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Jet Correlations at RHIC

MARCH 10-11, 2005

Organizers:

.M. Gyulassy, M. Tannenbaum, F. Wang

RIKEN BNL Research Center

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April **1'997** 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.

The RBRC has both a theory and experimental component. At present the theoretical group has **4** Fellows and **3** Research Associates **as** well as **11** RHIC Physics/University Fellows (academic year **2003-2004).** To date there are approximately **30** graduates from the program of which **13** have attained tenure positions at major institutions worldwide. The experimental group is smaller and has **2** Fellows and **3** RHIC Physics/University Fellows and **3** Research Associates, and historically 6 individuals have attained permanent positions.

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 senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC 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 seventy-three 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** and is still operational. A **10** teraflops QCDOC computer in under construction and expected to be completed this year.

N. P. Samios, Director
November **2004**

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

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Jet Correlations at RHIC

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Several striking features are observed at RHIC in heavy-ion collisions (but not in d+Au) relative to pp: Large pT hadron yields are suppressed; Leading and sub-leading hadron jet-like back-to-back correlations are suppressed; Leading and soft hadron correlations are enhanced; Baryon to meson ratio is enhanced in the intermediate pT region, and yet the baryons seem to possess jet-like characteristics; And elliptic flow at intermediate to high pT exhibits a pattern suggestive of the relevance of the constituent quark degrees of freedom. These and other observations suggest that jets are modified in the hot and dense medium created in central heavy ion collisions, and the created medium is qualitatively consistent with a strongly coupled Quark-Gluon Plasma.

However, the properties of the created medium are far from being fully understood. What is the degree of thermalization in heavy-ion collisions? How to probe thermalization experimentally? **Is** the away side correlation data a manifestation of sonic shock waves? **If** the jets are losing energy, where does the energy go? At what pT are effects from punching through of the away jet observable? What are the production mechanisms for large pT baryons (and mesons)? Is the relevance of the constituent quark degrees of freedom a proof of de-confinement?

This workshop will provide a forum to gather theorists and experimentalists and to stimulate discussions about what the data are telling us about the properties of the medium, what the remaining questions are, and how to address them experimentally and theoretically.

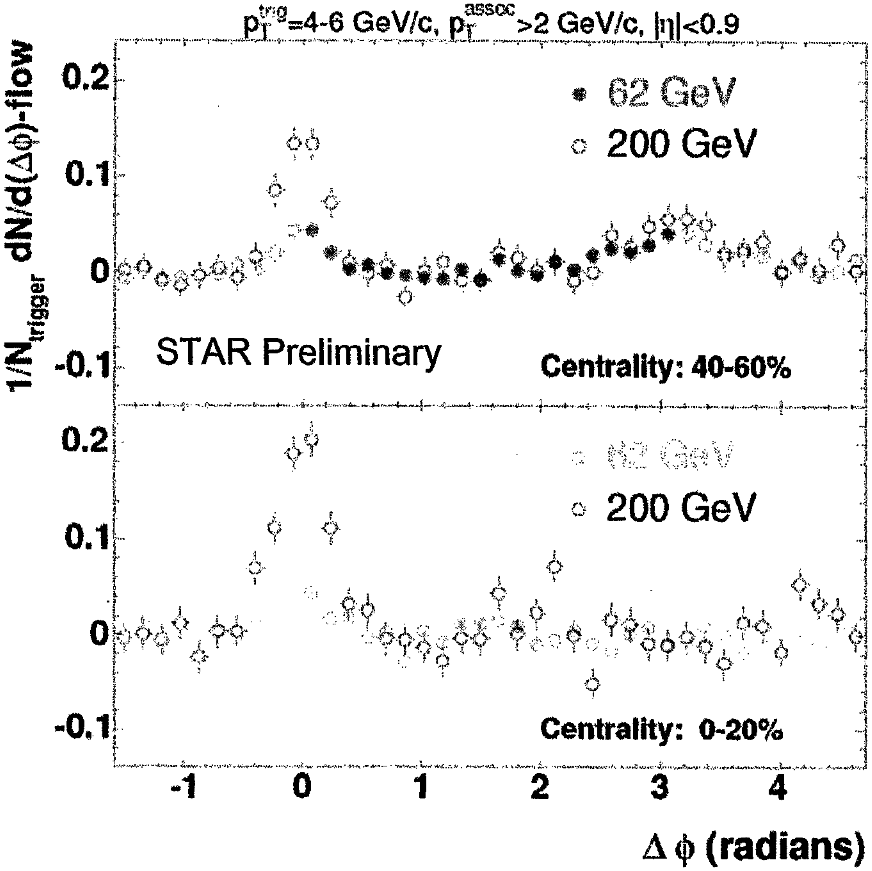
High-p_T Results from *STAR*

Carl A. Gagliardi
Texas A&M University

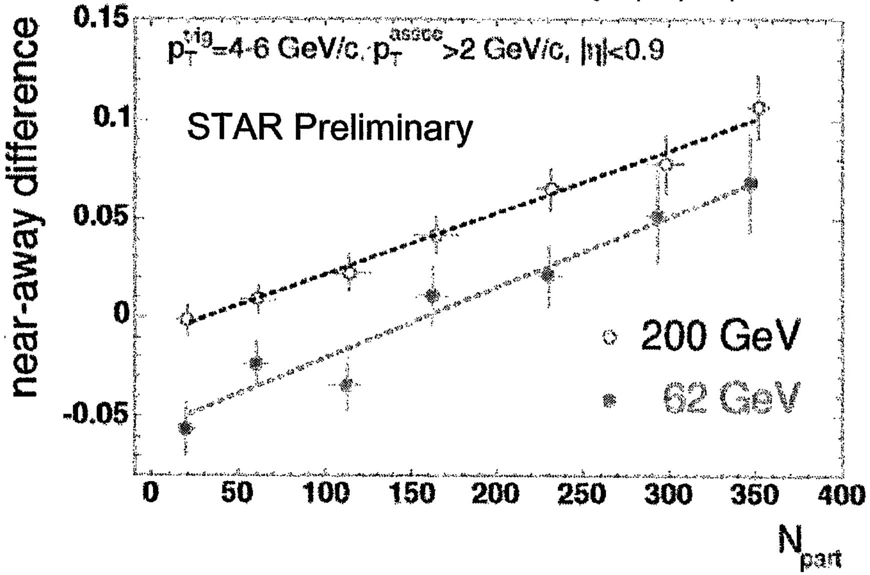
for the *STAR* **Collaboration**

- Introduction
- Spectra
- Elliptic flow
- Correlations
  ($\Delta\varphi$ and $\Delta\eta$)
- Forward physics

Di-Hadron Angular Distributions: 62 GeV vs 200 GeV Au+Au



Near: $|\Delta\varphi| < 0.8$
Away: $|\Delta\varphi-\pi| < 0.8$



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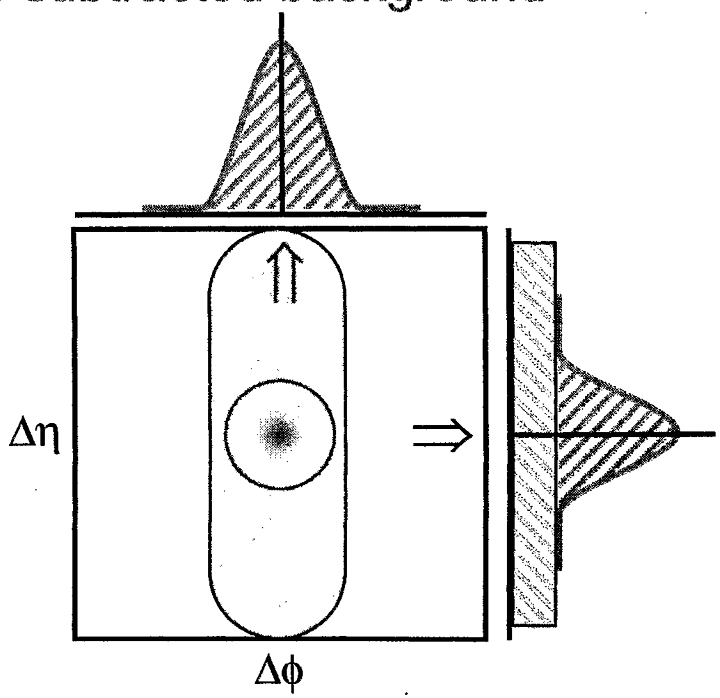
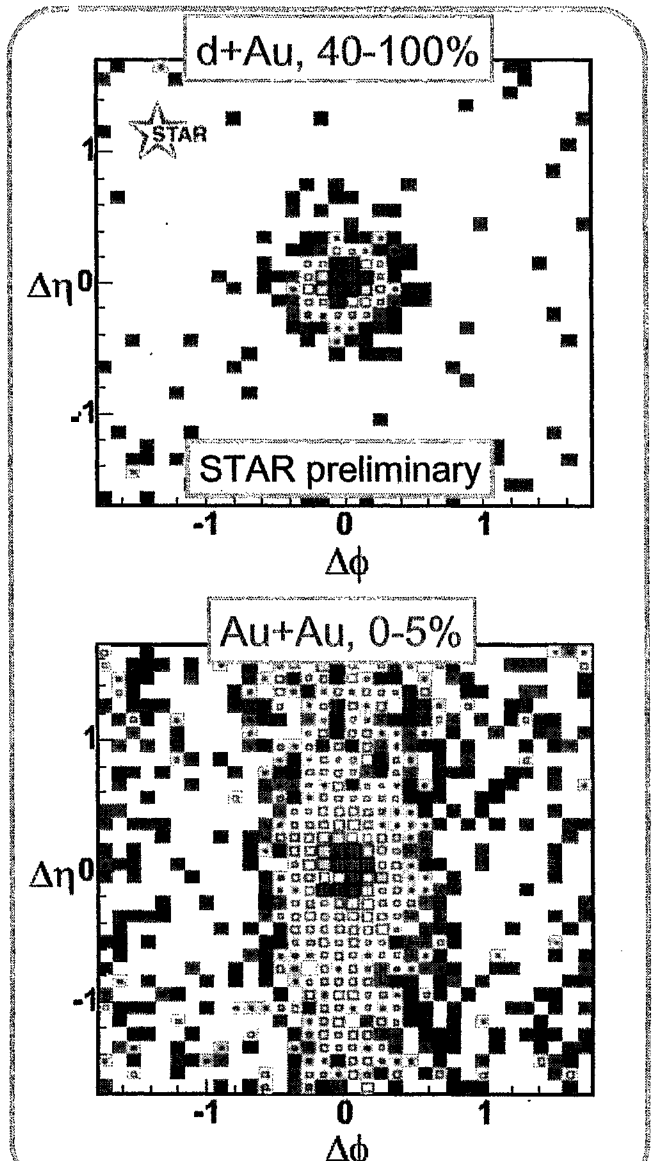
Near-side correlated yields are much reduced at 62 GeV

Away-side angular distribution is very similar

Extracting Near-Side Jet Yields

- In Au+Au, jetlike correlation sits on top of an additional, flat correlation in $\Delta\eta$
  - $\Delta\phi$: cannot differentiate between the two correlations
  - $\Delta\eta$: additional correlation gets grouped into subtracted background





3 < p_T(trig) < 6 GeV
2 < p_T(assoc) < p_T(trig)

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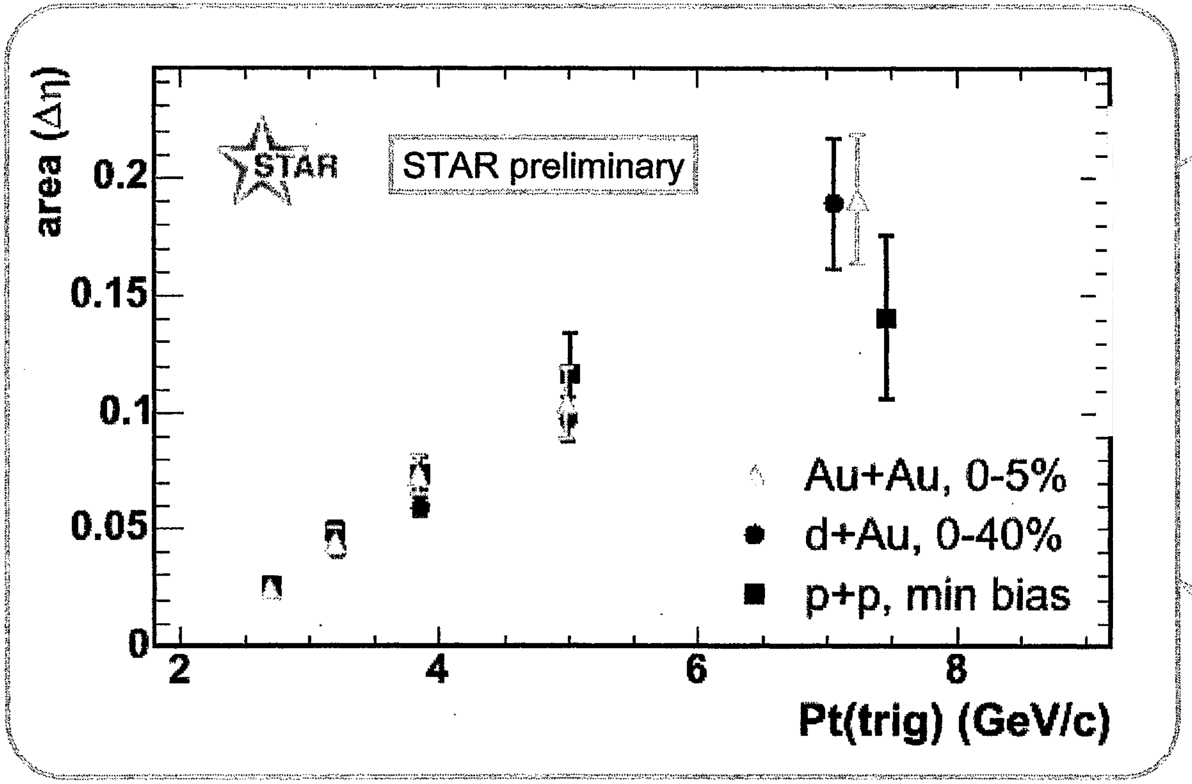
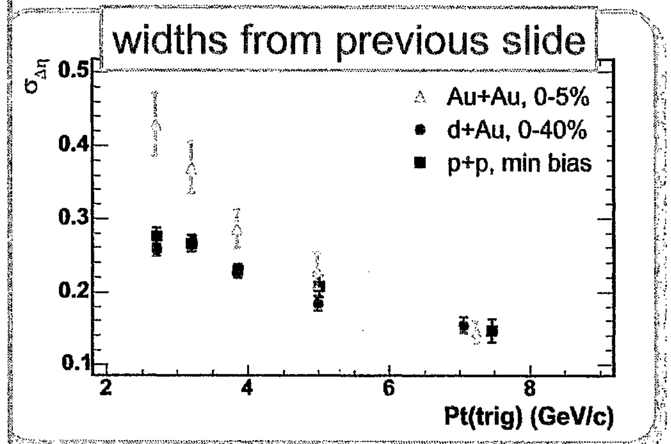
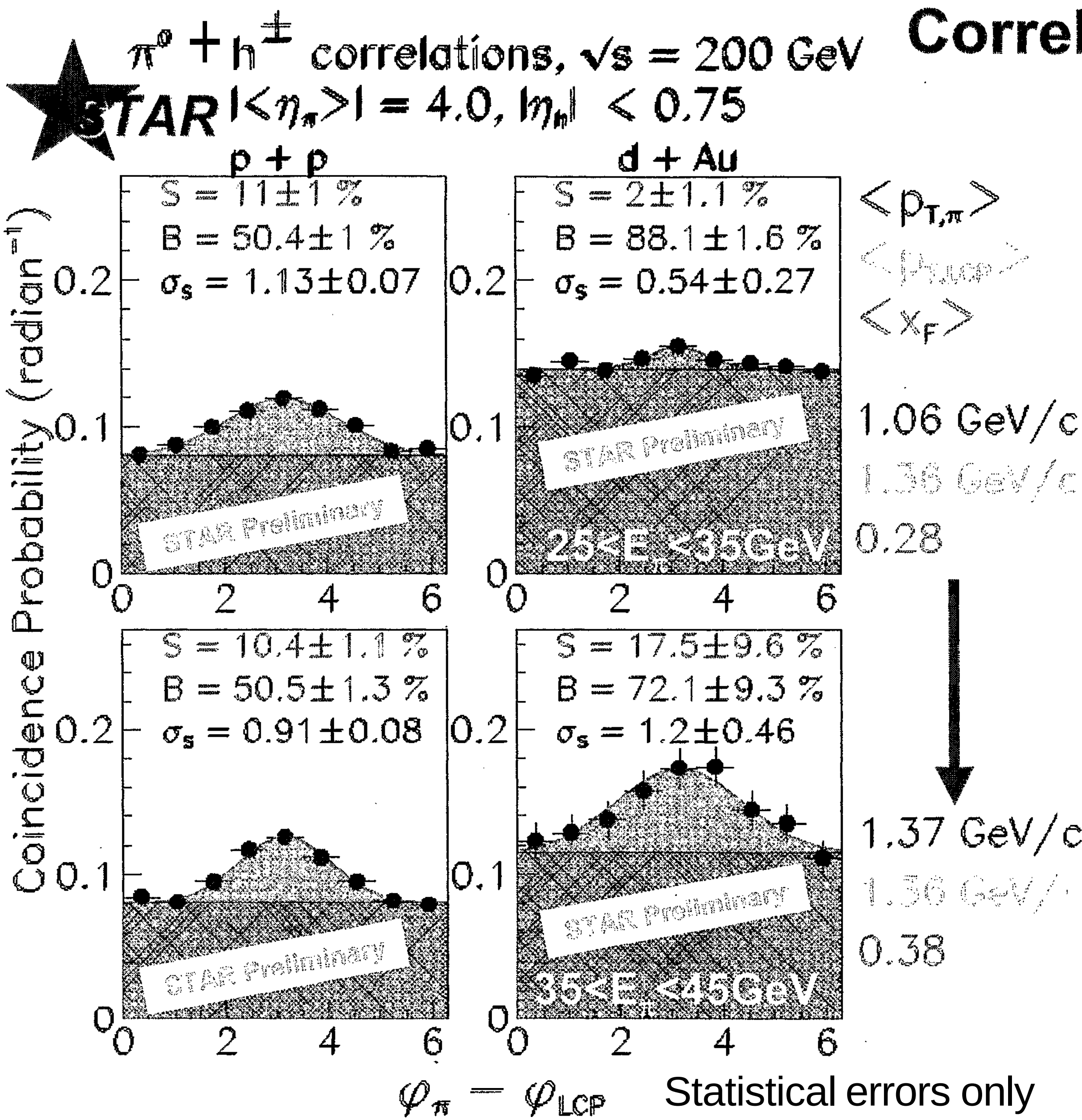
$\Delta\eta$: p_T(trig) Dependence of Correlated Yield





- Gaussian areas consistent within errors for all p_T(trig)
  - Yield growth with p_T(trig): more assoc. particles for higher-p_T parton
  - Correlation yield preserved despite broadening of correlation

Correlations in d+Au

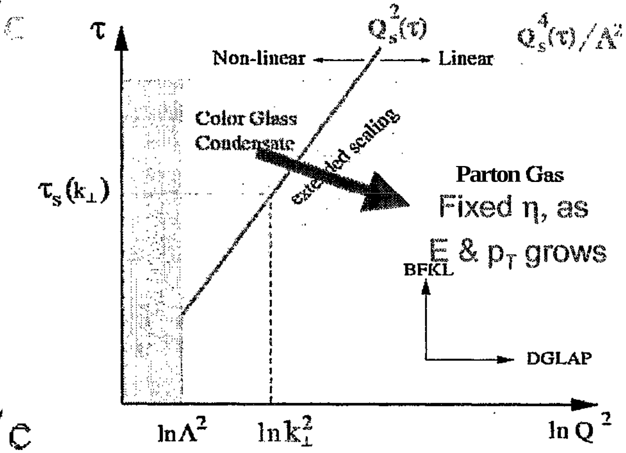


Statistical errors only

- are suppressed at small $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$

S_{pp}-S_{dAu}= (9.0 ± 1.5) %

Consistent with CGC picture



- are consistent in d+Au and p+p at larger $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$

as expected by HIJING

Conclusions

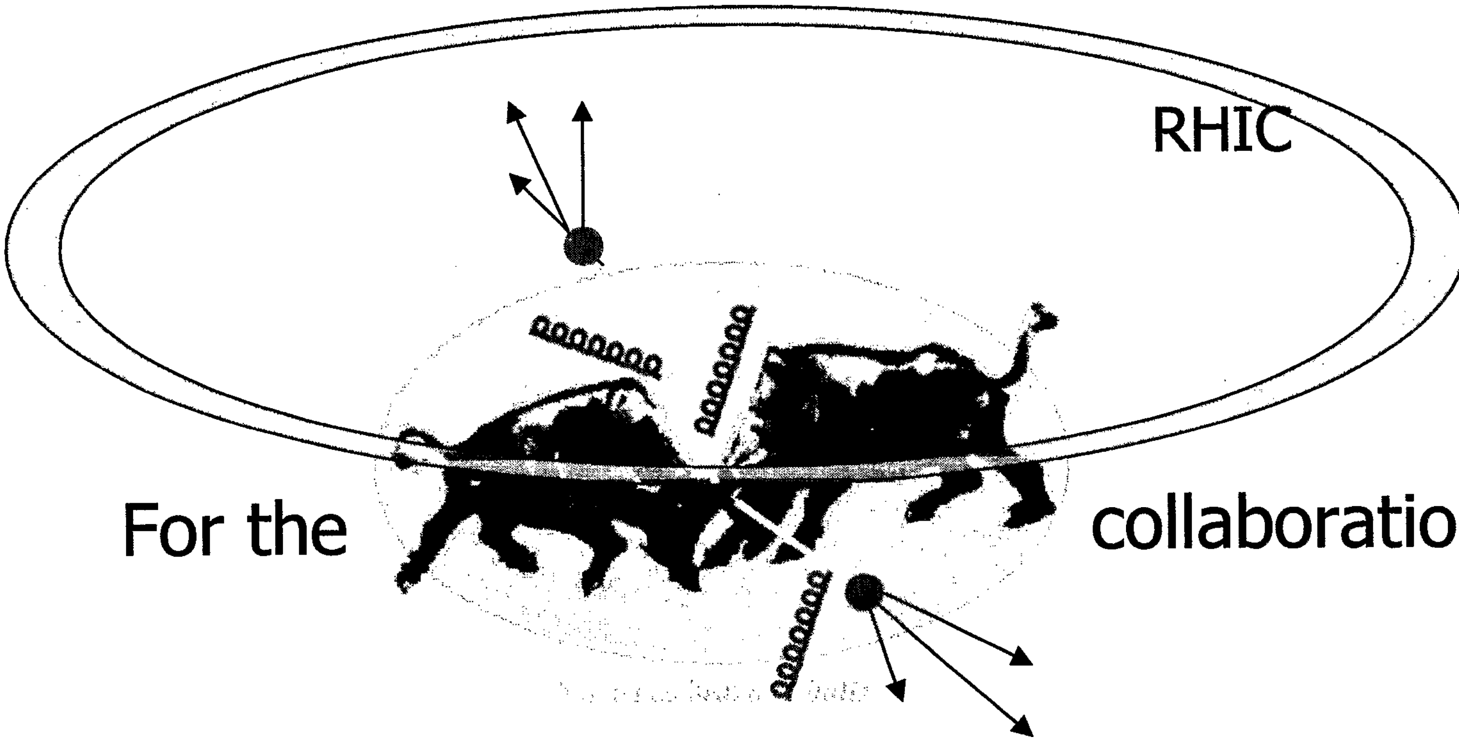
- **Jet quenching, elliptic flow, and di-hadron correlations** are all very similar in 62 GeV Au+Au to the results from 200 GeV Au+Au
- **Meson-baryon differences** are also present in d+Au and 62 GeV Au+Au at intermediate p_T

∞

- The **saturation picture** is consistent with back-front asymmetries and forward-midrapidity correlations in d+Au
- Not all of the near-side associated hadrons are part of **"the jet"**. What are the rest?

Jet results in PHENIX

Jiangyong Jia Columbia University, Nevis Labs



For the collaboration

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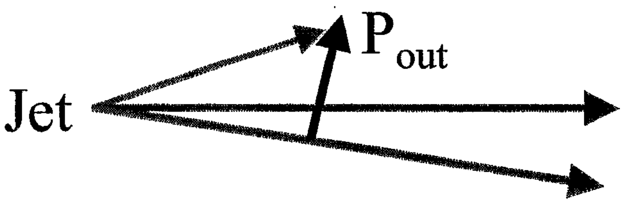
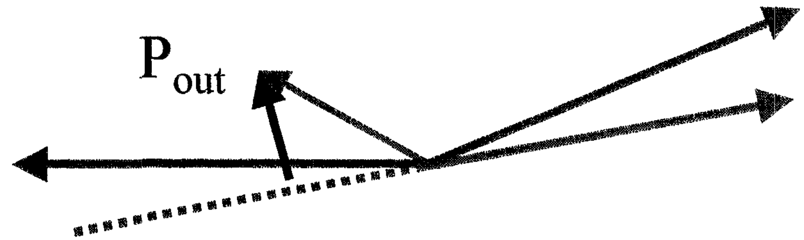
Pout for (di)jet Shape

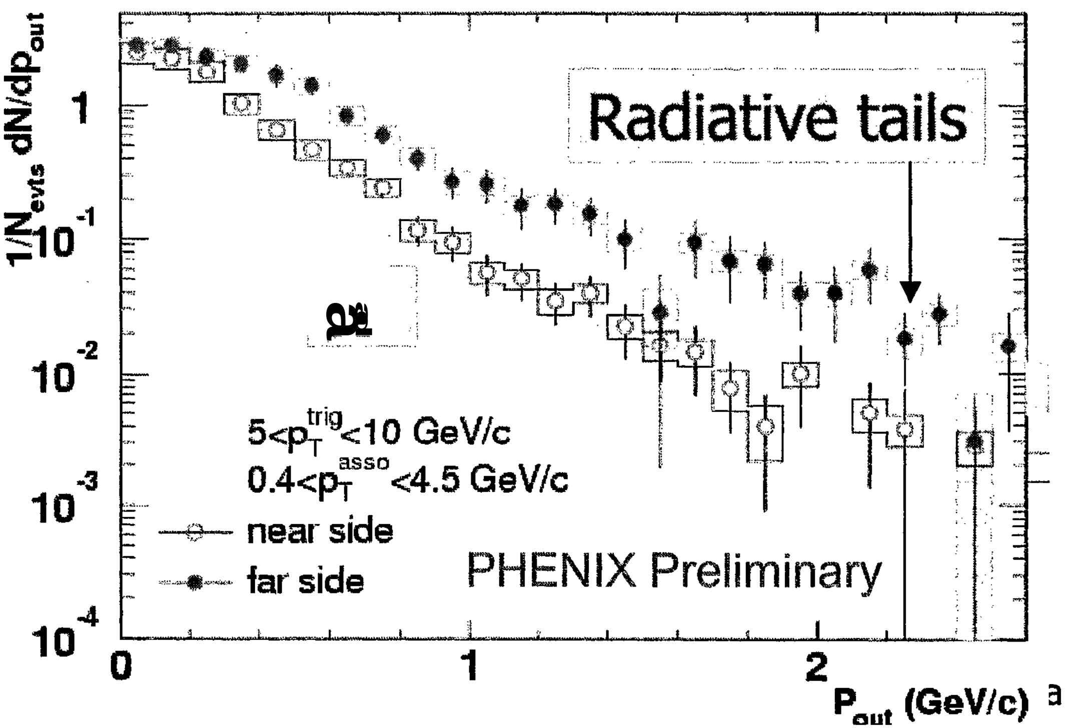




$$\langle p_{out}^2 \rangle \approx \langle j_T^2 \rangle + x_E^2 \langle j_T^2 \rangle \approx \langle j_T^2 \rangle$$

$$\langle p_{out}^2 \rangle \approx \langle j_T^2 \rangle + x_E^2 \langle j_T^2 \rangle + 2 x_E^2 z^2 \langle k_T^2 \rangle$$

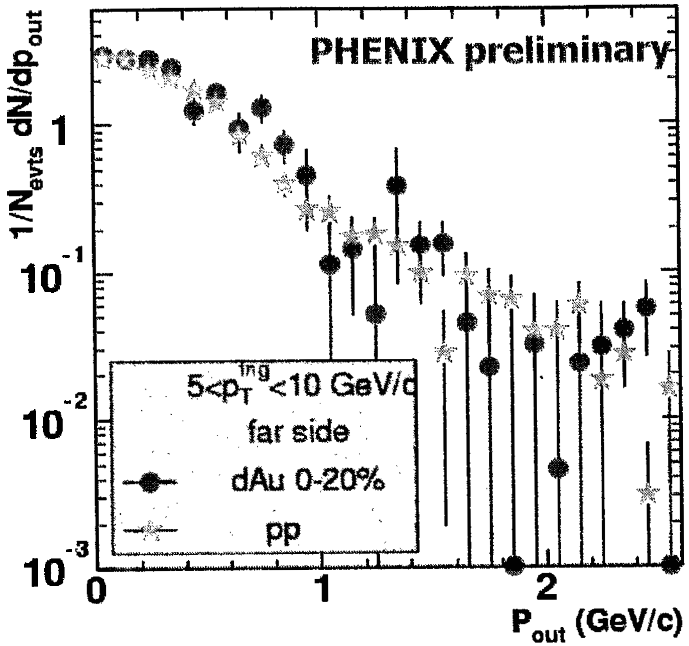
$$\boxed{2 x_E^2 z^2 \langle k_T^2 \rangle \approx \langle p_{out,far}^2 \rangle - \langle p_{out,\ ear}^2 \rangle}$$

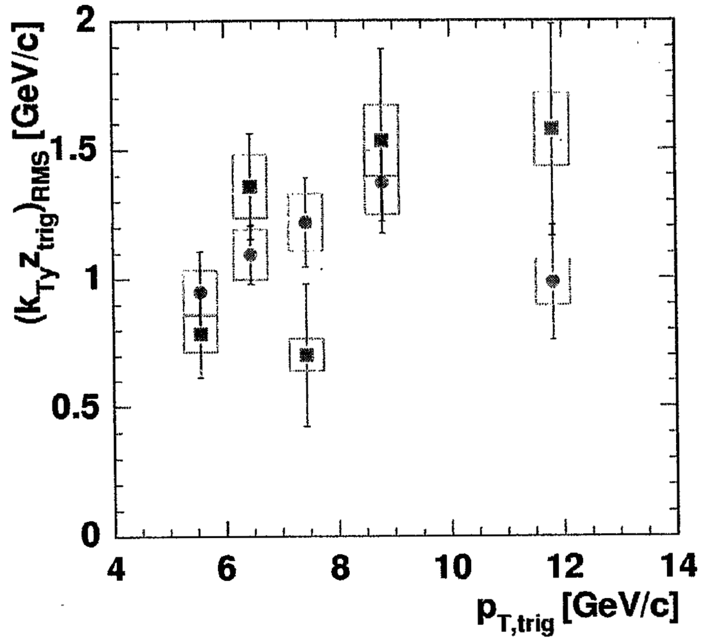


- By measuring pout pair-by-pair, more directly see the shape of the j_T/k_T dist's.
- See non-Gaussian tails – expected due to hard radiation.

dAu central vs pp

See N. Grau's talk





No apparent indication of increased k_T.

No sensitivity to multiple scattering?

$$\langle k_T^2\rangle_{pA} = \langle k_T^2\rangle_{pp} + C\cdot h_{pA}(b)\,.$$ C~ 0.2-0.4

0.8-1.6 $(GeV/c)^2$ in central collisions

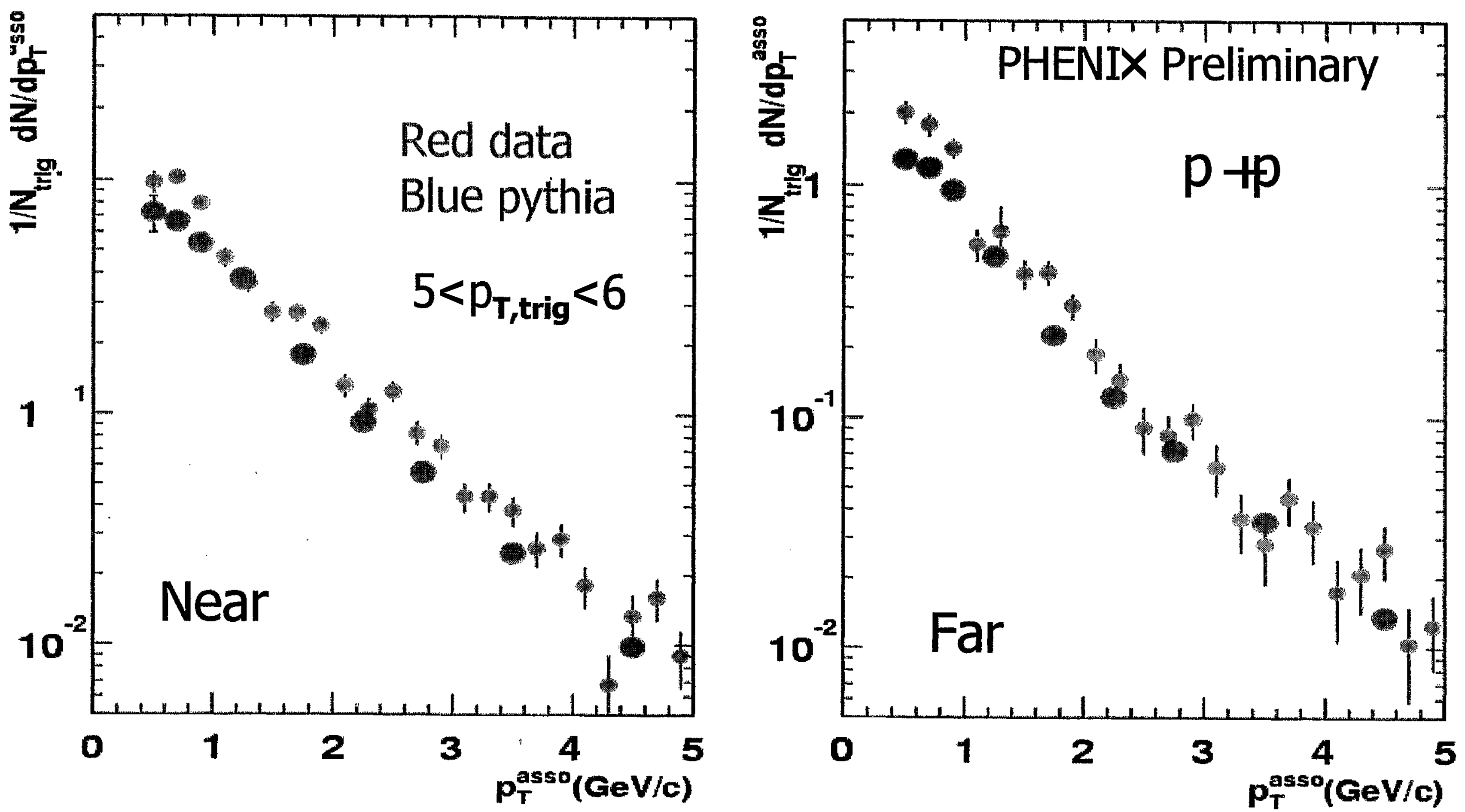
$$\langle k_\perp{}^2\rangle_{\mathrm{pA}} = \langle k_\perp{}^2\rangle_{\mathrm{Intrisic}} + \langle k_\perp{}^2\rangle_{\mathrm{Radiation}} + \langle k_\perp{}^2\rangle_{\mathrm{multi\text{-}scatter}}$$

<1$(GeV/c)^2$ **≈7$(GeV/c)^2$** **≈1$(GeV/c)^2$**

W.Volgelsang, hep-ph/0312320

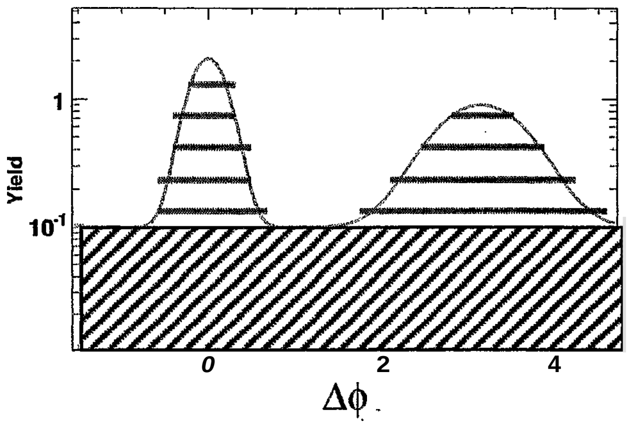
I.Vitev, Phys.Lett.B570:161,2003.

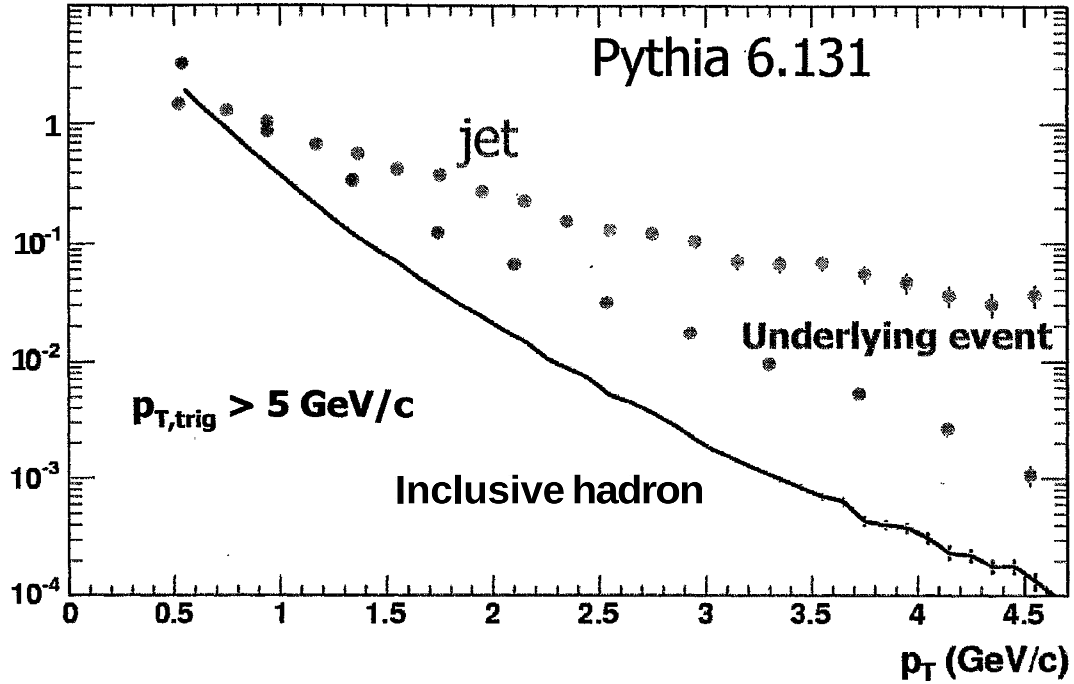
Compare jet yield with Pythia 6.131



We checked the Pythia high pT hadron yield, it's shape is consistent with PHENIX measurement

What Pythia tell us?





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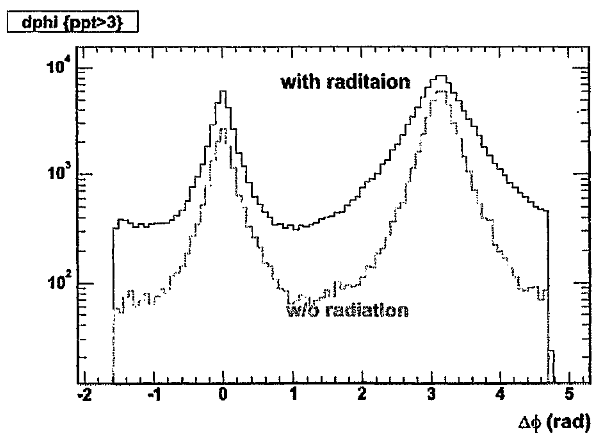
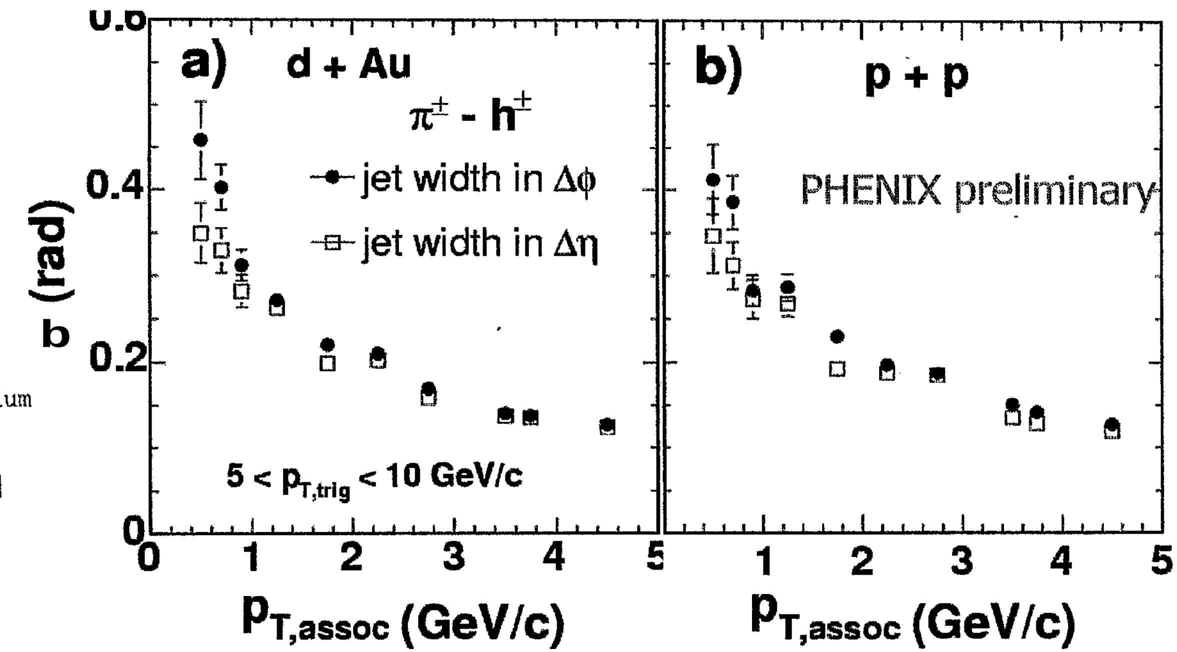


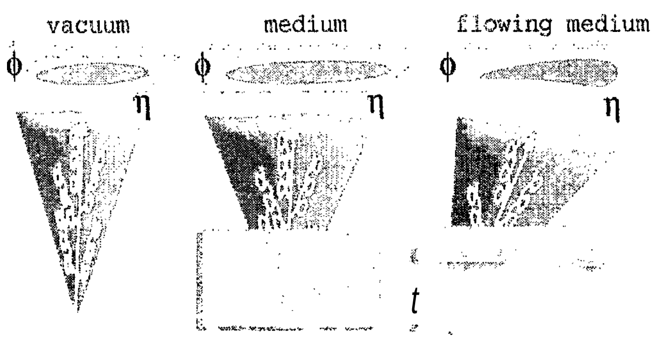
Consistent with radiative contribution

The underlying event is harder than the inclusive!

Study the jet shape in $\Delta\eta$ ($|\Delta\eta|<0.7$)

- PHENIX can measure the jet shape in $\Delta\eta$.
- Top down approach in AuAu: trigger on high pT and study the jet width as function of associated pT, as low as 0.4 GeV/c





Armesto et al., PRL93, 242301 (2004)
S.A. Voloshin, nucl-th/0312065

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Measuring Correlated Jet Pairs

Paul Stankus, ORNL

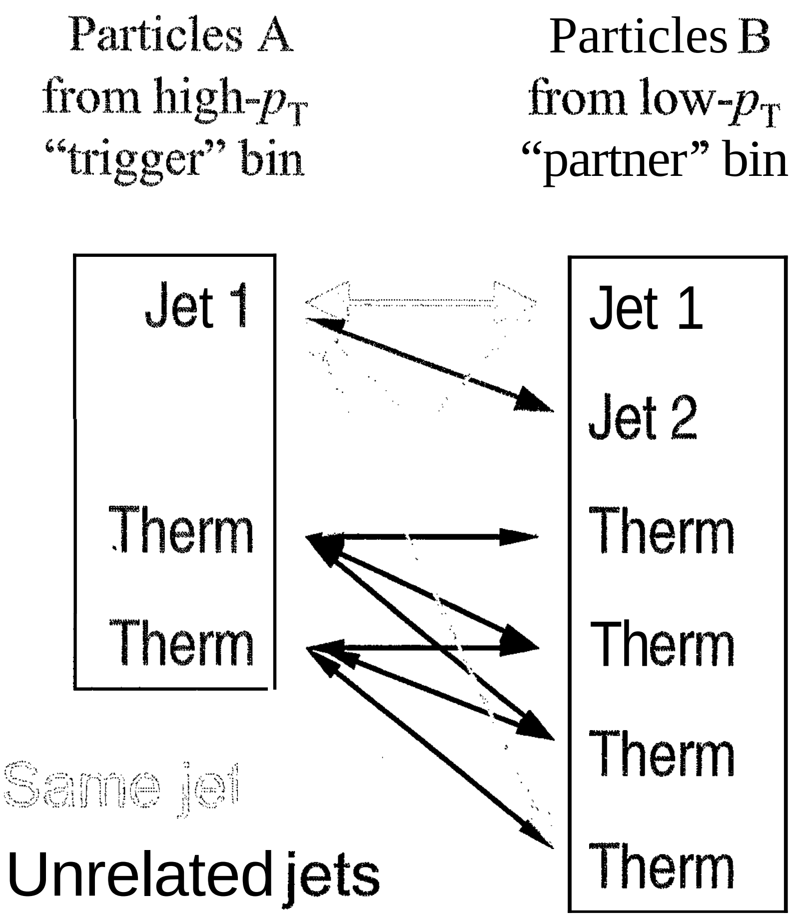
RIKEN JetMod Workshop

March 10, 2005

The two-source model

We *assume* that all hadrons come from one of two sources: jet fragmentation (prompt) or thermal/flow (multicollisional).

