Forward Physics at STAR

Status of analysis on forward and mid rapidity correlation measurements in p+p and d+Au

OGAWA, Akio

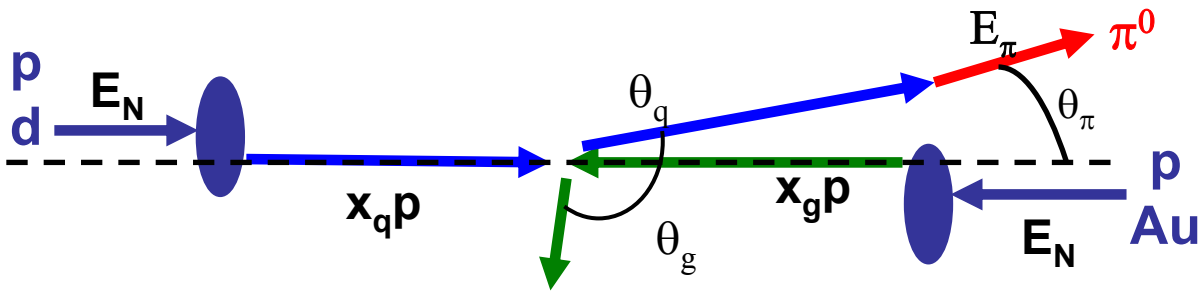
BROOKHAVEN NATIONAL LABORATORY

For STAR Collaboration

- Introduction - Forward physics in hadron collider
- RHIC, STAR experiment and Forward Pion Detector
- Do we understand forward π^0 production at hadron collider?
- Forward π^0 production as a probe for high-x quark & low-x gluons
  - Analyzing power with transverse polarized proton beams
  - Correlations with mid-rapidity $h^{\pm}$ in p+p and d+Au
- Conclusions and outlook

16 Friday 2004, Strbske Pleso, High Tatras, Slovakia, DIS 2004

Forward π^0 production in hadron collider



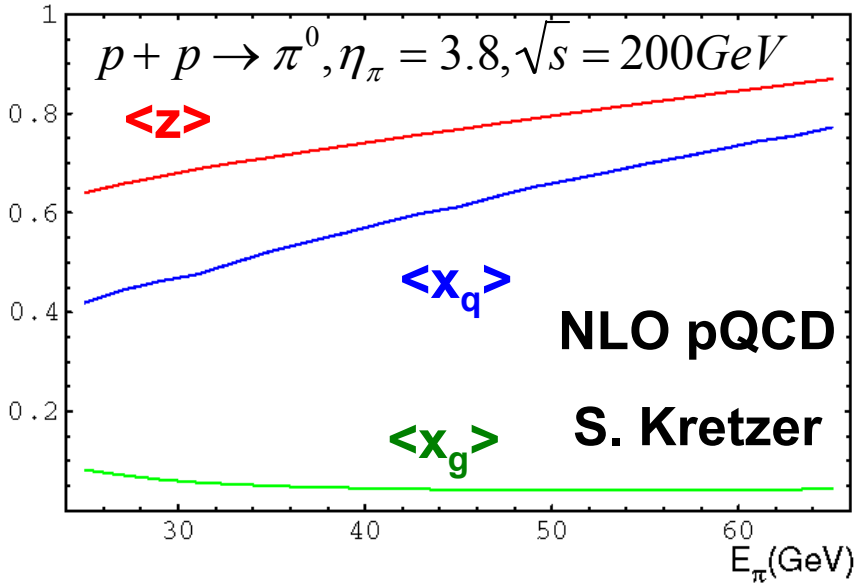
$$Q^2 \sim p_T^2 \qquad x_F \approx \frac{2E_\pi}{\sqrt{s}}$$

$$\sqrt{s} = 2E_N \qquad z = \frac{E_\pi}{E_q}$$

$$\eta = -\ln(\tan(\frac{\theta}{2})) \qquad x_q \approx x_F / \langle z \rangle \qquad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta g}$$

(collinear approx.)

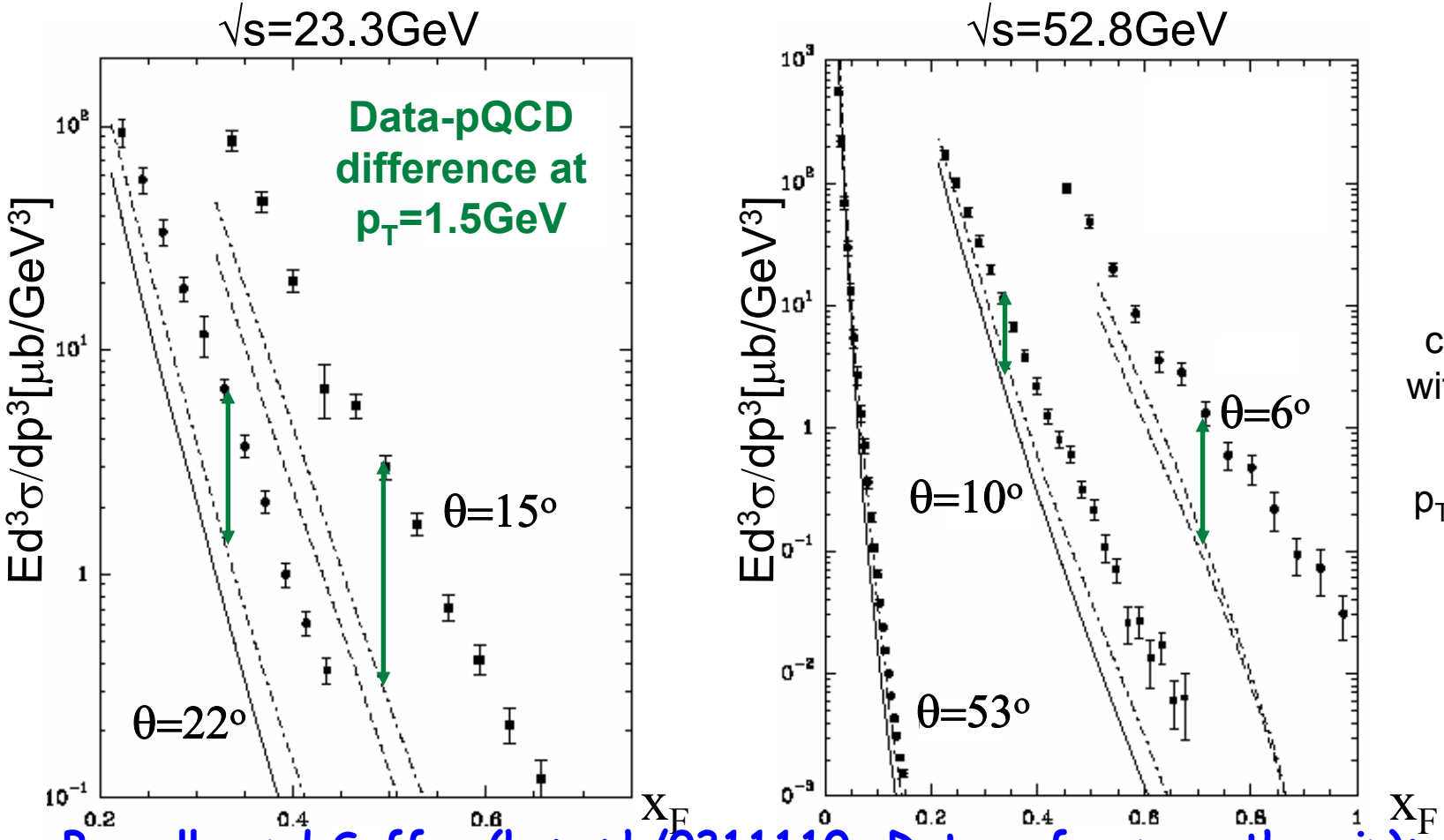
- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**
- Mostly **high-x valence quark** + **low-x gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <z> nearly constant and high ~ 0.8



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

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

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



2 NLO calculation with different scale:

p_T and $p_T/2$

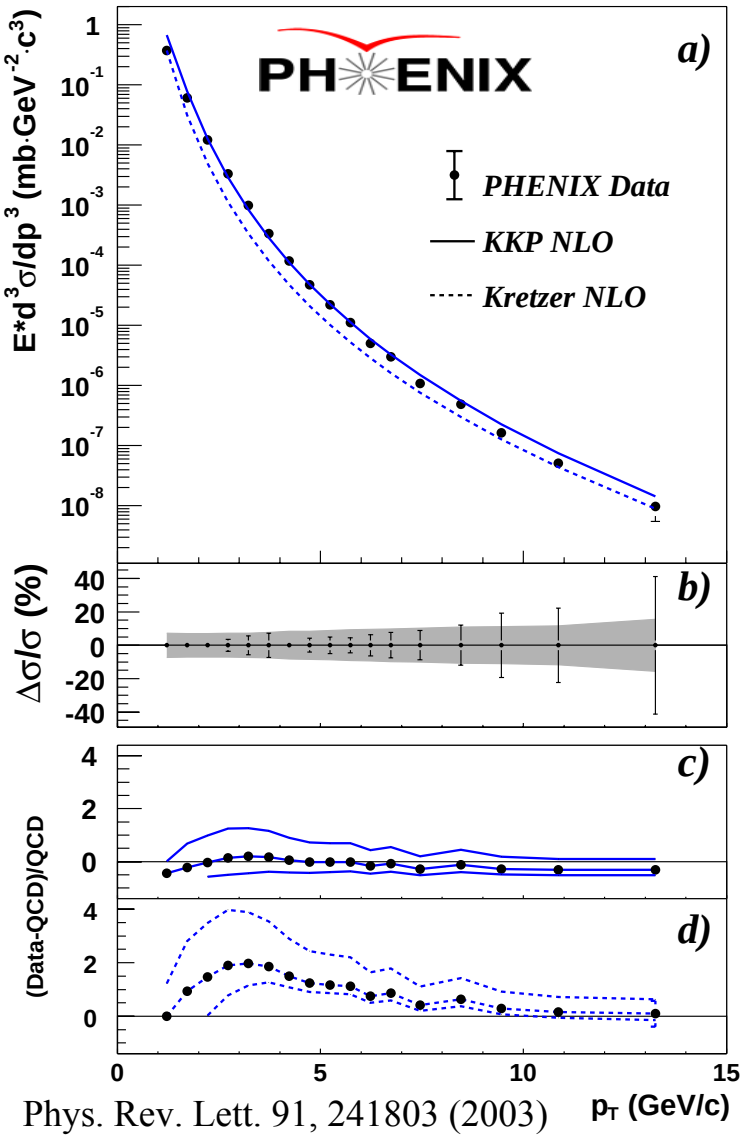
Bourelly and Soffer (hep-ph/0311110, Data references therein):

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?

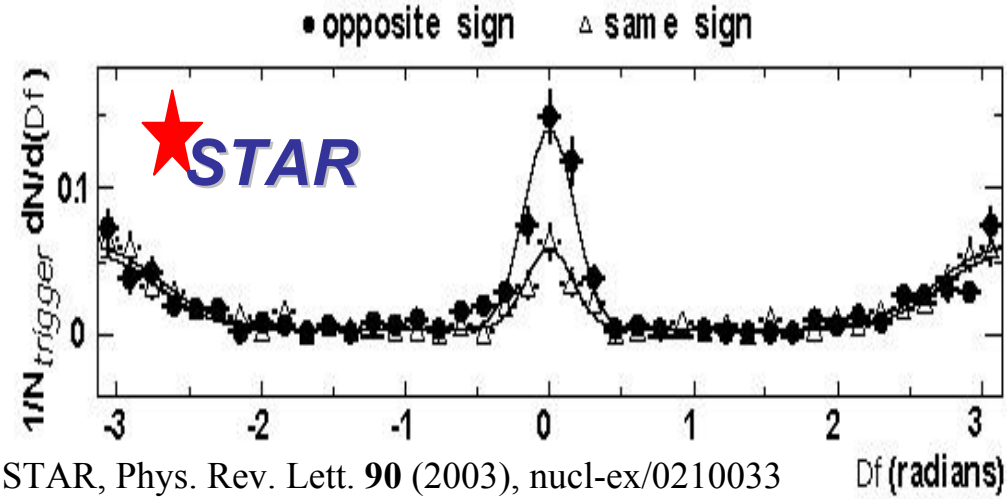
Inclusive π^0 cross section



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?

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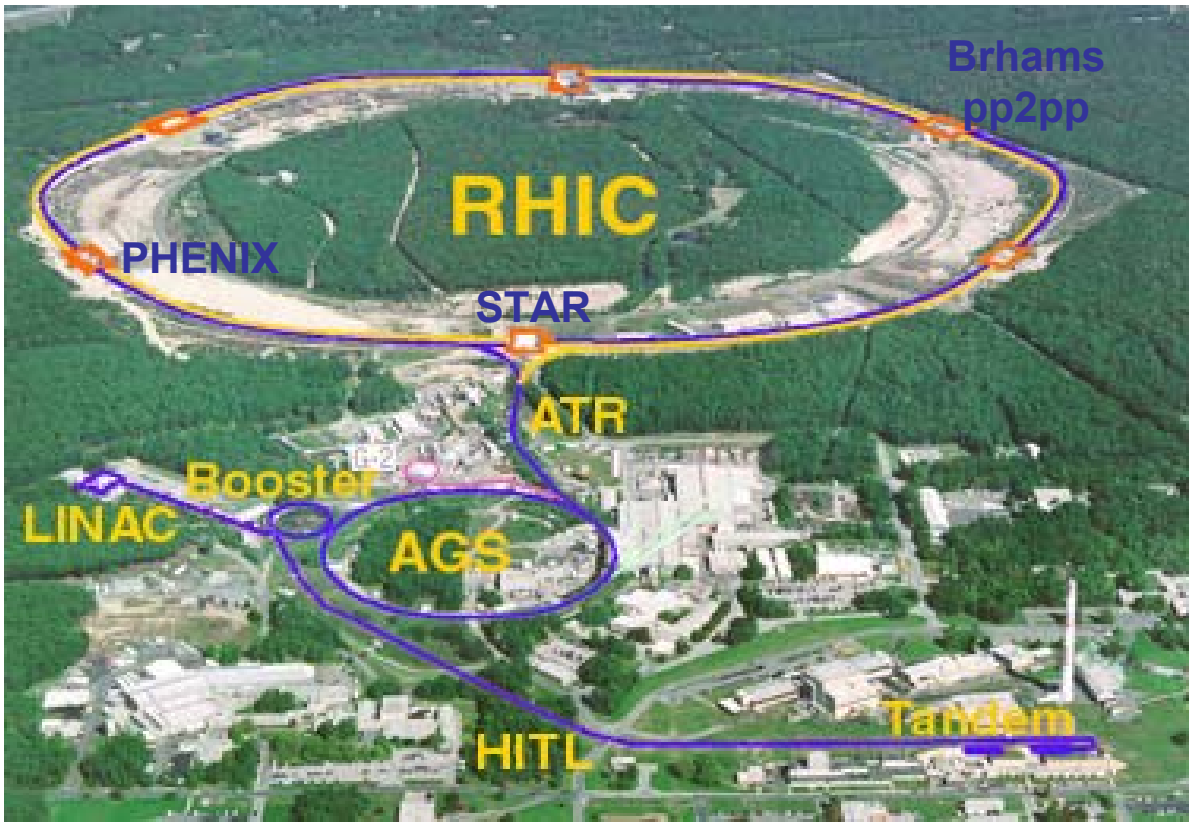
The Relativistic Heavy Ion Collider



