Neutral Pion Suppression at Forward Rapidities from d+Au Collisions at STAR

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for the STAR Collaboration

XIII International Workshop on Deep-Inelastic Scattering (DIS2005)

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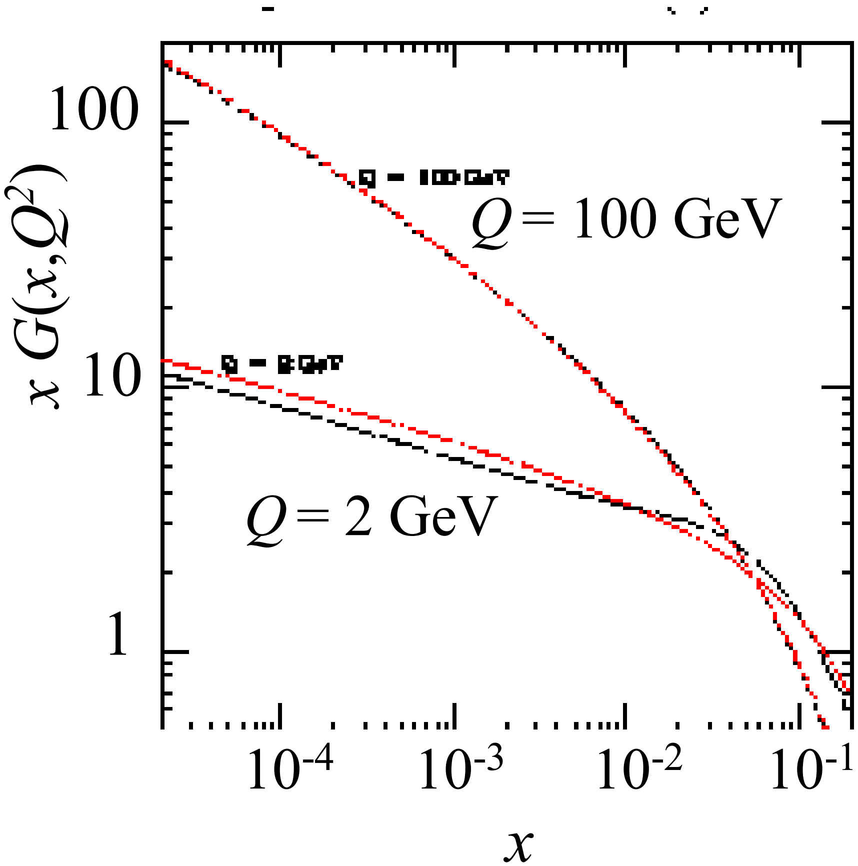
28 April 2005

Low-x physics = gluons

x = fraction of proton momentum carried by parton

The proton:

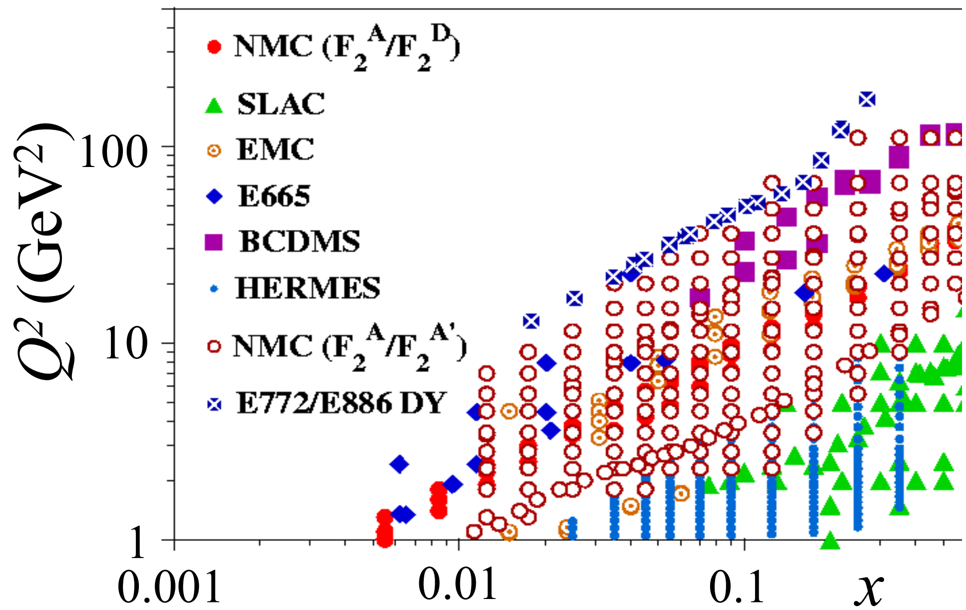
Accurate determinations of the proton's gluon structure have been extracted from scaling violations in inclusive Deep Inelastic Scattering (DIS)...



[J. Pumplin, *et al.*, JHEP 0207 (2002) 012]

The nucleus:

Naïvely expect density of gluons in nucleus ~ $A^{1/3}$...



[Hirai, Kumano, Nagai, PRC **70** (2004) 044905]

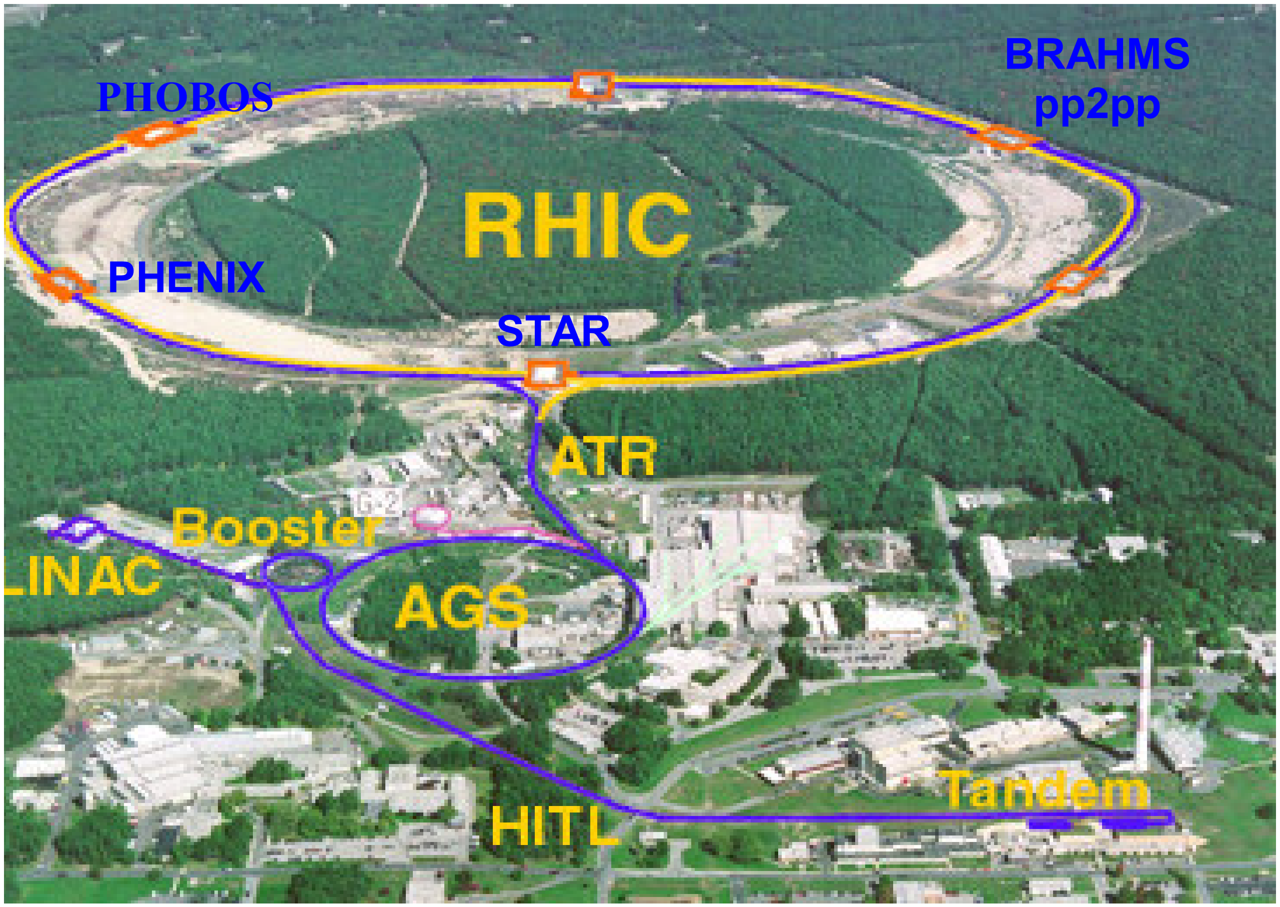
No collider data to constrain nuclear gluon distributions at low-*x*...

Problem: as x continues to decrease,

- the gluon density increases
- cross sections must remain finite

BROOKHAVEN NATIONAL LABORATORY

The Relativistic Heavy Ion Collider



Au-Au
- New state of matter
- QGP
- De-confinement

Deuteron-Au
- Nuclear modification
- Gluon saturation

Polarized proton-proton
- Nucleon Spin Structure
- Spin Fragmentation
- pQCD

RHIC is a QCD lab

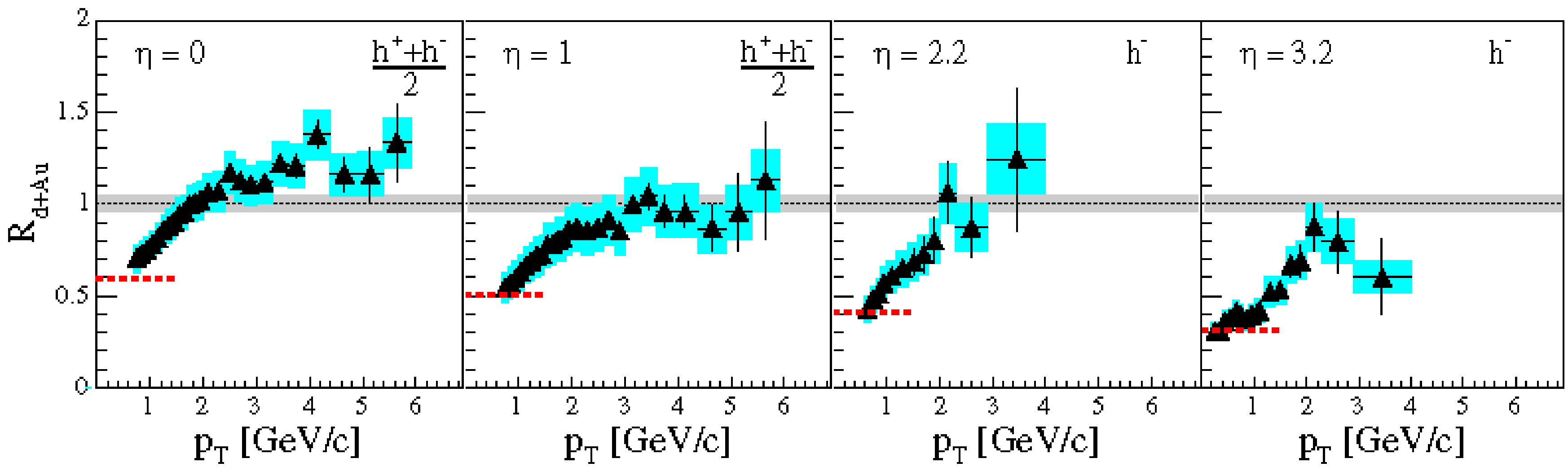
Forward Hadron Production at RHIC

Assume factorization to go from DIS to hadron collisions...

$$\sigma(x_n, x_m) \propto \sigma_{nm} f_n(x_n) f_m(x_m)$$

Nuclear modification factor:

$$R_{\mathrm{dAu}} = \frac{\sigma_{\mathrm{pp}}^{inelastic}}{\langle N_{binary} \rangle \sigma_{\mathrm{dAu}}^{inelastic}} \frac{\left. Ed^3\sigma / dp^3 \right|_{\mathrm{dAu}}}{\left. Ed^3\sigma / dp^3 \right|_{\mathrm{pp}}}$$



Suppression of inclusive h⁻ production of d+Au relative to p+p at forward rapidities… [I. Arsene, *et al*. (BRAHMS Coll.) PRL **93** (2004) 242303]

“Shadowing” in nuclear DIS emerging in hadronic collisions?

Many (recent) descriptions of low-x suppression...

A short list (*i.e.*, probably incomplete):

Saturation (Color Glass Condensate)

- Jalilian-Marian, NPA **748** (2005) 664.
- Kharzeev, Kovchegov, and Tuchin, PLB **599** (2004) 23; PRD 68 (2003) 094013.

Shadowing

- R. Vogt, PRC **70** (2004) 064902.
- Armesto, Salgado, and Wiedemann, PRL **94** (2005) 022002.

Multiple Scattering

- Qiu and Vitev, PRL **93** (2004) 262301; hep-ph/0410218.

Parton Recombination

- Hwa, Yang, and Fries, PRC **71** (2005) 024902.

Factorization breaking

- Kopeliovich, *et al.*, hep-ph/0501260.
- Nikolaev and Schaefer, PRD **71** (2005) 014023.

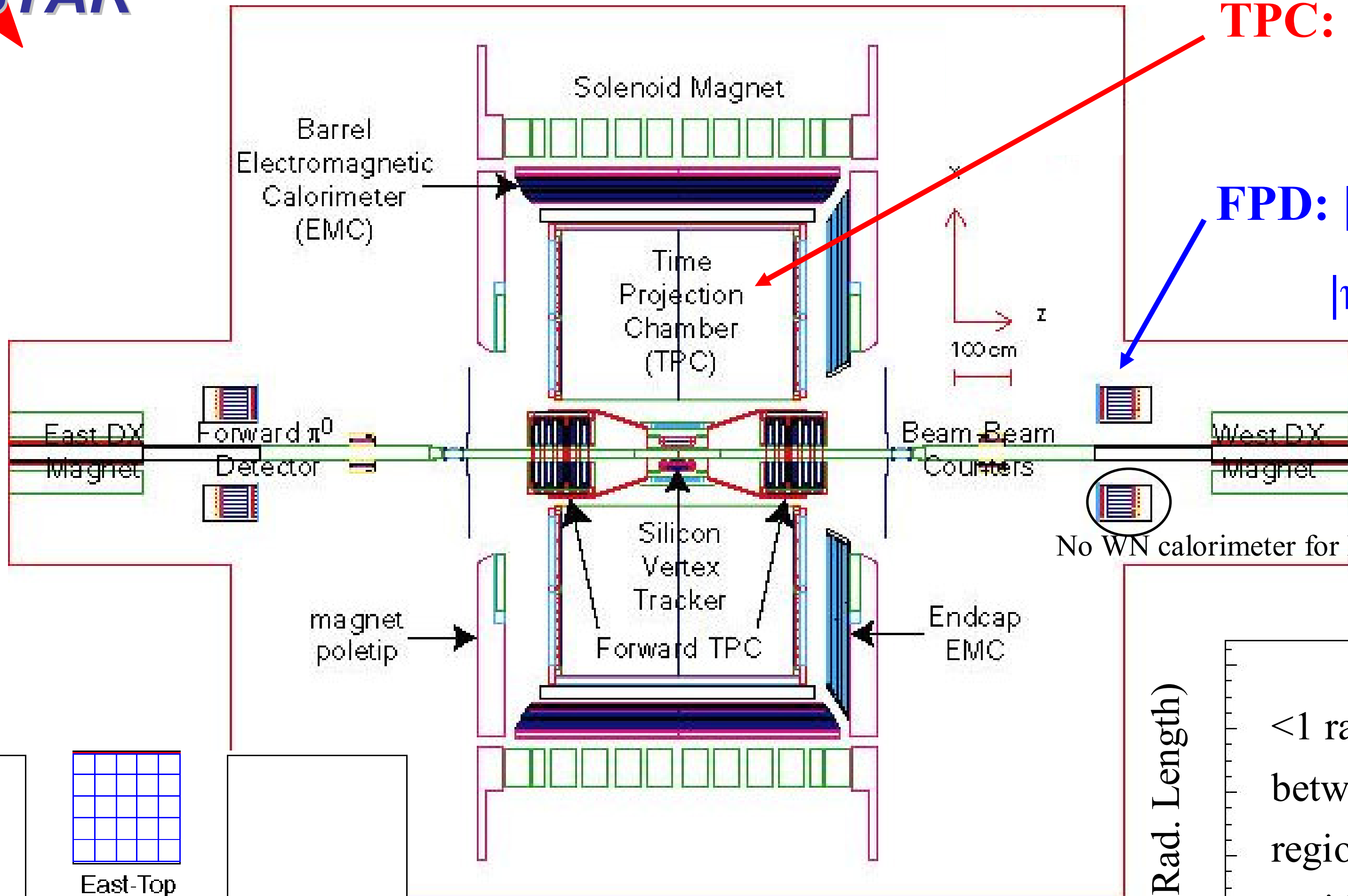
Others?

