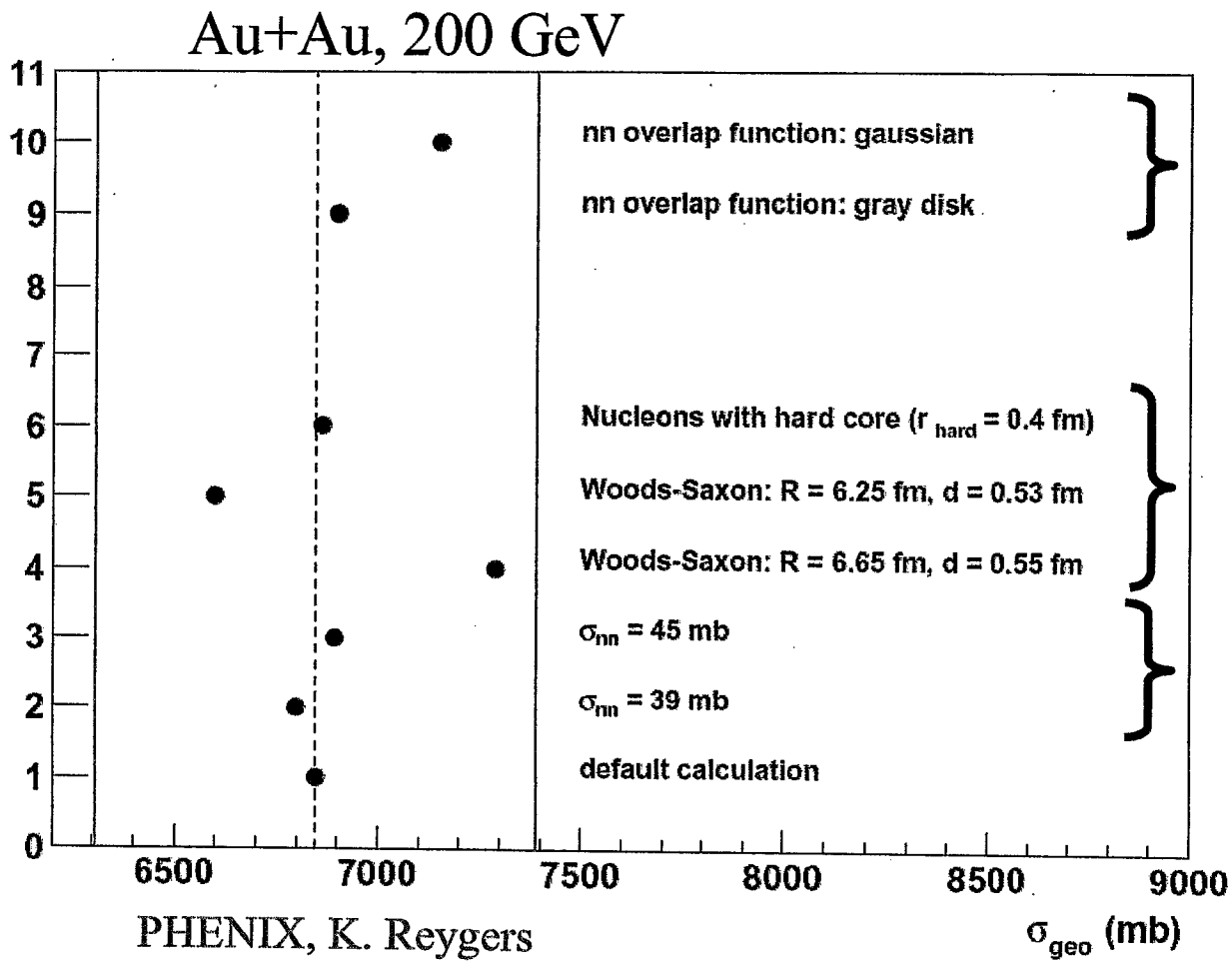
for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

Glauber Calculations: Summary

- Geometrical approach
- Assumptions?
  - No dynamics!
  - Straight line trajectories
  - No nucleon excitation
  - No explicit p_T dependence
- Assumptions most robust in central Au+Au
- Correlations/fluctuations become important in p+p limit

- Au+Au:
  - Systematics well understood
  - σ_{inel} : sensitive to n-n interaction
- d+Au
  - Glauber+UA5 agrees with forward N_{ch}
  - Robust selection of different centrality classes
- Consistency in N_{coll} calc.
  - PHENIX agrees with STAR
  - Minbias: 7.5 vs. 8.4 diff. due to trigger efficiencies

Cross Section: Systematics

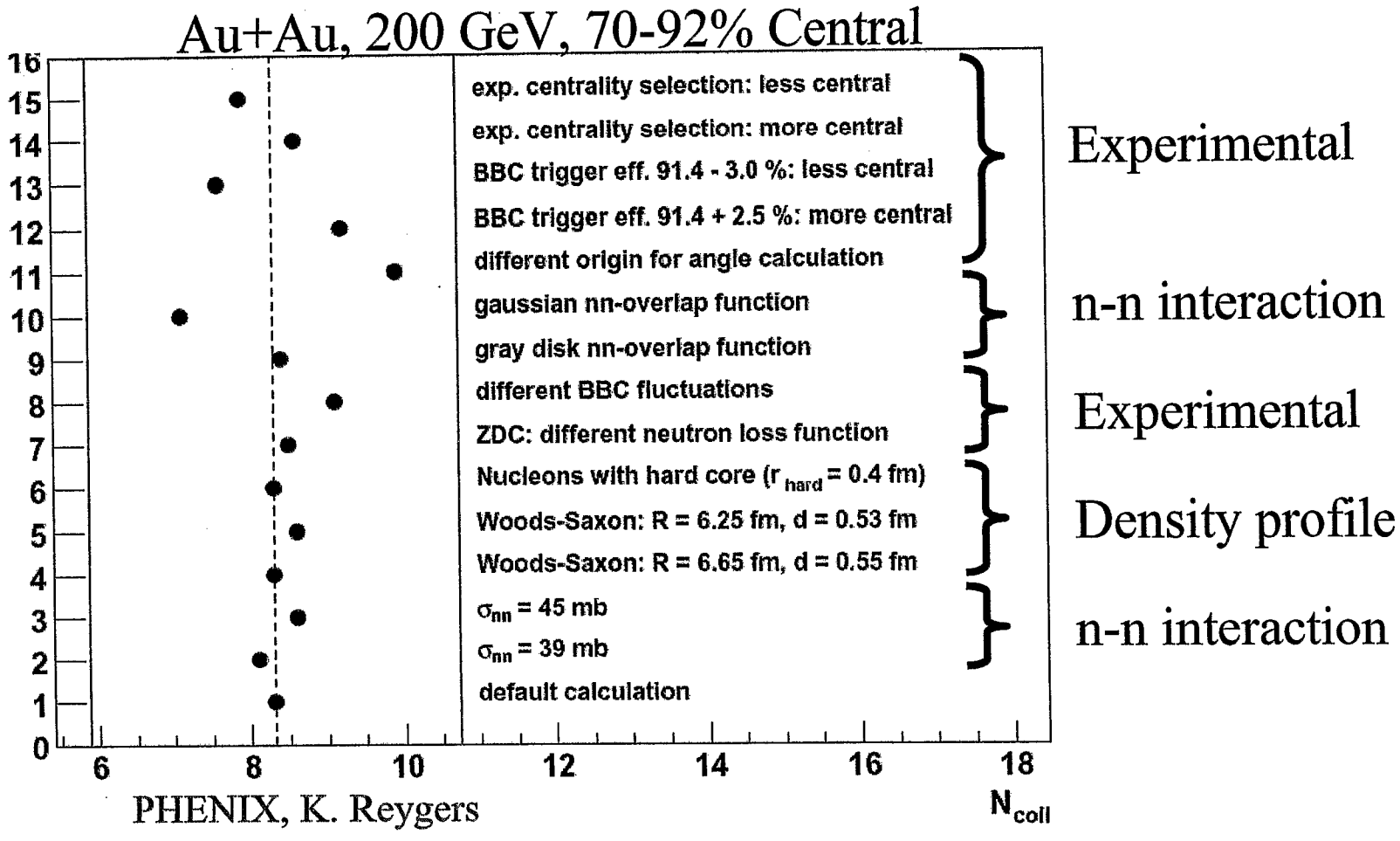


n-n interaction

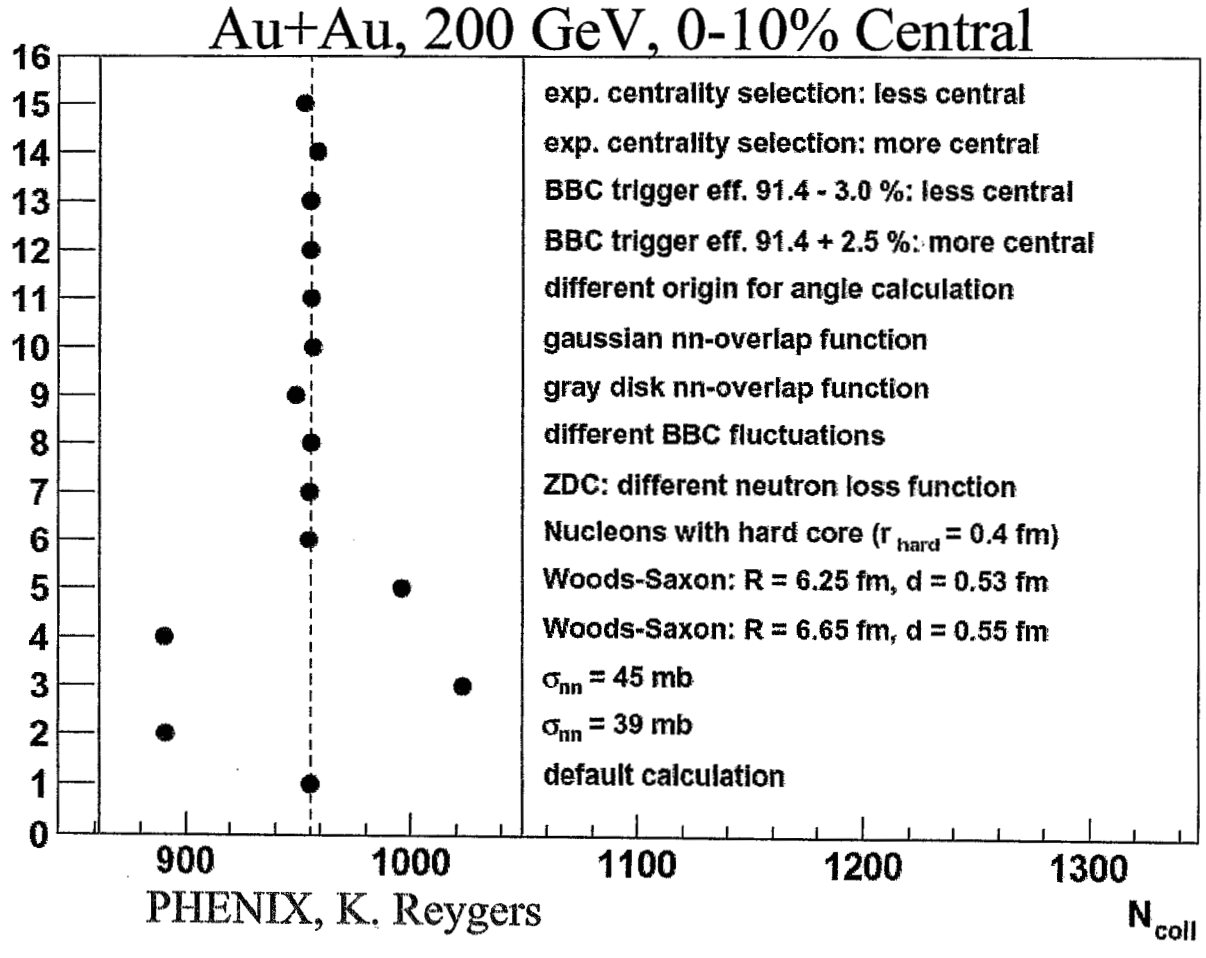
Density Profile

n-n interaction

$\langle N_{coll} \rangle$: Systematics



$\langle N_{coll} \rangle$: Systematics



$$R_{AA}(b) = \frac{d^2 N_{AuAu} / dp_T^2}{T_{AB}(b) \cdot d^2 \sigma_{pp} / dp_T^2}$$

$$T_{AB}(b) = N_{coll}(b) / \sigma_{inel}$$

$$\sigma_{inel} = 42 \pm 1 \text{ mb}$$

$$\Rightarrow \delta_{N_{coll}} \; ; \; 2.5\%$$

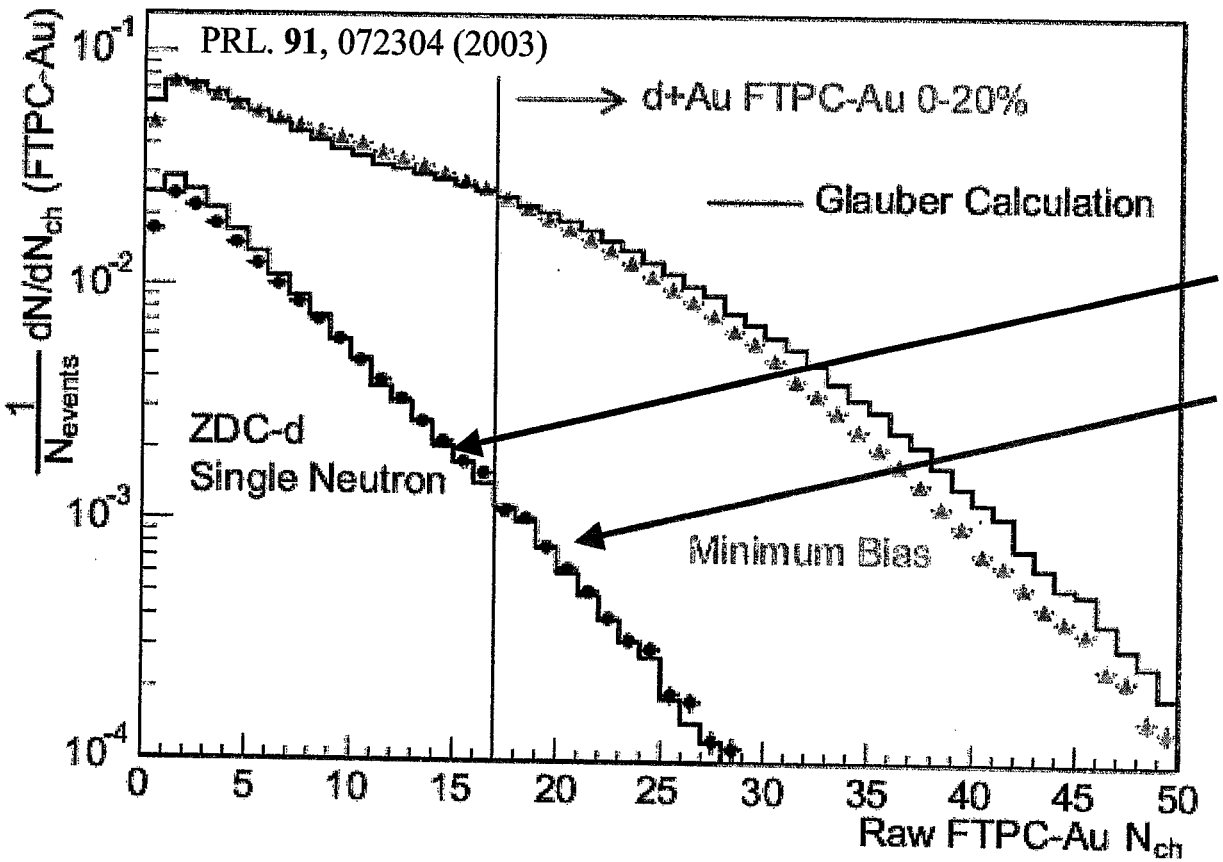
$$\Rightarrow \delta_{T_{AA}} < 0.5\%$$

Density profile dominant uncertainty

Avoiding "Trigger Bias" in d+Au

- Different experimental triggers at RHIC
  - STAR min-bias: ZDC-Au (95±3% of $\sigma_{hadronic}$)
- Study high p_T production for midrapidity
  - $|\eta|<1$
  - STAR TPC
- Define centrality using forward region
  - $2.8<\eta<3.8$ (Au fragmentation region)
  - STAR Forward TPC
  - Already measured for p+p at UA5
- Cross-checks:
  - Forward multiplicity studied vs. $\Delta\varphi$ w.r.t. leading TPC hadron: $N_{ch}(2.8<\eta<3.8)$ stable vs. leading particle p_T
  - Tag single neutron in the ZDC-deuteron direction

Simulating N_{ch} in d+Au



$$\sigma_{had.}^{MC} = 2.2 \pm 0.1\,\mathrm{b}$$

$$\sigma_{1-n}^{MC} = (.18 \pm .03)\sigma_{had}$$

$$\sigma_{1-n}^{Meas.} = (.19 \pm .01)\sigma_{had}$$

Class	N_{coll}
0-100% d+Au	7.5 ± 0.4
0-20% d+Au	15.0 ± 1.1
1-neut. d+Au	2.9 ± 0.2

Selecting significantly different event classes

Single Spin Asymmetries and QCD

John Collins,
Penn State Univ., 104 Davey Lab., University Park PA 16802

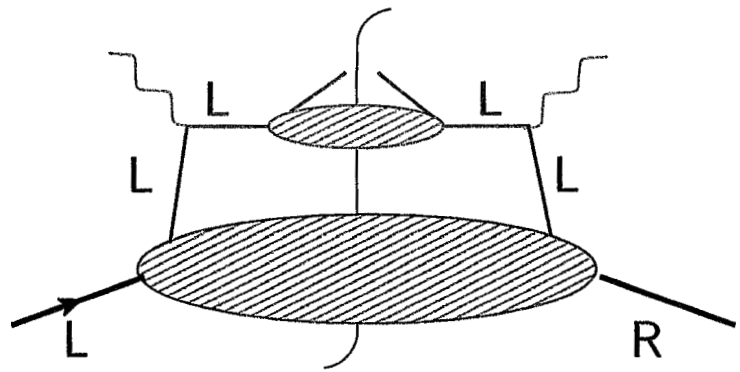
This talk introduced some of the main topics covered in the session on transverse single-spin asymmetries with hard scattering.

- An important long-term motivation is that SSAs provide a microscopic probe of chiral symmetry breaking.
- Leading-power SSA's can occur in azimuthal distributions of a particle's momentum transverse to an axis given by naive parton model ideas.
- Cases include Semi-Inclusive DIS in electron-hadron collisions, and Drell-Yan, high p_T dihadron, dijet, and photon-jet production in hadron-hadron collisions.
- These processes involve SSAs in the azimuthal distribution of parton transverse momentum in parton densities (Sivers function) and in fragmentation functions (Collins function).
- A correct treatment requires precise and valid operator definitions of these functions, particularly as regards the directions of the Wilson lines that make the operators gauge invariant.
- Time reversal gives a reversal of sign of the Sivers asymmetry between DIS and DY.
- The lines cannot be light-like. Related to this are Sudakov effects associated with gluon emission that dilute the SSA and that can be analyzed with the aid of non-light-like Wilson lines. (This uses an equation due to Collins and Soper.)
- Work is underway to analyze the universality or lack of it associated with k_T dependent fragmentation functions.

How to make high-p_T, SSA, leading power?

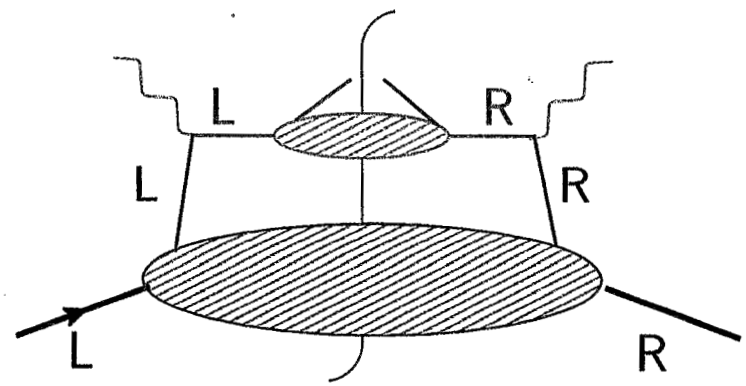
Incoming quark k_T (Sivers)
Orbital $L_z \implies$ azimuthal dep.:

$$\frac{dN}{\mathrm{d}^2 k_T} \propto \text{const} + \text{const}|k_T| \sin(\phi - \phi_S)$$



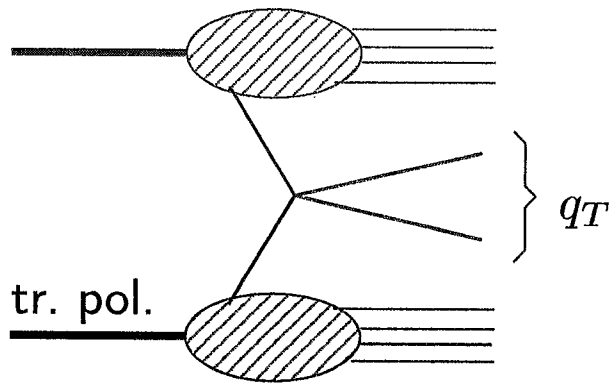
Quark poln. measurement

- Single-hadron azimuth
- Two-hadron azimuth
- Hadron (Λ) polarization



All cases: **Must have azimuthal angle to measure**

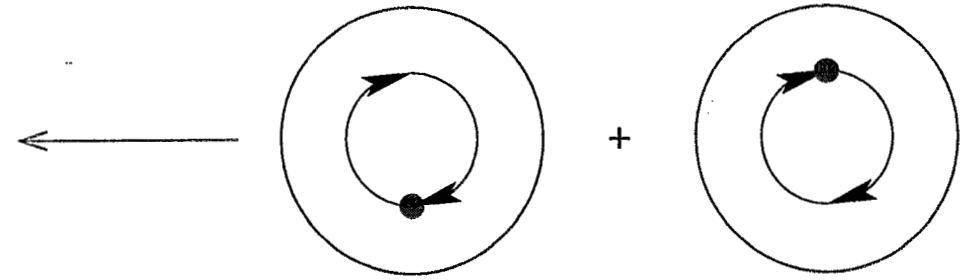
RHIC processes for SSA



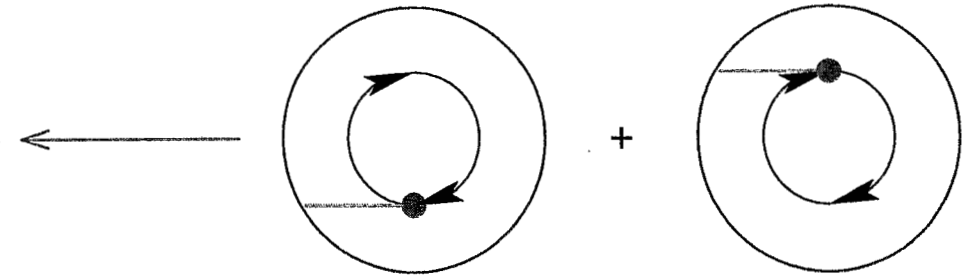
- Drell-Yan $\vec{q}_T$
- $\gamma + \text{jet}$ total $\vec{q}_T$
- $\text{jet} + \text{jet}$ total $\vec{q}_T$
  [Especially out-of-plane]
- But parton k_T much less than single-jet p_T
  $\Longrightarrow$ SSA in single-jet p_T is "higher twist", i.e., power suppressed.
- Etc.
- Also target fragmentation, but that's harder for theorists!

T reversal on Sivers asymmetry

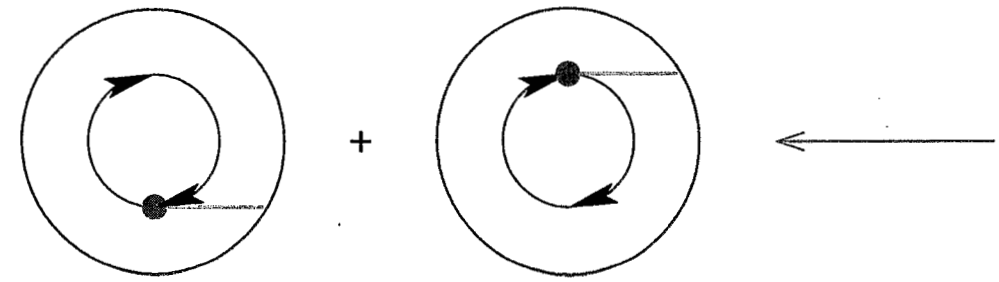
- No vector gluons
  Transverse deflections cancel
  $\Longrightarrow$ no Sivers SSA (TP)



- DIS in QCD: final-state glue
  $\Longrightarrow$ non-cancellation
  $\Longrightarrow$ Sivers SSA allowed



- Drell-Yan: initial-state glue
  $\Longrightarrow$ reversed sign of SSA
  "T-odd operator"



- Implement by Wilson lines in pdf definitions

Universality, with k_T-dependence pdfs, etc

- Precise gauge invariant defn. of pdf and frag fn. needs:
  - Wilson lines in operators

$$\text{FT of } \langle p, s|\ \overline{\psi}(y)\, W(y \text{ to } \infty)^\dagger\ W(0 \text{ to } \infty)\, \psi(0)\ |p, s\rangle$$

  - Direction:
    * Future or past?
    * Non-light-like: rapidity of line?
- Wilson line direction related to measurement:
  - Future $\Longleftrightarrow$ Outgoing struck parton
  - Past $\Longleftrightarrow$ Incoming anti-parton
  - Rapidity $\Longleftrightarrow$ y_{gluon} cutoff:
    * With light-like line: Divergences for $y_{\text{gluon}} \to -\infty$
    * $\Longrightarrow$ Need cutoff or "generalized renormalization"
    * Usual dogma about real-virtual cancellation does not apply
- Universality between all processes? (JCC & Metz)

Single Transverse Spin Asymmetry in the Pion Production at RHIC and EIC

YUJI KOIKE

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We study the single spin asymmetry (SSA) for the inclusive pion production in pp collision, $p + p^\uparrow \to \pi + X$ and SIDIS, $e + p^\uparrow \to e + \pi + X$. SSA is a "T-odd" observable which appears as an interference effect between the amplitudes with different phases in the T-invariant theory. In the literature, there have been two systematic frameworks for SSA. One is based on the so-called "T-odd" distribution/ fragmentation functions of quarks with intrinsic transverse momentum (k_T). Since this intrinsic k_T is of nonperturbative origin, it is suited for the description of SSA for the low-p_T pion production. The other is based on the twist-3 distribution/fragmentation functions in the framework of the collinear factorization. In this approach p_T of the final pion is generated from the partonic hard cross section and thus is suited for the describtion of SSA for the large-p_T pion production.

In this talk we present the analysis following the second approach. Given that unpolarized $pp \to \pi X$ can be well described by the NLO QCD for p_T as low as 1 GeV, our LO twist-3 analysis for the above processes provides a useful reference to interpret the recent RHIC-STAR data and also for the future EIC experiment.

A systematic formalism for the twist-3 cross section was developed by Qiu and Sterman. For $p + p^\uparrow \to \pi + X$, we have three contributions:

$$(A)\ G_F(x_1, x_2) \otimes q(x') \otimes \hat{q}(z) \otimes \sigma_A,$$

$$(B)\ \delta q(x) \otimes q(x') \otimes \widehat{E}_F(z_1, z_2) \otimes \sigma_B,$$

$$(C)\ \delta q(x) \otimes \widehat{E}_F(x_1', x_2') \otimes \hat{q}(z) \otimes \sigma_C,$$

and for $e + p^\uparrow \to e + \pi(p_T) + X$ we have two contributions:

$$(A')\ G_F(x_1, x_2) \otimes \hat{q}(z) \otimes \sigma_A',$$

$$(B')\ \delta q(x) \otimes \widehat{E}_F(z_1, z_2) \otimes \sigma_B',,$$

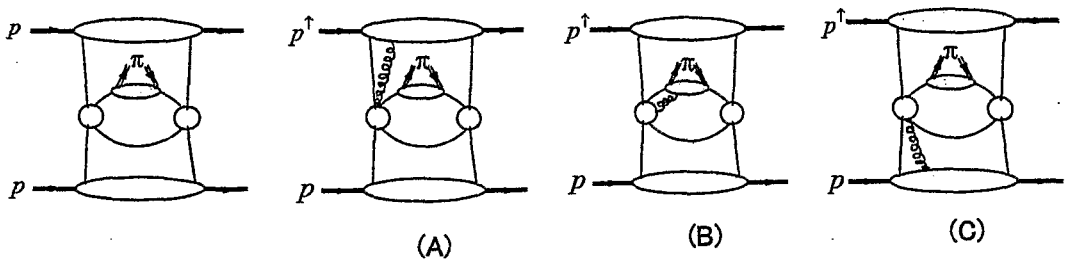
where $\delta q(z)$ is the transversity distribution. We have argued in this talk that (A) and (B) can be equally important sources for $p + p^\uparrow \to \pi + X$, while (C) is negligible. We have also studied the effect of G_F on the azymuthal asymmetry for $e + p^\uparrow \to e + \pi(p_T) + X$ by fixing its magnitude so as to reproduce A_N of FNAL-E704 and RHIC-STAR data.

Factorization for twist-3: three twist-3 cross sections

$$p^{\uparrow}(p, S_\perp) + p(p') \to \pi(p_\pi) + X,$$

$$\begin{aligned}
\Delta\sigma \;\sim\; & G_F(x_1, x_2) \otimes q(x') \otimes \hat{q}(z) \otimes \hat{\sigma}_A \quad (A) && \text{(Qiu\&Sterman' 99)} \\
+\; & \underline{\delta q(x)} \otimes q(x') \otimes \underline{\widehat{E}_F(z_1, z_2)} \otimes \hat{\sigma}_B \quad (B) && \text{(Koike' 02)} \\
+\; & \underline{\delta q(x)} \otimes \underline{E_F(x_1', x_2')} \otimes \hat{q}(z) \otimes \hat{\sigma}_C \quad (C) && \text{(Kanazawa\&Koike' 00)}
\end{aligned}$$

δq: transversity ——: chiral-odd



Unpolarized: twist-2

Polarized: twist-3

Characteristics of the result

★ (A),(B): large contribution in the forward region ($x_F \to 1$) owing to (i) the derivatives $\frac{d}{dx}G_F(x,x)$ and $\frac{d}{dz}\widehat{E}_F(z,z)$, and (ii) the properties of $\hat{\sigma}_A$ and $\hat{\sigma}_B$.

$A_N \propto_{x_F \to 1} M_N \left(O(\frac{p_T}{-U}) + O(\frac{1}{p_T})\right) \frac{1}{1-x_F}$: typical to twist-3.

$\frac{1}{1-x_F}$ behavior is due the ansatz:

$G_F(x,x) \equiv Kq(x)$ and $\widehat{E}_F(z,z) \equiv K'\widehat{q}(z)$ with flavor dependent factor K and K', $K_u = -K_d = 0.07$ and $K_u' = -0.11$, $K_d' = -0.19$.

★ (C): negligible due to the smallness of $\hat{\sigma}_C$ relative to (A) and (B).

★ Each soft-gluon pole function has the following physical interpretation due to its Dirac structure:

$G_F(x,x)$: Unpol. quark distribution in $\perp$ pol. target.

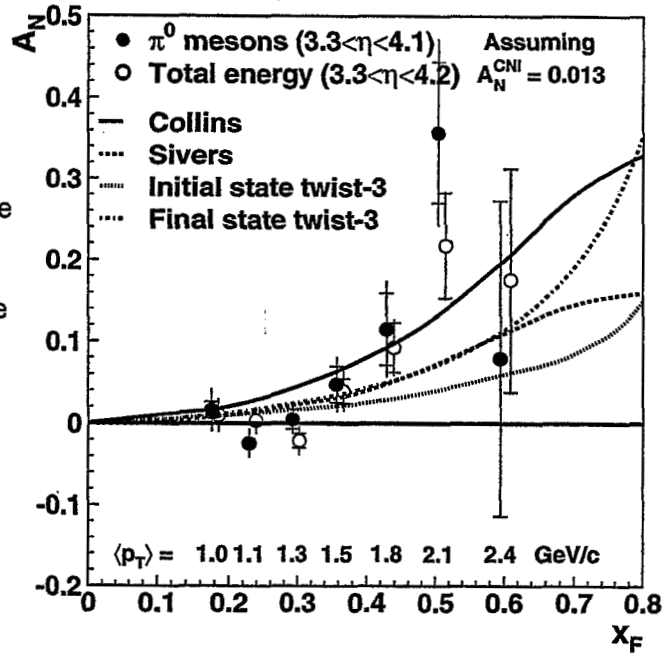
$\widehat{E}_F(z,z)$: Pion fragmentation from $\perp$ pol. quark.

$E_F(x,x)$: $\perp$ pol. quark distribution in unpol. target.

RHIC-STAR, hep-ex/0310068

(A): Initial state twist-3

(B): Final state twist-3



★Single Transverse Spin Asymmetry for $e+p^{\uparrow} \to e+\pi(p_T)+X$

No (or integrated) transverse momentum of π in $O(\alpha_s^0)$ (Jaffe & Ji, '92).

$$\Delta\sigma \propto g_T(x)\hat{q}(z)+\delta q(x)\hat{e}(z)/xz$$

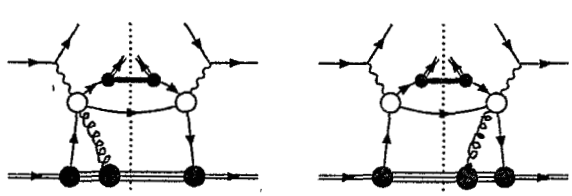
Transverse momentum is generated by the $O(\alpha_s)$ partonic hard cross section.

Similarly to $p+p^{\uparrow} \to \pi(p_T)+X$, we have two twist-3 contributions.

$G_F(x,x)\otimes\hat{q}(z)\otimes\sigma$ ⟶ This talk.

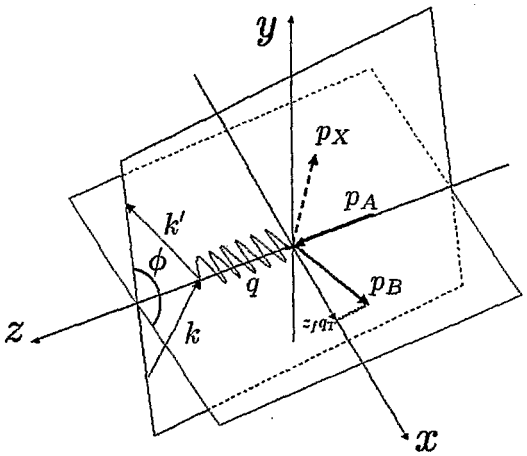
$\delta q(x)\otimes\hat{E}_F(z,z)\otimes\sigma'$ ⟶ Under study.

In this work, we focuss on the first contribution. By fixing the soft-gluon-pole function $G_F(x,x)$ in $p+p^{\uparrow} \to \pi(p_T)+X$, we will study its effect in SIDIS.



★"Hadron frame" for $e(k)+p(p_A,S_\perp)\rightarrow e(k')+\pi(p_B)+X$

(Meng, Olness, Soper('91)) photon-proton Breit frame



$$q=k-k'=(0,0,0,-Q)$$

$$p_A=(\frac{Q}{2x_{bj}},0,0,\frac{Q}{2x_{bj}})$$

$$p_B=\frac{z_f}{2}(1+\frac{q_T^{\ 2}}{Q^2},\frac{2q_T}{Q},0,\frac{q_T^{\ 2}}{Q^2}-1)$$

$p_T=z_f q_T$: $\perp$ mom. of hadron B

$$k=\frac{Q}{2}(\cosh\psi,\sinh\psi\cos\phi,\sinh\psi\sin\phi,-1)$$

$$\cosh\psi=\frac{2x_{bj}S_{ep}}{Q^2}-1$$

ϕ: Azymuthal angle between Lepton- and hadron- planes

$\perp$ Spin vector

$S_\perp=(0,\cos\Phi_S,\sin\Phi_S,0)$

Φ_S : Azymuthal angle measured from HADRON plane

★ Differential cross section for $e+p^\uparrow\rightarrow e+\pi(p_T)+X$

$$\frac{d^5\sigma}{dQ^2dx_{bj}dz_f dq_T^{\ 2}d\phi}=\sin\Phi_S(\sigma_0+\cos(\phi)\sigma_1+\cos(2\phi)\sigma_2)$$

The first $\sin\Phi_S$ behavior is the same as Siver's asymmetry!

Recall: Unpolarized cross section also has

$1,\ \cos(\phi),\ \cos(2\phi)$ decomposition (late 70's).

★Characteristics of the asymmetry

Define: Azymuthal asymmetries:

$$\langle\cos(n\phi)\rangle \equiv \frac{\int_0^{2\pi} d\phi \cos(n\phi) \frac{d^5\sigma^{av,pol}}{dQ^2 dx_{bj} dz_f dq_T{}^2 d\phi}}{\int_0^{2\pi} d\phi \frac{d^5\sigma^{av}}{dQ^2 dx_{bj} dz_f dq_T{}^2 d\phi}} = \frac{\sigma_n{}^{av,pol}}{(2)\sigma_0},$$

$(n = 0,1,2)$

$$\langle 1\rangle_N \sim_{z_f\to 1} \left(\frac{M_N q_T}{Q^2}\right) \frac{x_{bj}}{1-z_f} \sin\Phi_S \qquad \text{NOT} \quad \frac{1}{q_T} \quad !$$

Typical to twist-3

$\frac{d}{dx}G_F(x,x) \propto \frac{d}{dx}q(x)$ and $z_f \to 1$ forces $x \to 1$.

Model estimate: GRV98, KKP2000

★Summary

Single transverse-spin asymmetry for the large-p_T hadron production, $p + p^\uparrow \to \pi(p_T) + X$ and $e + p^\uparrow \to e + \pi(p_T) + X$, was studied in the framework of the QCD factorization.

For pp collision, rising A_N with x_F found in E704 and STAR can be obtained from two twist-3 cross sections. But at $p_T <$ a few GeV, A_N from the twist-3 cross sections behave as $\sim 1/p_T$.

For the single-spin azymuthal-asymmetry for $e + p^\uparrow \to e + \pi(p_T) + X$, we studied the effect of the soft-gluon pole function $\frac{d}{dx}G_F(x,x)$ fixed in $p + p^\uparrow \to \pi + X$:

$$\langle 1\rangle_N \propto_{z_f\to 1} \left(\frac{M_N q_T}{Q^2}\right) \frac{x_{bj}}{1-z_f} \sin\Phi_S$$

$\langle 1\rangle_N$ can be of $O(5\,\%)$.

$\langle\cos(n\phi)\rangle_N$ $(n = 1,2)$ is less than 1 %.

Quark Correlations and Single Spin Asymmetries

Matthias Burkardt (NMSU)

The Sivers asymmetry is analyzed in light-cone gauge. The average transverse momentum of the quark distribution is related to the correlation between the quark distribution and the transverse component of the gauge field at $x^- \pm \infty$. We then use finiteness conditions for the light-cone Hamiltonian to relate the transverse gauge field at $x^- = \pm\infty$ to the color density integrated over x^-. This result allows us to relate the average transverse momentum of the active quark to color charge correlations in the transverse plane.

Results presented have been published in:

1. M. Burkardt, "Quark correlations and single spin asymmetries," arXiv:hep-ph/0311013.
2. M. Burkardt and D. S. Hwang, "Sivers asymmetry and generalized parton distributions in impact parameter space," arXiv:hep-ph/0309072.
3. M. Burkardt, "Chromodynamic lensing and transverse single spin asymmetries," arXiv:hep-ph/0309269 and hep-ph/0302144.
4. M. Burkardt, Phys. Rev. D **66**, 114005 (2002); arXiv:hep-ph/0209179.

Sivers Asymmetry in $A^+ = 0$ gauge

$\hookrightarrow$ (LC gauge)

$$P(x, \mathbf{k}_\perp) = \int \frac{dy^- d^2\mathbf{y}_\perp}{16\pi^3} e^{-ixp^+y^- + i\mathbf{k}_\perp \cdot \mathbf{y}_\perp} \times \langle p, s \,|\bar{q}(y)\gamma^+ U_{[\infty^-, \mathbf{y}_\perp, \infty^-, \mathbf{0}_\perp]} q(0)|\, p, s\rangle .$$

$\hookrightarrow$ ... $\longrightarrow$

$$\begin{aligned}
\langle \mathbf{k}_\perp \rangle &\equiv \int dx \int d^2\mathbf{k}_\perp P(x, \mathbf{k}_\perp)\, \mathbf{k}_\perp \\
&= -\frac{g}{2p^+} \langle p, s \,|\bar{q}(0)\mathbf{A}_\perp(\infty^-, \mathbf{0}_\perp)\gamma^+ q(0)|\, p\rangle . \\
&= -\frac{g}{4p^+} \langle p, s \,|\bar{q}(0)\alpha_\perp(\mathbf{0}_\perp)\gamma^+ q(0)|\, p\rangle .
\end{aligned}$$

with $\alpha_\perp(\mathbf{x}_\perp) \equiv [\mathbf{A}_\perp(\infty^-, \mathbf{x}_\perp) - \mathbf{A}_\perp(-\infty^-, \mathbf{x}_\perp)]$

Finiteness Conditions

- Demand absence of infrared divergences in LC Hamiltonian for $x^- \longrightarrow \pm\infty$ (quarks: Antonucchio, Brodsky, Dalley , "ladder relations")

$\hookrightarrow$ "finiteness conditions" on states:

(1) $\partial^i \alpha_a^i(\mathbf{x}_\perp) \stackrel{!}{=} -\rho_a(\mathbf{x}_\perp)$, where $\rho_a(\mathbf{x}_\perp)$ is the total charge (quarks plus gluons) along a line with fixed $\mathbf{x}_\perp$

$$\rho_a(\mathbf{x}_\perp) = g \int dx^- \sum_q \bar{q}\gamma^+ \frac{\lambda_a}{2} q - f_{abc} A_b^i \partial_- A_c^i$$

(2) $\alpha_\perp(\mathbf{x}_\perp)$ must be pure gauge

$$\alpha_i(\mathbf{x}_\perp) = \frac{i}{g} U^\dagger(\mathbf{x}_\perp) \partial_i U(\mathbf{x}_\perp)$$

Finiteness Conditions

- $\partial^i \alpha_a^i(\mathbf{x}_\perp) \stackrel{!}{=} -\rho_a(\mathbf{x}_\perp)$ another reminder that gauge field at $x^- = \pm\infty$ cannot be set to zero in LC-gauge

$\hookrightarrow$ shows again the need for a careful prescription of the k^+-singularity in gauge field propagator

- Conditions on $\alpha_a^i(\mathbf{x}_\perp)$ very similar to Eqs. derived by McLerran, Venugopalan et al. in context of gluon distributions at small x

$\hookrightarrow$ $\alpha_a^i(\mathbf{x}_\perp)$ nonzero and potentially large, but what is the net effect for Sivers asymetry?

