Small-x and Forward Measurements in PHENIX

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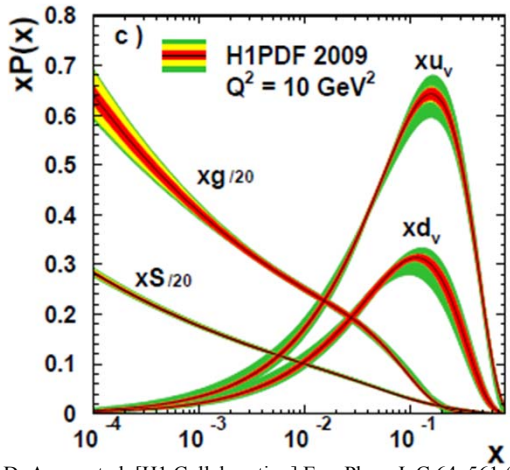
for the PHENIX Collaboration

Outline

- Cold Nuclear Matter and Small-x
  - J/Ψ production
  - hadron correlations
- Forward Spin Measurements
  - J/Ψ SSA at forward rapidity
- Upgrades and Future Prospects

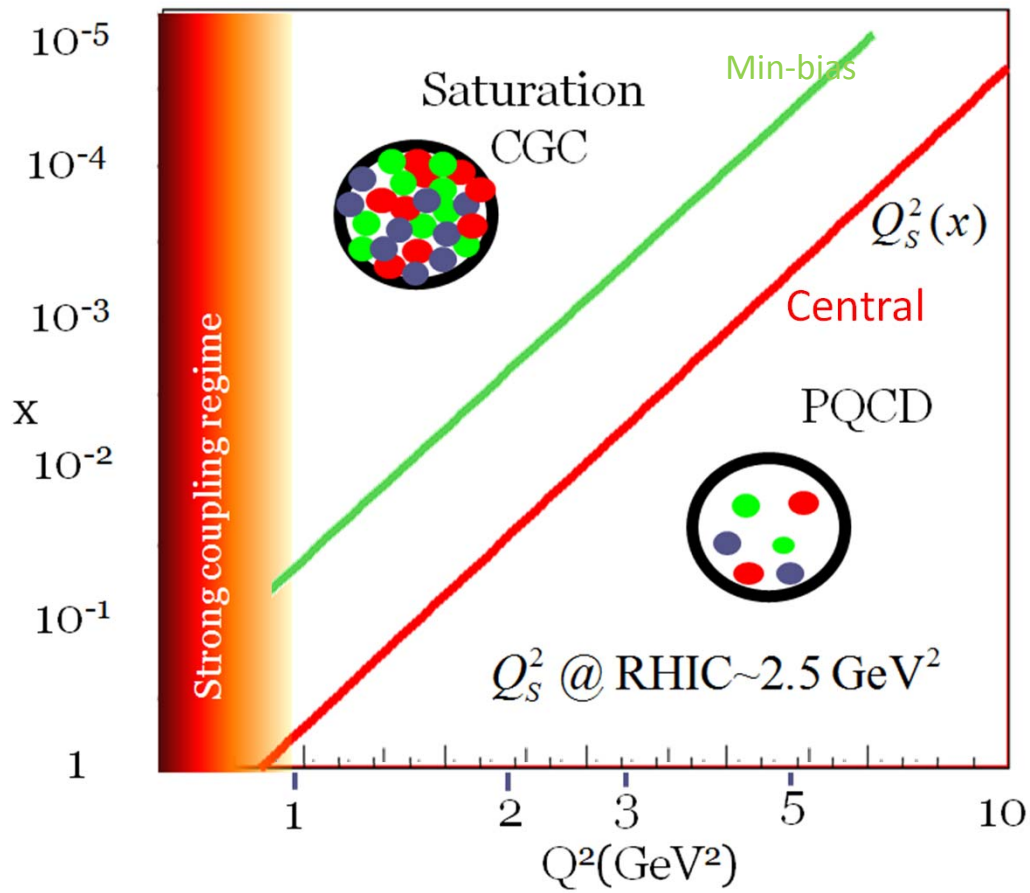
See Also WG6S1: Feng Wei

The Color Glass Condensate



F.D. Aaron et al, [H1 Collaboration] Eur. Phys. J. C 64, 561 (2009)

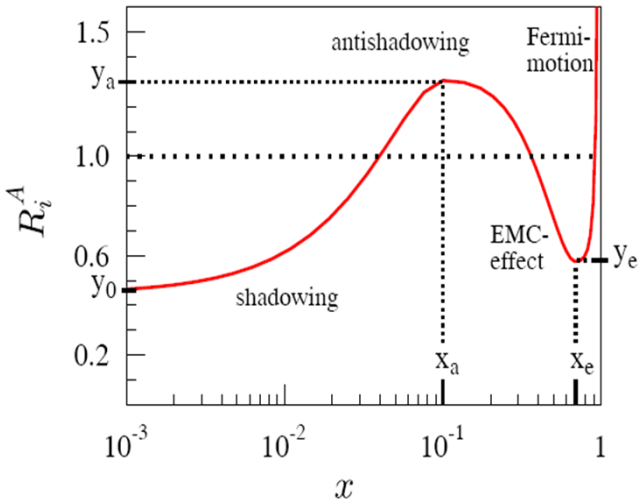
$$Q_S = Q_{0,S}\left(\frac{x_0}{x}\right)^{\lambda}$$



- High density leads to recombination of gluons, hence suppression @ low-x
- Characterized by Q_S
- Nuclear Amplification $xG_A = A^{1/3} xG_p$ (centrality)
- Region of validity: low-x (forward rapidity)

Nuclear Shadowing

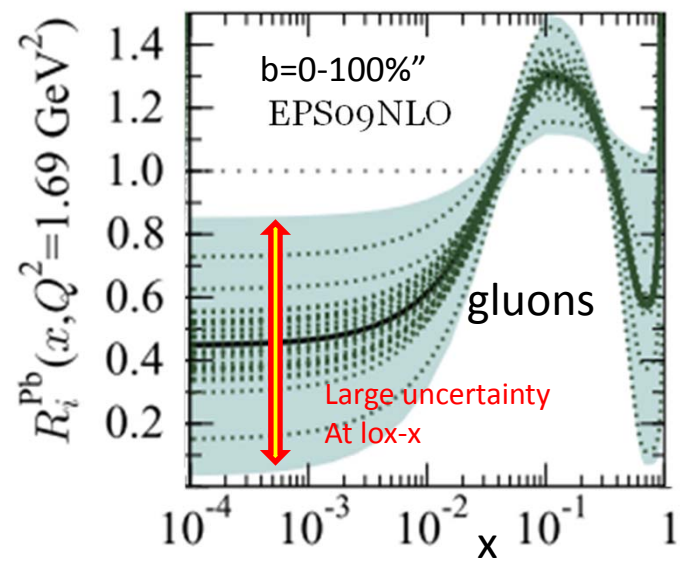
Nuclear PDF ≠ proton PDF



Fit data on nuclei:
SLAC, NMC, EMC
DIS+DY+PHENIX
midrapidty π^0

Lack of data
⇨large uncertainly
in gluon pdf
at low-x

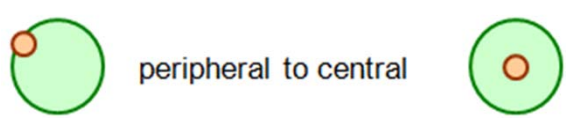
$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$