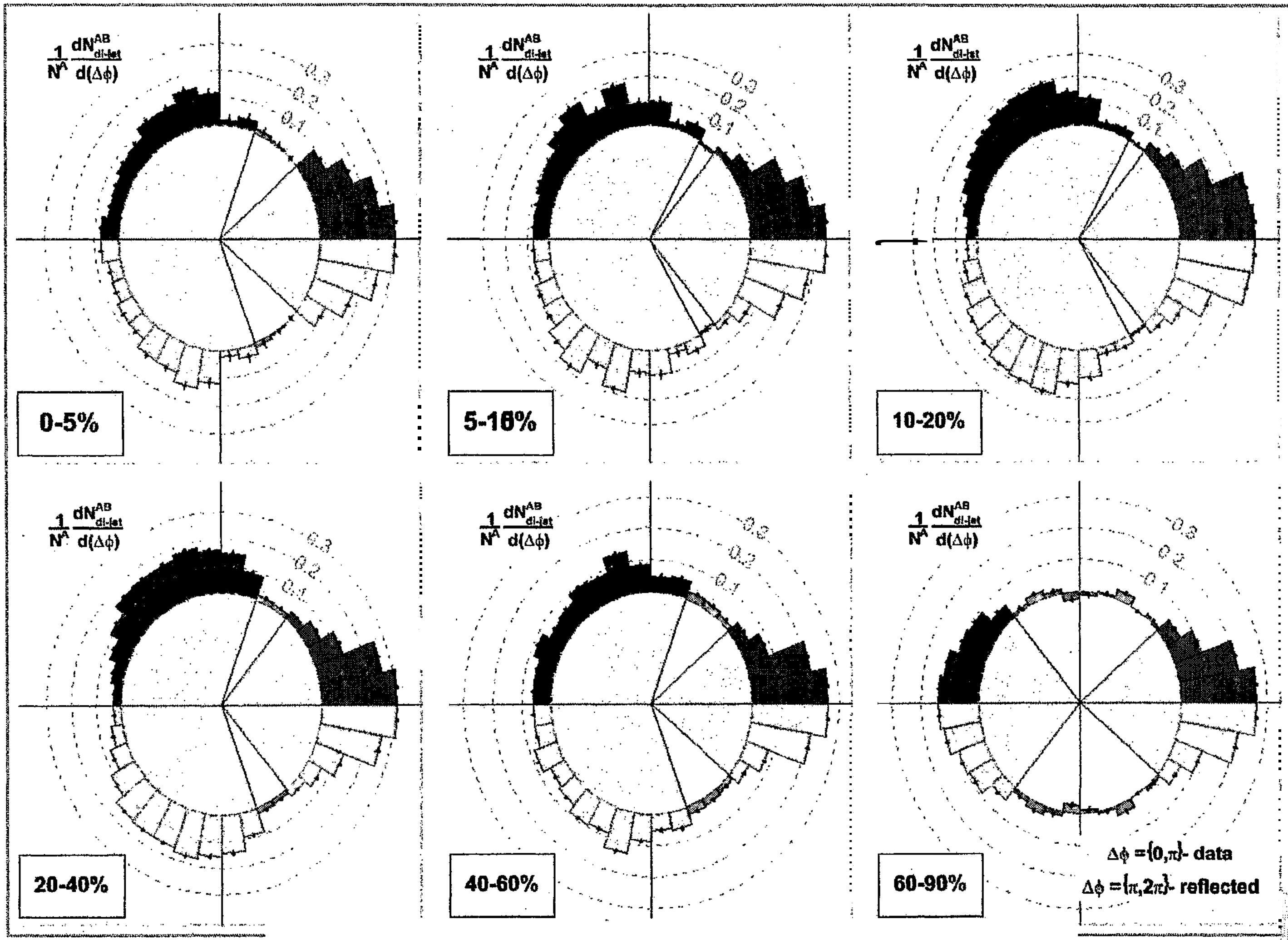
Goal: to count same-jet pairs and look at their distribution in relative angle.



The good stuff — Same jet

"Background" { Unrelated jets / Thermal-thermal

A data "teaser"



PHENIX Preliminary

Trigger particle $p_T > 2.5$ GeV is always to the right; shown is distribution of jet-pair partners $p_T > 1.0$ GeV over full ϕ.

Red: Near-side

Blue: Away-side

Dark: Data

Light: Reflected

See Wolf Holzmann's talk

An old Zen joke....

To see **the** same-jet **pairs, all** we have to **do** is subtract **away** the background, ie **all** the other **kinds of pairs.** It sounds so **simple!.** What **can we expect?**

1. Background pairs distribution should have quadrupole *shape*

If $\frac{dn^A}{d\phi^A} \propto \left[1+2\langle v_2^A\rangle \cos\left(2\left(\phi^A - \Phi^{\mathrm{RP}}\right)\right)\right]$ and $\frac{dn^B}{d\phi^B} \propto \left[1+2\langle v_2^B\rangle \cos\left(2\left(\phi^B - \Phi^{\mathrm{RP}}\right)\right)\right]$

then $\frac{dn^{AB}}{d(\Delta\phi)} \propto \left[1+2\langle v_2^A v_2^B\rangle \cos(2\Delta\phi)\right]$

Questions : **Is** $\langle v_2^A v_2^B\rangle = \langle v_2^A\rangle\langle v_2^B\rangle$?

Do we know $\langle v_2^A\rangle$ and $\langle v_2^B\rangle$?

2. Background pair *rate* follows from combinatorics

Pairs per event $n^{AB} \equiv \langle n_A n_B\rangle = n_A n_B(1+\xi)$

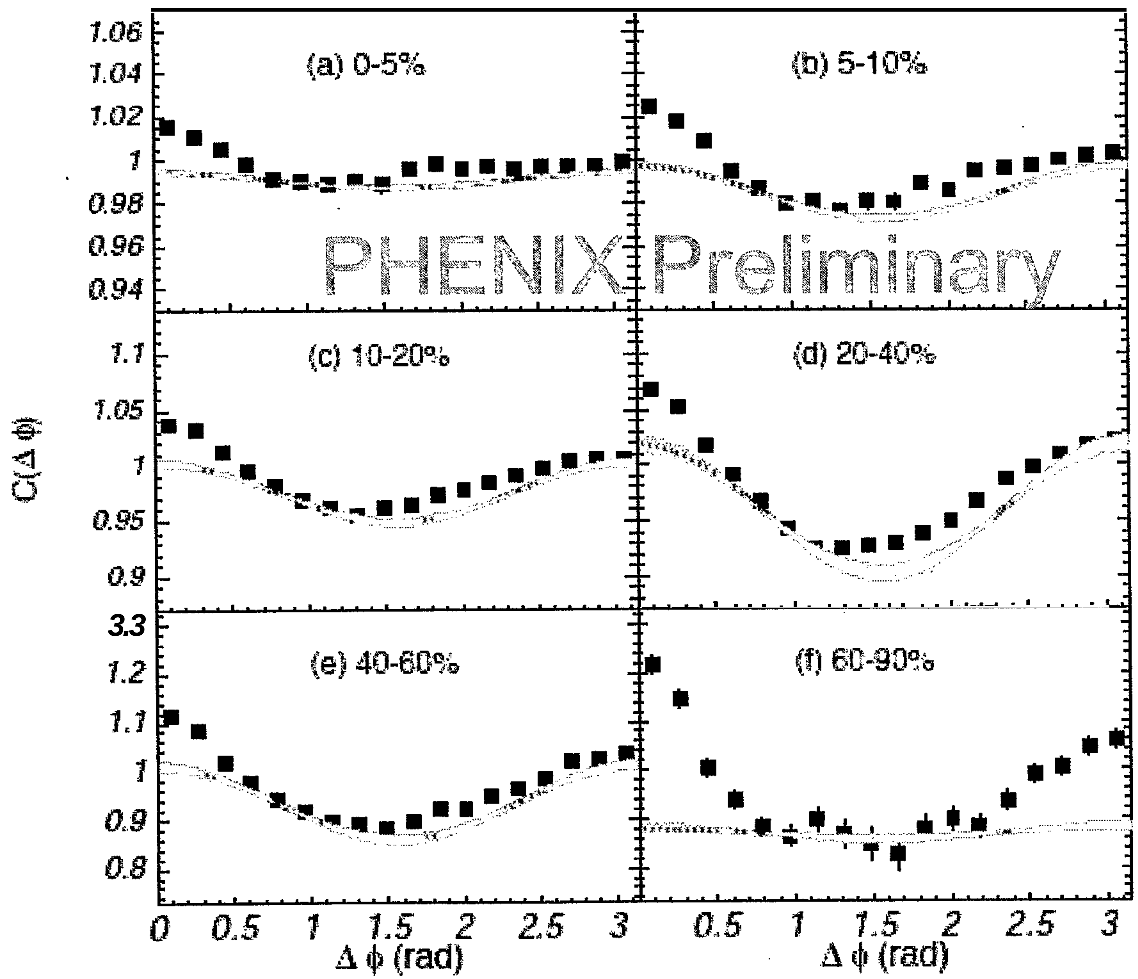
Correction for residual multiplicity correlations

Question : How well can we estimate ξ?

The self-finding minima

In this PHENIX charged particle pairs analysis we raise the background level until the background meets the data at one point; the remaining jet pairs distribution then have zero yield at minimum. We thus make *no assumption* about the shape of the jet pairs.

(For full explanation, see W. Holzmann's talk tomorrow morning.)



Trigger p_T>2.5 GeV; Partner p_T>1.0 GeV

Points to take home

1. The pairs distribution, the associated yield distribution, and the azimuthal correlation function contain essentially identical information.

2. Isolating jet pairs is equivalent to identifying non-jet pairs and subtracting them away (duh). Three methods used in PHENIX have different advantages and drawbacks:

   1. **Fitting.** Can give complete description of near- and away-side peaks, even if they overlap. Requires assumption about peak shape, can confuse wide peaks with backgrounds.

   2. **Absolute background normalization.** Requires no assumptions about peak shapes or background shapes, and can be used even when full $\Delta\phi$ acceptance is not available. Requires residual centrality correlation correction.

   3. **Anchored-floating, PHENIX example is ZYAM approach.** Requires no assumption of peak shapes or background rates. Requires v_2 measurements, and provides only lower limit on jet pairs.

Distributions of Charged Hadrons Associated with High pt Particles

Fuqiang Wang
Purdue University

for the Collaboration

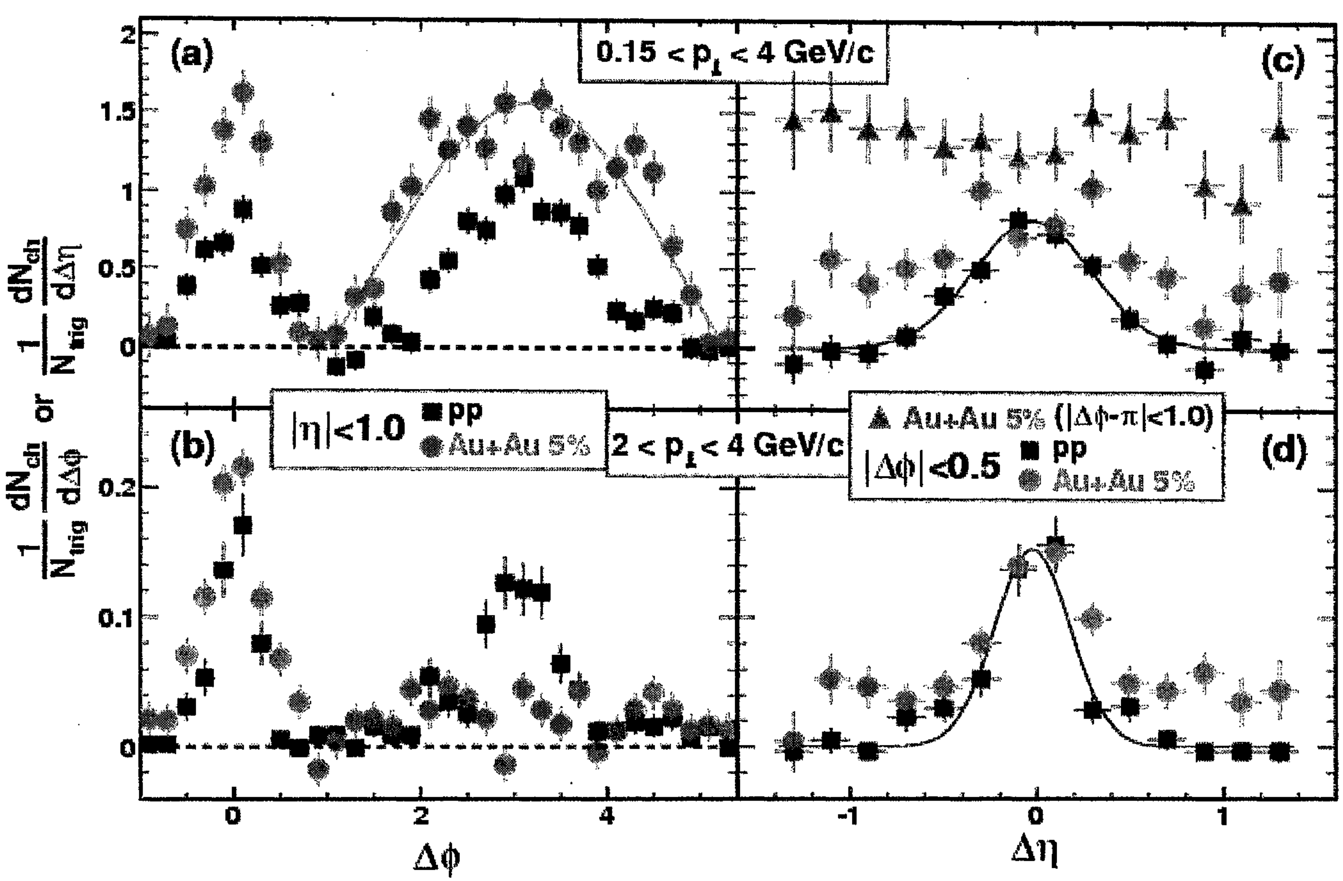
– OUTLINE –

motivation
results
summary

PURDUE
UNIVERSITY

Correlation functions

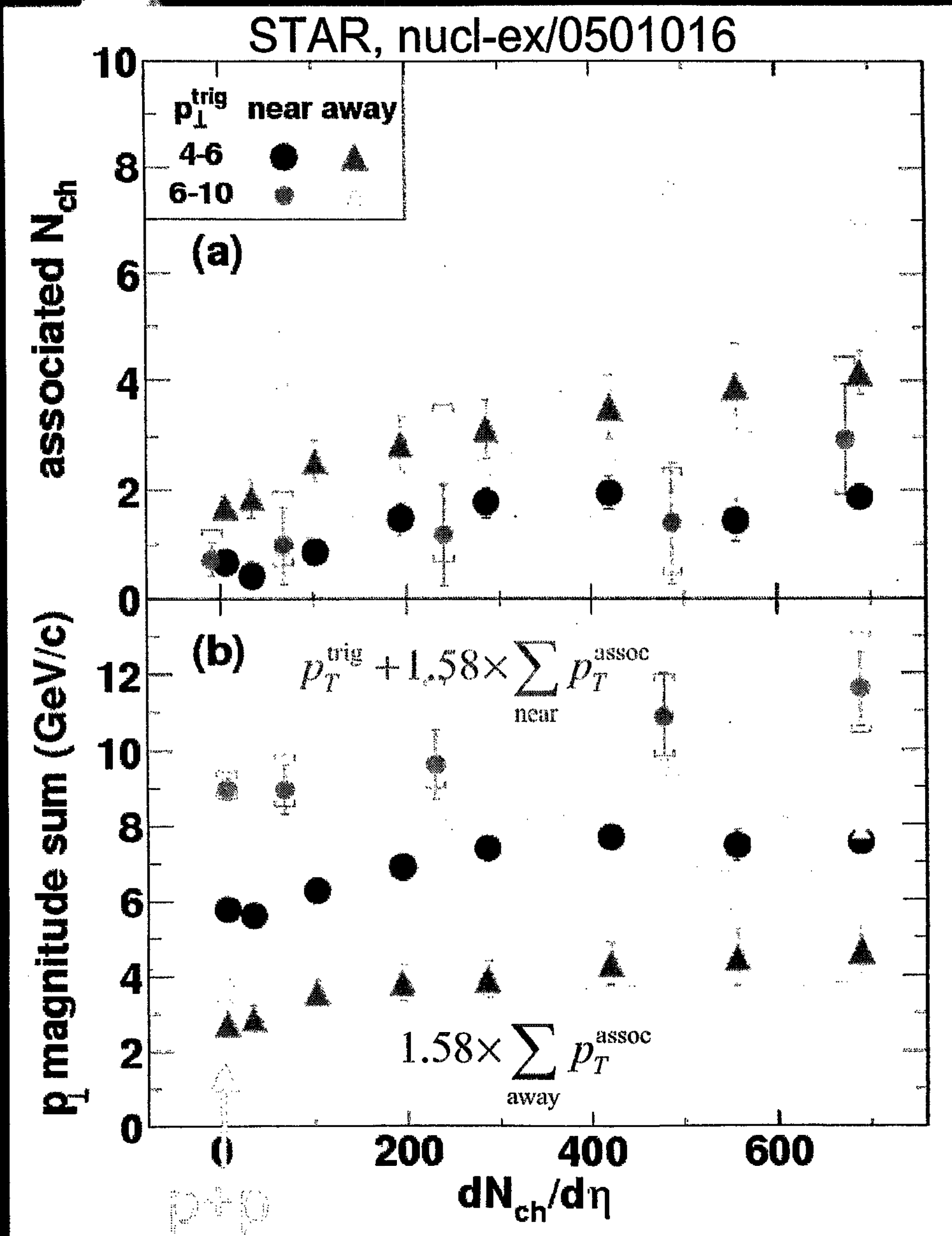
STAR, nucl-ex/0501016



Enhanced and broadened distribution at low p_T.

Away side suppression at high p_T.

Associated multiplicity and "energy"



Two p_T^{trig} windows: $4 \sim 6,\ 6 \sim 10$ GeV/c

$\langle p_T^{trig} \rangle = 4.5,\ 7.0$ GeV/c

Associated $p_T = 0.15 \sim 4$ GeV/c

The same final trigger particle selects a larger energy jet in central AA than in pp.

For the same final leading particle

($4 < p_T^{trig} < 6$ GeV/c):

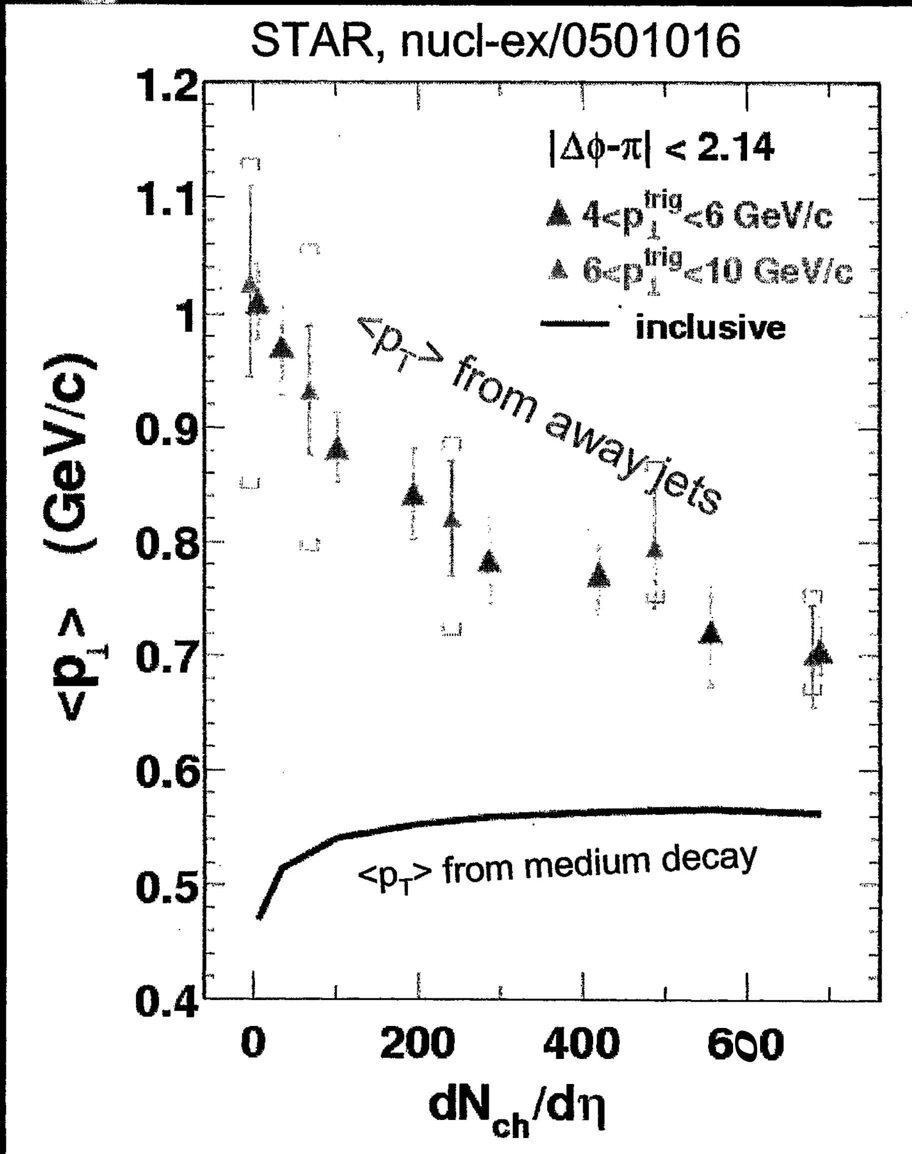
near side "jet" energy difference:

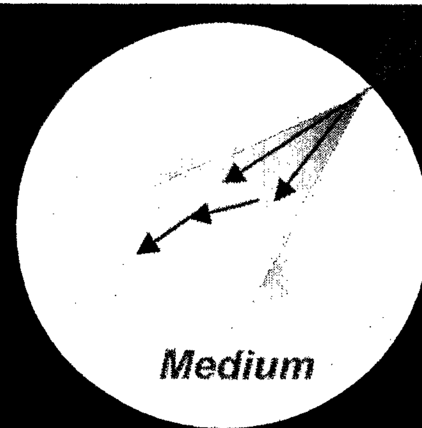
$E_{AA} - E_{pp} \approx 1.4 \pm 0.2 \pm 0.2$ GeV

away diff. in TPC $\approx 2.2 \pm 0.2 \pm 0.3$ GeV

Is this the amount of energy loss?

Away side $\langle p_T \rangle$





Two sources of particles:
hard: jet fragmentation products.
soft: bulk medium decay products.

Peripheral: $\langle p_T \rangle$ very different
Central: $\langle p_T \rangle$ not much different

Gradual decrease with centrality.
Similar for two trigger p_T windows.

Whatever interaction mechanisms, away-side jet products approach equilibration with the bulk medium traversed → thermalization of the bulk itself quite plausible.

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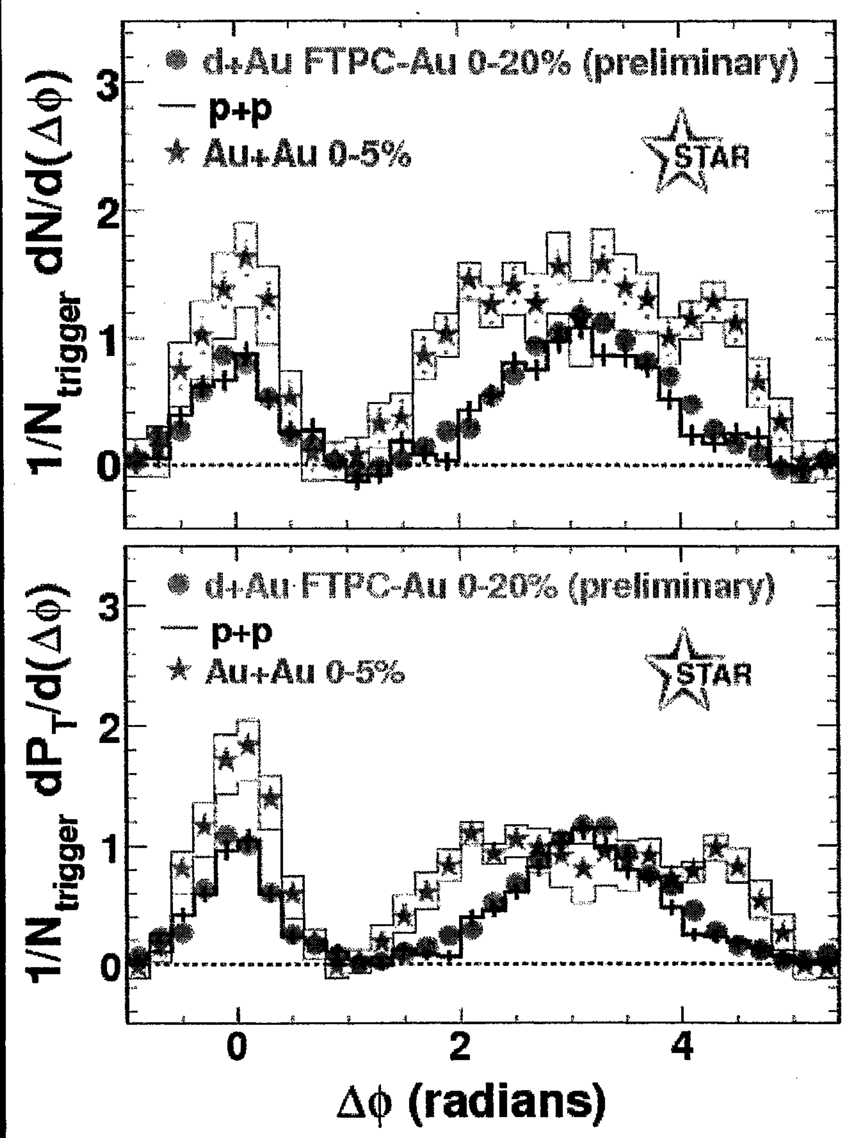
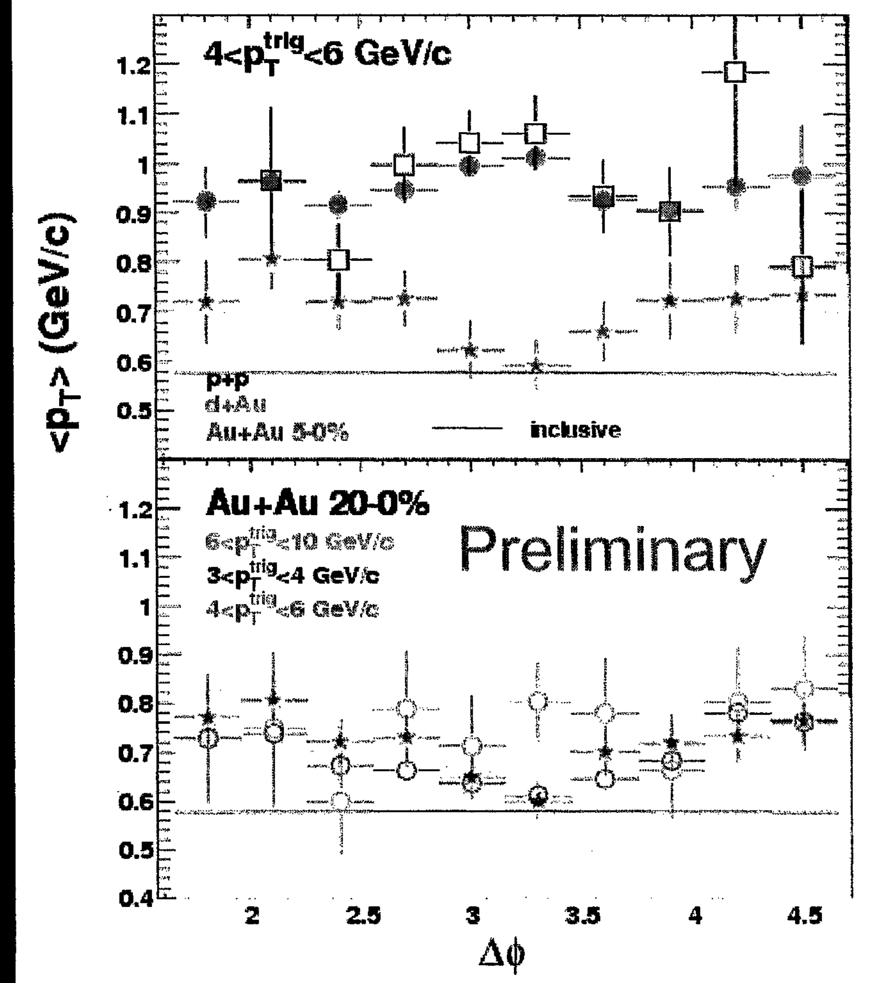
Novel behavior of away $<p_T>$





$<p_T>$ more robust than correlation functions.
Novel dip structure observed in central AA.
Energy loss effect? Mach shock wave?

Summary and open questions

- Statistical reconstruction of jets in pp, dA and AA. Connection between high p_T and low p_T physics.
- Same trigger p_T selects larger energy jets in AA than in pp.
  Near side associated multiplicity is enhanced.
- Away side correlation disappears at high p_T, and reappears at low p_T.
  Correlations functions broadened.
  Interplay between energy loss and Mach shock wave?
- Significant softening of spectra from pp to central AA. Partial thermalization between jets and bulk medium. Imply high degree of thermalization in medium itself.

To create and study QGP – a state of

deconfined ?

thermalized ✓?

quarks and gluons predicted by QCD at

high enerdy density ✓

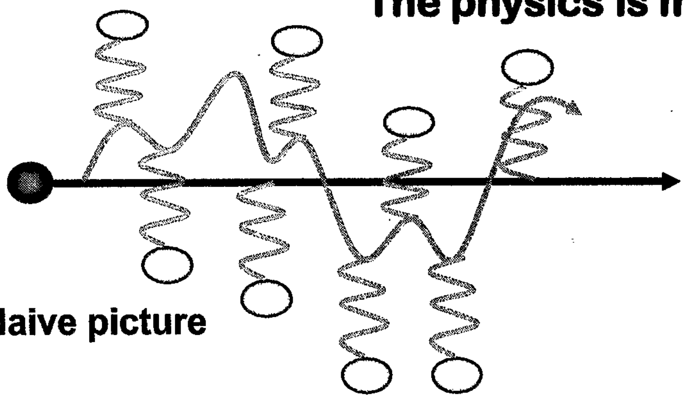
Large Angle Hadron Correlations from Medium-Induced Gluon Radiation

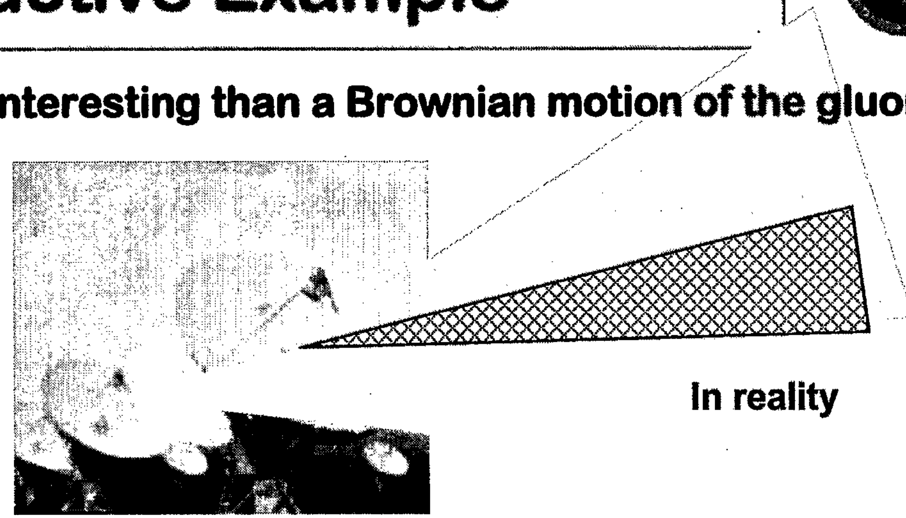
Ivan Vitev

Jet Correlations at RHIC, March 10-11, 2005
Brookhaven National Laboratory, Upton, NY

Instructive Example

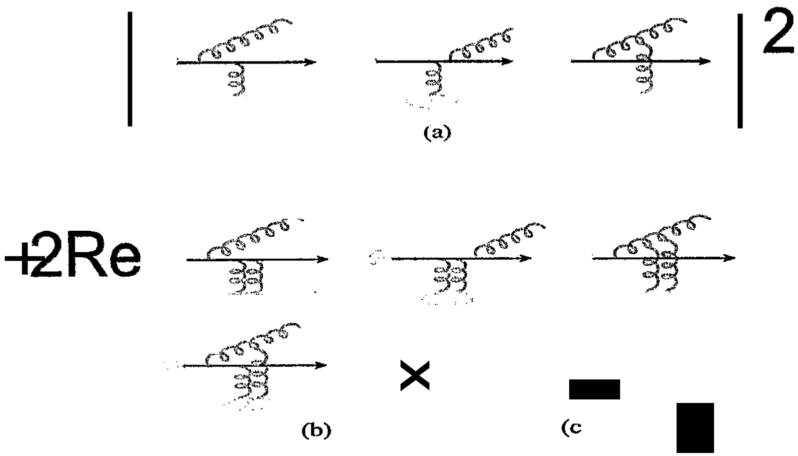
The physics is more interesting than a Brownian motion of the gluon





$$i(-i)=1 \qquad i\,(i)=-1=\cos(\pi)$$

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^{*}d\delta}\propto\left(\left|M_a\right|^2+2\,\mathrm{Re}\,M_b^{*}M_c\right)+\ldots$$



Solution to first order in the mean # of scatterings

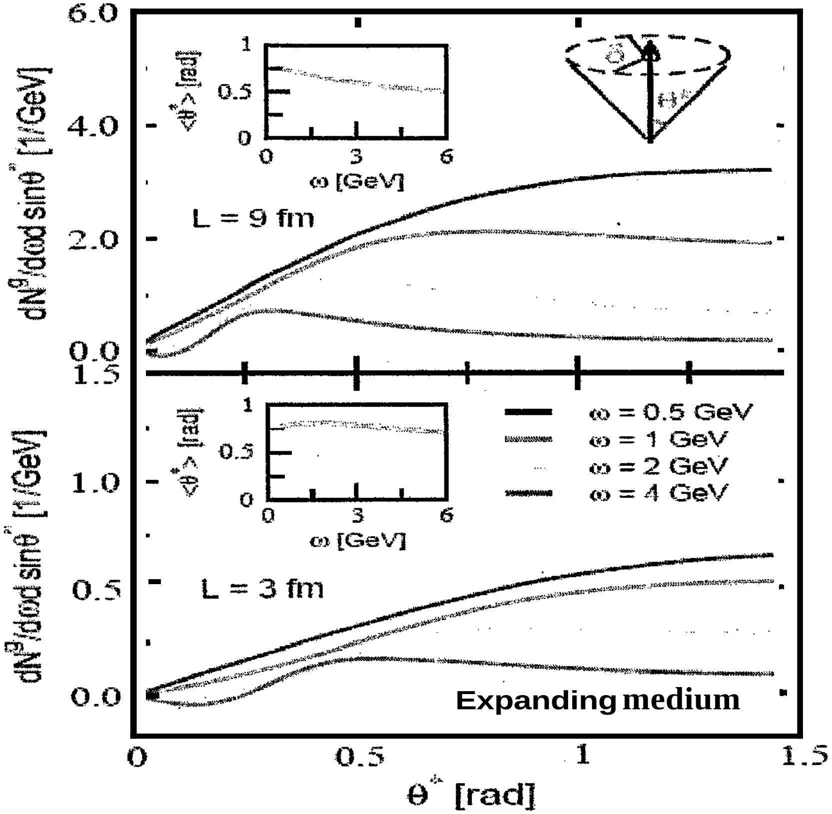
$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^{*}d\delta}\approx\frac{2C_R\alpha_s}{\pi^2}\int_{z_0}^{L}\frac{d\Delta z}{\lambda_g(z)}\int_0^{\infty}dq_\perp q_\perp{}^2\,\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp}$$

$$\times\int_0^{2\pi}d\alpha\,\frac{\cos\alpha}{(\omega^2\sin^2\theta^{*}-2q_\perp\omega\sin\theta^{*}\cos\alpha+q_\perp^2)}$$

$$\times\left[1-\cos\frac{(\omega^2\sin^2\theta^{*}-2q_\perp\omega\sin\theta^{*}\cos\alpha+q_\perp^2)\Delta z}{2\omega}\right]$$

I.V., hep-ph/0501255

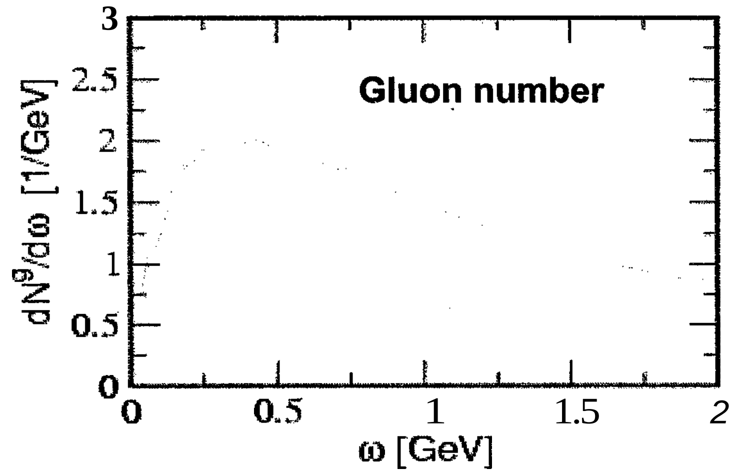
Angular and Frequency Behavior



I.V., **hep-ph/0501255**

- **Radiation is moderately large angle (cancellation near the jet axis)**
- **Finite gluon number**

$$l_f = \frac{2m}{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos a + q_\perp^2)} \sim \Delta z \sim L/2$$



- The **small** angle $\theta^* \to 0$ and **small** frequency $\omega \to 0$ behavior of the radiative spectrum is under perturbative control

Numerical Results

Define a measure for nuclear modifications to di-hadron correlations:

$$R_{AA}^{(2)} = \frac{d\sigma_{AA}^{h_1h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}{\langle N_{bin} \rangle d\sigma_{pp}^{h_1h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}$$

P_{T1} trigger:

- Fix the energy
- Ensure high Q^2,
- Minimize the effect on the near side
- Maximize the effect on the away side

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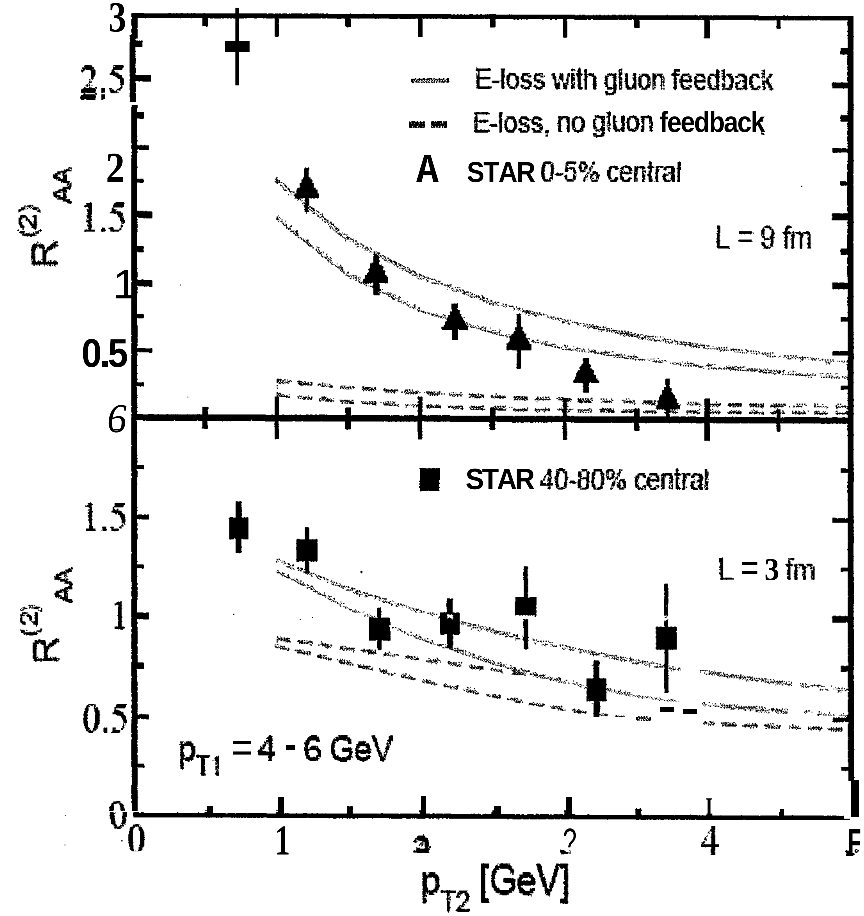
- The redistribution of the energy is a parameter free prediction
- For large energy loss - the radiative gluons dominate to unexpectedly high $p_{T2} \sim 10\ GeV$

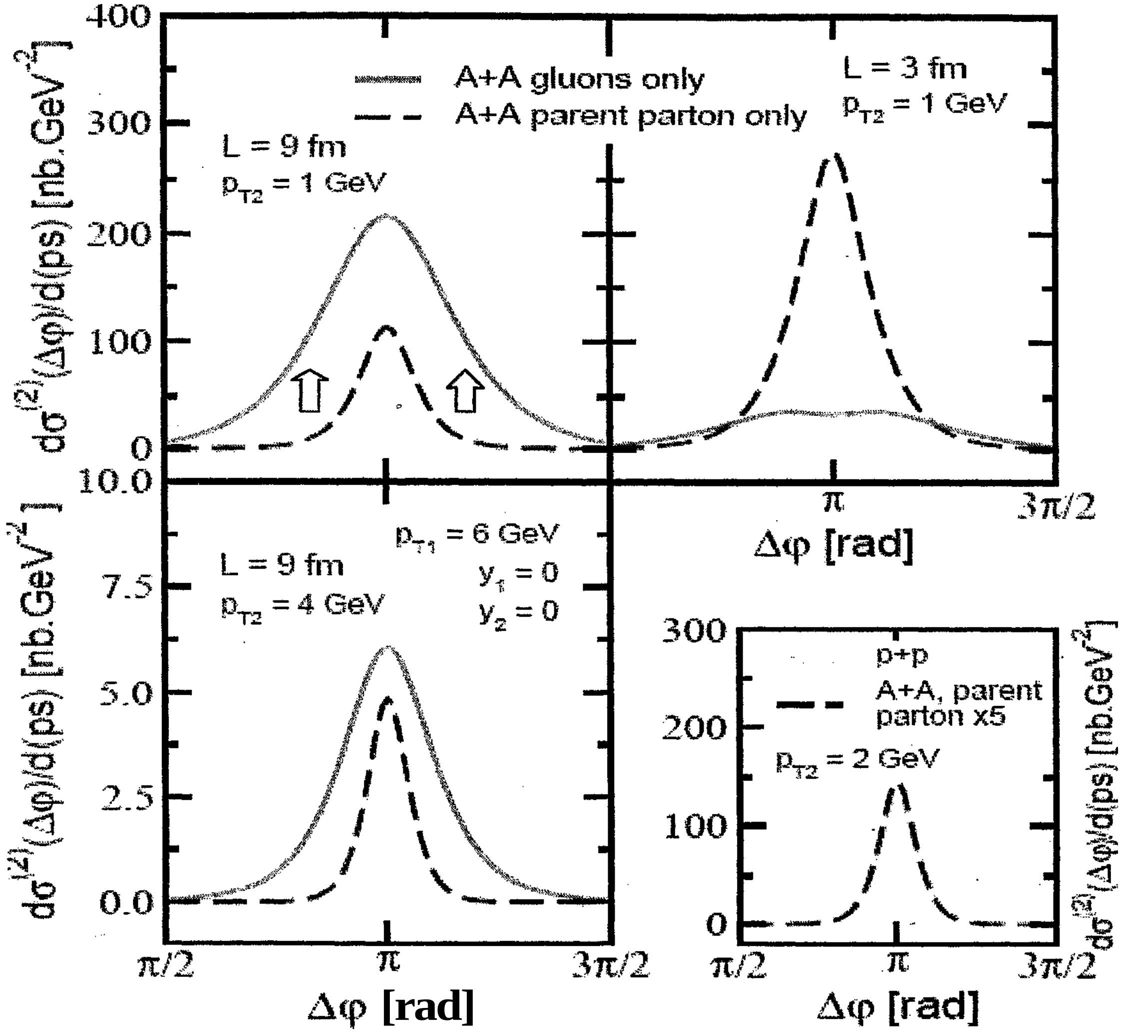


I.V., hep-ph/0501255

Data is from

J.Adams *et al.*, nucl-ex/0501016

Angular Di-Hadron Distribution



I.V., **hep-ph/0501255**

$$\sigma_{Far}(AA) > \sigma_{Far}(pp)$$

- **The width $|\Delta\varphi - \pi|$ of the large-angle correlations is dominated by medium induced gluon radiation**