Quark Correlations $\longleftrightarrow$ SSA

- lowest order (small g) solution to finiteness conditions

$$\alpha_a^i(\mathbf{x}_\perp) = -\int \frac{d^2\mathbf{y}_\perp}{2\pi} \frac{x^i - y^i}{|\mathbf{x}_\perp - \mathbf{y}_\perp|^2} \rho_a(\mathbf{y}_\perp)$$

(equivalent to treating FSI in lowest order perturbation theory).

- Insert into expression for Sivers asymmetry in LC-gauge

$\hookrightarrow$

$$\langle k_q^i \rangle = -\frac{g}{4p^+} \int \frac{d^2\mathbf{y}_\perp}{2\pi} \frac{y^i}{|\mathbf{y}_\perp|^2} \left\langle p, s \left| \bar{q}(0)\gamma^+ \frac{\lambda_a}{2} q(0) \rho_a(\mathbf{y}_\perp) \right| p, s \right\rangle$$

Universality of T-odd effects in single spin azimuthal asymmetries[1]

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Hadrons are incorporated in hard processes via distribution and fragmentation functions that show up in the parameterisation of matrix elements of specific quark and gluon operators. For hard processes involving a single hadron such as inclusive leptoproduction or 1-particle inclusive electron-positron annihilation the soft parts appearing at leading order involve correlators with two quark or two gluon fields separated along a light-like direction depending on a single momentum (fraction) $x = p^+/P^+$ for distribution functions contained in the correlator $\Phi(x)$, or on the fraction $z = P_h^-/k^-$ for fragmentation functions contained in the correlator $\Delta(z)$. The two quark fields in these correlators are connected by a straight-line gauge link arising from leading quark-quark-gluon matrix elements. In the parameterisation for Φ (Δ) that is relevant at leading order in hard processes, three distribution (fragmentation) functions appear, for unpolarized quarks, longitudinally and transversely polarized quarks.

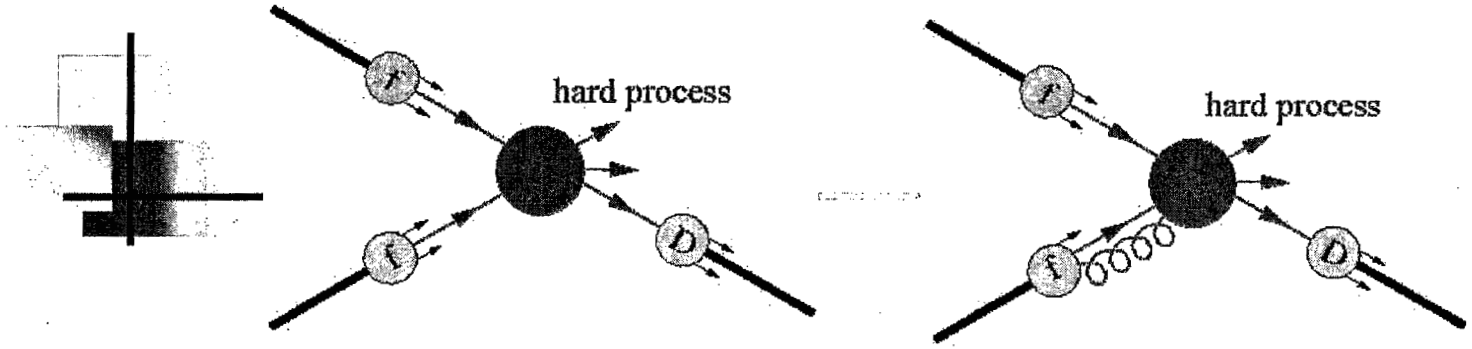
For processes in which two hadrons are involved, such as 1-particle inclusive leptoproduction or Drell-Yan scattering, the transverse momentum of the partons becomes important. It shows up in a (for our purposes) small scale. In the parameterisation of the correlators $\Phi(x,p_T)$ and $\Delta(z,k_T)$ it leads to a number of additional distribution and fragmentation functions. The additional parts vanish upon integration over transverse momenta, but they do show up in the correlator $\Phi_\partial(x)$, obtained after a weighting with transverse momentum. In the transverse momentum dependent correlators and in the weighted ones, which appear in specific hard processes, however, two *different* gauge links running via lightcone infinity appear, i.e. we have $\Phi^{[\pm]}(x,p_T)$ and $\Phi_\partial^{[\pm]}(x)$ and a similar situation for the case of fragmentation. For the integrated functions the $\pm$-dependence enters as a soft gluon matrix element leading to the form $\Phi_\partial^{[\pm]}(x) = \Phi_\partial(x) \pm \pi\Phi_G(x,x)$. For distribution functions the functions in Φ_∂ are time-reversal even (T-even), those in $\pi\Phi_G$ are T-odd. An example of such a T-odd function is the Sivers distribution function (unpolarized quarks in a transversely polarized nucleon). Comparing for instance leptoproduction and Drell-Yan scattering one finds opposite gauge link behavior and hence opposite signs for Sivers asymmetries. For fragmentation functions T-odd functions are present in both Δ_∂ and $\pi\Delta_G$. This makes a comparison of asymmetries involving the T-odd Collins function (transversely polarized quarks fragmenting into pions) in electron-positron annihilation and leptoproduction, two processes for which one also has opposite gauge link behavior more cumbersome.

T-odd functions have a clear experimental signature, showing up in single spin asymmetries. For both Sivers and Collins asymmetries first results in leptoproduction have been presented by HERMES. With single spin asymmetries as experimental signature, these effects may also distinctly show up in more complicated processes such as left-right asymmetries in pion production in $pp^\uparrow$ scattering measured at RHIC. Also here both Collins and Sivers effects are expected to play a role. At present, several issues dealing with factorisation and the gauge link structure for this process are under investigation in order to enable the comparison with other processes.

---

[1] D. Boer, P.J. Mulders and F. Pijlman, *Universality of T-odd effects in single spin and azimuthal asymmetries*, Nucl. Phys. B667 (2003) 201-241 [hep-ph/0303034]

Issues in hadroproduction



- Weighted functions will appear in L-R asymmetries (p_T now hard scale!)
- There are various possibilities with gluons, a.o.
  - $G(x,p_T)$ – unpolarized gluons in unpolarized nucleon
  - $\Delta G(x,p_T)$ – transversely polarized gluons in a longitudinally polarized nucleon
  - $G_T(x,p_T)$ – unpolarized gluons in a transversely polarized nucleon (T-odd)
  - $H^{\perp}(x,p_T)$ – longitudinally polarized gluons in an unpolarized nucleon
- Contributions of $\Phi_\partial(x,p_T)$ and $\pi\Phi_G$ not necessarily in one combination,

$$A_N \sim \ldots G(x_a) \otimes f_{1T}^{\perp(1)[-]}(x_b) \otimes D_1(z_c) + \ldots f_1(x_a) \otimes f_{1T}^{\perp(1)[+]}(x_b) \otimes D_1(z_c)$$

$$+ \ldots f_1(x_a) \otimes h_1(x_b) \otimes H_1^{\perp[-]}(z_c) + \ldots \cancel{f_1(x_a) \otimes h_1(x_b) \otimes H_1^{\perp[+]}(z_c)}$$

$$+ \ldots f_1(x_a) \otimes G_T(x_b) \otimes D_1(z_c)$$

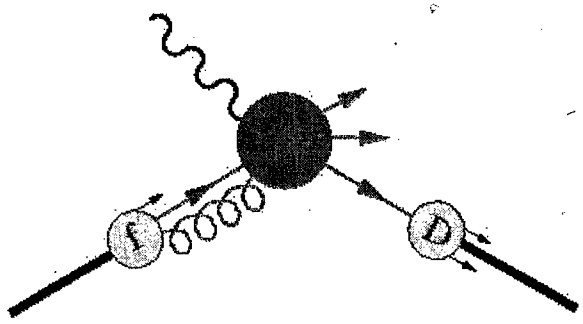
- Many issues to be sorted out

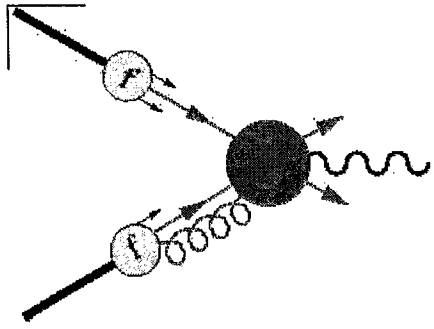
T-odd phenomena

- T-invariance does not constrain fragmentation
  - T-odd FF's (e.g. Collins function $H_1^{\perp}$)
- T-invariance does constrain $\Phi(x)$
  - No T-odd DF's and thus no SSA in DIS
- T-invariance does not constrain $\Phi(x,p_T)$
  - T-odd DF's and thus SSA in SIDIS (in combination with azimuthal asymmetries) are identified with gluonic poles that also appear elsewhere (Qiu-Sterman, Schaefer-Teryaev)
  - Sign of gluonic pole contribution process dependent
- In fragmentation soft T-odd and (T-odd *and* T-even) gluonic pole effects arise
  - No direct comparison of Collins asymmetries in SIDIS and e^+e^- (unless $\pi\Delta_G = 0$)

Summarizing SIDIS

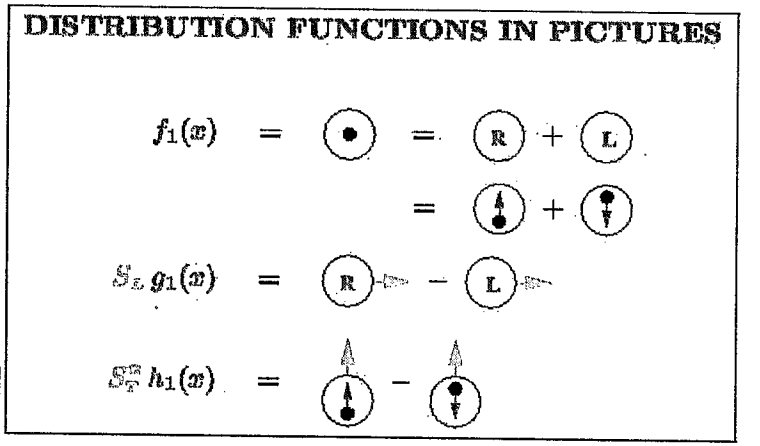
- **Beyond just extending DIS by tagging quarks ...**
- Transverse momenta of partons become relevant, appearing in azimuthal asymmetries
- DF's and FF's depend on two variables, $\Phi^{[\pm]}(x,p_T)$ and $\Delta^{[\pm]}(z,k_T)$
- Gauge link structure is process dependent (→ [±])
- p_T-dependent distribution functions and (in general) fragmentation functions are not constrained by time-reversal invariance
- This allows T-odd functions $h_1^{\perp}$ and $f_{1T}^{\perp}$ ($H_1^{\perp}$ and $D_{1T}^{\perp}$) appearing in single spin asymmetries

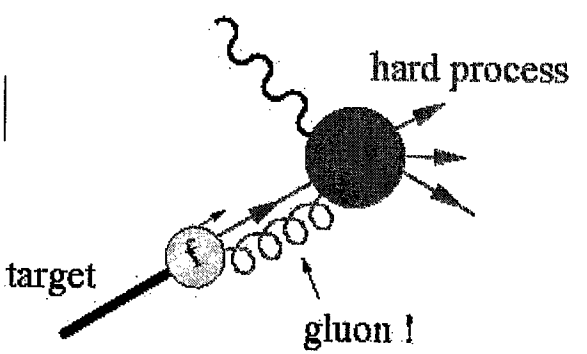




Summarizing DIS

- Structure functions (observables) are identified with distribution functions (lightcone quark-quark correlators)
- DF's are quark densities that are directly linked to lightcone wave functions squared
- There are three DF's
  $f_1^q(x) = q(x)$, $g_1^q(x) = \Delta q(x)$, $h_1^q(x) = \delta q(x)$
- Longitudinal gluons (A^+, not seen in LC gauge) are absorbed in DF's
- Transverse gluons appear at 1/Q and are contained in (higher twist) qqG-correlators
- Perturbative QCD → evolution





Novel Spin Effects in QCD*

Stanley J. Brodsky, SLAC
RIKEN BNL Research Center
RHIC High P_T Workshop, December 2003

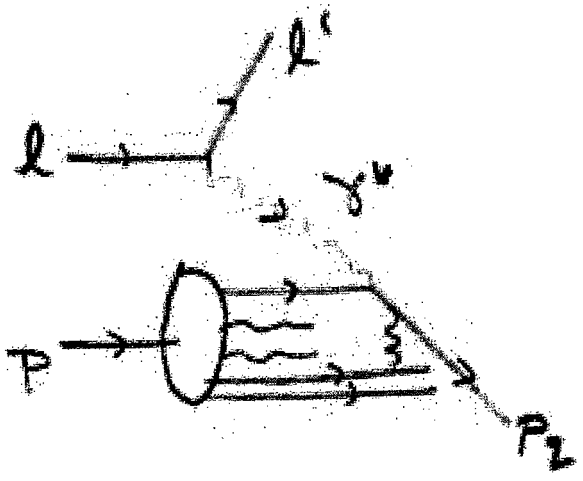
Measurements from HERMES, SMC, and Jlab show a significant single-spin asymmetry in semi-inclusive pion leptoproduction $\gamma^*(q)p \to \pi X$ when the proton is polarized normal to the photon-to-pion production plane. Hwang, Schmidt, and I [1] have shown that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to such single-spin asymmetries at leading twist in perturbative QCD; *i.e.*, the rescattering corrections are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj}. The existence of such single-spin asymmetries (the Sivers effect) requires a phase difference between two amplitudes coupling the proton target with $J_p^z = \pm\frac{1}{2}$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. The single-spin asymmetry which arises from such final-state interactions is in addition to the Collins effect which measures the transversity distribution $\delta q(x, Q)$. The Sivers effect also leads to a leading-twist target single-spin asymmetry for jet production in electroproduction where the thrust axis is used to define the production plane.

More generally, Hoyer, Marchal, Peigne, Sannino, and I [2] have shown that one cannot neglect the interactions which occur between the times of the currents in the current correlator even in light-cone gauge. For example, the final-state interactions lead to the Bjorken-scaling diffractive component $\gamma^* p \to pX$ of deep inelastic scattering. Since the gluons exchanged in the final state carry negligible k^+, the Pomeron structure function closely resembles that of the primary gluon. The diffractive scattering of the fast outgoing quarks on spectators in the target in turn causes shadowing in the DIS cross section. These effects highlight the unexpected importance of final- and initial-state interactions in QCD observables—they lead to leading-twist single-spin asymmetries, diffraction, and nuclear shadowing, phenomena not included in the light-front wavefunctions of the target computed in isolation. Alternatively, as discussed by Belitsky, Ji, and Yuan [3], one can augment the light-front wavefunctions by including the phases induced by initial and final state interactions. Such wavefunctions correspond to solving the light-front bound state equation in an external field. Similar initial and final state interactions also lead to Sivers-type single-spin asymmetries in Drell-Yan processes and inclusive hadron reactions such as $pp \uparrow\!\!\to \pi X$, and heavy quark production, processes which will be important to study in polarized proton experiments at RHIC.

[1] S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D **65**, 114025 (2002) [arXiv:hep-ph/0104291].
[2] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **530**, 99 (2002) [arXiv:hep-ph/0201296].
[3] A. V. Belitsky, X. Ji and F. Yuan, arXiv:hep-ph/0208038.

* Work supported by the Department of Energy, contract DE–AC03–76SF00515.

Unexpected Role of Final State Interactions in Deep Inelastic Scattering



gluon exchange after photon absorb

not in LF WF

- Single-spin asymmetry $\vec{S}_p \cdot \vec{q} \times \vec{p}_q$ Bjorken-scaling
- Diffraction at Leading Twist
- Nuclear Shadowing (interference of diff channels)
- Energy Loss, p_T Broadening

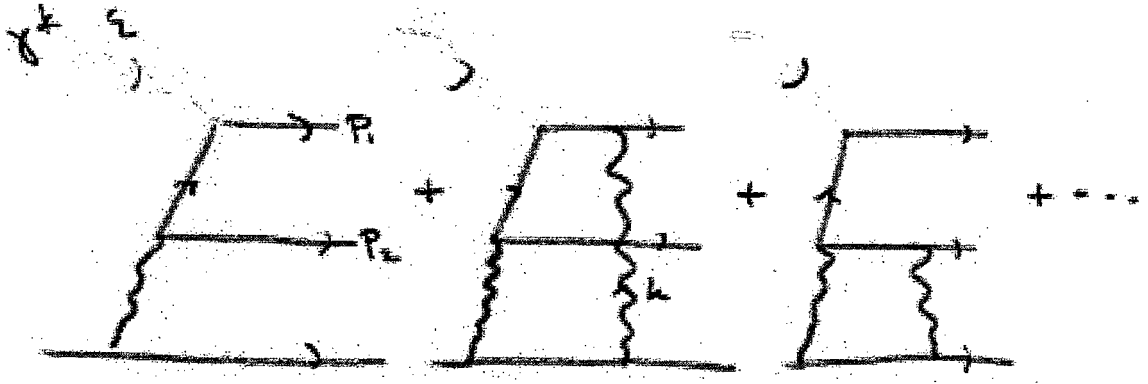
Diffraction, Nuclear Shadowing, Pomeron not in nuclear wavefunction!

- $\Delta L_{Ioffe} = \frac{2\nu}{Q^2} = \frac{1}{M x_{Bj}}$

Explicit calculation of FSI

BHMPS

$q^+ \leq 0$ frame



LFTOPT : gluon exchanged after photon acts

Find non-zero leading-twist FSI effect

Leading twist diffraction, E.L.and form

Shadowing correction, not Coulomb phase

Gauge - independent:

Checked: Feynman, LCG $[A^+=0]$ $\left\{\begin{matrix} ML \\ PV \\ k \end{matrix}\right.$ prescriptions

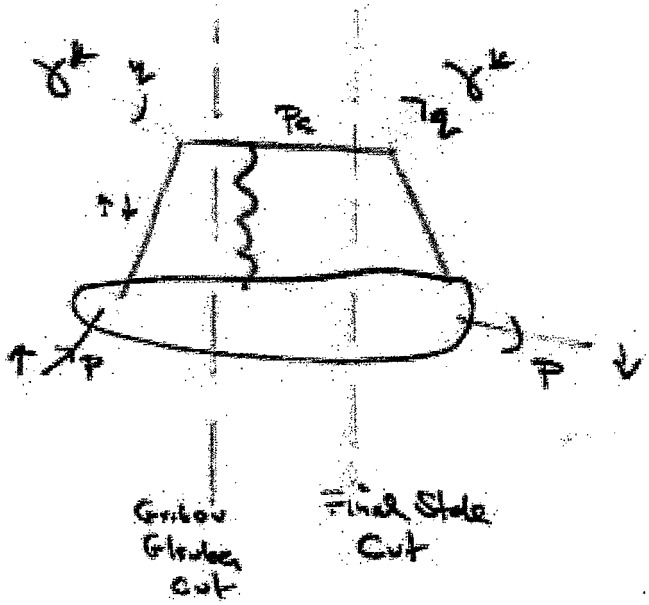
Lesson for LCG:

$$g^{\mu\nu} - \frac{n^\mu k^\nu + k^\nu n^\mu}{n\cdot k}$$

at pole: $n\cdot k = k^+ = O(\frac{1}{\nu})$.

Explicit calculation of FSI SSA

D. S. Hwang
I. A. Schmidt
SJB
hep/ph/0201296



Collins, X. Ji, Belitsky

Overlap of wavefunctions with $\Delta L_z = 1$

$$\left[e^{i(\chi_1 - \chi_2)}\right]$$

$\chi_1 - \chi_2$: IR Finite

$$i\,\vec{S}_p \cdot \vec{q} \times \vec{P}_q = i\,\vec{S}_p \cdot \vec{q} \times \vec{r}$$

$$\vec{P}_q = \vec{q} + \vec{r}$$

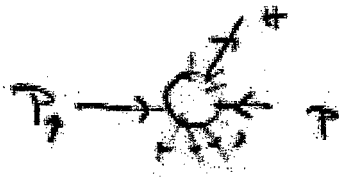
Dominant at large $r_\perp$:

$$P_y = A_n \cong \frac{\alpha_s(r_\perp^2)\, x_{Bj}\, M\, |\vec{r}_\perp|\, \ln r_\perp^2}{r_\perp^2 + M^2}$$

Bjorken scaling for finite $r_\perp$

Same matrix elements as $a_p = F_2(0)$

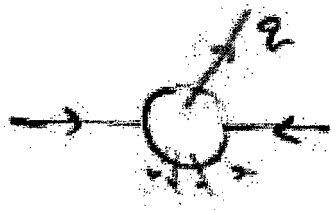
Single-Spin Asymmetry in $\vec{p}_\uparrow p$ collisions



$$i\,\vec{S}_p \cdot \vec{p}_\pi \times \vec{p}$$

T-odd Sivers Effect

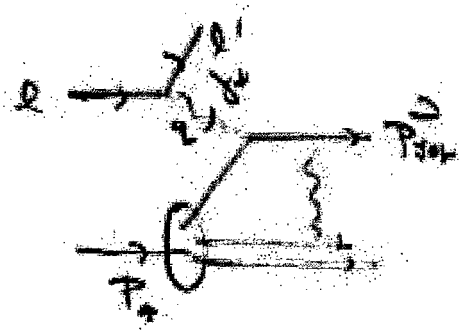
Jet Asymmetry

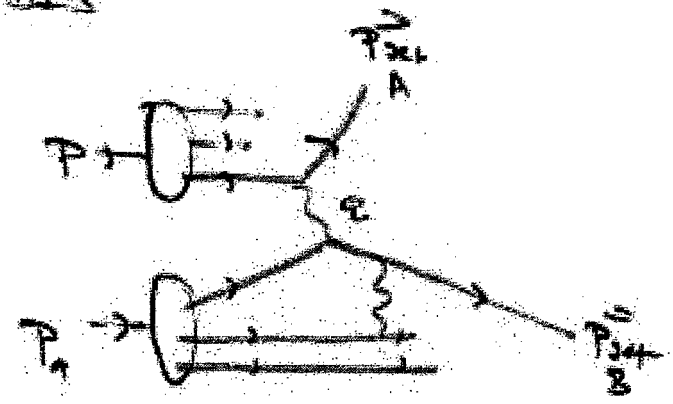


use thrust axis

$$i\,\vec{S}_p \cdot \vec{p}_{jet} \times \vec{p}$$

Analog Effect in DIS





$$i\,\vec{S}_{\vec{p}} \cdot \vec{p}_{jet} \times \vec{q}$$

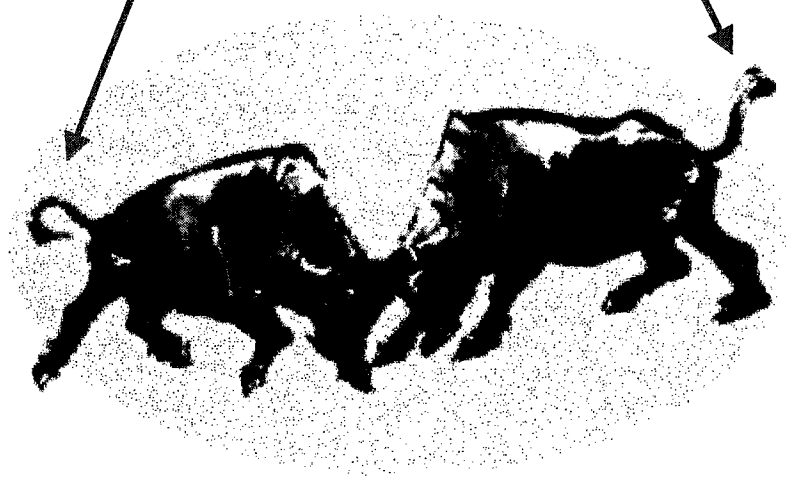
Leading Twist
BHS

$$i\,\vec{S}_{\vec{p}} \cdot \vec{p}_{jet_A} \times (\vec{p}_{jet_B} - \vec{p})$$

Leading Twist

The pQCD tails provide indicators of What the Bulk is doing

對撞生新態



核子重如牛

Nuclei as heavy as bulls
Through collision
Generate new states of matter

For full talk see:

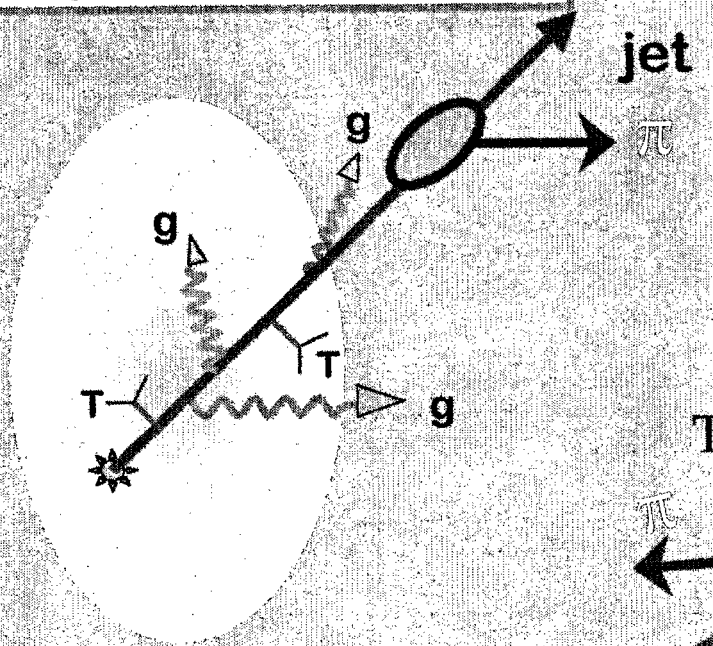
http://nt3.phys.columbia.edu/people/gyulassy/Talks/RBRC_120503/

High pT Tomography of the QGP

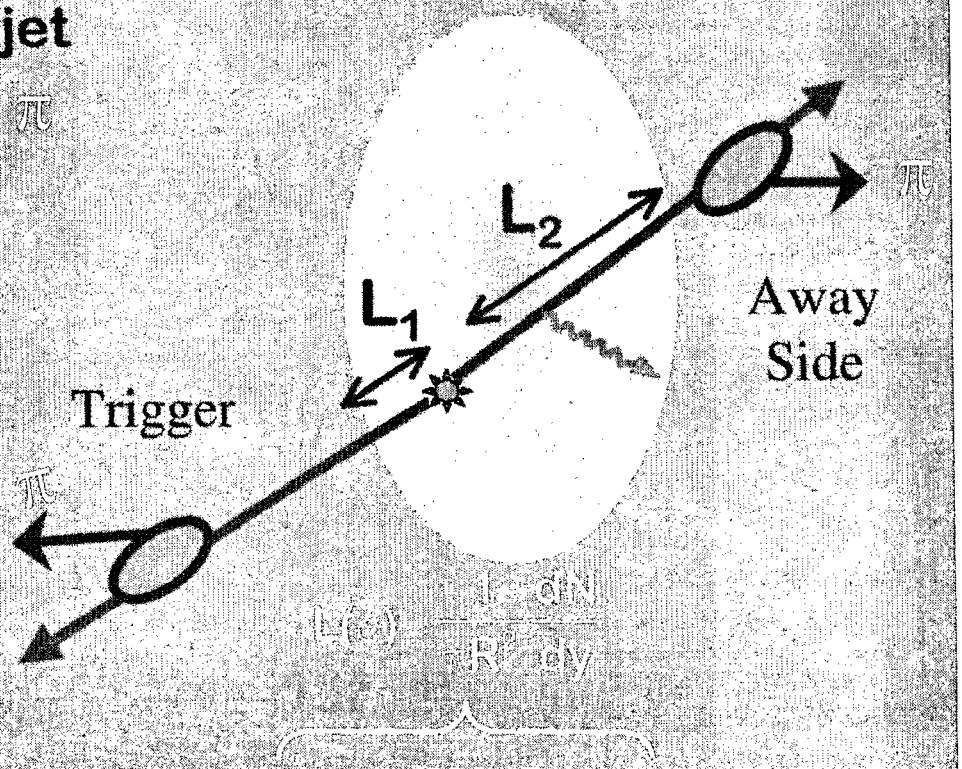
MG, I.Vitev, P. Levai; X.N. Wang, E.Wang, B.W.Zhang

Review nucl-th/0302077; Publ in Quark Gluon Plasma 3 (03)

Single Hadron Tomography



Di-Hadron Tomography



$$\Delta E_{GLV} \sim C_{Jet} C_T \alpha_s^3 \; \ell n \frac{p_T}{\mu^2 L} \int d\tau \, \tau \, \rho(\tau, r(\tau))$$

BNL12.4.03

Gyulassy 2

3 Milestones passed at RHIC

QGP =	P_{QCD}	+	pQCD	+	dA
=	$v_2(p_T,m)$	+	$(R+I)_{AA}$	+	$(R+I)_{DA}$
	1		2		3

1) Evidence for P_{QCD} via v_2 bulk collective flow of 10^4 π, K, p, Λ, Ξ

2) Evidence for pQCD jet quenching in Au+Au at RHIC

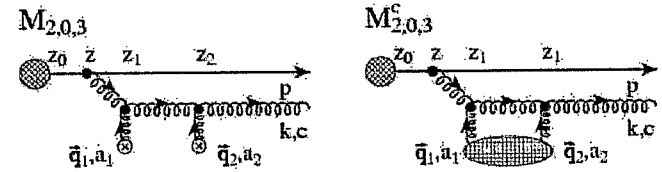
3) Evidence jet *un*-quenching in D+Au = Null Control

Conclusion: QGP Matter seen in AuAu at 200 AGeV

GLV Opacity Induced Radiation generalized to finite M

GLV: Nucl.Phys.B594(01)

M. Djordjevic, MG nucl-th/0310076 (03)



+ ...

$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\,\frac{L}{\lambda_g(i)}\left[\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i)\right]\right)\times$$

$$\times\left(-2\,\bar{\mathbf{C}}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\bar{\mathbf{B}}_{(m+1,\cdots,n)(m,\cdots,n)}\left[\cos\left(\sum_{k=2}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right)$$

Hard, Gunion-Bertsch, and Cascade ampl. in GLV generalized to finite M

$$\bar{\mathbf{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}\,, \qquad \bar{\mathbf{C}}_{(i_1i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2}$$

$$\bar{\mathbf{B}}_i = \bar{\mathbf{H}}-\bar{\mathbf{C}}_i\,, \qquad \bar{\mathbf{B}}_{(i_1i_2\cdots i_m)(j_1j_2\cdots j_n)} = \bar{\mathbf{C}}_{(i_1i_2\cdots j_m)}-\bar{\mathbf{C}}_{(j_1j_2\cdots j_n)}\,.$$

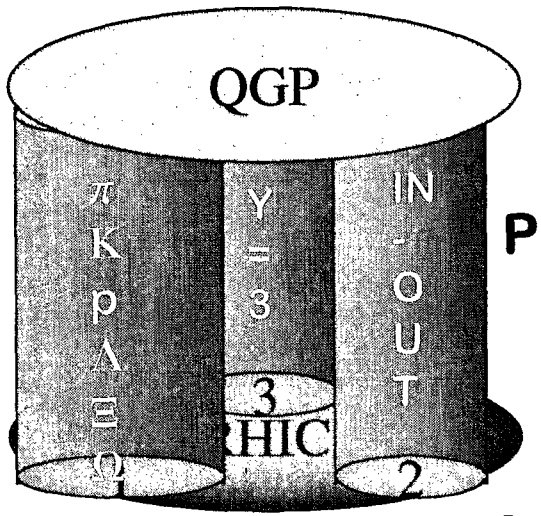
$$\omega_{(m,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2}{2xE} \rightarrow \Omega_{(m,\cdots,n)} \equiv \omega_{(m,\cdots,n)}+\frac{m_g^2+M^2x^2}{2xE}$$

Converging Evidence to QGP at RHIC

Null Control D+Au

+ dA(y=3)

BulkCollectivity
P_{QCD}



Parton Quenching
pQCD

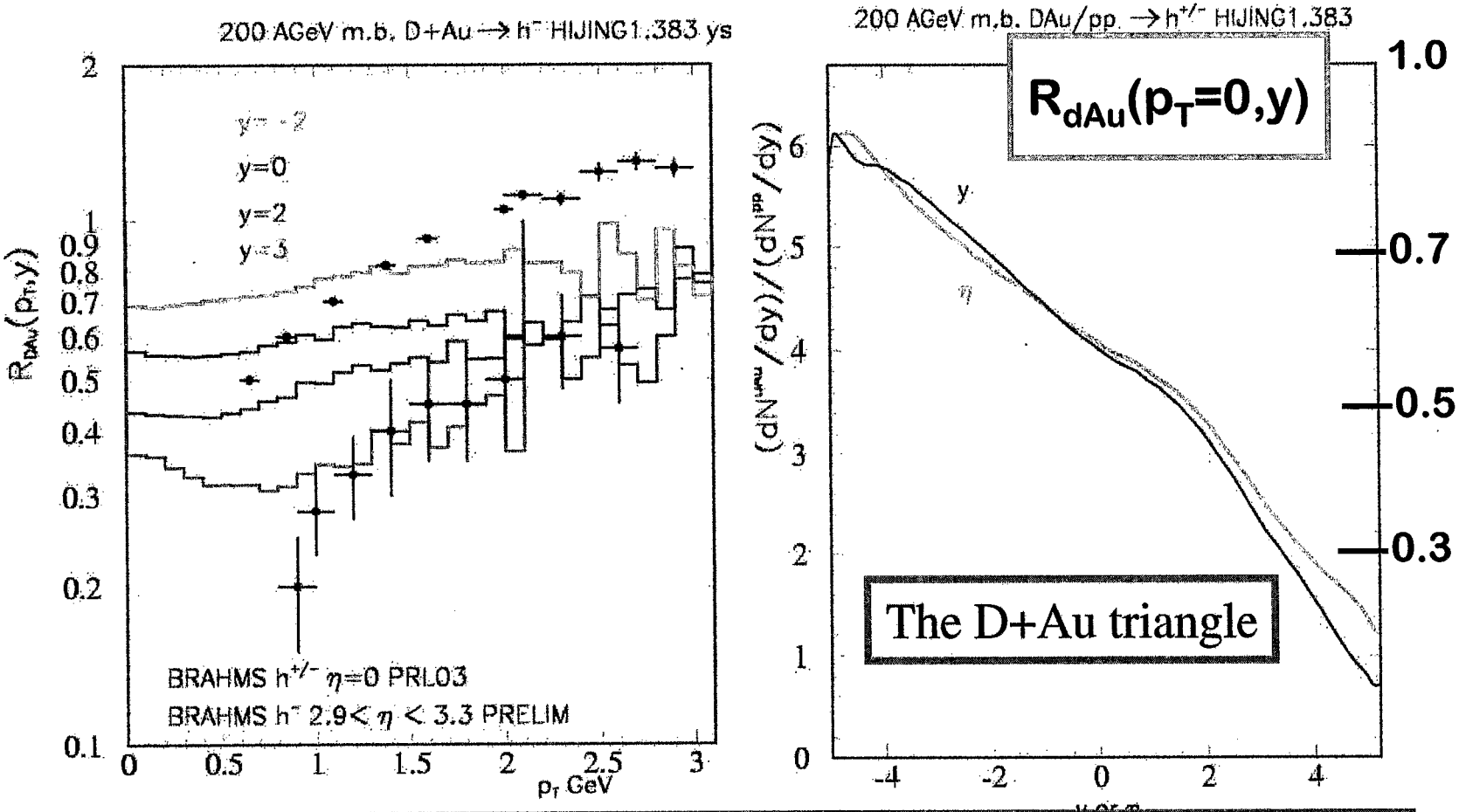
+ $v_1(y)$

+ $I_{AA}(\phi,\phi_R)$

$$QGP = P_{QCD} + pQCD + dA = v_2 + (R+I)_{AA} + (R+I)_{dA}$$

$$+ v_1 + I_{AA}(\phi,\phi_R) + dA(y=3)$$

A Low pT<1 GeV *Triangle* boundary condition controls forward $R_{dA}(y \sim y_D, pT<1) \sim 1/N_{coll}$ nuclear modification



The low pT D+Au triangle=Baryon conservation + asymp. freedom

High pT Physics at RHIC

A RIKEN BNL Research Center
Workshop, December 2003

PHOTONS AND GLUONS at RHIC

- some aspects -

R. Baier

Faculty of Physics
University of Bielefeld

CONTENT

- MOTIVATION
- dipol bremsstrahlung picture of
  production of real and virtual photons

  discussion for quark + nucleus $-- >$ dileptons (γ) $+X$

- $k_\perp$ factorization - pQCD factorization
- gluon saturation
- BFKL evolution and geometrical scaling
- expectations/predictions for
  large forward photon rapidities
- work in progress in collaboration with

  A. H. Mueller and D. Schiff

Motivation

Disentangle

final versus initial state effects

due to multi gluon interaction in the nucleus

Ideal tool

real photons and dileptons

(also: no fragmentation function)

restrict discussion to:

- $qA \to \gamma(\gamma^*)X$

  at medium and large p_T,

  but large forward photon rapidities $\Longrightarrow$

  exploring the $x \to 0$ region in the nucleus
  at fixed energy

- fixed QCD coupling α_s

Dipolformulation - $k_\perp$ factorized representation

$$\frac{d\sigma}{dz d^2k_\perp d^2b} = \frac{2\alpha_{\rm elm}}{(2\pi)^4}\frac{1+(1-z)^2}{z}\int \frac{d^2q_\perp}{q_\perp^2}\phi(\vec{q}_\perp,\vec{b},Y)$$

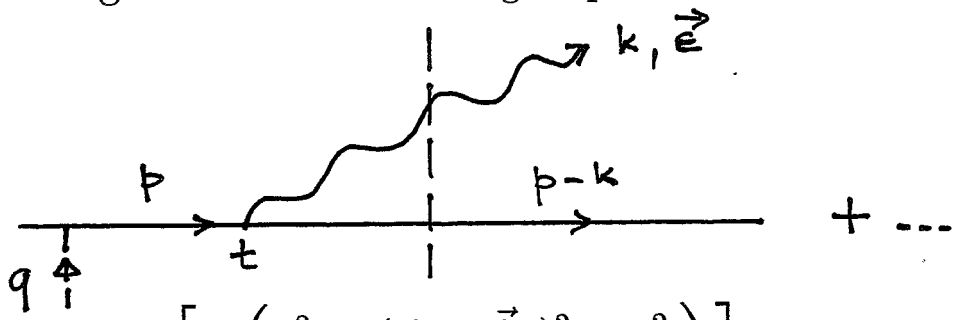
$$\cdot\left\{\frac{z^2q_\perp^2}{[k_\perp^2+\eta^2][(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2]} - \eta^2\left[\frac{1}{k_\perp^2+\eta^2} - \frac{1}{(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2}\right]^2\right\},$$

$$\phi(\vec{q}_\perp,\vec{b},Y) = \int d^2x_\perp e^{i\vec{q}_\perp\cdot\vec{x}_\perp}\vec{\nabla}^2_{x_\perp}N(\vec{x}_\perp;\vec{b},Y)$$

$$\text{Proof}: \frac{\vec{\epsilon}\cdot\vec{k}_\perp}{k_\perp^2+\eta^2} = i\int\frac{d^2x_\perp}{2\pi}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\vec{\epsilon}\cdot\vec{\nabla}_{x_\perp}K_0(\eta x_\perp)$$

$$= -i\eta\int\frac{d^2x_\perp}{2\pi}e^{i\vec{k}_\perp\cdot\vec{x}_\perp}\frac{\vec{\epsilon}\cdot\vec{x}_\perp}{x_\perp}K_1(\eta x_\perp)$$

Derivation: lightcone bremsstrahlung amplitudes



$$\Rightarrow \exp\left[it\left(\frac{k_\perp^2}{2k} + \frac{(\vec{p}_\perp - \vec{k}_\perp)^2}{2(p-k)} - \frac{p_\perp^2}{2p}\right)\right] = e^{it/t_{\rm form}}$$

$$\Longrightarrow e\left[\frac{\vec{\epsilon}\cdot\vec{k}_\perp}{k_\perp^2+\eta^2} - \frac{\vec{\epsilon}\cdot(\vec{k}_\perp - z\vec{q}_\perp)}{(\vec{k}_\perp - z\vec{q}_\perp)^2+\eta^2}\right]$$

[e.g. BDMS (1998)]

Evolution of $\phi(\vec{q}_\perp, \vec{b}, Y)$.

