# Forward Physics at RHIC

- 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
- Conclusions and outlook

L.C. Bland, BNL

NSAC Subcommittee Review

2-6 June 2004

BROOKHAVEN
NATIONAL LABORATORY

# What are the physics opportunities which forward p+p and p+A measurements offer?

- Sizable spin effects are observed in large rapidity particle production in $p_{\uparrow}$+p collisions at RHIC (and, at lower $\sqrt{s}$)

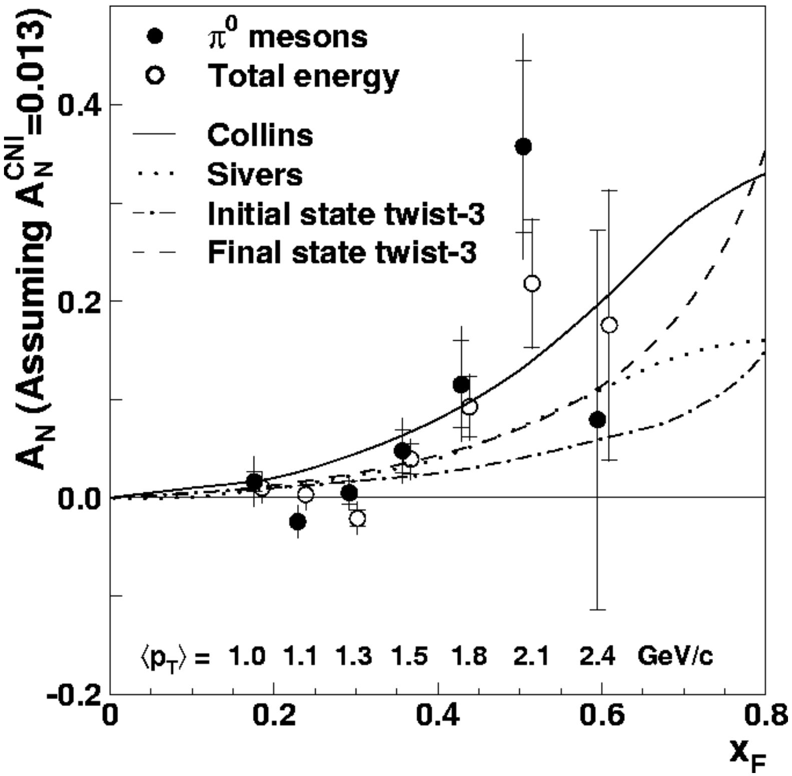
- Multiple effects contribute to dynamical origin of analyzing power:

  Transversity ⊗ spin-dep'nt fragmentation (Collins)

  Spin-correlated $k_T$ for initial-state quark (Sivers)

- Can these effects be discriminated in future measurements?

$p_{\uparrow}+p \rightarrow \pi^0+X$, $<\eta_\pi>=3.8$, $\sqrt{s}$ = 200 GeV

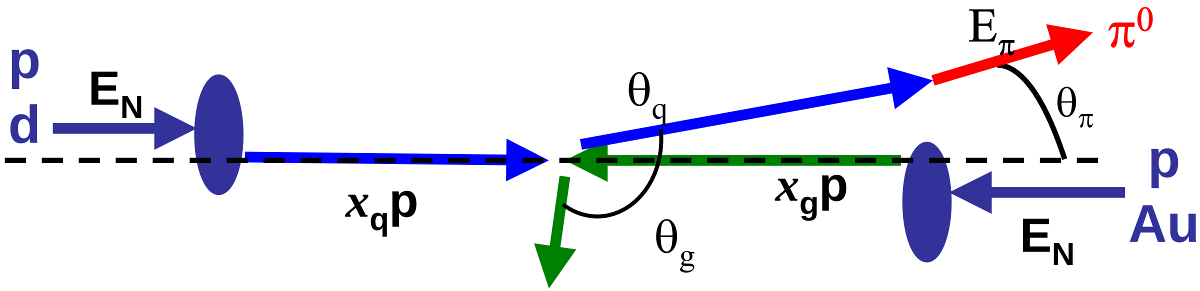



STAR

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

# Forward $\pi^0$ production in hadron collider

## QCD analog of low-*x* deep-inelastic scattering




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

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

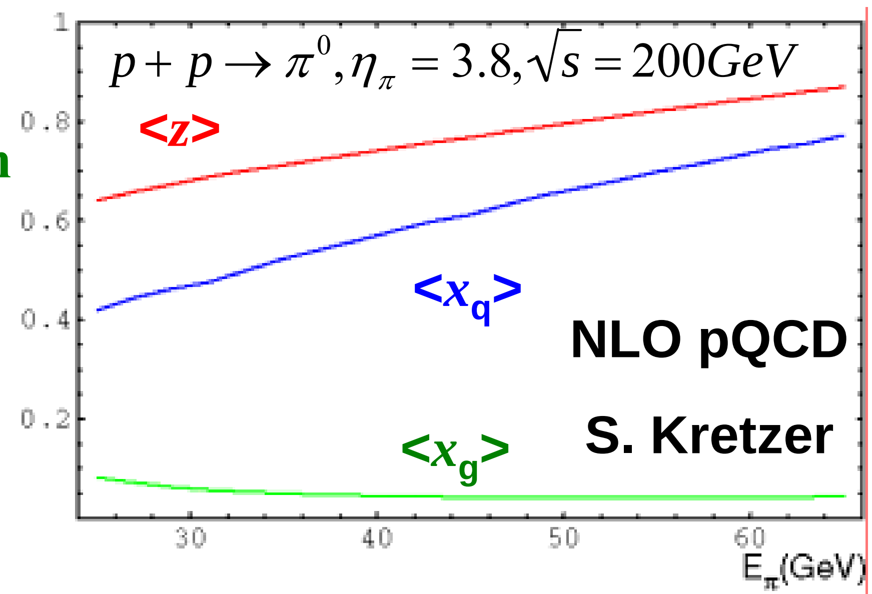
$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

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

(collinear approx.)

- **Large rapidity $\pi$ production ($\eta_\pi$~4) probes asymmetric partonic collisions**

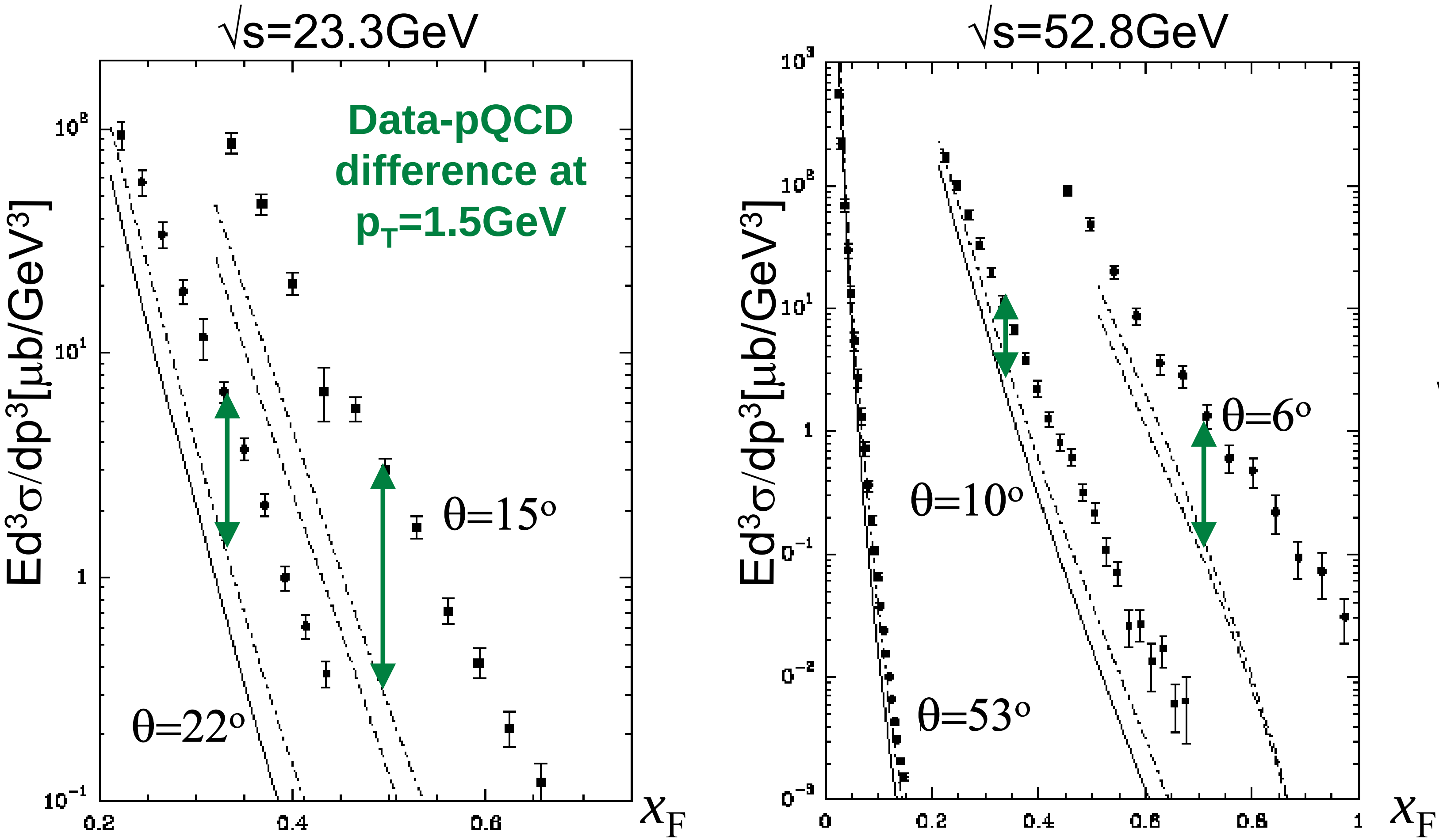
- Mostly **high-*x* valence quark** + **low-*x* gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <*z*> nearly constant and high ~ 0.8




- **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 $\pi^0$ production in p + p?

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




2 NLO calculations with different scales:

$p_T$ and $p_T/2$

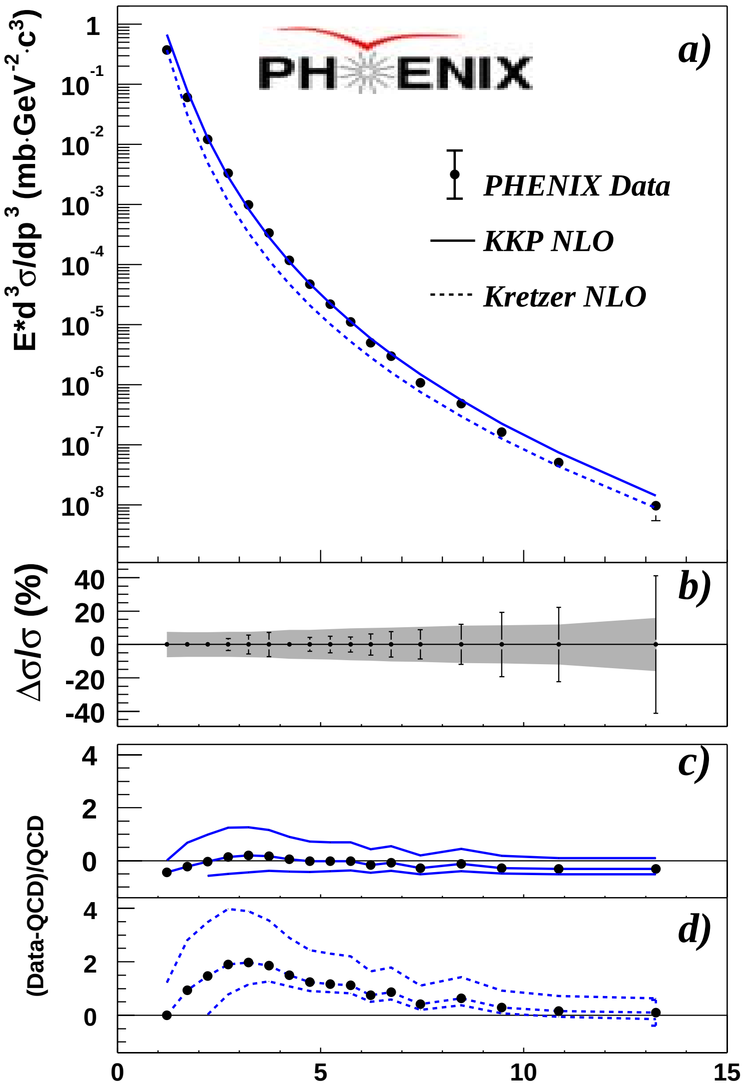
**Bourelly and Soffer (hep-ph/0311110, Data references therein):**

