Forward Physics

Present Status and Future Opportunities

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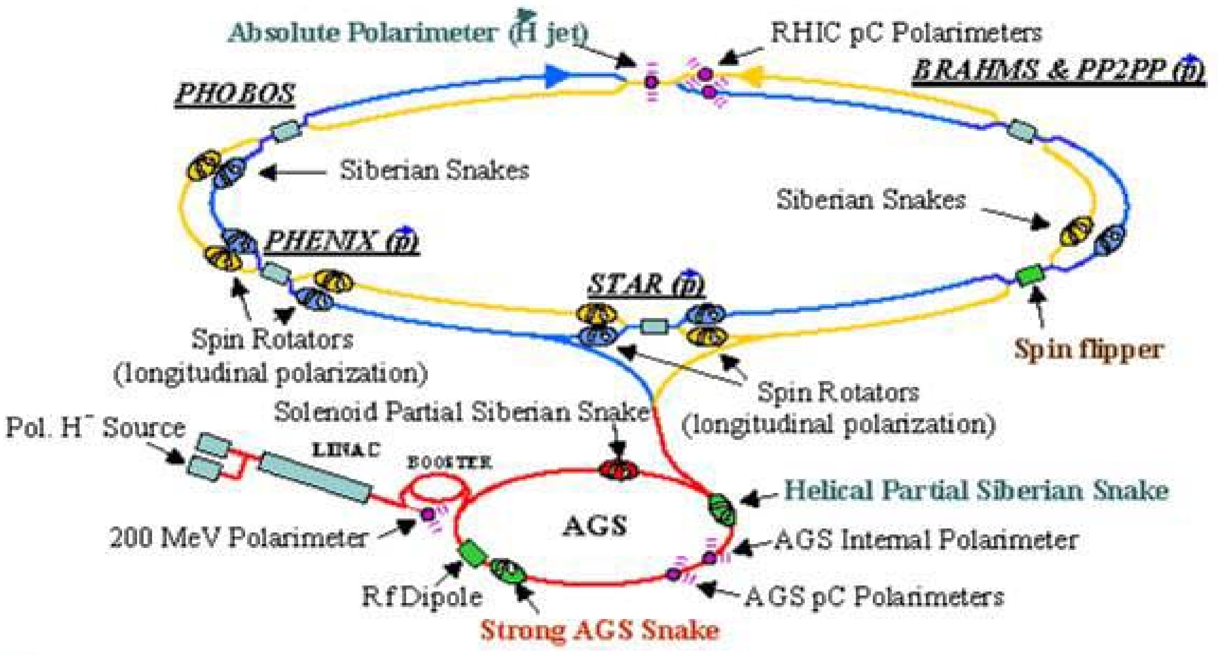
in collaboration with STAR

- Introduction - Forward physics in hadron collider
- STAR 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

1st Hard Probes Conference

Ericeira, Portugal (Nov. 2004)

RHIC pp accelerator complex



🟦 Installed and commissioned during run 4
🟫 Planned to be commissioned during run 5
🟥 Planned to be installed and commissioned in run 5

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory collides all types of ions (Au+Au, d+Au, and Cu+Cu planned for run 5) at CM energies $20 \leq \sqrt{s_{NN}} \leq 200$ GeV and spin polarized (transverse or longitudinal) protons at CM energies up to $\sqrt{s}=500$ GeV

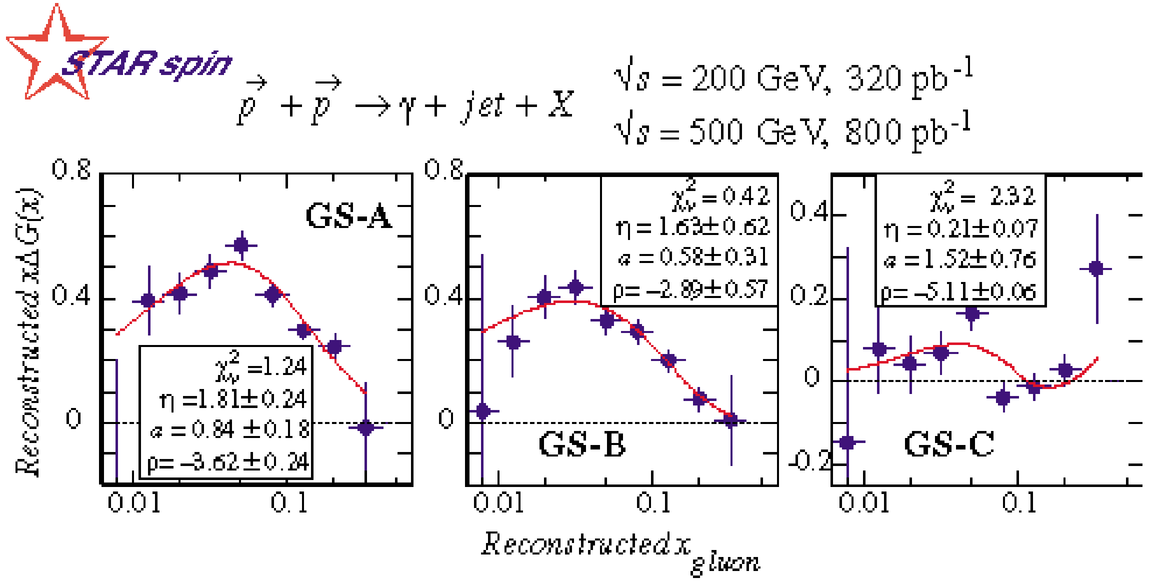
⇒ probe QCD states of matter and spin structure of proton

Objectives of RHIC spin

q(q̄) contribution — gluon contribution

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \underbrace{L_z^q + L_z^g}.$$

orbital angular momentum



Sensitivity of A_{LL} for γ+jet coincidences to three models of gluon polarization consistent with polarized deep inelastic scattering data.

Gehrmann and Stirling, Phys. Rev. D**53** (1996) 6100.

- **How does the proton get its spin?**

On average, quarks account for only ~20% of the proton's spin.

➢ how much do the gluons contribute to S_z?

➢ is there significant orbital angular momentum?

- **Are the sea antiquarks polarized?**

➢ parity-violating spin asymmetries in $W^\pm$ production are sensitive to quark and antiquark polarization.

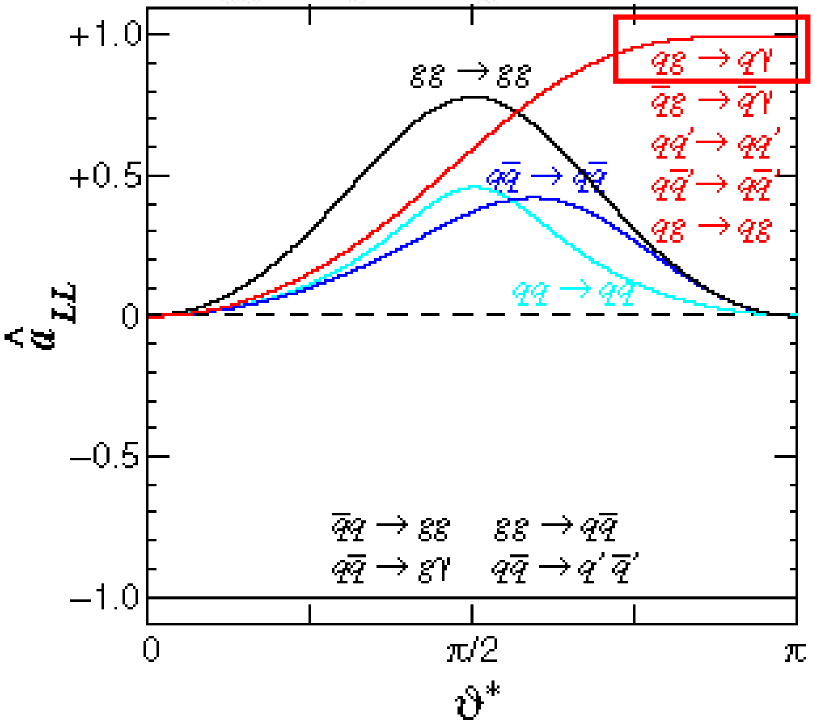
- **How does the transverse spin structure (transversity) compare to the longitudinal spin structure?**

Why Consider Forward Physics at a Collider?

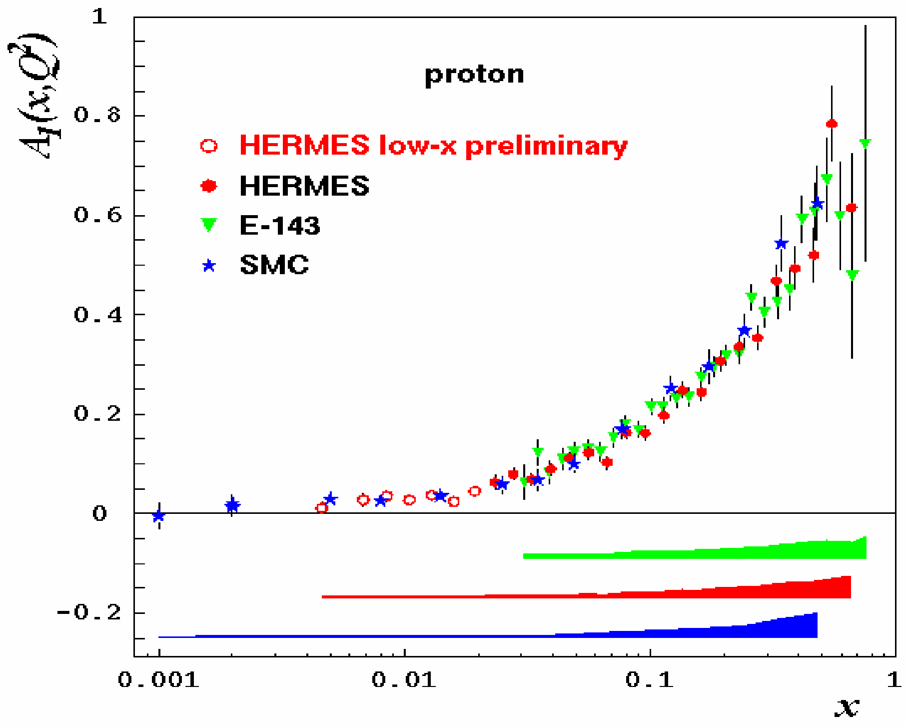
Dynamics

Spin-dependent partonic processes depend on scattering angle (θ*) and the quark polarization ($A_1{}^p$) is known from polarized DIS to be proportional to ln x.

$$\hat{a}_{LL} = \frac{\hat{\sigma}_{++} - \hat{\sigma}_{+-}}{\hat{\sigma}_{++} + \hat{\sigma}_{+-}} \quad \begin{cases} \hat{\sigma}_{++} \text{ equal helicity} \\ \hat{\sigma}_{+-} \text{ opposite helicity} \end{cases}$$



QCD Compton

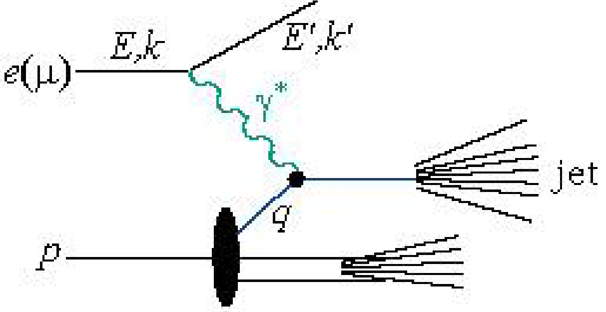


⇒ Important to measure p_T and rapidity dependence of particle yields and spin asymmetries.

Why Consider Forward Physics at a Collider?

Kinematics

Deep inelastic scattering

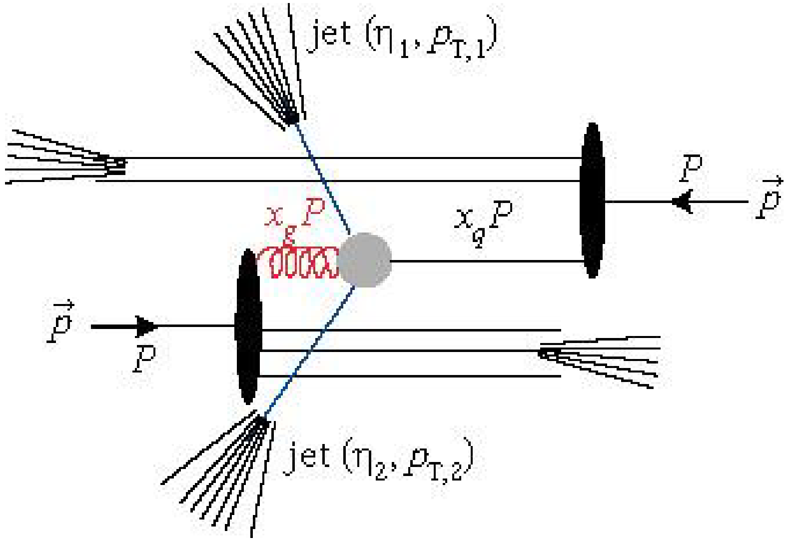


$$Q^2 = 2(EE' - \vec{k}\cdot\vec{k}')$$

$$\nu = E - E'$$

$$x = Q^2/2M\nu$$

Hard scattering hadroproduction



How can Bjorken x values be selected in hard scattering?