- BFKL from $N(\vec{q}_\perp, \vec{b}, Y)$:

$$\phi = 16\pi \int_c \frac{d\lambda}{2\pi i} \frac{\Gamma(2-\lambda)}{4^\lambda} \exp\left[2\bar{\alpha}_s \chi(\lambda) Y - (1-\lambda) \ln \frac{q_\perp^2}{Q_{MV}^2}\right]$$

initial condition at $Y = 0$: MV distribution with scale

$$Q_{MV}^2 = \frac{\alpha_s^2 C_F}{2} \left(\frac{A}{R_A^2}\right)$$

saddle point solution: $\bar{\alpha}_s Y$ large and vanishing saddle point for $q_\perp = Q_0(Y)$

– diffusion into saturation regime $q_\perp < Q_0(Y)$

– Y dependence even for $q_\perp = Q_0(Y)$, $\phi \sim 1/\sqrt{\alpha_s Y}$

- BFKL in presence of saturation - including non-linear BK-type effects

[A. H. Mueller and D. N. Triantafyllopoulos (2002)]

$\Longrightarrow$ successfull comparison with numerical solutions of the Balitzky-Kovchegov equation

[J. I. Albacete, N. Armesto, A. Kovner, C. A. Salgado, U. A. Wiedemann (2003)]

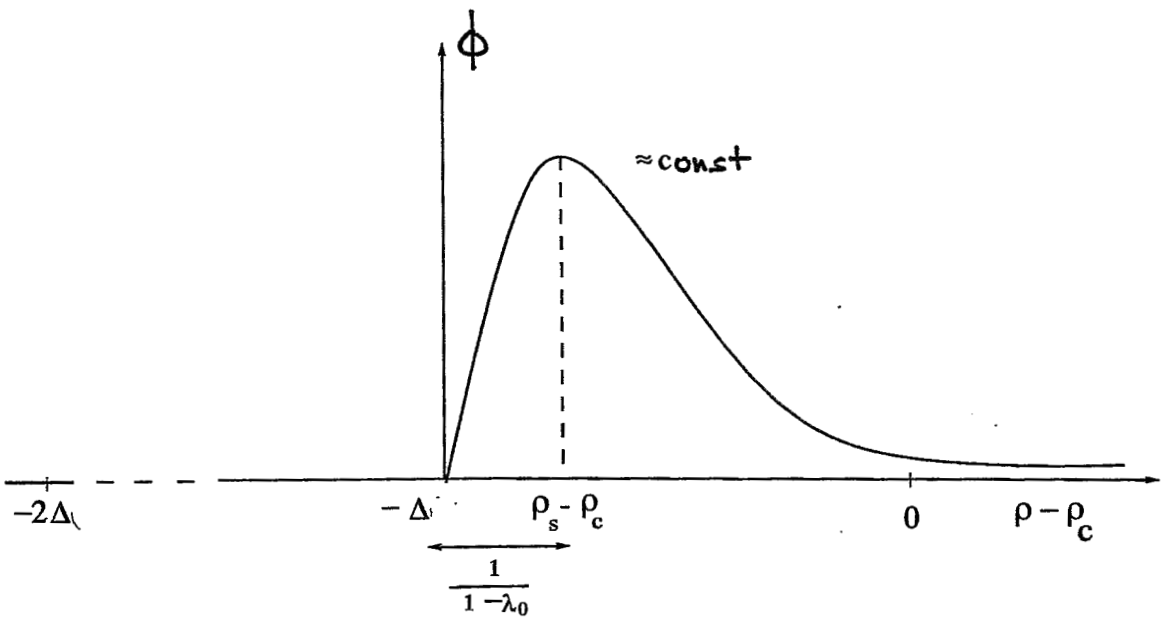
cutting out diffusion into saturation region, i.e.
require ϕ to vanish close to the saturation boundary

scaling "solution"

$$\phi = \phi_{max}\,(1-\lambda_0)\,[\ln\frac{q_\perp^2}{Q_s^2(Y)} + \frac{1}{1-\lambda_0}]\exp[-(1-\lambda_0)\ln\frac{q_\perp^2}{Q_s^2(Y)}]$$

with $\phi = \phi_{max} = \text{const}$ at $q_\perp = Q_s(Y)$, and

$$Q_s^2(Y) \simeq Q_c^2(Y) = Q_{MV}^2 \frac{\exp[2\bar{\alpha}_s \frac{\chi(\lambda_0)}{1-\lambda_0} Y]}{[4\bar{\alpha}_s \chi''(\lambda_0) Y]^{3/[2(1-\lambda_0)]}}$$



here: $\rho = \ln\frac{q_\perp^2}{Q_{MV}^2}$, $\rho_c = \ln\frac{Q_c^2(Y)}{Q_{MV}^2}$

[taken from A. H. Mueller and D. N. Triantafyllopoulos (2002)]

γ^* cross section at large Y

- replace

$$\phi \to \frac{(2\pi)^3 \alpha_s}{N_c}\, \phi(q_\perp/Q_s(Y), \vec{b}\,)$$

- $$\frac{d\sigma^{qA->\gamma^* X}}{d^2 b} = (k^2{}_\perp + \eta^2)\frac{d\sigma}{d(\ln z) d^2 k_\perp d^2 b} =$$
$$= \int \frac{d^2 q_\perp}{\vec{q}_\perp^2}\, H(\vec{k}_\perp, z\vec{q}_\perp, z)\, \phi(q_\perp/Q_s(Y), \vec{b})$$

  (for $\eta < k_\perp$)

- $$H(\vec{k}_\perp, \vec{q}_\perp, z) = \frac{\alpha_{elm}\alpha_s}{\pi N_c}[1 + (1-z)^2]\frac{\vec{q}_\perp^2}{(\vec{k}_\perp - \vec{q}_\perp)^2 + \eta^2}$$

- for $k_\perp$.. hard scale $\to$ SCALING

$$\frac{d\sigma^{qA->\gamma^* X}}{d^2 b} = \phi(k_\perp/(zQ_s(Y)), \vec{b}\,)\, F[\ln(k_\perp/zQ_s(Y)), \eta/k_\perp, z]$$

prediction for large Y

- parametric estimate for ratio

$$R_{pA}^{\gamma^*} = \frac{d\sigma^{qA->\gamma^* X}}{A\ d\sigma^{qp->\gamma^* X}}$$

- based on

$$\phi(k_\perp/Q_s(Y), \vec{b}\ ) \approx (\frac{k_\perp^2}{Q_s^2(Y)})^{\lambda_0 - 1}$$

(scaling regions of A and p overlap)

and

$$\frac{Q_s^2(Y)|_A}{Q_s^2(Y)|_p} = \frac{AR_p^2}{R_A^2} \approx A^{1/3}$$

- $$R_{pA}^{\gamma^*} \approx (\frac{R_A^2}{AR_p^2})^{\lambda_0} \approx A^{-\lambda_0/3}$$

i.e. suppression, independent on $k_\perp$ and Y

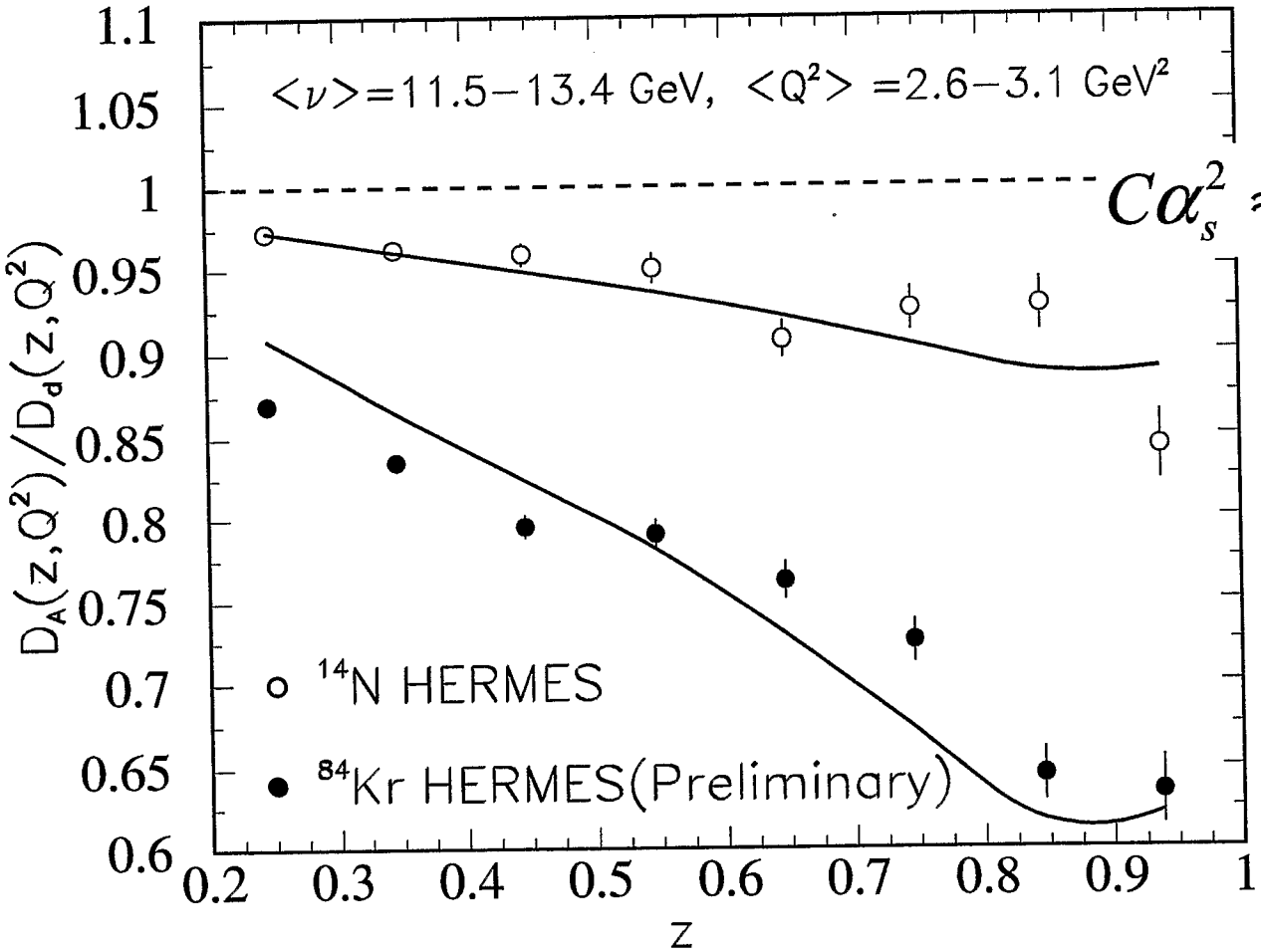
- c.f. with R_{pA} for produced gluons

Partonic energy loss or hadronic absorption?

- Energy dependence of jet quenching
- Centrality dependence of jet quenching
- Finite v2
- Same-side jet profile
- Data from CERN-SPS

Xin-Nian Wang
LBNL

HERMES data

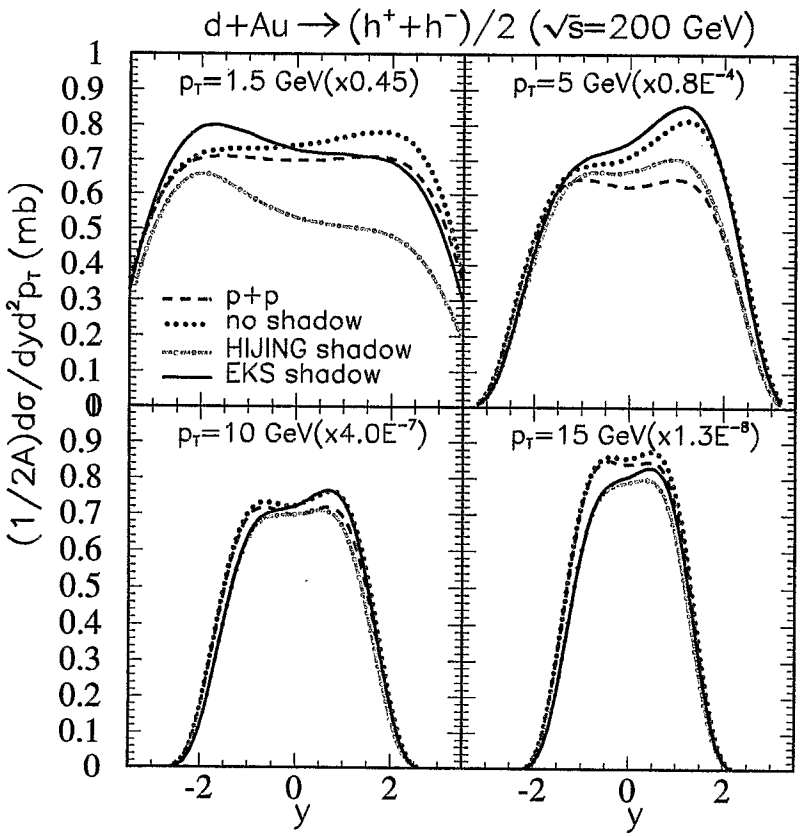


$$C\alpha_s^2 \approx 0.00065 \ \text{GeV}^2$$

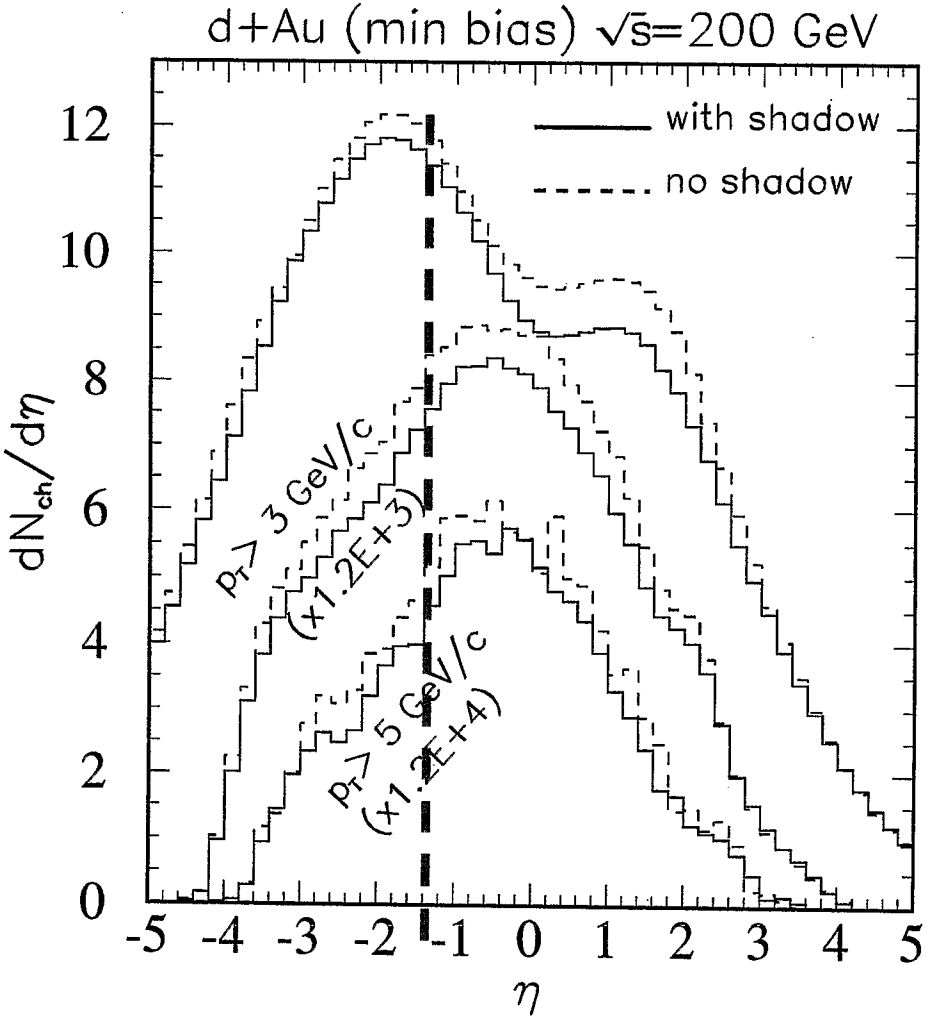
$$\frac{dE}{dx} \approx 0.5 \ \text{GeV/fm}$$

in Au nuclei

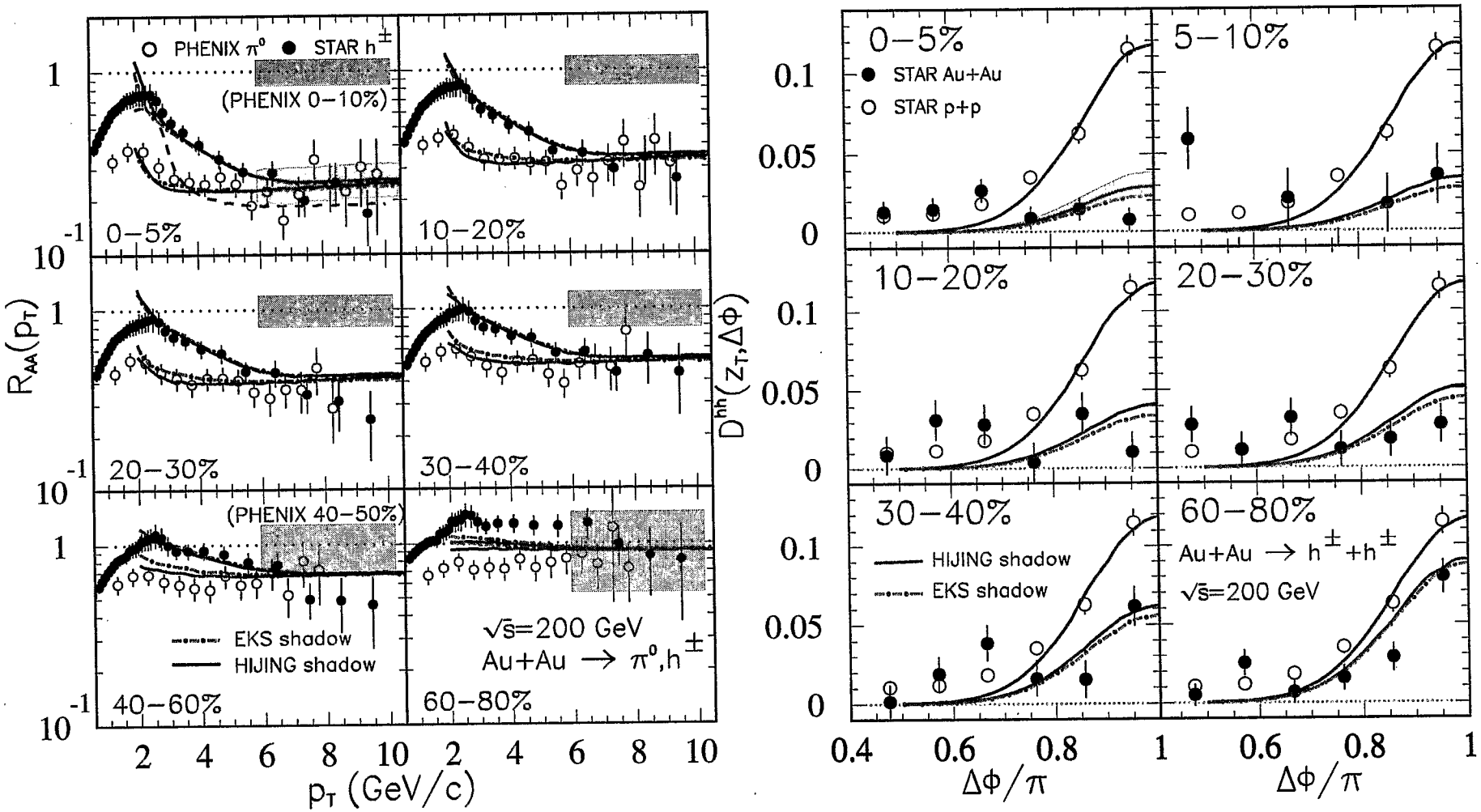
d+Au at large y



XNW, nucl-th/0303004



Single and dihadron Suppression



Partonic Energy Loss at RHIC

$$\Delta E \propto \alpha_s^3 \int_{\tau_0}^{R} d\tau \rho(\tau) \tau \ln\left(\frac{2E}{\tau \mu^2}\right)$$

$$\rho(\tau) = \rho_0 \frac{\tau_0}{\tau} \theta(R-r)$$

$$\Delta E = \Delta E_0 \frac{2\tau_0}{R_A}$$

ΔE_0 Energy loss in a static medium with density ρ_0

$$\Delta E = 5.5 \pm 1.6 \quad \text{GeV}$$

for E=10 GeV

$$\left(\frac{dE}{dx}\right)_0 \approx 13.8 \pm 3.9 \text{ GeV/fm} \Longleftrightarrow \left(\frac{dE}{dx}\right)_{\text{cold matter}} \approx 0.5 \text{ GeV/fm}$$

$$\tau_0 = 0.2 \text{ fm/c}$$

Separating the Process-Dependent and Process-Independent Dynamics at RHIC

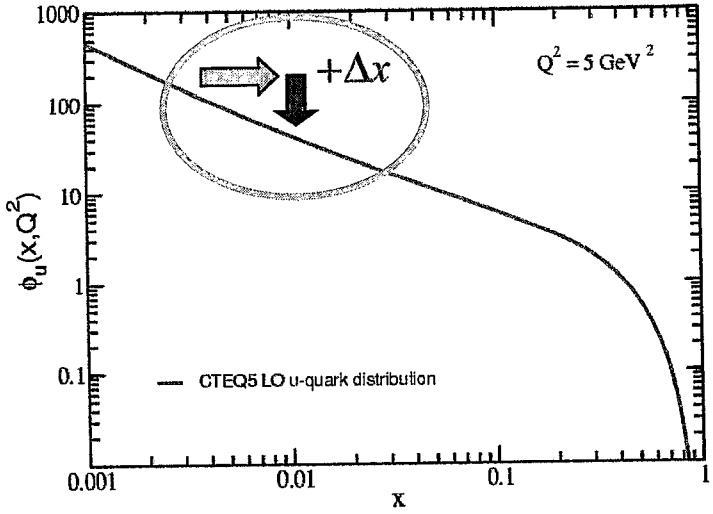
Ivan Vitev
Iowa State University, Ames, IA 50011

***BNL High-p_T Workshop*, December 2-6, 2003**
Brookhaven National Lab, Upton, NY

Momentum Fraction Shift Operator

For Q^2 ? ξ^2

- Derivative series on the leading twist collinear factorized pQCD cross section
- The series is dominated by its low order terms



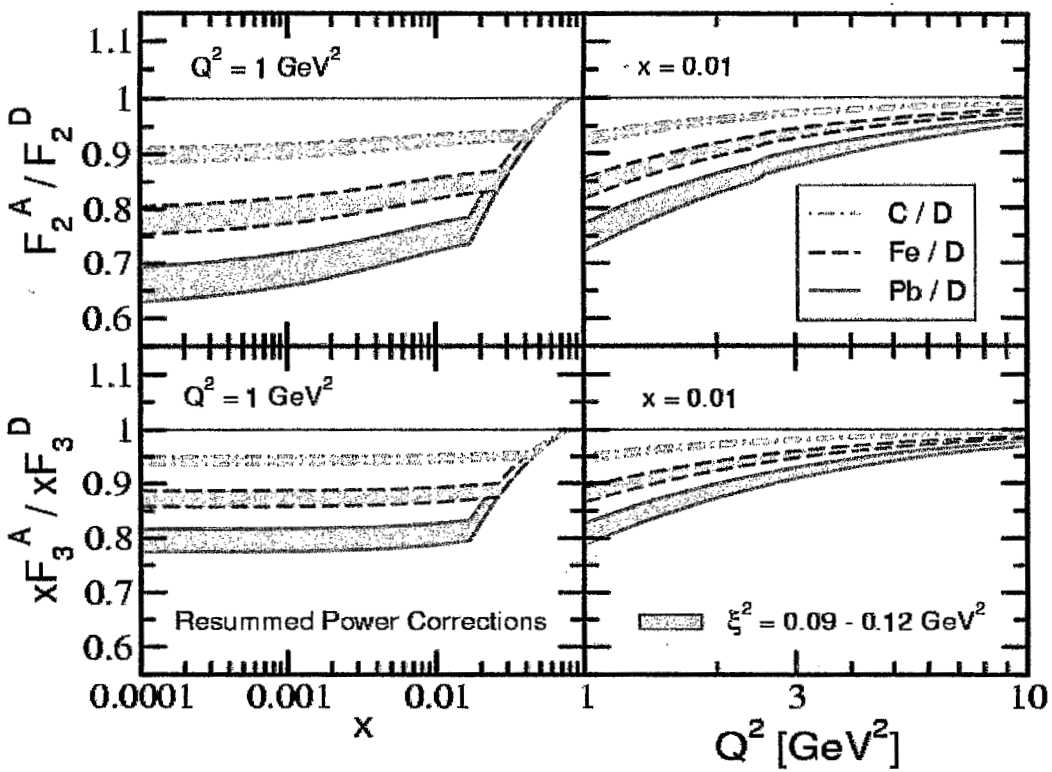
$$F_T^A(x,Q^2) = \sum_{n=0}^{N} \frac{A}{n!}\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(LT)}(x,Q^2)}{d^n x} \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2\right)$$

$$F_L^A(x,Q^2) = A\, F_L^{(LT)}(x,Q^2) + \sum_{n=0}^{N} \frac{A}{n!}\left(\frac{4\xi^2}{Q^2}\right)\left[\frac{\xi^2(A^{1/3}-1)}{Q^2}\right]^n x^n \frac{d^n F_T^{(LT)}(x,Q^2)}{d^n x}$$

$$\approx A\, F_L^{(LT)}(x,Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x,Q^2)$$

The main result

Numerical Results for $F_2(x,Q^2)$ and $xF_3(x,Q^2)$



Testable at the Fermilab NuMI facility

J. Morfin, J.Phys.G 29, (2003)

$$\phi_{sea}(x) \propto x^{-\alpha_{sea}}, \quad \alpha_{sea}\ ;\ 1.0$$

$$\phi_{val.}(x) \propto x^{-\alpha_{val.}}, \quad \alpha_{val.}\ ;\ 0.5$$

$$\xi^2 = 0.09 - 0.12\ GeV^2$$

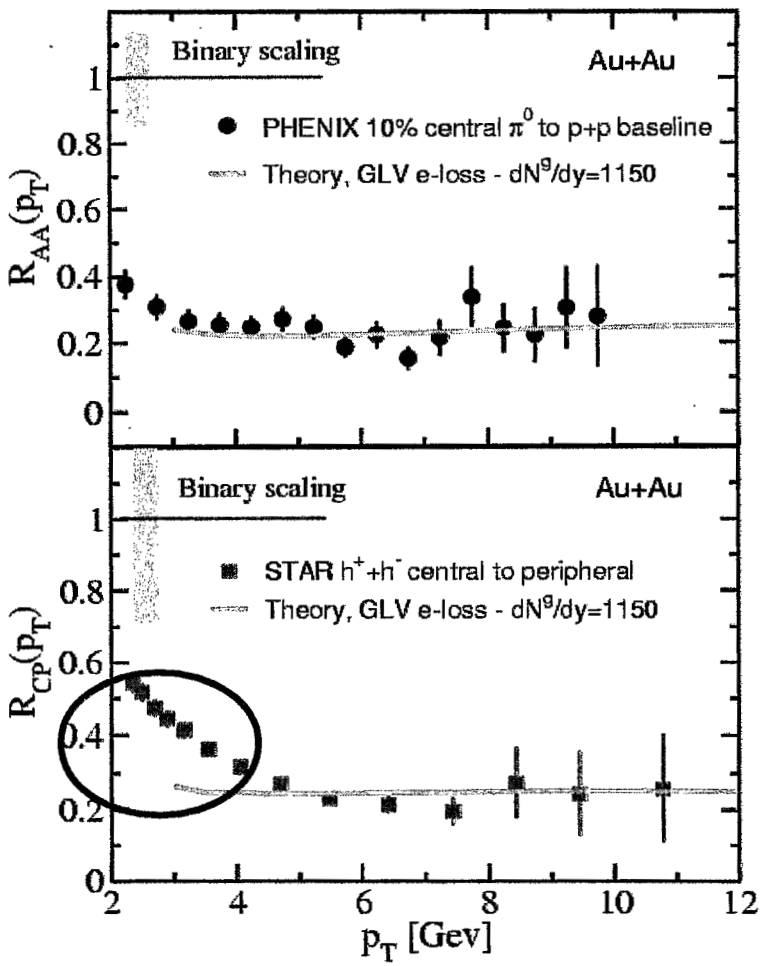
Analytic formula

$$R_{S/V}^{A/B} = \frac{F_2^A(x,Q^2)}{F_2^B(x,Q^2)} \Big/ \frac{xF_3^A(x,Q^2)}{xF_3^B(x,Q^2)} \approx 1 - (\alpha_{sea} - \alpha_{val.})(A^{1/3} - B^{1/3})\frac{\xi^2}{Q^2} + \ldots$$

Framework: Collinear factorized pQCD

J.W.Qiu, I.V., to appear on hep-ph

Comparison to Au+Au Data



B.Back *et al.* [PHOBOS], Phys.Rev.Lett. 91 (2003)

S.Adler *et al.* [PHENIX], Phys.Rev.Lett. 91 (2003)

S.Mioduszewski, [PHENIX collaboration]

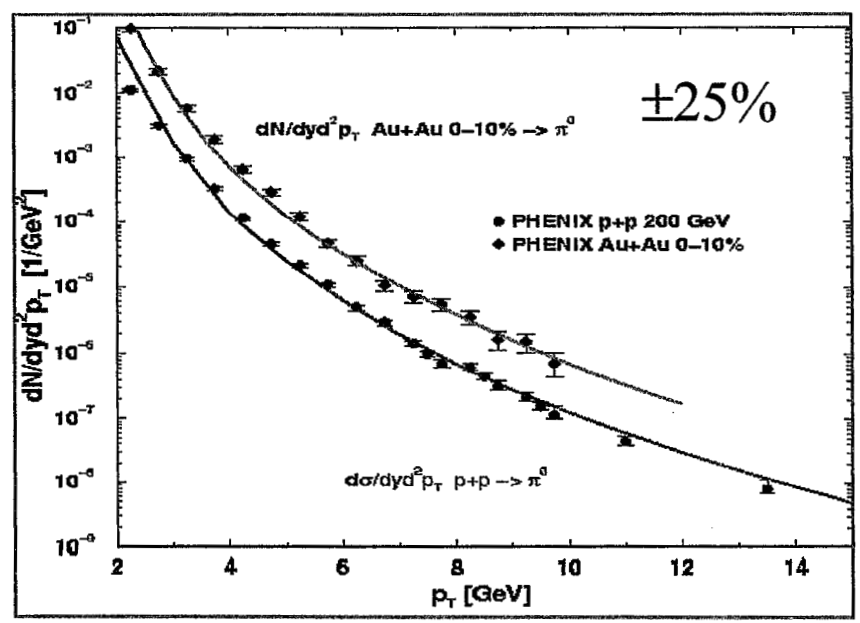
η follows the π^0

J. Frantz [PHENIX collaboration]

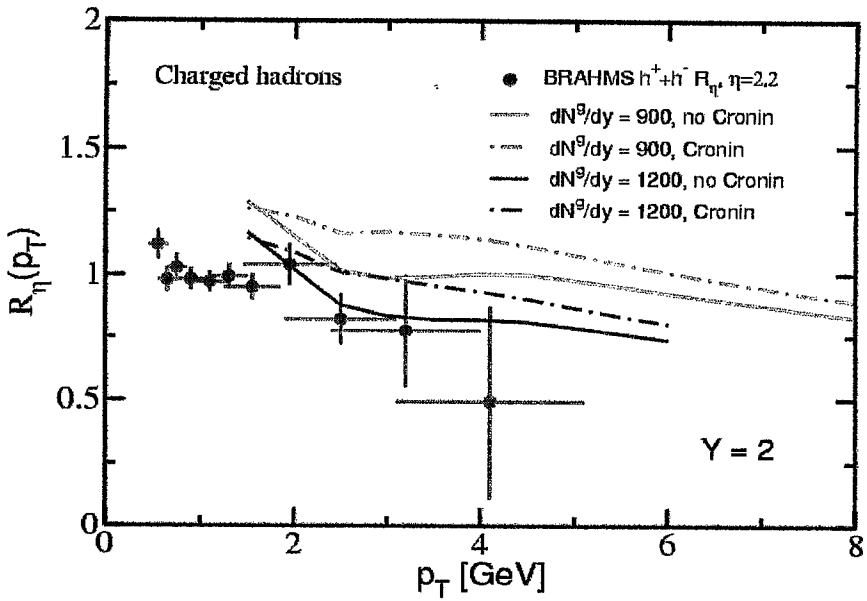
From $\pi^0 \rightarrow \gamma\gamma$

DNP meeting

Absolute scale comparison



Comparison to Au+Au Data R_η



A.Adil, M.Gyulassy, I.V., in preparation

$$R_\eta = R_{AA}(\eta) / R_{AA}(\eta = 0)$$

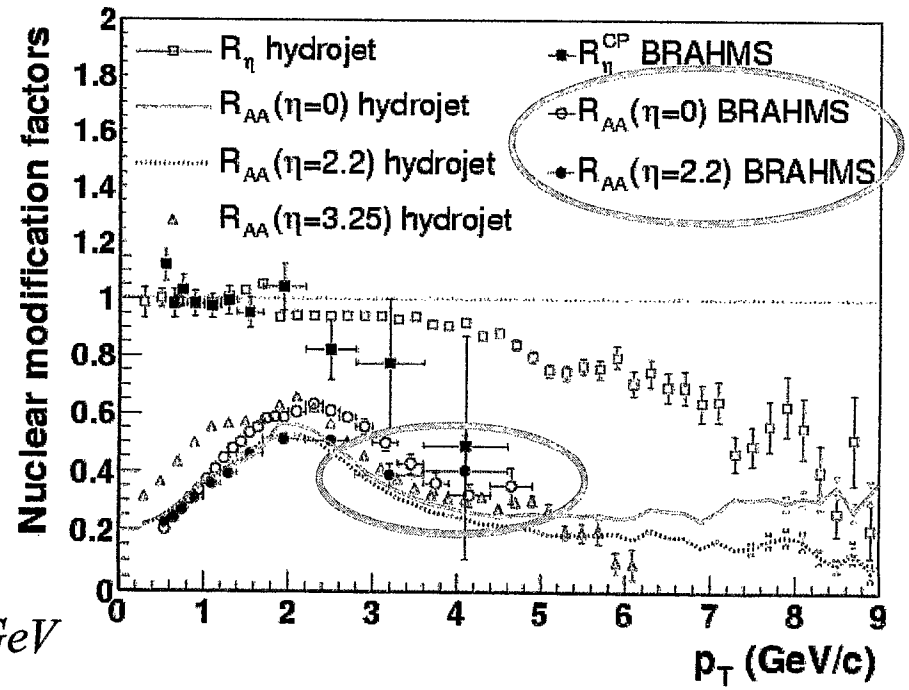
$$R_{AA} = \frac{dN_{AA}{}^{h} / dyd^2 p_T}{\langle T_{AA} \rangle d\sigma_{pp}{}^{h} / dyd^2 p_T}$$

Be careful with baryons for $p_T < 4-5\ GeV$

Perturbative calculation with initial and final state scattering

- **GLV energy loss in a 3D hydro**
- **Data is consistent with** $R_\eta = 1$

T.Hirano, Y.Nara, nucl-th/0307087



Energy Loss of High P_{T} Partons

Guy D. Moore (with Sangyong Jeon)

McGill University

- Overview and Review
- The approach
- The calculation
- Results: suppression of jets, with respect to pp, is nearly energy independent
- What remains to be done

So far: evolution through a finite slab

Assumed initial $p_\perp$ spectrum: $dN/d^2p_\perp \sim (p_\perp^2 + p_0^2)^{-5}$ with $p_0 \sim 1.75$ GeV [Wang and Wang]

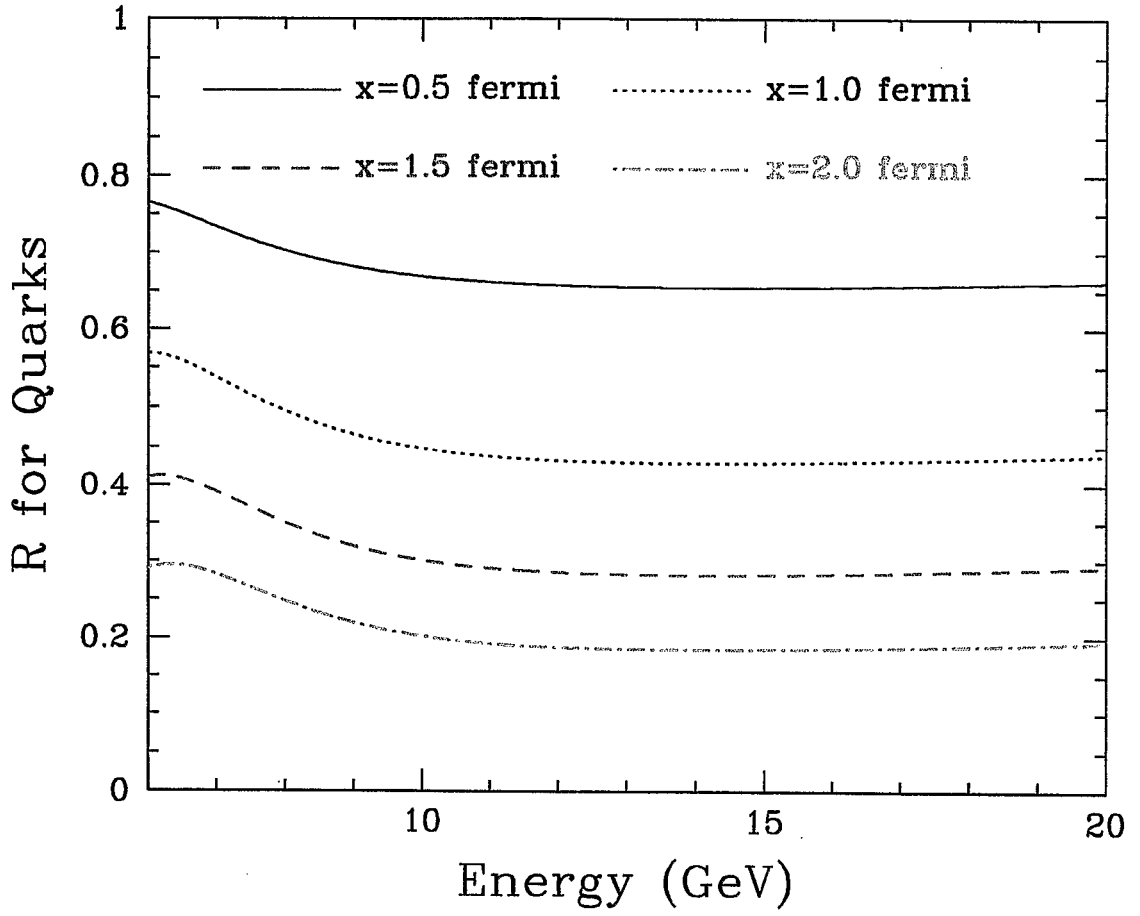
Result scales: Energy loss, writing E/T (T the temperature) and $x \times g_s^4 T$ (x the slab thickness), is "pure" result.

For presentation, we take $T = 400$ MeV, $\alpha_s = 1/3$

Plotted quantity:

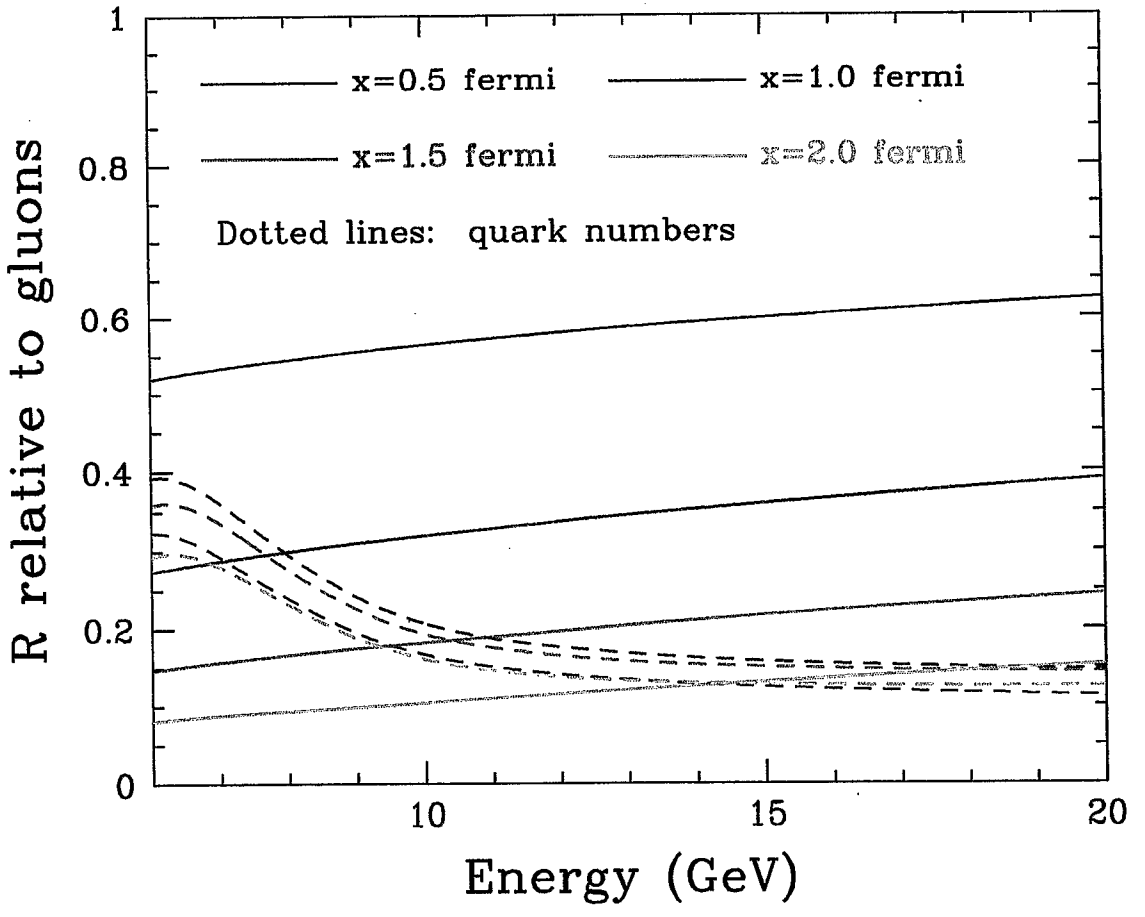
$$\tilde{R} \equiv \frac{\text{Final } dN/dp}{\text{Initial } dN/dp}$$

Initially Pure Quark Spectrum



Negligible glue produced.