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

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

# How can one infer the dynamics of particle production?

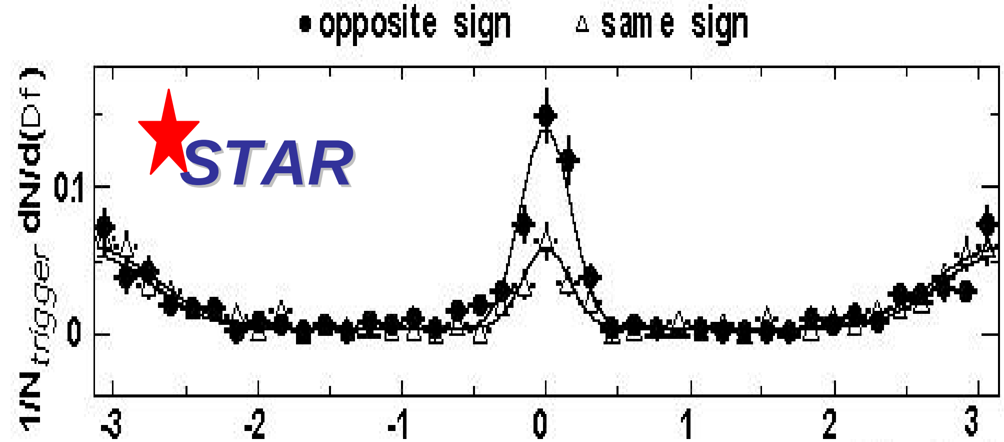
## Inclusive $\pi^0$ cross section




Phys. Rev. Lett. 91, 241803 (2003) $p_T$ (GeV/c)

