Forward Physics at STAR

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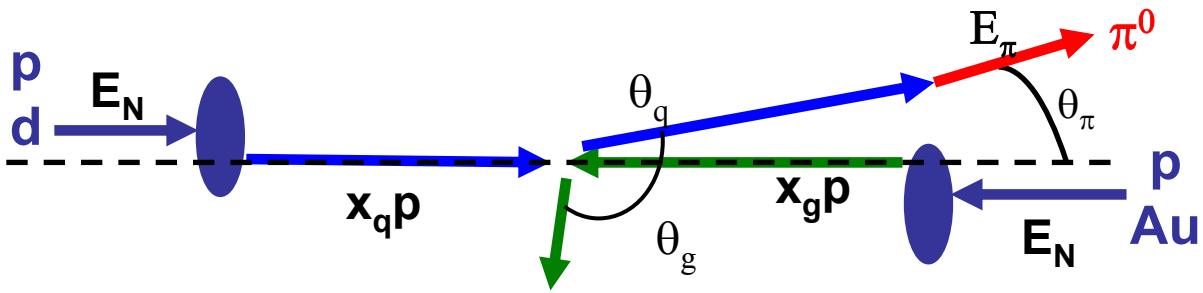
Workshop R4b: Forward Physics at RHIC

RHIC/AGS Users Meeting

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

Forward π^0 production in hadron collider

QCD analog of low-x deep-inelastic scattering



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

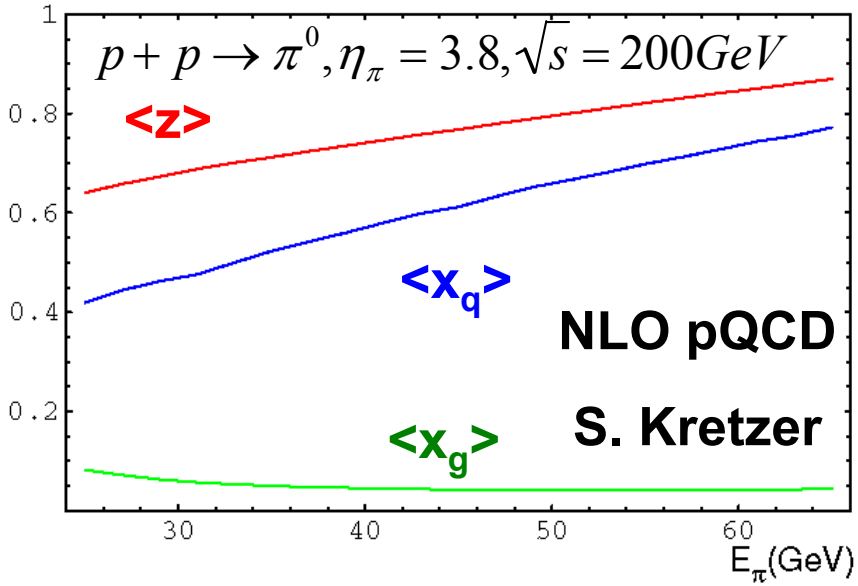
$$\sqrt{s} = 2E_N$$

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

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

(collinear approx.)

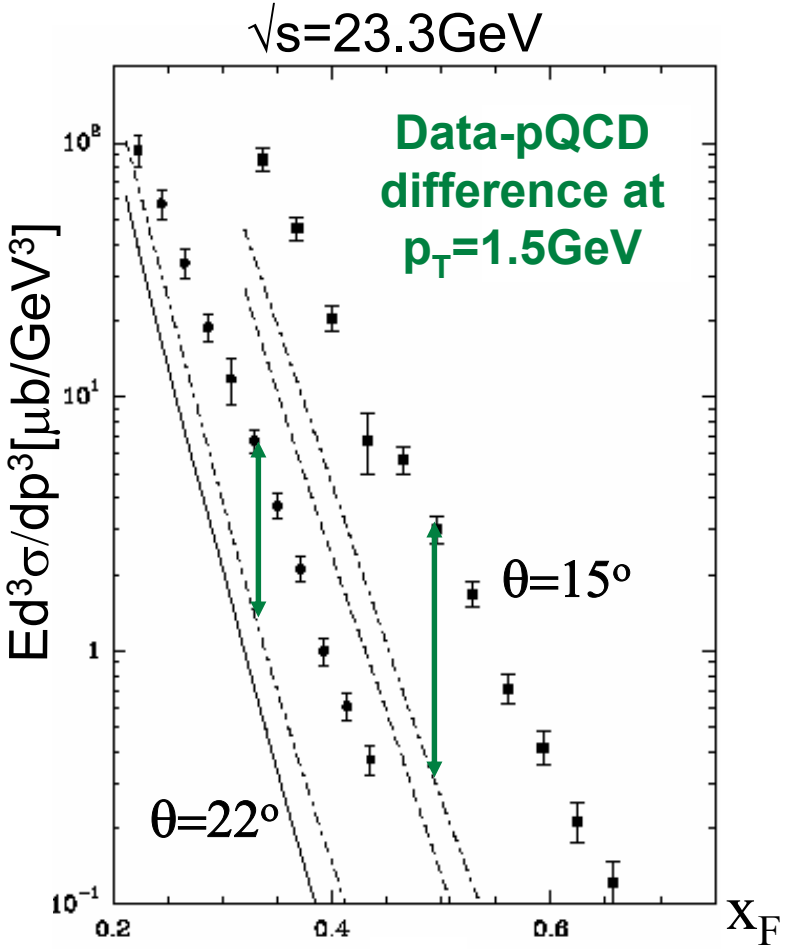
- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**
- Mostly **high-x valence quark** + **low-x gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <z> nearly constant and high ~ 0.8

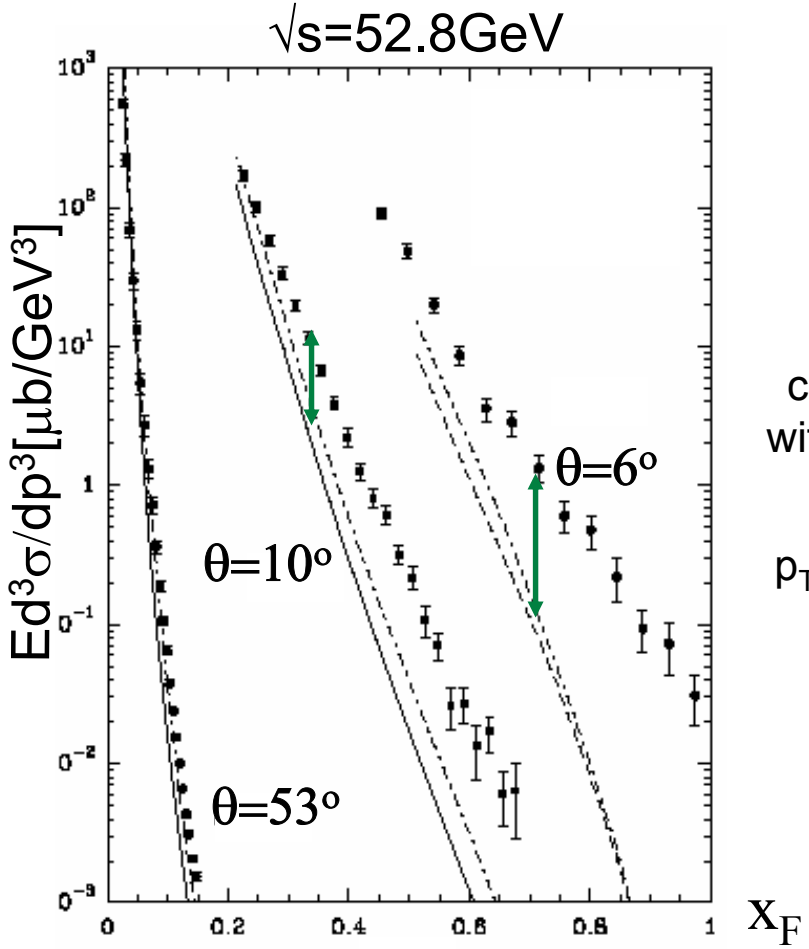


- **Large-x quark polarization is known to be large from DIS**
- **Directly couple to gluons = A probe of low x gluons**