Initially Pure Gluon Spectrum



Significant quarks: eventually, quarks dominate

Conclusions

We still need to include nuclear geometry, but

It is difficult to see how central result–very flat $\tilde{R}$–could change.

Initial state effects (Cronin, shadowing) not needed to explain $p_\perp$ independent suppression of high $p_\perp$ hadrons.

We expect the same flat behavior at the LHC.

It should be easy to extend this work to γ production by hard partons traversing the QGP.

PRODUCTION OF HIGH-p_t PARTICLES IN AuAu AND dAu.

Carlos A. Salgado

TH-Division, CERN, CH-1211 Geneva

The suppression of particles with high-p_t in central AuAu collisions, together with the observation of an enhancement in the control dAu collisions, is one of the main results from RHIC up to now. It clearly points to a strong interaction of the high-p_t parton with a formed dense state. This is consistent with the *jet quenching* interpretation. On the other hand, the recent (preliminary) data from BRAHMS of pion production in dAu at $y = 3$ show a strong suppression. To clarify the origin of these observations, an understanding of both initial and final state effects is necessary. The first part of the talk is devoted to the initial state effects. In the framework of collinear factorization, DGLAP evolution forbids a very strong gluon shadowing for $x \gtrsim 0.01$ when experimental data on scaling violations of the ratio F_2^{Sn}/F_2^C is taken into account. BRAHMS data would need a much stronger gluon shadowing. This is, in principle, not in disagreement with the previous statement, but seems unlikely that both DIS and BRAHMS data could be describe in this framework. Recent developments based on saturation physics could provide with such a large suppression maintaining at the same time the enhancement in central rapidities.

In the second part of the talk, the *jet quenching* interpretation of the suppression in central AuAu at $y = 0$ is reviewed. We briefly present a comparison with PHENIX data on π^0 suppression. In this implementation of the energy loss by medium induced gluon radiation, the suppression is related with a broadening in the k_t spectrum of the jets. Following this idea, we present the first attempts to study the medium modification of jet properties in different observables.

Based on:

C.A. Salgado, U.A. Wiedemann, hep-ph/0310079, Phys.Rev.**D68** (2003) 014008; Phys.Rev.Lett.**89** (2002) 092303

J.L. Albacete *et al.* hep-ph/0307179

K.J. Eskola, *et al.* Phys.Lett.**B532** (2002) 222; Eur.Phys.J. **C9** (1999) 61.

Constrains for gluons from DIS data

At small values of x, LO–DGLAP gives

$$\frac{\partial F_2^{p(n)}(x,Q^2)}{\partial \log Q^2} \propto xg(2x,Q^2).$$

This leads to

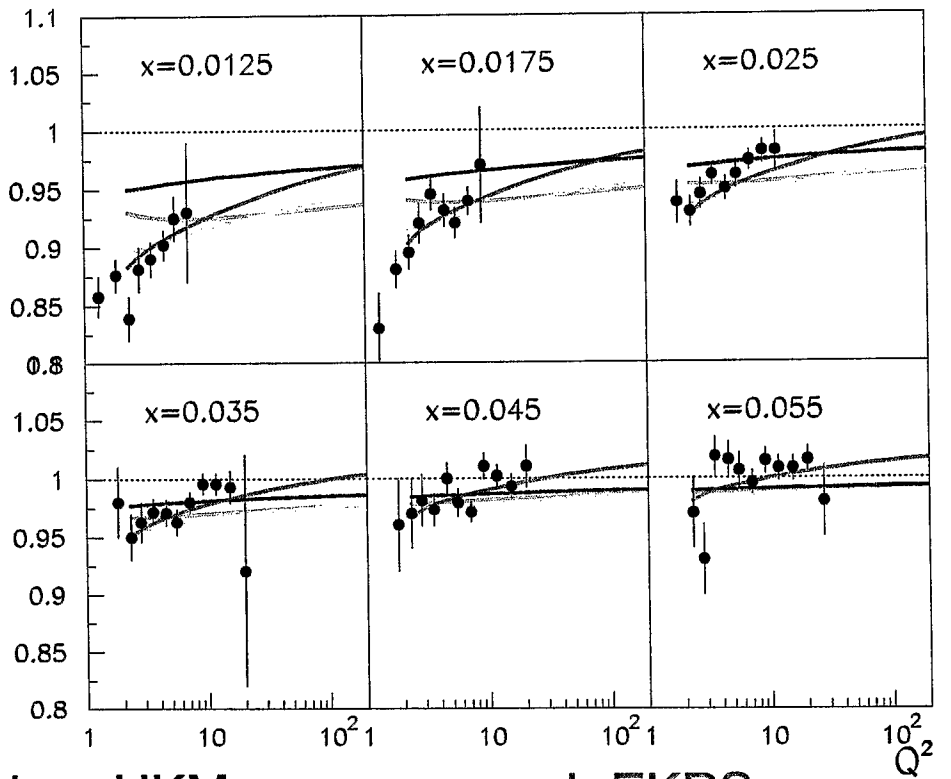
$$\frac{\partial R_{F_2}^A(x,Q^2)}{\partial \log Q^2} \propto \left\{ R_g^A(2x,Q^2) - R_{F_2}^A \right.$$

Q^2–dependence of F_2^{Sn}/F_2^C (NMC)

positive slope $\longrightarrow$

$$\boxed{R_g^A(2x,Q^2) \geq R_{F_2}^A(x,Q^2).}$$

(Eskola, *et al.*, PLB532, 222)



blue: HKM red: EKRS

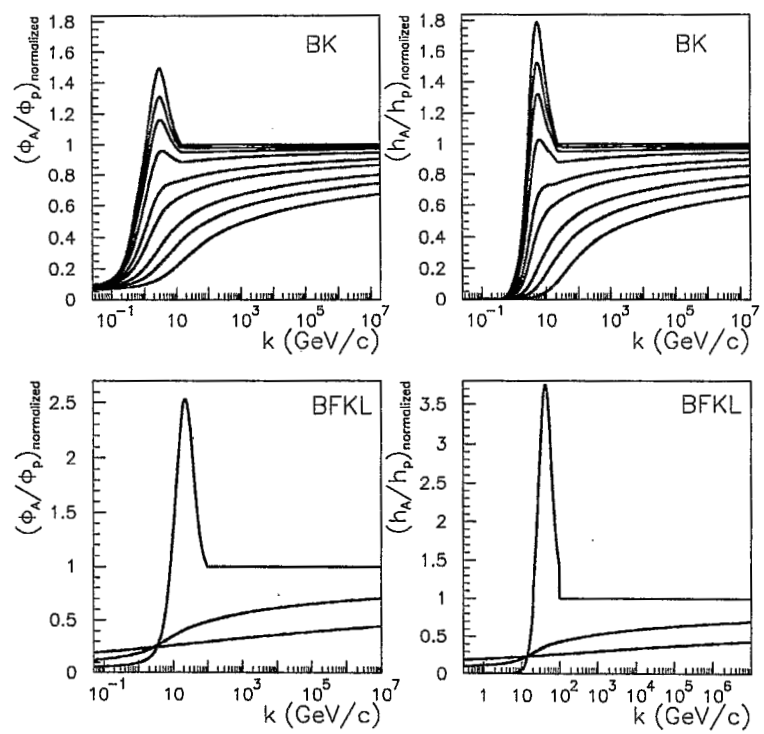
green: New HIJING

(Full DGLAP evolution)

BK and BFKL evolution erases Cronin enhancement

(Albacete, Armesto, Kovner, Salgado, Wiedemann, hep-ph/0307179)

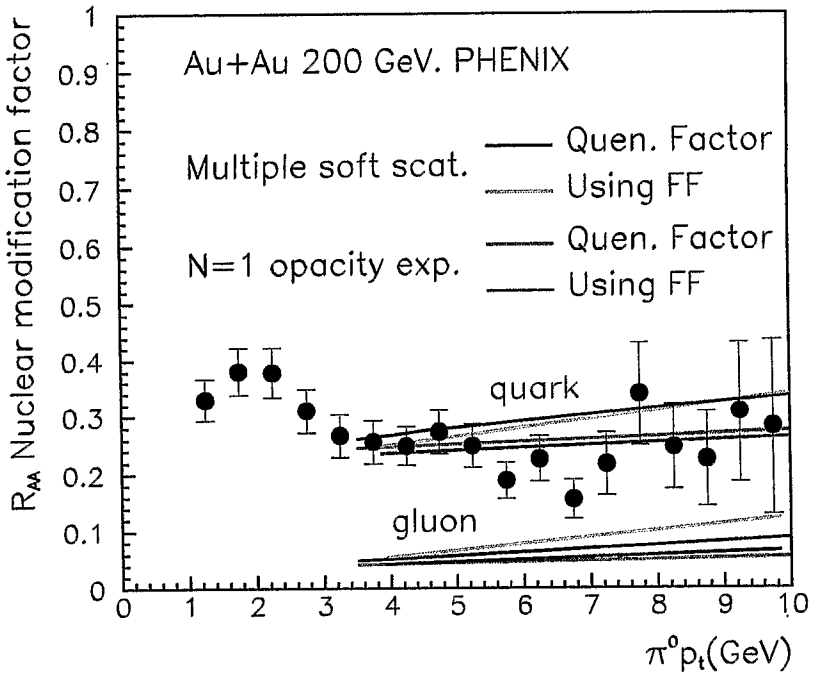
Taken MV as initial condition for BK evolution:



$\Phi \rightarrow$ MV (initial); $h(k) = k^2 \nabla_k^2 \Phi(k)$

$\frac{\alpha_s N_c}{\pi} Y$ =0, 0.05, 0.1, 0.2, 0.4, 0.6, 1, 1.4 and 2

Applications: Comparison with PHENIX data.



- Factor 5 suppression needs R$\sim$ 1000$\div$2000. But small-p_t region not well reproduced: additional effects? (shadowing, Cronin ...) Gyulassy, Levai, Vitev, Wang, Arleo ...
- Smallest values of p_t are in the limit of applicability of the calculations.
- Slope and magnitude of the effect are ok.

Gluon multiplicity inside the jet.

The characteristic angular distribution of the medium–induced gluon radiation could be better observed in the quantity

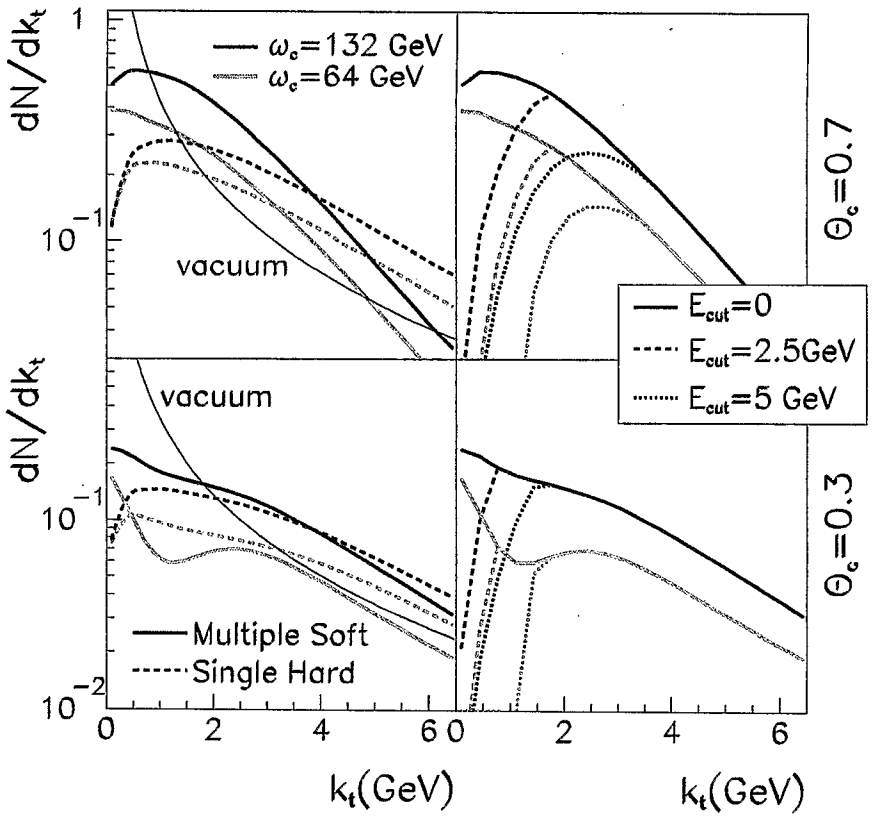
$$\frac{dN^{\rm jet}}{dk_\perp} = \int_{k_\perp/sin\theta_c}^{E} d\omega \frac{dI}{d\omega dk_\perp}$$

For the vacuum we simply use

$$\frac{dI_{\rm vac}}{d\omega dk_\perp} \sim \frac{1}{\omega}\frac{1}{k_\perp}$$

Needs a more quantitative analysis.

But, effect based mainly on kinematics!



(100 GeV jet)

NT@UW–03–034

Cronin Effect Versus High-p_T Suppression in pA Collisions

Yuri V. Kovchegov*

Department of Physics, University of Washington, Box 351560
Seattle, WA 98195

This presentation is based on work done in collaboration with D. Kharzeev and K. Tuchin [1], and was presented by K. Tuchin due to my illness.

We start by reviewing gluon production mechanism in pA collisions at very high energies. At moderately high energy the gluon production is given by McLerran-Venugopalan model. To find single-gluon inclusive production cross section one had to solve classical Yang-Mills equations. Corresponding cross section has been constructed in [2] and includes the effects of multiple rescatterings of the produced gluon on nucleons in the nucleus, as shown in the figure on slide **#1**. The same slide has an expression for the obtained cross section in terms of a gluon dipole's forward scattering amplitude on a nucleus. This formula leads to R^{pA} exhibiting low-p_T suppression and Cronin-like high-p_T enhancement, as shown in slide **#2** [3]. The height and position of the Cronin maximum are increasing functions of centrality.

Gluon production cross section for pA including the BK [4] evolution has been found in [6]. On of the many resummed diagrams is shown in the figure on slide **#3**. There one can also see the rules for including the quantum small-x evolution in the quasi-classical formula from slide **#1** [2]: the lowest order proton's wave function has to be replaced by the BFKL-evolved one, while the gluon dipole forward scattering amplitude has to be replaced by the BK-evolved one.

On slide **#4** we show what happens to R^{pA} as energy/rapidity increases: the effects of BK evolution is to introduce suppression of R^{pA} at all p_T. At very high energy/rapidity even the Cronin maximum disappears and R^{pA} flattens out at $R^{pA} \sim A^{-1/6}$. Therefore, at high energy/rapidity we expect Cronin enhancement to turn into suppression with R^{pA} becoming a decreasing function of centrality [1] (see also [7]). Our prediction is qualitatively different from predictions of other models based on multiple rescatterings only.

Recently presented preliminary BRAHMS Collaboration data on hadron production at forward rapidity in dAu collisions at RHIC show a clear suppression of R^{pA} at $p_T \leq 2.6$ GeV. Pending the final version of the data and future studies of R^{pA} at higher p_T and of dijet correlations, one may conclude that Saturation/Color Glass Condensate has been discovered at forward rapidity at RHIC.

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[1] D. Kharzeev, Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **68**, 094013 (2003) [arXiv:hep-ph/0307037].
[2] Y. V. Kovchegov and A. H. Mueller, Nucl. Phys. B **529**, 451 (1998) [arXiv:hep-ph/9802440].
[3] B. Z. Kopeliovich, J. Nemchik, A. Schafer and A. V. Tarasov, Phys. Rev. Lett. **88**, 232303 (2002) [arXiv:hep-ph/0201010]; R. Baier, A. Kovner and U. A. Wiedemann, Phys. Rev. D **68**, 054009 (2003) [arXiv:hep-ph/0305265].
[4] Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999) [arXiv:hep-ph/9901281];
[5] I. Balitsky, Nucl. Phys. B **463**, 99 (1996) [arXiv:hep-ph/9509348].
[6] Y. V. Kovchegov and K. Tuchin, Phys. Rev. D **65**, 074026 (2002) [arXiv:hep-ph/0111362].
[7] J. L. Albacete, N. Armesto, A. Kovner, C. A. Salgado and U. A. Wiedemann, arXiv:hep-ph/0307179.
[8] BRAHMS Collaboration preliminary data, presented by R. Debbe at the APS DNP 2003 Fall Meeting.

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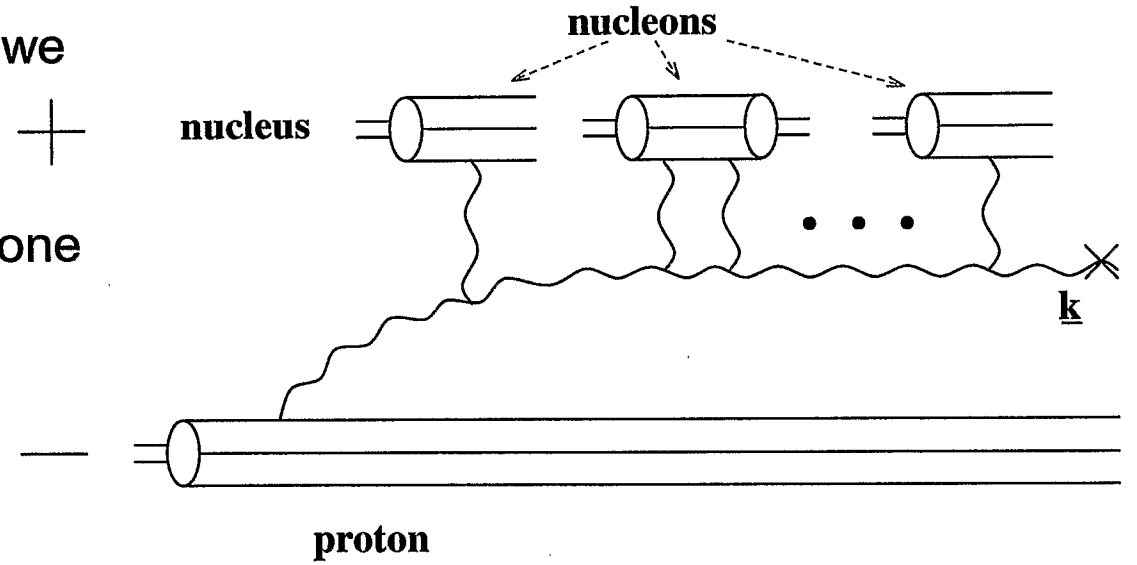
*This work is supported in part by the U.S. Department of Energy under Grant No. DE-FG03-97ER41014.

Gluon Production in pA: McLerran-Venugopalan model

Classical gluon production: we need to resum only the multiple rescatterings of the gluon on nucleons. Here's one of the graphs considered.



Yu. K., A.H. Mueller, hep-ph/9802440

Resulting inclusive gluon production cross section is given by

$$\frac{d\sigma}{d^2k\,dy} = \frac{1}{(2\pi)^2}\int d^2b\,d^2x\,d^2y\,e^{i\underline{k}\cdot(\underline{x}-\underline{y})}\,\frac{\alpha C_F}{\pi^2}\,\frac{\underline{x}\cdot\underline{y}}{x^2\,y^2}\left[N_G(x)+N_G(y)-N_G(\underline{x}-\underline{y})\right]$$

proton's wave function

With the gluon-gluon dipole-nucleus forward scattering amplitude

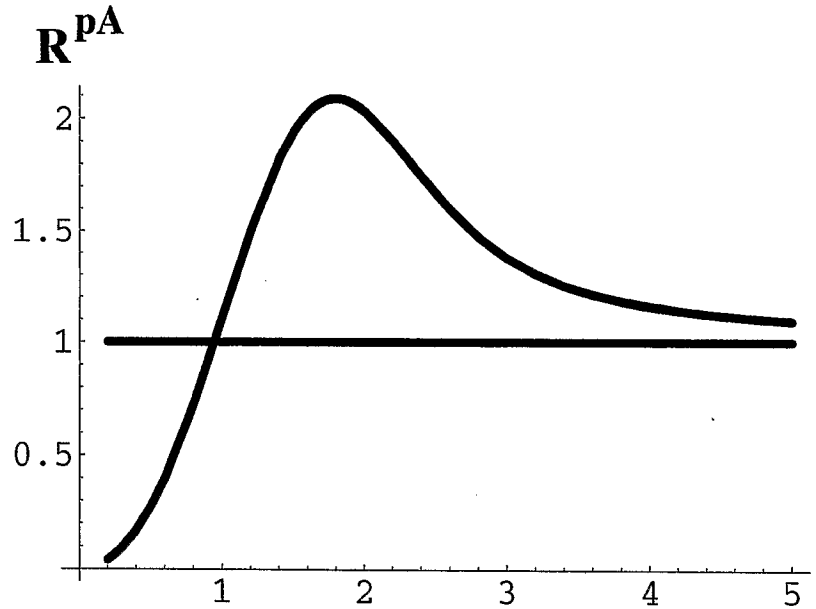
$$N_G(x, Y=0) = 1 - e^{-x^2 Q_s^2/4}$$

McLerran-Venugopalan model: Cronin Effect

Defining

$$R^{pA} = \frac{\dfrac{d\sigma^{pA}}{d^2k\,dy}}{A\dfrac{d\sigma^{pp}}{d^2k\,dy}}$$

we can plot it for the quasi-classical cross section calculated before. One can actually do the integration analytically obtaining



$$R^{pA}(k_T) = \frac{k^4}{Q_S^4}\left\{-\frac{1}{k^2} + \frac{2}{k^2}e^{-k^2/Q_S^2} + \frac{1}{Q_S^2}e^{-k^2/Q_S^2}\left[\ln\frac{Q_S^4}{4\Lambda^2 k^2} + Ei\left(\frac{k^2}{Q_S^2}\right)\right]\right\}$$

Classical gluon production leads to Cronin effect!

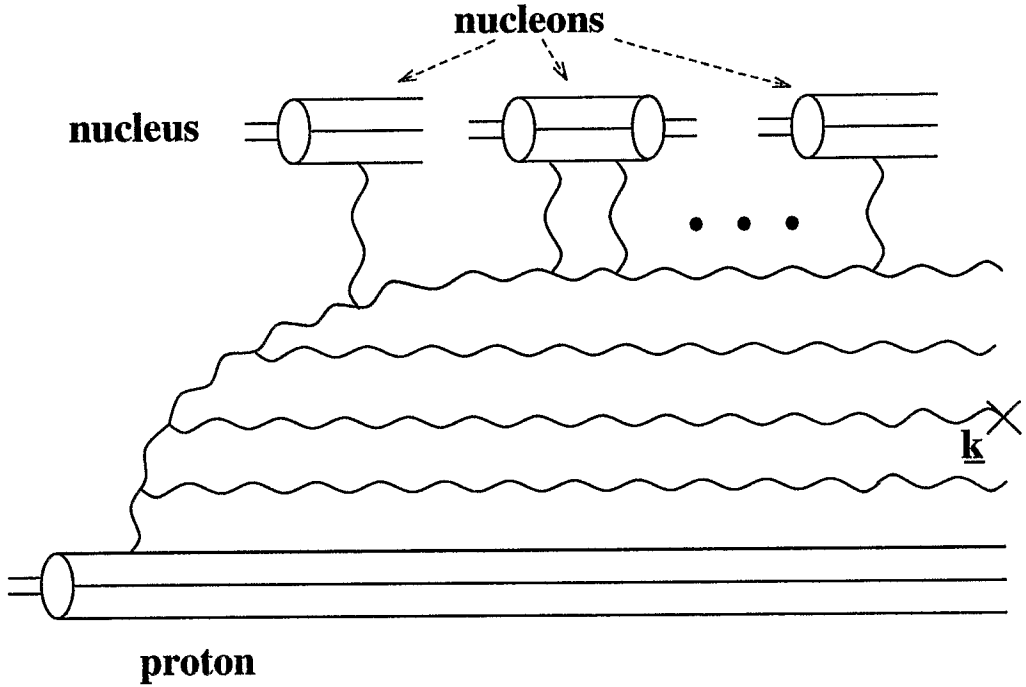
(see also B. Kopeliovich et al, '02, R. Baier et al, '03)

Including Quantum Evolution

To understand the energy dependence of particle production in pA one needs to include quantum evolution resumming graphs like this one. This resums powers of

$\alpha \ln 1/x = \alpha Y$.

This has been done in Yu. K., K. Tuchin, hep-ph/0111362.



The rules accomplishing the inclusion of quantum corrections are

Proton's LO wave function ⇨ Proton's BFKL wave function and $N(x, Y=0) \Rightarrow N(x, Y)$

where the dipole-nucleus amplitude N is to be found from (Yu. K., Balitsky)

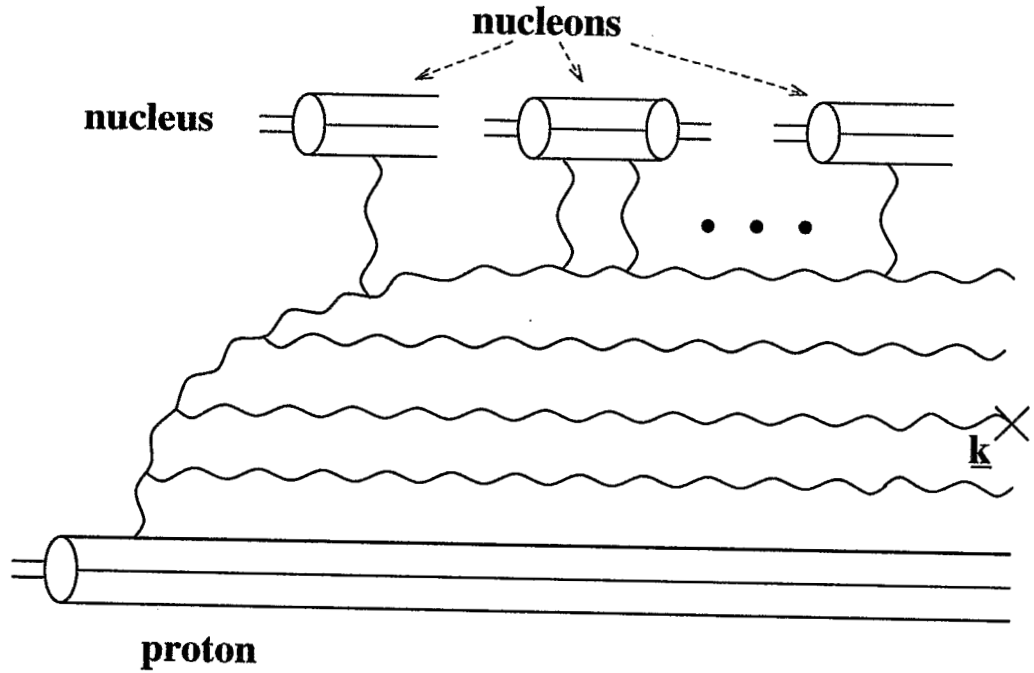
$$\frac{\partial N(Y, k^2)}{\partial Y} = \alpha_s K_{BFKL} \otimes N(Y, k^2) - \alpha_s [N(Y, k^2)]^2$$

Including Quantum Evolution

To understand the energy dependence of particle production in pA one needs to include quantum evolution resumming graphs like this one. This resums powers of

$\alpha \ln 1/x = \alpha Y$.

This has been done in Yu. K., K. Tuchin, hep-ph/0111362.



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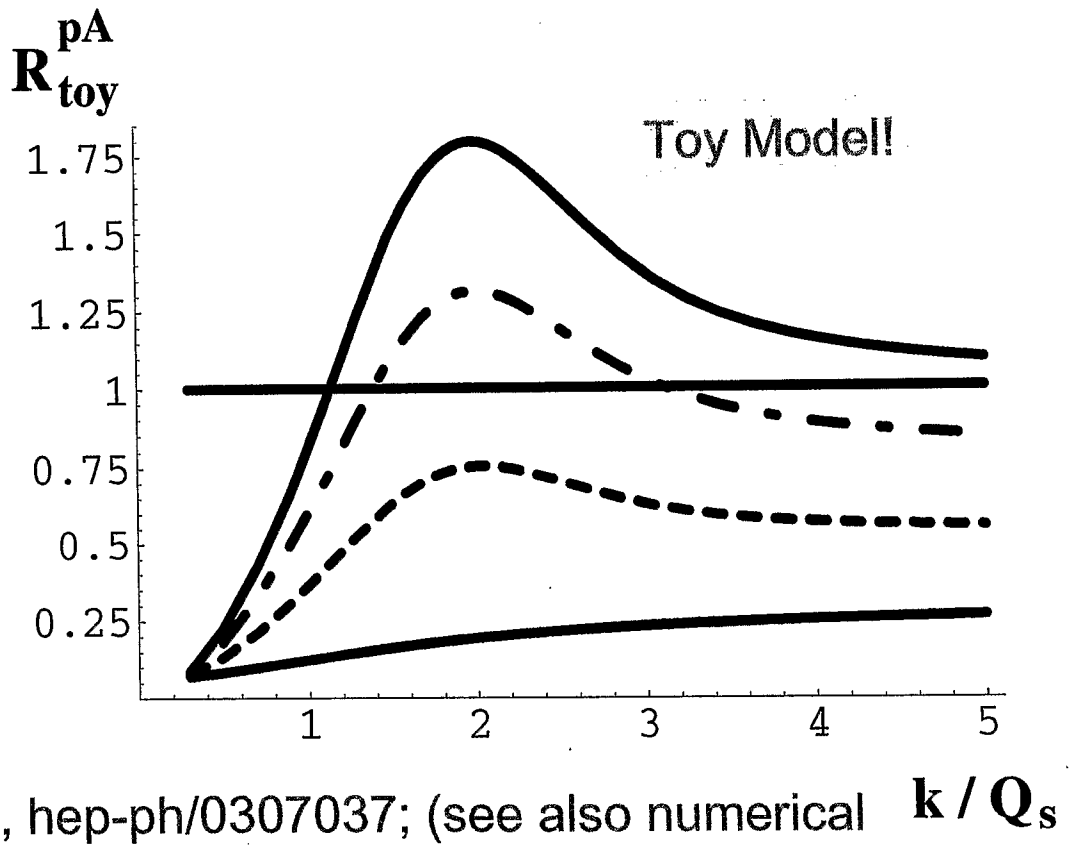
Our Prediction

Our analysis shows that as energy/rapidity increases the height of the Cronin peak decreases. Cronin maximum gets progressively lower and eventually disappears.

- Corresponding R^{pA} levels off at roughly at

$$R^{pA} \sim A^{-1/6}$$



D. Kharzeev, Yu. K., K. Tuchin, hep-ph/0307037; (see also numerical simulations by Albacete, Armesto, Kovner, Salgado, Wiedemann, hep-ph/0307179 and Baier, Kovner, Wiedemann hep-ph/0305265 v2.)

⇨At high energy / rapidity R^{pA} at the Cronin peak becomes a decreasing function of both energy and centrality.

Color Glass Condensate at RHIC

D. Kharzeev
Nuclear Theory Group
Physics Department
Brookhaven National Laboratory
Upton, NY 11973, USA

December 15, 2003

In this talk I review the main ideas of the Color Glass Condensate approach, and its applications to multi-particle production at high energies. The approach is shown to describe well the centrality, energy, and rapidity dependences of hadron multiplcities in Au-Au and d-Au collisions at RHIC. A special emphasis in this talk is put on the recent BRAHMS discovery of high p_t hadron suppression at forward rapidity $\eta \simeq 3$ in d-Au collisions, predicted theoretically in the CGC approach. I argue that the present RHIC data can be used to start mapping the "phase diagram" of high energy QCD. The future measurements, notably the study of back-to-back correlations, should allow for an unambiguous identification of the Color Glass Condensate.

QCD and the classical limit

QCD = Quark Model + Gauge Invariance

$$q(x) \longrightarrow \exp\left(i\omega_a(x)T^a\right)\ q(x),$$

$$\left[T^a, T^b\right] = i f^{abc} T_c$$

For $\tilde{A}_\mu = \dfrac{1}{g} A_\mu$,

$$L_{\mathrm{QCD}} = \sum_q \bar{q}(x)\left(i\gamma_\mu D^\mu - m_q\right) q(x) - \frac{1}{4g^2}\mathrm{tr}\ G^{\mu\nu}(x) G_{\mu\nu}(x);$$

Classical dynamics applies when the action is large: $(\hbar \longrightarrow 0)$

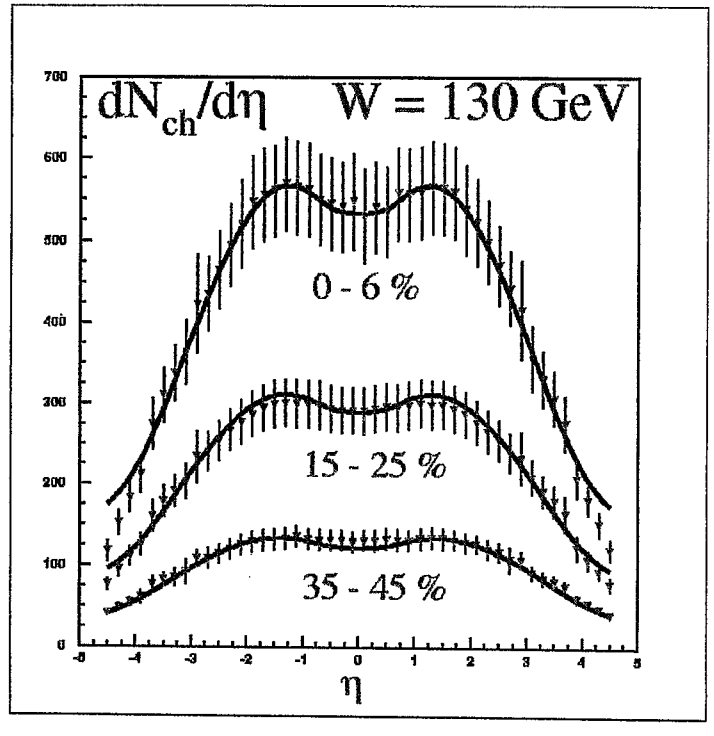
$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar} \int d^4x\ \mathrm{tr}\ G^{\mu\nu}(x) G_{\mu\nu}(x) \gg 1$$

=> Need weak coupling and strong fields

Color Glass Condensate describes the Au-Au data

Kharzeev & Levin, Phys. Lett. B523 (2001) 79

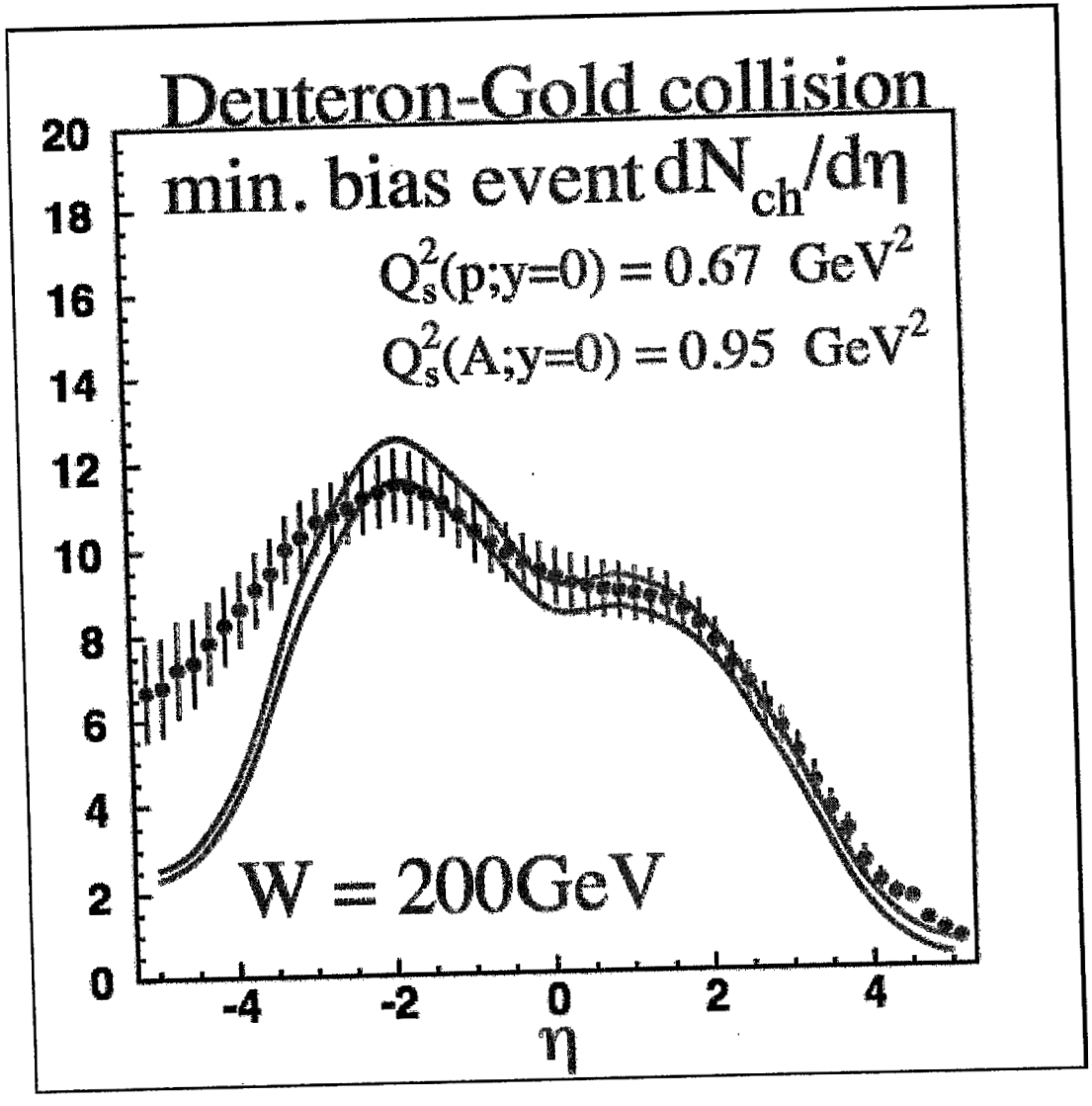
Au + Au at 130 GeV



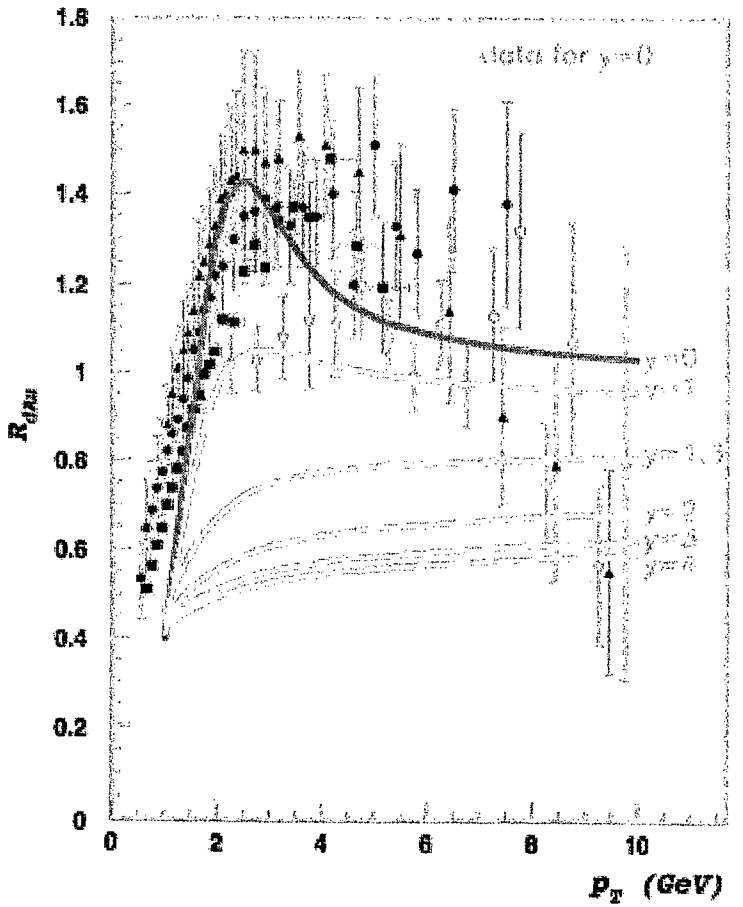
PHOBOS Coll., R. Noucier

- We need a simpler system such as d + Au in order to understand a complex system Au + Au
- The results of d+Au are crucial for testing the saturation approach

Most of the discrepancy disappears; Au fragmentation still a problem



Color Glass Condensate: confronting the data



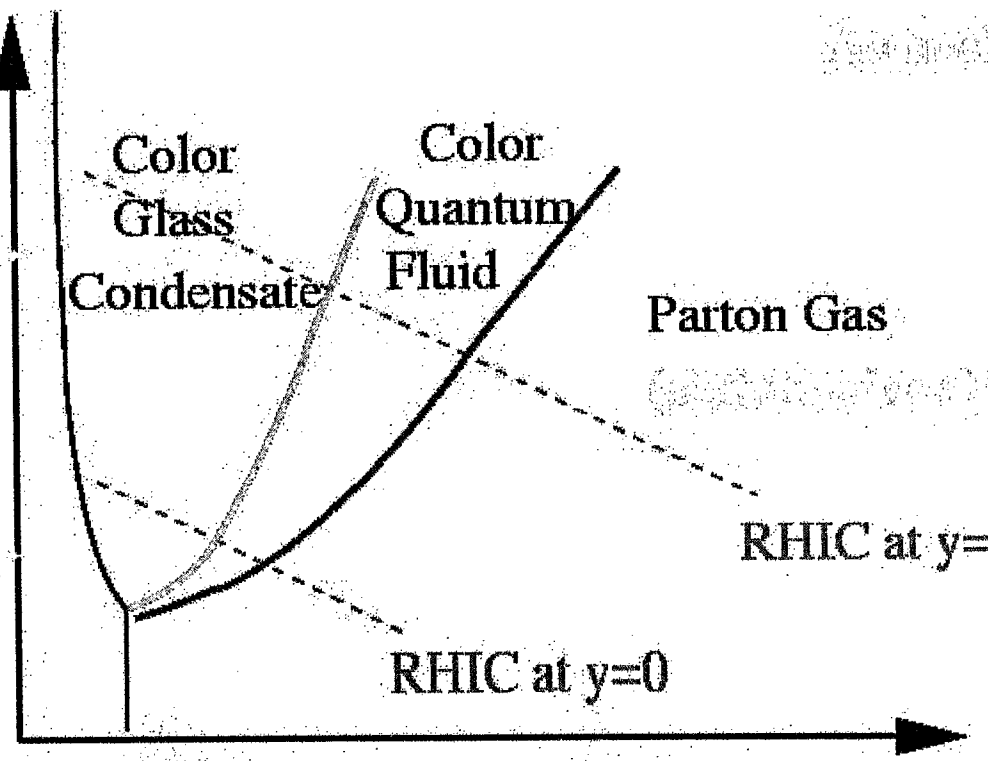
The effects of quantum Evolution in the CGC set in very rapidly

<u>RHIC energy is ideal</u>

talk by K. Tuchin/Yu.Kovchegov

DK, Yu. Kovchegov, K. Tuchin,
To appear

Phase diagram of high energy QCD and RHIC



Open Charm Production in Heavy-Ion Collisions and High Density QCD

Kirill Tuchin (BNL)

In collaboration with D. Kharzeev

hep-ph/0310358

k_T-factorization

The color filed of a high energy hadron (nucleus) is quasiclassical (McLerran & Venugopalan, Kovchegov). The typical transverse momentum of a parton in a high energy hadron (nucleus) is $Q_s \sim s^{\alpha_s}$ (Gribov, Levin, Ryskin). The chromoelectric field is

$$E \sim \frac{Q_s^2}{g}$$

It can produce $q\bar{q}$ pairs from vacuum if

$$gE \geq \frac{m}{\lambda} \sim m^2 \quad \Rightarrow \quad Q_s^2 > m^2$$

Thus, at large s transverse structure of hadrons is of crucial importance.