Au-Au

- New state of matter
- QGP
- De-confinement

Deuteron-Au

- Baseline for Au+Au
- Gluon saturation

Polarized proton-proton

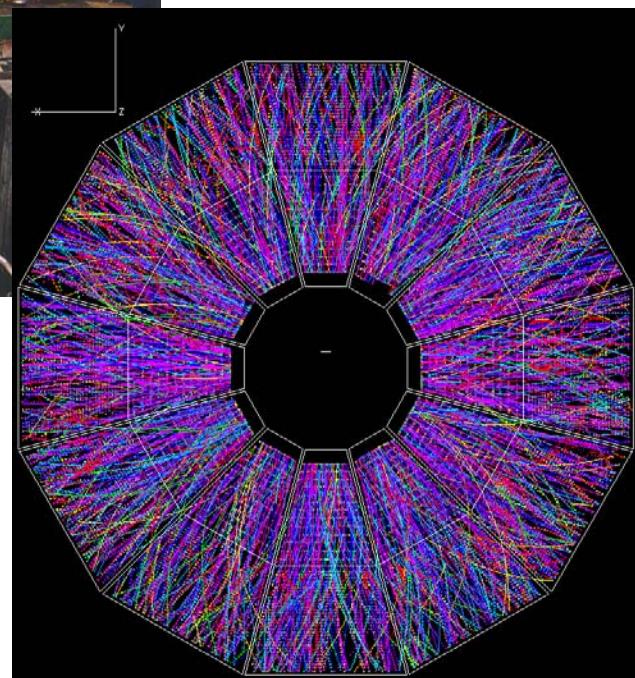
- Nucleon Spin Structure
- Spin Fragmentation
- pQCD

RHIC is a QCD lab

The

STAR

Collaboration



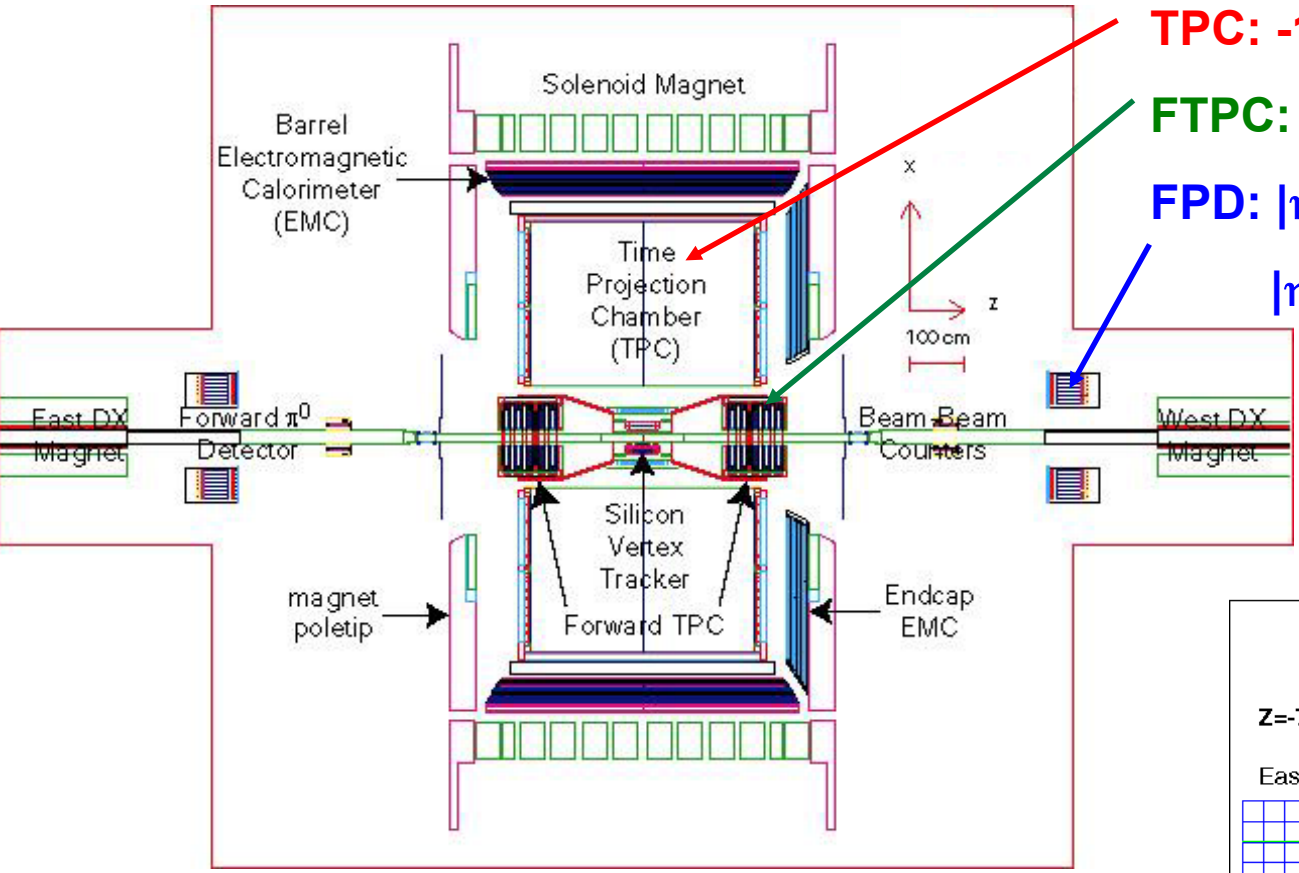
Solenoid Tracker At RHIC

506 collaborators

50 institutions

12 countries

STAR Detector

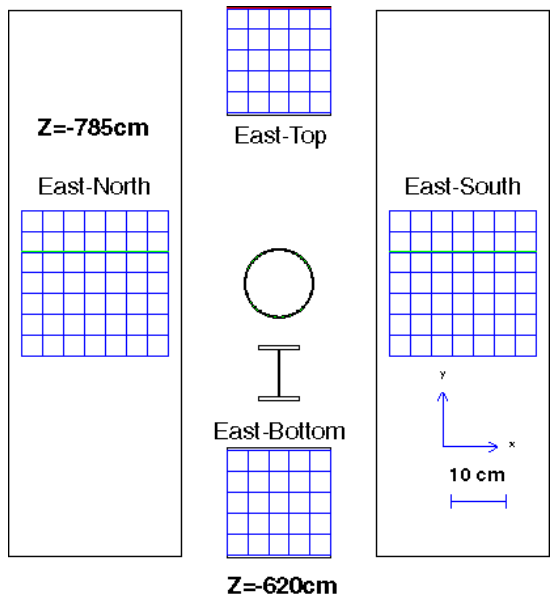


TPC: $-1.0 < \eta < 1.0$

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

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

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



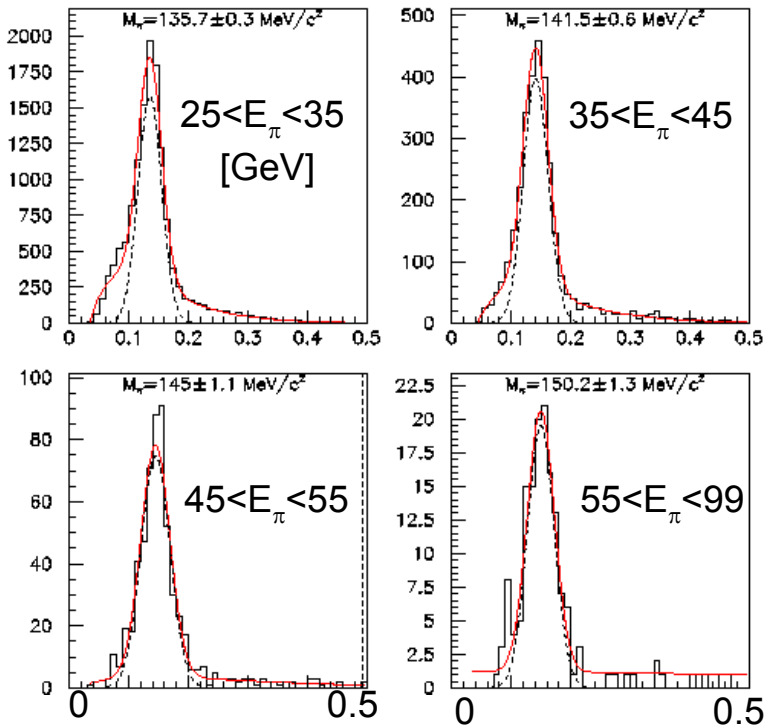
Forward π^0 Detector (FPD)

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

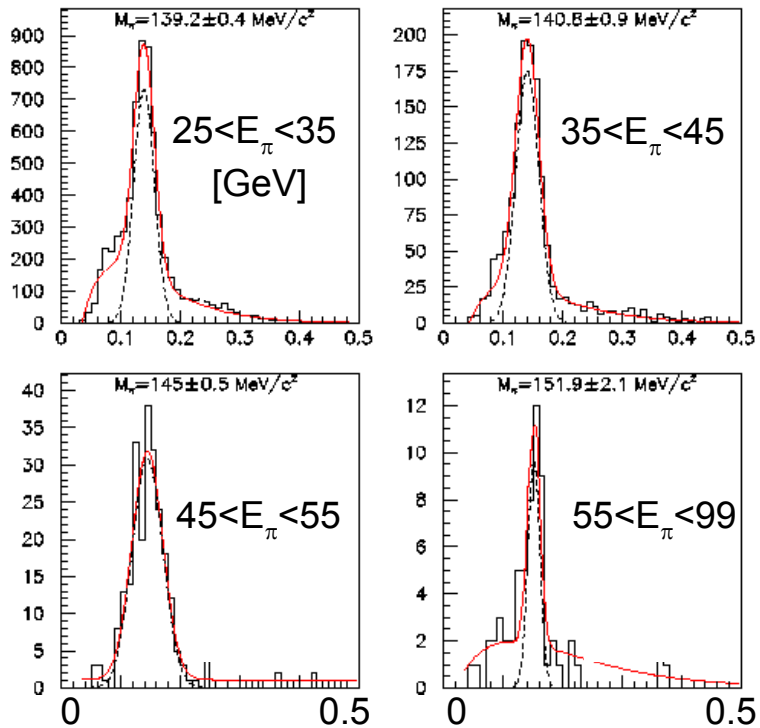
Di-photon Mass Reconstruction

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

p + p



d+Au

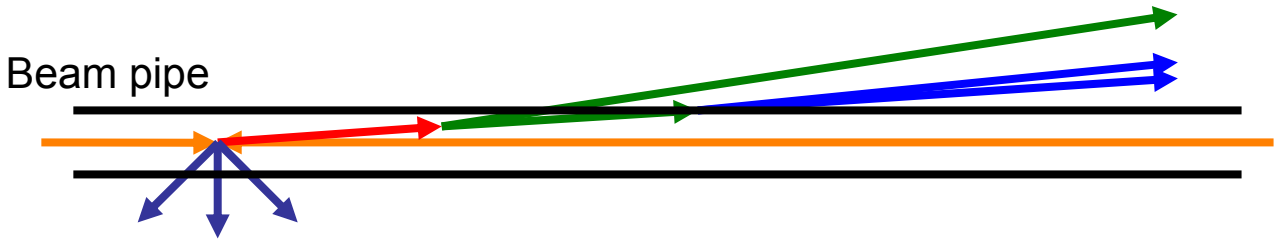


$M_{\gamma\gamma}$[GeV/c^2]

- Absolute gain determined from π^0 peak position for each tower
- current gain calibration known to ~10% ⇒ cross section in d+Au requires better calibrations
- systematics to be addressed using SMD

FTPC-FPD matching: Photon conversion in beam pipe

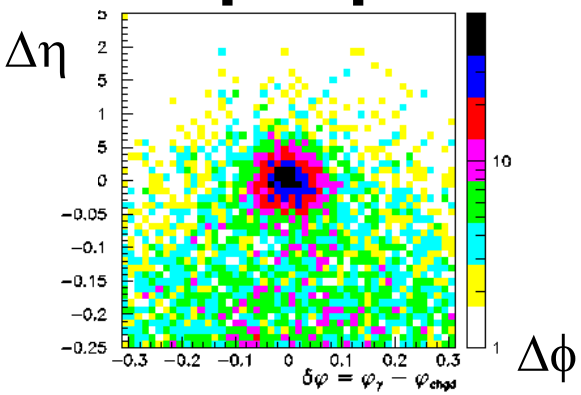
$\left.\begin{matrix} p + p \\ d + Au \end{matrix}\right\} \rightarrow \pi^0 (+ X) \rightarrow \gamma (+ \gamma) \rightarrow e^+ e^-$

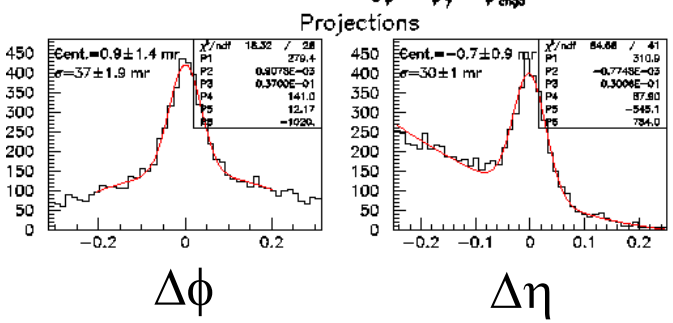


$\Delta\eta = \eta_{FPD} - \eta_{FTPC}$

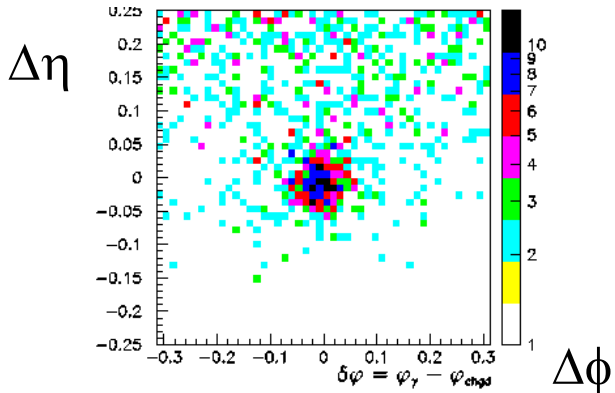
$\Delta\phi = \phi_{FPD} - \phi_{FTPC}$

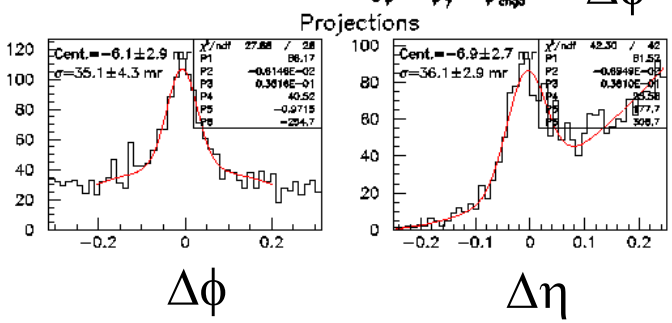
p + p





d+Au





FPD:

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

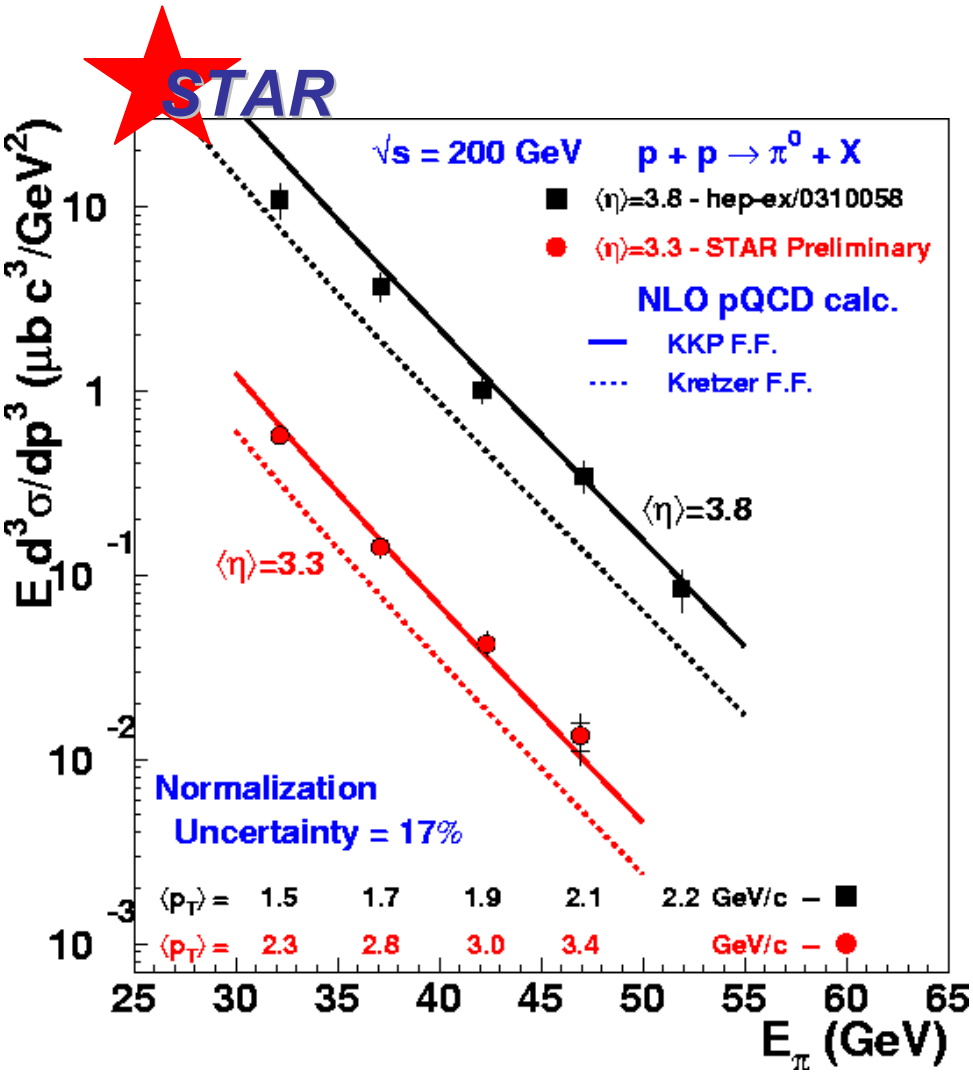
FTPC:

- $2.8 < |\eta| < 3.8$

⇒ FPD position known relative to STAR

⇒ Detector resolution for particle correlation is good

Forward π^0 Inclusive Cross Section



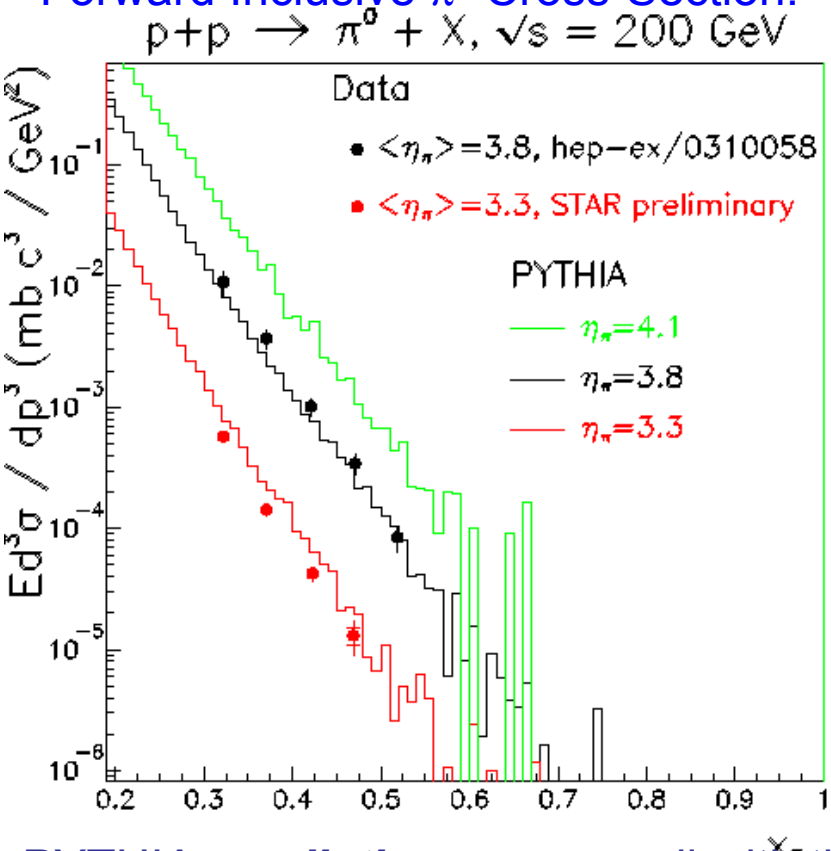
- STAR data at
  - ⟨η⟩= 3.8 (hep-ex/0310058, accepted to PRL, in press)
  - ⟨η⟩= 3.3 (hep-ex/0403012, Preliminary)
- NLO pQCD calculations at fixed η with equal factorization and renormalization scales = p_T
- Solid and dashed curves differ primarily in the g → π fragmentation function

STAR data consistent with Next-to-Leading Order pQCD calculations

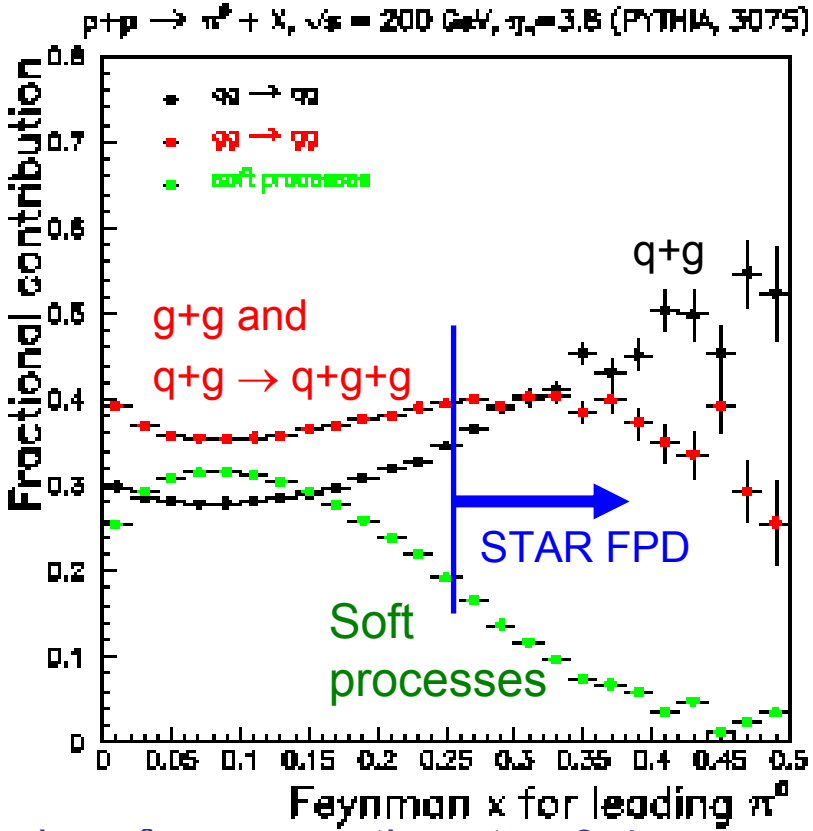
in contrast to data at lower √s (Bourelly and Soffer, hep-ph/0311110)

PYTHIA: a guide to the physics

Forward Inclusive π^0 Cross-Section:



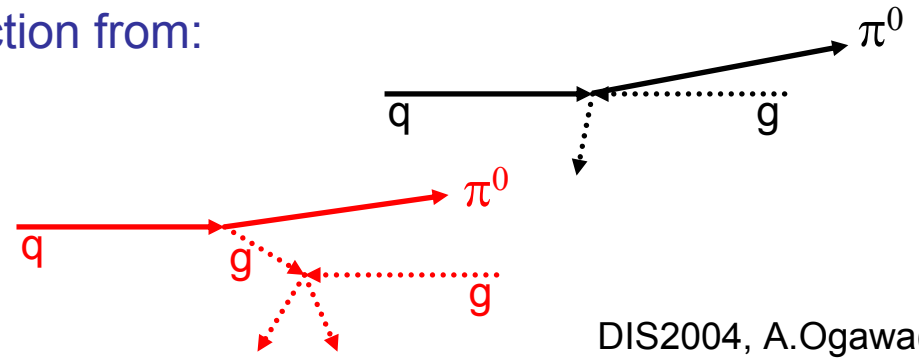
Subprocesses involved:



- 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:

- $q + g \rightarrow q + g$ **(2→2)** $\rightarrow \pi^0 + X$

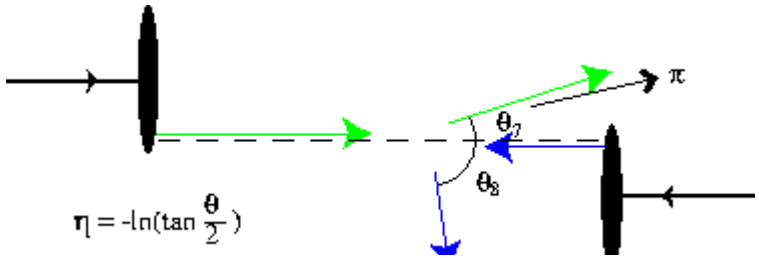
- $q + g \rightarrow q + g + g$ **(2→3)** $\rightarrow \pi^0 + X$

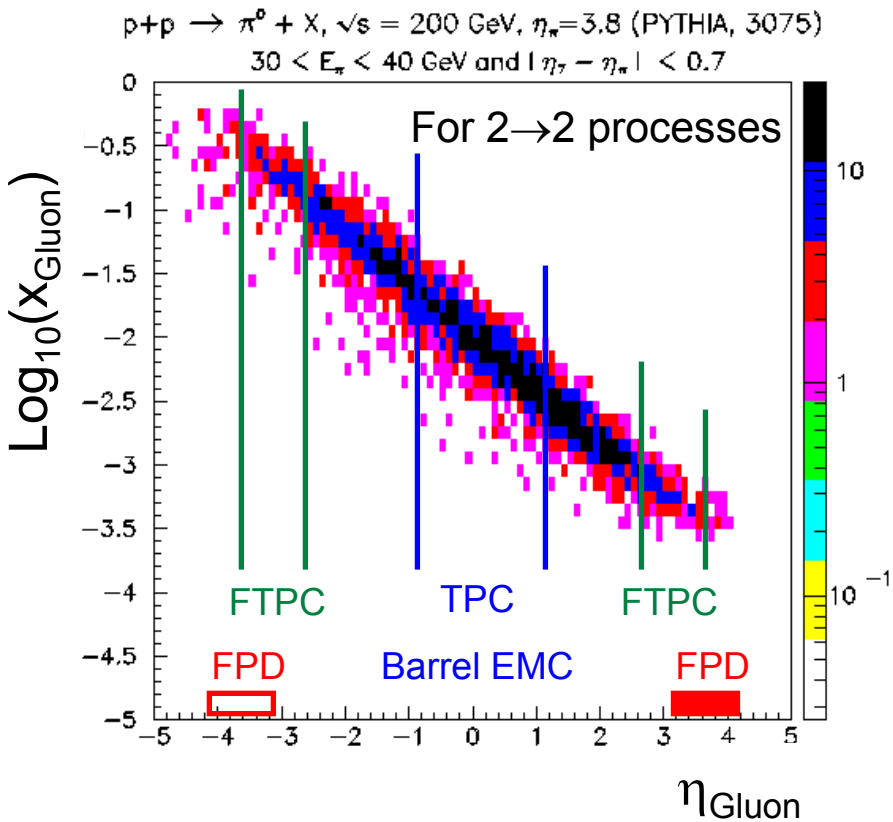


Inclusive is OK. How about 2 particles correlations?

And why forward physics at STAR / RHIC?

