RHIC Experiments 3
Forward Physics

- Introduction / Forward physics in hadron collider
- Do we understand forward particle production at hadron collider?
- Forward particle production as a probe of low-x gluons
  - Inclusive particle production at large rapidity
  - Correlations with mid-rapidity particles in p+p and d+Au
- Spin asymmetries
- Conclusions and outlook

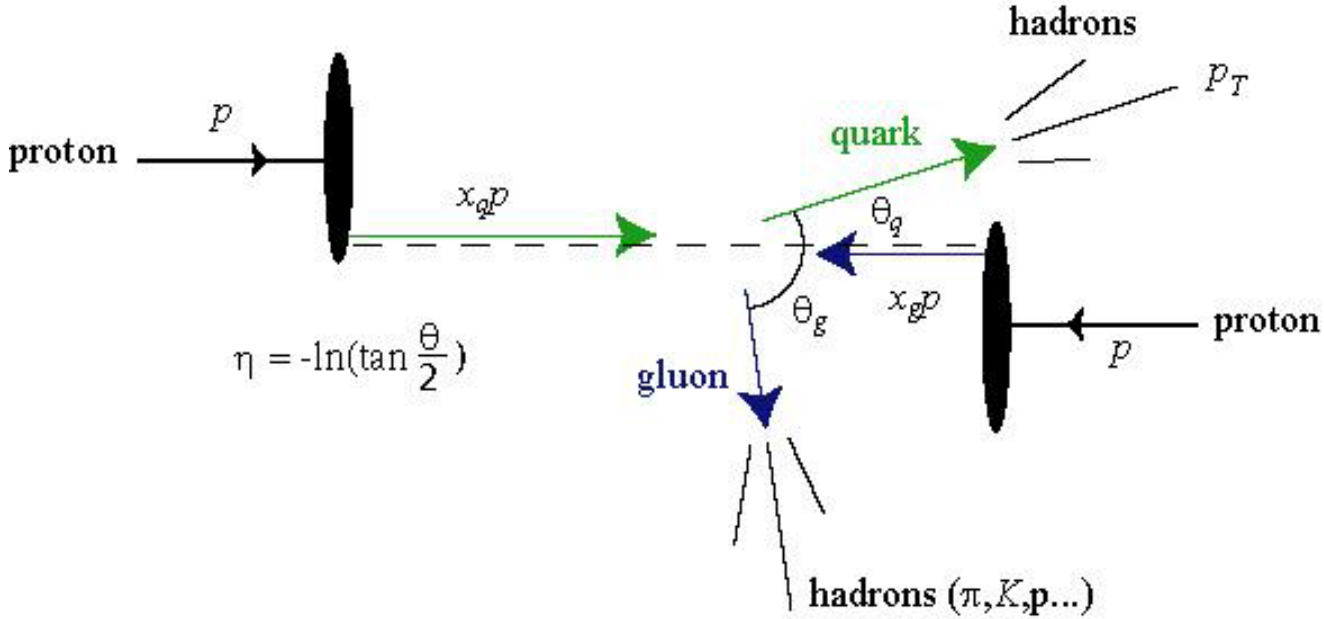
L.C. Bland, BNL

QCD Spin Physics Summer School

12 June 2004

BROOKHAVEN NATIONAL LABORATORY

When Hadrons Collide



Mapping onto deep-inelastic scattering kinematics…

$$Q^2 \approx p_T^2$$

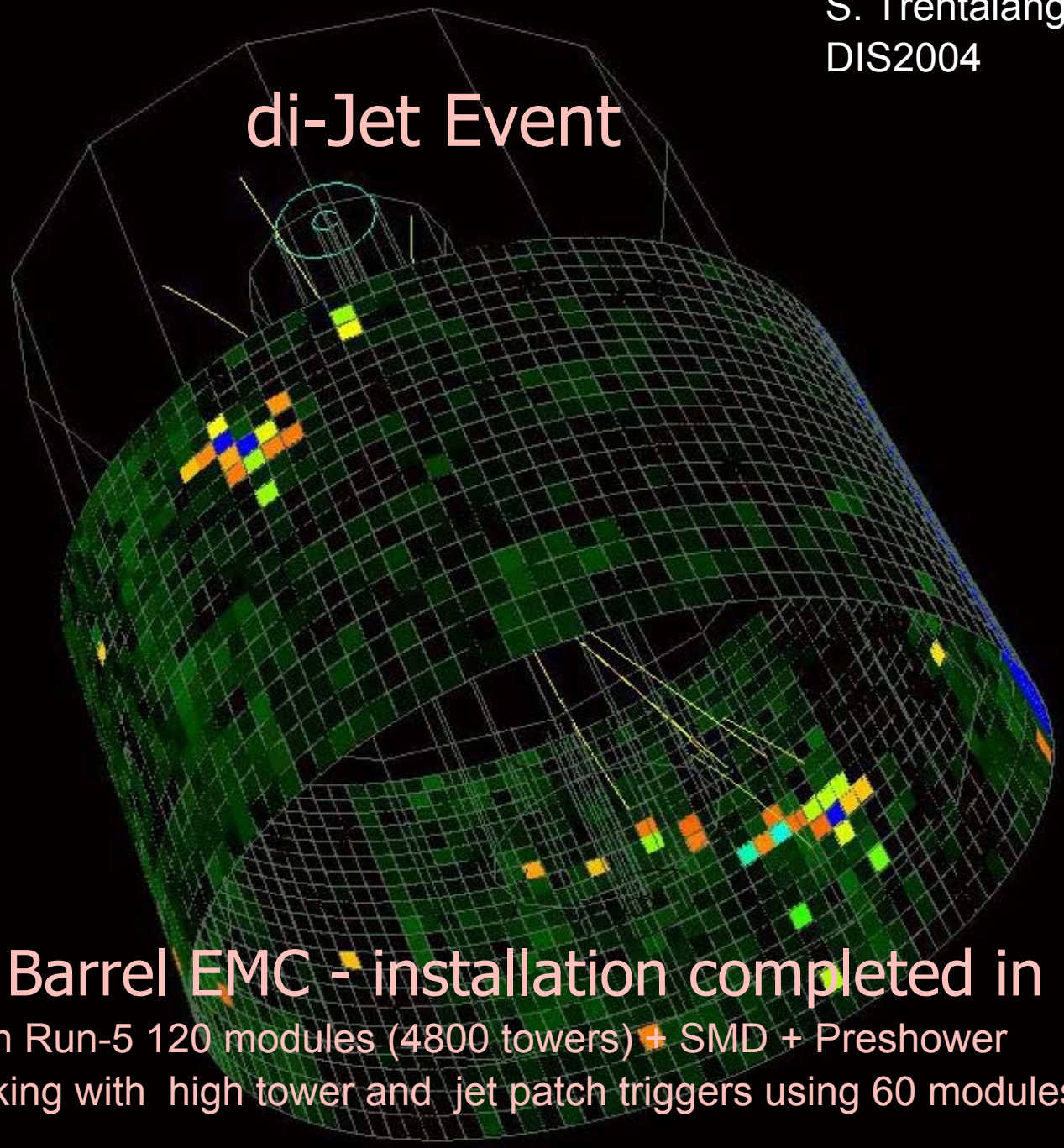
Assuming partons have no transverse momentum in initial state (collinear)…

$$x_q \approx \frac{p_T}{\sqrt{s}}\left(e^{+\eta_q} + e^{+\eta_g}\right)$$

$$x_g \approx \frac{p_T}{\sqrt{s}}\left(e^{-\eta_q} + e^{-\eta_g}\right)$$

S. Trentalange (UCLA),
DIS2004

di-Jet Event



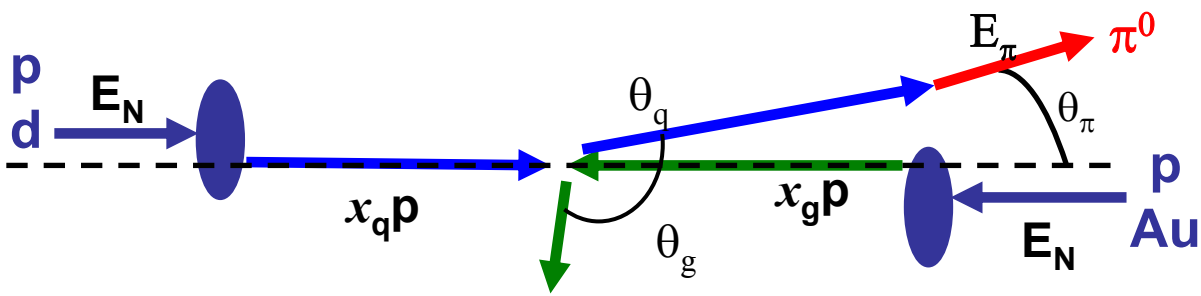
Full Barrel EMC - installation completed in 2005

In Run-5 120 modules (4800 towers) + SMD + Preshower

Run-4 data taking with high tower and jet patch triggers using 60 modules of BEMC

Forward π^0 production in hadron collider

QCD analog of low-x deep-inelastic scattering



$$Q^2 \sim p_T^2 \qquad x_F \approx \frac{2E_\pi}{\sqrt{s}}$$

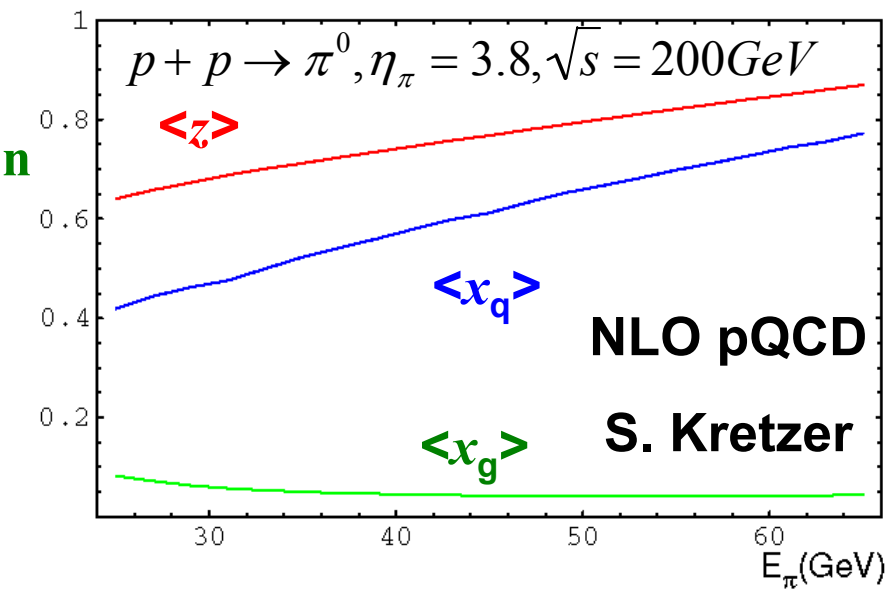
$$\sqrt{s} = 2E_N$$

$$\eta = -\ln(\tan(\frac{\theta}{2})) \qquad z = \frac{E_\pi}{E_q}$$

$$x_q \approx x_F / \langle z \rangle \qquad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta g}$$

(collinear approx.)

- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**



- Mostly **high-x valence quark** + **low-x gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <z> nearly constant and high ~ 0.8

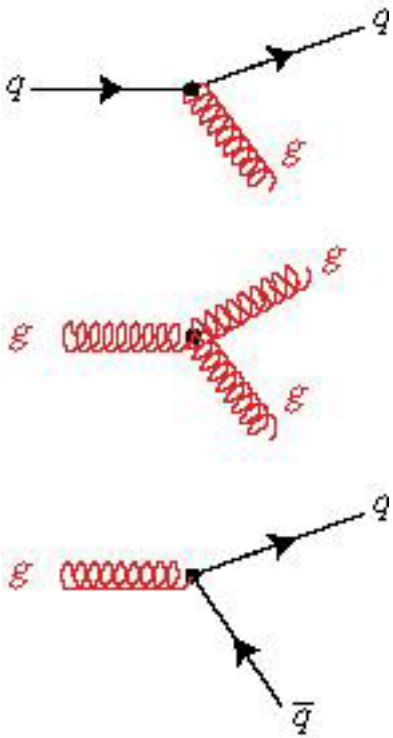
- **Large-x quark polarization is known to be large from DIS**
- **Directly couple to gluons = A probe of low x gluons**

Why Consider Large Rapidity Measurements?

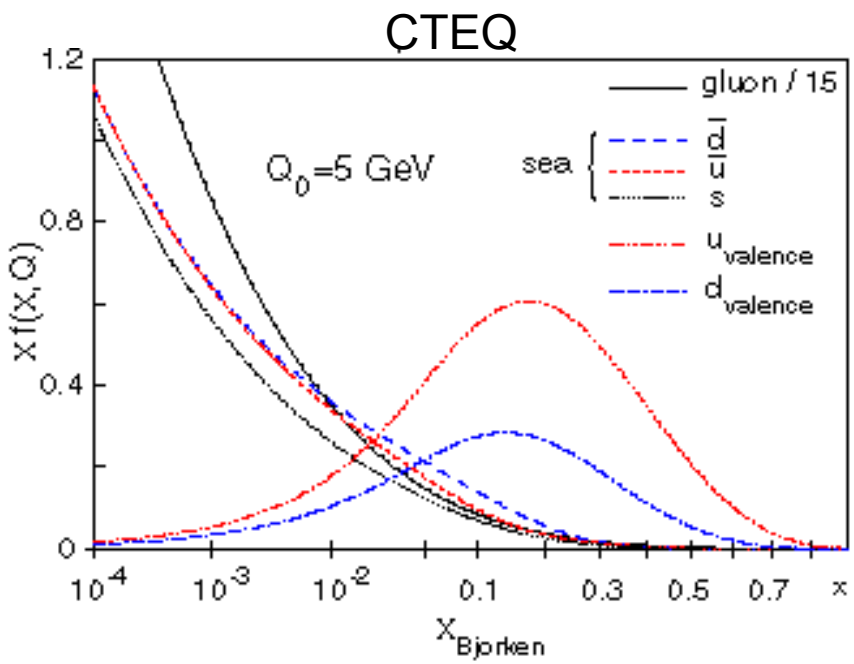
- quantify gluon saturation
- transverse spin physics
- gluon polarization at low x

Evolution of Parton Densities

parton splitting functions…



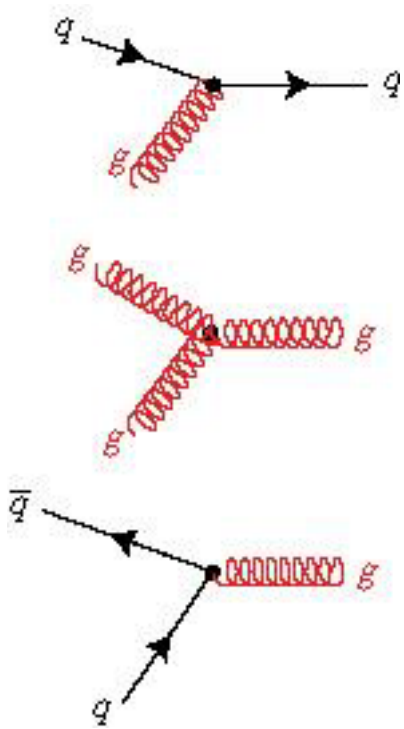
… increase parton densities as $x \to 0$ or $Q^2 \to \infty$



When quarks and gluons are confined within hadrons, parton densities increase when $x \to 0$ or $Q^2 \to \infty$.

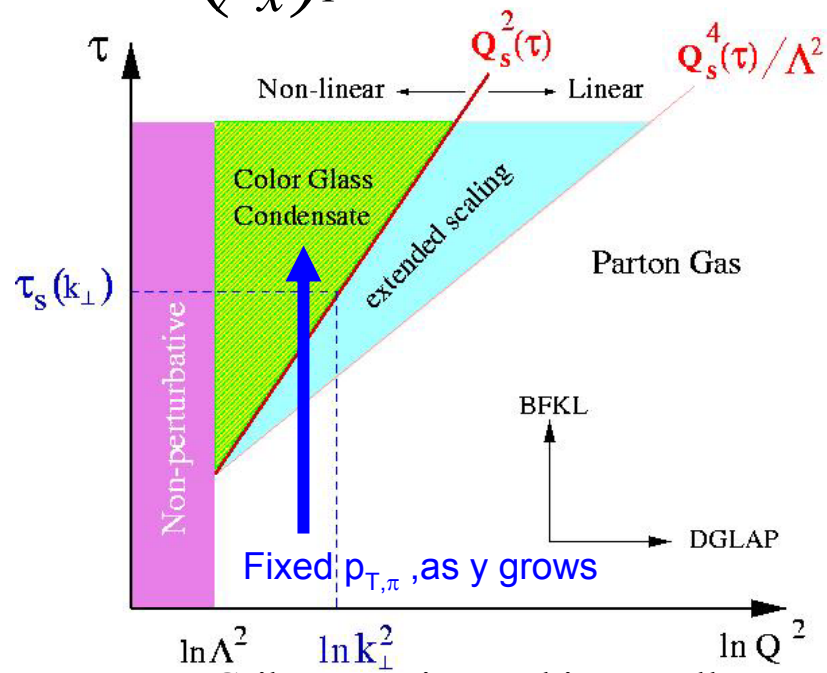
Saturation

At high parton densities, parton recombination reduces the number of partons…



$$\tau = \ln\left(1/x\right)$$

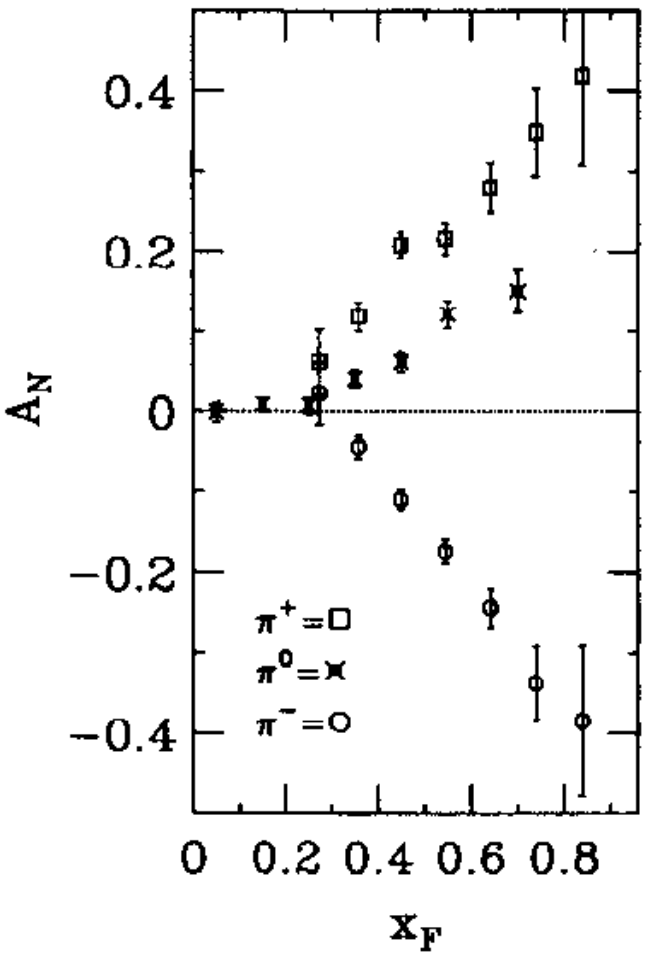
τ related to rapidity (y) of produced hadrons.



Gribov, Levin, Ryskin, Mueller, Qiu, McLerran, Venugopalan, Kharzeev,…

The ‘color glass condensate’ is thought to be a state of matter within the proton where the gluon density is saturated.

Forward Transverse Spin Physics



Non-zero values of A_N have been observed in FNAL E704…

$$p_\uparrow + p \rightarrow \pi + X$$

$$\sqrt{s} = 20 \text{ GeV}, \; 0.5 < p_T < 2.0 \text{ GeV/c}$$

Theoretical models that explain the E704 data also predict non-zero A_N for pion production at RHIC at $\sqrt{s} = 200$ GeV. There are multiple possible dynamical sources:

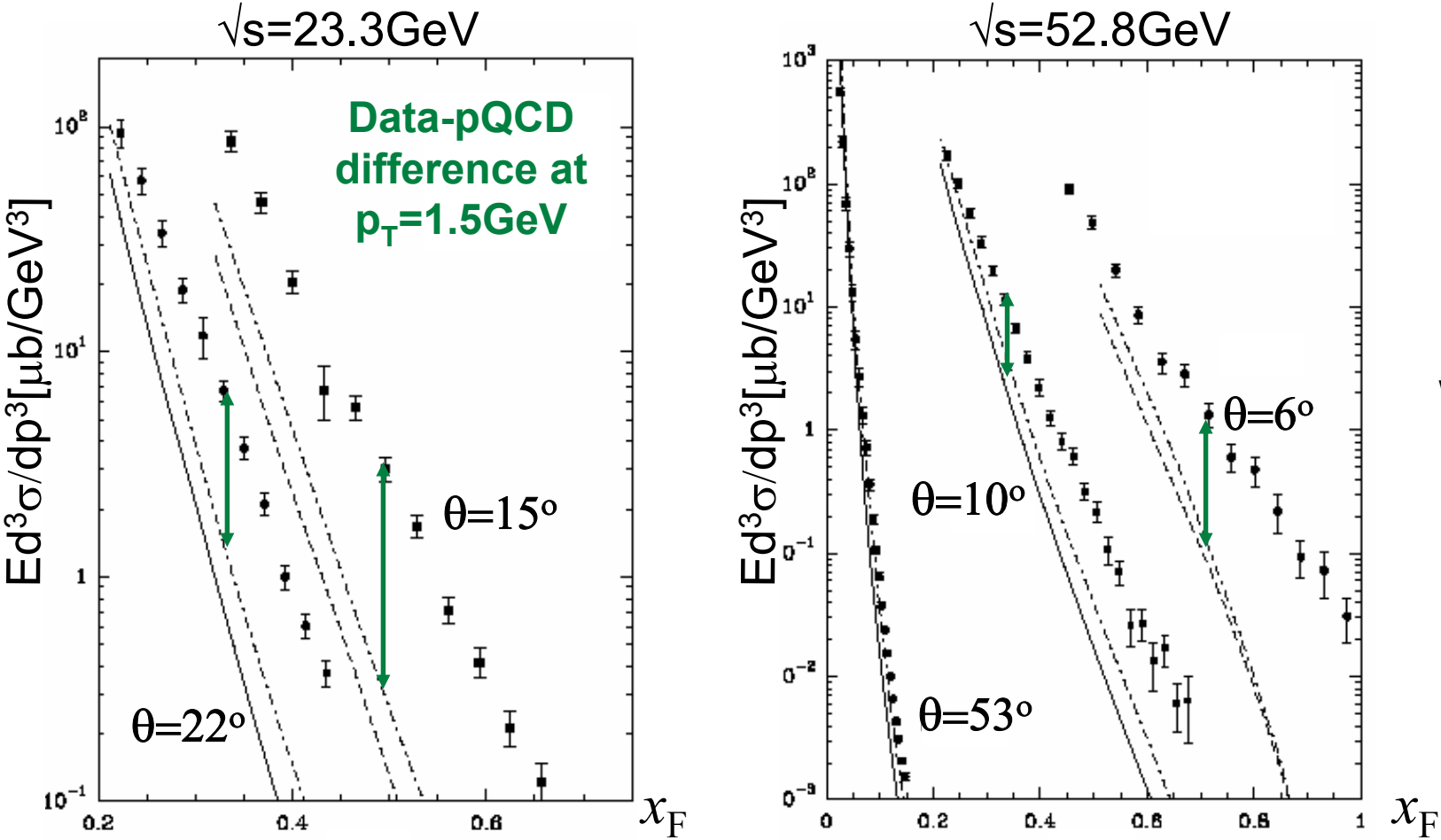
- Collins effect $\Rightarrow$ *transversity* $\otimes$ spin-dependent fragmentation
- Sivers effect $\Rightarrow$ spin- and $k_\perp$-dependent distribution function
- Higher-twist effect

π^0 - D.L. Adams, et al. Phys. Lett. B261 (1991) 201.