Assume:

1. Initial partons are collinear
2. Partonic interaction is elastic

$$\Rightarrow p_{T,1} \approx p_{T,2}$$

$$\Rightarrow \quad x_q \approx p_T/\sqrt{s}\,(\,e^{+\eta_1} + e^{+\eta_2}\,)$$

$$x_g \approx p_T/\sqrt{s}\,(\,e^{-\eta_1} + e^{-\eta_2}\,)$$

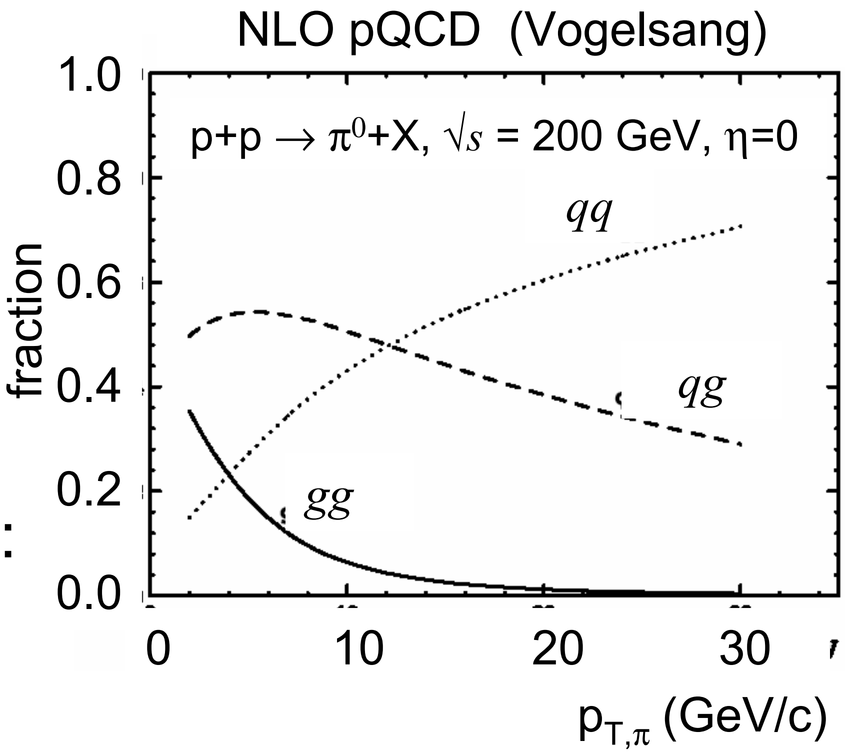
Studying pseudorapidity, η=-ln(tanθ/2), dependence of particle production probes parton distributions at different Bjorken *x* values and involves different admixtures of *gg*, *qg* and *qq'* subprocesses.

Simple Kinematic Limits

Mid-rapidity particle detection:

$\eta_1 \approx 0$ and $<\eta_2> \approx 0$

$$\Rightarrow x_q \approx x_g \approx x_T = 2\, p_T / \sqrt{s}$$



Large-rapidity particle detection:

$\eta_1 >> \eta_2$

$$\Rightarrow x_q \approx x_T\, e^{\eta_1} \approx x_F \text{ (Feynman } x\text{), and}$$

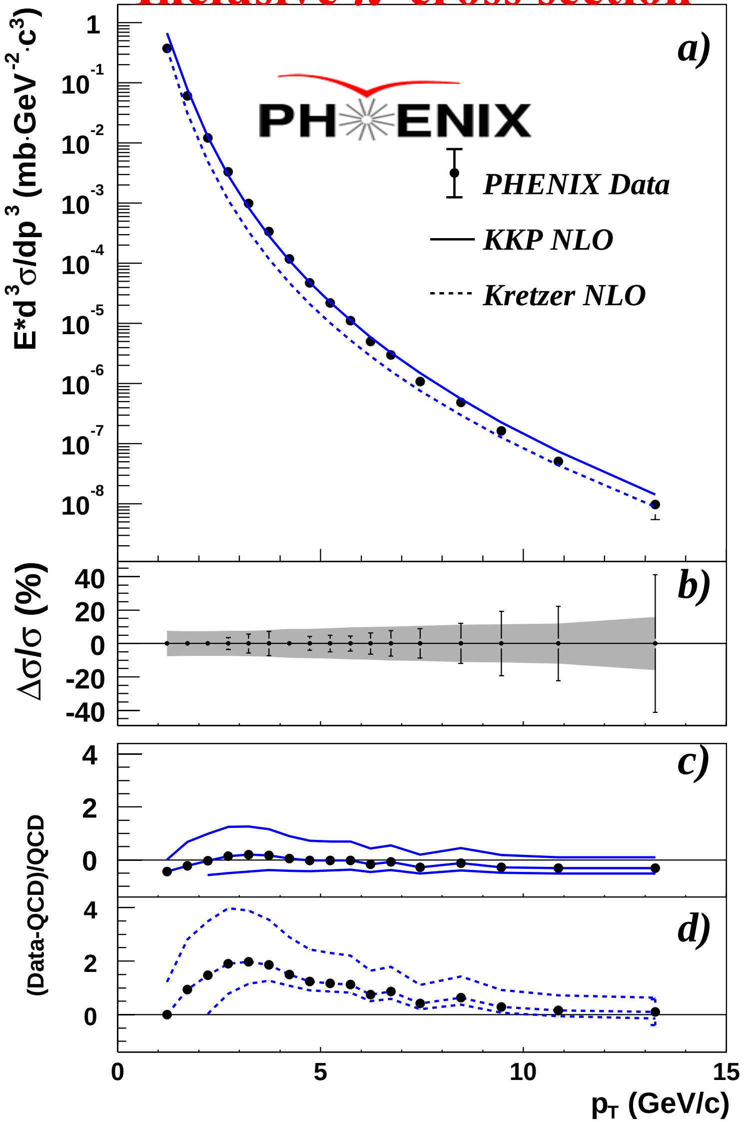
$$x_g \approx x_F\, e^{-(\eta_1+\eta_2)}$$

⇒ Large rapidity particle production and correlations involving large rapidity particle probes low-x parton distributions using valence quarks

How can one infer the dynamics of particle production?

Particle production and correlations near η≈0 in p+p collisions at √s = 200 GeV

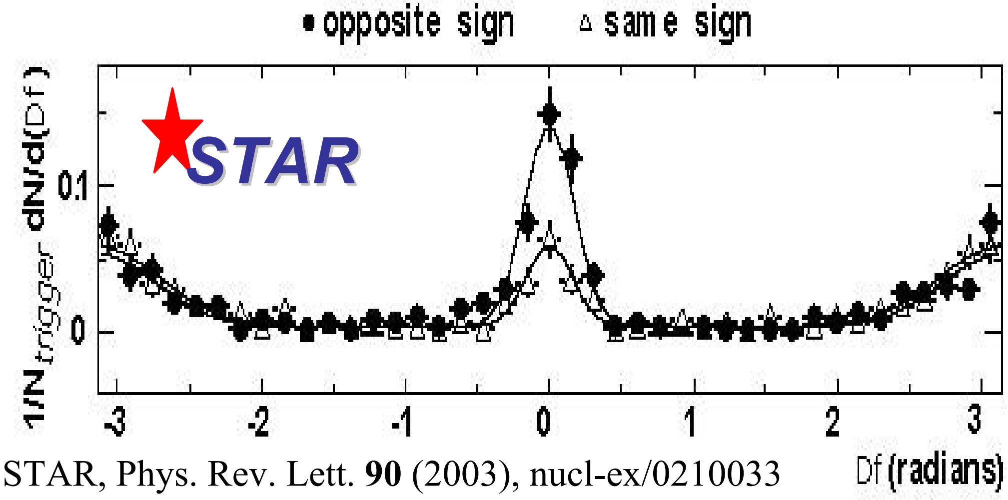
Inclusive π^0 cross section



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

hep-ex/0304038

Two particle correlations

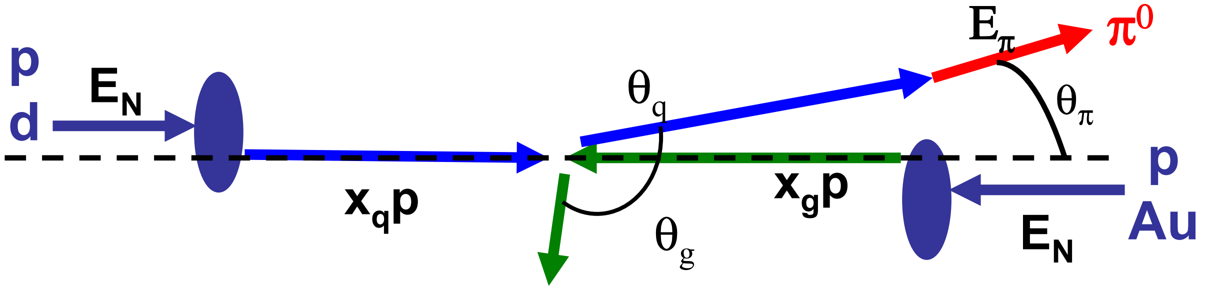


STAR, Phys. Rev. Lett. **90** (2003), nucl-ex/0210033

At √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?

Forward π^0 production in hadron collider



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

$\sqrt{s} = 2E_N$

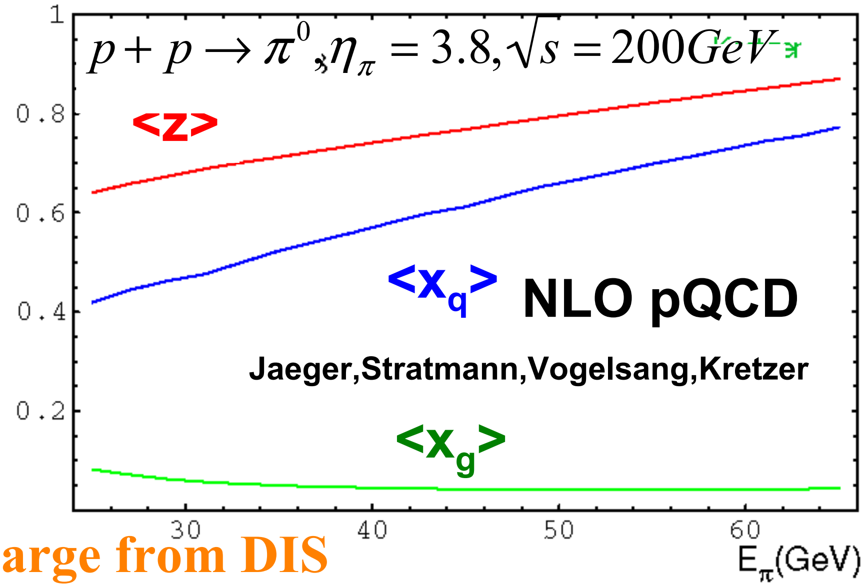
$\eta = -\ln(\tan(\frac{\theta}{2}))$ $\quad z = \frac{E_\pi}{E_q}$

$x_q \approx x_F / \langle z \rangle$ $\quad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta_g}$

(collinear approx.)

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

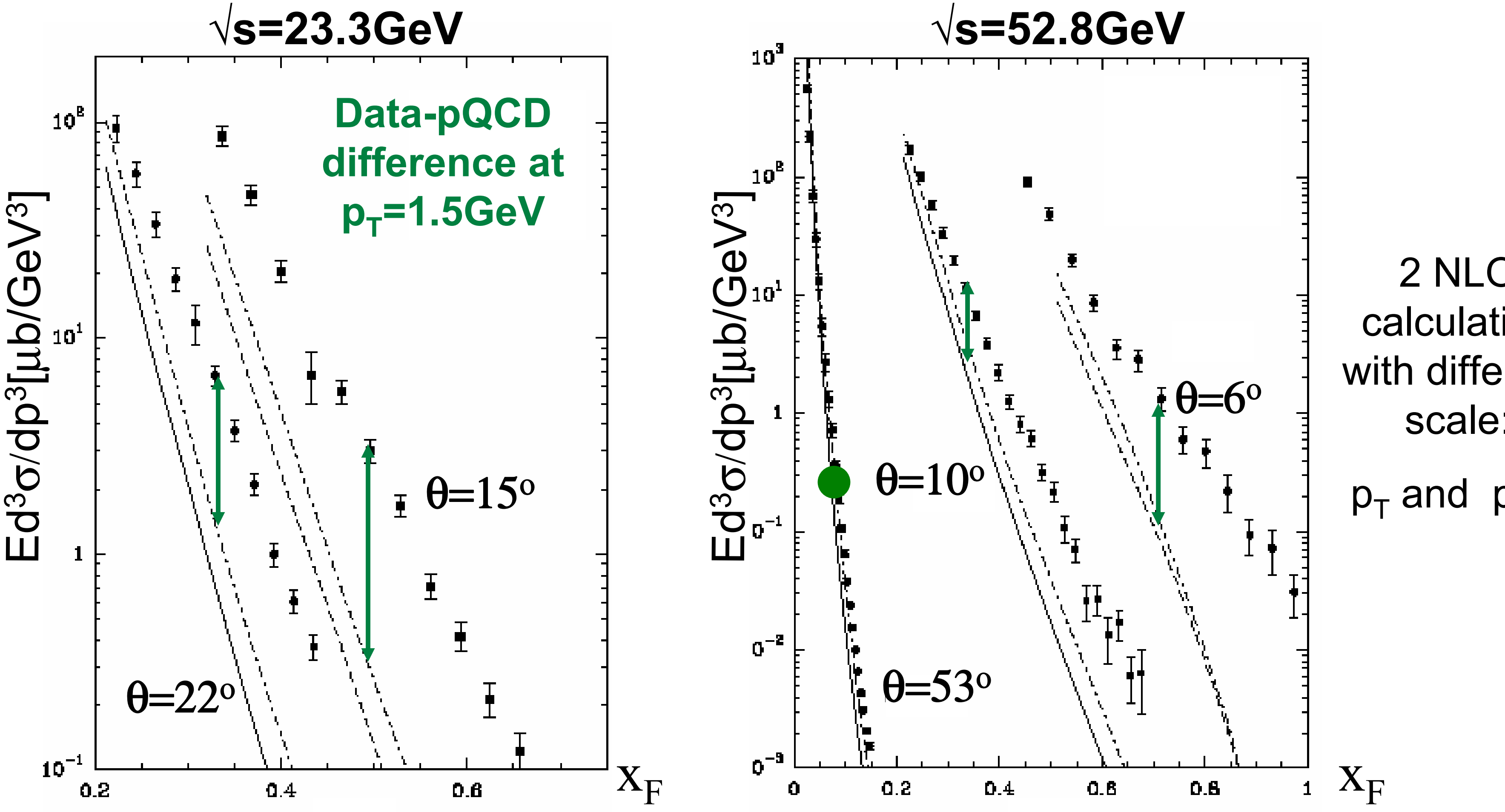
- Mostly **high-x valence quark** + **low-x gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <z> nearly constant and high 0.7 ~ 0.8



- **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….