hep-ex/0304038

## Two particle correlations

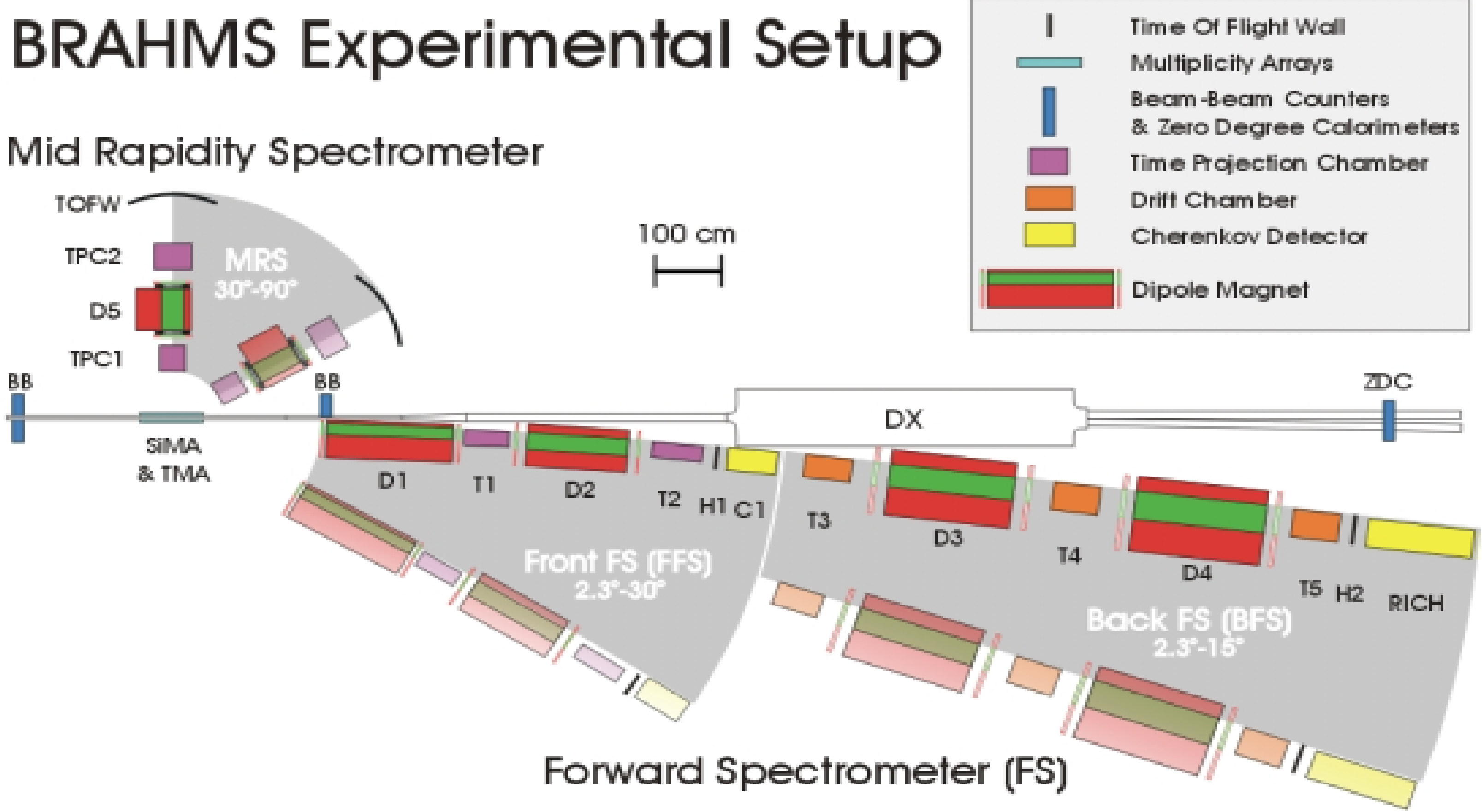


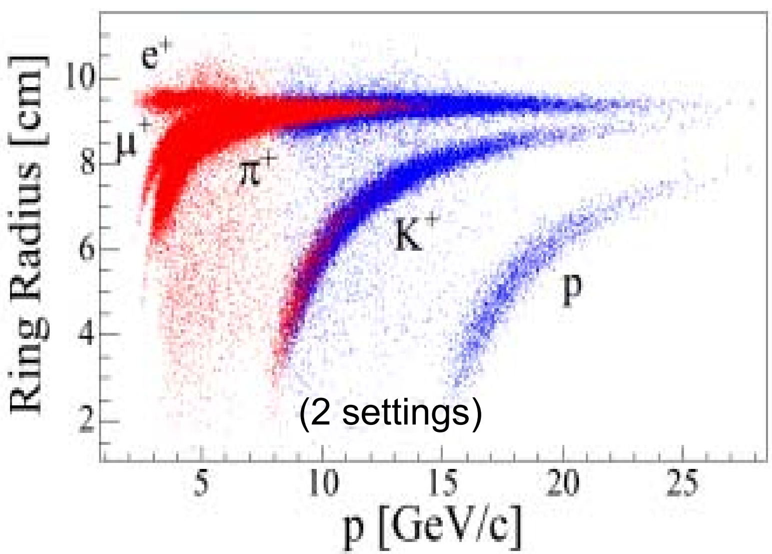

STAR, Phys. Rev. Lett. **90** (2003), nucl-ex/0210033

At √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?**

# BRAHMS Experimental Setup



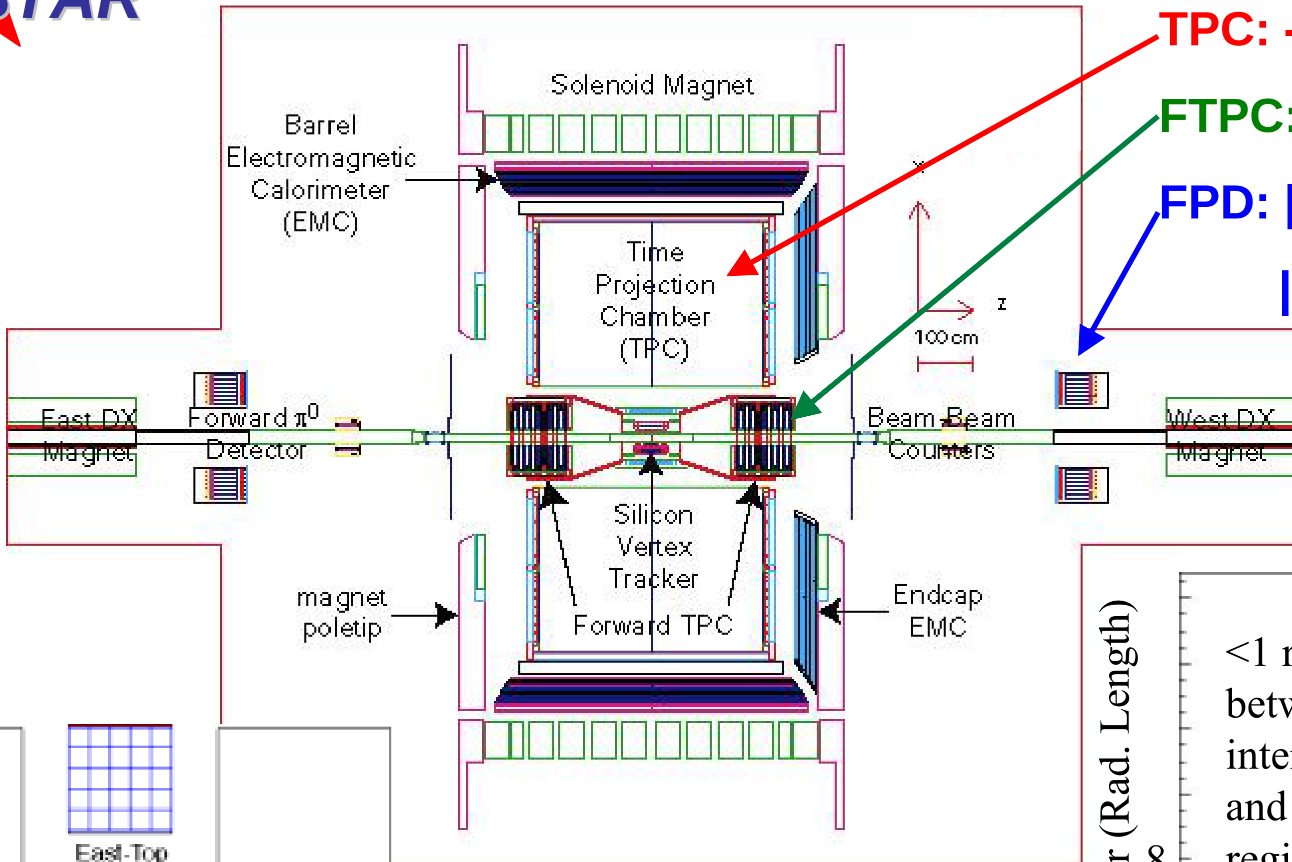




## *CHERENKOV*

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

# STAR Detector

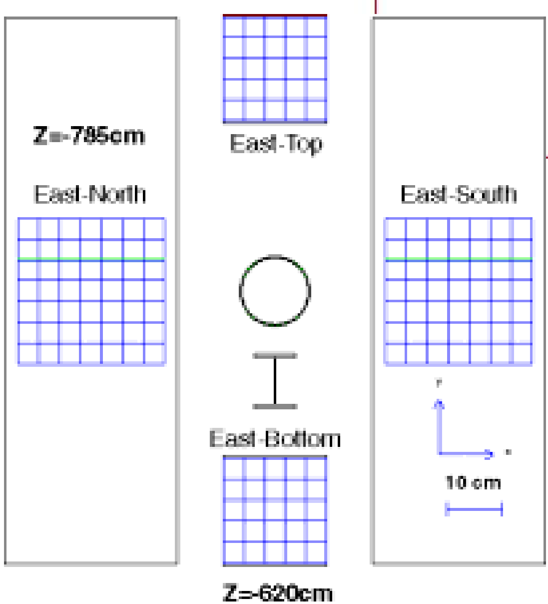


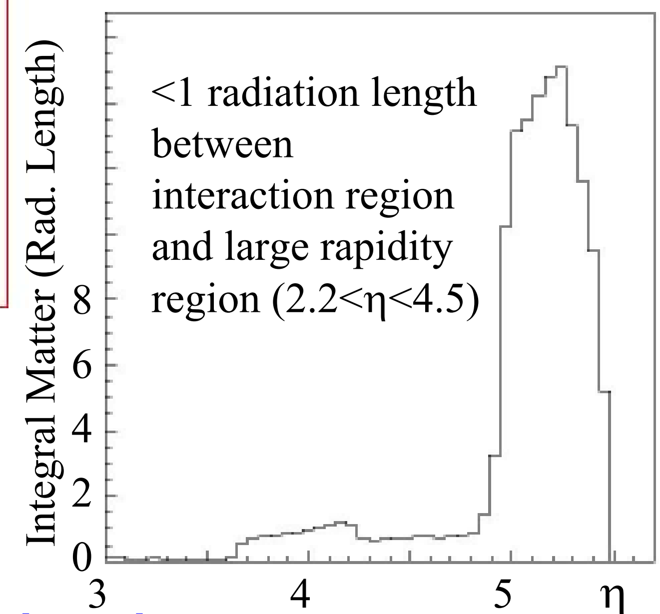

TPC: $-1.0 < \eta < 1.0$

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

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

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



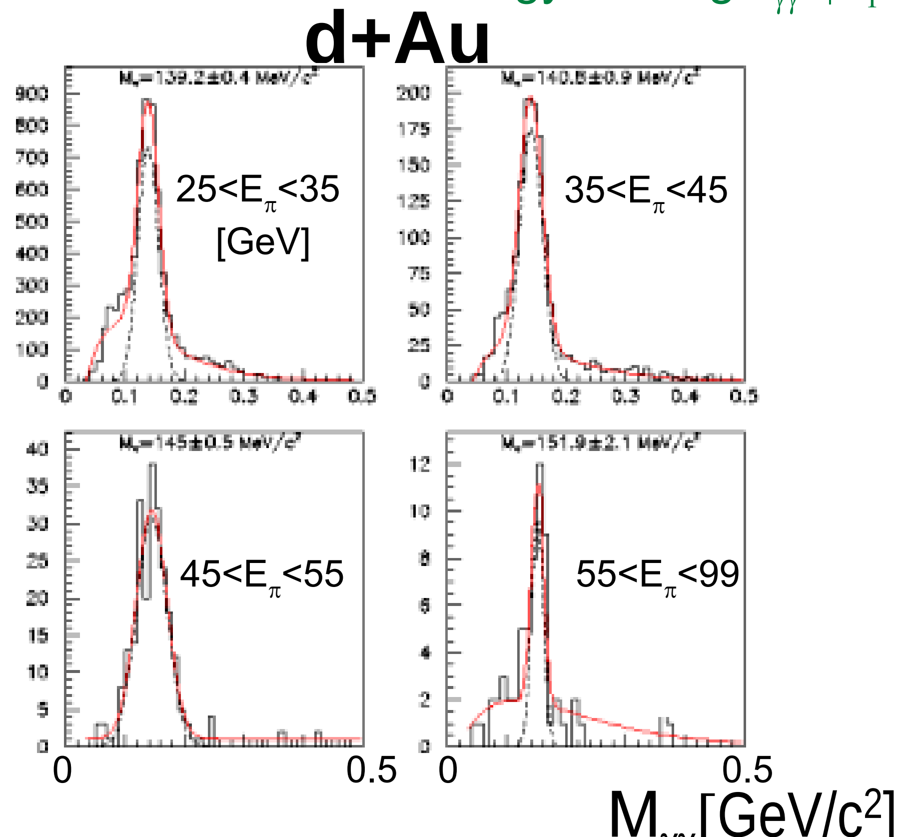




**Forward $\pi^0$ Detector (FPD)**

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

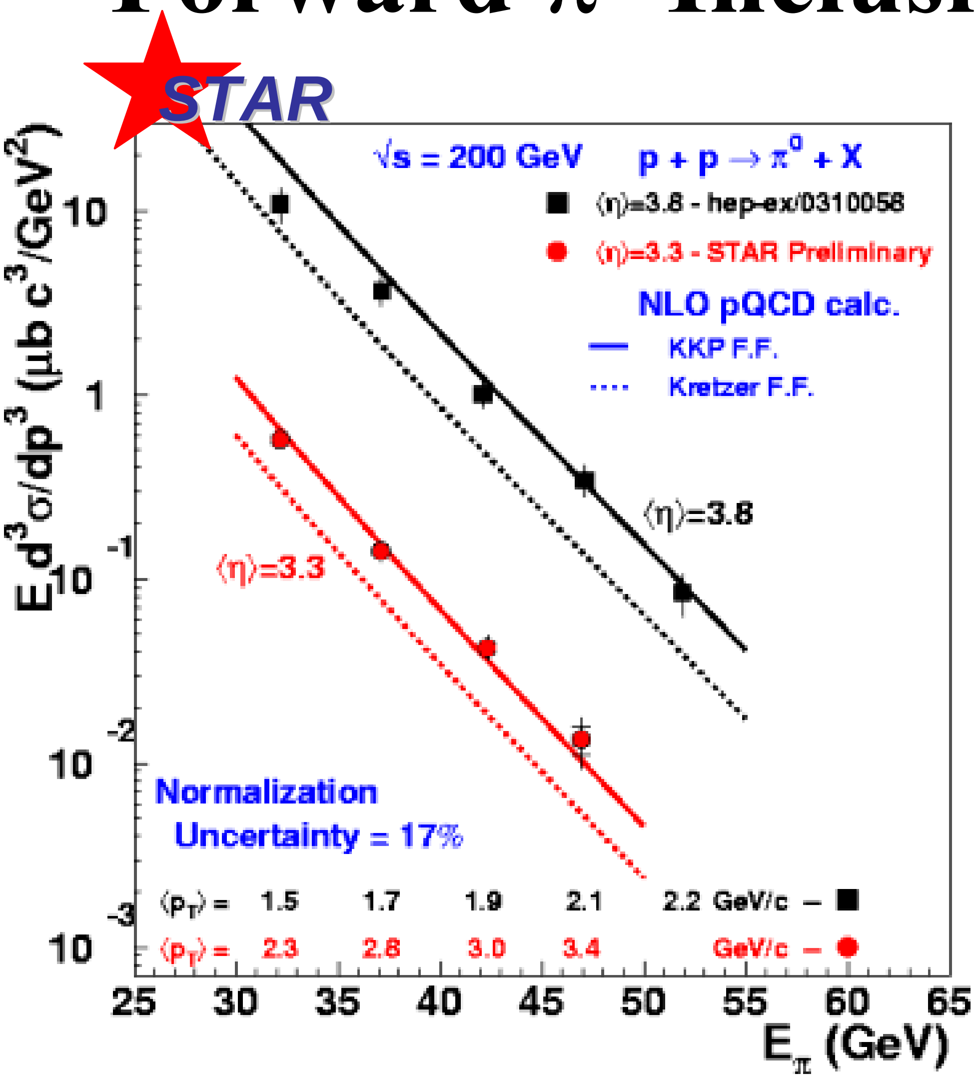
# Di-photon Mass Reconstruction

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




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

# Forward $\pi^0$ Inclusive Cross Section



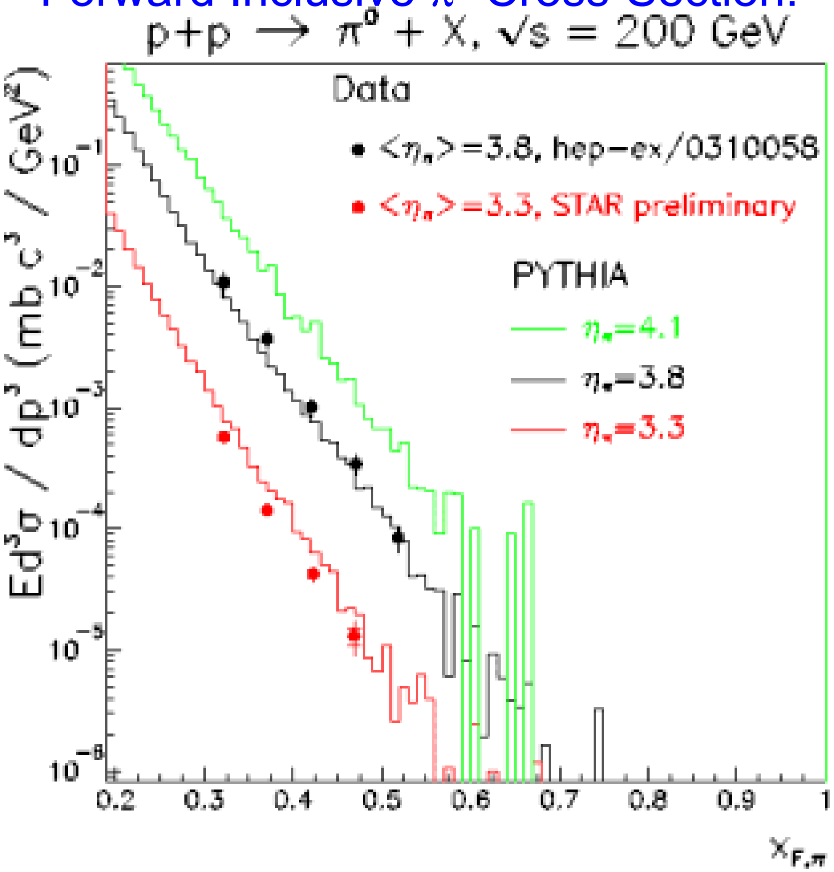

- STAR data at
  - $\langle\eta\rangle$= 3.8 (PRL **92**, 171801 (2004); hep-ex/0310058)
  - $\langle\eta\rangle$= 3.3 (hep-ex/0403012, Preliminary)
- NLO pQCD calculations at fixed $\eta$ with equal factorization and renormalization scales = $p_T$
- Solid and dashed curves differ primarily in the $g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

**STAR data consistent with Next-to-Leading Order pQCD calculations in contrast to data at lower $\sqrt{s}$ (Bourelly and Soffer, hep-ph/0311110)**

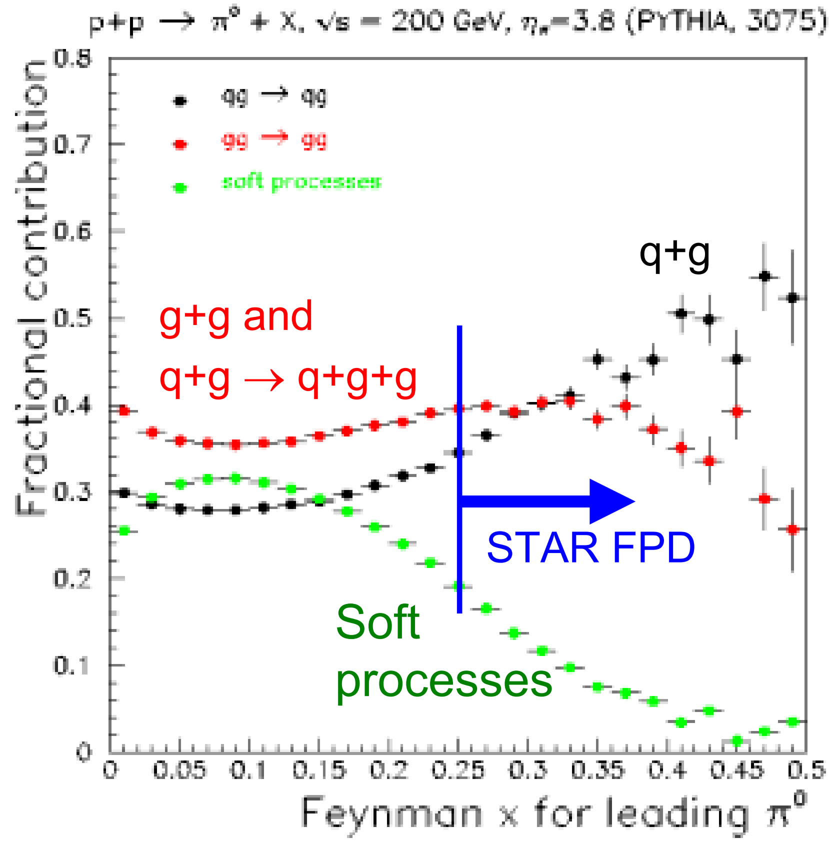
**What about particle correlations?**

# PYTHIA: a guide to the physics

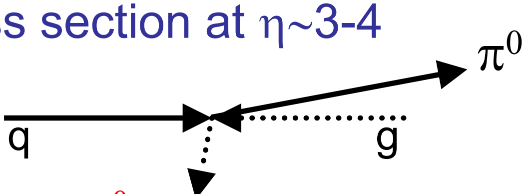
Forward Inclusive $\pi^0$ Cross-Section:



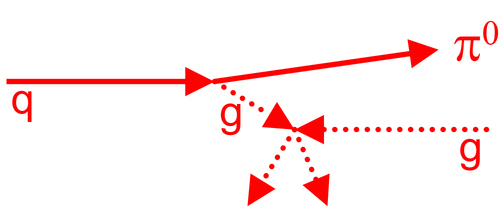

Subprocesses involved:




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

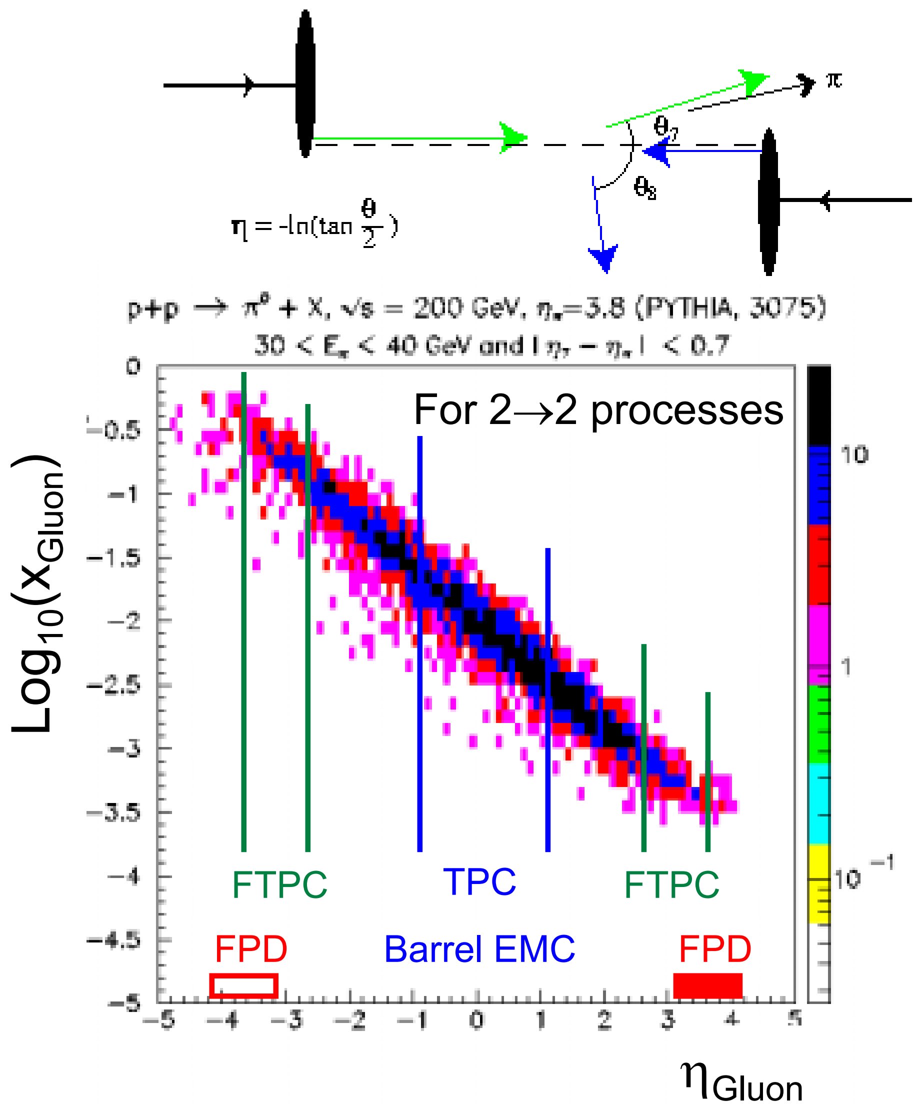



- q + g → q + g **(2→2)** → $\pi^0$ + X
- q + g → q + g + g **(2→3)** → $\pi^0$ + X