$\pi^\pm$ - D.L. Adams, et al. Phys. Lett. B264 (1991) 462

But, do we understand forward π^0 production in p + p?

At $\sqrt{s}$ << 200 GeV, not really….



2 NLO calculations with different scales:

p_T and $p_T/2$

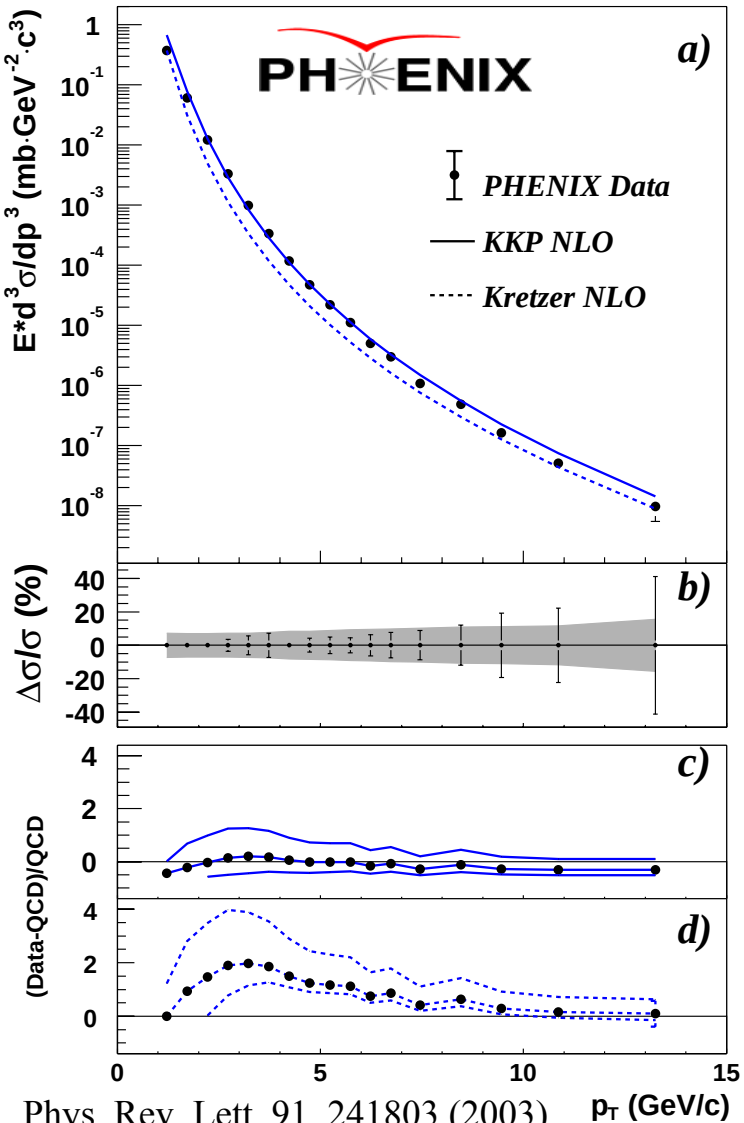
Bourelly and Soffer (hep-ph/0311110, Data references therein):

NLO pQCD calculations underpredict the data at low $\sqrt{s}$ from ISR

$\sigma_{data}/\sigma_{pQCD}$ appears to be function of θ, $\sqrt{s}$ in addition to p_T

How can one infer the dynamics of particle production?

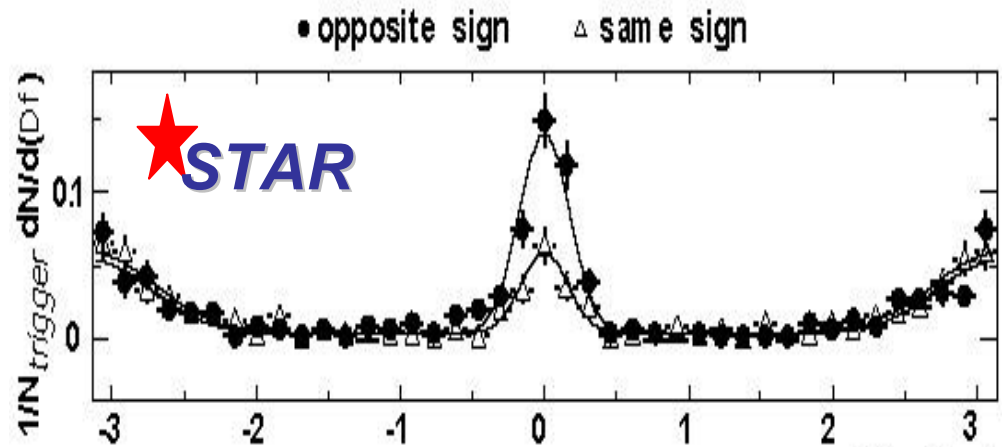
Inclusive π^0 cross section



Phys. Rev. Lett. 91, 241803 (2003)

hep-ex/0304038

Two particle correlations



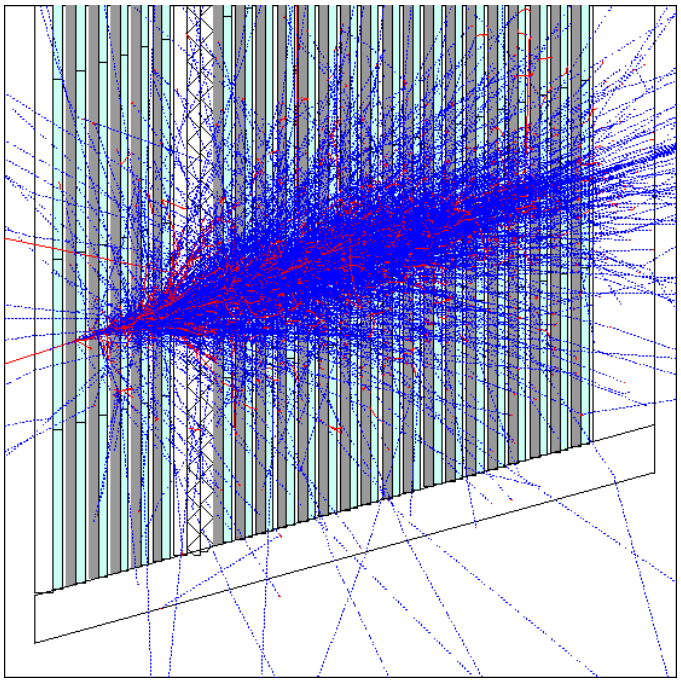
STAR, Phys. Rev. Lett. **90** (2003), nucl-ex/0210033

At $\sqrt{s}$ = 200GeV and **mid-rapidity**, both **NLO pQCD** and **PYTHIA** explains p+p data well, down to p_T~1GeV/c, consistent with partonic origin

Do they work for forward rapidity?

How to Measure High Energy Photons

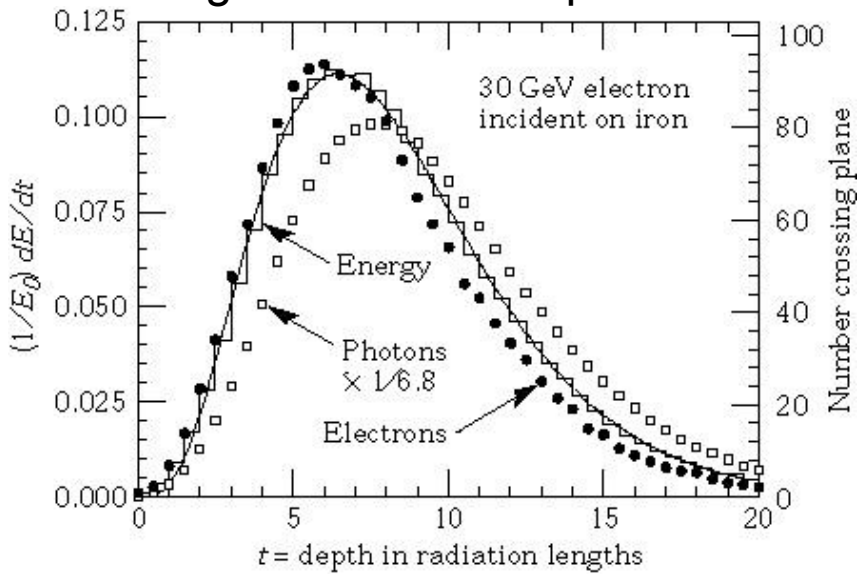
shower maximum detector



GEANT simulation of interaction of 30 GeV photon with a lead+scintillator sampling calorimeter

Energy deposition versus depth (PDG)

Logitudinal shower profile



A shower maximum detector permits measurement of transverse profile of electromagnetic shower

How to Measure High Energy π^0

Measure the quantities:

$$\text{total energy of } \pi^0 = E_{tot} = E_{\gamma 1} + E_{\gamma 2}$$

$$\text{photon energy sharing} = z_{\gamma\gamma} = \frac{\left|E_{\gamma 1} - E_{\gamma 2}\right|}{E_{tot}}$$

$$\text{distance between photons} = d_{\gamma\gamma} \text{ at } z_{vert} \text{ from } \pi^0 \to \gamma\gamma \text{ decay vertex}$$

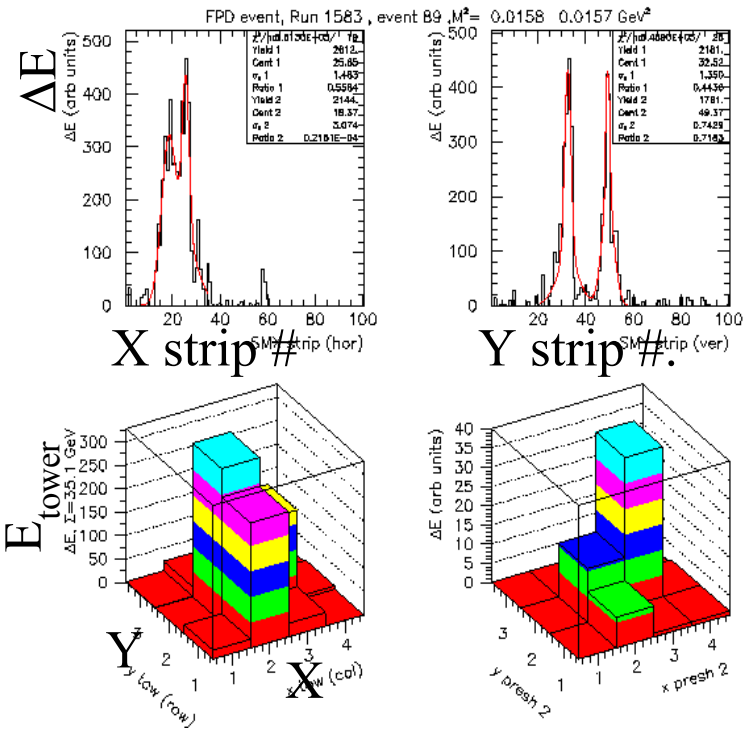
$$\text{opening angle between photons} = \phi_{\gamma\gamma} = \tan^{-1}\left(\frac{d_{\gamma\gamma}}{2z_{vert}}\right)$$

Then, compute the invariant mass

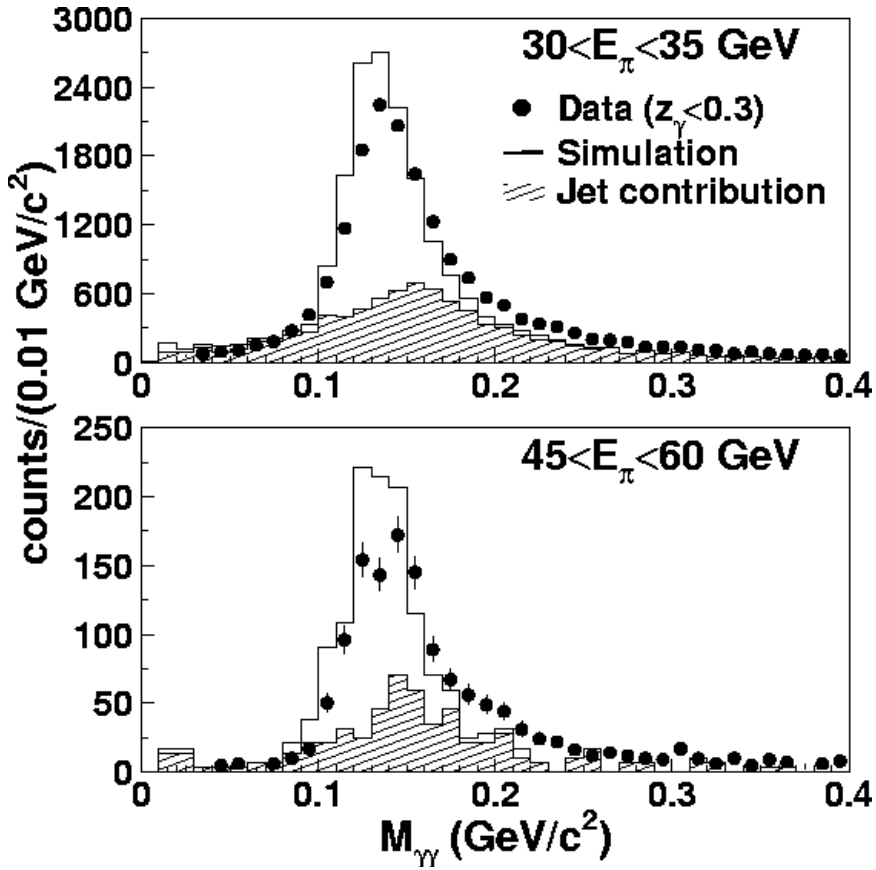
$$M_{\gamma\gamma} = E_{tot}\sqrt{1 - z_{\gamma\gamma}^2}\,\sin\left(\frac{\phi_{\gamma\gamma}}{2}\right)$$

$$M_{\gamma\gamma} \approx E_{tot}\sqrt{1 - z_{\gamma\gamma}^2}\,\frac{d_{\gamma\gamma}}{2z_{vert}}$$

How Well Does it Work?



35 GeV π^0 event reconstruction



Additional energy is deposited in the calorimeter primarily from multiple π^0's accompanying the leading π^0.The forward jet manifests itself as a large-mass tail in the Mgg distribution. (Fig. 1 of hep-ex/0310058)

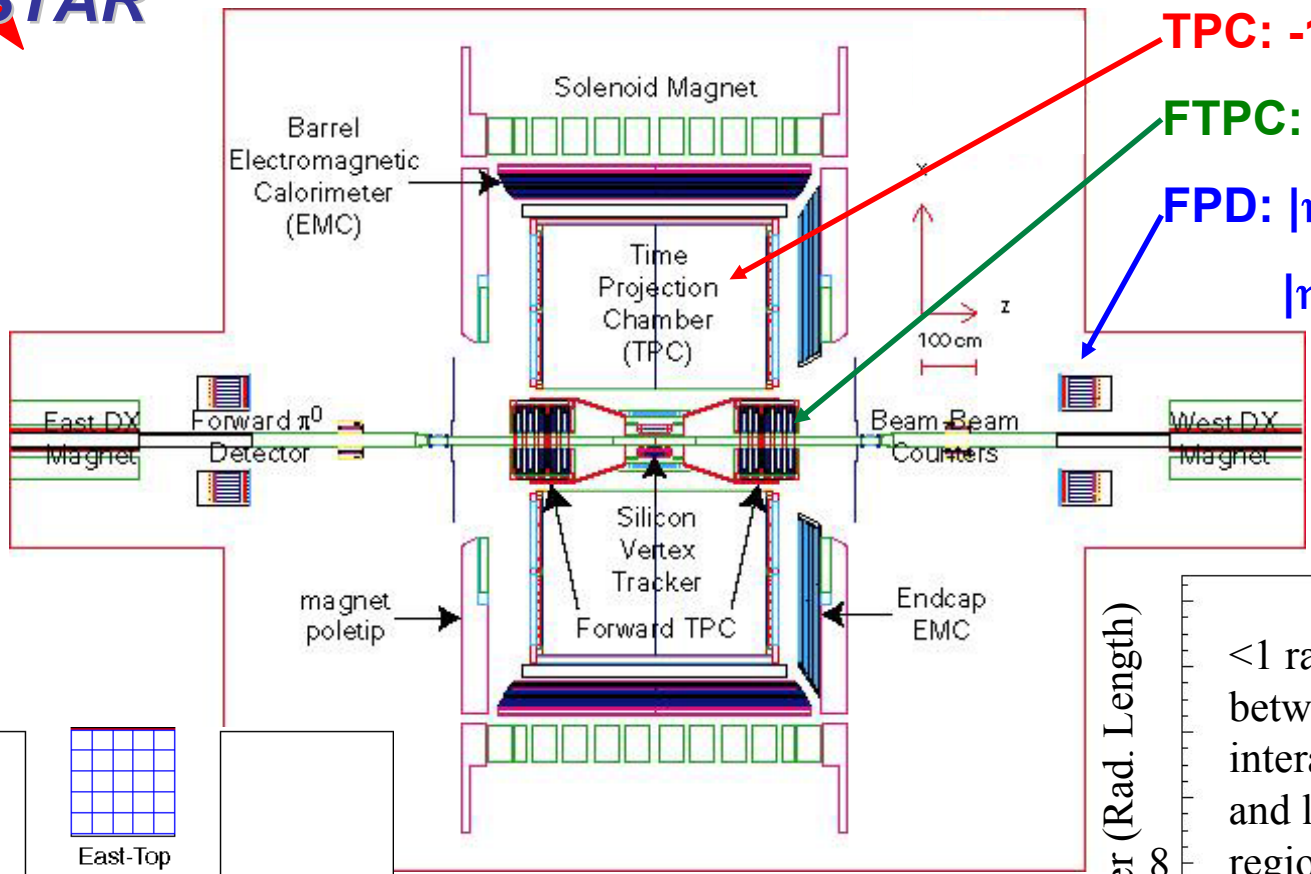
STAR Detector

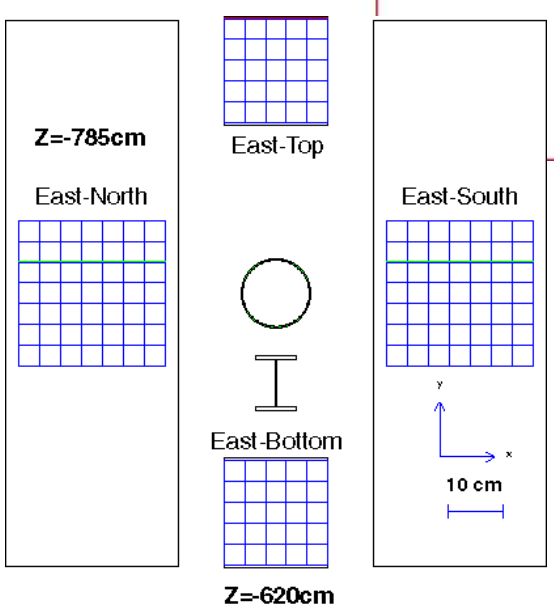
TPC: $-1.0 < \eta < 1.0$

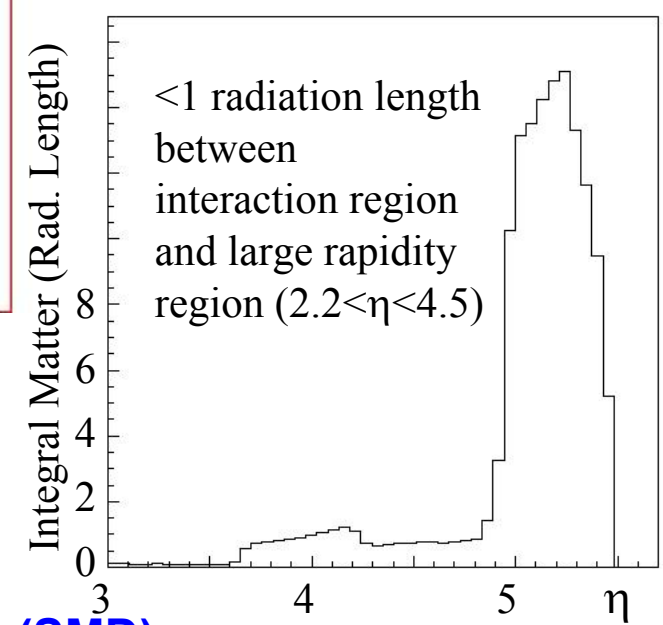
FTPC: $2.8 < |\eta| < 3.8$

FPD: $|\eta| \sim 3.8$ (p+p)