Data-pQCD difference at p_T=1.5GeV

2 NLO calculation with different scale:

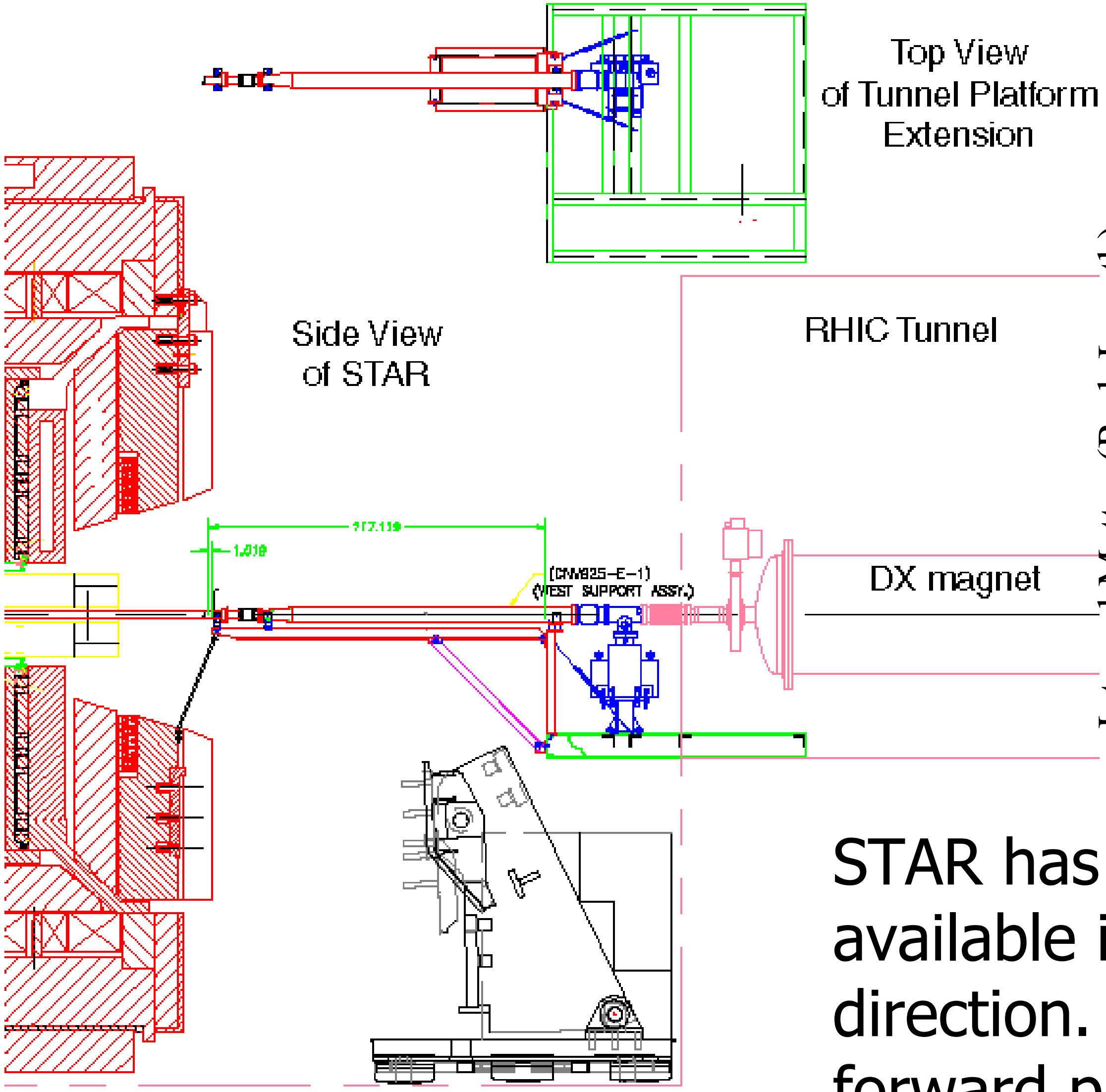
p_T and $p_T/2$

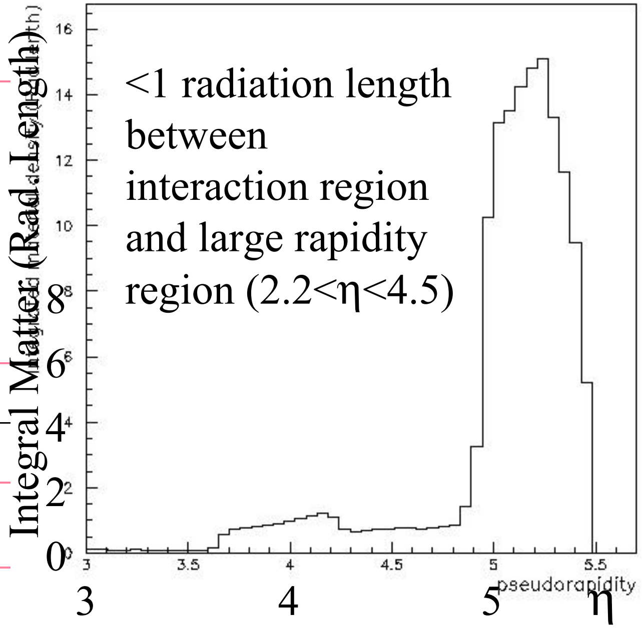
Bourrely and Soffer (hep-ph/0311110, Data references therein):

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

Forward Physics at STAR





<1 radiation length between interaction region and large rapidity region (2.2<η<4.5)

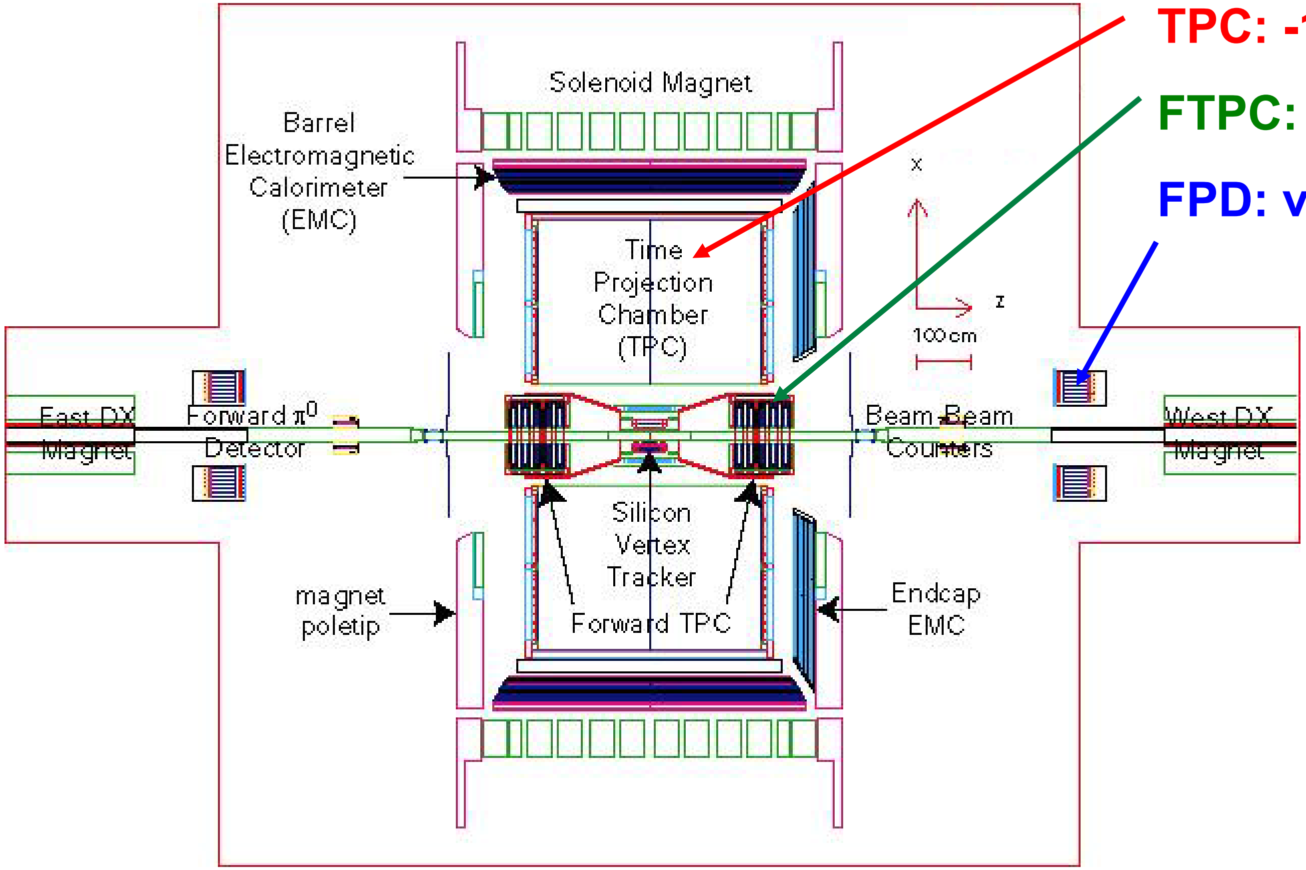
STAR has significant space available in the forward direction. ⇒ well suited to forward particle detection.

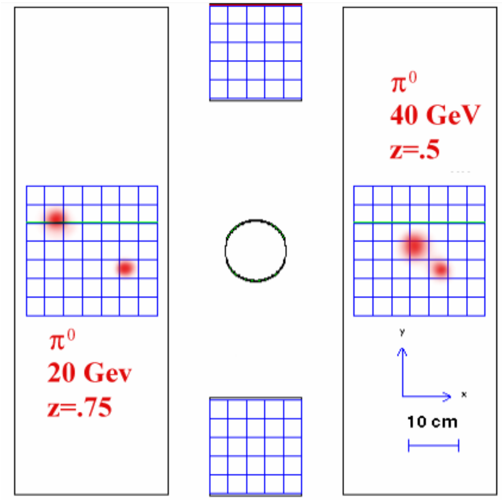
STAR Detector

TPC: $-1.0 < \eta < 1.0$

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

FPD: variable, $3.3 \leq |\eta| \leq 4.0$





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

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

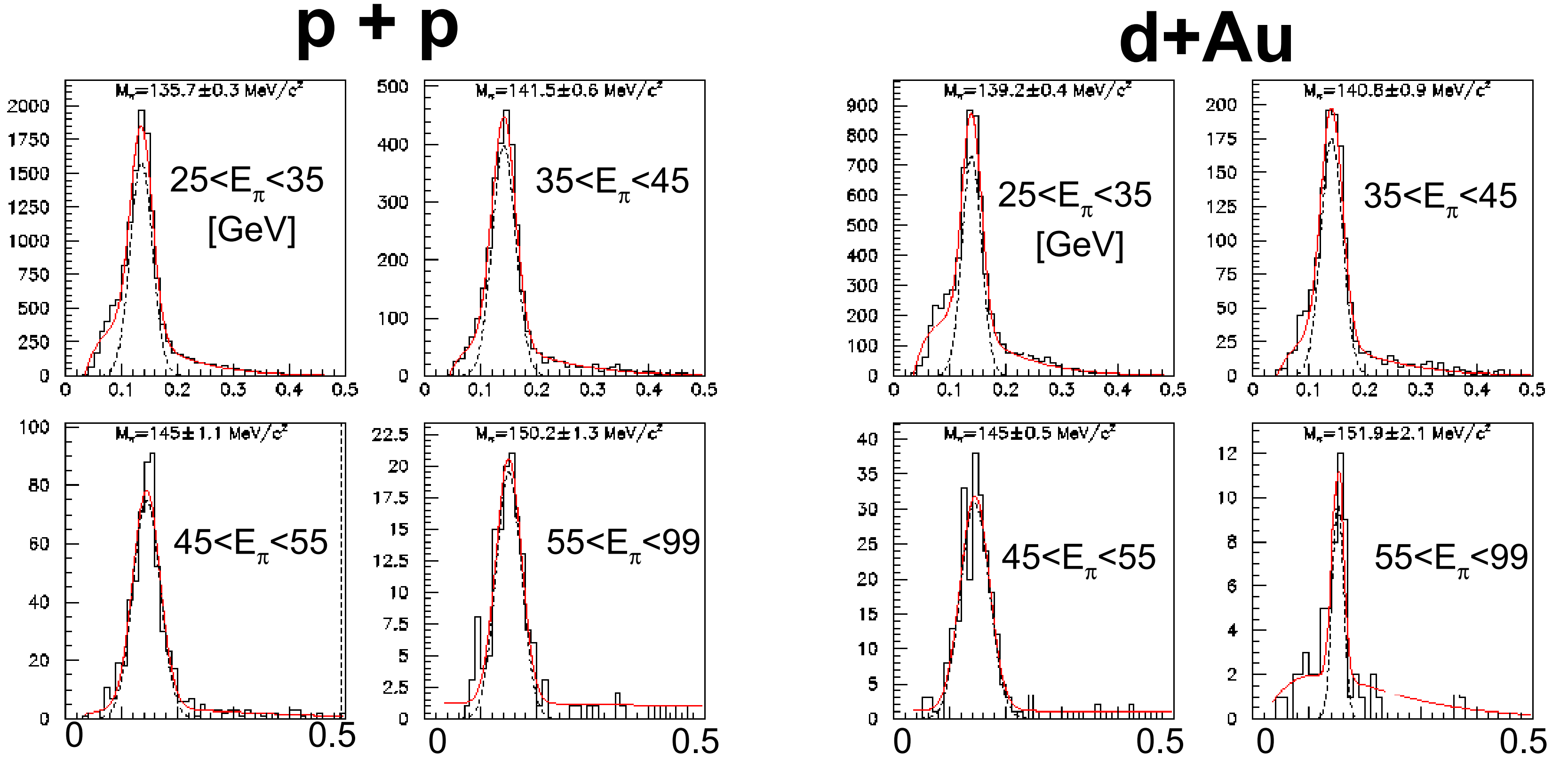
Forward π^0 Detector (FPD)