# 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**

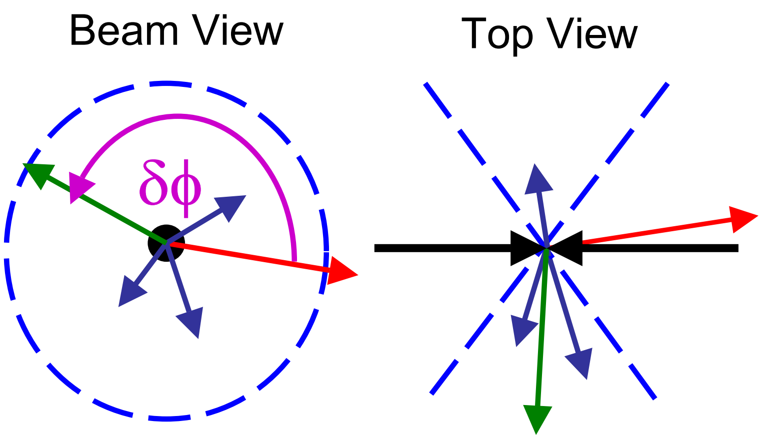
**Spin effects with rapidity interval correlations?**

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

# Back-to-back Azimuthal Correlations

**with large rapidity interval (Mueller-Navelet dijets)**




**Trigger by forward $\pi^0$**

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

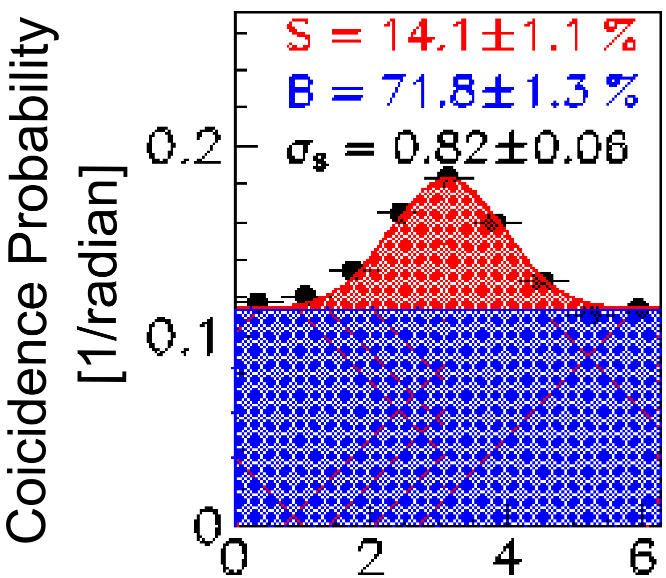
**Midrapidity $h^\pm$ tracks in TPC**

- $-0.75 < \eta < +0.75$

**Leading Charged Particle(LCP)**

- $p_T > 0.5$ GeV/c

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

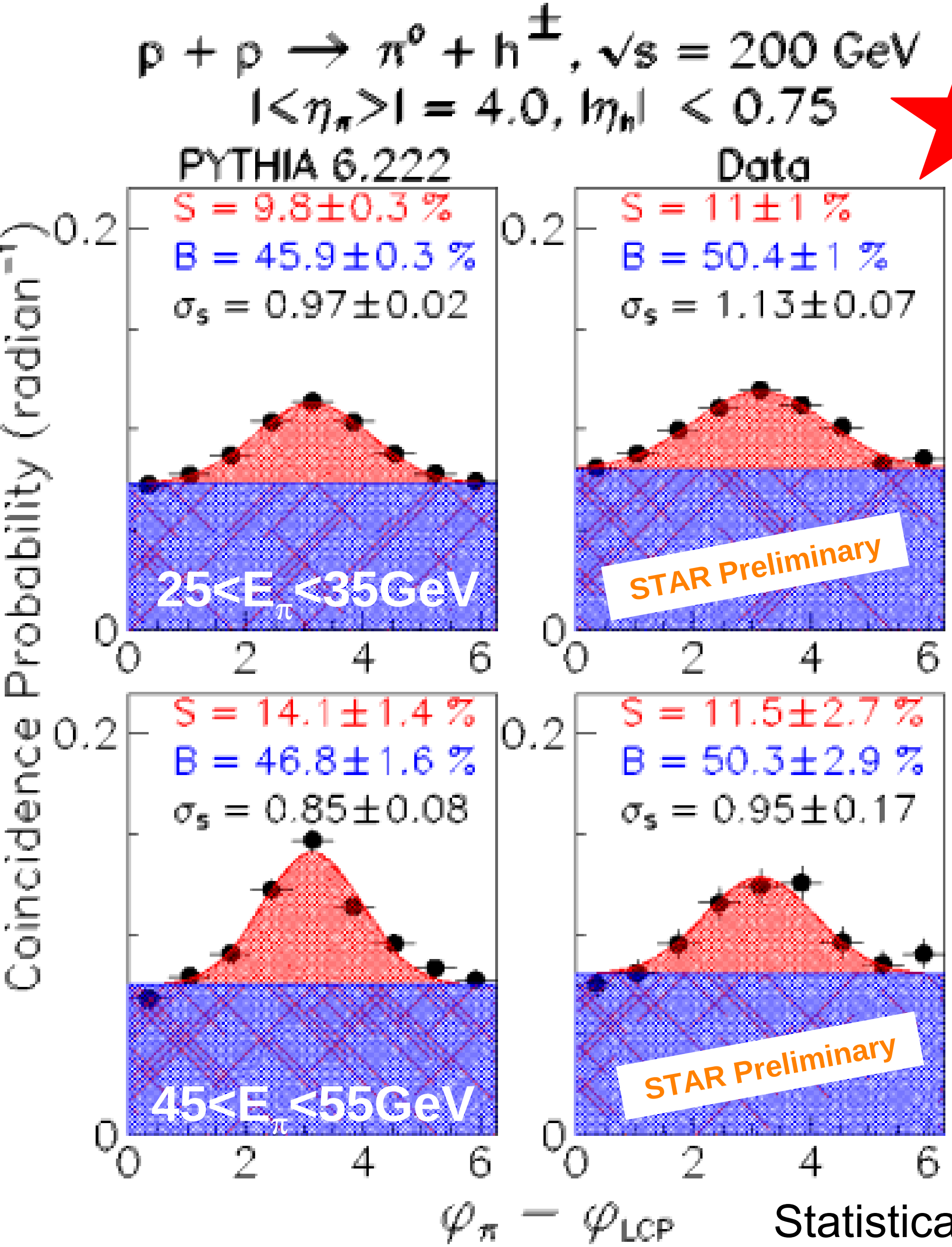



$\delta\phi = \phi_\pi - \phi_{LCP}$

S = Probability of "correlated" event under Gaussian

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

$\sigma_s$ = Width of Gaussian




Statistical errors only

**PYTHIA (with detector effects) predicts**

- **"S" grows with $<x_F>$ and $<p_{T,\pi}>$**
- **"$\sigma_s$" decrease with $<x_F>$ and $<p_{T,\pi}>$**

**PYTHIA prediction agrees with data**

Larger intrinsic $k_T$ required to fit data

# Do we understand forward $\pi^0$ production at RHIC?

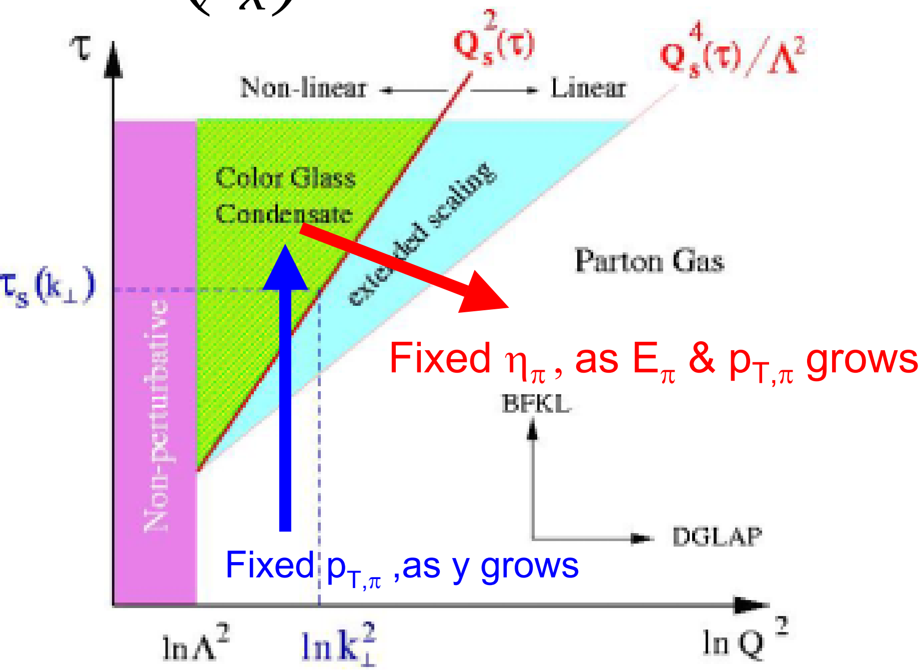
- **NLO pQCD** agrees with inclusive cross section measurement, unlike lower $\sqrt{s}$ data
- **PYTHIA** (LO pQCD + parton showers simulation) agrees with inclusive cross section measurement, unlike lower $\sqrt{s}$ data
  - PYTHIA says large $x_F$, large $\eta$ $\pi^0$ come from $2 \rightarrow 2$ (&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

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

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

# d + Au: Possible Color Glass Condensate at RHIC?

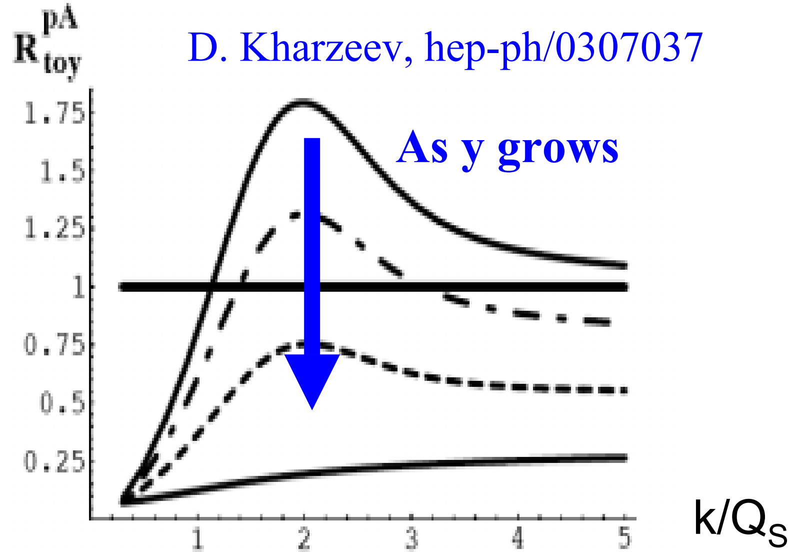
$$\tau = \ln\left(1/x\right)$$ τ related to rapidity of produced hadrons.