$|\eta| \sim 4.0$ (p+p, d+Au)

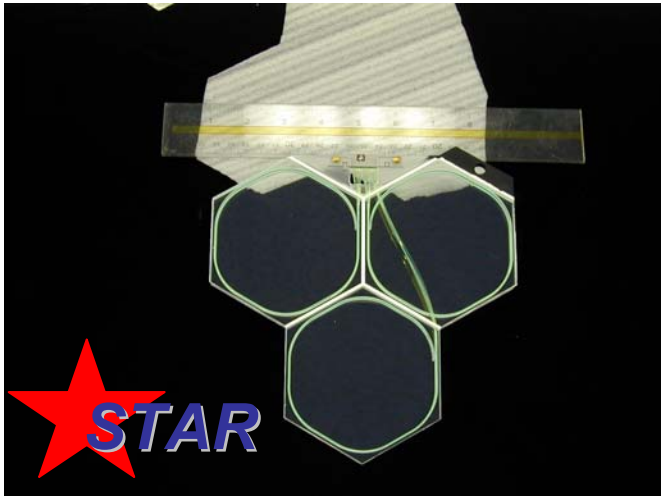






Forward π^0 Detector (FPD)

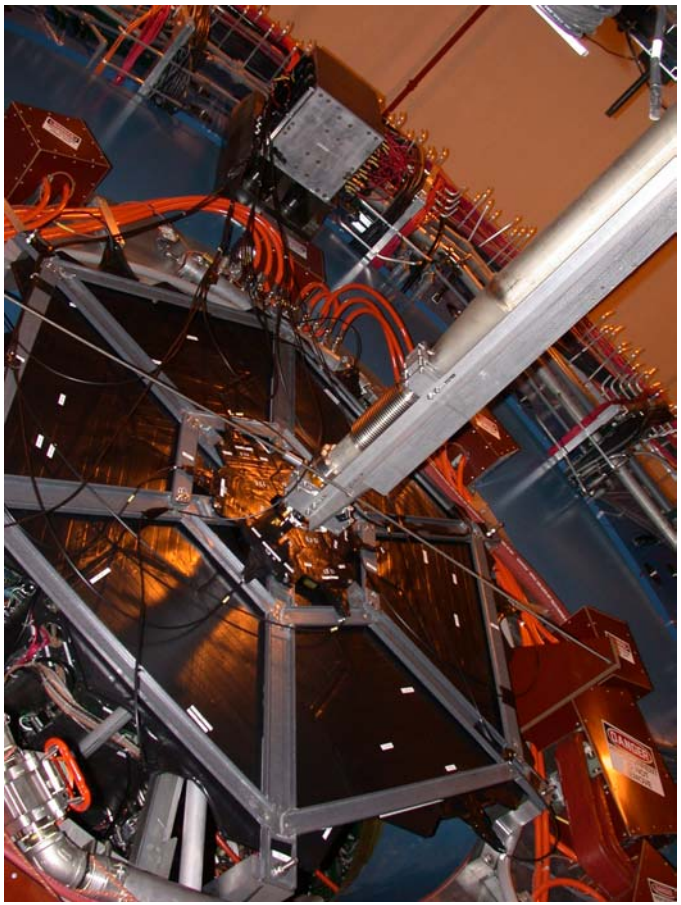
- **Pb-glass EM calorimeter**
- **Shower-Maximum Detector (SMD)**
- **Preshower**

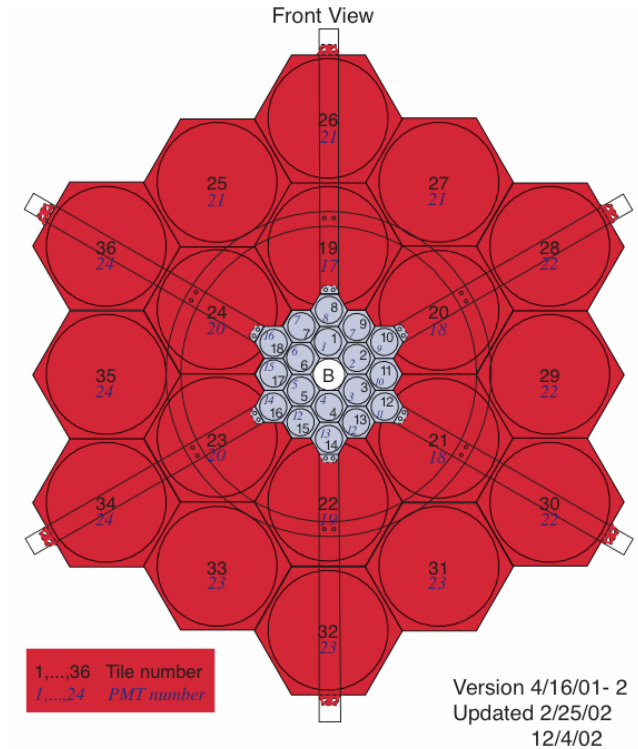


Beam Beam Counter

1cm thick scintillator hex tiles with PMT readout (2.1<|η|<5)

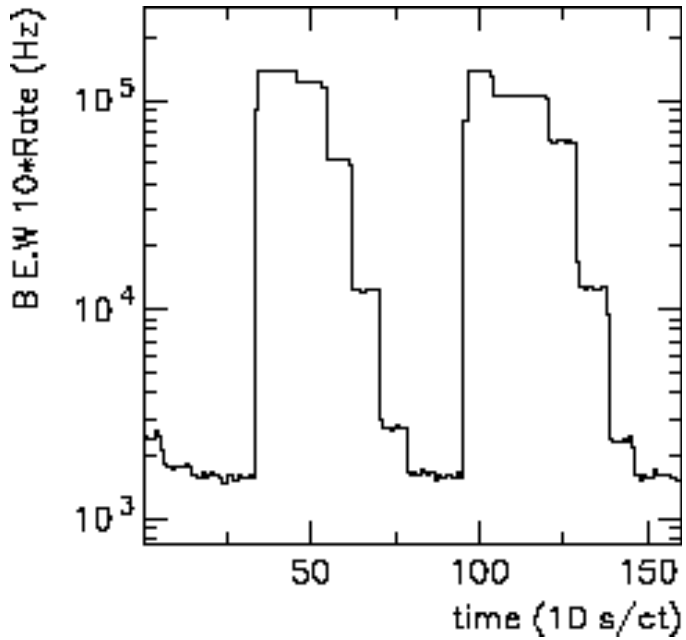
- Feed back to RHIC to make collisions at STAR
- Measure relative luminosity ~10^{-3} level
- Measure absolute luminosity ~ 8% level
- Minimum bias trigger (covers 53% of σ_{tot} for pp)
- Reject beam gas events from biased trigger
- Measure multiplicity at forward rapidity
- A_N for forward charged particles





Absolute Luminosity Measurement

Absolute normalization from BBC E.W:



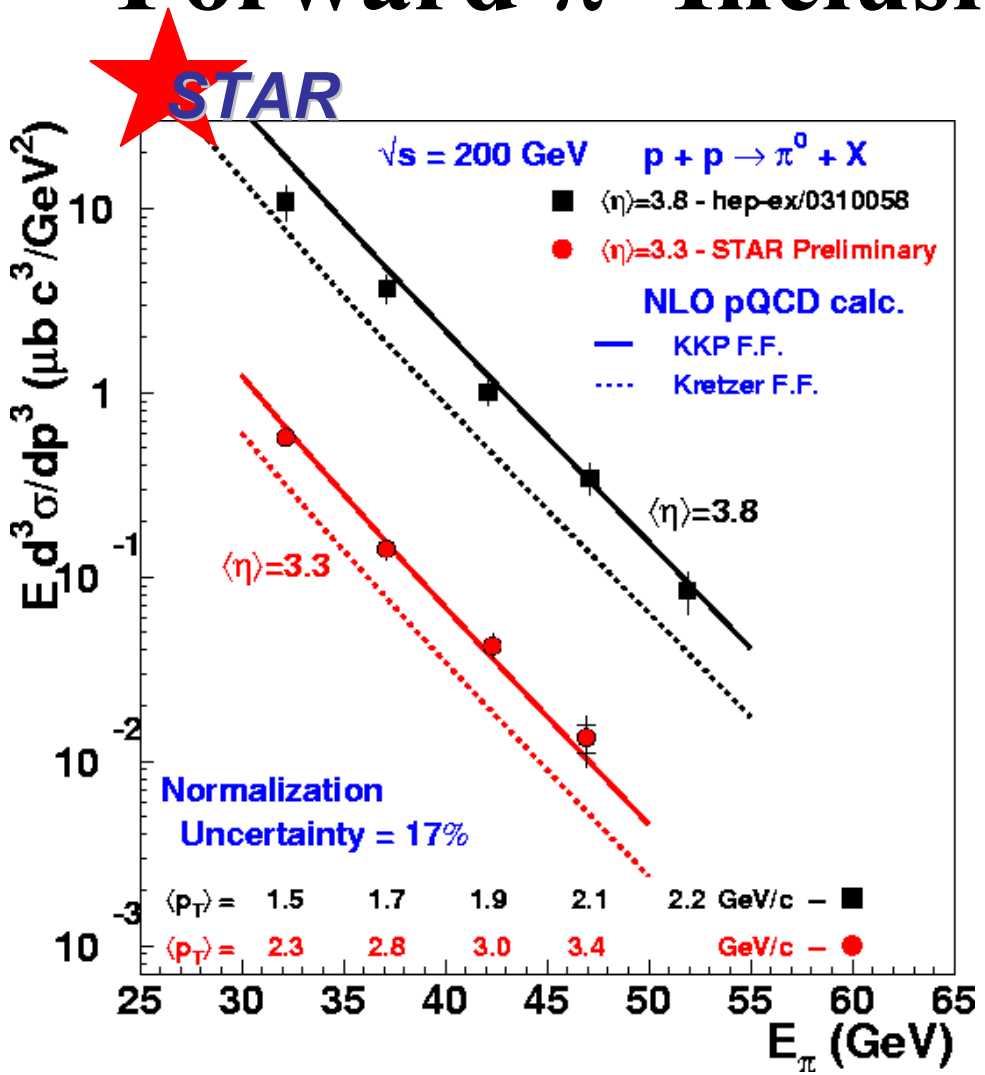
-BBC E•W coincidence rate vs time during a **Van der Meer scan** that **determines the beam size,** and hence the luminosity, by controlled relative steering of the colliding beams.

From Van der Meer scan: σ_{BBC} = 26.1±0.2(stat.)±1.8(syst.) (A.Drees and X. Zu)

From simulations: BBC "sees" 53 ±5% of pp σ_{tot} or

(J.Kiryluk) 87±8% of non-elastic, non-diffractive σ

Forward π^0 Inclusive Cross Section



- STAR data at
  - $\langle\eta\rangle$= 3.8 (PRL **92**, 171801 (2004); hep-ex/0310058)
  - $\langle\eta\rangle$= 3.3 (hep-ex/0403012, Preliminary)
- NLO pQCD calculations at fixed η with equal factorization and renormalization scales = p_T
- Solid and dashed curves differ primarily in the $g \rightarrow \pi$ fragmentation function

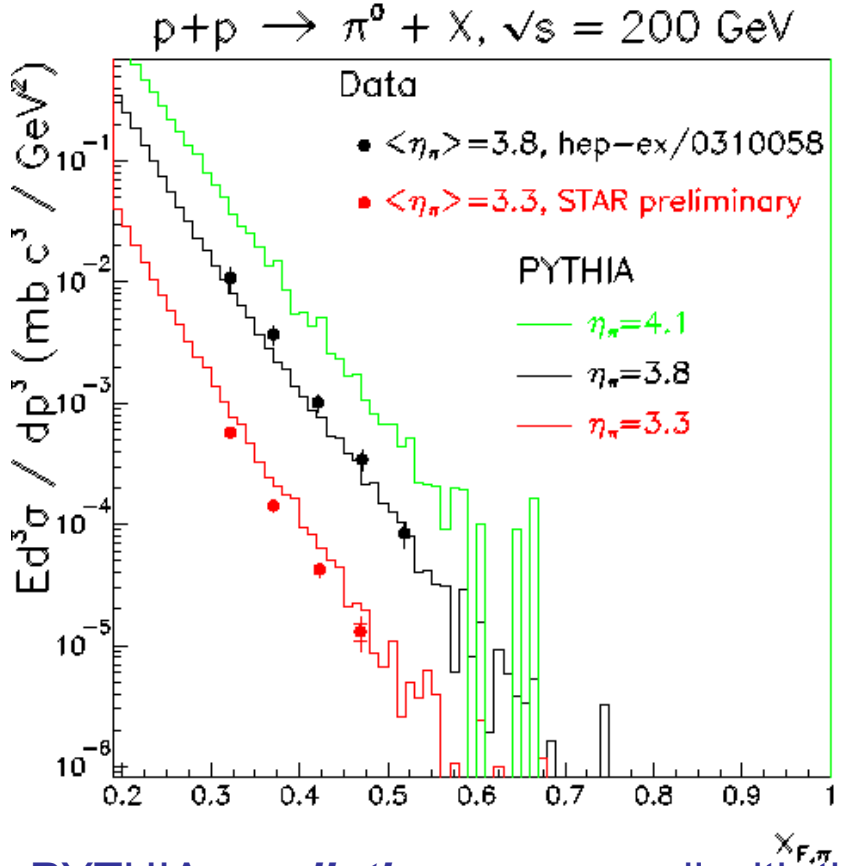
STAR data consistent with Next-to-Leading Order pQCD calculations in contrast to data at lower √s (Bourelly and Soffer, hep-ph/0311110)

What about particle correlations?

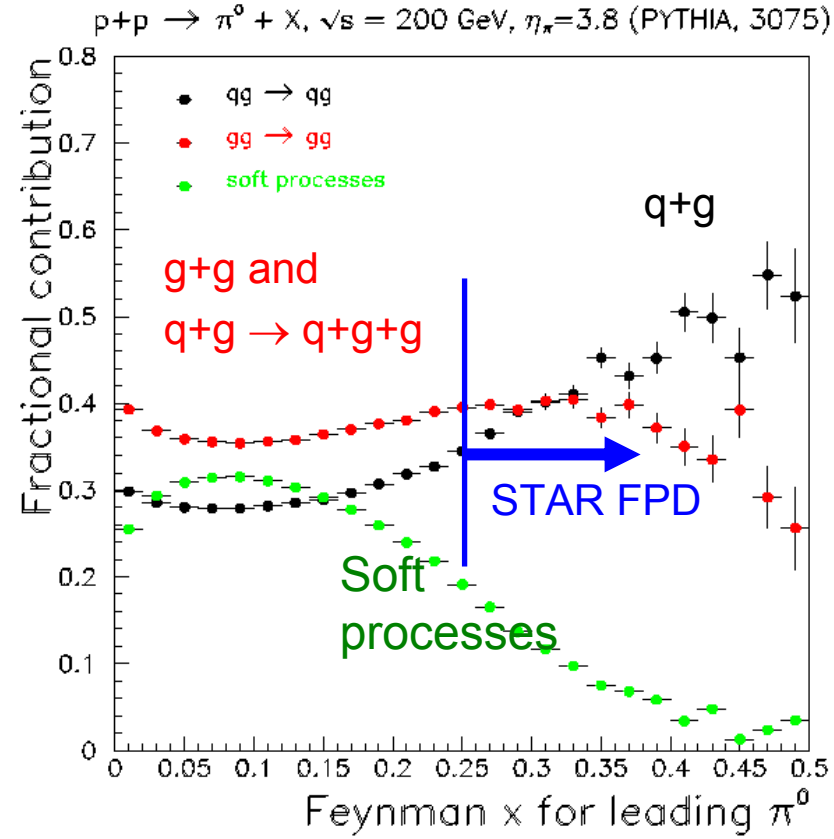
PYTHIA: a guide to the physics

T. Sjostrand, Comp. Phys. Comm. 82 (1994) 74

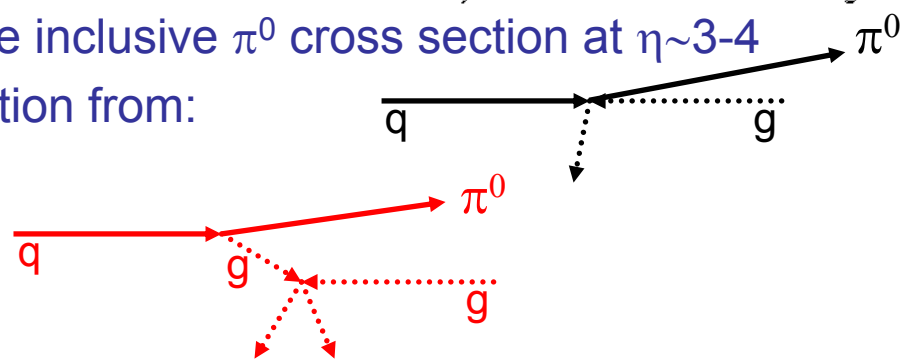
Forward Inclusive π^0 Cross-Section:



Subprocesses involved:

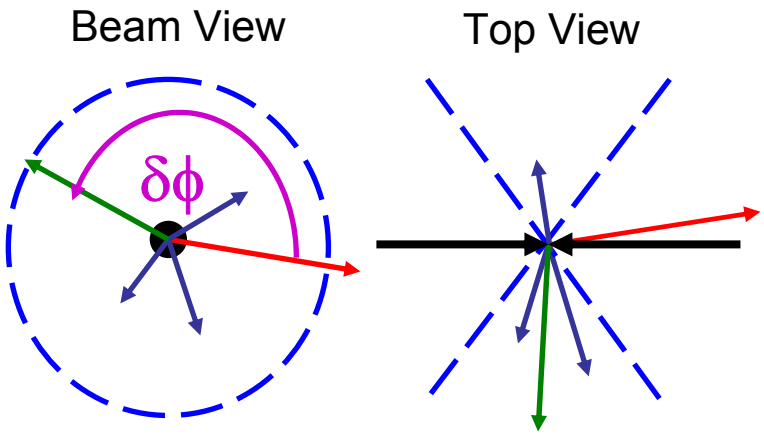


- PYTHIA ***prediction*** agrees well with the inclusive π^0 cross section at η~3-4
- Dominant sources of large x_F π^0 production from:
- q + g → q + g **(2→2)** → π^0 + X
- q + g → q + g + g **(2→3)** → π^0 + X



Back-to-back Azimuthal Correlations

with large rapidity interval (Mueller-Navelet dijets)



Trigger by forward π^0

- $E_p > 25$ GeV
- $\langle \eta_\pi \rangle = 4$

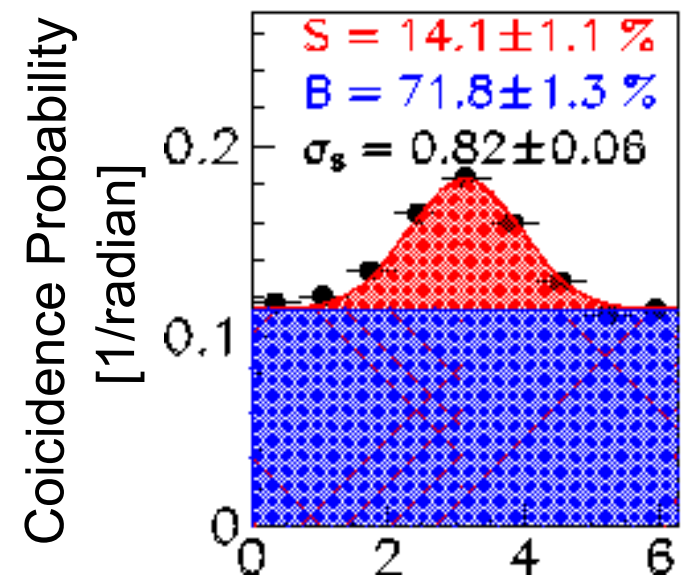
Midrapidity $h^\pm$ tracks in TPC

- $-0.75 < \eta < +0.75$

Leading Charged Particle(LCP)

- $p_T > 0.5$ GeV/c

Fit $\delta\phi = \phi_\pi - \phi_{LCP}$ normalized distributions and with Gaussian+constant

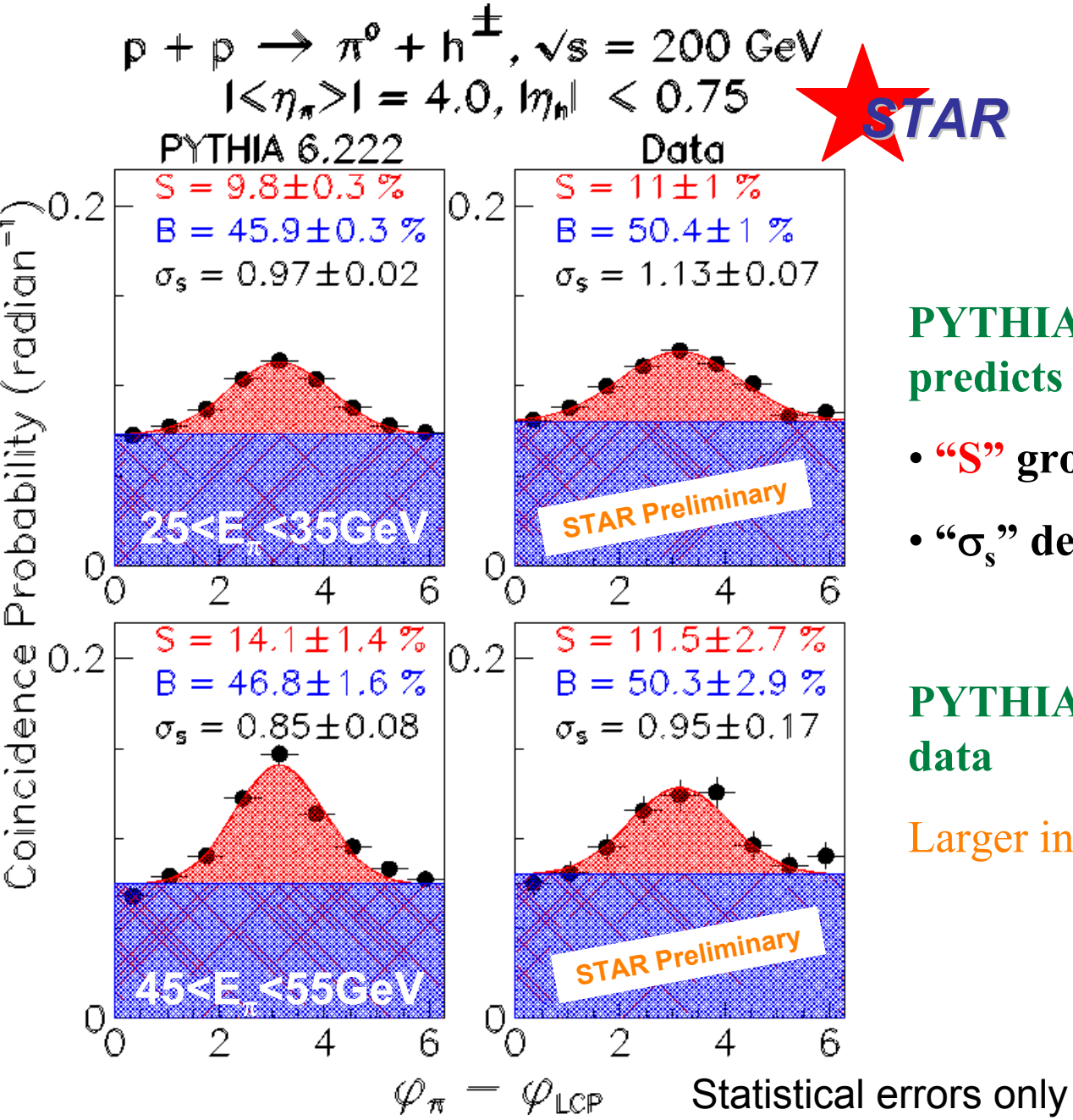


$$\delta\phi = \phi_\pi - \phi_{LCP}$$

S = Probability of "correlated" event under Gaussian

B = Probability of "un-correlated" event under constant

σ_s = Width of Gaussian



Statistical errors only

PYTHIA (with detector effects) predicts

- **"S" grows with $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**
- **"σ_s" decrease with $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

PYTHIA prediction agrees with data

Larger intrinsic k_T required to fit data

A. Ogawa (BNL), DIS2004

Do we understand forward π^0 production at RHIC?