Eskola , Paukkunen, Salgado, JHP04 (2009)065

We will add two things:

1) Assume a linear dependence on density-weighted longitudinal nuclear thickness
→ impact parameter (centrality) dependence



2) For the J/Ψ include σ_{br} to account for the breakup of the c-cbar pair while passing through the nucleus.

J/Ψ Production in PHENIX

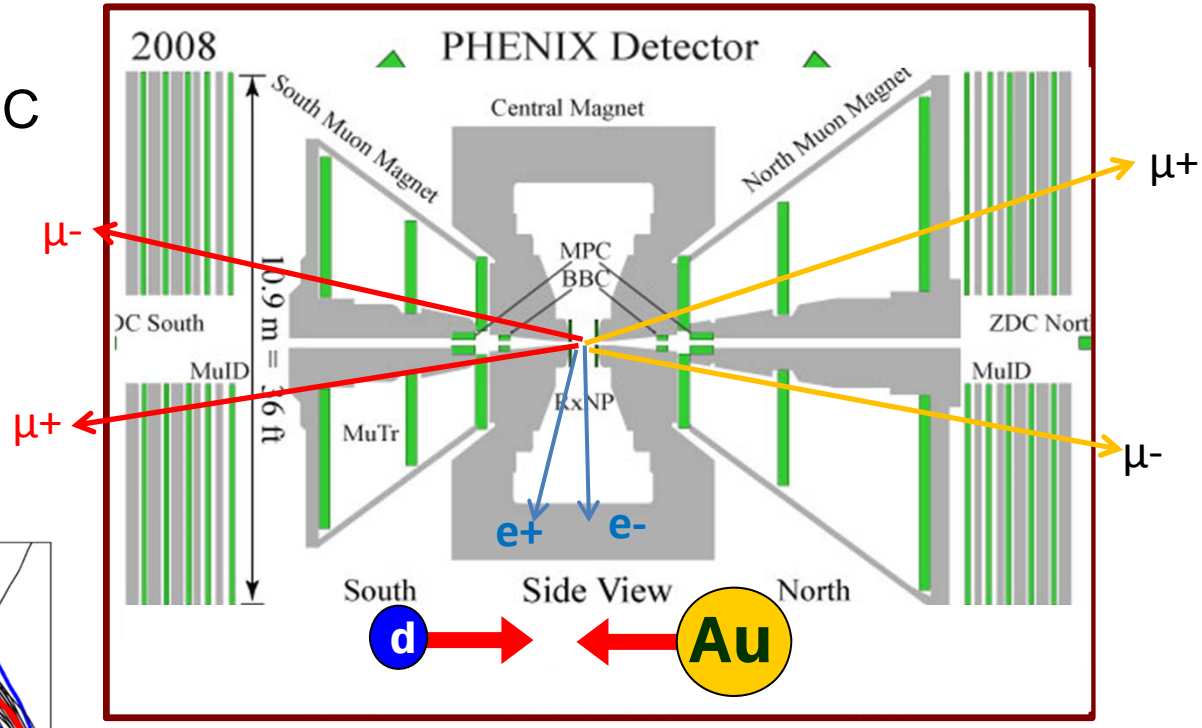
g+g → J/ψ dominant @RHIC

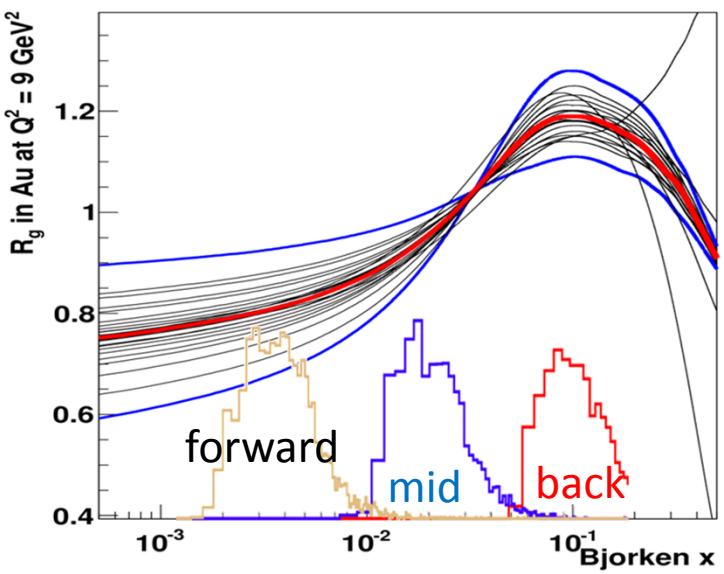
Nice coverage in y or equivalently x(Au) forward