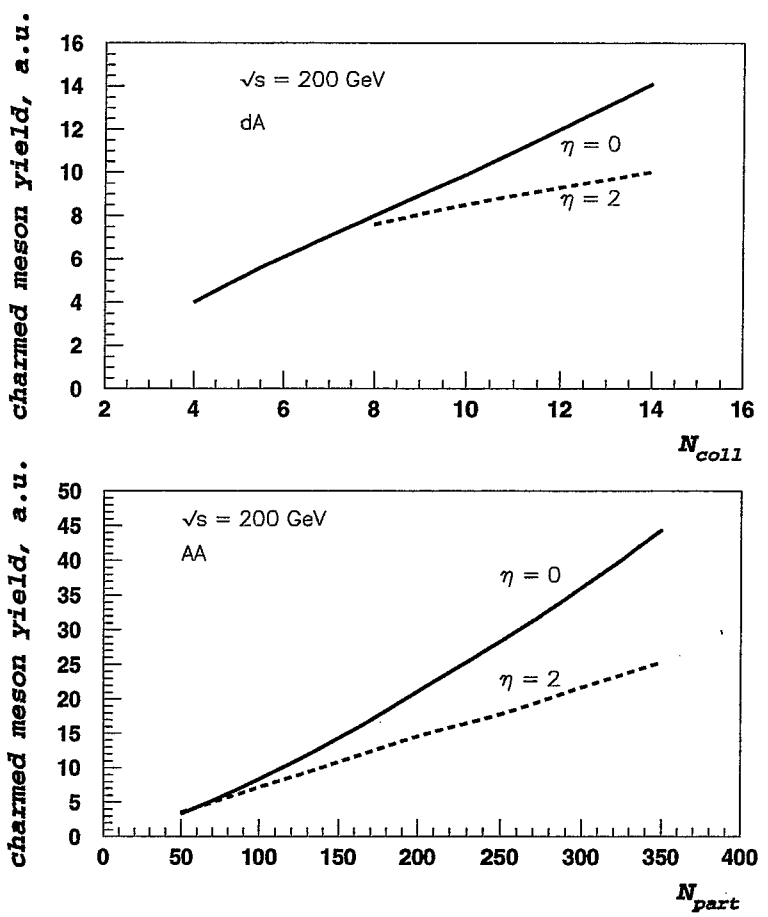
For pp it can still be factorized in the transverse momentum plane

$$\frac{d\sigma_{\rm cc}}{d^2k_\perp\, dy_1\, dy_2} =$$

$$\int d^2q_{\perp 1} \int d^2q_{\perp 2}\, \phi(y_1, q_{\perp 1})\, \mathcal{A}_{gg}\left(\hat{s}, \hat{t}, \hat{u}, q_{\perp 1}^2, q_{\perp 2}^2\right) \phi(y_2, q_{\perp 2}),$$

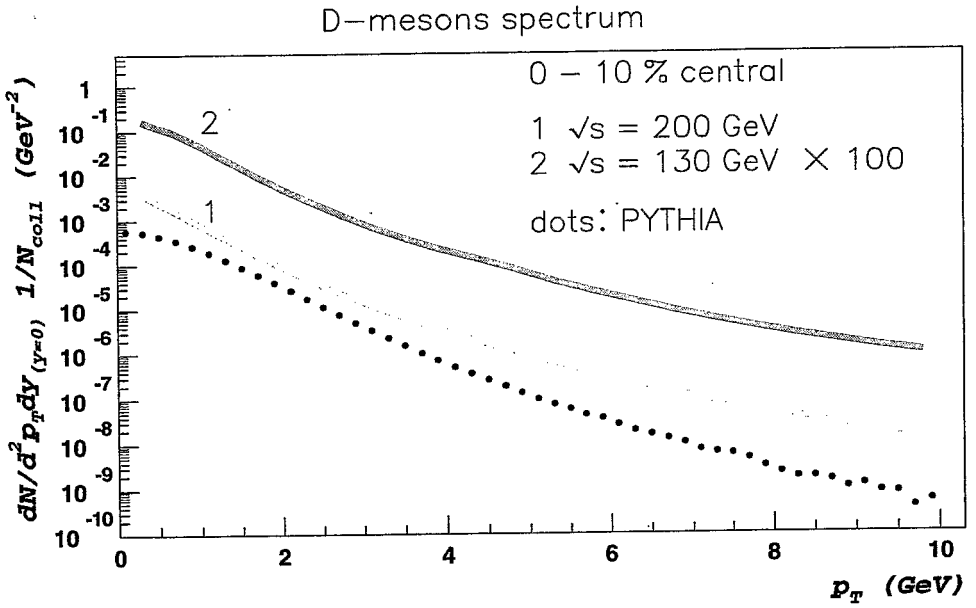
where $\phi(y, q_\perp) = \frac{dxG(y,q_\perp)}{dq_\perp^2}$ (Levin at. al. , Catani et. al. , Collins & Ellis).

Scaling of charm spectra with atomic number A



Suppression of the charm yield is clearly seen at the forward rapidity. This is the universal feature of all semihard processes (saturation).

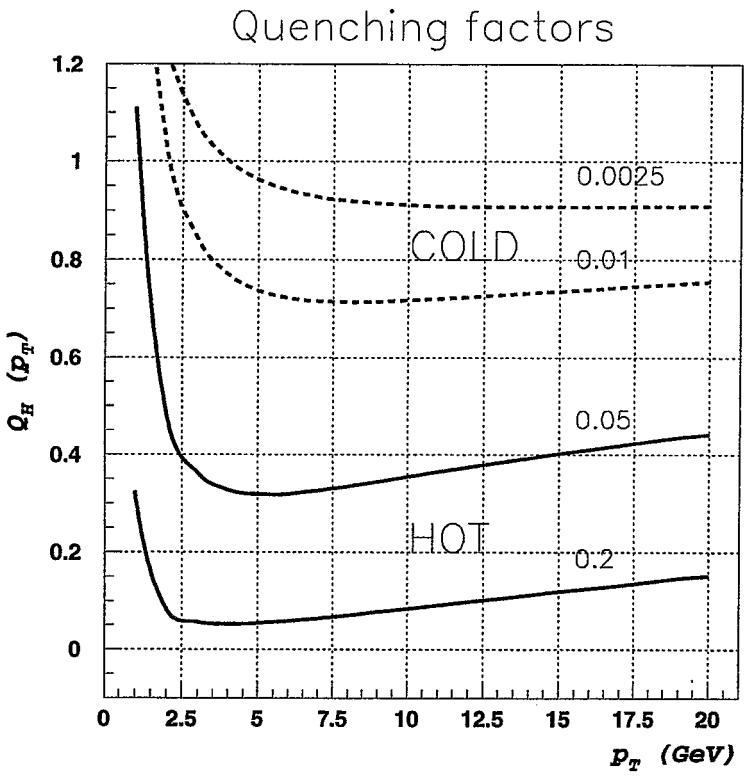
Open charm spectrum



Dots: results of PYTHIA model for the same parameters as used by PHENIX.

Due to $N_{\rm coll}$ scaling at $\eta \simeq 0$ shown spectra coincide with open charm spectra in pp.

Quenching of open charm at RHIC



$\hat{q} = 0.2,\ 0.05,\ 0.01,\ 0.0025$ GeV^3; $L = 5$ fm.

Conclusions

1. In the midrapidity $Q_s \simeq m$, therefore open charm spectrum in AA and dA scales with number of binary collisions.

2. At forward rapidity the spectrum scales with $N_{\rm part}$. Therefore, $R_{AA}^{\rm charm}$ and $R_{dA}^{\rm charm}$ decrease with centrality at $y = 2$:

$$R_{\rm AA}^{\rm charm} \sim 1/A^{1/3} \sim 1/\sqrt{N_{\rm part}^{1/3}} \simeq 0.5$$

$$R_{\rm dA}^{\rm charm} \sim 1/A^{1/6} \sim 1/\sqrt{N_{\rm part}^{\rm Au}} \simeq 0.75$$

3. The open charm spectrum calculated in CGC is significantly harder than that in the parton model.

4. The quenching of the open charm spectrum is almost p_T independent at $2 < p_T < 15$ GeV due to the dead cone effect.

Proton Nucleus Collisions at High Energy

J. Jalilian-Marian, University of Washington

for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

Summary

- CGC in pA collisions
  - Shadowing + Cronin
  - Classical $\rightarrow$ suppression and enhancement
    - Mid rapidity RHIC
  - Quantum evolution $\rightarrow$ suppression
    - Forward rapidity at RHIC
    - Mid to Forward rapidity at LHC
- Probing the "phase" diagram of QCD
  - Hadrons
  - Photons, dileptons, etc.
  - Photon + jet (direct probe of σ_{dipole})
- Rapidity, p_t and centrality dependence
- Correlations

PA and the CGC

- Proton: dilute system of quarks and gluons
- Nucleus: Color Glass Condensate
  - Gluons at small x
    - Quarks are subdominant
  - Classical approximation ("Glauber")
  - Quantum evolution
    - $\alpha_s \, log 1/x$: included
    - $\alpha_s \, log Q^2$: not included
  - Unified treatment of shadowing and "Cronin"
- Predictions: mid rapidity vs. forward rapidity
  - Classical
  - Quantum

pA and the CGC

- Quark "production"

$$\frac{d\sigma^{pA}}{dy\, d^2b_t\, d^2k_t} \sim \int d^2r_t\, e^{ik_t\cdot r_t}\, \sigma_{dipole}(x, r_t, b_t)$$

- Gluon production

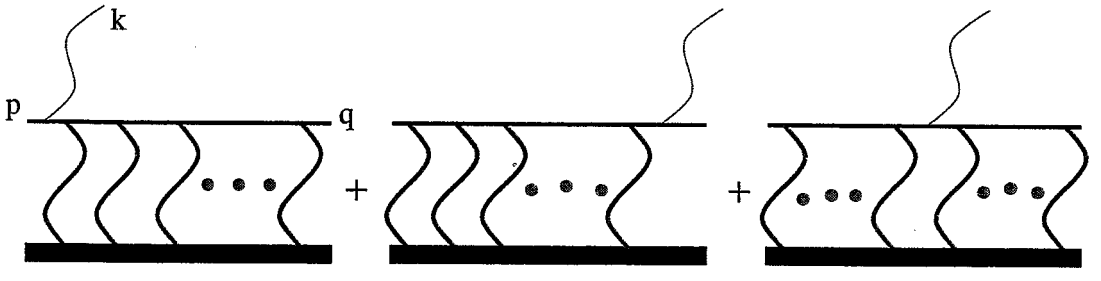
$$\frac{d\sigma^{pA}}{dy\, d^2b_t\, d^2k_t} \sim \int \frac{d^2r_t}{r_t^2}\, e^{ik_t\cdot r_t}\, \sigma_{dipole}(x, r_t, b_t)$$

- Dipoles (fundamental and adjoint): universal ingredients

- No fragmentation functions yet

pA and the CGC

- Photon production



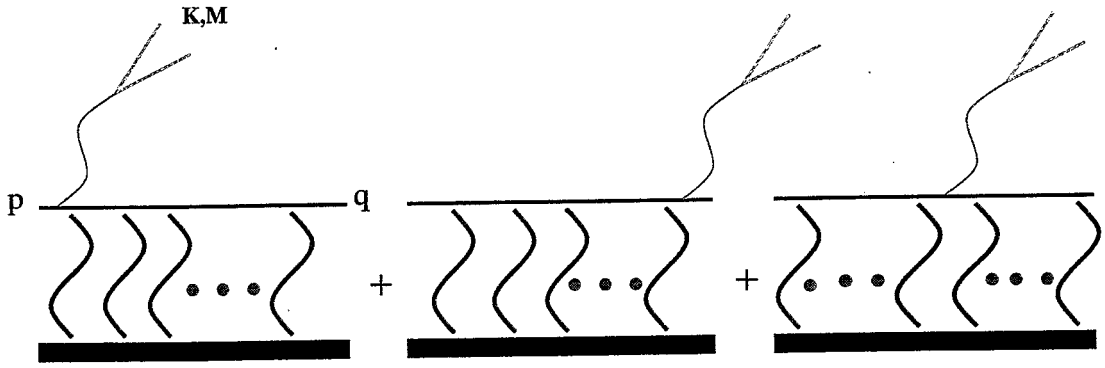
$$\frac{d\sigma^{q\to q\gamma}}{dz\, d^2b_t\, d^2k_t} = \frac{2\alpha_{em}}{(2\pi)^4 k_t^2} \frac{[1+(1-z)^2]}{z}$$
$$\int d^2l_t \frac{z^2 l_t^2}{[k_t - z l_t]^2}\, \widehat{\sigma}_{dipole}(x, b_t, l_t)$$

with $z = k^-/p^-$ and $l_t = q_t + k_t$

F.G. and J.J-M. (PRD66, 014021, 2002)

pA and the CGC

- Dilepton production



$$\frac{d\sigma^{q\,A\to q\,l^+l^-\,X}}{dz\,d^2b_t\,d^2k_t\,d\log M^2} = \frac{2\alpha_{em}^2}{3\pi}\int \frac{d^2l_t}{(2\pi)^4}\,\widehat{\sigma}_{dipole}(x,b_t,l_t)$$

$$\Big\{\Big[\frac{1+(1-z)^2}{z}\Big]\frac{z^2 l_t^2}{[k_t^2+M^2(1-z)][(k_t-zl_t)^2+M^2(1-z)]}$$

$$-z(1-z)\,M^2\Big[\frac{1}{[k_t^2+M^2(1-z)]}-\frac{1}{[(k_t-zl_t)^2+M^2(1-z)]}\Big]^2\Big\}$$

with $l_t = q_t + k_t$

F.G. and J.J-M. (PRD66, 094014, 2002)

Cronin effect vs. geometrical shadowing in d + Au collisions: pQCD vs. CGC

A. Accardi and M. Gyulassy (Columbia U.)

The Cronin effect consists in the nuclear modification of the transverse momentum spectrum of hadrons with respect to what is to be expected from a naive superposition of nucleon-nucleon collisions. This effect has been attributed to multiple scatterings of the projectile partons, see Ref. [1] for a review of theoretical models. The effect of semi-hard parton rescatterings on the transverse momentum distribution of minijets has been computed in [2] to all orders in the number of scatterings.

The Cronin effect was studied in Ref. [3] in the context of GE models. These models incorporate parton multiple scatterings and unitarity in pQCD in a consistent way. Moreover, they include a detailed parton kinematics and reproduce, in the limit of $A = 1$ or at high-p_T, the hadron transverse spectra as computed in the pQCD parton model. The analysis of pp spectra allows to fix the free parameter of the model, and to compute the spectra in pA collisions without further assumptions. In Ref. [4], this formalism was shown to be equivalent to computations in the McLerran-Venugopalan model, Ref. [5].

We tested our computation of the Cronin effect in minimum bias collisions at $\sqrt{s} =$ 27.4 GeV. The same formalism applied to the recently measured PHENIX $d + Au$ data at $\sqrt{s} = 200$ AGeV tends to overestimate by $\sim 20 - 30\%$ the Cronin effect for π^0 at $y = 0$, $p_T = 3$ GeV. This suggest that dynamical shadowing effects begin to play a role in suppressing the parton and hadron spectra already in $d + Au$ collisions.

Our results are surprisingly similar to predictions based on approximated GE phenomenological models [6], in spite of the inclusion of geometrical shadowing in our GE approach. This provides further evidence for the possible existence of moderate shadowing in the $x \sim 0.01 - 0.1$ range as explored in those references. However, radical gluon shadowing as predicted in [7] is not supported by the data. It remains to be seen if the most recent variations of saturation models can be fine tuned to account to the thusfar featureless $R_{dAu} \sim 1$ RHIC data. Analysis of the centrality dependence of the Cronin effect at RHIC $\eta = 0$ confirms the absence of strong dynamical shadowing. Measurements in the foreward pseudorapidity region will explore the $x \gtrsim 10^{-3}$ region, where dynamical shadowing may play a dominant role. Comparison of the GE model baseline computation with experimental data will allow to measure its magnitude.

1. A. Accardi, arXiv:hep-ph/0212148.
2. A. Accardi and D. Treleani, Phys. Rev. D **64** (2001) 116004.
3. A. Accardi and M. Gyulassy, arXiv:nucl-th/0308029.
4. A. Accardi and M. Gyulassy, arXiv:nucl-th/0304083.
5. A. Dumitru and J. Jalilian-Marian, Phys. Rev. Lett. **89** (2002) 022301, and Phys. Lett. B **547** (2002) 15; F. Gelis and J. Jalilian-Marian, Phys. Rev. D **67** (2003) 074019.
6. X. N. Wang, Phys. Rev. C **61** (2000) 064910. Y. Zhang, G. Fai, G. Papp, G. G. Barnafoldi and P. Levai, Phys. Rev. C **65** (2002) 034903. I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89** (2002) 252301; I. Vitev, *private communication.*
7. D. Kharzeev, E. Levin and L. McLerran, Phys. Lett. B **561** (2003) 93; D. Kharzeev, Y. V. Kovchegov and K. Tuchin, arXiv:hep-ph/0307037.

Cronin effect vs. geometric shadowing in dA collisions: pQCD vs. CGC

Alberto Accardi (Columbia U.)

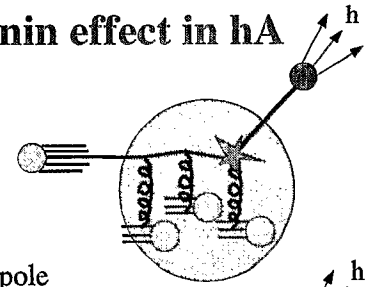
Based on
A.A., M.Gyulassy, nucl-th/0308029

Part I - Minijet production in pA collisions: Glauber-Eikonal models
- pQCD + Glauber rescatterings of partons
- From pp to pA collisions
- Geometric shadowing and saturation

Part II - Cronin effect on π in pA / dA collisions
- Fermilab and RHIC data
- pQCD vs. CGC
- Centrality dependence

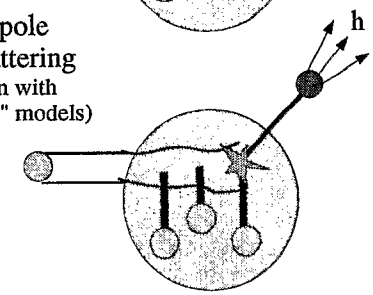
pQCD models for Cronin effect in hA

Glauber-Eikonal models
- hard partonic -
Kuhn '76; Kryzwicky '79; Lev-Petersson '83;
A.A., M.Gyulassy



Colour dipole model
- soft partonic -
Kopeliovich et al.
see talk

colour dipole multi scattering
(connection with "saturation" models)



Glauber-Eikonal Approximated
- soft partonic/hadronic -
X.N. Wang et al.
I.Vitev et al.
P.Levai et al.
G.Fai, X.F.Zhang

A.A. and M.Gyulassy, **nucl-th/0308029**
Review and refs.: **A.A. hep-ph/0212148**

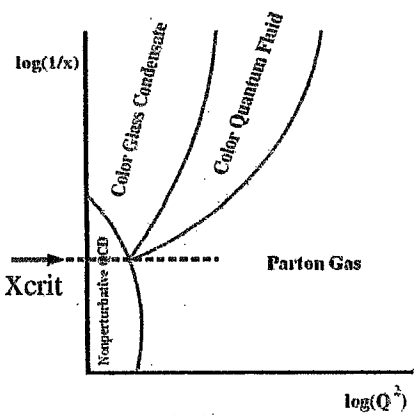
Saturation models - a broad category

MV model ("classical" YM)
Kovchegov
Dumitru, Gelis, Jalilian-Marian
Jalilian-Marian, Nara, Venugopalan
see talk

MV model plus BK evolution
Kovchegov, Tuchin
Albacete, Salgado et al.
see talk

CGC = MV + quantum evolution
Iancu, Itakura, McLerran + ...

CGC inspired models
Kharzeev, Levin, McLerran
Kharzeev, Kovchegov, Tuchin
see talk



QUESTIONS...

How small is xcrit?
Where does RHIC stand?

First act: pp collisions

Single scattering
= LO in pQCD

renormalization scale — fragmentation scale

$$\frac{d\sigma^{pp}}{d^2p_t} = K \int dx \sum_i f_{i/h}(x,Q_p^2) \underbrace{\int dx' \sum_j f_{j/A}(x',Q_p^2) \frac{d\sigma^{ij}_{pQCD}}{d^2p_T}}_{=d\sigma^{iN}/d^2p_T} \int dz D_{i\to h}(z,Q_h^2)$$

K-factor
(simulates NLO)

IR regulator

where $\frac{d\sigma^{iN}}{d^2p_T} \approx \int_{\frac{4p_T^2}{x\sqrt{s}}}^{1} dx' f_{j/A}(x',Q^2) \frac{C^{ij}}{(p_T^2+p_0^2)^2} \propto \frac{1}{(p_T^2+p_0^2)^{2+n}}$ = parton-nucleon cross section

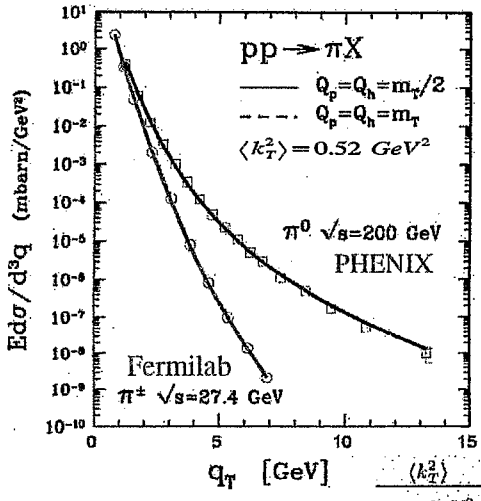
a) CHOOSE the scales: $Q_p = Q_h = m_T/2$ (or $Q_p = Q_h = m_T$)

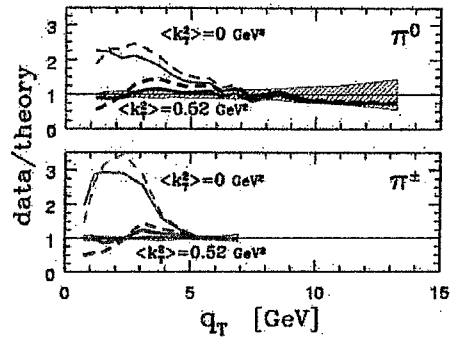
b) Intrinsic $\langle k_T^2 \rangle = 0.52$ GeV² from PHENIX and low-E *pp* data

c) FIT K=K(s) to the **high-pT** tail of the hadron spectrum
(χ^2 fit - sensitive to the choice of scales)

d) FIT p0 = p0(s) to the **low-pT** hadron spectrum
(rather stable against the choice of scales)

Results of the fit





Fit procedure: Eskola, Honkanen '02

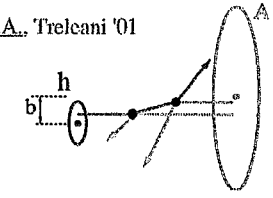
$\langle k_T^2\rangle$	$Q_p = Q_h$	$\sqrt{s} = 27.4$ GeV	$\sqrt{s} = 200$ GeV
0.52 GeV²	$m_T/2$	$p_0 = 0.8 \pm 0.1$ GeV	$p_0 = 1.0 \pm 0.1$ GeV
		$K = 1.27 \pm 0.03$	$K = 0.88 \pm 0.03$
	m_T	$K = 4.26 \pm 0.17$	$K = 1.78 \pm 0.11$
0 GeV²	$m_T/2$	$K = 4.04 \pm 0.11$	$K = 1.04 \pm 0.06$
	m_T	$K = 13.2 \pm 0.4$	$K = 2.20 \pm 0.16$

from PHENIX prelim. (nucl-ex/0306031)

Second act: pA collision and Cronin effect

Multiple parton scattering Calucci, Treleani '90-'91 & A.A., Treleani '01

Assuming: generalized collinear factorization
factorization of the n-body cross-section
only elastic parton scatterings



$$\frac{d\sigma^{iA}}{d^2p_t} = K\sum_{n=1}^{\infty}\frac{1}{n!}\int d^2b\int d^2k_1\cdots d^2k_n \times \underbrace{\frac{d\sigma^{iN}}{d^2k_1}T_A(b)\times\cdots\times\frac{d\sigma^{iN}}{d^2k_n}T_A(b)}_{\text{n-fold parton rescattering}}\ e^{-\sigma^{iN}(p_0)T_A(b)} \times \delta^{(2)}\left(\sum \mathbf{k}_i - \mathbf{p}_t\right)$$

unitarity factor (probability conserv.)

and: $$\frac{d\sigma^h_{pA}}{d^2p_t} = \sum_i f_{i/p}\otimes\frac{d\sigma^{iA}}{d^2p_t}\otimes D_{i\to h} + A\sum_j f_{j/A}\otimes\frac{d\sigma^{jp}}{d^2p_t}\otimes D_{j\to h}$$

- **pA = unitarized multiple parton scatterings on free nucleons**
- **Spectra in pp coll. as limiting case (high-pT or A->1)** $\frac{d\sigma^h_{pA}}{d^2p^h_T} \underset{p_T\to\infty}{\to} A\frac{d\sigma^h_{pp}}{d^2p^h_T}$
- **No extra free parameters**
- **"Geometric" shadowing included** by Glauber rescatterings
- **"Dynamical" shadowing NOT included** (no geom.scaling, no gluon, no EKS98, ...)

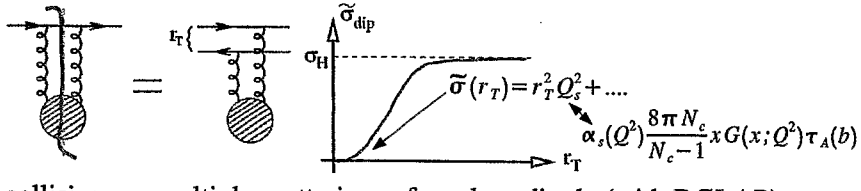
Dipole representation: Glauber-Eikonal pQCD "is" saturation

Resummation of pt-spectrum possible in coordinate-space:

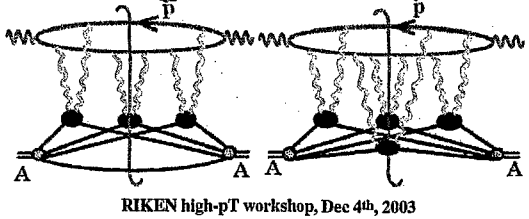
$$\frac{d\sigma^{iA}}{d^2p_T} = \int\frac{d^2r_T}{4\pi^2}e^{-i\vec{k}_T\cdot\vec{r}_T}\left[e^{-\tilde{\sigma}^{iN}(r_T)T_A(b)} - e^{-\sigma^{iN}T_A(b)}\right]$$

same as Jal.-Mar. et al. see A.Mueller's talk

where $\tilde{\sigma}^{iN}(r_T) = \int d^2k\left[1-e^{-i\vec{k}\cdot\vec{r}_T}\right]\frac{d\sigma^{iN}}{d^2k}$ is a dipole cross-section



- pA collisions as multiple scatterings of a colour dipole (with DGLAP)
- Universality: can be used also for DIS, photons, dileptons...



Saturation vs. Glauber-Eikonal

Saturation models:

- prefactors not under control:
  y-dependence of Q_{sat}, not absolute value
  width of geom.scaling window: $Q_{gs}=Q^2_{sat}/Q_0^{=?}$
- spectra stricly = $1/p_T^4$
- no quarks
- no kinematic limits

} can't reproduce hadron spectra in pp collisions

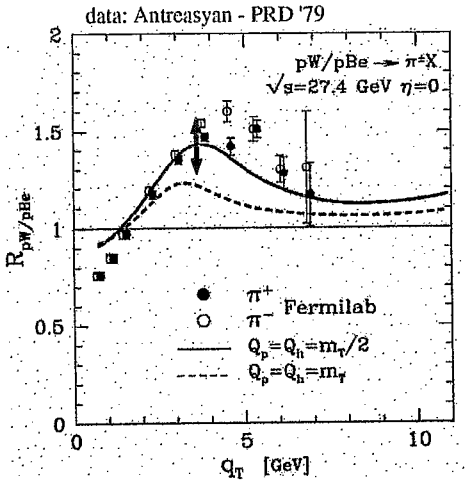
Glauber-Eikonal model:

"equivalent to saturation models" - with the difference that:

- kinematics + q&g: # spectra in p+p OK
  # Cronin at low energy OK
- DGLAP evolution included in PDF's
- includes "geometric shadowing" = unitarization of DGLAP nucleons
- does not include "dynamical shadowing"

Baseline to measure dynamical shadowing and x_{crit}

Cronin effect on pions at Fermilab

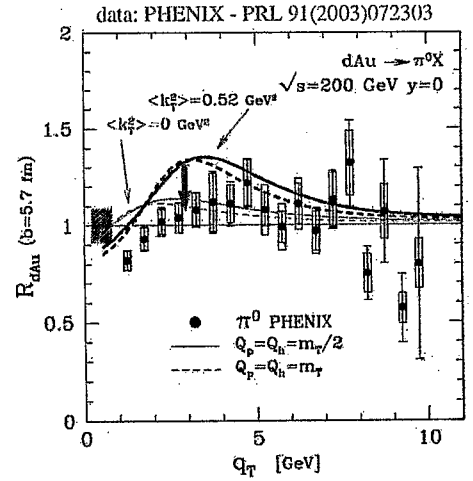


↕ = theoretical error due to fit of $p_0 = 0.8 \pm 0.1$ GeV (it's max. at the peak, dies away far from it)

With Q=mT/2 we reproduce the data quite well.

NOTE: Q=mT/2 was the optimal choice also in pp coll's

Cronin effect on pions at PHENIX



Beware: Theoretical errors ~10% at the peak.
Large experimental systematic errors

Computation compatible with data inside <u>exper.</u> and <u>theor. errors</u>

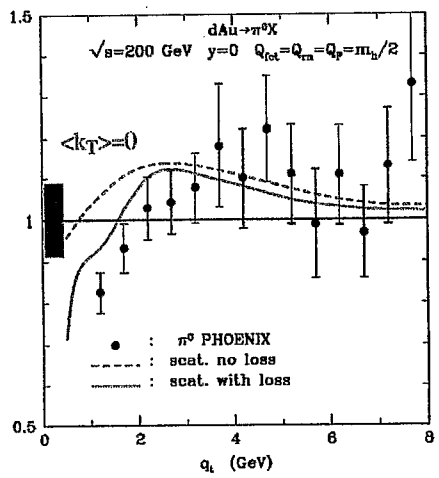
Tends to overestimate the data

⇒ **Possible indication of dynamical shadowing**

However:
<u>radiative and collisional en. loss.</u> (here neglected) may slightly suppress the spectrum at low pT, barring shadowing...

Details do matter!

Cattaruzza, Treleani, in preparation

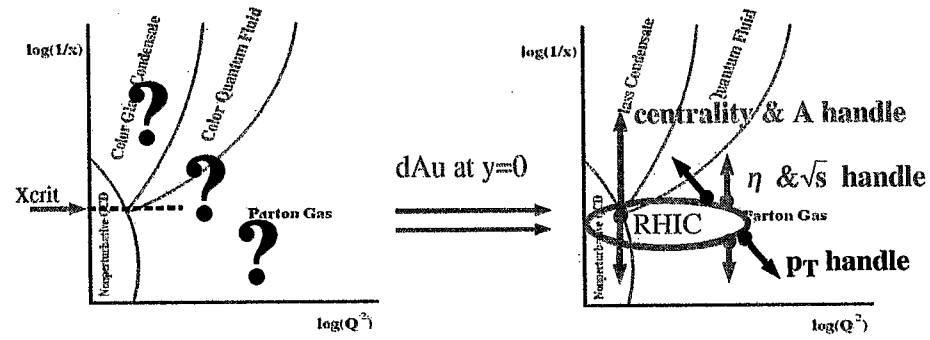


Elastic energy loss:
parton energy is conserved, but x is not!

- $x \to x + \Delta x$
- negligible at high-p_T
- **large correction at low-p_T**

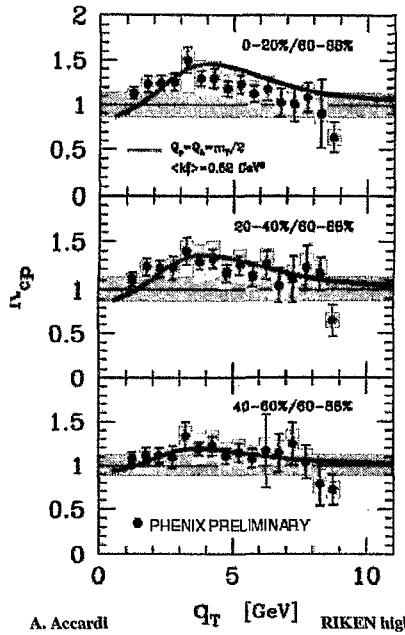
Details ignored in CGC models, like $1/p_T^{4+n}$, kinematic boundaries, elastic energy loss, **are quantitatively important: may turn an indication of CGC into a null signal...**

Where does RHIC stand?



We have handles to move inside and outside of the saturation region

Let's use a handle: the central/peripheral ratio



In exp. data, part of ystematic errors drop out: shape and height of peak are better measured.

If dynamical shadowing is at work,
⟹ stronger suppression in central than in peripheral collisions

dAu ≅ sum of pp + unitarity
Not much room for saturation

(R_{dAu} not in so nice agreement: systematic errors need better understanding)

Exp. data ⟶ T.Awes, DNP Tucson

Conclusions

The Glauber-Eikonal model (= pQCD + rescatterings) allows to compute pA collisions starting from pp spectra

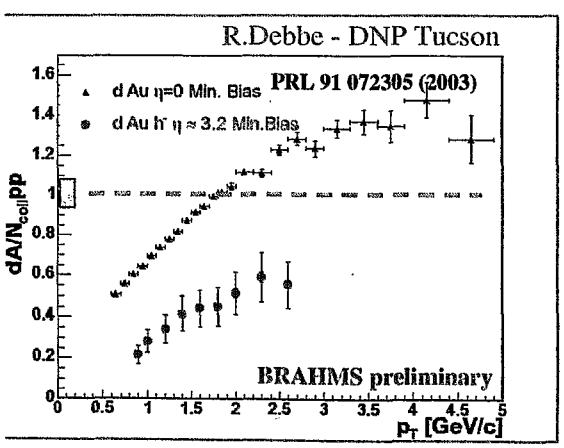
- Correct hadron spectrum in the "pp" limit
- Correct magnitude of Cronin effect for pions, **no extra "ad hoc" phenomenological parameters**
- Flavour dependence still to be understood

dAu ≅ unitarity + sum of pp = "geometric shadowing + Cronin"

can find "dynamical shadowing" by comparing GE baseline with exp. data

Little room for new dynamics at RHIC η=0, what about η=3?

What about η = 3 ?



What did BRAHMS discover?

- just blackness of nucleus ?

- or some novel exciting QCD?

"We began to appreciate (η=3 & CGC models), now it's time to compute (GE pQCD)!"

(freely adapted from J.H.Lee)

$Q\bar{Q}$ production in high-energy hadronic interactions

François Gelis

Abstract

In recent years, the color glass condensate picture has known many successes in the study of very high-energy pp, pA and AA interactions. This approach describes the colliding projectiles in terms of classical color sources, which generate a classical color field which is used to describe the small-x content of the projectiles wave function. This has been used for instance in order to calculate inclusive gluon production in high-energy collisions.

In this talk, I use the same approach in order to calculate the production of quark-antiquark pairs. In order to perform this calculation, one has to compute the quark propagator in the classical color field that describes the collision. The time-ordered quark propagator can be used to obtain the exclusive probability to produce exactly one pair, while the retarded quark propagator gives the average pair multiplicity in a collision.

Applied to pp collisions, where we can limit the calculation to the first order in the hard color sources, this method enables to recover easily the well-known results obtained in 1991 by Collins and Ellis. I'm also discussing the same calculation for pA collisions, where one should perform the calculation to all orders in the source describing the nucleus, in order to take into account its larger density of partons. In this case, the central question of $k_\perp$-factorizability is still uncertain.

Finally, I explain how one could perform the same calculation in the case of AA collisions (i.e. to all orders in both sources), by first reformulating the problem in terms of finding retarded solutions of the Dirac equation in an external classical color field.