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 $p_T/2$

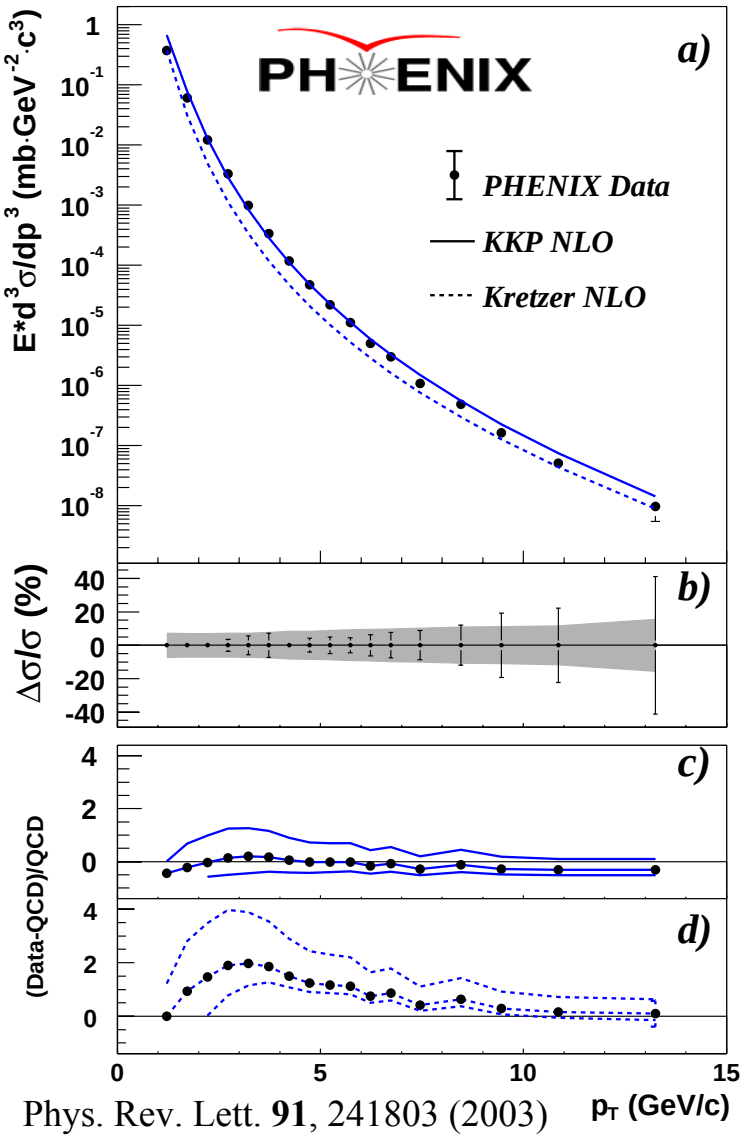
Bourelly and Soffer (hep-ph/0311110, Data references therein):

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?

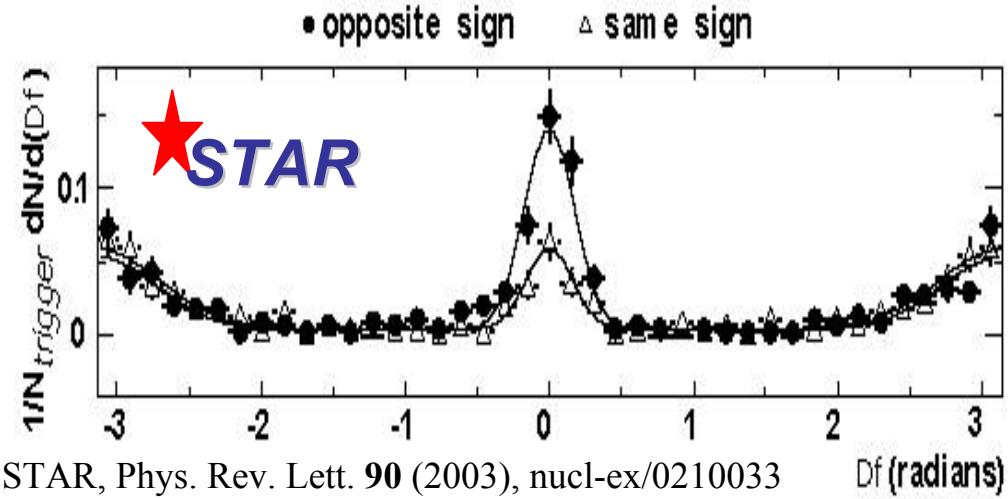
Inclusive π^0 cross section



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

hep-ex/0304038

Two particle correlations

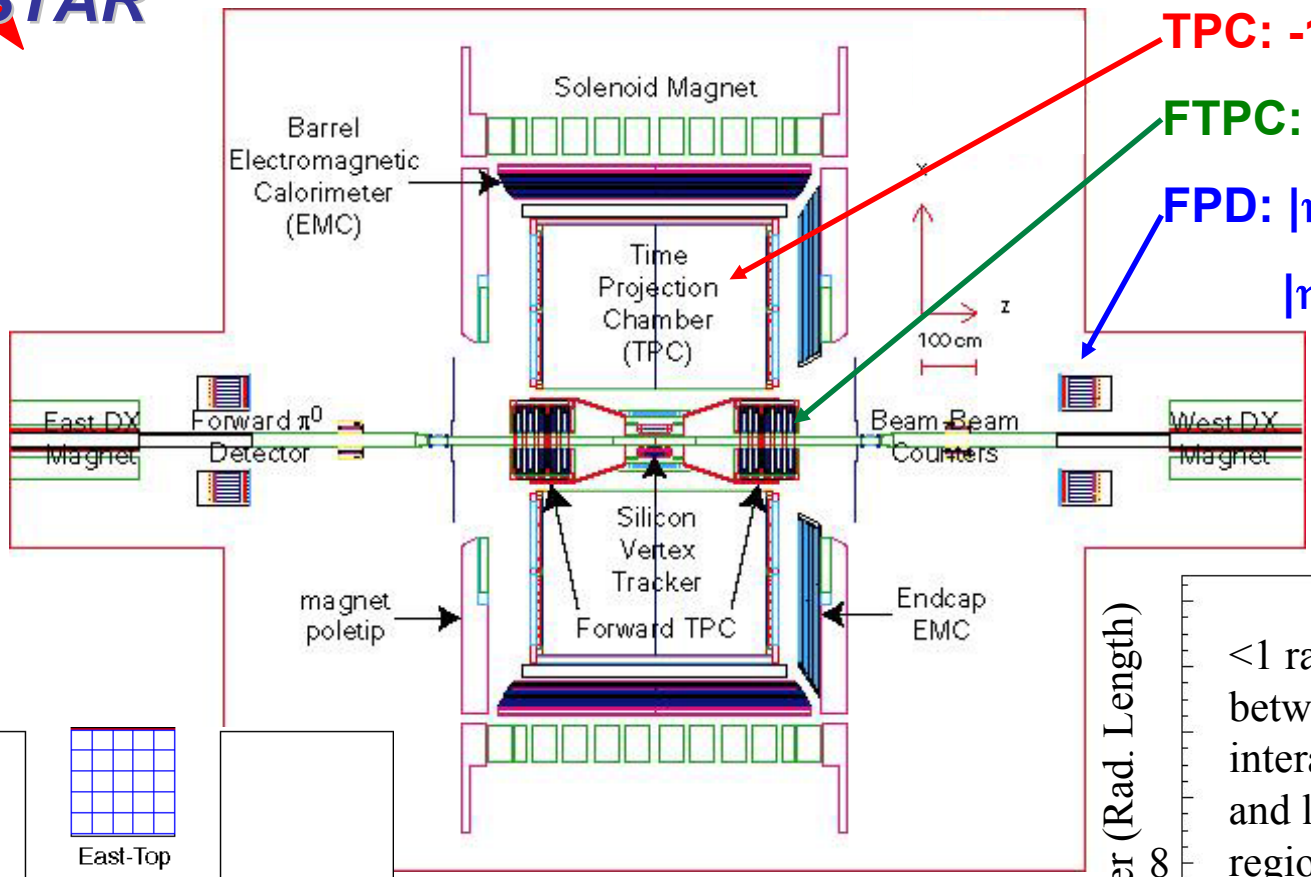


STAR, Phys. Rev. Lett. **90** (2003), nucl-ex/0210033

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?