y *x*~0.005

mid *y* *x*~0.03

backward *y* *x*~0.1

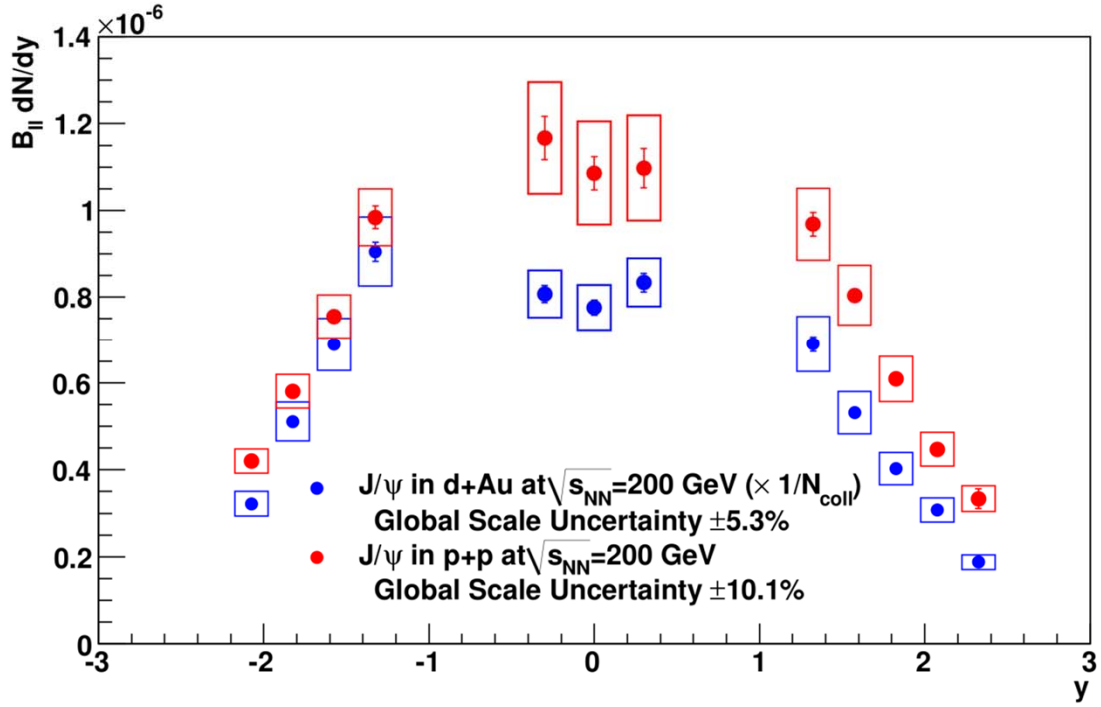




- e^+e^- $-0.35<\eta<0.35$
- $\mu^+\mu^-$ $1.2<|\eta|<2.4$

J/Ψ dN/dy for p+p and d+Au

- Unbiased distributions (0-100%)
- Scaled by $1/N_{coll}$
- Pattern of suppression clearly evident

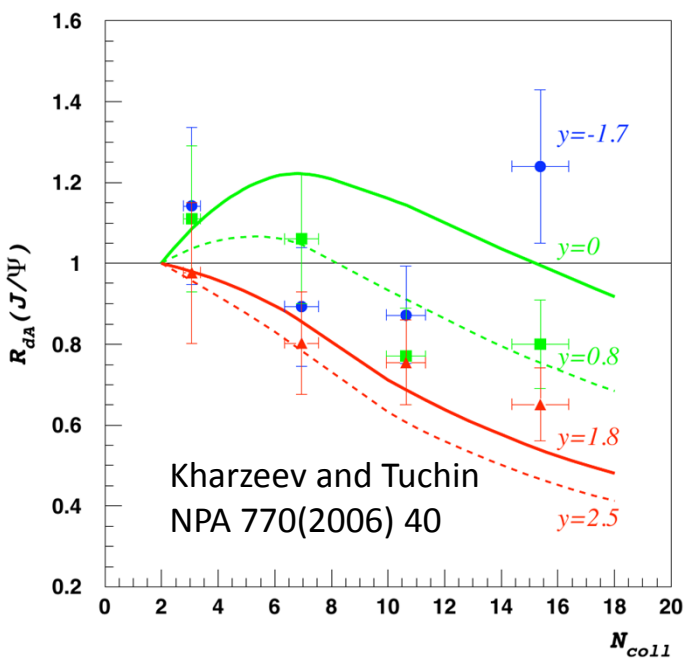


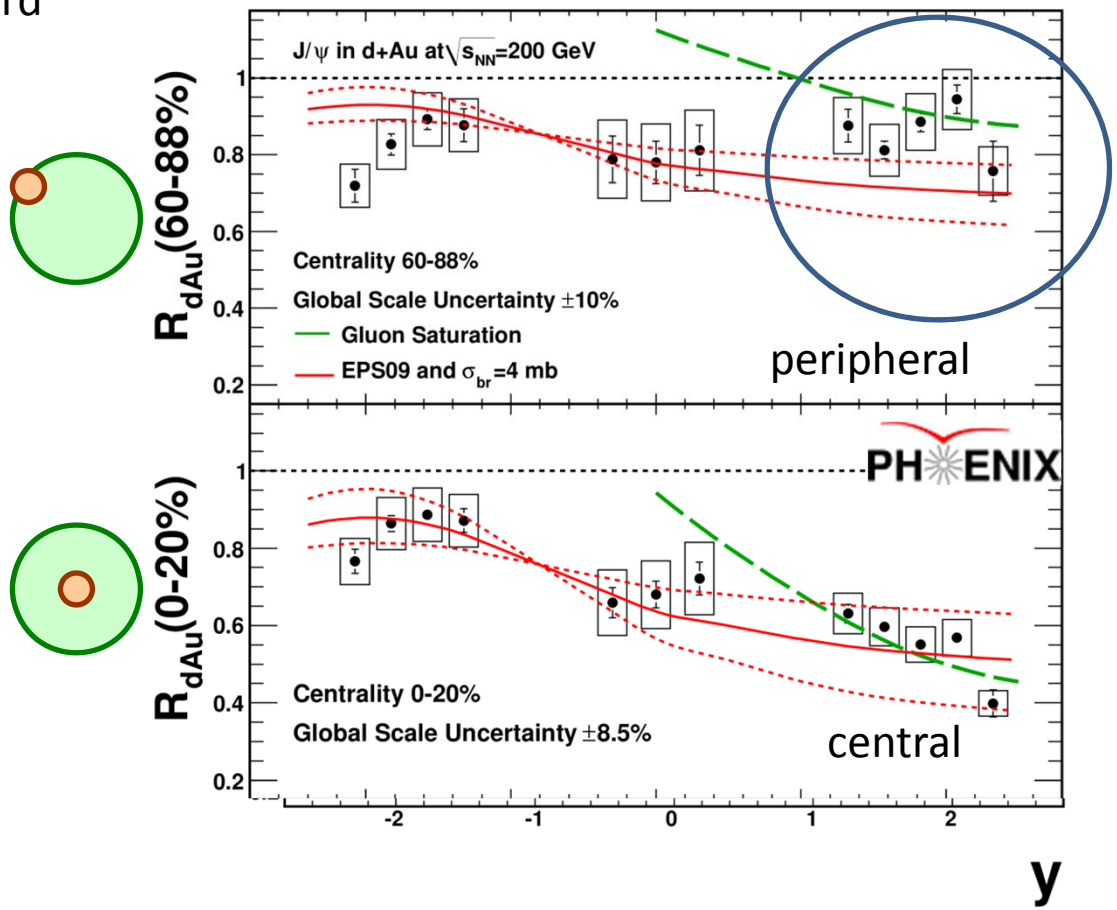
R_{dAu} vs. Centrality

EPS09 nuclear PDF + σ_{br} = 4 mb is now deviating from the peripheral data

$$R_{dAu} = \frac{1}{N_{coll}} \frac{\text{Yield dAu}}{\text{Yield pp}}$$

Gluon saturation matches the forward rapidity points relatively well, but not at mid-rapidity