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

Di-photon Mass Reconstruction

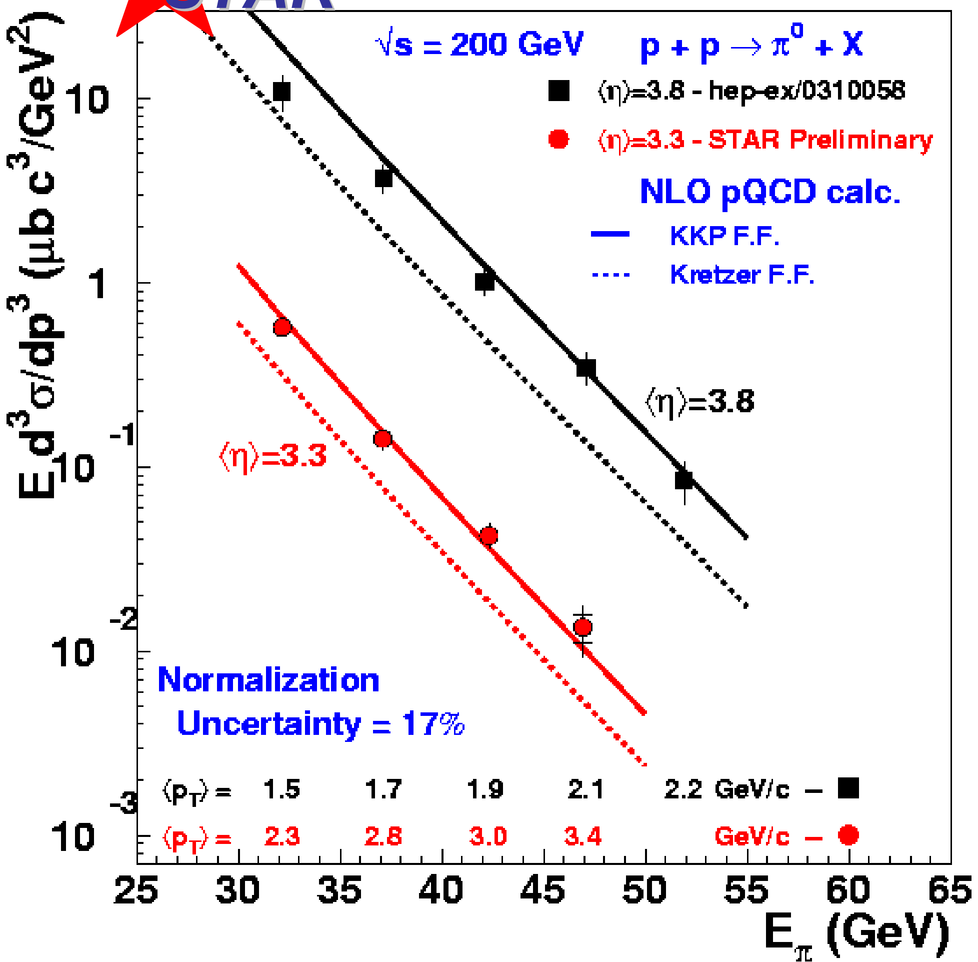
STAR Forward π^0 Detector (Run 3)

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



- Absolute gain determined from π^0 peak position for each tower
- current gain calibration of FPD from run 3 known to ~10%
⇒ cross section in d+Au requires better calibrations
- systematics to be addressed using SMD

Forward π^0 Inclusive Cross Section



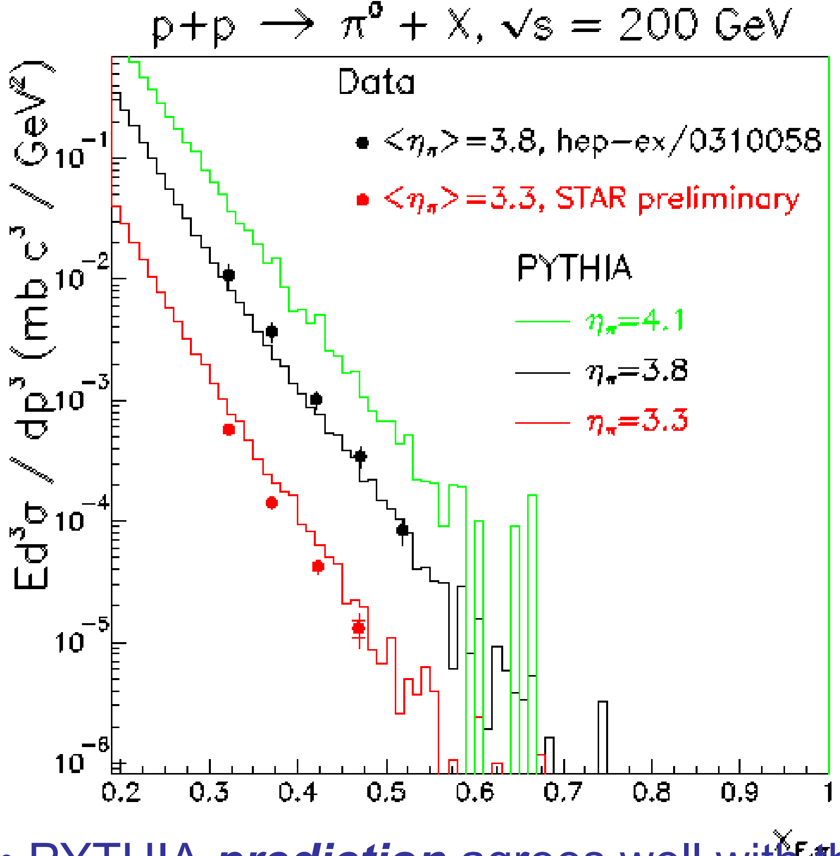
- STAR data from run-2 prototype FPD at
  - ⟨η⟩= 3.8 (hep-ex/0310058, Phys. Rev. Lett. **92** (2004) 171801)
  - ⟨η⟩= 3.3 (hep-ex/0403012, Preliminary)
- NLO pQCD calculations at fixed η with equal factorization and renormalization scales = p_T
- Solid and dashed curves differ primarily in the g → π fragmentation function

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

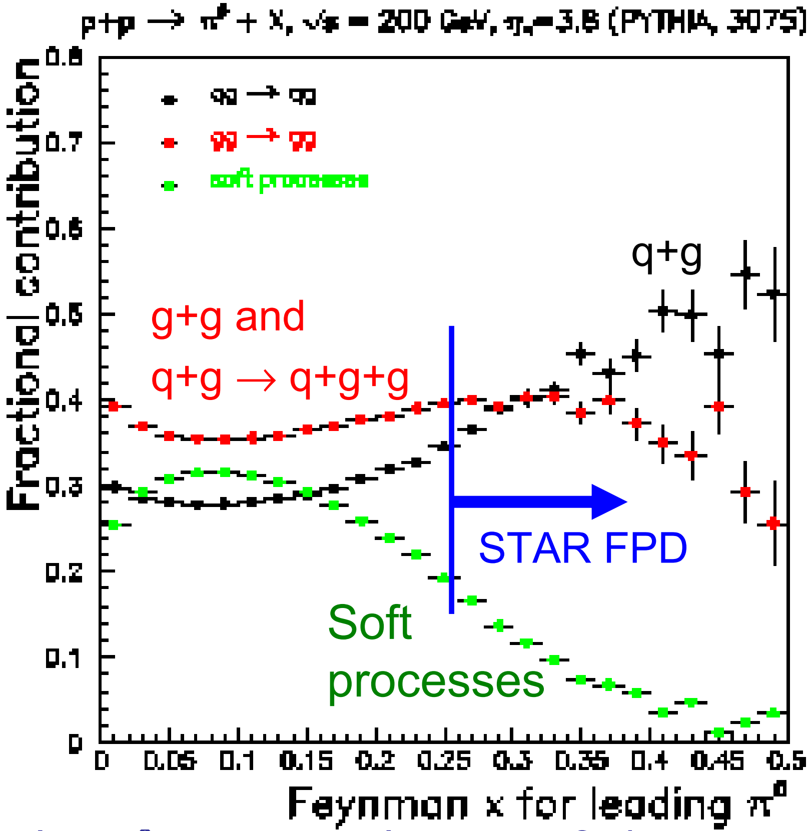
What about particle correlations?

PYTHIA: a guide to the physics

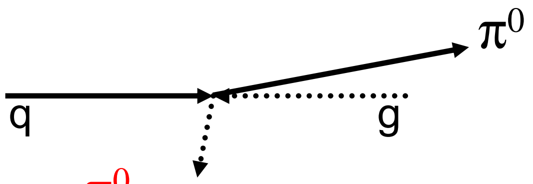
Forward Inclusive π^0 Cross-Section:



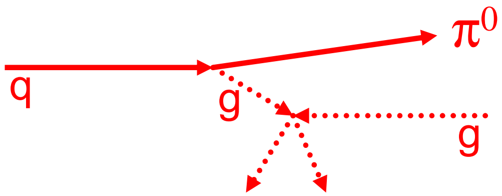
Subprocesses involved:



- 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:



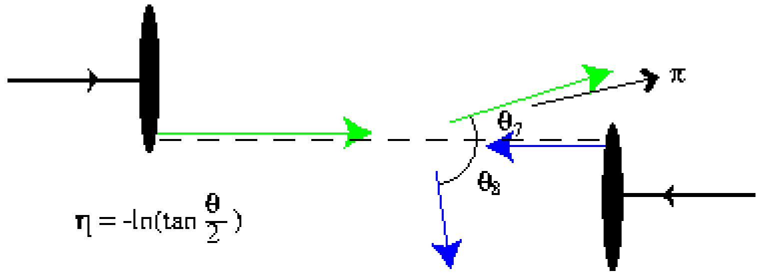
- q + g → q + g **(2→2)** → π^0 + X

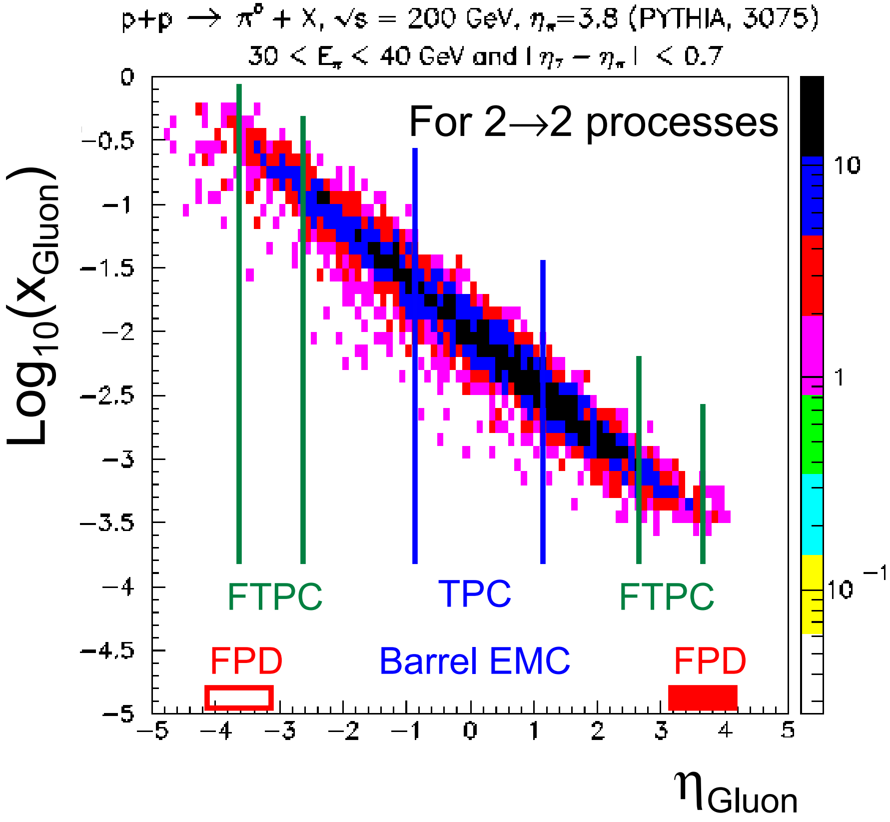


- q + g → q + g + g **(2→3)** → π^0 + X

Why forward physics at STAR?

Rapidity interval (forward - mid rapidity) correlations





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

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

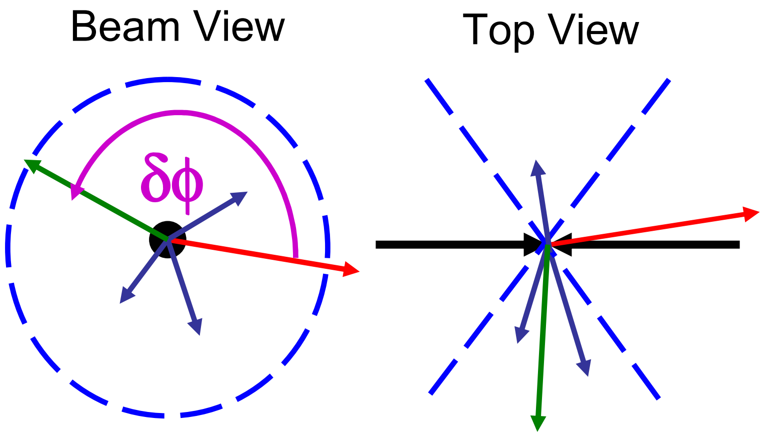
Spin effects with large Δη correlations?