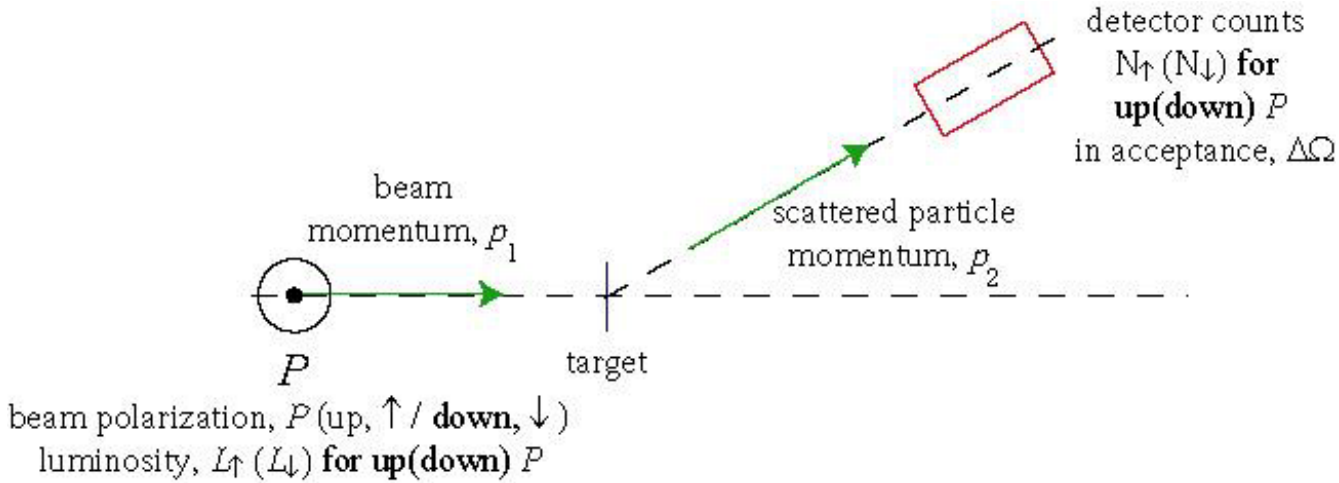
- **NLO pQCD** agrees with inclusive cross section measurement, unlike lower $\sqrt{s}$ data
- **PYTHIA** (LO pQCD + parton showers simulation) agrees with inclusive cross section measurement, unlike lower $\sqrt{s}$ data
  - PYTHIA says large x_F, large η π^0 come from $2 \rightarrow 2$ (& $2 \rightarrow 3$) **parton scattering, with small contributions from soft processes**
- **Back-to-back large rapidity interval particle correlations agree with PYTHIA**

$\Rightarrow$ **Forward π^0 meson production at RHIC energies comes from partonic scattering**

Important result for:
- Spin effects
- Comparison with d + Au
- Flavor tagging

G. Rakness (Penn State/BNL),
AGS/RHIC Users Meeting (5/2004)

Measurements with Polarized Beam



Polarization dependent yields…

$$N_{\uparrow} = L_{\uparrow}\sigma_0(1 + PA_N)$$

$$N_{\downarrow} = L_{\downarrow}\sigma_0(1 - PA_N)$$

$$\text{Assuming } P = P_{\uparrow} = P_{\downarrow}$$

$$\varepsilon = PA_N = \frac{N_{\uparrow}/L_{\uparrow} - N_{\downarrow}/L_{\downarrow}}{N_{\uparrow}/L_{\uparrow} + N_{\downarrow}/L_{\downarrow}} = \frac{N_{\uparrow} - RN_{\downarrow}}{N_{\uparrow} + RN_{\downarrow}}$$

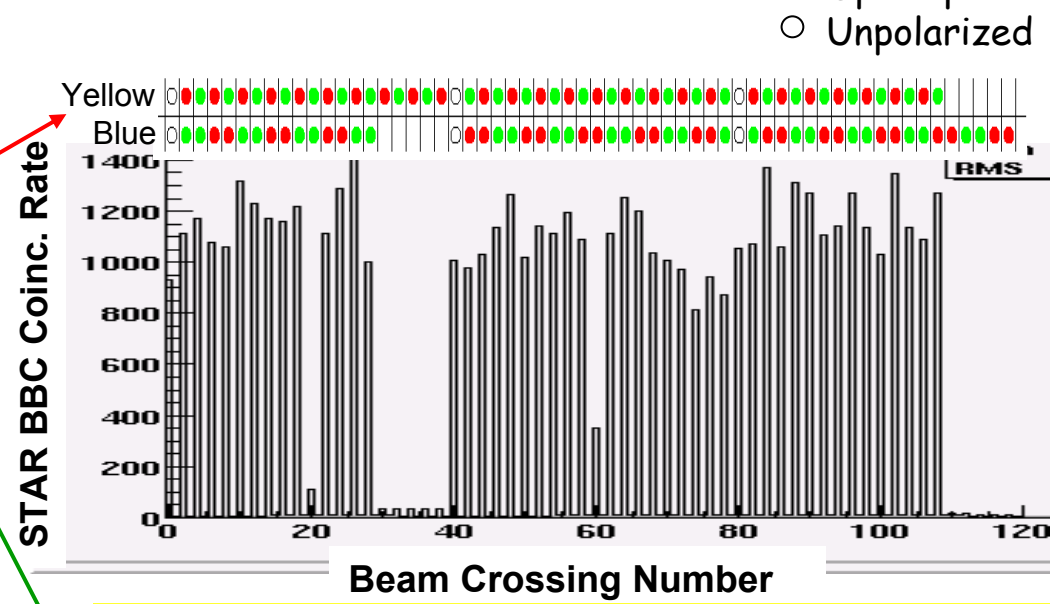
$$\text{where } R = \frac{L_{\uparrow}}{L_{\downarrow}}$$

… provide spin asymmetry, ε and physical observable (analyzing power),

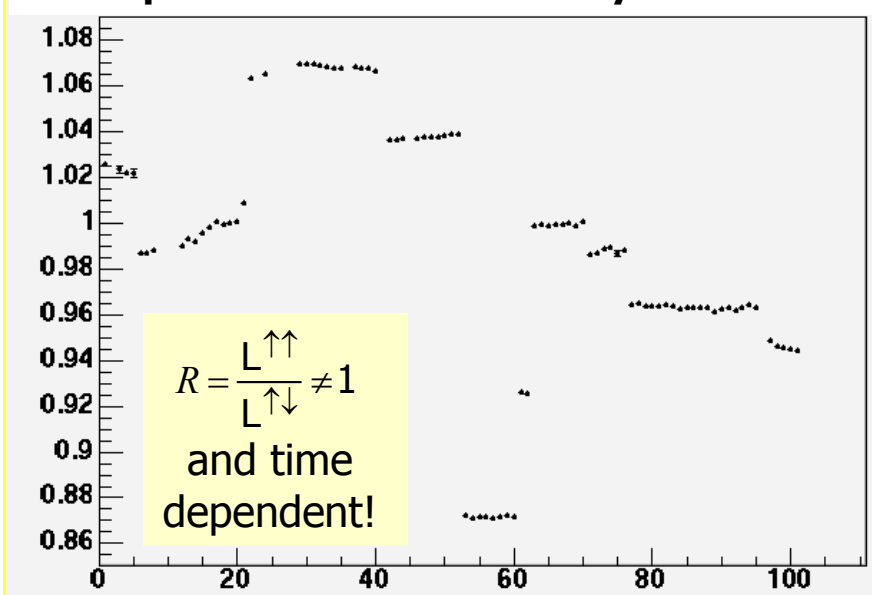
$$A_N = \varepsilon / P$$

Relative Luminosity Monitoring

- RHIC stores up to 120 bunches per ring
- Different bunches injected with different spin orientation
- Collision luminosity can vary significantly with spin combination
- Precision of relative luminosity monitoring critical – demonstrated better than 10^{-3} in 2002 run
- Special problem for A_{LL} measurements: asymmetry ϕ-independent, shows up <u>only</u> as yield change per integrated luminosity unit
- Must demonstrate that L monitor reaction does not have its own A_{LL} of magnitude comparable to physics of interest $\Rightarrow$ comparisons of different L monitors



Example of Relative Luminosity from Run 2

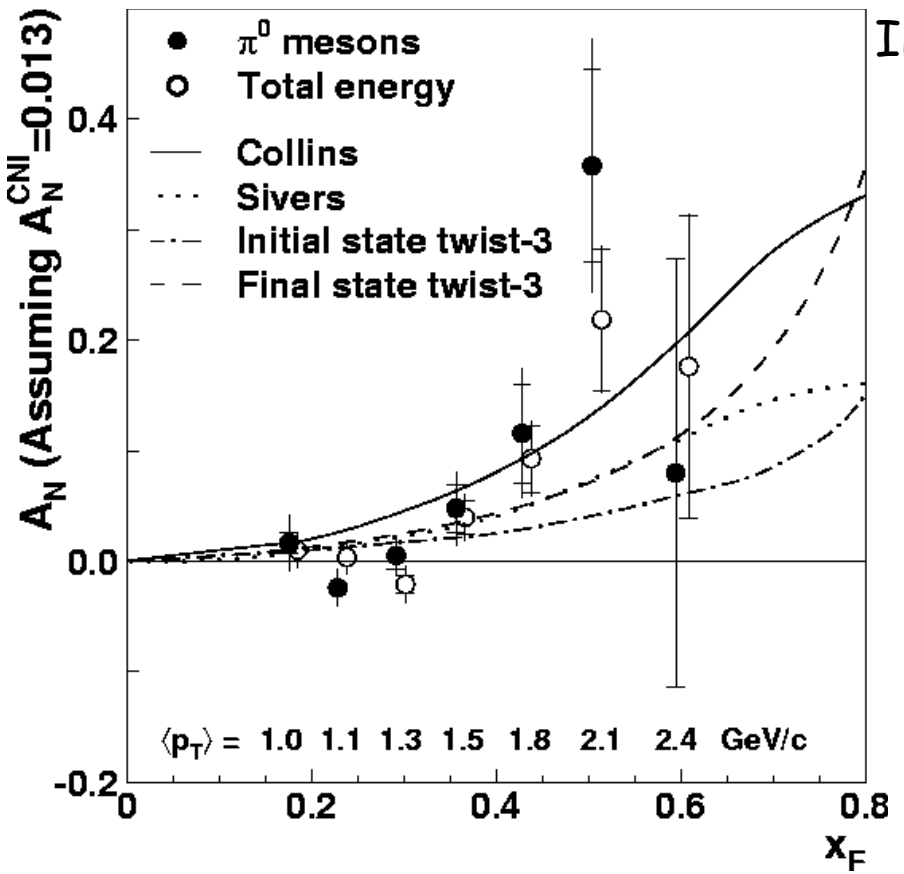


Large Analyzing Powers at RHIC

First measurement of A_N for forward π^0 production at $\sqrt{s}$=200GeV

STAR

STAR collaboration, hep-ex/0310058, accepted by Phys. Rev. Lett. (in press)



Similar to FNAL E704 result at $\sqrt{s}$ = 20 GeV

In agreement with several models including different dynamics:

- Sivers: spin and $k_\perp$ correlation in initial state (related to orbital angular momentum?)
- Collins: Transversity distribution function & spin-dependent fragmentation function
- Qiu and Sterman (initial-state) / Koike (final-state) twist-3 pQCD calculations

BBC Transverse Single Spin Asymmetries

Single spin asymmetries measured for p+p -> A + X, where A – hit(s) in the BBC

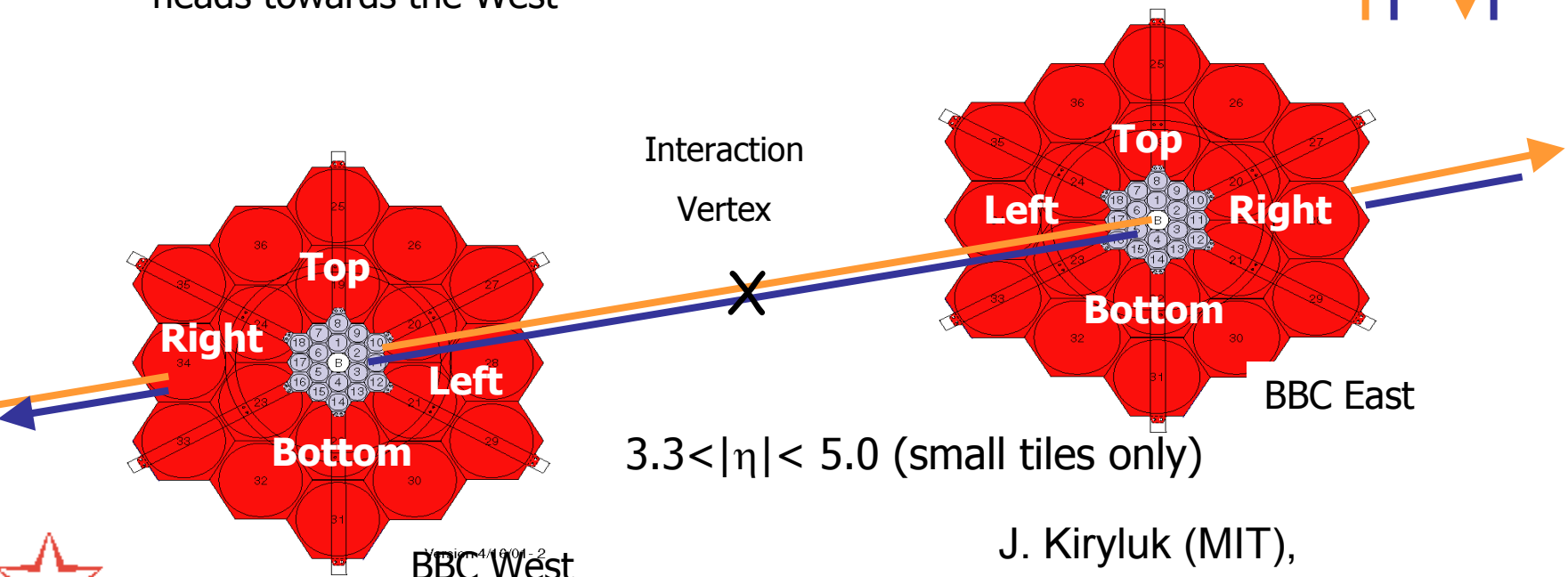
$$\varepsilon = P_{beam} \times A_N \approx \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}$$

L(R) – number of counts in Left (Right) or Top (Bottom) in the BBC East or BBC West (small annuli) counted every bunch crossing by the scaler system

The BBC East and West data sets sorted by beam polarization states:

1. **Polarized Yellow beam** (sum over Blue beam polarization states) heads towards the East

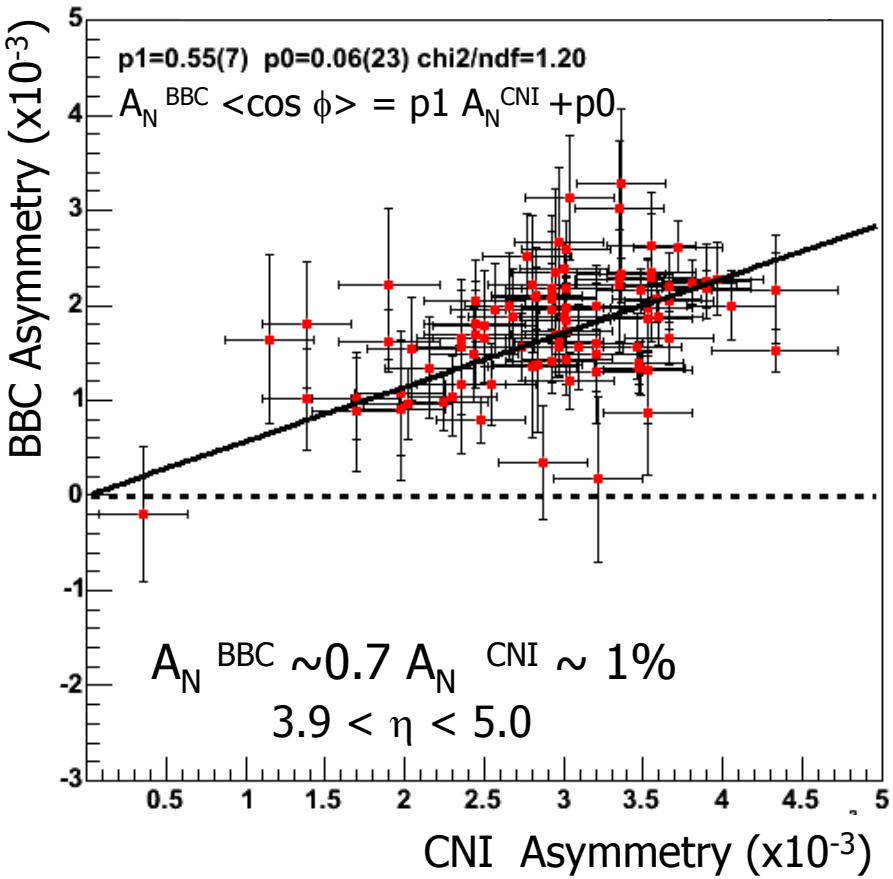
2. **Polarized Blue beam** (sum over Yellow beam polarization states) heads towards the West

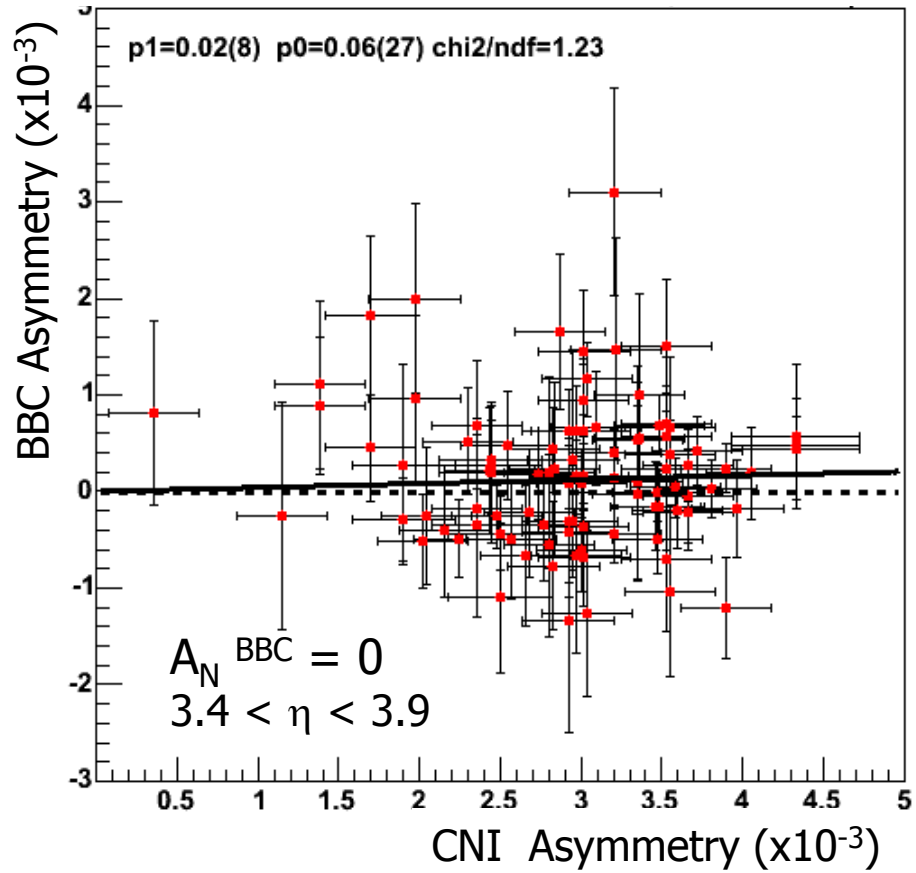


3.3<|η|< 5.0 (small tiles only)