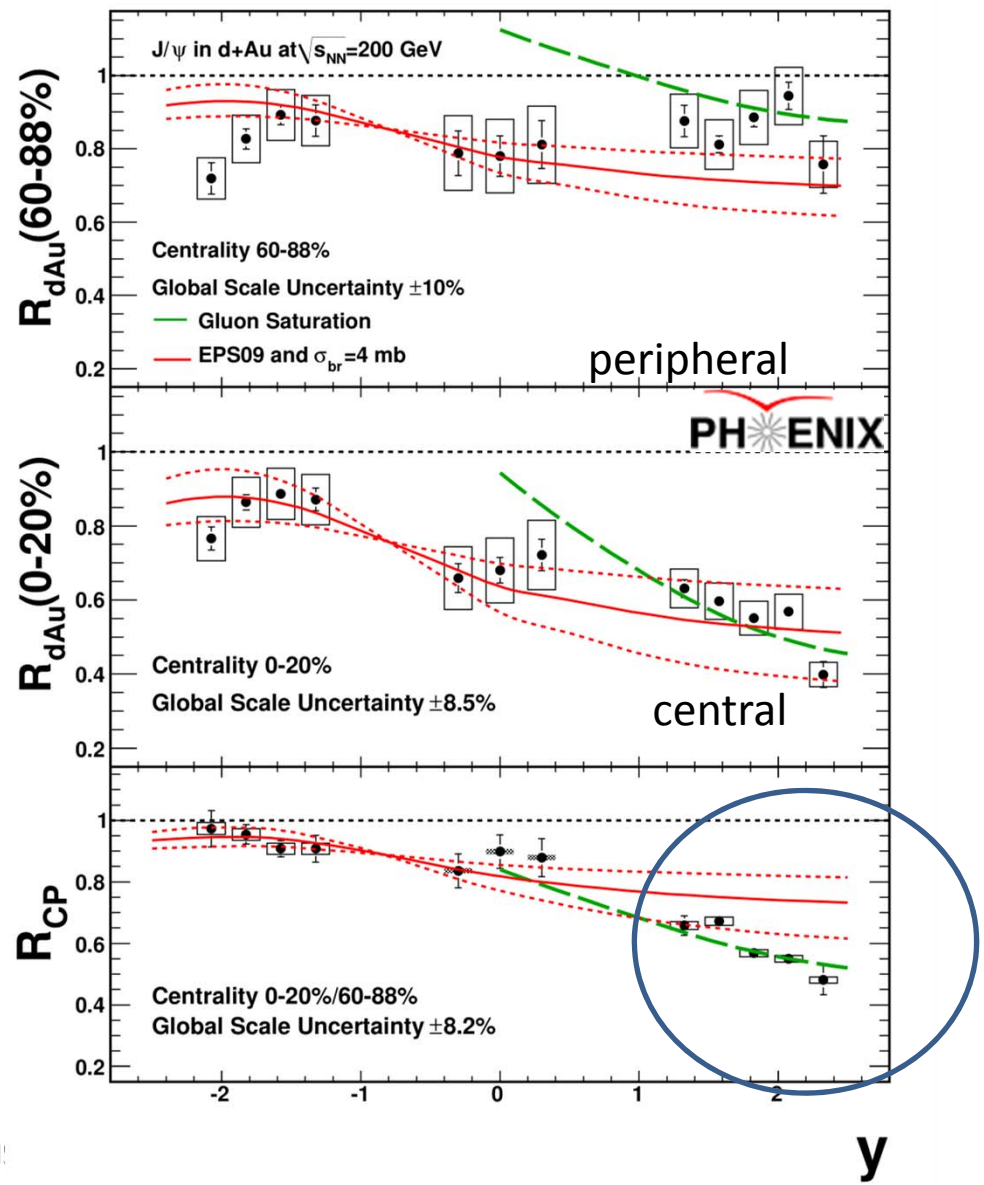
Double Ratio R_{CP}

$$R_{CP} \equiv \frac{R_{dAu}(central)}{R_{dAu}(peripheral)}$$

R_{CP} has the advantage of cancelling most of the systematic uncertainties.

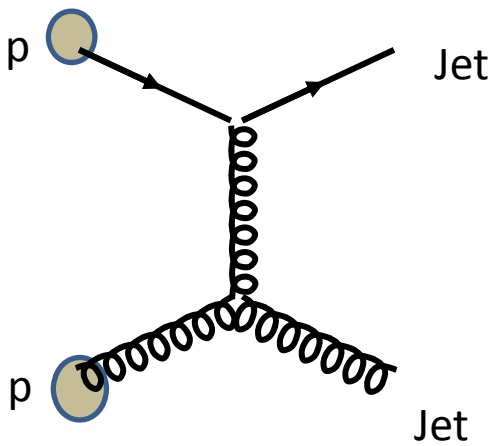
Now with reduced errors the EPS09 PDF and $\sigma_{breakup}$=4mb does not match the data