- **Reassessment of the origin of small and moderate p_T away triggered hadrons**

Because:

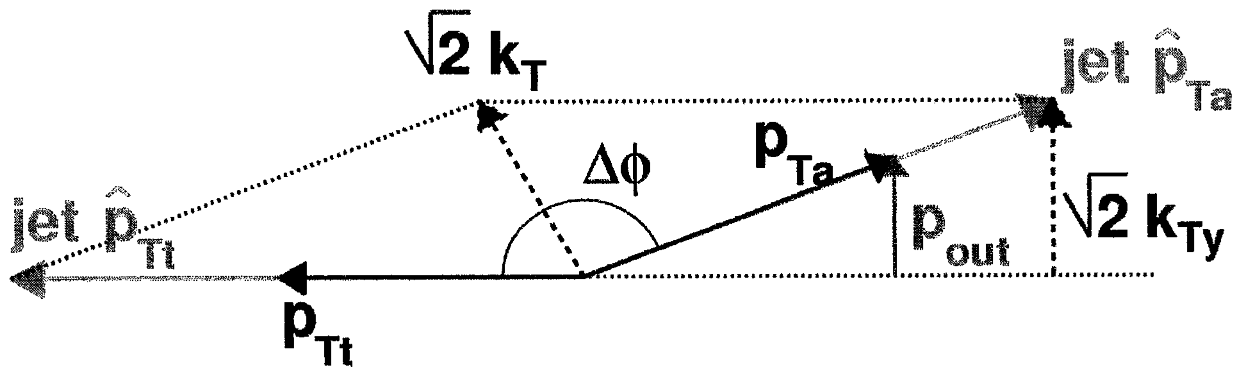
$$\sigma_{Far} \approx \frac{\sqrt{\langle k_T^2 \rangle_{vac}}}{p_{Tc}} \rightarrow \frac{\sqrt{\langle k_T^2 \rangle_{tot}}}{[p_{Tc}/(1-\varepsilon)]}$$

j_T, k_T and Fragmentation Functions in P+P

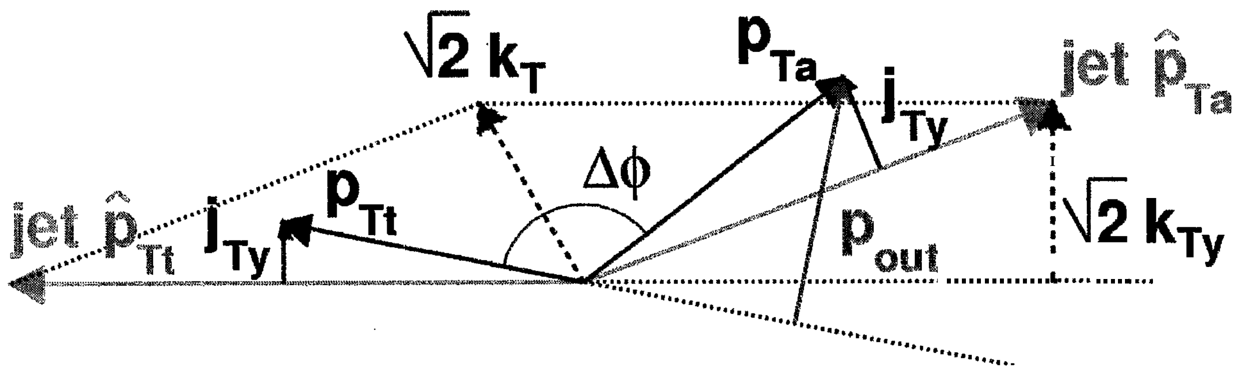
Jan Rak, UNM
March 10,2005

for
Jet Correlations at RHIC Workshop
RIKEN BNL Research Center

Jet kinematics



$$\langle p^2_{out}\rangle = \langle p^2_{Ta}\ \sin^2\Delta\varphi\rangle \approx \boxed{2\langle k^2_{Ty}\rangle\,\langle z^2_{a}\rangle} \approx 2\langle k^2_{Ty}\rangle\langle z^2_{t}\rangle x^2_{h} \qquad x_h = p_{Ta}/p_{Tt}$$



$$\langle | p_{out} |\rangle^2 \cong x_h^2[2\langle | k_{Ty} |\rangle^2 \langle z_t\rangle^2 + \langle | j_{Ty} |\rangle^2] + \langle | j_{Ty} |\rangle^2$$

Feynman, Field, Fox and Tannenbaum (see *Phys.* **Lett.** *97B (1980)* ***163)***

$$\langle | p_{out} |\rangle^2 = x_E^2[2\langle | k_{Ty} |\rangle^2 + \langle | j_{Ty} |\rangle^2] + \langle | j_{Ty} |\rangle^2$$

x_E = two particle equivalent of the fragmentation variable *z*.

$$x_E = -\frac{\vec{p}_T \cdot \vec{p}_{Ttrigg}}{|\vec{p}_{Ttrigg}|^2}$$

j_T with associated and trigger p_T

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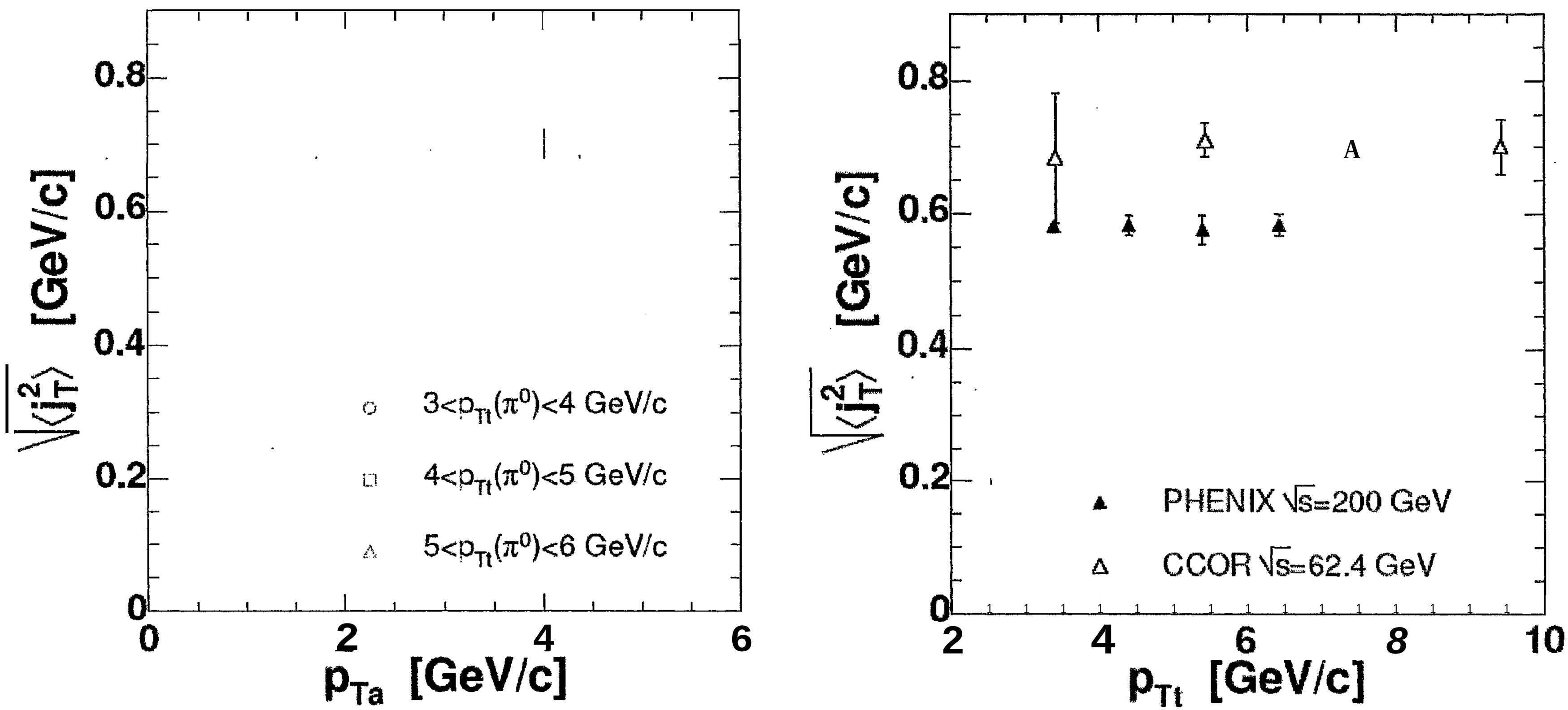
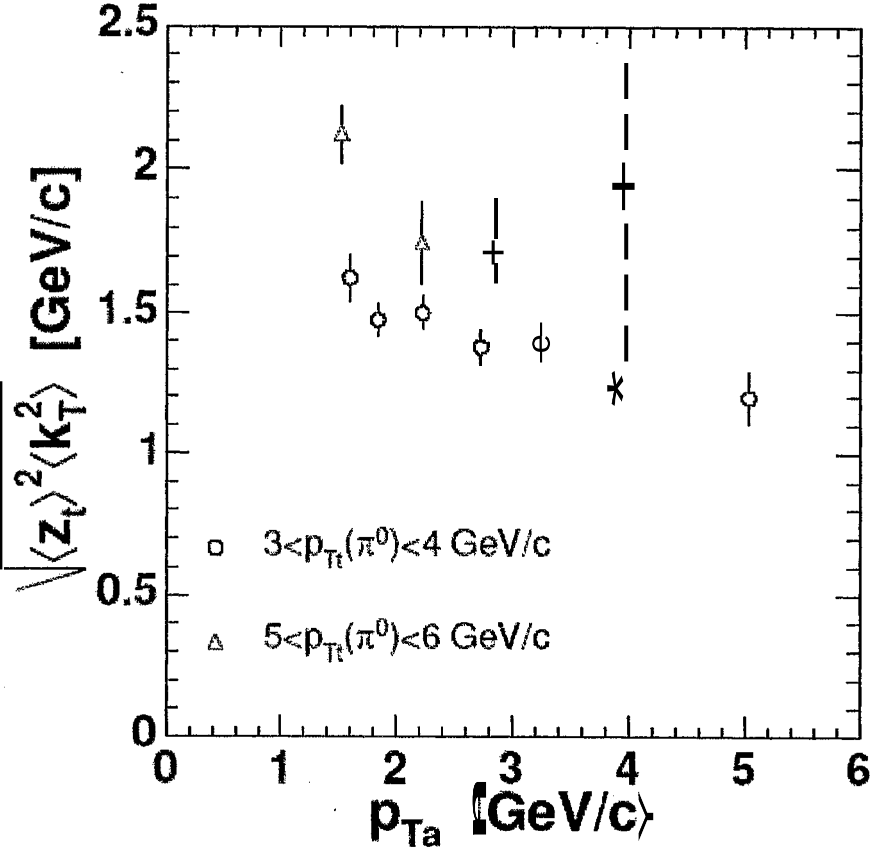
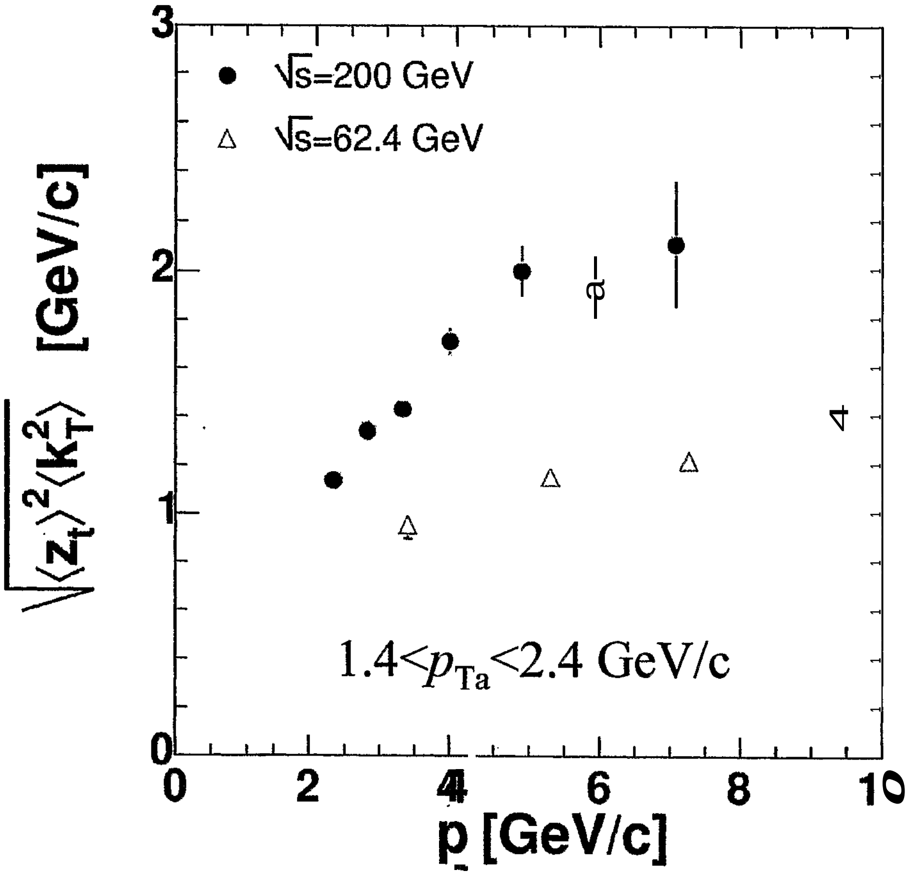


However, the $\langle j^2_{Ty}\rangle$ analysis done at $\sqrt{s}$=62 GeV explicitly neglected $\langle z_t\rangle$. This may explain the slightly larger value seen by CCOR collaboration.

$z_t k_T$ "puzzle"





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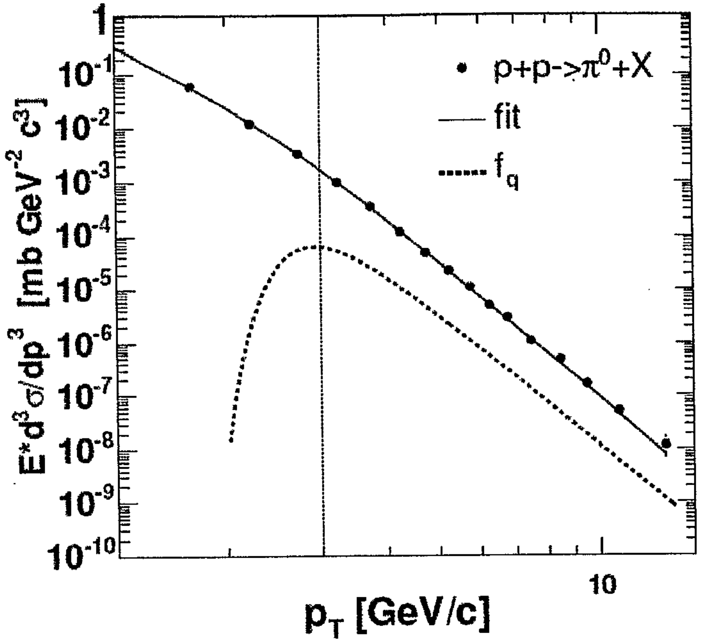
Assumption: *For fixed* p_{Tt} *the parton momentum (jet energy) is fixed,* p_{Ta} *samples the different region of fragmentation at fix* Q^2 $\Rightarrow \langle z_t \rangle \langle k_T \rangle$ *should be constant*

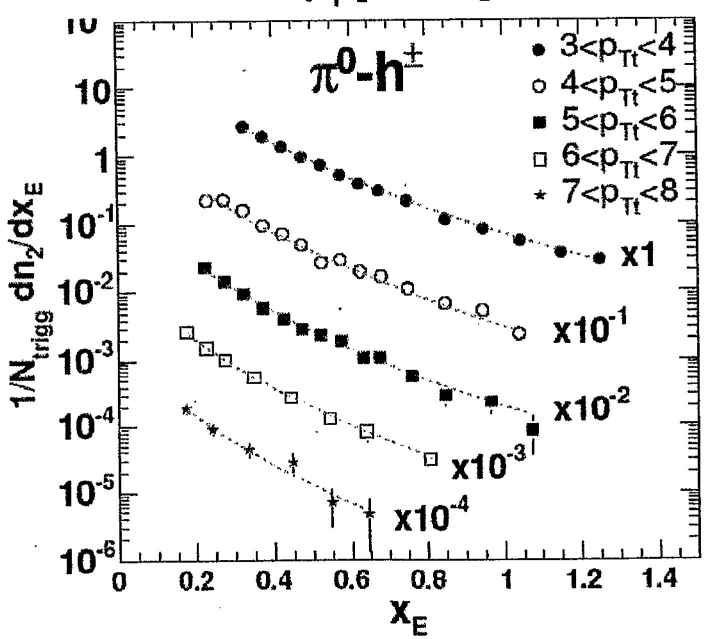
THIS IS CLEARLY WRONG

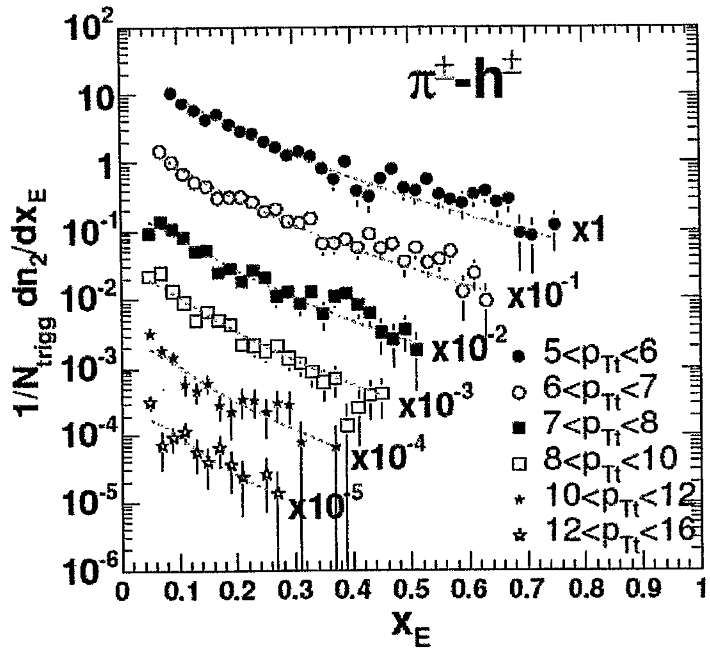
Global fit to the inclusive and associated distribs.



$$f_q(\hat{p}_T) \propto \frac{1}{(M_0^2 + \hat{p}_T^2)^{n/2}}$$

$$D(z) \propto z^{-\alpha}(1-z)^{\beta}(1+x)^{\gamma}$$





Fragmentation function and $\langle z \rangle$

These are preliminary results from QM04 – final are under collaboration review.

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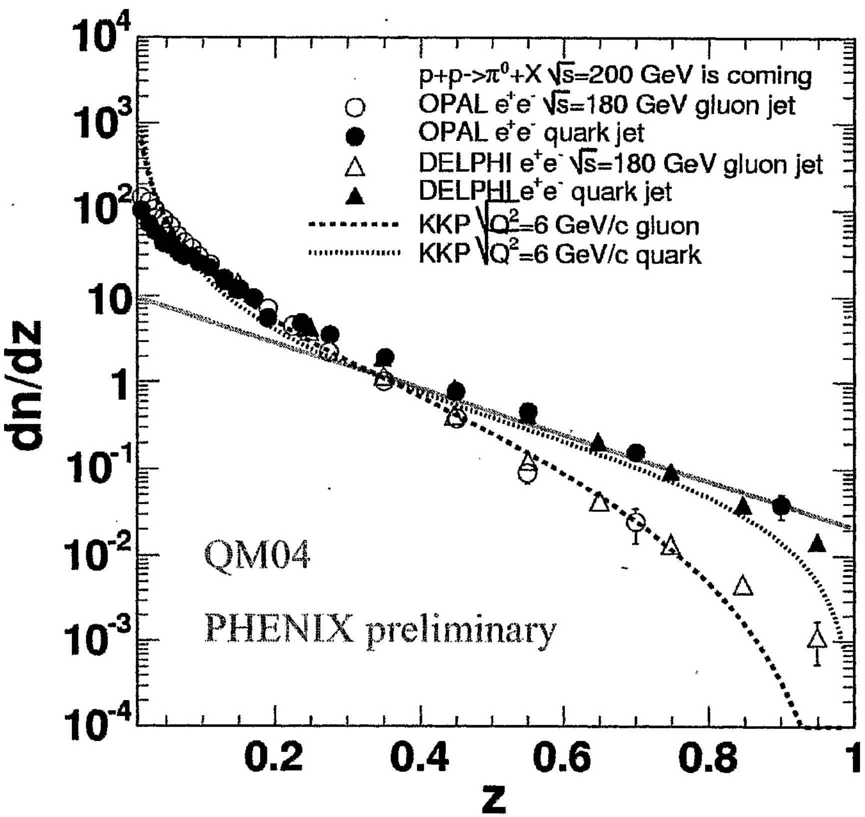

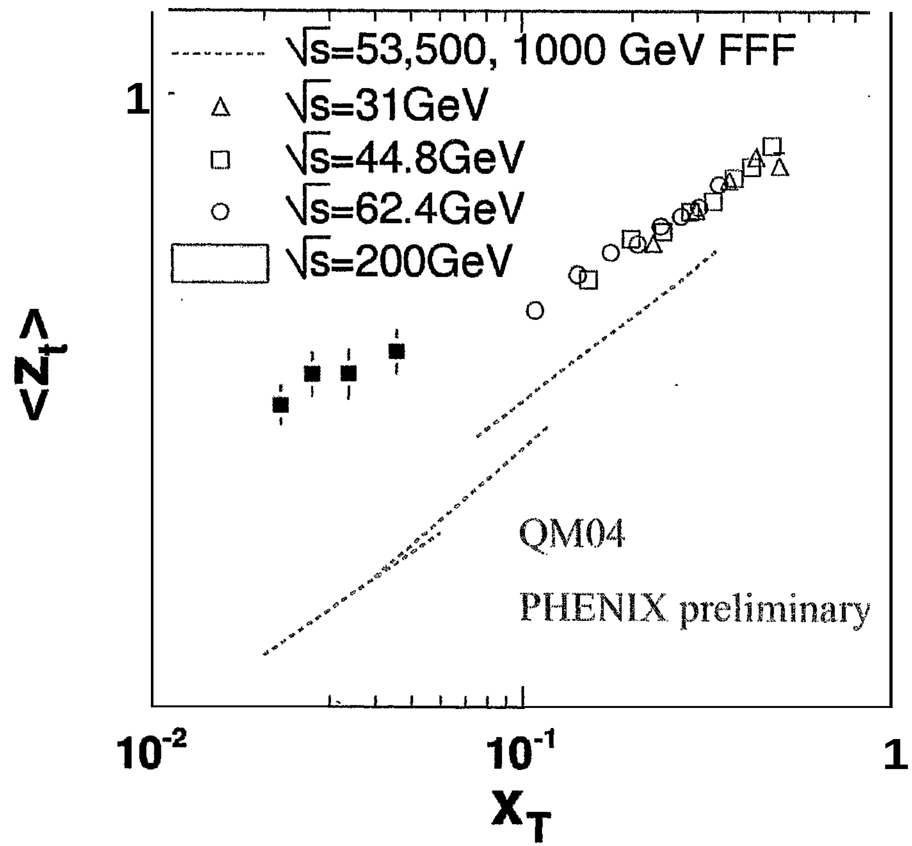

The QM analysis did not account for "conditioanl fragmentation. The $D(z) \propto \exp(-z/\langle z \rangle)$ assumption is also not well justified.

High-p, azimuthal correlations in d+Au collisions at RHIC

Jana Bielcikova (Yale University),
for the STAR Collaboration

BNL, **March** 10-11,2005

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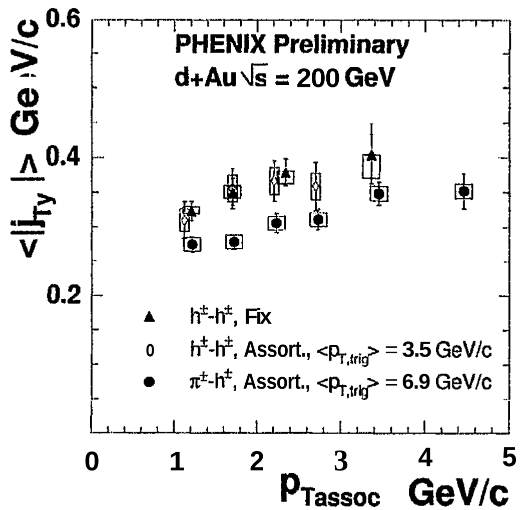
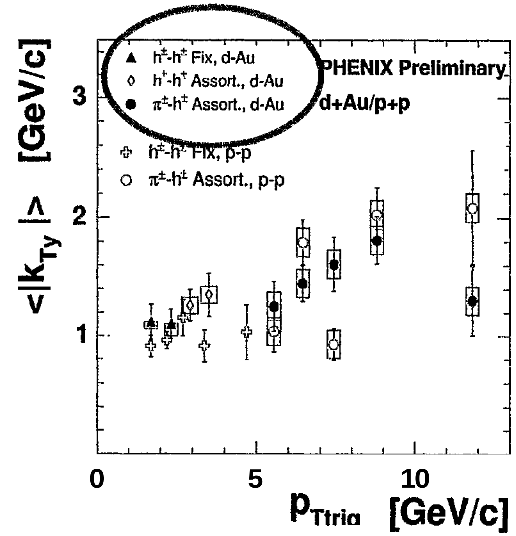
Outline:

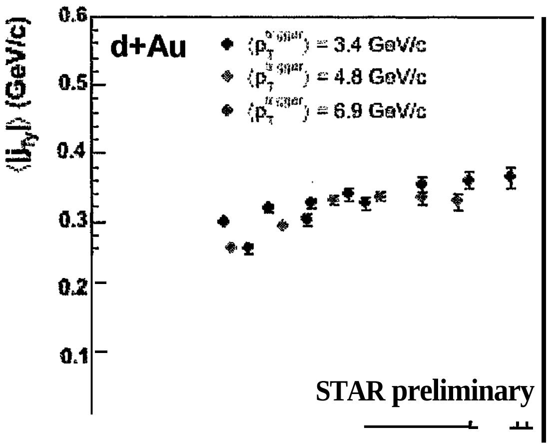
- **Physics motivation: [redacted] vs [redacted] collisions**
- **Charged-charged correlations**
- **Identified correlations: photon-charged,**
  A, $\bar{\Lambda}$, K^0_s-charged
- **Summary**

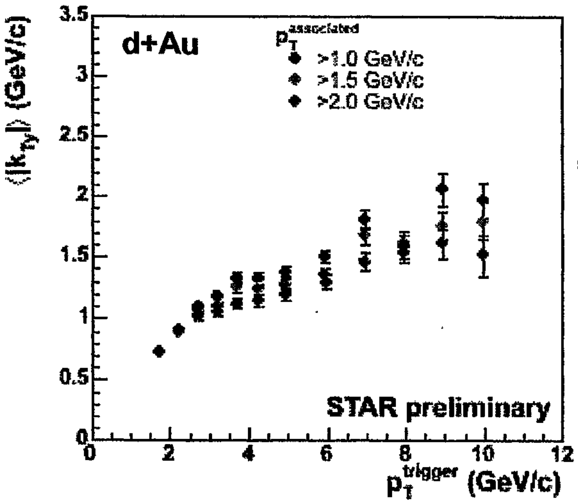
<|j_{Ty}|>, <|k_{Ty}|>: STAR/PHENIX comparison





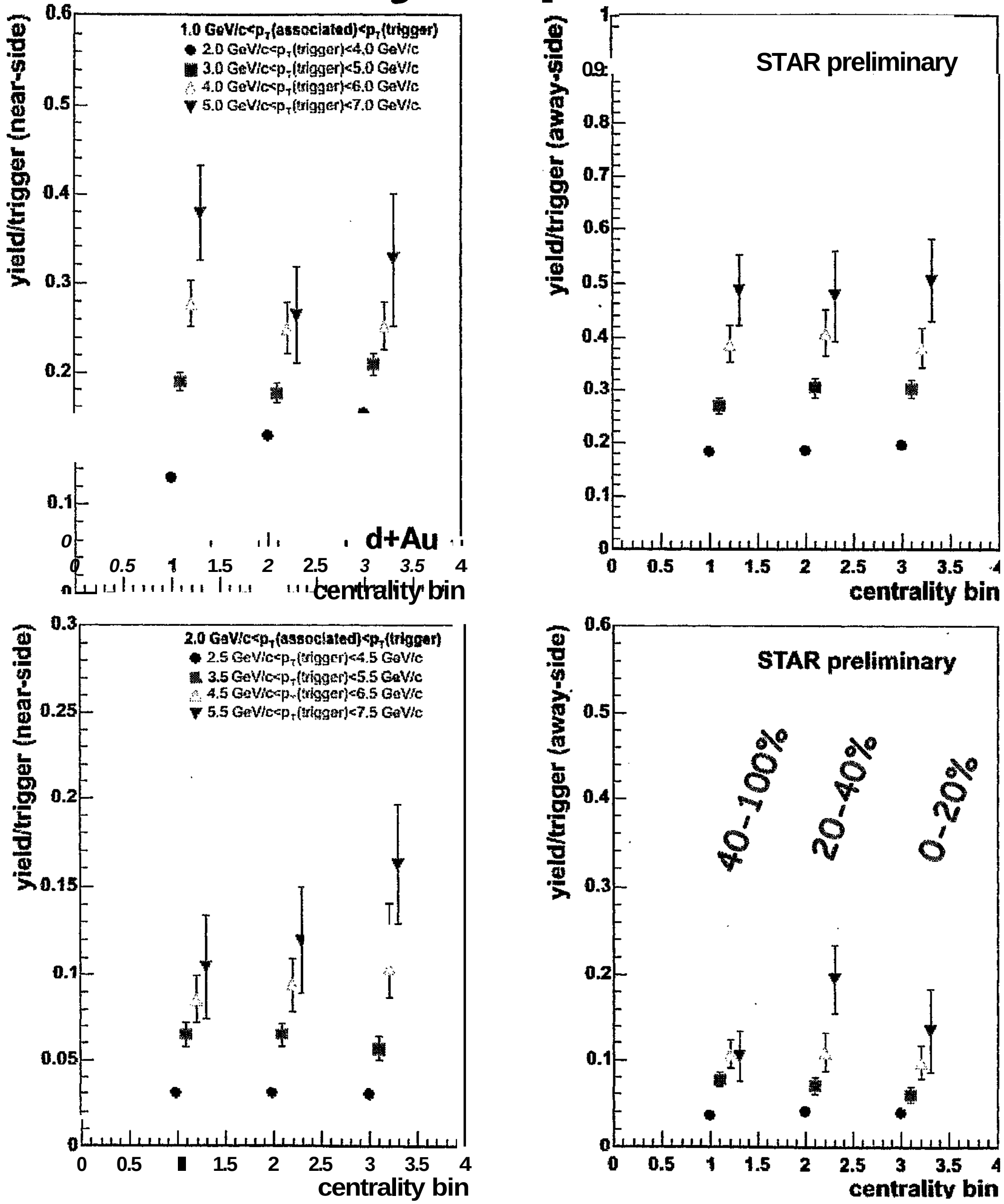
PHENIX: J. Rak (QM'04)
J.Phys.G30 (2004) S1309





- **Very** good **agreement between** STAR/PHENIX ☺

Centrality dependence of conditional yield



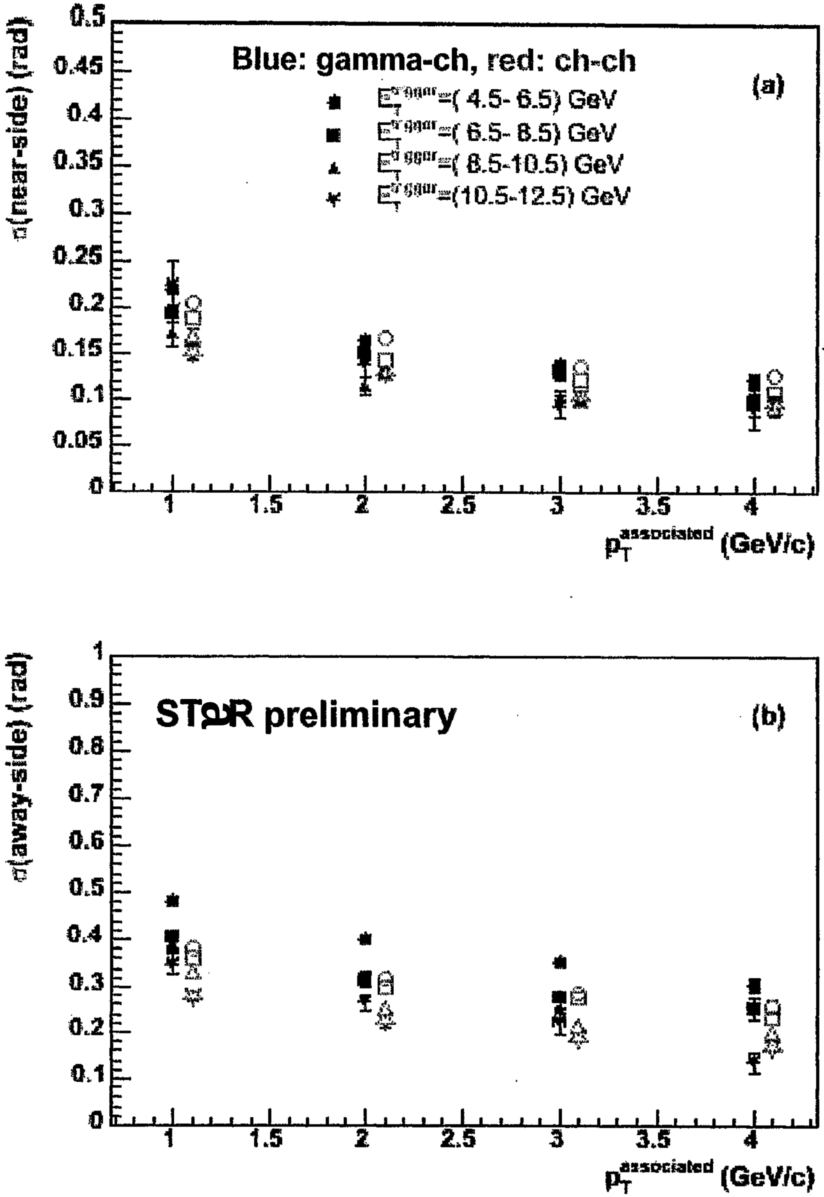
ch-ch correlations

- **Within errors there is no apparent dependence of the conditional yield on centrality in d+Au**

$$\frac{\text{yield}(0-20\%)}{\text{yield}(40-100\%)} \approx 1$$

- What does recombination model predict ?

p_T (E_T) dependence of Gaussian width



- no significant difference between ch-ch and γ-ch correlations

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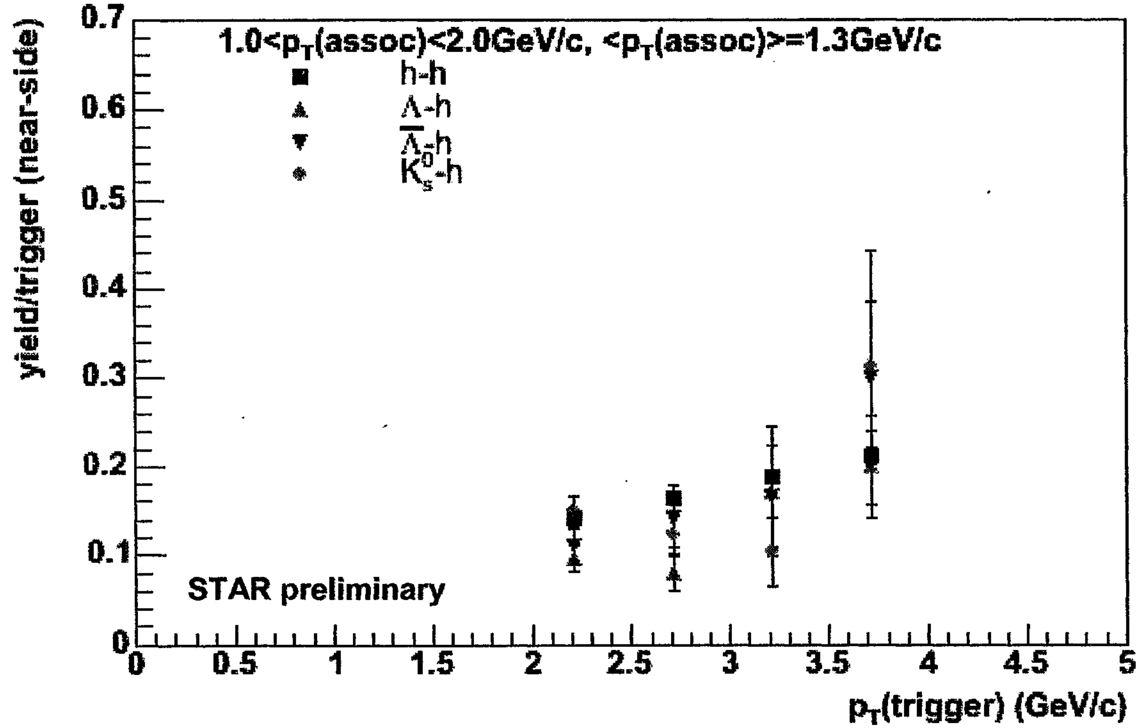
p_T(trigger) dependence in d+Au: is there a difference between $\Lambda/\bar{\Lambda}$?



Within statistical errors the yield/trigger does not depend on type of studied strange trigger particle

-> see Ying Guo's (STAR) talk on Friday on 'Strange particle correlations in Au+Au'

Summary

We have discussed properties of Gaussian width + yield
of near-side and away-side correlation peaks
in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

(vs $p_T^{associated}$, $p_T^{trigger}$, centrality, trigger particle species)

Findings:

4 • no apparent centrality dependence of ch-ch correlations
(contradicts expectations from parton recombination model)
- $\langle j_T \rangle \approx 500$ MeV/c for $p_T > 2.0$ GeV/c
- $\sqrt{\langle k_T^2 \rangle}$ rises from 1.5 to 3.0 GeV/c for p_T=2-10 GeV/c
- no difference between trigger particles (ch, γ, Λ, $\bar{\Lambda}$, K^0_s)
(Gaussian width, yield)

More results from STAR are coming soon. Stay tuned!