STAR Detector

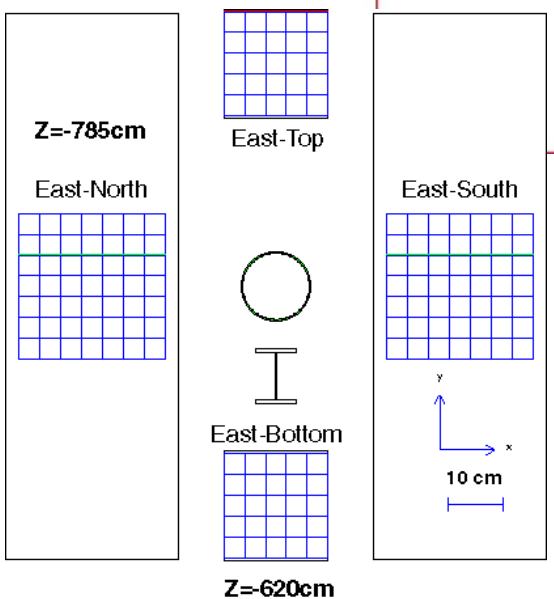


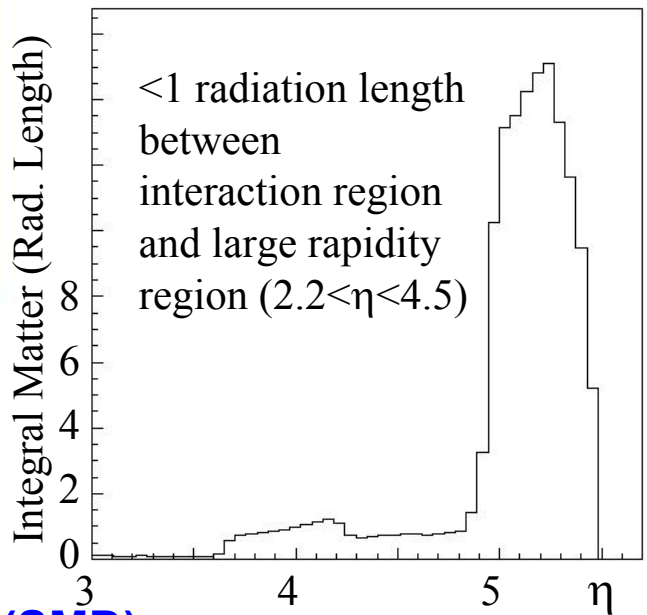
TPC: $-1.0 < \eta < 1.0$

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

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

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



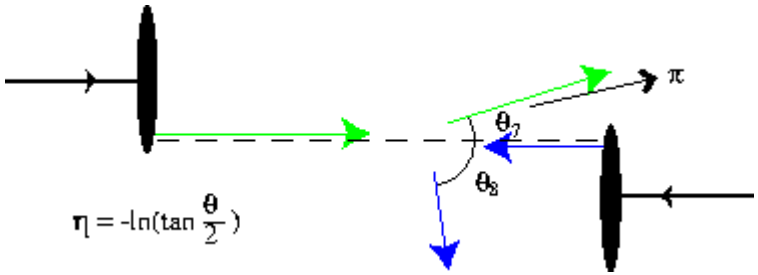


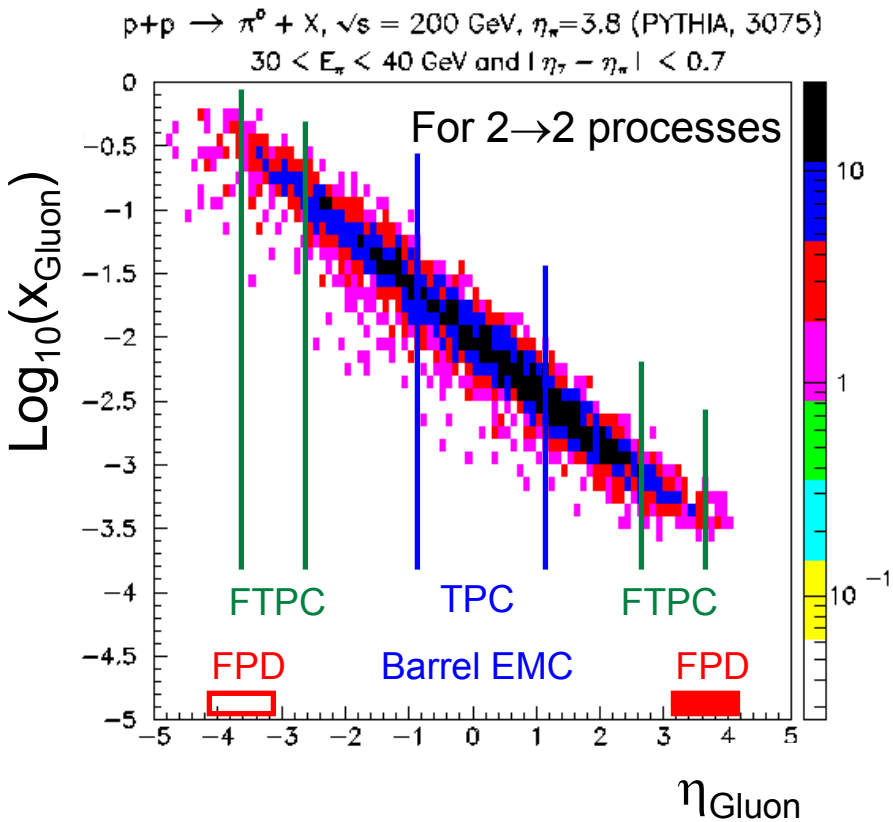
Forward π^0 Detector (FPD)

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

Why forward physics at STAR?

Correlations with forward π^0 meson…





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

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

Spin effects with correlations?

Nuclear enhancement of gluon field :

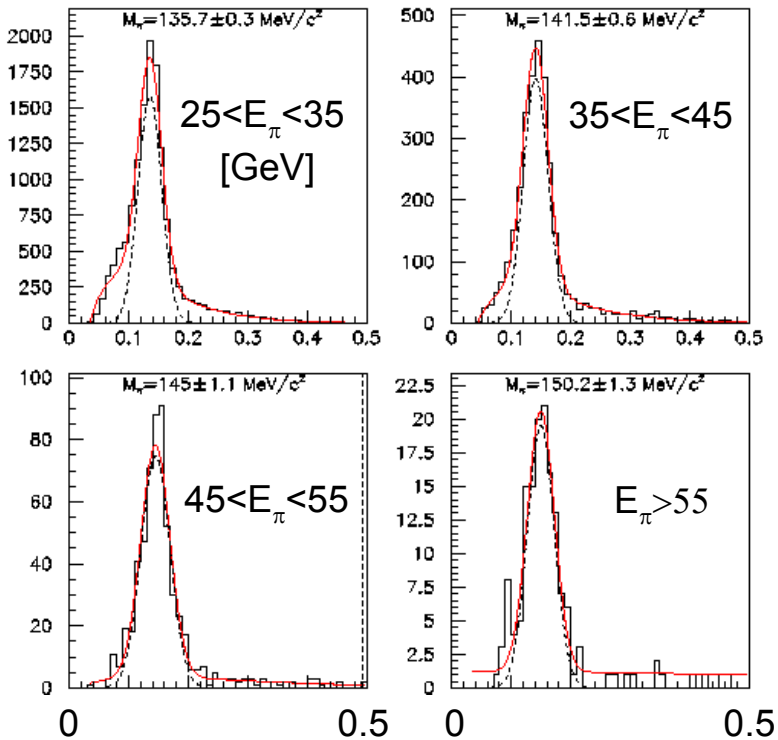
$A^{1/3}x \sim 6x$ (Au case)?

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

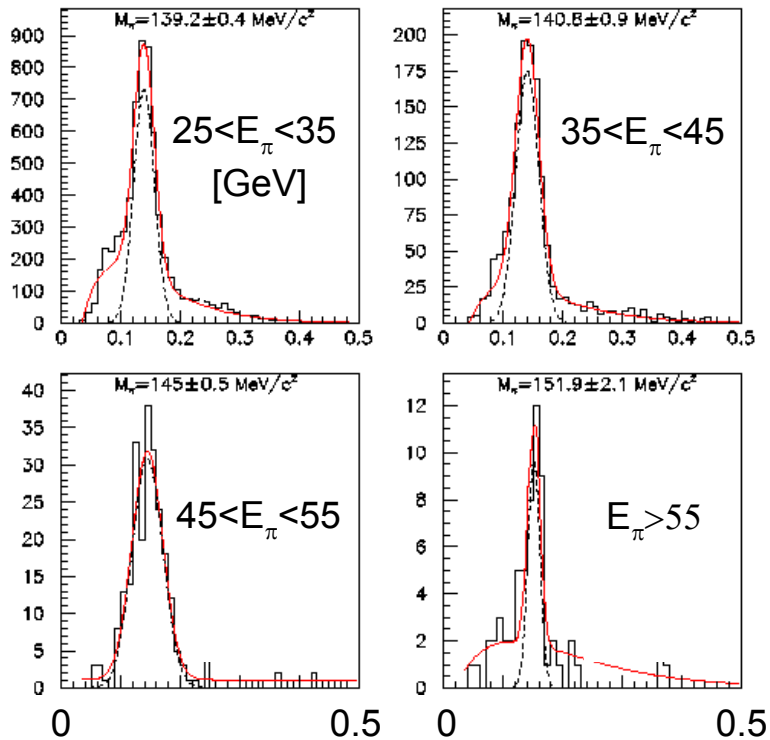
Di-photon Mass Reconstruction

- 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

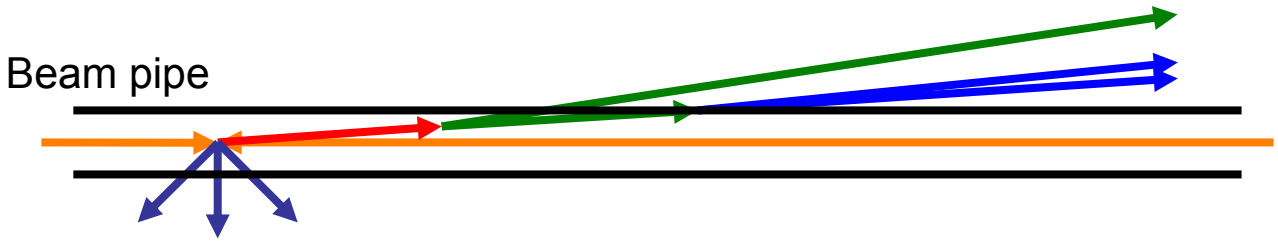


$M_{\gamma\gamma}$[GeV/c^2]

- Absolute gain determined from π^0 peak position for each tower
- current gain calibration known to ~10% $\Rightarrow$ cross section in d+Au requires better calibrations… corrections underway…
- systematics with SMD