- ...

Some experimental issues that can be addressed at STAR:

- Rapidity dependence?
- Isospin?
- p+p under control?
- What x-values are probed?
- Monojet?

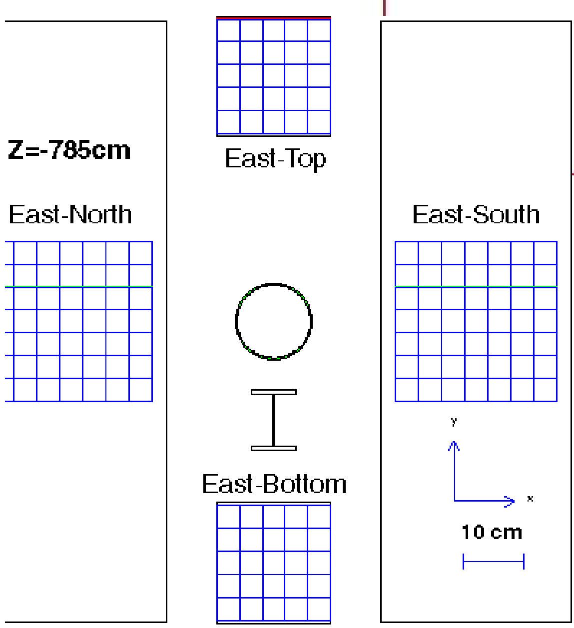
STAR Detector



TPC: -1.0 < η < 1.0

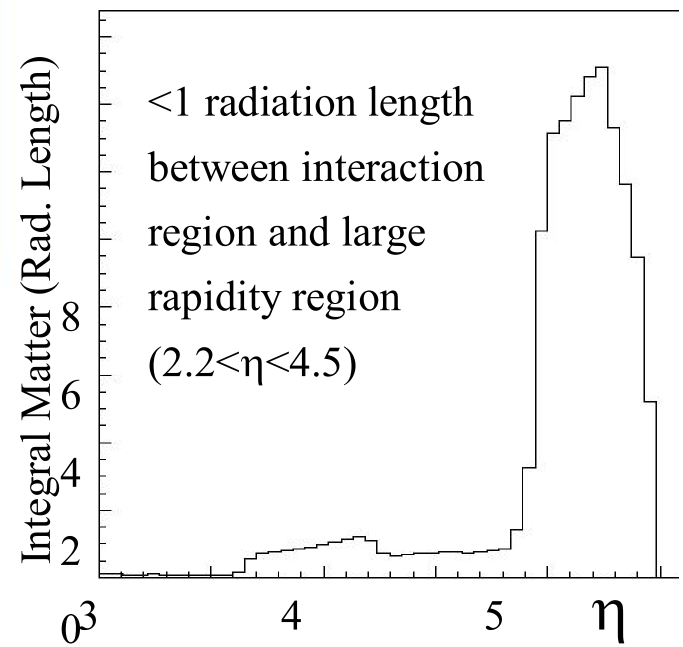
FPD: |η| ~ 3.8 (p+p)

|η| ~ 4.0 (p+p,d+Au)

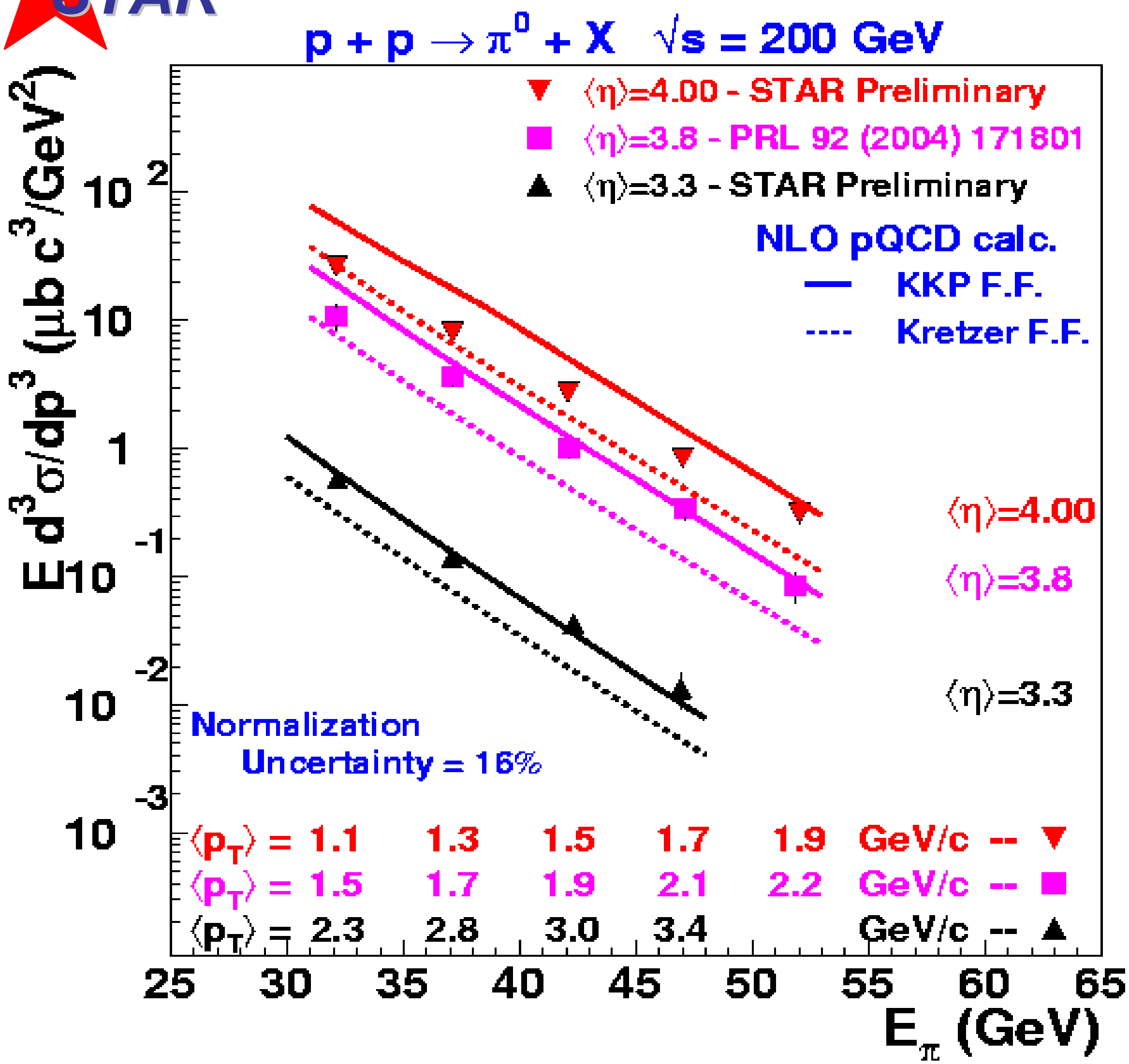


Forward π^0 Detector (FPD)

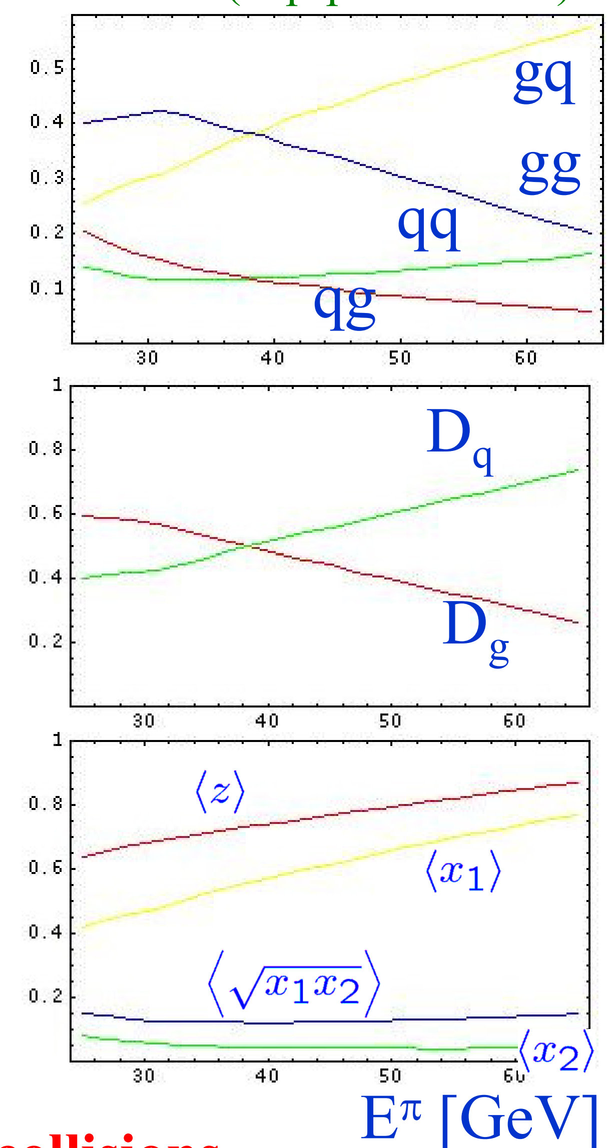
.= Pb-glass electromagnetic calorimeter + Preshower



NLO pQCD compared with forward $p + p \rightarrow \pi^0 + X$

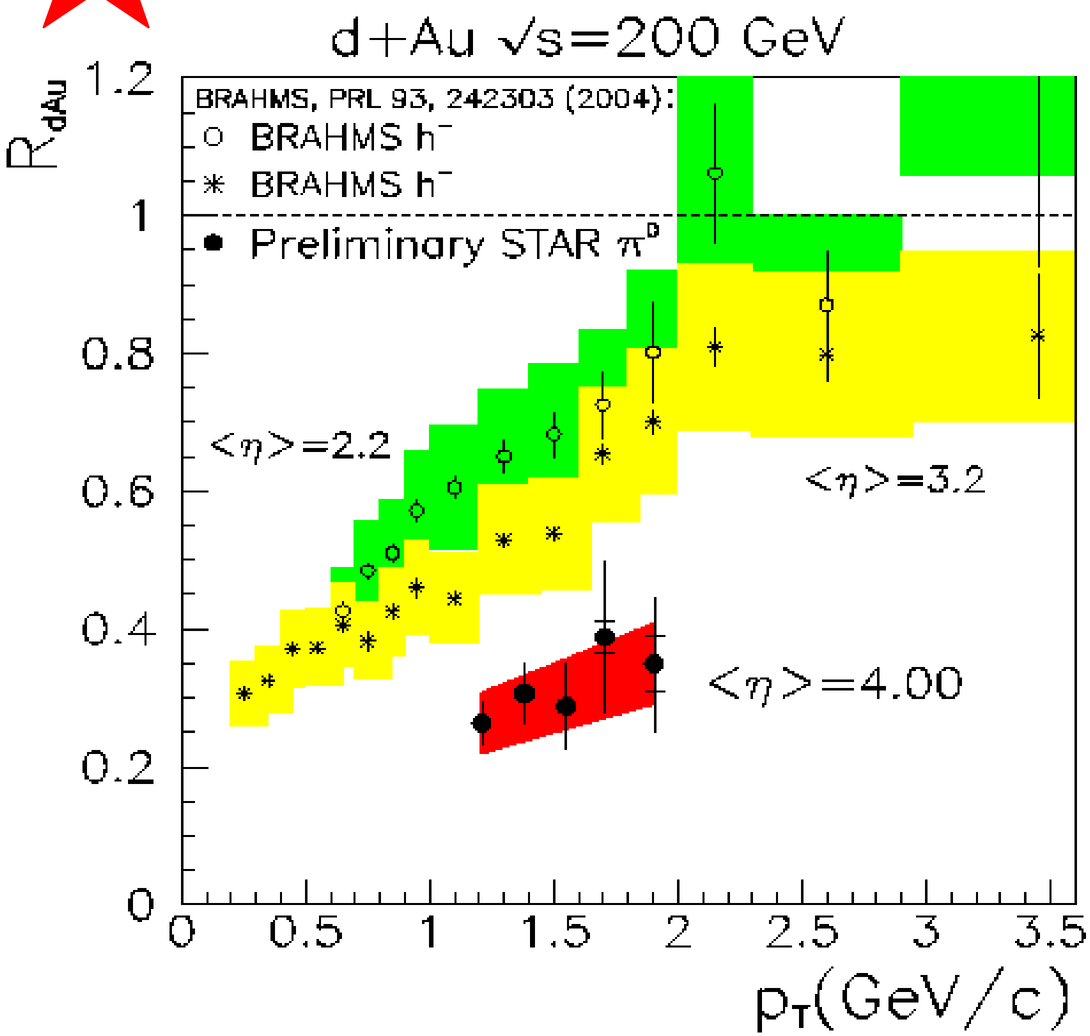


Process breakdown:
Kretzer (hep-ph/0410219)



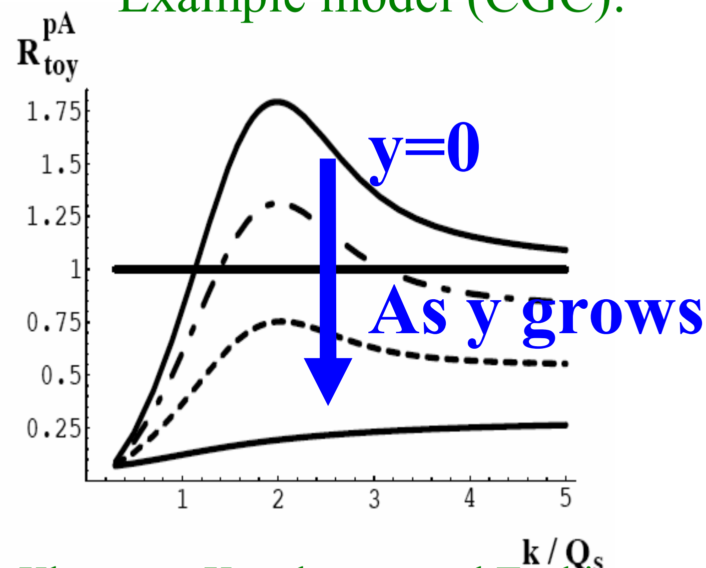
Inclusive forward π^0 production in p+p collisions consistent with NLO pQCD calculations at √s = 200 GeV, in contrast to lower √s [Bourrely and Soffer, EPJ C **36** (2004) 371]

η Dependence of R_{dAu}



$$R_{dAu} = \frac{\sigma_{pp}^{inelastic}}{\langle N_{binary}\rangle \sigma_{dAu}^{inelastic}} \frac{Ed^3\sigma/dp^3\big|_{dAu}}{Ed^3\sigma/dp^3\big|_{pp}}$$

Example model (CGC):



Kharzeev, Kovchegov, and Tuchin, Phys. Rev. D **68** , 094013 (2003)