Rapidity gap (forward - mid rapidity) correlations





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

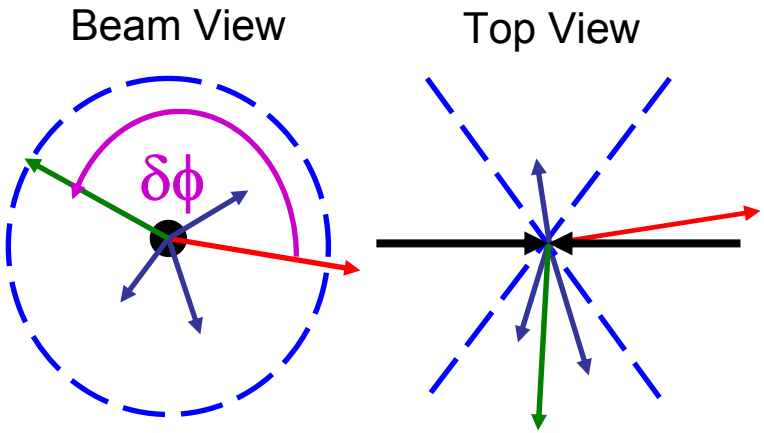
Broad rapidity-gap range at STAR enables broad coverage of parton kinematics

Spin effects with rapidity gap 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: $2.8 < |\eta| < 3.8$

Back-to-back Azimuthal Correlations
with large rapidity gap



Trigger by forward π^0

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

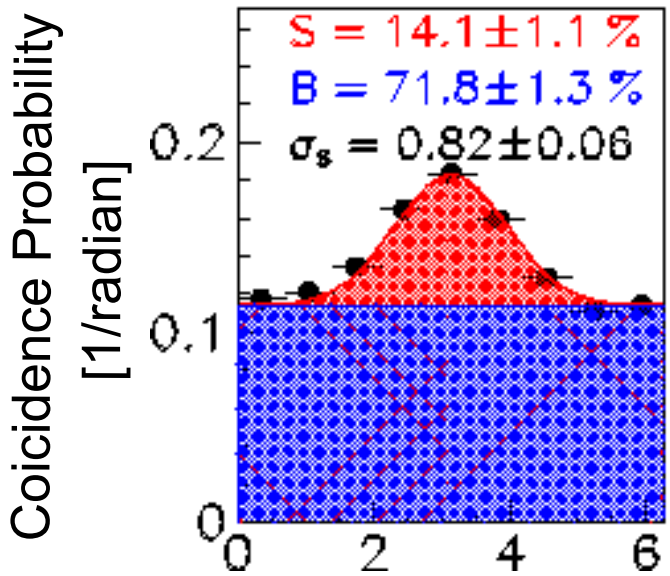
Midrapidity $h^\pm$ tracks in TPC

- **$-0.75 < \eta < +0.75$**

Leading Charged Particle(LCP)

- **$p_T > 0.5$ GeV/c**

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

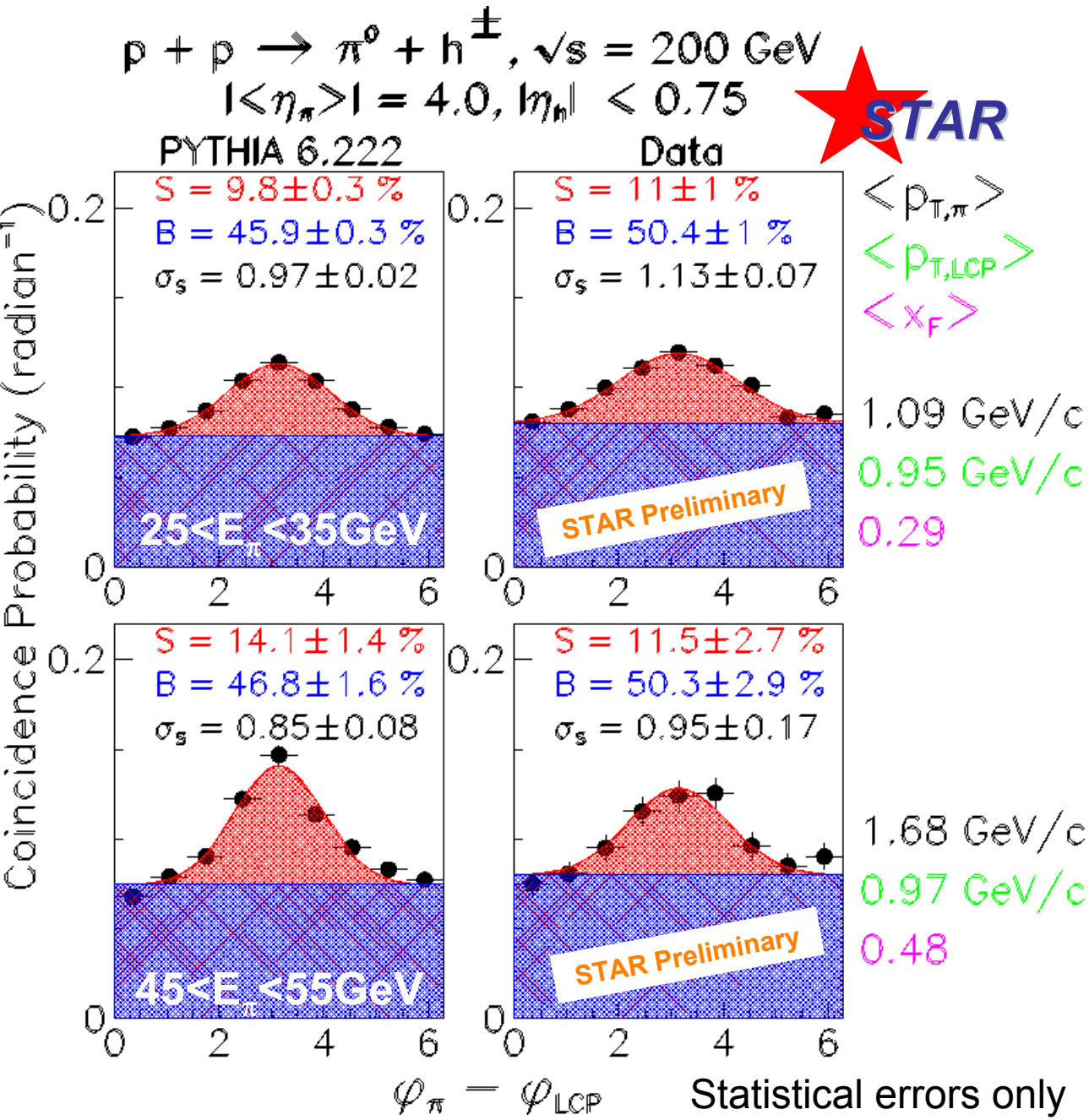


$$\delta\phi = \phi_\pi - \phi_{LCP}$$

S = Probability of "correlated" event under Gaussian

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

σ_s = Width of Gaussian



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

Q: Do we understand forward π^0 production at p+p collider?

- **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 gap particle correlations agree with PYTHIA**

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

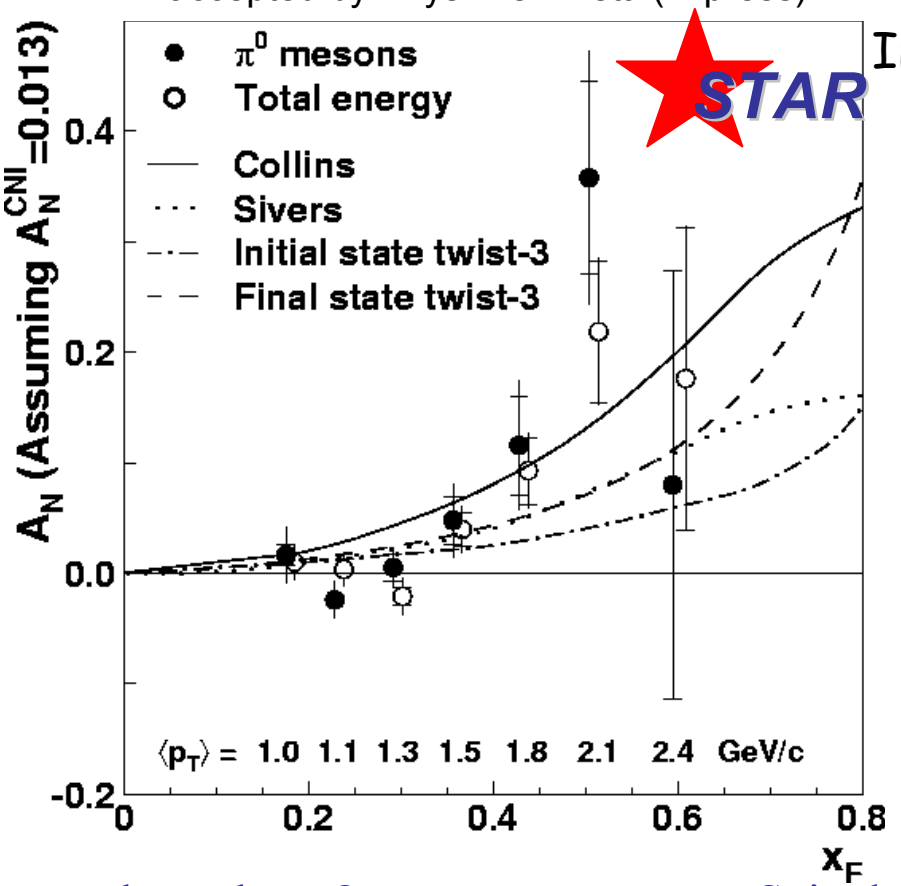
Important result for:

- Spin effects
- Comparison with d + Au
- Flavor tagging

Large Analyzing Powers at RHIC

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

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:

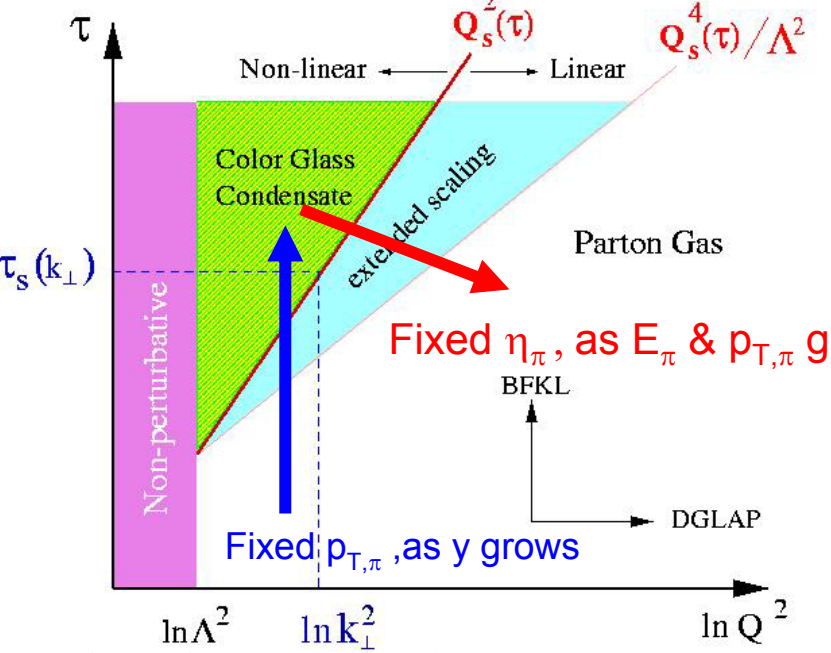
- Sivers: spin and $k_\perp$ correlation in initial state (related to orbital angular momentum?)
- Collins: Transversity distribution function & spin-dependent fragmentation function
- Qiu and Sterman (initial-state) / Koike (final-state) twist-3 pQCD calculations

- p_T dependence?
- x_F<0?
- A_N with mid-rapidity correlation?
- Spin dependence in jet?
- Heavy flavors??
- Related to "gluon saturation"???

d + Au: Possible Color Glass Condensate at RHIC?

General expectations of CGC:

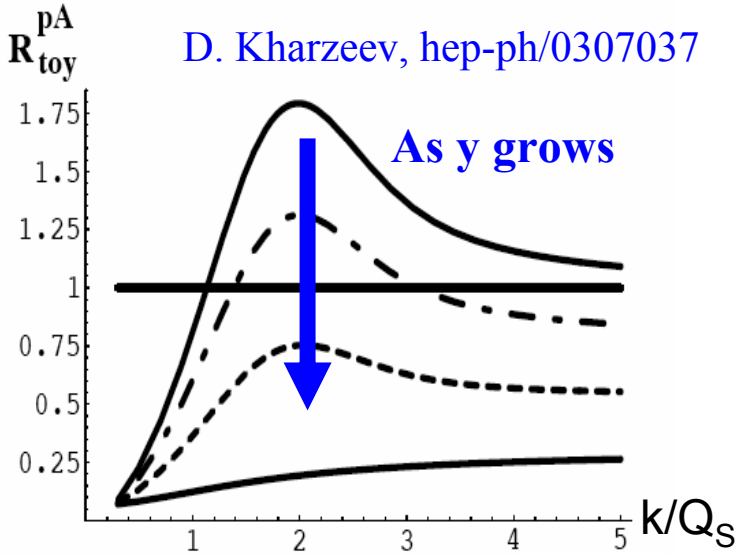
$\tau = \ln\left(1/x\right)$ τ related to rapidity of produced hadrons.



Edmond Iancu and Raju Venugopalan, hep-ph/0303204

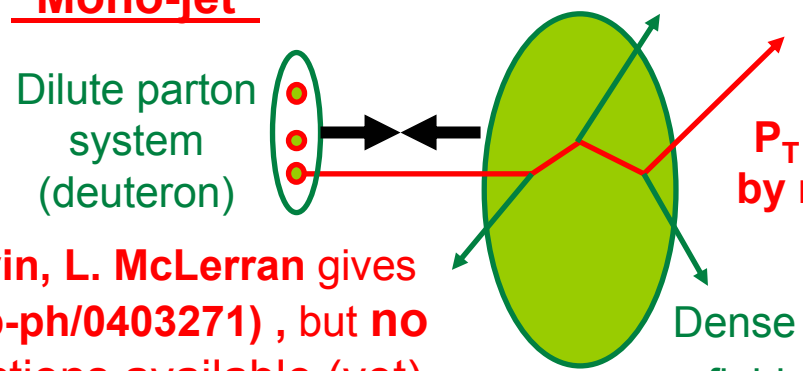
Suppression of forward particle production

D. Kharzeev, hep-ph/0307037



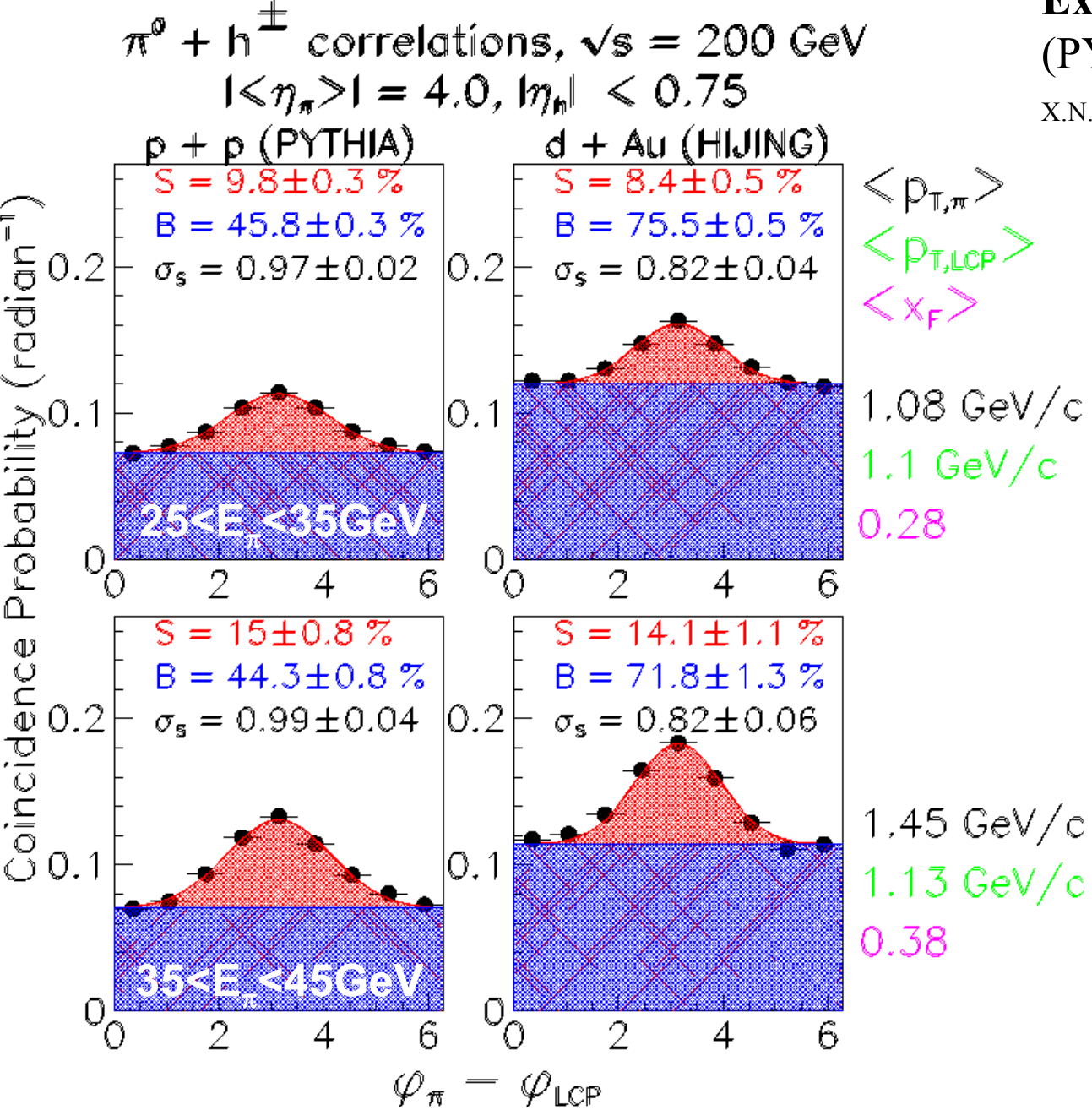
Brahms data shows evidence ? (nucl-ex/0403005)