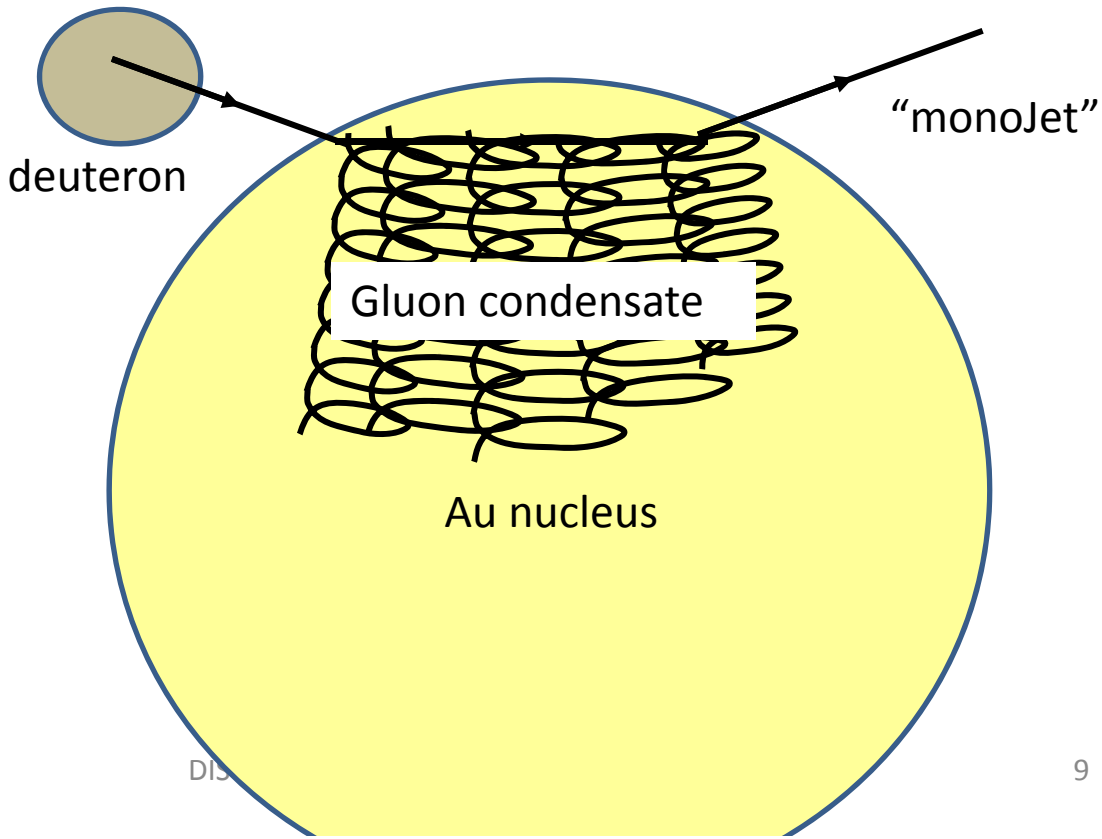
The CGC model works at least in the forward region



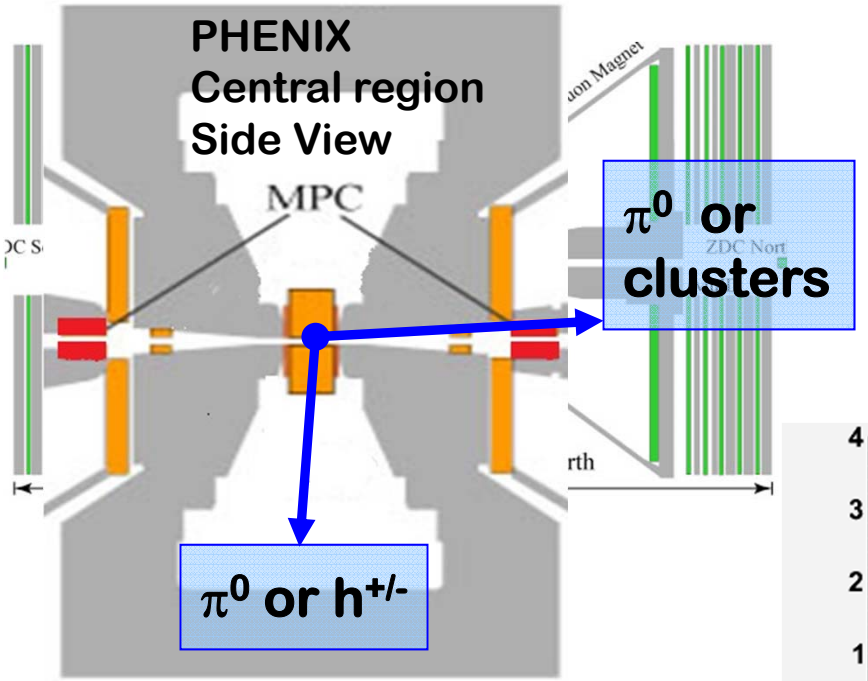
Pion Correlations

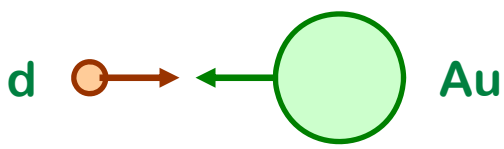
- In the CGC gluons overlap and form a condensate
  - This modifies the ordinary picture of 2->2 scattering
  - The “probe” parton scatters and fragments to a jet
  - However, the condensate recoils against the probe and emits gluons



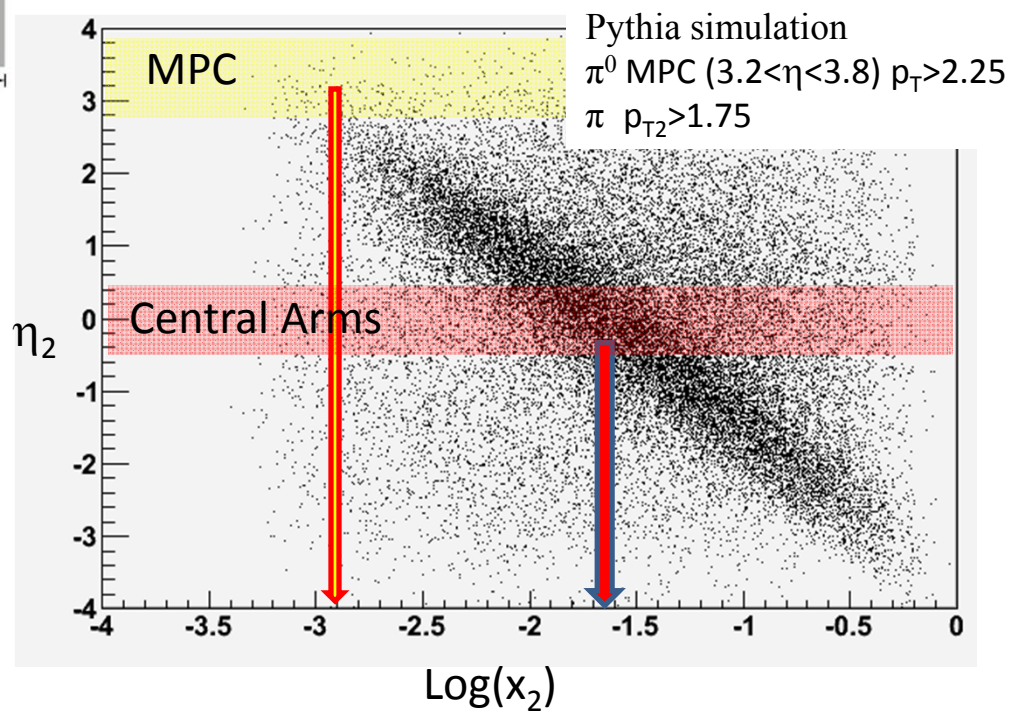


The Muon Piston Calorimeters





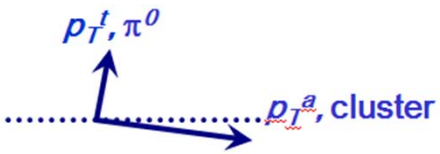
1) Particle into MPC
   e.g. π^0 MPC ($3.2<\eta<3.8$) $p_T>2.25$
2) Choose 2nd particle with $p_{T2}>1.75$ azimuthally opposite
3) plot η_2 vs. x_2