FTPC-FPD matching: Photon conversion in beam pipe

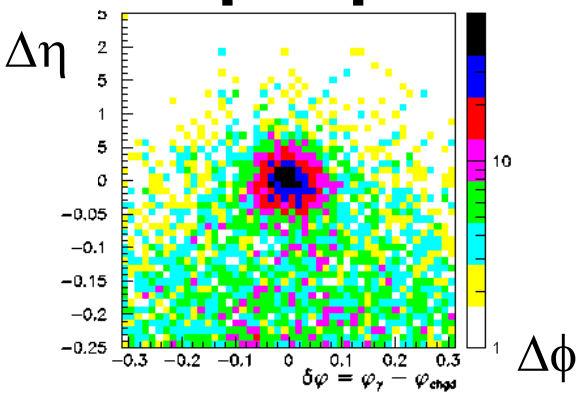
$\left.\begin{matrix} p + p \\ d + Au \end{matrix}\right\} \rightarrow \pi^0 (+ X) \rightarrow \gamma (+ \gamma) \rightarrow e^+ e^-$

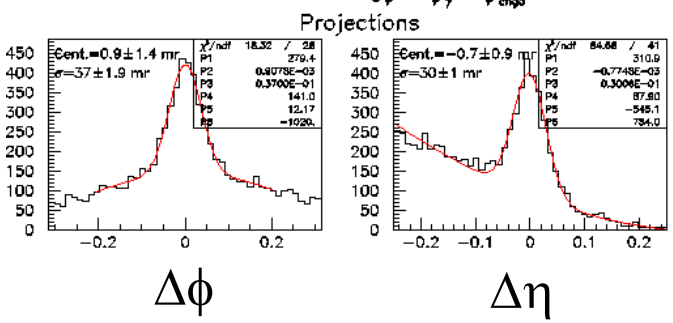


$\Delta\eta = \eta_{FPD} - \eta_{FTPC}$

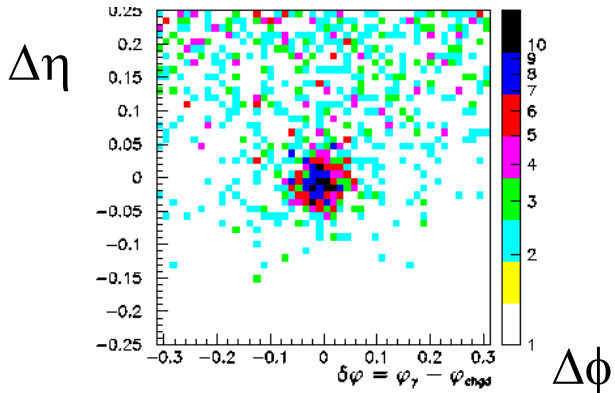
$\Delta\phi = \phi_{FPD} - \phi_{FTPC}$

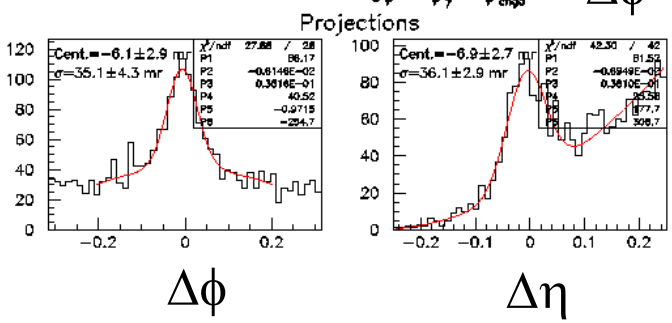
p + p





d+Au





FPD:

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

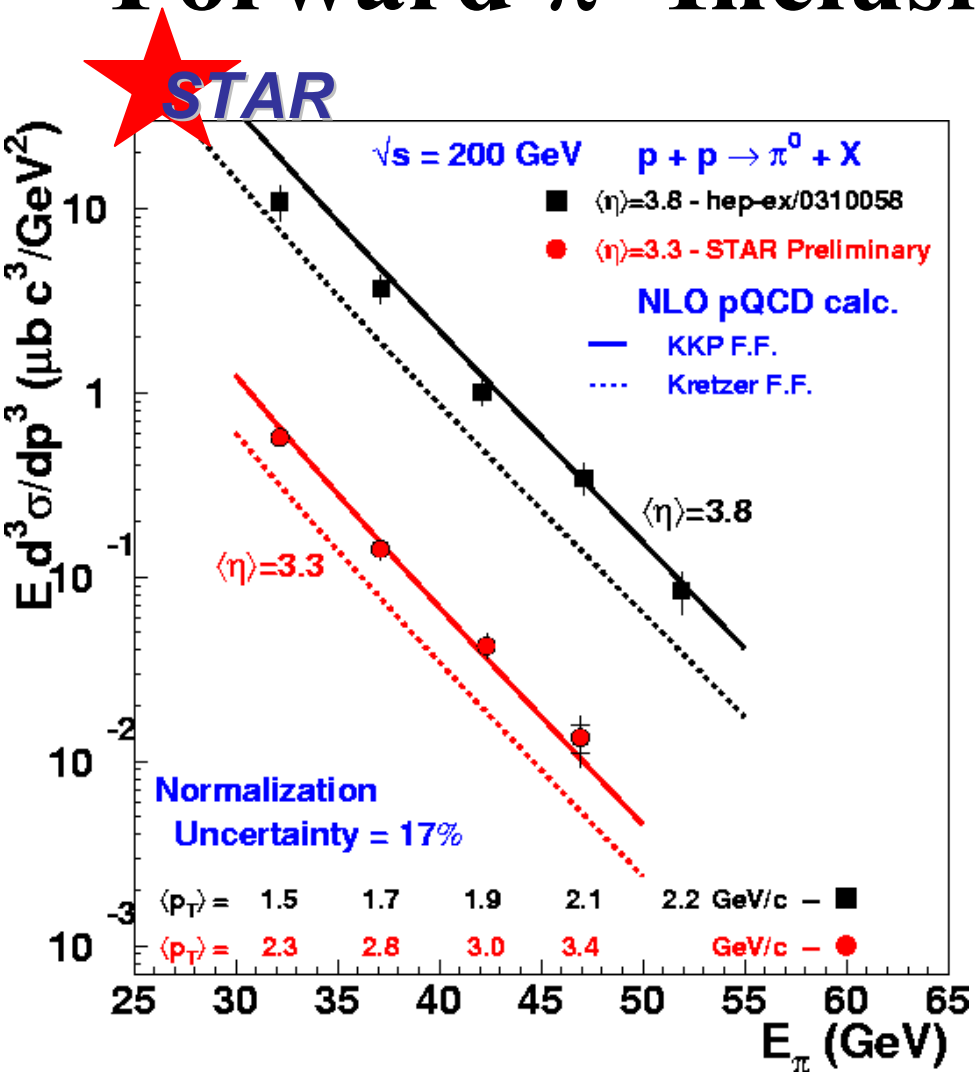
FTPC:

- $2.8 < |\eta| < 3.8$

$\Rightarrow$ FPD position known relative to STAR

$\Rightarrow$ Detector resolution for particle correlation is good

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 → π fragmentation function

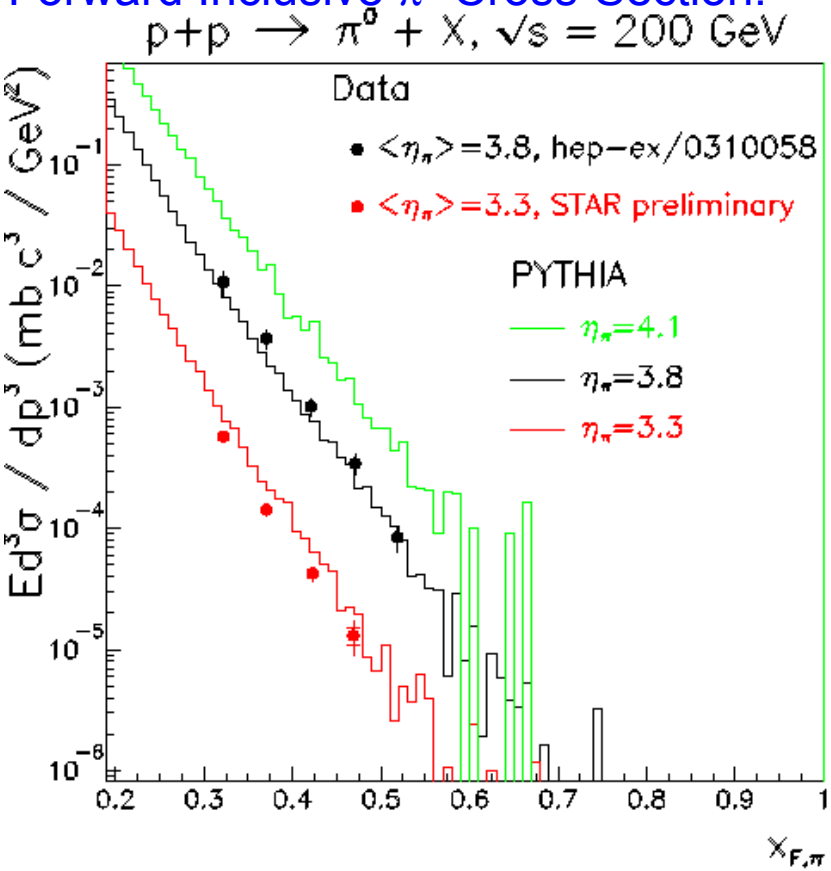
STAR data consistent with Next-to-Leading Order pQCD calculations