□ Observe **significant rapidity dependence**, similar to expectations from models which **suppress gluon density** in heavy nuclei

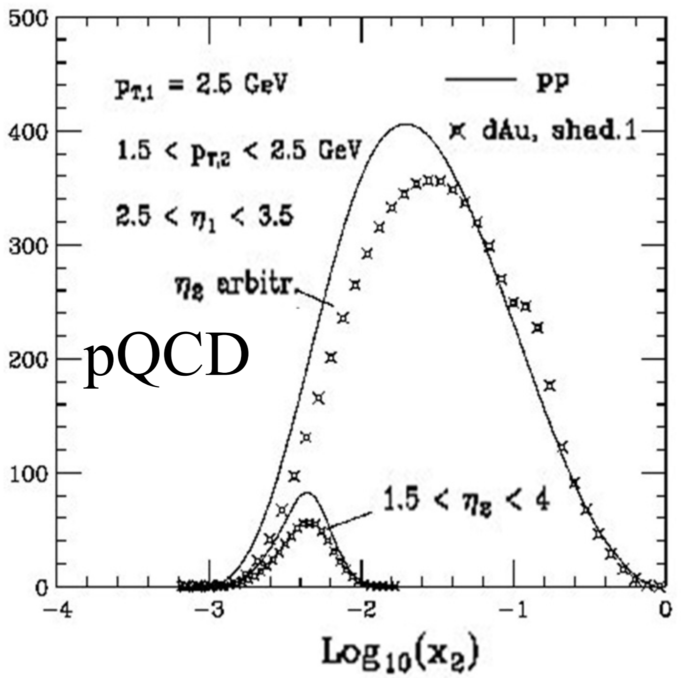
• □ R_{dAu} for □[0] **systematically below** linear extrapolation of h□ data to □=4, consistent with expectations that **p + p → h⁻ is isospin suppressed** at large η

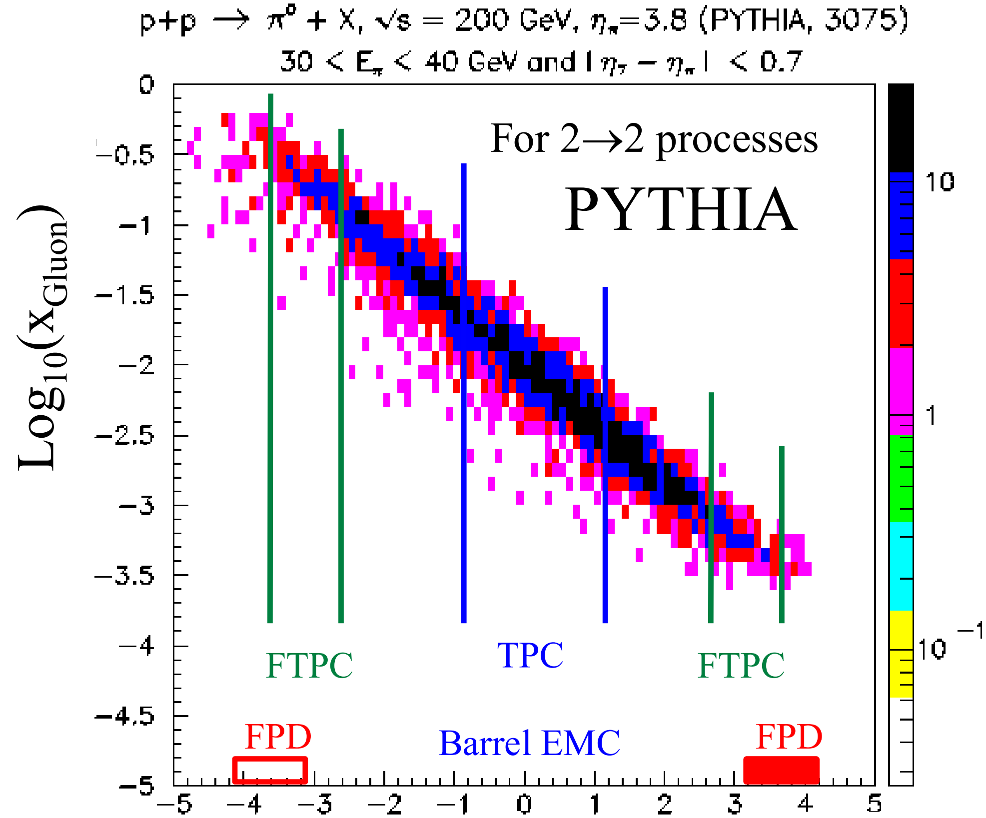
[Guzey, Strikman and Vogelsang, Phys. Lett. B **603**, 173 (2004)]

Measure two hadrons in final state

See L.C. Bland, *et al.*, hep-ex/0502040

Guzey, Strikman, and Vogelsang, Phys. Lett. B **603** (2004) 173.





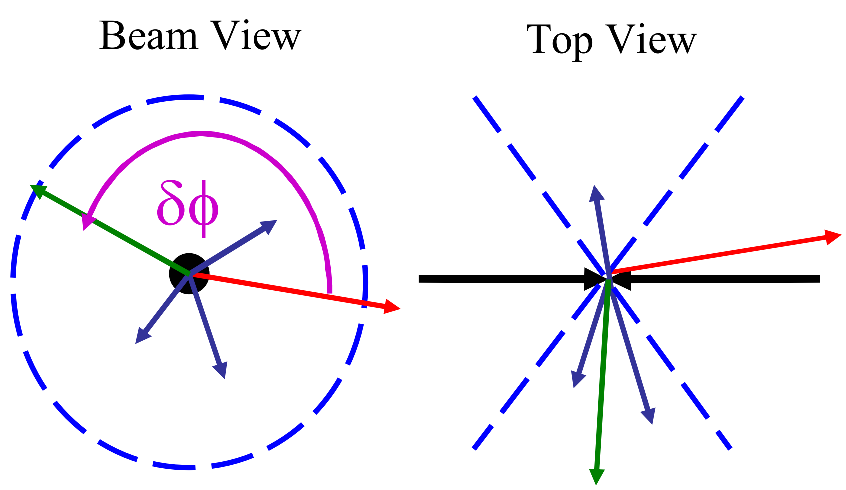
- For 2 2 processes:
  - x_{Bj} correlated with of away-side particle
  - strong azimuthal correlation expected (back-to-back peak)

$$x^+ = \frac{\cdots}{\sqrt{s}}\left(e^{+\eta 1} + e^{+\eta 2}\right) \rightarrow x_{\cdots}$$

$$x^- = \frac{\cdots}{\sqrt{s}}\left(e^{-\eta 1} + e^{-\eta 2}\right) \rightarrow \frac{\cdots}{\sqrt{s}} e^{-\eta 2}$$

 Analysis of di-hadron azimuthal and rapidity correlations can give insight on particle production mechanism...

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



Trigger by forward π^0

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

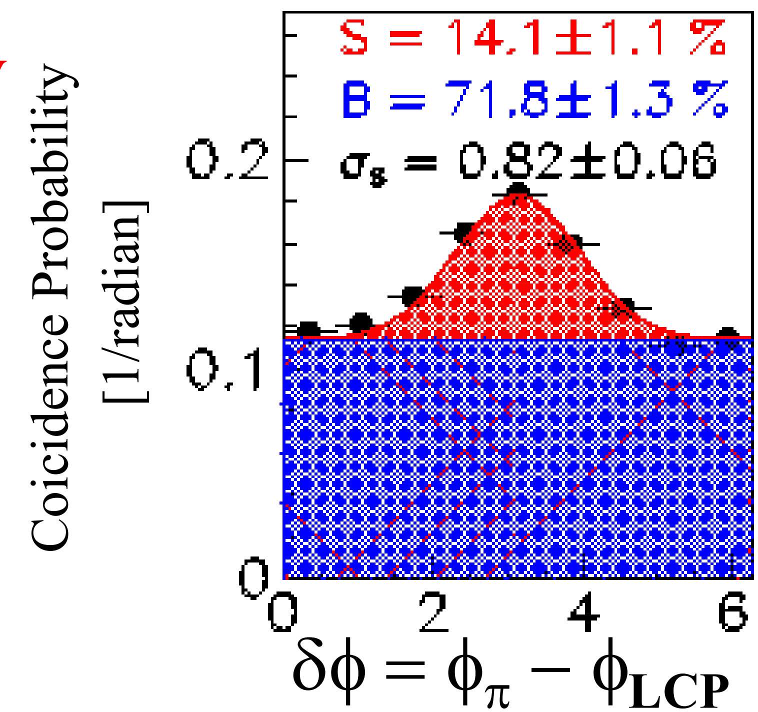
Midrapidity $h^\pm$ tracks in TPC

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

Leading Charged Particle(LCP)

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

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



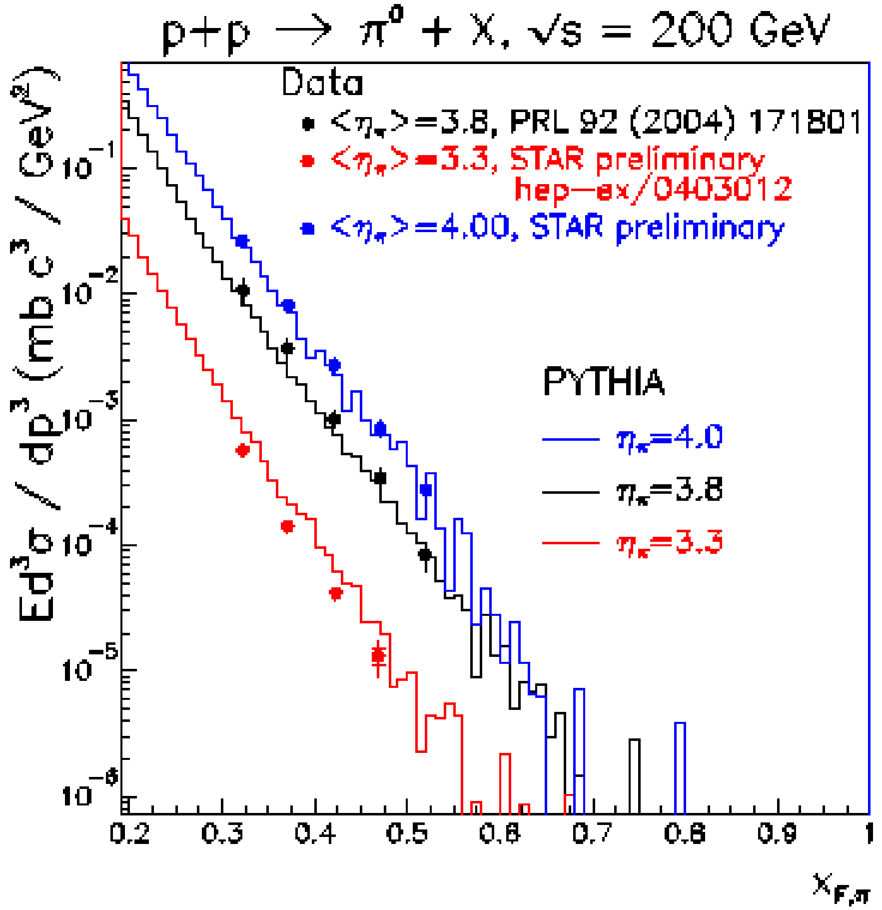
S = Probability of "correlated" event under Gaussian

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

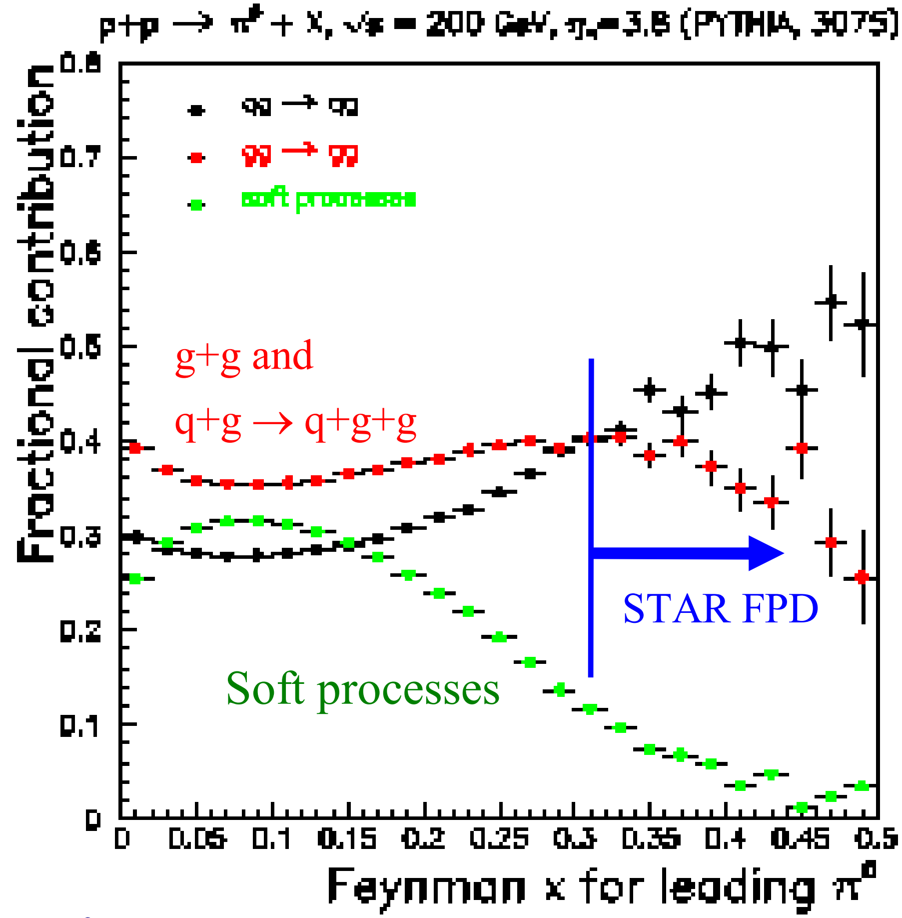
σ_s = Width of Gaussian

PYTHIA: a guide to the physics

Forward Inclusive π^0 Cross-Section:



Subprocesses involved:

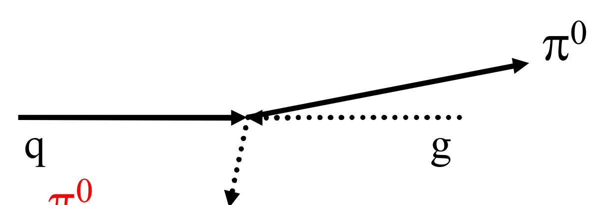


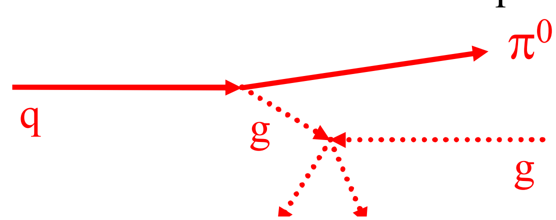
• PYTHIA ***prediction*** agrees well with the inclusive π^0 cross section at η~3-4