2nd Particle in central arm: x_2 ~ .03

2nd Particle in MPC: x_2 ~ .001

Central Arm + MPC Correlations

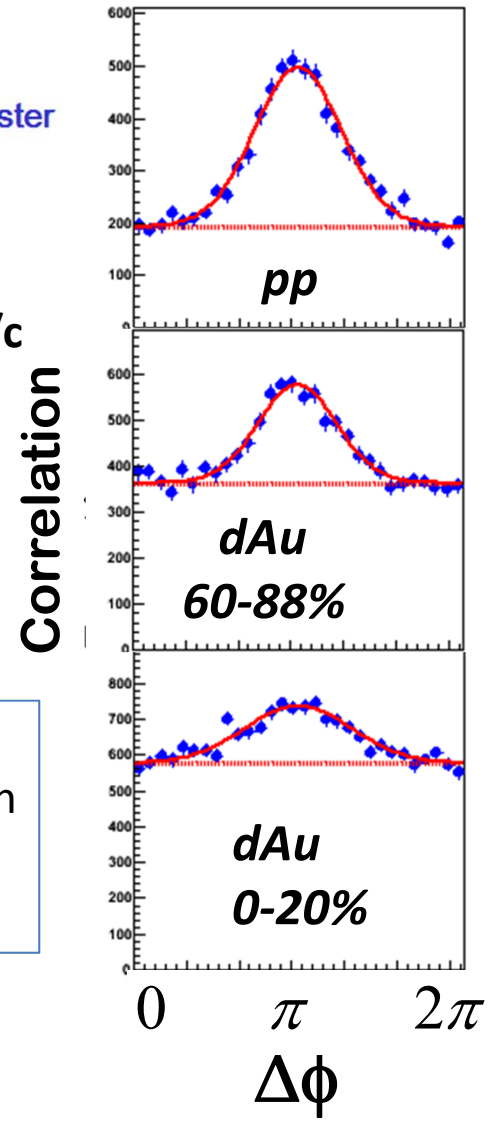


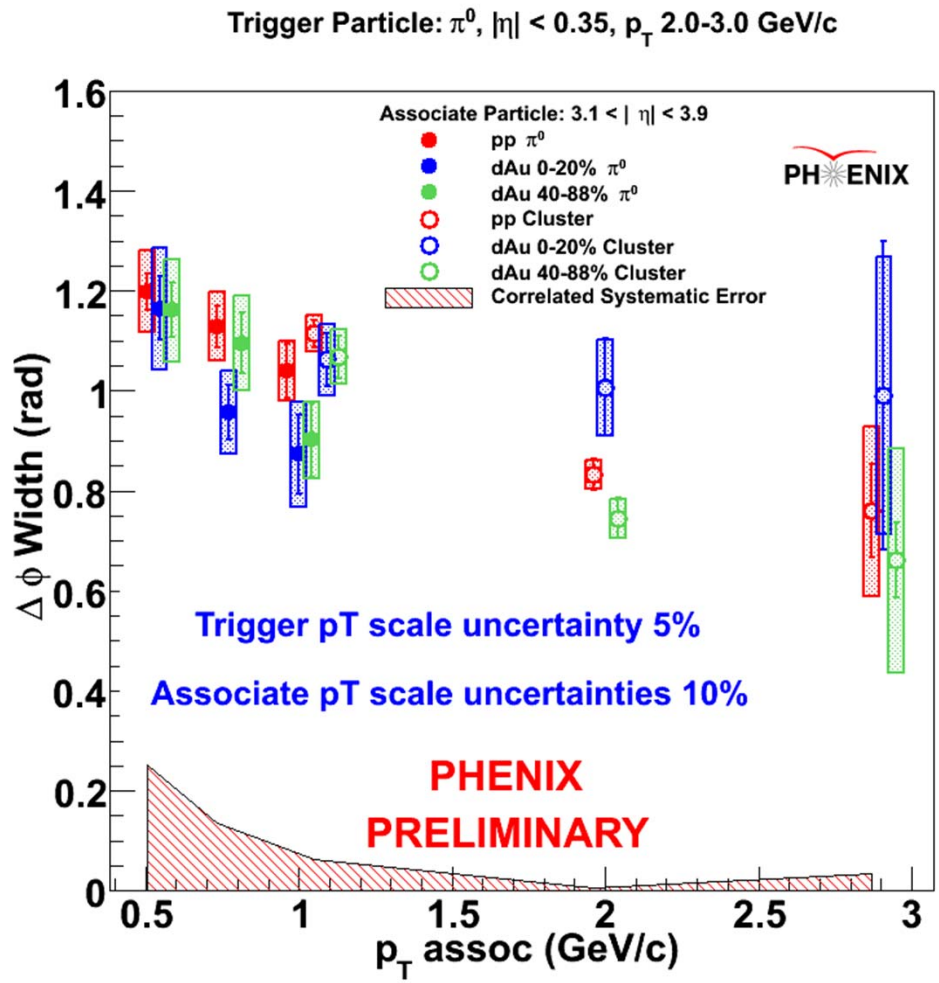
***2.0 < p_T^t < 3.0* GeV/c**

for all plots

No consistent difference between correlation widths in p+p and d+Au

<p_T^a>=2.00 GeV/c





Correlations with MPC

Peripheral events

- pp and dAu are same

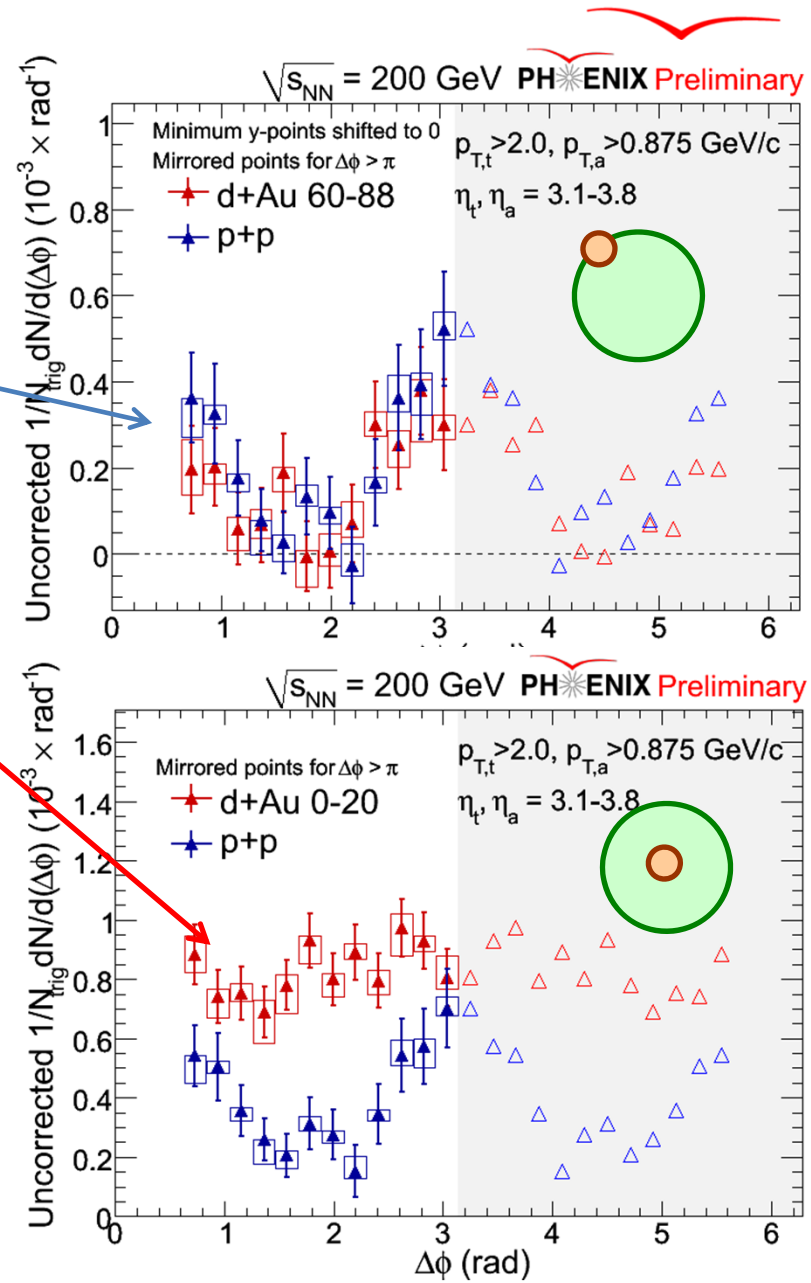
Central events

- dAu looses correlated peak

Qualitative agreement with a CGC picture

Careful with conclusions – correlations could arise from MPI (not 2->2)

Quantitative analysis underway, publication forthcoming (soon)…



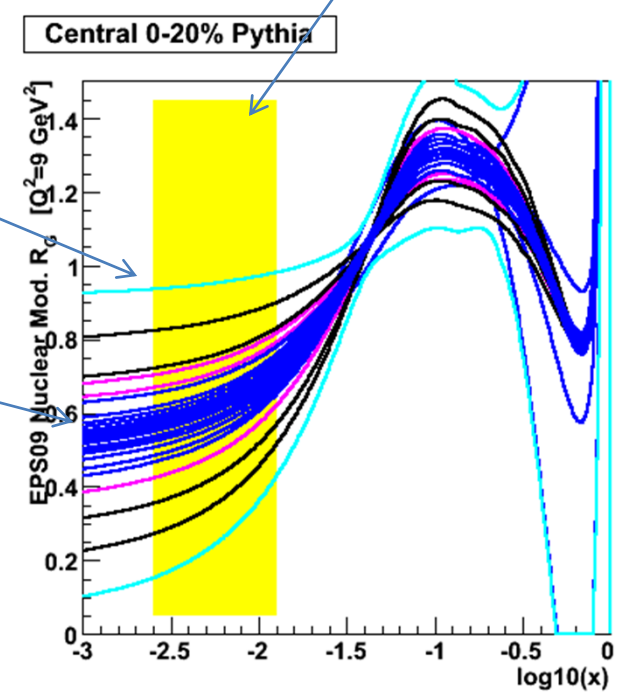
Direct Photons - A Complimentary Probe?

- Direct photons are "cleaner" from a theoretical standpoint