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

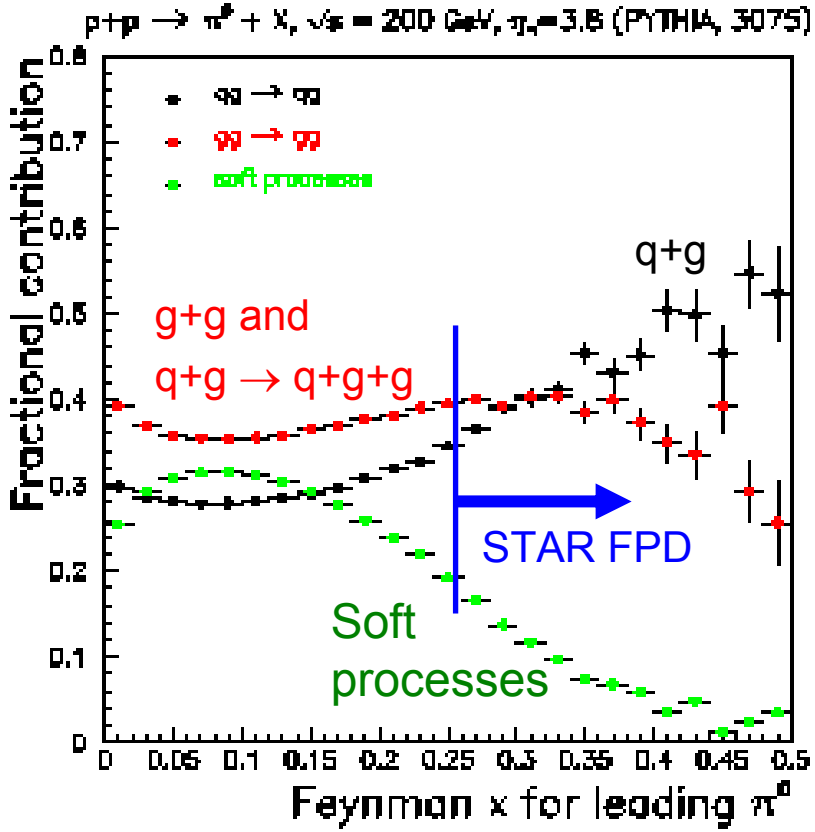
What about particle correlations?

PYTHIA: a guide to the physics

Forward Inclusive π^0 Cross-Section:



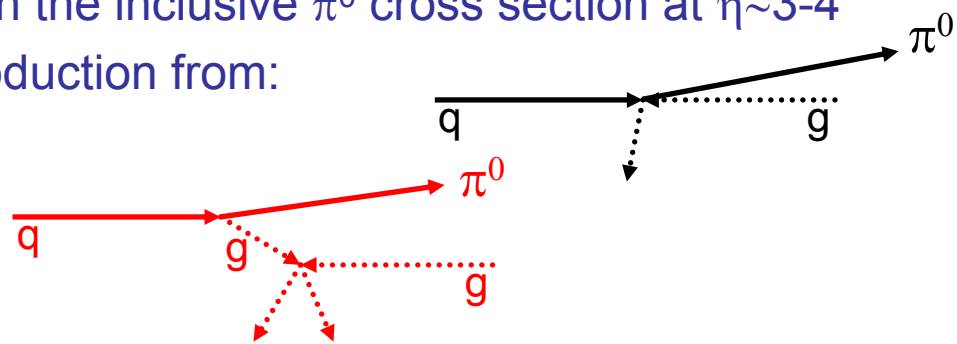
Subprocesses involved:



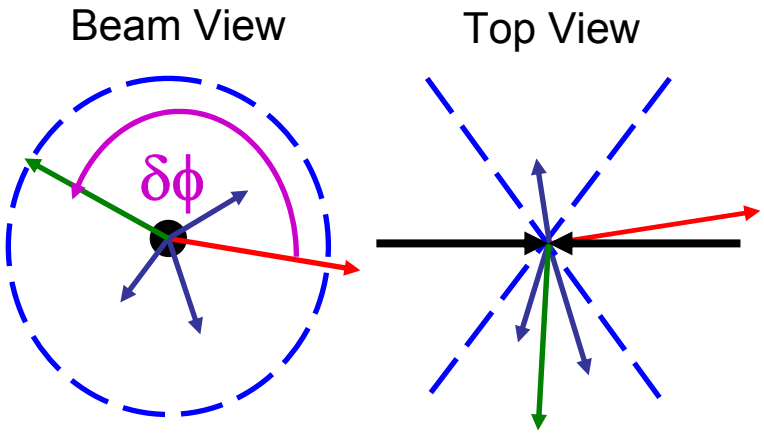
- PYTHIA ***prediction*** agrees well with the inclusive π^0 cross section at η~3-4
- Dominant sources of large x_F π^0 production from:

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

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



Back-to-back Azimuthal Correlations with large $\Delta\eta$



Trigger by forward π^0

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

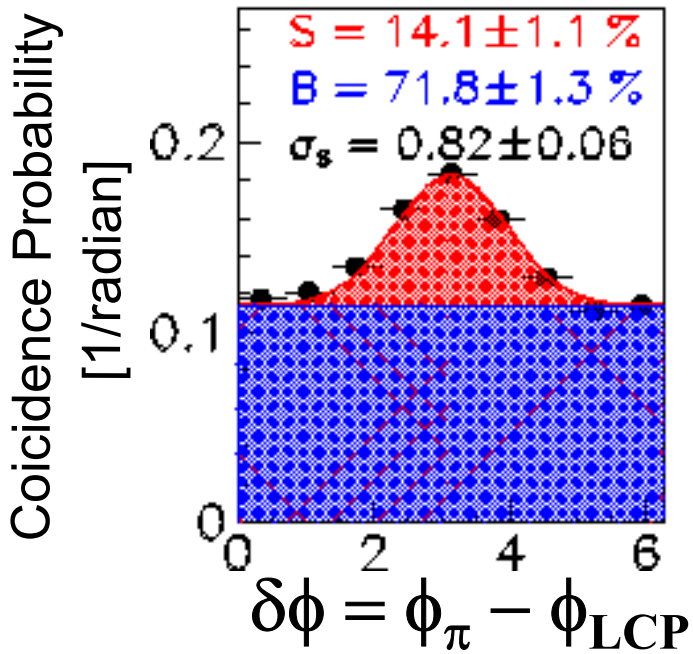
Midrapidity $h^\pm$ tracks in TPC

- $-0.75 < \eta < +0.75$

Leading Charged Particle(LCP)

- $p_T > 0.5$ GeV/c

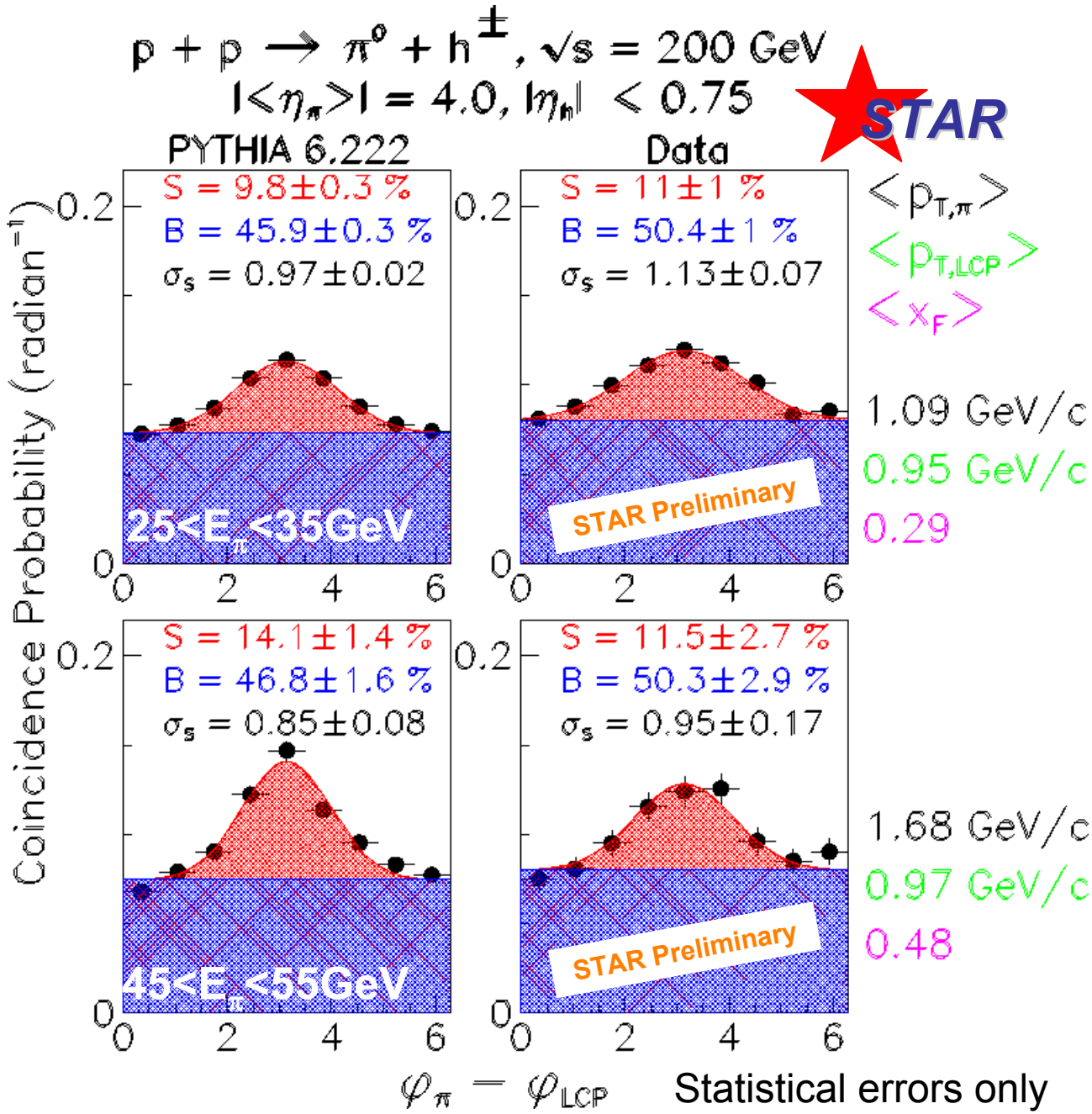
Fit $\delta\phi = \phi_\pi - \phi_{LCP}$ normalized distributions and with Gaussian+constant