Thank you! ☺

Jet Structure From Di-hadron Correlations in d+Au Collisions

Nathan Grau
Iowa State University
For the PHENIX Collaboration

Correlation Functions in p+p and d+Au

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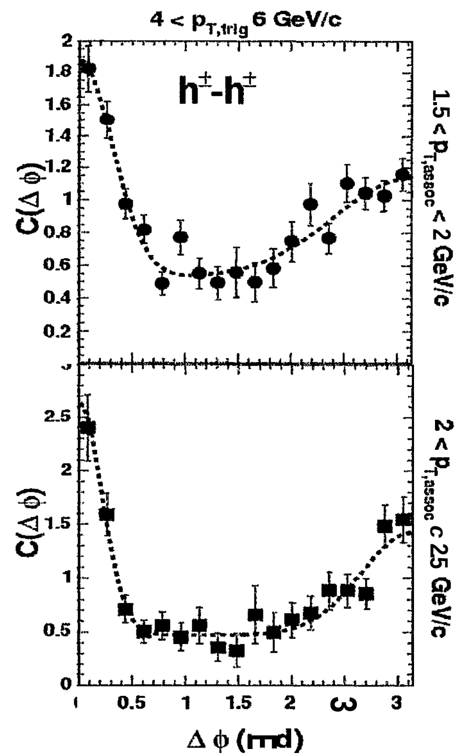
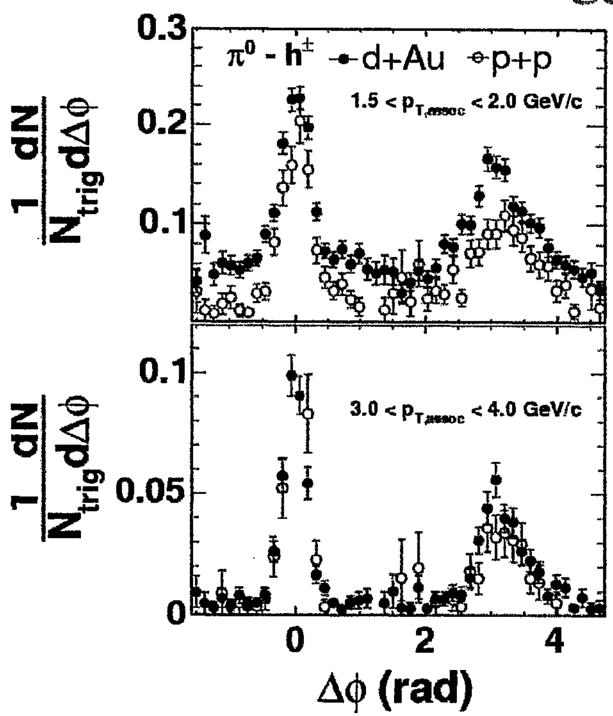
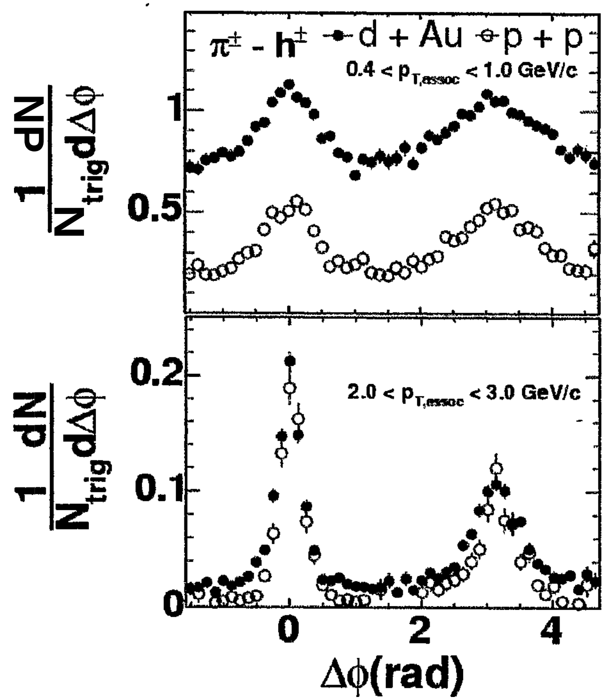


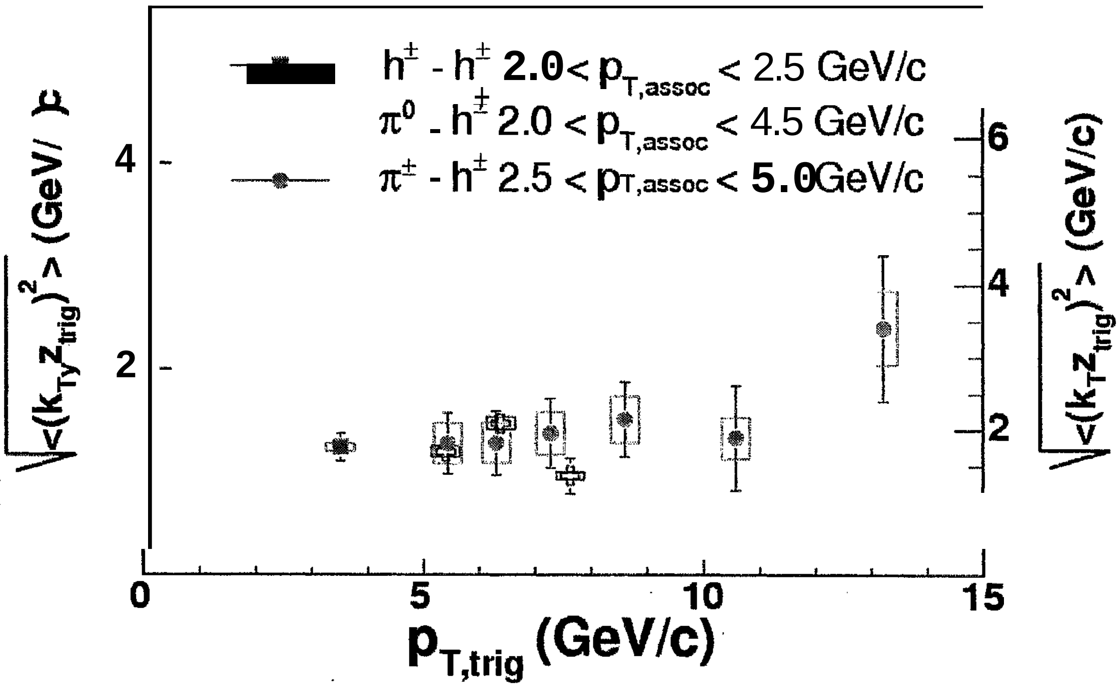
Pion trigger 5-10 GeV/c





$k_{Ty}z_{trig}$

- $k_{Ty}z_{trig}$ for different trigger p_T ranges and different trigger particles
- $k_{Ty}z_{trig}$ flat with $p_{T,trig}$



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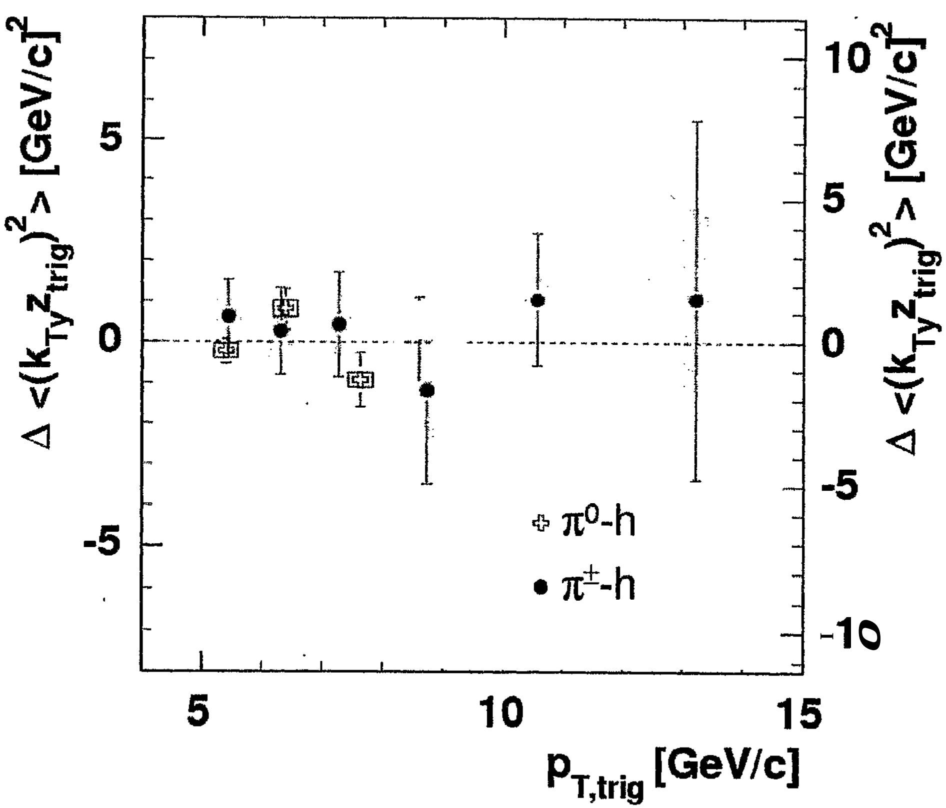
Comparison to p+p



$$\Delta\langle k_T^2\rangle = \langle k_T^2\rangle_{p+A} - \langle k_T^2\rangle_{p+p}$$

- Weighted averages of separate data

$$\pi^0 : \Delta\left\langle \left(k_T z_{trig}\right)^2 \right\rangle = -0.10 \pm 0.35 \pm 0.16\ (\mathrm{GeV/c})^2$$

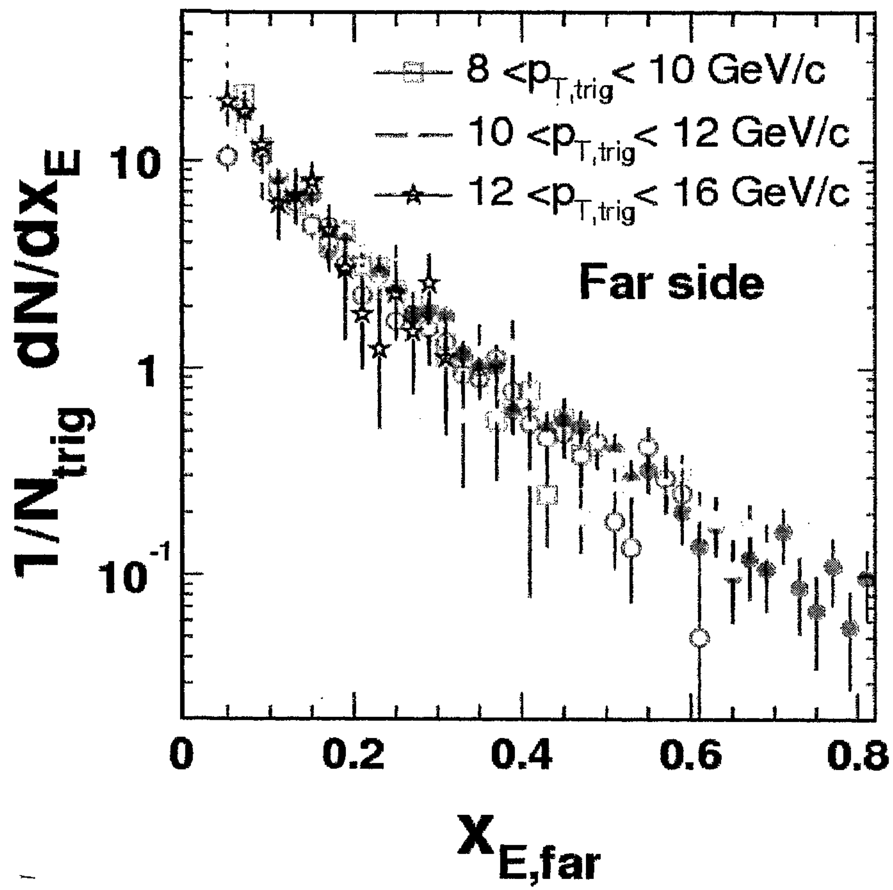
$$\pi^{\pm} : \Delta\left\langle \left(k_T z_{trig}\right)^2 \right\rangle = 0.64 \pm 0.78 \pm 0.42\ (\mathrm{GeV/c})^2$$

- Weighted average of combined data

$$\Delta\left\langle \left(k_T z_{trig}\right)^2 \right\rangle = 0.01 \pm 0.31 \pm 0.14\ (\mathrm{GeV/c})^2$$

dN/dx_E Results

- x_E distributions for trigger $\pi^{+/-}$ for several different trigger ranges
- Overlap of data indicative of fragmentation independent of parton momentum.



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Scaling of dN/dx_E

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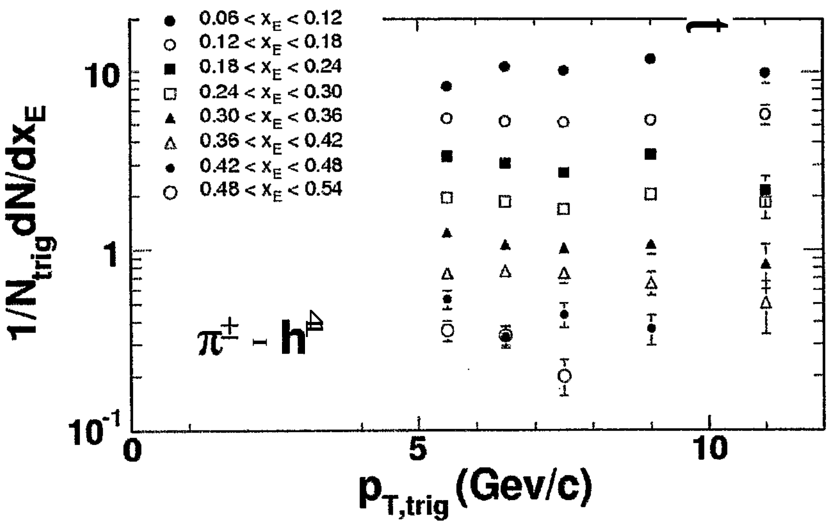
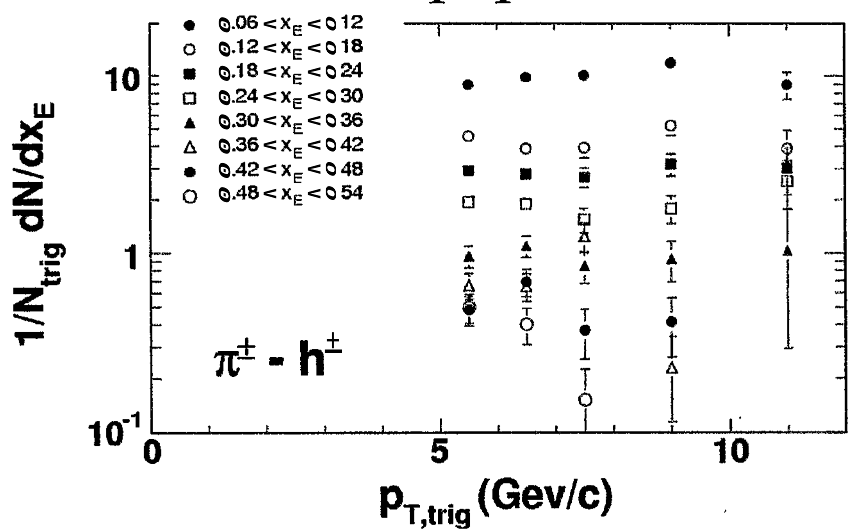
d+Au Min Bias



p+p



Scaling with p_{Ttrig} found at lower root-s at ISR

Scaling holds for p+p and d+Au at RHIC.

Jet studies in heavy ion collisions

Carlos A. Salgado

CERN Physics Department, Theory Division, CH-1211 Geneva

The main mechanism of energy- loss of a high-energetic particle traversing a dense medium is the induced gluon radiation. The double-differential (in k_t and ω) of these radiated gluons is known and has been successfully applied to describe the suppression observed in high-pt inclusive particle measurements in central nucleus-nucleus collisions. These inclusive measurements present, however, serious limitations for the characterization of the medium: the different trigger-bias effects translate into a small sensitivity of the suppression to the density of the medium. Several possibilities have been proposed in order to cure this deficiency. On the one hand, the effect on heavy quarks propagating in a medium is known to be smaller and the corresponding suppression is also smaller. On the other hand, the experimental observation of the associated medium-induced radiation would allow for a much better characterization of the medium. We have presented several medium-modified jet observables in this framework and identified some hot-spots where these effects could be large for large jet energies (100 GeV). The main problem for true jet studies in heavy ion collisions is the large multiplicity background. The modification of the jet properties profits, however, from the infrared and collinear finiteness of the medium-induced gluon radiation. This absence of infrared or collinear divergences is due to formation time effects and controlled by coherence factors.

The medium-modified gluon radiation is asymmetric in the case of a flowing medium. The *particle wind* that the emitted gluons feel induces a preferred direction for the emission. We have explored this effect for the case of RHIC where we expect a larger jet broadening in the longitudinal than in the &direction and a new contribution to the high-p_t elliptic flow.

Based on:

N. Armesto, **A.** Dainese, C. **A.** Salgado and U. **A.** Wiedemann, **hep-ph/0501225**

N. Armesto, C. **A.** Salgado and U. **A.** Wiedemann, **hep-ph/0411341**

N. Armesto, C. A. Salgado and U. **A.** Wiedemann, **Phys.** Rev. Lett. **93 (2004) 242301**

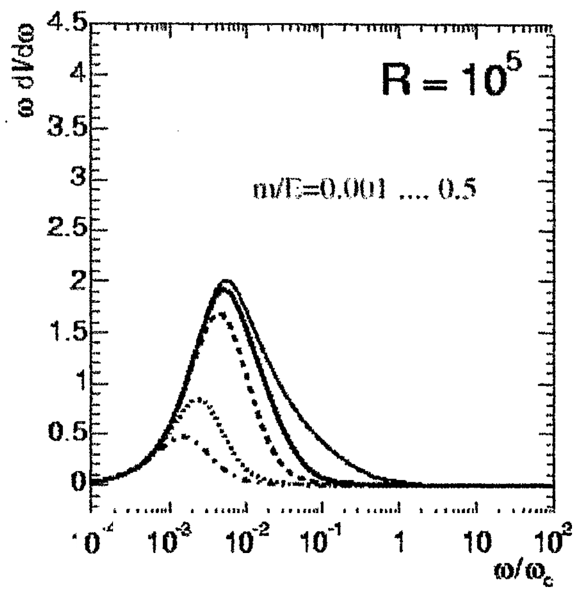
K.J. Eskola, H. Honkanen, **C.A.** Salgado and U.A. Wiedemann, **Nucl.Phys.A 747 (2005) 511**

N. Armesto, C. **A.** Salgado and U. A. Wiedemann, **Phys.** Rev. D **69 (2004) 114003**

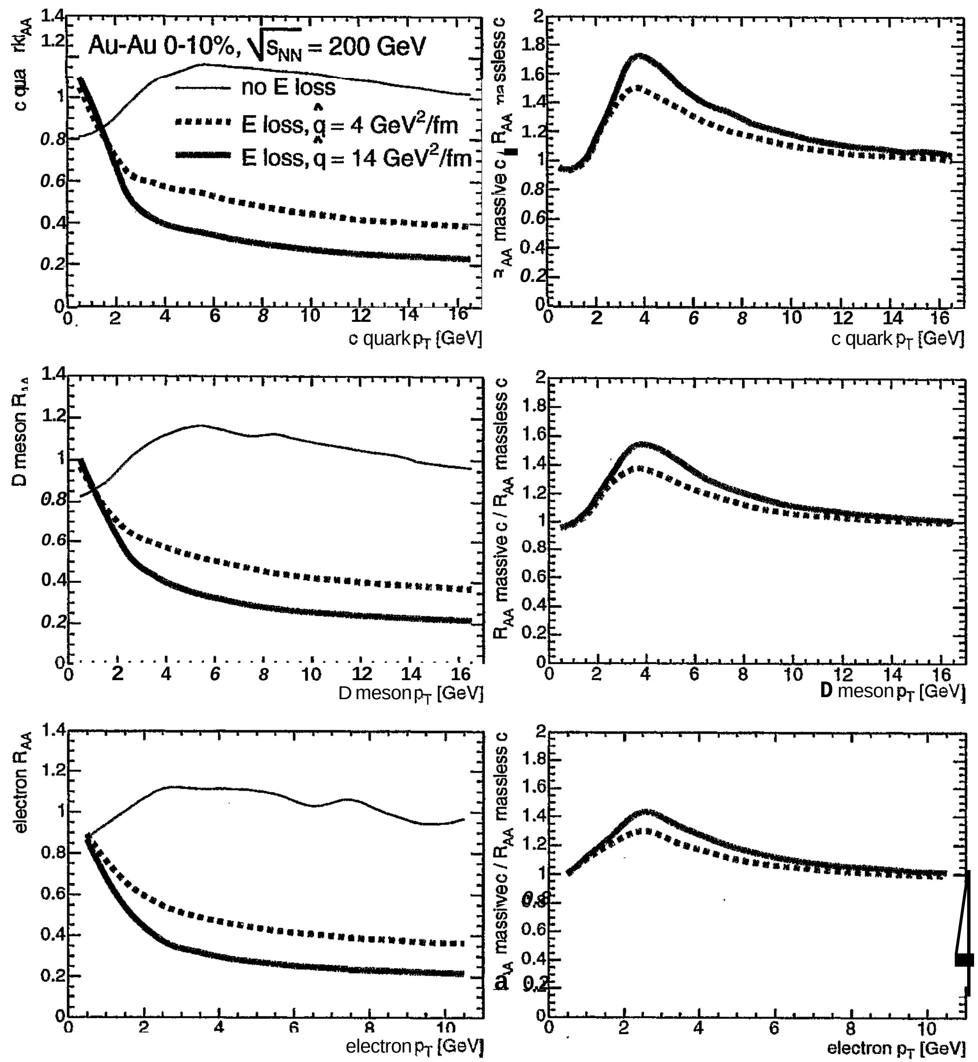
C. A. Salgado and U. **A.** Wiedemann, **Phys.** Rev. Lett. **93 (2004) 042301**

Massive quarks

- Mass effects suppress gluon radiation [Dokshitzer, Kharzeev (2001); Zhang, Wang, Wang (2004); Djordjevic, Gyulassy (2004); Armesto, Salgado Wiedemann (2004)]



(vacuum → dead-cone effect)



[Armesto,Dainese,Salgado,Wiedemann 2005]

- No additional parameters for predictions.

Gluon multiplicity inside the jet.

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

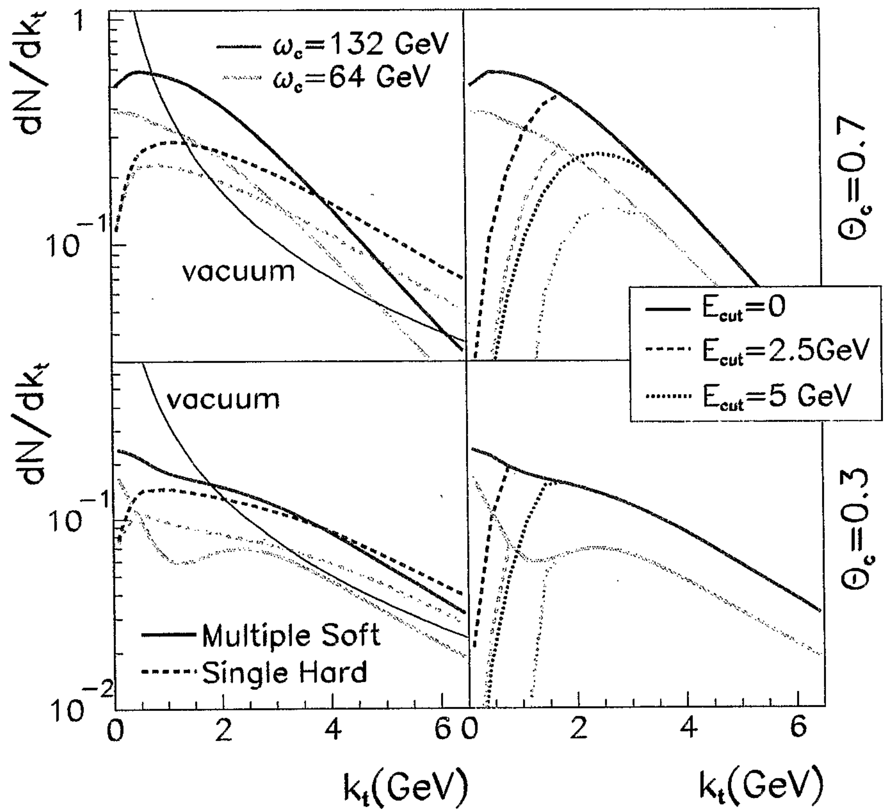
$$\frac{dN^{\rm jet}}{dk_\perp} = \int_{k_\perp/sin\theta_c}^{E} d\omega \frac{dI}{d\omega dk_\perp}$$

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 (hadronization...).

But, effect based mainly on kinematics remember $k_t^2 \sim \hat{q}L(\sim Q^2_{\rm sat})$



(100 GeV jet)

Jet shapes in a flowing medium

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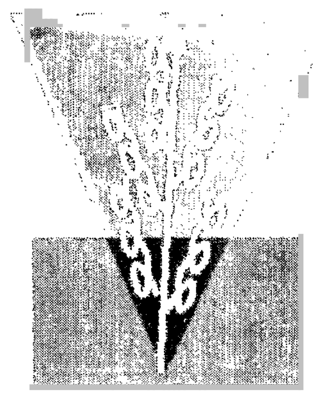
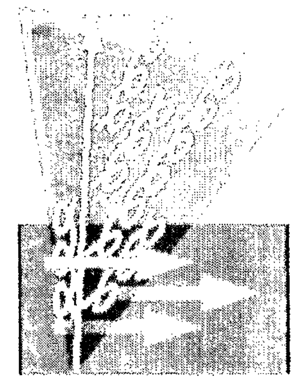
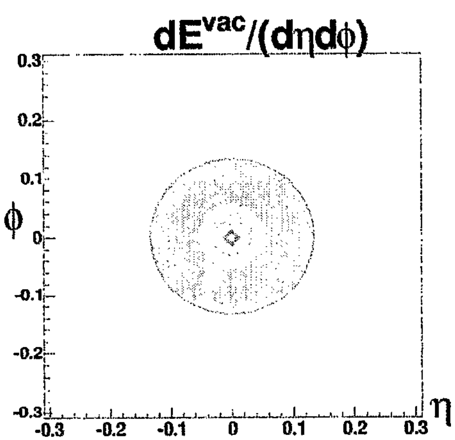
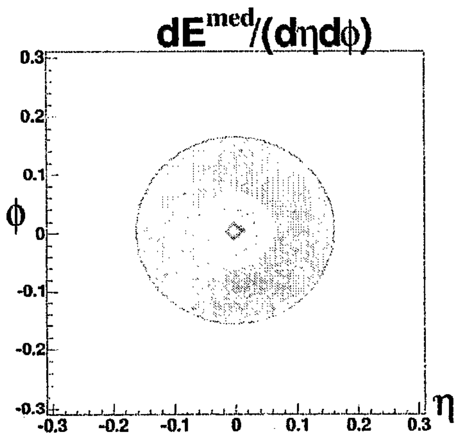
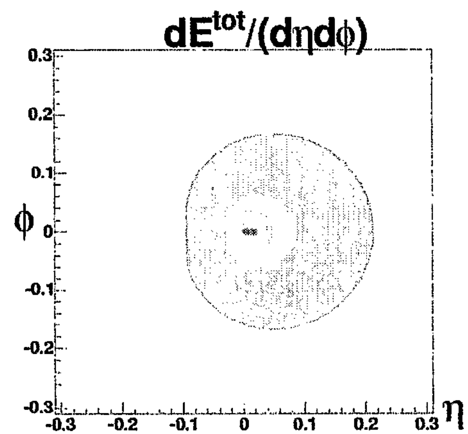
Vacuum	Medium:	Flowing medium:
(reference)	broadening	anisotropic shape











Longitudinal flow

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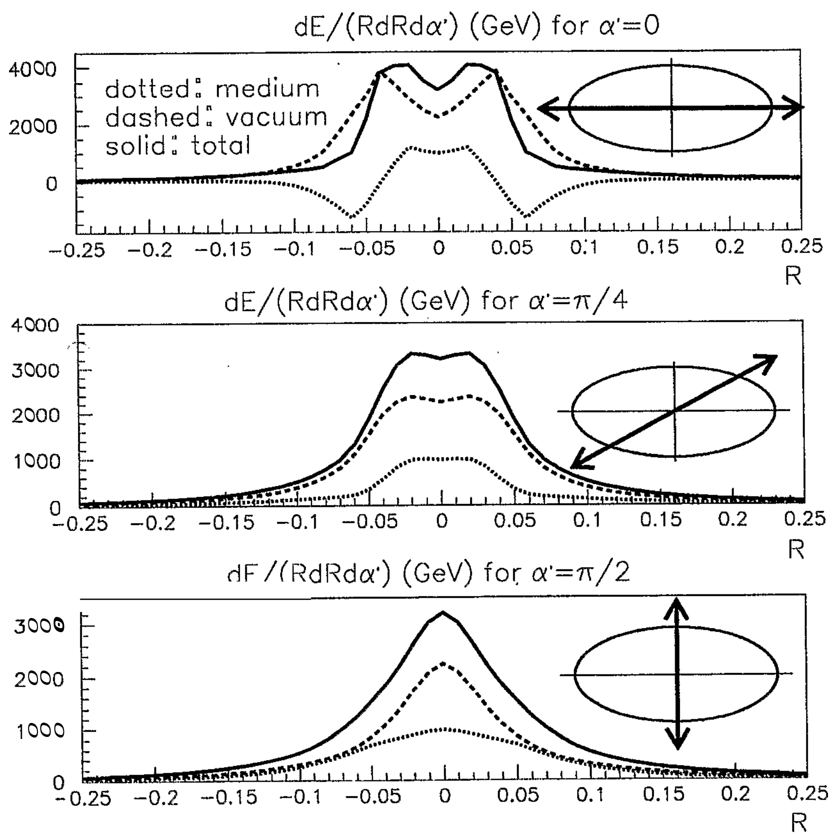
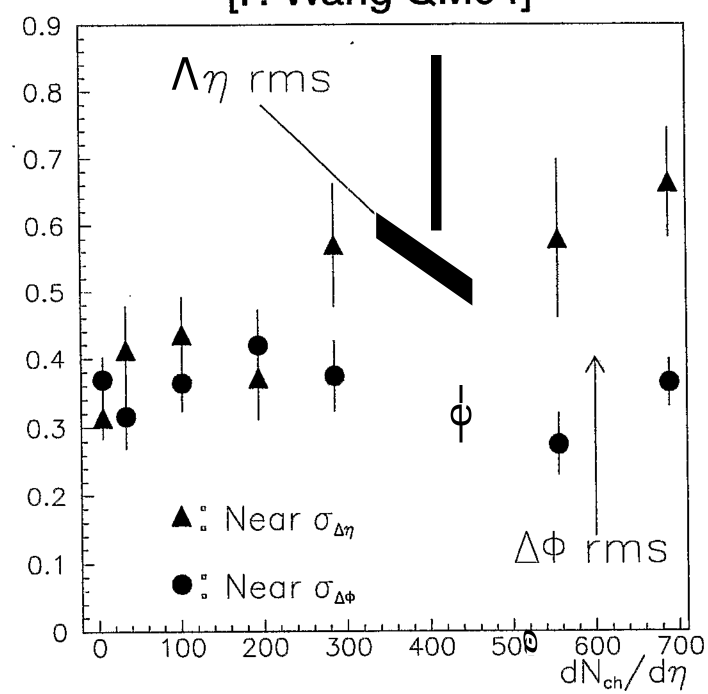
Jet energy distributions for a flow directed in the $\pm z$ directions.



$E_{\text{jet}} = 100$ GeV, $\Delta E = 23$ GeV.
$q_0 = \mu$

Estimation of the effect for the case of RHIC (STAR preliminary)

[F. Wang QM04]



Band corresponds to $q_0/\mu = 2 \div 4$
Broadening in the η-direction more important than in ϕ-direction.

Conclusions

- Inclusive particle production presents limitations in the characterization of the medium.
  - Study less inclusive observables
- Jet–broadening directly related to energy loss by medium–induced gluon radiation.
  - Measure jet structure in HIC (control over multiplicity background)

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- A flow field in the medium produces additional (anisotropic) gluon radiation
  - Asymmetric jet shapes (elongation in η-direction)
  - Contributes to v_2 and suppression (can this explain the opacity problem?)
- First jet observables sensitive to the dynamics of the medium.
  - Study the space–time–momentum picture of the collision with high-p_t particles.

The Medium Modification of Two Hadron Correlations

Abhijit Majumder
Nuclear Science Division, Lawrence Berkeley National Laboratory
MS:70R0319, Berkeley, California 94720

In the study of jet suppression, correlations between two high p_T hadrons in azimuthal angle are used to study the change of jet structure. While the back-to-back correlations are suppressed in central $Au+Au$ collisions, indicating parton energy loss, the same-side correlations show a rise above the $p-p$ value for the most central collisions and drop below the $p-p$ value for semi-peripheral events. In two particle correlations in Deep-inelastic scattering off a large nucleus, one notes a minimal variation with atomic mass of the nucleus used. In this case the associated particle multiplicity shows a slow drop with momentum fraction of the associated particle. Given the experimental kinematics, this is considered as an indication of parton hadronization outside the medium. However, since the same-side correlation corresponds to two-hadron distribution within a single jet, the observed phenomenon is highly nontrivial. Why a parton with a reduced energy would give an enhanced two hadron distribution in a heavy-ion collision?

To answer this question we study the dihadron fragmentation functions and their evolution in the process of e^+e^- annihilation. Under the collinear factorization approximation and facilitated by the cut vertex technique, the two hadron inclusive cross section at leading order (LO) is shown to factorize into a short distance parton cross section and a long distance dihadron fragmentation function (see slide **9).** We provide a rigorous definition of such dihadron fragmentation function in terms of parton matrix elements and derive its DGLAP evolution with the energy scale of the reaction at leading log. This has been presented in detail in Refs. [1, 2, 3]. We note that the ratio of the dihadron to the single hadron fragmentation functions shows minimal change with the energy scale of the fragmentation functions (slide 12). This is expressly true for gluon fragmentation. The cause for this is identified as due to the new additive contribution from the independent fragmentation piece, where a quark or gluon jet splits into two partons with large rapidity and sufficient transverse momentum between them to allow for these to fragment independently of each other.

Modifications to the dihadron fragmentation functions due to medium enhanced higher twist effects are computed for two hadron inclusive cross sections in deep-inelastic scattering (DIS) off large nuclei. The modification is similar, formally, to that for the single fragmentation functions. As a result, comparisons with the data for single particle production, lead to the determination of the overall normalization constant and there remain no free parameters in the prediction of the modification of two particle productions. In spite of such constraints, the medium modification of the double fragmentation functions are found to be in excellent agreement with the data. These are presented in slides 20 and 22 and in Refs. [4, **5, 6**]

The medium modifications of the dihadron fragmentation functions are then generalized to include modifications in a hot deconfined environment of a Quark Gluon Plasma. In such a scenario, one also has to include the effects of trigger bias: due to energy loss the initial energy of a parton in a nucleus-nucleus collision is much larger than that in a p-p collision. This leads to the detected hadrons acquiring a lower momentum fraction z than they would have 'had in a $p-p$ event. This leads to the enhancement for the most central event. One also has to include effects from the Cronin effect in peripheral collisions which has an opposite effect as compared to the trigger bias caused due to energy loss. The results obtained, show very good agreement with the experimental results and have been presented in slide 24 Refs. [5].

References

[1] **A.** Majumder and X. N. Wang, Phys. Rev. D **70,** 014007 (2004) [arXiv:hep-ph/0402245].

[2] A. Majumder, J. Phys. G **30,** S1305 (2004) [arXiv:hep-ph/0404292].

[3] A. Majumder and X. N. Wang, arXiv:hep-ph/0411174.

[4] **A.** Majumder and X. N. Wang, J. Phys. **G,** *to appear* arXiv:hep-ph/0410078.

[5] **A.** Majumder, E. Wang and X. N. Wang, arXiv:nucl-th/0412061.

[6] A. Majumder and X. N. Wang, to *be published* (2005).

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Dihadron fragmentation in e^+e^- Collisions

The basic process may be factorized as:

$$\frac{d^2\sigma}{dz_1 dz_2} = \sigma_0 [D_q(z_{1,} z_{2,} \mu) + D_{\bar{q}}(z_{1,} z_{2,} \mu)]$$

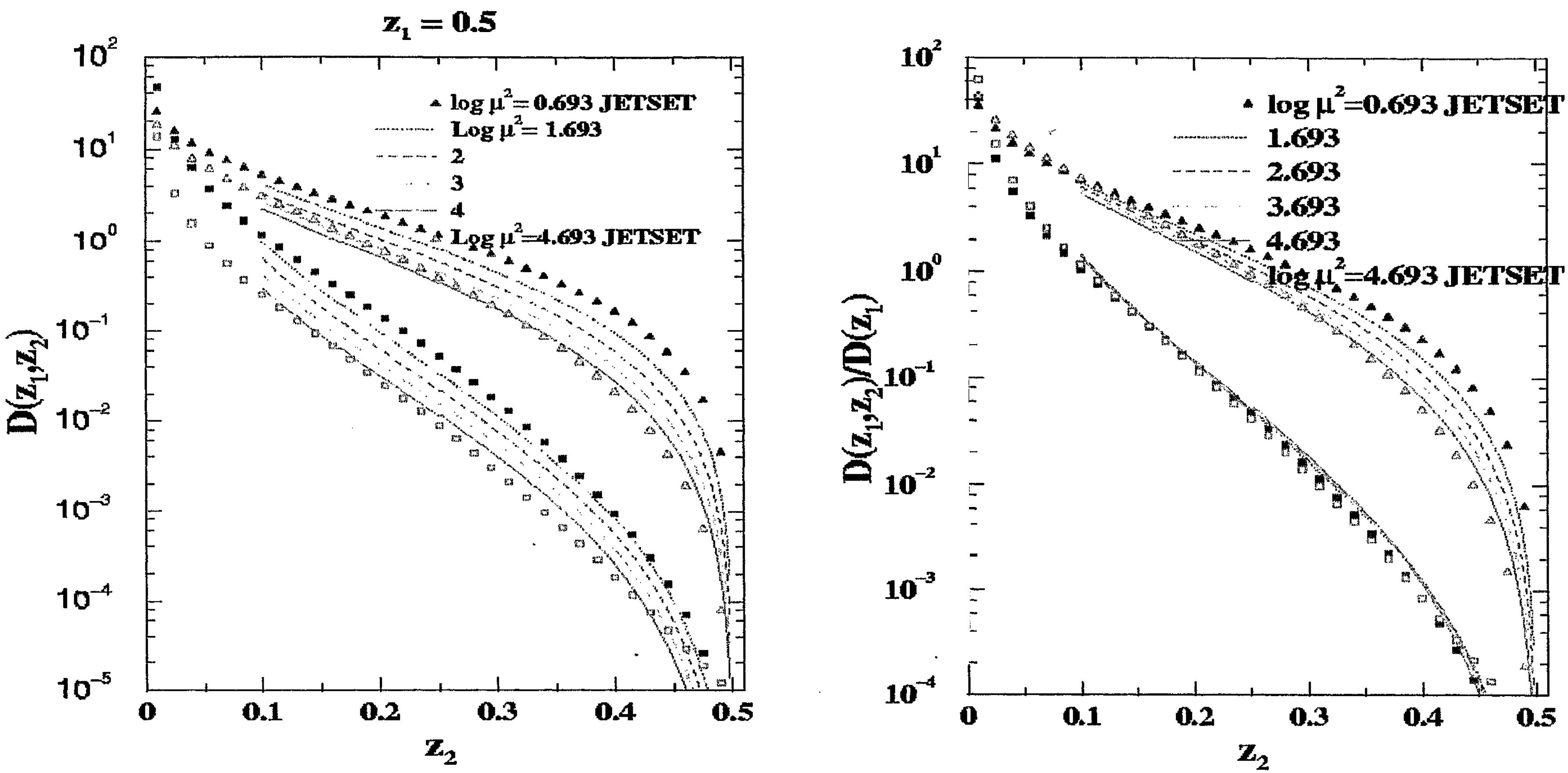
$\sigma_0 =$ ***Hard*** *Cross section*

$D_q(z_{1,} z_{2,} \mu) =$ *Dihadron fragmentation function*

Can be factorized from hard process if $\lambda^2_{QCD} \ll \mu^2 \ll Q^2$

Measure the function at the scale μ, can be done in 2 ways

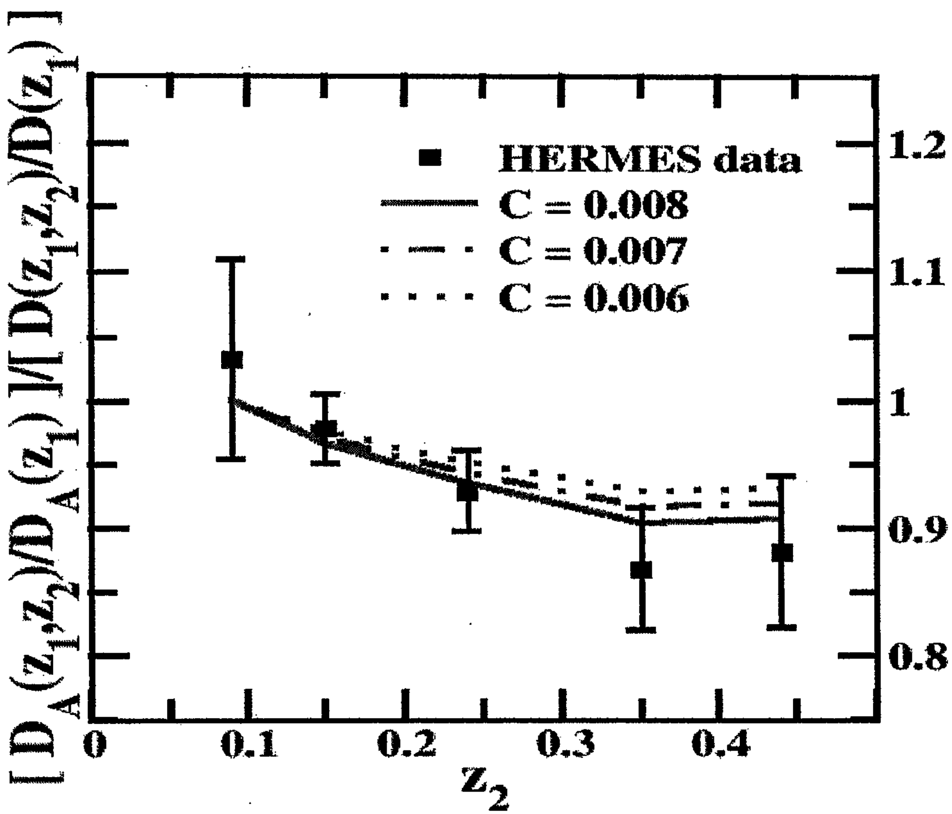
$$\text{Event generator distribution}: D(z_{1,} z_{2,} \mu) = \frac{1}{N_{events}} \frac{dN}{dz_1 dz_2}$$



Quark and Gluon evolution fits event generator data very well!

Thus we can understand evolution of DFF from QCD.

Note: the double to single ratio shows little change

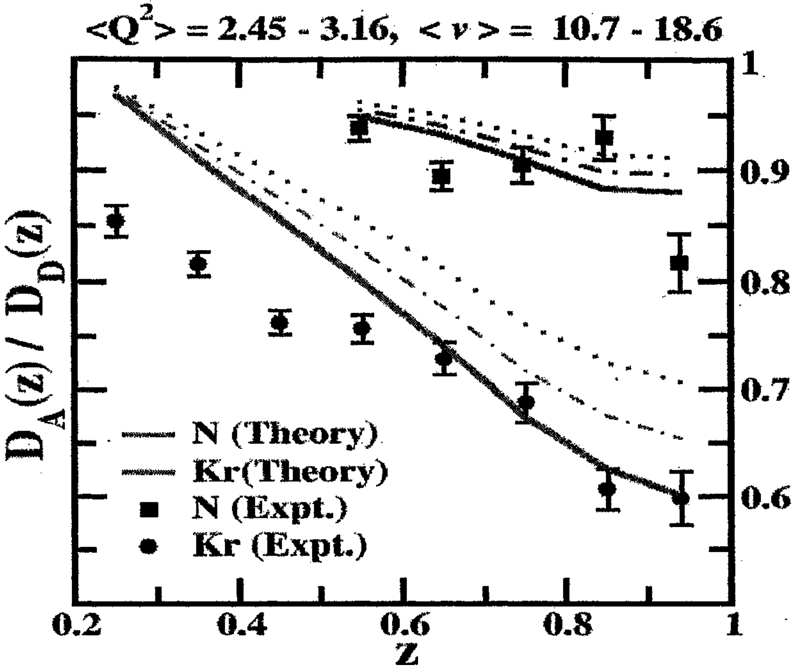


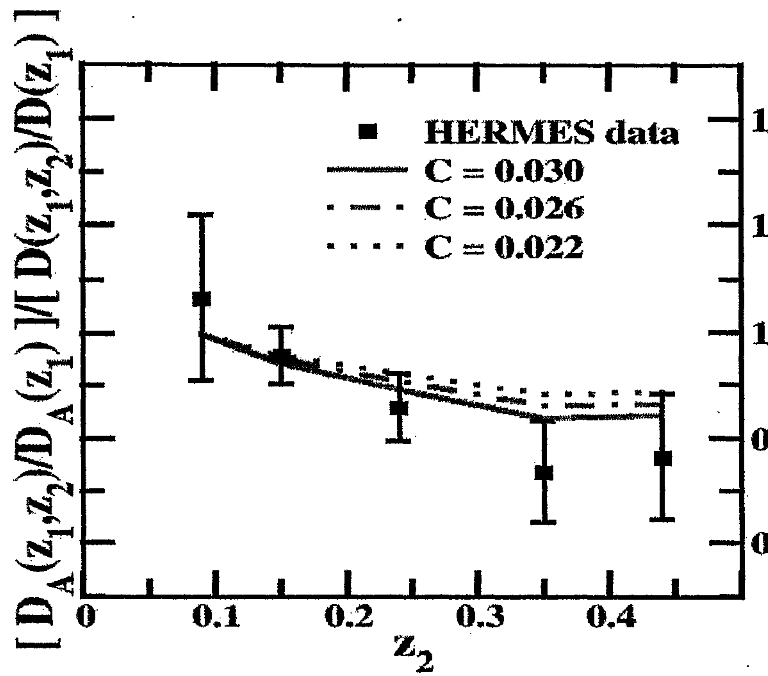
The theory curve is the number of pairs with one hadron at $z_1 = 0.5$ and one at z_2.

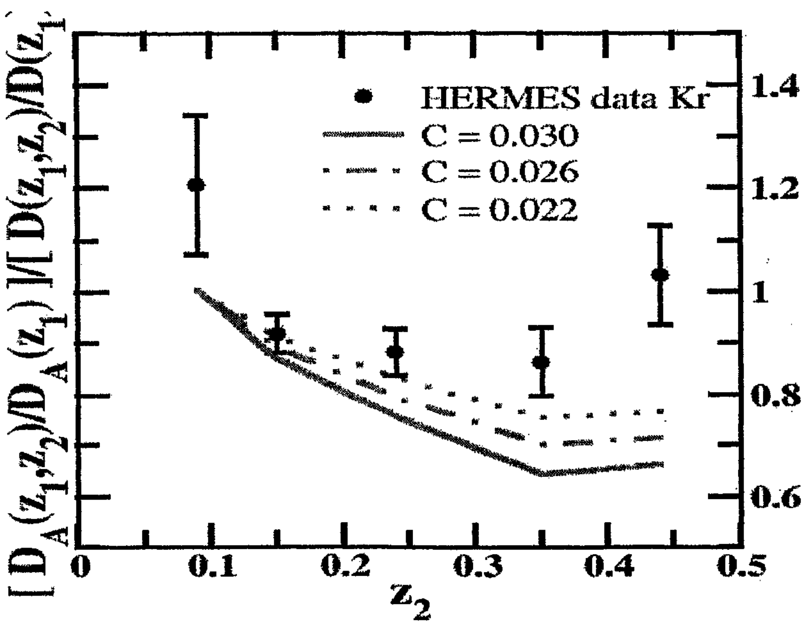
The expt. curve is the number of events with a subleading hadron at z_2, and $z_1 > 0.5$.

Theory curve: (FF(2h)/FF(1h) in A) / (FF(2h)/FF(1h) in vac.)

$$\textbf{\textit{Expt ratio}} = \frac{\dfrac{\textbf{No.}\ \textit{of events with at least 2 hadrons with } z_1 > 0.5}{\textbf{No.}\ \textit{of events with at least one hadron with } z > 0.5}}{\textit{same ratio on deuterium}}$$







dE/dx = 0.5 GeV/fm

Perhaps at Larger A one needs to go to higher order power corrections.

Dihadron results for hot medium

Use the same overall constant **C** *as for singles*

Results include the effect of trigger bias.

Initiating parton in a heavy-ion collision has higher energy than that in p-p collision,

Use the single inclusive results to get mean E_{parton} *for a given* E_{hadron}.

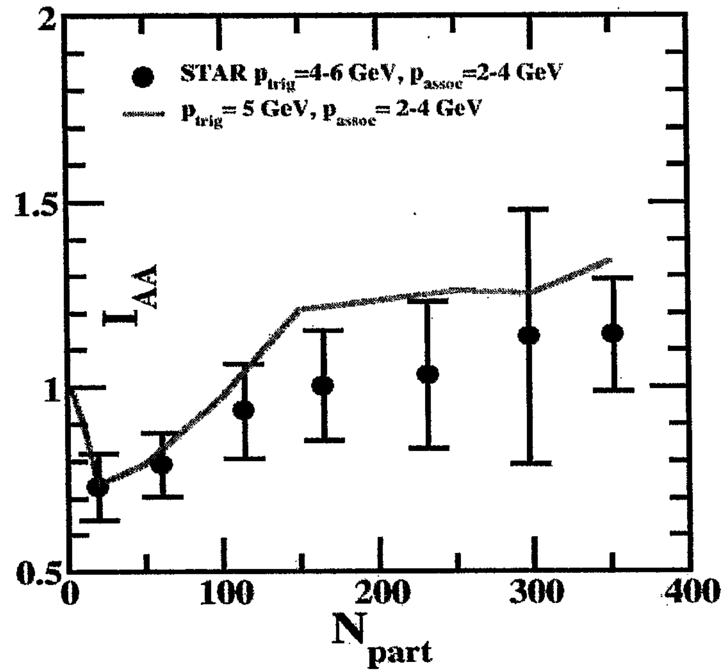
$$z = \frac{E_{hadron}}{E_{parton}}$$

If E_loss dominates

$z_{AA} < z_{pp}$, $D(z_{AA}) > D(z_{pp})$

If Cronin effect dominates,

$z_{AA} > z_{pp}$, $D(z_{AA}) < D(z_{pp})$



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Conical Flow induced by Quenched QCD Jets

8 **Jorge Casalderrey-Solana,**

Edward Shuryak and Derek Teaney,

hep-ph/0411315

SUNY Stony Brook

Jet Quenching and Energy Loss

- High p_t particles lose energy in the medium

  Radiative losses (main effect)

  Collision losses

  Ionization losses

  (bound states)

  $$\frac{dE}{dx} \approx 2\frac{GeV}{fm}$$ Shuryak+Zahed, hep-ph/0406 100

- The second type of losses are deposited in the medium and modify its properties.
- We study this modification through hydrodynamics.