  - No re-interaction with nucleus
  - No fragmentation function dependence
  - Clean LO kinematics if companion jet detected
- However, they are much more complicated experimentally
  - Direct vs. fragmentation photons
- Studied for a calorimeter $1.5<\eta<2.5$ in PHENIX

acceptance

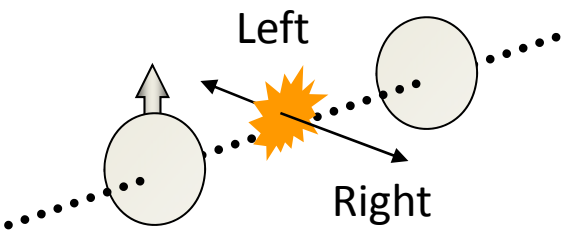
EPS09 90% C.L.

Blue curves +/-1 sigma of simulated data. Purple curves at 90% C.L.



A very tough measurement to make!

Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

A_N difference in cross-section between particles produced to the left and right

Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N O(10^{-4}) Theory

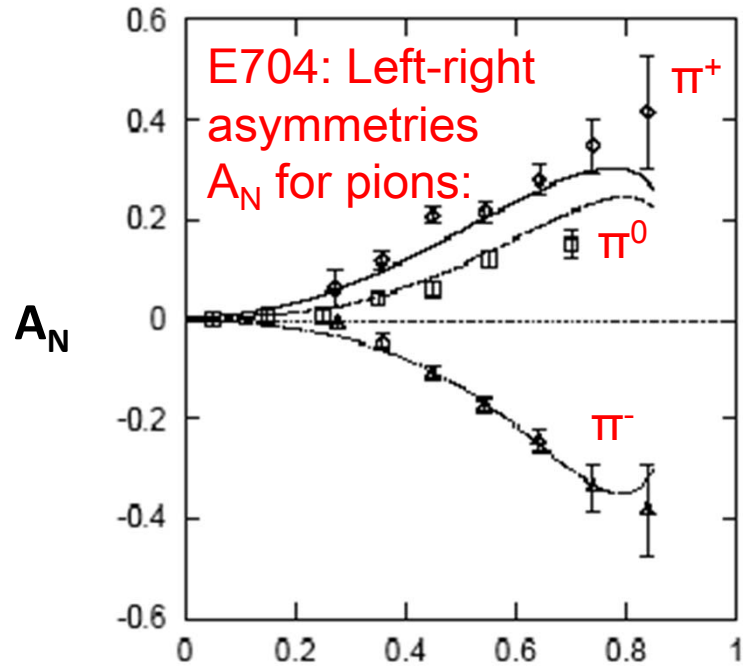
Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$