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

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 $\Delta\eta$ particle correlations agree with PYTHIA**

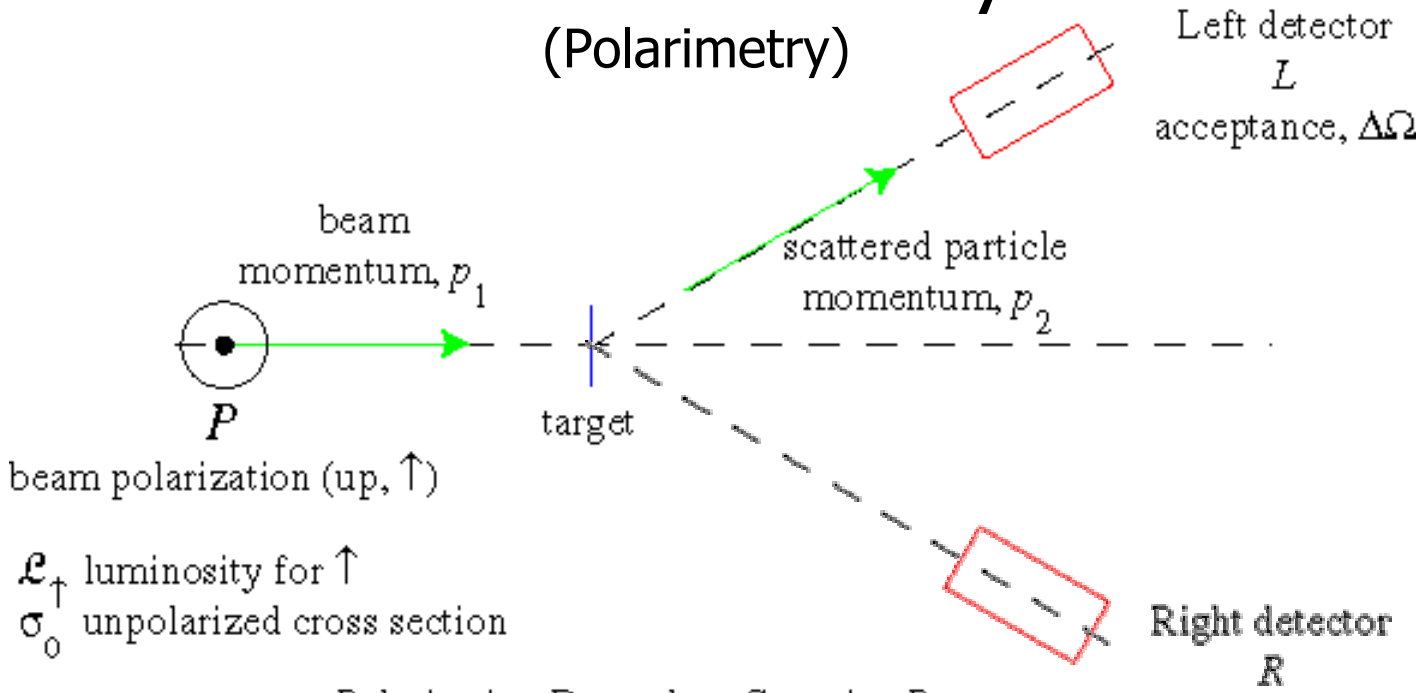
$\Rightarrow$ **Forward π^0 meson production at RHIC energies comes from partonic scattering**

Important result for:

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

Measurements with Transversely Polarized Beam

(Polarimetry)



Polarization Dependent Counting Rates

$$L_\uparrow = (\mathcal{L}_\uparrow \sigma_0)\,\Delta\Omega\,(1 + PA) \qquad R_\uparrow = (\mathcal{L}_\uparrow \sigma_0)\,\Delta\Omega\,(1 - PA)$$

$$L_\downarrow = (\mathcal{L}_\downarrow \sigma_0)\,\Delta\Omega\,(1 - PA) \qquad R_\downarrow = (\mathcal{L}_\downarrow \sigma_0)\,\Delta\Omega\,(1 + PA)$$

Polarization Asymmetries

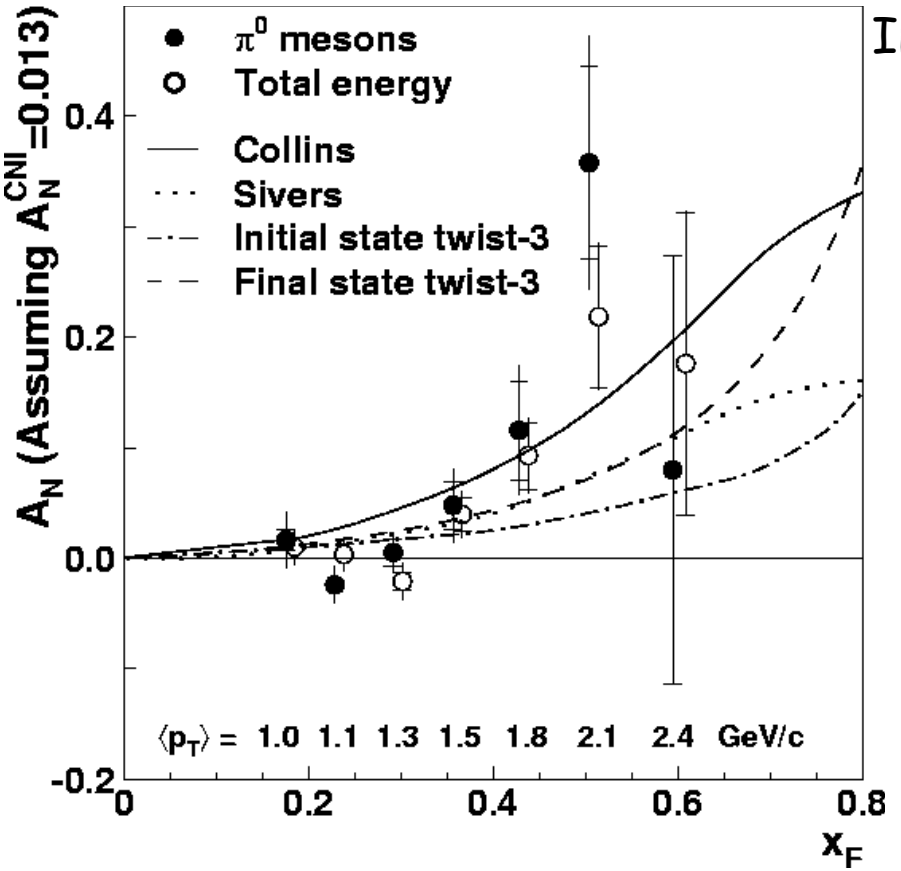
$$\varepsilon = PA = \frac{L_\uparrow / \mathcal{L}_\uparrow - L_\downarrow / \mathcal{L}_\downarrow}{L_\uparrow / \mathcal{L}_\uparrow + L_\downarrow / \mathcal{L}_\downarrow} \qquad \varepsilon = PA = \frac{(L_\uparrow R_\downarrow)^{1/2} - (L_\downarrow R_\uparrow)^{1/2}}{(L_\uparrow R_\downarrow)^{1/2} + (L_\downarrow R_\uparrow)^{1/2}}$$

Large Analyzing Powers at RHIC

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

STAR

STAR collab., PRL **92**, 171801 (2004); hep-ex/0310058.