J. Kiryluk (MIT),
AGS/RHIC Users Meeting (5/2004)

Transverse Single Spin Asymmetries
BBC Run-3 (Preliminary) Results





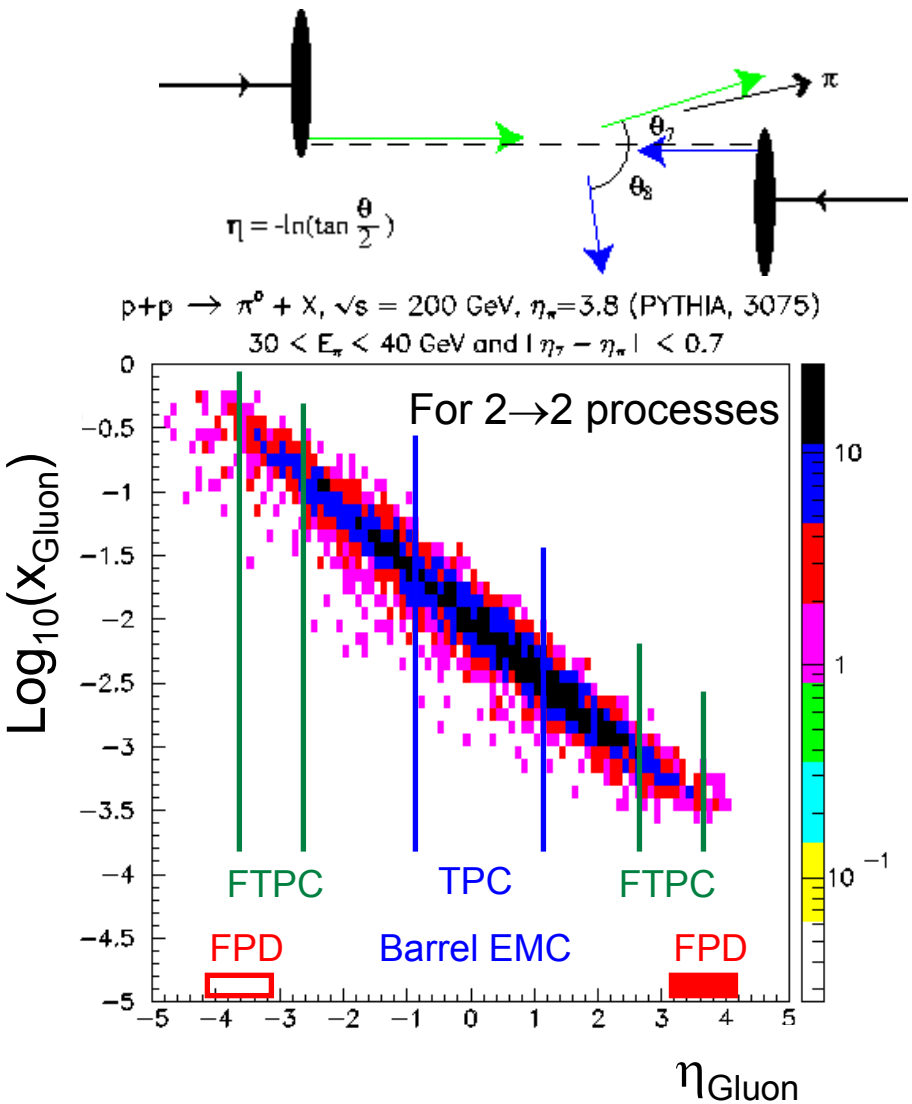
- Unexpected A_N of unknown origin measured with the BBC
- Strong pseudorapidity dependence of A_N for $x_F>0$ and $A_N = 0$ for $x_F<0$
- BBC - fast local polarimeter at STAR

J. Kiryluk (MIT),

AGS/RHIC Users Meeting (5/2004)

Why forward physics at RHIC?

Rapidity interval (forward + mid-rapidity) correlations



Broad rapidity range at STAR enables nearly complete coverage of recoil parton kinematics

Wide acceptance mid-rapidity detector & unobstructed view at forward rapidity

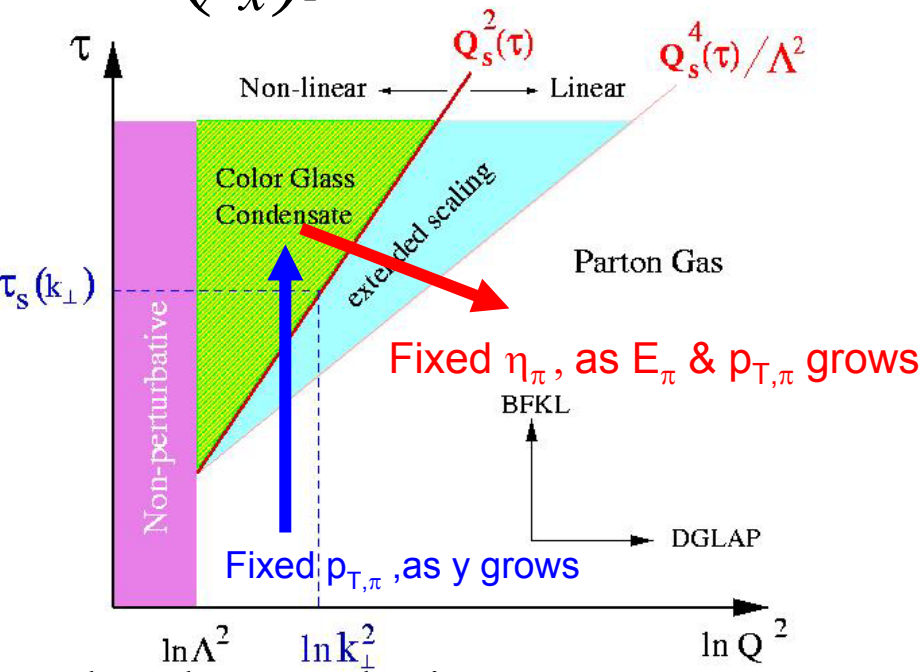
Spin effects with rapidity interval correlations?

Nuclear enhancement of gluon field : $A^{1/3}x \sim 6x$ (Au case)?

- FPD: $|\eta| \sim 4.0$
- TPC and Barrel EMC: $|\eta| < 1.0$
- Endcap EMC: $1.0 < \eta < 2.0$
- FTPC: $2.8 < |\eta| < 3.8$

d + Au: Possible Color Glass Condensate at RHIC?

$\tau = \ln\left(1/x\right)$ τ related to rapidity of produced hadrons.

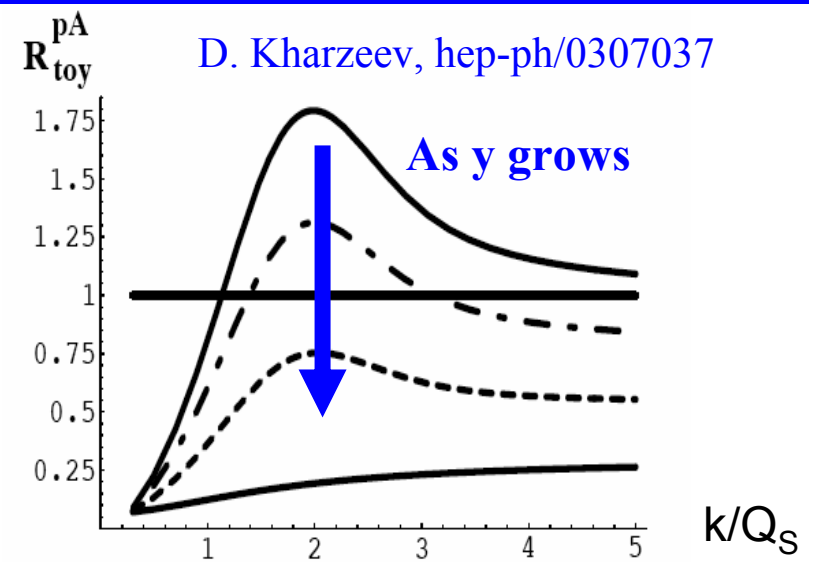


Edmond Iancu and Raju Venugopalan, hep-ph/0303204

General expectations of CGC:

Suppression of forward particle production

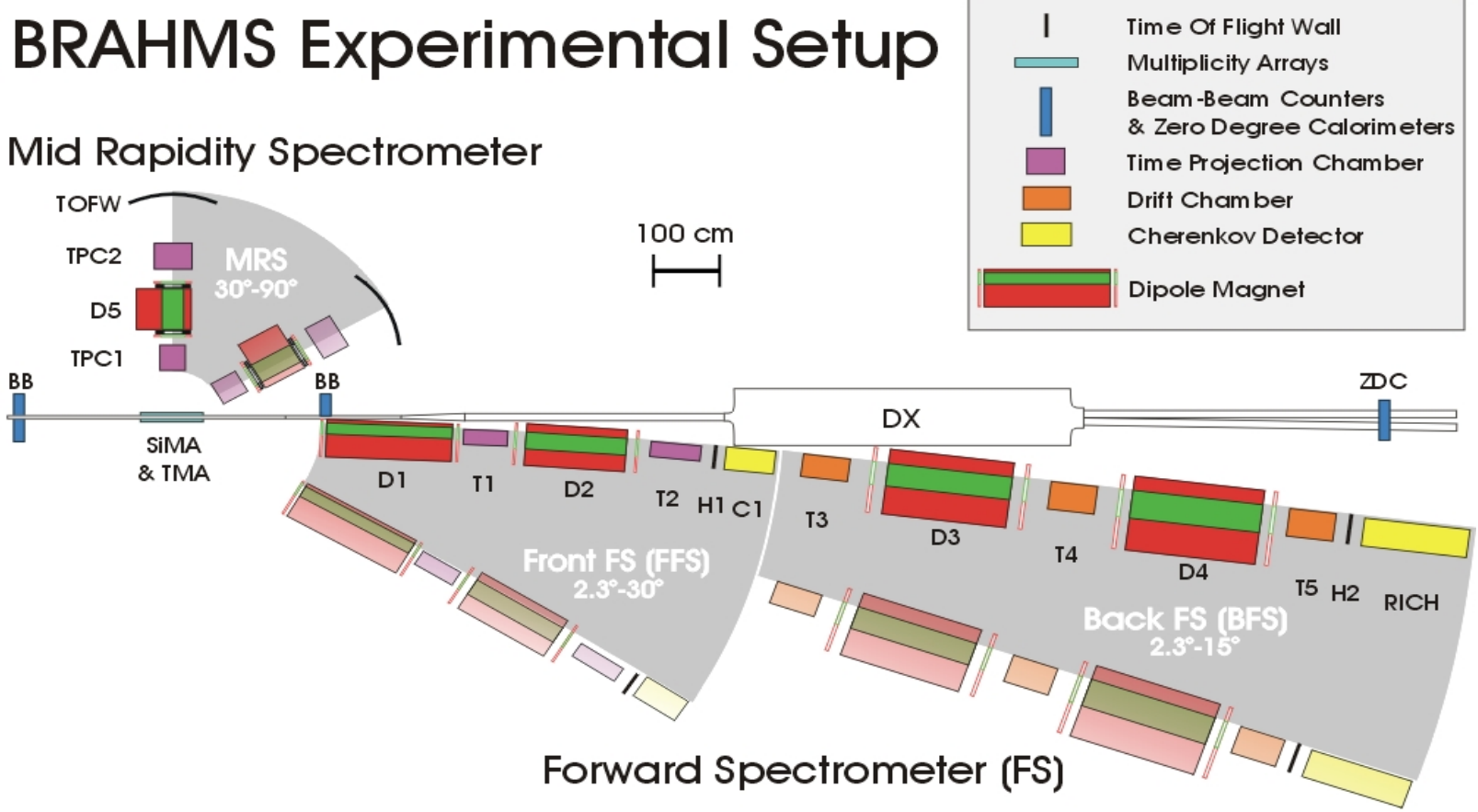
D. Kharzeev, hep-ph/0307037

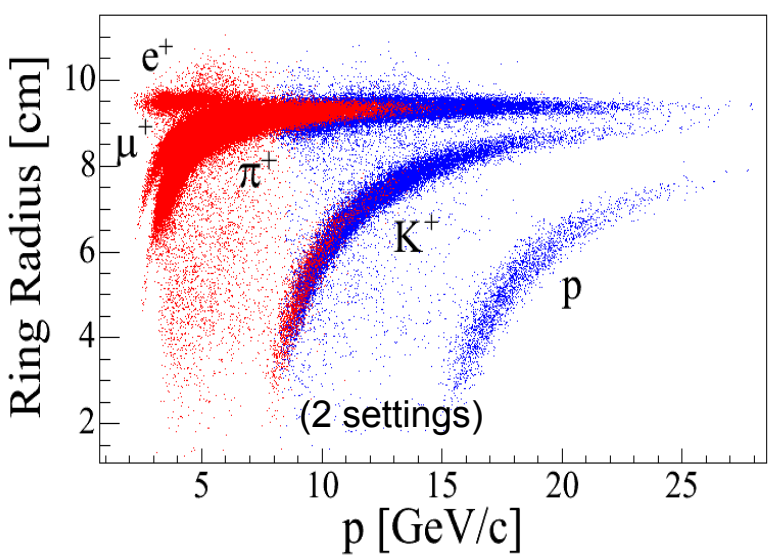


Brahms data shows evidence ?

(nucl-ex/0403005)

BRAHMS Experimental Setup





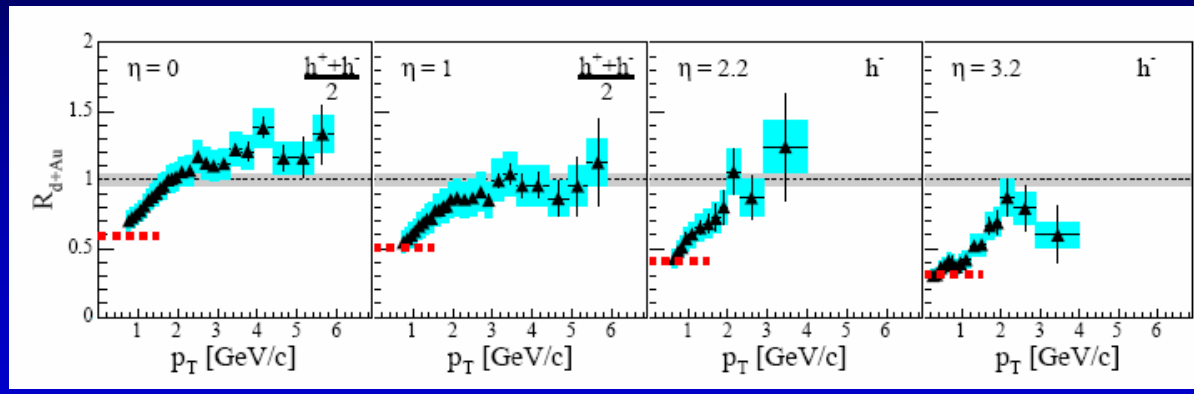
CHERENKOV

RICH: Cherenkov light focused on spherical mirror → ring on image plane

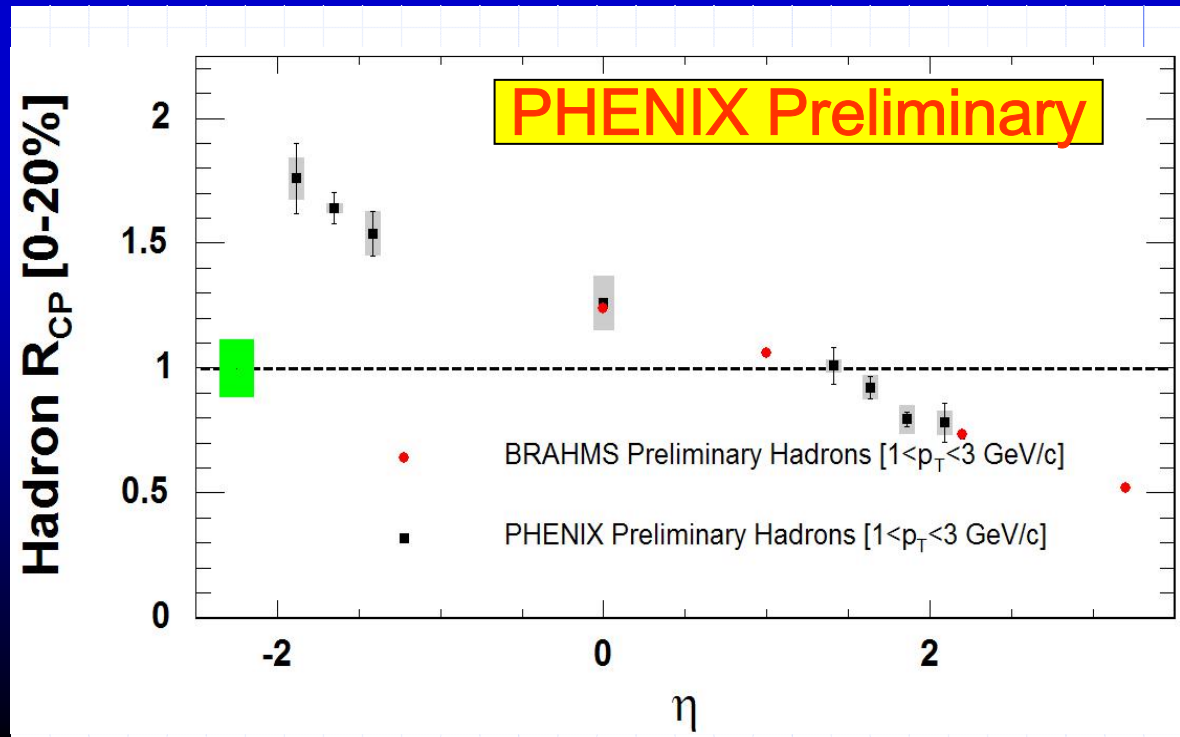
Ring radius vs momentum gives PID
π / K separation 25 GeV/c
Proton ID up to 40 GeV/c

d+Au Viewed Through Colored Glass

- BRAHMS publication (nucl-ex/0403005)
  - Dependence on
    - Pseudorapidity
    - Centrality
  - Qualitatively consistent with CGC



- PHENIX Preliminary Result
  - Consistent with trend observed by BRAHMS
  - Extends these measurements to Au fragmentation regime



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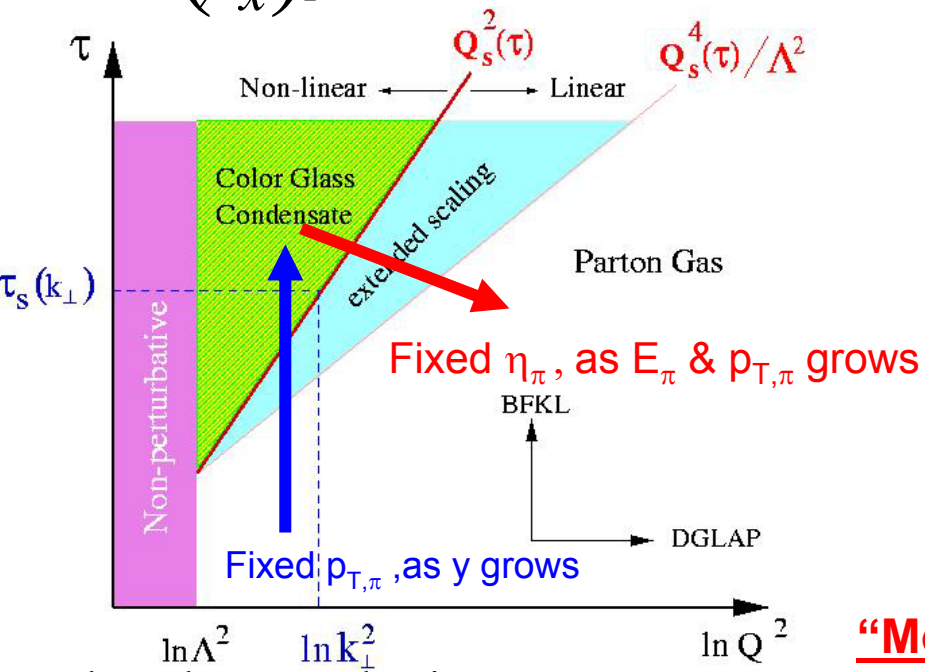

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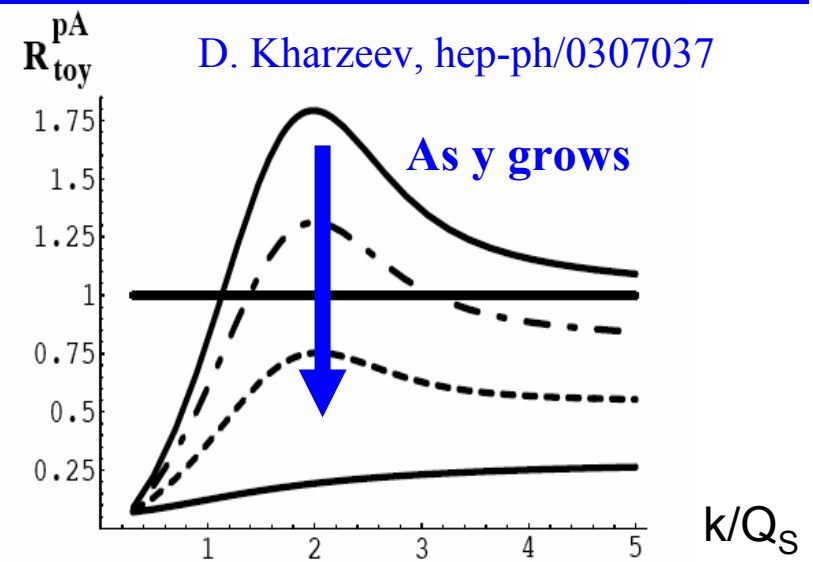
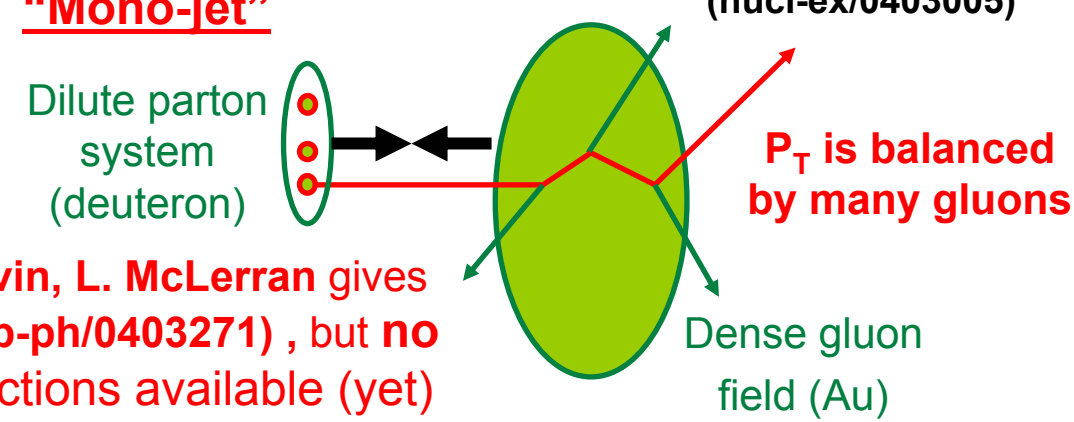


Brahms data shows evidence ?