1

$Q\bar{Q}$ production in a field $A(t)$

Baltz, FG, McLerran, Peshier (2001)

- Probability to create (exactly) one pair:

$$P_1 = |\langle 0_{\rm in}|0_{\rm out}\rangle|^2 \int \frac{d^3\vec{p}}{(2\pi)^3 2E_{\boldsymbol{p}}} \frac{d^3\vec{q}}{(2\pi)^3 2E_{\boldsymbol{q}}} \left|\overline{u}(\vec{q})\mathcal{T}_F v(\vec{p})\right|^2$$

  ▷ $\mathcal{T}_F$ is the t-ordered quark propagator in the external field
  ▷ $\langle 0_{\rm in}|0_{\rm out}\rangle$ is the vacuum-to-vacuum transition amplitude (sum of vacuum diagrams), required by unitarity

- Average pair multiplicity:

$$\overline{n} = \int \frac{d^3\vec{p}}{(2\pi)^3 2E_{\boldsymbol{p}}} \frac{d^3\vec{q}}{(2\pi)^3 2E_{\boldsymbol{q}}} \left|\overline{u}(\vec{q})\mathcal{T}_R v(\vec{p})\right|^2$$

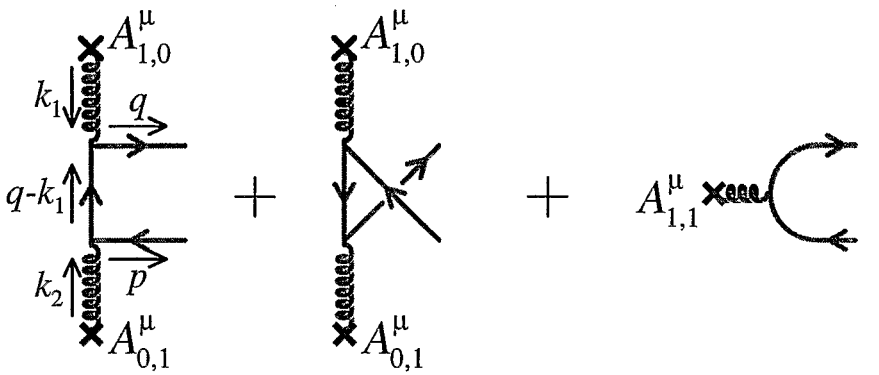
  ▷ $\mathcal{T}_R$ is the retarded quark propagator in the external field

Dilute regime: pp (1/5)

FG, Venugopalan (2003)

- At leading order in the hard sources ρ_1, ρ_2:

$$\mathcal{M} = \overline{u}(\vec{q})\mathcal{T}_R v(\vec{p}) =$$



$$= \mathcal{M}_{\text{abelian}}(\vec{q},\vec{p}) + \mathcal{M}_{3g}(\vec{q},\vec{p})$$

- **Notes:**
  - $A^\mu_{1,0}$, $A^\mu_{0,1}$, $A^\mu_{1,1}$ are the color fields at order ρ_1, ρ_2, $\rho_1\rho_2$
  - $P_1 = \overline{n}$ at this order (retarded = time ordered)

Semi-dense regime: pA (1/3)

Blaizot, FG, Venugopalan (work in progress)

- ρ_1 is a weak source, ρ_2 is a strong source
  $\Rightarrow$ we want the pair production amplitude to first order in ρ_1 and to all orders in ρ_2
- Required steps:
  - find the gauge field $A^{\mu}_{1,\infty}$
  - find the quark propagator (**Note:** $P_1 = \overline{n}$)
- $k_\perp$-factorization ?
  - it is known to work at this order for gluon production
  - does it work for $Q\bar{Q}$ production ?
  - with an universal "unintegrated gluon distribution" ?

Dense regime: AA (1/7)

FG, Kajantie, Lappi (work in progress)

- Alternate representation of the amplitude:

$$\overline{u}(\vec{q})\mathcal{T}_R v(\vec{p}) = \lim_{t\to+\infty} \int d^3\vec{x}\ \phi^\dagger_{\boldsymbol{q}}(t,\vec{x})\psi_{\boldsymbol{p}}(t,\vec{x})$$

$$(i\partial\!\!\!/_x - g A\!\!\!/(x) - m)\psi_{\boldsymbol{p}}(x) = 0\ ,\ \psi_{\boldsymbol{p}}(t,\vec{x}) \underset{t\to-\infty}{\longrightarrow} v(\vec{p})e^{ip\cdot x}$$

$$\phi_{\boldsymbol{q}}(t,\vec{x}) = u(\vec{q})e^{-iq\cdot x}$$

- On a surface of constant proper time:

$$\overline{u}(\vec{q})\mathcal{T}_R v(\vec{p}) = \lim_{\tau\to+\infty} \tau \int d\eta d^2\vec{x}_\perp\ \widetilde{\phi}^\dagger_{\boldsymbol{q}}(\tau,\eta,\vec{x}_\perp)\widetilde{\psi}_{\boldsymbol{p}}(\tau,\eta,\vec{x}_\perp)$$

$$\widetilde{\phi}_{\boldsymbol{q}} \equiv e^{-\frac{\eta}{2}\gamma^0\gamma^3}\phi_{\boldsymbol{q}}\ ,\ \widetilde{\psi}_{\boldsymbol{p}} \equiv e^{-\frac{\eta}{2}\gamma^0\gamma^3}\psi_{\boldsymbol{p}}$$

$$t = \tau\cosh(\eta)\ ,\ z = \tau\sinh(\eta)$$

Saturation and BFKL dynamics in the HERA data at small x

K. Itakura (SPhT, CEA/Saclay)

based on E. Iancu, KI, S. Munier, hep-ph/0310338

We show that the HERA data for the inclusive structure function $F_2(x, Q^2)$ for x ¡ 0.01 and $0.045 < Q^2 < 45GeV^2$ can be well described within the color dipole picture, with a simple analytic expression for the dipole-proton scattering amplitude, which is an approximate solution to the non-linear evolution equations in QCD. For dipole sizes less than the inverse saturation momentum $1/Q_s(x)$, the scattering amplitude is the solution to the BFKL equation in the vicinity of the saturation line. It exhibits geometric scaling and scaling violations by the diffusion term. For dipole sizes larger than $1/Q_s(x)$, the scattering amplitude saturates to one. The fit involves three parameters: the proton radius R, the value x_0 of x at which the saturation scale Q_s equals 1 GeV, and the logarithmic derivative of the saturation momentum λ. The value of λ extracted from the fit turns out to be consistent with a recent calculation using the next-to-leading order BFKL formalism.

Physics required in $x < 0.01,\ Q^2 \lesssim 50\text{GeV}^2$

Saturation for $Q^2 < Q_s^2(x)$ [Levin-Tuchin, Iancu-McLerran]

asymptotic form of the scattering amplitude

$$\mathcal{N}(x, r_\perp) \simeq 1 - \exp\left\{-\frac{1}{2c}\ln^2 r_\perp^2 Q_s^2(x)\right\}$$

as solutions to BK and JIMWLK equations.

BFKL dynamics in $Q_s^2 < Q^2 < Q_s^4/\Lambda^2 \sim 50\text{GeV}^2$

[Iancu-KI-McLerran, Mueller-Triantafyllopoulos]

saddle point approx. + saturation boundary,

expand w.r.t. $\ln 1/r_\perp^2 Q_s^2 = \ln 1/r_\perp^2\Lambda^2 - \ln Q_s^2/\Lambda^2$

$$\mathcal{N}(x, r_\perp) \simeq \underbrace{\left(r_\perp^2 Q_s^2\right)^\gamma}_{\text{geometric scaling}} \underbrace{\exp\left\{-\frac{c}{2\beta\lambda Y}\left(\ln\frac{1}{r_\perp^2 Q_s^2}\right)^2\right\}}_{\text{diffusion, scaling violation}}$$

- Leading: scaling is valid in $Q_s^2 < 1/r_\perp^2 < Q_s^4/\Lambda^2$
  with "Anomalous dimension" $\gamma \simeq 0.63 < 1$
  saddle point satisfying saturation condition
- $\kappa \equiv \beta/c = \chi''(\gamma)/\chi'(\gamma) \sim 48.5/4.88 \sim 9.9$
  $\chi(\gamma)$: Mellin transform of the BFKL kernel
- λ: saturation exponent $Q_s^2(Y) \propto e^{\lambda Y}$ $(Y = \ln 1/x)$

A CGC fit to the HERA data

Iancu, KI, Munier, hep-ph/0310338

$\sigma_{\rm dipole}(x, \mathbf{r}) = 2\pi R^2 \mathcal{N}(rQ_s, Y)$, $Q_s^2(x) = (x_0/x)^\lambda$GeV^2,

$$\mathcal{N}(rQ_s, Y) = \mathcal{N}_0 \left(\frac{r^2 Q_s^2}{4}\right)^{\gamma + \frac{\ln(2/rQ_s)}{\kappa\lambda Y}} \quad \text{for} \quad rQ_s \leq 2$$

$$\mathcal{N}(rQ_s, Y) = 1 - \mathrm{e}^{-a \ln^2(b\, rQ_s)} \quad \text{for} \quad rQ_s > 2$$

$\gamma = 0.63, \ \kappa = 9.9$

(fixed by LO-BFKL, but don't change a lot in resummed NLO)

a, b fixed by continuity at $rQ_s = 2$ where $\mathcal{N} = \mathcal{N}_0$.

3 parameters R, x_0 and λ (The same as in GBW. $\sigma_0 = 2\pi R^2$)

R : proton radius. non-perturbative.

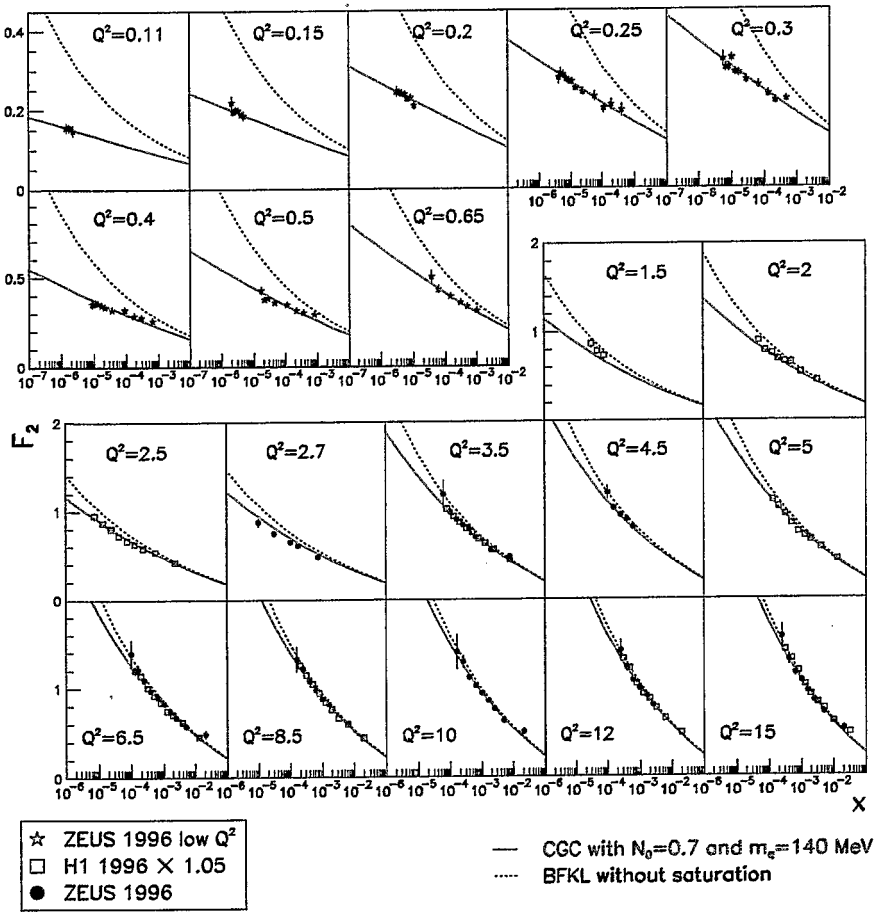
x_0 : the value of x at which Q_s becomes 1 GeV. non-perturbative.

λ : saturation exponent. Perturbatively computable. Known up to resummed NLO $\lambda \sim 0.3$ [Triantafyllopoulos] but left to be fitted (due to ambiguity in the resummed NLO).

Fit to the new ZEUS data for $F_2(x, Q^2)$ within

$$\boxed{x \leq 10^{-2} \text{ and } 0.045 \leq Q^2 \leq 45\text{GeV}^2}$$

A CGC fit to the HERA data



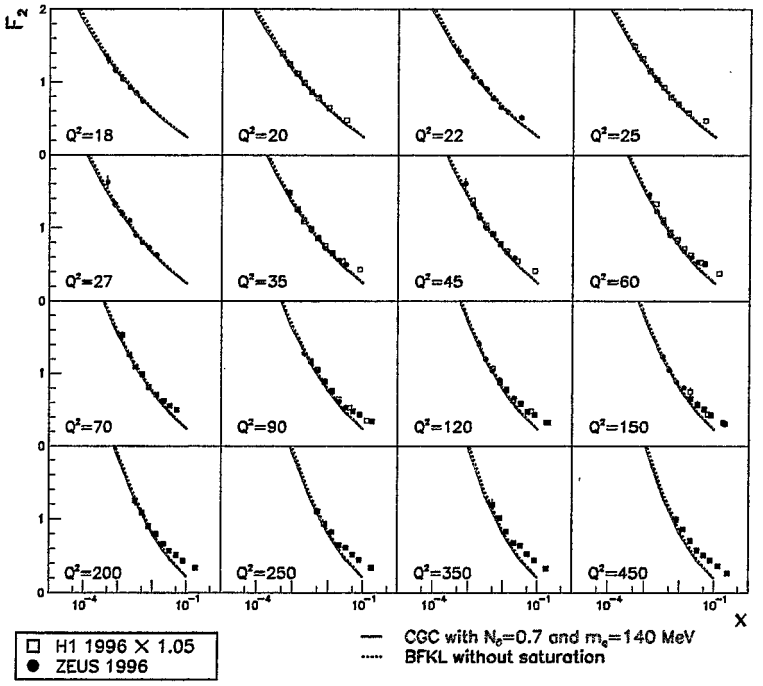
F_2 as a function of x in bins of $Q^2 \leq 15\text{GeV}^2$.

red line: CGC with $\mathcal{N}_0 = 0.7$ and $m_q = 140\text{MeV}$

blue line: BFKL without saturation

$R = 0.641\text{fm}$ ($\sigma_0 = 2\pi R^2 = 25.8\text{mb}$), $x_0 = 0.267 \times 10^{-4}$, $\lambda = 0.253$ with $\chi^2/dof = 0.81$ (156 data points)

A CGC fit to the HERA data



Larger Q^2: (The fit is extrapolated in bins $Q^2 \geq 60\text{GeV}^2$.)

- $\lambda \sim 0.25 \div 0.29$ (dep. on $\mathcal{N}_0$) is in agreement with the resummed NLO BFKL result
- Scaling violation is essential (4 param. fit w/o diffusion doesn't work well $\chi^2/dof \sim 1.4$, where the 4th param is γ.)
- BFKL w/o saturation cannot reproduce the data well
- Good agreement even for $Q^2 \ll 1$ GeV^2 (quark-hadron duality)
- Deviation at high Q^2 is due to the absence of DGLAP evolution

The Small-x Message from HERA

J.Bartels, Hamburg University and BNL Nuclear Theory

Abstract: An attempt is made to summarize the main results of small-x physics at HERA. For the proton structure function, we discuss the idea of saturation in the low-Q^2/small-x region, and we review the arguments in favor of this attractive hypothesis. We emphasize the importance of a direct measurement of the longitudinal structure function F_L. The investigation of diffraction in deep inelastic scattering allows to adress the dependence of $\gamma^* p$ scattering cross section on impact parameter. As to the theoretical developments which have been initiated by the HERA measurements, highlights of recent BFKL studies are briefly summarized. This includes the NLO corrections to the photon impact factor, and to the jet vertex used for the forward jets at HERA and for the Mueller-Navelet jets at the Tevatron and for the LHC. Finally, we briefly discuss recent attempts to find b-dependent dipole cross sections.

The Small-x Message from HERA

Jochen Bartels

Hamburg University and BNL Nuclear Theory

This talk: two 'messages'

- Structure Functions
- Diffraction (more work to be done)

Has stimulated (ongoing) theoretical work, e.g.

- QCD dipole picture
- concept of saturation
- concept of unintegrated parton densitites
- BFKL field theory

Structure Functions

Seen: strong rise of F_2 at small x and low Q^2
(new kinematic regime).
Question: what does it mean?

(i) How far down in Q^2 and/or x can we describe F_2 by (leading twist) DGLAP evolution:
the picture of quasi-free (dilute) partons inside the proton?

Fits seems to work well even at rather low Q^2 and small x, but there are several warnings and doubts:

- small (even negative) gluon at low Q^2
- sensitivity to higher order corrections
- positive curvature of DGLAP not seen in the data
- higher twist studies indicate potential cancellation of twist four in $F_2 = F_T + F_L$, but not in F_L.
  Needs more theoretical work.

Need for a measurement of F_L:

- interesting per se
- potentially very useful for testing validity of leading twist DGLAP: large variations even within DGLAP
- theoretical argument from above: F_L could have large twist four correction

Theory: BFKL

What has HERA contributed to 'proof of existence' of BFKL:

- (i) BFKL in F_2 (?)
- (ii) BFKL in forward jets
- (iii) BFKL in diffractive vector production at large t

Ad (ii): Data show rise of the jet cross section (weaker than LO BFKL).
So far: LO calculation only
Status of NLO corrections:

- jet vertex: NLO calculations finished
  novel type of pQCD calculation:
  interface between collinear and BFKL approximation
  (subtraction of collinear poles and central region)
  Wait for numerical analysis: Mueller-Navelet jets at Tevatron and at LHC.
- photon impact factor: virtual and real corrections
  analytic part complete; numerics of real corrections
  need to simplify virtual corrections

Ad (iii): successfull agreement of LO BFKL with data.

Summary

Accomplished:

- Evidence for saturation: gluons at small x are becoming dense
- DIS Diffraction: distribution in transverse space
- Theory: from small b towards large b

Wanted:

- Measurement of F_L
- DIS on nuclei
- polarized structure functions at small x
- More theoretical work

RHIC initial conditions with the QCD sphalerons: a reduced shadowing and enhanced jet quenching

Edward Shuryak, Stony Brook

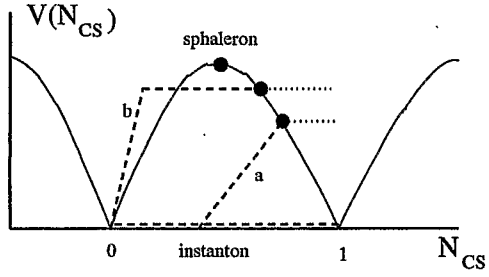
- "Small gluonic spots" in DIS and diffraction
- The instanton/sphaleron mechanism of high energy collisions (pp, DIS $\gamma^* p$, double DIS $\gamma^* \gamma^*$)
- AA collisions (at RHIC): a CGC with a topological structure?
- => prompt quark production
- =>reduced shadowing due to "lumpy glue"
- => enhanced jet quenching due to stronger field

Classical Glue in pp and AA (at RHIC?)

• Color Glass Condensate (CGC): due to high parton density at small x => large occupation numbers => classical YM field => nonperturbative dynamics
McLerran-Venugopalan model: a saturated random Gaussian field.
Venugopalan,Krasnitz et al: explosive behavior, 1/2 gluons gets physical
small perturbative quark production

• The CGC can also be made of topological clusters – sphalerons, or interrupted instantons. (A jump from under the barrier on the barrier.) Leads to prompt production of quarks: $\bar{u}u\bar{d}d\bar{s}s$ produced per cluster, plus few gluons: Maybe this is the Rapid Entropy Generator we badly need

Quantum Mechanics of the tunneling glue



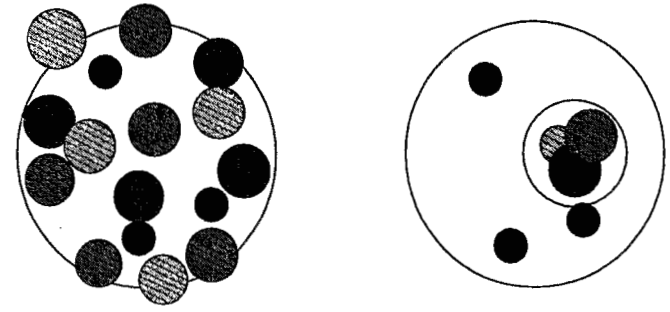
- The energy of Yang-Mills field versus the Chern-Simons number $N_{CS} = \int d^3x K_0$ is a periodic function, with zeros at integer points.
- The *instanton* (the lowest dashed line) describes tunneling between vacua. It is a path at E=0, it starts and ends at no field strength
- If energy is deposited, the paths (the dashed lines) goes up and emerge from ''under the barrier'' into real (Minkowskian) world at the turning points, where momenta (in the $A_0 = 0$ gauge) "$\vec{p}$" $= \frac{d\vec{A}}{dt} = \vec{E} = 0$ => the field is magnetic
- Real time motion outside the barrier (shown by horizontal dotted lines) => explosions
- The maximal cross section corresponds to the top of the barrier, called the sphaleron =''ready to fall'' in Greek, according to Klinkhammer and Manton

''Small gluonic spots'' in DIS and diffraction

- myths of 1970's: all glue in the nucleon is radiated off the valence quarks, by DGLAP/BFKL pert.process
- Not true at all:

(i) there is a lot of glue even at low normalization $\mu \sim 1\,GeV$

(ii), most important, its $R_{r.m.s.} \sim .3 - .4\,fm$ is smaller than for quarks. Obviously a glue cannot be radiated from quarks as size never decreases in a random walk



Snapshots of the nucleon: ''large pizza'' vs ''small gluon spot''

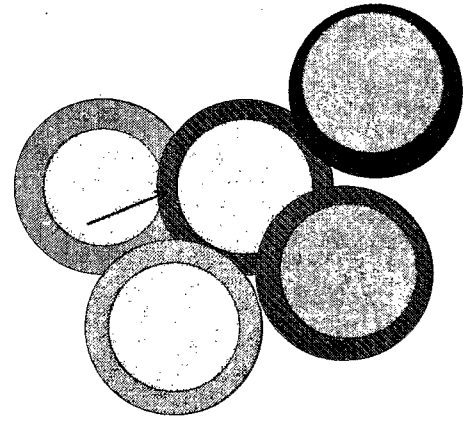
Jet quenching in Color Glass Condensate the energy loss of a quark during the CGC time period Δt_{CGC}

$$\frac{\Delta E_{CGC}}{E} \approx .3(\frac{H}{1\,GeV^2})^{2/3}(\frac{\Delta t_{CGC}}{.5\,fm})(\frac{1\,GeV}{E})^{1/3}$$

The gluon loss is about twice that.

•Jet Quenching on the Exploding Sphalerons

At t=0 sphalerons form a dilute gas and thus cannot affect most of the jets. This however must happen later: exploding shells => foam-like structure at $t = .6 - .8\,fm$

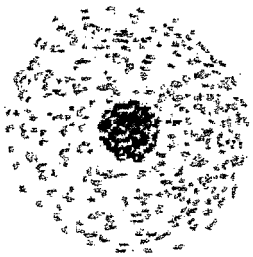


$$\frac{\Delta E_{clust}}{E} \approx .21(\frac{H}{.2\,Gev^2})^{2/3}(\frac{1\,GeV}{E})^{1/3}$$

As usual, the gluon energy loss is about twice larger

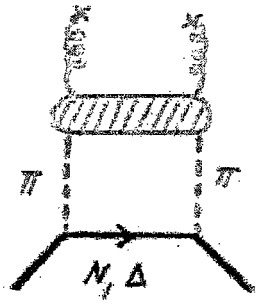
Chiral dynamics and the transverse size of the gluon distribution at small x

M. Strikman, C. Weiss hep-ph/0303191



$b \sim \frac{1}{M_\pi}$

$g(x, b)$ $(x \sim 10^{-2} \ldots 10^{-3})$



"pion cloud"

Gluon distribution in nucleon at $b \sim \frac{1}{M_\pi}$ governed by chiral dynamics!

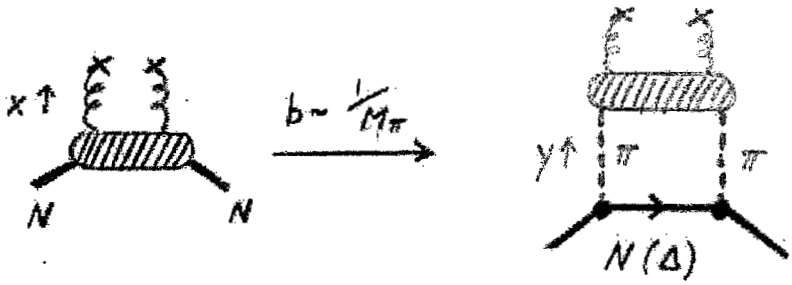
→ Increase of transverse size $\langle b^2 \rangle$ for $x \ll \frac{M_\pi}{M_N}$

→ Ultraperipheral hard exclusive processes
$\gamma + N \to J/\psi + N + \pi$ [HERA, EIC]

→ Implications for $\bar{p}p$ at Tevatron
pp at LHC, RHIC

[→ M. Strikman, this meeting]

● Gluon distribution at $b \gtrsim \frac{1}{M_\pi}$: Chiral dynamics ⑤



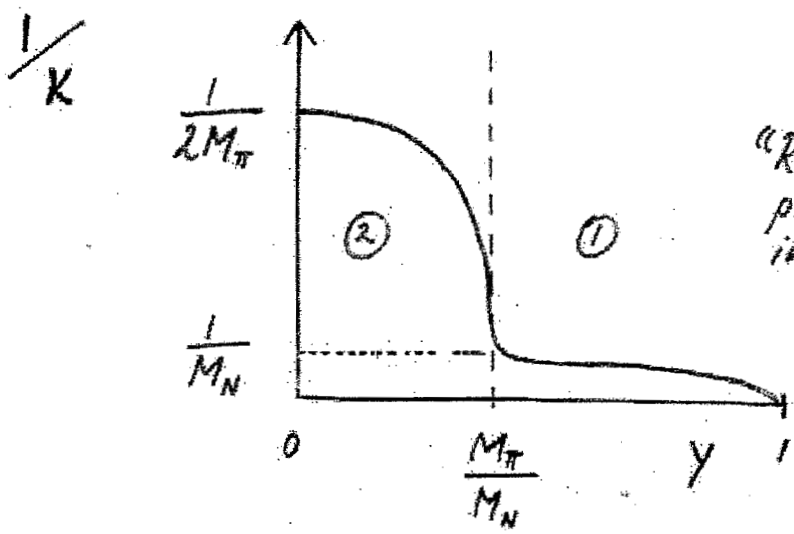
$g_\pi\left(\frac{x}{y}\right)$ gluon distribution in pion

$f_\pi(y, b)$ "pion distribution" in nucleon (calculable!)

$$g(x, b) \sim \int_x^1 \frac{dy}{y}\, g_\pi\left(\frac{x}{y}\right) f_\pi(y, b)$$

[Neglect "intrinsic" transverse size of pion ($\ll b$)]

$$f_\pi(y, b) \overset{b \to \infty}{\sim} \frac{e^{-kb}}{b} \quad \text{"Yukawa tail"}$$



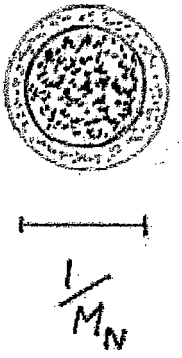
"Range" of pion distribution in nucleon

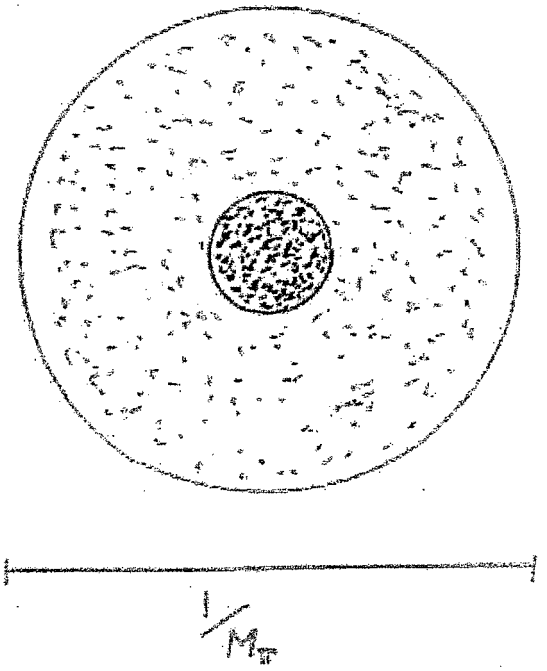
... Two regimes!

→ Gluon density in nucleon ($y \geq x$!)

$\boxed{x \gtrsim \frac{M_\pi}{M_N}}$

$\boxed{x \ll \frac{M_\pi}{M_N}}$





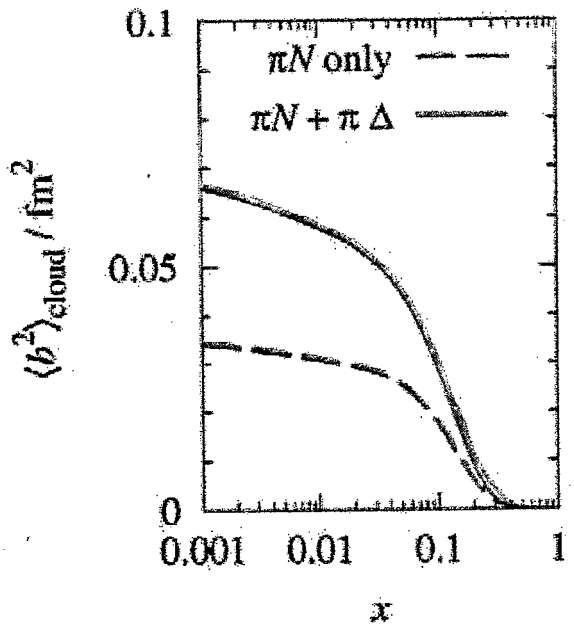
pion cloud "hidden" in average configurations

pion cloud "visible"

Pion cloud distinct from average configurations only for $x \ll M_\pi / M_N$

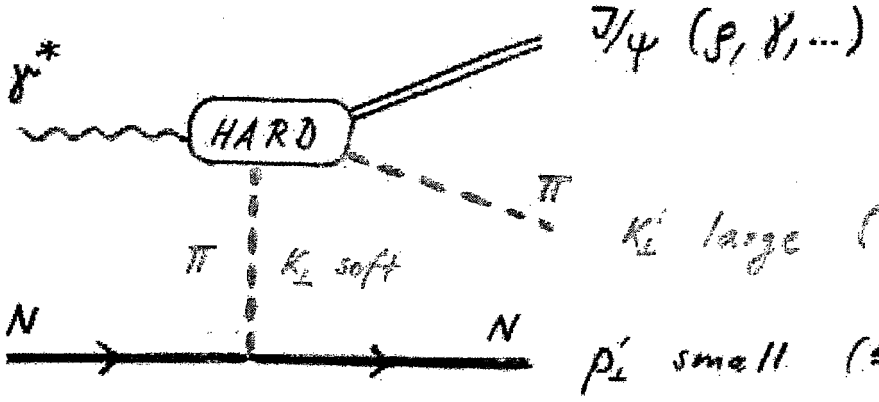
- Effect on "overall" transverse size of nucleon (7)

$$\langle b^2 \rangle = \underbrace{\langle b^2 \rangle_{bulk}}_{\approx\ 0.3\ fm^2} + \underbrace{\langle b^2 \rangle_{cloud}}_{\text{Integrate Yukawa tail } (b > b_0)\ !}$$



"Freeing" of pion cloud causes ~20% increase of transverse size of nucleon for $x \ll M_\pi / M_N$

- Ultraperipheral hard exclusive processes with pion knockout

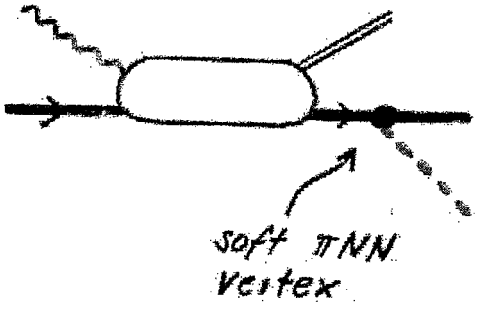


$k_\perp'$ large ($\gtrsim 2$ GeV)!

$p_\perp'$ small ($\lesssim 0.5$ GeV)

[HERA, EIC]

vs.



suppressed!

Impact parameter analysis: $\vec{k}_\perp \to \vec{b}$

... Select large distances $b \sim 1/m_\pi$

Possible to measure gluon distribution in pion (including t-dependence)

PHYSICS, PLANS AND STATUS OF eRHIC

Abhay Deshpande
RIKEN BNL Research Center

Addition of a high intensity and high energy electron/positron beam facility to the RHIC complex will significantly enhance RHIC's ability to investigate fundamental and universal aspects of QCD. A 10 GeV electron/positron beam facility is presently being planned, although collisions with low energy beams as low as 5 GeV are also envisioned. The facility will consist of a full energy linac (~ 500 m long) injecting in to a storage ring (1/3 the size of the RHIC) [slide 1] . Synchrotron radiation in this ring will enable the electrons/positrons to achieve up to 70% polarization in about 22 minutes. The electrons/positrons will then collide with either the polarized proton beams of RHIC and study the nucleon spin in a completely new kinematic range, or they will collide with the heavy ion beams of the RHIC and investigate hard scattering in nuclear media for the first time in high center of mass energy [slides 2,3].

The scientific frontier [slides 4,5,6,7] open to eRHIC includes investigations of the nucleon structure including un-polarized and polarized spin structure of the nucleon, the understanding of which presently is extremely limited (especially the nucleon spin structure). Because eRHIC would allow us to collide the electron beams with various different heavy ion beams and at different energies, it will allow us to study in addition the meson structure, the nuclear structure and phenomena, the phenomenon of hadronization, and study in detail gluon matter under extreme condistion predicted by some some theories of nuclei in the recent literature [slide 7]. Evidence of existence of such medium has already surfaced during the recent d-A physics runs of the RHIC [BRAHMS preliminary results in this workshop]. If discovered at RHIC, this will need a detailed study in future to understand this state of matter using eRHIC.

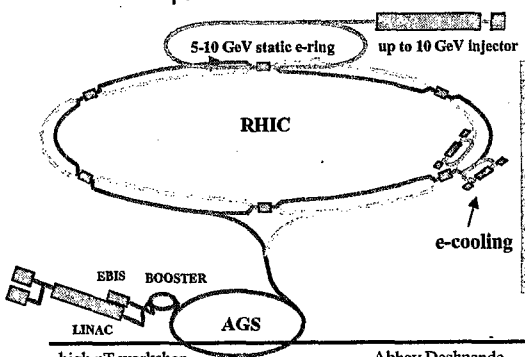
The design of the electron beam complex is such that it does not interfere with the RHIC running until the very last year or so of its completion when the interaction region would have to be built. The electron beam complex is planned out side of the RHIC tunnel. When eRHIC runs, the two experiments at RHIC, PHENIX and STAR, would be able to take data simultaneously, completely normally; this is a precondition under which eRHIC design is being developed. The choice of the yellow beam species in RHIC would have to be decided amongst the three detector collaborations (PHENIX, STAR & eRHIC).

The detector for eRHIC is expected to be hermetic, have good particle identification capability, central and forward tracking detector systems, and compensated electromagnetic and hadronic calorimetry. Special attention is being given to include capability to do low x and low Q2 physics to investigate new and interesting physics which is emerging from present HERA data. A close cooperation between the physics, the IR design and the accelerator groups is going to be crucial for the success of this project, and is being pursued.

Proposal under consideration

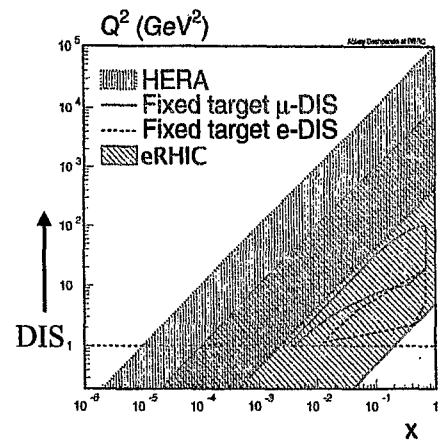
eRHIC at BNL

A high energy, high intensity polarized electron/positron beam facility at BNL to collide with the existing RHIC heavy ion and polarized proton beam would significantly enhance RHIC's ability to probe fundamental and universal aspects of QCD



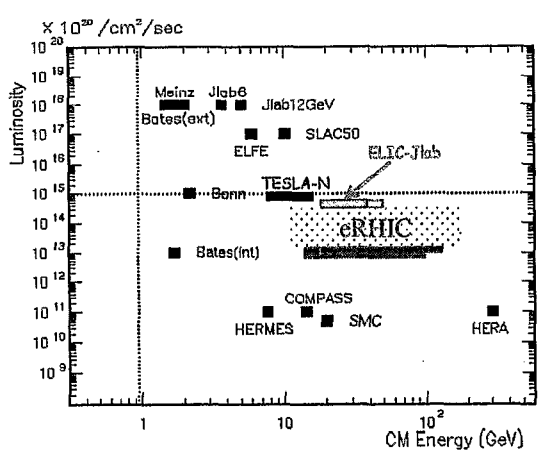
- Linac+e-ring+RHIC
  Linac+Ring Design (backup)
- Linac+e-ring outside RHIC tunnel
- Main design 10 GeV e beams, 5 GeV possible
- e-facility OUTSIDE the RHIC tunnel
- Operations do NOT interfere with RHIC operations

eRHIC vs. Other DIS Facilities (I)



- New kinematic region
- E_e = 5-10 GeV
- E_p = 30 - 250 GeV
- Sqrt(s) = ~25 - 100 GeV
- Kinematic reach of eRHIC
  $x = 10^{-4} \rightarrow \sim 0.7$ ($Q^2 > 1$ GeV^2)
  $Q^2 = 0 \rightarrow 10^4$ GeV
- Polarized e, p and light ion beams -- ~70%
- Heavy ion beams of ALL elements!
- High Luminosity
  L > (at least) 10^{33} cm^{-2} sec^{-1}

eRHIC vs. Other DIS Facilities



eRHIC:
- >> Variable beam energy
- >> p → U hadron beams
- >> Light Ion polarization
- >> Large Luminosity
- >> Huge Kinematic reach

ELIC: electron-light ion collider at Jlab
- >> Variable beam energy
- >> Light Ion polarization
- >> Huge Luminosity

Scientific Frontiers Open to eRHIC

- Nucleon Structure: polarized & unpolarized e-p/n scattering
  -- Role of quarks and gluons in the nucleon
  >> Unpolarized quark & gluon distributions, confinement in nucleons
  >> Spin structure: polarized quark & gluon distributions
  -- Correlation between partons
  >> hard exclusive processes leading to Generalized Parton Distributions (GPD's)
- Meson Structure:
  -- Mesons are goldstone bosons and play a fundamental role in QCD
- Nuclear structure: unpolarized e-A scattering
  -- Role of quarks and gluons in nuclei, confinement in nuclei
  -- e-p vs. e-A physics in comparison and variability of A: from d→U
- Hadronization in nucleons and nuclei & effect of nuclear media
  -- How do partons knocked out of nucleon in DIS evolve in to colorless hadrons?
- Partonic matter under extreme conditions
  -- e-A vs. e-p scattering; study as a function of A

Unpolarized DIS e-p at eRHIC

- Large(r) kinematic region already covered at HERA but additional studies at eRHIC are possible & desirable
- Uniqueness of eRHIC: high luminosity, variable Sqrt(s), He3 beam, improved detector & interaction region
- Will enable precision physics:
  - -- He3 beams → neutron structure → d/u as x→0, dbar(x)-ubar(d) [1]
  - -- precision measurement of $\alpha_S(Q^2)$ [1]
  - -- precision photo-production physics [1]
  - -- precision gluon distribution in x=0.001 to x=0.6 [1]
  - -- slopes in $dF_2/d\ln Q^2$ *(Transition: QCD-to-pQCD & low* [1]
  - -- flavor separation (charm and strangeness) [2]
  - -- exclusive reaction measurements [2,3]
  - -- nuclear fragmentation region measurements [2,3]

Luminosity Requirement

Polarized DIS at eRHIC

- Spin structure functions g_1 (p,n) at low x, high precision [1]
  -- g_1(p-n): Bjorken Spin sum rule better than 1% accuracy
- Polarized gluon distribution function $\Delta G(x,Q^2)$ [1]
  -- at least three different experimental methods
- Precision measurement of $\alpha_S(Q2)$ from g_1 scaling violations [1]
- Polarized s.f. of the photon from photo-production [1]
- Electroweak s. f. g_5 via $W^{+/-}$ production [1,2]
- Flavor separation of PDFs through semi-inclusive DIS [1]
- Deeply Virtual Compton Scattering (DVCS) [1,2]
  >> Gerneralized Parton Distributions (GPDs) [3]
- Transversity [1]
- Drell-Hern-Gerasimov spin sum rule test at high ν [1]
- Target/Current fragmentation studies [2,3]
- ... etc....