Basic Assumptions

- The deposited energy thermalizes at a scale:

$$\Lambda \approx \Gamma_s = \frac{\eta}{e+p}\frac{4}{3}$$

- Minimal value $\Gamma_s \approx (4\pi T)^{-1} << (P_{jet})^{-1}$ point-like

- The modification of the properties of the medium is small

$$E^{deposited} << \varepsilon V^{deposited}$$

- The linearized hydrodynamic description is valid:

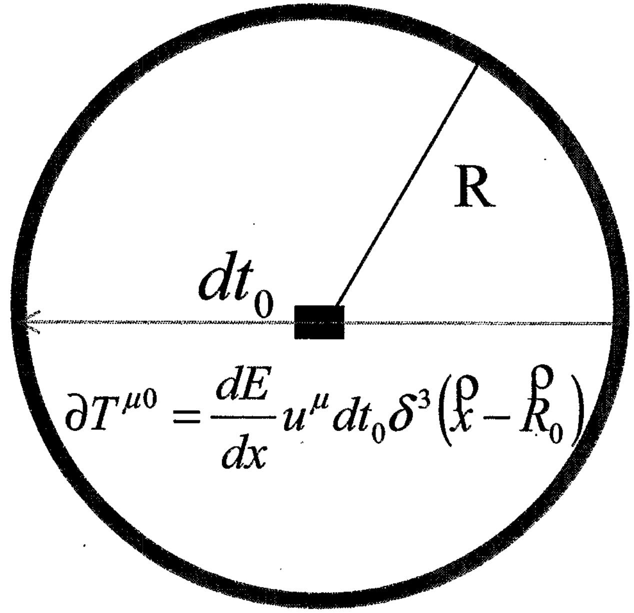
$$\partial_\mu \delta T^{\mu\nu} = 0$$

Linearized Equations

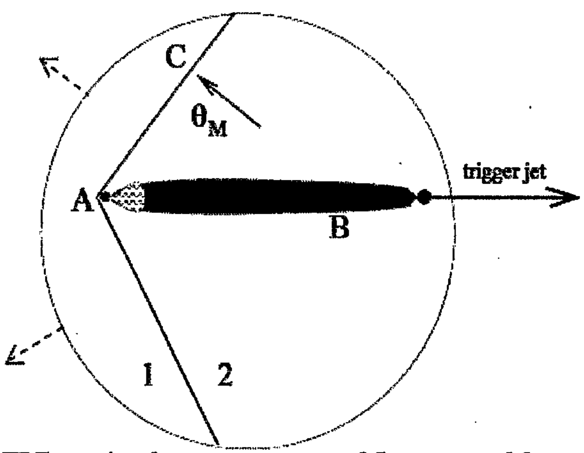
Medium at rest

Infinitesimal displacement

$$\frac{d\partial\varepsilon}{dt_0} = [illegible]\ \frac{1}{c_s}\left(\frac{\partial}{\partial t} - \frac{\partial}{\partial x}\right)\frac{\left(P_- - P_+\right)}{4\pi R^2}$$



$$P_{\pm} = \frac{1}{\left(2\pi\Gamma_s\left(t - t_0\right)\right)^{1/2}} e^{-\frac{\left(r \pm c_s\left(t - t_0\right)\right)^2}{2\Gamma_s\left(t - t_0\right)}}$$



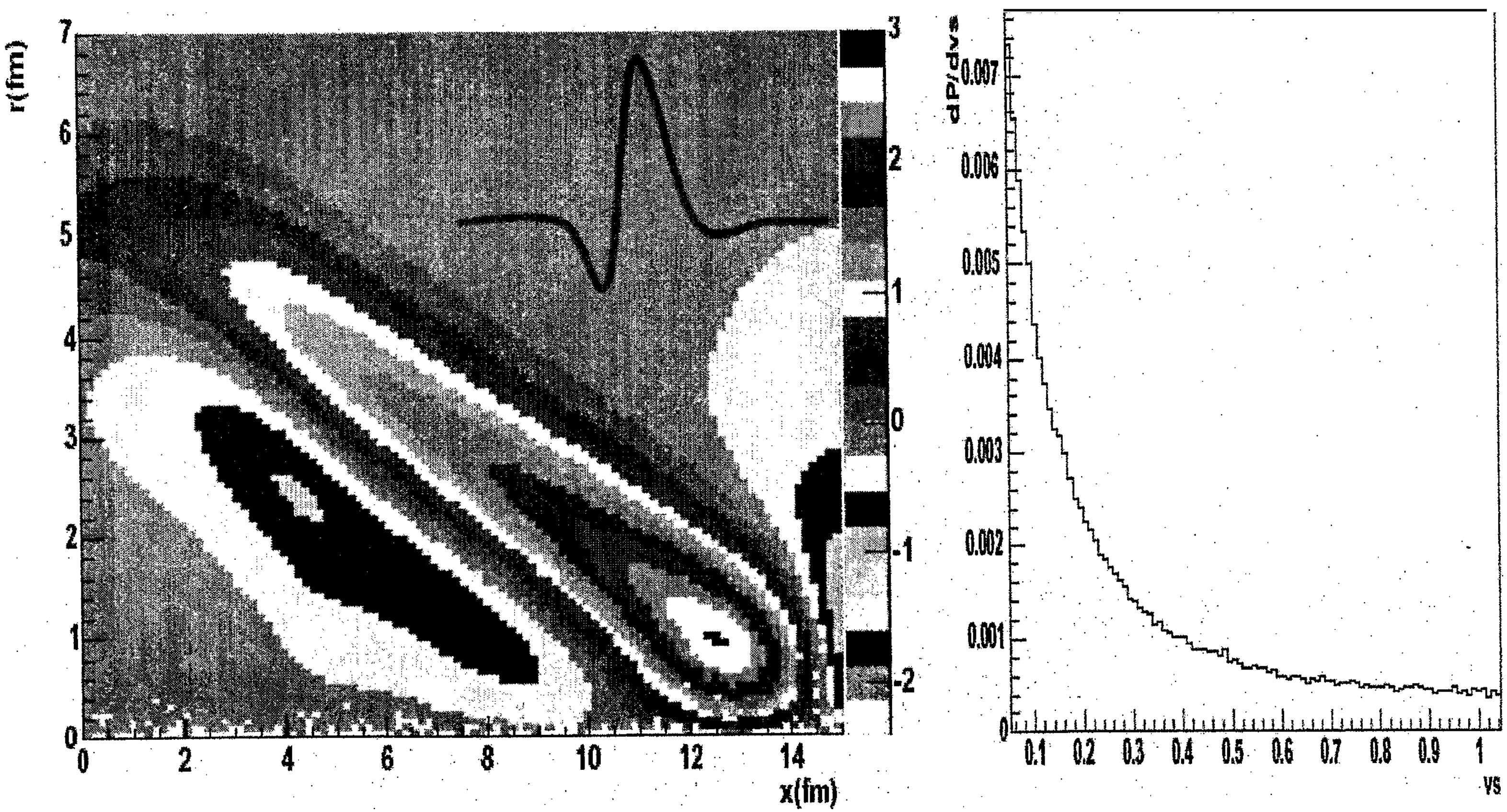
Summing all contributions

$$\partial\varepsilon = \int_{t_i}^{t_f} dt_0 \theta(t - t_0) d\partial\varepsilon$$

Mach Cone $\Rightarrow$ $\cos(\theta_M) = c_s$

Distribution of radial velocity v_P (left) and modulus v (right).

(note the positive and negative parts of the wave)



How to observe it?

- the direction of the flow **is normal to the Mach cone,** defined entirely by the ratio of the speed of sound to the speed of light
- Unlike the (QCD) radiation, **the angle is not shrinking (1/γ) with the increase of the momentum of the jet but is the same for all jet momenta**
- **At high enough p_t a punch through is expected$_a$ filling the cone**

(Non-conical) jet-induced shocks in the QGP

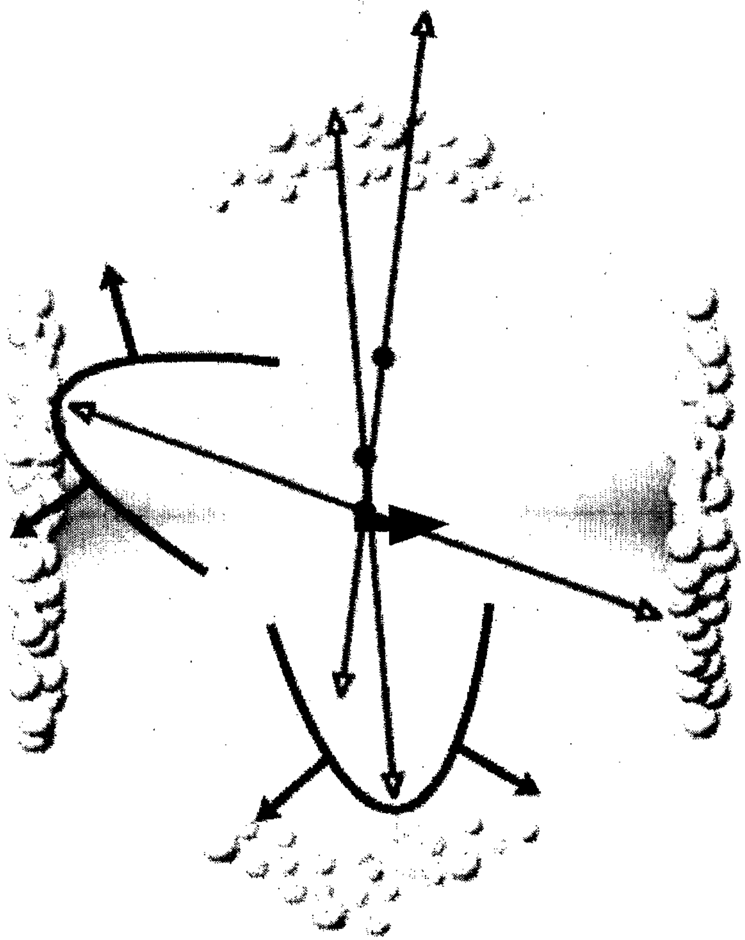
A. Dumitru, J.W. Goethe Univ., Frankfurt
with K. Paech, H. Stocker, D. Rischke

- **Stopped away-side jet can induce shock in plasma**
- **Probably no Mach cone in expanding background**
- **Plasma torn apart by shock wave -->
  no smoldering log...**

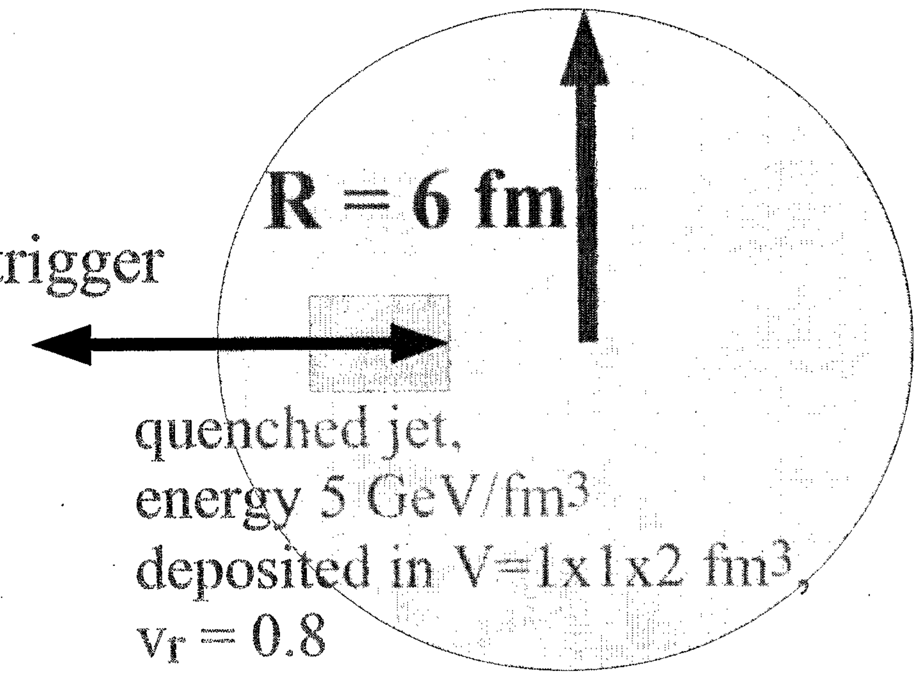
- **Dependence on plasma EoS ?**
- **pT cuts on away side ?**
- **Enhanced γ-bremsstrahlung on away side ?**
- **rotation to jet axis ?**

H.Stöcker, nucl-th/0406018: Jets in QG-Plasma=Machshocks, Wakes
PROOF OF THERMALIZED PLASMA!

Jets interact in the plasma, causing wakes and shock waves relative to jet-axis



Numerical Simulations

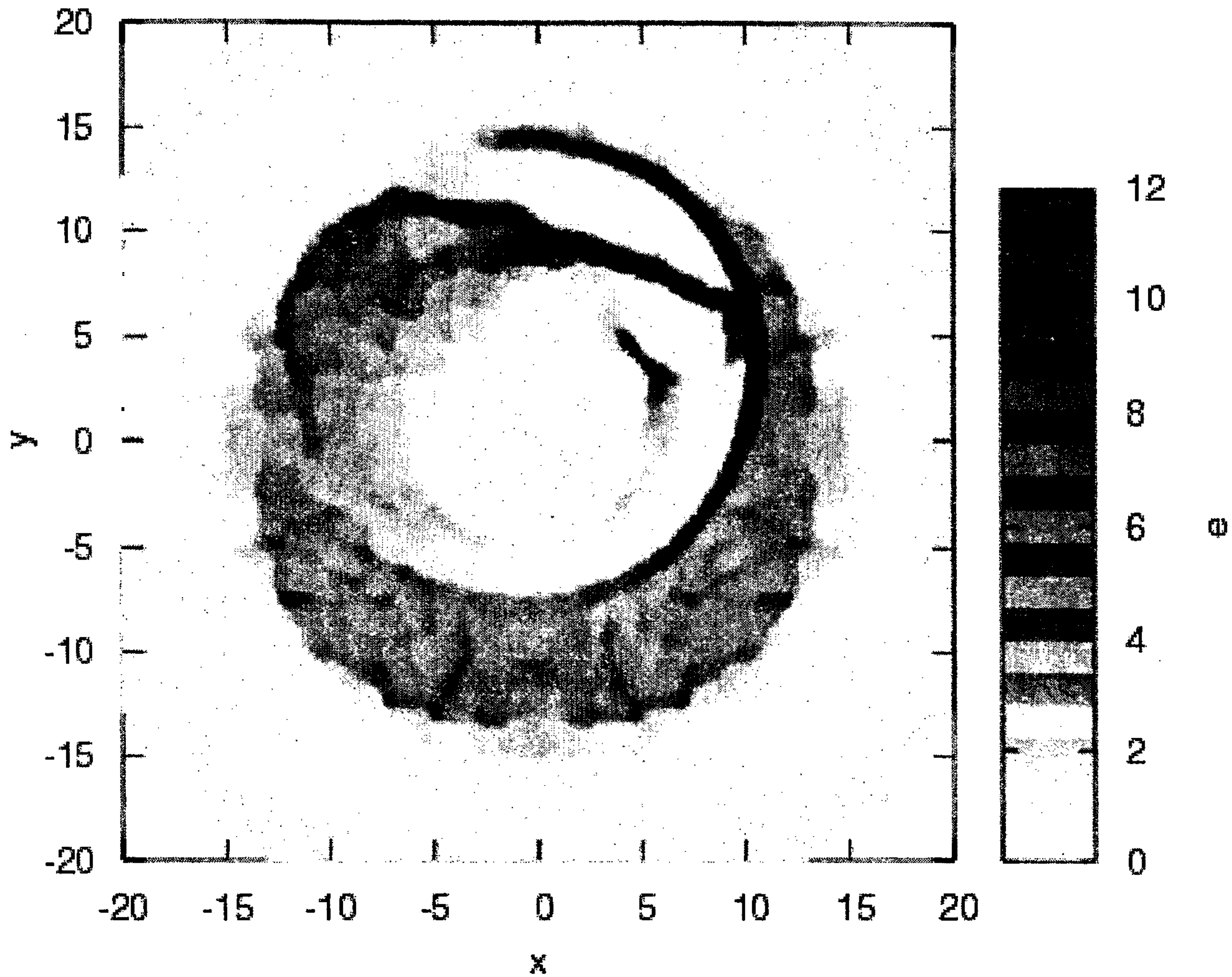


p=e/3 or p=(e-4B)/3

$$v_i \approx 0\,, \quad e_i \approx 8\ GeV/fm^3$$

$T^{0i} = (e+p)\,\gamma^2\, v^i \approx 15\ GeV/fm^3$ -->

$VT^{0i} \approx 30$ GeV !!



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⋆ **In these simulations at least, one rather sees a "bow shock" than a Mach cone (background is not static)**

Jet Structure of Baryons and Mesons in Nuclear Collisions.

Brian Cole & Barbara Jacak for the PHENIX Collaboration

One of the surprises at RHIC is the large enhancement of 2-5 GeVc p_T baryon production in central Au+Au collisions, compared to p+p. The production mechanism may be soft, i.e. baryon formation by recombination of thermal quarks boosted by the radial expansion of the system. Alternatively, the hot, dense medium may modify the jet fragmentation function, as the formation time of these baryons is shorter than the time required to traverse the system.

PHENIX has shown that these baryons have accompanying hadrons at the same rate as intermediate mass mesons. On the away-side, the probability of an accompanying hadron is similar for trigger baryons and mesons. These jet-like features rule out purely soft explanations of the enhancement. Quantitative comparison of the conditional yield of accompanying hadrons and their p_T distributions indicates coupling of the fragmenting jet to the medium. Models allowing coalescence of fragmentation quarks with those drawn or accelerated from the surrounding medium are able to reproduce the data.

PHENIX

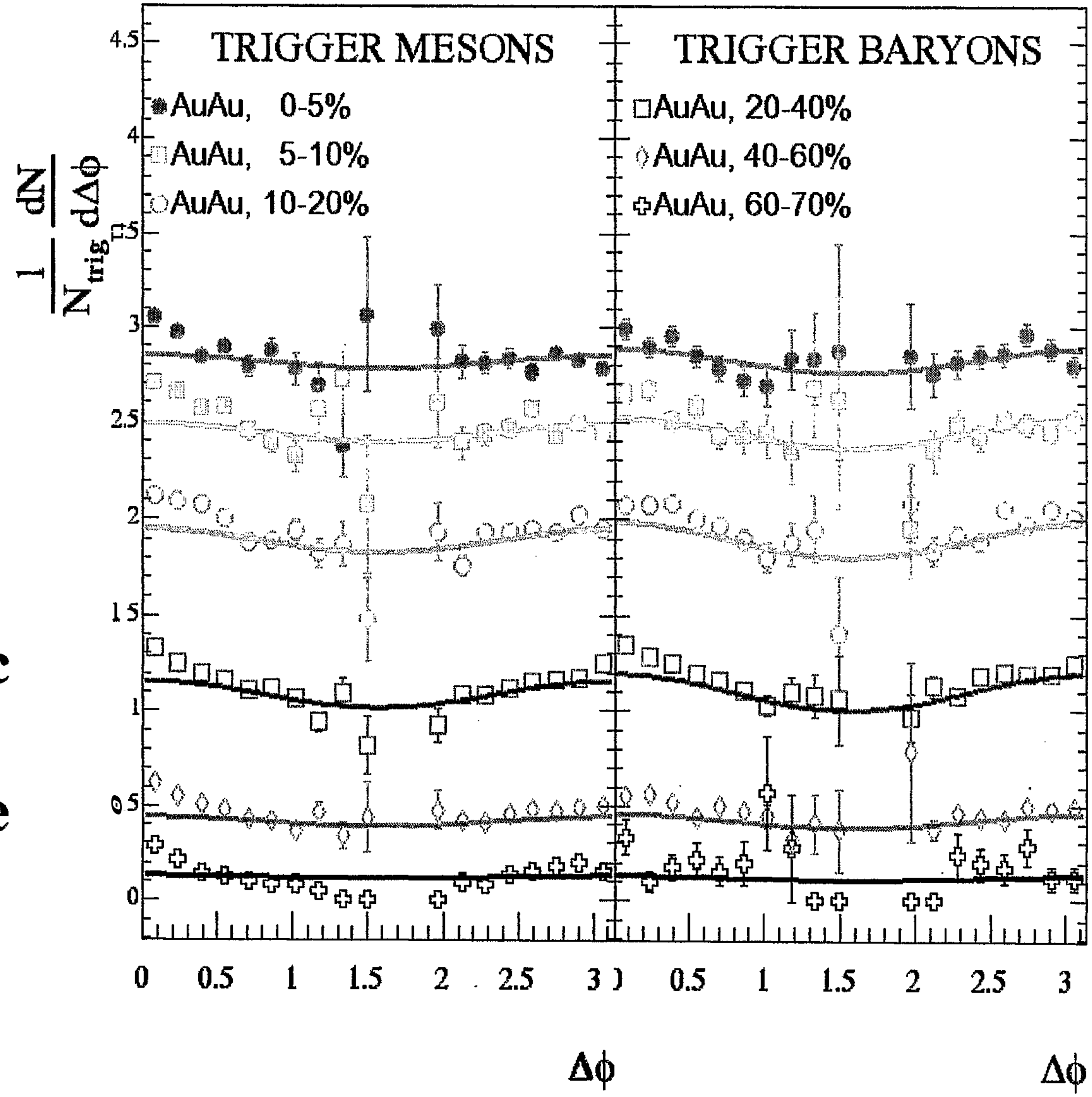
2 particle correlations

Select particles with p_T= 2.5-4.0GeV/c

Identify them as mesons or baryons via time-of-flight

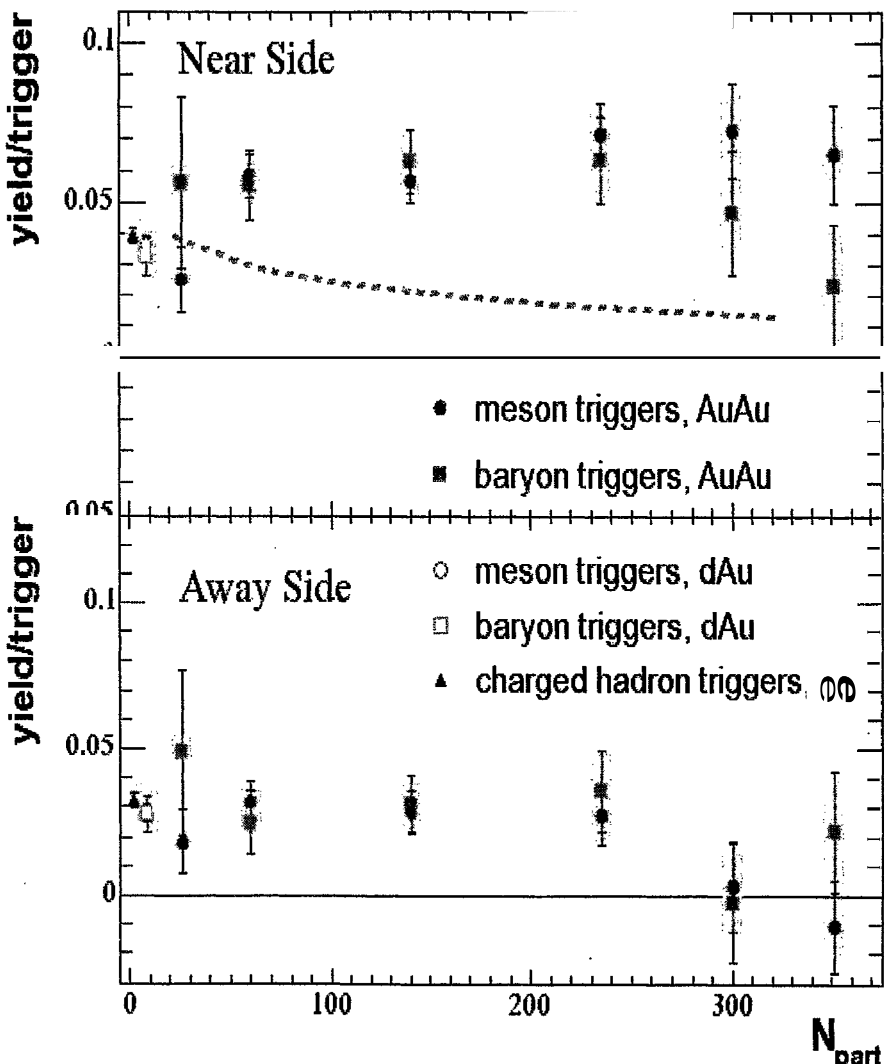
Find second particle with p_T = 1.7-2.5GeV/c

Plot distribution of the pair opening angles; integrate over 55°



PHENIX

intermediate p_T baryons ARE from jets



Jet partner ~ equally likely for trigger baryons & mesons!

Same side: slight decrease with centrality for baryons
Dilution from boosted thermal p, pbar?

Away side: partner rate as in p+p confirms jet source of baryons!
"disappearance" of away-side jet into narrow angle for both baryons and mesons

PHENIX

Formation time of fragmentation hadrons

- **Uncertainty principle relates hadron formation time to hadron size, R_h and mass, m_h**

  In laboratory frame: $\tau_f \sim R_h (E_h / m_h)$

  consider 2.5 GeV p_T hadrons

  $\tau_f \sim$ 9-18 fm/c for pions; $R_h \sim$0.5-1 fm

  $\tau_f \sim$ 2.7 fm/c for baryons ($R_h \sim$1 fm)

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- **Alternatively, consider color singlet dipoles from combination of q & $\bar{q}$ from gluon splitting**

  Using gluon formation time, can estimate

  $\tau_f \sim 2E_h (1-z)/(k_T^2+m_h^2)$

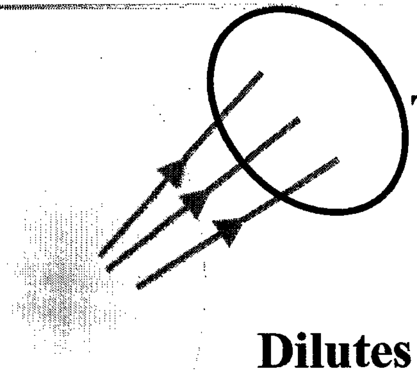
  for $z = 0.6-0.8$ and $k_T \sim \Lambda_{QCD}$: τ_f baryons ~ 1-2 fm/c

R(Au nucleus) ~ 7 fm

→ Baryon formation is INside the medium!

PHENIX

What's going on?

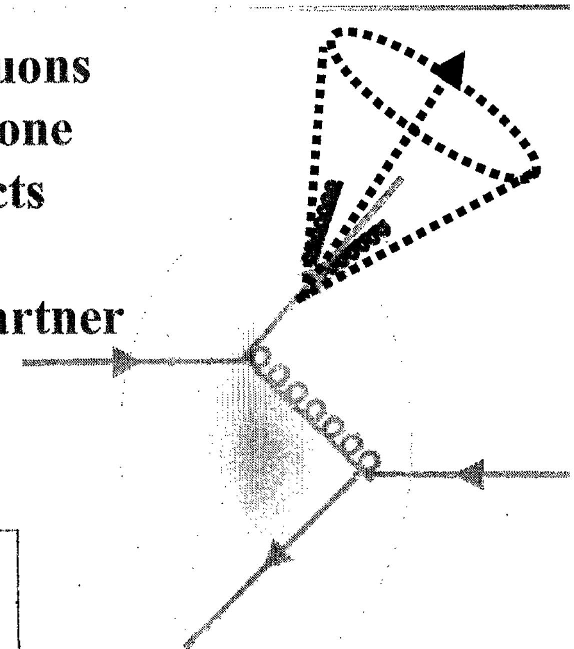


Thermal quark recombination

Dilutes jet partner yield

Radiated gluons inside jet cone + wake effects

Increases partner yield



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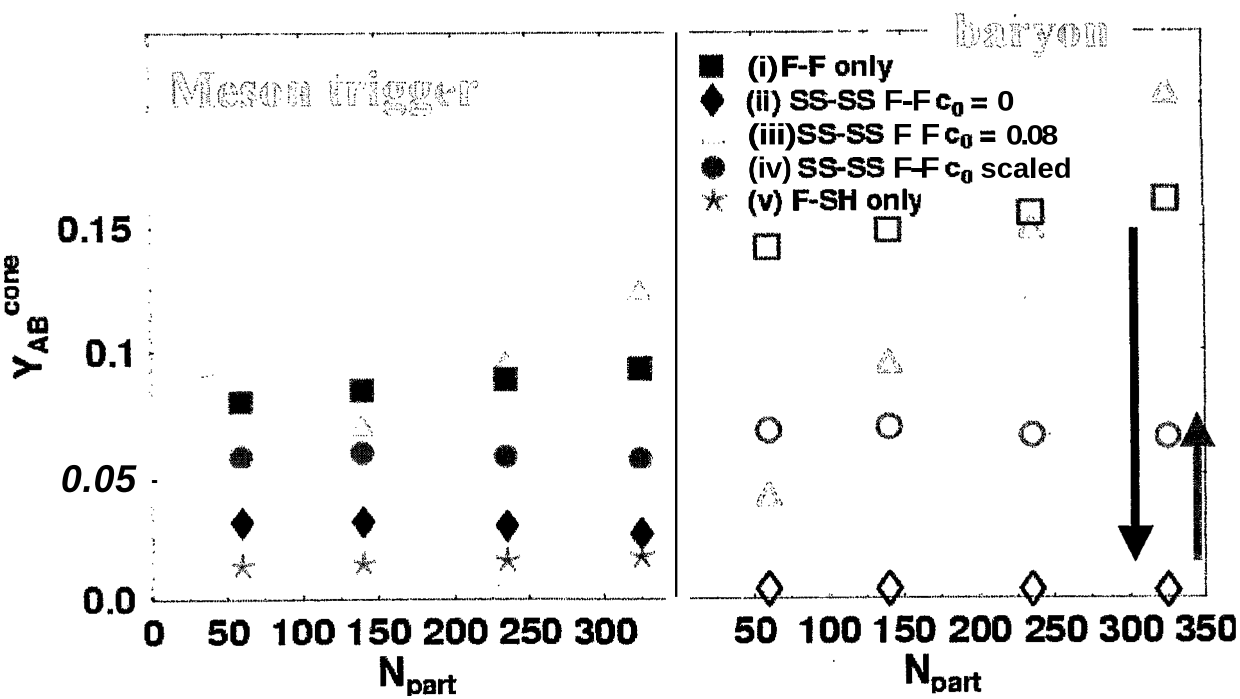
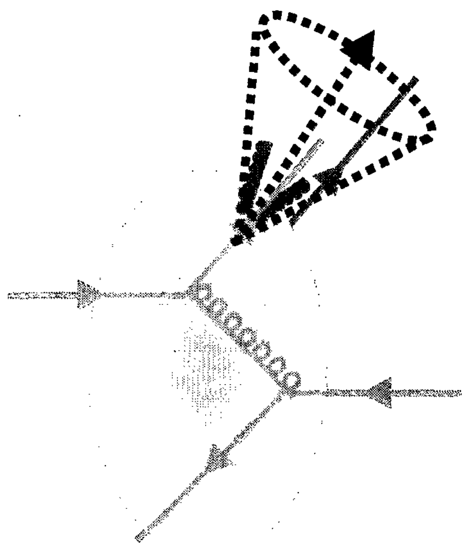
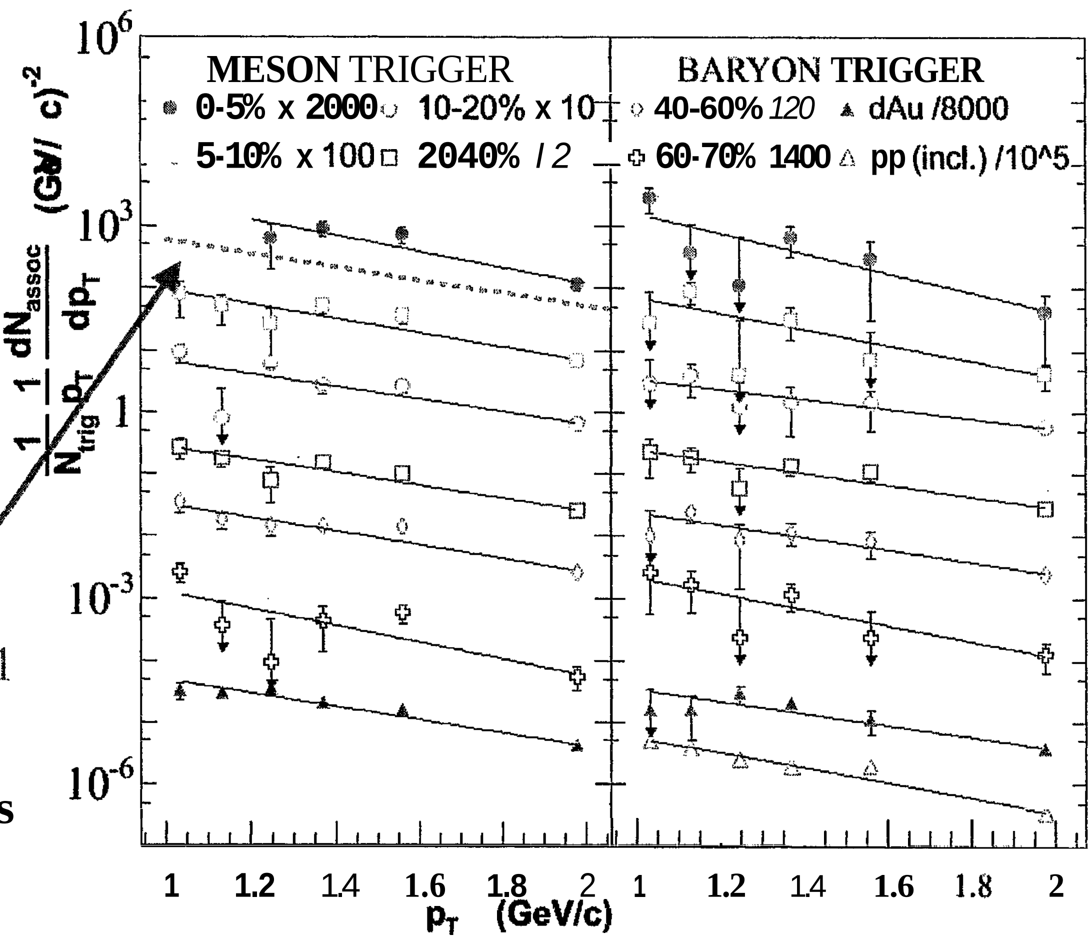


Fries, Bass & Mueller
nucl-th/0407 102

Compare to hard-soft recombination



π trigger & π associated
Hwa & Yang nucl-th/0407081



Soft-hard recomb. also explains baryon Cronin effect!
No jet-correlated medium flow

PHENIX

Identified trigger particle correlations at intermediate p_T

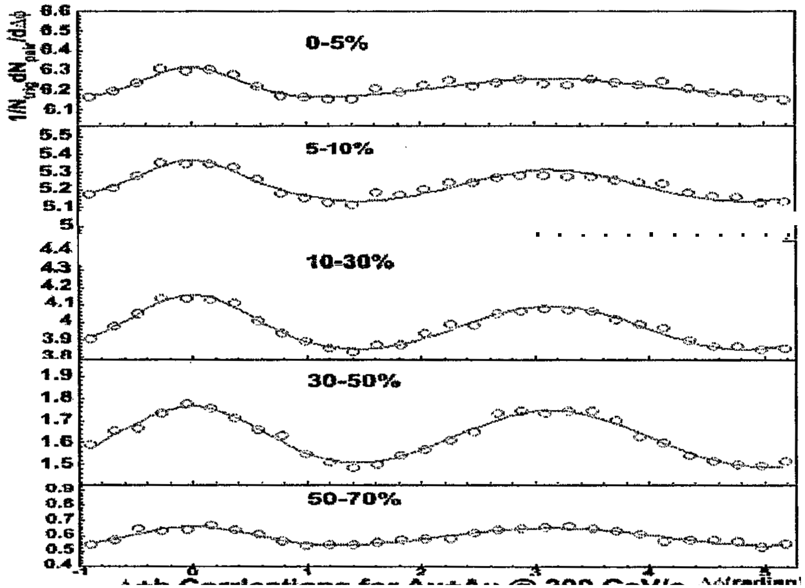
Ying Guo *for STAR Collaboration*
Wayne State University

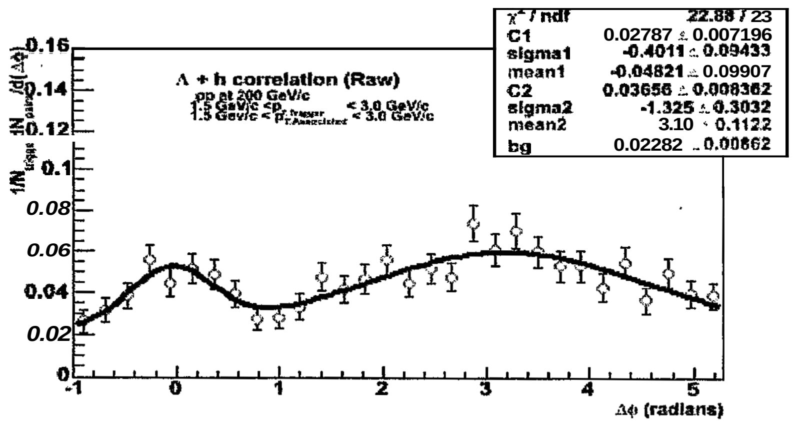
RIKEN Jet Correlation Workshop
BNL March 11th, 2005

Motivation

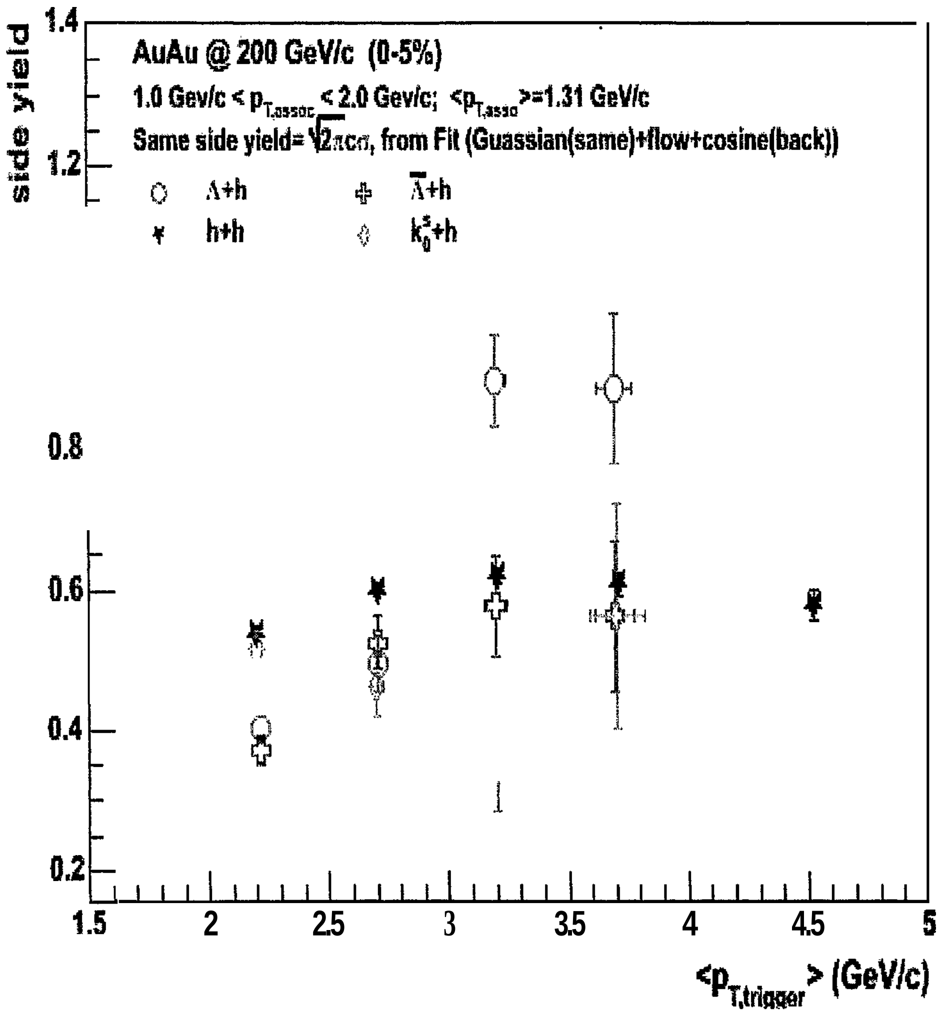
- Get a better understanding of the high p_T azimuthal correlations
- Particle identified jet correlation study provides us with additional information about jet quenching and medium effects.
- The strange particle identified jet correlation can be used as a probe to study the flavor dependence of the strong interaction and the fragmentation process (e.g. quark vs gluon jet, recombination vs. fragmentation, etc.).

Sample Λ +h correlations in AuAu and pp





Same side yield for different trigger particle species



Indication of different trigger p_T dependence for different trigger particle species..