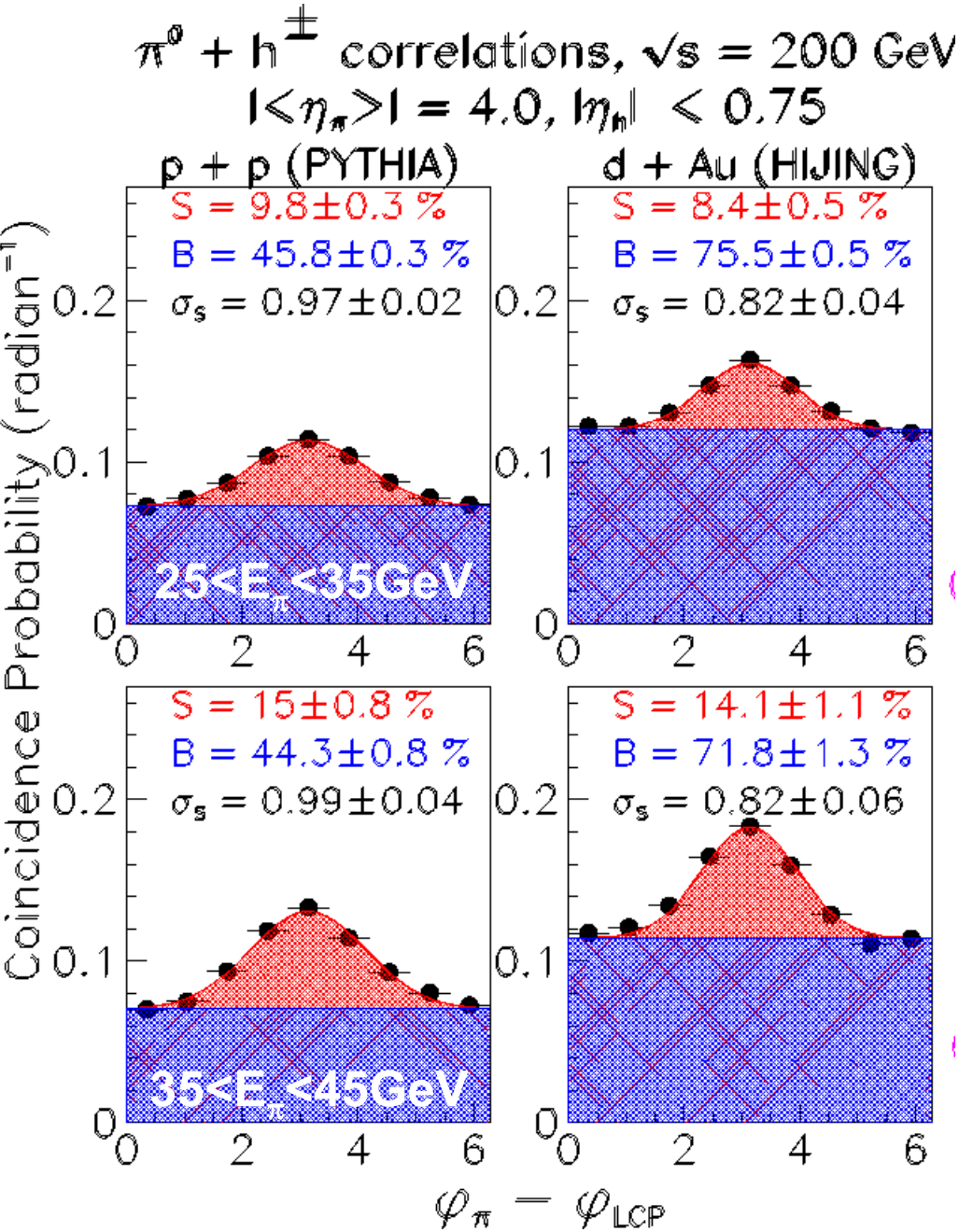
(nucl-ex/0403005)

"Mono-jet"



D.Kharzeev, E. Levin, L. McLerran gives physics picture **(hep-ph/0403271)** , but **no** quantitative predictions available (yet)

→ **Exploratory studies of large rapidity interval particle correlations at STAR**



Expectation from HIJING
(PYTHIA+nuclear effects)

X.N.Wang and M Gyulassy, PR D44(1991) 3501

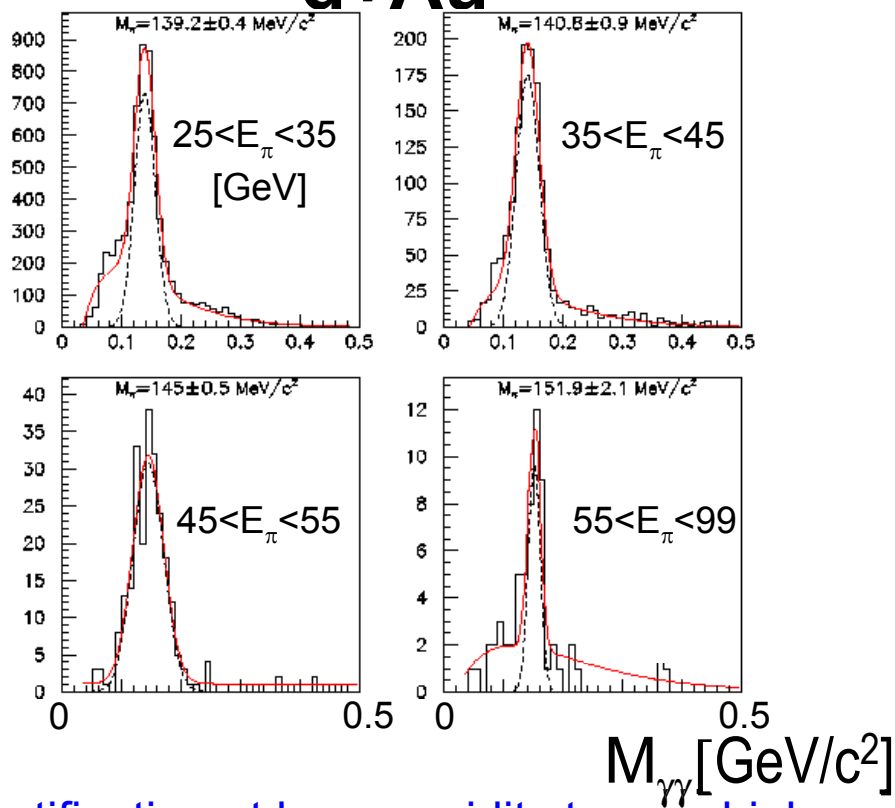
with detector effects

- **HIJING predicts clear correlation in d+Au**
- **Small difference in "S" and "σ_s" between p+p and d+Au**
- **"B" is bigger in d+Au due to increased particle multiplicity at midrapidity**

Di-photon Mass Reconstruction

- Pb-glass reconstruction (no SMD)
- Number of photons found = 2
- Fiducial volume > 1/2 cell width from edge
- Energy sharing $z_{\gamma\gamma}=|E_1-E_2| / (E_1+E_2) < 0.7$

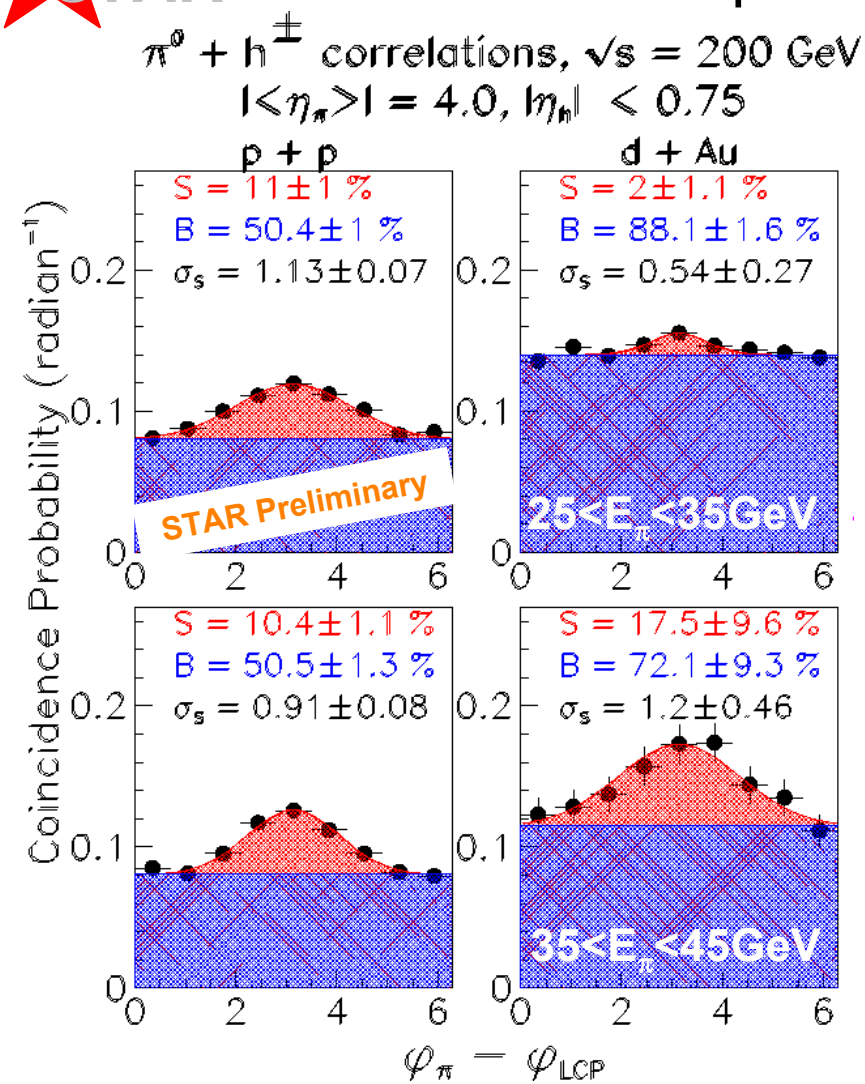
d+Au



- Robust particle identification at large rapidity to very high energies using electromagnetic calorimetry
- Absolute gain determined from π^0 peak position for each tower
- gain calibration presently known to only ~10% ⇒ cross section in d+Au requires better calibrations (work is underway)

dAu Particle Correlations:

probing low x

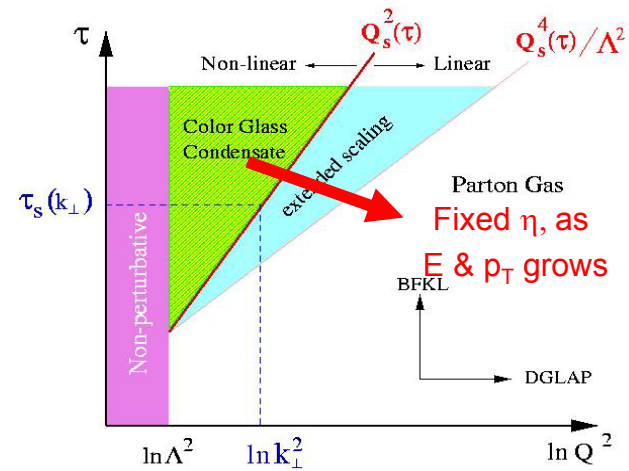


Statistical errors only

Large $\Delta\eta$ π^0+h$^{\pm}$ correlations

- **Suppressed at small $\langle x_F \rangle$, $\langle p_{T,\pi} \rangle$**

Consistent with CGC picture



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

as expected by HIJING

A. Ogawa (BNL), DIS2004

Conclusions

- **Forward hadron production at hadron-hadron collider selects high-*x* quark + low-*x* gluon scatterings.**

- **Forward π^0 meson production at RHIC energies is consistent with partonic scattering calculations, unlike at lower $\sqrt{s}$.**
  - **Analyzing power for forward π^0 mesons is large at RHIC.**

- **Large rapidity interval particle correlations in d+Au differ from p+p in a direction consistent with CGC picture.**

$\Rightarrow$ More data with d(p)+Au (and quantitative theoretical understanding) is required to make definitive physics conclusions

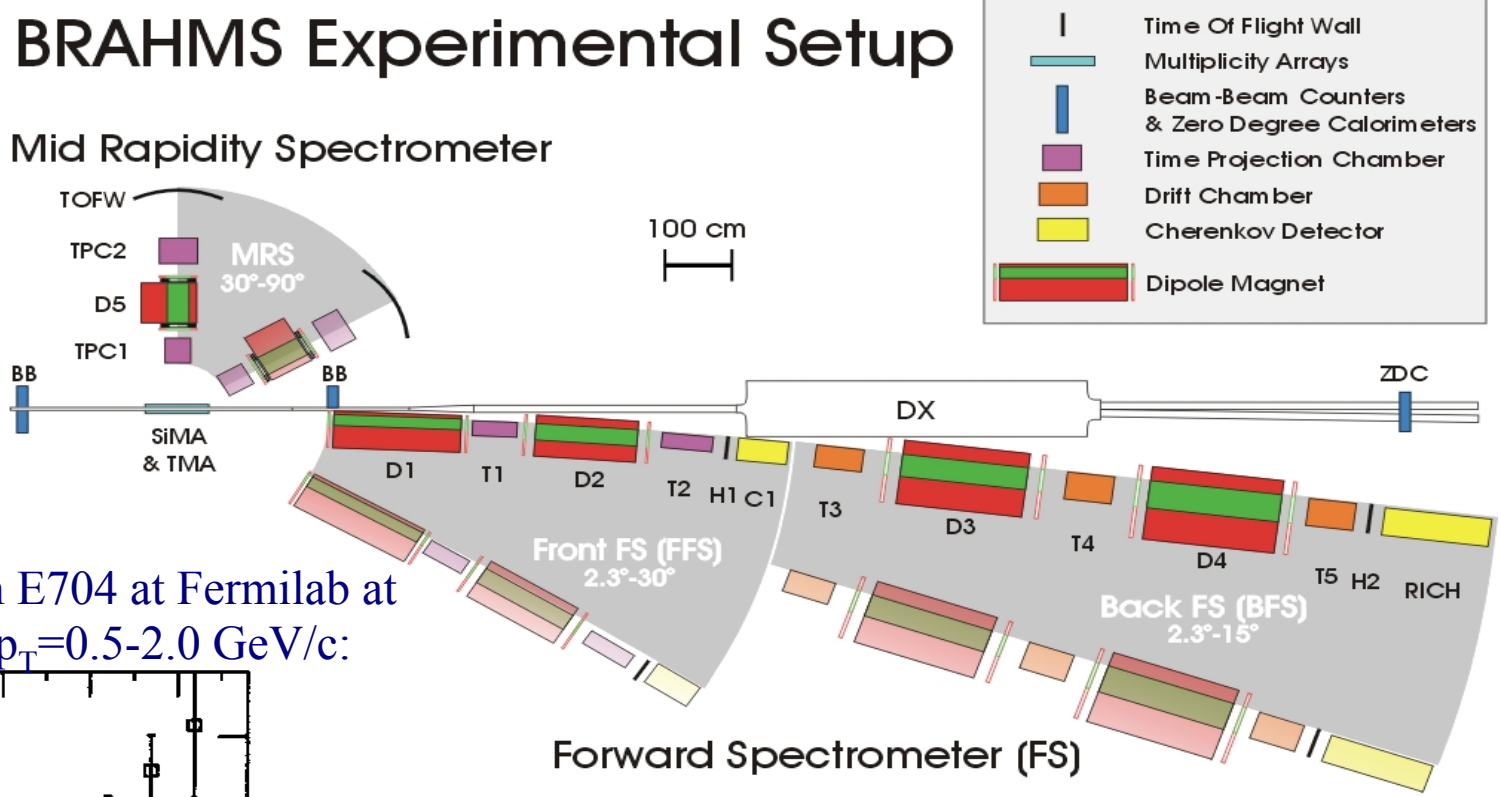
Outlook for RHIC-I

in $p_\uparrow + p_\uparrow$ (transverse & longitudinal) and $p_\uparrow$(d)+nucleus

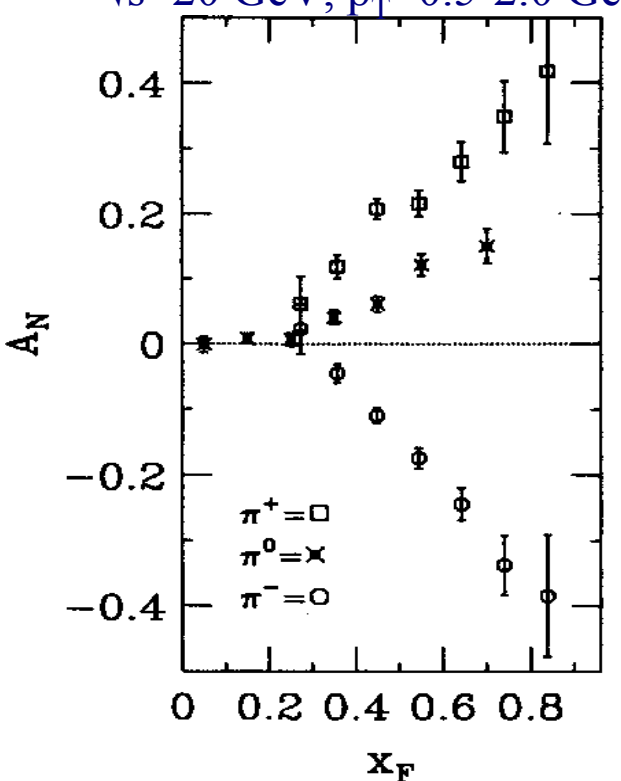
- **p+p/d+Au comparisons**
  - ➢ improve forward instrumentation at RHIC
  - ➢ establish rapidity dependence of saturation scale
    - ⇒ $R_{d(p)A}$ measurements for heavy-flavor mesons and γ
    - ⇒ particle correlations over extended $\Delta\eta$ range

- **Spin asymmetries with polarized p+p**
  - ➢ potential sensitivity to low-x ΔG via π^0 and γ A_{LL} measurements
  - ➢ disentangle dynamical origin of large-x_F analyzing power
    - ⇒ Brahms measurement of A_N for large x_F charged pions

BRAHMS Experimental Setup



A_N measured in E704 at Fermilab at $\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV/c:



BRAHMS proposal:

measure A_N for $p_\uparrow p \rightarrow \pi^\pm + X$ at $\sqrt{s}$=200 GeV, η_π~3.9

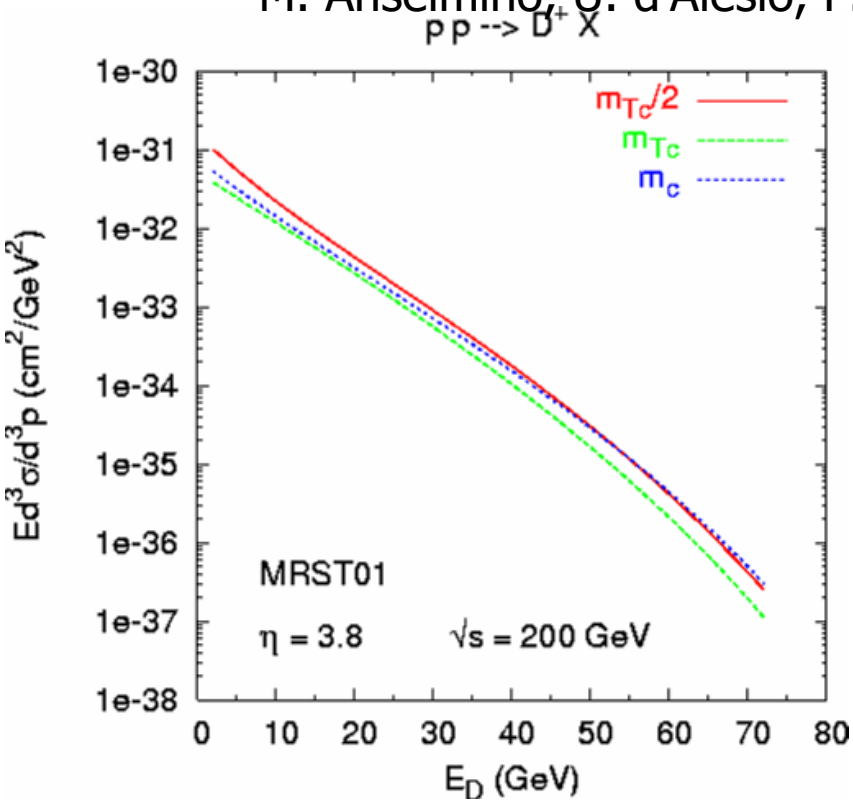
π^+ *measurements*			π^- *measurements*		
x_F	p_T(GeV/c)	Cts/hour	x_F	p_T(GeV/c)	Cts/hour
0.21	1.0	6454	0.21	1.0	5296
0.25	1.4	1068	0.25	1.4	807
0.30	1.9	163	0.30	1.9	91
0.35	2.5	24	0.35	2.5	12

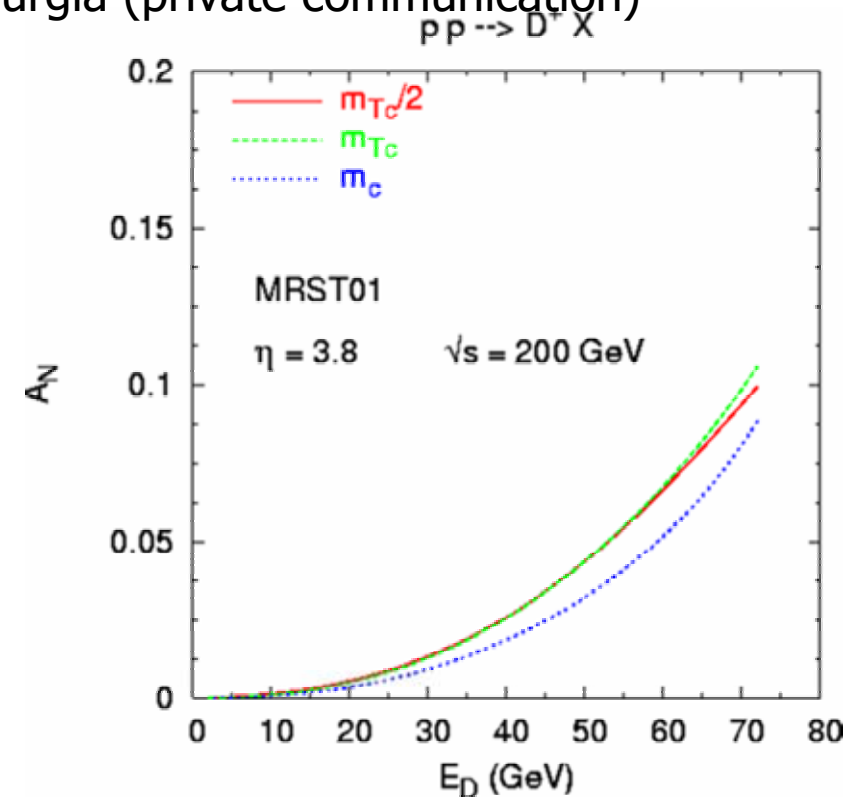
Rate estimates
Assume
L ~ 1.5 $\mu b^{-1}s^{-1}$

Charmed Meson Production in $p_\uparrow$+p (and $p_\uparrow$+Au?)