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

- FPD: |η| ~ 4.0
- TPC and Barrel EMC: |η| < 1.0
- Endcap EMC: 1.0 < η < 2.0
- FTPC: 2.8 < |η| < 3.8

Back-to-back Azimuthal Correlations

with large rapidity interval



Trigger by forward π^0

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

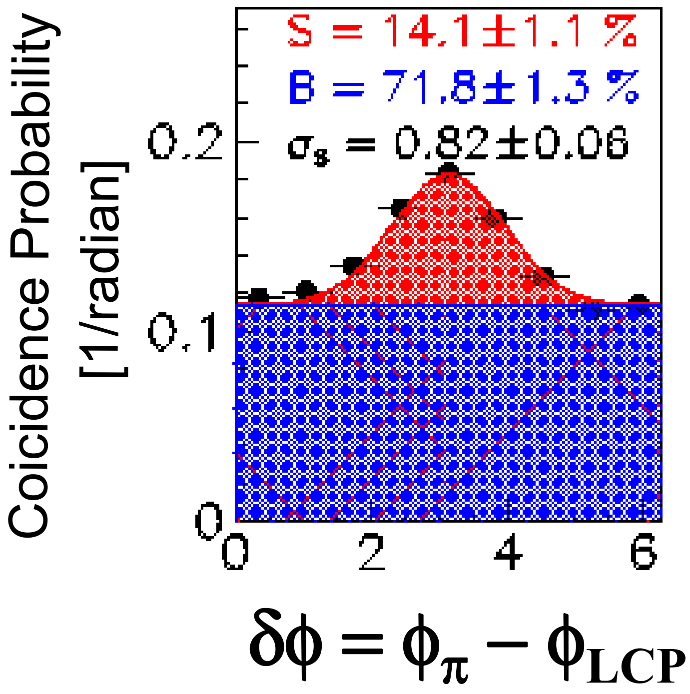
Midrapidity $h^\pm$ tracks in TPC

- $-0.75 < \eta < +0.75$

Leading Charged Particle(LCP)

- $p_T > 0.5$ GeV/c

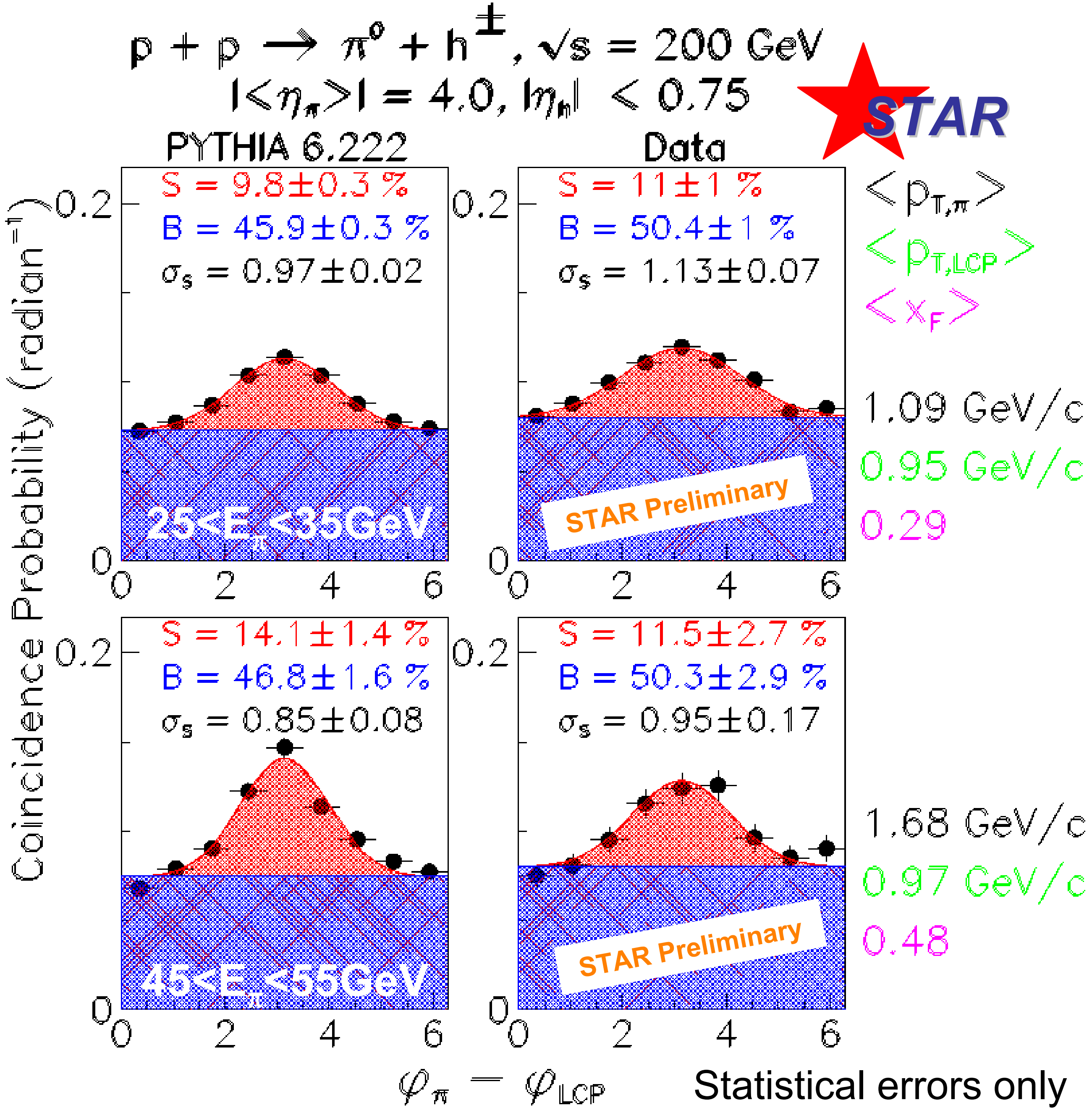
Fit $\delta\phi = \phi_\pi - \phi_{LCP}$ normalized distributions and with Gaussian+constant



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

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**

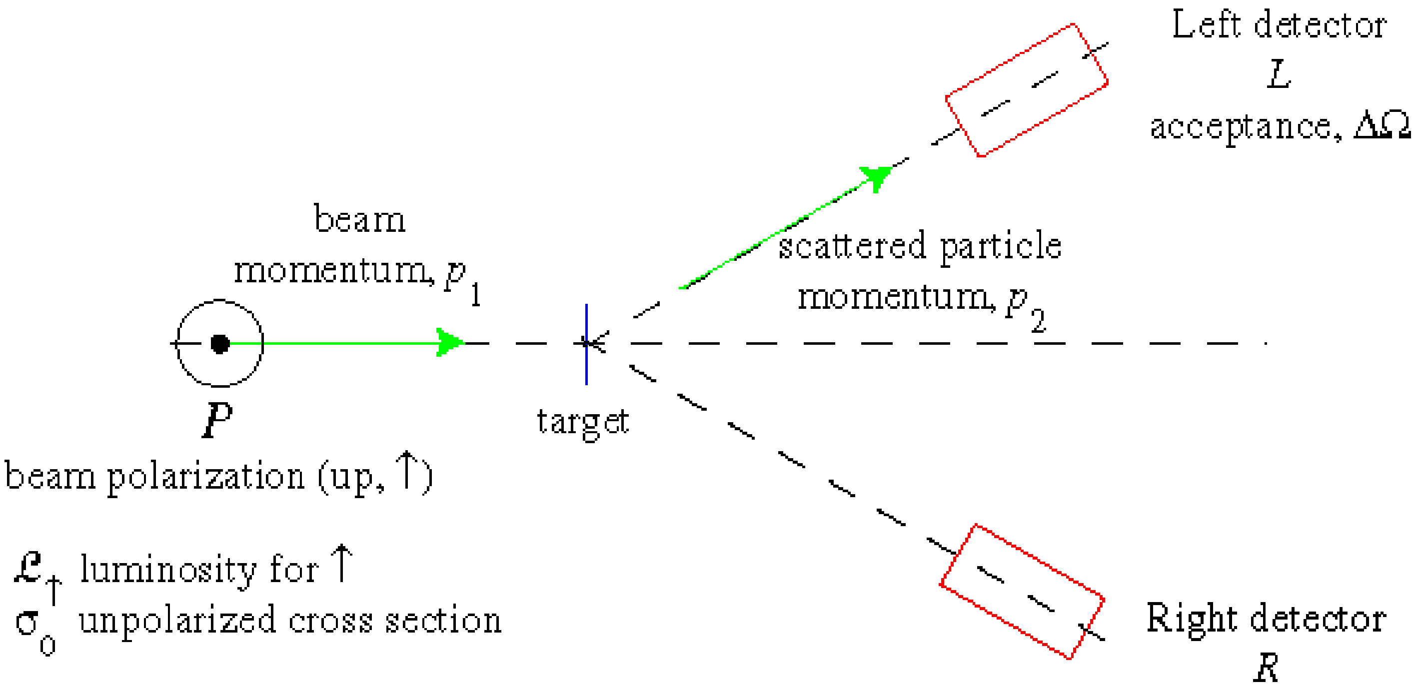
- **Back-to-back large rapidity gap particle correlations agree with PYTHIA**

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

Important result for:

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

Measurements with Transversely Polarized Beam



$\mathcal{L}_\uparrow$ luminosity for ↑

σ_0 unpolarized cross section

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

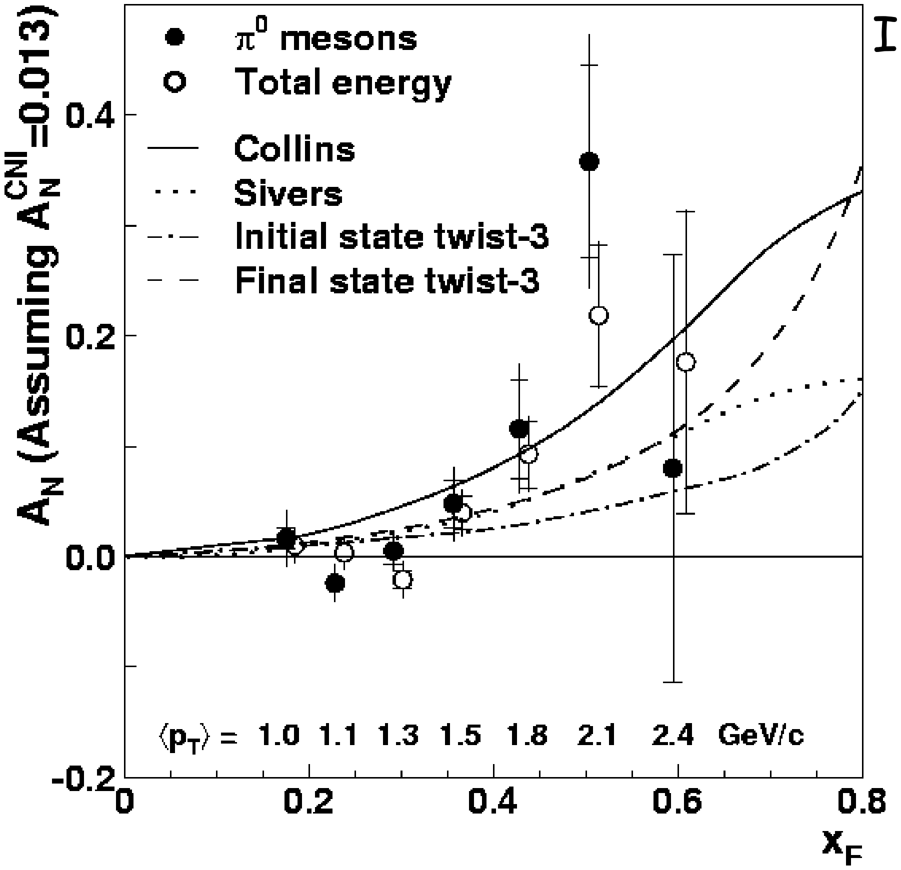
$$\varepsilon \;=\; PA \;=\; \frac{L_\uparrow / \mathcal{L}_\uparrow - L_\downarrow / \mathcal{L}_\downarrow}{L_\uparrow / \mathcal{L}_\uparrow + L_\downarrow / \mathcal{L}_\downarrow} \qquad \varepsilon \;=\; PA \;=\; \frac{(L_\uparrow R_\downarrow)^{1/2} - (L_\downarrow R_\uparrow)^{1/2}}{(L_\uparrow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

Large Analyzing Powers at RHIC

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

STAR

STAR collaboration, hep-ex/0310058,
Phys. Rev. Lett. **92** (2004) 171801



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

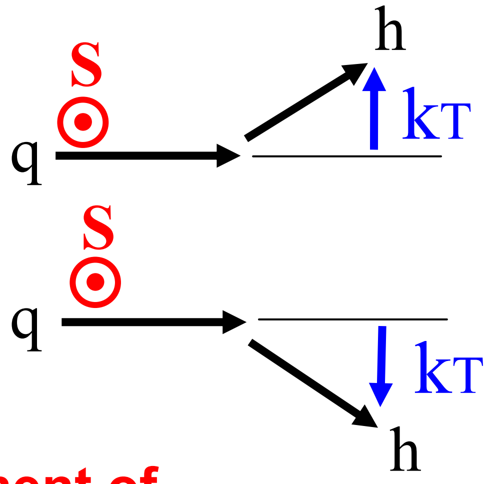
In agreement with several models including different dynamics:

- 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 ⇒ 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

Time/luminosity dependent

d calibration

FTPC-FPD matching

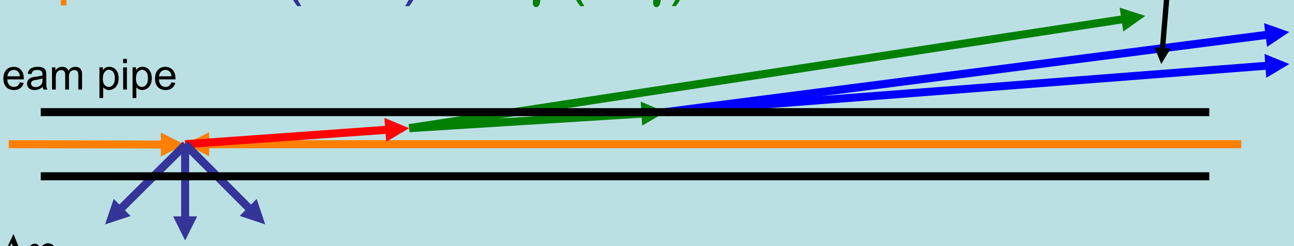
Photon conversion in beam pipe

$p + p \rightarrow \pi^0 (+ X) \rightarrow \gamma (+ \gamma) \rightarrow e^+ e^-$