"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 gap particle correlations at STAR**

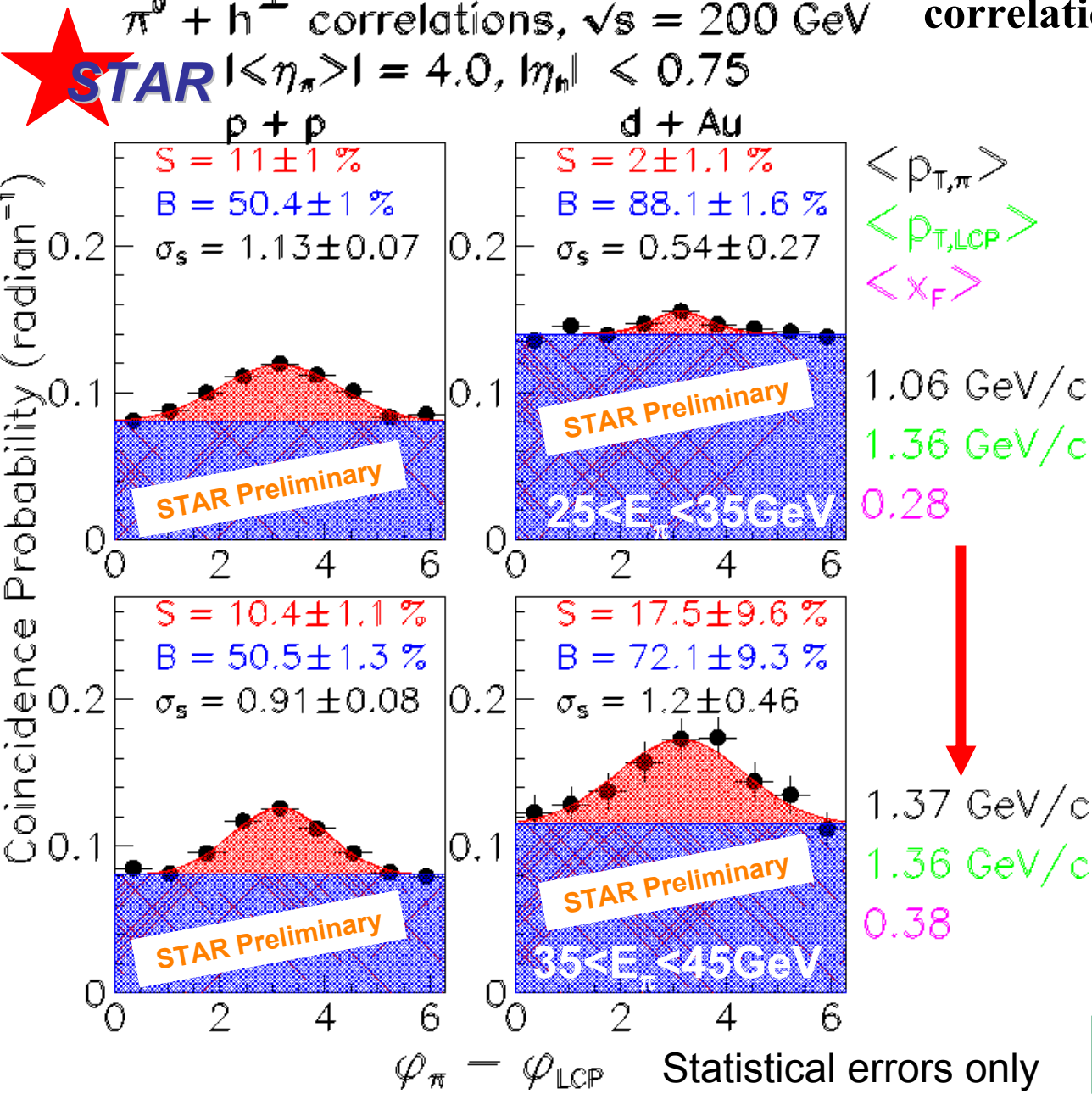


Expectation from HIJING
(PYTHIA+nuclear effects)

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**



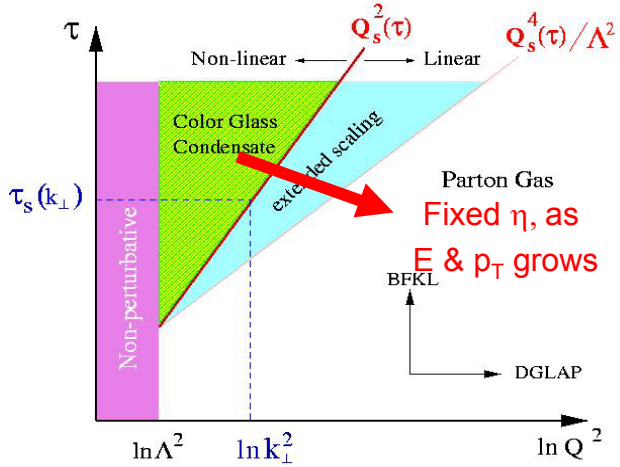
Statistical errors only

Large rapidity gap π^0+h$^{\pm}$ correlation data…

- **are suppressed in d+Au relative to p+p at small $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

S_{pp}-S_{dAu}= (9.0 ± 1.5) %

Consistent with CGC picture

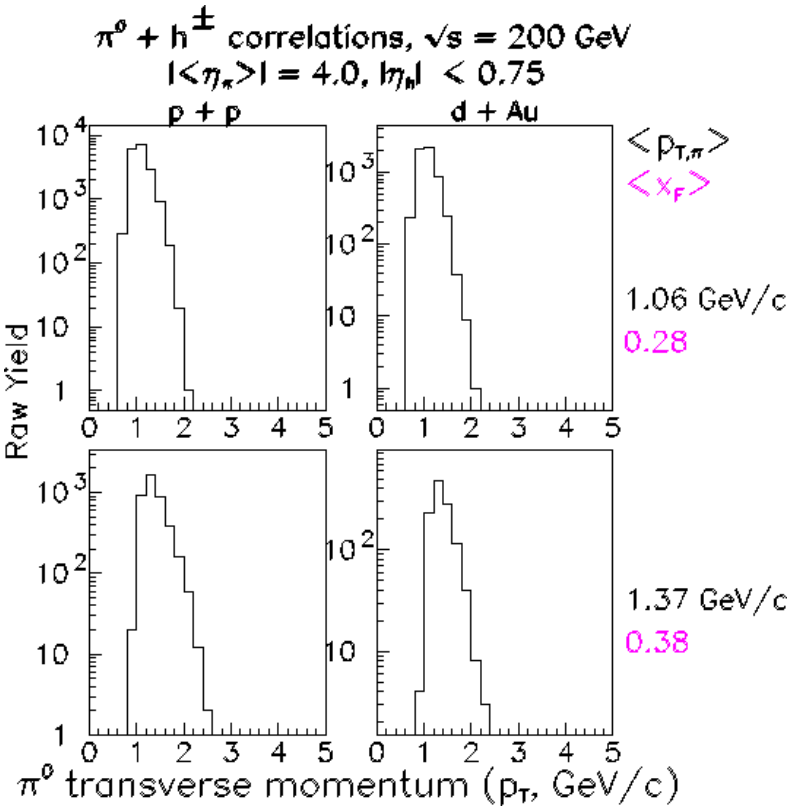


- **are consistent in d+Au and p+p at larger $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

as expected by HIJING

Systematic studies

π^0 spectra looks same



- cross section in d+Au requires better than 5% calibrations

Behavior of d+Au and p+p correlations is insensitive to treatment of mid-rapidity $h^{\pm}$:

- **LCP**
- **Inclusive**
- **Vector sum of momenta**
- **Changing pT thresholds & window**

→ Quantitative theoretical understanding of correlations is required (where and how to look for physics signal…)

Detector effects / systematic errors have been studied:

- TPC efficiency & resolution
- η range of $h^{\pm}$ and range of collision vertex
- FPD calibrations
- Fitting functions

Detailed systematic error estimate underway

Conclusions

- **Forward hadron production at hadron-hadron collider selects high-x (thus high polarization) quark + low-x gluon scatterings**

- **Forward π^0 meson production at RHIC energies is consistent with partonic scattering calculations, unlike at lower $\sqrt{s}$**

  - **Inclusive cross section is consistent with NLO pQCD calculations and PYTHIA(LO pQCD + parton showers)**

  - **Large rapidity gap correlations in p+p agree with PYTHIA prediction**

- **Analyzing power for forward π^0 mesons is large at RHIC**

- **Large rapidity gap correlations in d+Au differ from p+p in a direction consistent with CGC picture. More data with d+Au (and quantitative theoretical understanding) is required to make definitive physics conclusions**

Outlook

- **p+p with transverse polarization**
  - Higher precision A_N measurement vs x_F and p_T
  - A_N for negative x_F
  - Disentangling the dynamics of A_N via
    - A_N with mid rapidity correlation
    - Forward jet ?
    - heavy mesons or direct photons ?
- **p+p with longitudinal polarization**
  - Potential sensitivity to ΔG with π^0 and direct photon
- **d+Au**
  - Precision measurement with d+Au with extended $\Delta\eta$ range
  - R^{dA} measurement
- **Expanding acceptance for heavy mesons/direct photon?**
- **Adding hadron calorimetry?**

RHIC delivered more than design luminosity for Au+Au 2004 Jan-Apr run.

As of last week, RHIC have reached ~50% polarization!

Backup slides

Future Options/Possibilities for p+p, d+Au, and Au+Au(?)

Option I –

- **Complete FPD calorimeters**
- **Add remote positioning for pseudorapidity scan**

Possibility II –

- **Move FPD closer to collision point**
- **Back FPD by hadronic calorimetry $\Rightarrow$ forward jet measurements**

Possibility III –

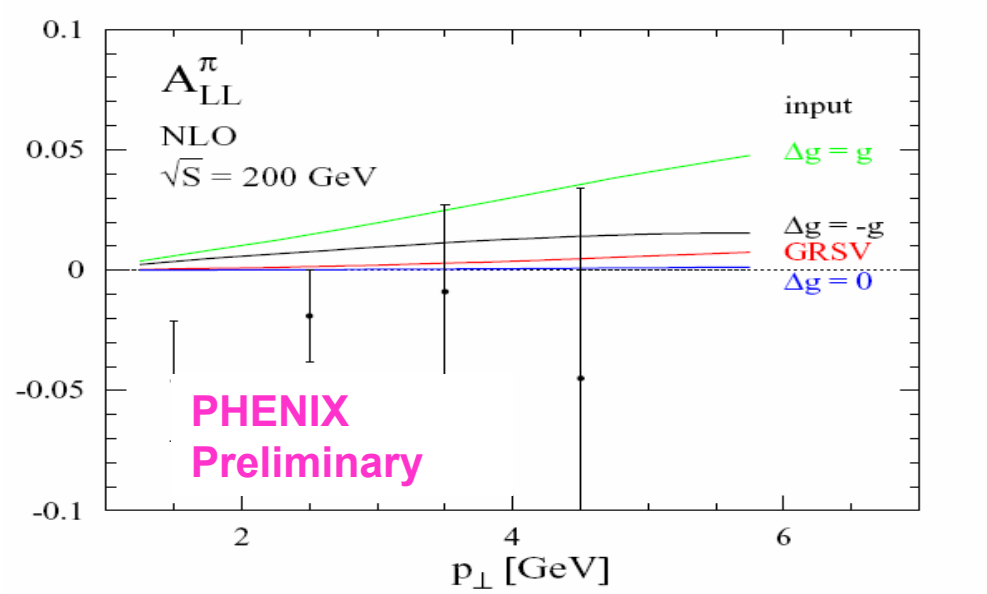
- **Transform FPD into Forward Meson Spectrometer with additional Pb-glass presently available from Protvino, positioned to be compatible with future addition of hadronic calorimetry**

$\Rightarrow$ **Forward heavy mesons (neutral only): $\omega \rightarrow \pi^0\gamma$, $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \gamma\gamma$, $K_{short} \rightarrow \pi^0\pi^0$, $D^0 \rightarrow K_{short}\pi^0$(?),…**

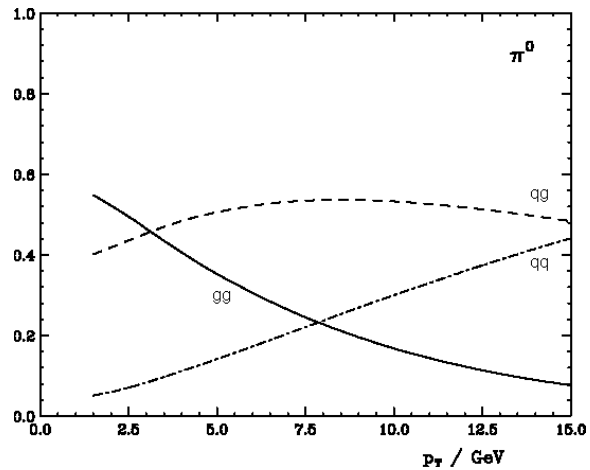
$\Rightarrow$ **Forward direct photons**