Luminosity Requirement

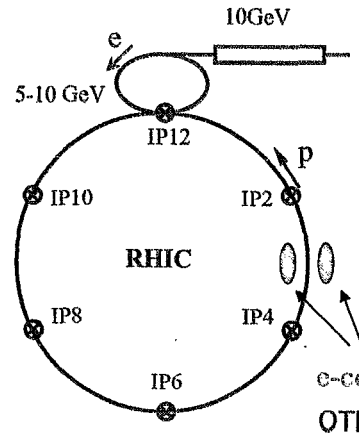
Highlights of e-A Physics at eRHIC

- Study of e-A physics in Collider mode for the first time
- QCD in a different environment

- Clarify & reinforce physics studied so far in fixed target e-A & μ-A experiments including target fragmentation
  QCD in: $x > [1/(2m_N R_N)] \sim 0.1$ (high x)
  QCD in: $[1/(2m_N R_A)] < x < [1/(2m_N R_N)] \sim 0.1$ (medium x)
  Quark/Gluon shadowing
  Nuclear medium dependence of hadronization

- .... And extend in to a very low x region to explore:
  saturation effects or high density partonic matter also called the Color Glass Condensate (CGC)
  QCD in: $x < [1/(2m_N R_A)] \sim 0.01$ (low x)

Present Lay Out of the Collider at BNL



- Proposed by BINP & MIT/Bates + BNL with input from DESY
- E-ring is 1/3 of RHIC ring; linac ~500m
- Collisions in one interaction region
  >> **Multiple detectors under consideration**
- Collision energies Ee=5-10 GeV
- Injection linac 10 GeV
- Lattice based on "superbend" magnets
- Self polarization using Sokolov Ternov Effect: (14-22 min pol. Time)
- **IP12, IP2 and IP4 are possible candidates for collision points**

e-cooling → **R&D needed & started**

OTHER : Ring with 6 IPS, Linac-Ring, Linac-Re-circulating ring

A Detector for eRHIC → A 4π Detector

- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector detection (DVCS)
- ~Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing E_T for neutrino final states (W decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics

- "At least one" second detector could be "rolled" in from time to time.... ...under consideration

- eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity

Present Activities

- **Accelerator & IR Design WG:**
  - BNL-MIT/Bates collaboration on e-ring design
  - BNL-JLAB collaboration on linac design
  - Weekly meetings, monthly video meetings
  - Constant communication with Detector/Physics WG
  - ZDR Ready by January 2004: Outside BNL Review March04
- **Physics & MC WG:** (Theorists/Experimentalists: Welcome to Join!)
  - BNL, Colorado U., Jlab, LBL, MIT, UIUC (researchers+students)
  - Meet every three months
  - Setup MC generators start studies of physics processes including available detector acceptances
  - Will iterate with the detector/IR design and provide input guidance on the final detector design
- **Detector Design:** Will be taken up in detail in the coming year

- 2004 Meetings: January(BNL), **April(Jlab),** August(??), Nov/Dec(BNL)

QCD & Hadronic Physics Experiments around the world

- HERA: H1, ZEUS, HERMES
  - End data taking ~2006
  - End analysis ~2008/9
  - Groups looking for construction & physics projects, of course there is LHC... but...
- CERN: COMPASS
  - Future beyond 2007/8 uncertain for polarized DIS program
  - Results ready by 2007/8
- SLAC: EXXX
  - Spin & parity violation programs nothing beyond 2003
- RHIC II: RHIC Spin
  - Up to 2012/13(?)
  - RHIC II heavy ion program how much beyond this date?

eRHIC construction 2017???!!

A possible time line for eRHIC...

- *"Absolutely Central to the field..." NSAC 2001-2 Long Range Planning document summary; high on R&D recommendation projects.*
- *Highest possible scientific recommendation from NSAC Subcommittee February/March 2003, Readiness Index 2*
- *One of the 28 "must-do" projects in the DOE's list*

- eRHIC: Zero-th Design Report (Physics + Accelerator Lattice)
  → Requested by BNL Management: January 2004
  → e-cooling R&D money started (with RHIC II) some DOE+some BNL internal

FOLLOWING THIS TIME LINE FOR GETTING READY:

- Expected "formal" approval 2005-6 Long Range Review (Ready CD0)
- Detector R&D money could start for hardware 2008 (CD1)
- Ring, IR, Detector design(s) 2009(CD2)
- Final Design Ready 2010 (CD3) → begin construction
- ~3/5 years for staged detector and IR construction without interfering with the RHIC running
- *First collisions with partial detector: 2012/13(???)*

RHIC II

Y. Akiba, RIKEN / RBRC

for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

Summary

- Rare probe physics is the next step in the study of the high density matter created at RHIC
  - VERY high p_T measurement
  - Heavy Quark and Quarkonium
  - Thermal radiation (photon and di-lepton)
- With the present RHIC (Ldt ~ 1/nb (Au+Au) max.)
  - High p_T up to ~20 GeV/c (π^0 and direct photon)
  - Good J/ψ measurement.
  - Charm measurement
  - Thermal dilepton and photon (systematics and detector limited)
- RHIC II (x10 of RHIC)
  - High p_T up to ~30 GeV
  - Very rare physics
    - Upsilon, high statistics J/ψ, ψ', direct γ+jets, etc
  - High p_T physics and rare probe physics in lower energy

Future direction – rare probes

RHIC NOW

- A very dense matter is formed
- The matter formed is very opaque, and appears to be partonic
- The matter appears to be thermalized rapidly

NEXT STEP at RHIC

- Quantitative investigation of the high density matter formed at RHIC.

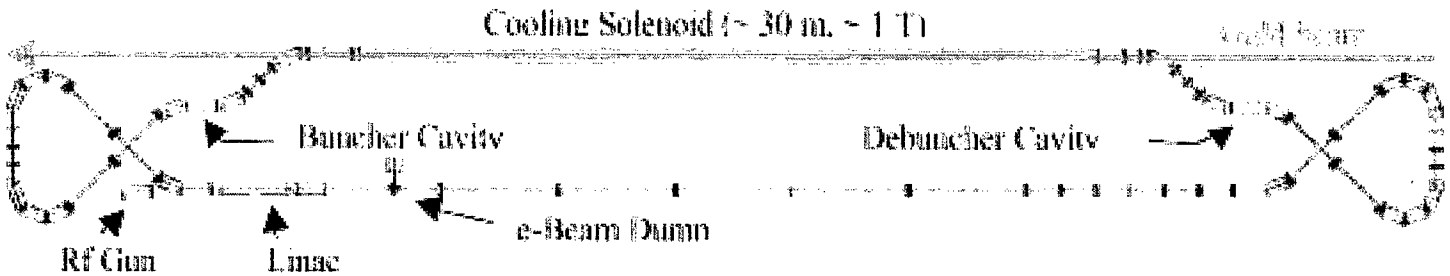
HOW?

A. Study the early stage of the collision → Rare Probe physics
  - Very hight P_T
    - high pT hadron, high pT hadron pairs
  - Heavy Quarks
    - open charm, open beauty, J/Y, Y
  - Direct EM radiations
    - Direct photon, gamma+jets
    - Thermal photon, thermal di-leptons

B. Systematic study → multiple beam modes
  - Au+Au (U+U), light ion, p+A (d+A), and p+p
  - Energy scan

Both requires a high luminosity

RHIC-II

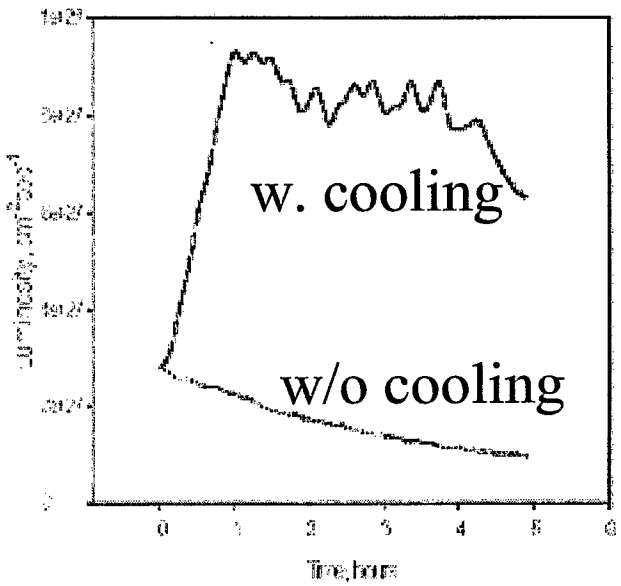


- High Intensity upgrade of RHIC with "electron coolinig"
- Higher luminosity with longer luminosity lifetime
- $L_{ave} = 8x10^{27}$
  - 40 times of RHIC design
  - 10 times of maximum w/o upgrade

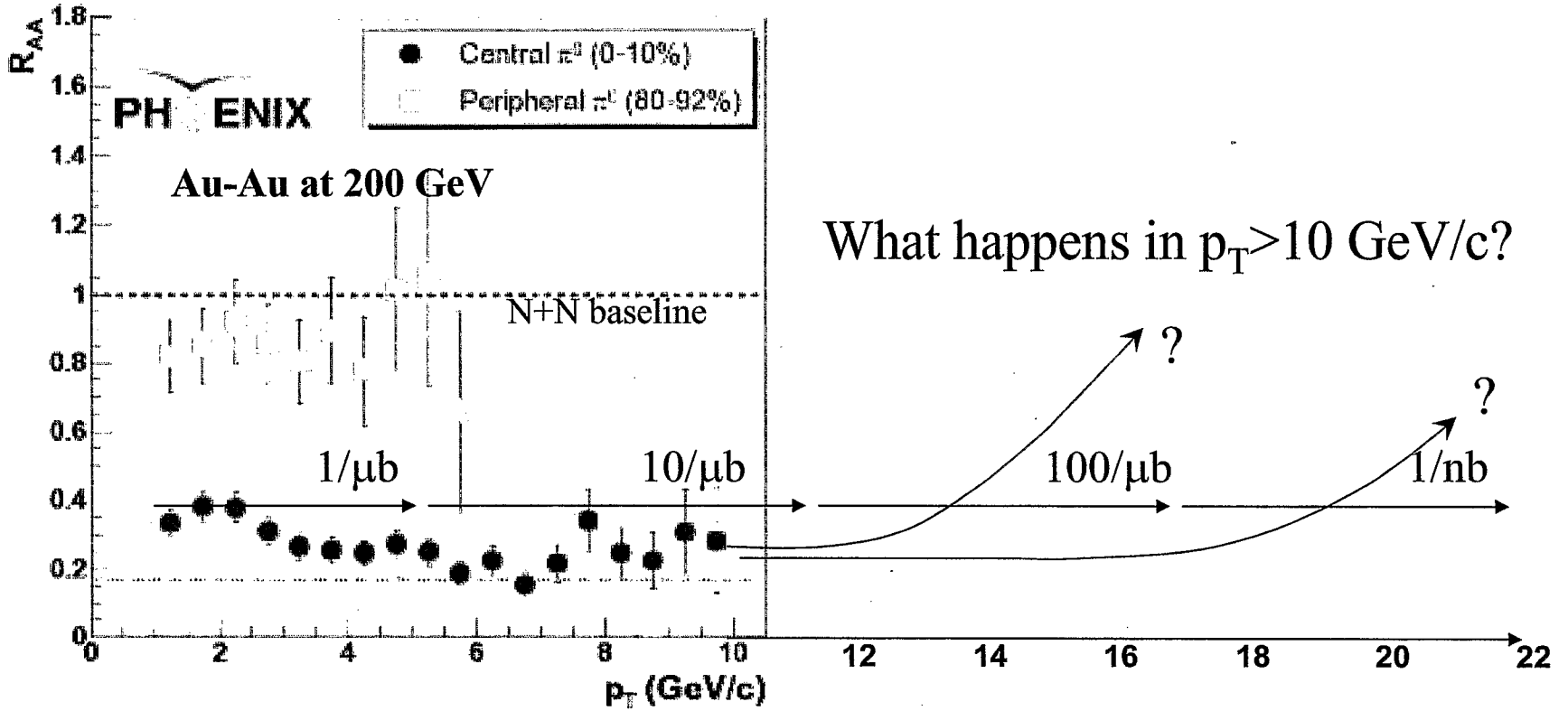
→ 10 to 20 nb^{-1}/year of Au+Au collision (or U+U collision)

x1000 times of RUN-2 data

x100 times of RUN-4 data (expected)



High P_t π^0



p_T reach in RUN4 (100/μb) will be ~17 GeV/c

p_T reach of max. RHIC(1/nb) is ~24 GeV/c

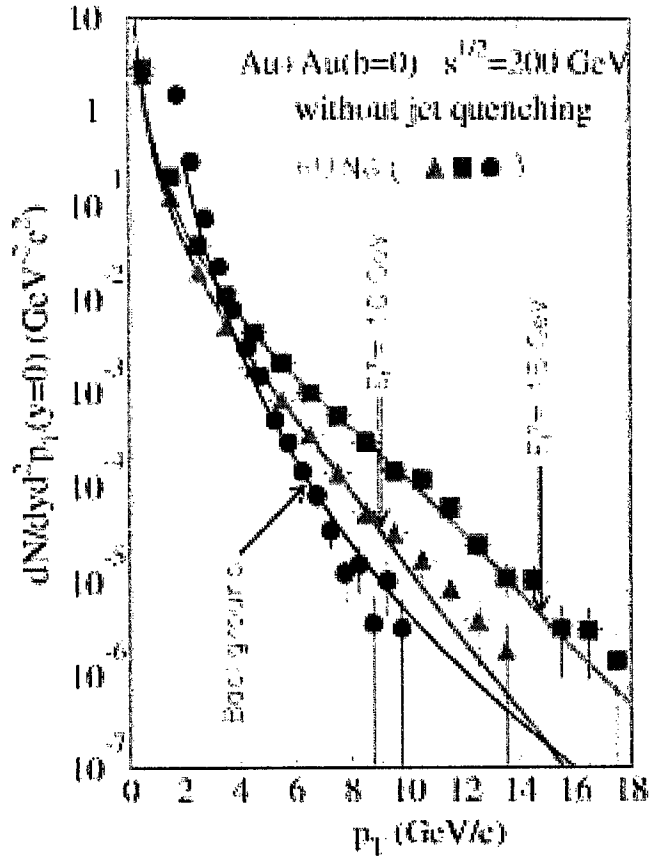
p_T reach of RHIC-II (10/nb) is ~ 30 GeV/c

(γ/π^0 separation becomes an issue in p_T>20 GeV/c in PHENIX)

Q: How high p_T do we want to reach?

γ + jets (fragmentation in medium)

XNWang 97



- A direct way to measure the modification of jets in the dense matter
- The pT of the direct photon fixed the pT of the scattered quark
- Requires a very large integrated luminosity to measure
- A rough estimate of event rate (in PHENIX)

  $p_T(\gamma)$=10 GeV/c

  ~1000 for 1/nb

  ~10,000 for 10/nb (RHIC-II)

  $p_T(\gamma)$=15 GeV/c

  ~1000 for 10/nb (RHIC-II)

Heavy Ion Physics at the LHC: experimental prospects

Bolek Wyslouch
MIT

RIKEN BNL Research Center Workshop
"High pt Physics at RHIC"

December 5, 2003

LHC parameters

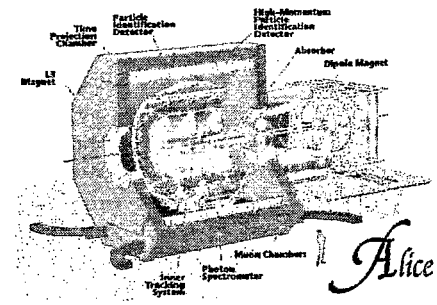
- Heavy Ions expected one year after start with protons (2008)
  - Each year expect 10^6 seconds of beam (p+p 10^7s)
- New accelerator territory: nuclear electromagnetic interactions in peripheral collisions limit luminosity and beam lifetime
- Exact schedule and ramp up is being discussed but there is a possibility of one or two years of "Early" mode of operation with reduced number of bunches

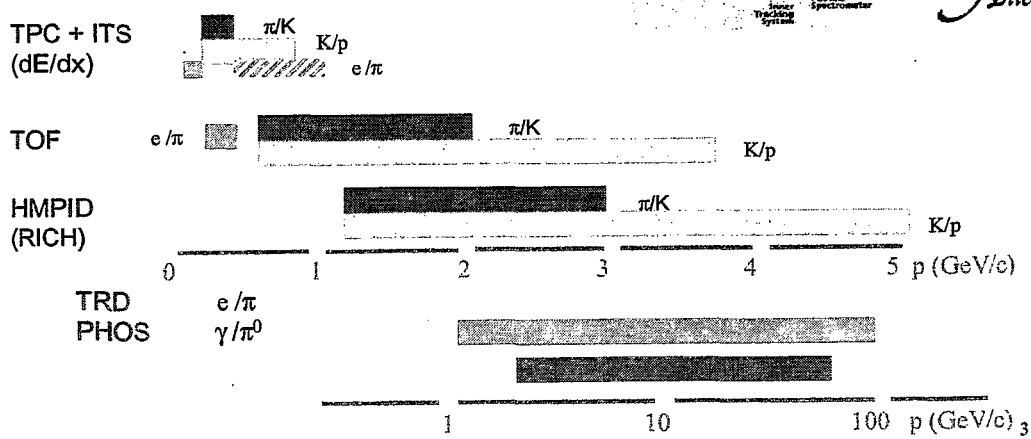
Parameter	Nominal	Early
Energy/nucleon	2759	2759
Ions/bunch	$7\ 10^7$	$7\ 10^7$
Bunches	592	62
Transverse beam size (RMS)	16 μm	23 μm
Longitudinal bem size(RMS)	8 cm	8 cm
Peak Luminosity	$1\ 10^{27}$	$5.4\ 10^{25}$

2

ALICE in short

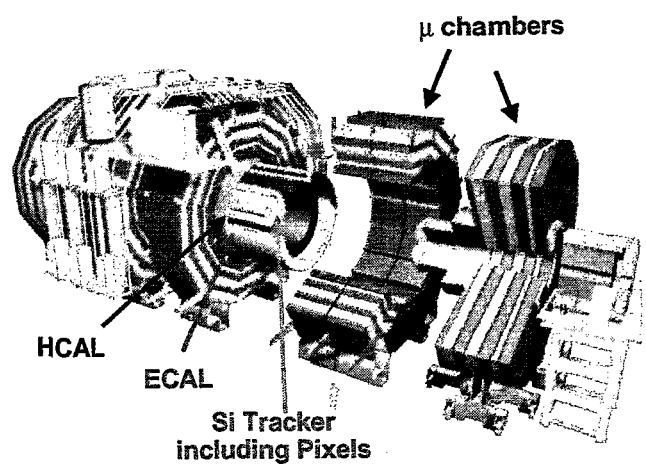
A multipurpose experiment, with excellent tracking and secondary vertex capability, electron and muon detection and high resolution γ spectrometer. Unique Particle Identification complex.





CMS as a Detector for Heavy Ion Physics

- **High Resolution and High Granularity Calorimetry**
  - Hermetic coverage up to $|\eta|<5$ ($|\eta|<7$ *proposed using CASTOR*)
  - *Zero Degree Calorimeter (proposed)*
- **Tracking μ from Z^0, J/ψ, Υ**
  - Wide rapidity range $|\eta|<2.4$
  - Efficient suppression of π, $K \rightarrow \mu$ background
  - Excellent $M_{\mu\mu}$ mass resolution ~50 MeV @ Υ
- **Silicon Tracker**
  - excellent resolution and low fake rate at very high multiplicities
- **DAQ and Trigger**
  - High rate capability for A+A, p+A, p+p
  - High Level Trigger capable of full reconstruction of most HI events in real time



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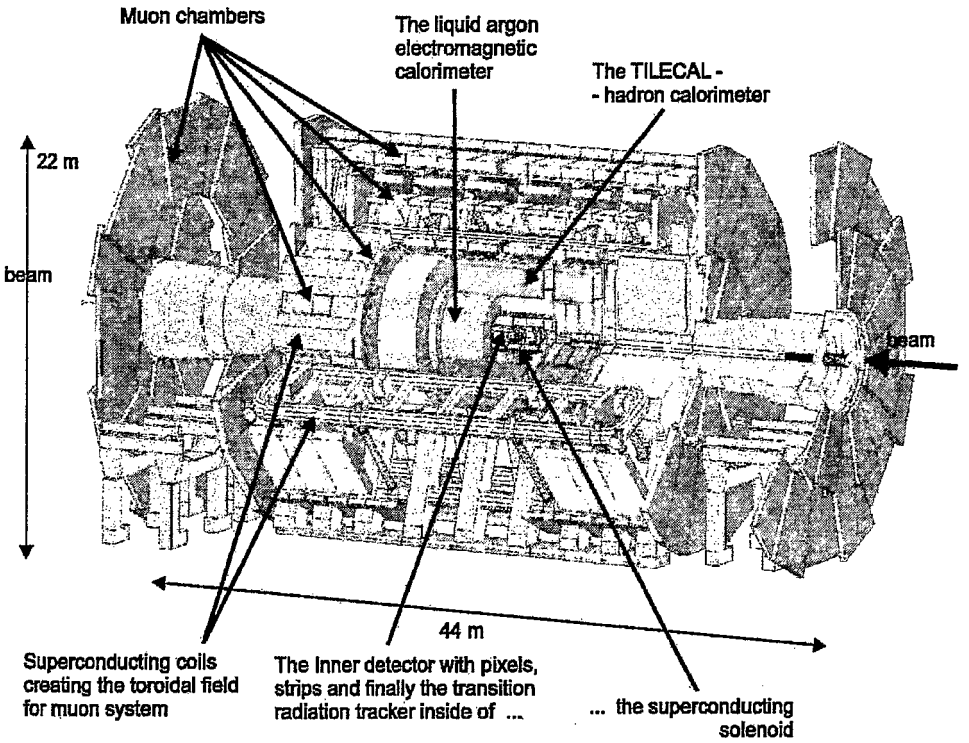
ATLAS Detector

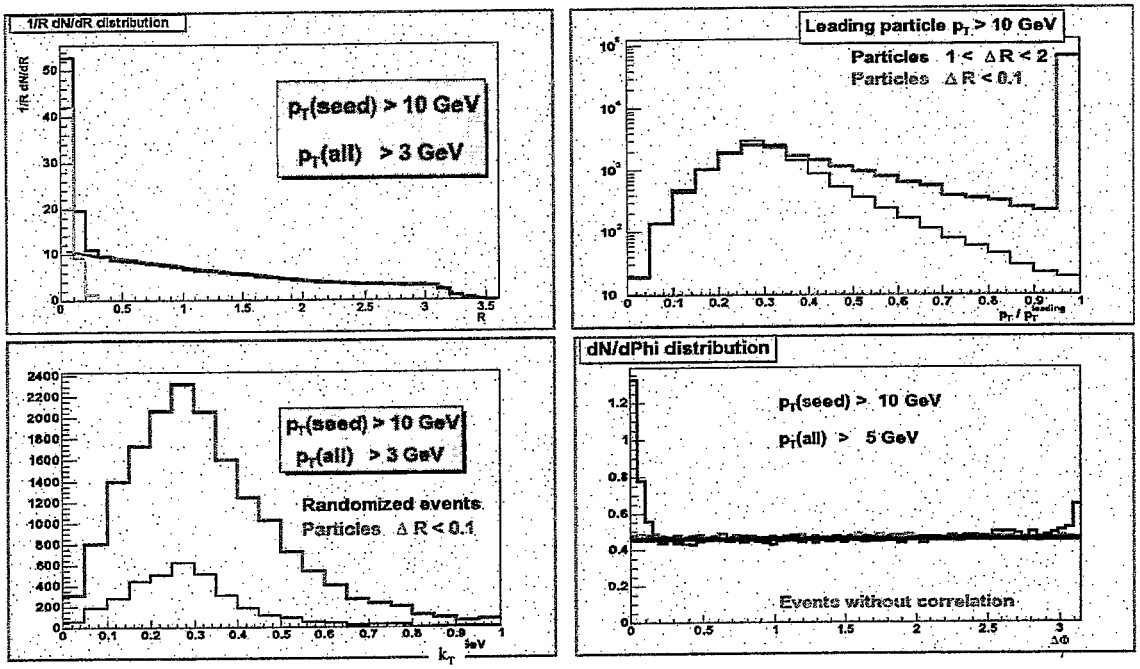


LHC: high p_T frontier in heavy ion physics Study of the hot medium

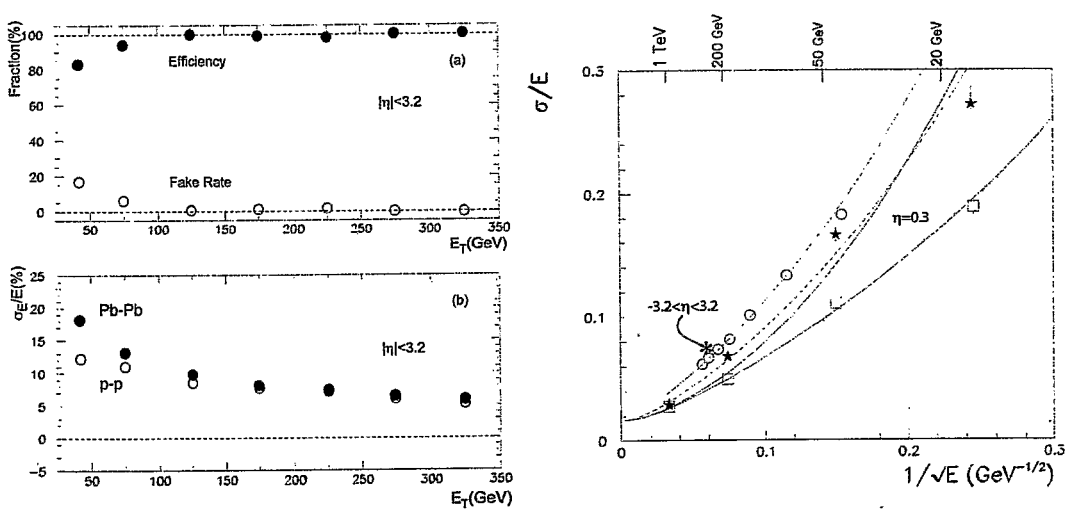
- **Compared to RHIC**
  - **Increased cross sections for high p_T particle production**
    - Experimentally accessible hadrons or jets and photons with p_T>20 GeV and more
  - **Large cross sections for production of heavy quarks and quarkonia**
    - Upsilon cross section ~50-100 times larger
    - Possibility of studying relative production of different members of quarkonium family
    - b-jets identifiable using standard b-tagging techniques
- **Unique to LHC**
  - **Clearly identified jets**
    - Jets with energies extending to few 100 GeV
    - Correlated jet-jet, jet-γ production
  - **Experimentally accessible production of vector bosons (Z^0, W)**
    - Single Z, W production
    - Correlation with jets (Z^0-jet)
- **Before LHC starts**
  - **Develop theoretical tests and models**
  - **Develop experimental techniques**

6

Spatial Correlation with Leading Particles (ALICE)



Jet Energy reconstruction (ATLAS)

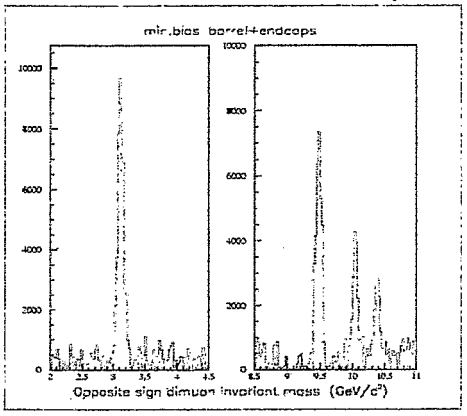


Jet reconstruction efficiency (left top) and resolution (left bot) compared to pp over the full simulated rapidity range. Right, jet energy resolution over full simulated rapidity range (circles) compared to pp jet energy resolution at full LHC luminosity at η=0.3 (start). Squares are for pp at low luminosity.

8

Quarkonia (CMS)

J/ψ Υ family



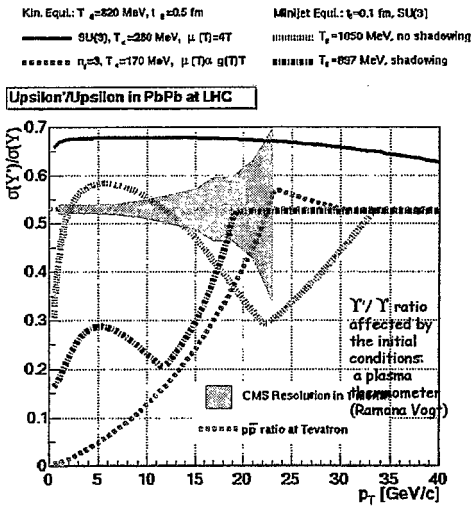
Yield/month (kevents, 50% eff)

	Pb+Pb	Sn+Sn	Kr+Kr	Ar+Ar
J/psi	28.7	210	470	2200
psi'	0.8	5.5	12	57
Upsilon	22.6	150	320	1400
Upsilon'	12.4	80	180	770
Upsilon"	7	45	100	440

Detailed studies using full simulation, reconstruction, background subtraction dN/dy studied from 2500 to 8000

Very large event rate

Uses muon detector, outer tracker, pixels



Summary

- **LHC will collide heavy ions at unprecedented energies**
  - **Plasma hotter, larger and longer lived**
  - **More hard probes available to study hot nuclear matter**
- **Experiments are being readied**
  - **Wide spectrum of capabilities, complementary**
- **The knowledge gained at RHIC will be extended to new energy domain**
  - **Confirm, match and extend RHIC results**
- **Development of new tools and methods**
  - **Experimental**
  - **Theoretical**

Glauber Symposium

P. Steinberg, BNL

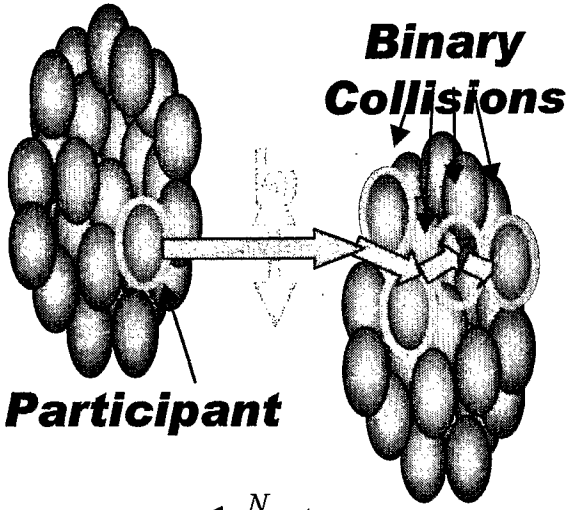
for
"High pT Physics at RHIC"
Workshop
December 2-6, 2003
RIKEN BNL Research Center

Glauber Symposium

- Simple assumptions
  - Woods-Saxon nuclei
  - Nucleons travel in straight lines (eikonal approximation)
  - Interactions controlled by NN inelastic cross section measured in pp collisions
  - First collision does not change cross section

Glauber is the

<u>real</u> initial state!

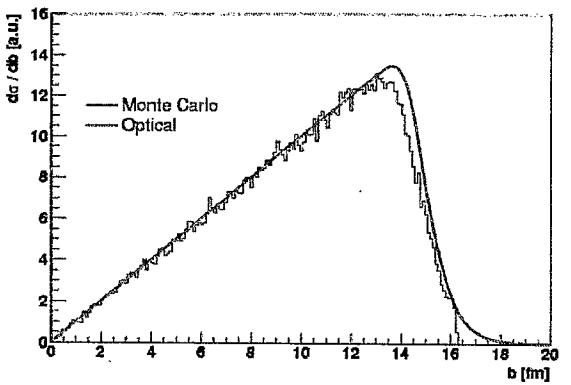


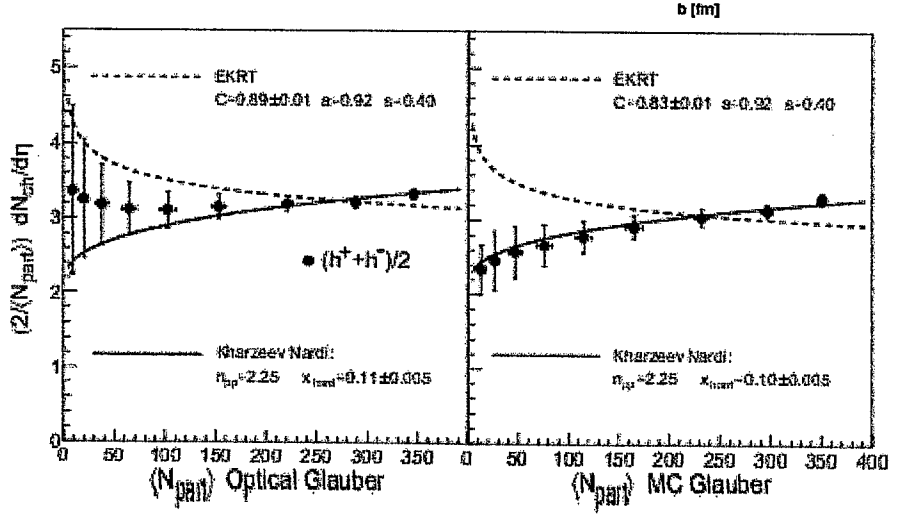
$$N_{coll} = \frac{1}{2}\sum_{1}^{N_{part}} \nu_i \propto N_{part}^{4/3}$$

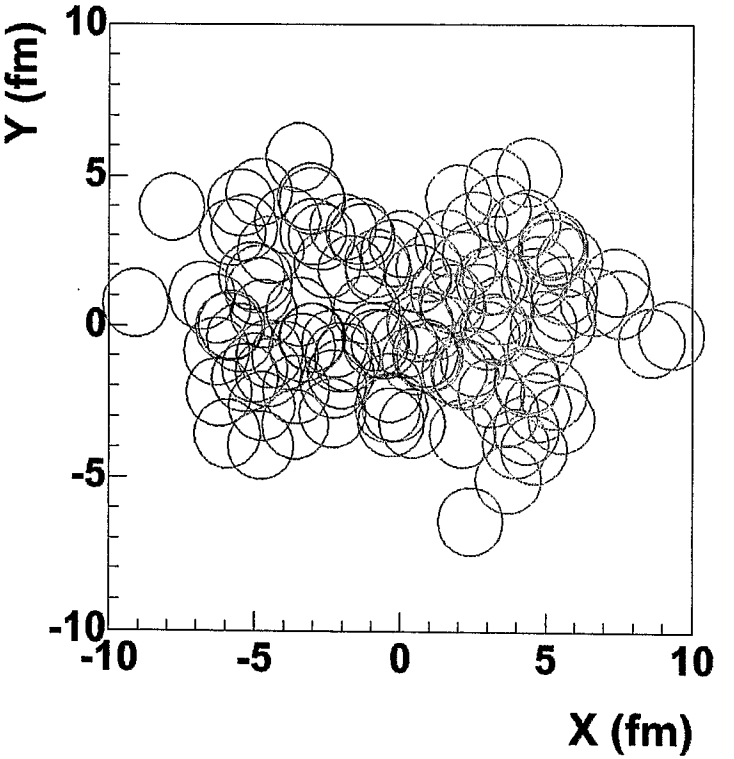
MC vs. Optical

- In optical Glauber, we average over the nuclear density independent of its interaction w/ another hadron or nucleus
- In MC, fluctuations at edge reduce cross section!

M. Miller







Important differences in extraction of N_{part}

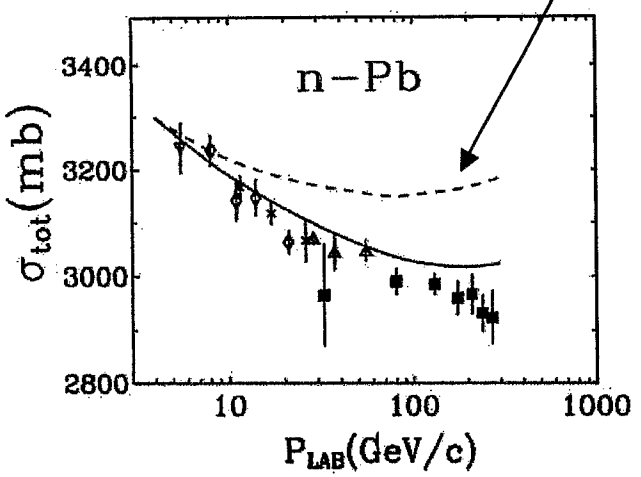
MC vs. Optical: Gribov

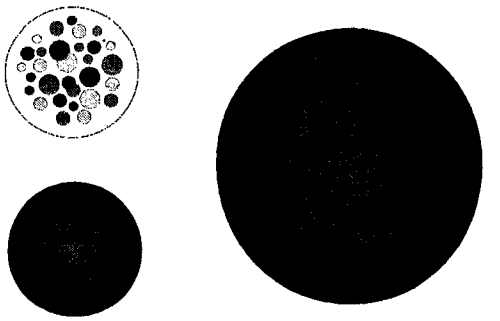
- Let's recall Boris' discussion of Gribov's inelastic shadowing corrections
- In his context, the hA cross section is

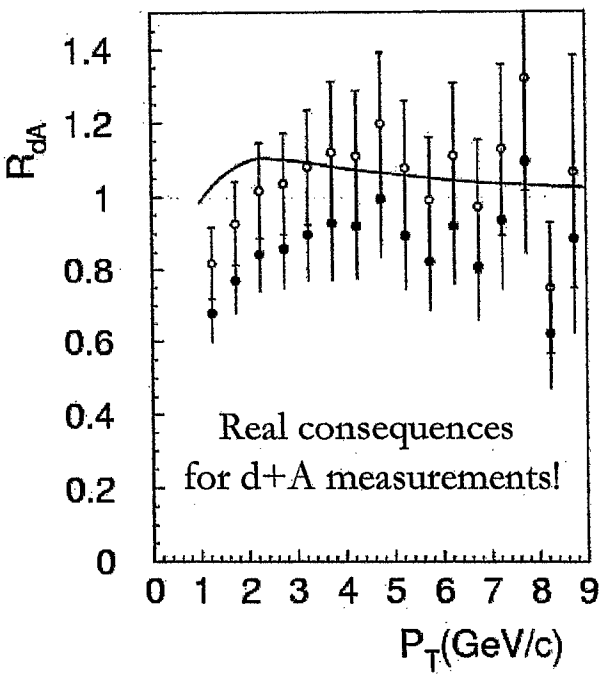
$$\sigma_{hA} = 2\int d^2b\left[1-\left\langle e^{-\frac{1}{2}\sigma_i T_A(b)}\right\rangle_i\right]$$

$$\leq 2\int d^2b\left[1-e^{-\frac{1}{2}\langle\sigma_i\rangle T_A(b)}\right]$$

- So we average over the hadron configurations <u>before</u> it hits the nucleus
  - No "hiding", so larger cross section







Definitions for R | Brian's Request

$$R_{AB}(b) = \frac{1}{AB}\frac{\frac{d\sigma_{AB}^{X}}{dp_T}}{\frac{d\sigma_{NN}^{X}}{dp_T}} = \frac{1}{T_{AB}(b)}\frac{\frac{dN_{AB}}{dp_T}}{\frac{d\sigma_{NN}^{X}}{dp_T}}$$

$$= \frac{1}{N_{coll}}\frac{\frac{dN_{AB}}{dp_T}}{\frac{dN_{NN}}{dp_T}}$$

"Cronin"	RHIC	PHOBOS
Pure cross sections, nuclear masses	"Process independent"	"No" cross section needed!
Impossible at RHIC, also "minbias" only	Requires $d\sigma/dp_T$ from Vernier scan	N_{coll} still needs it!

- A ratio that expresses the relative likelihood of a hard process, given a certain overlap of nuclear matter

$$P_{hard}^{AB}(b) \propto T_{AB}(b) P_{hard}^{NN}$$

- Want to remove dependence on precise cross section
- Questions arose about normalization
- For me, what about $N_{coll} = 1$ or more?

Summary

- Glauber model is an important part of our understanding of the initial state
  - Miller: Details of the implementation matter (MC vs. Glauber). N_{coll} is linearly sensitive to σ_{NN}.
  - Kopeliovich: The details are most important when considering the edges! Nuclei are more transparent on average than naïve expectations
  - Cole: N_{coll} is a fiction, only the average density can allow model-independent conclusions
- Thanks to all for great discussions!

Andrei Belitsky
Summary
High pT Physics at RHIC Workshop, December 2-6, 2003

Since the discovery of the spin crisis by the EMC, the spin physics has become a topic of intensive theoretical and experimental studies in the last decade. At this meeting there were two sessions dedicated to this field. The two extensive review talks held on Tuesday were concerned with the RHIC spin program, while the whole morning session on Thursday was devoted to the discussion of spin asymmetries. Let us briefly sketch the main issues addressed there. Spin asymmetries in pion electroproduction in DIS and hadron collisions were discussed and two competing mechanism which generate them were addressed: the Sivers effect and the Collins effect. On the microscopic level the former arises from a phase in a parton distribution while the latter from a phase in a fragmentation function. In the latter case it is a consequence of a correlation of the transverse momentum of the outgoing hadron and the spin of the fragmenting quark. It existence complies with fundamental symmetries in QCD. On the other hard, the Sivers effect requires the presence of non-canceling final state interactions in an unintegrated parton distribution. This was long thought to be in contradiction with the time-reversal invariance and thus forbidden in QCD. The breakthrough in understanding and establishing a firm ground for the existence of this phenomenon is due to Stan Brodsky and his collaborators, who discovered a non-vanishing result in a field-theoretical calculation for the asymmetry. Among other topics Stan Brodsky discussed this fascinating subject in his talk. John Collins addressed this question in his talked and explained Brodsky's result in terms of Wilson lines present in a gauge-invariant definition of parton distributions. Piet Mulders reviewed and extended this discussion to physical gauges where the light-cone gauge links apparently is absent and emphasized the singular nature of the light-cone gauge as a clue to unravel the puzzle. Matthias Burkardt gave a physical picture which unfolds via measurements of the Sivers function and what information on the nucleon structure one can probe via this novel function. Yuji Koike reviewed his work on spin asymmetries in electroproduction of hadrons with large transverse momentum and the how to describe them in a consistent twist-three formalism.