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

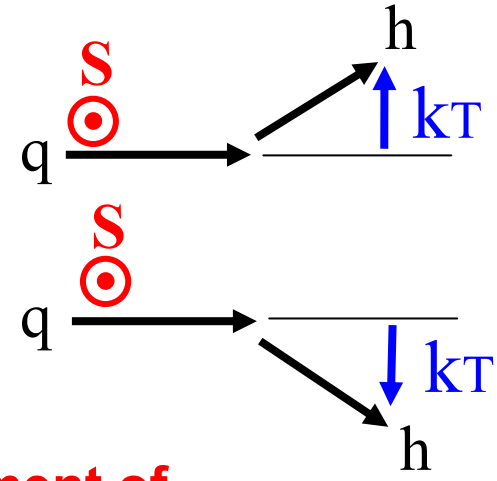
In agreement with several models including different dynamics:

- 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

Dynamical Origins of Forward Analyzing Power (I)

Collins effect:

Transversely polarized quark in the final state can fragment into more (or less) hadrons to Left than Right



Isolating Collins effect requires measurement of

- Collins angle: $\cos \phi_C = (\mathbf{p}_q \times \mathbf{p}_h) \bullet \mathbf{S}$
- thrust axis of jet

Provides information on

- transversity distribution: $\delta q(x,Q^2) = q_\uparrow(x) - q_\downarrow(x)$ (required to make final-state transversely polarized quark)
- for non-relativistic quarks, $\delta q(x,Q^2) = \Delta q(x,Q^2) = q_+(x) - q_-(x)$, helicity distribution $\Rightarrow$ transversity/helicity distribution differences probe hadronic structure

Dynamical Origins of Forward Analyzing Power (II)

Sivers effect:

Flavor-dependent correlation between the proton spin (S_p), momentum (P_p) and transverse momentum (k_T) of the unpolarized partons inside. (Initial state effect)

$$f_q(x, k_T, s_P) = f_q(x, k_T) + \frac{1}{2}\Delta_q^N f_q(x, k_T)\frac{S_P \cdot (P_p \times k_T)}{|S_P||P_P||k_T|}$$

Where Δ_q^N is the Sivers Function – probed in inclusive particle production via 'trigger bias' selection of k_T

Related to partonic orbital angular momentum within proton

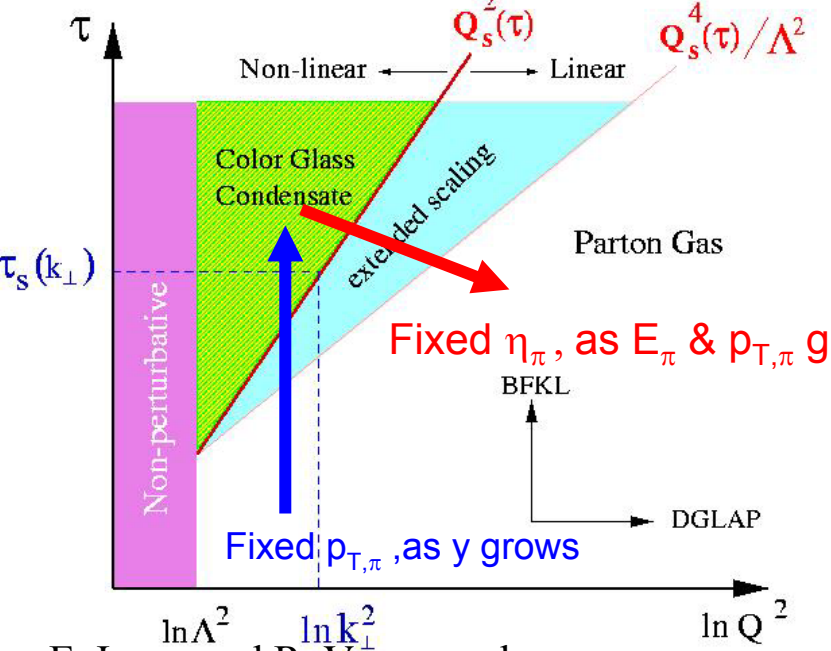
Future Large-Rapidity Transverse Spin Asymmetry Studies

- Disentangle Collins and Sivers effects
  - separate x_F and p_T dependences
  - $x_F<0$?
  - A_N with mid-rapidity $h^{\pm}$ correlation?
  - Spin dependence in jet?
  - A_N for mesons with heavy flavors?
- Establish 'universality' between p+p and semi-inclusive DIS
  - A_N for Drell-Yan

d + Au: Possible Color Glass Condensate at RHIC?

General expectations of CGC:

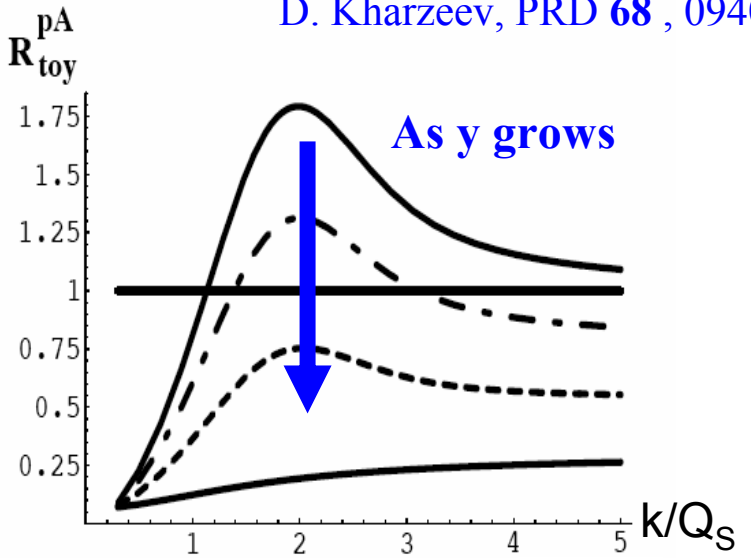
$\tau = \ln\left(1/x\right)$ τ related to rapidity of produced hadrons.



E. Iancu and R. Venugopalan,

Suppression of forward particle production

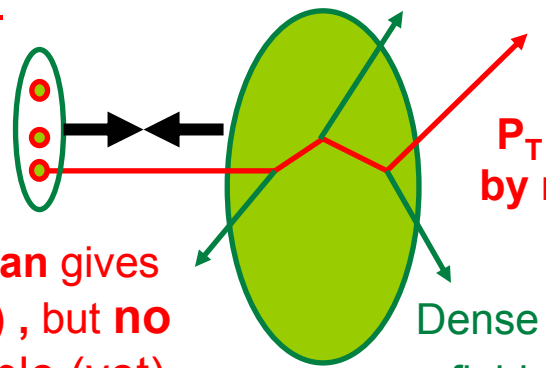
D. Kharzeev, PRD **68** , 094013



Brahms data shows evidence **?**

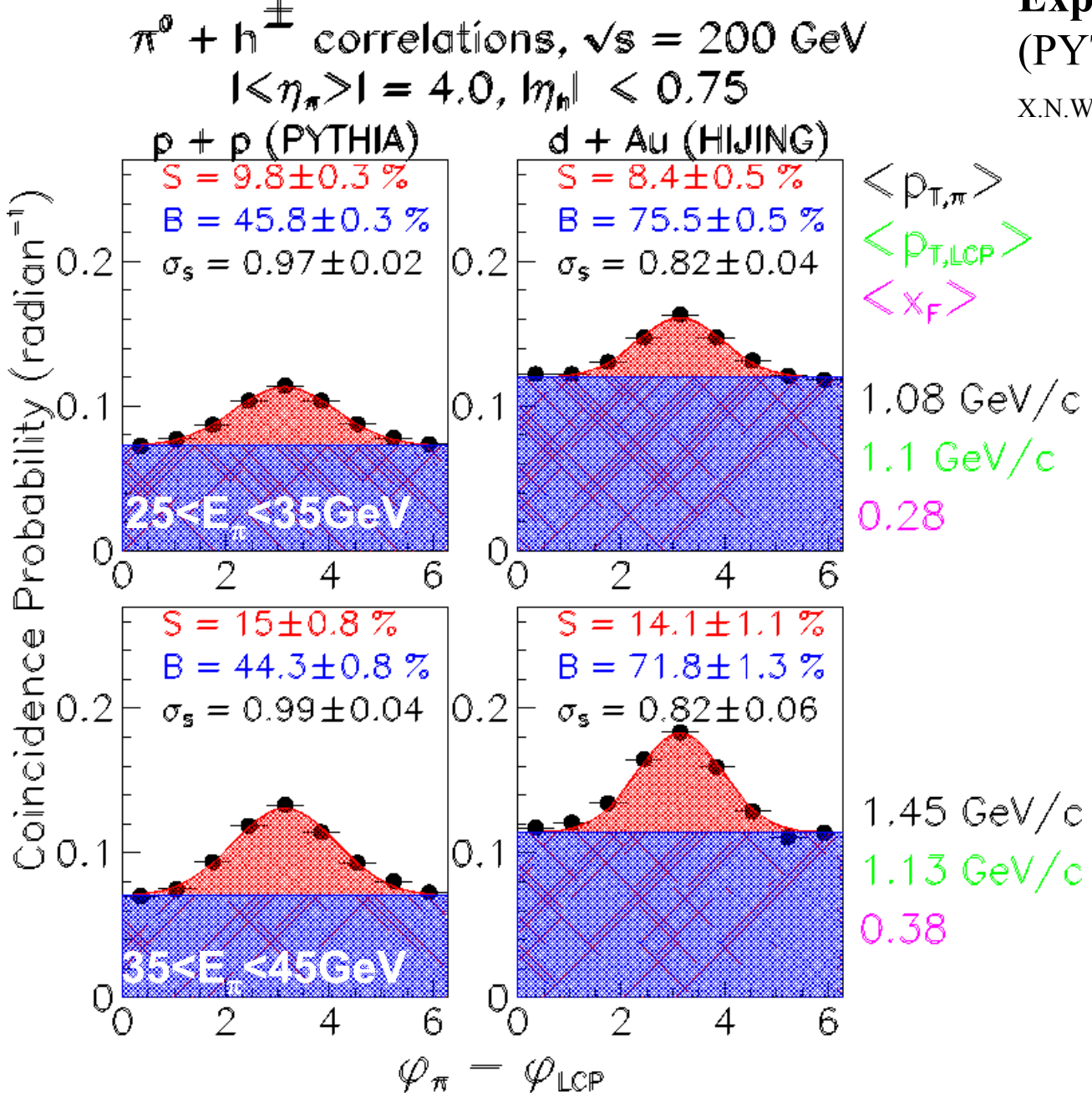
(nucl-ex/0403005)