Edmond Iancu and Raju Venugopalan, hep-ph/0303204

## General expectations of CGC:

**Suppression of forward particle production**

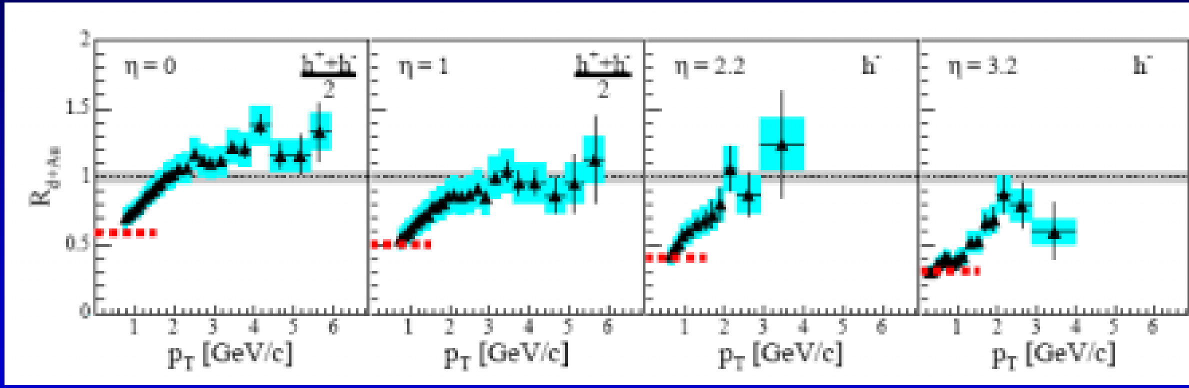



Brahms data shows evidence **?**

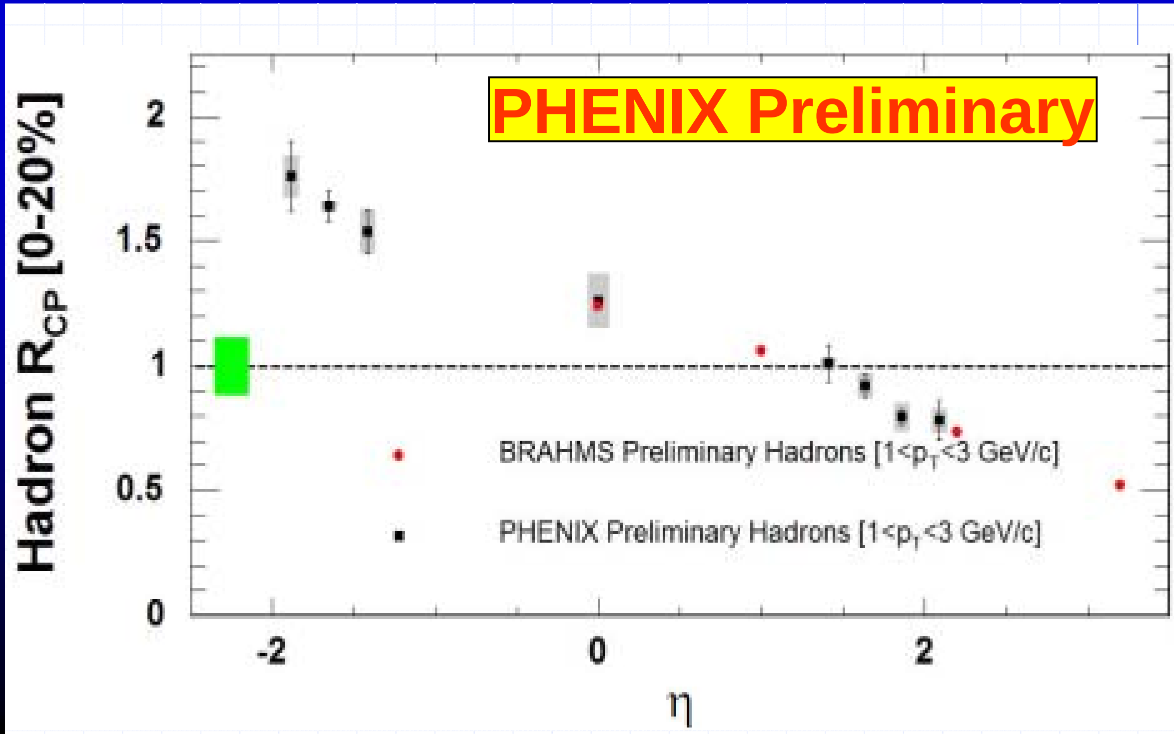
**(nucl-ex/0403005)**

# 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



# d + Au: Possible Color Glass Condensate at RHIC?

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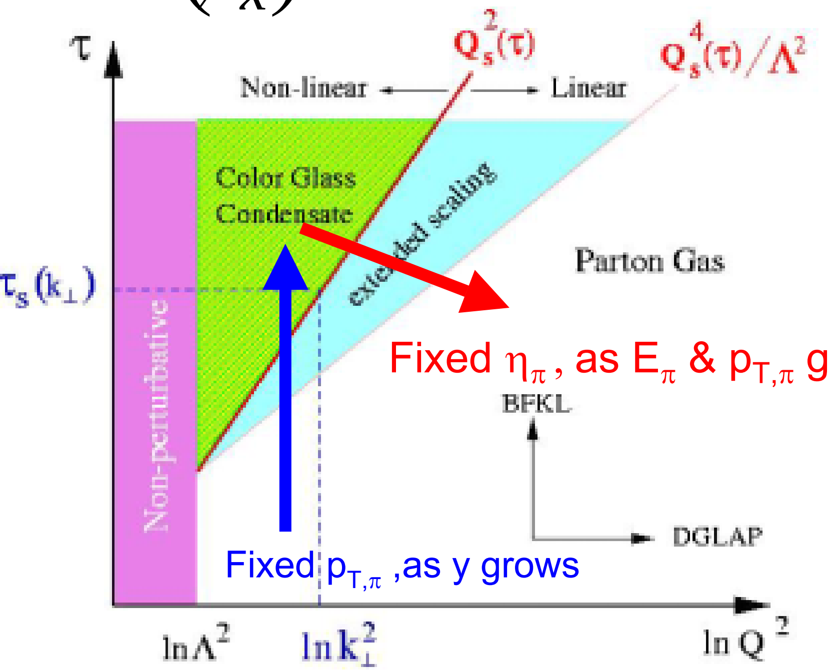


Edmond Iancu and Raju Venugopalan, hep-ph/0303204

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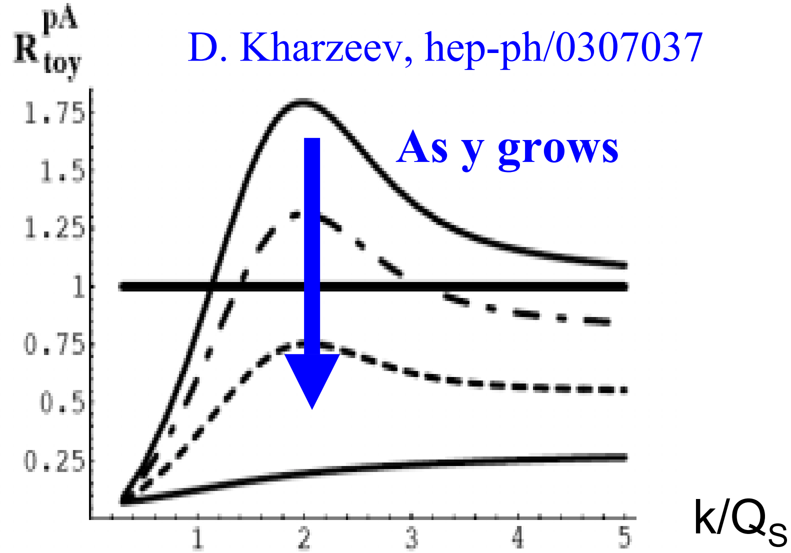
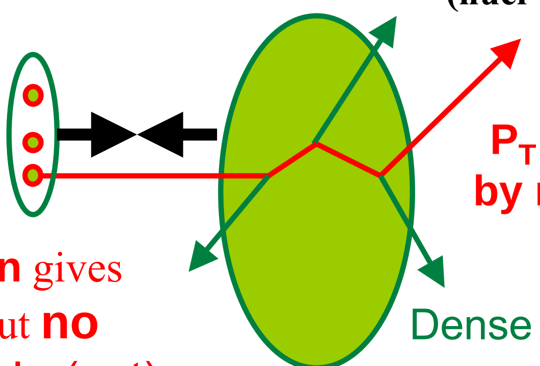



Brahms data shows evidence **?**

**(nucl-ex/0403005)**

**"Mono-jet"**

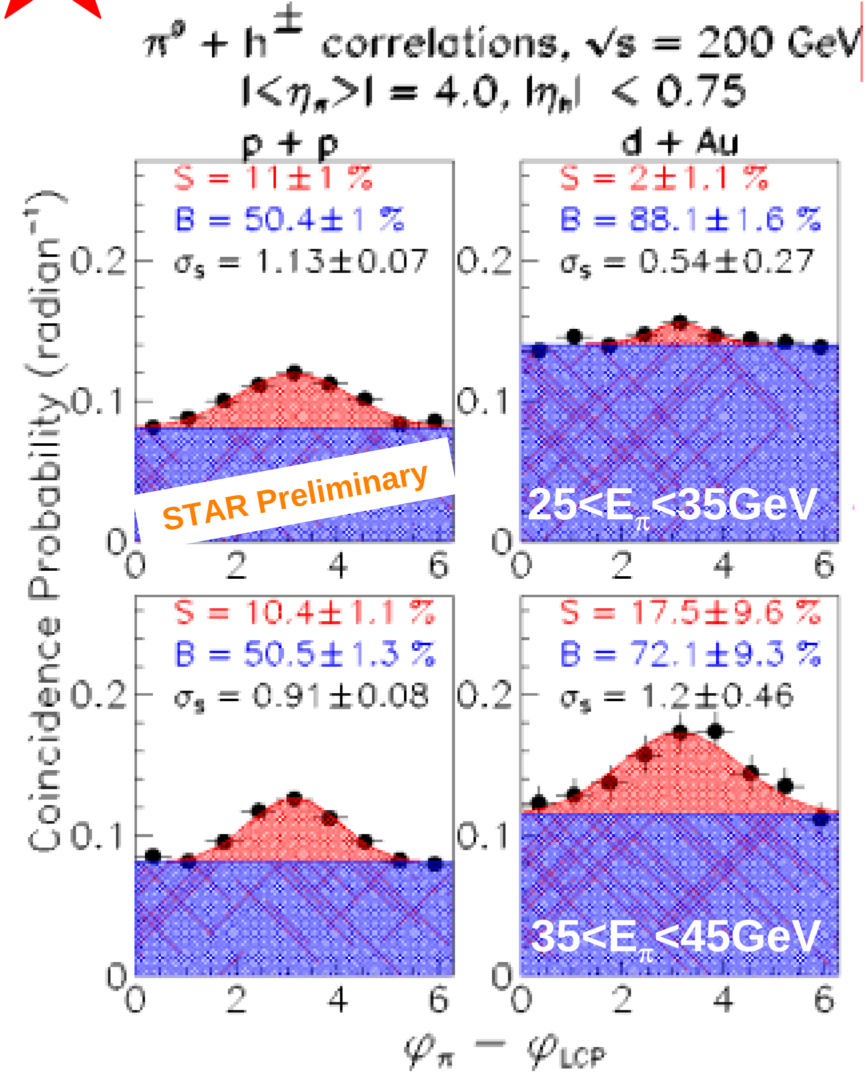



**D.Kharzeev, E. Levin, L. McLerran** gives physics picture **(hep-ph/0403271)** , but **no** quantitative predictions available (yet)

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

# dAu Particle Correlations:

probing low *x*

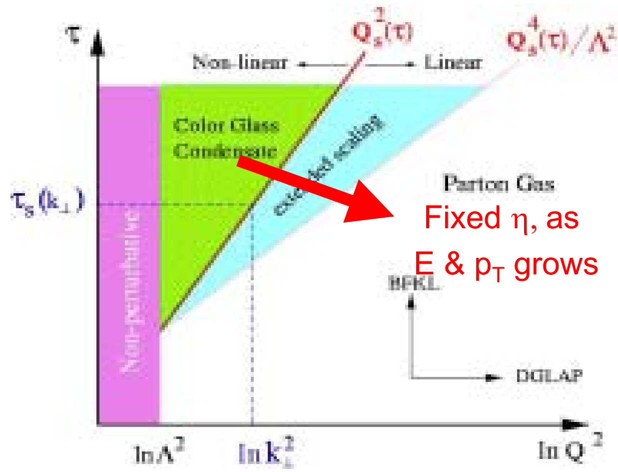



Statistical errors only

**Large $\Delta\eta$ $\pi^0$+$h^{\pm}$ 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**

# Conclusions

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

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

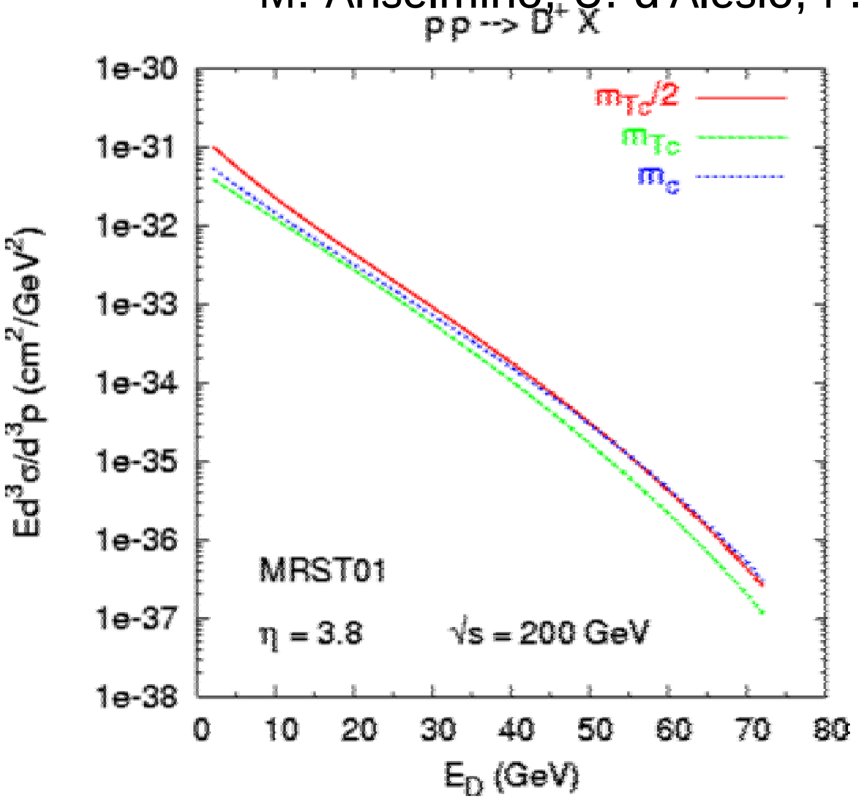
- **p+p/d+Au comparisons**
  - improve forward instrumentation at RHIC
  - establish rapidity dependence of saturation scale
    - ⇒ $R_{d(p)A}$ measurements for heavy-flavor mesons and $\gamma$
    - ⇒ particle correlations over extended $\Delta\eta$ range