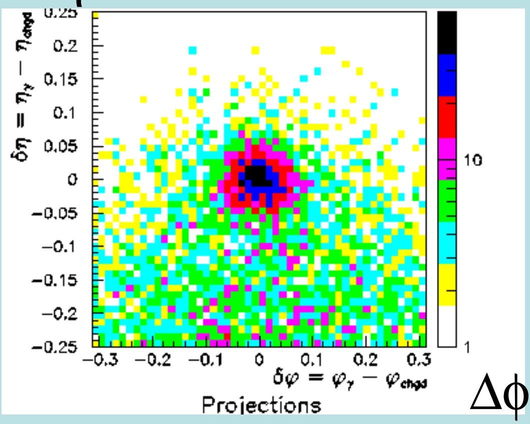
Beam pipe

Track in FTPC

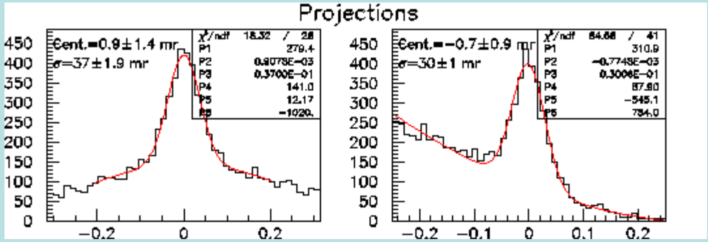
Hit in FPD



Δη



Δφ



Δφ Δη

⇒ FPD position known relative to STAR

(Recon. Eff.)(Frac. of 2 contained γ)

100 25 50 100 50 50 10

25 30 35 40 45 50 55

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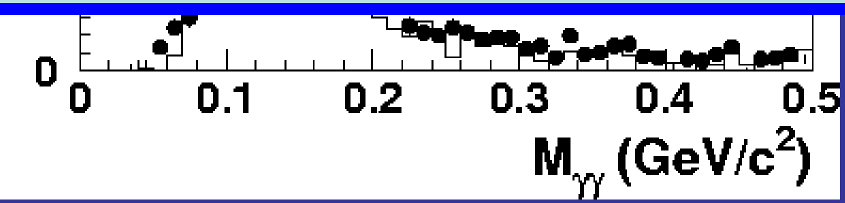
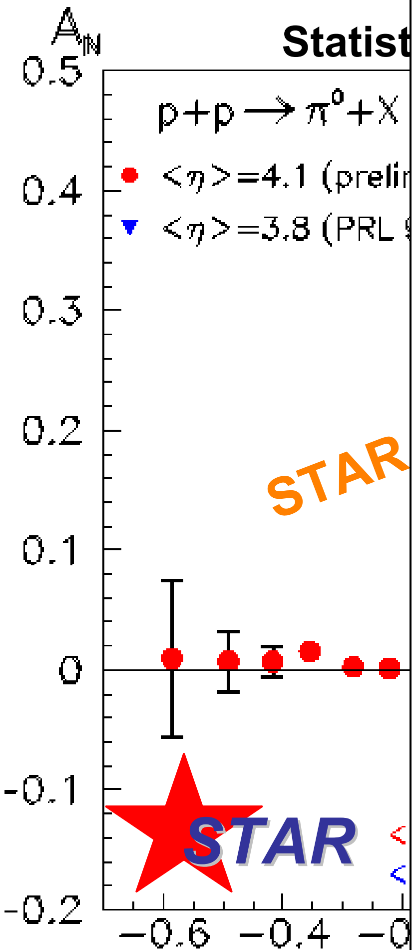


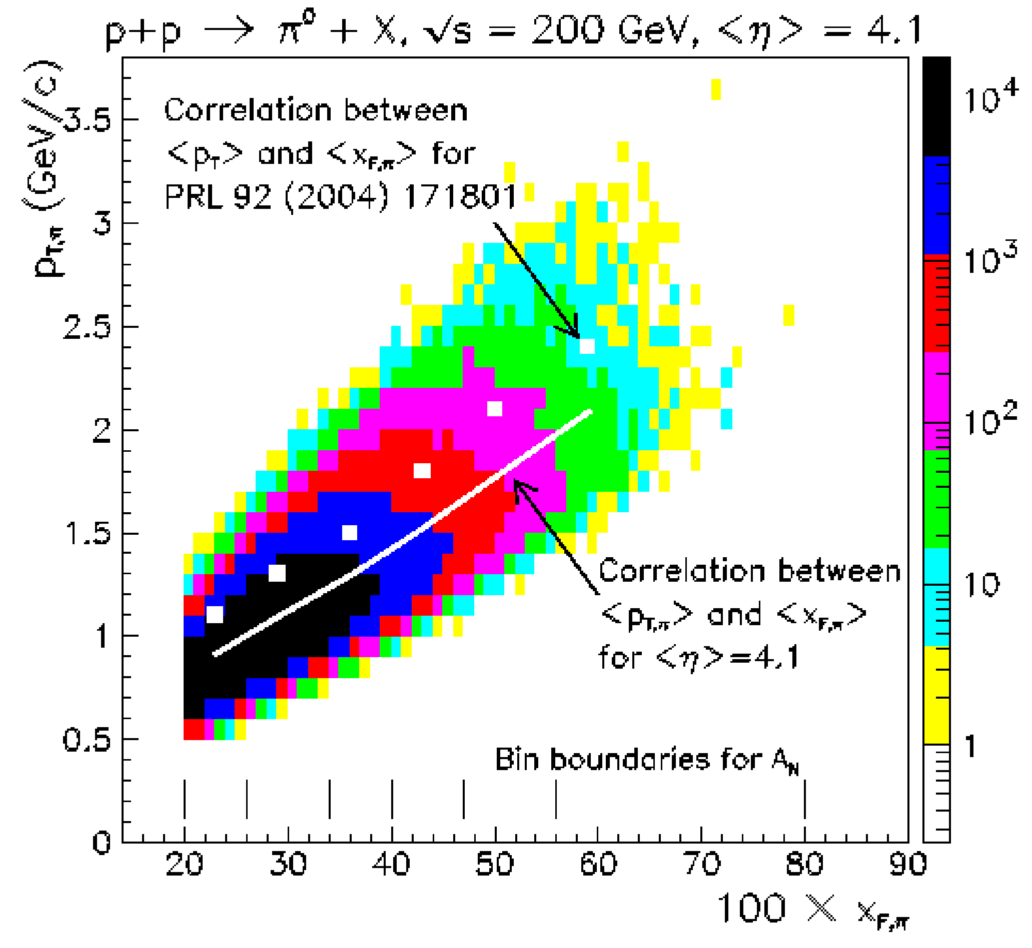
0 5 10

2nd mom

Measurement of A_N for fo =200GeV



x_F and p_T range of the data



positive x_F has

e to be non-zero &

ed data

ent of negative x_F

nd is consistent

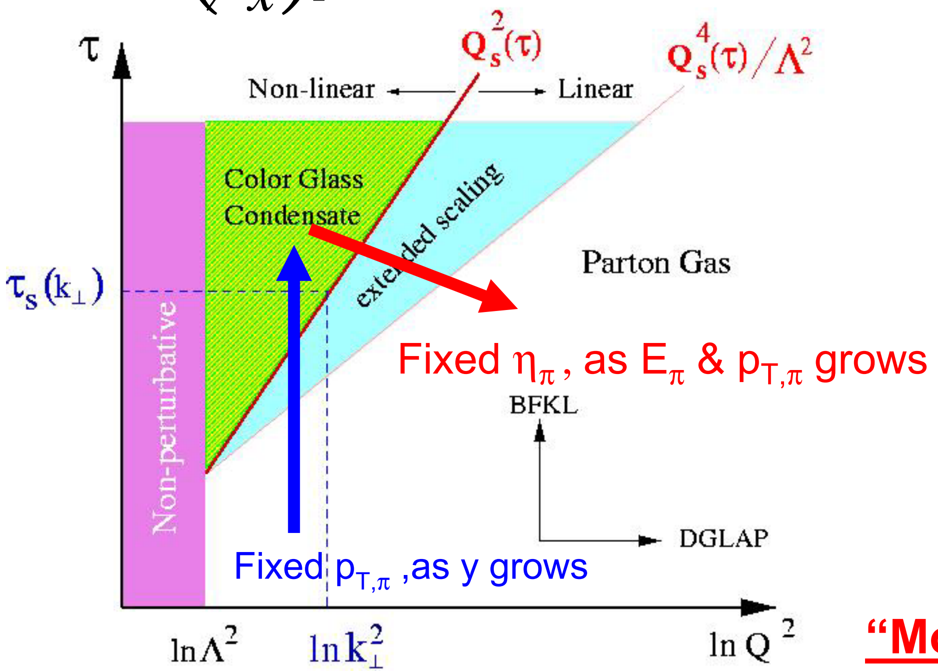
Sivers function

Mapping of A_N in x_F and p_T plane has begun !

d + Au: Possible Color Glass Condensate at RHIC?

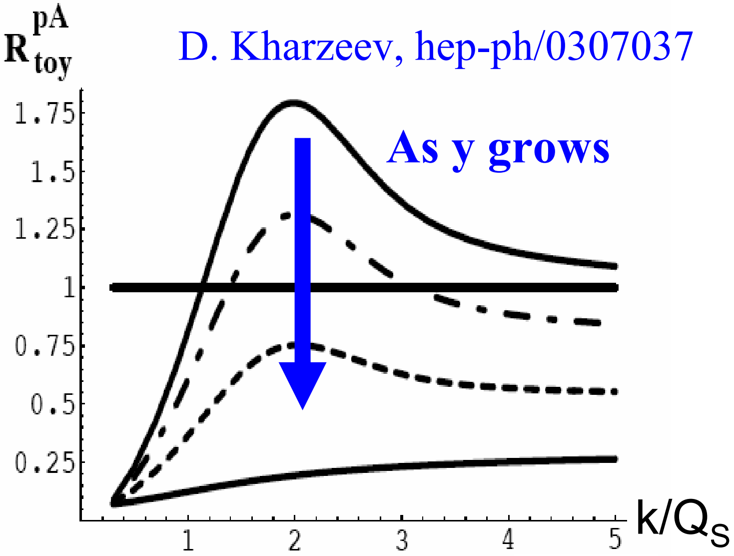
General expectations of CGC:

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



Edmond Iancu and Raju Venugopalan, hep-ph/0303204

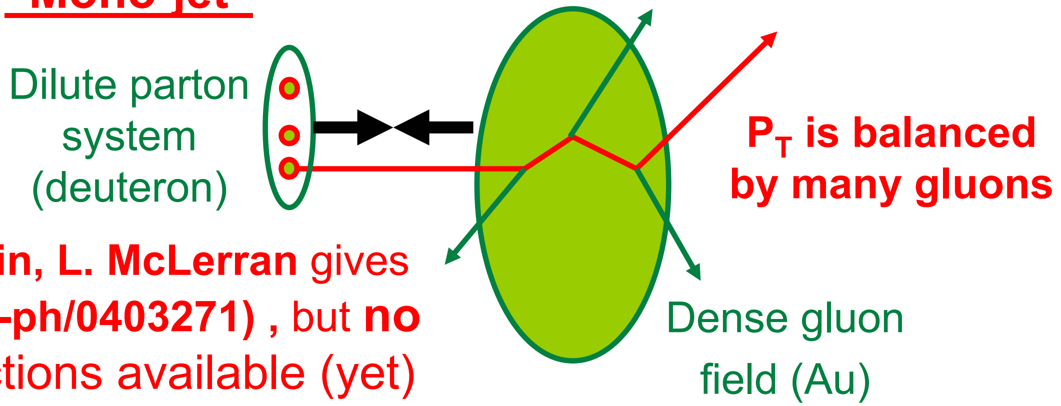
Suppression of forward particle production



Brahms data shows evidence **?**

(nucl-ex/0403005)

“Mono-jet”

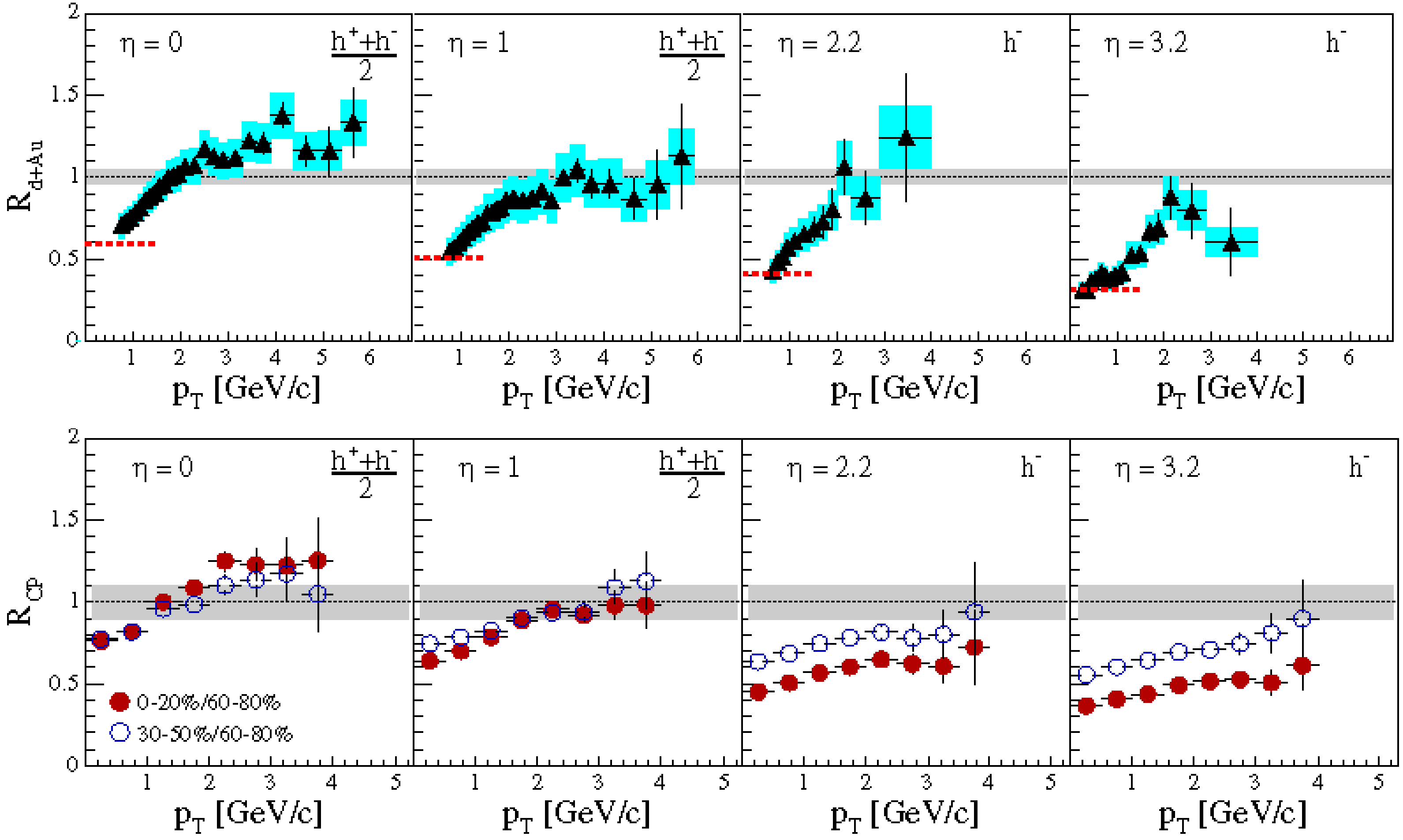


D.Kharzeev, E. Levin, L. McLerran gives physics picture **(hep-ph/0403271)** , but **no** quantitative predictions available (yet)