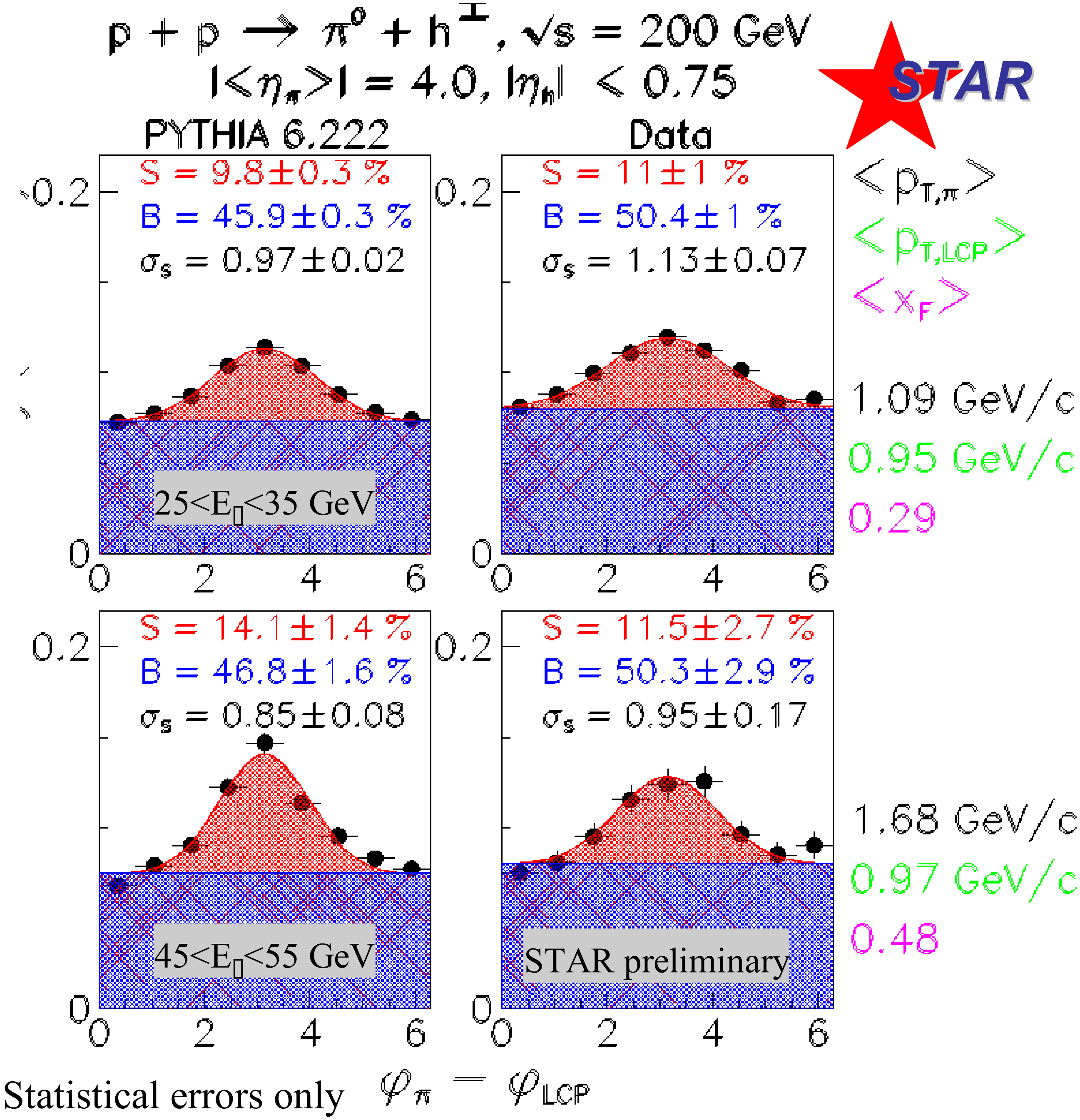
• Dominant sources of large x_F π^0 production from:

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

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







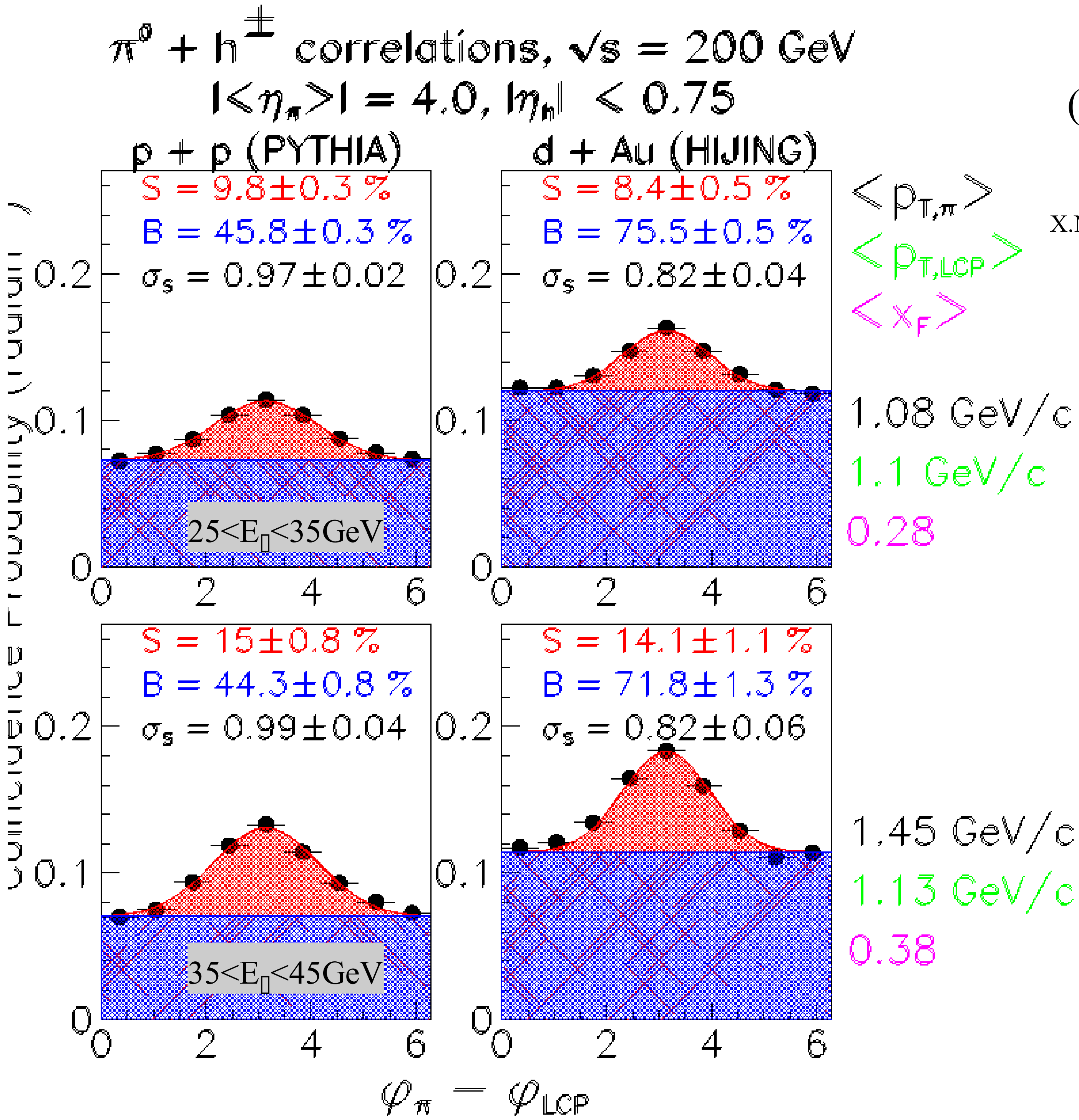
PYTHIA=LO pQCD with parton showers (including detector effects), predicts

- S grows with $\langle x_F \rangle$ ($\langle p_{T,\pi} \rangle$)
- σ_S decreases with $\langle x_F \rangle$ ($\langle p_{T,\pi} \rangle$)

PYTHIA prediction agrees with p+p data

Larger intrinsic k_T required to fit data (see Abazov, *et al.*, hep-ex/0409040)

⇒ Partonic scattering good language to discuss forward π^0 production from p+p collisions at $\sqrt{s}$ = 200 GeV...



Expectation from HIJING
(PYTHIA+shadowing +nuclear effects)

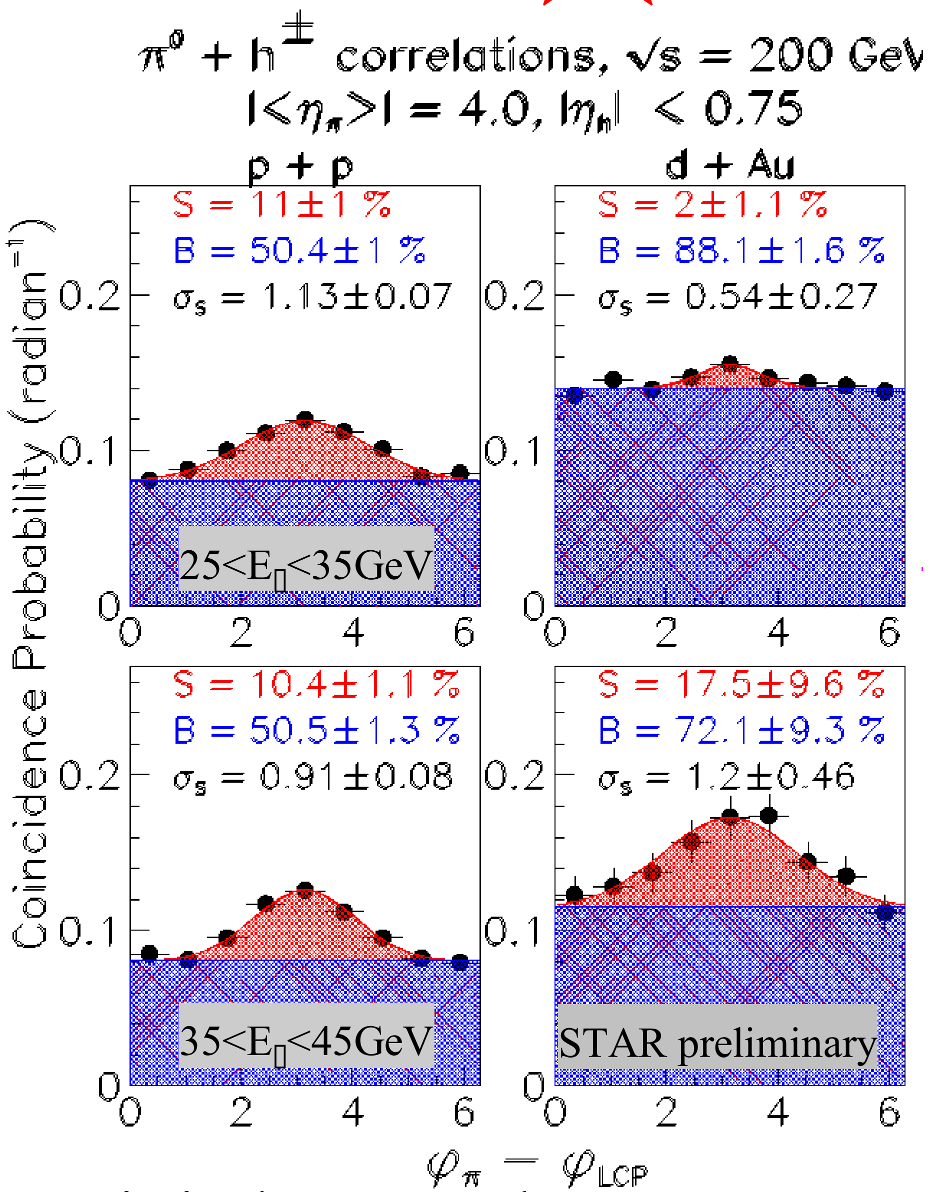
X.N.Wang and M Gyulassy, PR D44(1991) 3501

with detector effects

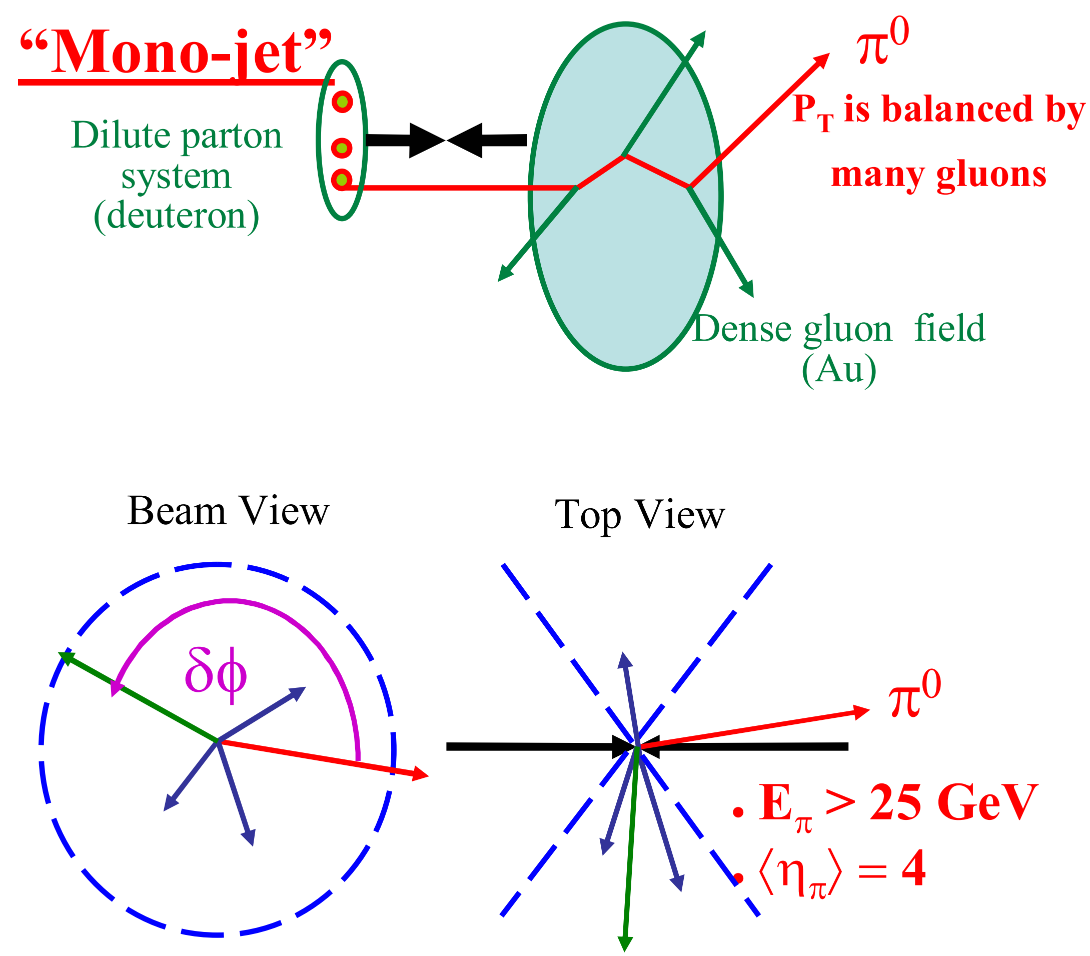
- **HIJING predicts clear correlation in d+Au**
- Small difference in "S" and "σ_s" between p+p and d+Au
- "B" is bigger in d+Au due to increased particle multiplicity at midrapidity