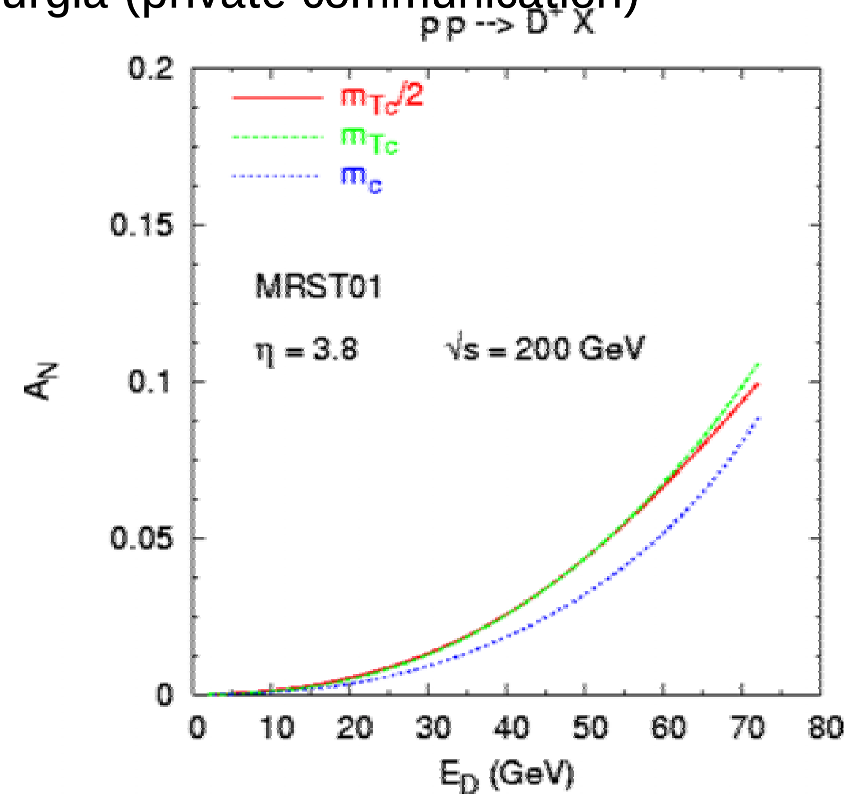
- **Spin asymmetries with polarized p+p**
  - potential sensitivity to low-$x$ $\Delta G$ via $\pi^0$ and $\gamma$ $A_{LL}$ measurements
  - disentangle dynamical origin of large-$x_F$ analyzing power
    - ⇒ Brahms measurement of $A_N$ for large $x_F$ charged pions

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

Isolating the Sivers function

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



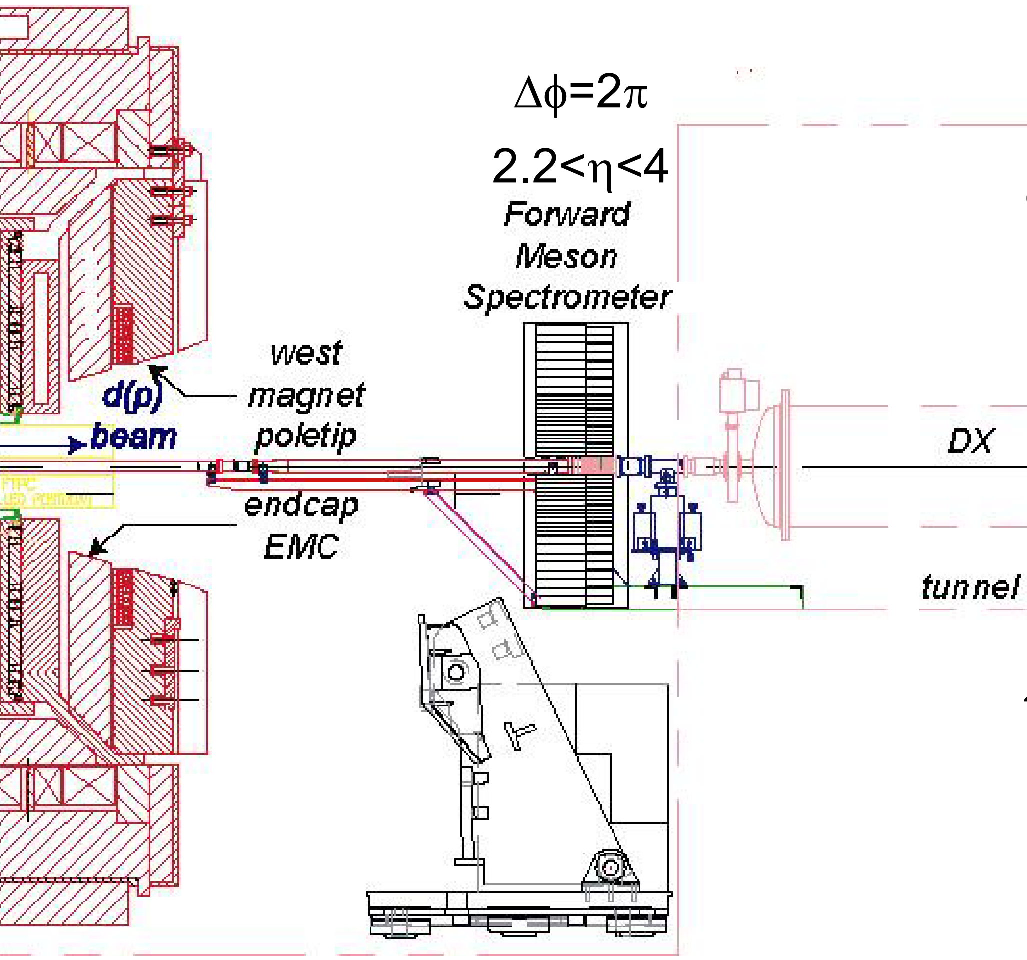

- $q+\bar{q} \rightarrow c+\bar{c}$ favored over $g+g \rightarrow g+g$ and $q+g \rightarrow q+g$ at large $x_F$
- no contribution from spin-dependent fragmentation (Collins effect)
- tests universality of spin / $k_\perp$ correlated distribution functions (Sivers function):

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

STAR

# Forward Meson Spectrometer

## Conceptual Design




### Physics Motivation:

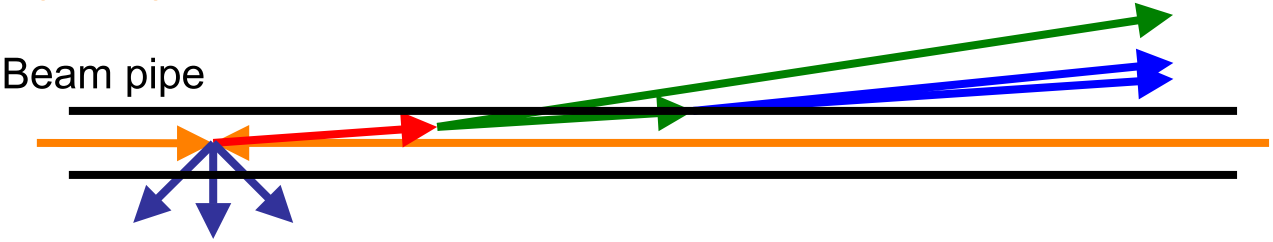
- probing gluon saturation in p(d)+A collisions via…
  - ➢ large rapidity particle production ($\pi^0,\eta,\omega,\eta',\gamma,K^0,D^0$) detected through all $\gamma$ decays.
  - ➢ di-jets with large rapidity interval (Mueller-Navelet jets)
- disentangling dynamical origins of large $x_F$ analyzing power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

(See also R. Debbe contribution on 6/4)

# Backup slides

# FTPC-FPD matching: Photon conversion in beam pipe

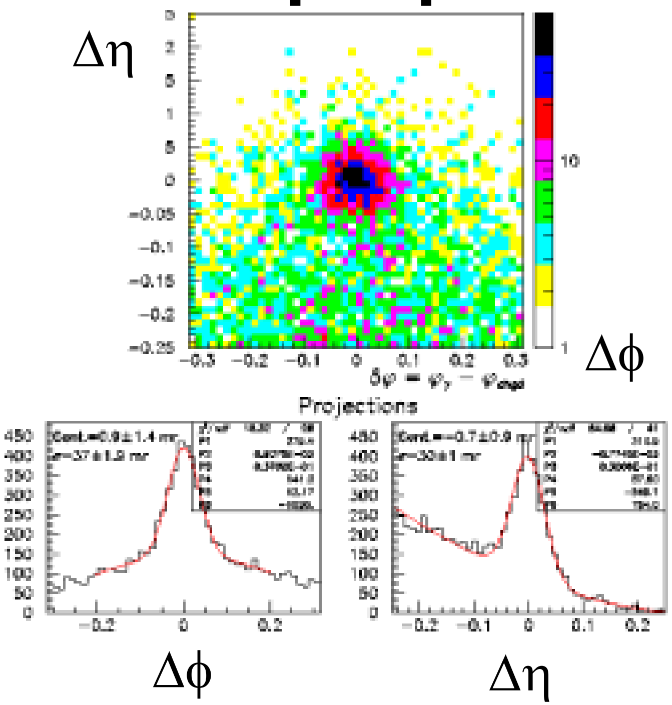
$\left.\begin{array}{c} p + p \\ d + Au \end{array}\right\} \rightarrow \pi^0\ (+\ X) \rightarrow \gamma\ (+\ \gamma) \rightarrow e^+\ e^-$