Spin talks at this meeting

Tuesday, December 2

11:00 - 11:45 M. Stratmann: *Spin physics*
11.45 - 12:30 B. Surrow: *Experimental aspects of the RHIC SPIN program*

Thursday, December 4

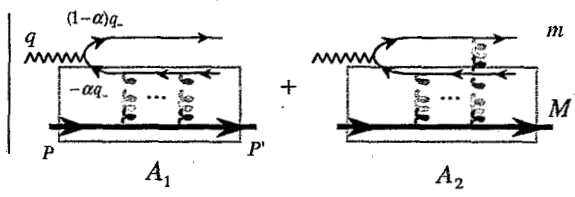
9:00 - 9:45 J.C. Collins: *Single spin asymmetries and QCD*
9:45 - 10:15 Y. Koike: *Single transverse spin asymmetry for the pion production at RHIC and EIC*
10:15 - 10:45 M. Burkardt: *Quark correlations and single spin asymmetries*
11:00 - 11:45 P. Mulders: *Universality of T-odd effects in single spin azimuthal asymmetries*
11:45 - 12:15 S.J. Brodsky: *Novel spin effects in QCD*

Much ado about ...final state interactions

Brodsky's critique of parton probability interpretation of QCD PDFs: Compute structure functions in the aligned-jet kinematics which must correspond to twist-two parton distributions.

$$\alpha \sim \Lambda^2_{QCD}/Q^2$$

$$F(x_B) = \left| \quad + \quad \right|^2$$



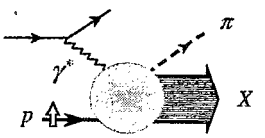
They find that in the light-cone gauge, the diagrams A_2 contribute though one would expect that they won't if one naively assumes that the aligned-jet is a light-like Wilson line. Conclusion:

$$\psi e^{i\varphi} \Longrightarrow F(x_B) \neq q(x_B) \Longleftarrow \psi$$

S.J.Brodsky et al.'00

Other sources of leading spin asymmetries?

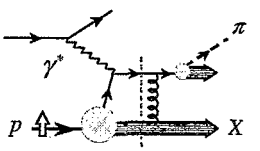
Consider single proton-spin asymmetry in semi-inclusive DIS $ep \to e'\pi X$:



$$A \sim \vec{S}\cdot[\vec{q}\times\vec{p}_\pi]$$

requires amplitudes with different phases

- Conventional calculation: twist-3 effect → power suppressed in scaling limit.
- Brodsky et al.'s calculation: asymmetry scales in Bjorken limit.

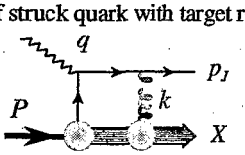


S.J.Brodsky, D.S.Hwang, I.Schmidt '02

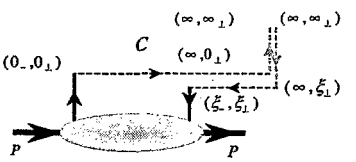
Non-canceling final state interactions? Failure of factorization?
Stan Brodsky: Is the handbag approximation for DVCS accurate?

Gauge invariant parton distributions

Final state interactions of struck quark with target remnants:



$$q(x,k_\perp)=\frac{1}{2}\int\frac{d\xi_-}{2\pi}\frac{d^2\xi_\perp}{(2\pi)^2}e^{-ix\xi_-+ik_\perp\cdot\xi_\perp}\langle P|\overline{\psi}(\xi_-,\xi_\perp)[\infty,\infty_\perp;\xi_-,\xi_\perp]_C^\dagger\gamma_+[\infty,\infty_\perp;0,0_\perp]_C\psi(0,0_\perp)|P\rangle$$



$$[\infty,\infty_\perp;\xi_-,\xi_\perp]_C \equiv P\exp\left(-ig\int_{\xi_\perp}^{\infty}dz_\perp\cdot A_\perp(\infty,z_\perp)\right)P\exp\left(-ig\int_{\xi_-}^{\infty}dz_-A_+(z_-,\xi_\perp)\right)$$

Final state interactions generate a non-trivial phase!

A.B., X.Ji, F.Yuan '02
D.Boer, P.Mulders, F.Pijman '02

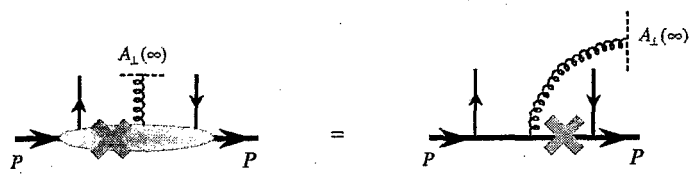
T-odd structures

Lorentz decomposition:

$$q(x,k_\perp) = P_+ f(x,k_\perp) - [k_\perp \times S_\perp] f_{1T}^{\perp}(x,k_\perp)$$

Sivers function

D.Sivers '90
D.Boer, P.Mulders '97



- Imaginary part of the distribution function generates the Sivers function and mimics the T-odd effects.
- Light-cone GPDs, which arise in DVCS and hard exclusive meson production, are real and there no final state interaction phases resulting from them.

Twist-two vs. twist-three asymmetries

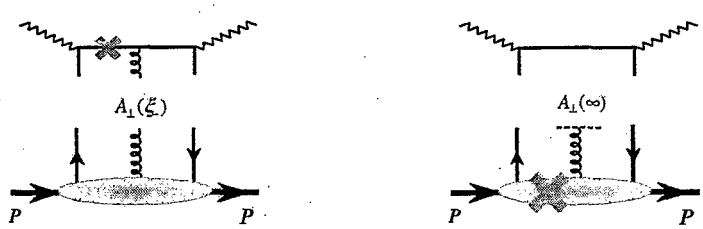
Large-kT: Twist-three
(power suppressed)

$$\frac{\langle \bar{\psi} G \psi \rangle}{Q^1}$$

Small-kT: "Twist-two"
(scales)

$$\frac{\langle \bar{\psi} \psi \rangle}{Q^0}$$

in light-cone gauge



A phase in the
coefficient function

Y. Koike (this conference)

A phase in the
parton distribution

S.J. Brodsky, J.Collins, P. Mulders
(this conference)

Quark correlations and SSA

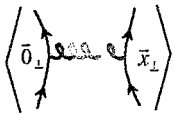
M.Burkardt '03

Average transverse momentum of quarks in the proton:

$$\langle \vec{k}_\perp \rangle = \int dx \int d^2k_\perp \vec{k}_\perp q(x,k_\perp)$$

Transverse momentum (to lowest order in QCD coupling) is a (quark) density-density correlation with Coulomb gluon-exchange. The gluon degrees of freedom are "integrated out".

$$\langle \vec{k}_\perp \rangle \sim \int d^2x_\perp \langle p | \rho^a(0) \frac{\vec{x}_\perp}{\vec{x}_\perp^2} \int dx^+ \rho^a(x^+, \vec{x}_\perp) | p \rangle =$$



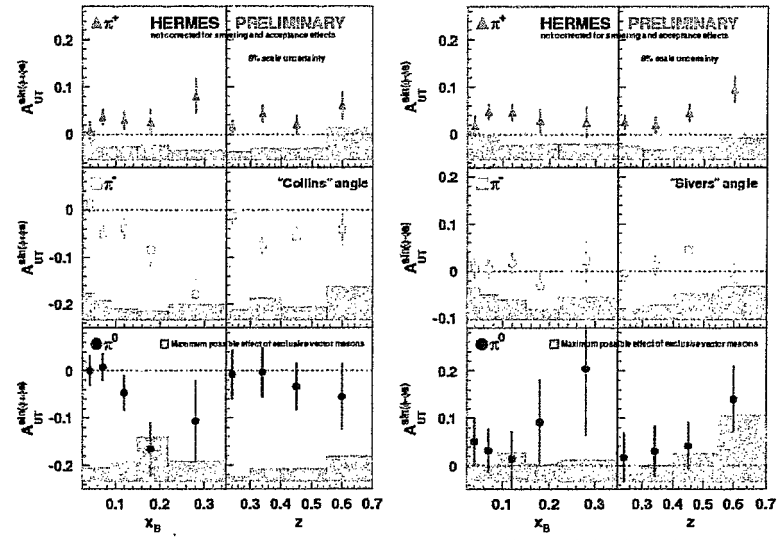
with quark density operator:

$$\rho^a(x) = \overline{q}(x)\gamma^+ t^a q(x)$$

Message: use to evaluate the magnitude of the Sivers effect in gluon-free models, like χQSM.

Collins and Sivers effects @ HERMES

Cf. E704



From N.Makins (Greece. Oct.2003) Analysis by G.Schnell, R.Seidl, U.Elschenbroich'03

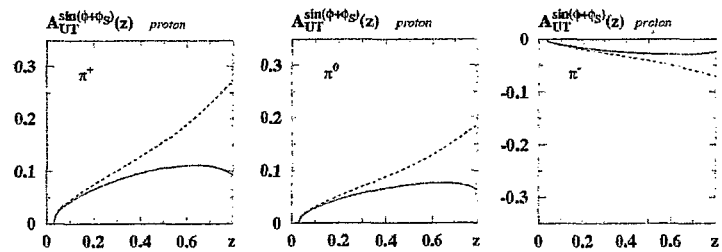
Collins effect: models, models, models, ...

- Previous analyses of longitudinal HERMES data neglected the Sivers effect;
- Good description of the data in terms of Collins effect alone;

Transverse-spin asymmetries:

Collins effect in χQSM (Sivers function is zero in χQSM: no gluons)

Def: 2 x HERMES

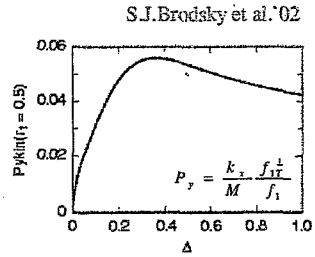


P.Schweitzer, A.Bacchetta '03

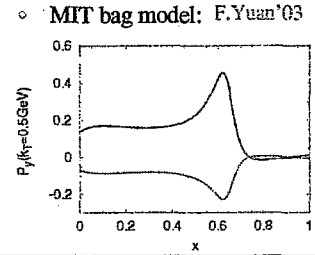
Not consistent with the data for π^- and π^0!

Sivers: models, models, models, ...

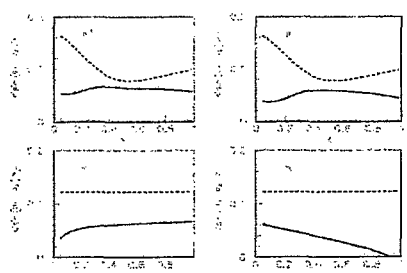
- Scalar-diquark--quark model: S.J.Brodsky et al.'02



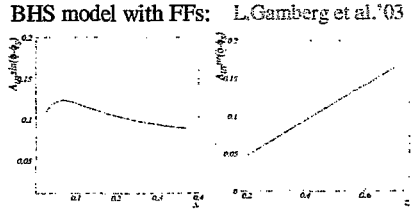
- MIT bag model: F.Yuan'03



- Scalar- and axial-diquark--quark model: A.Bacchetta et al.'03



- BHS model with FFs: L.Gamberg et al.'03



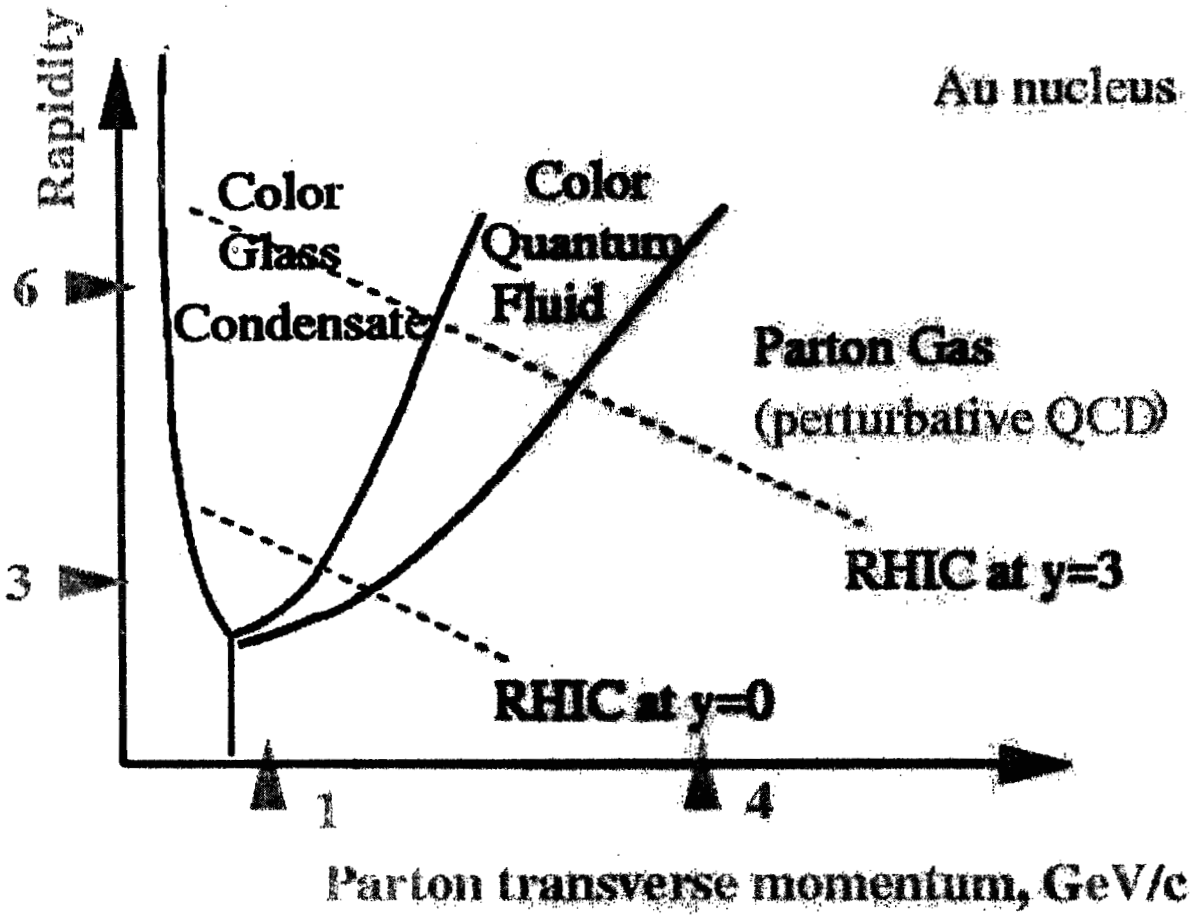
Nuclear Theory Summary of "High-$p_\perp$ Physics @ RHIC"

A. Dumitru

- Au+Au, $y=0$: consensus reached on high-$p_\perp$ suppression of single-inclusive distributions: final-state effect, presumably e-loss

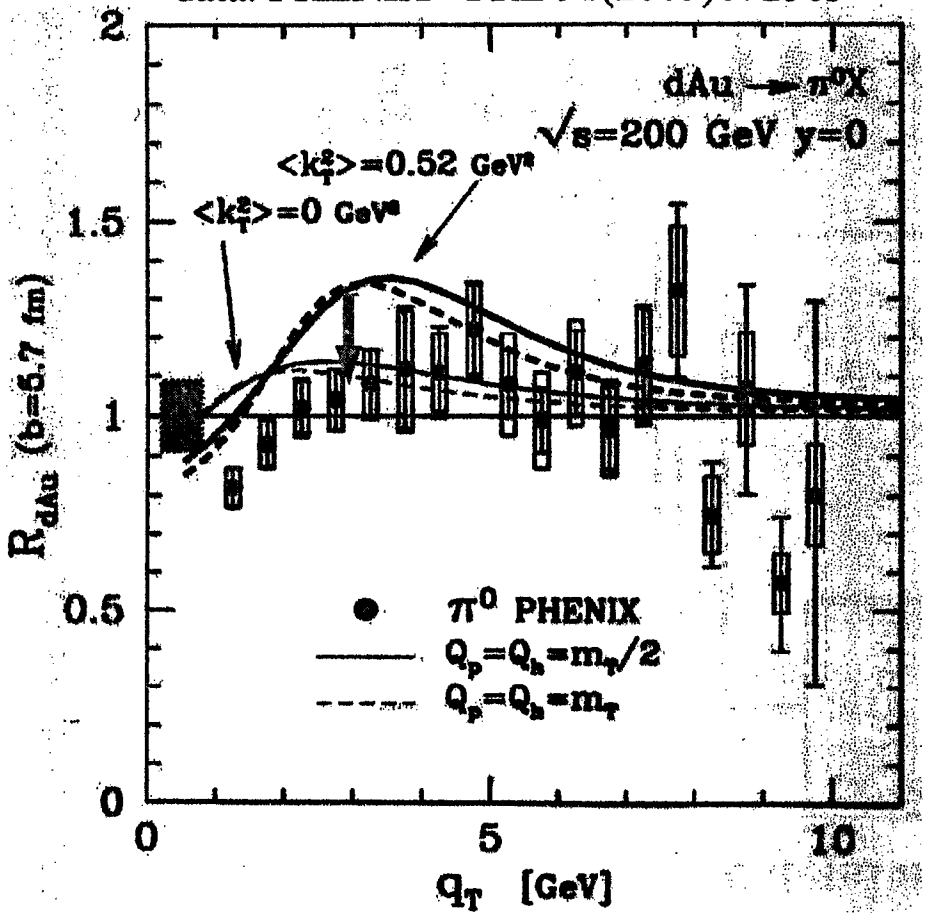
- d+Au, $y=0$:
  - $dN/d\eta$ from CGC works!
  - $dN/dp_\perp$ @ $\eta=0$ requires only moderate, if any, LT shadowing + Cronin
  - $dN/dp_\perp$ @ $\eta=3$ requires strong LT shadowing → perhaps the first glimpse @ scaling regime <u>above</u> saturation regime (no consensus yet)
  - can one identify the high-density regime @ $p_\perp \lesssim Q_s$?

Phase diagram of high energy QCD and RHIC



Cronin effect on pions at PHENIX

data: PHENIX - PRL 91(2003)072303



Beware: Theoretical errors ~10% at the peak.
Large experimental systematic errors

Computation compatible with data inside <u>exper.</u> and <u>theor. errors</u>

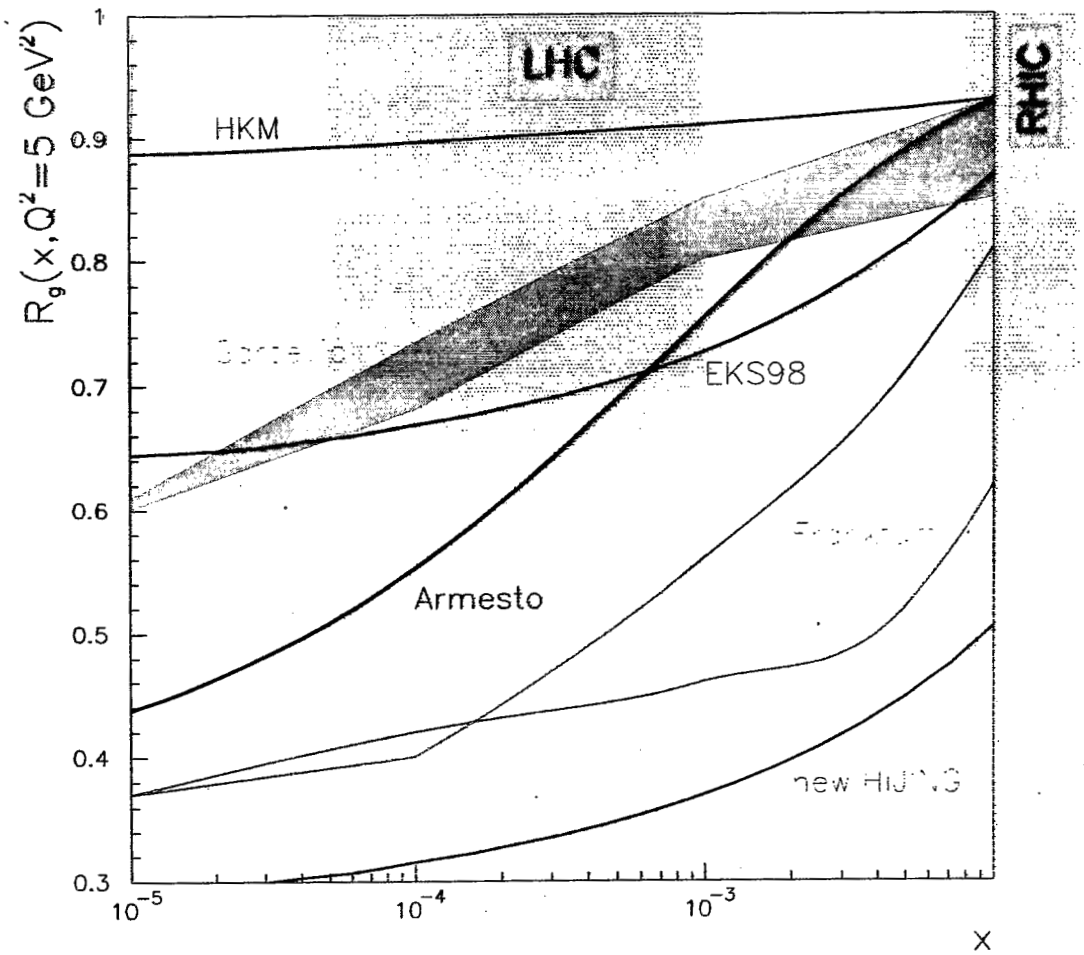
Tends to overestimate the data

⇒ **Possible indication of dynamical shadowing**

However:
<u>radiative and collisional en. loss.</u> (here neglected) may slightly suppress the spectrum at low p_T, barring shadowing...

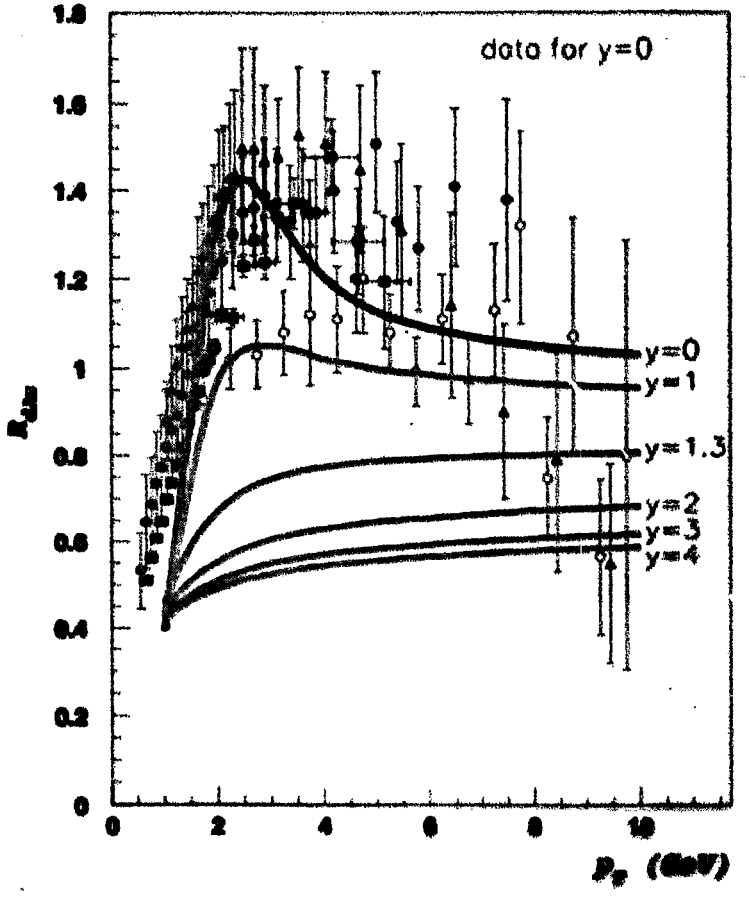
Conventional approach to PA

- Shadowing
  - Parameterization: initial condition + DGLAP
  - Calculation: use relation to diffraction



From N. Armesto and C.A. Salgado (hep-ph/0301200)

Color Glass Condensate: confronting the data



The effects of quantum Evolution in the CGC set in very rapidly

<u>RHIC energy is ideal</u>

talk by K. Tuchin/Yu.Kovchegov

DK, Yu. Kovchegov, K. Tuchin,
To appear

Outlook*

Stanley J. Brodsky, SLAC
RIKEN BNL Research Center
RHIC High p_T Workshop, December 2003

One of the most remarkable observations at RHIC [1] is the nearly complete quenching of away-side hadrons produced opposite a detected high p_T hadron in central $AuAu$ collisions at $\sqrt{s_{NN}} = 200$ GeV. This strong suppression implies a jet energy loss $dE/dx \sim 15$ GeV/fm, some 30 times larger than the jet energy loss seen in pp, dA, and peripheral ion-ion collisions [2]. The observation of anomalous jet quenching at RHIC is perhaps the strongest evidence that a new phase of hot, dense hadronic matter has been produced in high energy ion-ion collisions. A possible dynamical mechanism for initiating this phenomenon in QCD is illustrated in transparency [2]: a soft gluon produced from an initial hard nucleon-nucleon collision can Compton back-scatter from the quark of another nucleon, efficiently converting its quark energy to gluonic energy in analogy to laser back-scattering on a high energy electron beam. The back scattering of soft gluons can occur repeatedly as the heavy nuclei approach, producing a gluon "avalanche" and a dense field of quark and gluon quanta which finally coalesce to a high multiplicity of hadrons.

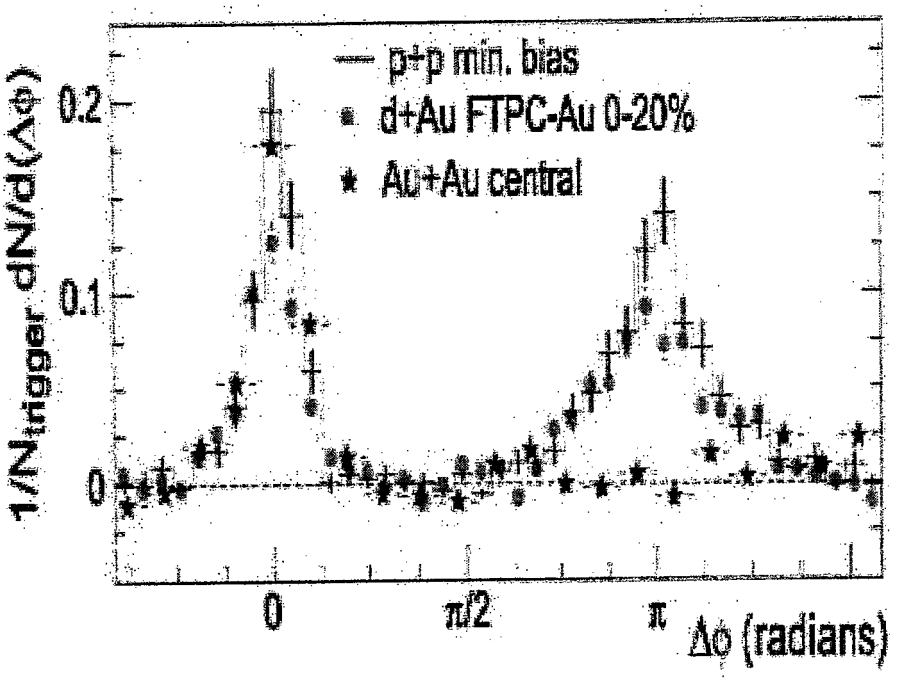
In this talk, I also discussed a number of other novel aspects of high p_T hadron production at RHIC, including (1) the formation of hadrons and the suppression of quarkonium due to the coalescence of comoving partons; (2) the importance of higher twist and semi-exclusive hard scattering subprocesses in $pp \to HX$, such as $uu \to p\bar{d}$ and $up \to up$ reactions; despite their relative suppression in inverse powers of p_T, such subprocesses can nevertheless dominate over conventional quark and gluon scattering reactions. This is especially important for high p_T baryon production—because of the more effective use of hadron energy by higher twist subprocesses; (3) the effects of color transparency in direct high p_T hadron production; (4) the interesting effects of high x intrinsic charm quarks including $s\bar{c} \to W^-$ production subprocesses; (5) the elimination of the renormalization scale ambiguities; (6); unusual aspects of diffraction, nuclear shadowing, and antishadowing; and (7) the use of single-spin high p_T asymmetries as signals for initial and final state QCD interactions.

The upcoming RHIC experimental program, including polarized pp collisions is extraordinarily interesting and diverse. The central challenge is to quantify the conditions and identify the specific signals of novel nuclear QCD matter and phenomena, such as anomalous direct photon and lepton pair production, anomalous heavy quark and quarkonium signals, and the anomalous production of anti-nuclei.

[1] An excellent summary of recent results from RHIC on hard scattering processes in Au+Au, p+p, and d+Au collisions is given in D. d'Enterria, arXiv:nucl-ex/0309015.

[2] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077.

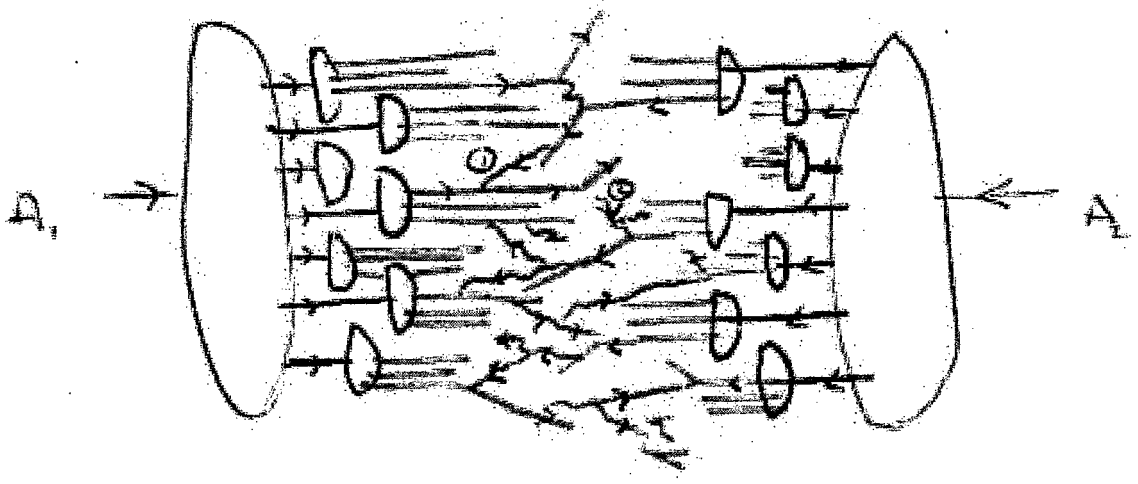
* Work supported by the Department of Energy, contract DE–AC03–76SF00515.



Remarkable suppression of away side particles

STAR Collab. PRL91, 072304 (2003)

Model for Formation of Q, g Plasma



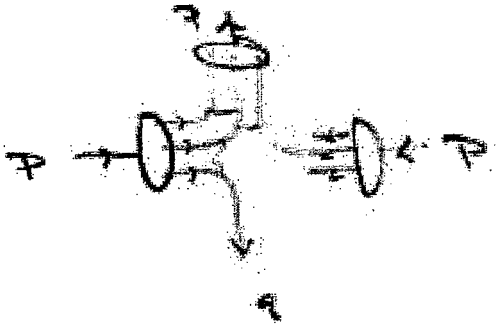
Analog of back-scattered Laser

- Compton produces high energy polarized photon beam.
- In heavy ions: converts quark energy to gluonic energy
- Colliding mirrors: Cascading gluons
  - { converts heavy ion energy to high density gluons, $q\bar{q}$

Exclusive - Inclusive Duality ⇒ "Direct" Production

$$pp \to pX \cong pp \to p p^*$$

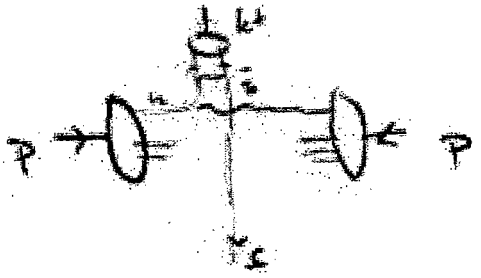
at fixed s, t, M_X^2



$up \to up$

- No same-side jet
- no beam fragments
- analog of QIM in $\gamma p \to \rho p$
- dominant at large M_X

Related subprocesses



$ug \to k^+ s$

- Direct meson production
- no same-side jet

$$\frac{d\sigma}{d^2p_\perp dz}(pp \to k^+ X) \sim \frac{p_\perp^2}{p_T^6}(1-x_T)^5$$

⇒ Implications of "Direct Hadron Production" for RHIC

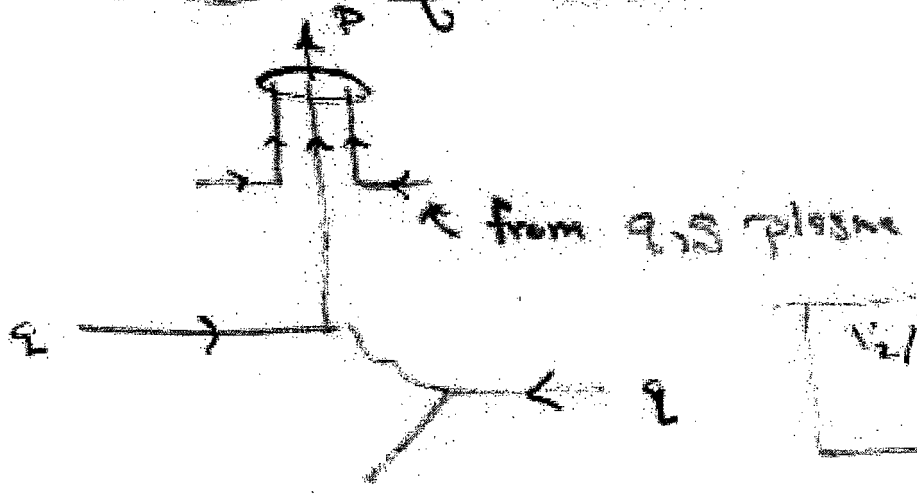
$pA \to KX$:
- Color transparency: No FSI, Energy loss
- No final state hadronization
- No comovers

Muller
SLB
Kopeliovich

"Recombination"

Another model for large p_T baryon production in central A-A collisions

Coalescence & Convoy



R. Fries
B. Müller

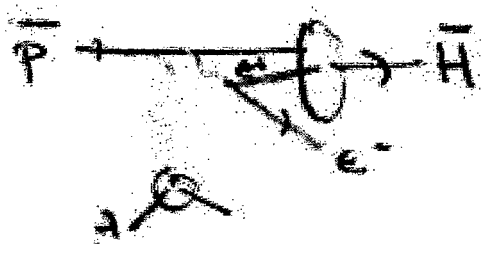
v_2/n vs p_T/n scaling

$n=1$ baryons
$n=2$ mesons

picks up motion q plasma

Recombination analogous to antihydrogen production

CERN, FNAL



quantum mechanical analysis

(n-shell)

Schmidt
Munz, SJB

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RIKEN BNL Research Center Workshop

High pT Physics at RHIC

December 2-6, 2003

Physics Dept., Brookhaven National Laboratory

*******AGENDA*******

All talks to be held in the Large Seminar Room, first floor, Physics Bldg. 510

Tuesday, December 2

Morning Session

08:30 – 09:00 Registration

09:00 – 09:15 Welcome – S. Aronson, BNL

09:15 – 10:00 Opening Talk – A. Mueller, Columbia University

10:00 – 10:45 High pt Results – D. d'Enterria, Columbia University

10:45 – 11:00 COFFEE BREAK

11:00 – 11:45 Spin Physics – M. Stratmann, University of Regensburg

11:45 – 12:30 Experimental Aspects of the RHIC Spin Program – B. Surrow, BNL/MIT

12:30 – 14:15 LUNCH

Afternoon Session

14:15 - 15:00 Highlights from the DNP Meeting – J. H. Lee, BNL

15:00 – 15:30 COFFEE BREAK

15:30 – 16:30 Lattice Gauge Theory and Heavy Ion Collisions - Colloquium by F. Karsch

16:45 – 17:30 Production of Heavy Quarks & Quarkonium – E. Braaten, Ohio State University

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Wednesday, December 3

Morning Session

09:00 – 09:45 pQCD for High pT Reactions – G. Sterman, SUNY Stony Brook

09:45 – 10:15 QCD Hard Scattering and Massive Hadron Pair Production – J. Owens, Florida State University

10:15 – 10:45 CTEQ Global Analysis – J. Pumplin, Michigan State University

10:45 – 11:00 COFFEE BREAK

11:00 – 11:45 Low Mass Dilepton Production at High p_T as a Probe of Gluon Density – J. Qiu, Iowa State University

11:45 – 12:30 Multijet Production as a Centrality Trigger for pp Collisions – M. Strikman, Penn State University

12:30 – 14:00 LUNCH

Afternoon Session

14:00 – 14:20 Hadron Production at RHIC at Intermediate and High p_T: Recombination and Fragmentation – R. Fries, University of Minnesota

14:20 – 14:40 The Dihadron Fragmentation Function and its Evolution – A. Majumder, LBNL

14:40 – 15:00 Nuclear PDFs at Next to Leading Order – D. de Florian, Universidad de Buenos Aires

15:00 – 15:15 COFFEE BREAK

Glauber Symposium – Chair: D. Morrison

15:15 – 16:00 Gribov's Corrections to the Normalization of High-pT Data / Space-time Development of in-medium Hadronization – B. Kopeliovich, Max-Planck-Institut

16:00 – 16:45 TBA – B. Cole, Columbia University / BNL

16:45 – 17:30 Application of the Monte Carlo Glauber Model in d+Au Collisions – M. Miller, Yale University

17:30 – Discussion – P. Steinberg, BNL

Thursday, December 4

Morning Session

09:00 – 09:45 Single Spin Asymmetries and QCD – J. Collins, Penn State

09:45 – 10:15 Single Transverse Spin Asymmetry for the Pion Production at RHIC and EIC – Y. Koike, BNL / Niigata University

10:15 – 10:45 Quark Correlations and Single Spin Asymmetries – M. Burkardt, NMSU

10:45 – 11:00 COFFEE BREAK

11:00 – 11:45 Universality of T-odd Effects in Single Spin Azimuthal Asymmetries – P. Mulders, Vrije Universiteit

11:45 – 12:15 Novel Spin Effects in QCD – S. Brodsky, SLAC

12:15 – 14:00 LUNCH

Afternoon Session

14:00 – 14:45 The High pT View of the QGP at RHIC – M. Gyulassy, Columbia University

14:45 – 15:30 Photons and Gluons at RHIC, some aspects – R. Baier, Universitaet Bielefeld

15:30 – 15:45 COFFEE BREAK

15:45 – 16:30 Why Jet Quenching is Caused by Parton Energy Loss – X.-N. Wang, LBNL

16:30 – 17:00 Separating the Process-Dependent and Process-Independent Dynamics at RHIC – I. Vitev, Iowa State University

17:00 – 17:30 Energy Loss of High p_T Partons – G. Moore, McGill University

17:30 – 18:00 Production of High-pt Particles in AuAu and dAu Collisions at RHIC – C. Salgado, CERN

19:00 Banquet – Atlantis Marine World Aquarium, Riverhead

Friday, December 5

Morning Session

09:00 – 09:45 Color Glass Condensate at RHIC – D. Kharzeev, BNL

09:45 – 10:30 Cronin Effect Versus High-p_T Suppression – K. Tuchin (BNL) and Y. Kovchegov (University of Washington)

10:30 – 11:00 Proton Nucleus Collisions at High Energy – J. Jalilian-Marian, University of Washington

11:00 – 11:15 COFFEE BREAK

11:15 – 11:35 Cronin Effect Versus Geometrical Shadowing in dAu Collisions at RHIC – A. Accardi, Columbia University

11:35 – 11:55 Quark-antiquark Production in High-Energy Hadronic Interactions – F. Gelis, SPhT/CEA

11:55 – 12:15 Saturation and BFKL Dynamics in the HERA Data at Small x – K. Itakura, SPhT/CEA

12:20 – 14:00 LUNCH

Afternoon Session

14:00 – 14:40 The "Small-x Message" from HERA – J. Bartels, BNL

14:40 – 15:20 Initial Conditions with the QCD Sphalerons: the Modified Shadowing and Jet Quenching – E. Shuryak, SUNY Stony Brook

15:20 – 15:45 Chiral Dynamics and the Transverse Size of the Gluon Distribution at Small x – C. Weiss, Regensburg University

15:45 – 16:00 COFFEE BREAK

16:00 – 16:30 eRHIC Physics, Design Status – A. Deshpande, BNL

16:30 – 17:00 RHIC II – Y. Akiba, BNL/RIKEN

17:00 – 17:30 LHC – B. Wyslouch, MIT

Saturday, December 6

Morning Session – Summary Talks

09:00 – 09:30	Rapporteur on the Glauber Symposium – P. Steinberg, BNL
09:30 – 10:00	Rapporteur on Spin Physics – A. Belitsky, University of Maryland
10:00 – 10:30	Rapporteur on Initial and Final Stage High pT Physics – A. Dumitru, University of Frankfurt
10:30 – 11:15	Outlook – S. Brodsky, SLAC
11:15 – 12:00	Discussion
12:00	Workshop Adjourns

Additional RIKEN BNL Research Center Proceedings:

Volume 60 – Lattice QCD at Finite Temperature and Density – BNL -
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Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
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Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
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RIKEN BNL RESEARCH CENTER

High pT Physics at RHIC

December 2-6, 2004

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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Speakers:

A. Accardi	Y. Akiba	S. Aronson	R. Baier	J. Bartels
A. Belitsky	E. Braaten	S. Brodsky	M. Burkardt	B. Cole
J. Collins	D. d'Enterria	D. de Florian	A. Deshpande	A. Dumitru
R. Fries	F. Gelis	M. Gyulassy	K. Itakura	J. Jalilian-Marian
F. Karsch	D. Kharzeev	Y. Koike	B. Kopeliovich	Y. Kovchegov
J. H. Lee	A. Majumder	M. Miller	G. Moore	A. Mueller
P. Mulders	J. Owens	J. Pumplin	J. Qiu	C. Salgado
E. Shuryak	P. Steinberg	G. Sterman	M. Stratmann	M. Strikman
B. Surrow	K. Tuchin	I. Vitev	X.-N. Wang	C. Weiss
B. Wyslouch				

Organizers: S. Kretzer, D. Morrison, R. Venugopalan, W. Vogelsang