Exploratory d+Au → π⁰ + h^± + X Correlations

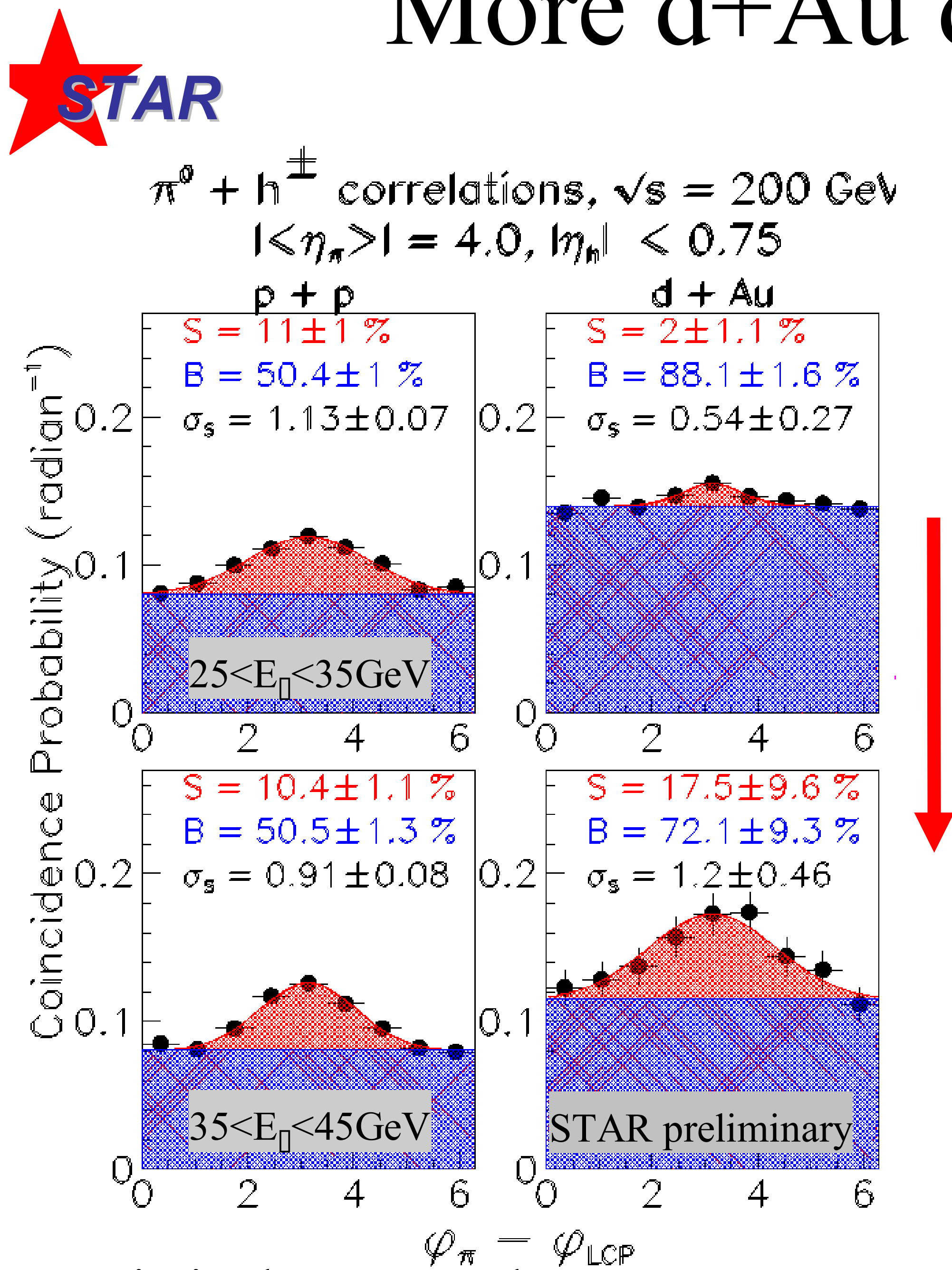
STAR Preliminary Data



Statistical errors only



More d+Au data needed…

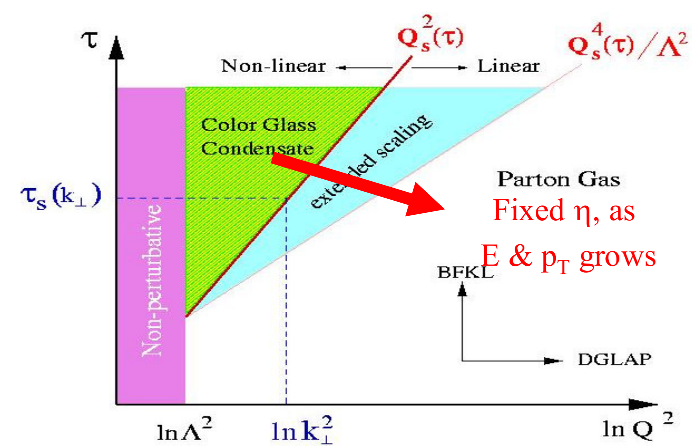


Statistical errors only

Large Δη π^0+$h^\pm$ correlations:

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

Consistent with CGC picture



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

More data needed to measure dependence on p_T, , flavor…

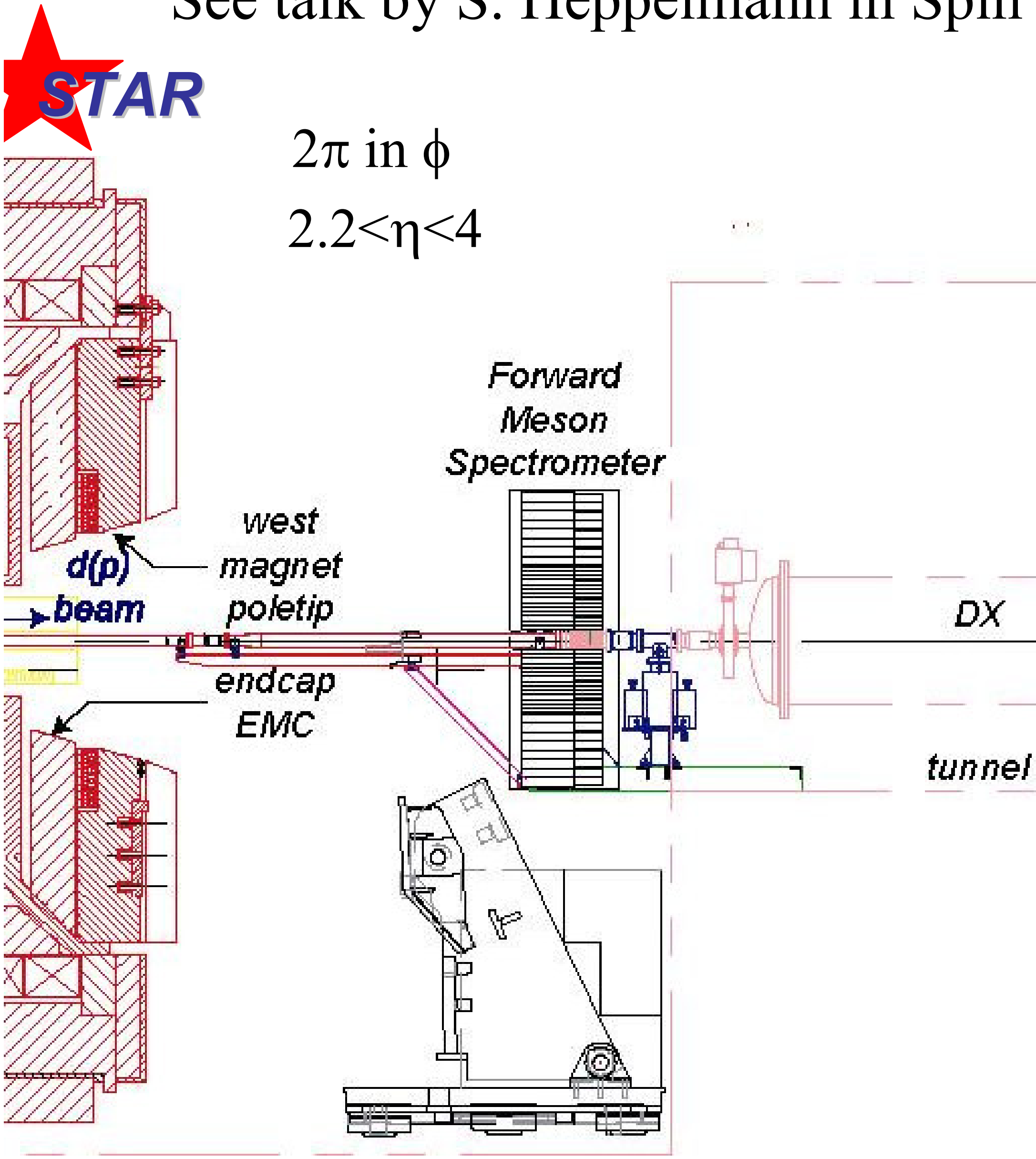
Outlook at STAR: Forward Meson Spectrometer

L. C. Bland, *et al.*, hep-ex/0502040

See talk by S. Heppelmann in Spin parallel session, 29 April

2π in ϕ

$2.2<\eta<4$

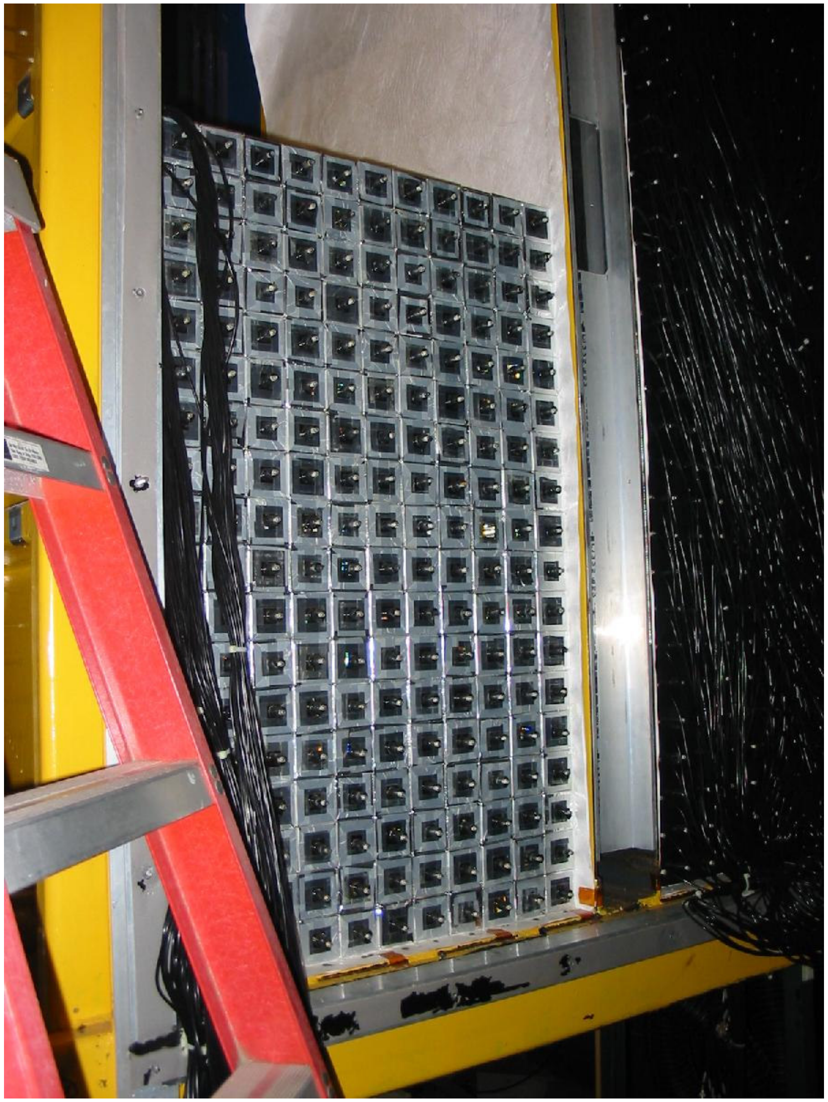


Physics Motivation:

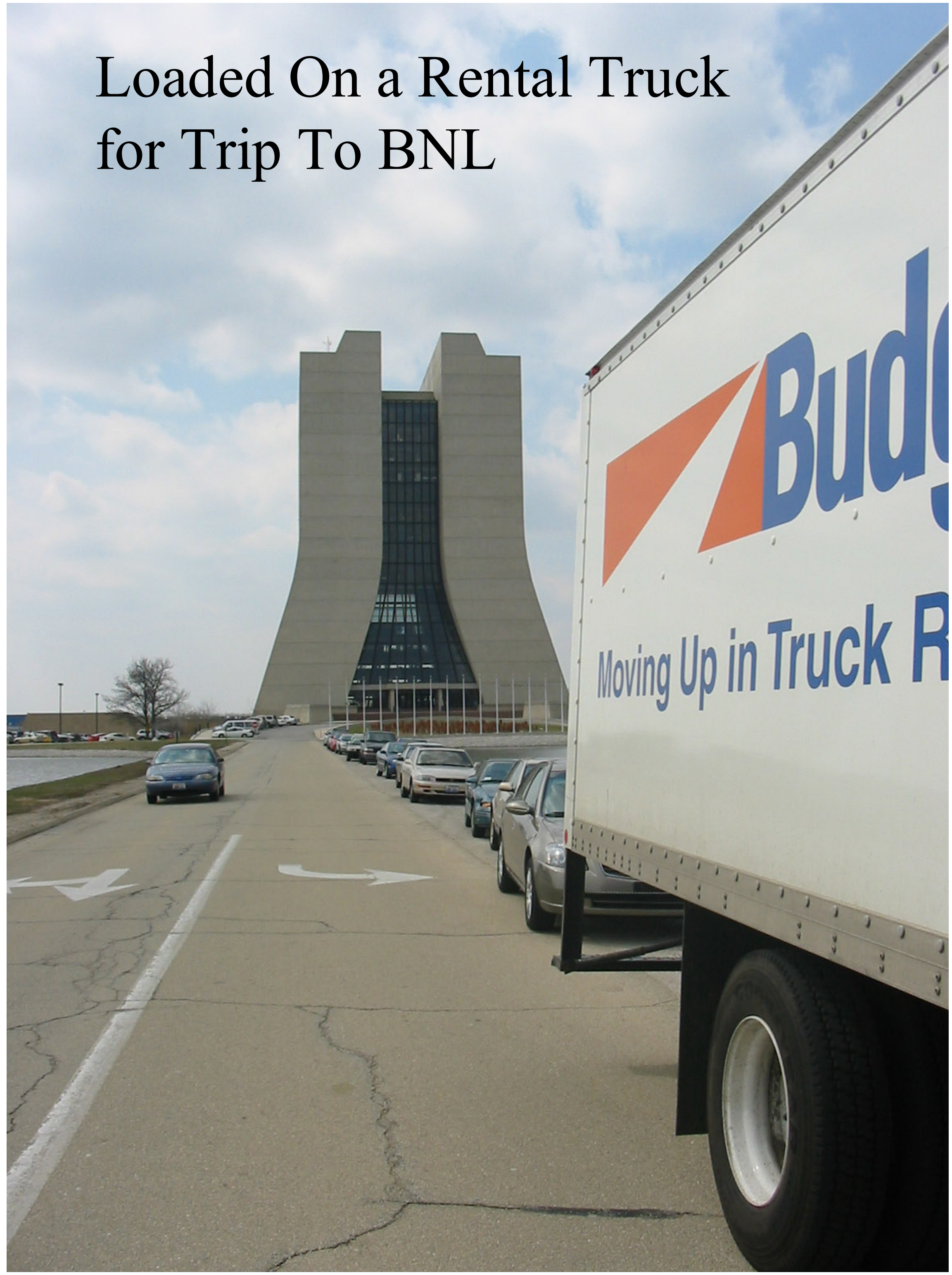
- probing gluon saturation in p(d)+A collisions via…
  - large rapidity particle production ($\pi^0,\eta,\omega,\eta',\gamma,K^0,D^0$) detected through all γ decays
  - forward π^0–π^0 probes gluons with smallest x in Au nucleus
  - di-jets with large rapidity interval (Mueller-Navelet jets): full EM calorimetry coverage from 4 < □ < -1
- disentangling dynamical origins of large x_F analyzing power in $p_\uparrow+p$ collisions

□ To be built from existing calorimetry from FNAL E831 (Colorado)

New FMS Calorimeter



Lead Glass From FNAL E831



Loaded On a Rental Truck
for Trip To BNL

Conclusions

Forward □ production at □s = 200 GeV:

- ... is consistent with partonic scattering calculations in p+p collisions
    - Inclusive cross section agrees with NLO pQCD and PYTHIA
    - Large □ correlations agree with PYTHIA
  - Selects collisions of high-x quarks with low-x gluons

- ... is different in exploratory d+Au collisions (d-side):
    - Inclusive yield normalized to p+p is suppressed
        - Trend expected in models that suppress gluon density in nuclei
        - Shows evidence of isospin effects
    - Large □ correlations are suppressed relative to p+p
        - Direction of suppression qualitatively consistent with CGC