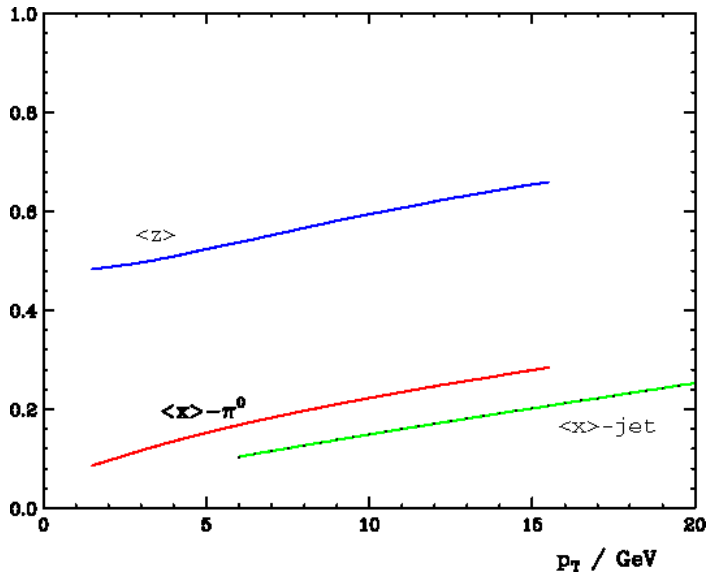
Towards ΔG at RHIC…

Double spin-correlation for midrapidity π^0:



Partonic processes:



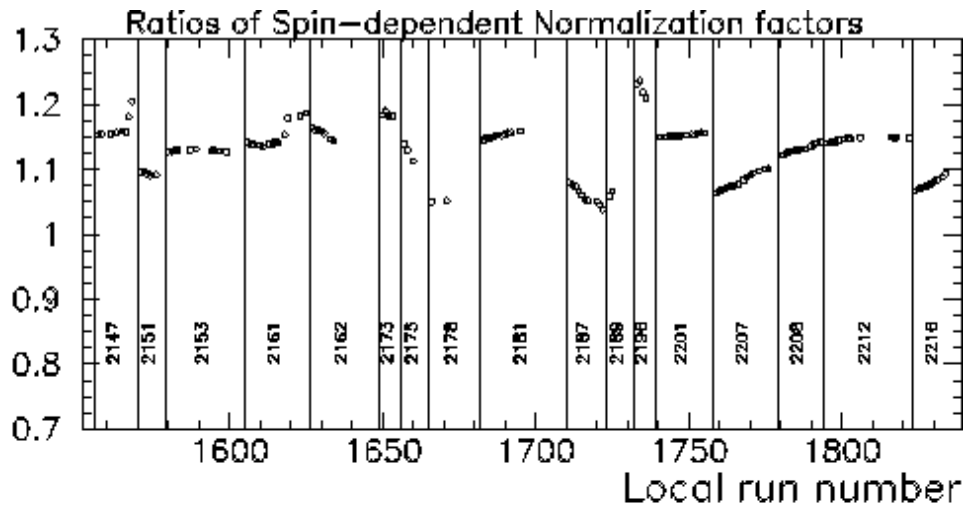


- Inclusive π surrogate for jet…
- Midrapidity particle production primarily from partons with equal and opposite x…
- A_{LL} not large and positive

Spin-dependent normalizations

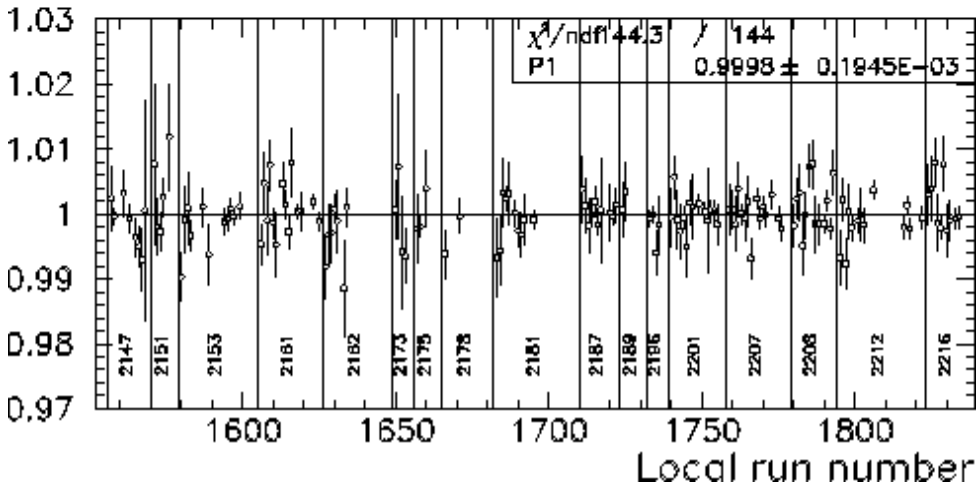
- 55 beam crossings of varying polarization and specific luminosity occurs every 213ns
  - Relative luminosity normalization performed with BBC's…

$$\frac{Lumi_{up}}{Lumi_{down}}$$



← Correction on the order of ~1.15...

$$\frac{Livetime_{up}}{Livetime_{down}}$$

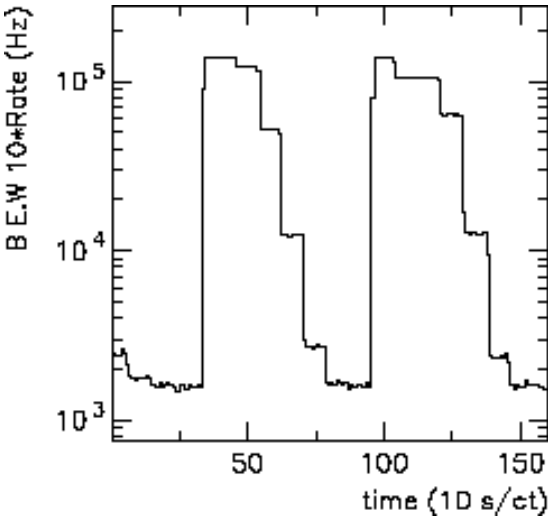


← Relative livetime correction stable and consistent with 1.000

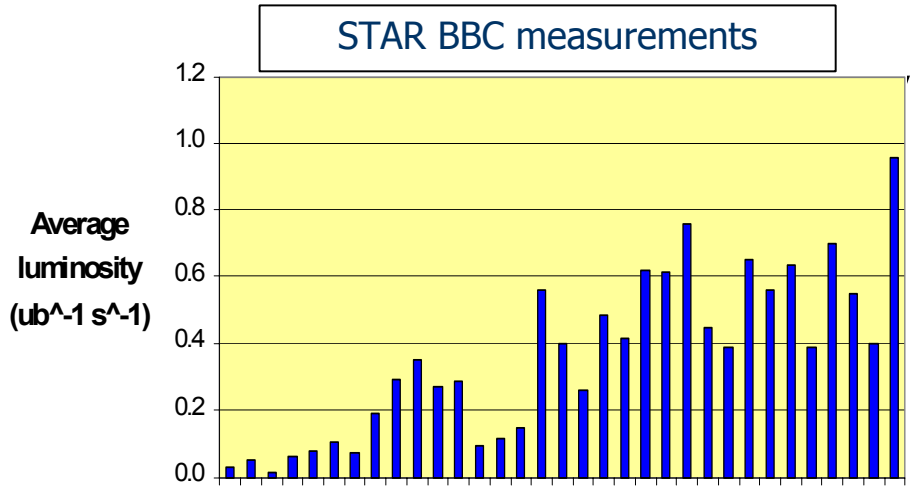
STAR spin

Absolute Luminosity Measurement

Absolute normalization from BBC E.W:

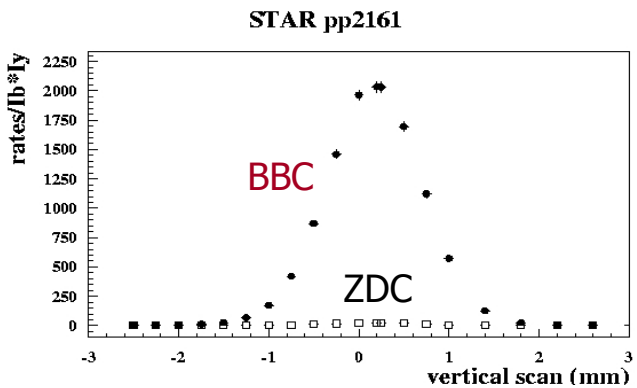


-BBC E•W coincidence rate vs time during a **Van der Meer scan** that **determines the beam size,** and hence the luminosity, by controlled relative steering of the colliding beams.



Day of the run (from 12/20/2001)

Scaler info sent to RHIC to enable MCR to steer beams at STAR



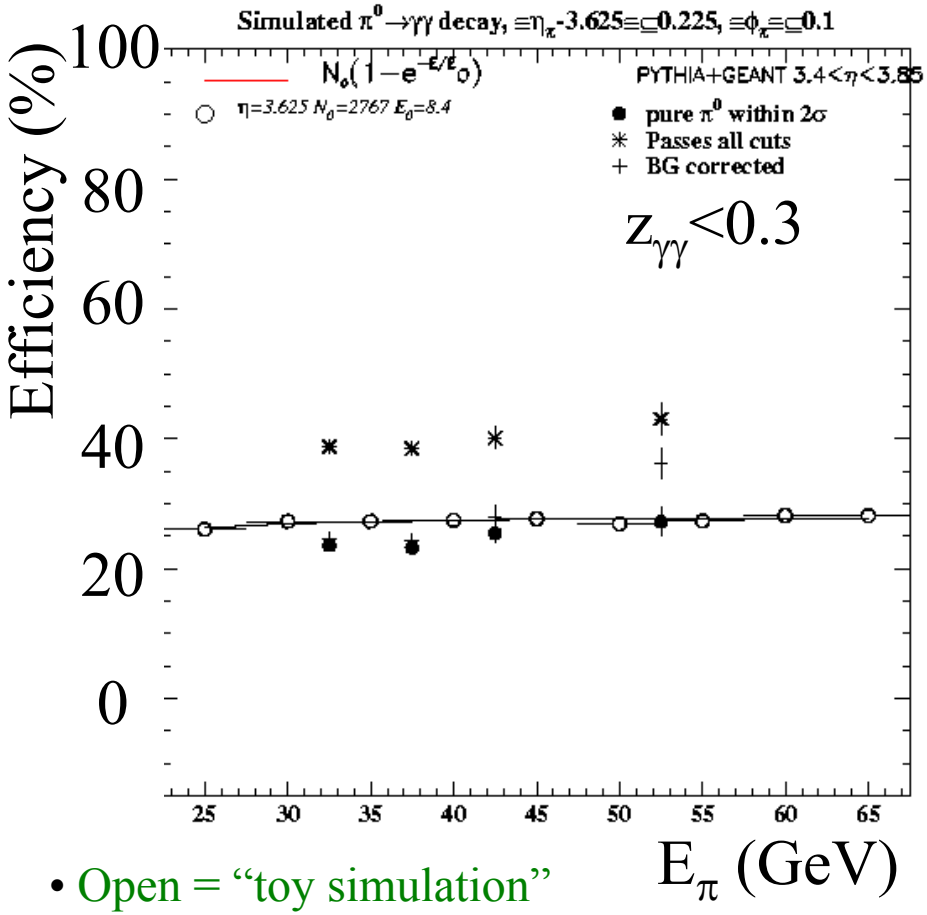
- RHIC delivers 10^{30} cm^{-2} s^{-1}
- Integrated luminosity recorded@STAR ~0.3 pb^{-1}

From simulations: BBC "sees" 53% of tot pp cross section,

Rate of 27 kHz ~ Luminosity of 10^{30} cm^{-2} s^{-1}

J. Kiryluk (MIT), A. Drees (BNL)

Efficiency Correction



Efficiency driven by geometry of 2γ in "box"

- Open = "toy simulation"
- Closed = PYTHIA + GEANT pure π^0
- * = PYTHIA + GEANT no jet contribution corr.
- + = PYTHIA + GEANT corr. for jet contribution

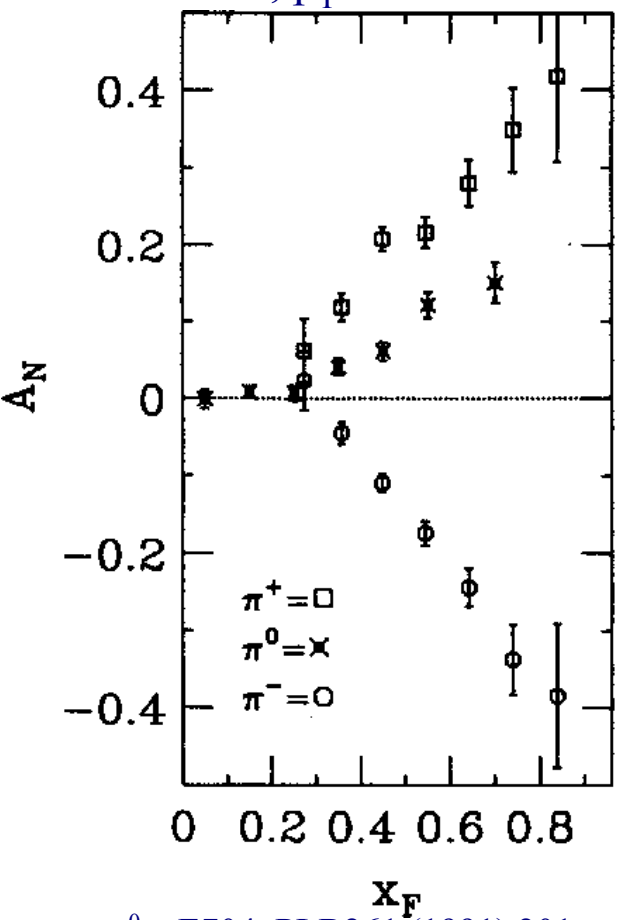
Analyzing powers in forward π production

…A_N expected to be small from chiral properties of QCD…

Kane, et al., PRL 41 (1978) 1689

E704: $p_{\uparrow} + p \rightarrow \pi + X$

$\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV/c:



. π^0 – E704, PLB261 (1991) 201.

. $\pi^{+/-}$ - E704, PLB264 (1991) 462.