Systematic Errors:

- Uncorrelated background -- 8–10%
- Flow – 2.1~2.6%
- Fitting method – 3%
- misidentified V0s < 1%
- trigger bias <1.5%

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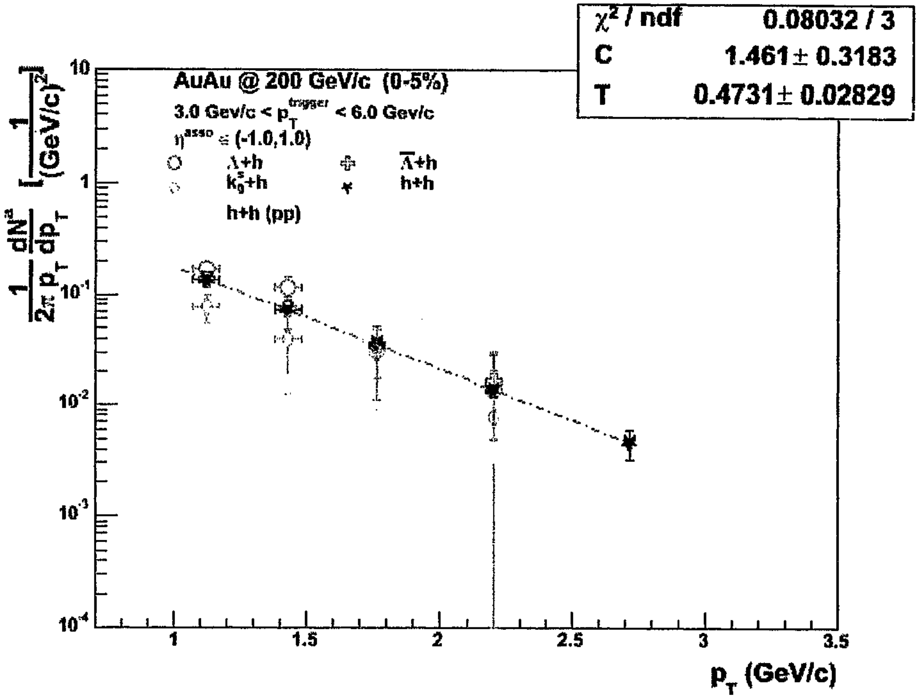
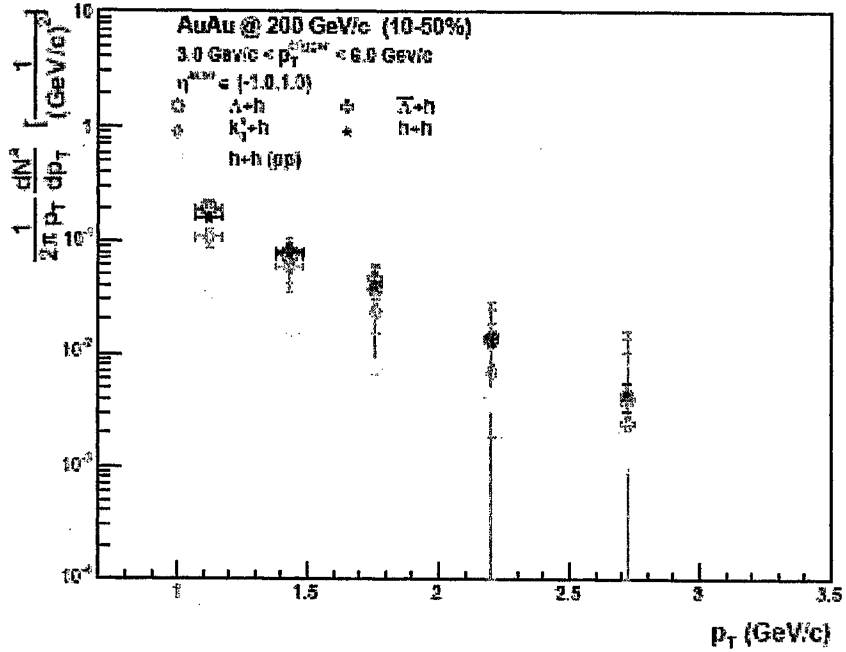
Same side associated particle spectra



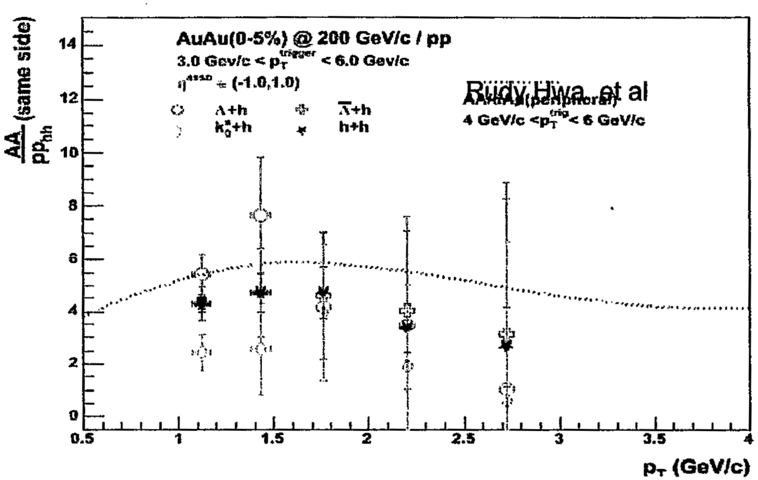


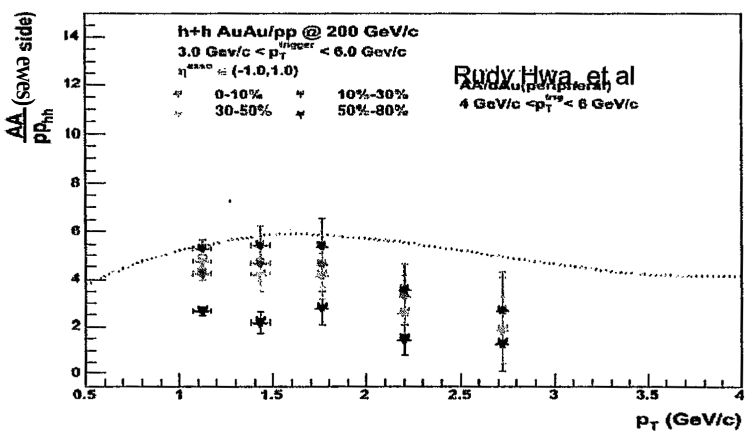
➢In agreement with thermal distribution ?

➢ large AA/pp ratio.

➢No significant difference between distribution different trigger particle species.

Large AA/pp ratio for different trigger particle species





- Approaches unity at higher pT
- Approaches unity in peripheral collisions

Conclusions:

- Correlations with different identified trigger particles have been measured for different centrality bins in AuAu collisions.
- The large AA/pp ratio for different particle species and the trigger pT dependence shows that fragmentation and its medium modification alone can not describe the same side yield in central AuAu collisions for intermediate pT range.
- Indication of different trigger pT dependence for different trigger particle species at high trigger pT..

Identified high p_T spectra and Open charm from STAR

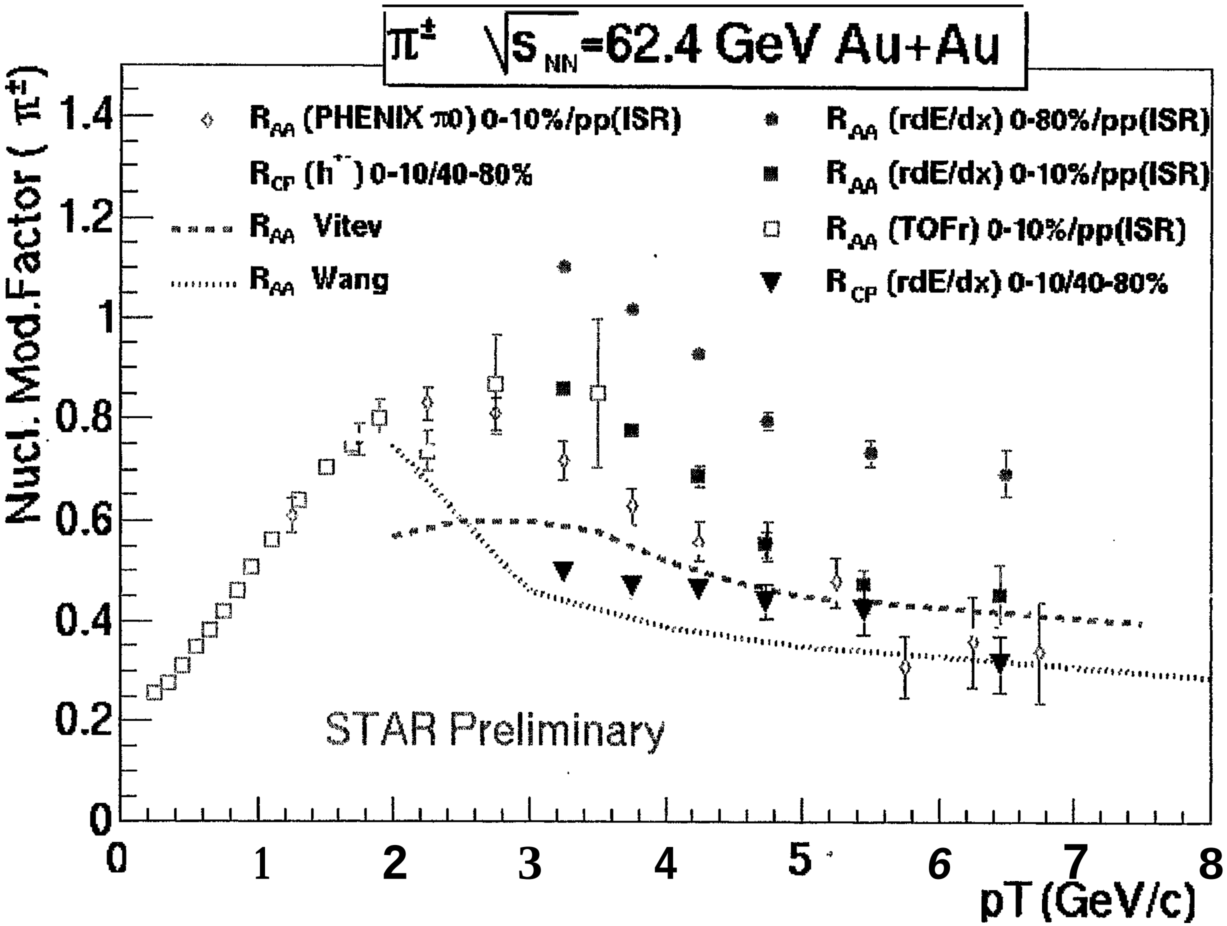
1. Identified hadrons at high pT
   - dE/dx at relativistic rise
   - p, π Spectra in d+Au, Au+Au (p_T>5 GeV/c)

Zhangbu Xu (BNL)

for the STAR Collaboration

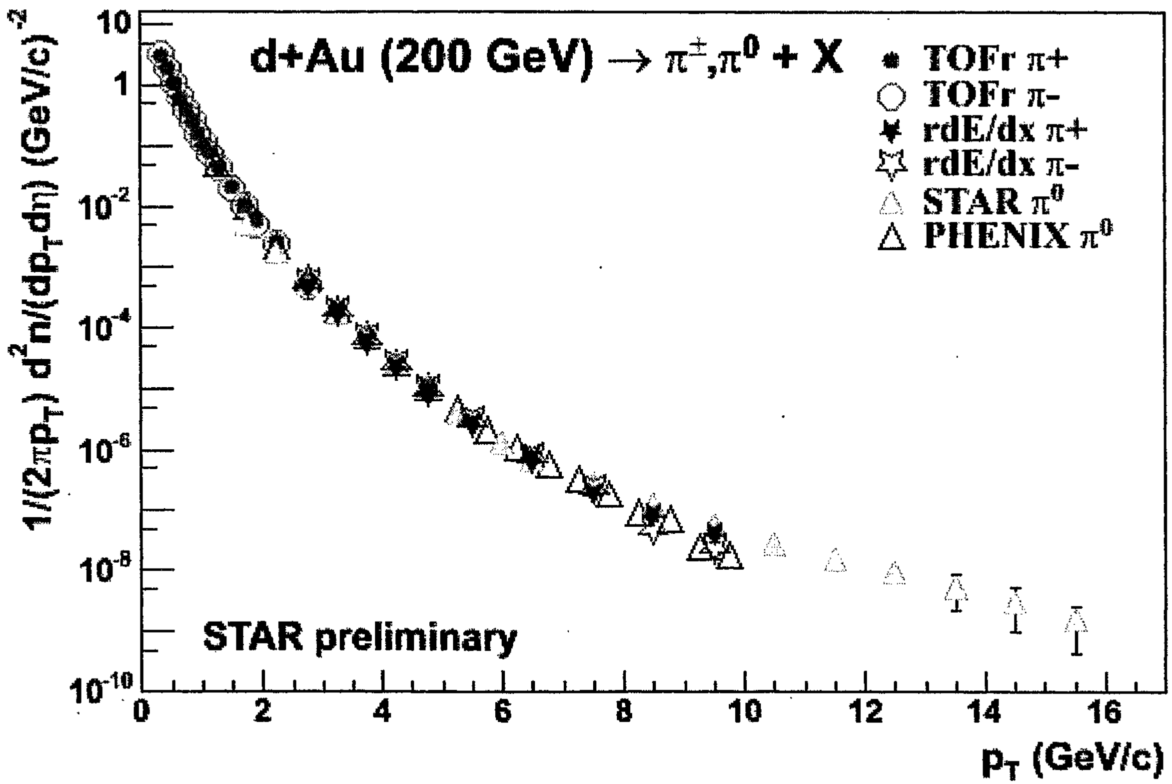
2. Open Charm at RHIC
   - Charm Cross Section and Spectra
   - Compatibility of Current Measurements
   - Need detector upgrades

$\pi^{\pm}$ Nucl. Mod. Factor



- R_{CP} h+- 20% higher than n+- pT=3-4 GeV/c consistent with h/pi ratio
- Vitev prediction at dN/dy=650
- TOFr agrees with dE/dx π+-
- ISR pp parametrization same as PHENIX
- Estimated Syst. Error: 5-10%

Particle ID above 10 GeV/

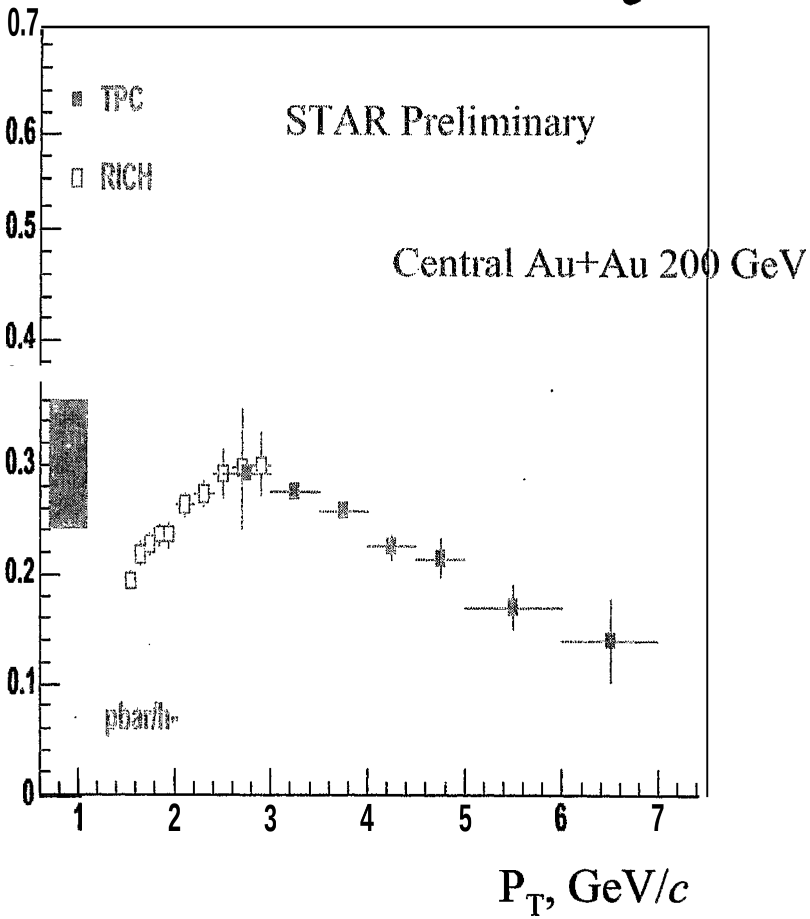


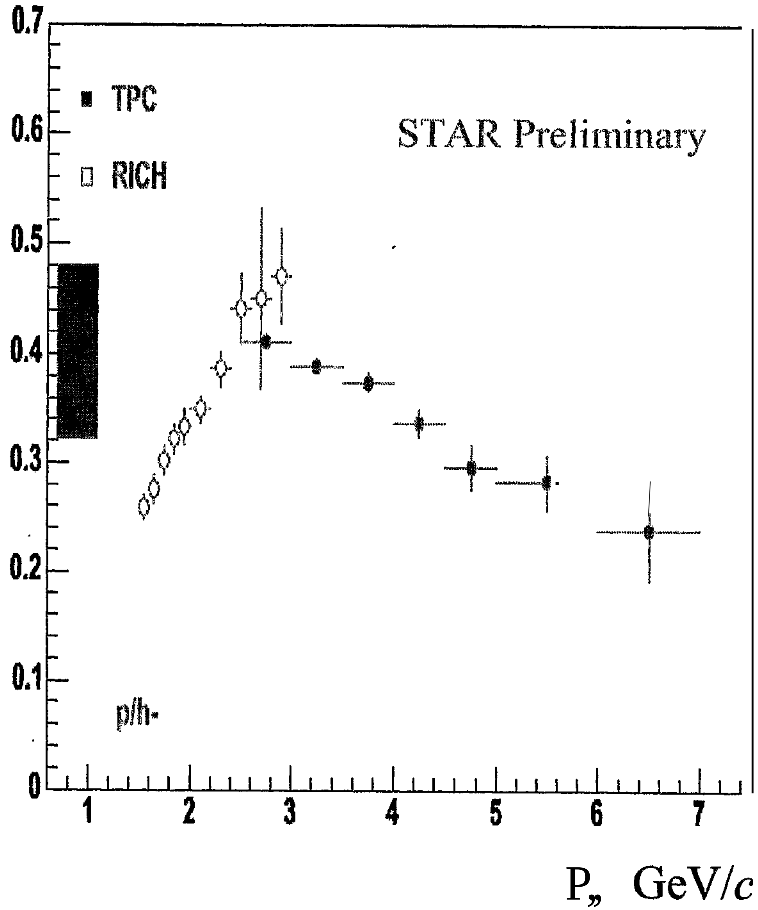
Charged hadrons: statistics limited

Neutral pions: triggered in EMC (A. Mischke (STAR) nucl-ex/0412045)

p+p reference work in progress

Baryon Production





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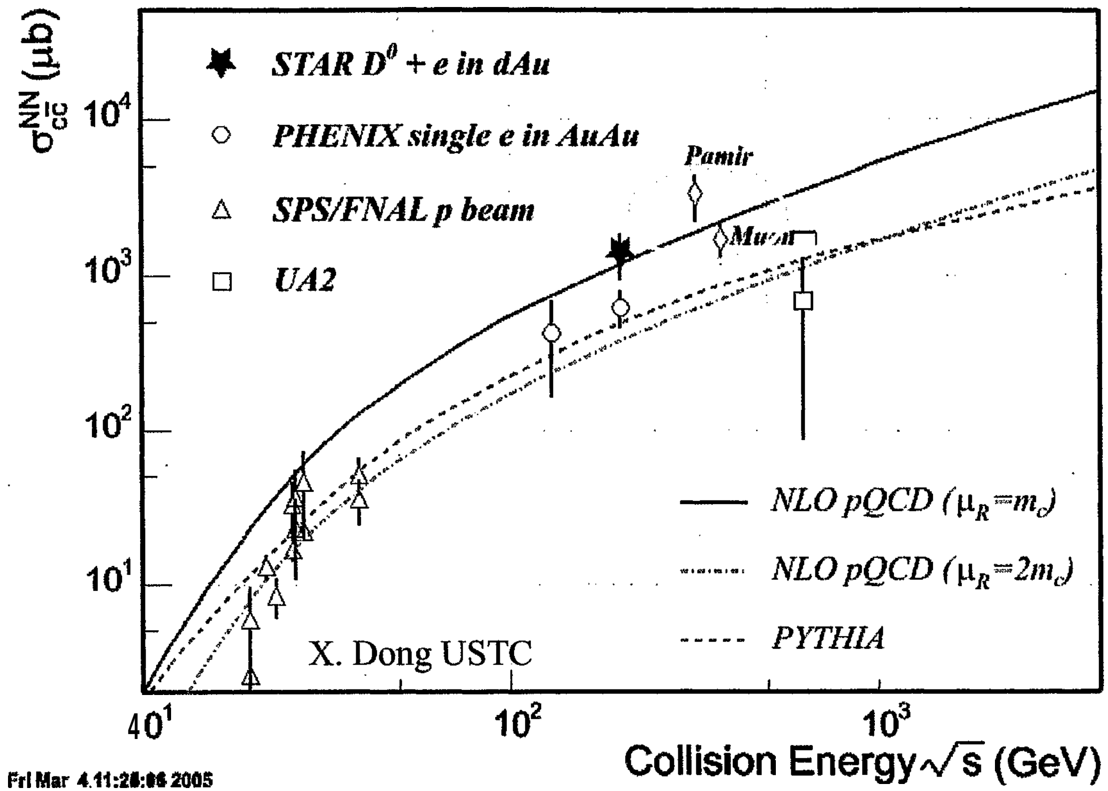
Proton (relative) yield decreases rapidly beyond p_T=3 GeV/c!

pion, proton spectra at high p_T; PID jet correlations

Charm Total Cross Section



Data
STAR/PHENIX: x2 (<2σ)?
Lower Energies: inconsistent?

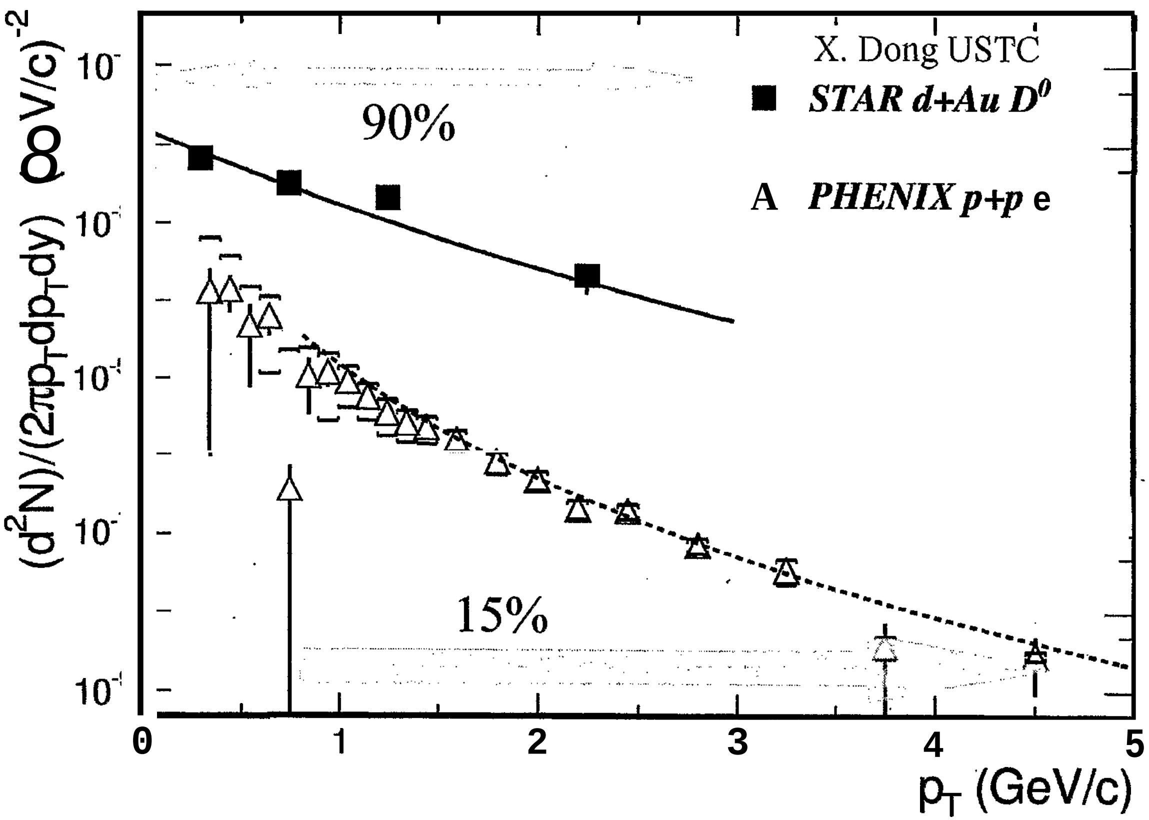
Models:
PHENIX: consistent with default PYTHIA,pQCD
STAR: >3 above ?
Energy dependence μ_R **and** μ_F**?**

Need smaller errors to constrain pQCD and determine the effects in Cosmic Ray Showers

Can we confirm or rule out Cosmic Ray experiments (Parnir, Muon, Tian Shan) under similar conditions?

Pamir, Nuovo Cim 24c (2001) 557; NPB 122(2003) 353c

Combine STAR/PHENIX Charm



STAR: PRL 94(2005)

PHENIX p+p (QM04):
S. Kelly et al. JPG30(2004) S1189

Discrepancy between STAR and PHENIX should be resolved!
J. Stachel, ICPAQGP05 Summary talk

No discrepancy?

σ_{cc}=1.1±0.1 ± 0.3 mb

STAR (1.4) PHENIX *(0.7)*

D0 <pT> = 1.3 GeV/c

D→e <pT> ~= 0.5 GeV/c

Conclusions

- Charged hadron identification at high pT can be done with STAR TPC (+TOF)
- Au+Au 62.4 GeV
  - h/π ratios depend on charge, centrality and pT
  - R_{CP} of h and pions approach each at pT~=5 GeV/c
- Au+Au 200 GeV
  - Identification at high pT possible, p/h ratios decrease at pT>3 GeV/c
- Rapidity Asymmetry of pions in d+Au follows closely that of inclusive hadrons
- More and exciting results from high pT PID soon.

- Charm cross sections measured in p+p, d+Au and Au+Au(soon).
- Comparisons to Models and other experiments discussed
- Open Charm measurements at RHIC exciting, but also have limitations/puzzles so far.
- Vertex detector upgrades needed!

What can we learn about the sQPG at RHIC from Azimuthal Angular Correlation Measurements?

Wolf G Holzmann

From the transverse energy distributions, there is evidence for the creation of matter with energy density well above that required for a deconfined phase of quarks and gluons (QGP) in mid-central to central Au+Au collisions at RHIC.
Substantial elliptic flow signals indicate that the medium is thermalized early and undergoes rapid collective expansion.
This picture of hydrodynamic expansion is further corroborated by the observation of strong radial flow and possible indications of a large emitting source from an HBT-Imaging analysis. The hydrodynamic evolution of the system implies strongly interacting matter at RHIC.
This matter is expected to modify the properties of jets, copiously produced at top RHIC energies. At the center of the discussion is the'question of how this modification might take place. The study of jet characteristics (topologies and yields) via azimuthal angular correlation functions holds much potential to provide answers.

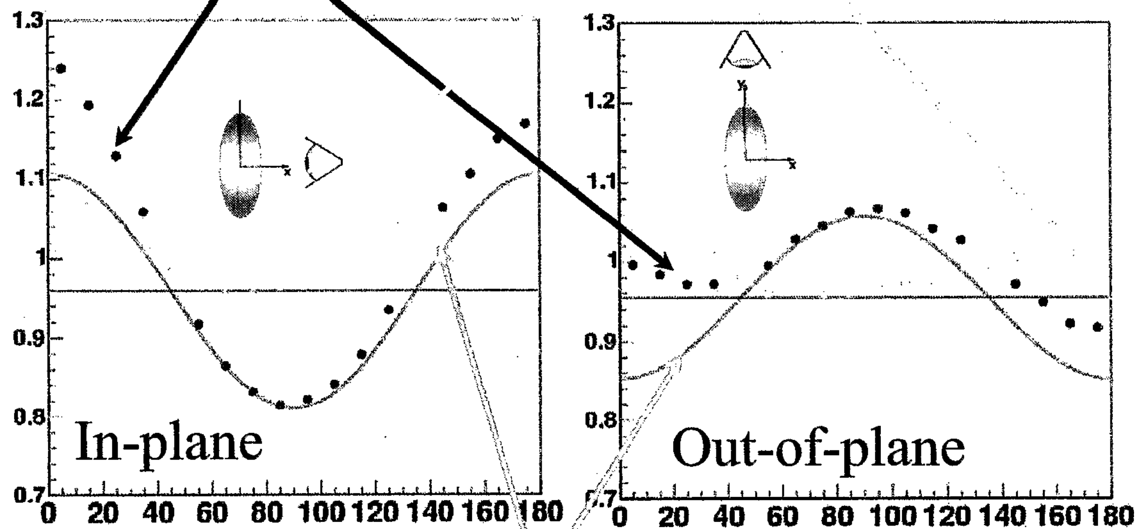
NUCLEAR CHEMISTRY
@ STONY BROOK

Why is the correlation probe so compelling?

Jet Function

Correlation Function

Azimuthal Correlations are derived from Harmonic and di-jet contributions



$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0\left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \right]$$

Harmonic

Azimuthal Correlations Provide Direct Access to the Properties of the High Energy Density Matter Created at RHIC

ZYAM Decompostion of Correlation Function

Ajitanand et al. (nucl-ex/0501025)

Two source model : Flow (H) & Jet (J)

$$\overbrace{C(\Delta\phi)}^{\text{Correlation Function}} = a_0\left[\overbrace{H(\Delta\phi)}^{\text{Harmonic}} + \overbrace{J(\Delta\phi)}^{\text{Jet Function}}\right]$$

$$\overbrace{J(\Delta\phi)}^{\text{Jet Function}} = \frac{\left[C(\Delta\phi) - a_0 H(\Delta\phi)\right]}{a_0}$$

a_0 is obtained without putting any constraint on the Jet shape by requiring

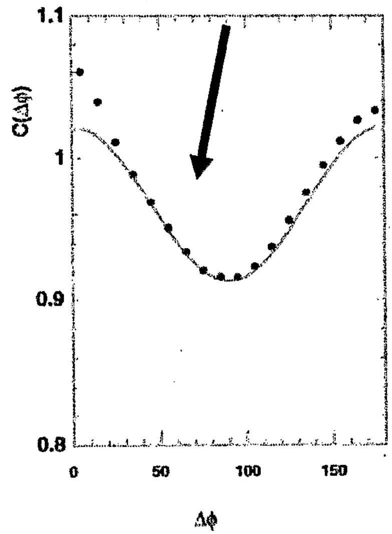
$$J(\Delta\phi_{\min}) = 0$$

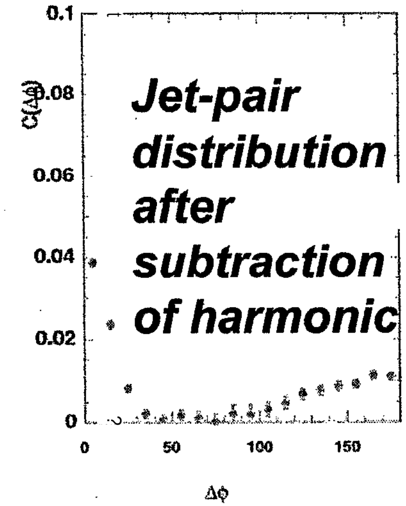
i.e. Zero Yield At Minimum (ZYAM)

H(v2)

Obtain v_2 externally (from RP measurement with Large η gap)

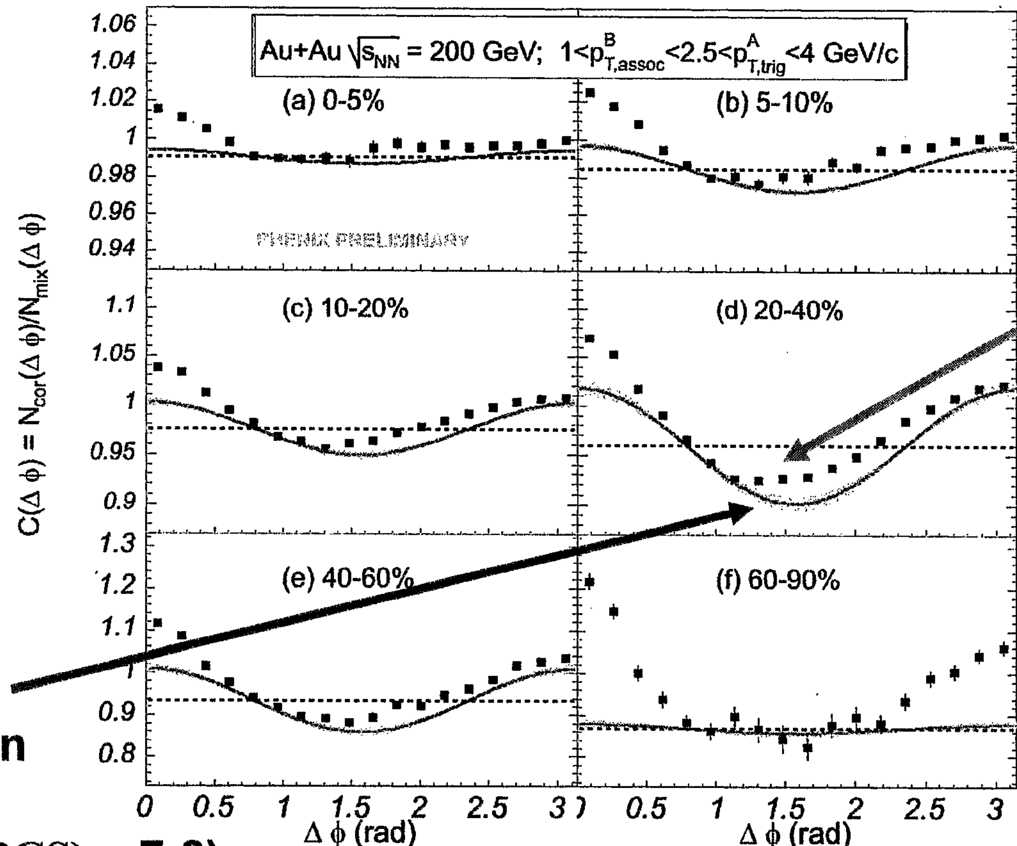
Correlation function with harmonic and jet contributions





Extensive simulation studies support the robustness and reliability of the decomposition procedure!

Application of ZYAM Method to PHENIX Data

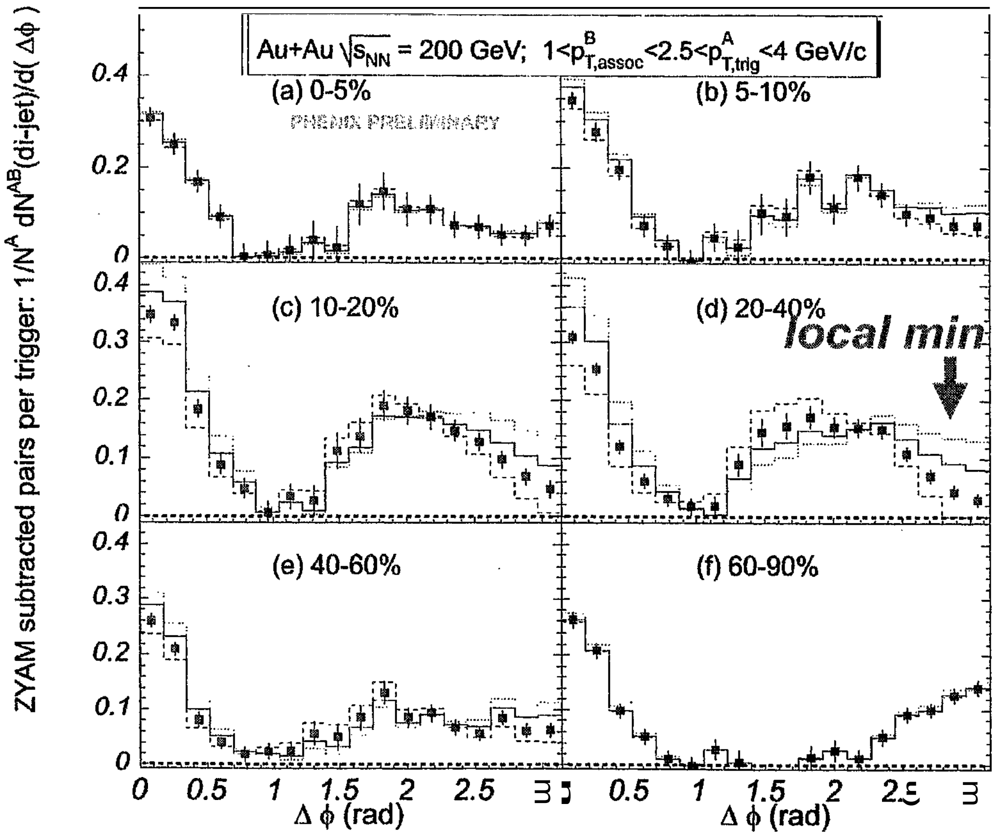


v_2 from BBC Reaction Plane ($\Delta\eta$(BBCN-BBCS) = 7-8)

Minimum of CFctn < 90 deg Modified away-side jet

Reliable decomposition of the data into jet-function and harmonic achieved.

Jet-pair distributions after subtraction of harmonic term

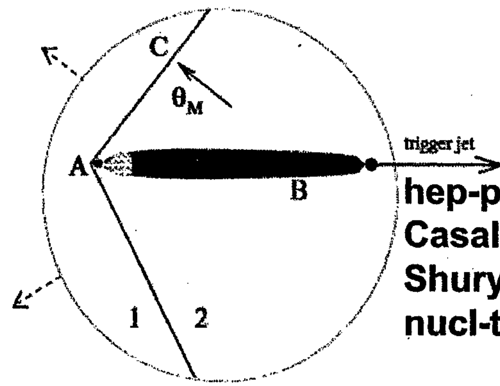


Significant Broadening and Strong Modification of away-side Jet observed!

(Folded into 0-π)

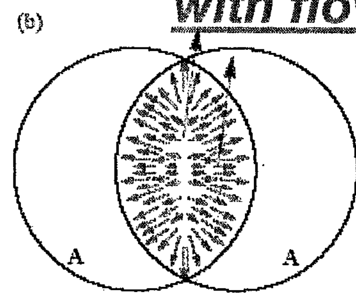
How crazy are those shapes?

Wake effect or "sonic boom"



hep-ph/0411315
Casalderrey-Solana, Shuryak,Teaney
nucl-th/0406018 Stoecker

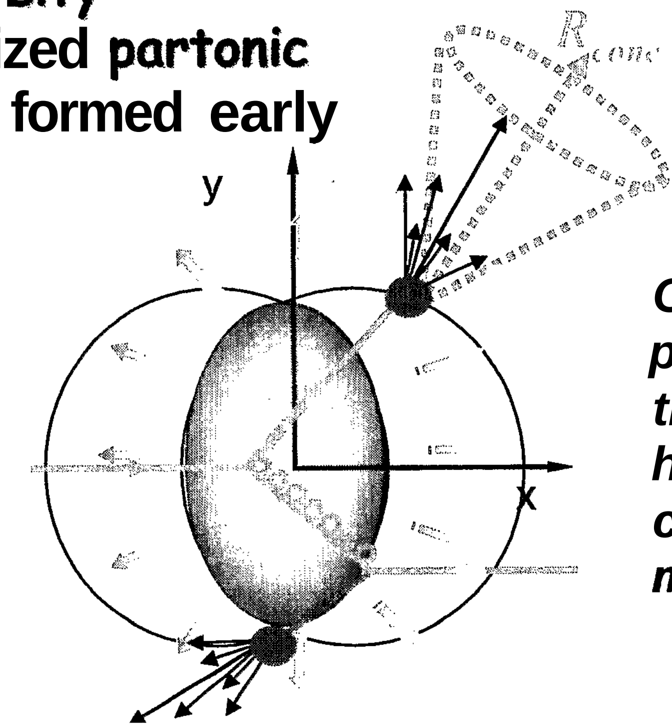
Correlations of Jets with flowing medium



hep-ph/0411341
Armesto,Salgado,Wiedemann

Possible Emerging Picture

High Density Thermalized partonic material formed early



One might conjecture, that hard scattered partons, produced early in the collison, traverse the rapidly expanding, thermalized high-energy density matter and thus could couple with the flowing bulk partonic material.

Correlation measurements suggest compelling evidence for strongly interacting high energy density matter not heretofore seen!

High pt 2-particle correlations: background issues

Sergei A. Voloshin

Wayne State University, Detroit, Michigan

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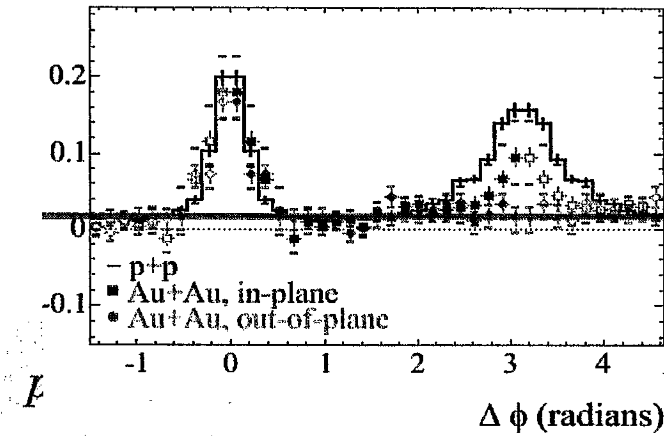
Outline:

- Background and the spatial distribution of fast partons inside a nucleon.
- Background, the momentum conservation, and "thermalization" of the away-side jet.
- New "background" for the correlation jet study: Correlations due to transverse radial flow
  - > p_t correlations
  - > Elongation of rapidity correlations with centrality; narrowing of the Charge Balance Function in $\Delta\eta$.
  - > Azimuthal correlations & Balance function in $\Delta\varphi$
  - > High pt - medium/low pt correlations: (and 'jet tomography')

-Summary

Background value and probabilities of multiple hard collisions



$$\tilde{B}(\Delta\varphi) = \frac{\rho_2(\Delta\varphi)}{n_1(p_{\perp 1})} - \frac{n_2(p_{\perp 2})}{2\pi} F\, f(\Delta\varphi)$$

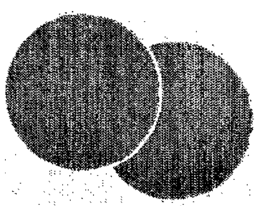
The values of the background larger than given by the inclusive single particle spectrum means that the probability of two hard collisions is larger than the square of probabilities of single hard collision.

What defines the value of the uncorrelated background?
Why is it larger then determined by inclusive single particle spectrum, which would correspond to the case of independent hard collisions?

■ The probability of hard collision is proportional to the area A of the overlap region, then

$$\frac{p_2}{p_1^2} = \frac{\langle A^2\rangle}{\langle A\rangle^2} > 1$$

for two overlapping discs and average over *bdb*, this ratio is rather large, 4-64/(3π²) ≈1.84 ,... but still lower than the experimental value, of about 2.5 (?)



Consider a case when more energetic **partons** are distributed in a region occupying only a fraction *q* of the total area (occupied by soft **partons**). Then

$$\frac{p_2}{p_1^2} = \frac{1.84}{q}$$

This idea is basically the same as of Strikman-Frankfurt-Weiss hep-th/0410307, but they link it to 4-jet cross-section

Momentum conservation

Borghini, Dinh, Ollitrault, PRC 62 (2000) 034902

$$\frac{dN_{12}}{d\Delta\phi} \propto 1 - \frac{2\vec{p}_1\vec{p}_2}{\sum p_i^2}$$

$$f(\Delta\varphi) \propto 1 + 2\langle\cos(\Delta\phi)\rangle\cos(\Delta\phi)$$

$$\langle\cos(\Delta\phi)\rangle = -\frac{\langle p_{t,trig}\, p_{t,asso}\rangle}{N_{system}\langle p_t^2\rangle_{over\ N_{system}}}$$

N_{system} - number of particles in the system, all of them equally "participate" in the momentum balance.
Assumption: $N_{system} \gg 1$ (needed to apply CLT)

Results of the **fit** to the data is consistent with $N_{system} = N_{total}$ and this creates a common confusion: how **all** the particles could participate?

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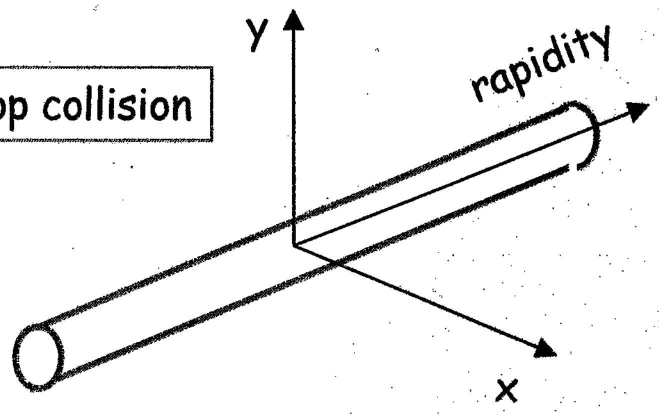
$$\langle\cos(\Delta\phi)\rangle = -\frac{w\langle p_{t,trig}\, p_{t,asso}\rangle}{N_{mom}\langle p_t^2\rangle_{over\ N_{mom}}}$$

N_{mom} - number of particles "participating", in the momentum conservation.
w - probability that a given "associated" particle belongs to N_{mom}.

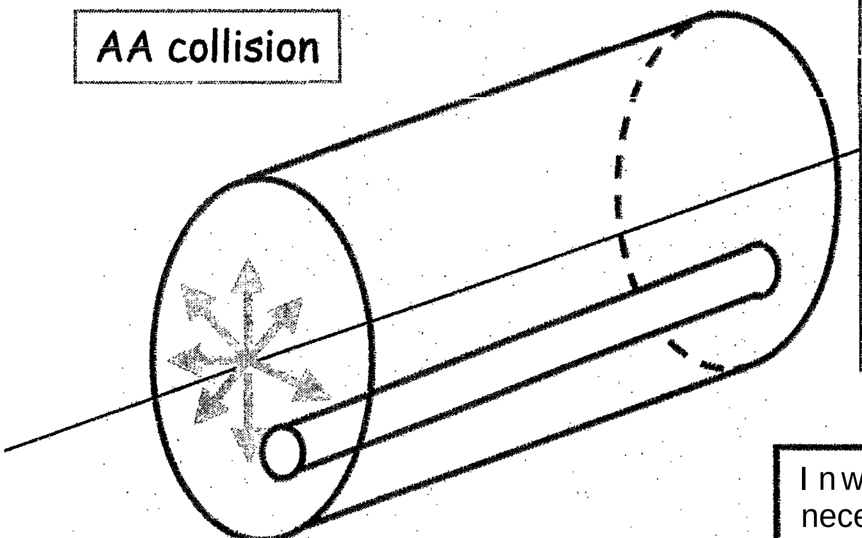
If $dN_{mom}/dy \sim dN_{ch}/dy$, $w/N_{mom}=1/N_{total}$.