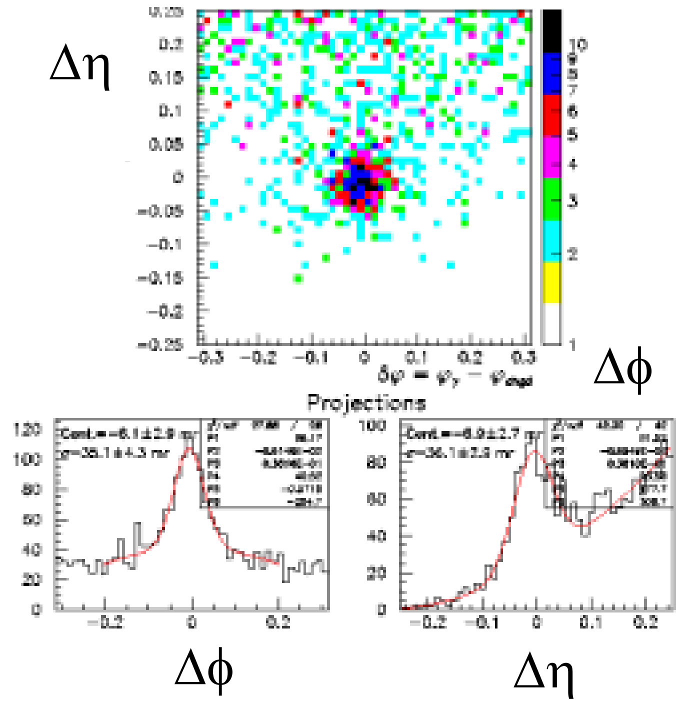

$\Delta\eta = \eta_{FPD} - \eta_{FTPC}$

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

## 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 < |η| < 3.8

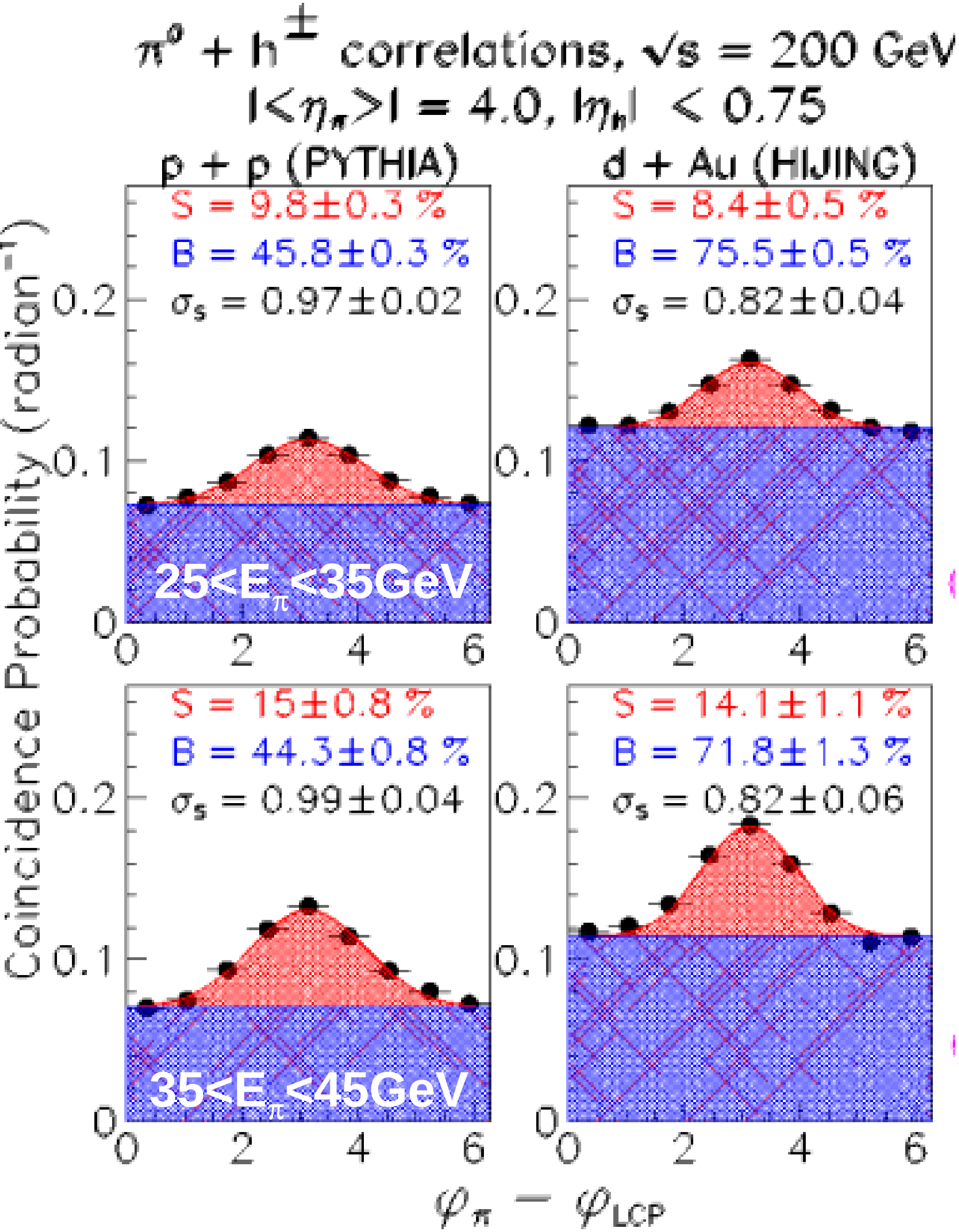
⇒ FPD position known relative to STAR

⇒ Detector resolution for particle correlation is good

## Expectation from HIJING (PYTHIA+nuclear effects)

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

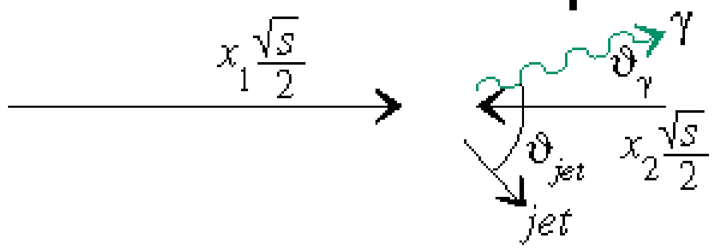
**with detector effects**




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

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

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

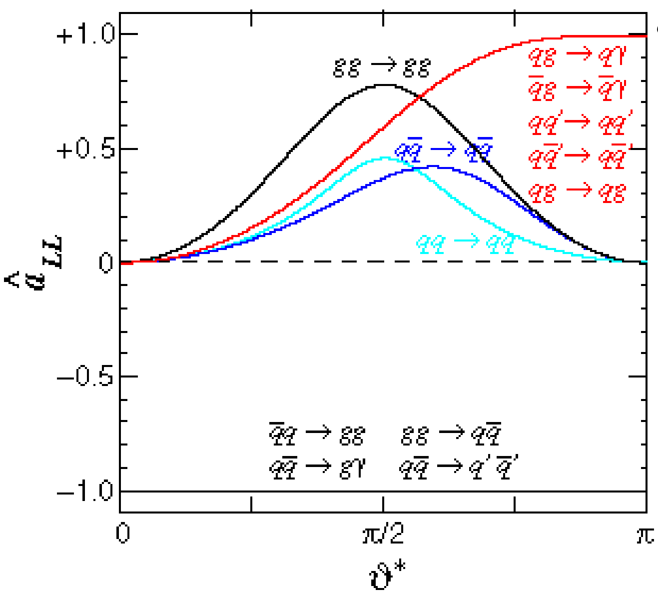



• Large $x_F$ jet production primarily selects *qg* scattering from other subprocesses.

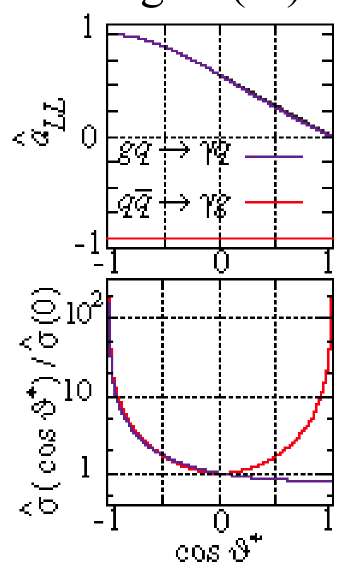
*Assume collinear collisions and apply conservation of momentum* $\Rightarrow$

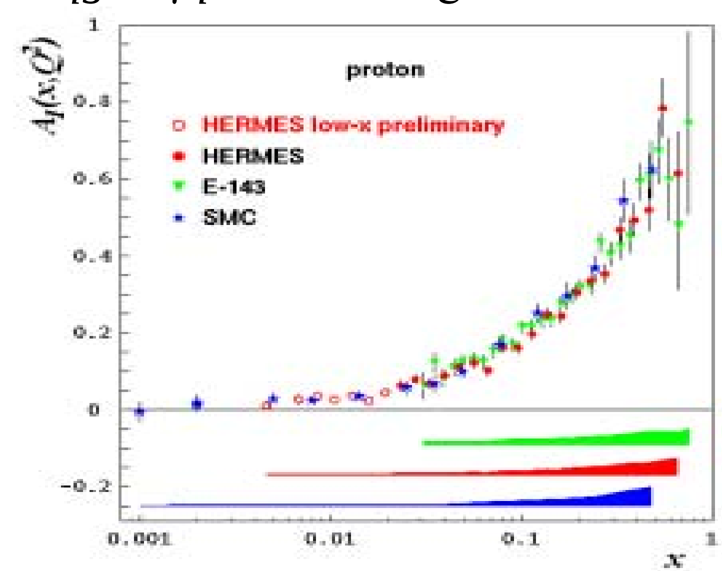
$$x_1 \sim \frac{x_T}{2}\left(e^{+\eta_\gamma} + e^{+\eta_{jet}}\right) \xrightarrow[\eta_\gamma > \eta_{jet}]{} \frac{x_T}{2}\, e^{+\eta_\gamma}$$

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



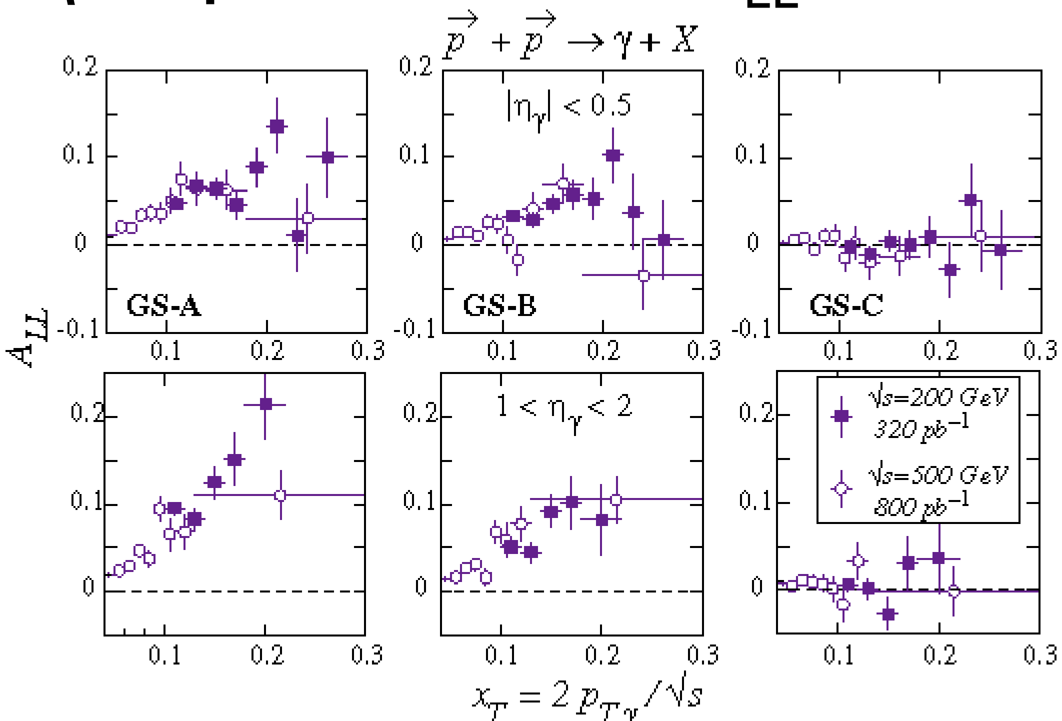

• there are large spin effects in QCD hard scattering processes at 'forward' angles ($\theta^*$). Note: $qg \rightarrow \gamma q$ also has large $\sigma$ as $\theta^* \rightarrow \pi$.



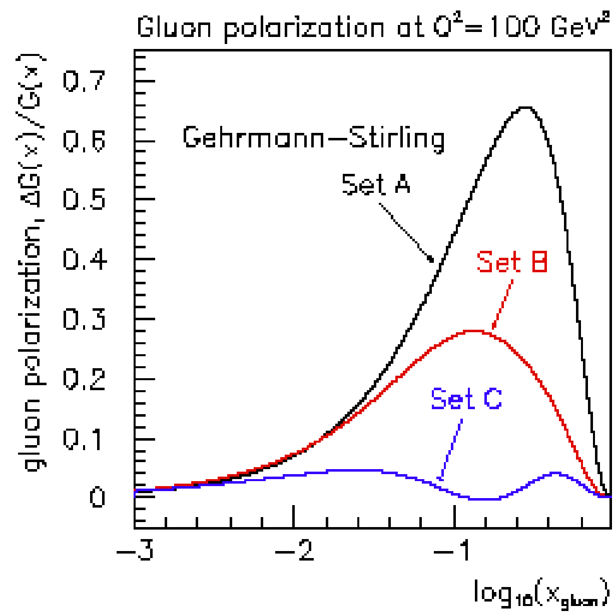




• charge-squared weighted quark polarizations ($g_1/F_1$) within the proton are large in the large-$x$ valence region $\Rightarrow$ large quark polarization to provide good 'analyzer' of gluon polarization.

# η dependence of $A_{LL}$ for inclusive γ production




LCB, hep-ex/9907058

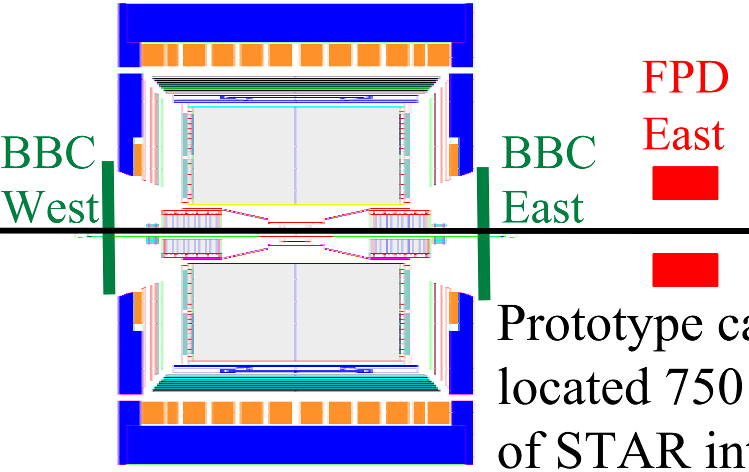



- larger spin effects at more forward angles. Expect at even more forward angles that the *sensitivity* (convolution $\hat{a}_{LL} \otimes A_1^p$) will increase. Since large η probes small $x_{gluon}$, gluon polarization may decrease because of sharp increase of unpolarized gluon density as $x_{gluon}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

- 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.

# Run-2 Prototype FPD

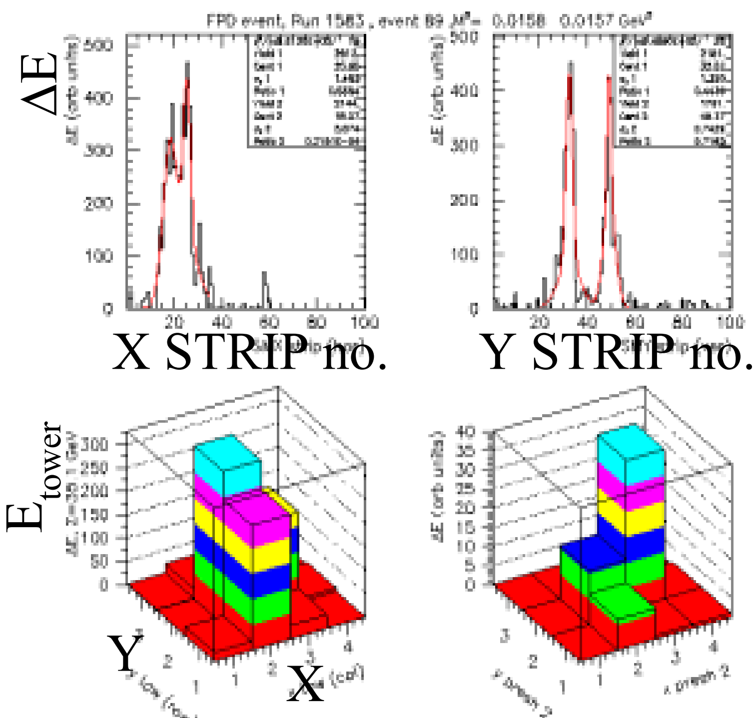



Prototype calorimeter located 750 cm ($z_{vert}$) east of STAR interaction region

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.