... More data and quantitative theoretical understanding are needed to make definitive physics conclusions…

The tools are coming into place to study low-*x* physics at RHIC

Backup transparencies

Inclusive π^0 cross section vs. p_T at fixed x_F

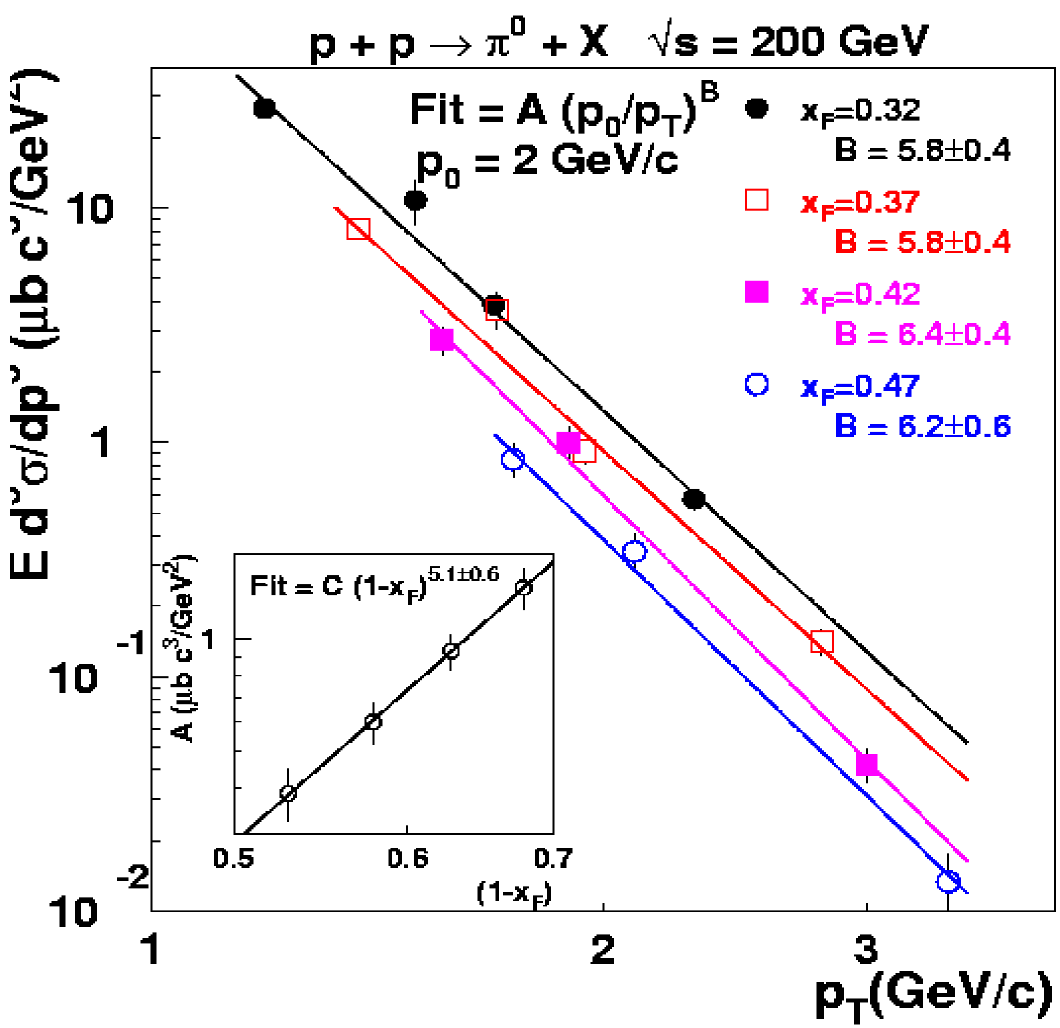
Similar analyses performed prior:

CERN ISR [J. Singh, *et al.*, (CHLM Collab.) NP **B140**, 189 (1978)]

- π^0 production at $\sqrt{s}$=45 GeV, $0.55<p_T<1.05$ GeV/c, $x_F>0.3$

BNL RHIC [S. S. Adler, *et al.*, (PHENIX Collab.) PRL **91**, 241803 (2003)]

- π^0 production at $\sqrt{s}$=200 GeV, $1<p_T<14$ GeV/c, $x_F=0$



CONCLUSIONS:

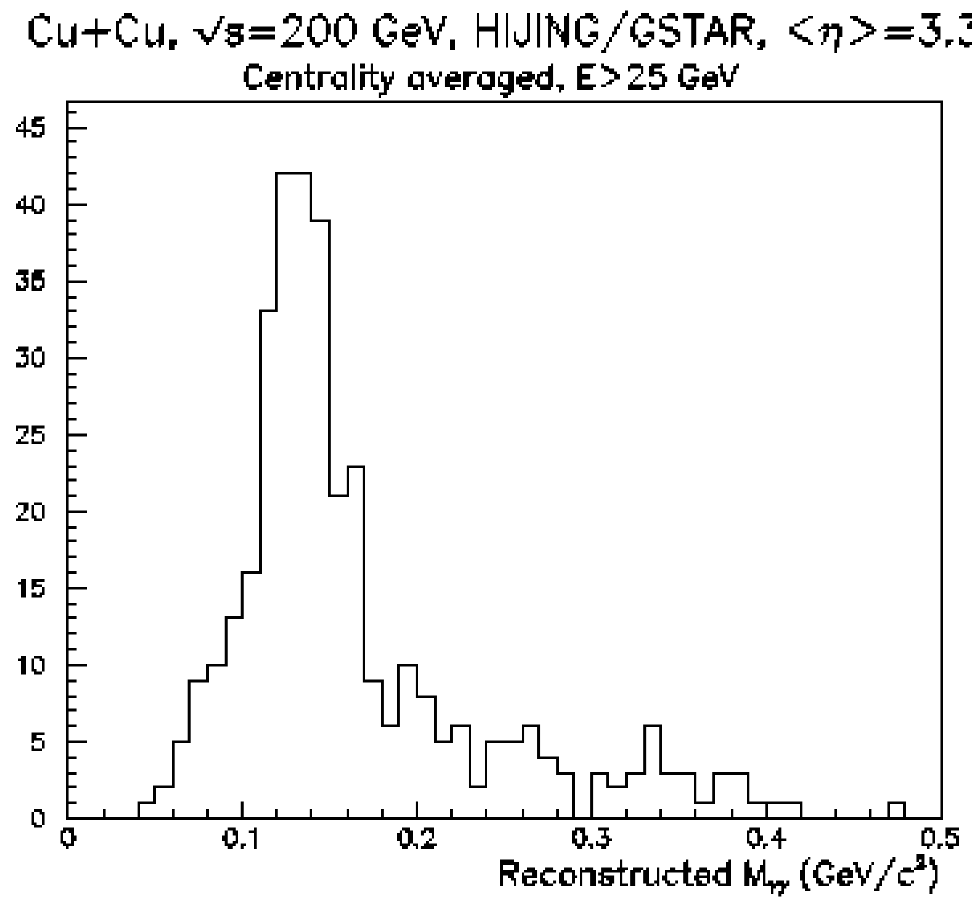
- For $0.3<x_F<0.5$, π^0 production:
  - **$\sim (1/p_T)^6$**
  - **independent of x_F**
- At p_T=2 GeV/c, π^0 production:
  - **$\sim (1-x_F)^5$**
  - ISR at p_T=1.05 GeV/c, $x_F>0.3$:
    - π^+: $0.12\,(1-x_F)^{4.35} + 0.41\,(1-x_F)^{2.93}$
    - π^-: $0.55\,(1-x_F)^{5.24} + 0.09\,(1-x_F)^{3.02}$

Near-Term Future Plans

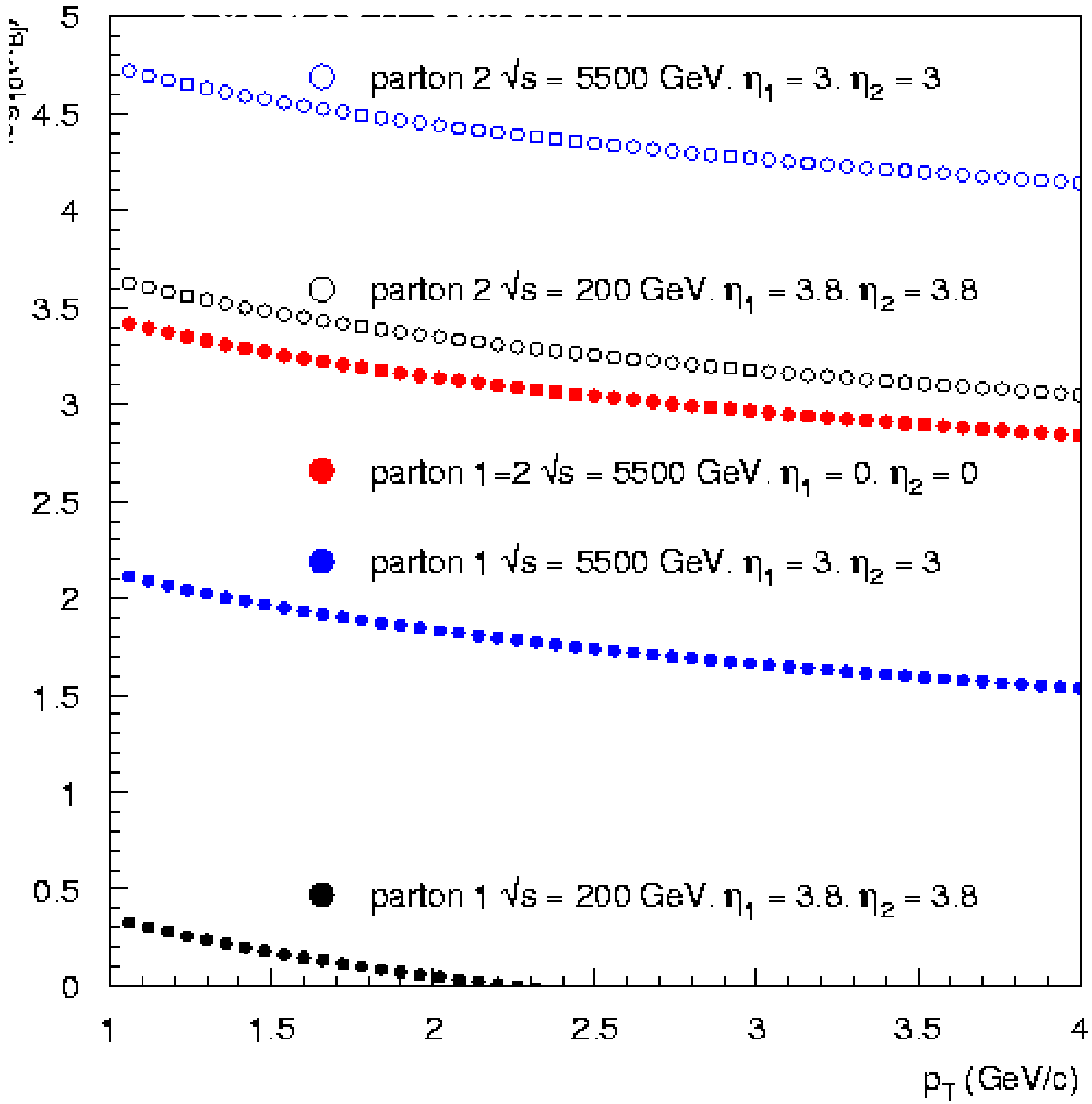
Simulations suggest that forward detection is feasible in centrality-averaged Cu+Cu collisions at $\sqrt{s}$=200 GeV. In addition to establishing R_{CuCu} at large rapidity, the FPD can trigger full STAR readout to examine particle correlations with large-rapidity π^0. This can be useful to study flavor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

reconstruction of

HIJING + GEANT simulations



x_{Bj} at RHIC and LHC



Collinear partons with momentum fractions x^+, x^- elastically scatter to η1, η2:

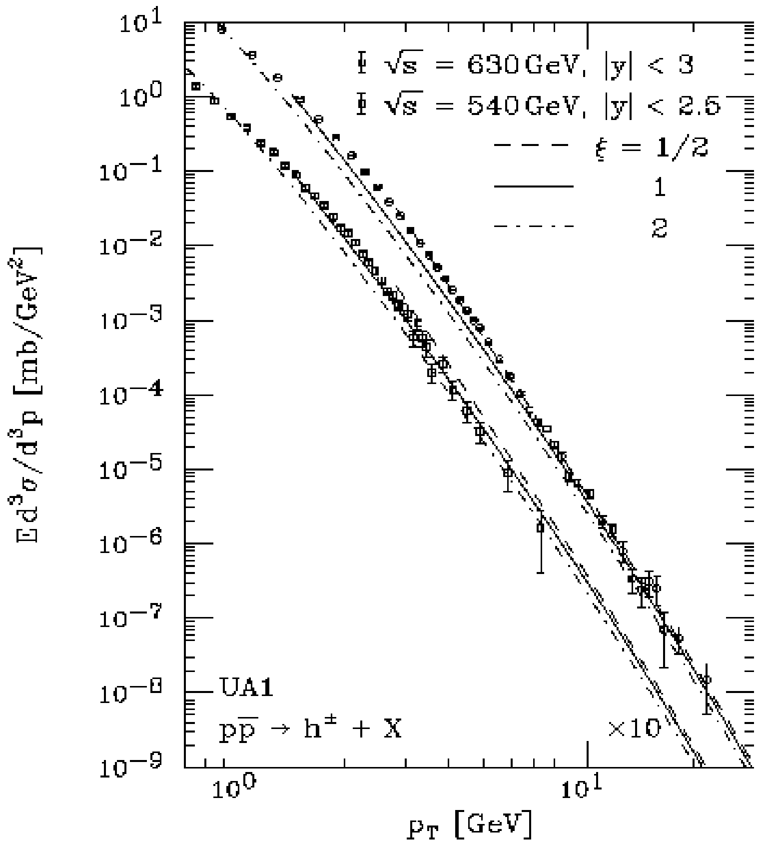
$$x^+ = \frac{p_T}{\sqrt{s}}\left(e^{+\eta 1} + e^{+\eta 2}\right) \to x_F$$

$$x^- = \frac{p_T}{\sqrt{s}}\left(e^{-\eta 1} + e^{-\eta 2}\right) \to \frac{p_T}{\sqrt{s}} e^{-\eta 2}$$

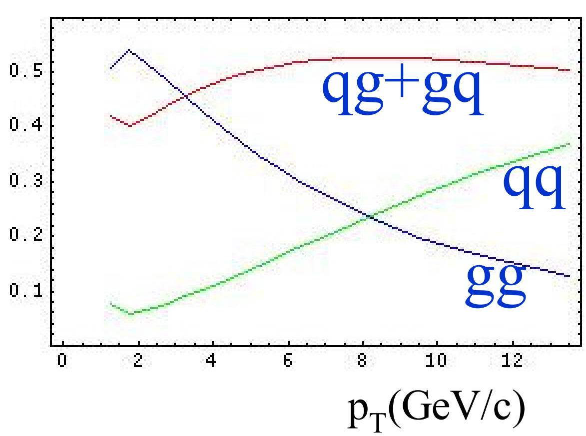
New kinematic regimes will soon be explored in nuclei both at RHIC and at the LHC…