Radial flow → 2- particle correlations

pp collision



AA collision



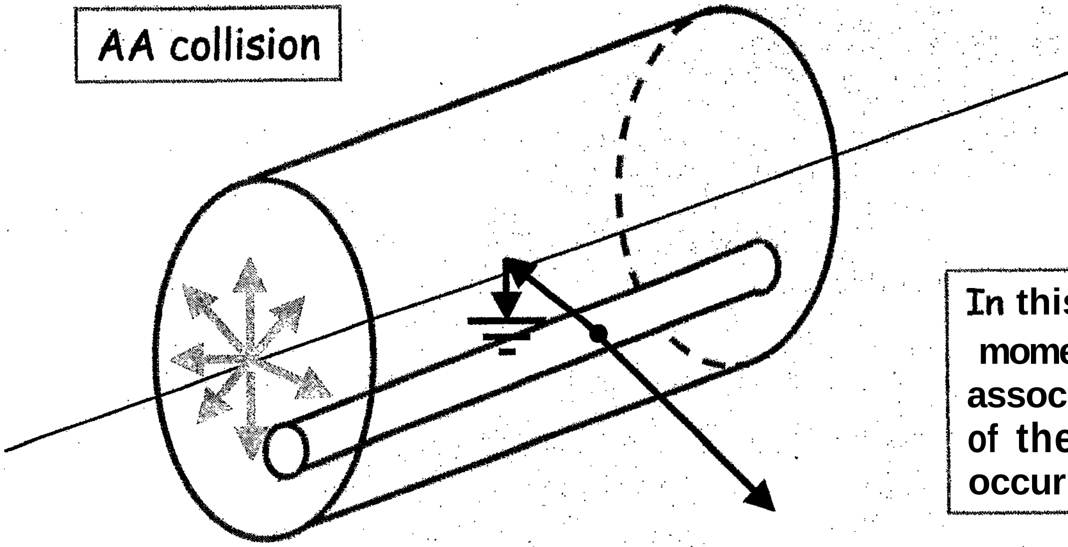
All particles produced in the same NN-collision (qq-string) experience the transverse radial "push" that is
(a) in the same direction (leads to correlations in phi)
(b) the same in magnitude (→ correlations in p_t)
→ **Position-momentum correlations caused by transverse** expansion "brings" totally **new mechanism for momentum correlations, not present in NN-collisions**

Just a few "**details**":
-Long range rapidity correlations ("bump"- narrow in phi and wide in rapidity, charge independent)
-Stronger 2-particle pt correlation in narrow phi bins
-Narrowing of the charge balance function
($\Delta p_z \approx m_t \sinh(\Delta y)$ **-- increase in m_t → decrease in rapidity separation)** [same as in S. Pratt et al, in "late hadronization scenario"]
- Charge correlations in phi. Azimuthal Balance function

Everything evolving with centrality (radial flow)

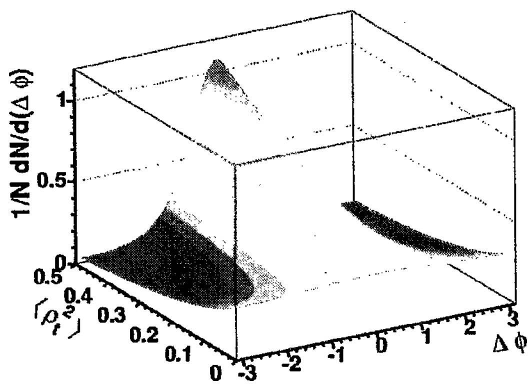
In what follows, radial expansion is treated as given. Not necessarily as due to pressure in thermalized matter, could be considered a la "parton wind"; but numerical calculations are done in the blast wave model.

AA collision. "Single jet tomography".



In this picture, the transverse momentum of the (Same side, large $\Delta\eta$) associated particles would be a measure of the space position the hard scattering occurred

The plot on the right shows particle azimuthal distribution (integrated over all pt's) with respect to the boost direction.
In order to compare with data it should be also convoluted with jet azimuthal distribution relative to radial direction.



summary

1. Please, present/publish the background values from single inclusive spectra and all "fudge" factors. They potentially contain interesting physics.
2. The "away-side" correlations could be as "wide" as ~ $-\cos(\Delta\varphi)$.

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1. Transverse radial flow leads to strong space-momentum correlation. In combination with space correlations between particles created in the same NN collision, it leads to characteristic two (and many) particle rapidity, transverse momentum, and azimuthal correlations.

2. This phenomenon provides a natural (at present, qualitative) explanation of the centrality dependence of mean p_t pseudorapidity/azimuthal angle correlations. It can be further used to study the details of the system equilibration/thermalization and evolution (e.g. thermalization time, velocity profile, etc.)

3. Transverse radial flaw "push" of particles created in the same NN collision where hard scattering occurred + jet quenching leads to azimuthal correlations of high pt "trigger" particle with "soft" particles at rather different rapidity. The mean transverse momentum of the associated particles would be a measure of how deep in the system the hard collision occurred.

High-pT correlations from parton transport

Denes Molnar
Ohio State University, Columbus, OH, USA

Jet Correlation Workshop

March 10 11, 2005, RIKEN/BNL Research Center, Upton, NY

- **Implications of an opaque parton soup**

DM & Gyulassy NPA697 ('02); DM & Huovinen PRL94 ('05); DM nucl-th/041041

- **Quark number scaling of v_2 and quark coalescence**

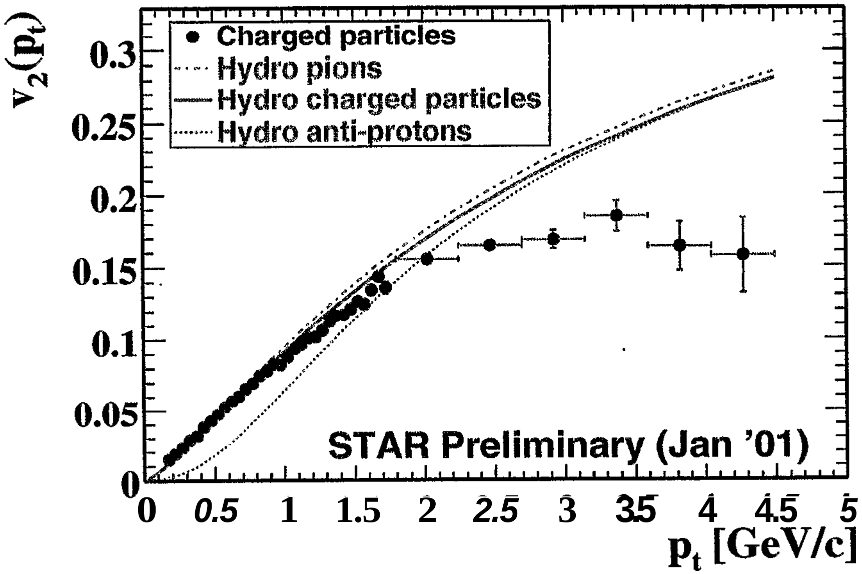
DM & Voloshin PRL91 ('03) 092301; DM nucl-th/0406066, nucl-th/0408044

- **Where v_2 comes from at moderately high p_T**

DM in progress

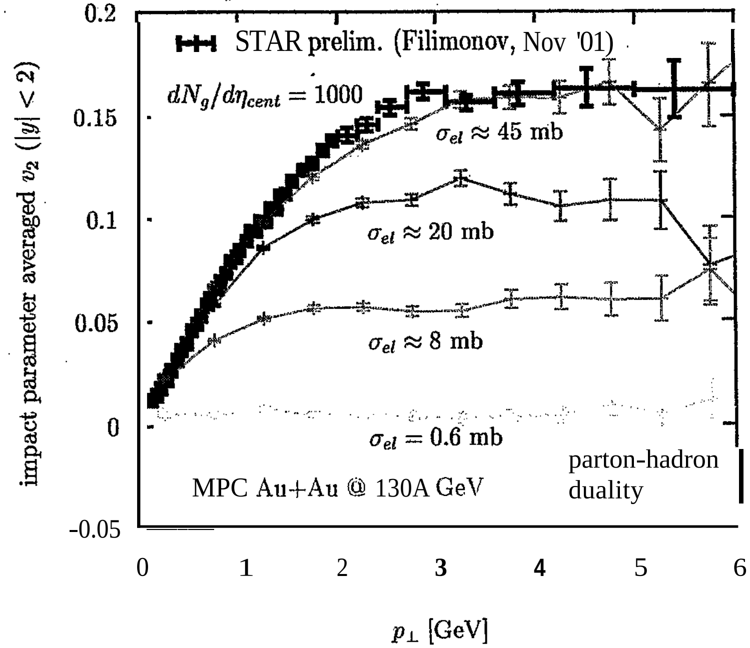
Kolb, Heinz et al

ideal hydro $v_2(6GeV)/v_2(3GeV) > 1.5$



Dm & Gyulassy

covariant parton transport ~ 1



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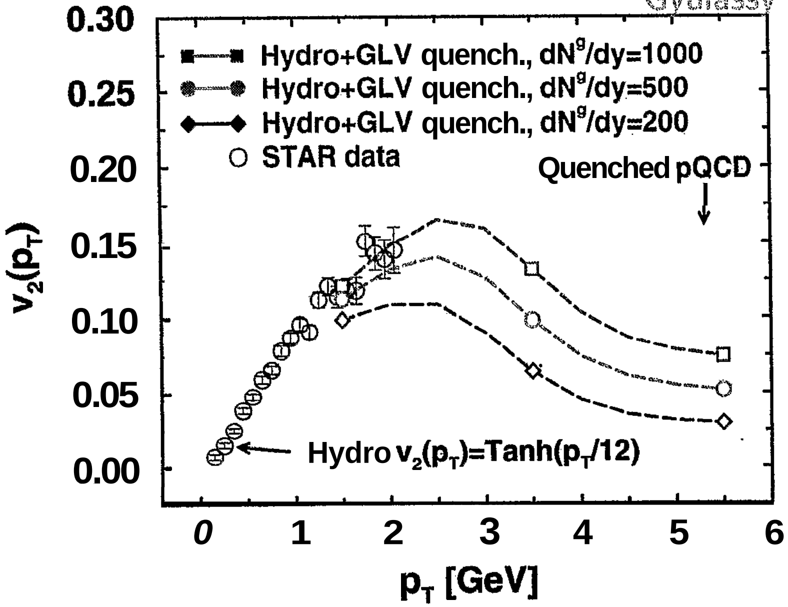
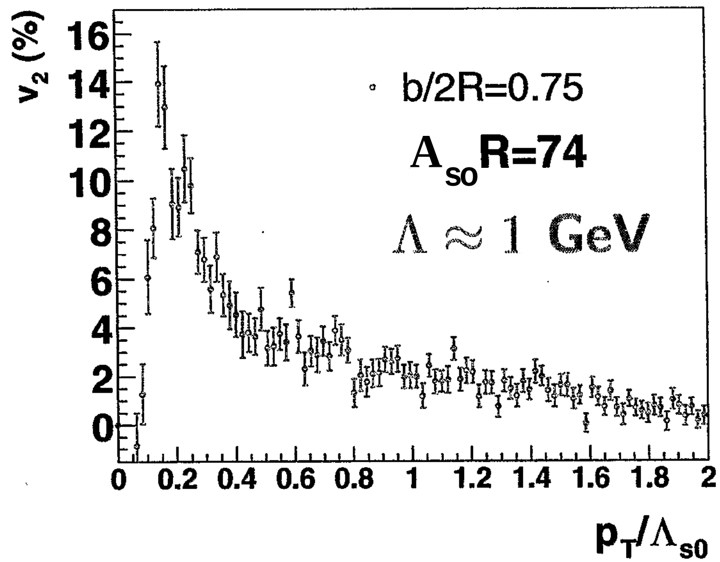
parton energy loss $\sim 0.4 - 0.5$

Gyulassy & Vitev



classical Yang-Mills ...

Krasnitz, Nara, Venugopalan



from coalescence formula

$$\frac{dN_M(\vec p)}{d^3p} = g_M \int (\prod_{i=1,2} d^3x_i d^3p_i) W_M(x_1 - x_2, \vec p_1 - \vec p_2) f_\alpha(\vec p_1, x_1) f_\beta(\vec p_2, x_2) \delta^3(\vec p - \vec p_1 - \vec p_2)$$

$$\frac{dN_B(\vec p)}{d^3p} = g_B \int (\prod_{i=1,2,3} d^3x_i d^3p_i) W_B(x_{12}, x_{13}, \vec p_{12}, \vec p_{13}) f_\alpha(\vec p_1, x_1) f_\beta(\vec p_2, x_2) f_\gamma(\vec p_3, x_3) \delta^3(\vec p - \sum \vec p_i$$

hadron yield   space-time   hadron wave-fn.   quark distributions

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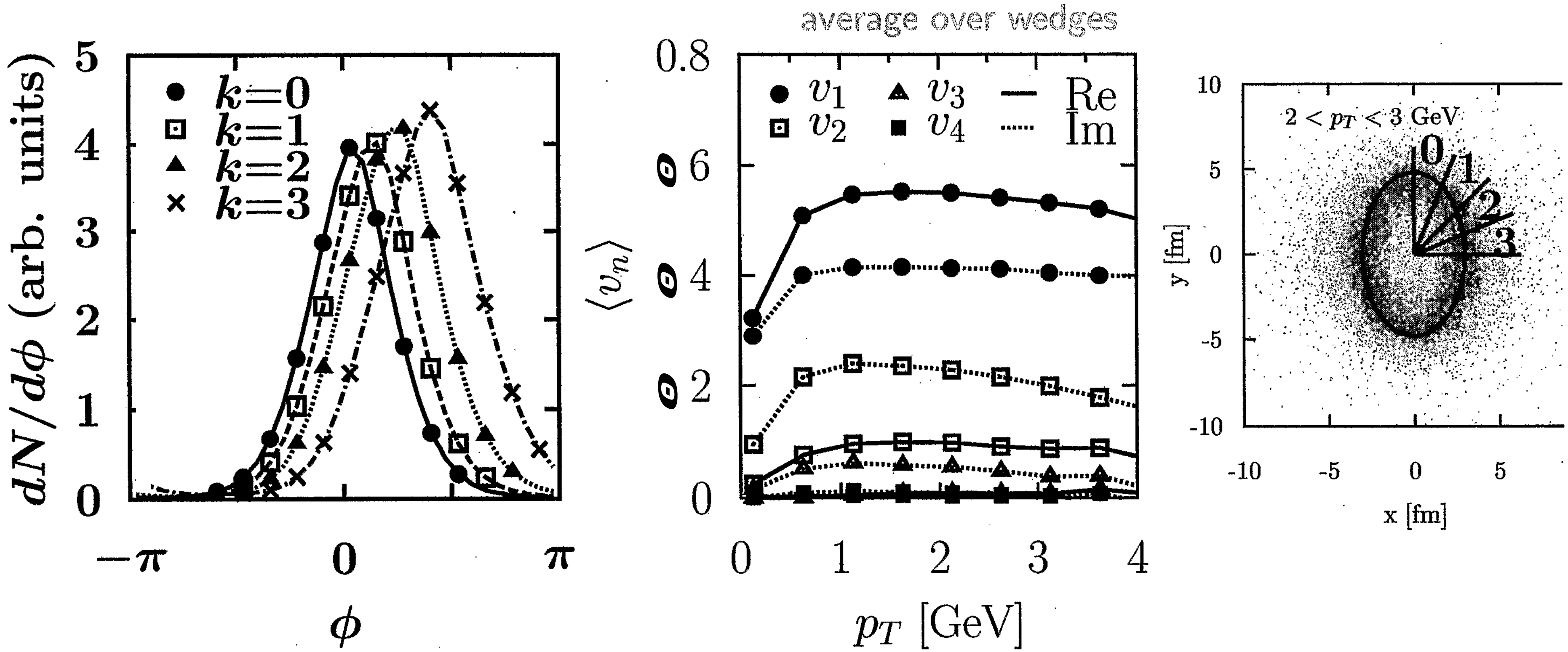
v_2 scaling arises trivially if:

1. no other hadronization channels play a role
2. only small harmonic modulations $|v_2| \ll 1$, $|v_n| \ll$ +
3. spatial dependence can be ignored (e.g., factorizes out)
4. narrow wave functions $W \sim \delta^3(\Delta x)\delta^3(\Delta p)$

Are these conditions satisfied?

3. Surface emission → $|v_n| \sim \mathcal{O}(1)$

local $\cos(n\phi)$ **and** $\sin(n\phi)$ **anisotropies → use** $v_n \equiv \langle \cos(n\phi) + i\sin(n\phi)\rangle$



large $|v_n| \sim 1$**, almost Gaussian peaks** - $dN/d\phi \sim \exp[-(\phi-\phi_0)^2/(2\sigma^2)]$

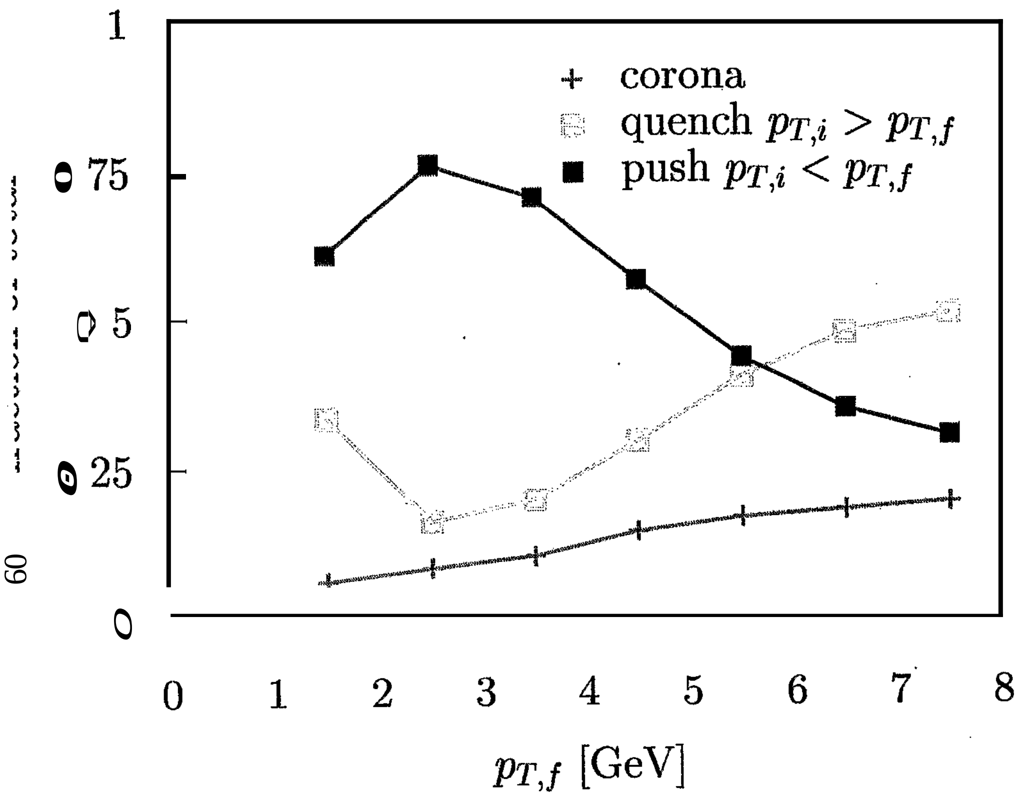
$\langle\cos(2\phi)\rangle = \cos(2\phi_0)\cdot|v_2|$ → **varies with transverse coordinate**

DM, nucl-th/0408044

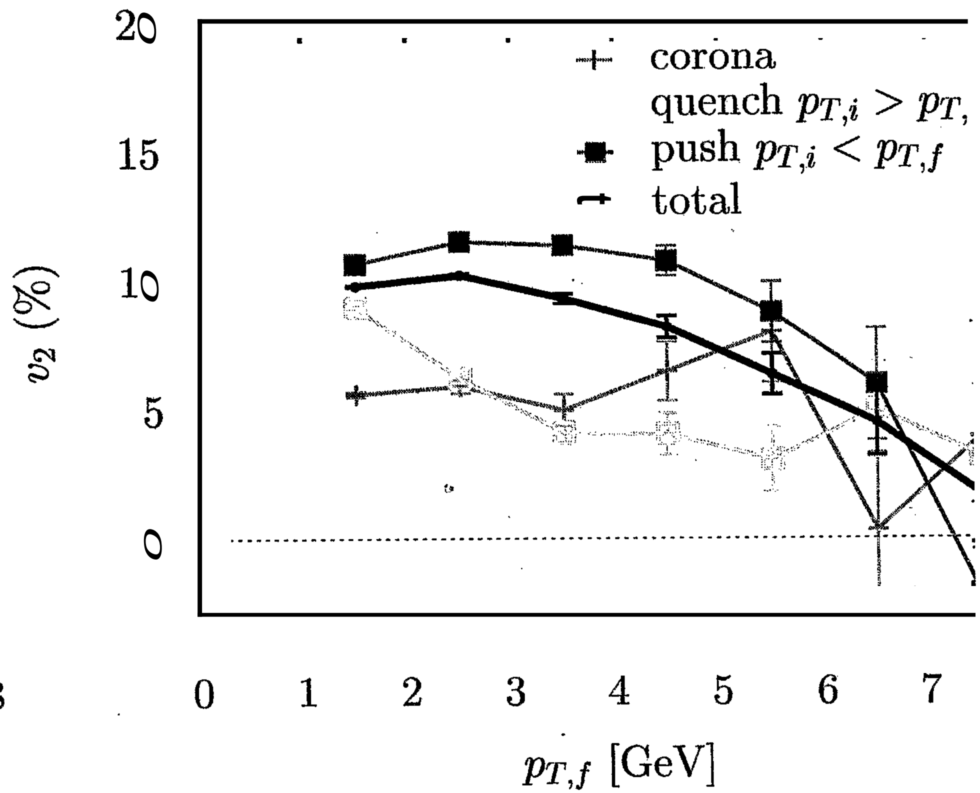
⇒ **new scaling:** $|v_{n,B}(3p_T)| \simeq |v_{n,q}(p_T)|^{1/3}$, $|v_{n,M}(2p_T)| \simeq |v_{n,q}(p_T)|^{1/2}$

corona/quench/push fractions

DM '05:



elliptic flow contributions vs pT



rapid v_2 drop from quench at high p_T is compensated by large v_2 of "pushed-up" partons

combined $v_2(p_T)$ still decreases at high p_T, but more slowly

Summary

- A significant fraction of initially soft partons can end up at high p_T and moderate drop of v_2
  - cannot ignore cross-talk between soft and hard even at $p_T \sim 6 - 7$ GeV, for $6\times$ perturbative opacities
  - expect even stronger effect for the strongly-coupled RHIC plasma ($15\times$ perturbative opacities)
  - precision data should settle whether we "need" such a component to supplement quenching results

- The observed quark number scaling of v_2 is truly remarkable. **From parton transport theory**
  - significant fragmentation contributions
  - strong space-momentum correlations (spatial anisotropies)
  - and surface emission

each spoil the scaling. The scaling may hold accidentally, however, there seems to be no guarantee that the scaled v_2 gives the v_2 of quarks at hadronization. Does even the ϕ meson scale??

Recombination and Hadron Correlations

Rainer Fries

University of Minnesota

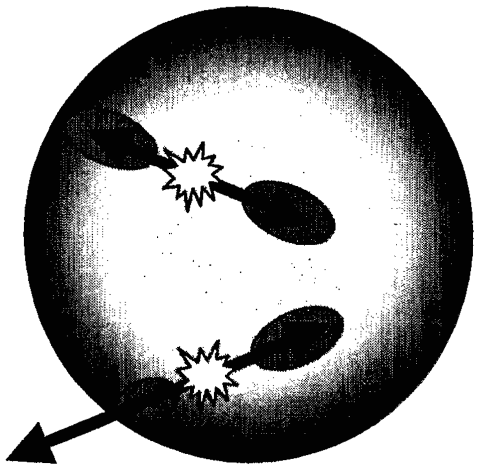
Talk at the RIKEN Workshop *Jet Correlations at RHIC*

Brookhaven National Lab March 11, 2005

Hot Spots

- **Strong energy loss (dE/dx up to 14 GeV/fm,** X.N. **Wang)**
  - **a lot of quenched/partially thermalized jets**
  - **Localized deposition of energy and momentum**

⇨ Hot Spots?



- Hot **spot can be correlated with remaining jet**
- **Partons in the hot spot can be correlated with themselves**

Associated Yield

- List of assumptions
  - Only look at near side
  - Small correlations, keep only terms linear in c_0 and v_2
  - Narrow wave functions
  - Correlations constant over volume V_c
- Associated yield

$$Y_{AB}(\Delta\phi) = \frac{1}{N_A}\left(\frac{dN_{AB}}{d(\Delta\phi)} - \frac{d(N_A N_B)}{d(\Delta\phi)}\right)$$

- Here

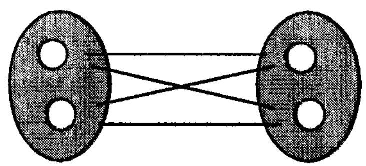
[redacted]

$$C_0 = c_0 \frac{V_c}{V_\Sigma}$$

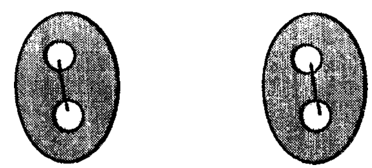
Amplifications of Correlations

- Q: Amplification factor
- Count 2-parton pairs between the 2 hadrons; for effects linear in c_0, only 1 correlation allowed.

Q=4	Meson-meson
Q=6	Meson-baryon
Q=9	Baryon-baryon



4 pairings that lead to meson correlations



2 pairings without correlating the mesons

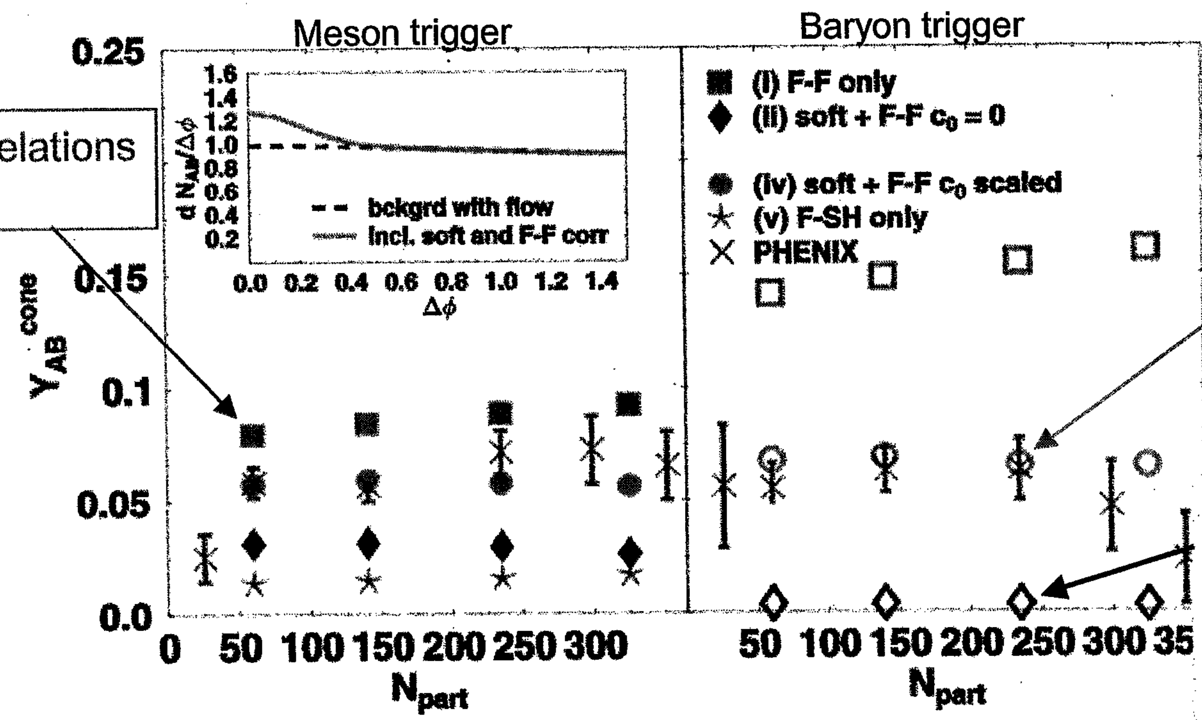
- Uncorrelated background (for meson-meson)

$$N_A N_B /(2\pi)\left(1+2C_0+2\overline{v}_2^A\overline{v}_2^B\cos(2\Delta\phi)\right)$$

Numerical Example

- **Proof of principle using Duke parametrization**
  - ⇨ consistent with spectra and ratios!

$$Y_{AB}^{\text{cone}} = \int_0^{0.94} d(\Delta\phi) Y_{AB}(\Delta\phi)$$



Large correlations from F-F.

F-F and SS-SS with C_0=0.08x100/N_{part} (V_c~const.)

Lower associated yield when adding SS-SS without correlations (C_0=0), especially for baryon triggers.

Consistency with PHENIX data can be reached.

RJF, Muller, Bass: nucl-th/0407102, PRL in print

Conical or Radial Flow?

- Flowing hot **spot?**
  - Defocussing through radial flow
- Different from conical flow
  - η-φ picture

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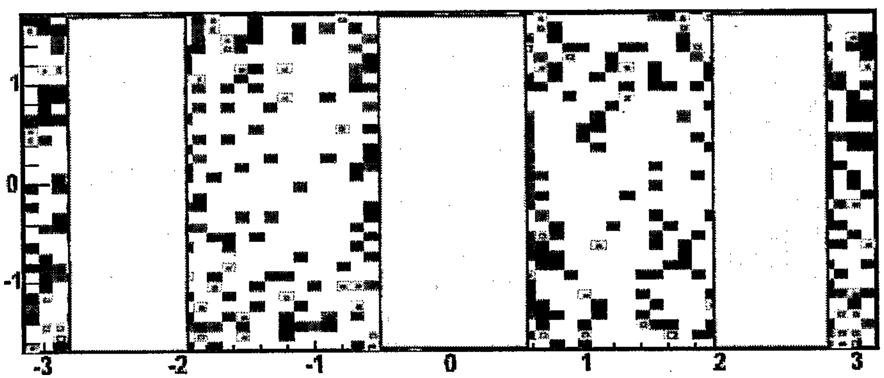
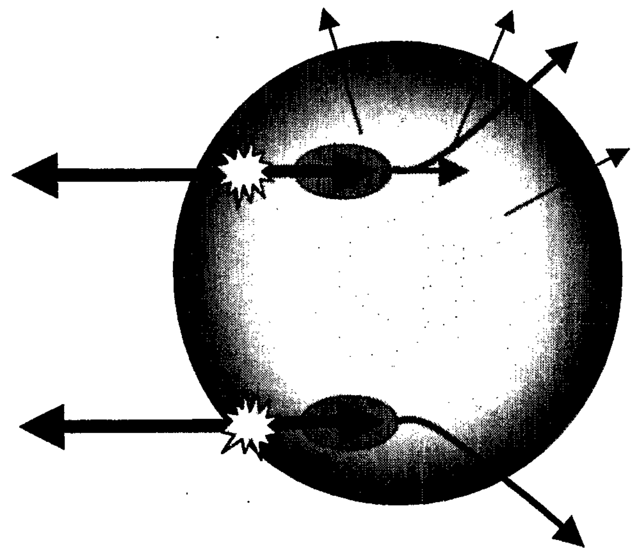




→ **A. Dumitu's talk**

Parton and Hadron Correlations in Jets

Rudolph C. Hwa
University of Oregon

RIKEN Workshop on Jet Correlations

BNL, March 2005

Correlation function

$$C_2(1,2) = \rho_2(1,2) - \rho_1(1)\rho_1(2)$$

$$\rho_2(1,2) = \frac{dN_{\pi_1\pi_2}}{p_1 dp_1 p_2 dp_2} \qquad \rho_1(1) = \frac{dN_{\pi_1}}{p_1 dp_1}$$

$$F_4 = (\mathbf{TT} + \mathbf{ST} + \mathbf{SS})_{13}(\mathbf{TT} + \mathbf{ST} + \mathbf{SS})_{24}$$

Factorizable terms: $(\mathbf{TT})_{13}(\mathbf{TT})_{24}$ $(\mathbf{ST})_{13}(\mathbf{TT})_{24}$ $(\mathbf{TT})_{13}(\mathbf{ST})_{24}$

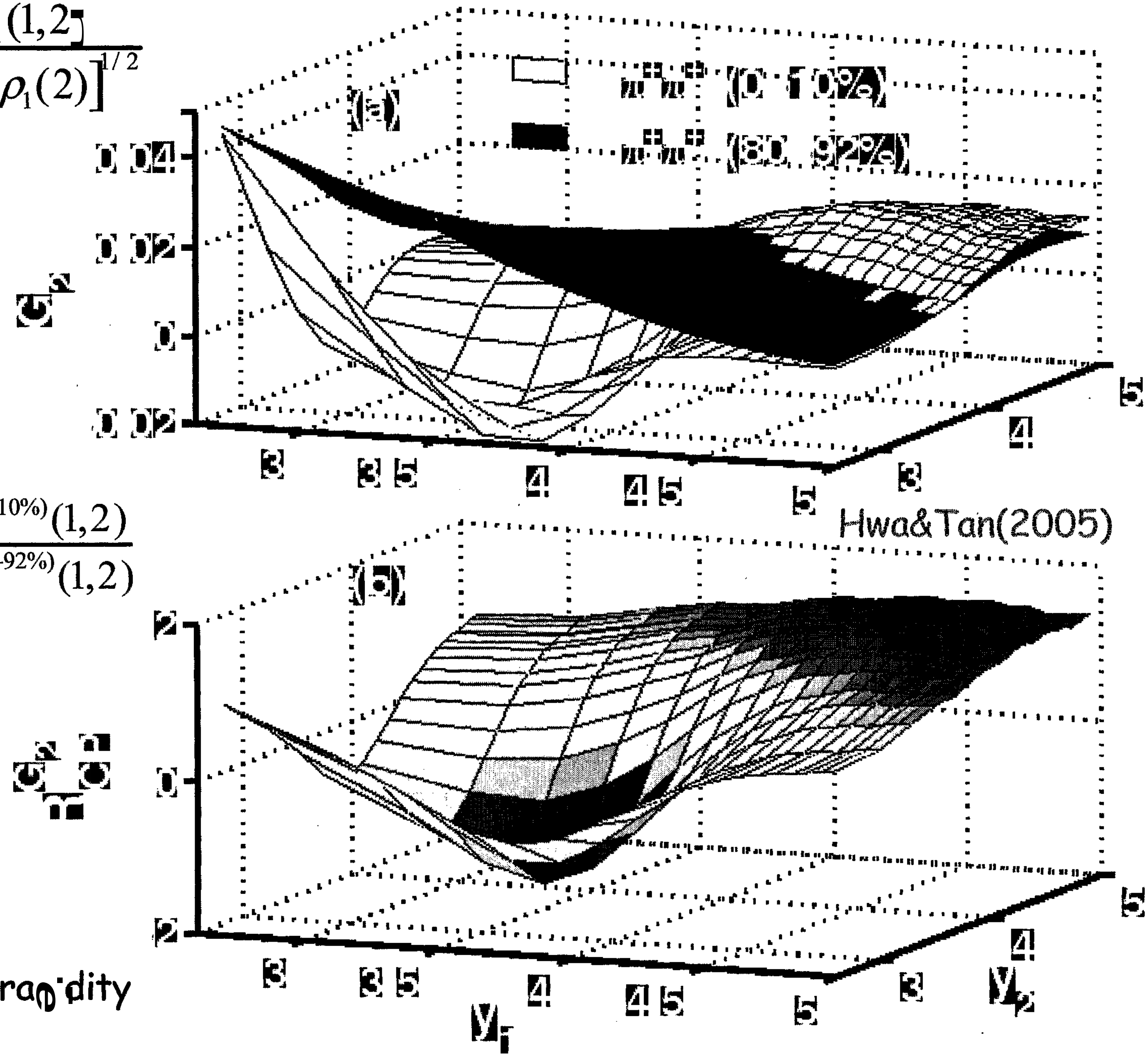
Do not contribute to $C_2(1,2)$

Non-factorizable terms $(\mathbf{ST} + \mathbf{SS})_{13}(\mathbf{ST} + \mathbf{SS})_{24}$

↑ **correlated** ↑

$$G_2(1,2) = \frac{C_2(1,2)}{\left[\rho_1(1)\rho_1(2)\right]^{1/2}}$$

$$R_{CP}^{G_2}(1,2) = \frac{G_2^{(0-10\%)}(1,2)}{G_2^{(80-92\%)}(1,2)}$$



y = transverse rapidity

Physical reasons for the big dip:

(a) central: (ST)(ST) dominates

S-S correlation weakened by separate recombination with uncorrelated (T)(T)

(b) peripheral: (SS)(SS) dominates

SS correlation strengthened by double fragmentation

The dip occurs at low p_T because at higher p_T power-law suppression of $\rho_1(1)\,\rho_1(2)$ results in $C_2(1,2) \sim \rho_2(1,2) > 0$

For **STST** recombination

$$F_4' = \xi \sum_i \int dk k f_i(k) \mathbf{T'}(q_3)\{\mathbf{S}(q_1),\mathbf{S}(q_2)\}\mathbf{T'}(q_4) e^{-\psi^2/2\sigma^2(q_2/k)} \Big|_{\psi=2\tan^{-1} g(\eta,\eta_1)}$$

enhanced thermal ($\mathbf{T'}(q_3)$, $\mathbf{T'}(q_4)$)

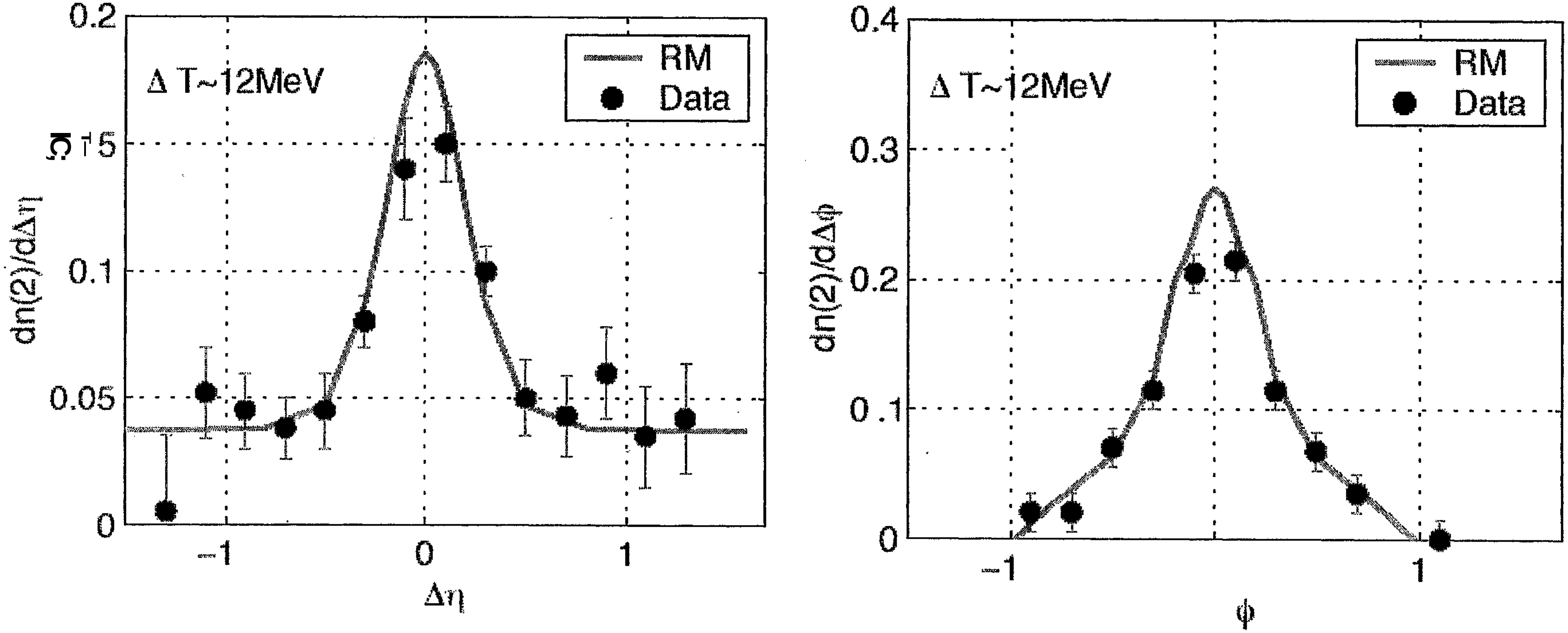
trigger ($\{\mathbf{S}(q_1),\mathbf{S}(q_2)\}$)

associated particle ($\mathbf{S}(q_2)\}\mathbf{T'}(q_4) e^{-\psi^2/2\sigma^2(q_2/k)}$)

Sample with trigger particles and with background subtracted

$$F_4^{tr-bg} = \sum \int \mathrm{L}\ (\mathbf{ST'})_{13}\underbrace{(\mathbf{T'T'}-\mathbf{TT})_{24}}_{\text{Pedestal}} + (\mathbf{ST'})_{13}\underbrace{(\mathbf{ST'})_{24}}_{\text{peak in }\Delta\eta\ \&\ \Delta\phi}$$

STAR data



The pedestal is due to enhanced thermal source having ΔT higher in T′. It is extended in Δη because the enhanced thermal partons expand with longitudinal expansion of the bulk medium, unlike in the φ direction where radial expansion does not affect Δφ.

Chiu & Hwa (2005)

Jet Physics in Heavy Ion Collisions at the LHC

Andreas Morsch (CERN, Geneva, Switzerland)

Copious production of jets in PbPb collisions at the LHC

- < 20 GeV many overlapping jets/event
  - Jet studies via inclusive leading particle correlation
- **6** 10^5 Jets $E_T > 100$ GeV for $|y|<0.5$

Background conditions require jet identification and reconstruction in reduced cone $R <$ *0.3-0.5*

We will measure jet structure observables (k_T, fragmentation function, jet-shape) for reconstructed jets:

- High-p_T capabilities (calorimetry) needed to reconstruct parton energy
- Good low-p_T capabilities are needed to measure particles from medium induced radiation.

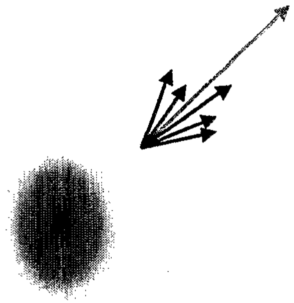
In particular ALICE needs calorimetry (EMCAL) for triggering and jet reconstruction

- **...** and this would make it the ideal detector for jet physics at the LHC covering the needed low and high-p_T capabilities + particle ID.

The development of QCD would have been impossible without the feedback and constant pressure from experimental data. Let's keep the pressure up to a maximum during the LHC era !

Naturally the next step: Reconstructed jets ...

Leading Particle



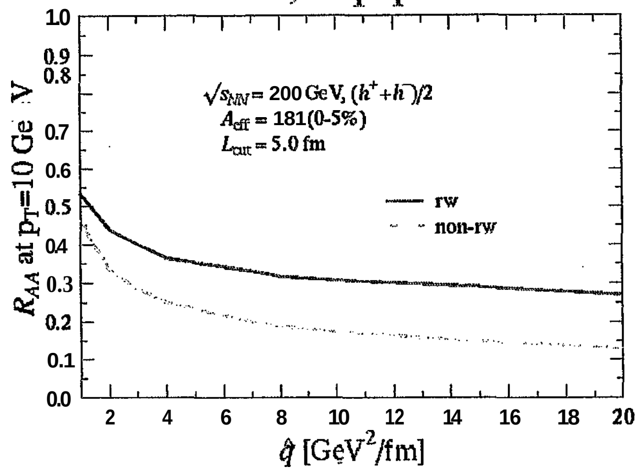
The leading particle as a probe becomes fragile in several respects:

Surface emission "trigger bias" leading to

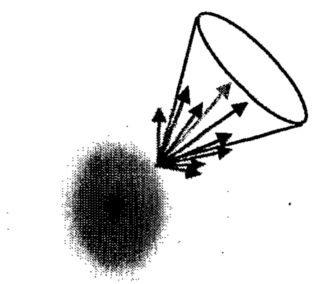
- Small sensitivity of R_{AA} to variations of transport parameter q^{hat}.
- Yields lower limit on color charge density.

For increasing in medium path length L leading particle is less and less correlated with jet 4-momentum.

Eskola et al., hep-ph/0406319



Reconstructed Jet



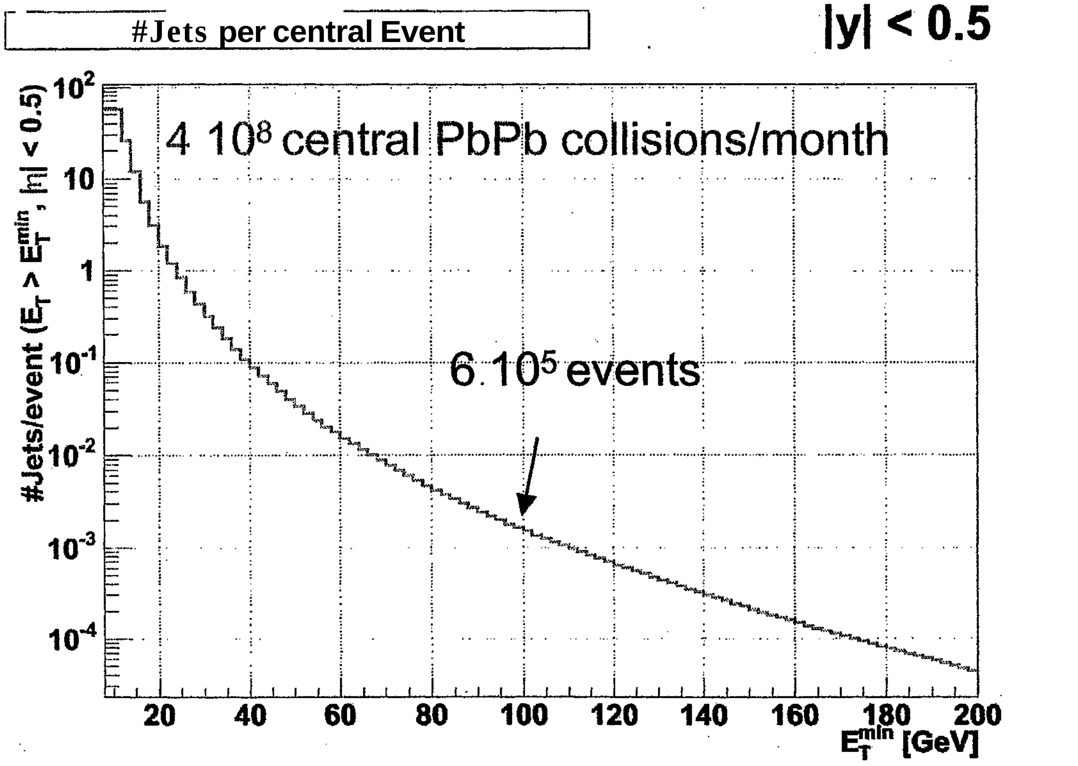
Ideally, the analysis of reconstructed jets will allow us to measure the original parton 4-momentum and the jet structure (longitudinal and transverse). From this analysis a higher sensitivity to the medium parameters (transport coefficient) is expected.