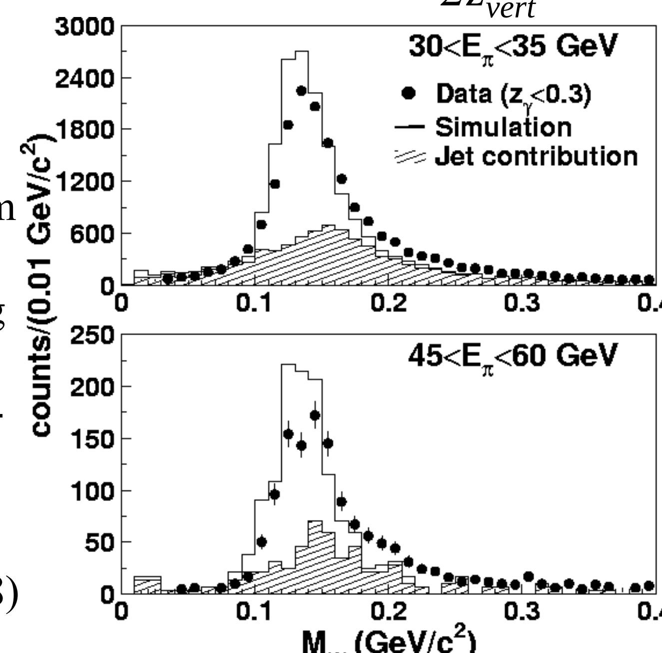
$$M_{\gamma\gamma} = E_{tot}\sqrt{1 - z_{\gamma\gamma}^2}\,\sin\left(\frac{\phi_{\gamma\gamma}}{2}\right)$$

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




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

(Fig. 1 of hep-ex/0310058)



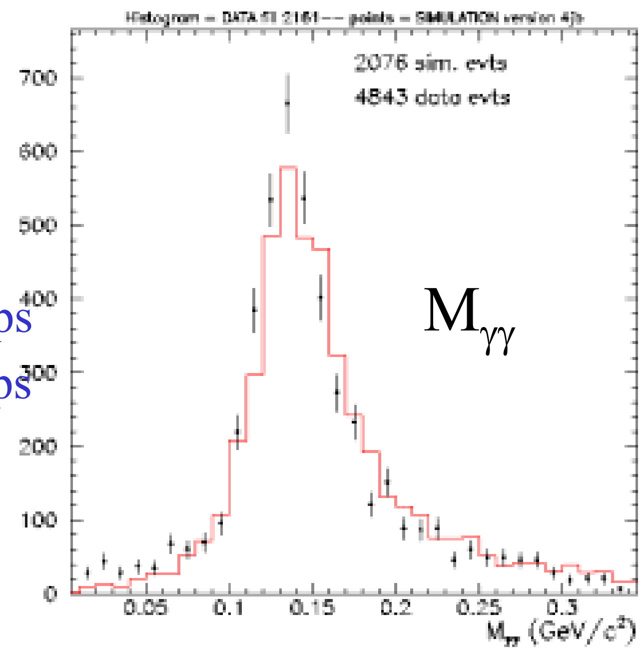
# Simulation of pEEMC in STAR

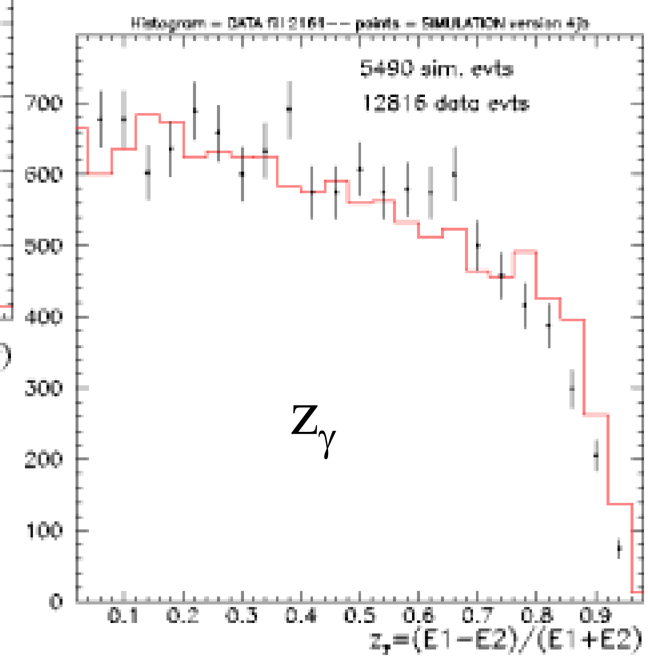
Scheme:

- 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
- $z_\gamma$<0.3



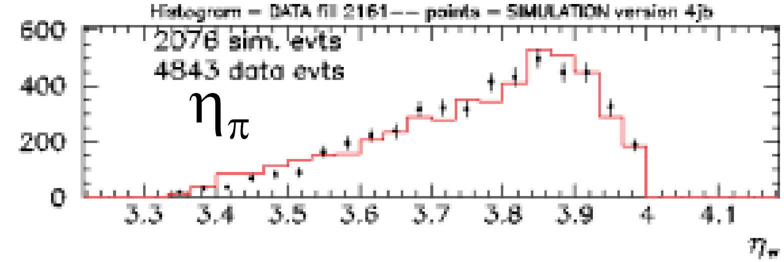



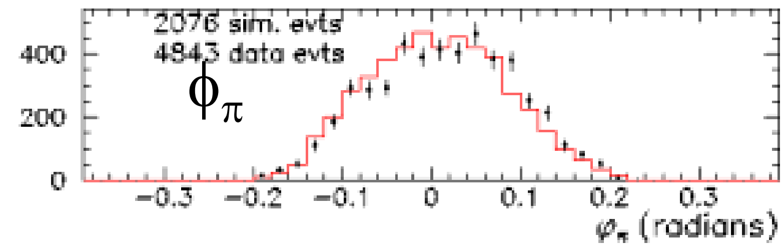

- Histogram = data
- Points = simulation norm. to data

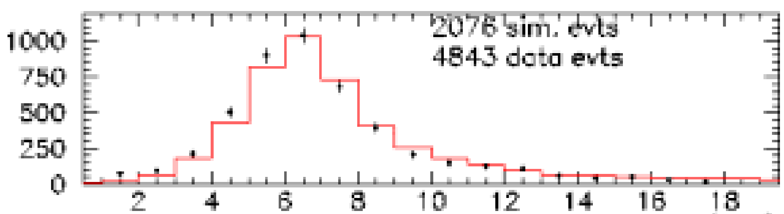
STAR spin

# Simulation of pEEMC (cont.)

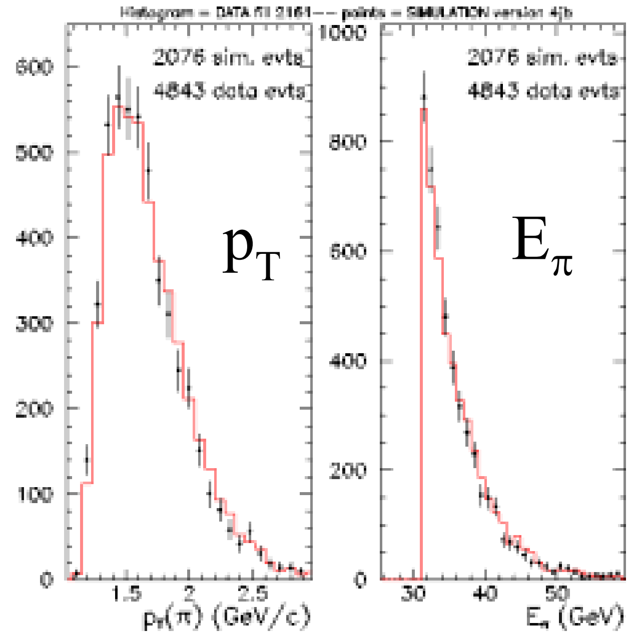
Angular variables:



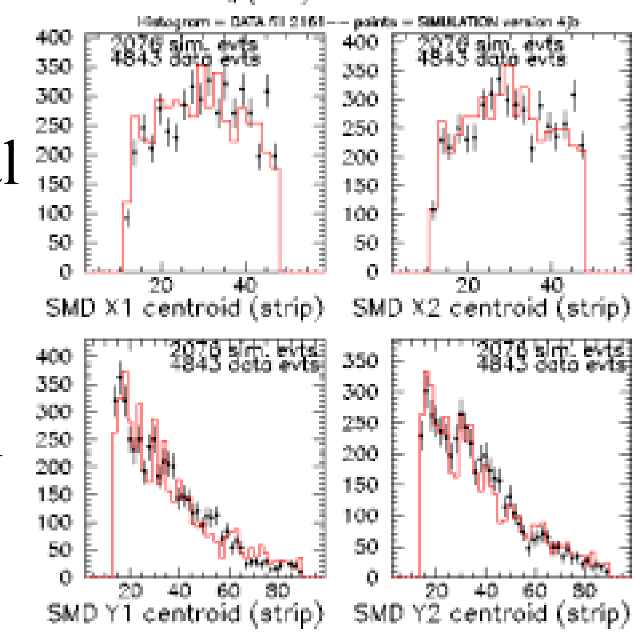

Photon separation at pEEMC (cm)




Single photon positions:

vertical

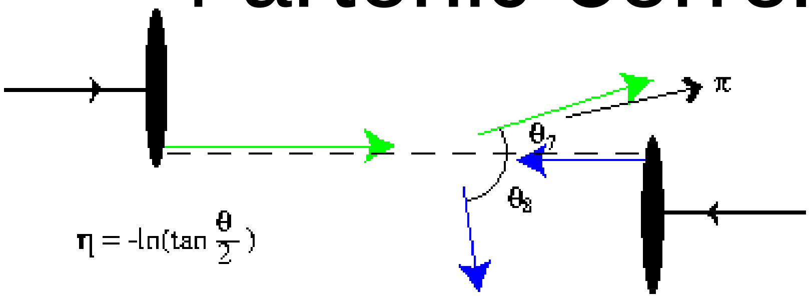
horizontal

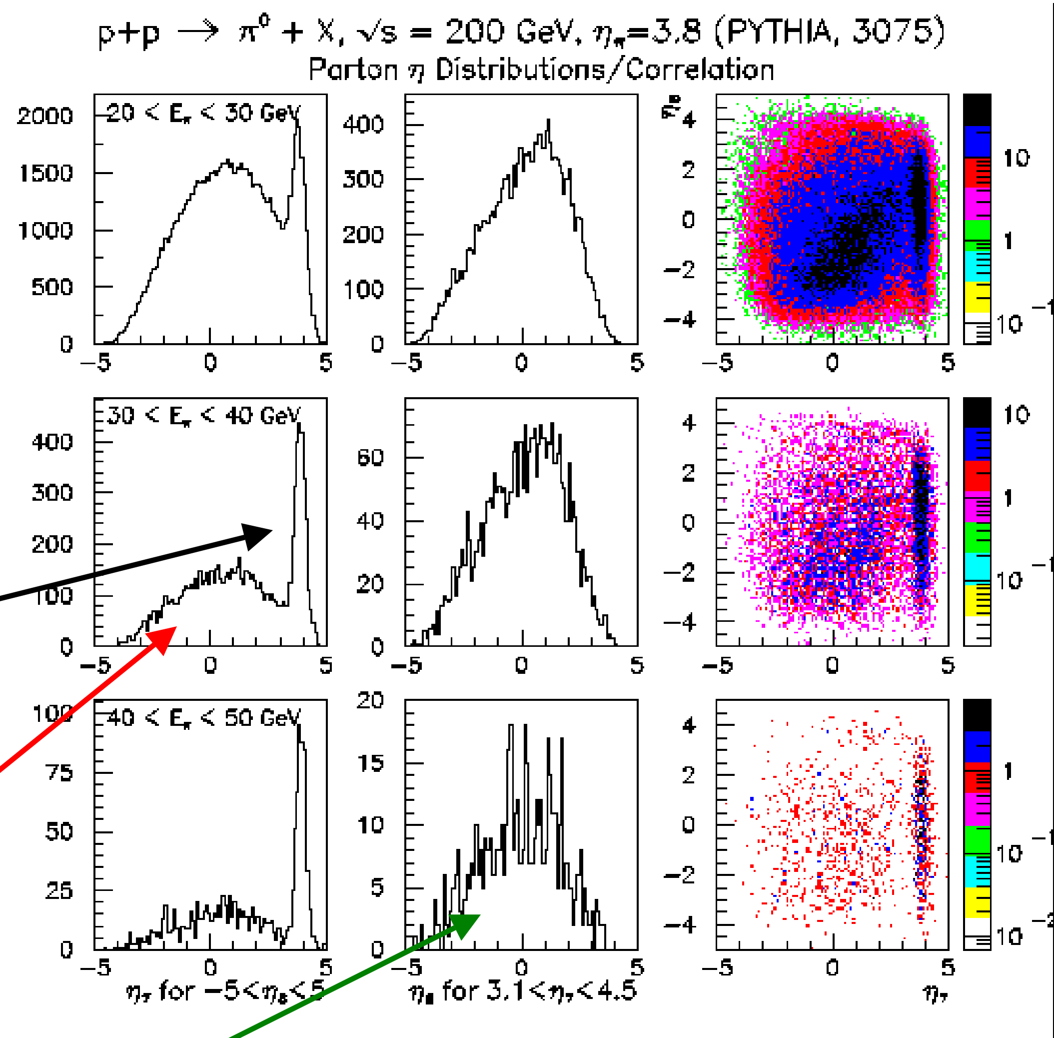



**PYTHIA+GEANT simulation describes data---$\pi^0$ mesons and background from collisions...**

STAR spin

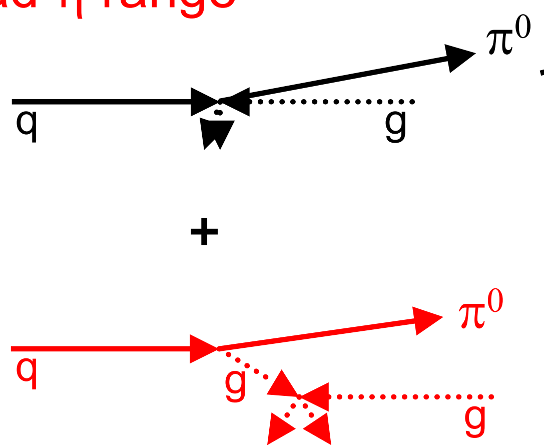
# Partonic Correlations from PYTHIA




Large energy deposited at $\eta$=3.8

- one parton in hard scattering with peak in forward direction + broad $\eta$ range




- other parton spread over broad $\eta$ 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
  - flavor tagging of partonic scattering
  - longitudinal/transverse spin effects, selected on Bjorken $x$ values of colliding partons
  - probe rapidity dependence of saturation scale

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