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

Final Results for forward d+Au h± production from Brahms

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

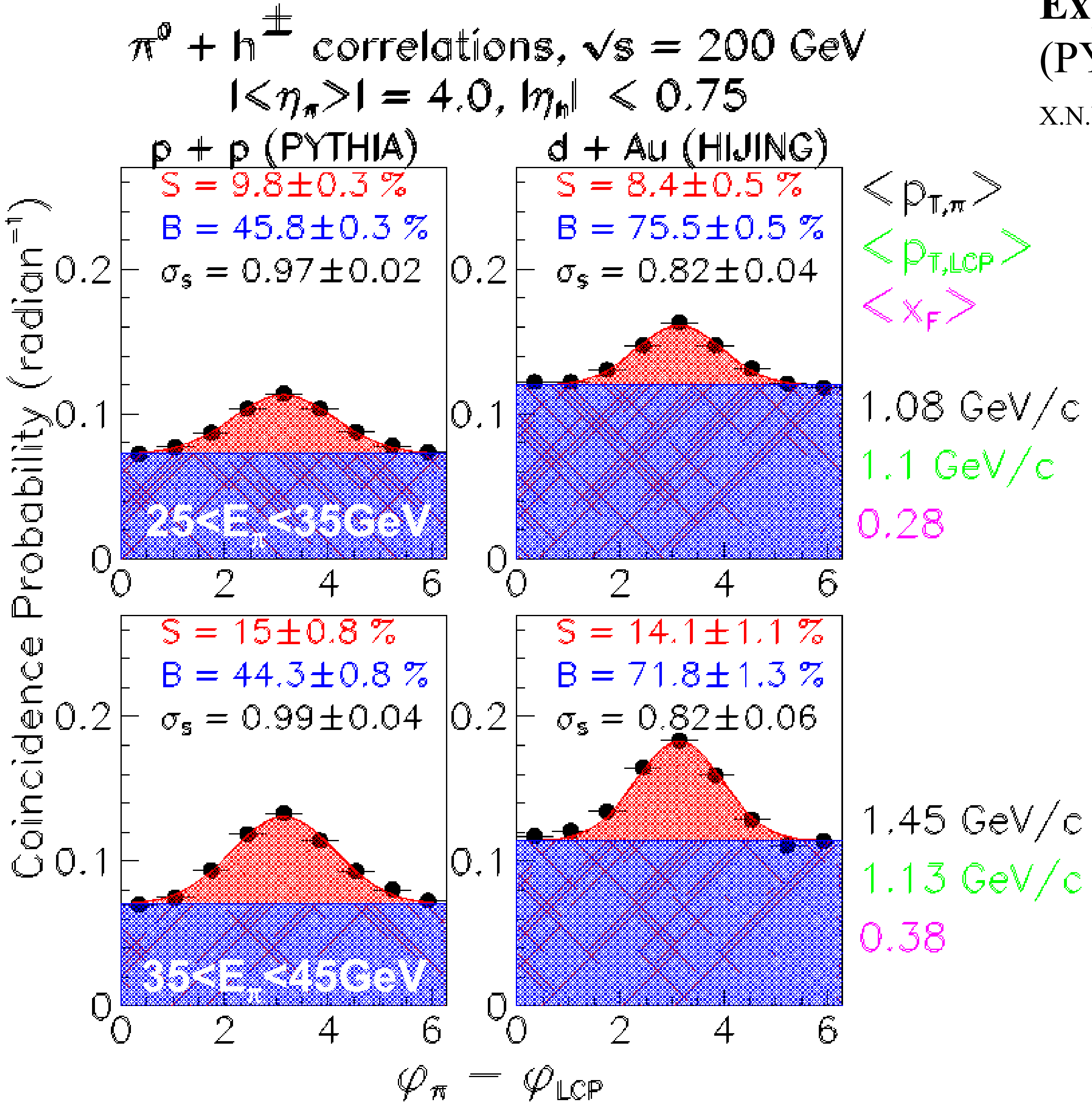


Suppression of inclusive hadron production at forward rapidities of d+Au relative to p+p observed at BRAHMS…

What about back-to-back correlations?

Expectation from HIJING (PYTHIA+nuclear effects)

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



with detector effects

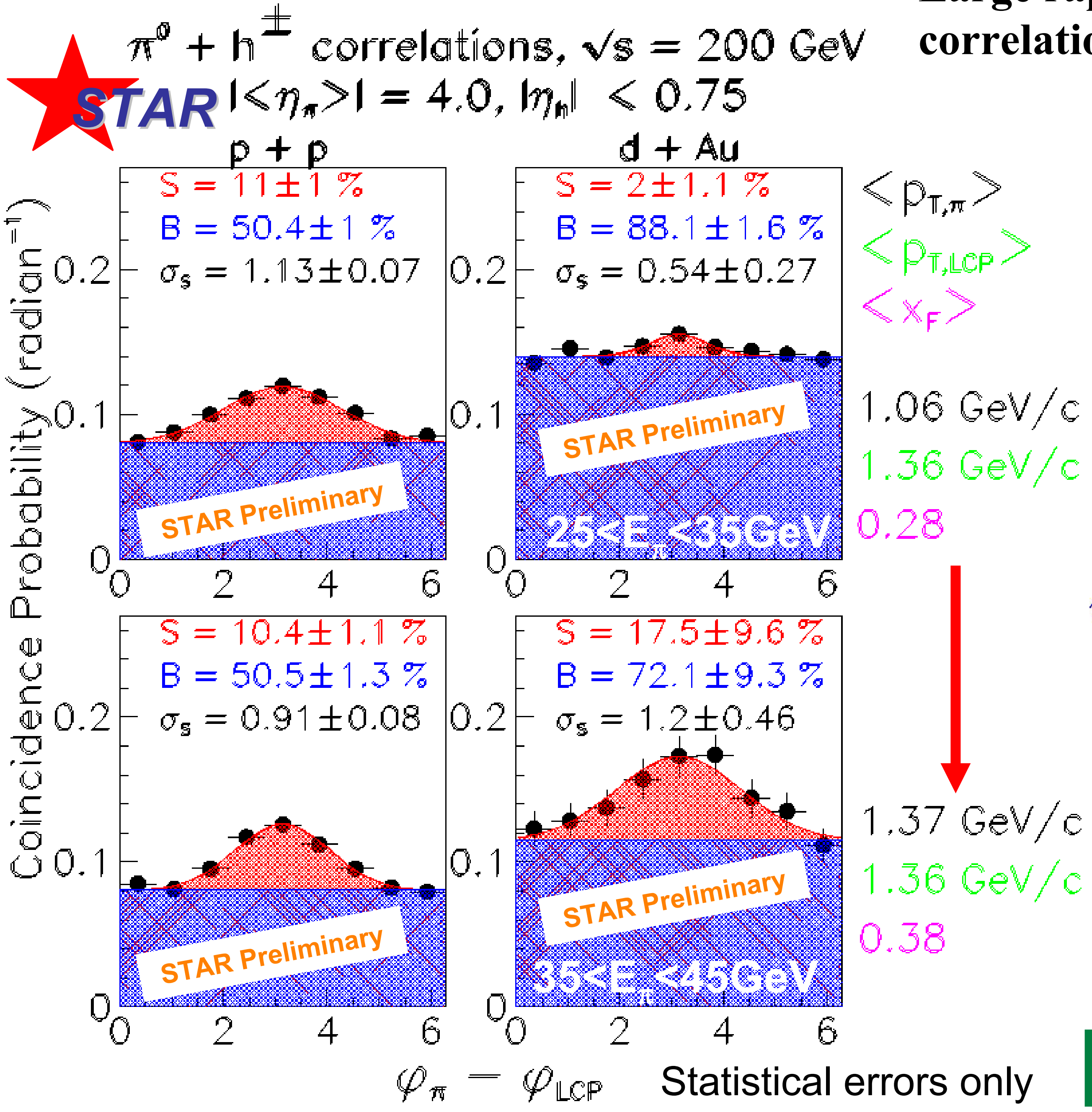
- **HIJING predicts clear correlation in d+Au**
- **Small difference in "S" and "σ_s" between p+p and d+Au**
- **"B" is bigger in d+Au due to increased particle multiplicity at midrapidity**

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

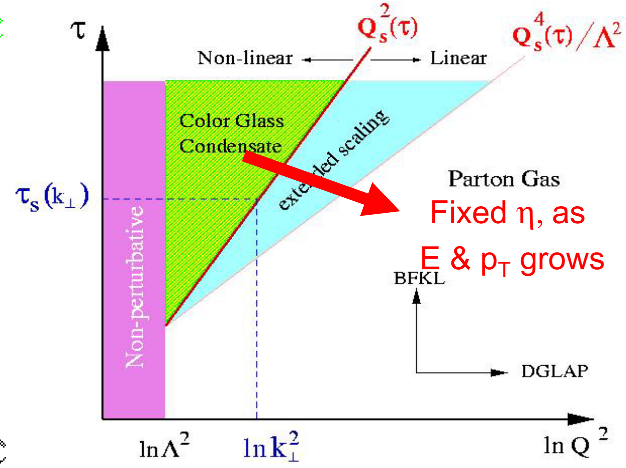
- are suppressed in d+Au relative to p+p at small $<x_F>$ and $<p_{T,\pi}>$

S_{pp}-S_{dAu}= (9.0 ± 1.5) %

Consistent with CGC picture



Statistical errors only



Fixed η, as E & p_T grows

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

as expected by HIJING

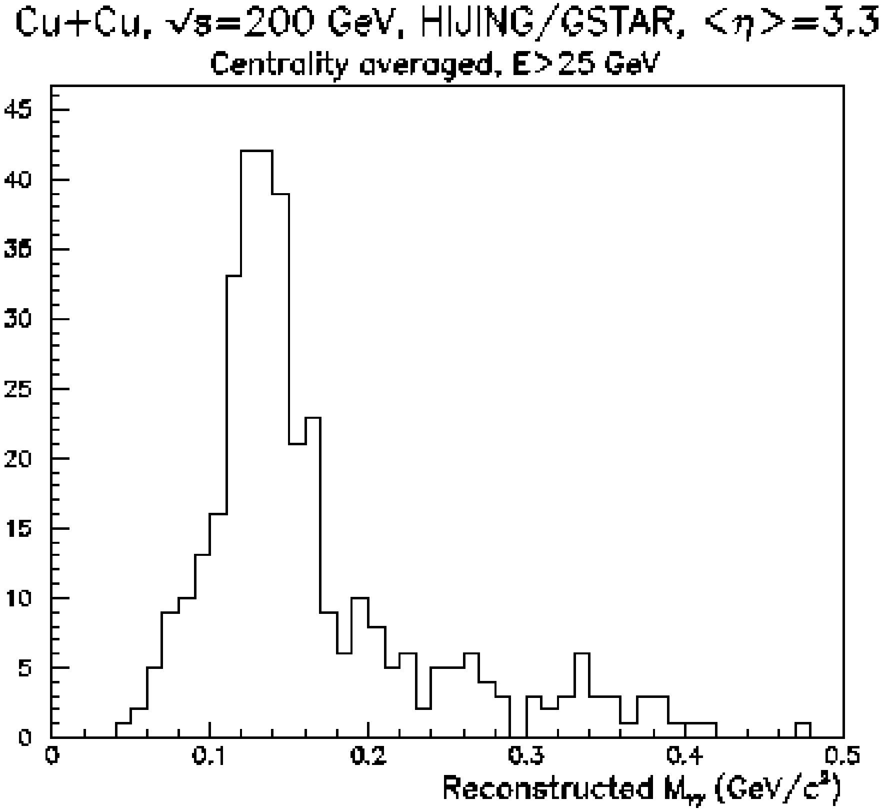
Conclusions

- **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 interval correlations in p+p agree with PYTHIA prediction**
- **Analyzing power for forward π^0 mesons is large at RHIC**
- **Large rapidity interval 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.**