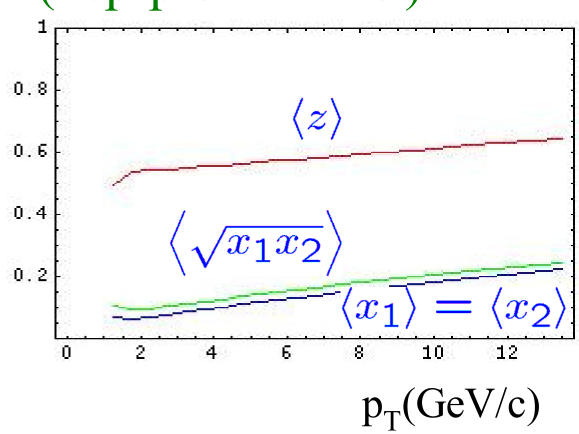
NLO pQCD compared with midrapidity p+p

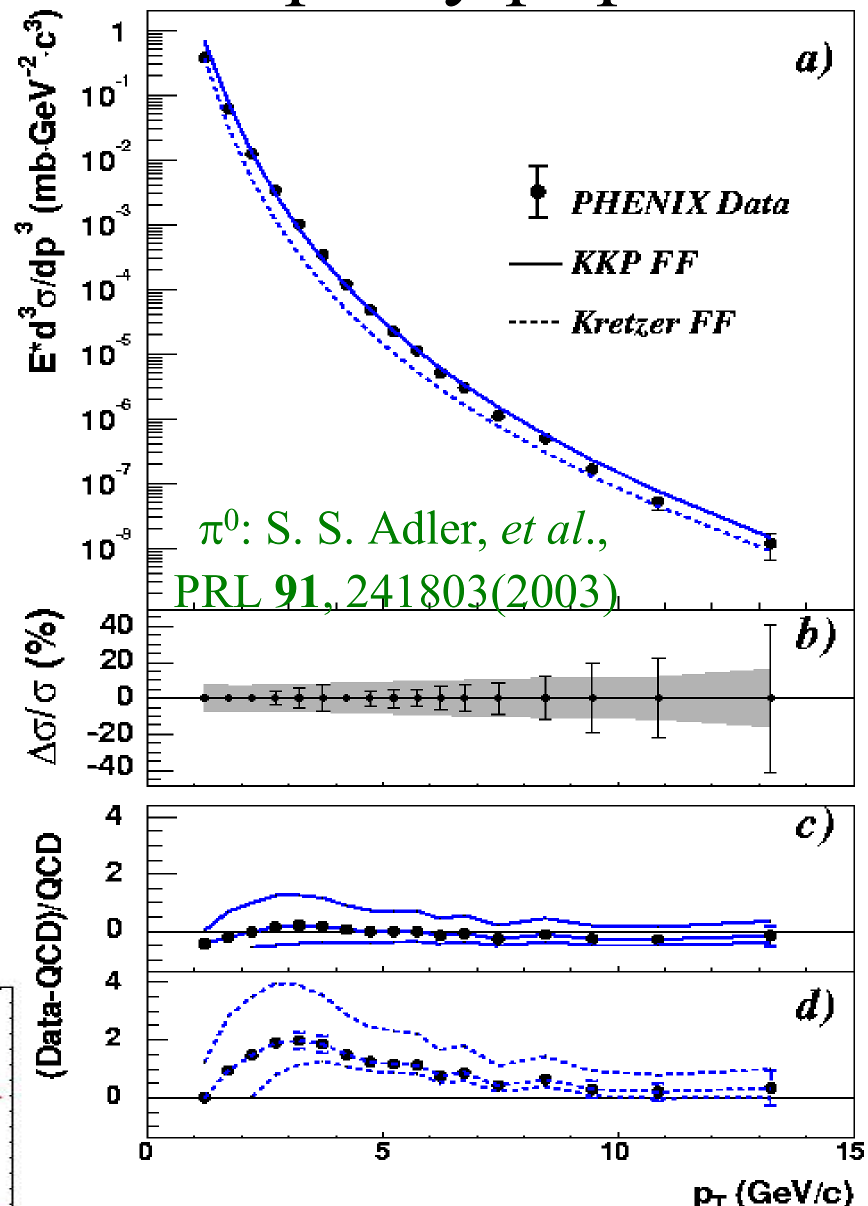
Analysis of h$^{\pm}$: KKP, NP **B597**, 337 (2001)



Process breakdown: Kretzer (hep-ph/0410219)



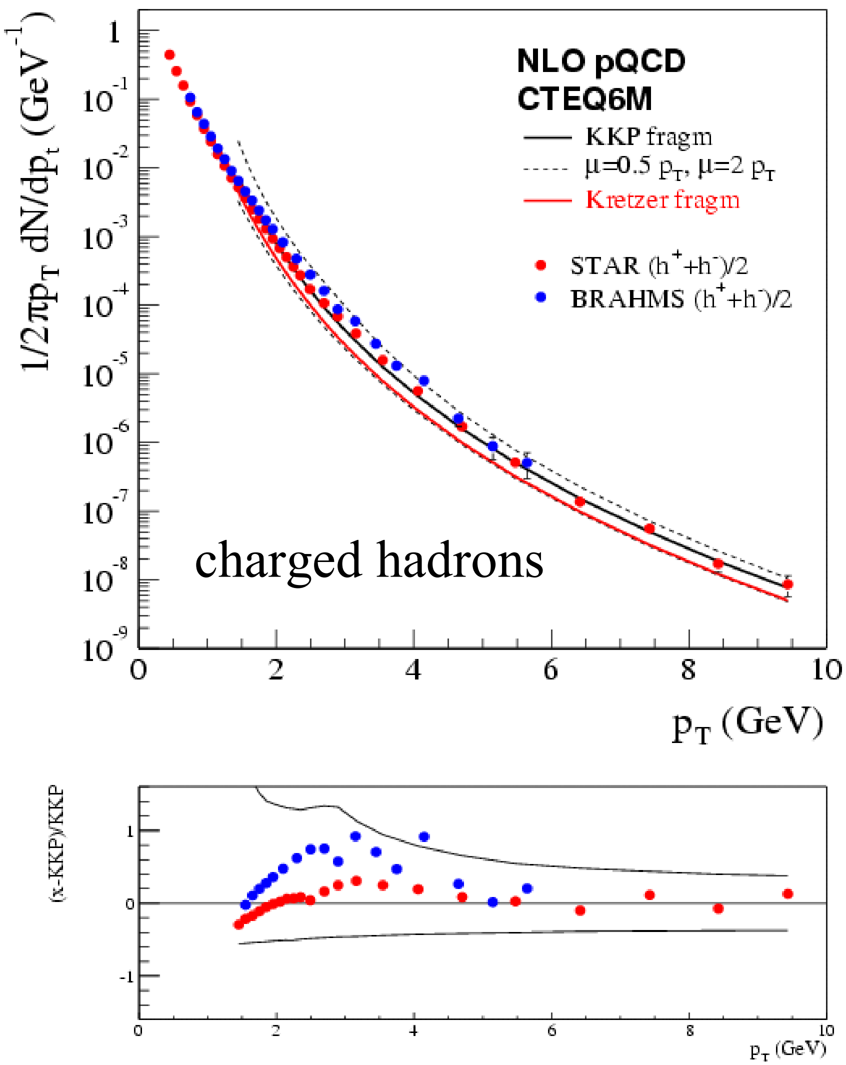


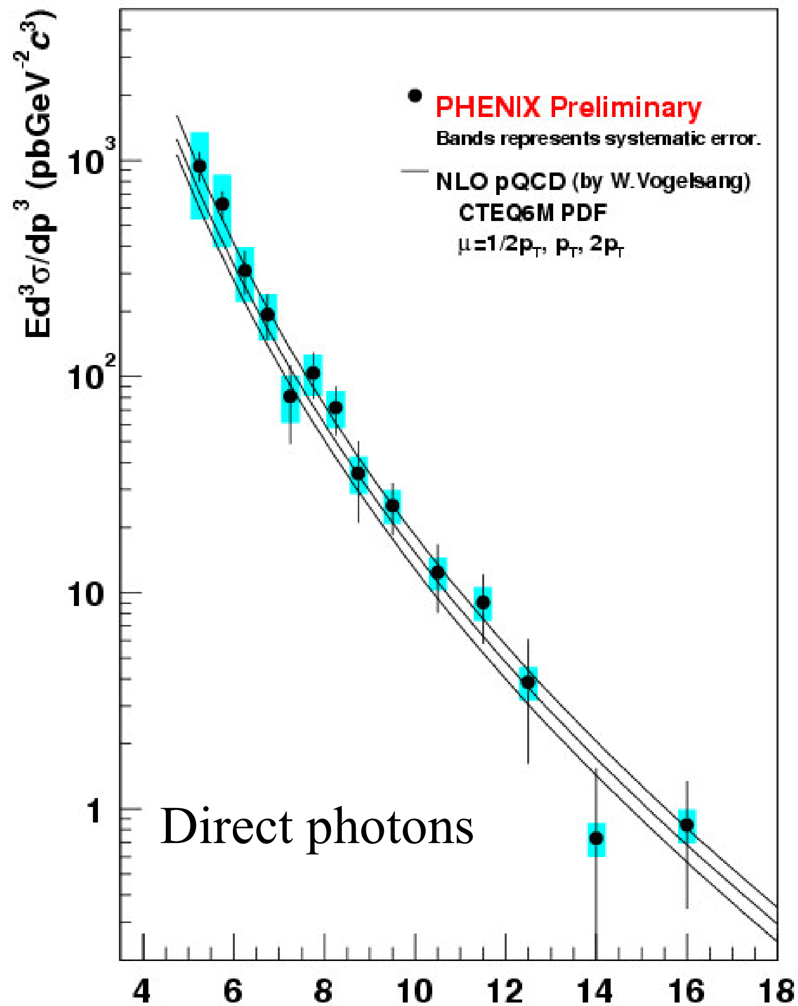


π^0: S. S. Adler, *et al.*, PRL **91**, 241803(2003)

Partonic scattering good model to describe p+p collisions at $\sqrt{s}$ = 200 GeV

p+p midrapidity production cross sections in comparison to NLO pQCD



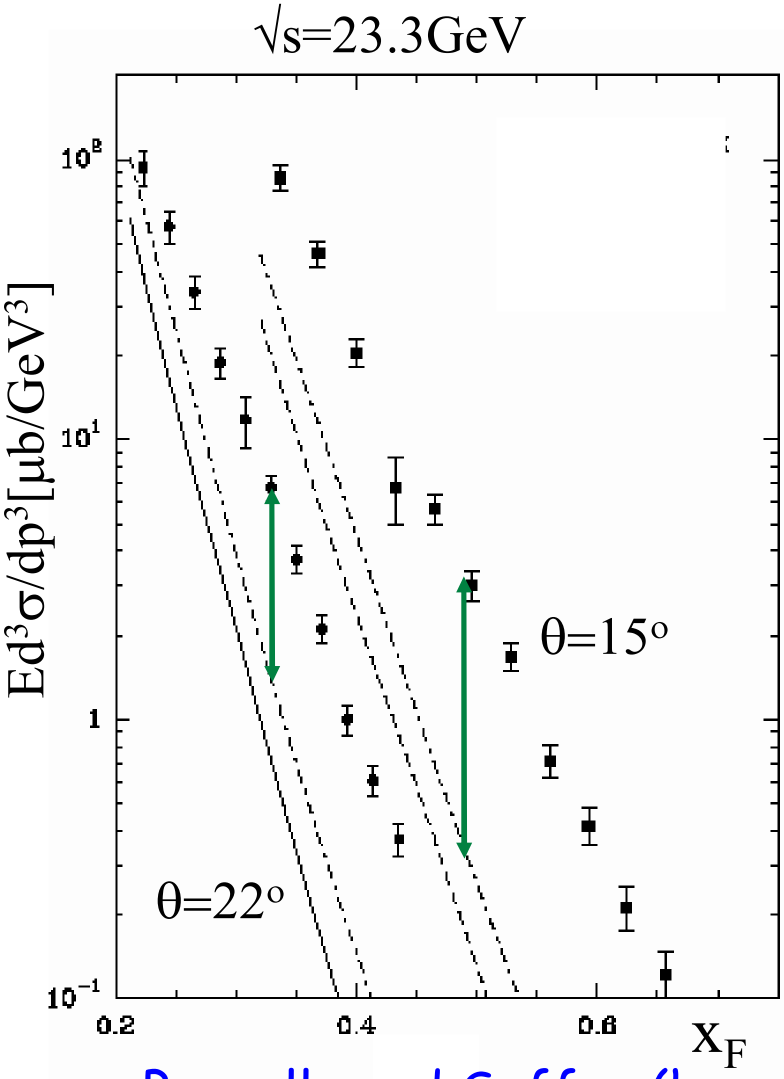


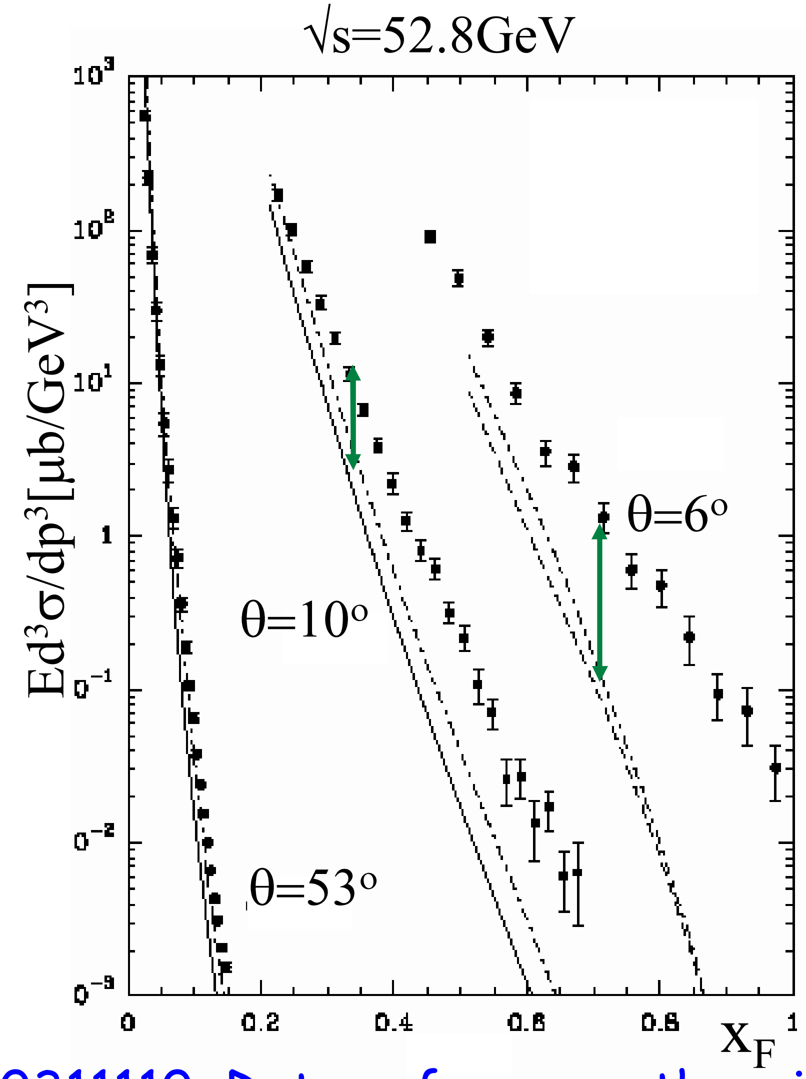
PHENIX, hep-ex/0502006

Fixed order pQCD calculations agree with data for several different reactions...