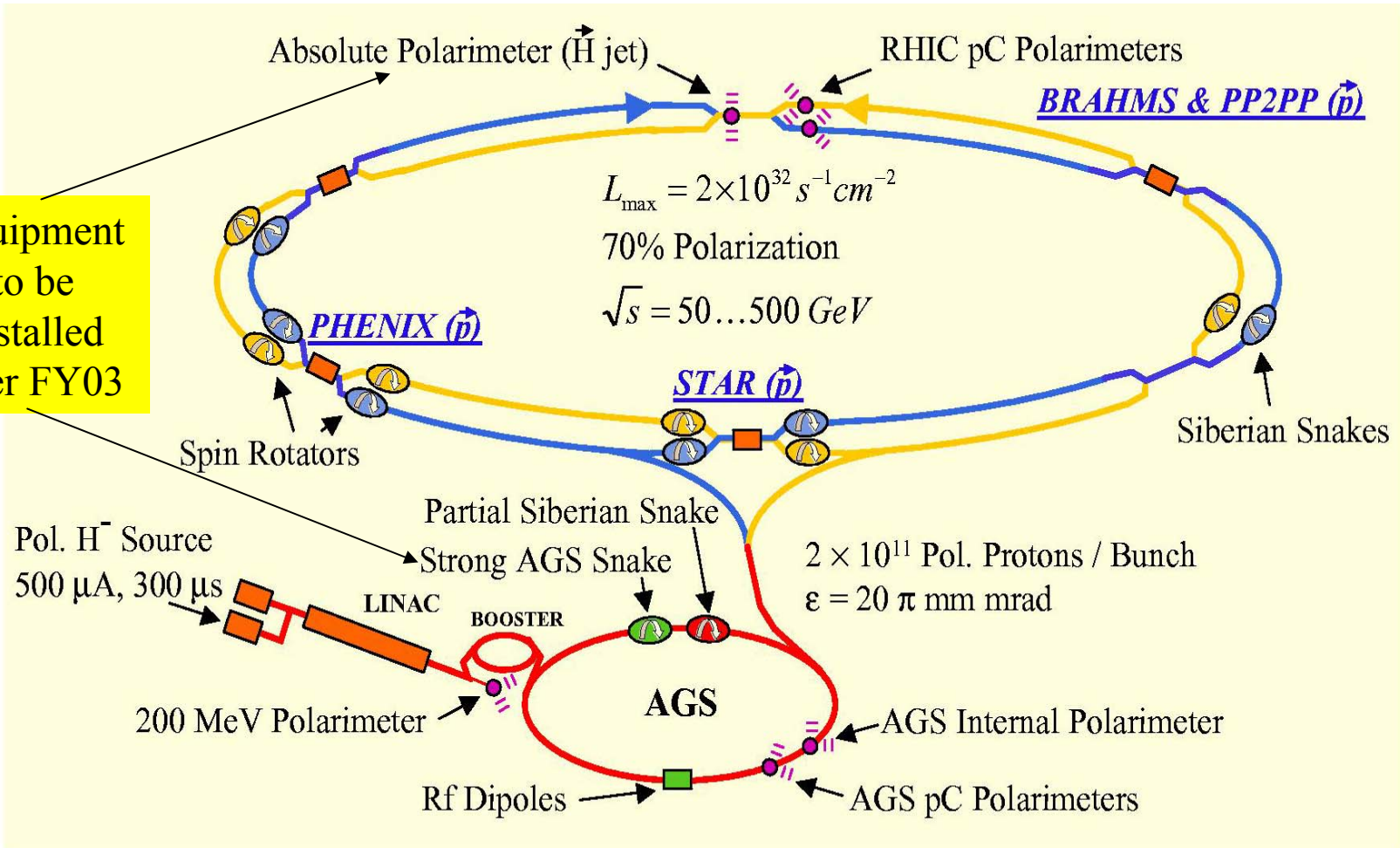
Extensions to naïve pQCD to accommodate large transverse spin effects…

- Transversity structure function + Collins (spin dependent) fragmentation function
- k_T in polarized parton distributions (orbital angular momentum)
- Higher twist effects

. Anselmino, et al., PLB442(1998)470
. Anselmino, et al., PRD 60(1999)054027
. Qiu and Sterman, PRD 59(1998)014004

- **Large analyzing powers observed where naïve pQCD expects little…**

Polarized Proton Operation at RHIC

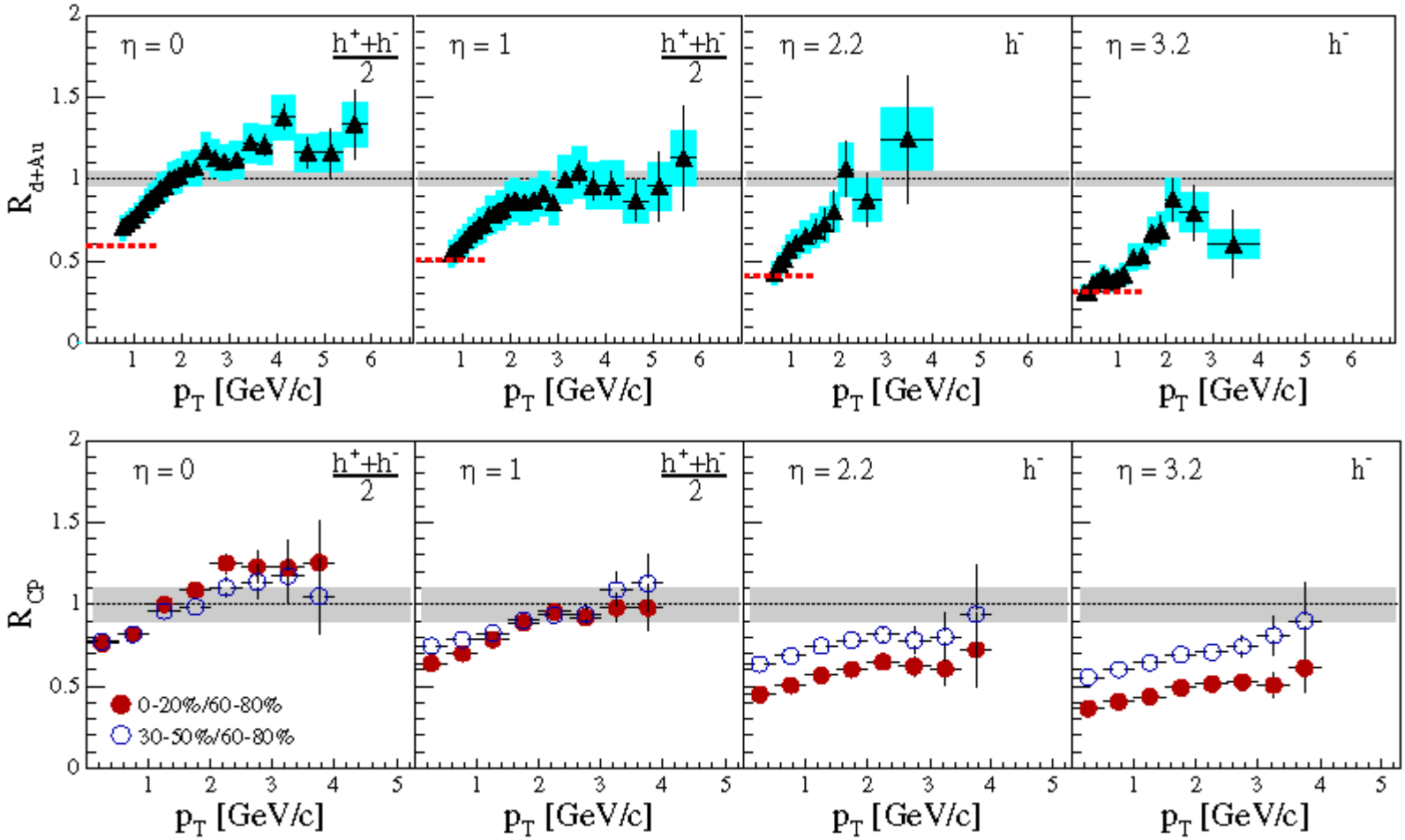


Equipment/developments for runs 2 (1/02) and 3 (3/03 → 5/03)...

- Helical dipole snake magnets
- CNI polarimeters in RHIC,AGS
  → fast feedback
- β*=1m operataion
- spin rotators → longitudinal polarization

Final Results for forward d+Au $h^{\pm}$ production from Brahms

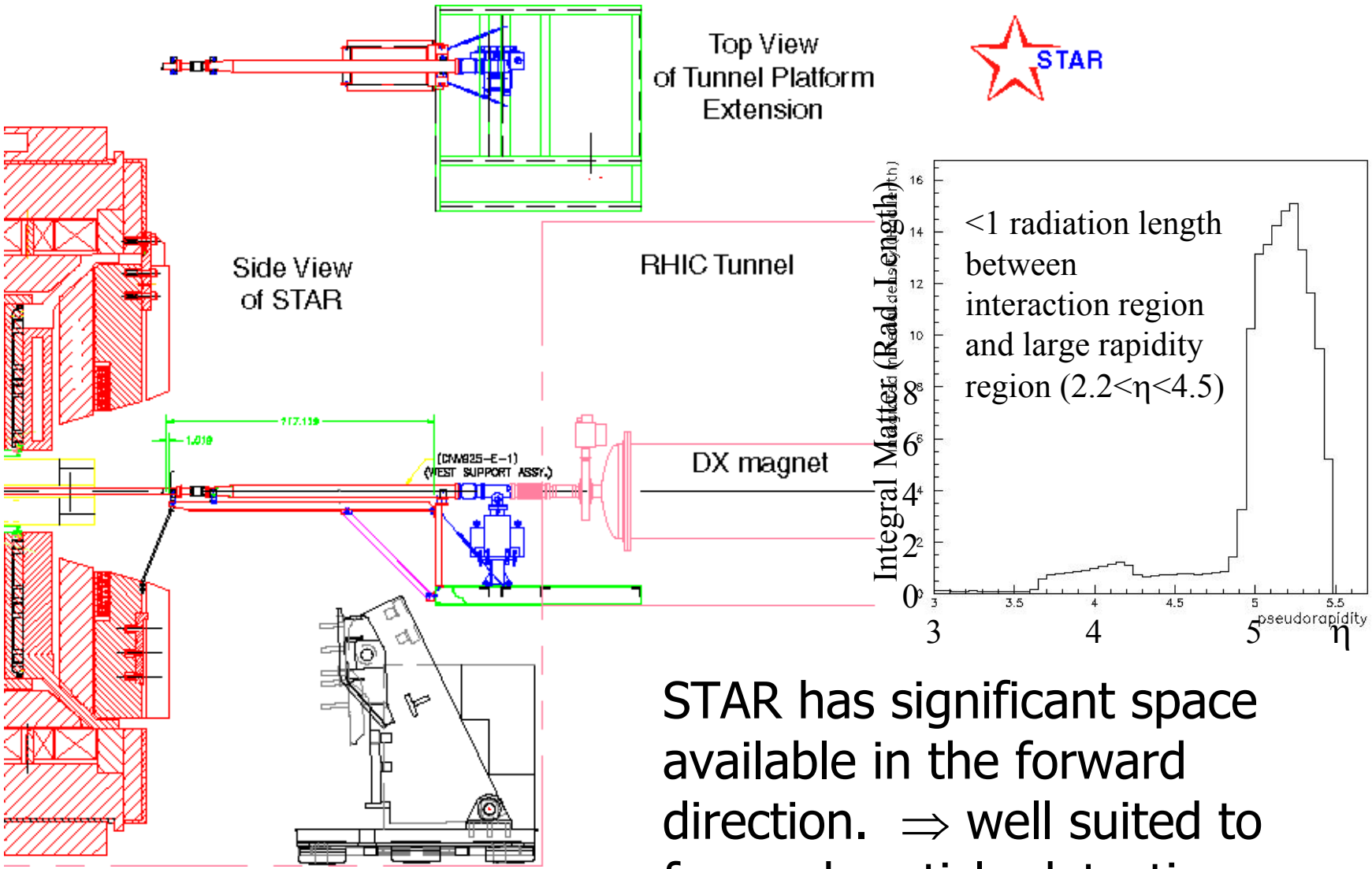
I. Arsene et al. (Brahms Collaboration)
submitted to PRL nucl-ex/0403005



Suppression of inclusive hadron production at forward rapidities of d+Au relative to p+p observed at BRAHMS…

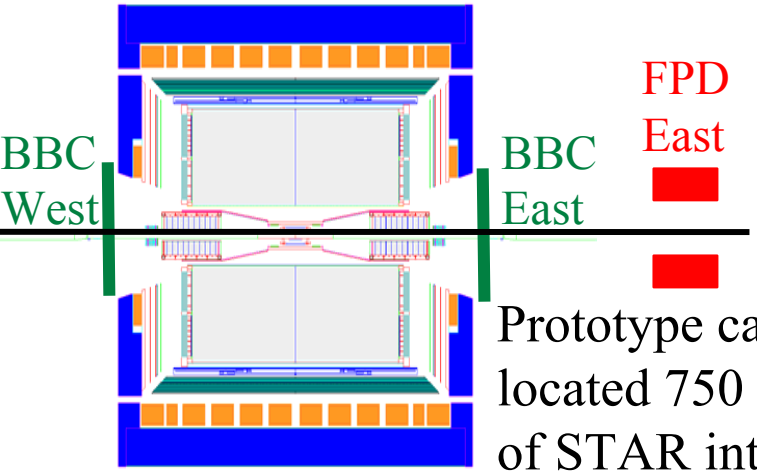
What about back-to-back correlations?

Forward Physics at STAR

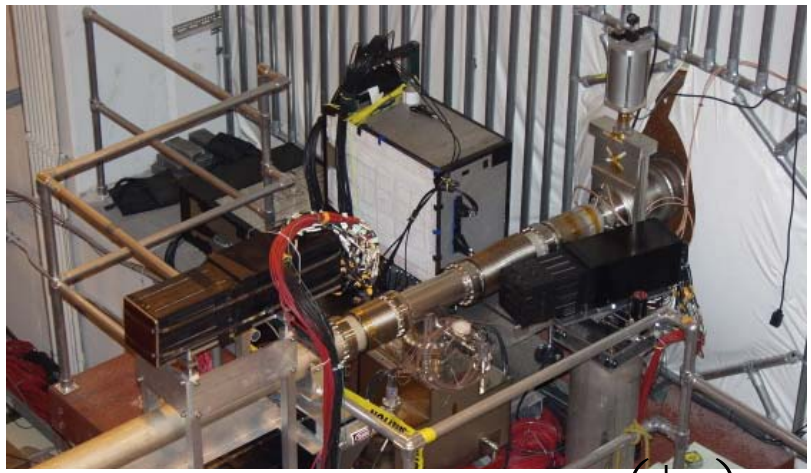


STAR has significant space available in the forward direction. $\Rightarrow$ well suited to forward particle detection.

Run-2 Prototype FPD



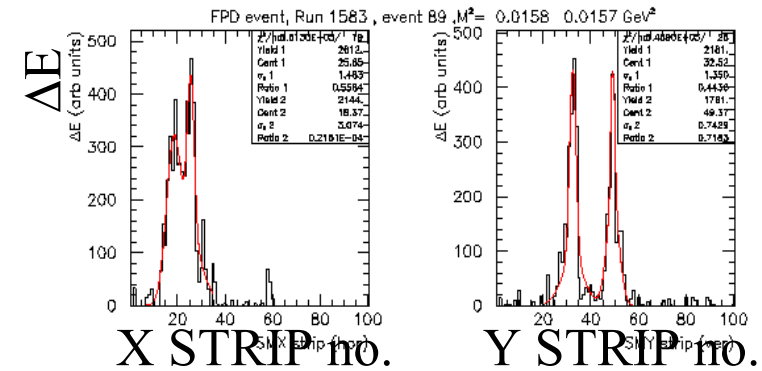
Prototype calorimeter located 750 cm (z_{vert}) east of STAR interaction region

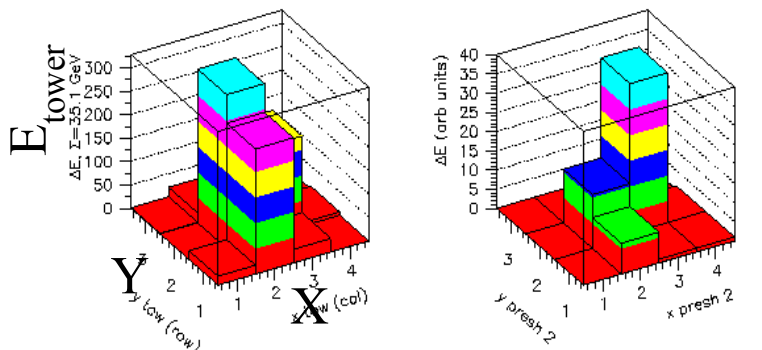


Identify/reconstruct high-energy $\pi^0 \rightarrow \gamma\gamma$ by measuring total energy (E_{tot}) in the calorimeter and the energy sharing ($z_{\gamma\gamma}$) and di-photon separation ($d_{\gamma\gamma}$) with a scintillator-strip shower maximum detector.