"Mono-jet"



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

→ **Exploratory studies of large Δη particle correlations at STAR**

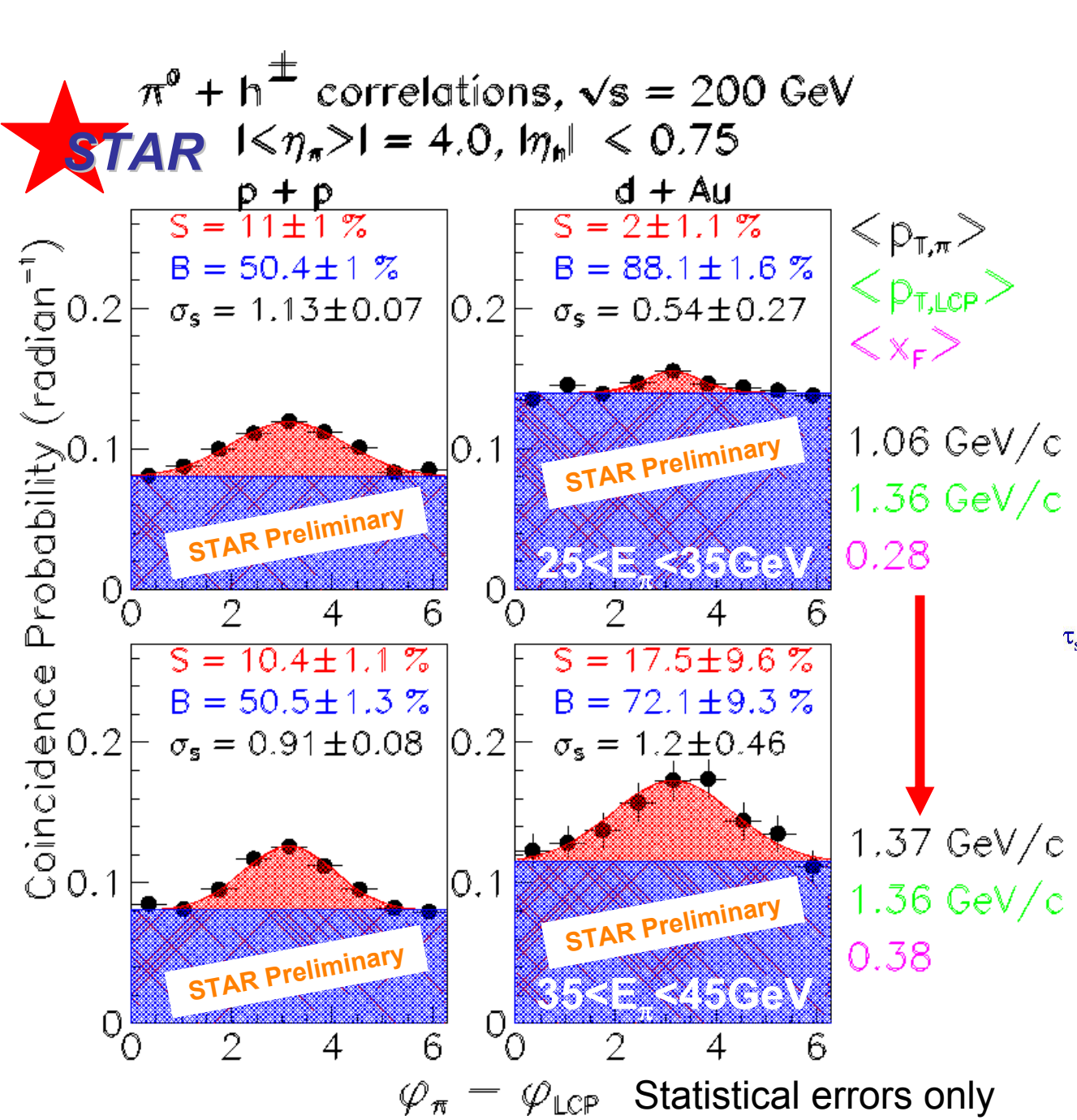


Expectation from HIJING
(PYTHIA+nuclear effects)

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**

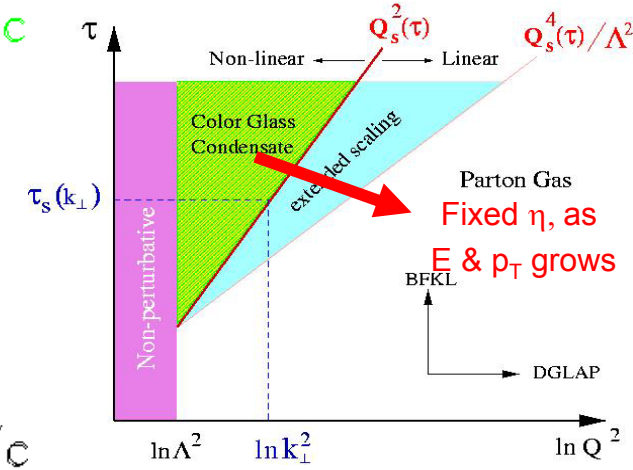


Large $\Delta\eta$ π^0+h$^{\pm}$ correlation data…

- **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

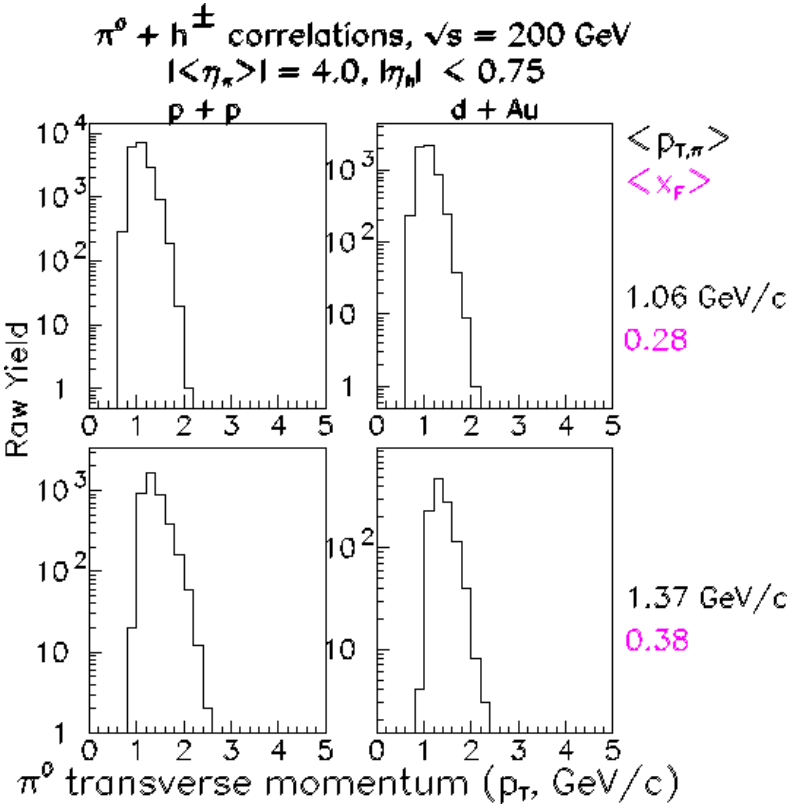


- **consistent in d+Au and p+p at larger $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$**

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 $\Delta\eta$ correlations in p+p agree with PYTHIA prediction**
- **Analyzing power for forward π^0 mesons is large at RHIC**
- **Large $\Delta\eta$ 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**