Forward π^0 Production in p + p collisions at $\sqrt{s} << 200$ GeV

Data-pQCD difference at p_T=1.5GeV/c





2 NLO calculation with different scale:

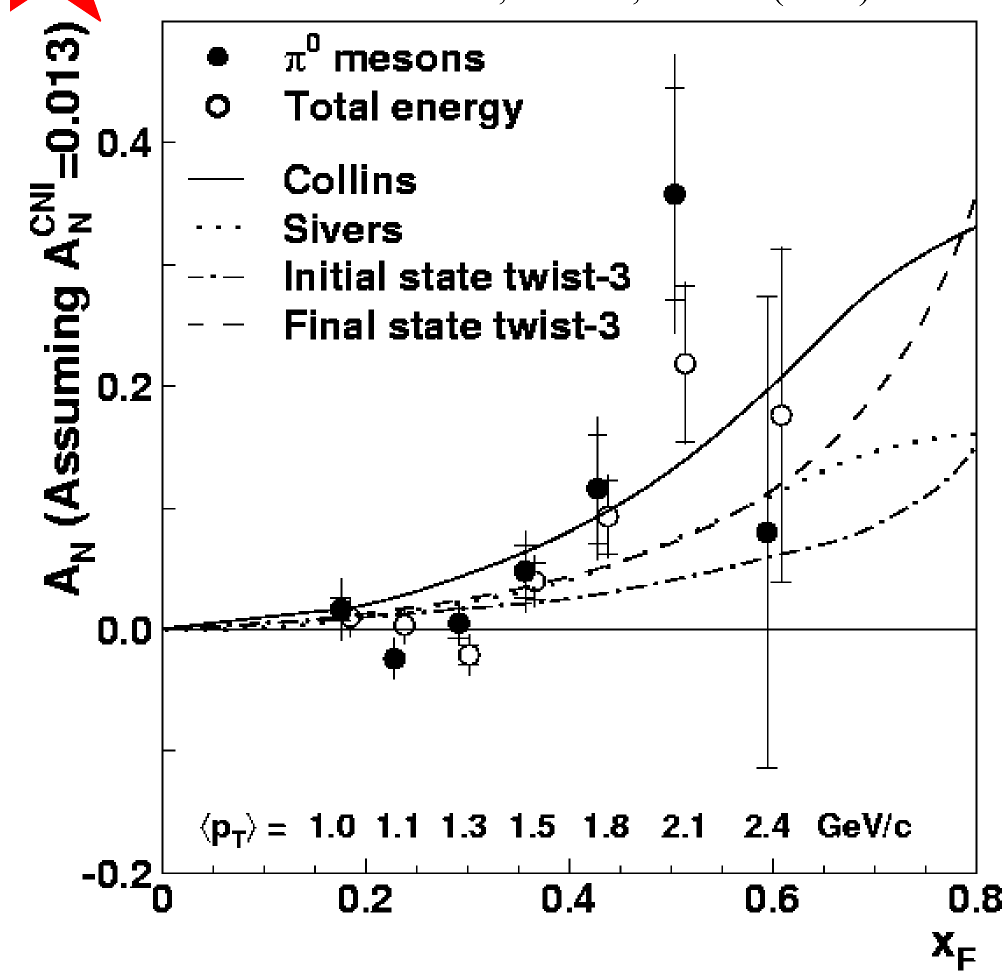
p_T and $p_T/2$

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

Large Analyzing Powers at RHIC at $\eta = 3.8$

STAR collab., PRL **92**, 171801 (2004)



$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$ = azimuthal asymmetry in particle yields from a transversely polarized beam on an unpolarized target

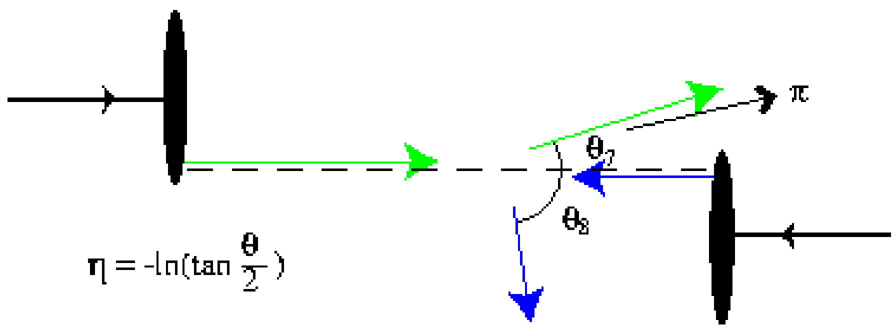
Similar to FNAL E704 result at $\sqrt{s}$ = 20 GeV

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

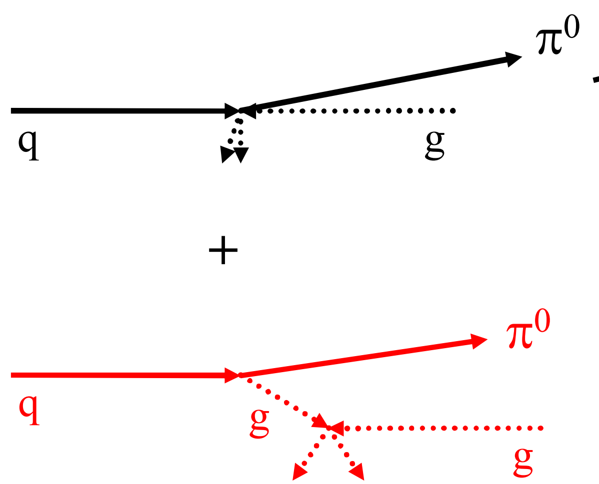
First measurement of A_N for forward π^0 production at $\sqrt{s}$=200GeV

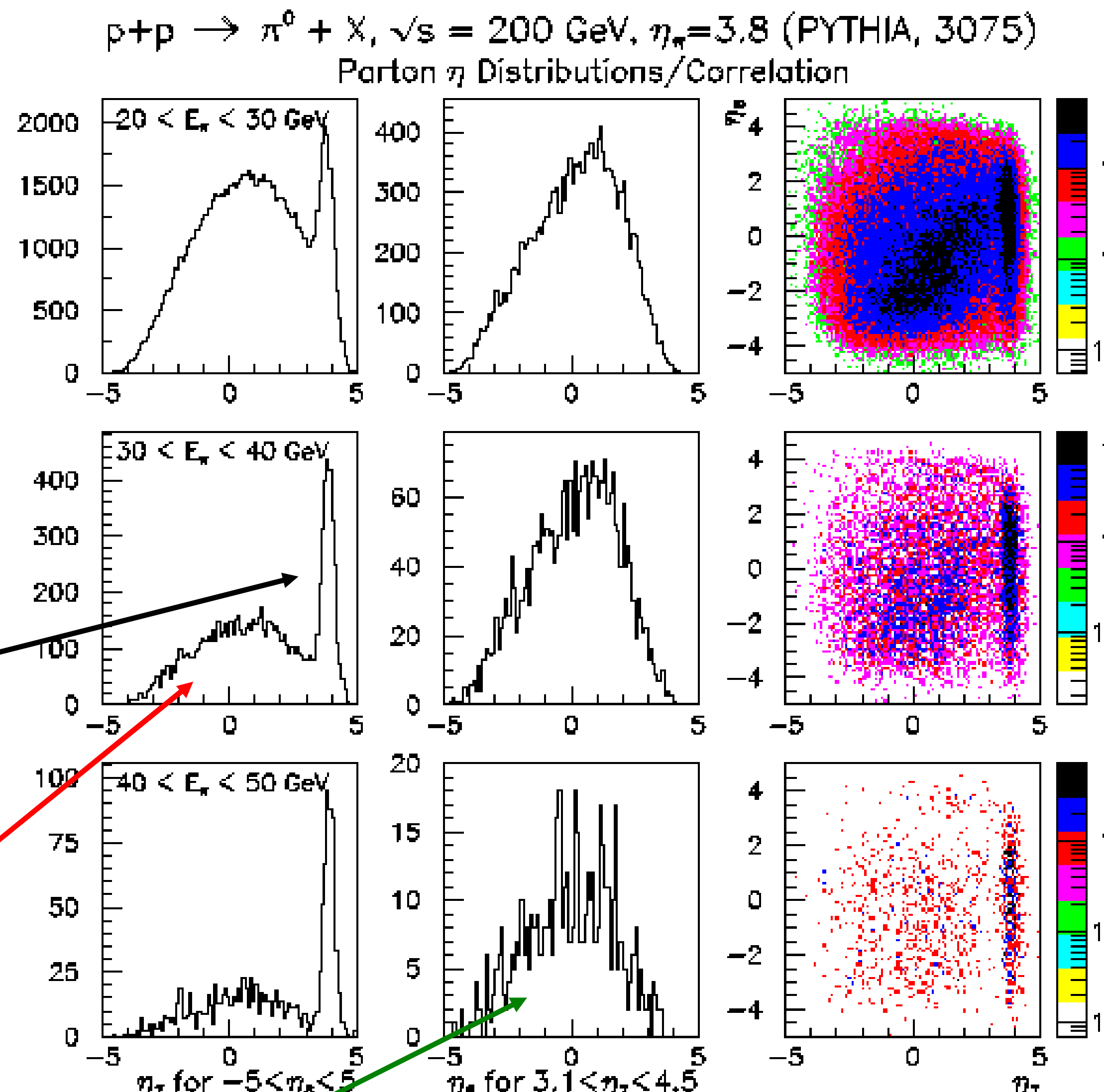
Partonic Correlations from PYTHIA



Large energy deposited at η=3.8

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

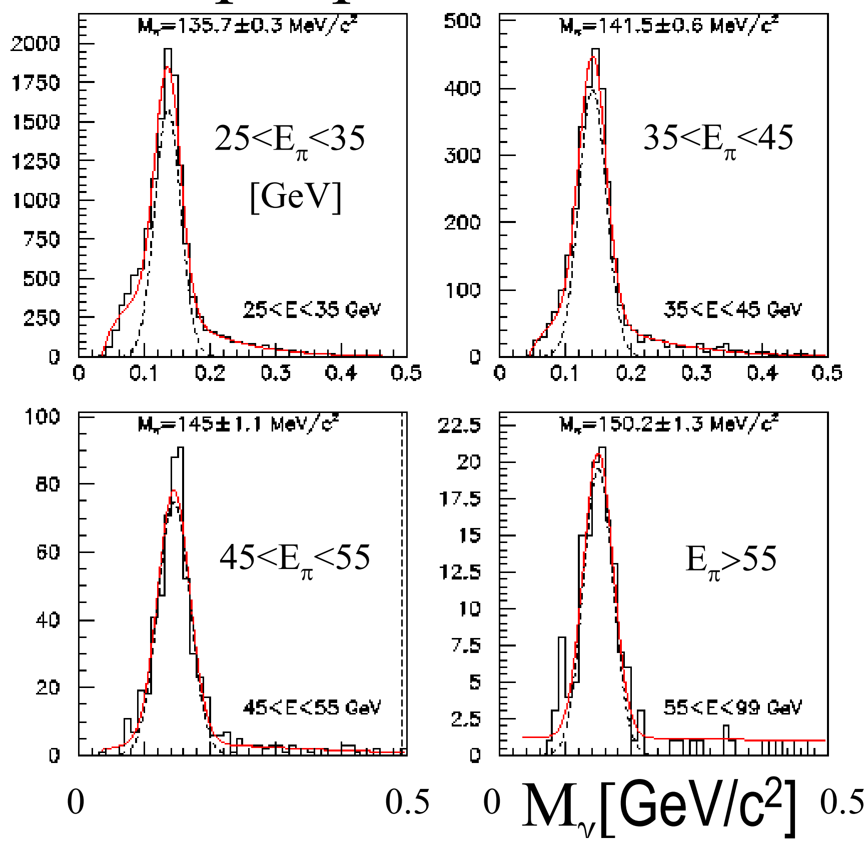


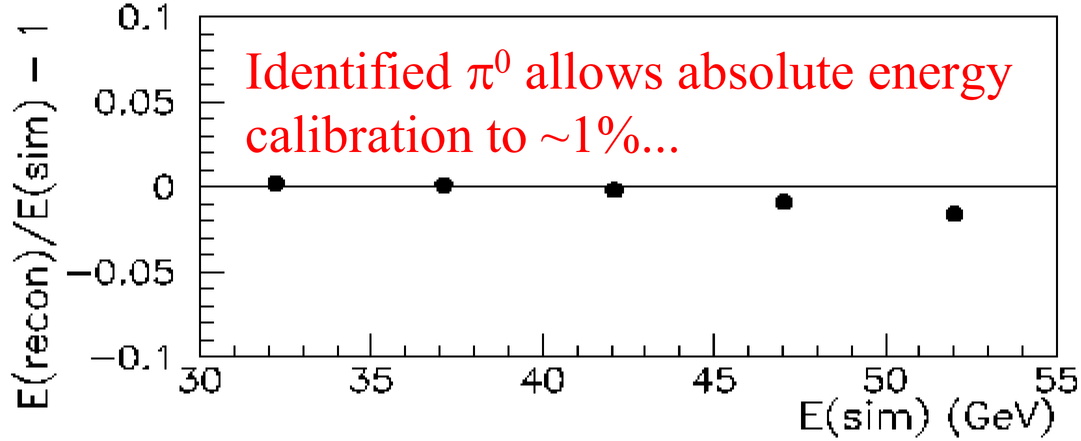


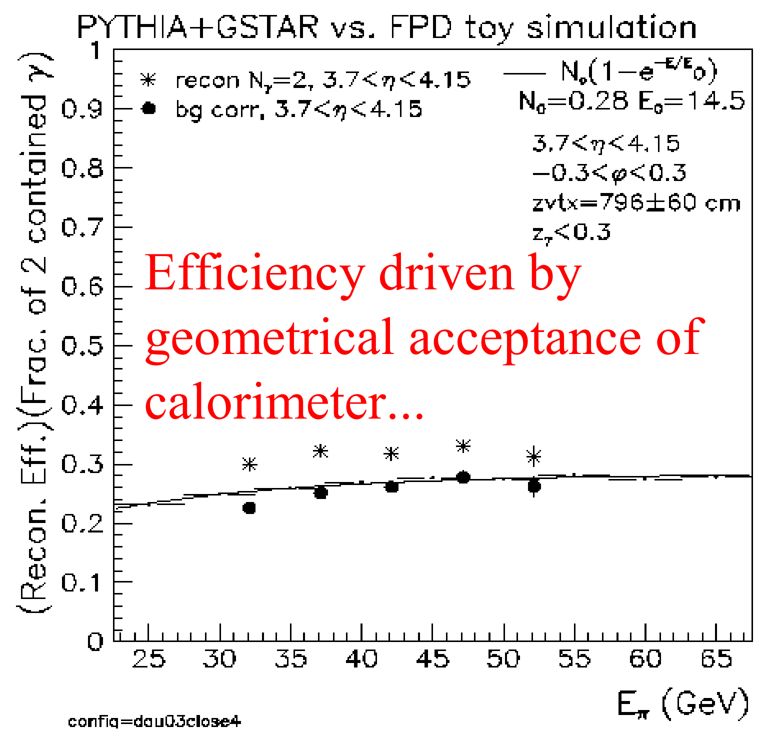
- other parton spread over broad η range

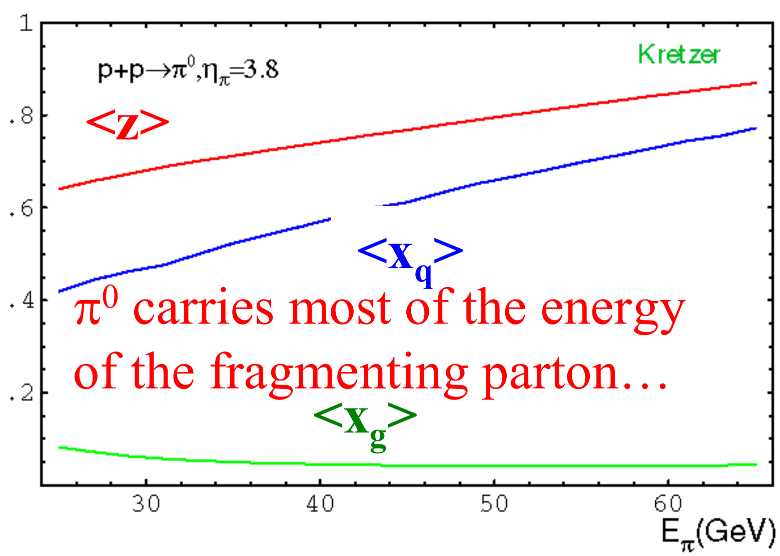
Some advantages of π^0 mesons/experimental details...

$p + p \rightarrow \pi^0 + X$









…and pions are well described by NLO pQCD calculations over a broad rapidity window at large $\sqrt{s}$…