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

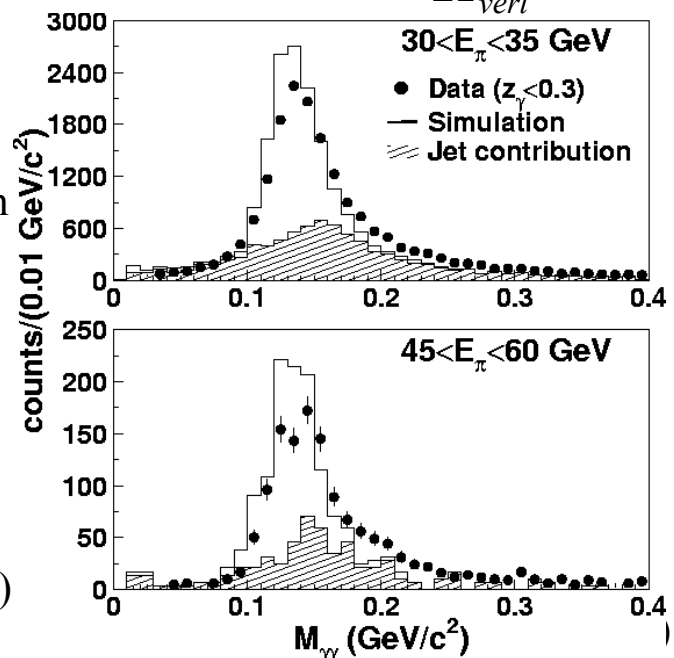
$$M_{\gamma\gamma} \approx E_{tot}\sqrt{1-z_{\gamma\gamma}^2}\,\frac{d_{\gamma\gamma}}{2z_{vert}}$$





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)



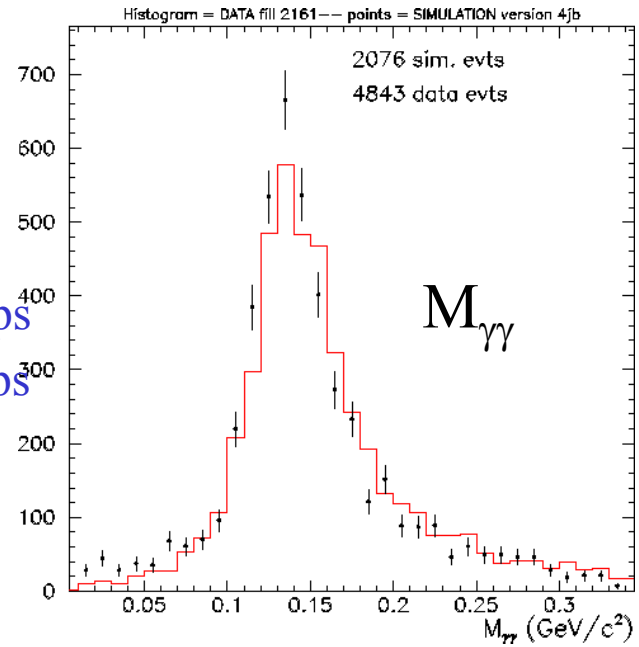
Simulation of pEEMC in STAR

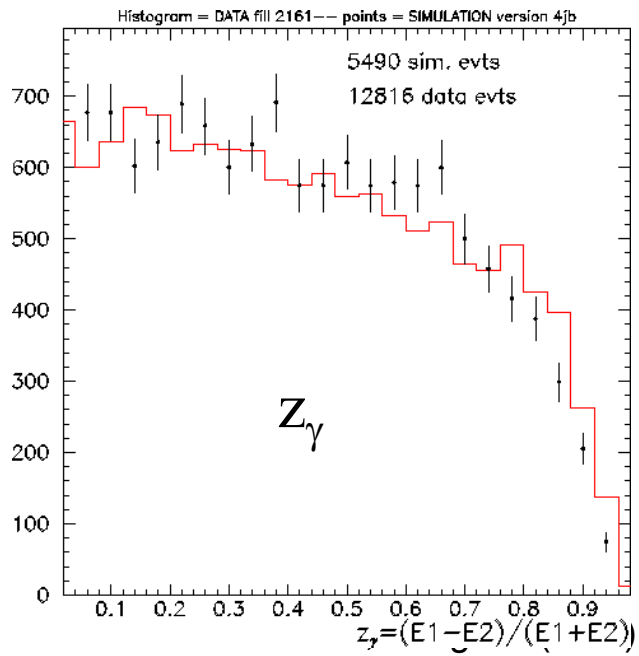
Scheme:

- 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



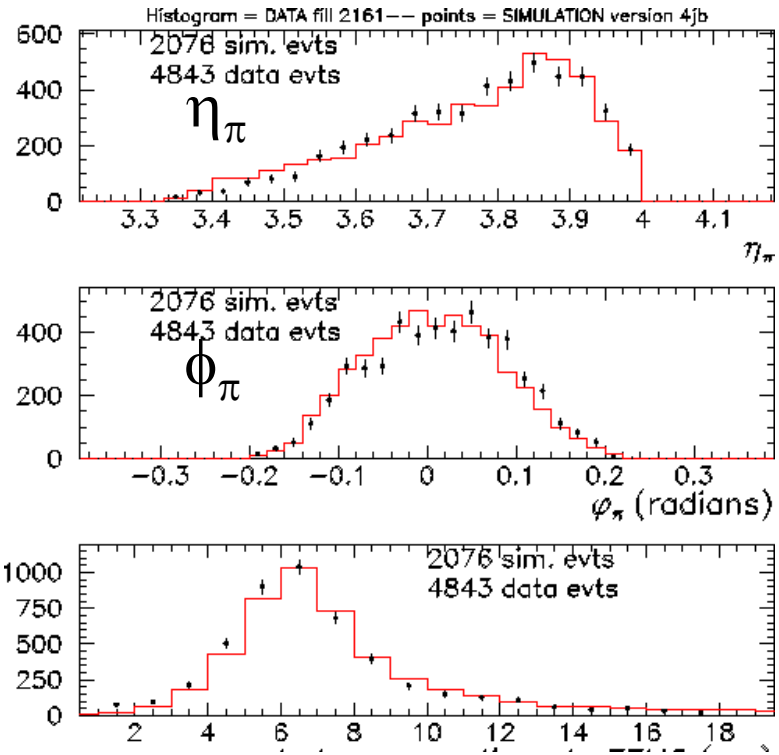


- Histogram = data
- Points = simulation norm. to data

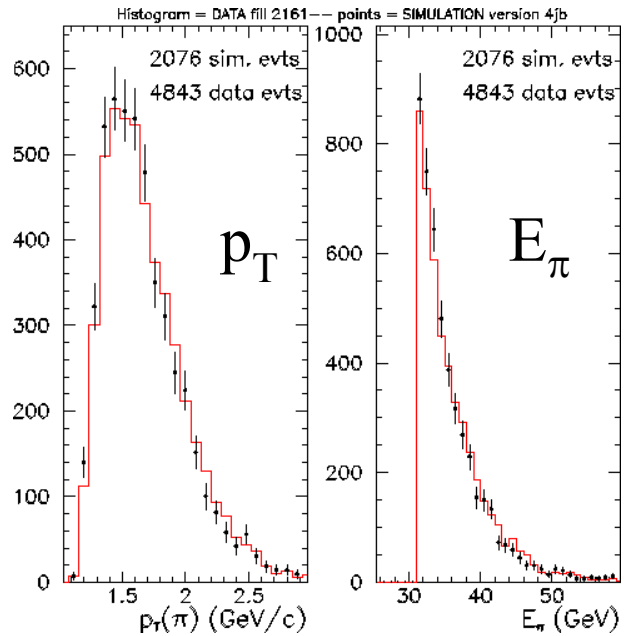
STAR spin

Simulation of pEEMC (cont.)

Angular variables:

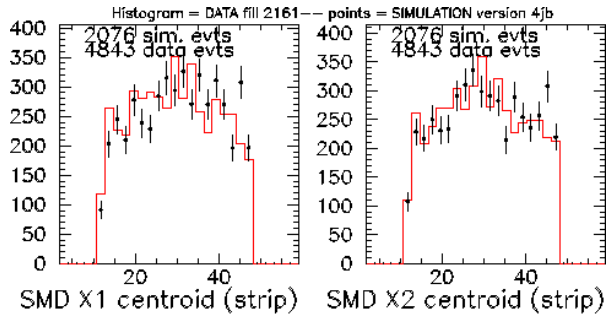


Photon separation at pEEMC (cm)

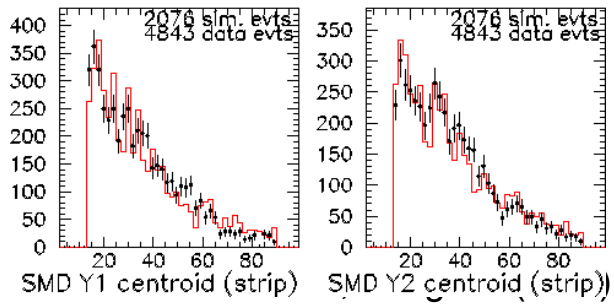


Single photon positions:

vertical



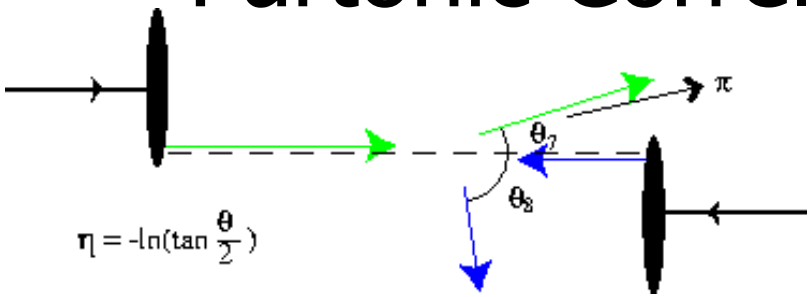
horizontal



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

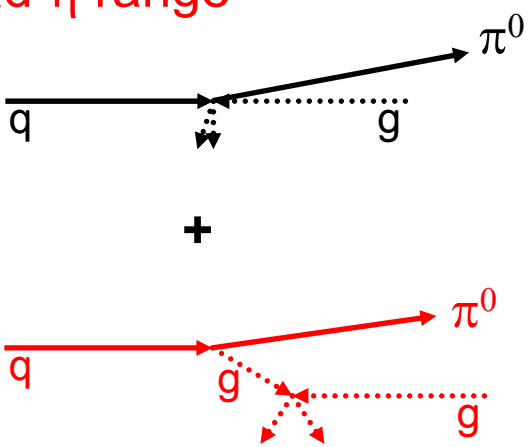
STAR spin

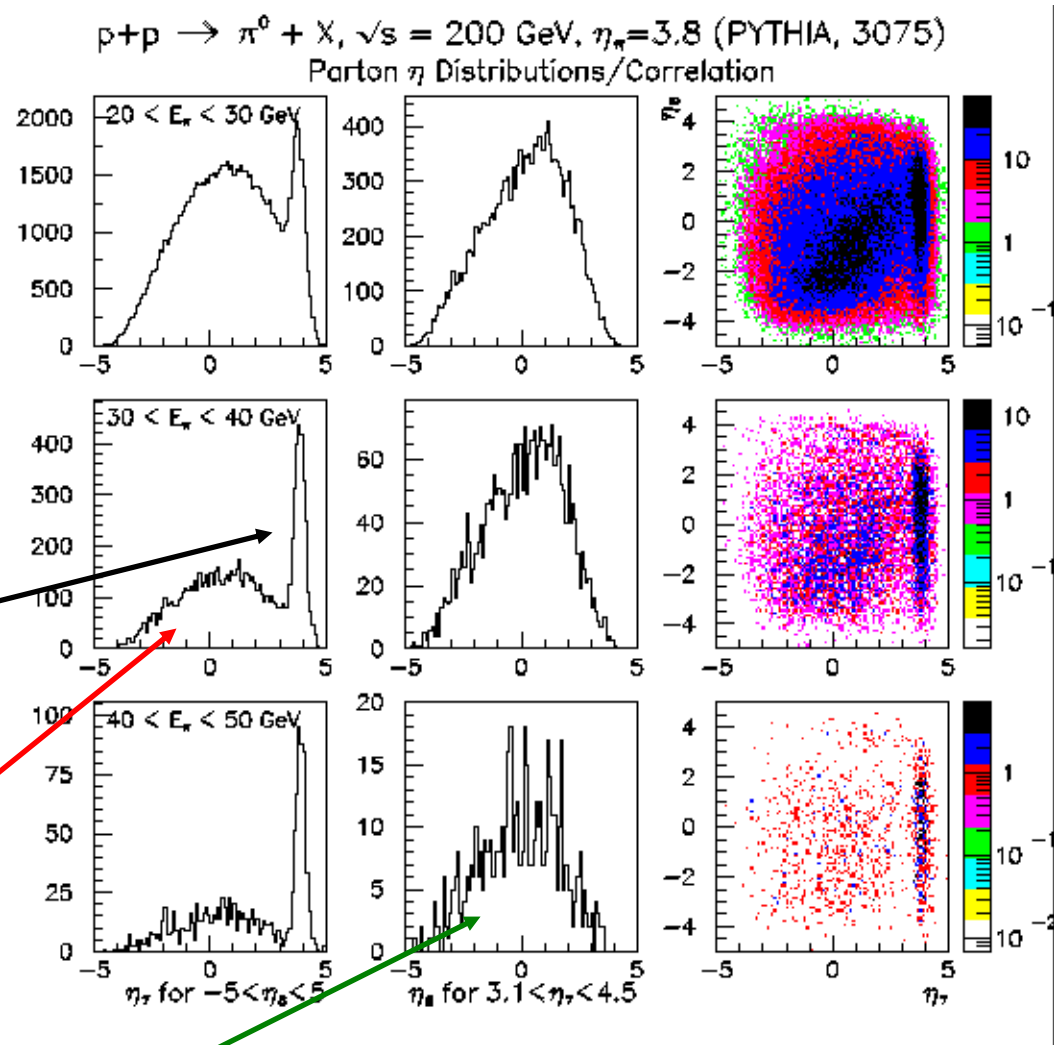
Partonic Correlations from PYTHIA



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