Near-Term Future Plans

reconstruction of
HIJING + GEANT simulations

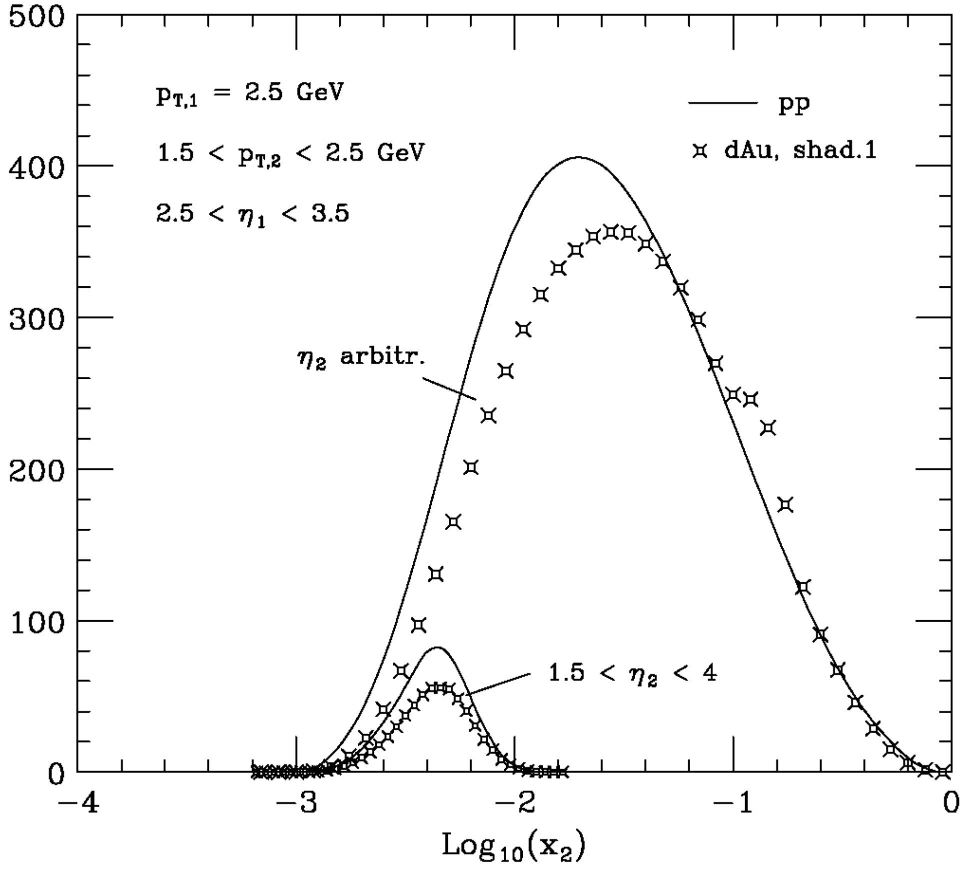
Simulations suggest that forward detection is feasible in centrality-averaged Cu+Cu collisions at √s=200 GeV. In addition to establishing R_{CuCu} at large rapidity, the FPD can trigger full STAR readout to examine particle correlations with large-rapidity π^0. This can be useful to study flavor dependence of recoil jets at midrapidity.



Limitations of the Existing FPD

- Limited pseudo-rapidity coverage at any one time
- Strong $\eta - x_F - p_T$ acceptance correlations
- Only suitable for π^0
  - Too small for direct photon isolation cuts
  - Too small to contain heavier meson decay products
- Limited solid angle for correlation studies
- A larger detector would be **extremely valuable**

d+Au → π^0+π^0+X correlations



Guzey, Strikman, and Vogelsang, hep-ph/0407201

Detector Scaling:

Heavier Mesons with Larger Detectors

π^0
- M=.135 GeV 2 photons
  - 7x7 (3.8 cm) blocks

η
- M=.548 GeV 2 photons
  - 28 x 28 (3.8 cm) blocks

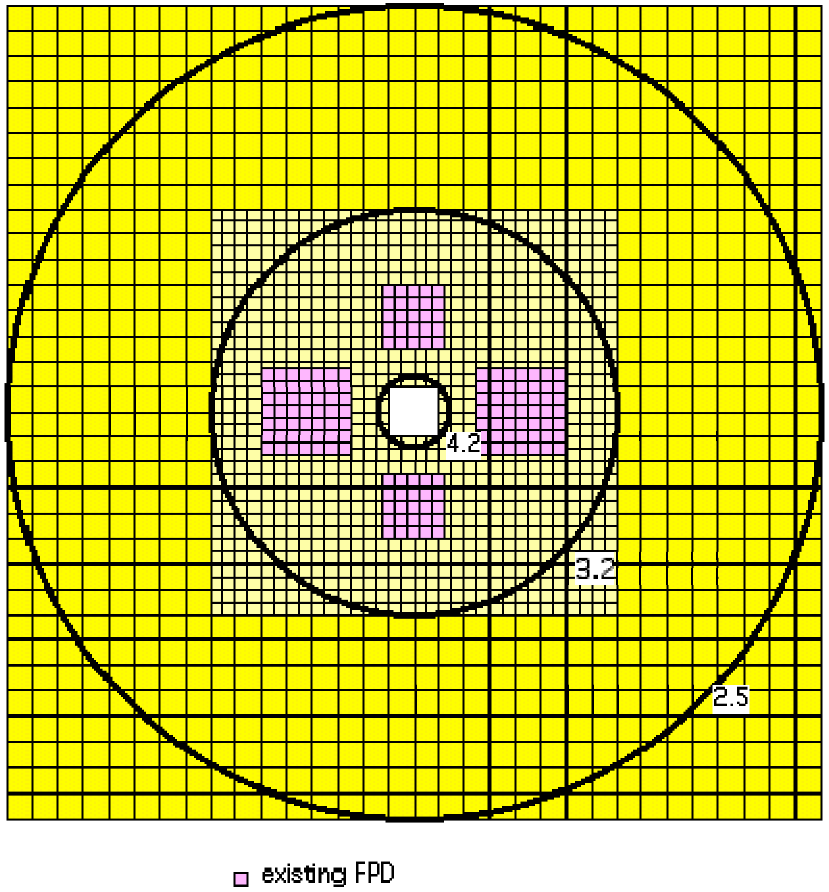
k_{short}
- M=.498 GeV 4 photons
  - 25 x 25 (3.8 cm) blocks

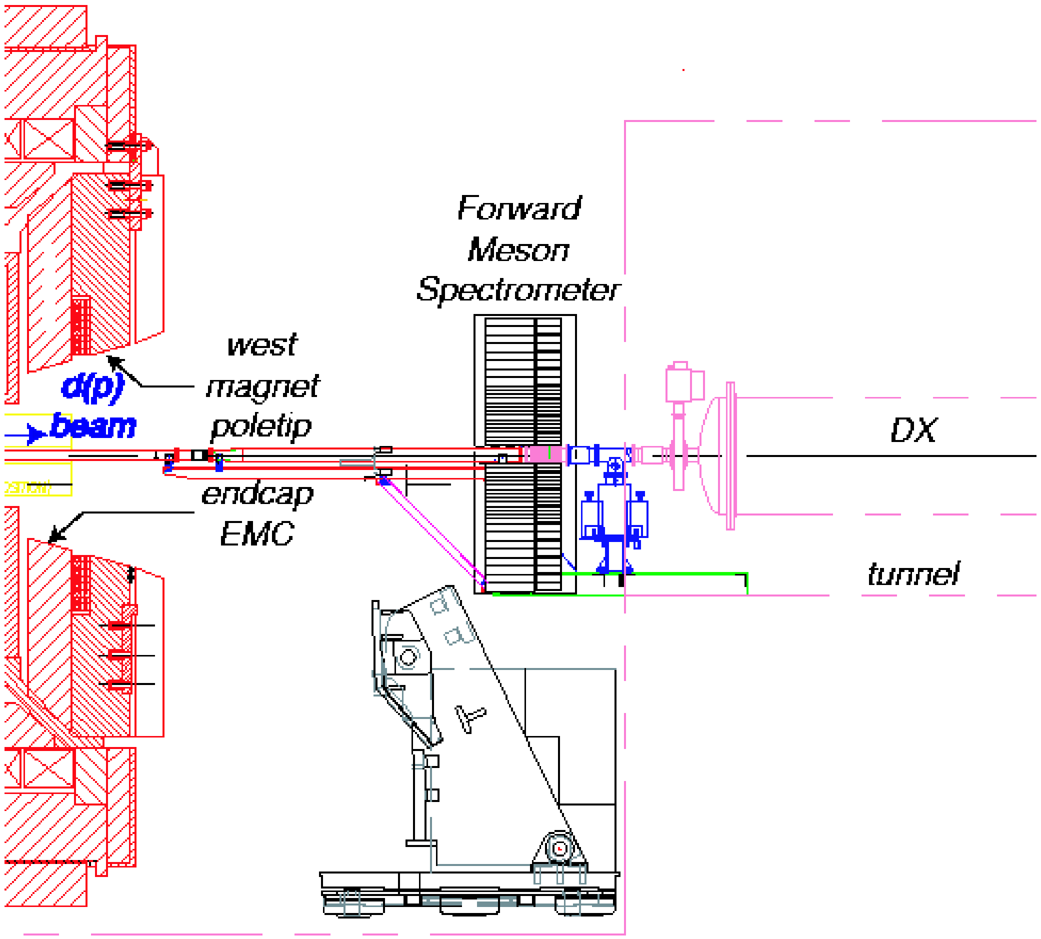
ρ, ω, η'
- M=.7 – 1.0 GeV 2-6 photons
  - 50 x 50 (3.8 cm) blocks

D^0
- M=1.8 GeV 4-6 photons
  - 90 x 90 (3.8 cm) blocks (Approximately Filling the forward region)

Forward Meson Spectrometer for ***STAR***

~1500 Pb-glass crystals
with cell size:
3.8 cm inner
7.6 cm outer





2π azimuthal extent spanning Δη≈2
~2.4m square calorimeter wall

Forward Meson Spectrometer

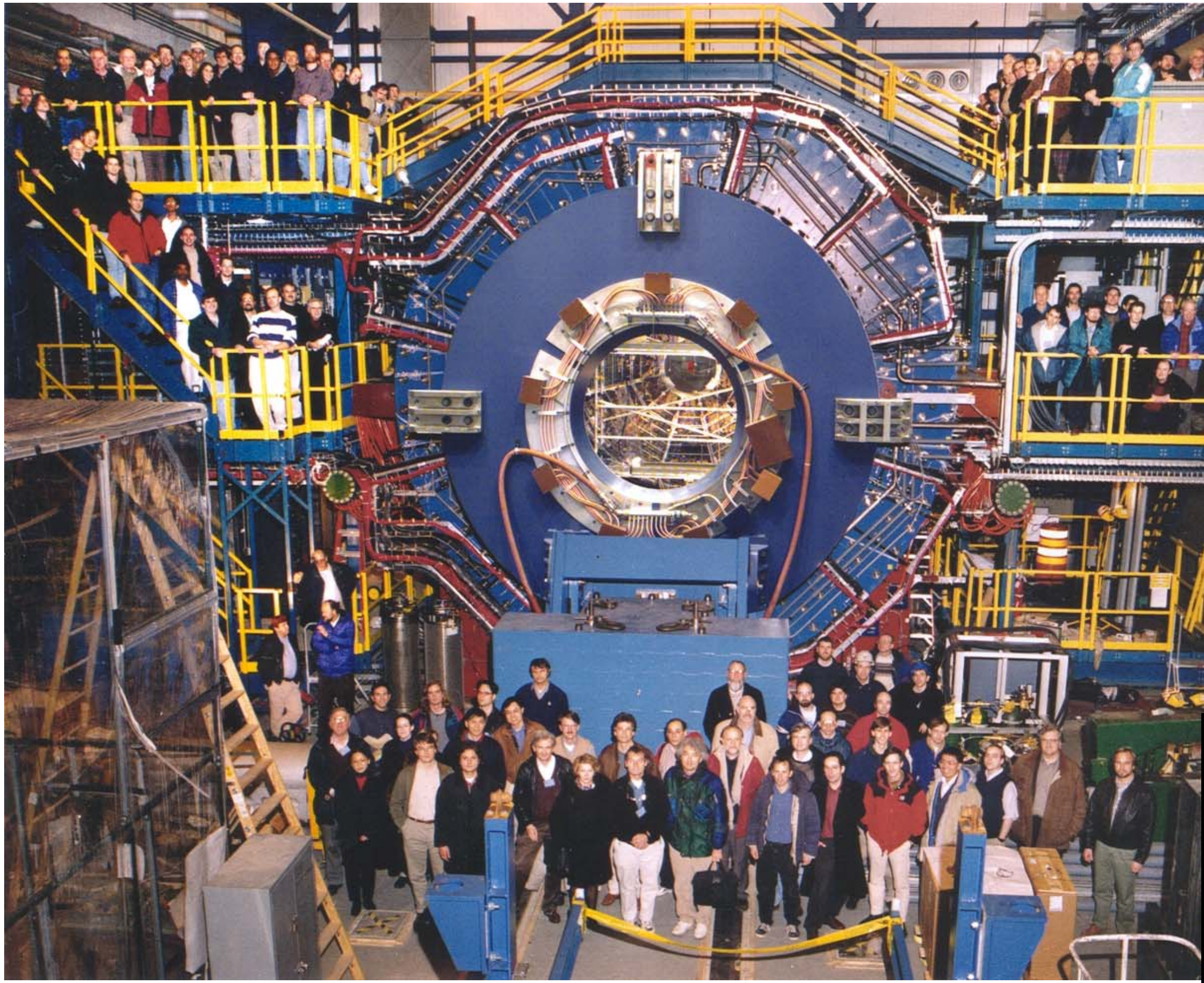
Status

- Required Pb-glass has been identified
- Electronics design underway
- Mechanical support appears straightforward
- In addition to π^0, have PYTHIA event simulation and reconstruction for
  - η (two photon decay)
  - ω (three photon decay)
  - K_S (four photon decay)
- Proposal to NSF in preparation

STAR Forward Meson Spectrometer

Physics Program

- **Origin of the transverse spin asymmetry**
  - Sivers: parton orbital motion?
  - Collins: transversity?
  - Twist-3 correlations?
- **Gluon polarization at very low x**
  - A_{LL} for forward π^0 and forward jets
  - A_{LL} for forward direct photons and γ + jets
- **Gluon density in heavy nuclei at very low x**
  - Identified meson and γ yields vs. x_F and p_T
  - Correlations with identified mesons



The STAR Collaboration

Solenoid Tracker At RHIC

566 collaborators
51 institutions
12 countries