Isolating the Sivers function

M. Anselmino, U. d'Alesio, F. Murgia (private communication)



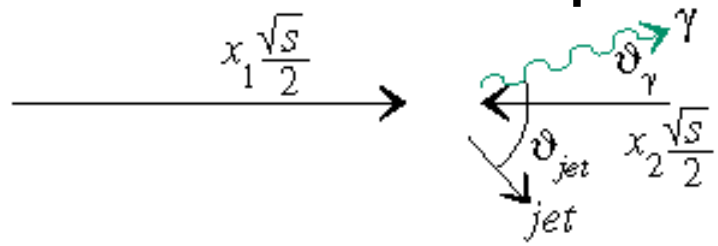


- $q+\bar{q} \rightarrow c+\bar{c}$ favored over g+g→g+g and q+g →q+g at large x_F
- no contribution from spin-dependent fragmentation (Collins effect)
- tests universality of spin / $k_\perp$ correlated distribution functions (Sivers function):

  ⇒ compare $p_\uparrow$+p to semi-inclusive DIS.

Why Consider Forward Spin Physics (A_{LL})?

• For large $x_F = x_1 - x_2$, get kinematic selection of asymmetric partonic collisions.



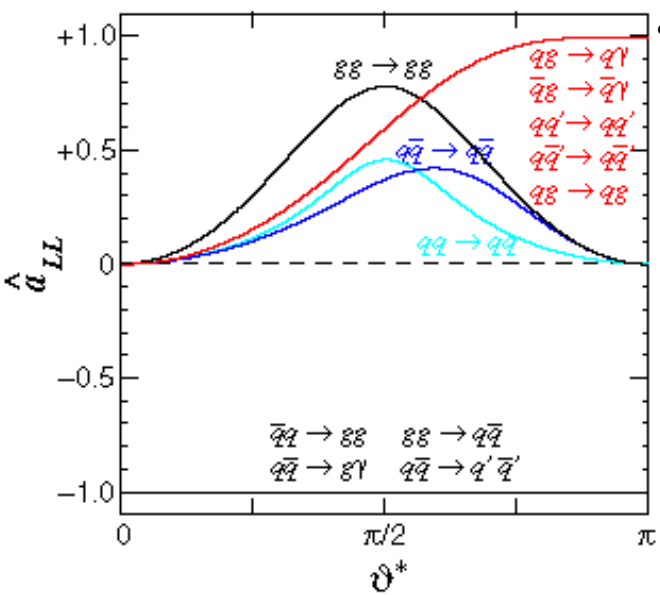
• Large x_F jet production primarily selects qg scattering from other subprocesses.

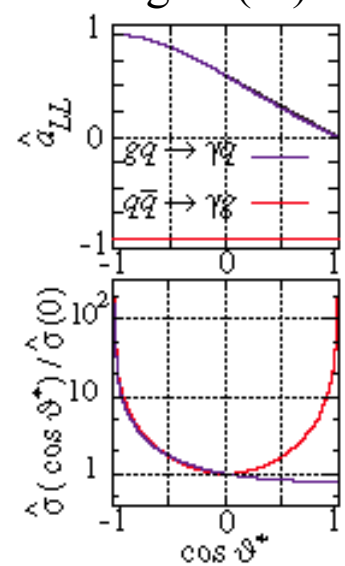
Assume collinear collisions and apply conservation of momentum $\Rightarrow$

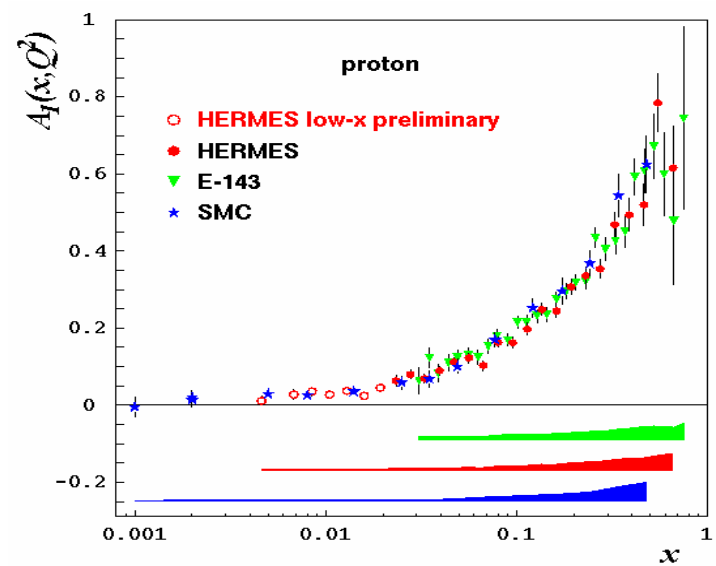
$$x_1 \sim \frac{x_T}{2}\left(e^{+\eta_\gamma} + e^{+\eta_{jet}}\right) \xrightarrow[\eta_\gamma > \eta_{jet}]{} \frac{x_T}{2}\, e^{+\eta_\gamma}$$

$$x_2 \sim \frac{x_T}{2}\left(e^{-\eta_\gamma} + e^{-\eta_{jet}}\right) \longrightarrow \frac{x_T}{2}\, e^{-\eta_{jet}}$$

• there are large spin effects in QCD hard scattering processes at 'forward' angles (θ^*). Note: $qg \to \gamma q$ also has large σ as $\theta^* \to \pi$.

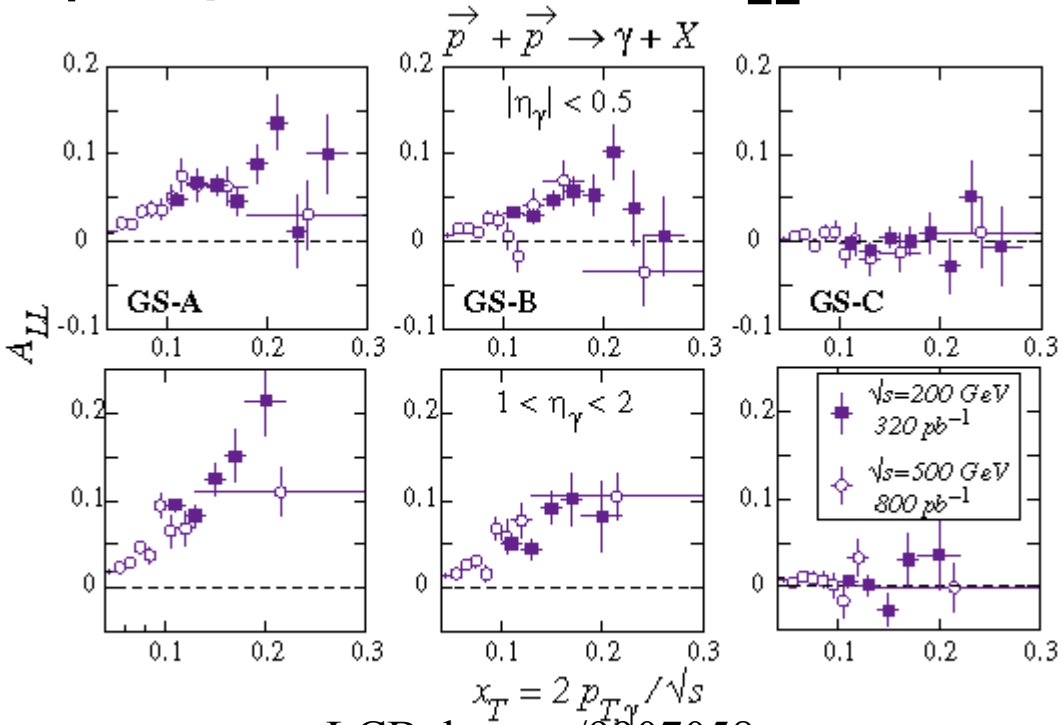




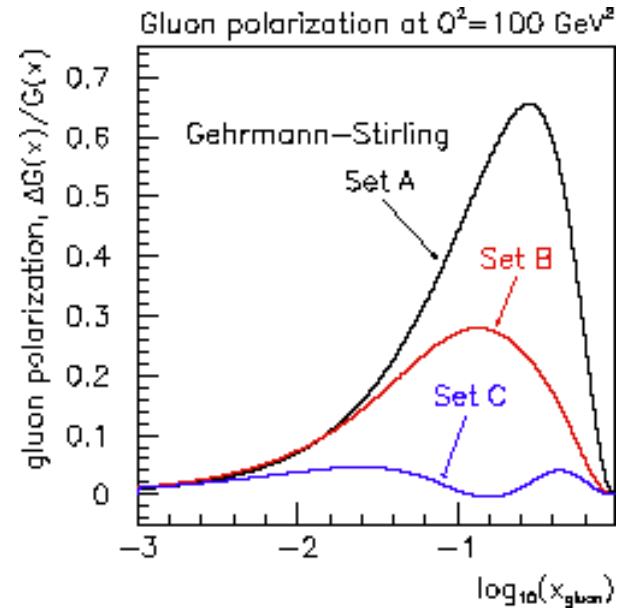


• charge-squared weighted quark polarizations (g_1/F_1) within the proton are large in the large-x valence region $\Rightarrow$ large quark polarization to provide good 'analyzer' of gluon polarization.

η dependence of A_{LL} for inclusive γ production



LCB, hep-ex/9907058



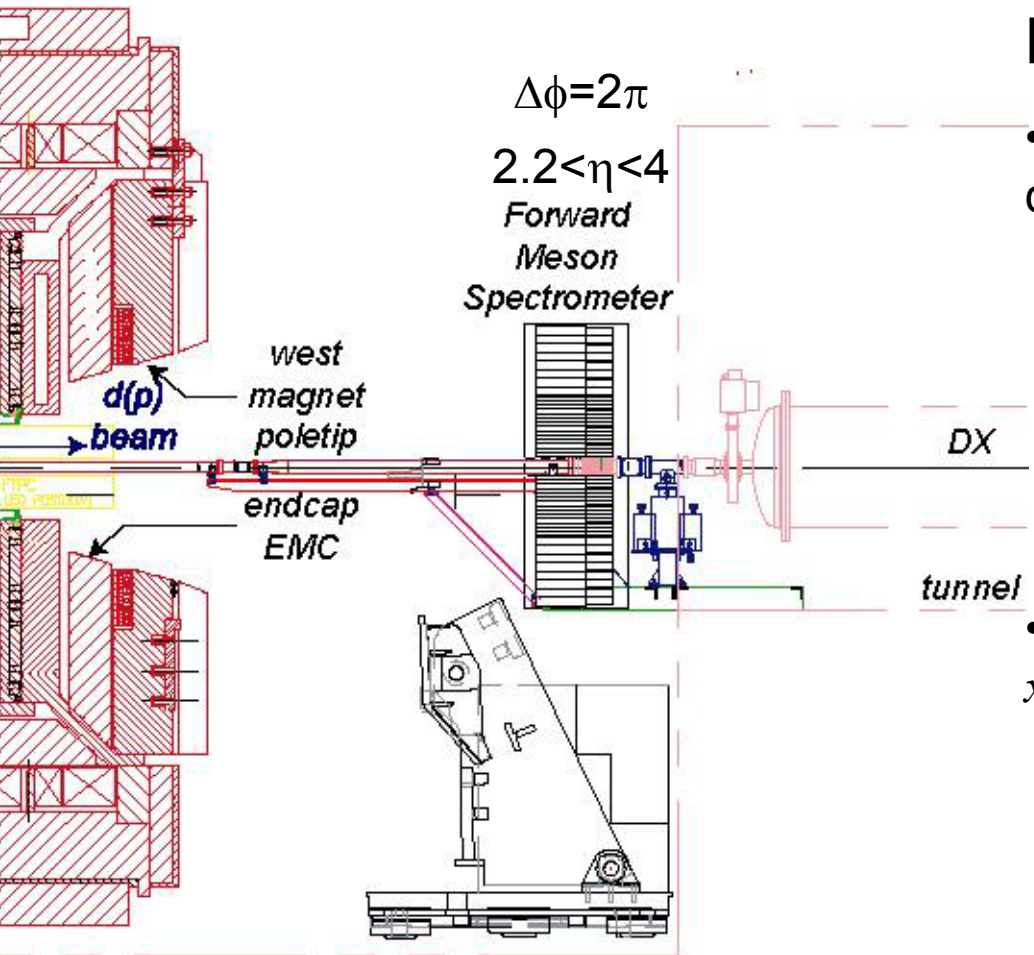
• larger spin effects at more forward angles. Expect at even more forward angles that the *sensitivity* (convolution $\hat{a}_{LL} \otimes A_1^p$) will increase. Since large η probes small x_{gluon}, gluon polarization may decrease because of sharp increase of unpolarized gluon density as $x_{gluon} \to 0$.

• expect the $(\pi^0+\eta^0)/\gamma$ ratio to be more favorable at forward angles than at midrapidity.

• expect sensitivity to gluon polarization for forward jet (as well as γ) production.

Forward Meson Spectrometer

Conceptual Design



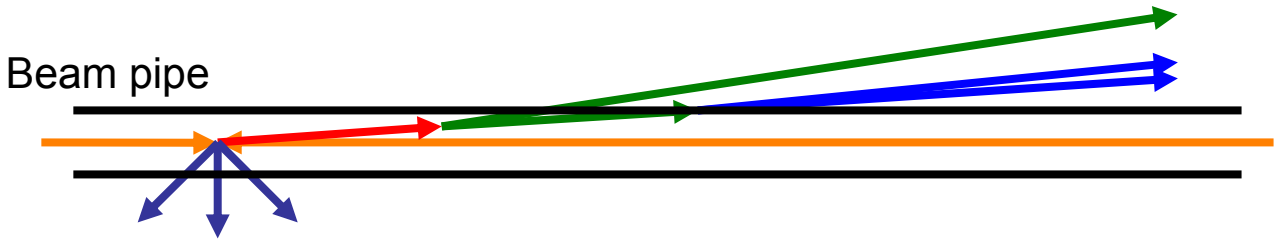
Physics Motivation:

- probing gluon saturation in p(d)+A collisions via…
  - large rapidity particle production (π^0,η,ω,η',γ,K^0,D^0) detected through all γ decays.
  - di-jets with large rapidity interval (Mueller-Navelet jets)
- disentangling dynamical origins of large x_F analyzing power in $p_\uparrow$+p collisions.

Backup slides

FTPC-FPD matching: Photon conversion in beam pipe

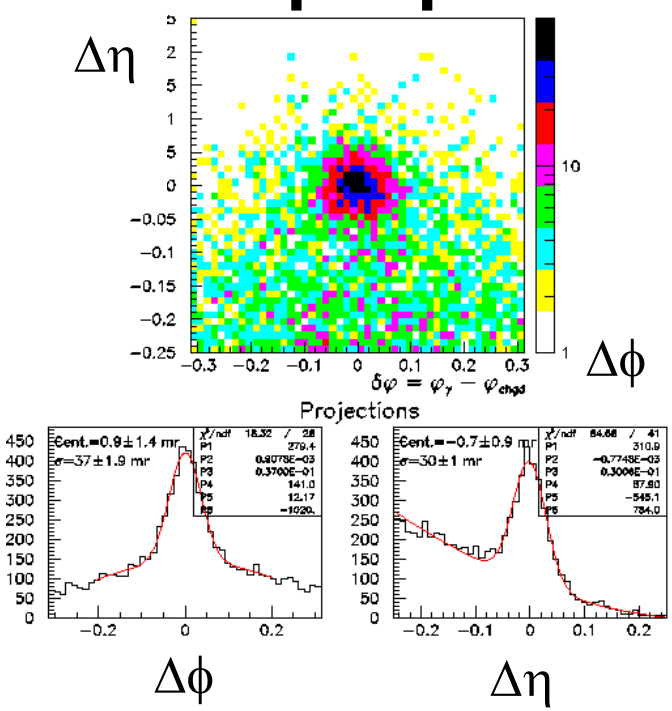
$\left.\begin{matrix} p + p \\ d + Au \end{matrix}\right\} \rightarrow \pi^0 (+ X) \rightarrow \gamma (+ \gamma) \rightarrow e^+ e^-$



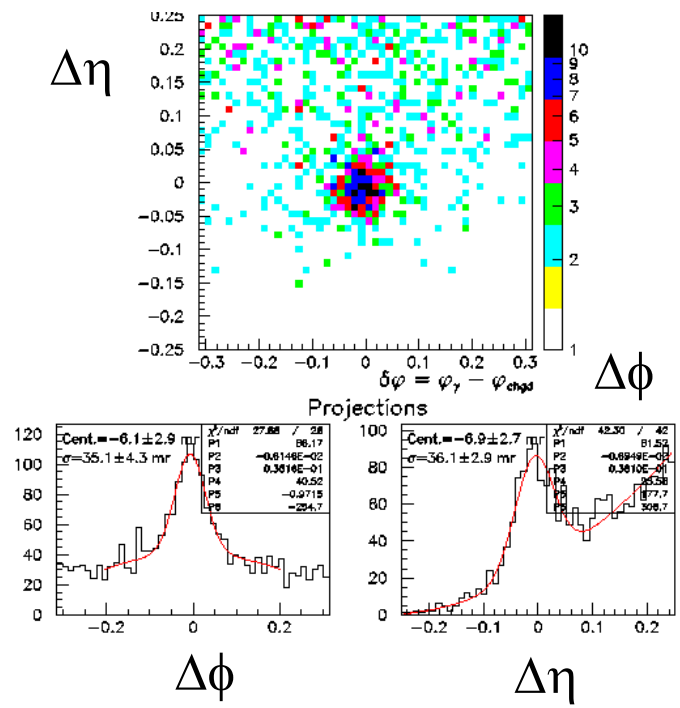
$\Delta\eta = \eta_{FPD} - \eta_{FTPC}$

$\Delta\phi = \phi_{FPD} - \phi_{FTPC}$

p + p



d+Au



FPD:

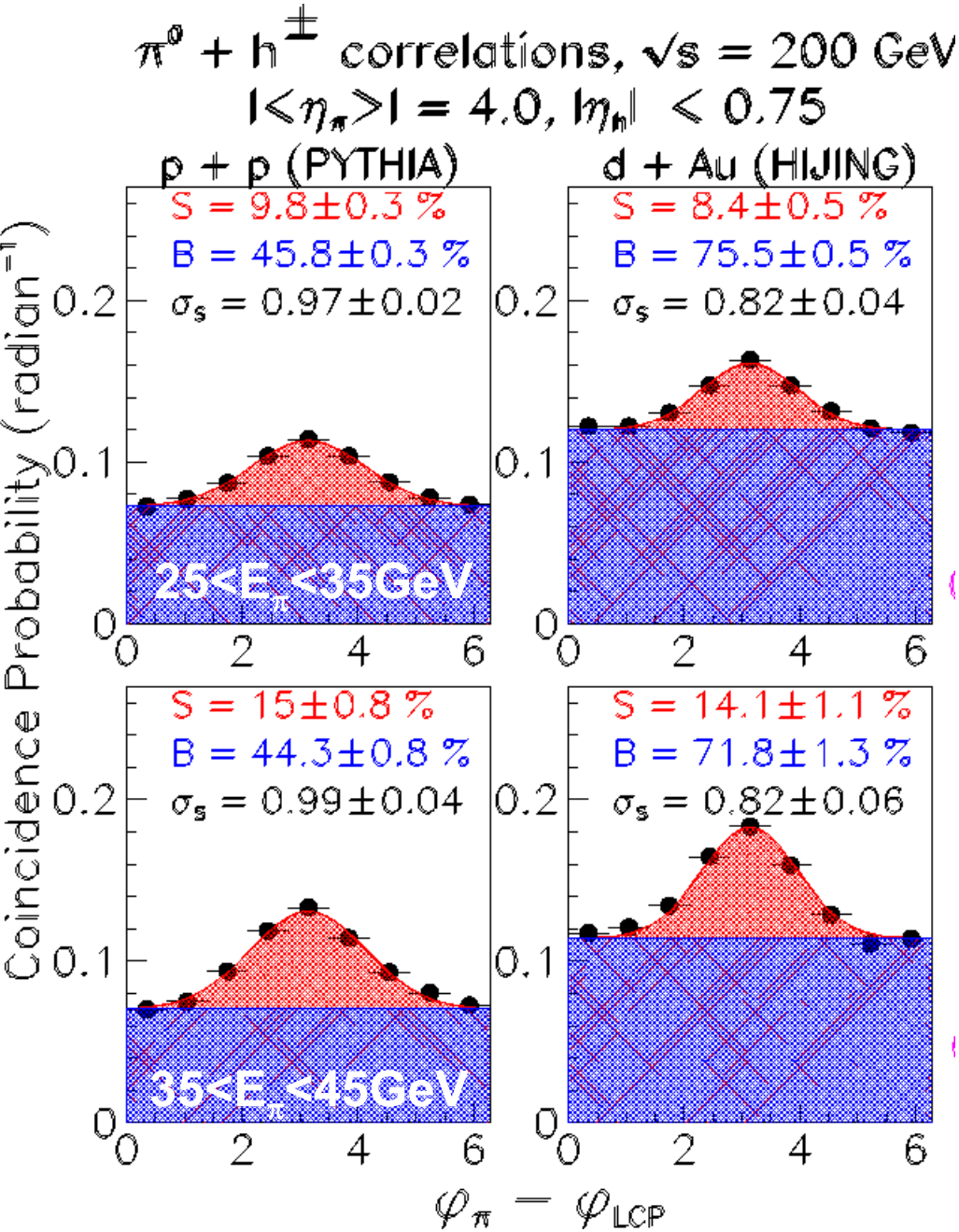
- $E_{FPD} > 25$ GeV
- $z_\gamma < 0.7$
- $N_\gamma = 2$
- fiducial volume cut > 1/2 cell width from edge