- Jet as an entity (parton hadron duality) stays unchanged
- Map out observables as a function of parton energy

Jet rates at LHC

Copious production:

Several jets per central PbPb collisions for $E_T < 20$ GeV

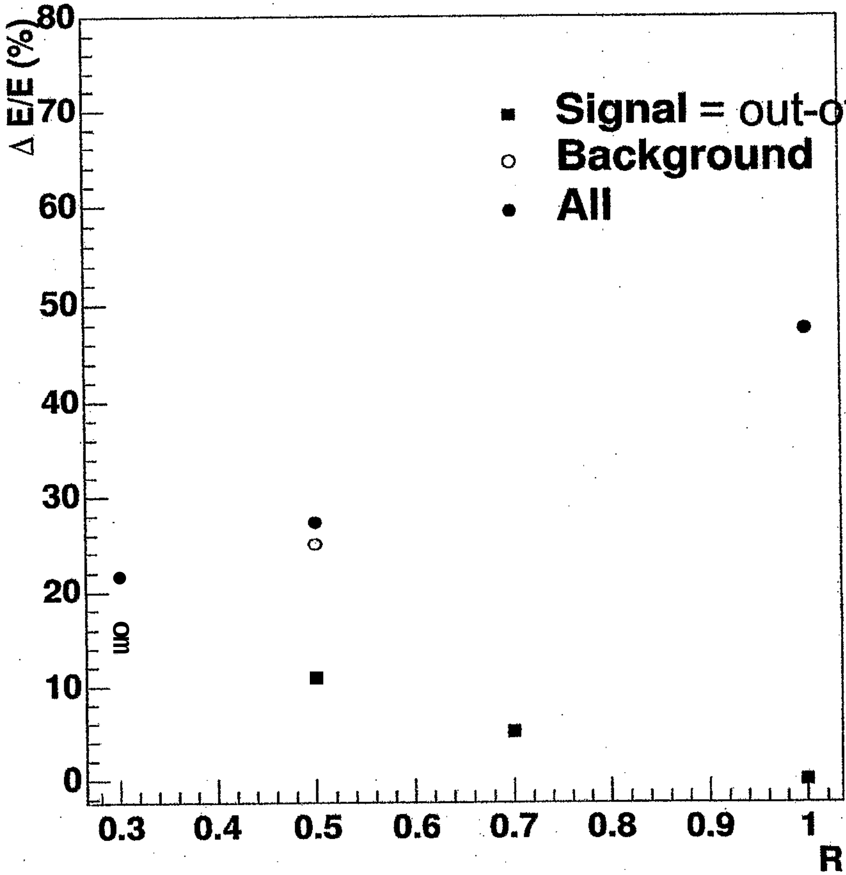


E_T threshold	N_{jets}
50 GeV	2×10^7
100 GeV	6×10^5
150 GeV	1.2 x 105
200 GeV	2.0 x 104

However, for measuring the jet fragmentation function close to $z =$ ▮ $\geq 10^4$ jets are needed. In addition you want to bin, i.e. perform studies relative to reaction plane to map out L dependence. Need trigger !

More quantitatively ...

Intrinsic resolution limit for E_T = 100 GeV



For R < 0.3:

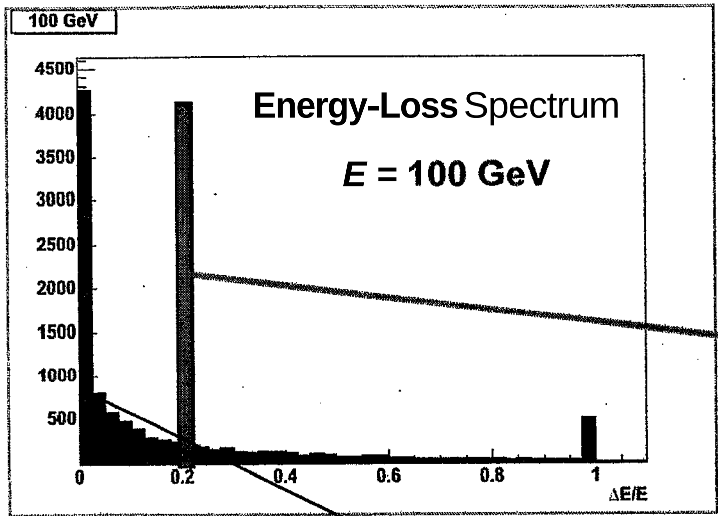
$\Delta E/E$ = 16% from Background (conservative dN/dy = 5000)

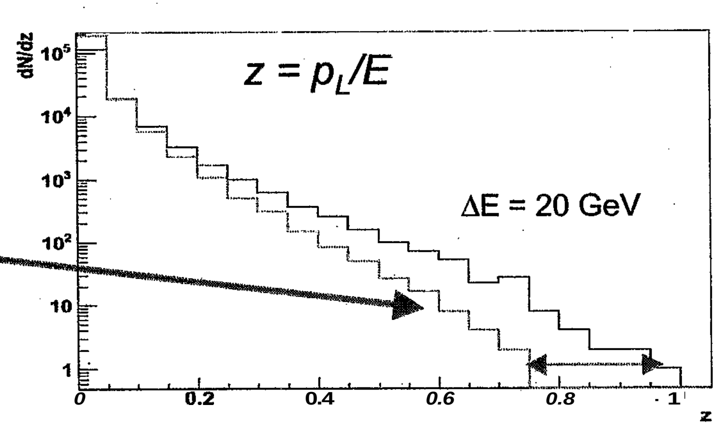
14% from out-of-cone fluctuations

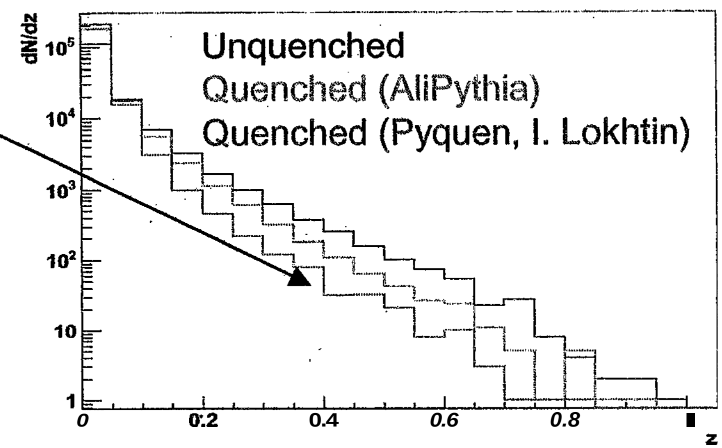
Jet reconstruction for E_{Jet} > 50 GeV should be possible at LHC.

Not included in this estimate: Expected "quenching" or even thermalisation of the underlying event.

Interpretation of Fragmentation Functions







Intrinsic limit on sensitivity due to higher moments of the expected $\Delta E/E$ distribution.

Possible additional bias due to out-of-cone radiation.

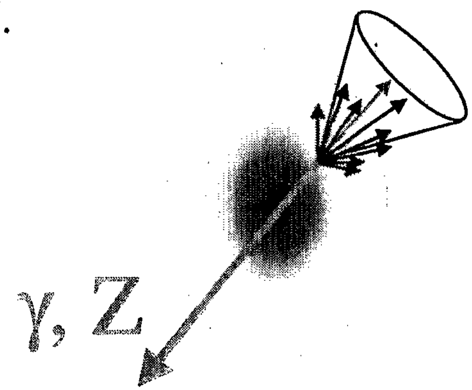
$$E_{\mathrm{rec}} < E_{\mathrm{parton}}$$

$$z_{\mathrm{rec}} = p/\mathrm{E}_{\mathrm{rec}} > z_{\mathrm{hadron}}$$

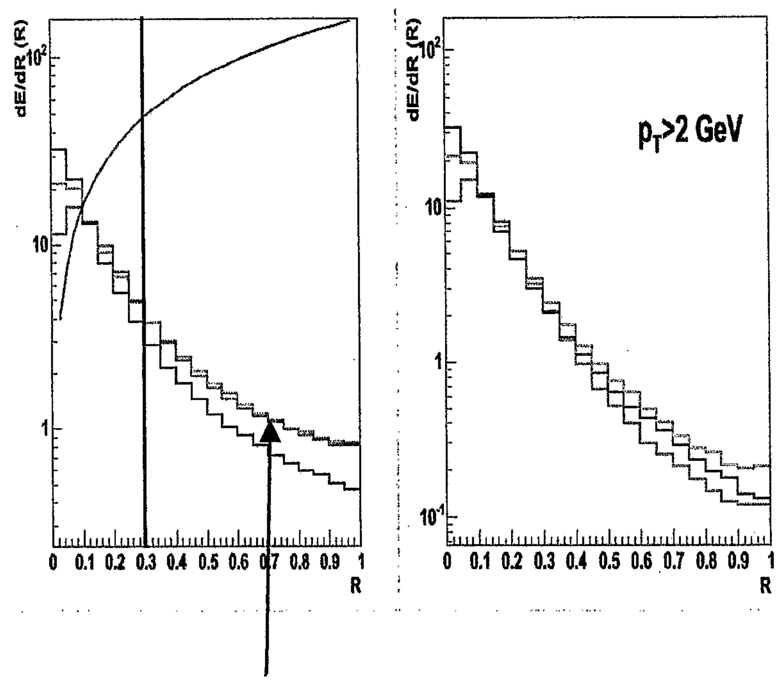
Limit experimental bias ...

By measuring the jet profile inclusively.

Low-p_T capabilities are important since for quenched jets sizeable fraction of energy will be carried by particles with $p_T < 2$ GeV.



Quenched (AliPythia)
Quenched (Pyquen)



Energy radiated outside cone

Not visible after p_T-cut.

Out-of-cone radiation has low p_T !

Exploit γ-jet correlation

$E_\gamma = E_{jet}$

Caveat: limited statistics

$\mathcal{O}(10^3)$ smaller than **jet** production

Does the decreased systematic error compensate the increased statistical error ?

Certainly important in the intermediate energy region $20 < E_T < 50$ GeV.

What Can Intra-jet, Di-jet and γ-Jet Correlations

Tell Us at RHIC II ?

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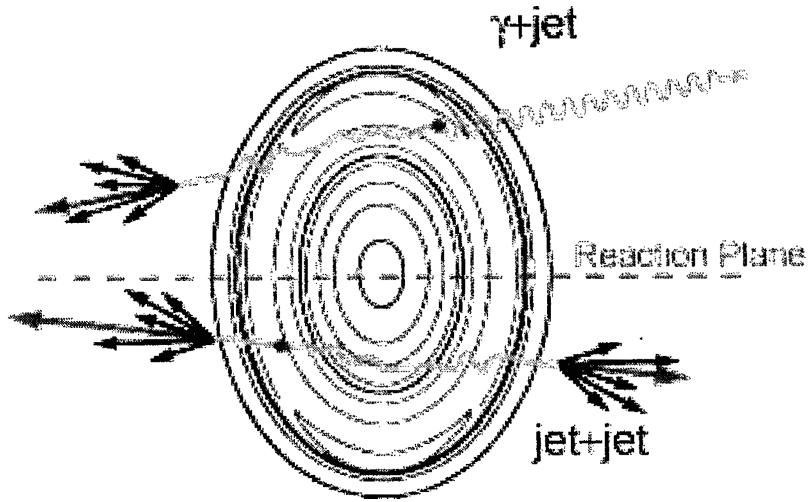
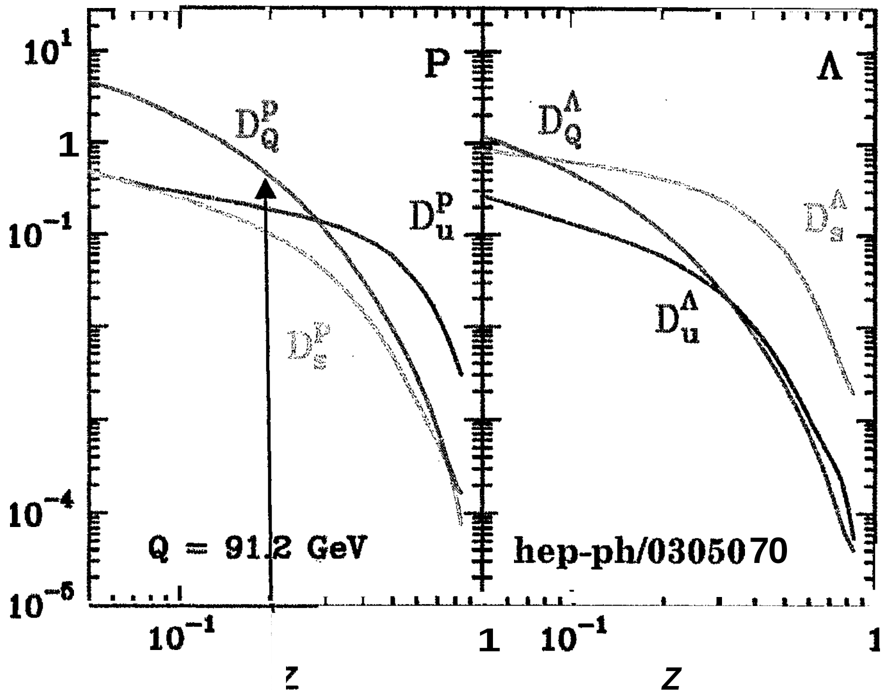


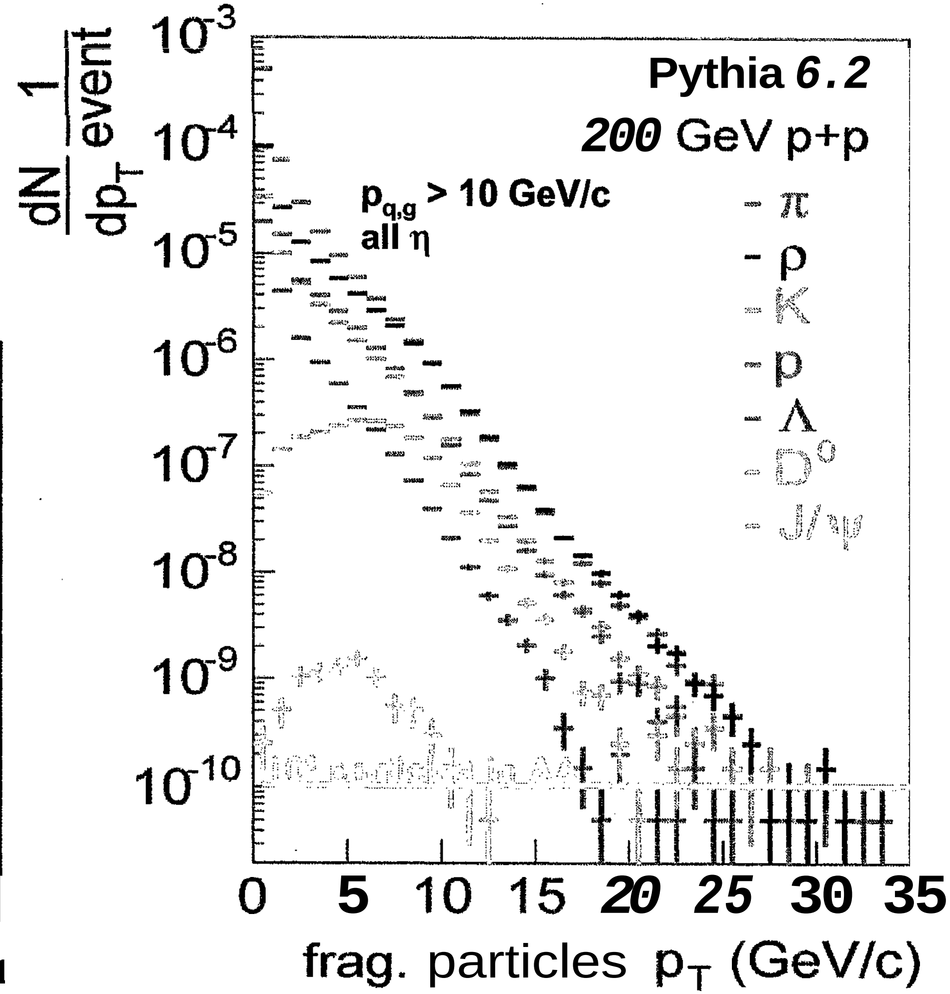
John W. Harris, Yale University

Understanding Hadronization, Fragmentation & Medium Modification from Jet Quenching?

Each flavor parton contributes differently to fragmentation function
(see Bourrely & Soffer, hep-ph/0305070)

In AA collision - should lose different amounts of energy in opaque medium.



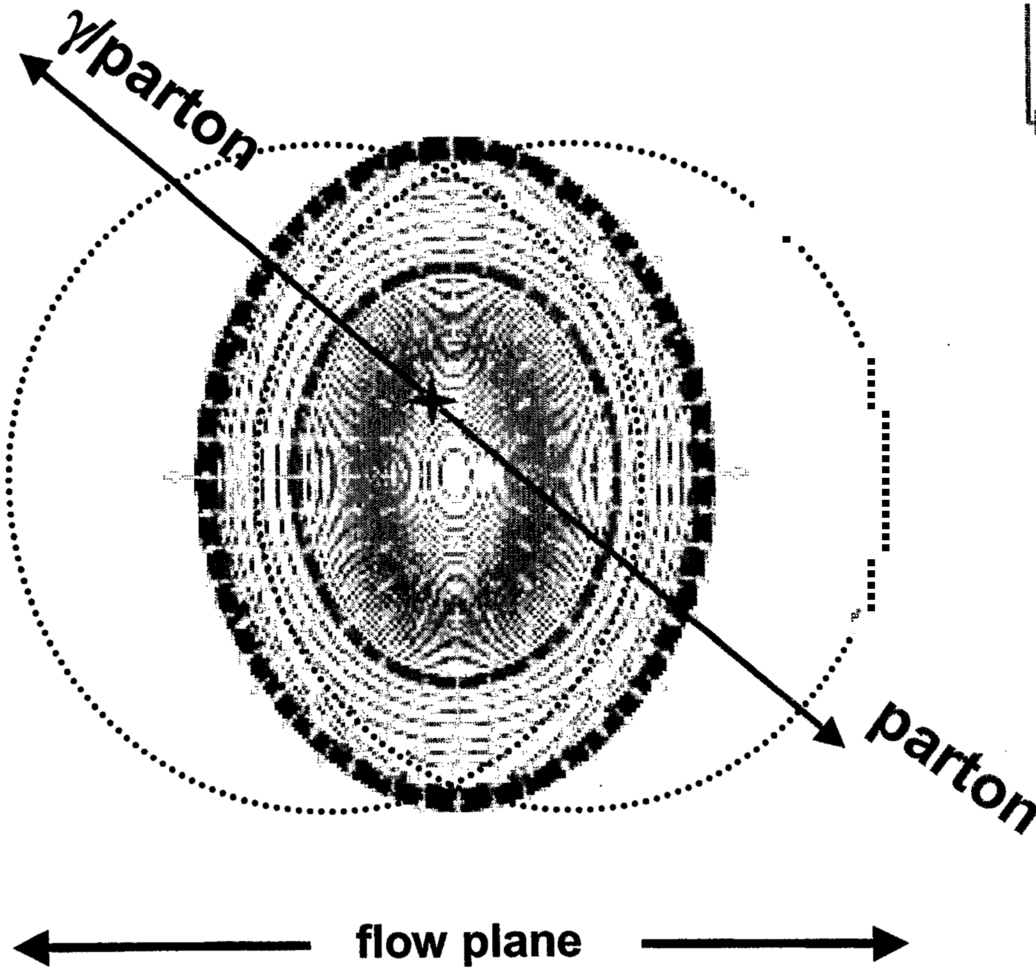


2 GeV/c proton from fragmentation of 10 GeV parton!
What is effect of heavy quark propagation on p/π ratio?

Detailed "Tomography" of the QGP

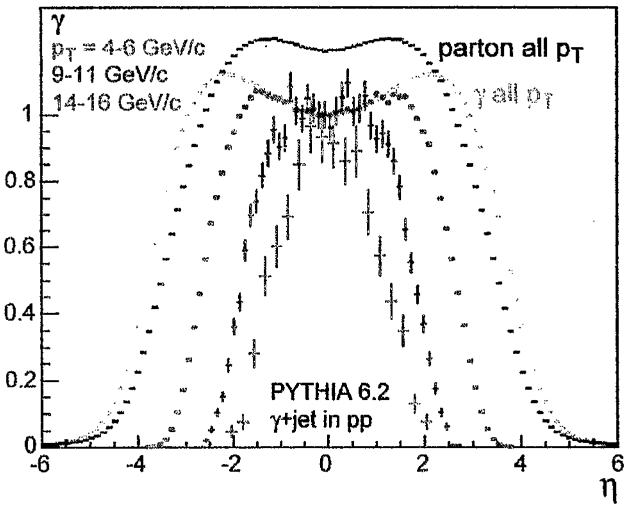
$$F_{QGP}(\rho_g^{QGP}) = f_{initial}(\sqrt{s}, A_1+A_2, b, x_1, x_2, Q^2) \cdot f_{QGP}(p_T^{\gamma}, y^{\gamma}, \phi^{\gamma}, p_T^{jet}, y^{jet}, \phi^{jet}, \text{flavor}^{jet}, \phi^{flow})$$

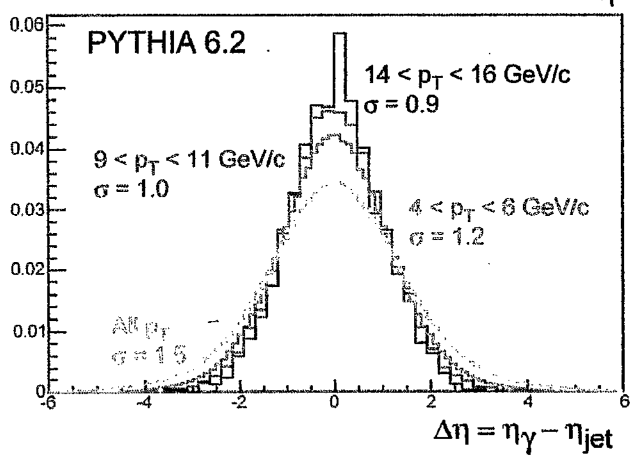
flavor^{jet} → { gluon, light-quark, d-quark, b-quark }



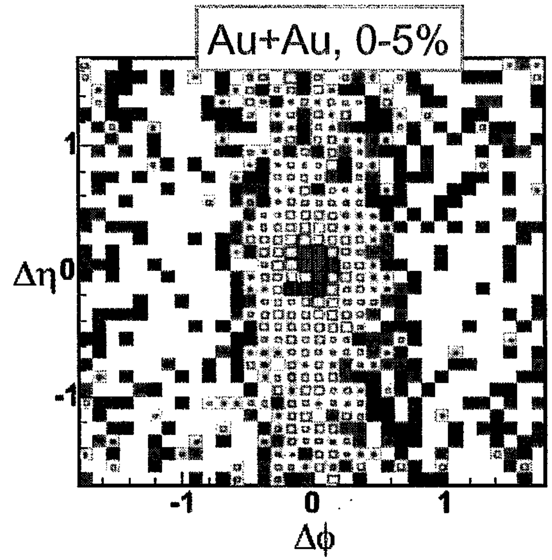
Jets Broaden Significantly in Pseudorapidity!

Kinematics in η and p_T in pp (γ+jet)

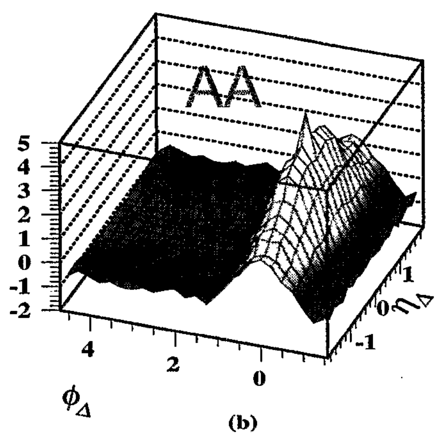




Broadening in η and ϕ pp $\rightarrow$ AA



200 GeV, $|\Delta\phi| < 0.7$
$2.5 < p_T(\text{trig}) < 4$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$



STAR results on correlations for $p_T < 2$ GeV/c

$\Delta\eta$ elongation even on near-side!

Large acceptance for γ's, high p_T particles, jets (energy) essential to understand jets, high p_T correlations and x-dependence (esp. forward - low x) $\Rightarrow$ with tracking + EMCAL (+ ....)

Questions for Future Jet Correlation Studies at RHIC (II)

Can we probe the medium for quantitative information (beyond gluon density)?

- Degrees of freedom - coupling strength?
- Gluon vs quark vs heavy flavor probes?
- Transport coefficients (viscosity, diffusion coefficient)

New effects to utilize?

- Macroscopic response of medium - shock waves, wakes – c_s?
- Effect of Flowing medium on parton propagation!

Can we develop a quantitative understanding of hadronization?

Can we find new probes of chiral symmetry restoration?

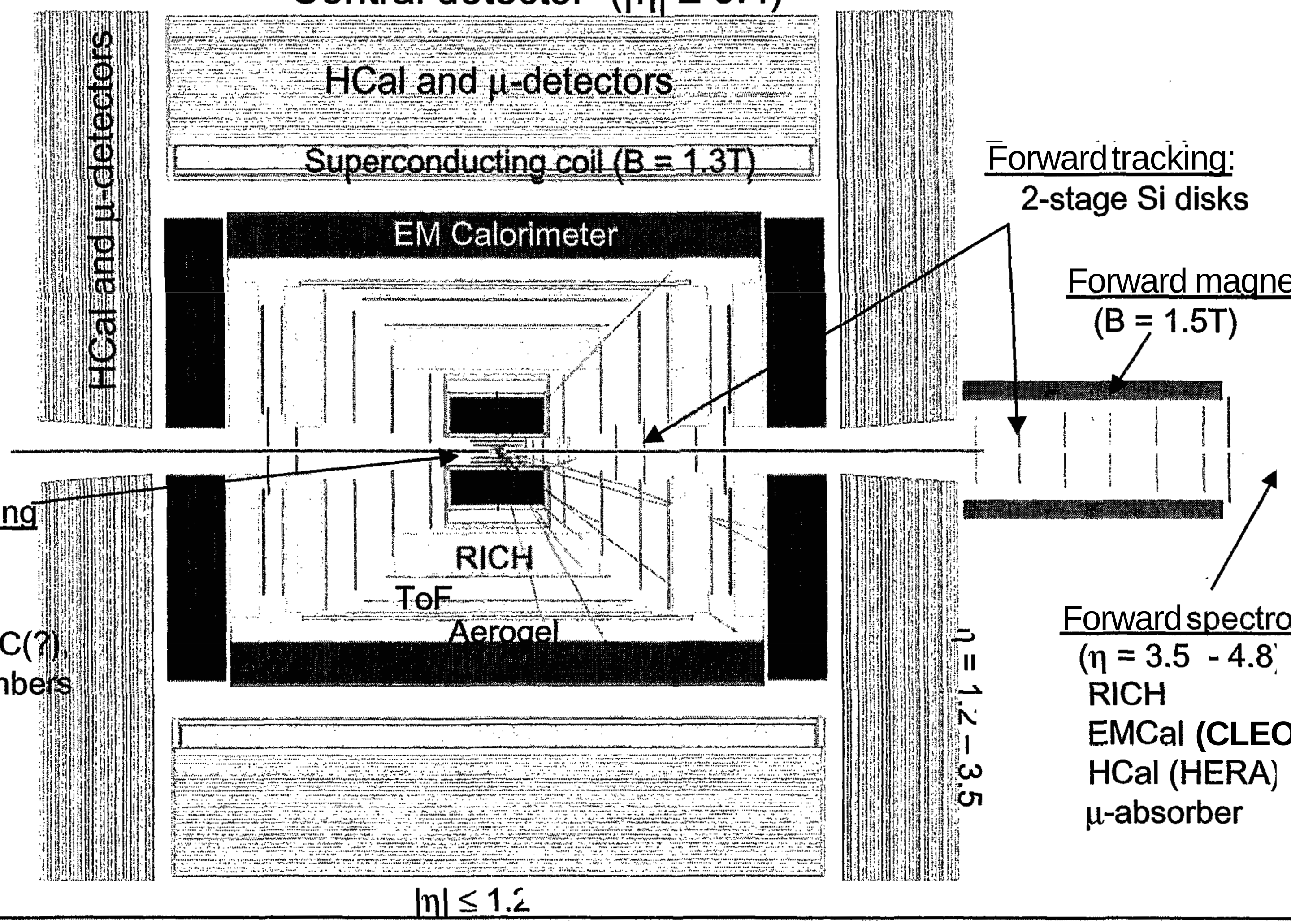
- Hadronization inside/outside of medium?

> Significant physics capabilities only with **RHIC II** (~2012) & **new detector**(s)
>
> B-physics, γ-jet, flavor-tagged jets, PID fragmentation functions
>
> Deconfinement: χ_c, ψ', Υ (1s), Υ (2s), Υ (3s)

New RHIC II Detector: nucl-ex/0503002

The RHIC physics program **will** NOT be **complete** without RHIC II

Central detector ($|\eta| \leq 3.4$)



Forward tracking:
2-stage Si disks

Forward magnet
(B = 1.5T)

Vertex tracking

Tracking:
Si, mini-TPC(?),
μ-pad chambers

PID:
RICH
ToF
Aerogel

Forward spectrometer:
(η = 3.5 - 4.8)
RICH
EMCal **(CLEO)**
HCal (HERA)
μ-absorber

The RHIC II program **will** NOT be successful without a comprehensive new detector!

Summary and Outlook

Xin-Nian Wang (LBNL)

RBRC workshop on jet correlations

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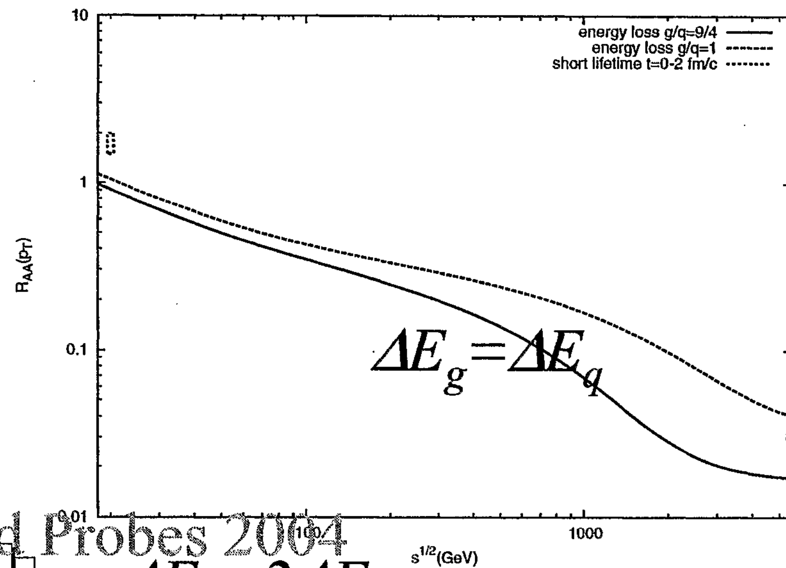
- Energy dependence of jet quenching
- Azimuthal angle dependence of jet quenching
- Hadrons correlations in jets
  - Dihadron fragmentation function
  - Jet cone structure
- Heavy quark energy loss
- Future of jet quenching

March 11,2005

Effect of non-Abelian energy loss

Qun Wang & XNW nucl-th/0410079

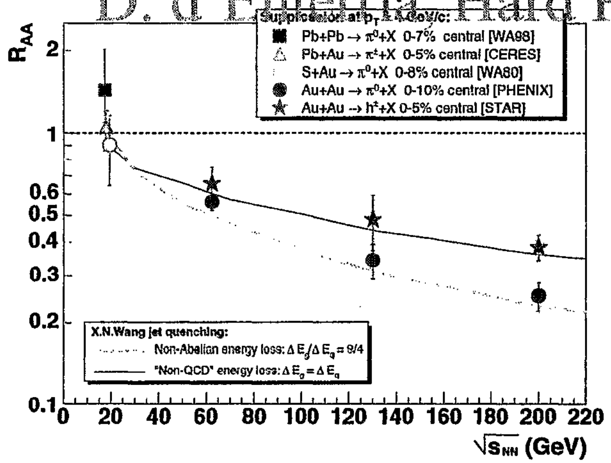


$\Delta E_g = \Delta E_q$

Eskola
Honkanen
Salgado
Wiedemann

D. d'Enterria, Hard Probes 2004

$\Delta E_g = 2\Delta E_q$



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Angular distribution of radiative gluons

Vitev

Radiation in vacuum

$$\frac{dN_g}{dz dk_T^2} = \frac{\alpha_S}{2\pi} C_F \frac{1+(1-z)^2}{z} \frac{1}{k_T^2}$$

$$\frac{dN_g}{d\theta} \infty \frac{1}{\theta}$$

Induced Bremsstrahlung:

$$\frac{dN_g}{dz dk_T^2} = cmR \frac{C_A \alpha_S^2}{N_c} \frac{1+(1-z)^2}{z} \frac{1}{k_T^2 (k_T^2 + \mu^2)} \left(1 - e^{-\left(\frac{R}{\tau_f}\right)^2} \right)$$

$$\tau_f = \frac{2Ez(1-z)}{k_T^2}$$

$$\theta_{\max} \approx \sqrt{\frac{(1-\omega_g / E)}{2R\omega_g}}$$

Further interaction of the radiated gluons with the medium?

What about DIS e+A?

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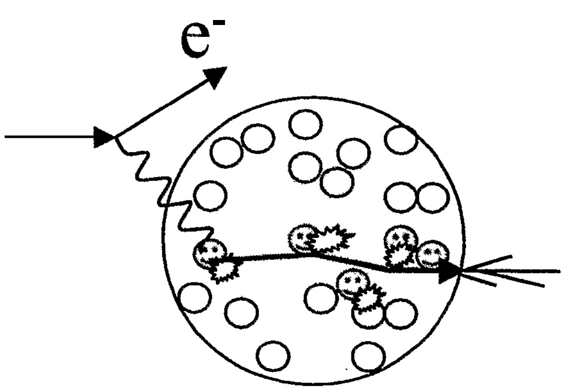
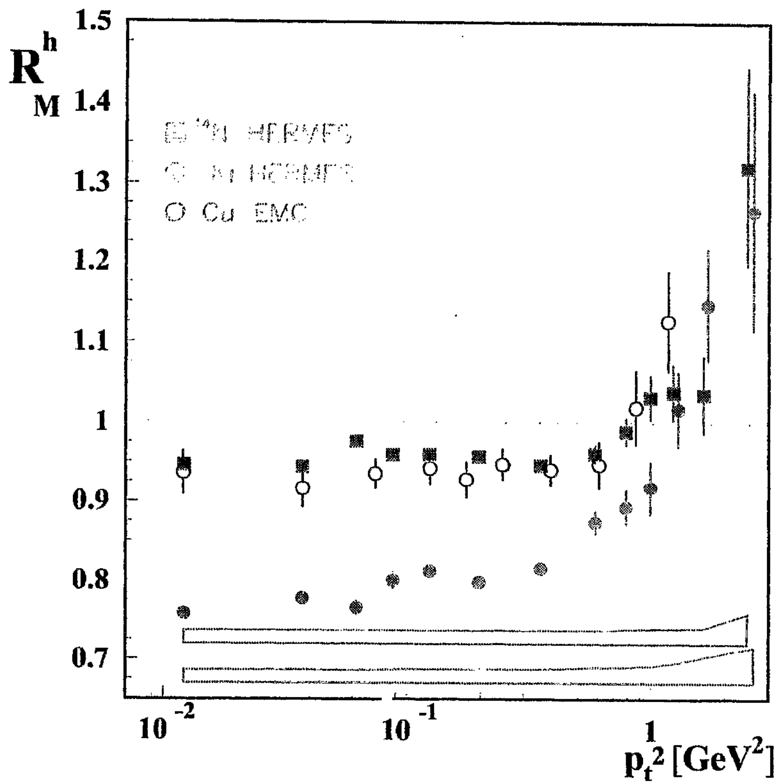
Jet quenching observed





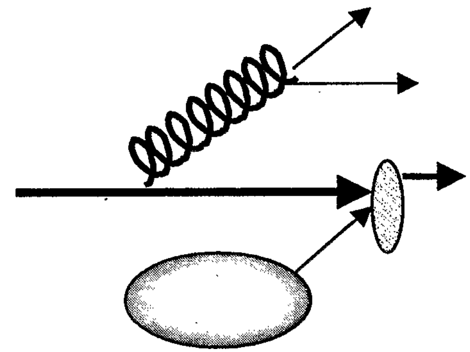
pT broadening of leading hadron
or suppression of low pt hadrons:

Dominance of leading hadrons from the jet with reduced energy

Usefulness of dihadron distribution (fragmentation)

Modification due to recombination

Majumder, E.Wang & XNW'04



$$\langle O \rangle \equiv \frac{Tr\left[e^{-\beta\hat{H}} O\right]}{Tr e^{-\beta\hat{H}}}$$

$$D_{q\to h}(z_h, Q^2) \approx D^0_{q\to h}(z_h)$$

$$+\int \frac{dz}{(1-z)^2} F_q^{\bar{q}}((1-z)z_h, Q^2) f^{th}_{\bar{q}}(z) R^h_{q\bar{q}}(z)$$

$$+V \int \frac{d^2 P_{\perp h}}{2P^+(2\pi)^3} \int \frac{d^2 q_\perp}{(2\pi)^3} \int_0^1 dx f_q(q_\perp, x) f_{\bar{q}}(P_{\perp h} - q_\perp, 1-x) R^h_{q\bar{q}}(x, q_\perp)$$

Hwa &Yang
Fries et al
Greco&Ko

$F_q^{\bar{q}q}(z_1, z_2, Q^2)$ 2-quark distribution ⟺ $F_q^{\bar{q}}(z, Q^2)$ Single quark distribution

Summary

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- Beginning of jet tomography study
  - Details of modified fragmentation
  - Heavy quark fragmentation
  - Dihadron fragmentation
  - Jet-gamma events

Jet Correlations at RHIC
March 10-11,2005
A RIKEN BNL Research Center Workshop

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RIKEN BNL Research Center Workshop

Jet Correlations at RHIC

March 10-11,2005

Snyder Seminar Room, Bldg. 911 ~ Brookhaven National Laboratory

*******AGENDA*******

Thursday, March 10

8:30-9:00 Registration, Bldg. 911 AGS, Snyder Seminar Room Lobby

Morning Session - Session Chair, Brian Cole – Columbia

9:00-9:45	Carl Gagliardi, Texas A&M ~ High-pT Results from STAR
9:45-10:30	Jiangyong Jia, Columbia ~ Overview of Jet Measurement in PHENIX
10:30-11:00	***Coffee Break***
11:00-11:35	Paul Stankus, ORNL ~ Measuring Jet-Induced Correlated Hadron Pairs
11:35-12:10	Fuqiang Wang, Purdue ~ Distributions of Charged Hadrons Associated with High pt Particles
12:10-12:45	Ivan Vitev, LANL ~ Large Angle Hadron Correlations from Medium-Induced Gluon Radiation
12:45-2:00	*LUNCH*

Afternoon Session - Session Chair, Mike Tannenbaum - BNL

2:00-2:35	Jan Rak, UNM ~ j_T, k_T and Fragmentation Functions in p+p
2:35-3:10	Jana Bielcikova, Yale ~ High-pT Correlations in d+Au Collisions at RHIC
3:10-3:45	Nathan Grau, Iowa State ~ Jet Structure from Di-Hadron Correlations in d+Au Collisions
3:45-4:15	***Coffee Break***
4:15-4:50	Carlos Salgado, CERN ~ Jet Studies in Heavy Ion Collisions
4:50-5:25	Abhijit Majumder, LBNL ~ The Medium Modification of Two Hadron Correlations
5:25-6:00	Jorge Casalderra Solana, USB ~ Conical Flow Induced'by QCD Jets
6:00-6:35	Adrian Dumitru, Univ. of Frankfurt ~ Jet Induced Mach **Shock** Waves
6:45-8:30	*RECEPTION @ Berkner **Hall Lobby***

RIKEN BNL Research Center Workshop

Jet Correlations at RHIC

March 10-11,2005

Snyder Seminar Room, Bldg. 911 ~ Brookhaven National Laboratory

*******AGENDA*******

Friday, March 11

Morning Session - Session Chair, Tim Hallman - BNL

9:00-9:35	**Brian** Cole/Barbara Jacak, USB ~ Jet Correlations with Identified Mesons and Baryons
9:35-10:10	Ying Guo, Wayne State Univ. ~ Identified Particle Correlations at Intermediate pT Range
10:10-10:45	Zhangbu Xu, BNL ~ Identified high-pt Spectra and Open Charm from STAR
10:45-11:15	***Coffee Break***
11:15-11:50	Wolf Holtzman, USB - Decomposition of Flow and Jet Correlations
11:50-12:25	Sergey Voloshin, **WSU** ~ High pT two-particle Correlations: "Background" Issues
12:25-1:00	Denes Molnar, OSU ~ High-pT Correlations from Parton Transport Theory
1:00-2:00	*LUNCH*

Afternoon Session - Session Chair, Miklos Gyulassy - Columbia

2:00-2:35	Rainer Fries, Minnesota ~ Recombination and Hadron Correlations
2:35-3:10	Rudy Hwa, Oregon ~ Parton and Hadron Correlations in Jets
3:10-3:40	***Coffee Break***
3:40-4:15	Andreas Morsch, CERN ~ Jet Physics in Heavy Ion Collisions at the LHC
4:15-4:50	John Harris, Yale ~ What Can Intra-Jet, Di-Jet, and Photo-Jet Correlations Tell Us at RHIC II?
4:50-5:35	Xin-Nian Wang, LBNL ~ Summary & Outlook
5:35	Adjourn

Additional RIKEN BNL Research Center Proceedings:

Volume 73 – Jet Correlations at RHIC, March 10-11,2005 – BNL-
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11,2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9,2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6,2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21,2004), XXV (May 27, 2004), XXVI (June 1,2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15,2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6,2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674

Additional RIKEN BNL Research Center Proceedings:

Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics 111& IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR 11: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 3 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 2 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 1 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume **9** – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume **8** – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634

Additional RIKEN BNL Research Center Proceedings:

Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics – BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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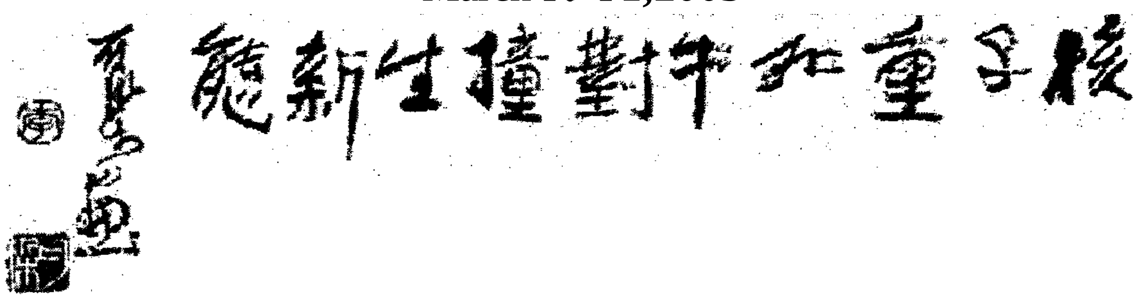
RIKEN BNL RESEARCH CENTER

Jet Correlations at RHIC

March 10-11,2005



Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
*T.D. **Lee***

Speakers:

J. Bielcikova	A. Dumitru	R. Fries	C. Gagliardi	N. Grau
Y. Guo	J. Harris	W. Holtzman	R. Hwa	B. Jacak
J. Jia	A. Majumder	D. Molnar	A. Morsch	J. Rak
C. Salgado	J. Casalderrey Solana	P. Stankus	I. Vitev	S. Voloshin
F. Wang	X-N. Wang	Z. Xu		

Organizers: M. Gyulassy, M. Tannenbaum, F. Wang