FTPC:

- $2.8 < |\eta| < 3.8$

⇒ FPD position known relative to STAR

⇒ Detector resolution for particle correlation is good



Expectation from HIJING
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X.N.Wang and M Gyulassy, PR D44(1991) 3501

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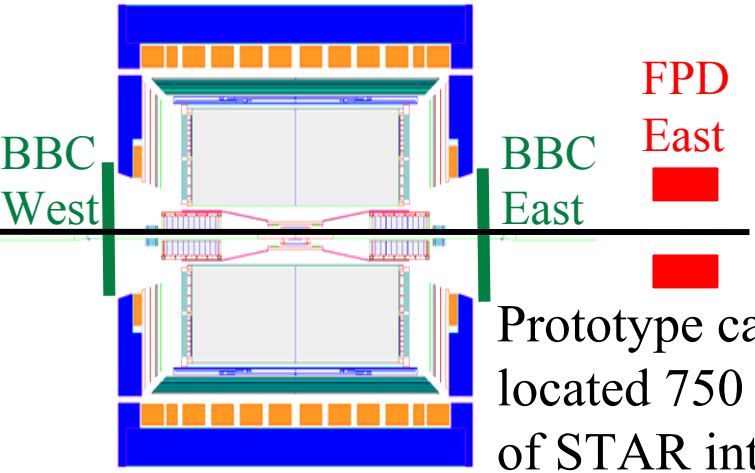
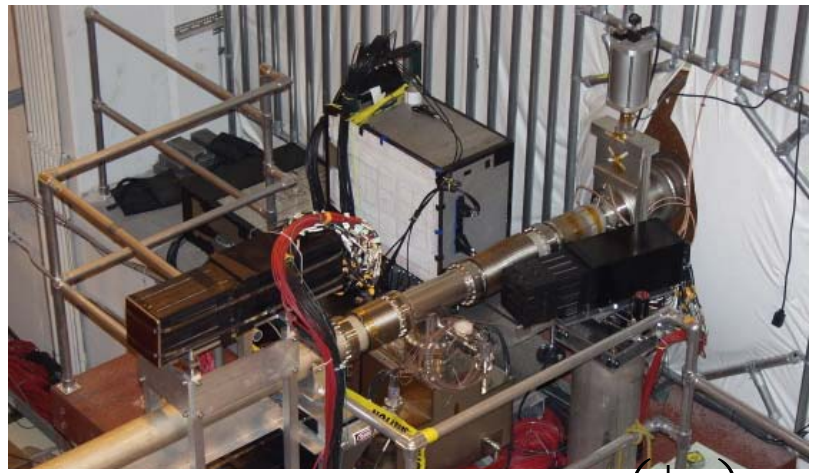
Run-2 Prototype FPD



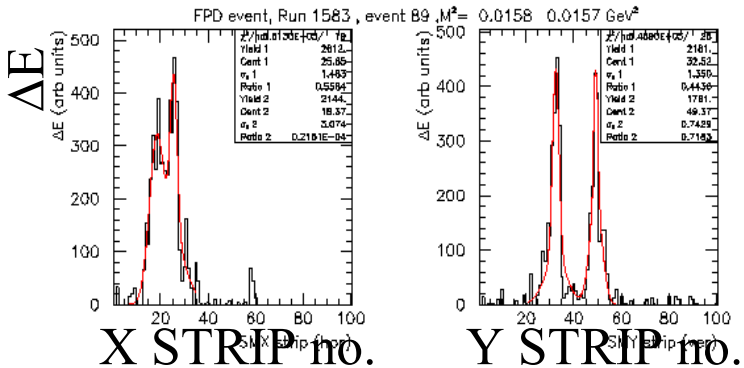
Prototype calorimeter located 750 cm (z_{vert}) east of STAR interaction region

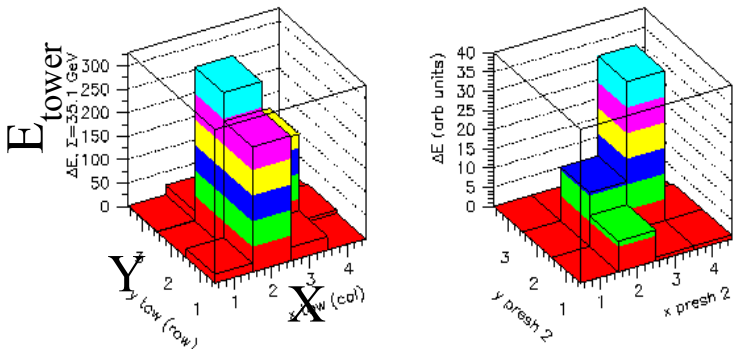


Identify/reconstruct high-energy $\pi^0 \rightarrow \gamma\gamma$ by measuring total energy (E_{tot}) in the calorimeter and the energy sharing ($z_{\gamma\gamma}$) and di-photon separation ($d_{\gamma\gamma}$) with a scintillator-strip shower maximum detector.

$$M_{\gamma\gamma} = E_{tot}\sqrt{1-z_{\gamma\gamma}^2}\,\sin\left(\frac{\phi_{\gamma\gamma}}{2}\right)$$

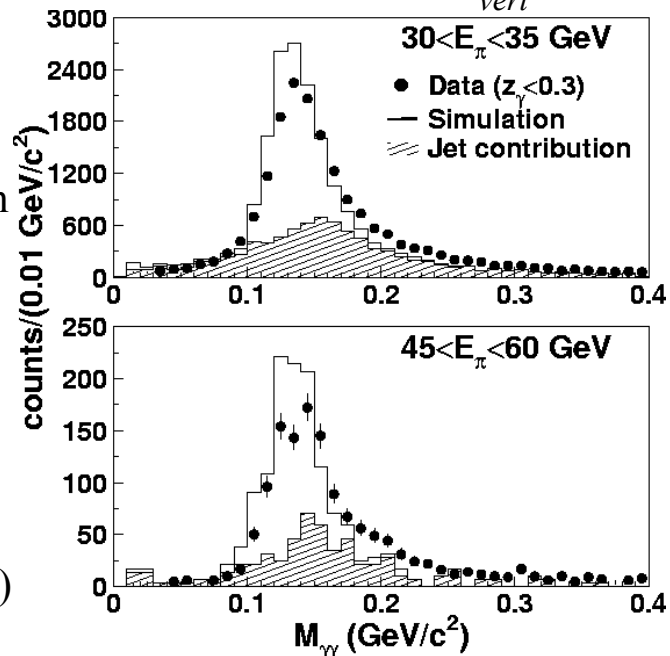
$$M_{\gamma\gamma} \approx E_{tot}\sqrt{1-z_{\gamma\gamma}^2}\,\frac{d_{\gamma\gamma}}{2z_{vert}}$$





Additional energy is deposited in the calorimeter primarily from multiple π^0's accompanying the leading π^0. The forward jet manifests itself as a large-mass tail in the $M_{\gamma\gamma}$ distribution.

(Fig. 1 of hep-ex/0310058)



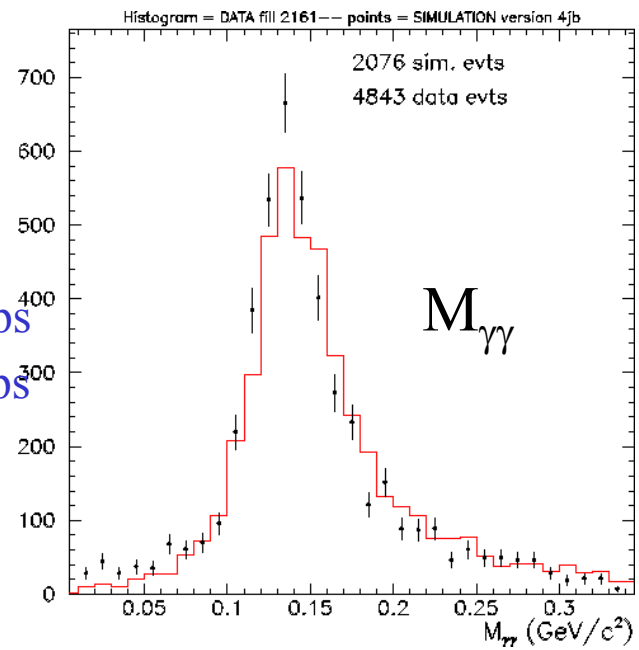
Simulation of pEEMC in STAR

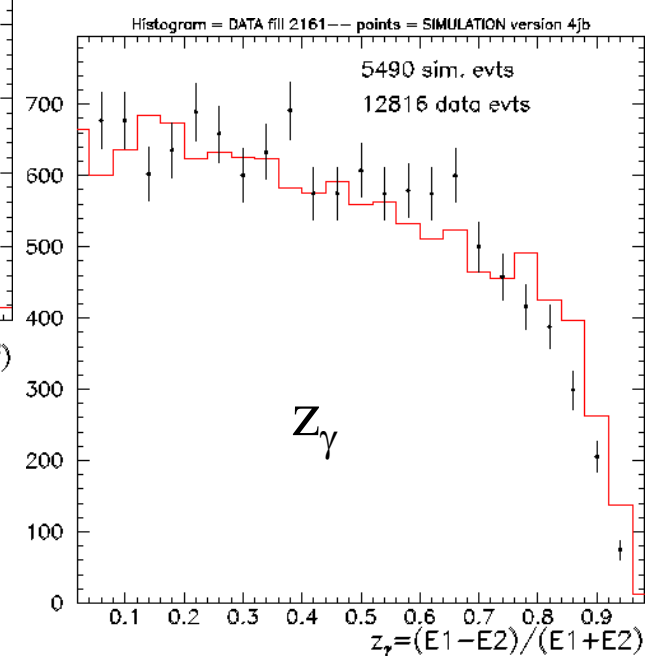
Scheme:

- Events generated with PYTHIA (min bias)
- Events stored if >25 GeV pointing to "box"
- Full PYTHIA record included with events
- GEANT simulation of pEEMC
- Reconstruct using algorithm applied to data

Cuts applied:

- E_{tow}>31 GeV
- 13 < SMD-Y centroid < 90 strips
  12 < SMD-X centroid < 48 strips
- SMD-X or SMD-Y > 1 peak
- z_γ<0.3

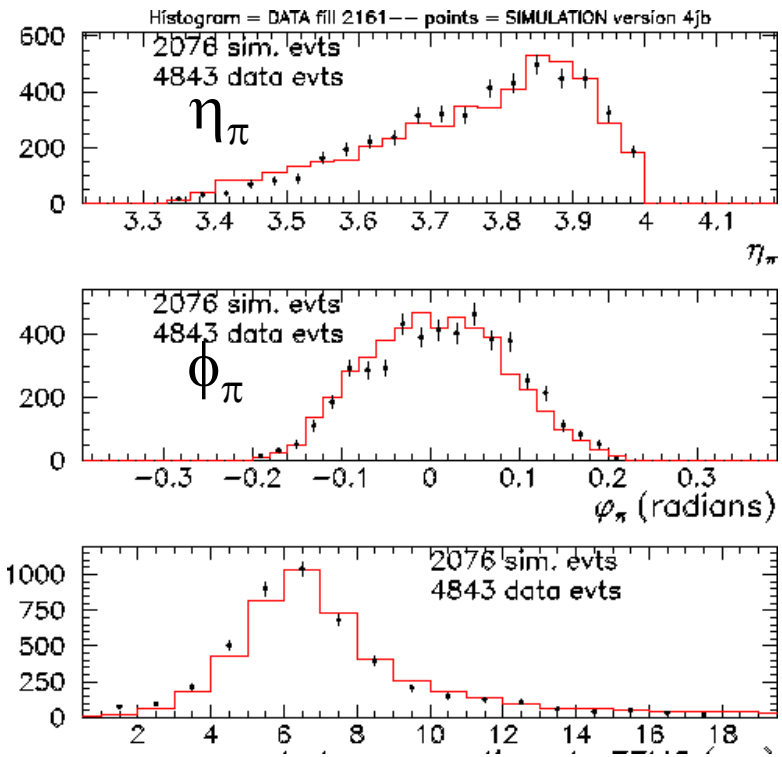




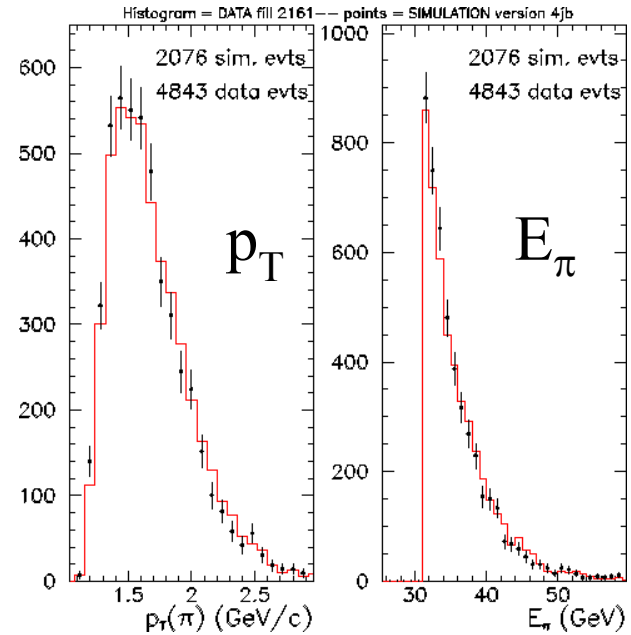
- Histogram = data
- Points = simulation norm. to data

Simulation of pEEMC (cont.)

Angular variables:

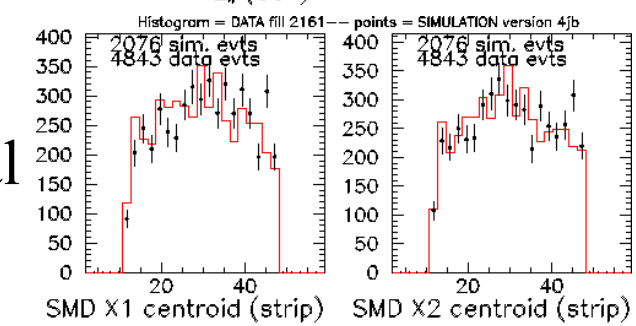


Photon separation at pEEMC (cm)

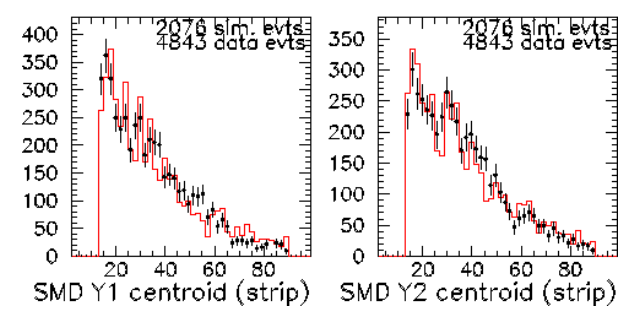


Single photon positions:

vertical

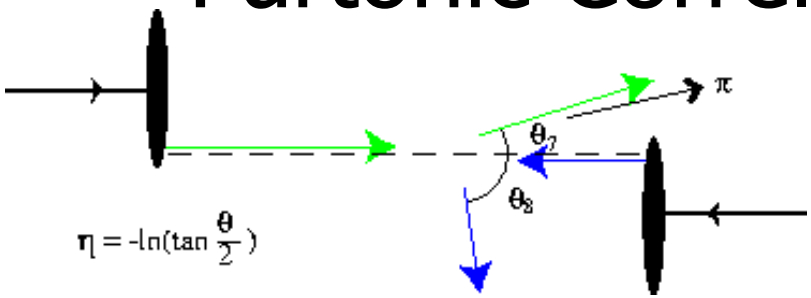


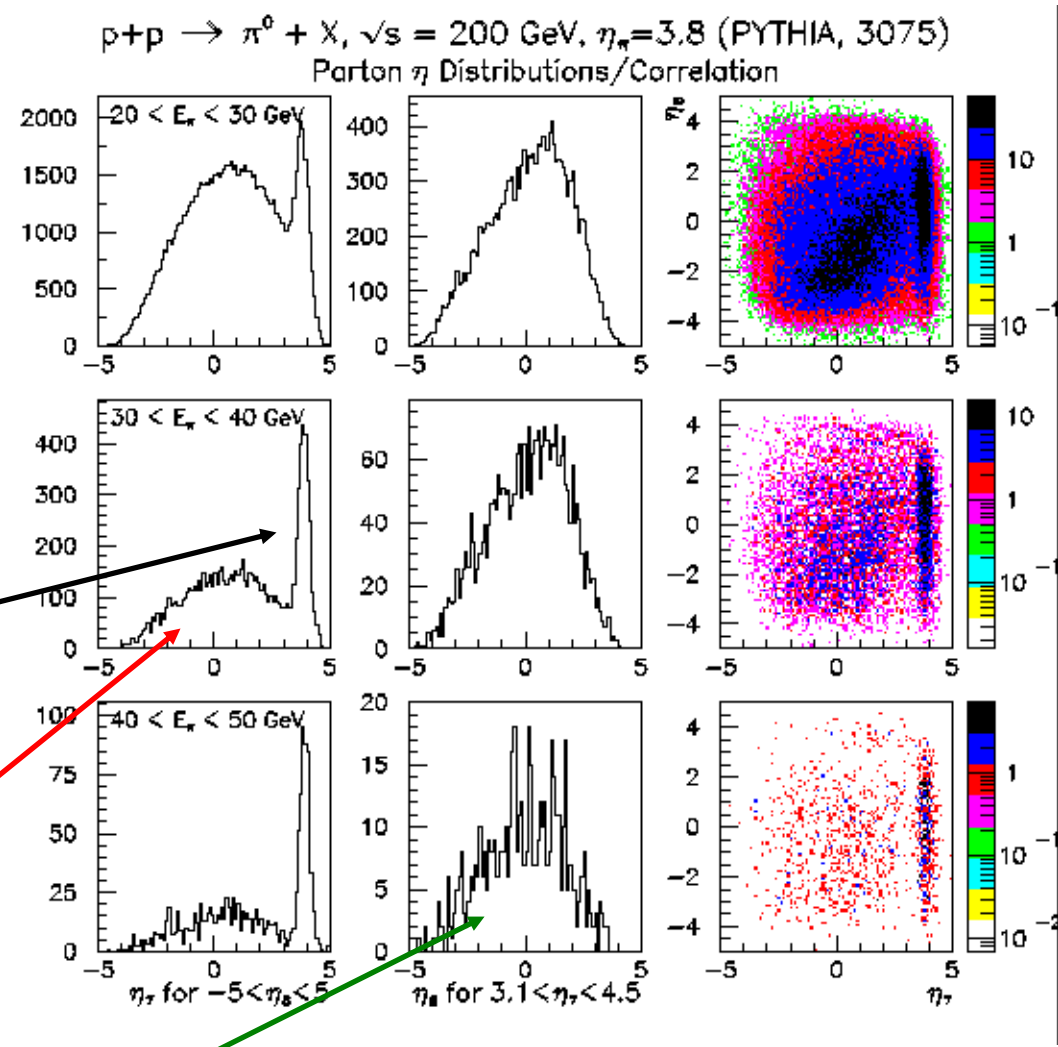
horizontal



PYTHIA+GEANT simulation describes data---π^0 mesons and background from collisions...

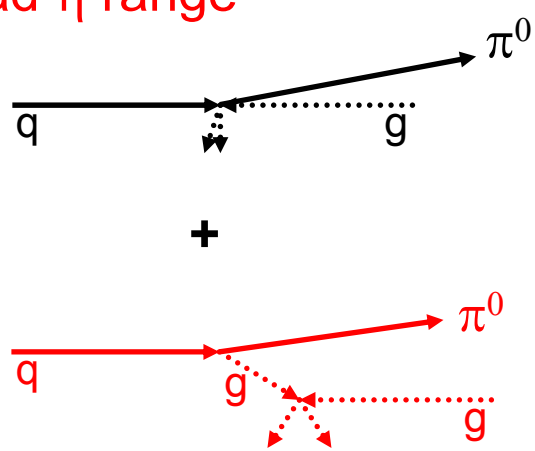
Partonic Correlations from PYTHIA





Large energy deposited at η=3.8

- one parton in hard scattering with peak in forward direction + broad η range



•other parton spread over broad η range

Forward Physics at RHIC-II

in $p_\uparrow + p_\uparrow$ (transverse & longitudinal) and $p_\uparrow$(d)+nucleus

- ‘hard scattering’ particle correlations spanning large rapidity difference
  - o flavor tagging of partonic scattering
  - o longitudinal/transverse spin effects, selected on Bjorken x values of colliding partons
  - o probe rapidity dependence of saturation scale

- Large rapidity Drell-Yan (electroweak probes)
  - o quantify Sivers function (spin / $k_\perp$ correlated distribution function)
  - o probe gluon saturation