$$\sqrt{s} = 20\,\text{GeV}$$

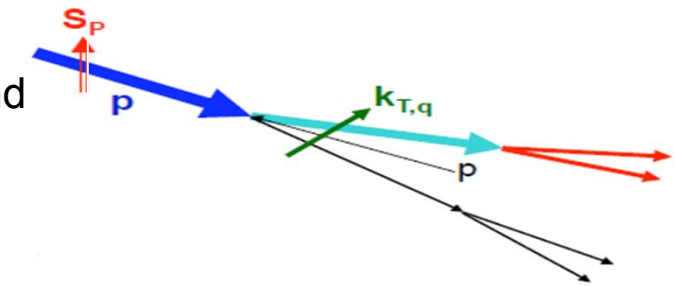
A_N O(10^{-1}) Measured



$$x_F = \frac{2p_L}{\sqrt{s}}$$

Sources of Asymmetry

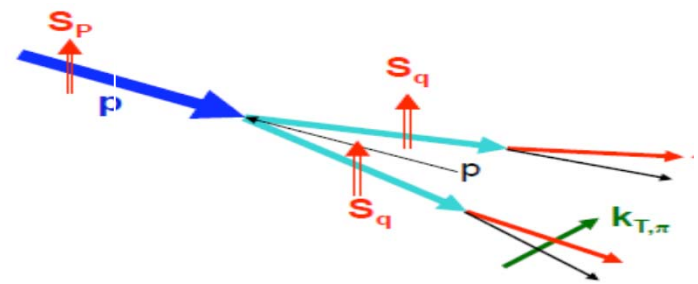
- Transverse Momentum Dependent (TMD)
  - **Sivers effect:** Correlation between nucleon spin and parton k_T.



Phys. Rev. D, 41, 83 (1990)
Phys. Rev. D, 43, 261, (1991)

$$d\sigma^{\uparrow} \propto \underbrace{\bar{f}_{1T}^{\perp q}(x,k_{\perp}^{2})}_{\text{Sivers distribution}} \cdot D_{q}^{h}(z)$$

  - **Collins effect:** Transversity distributions + Spin dependent fragmentation functions

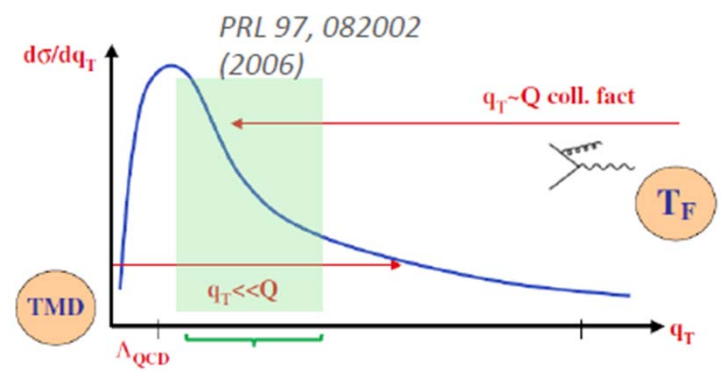


Nucl. Phys. B, 396, 161 (1993)

$$d\sigma^{\uparrow} \propto \underbrace{\delta q(x)}_{\text{Transversity}} \cdot \underbrace{H_{1}^{\perp}(z_{2},\bar{k}_{\perp}^{2})}_{\text{Collins FF}}$$

- Higher-twist effects
  - Quark-gluon correlation (field interference)
  - Gluon-gluon correlation

(Phys. Rev. D, 59, 014004 (1998))



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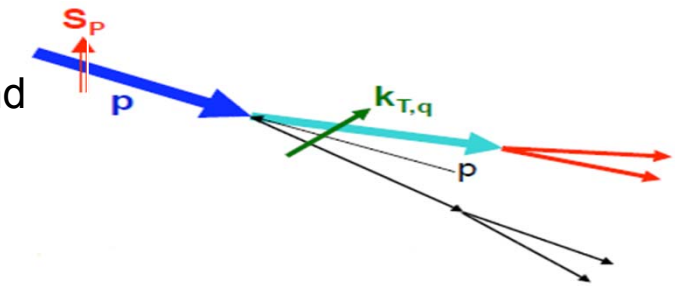
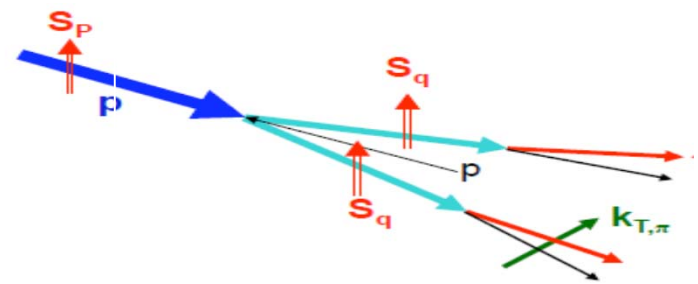


No TMD factorization in p+p?

  - effect: Transversity distributions + Spin dependent fragmentation functions



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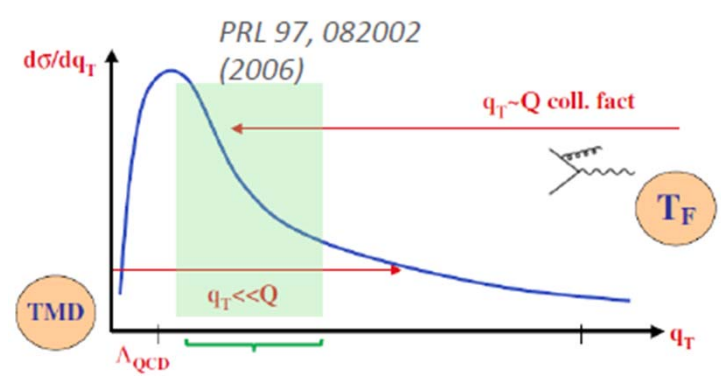
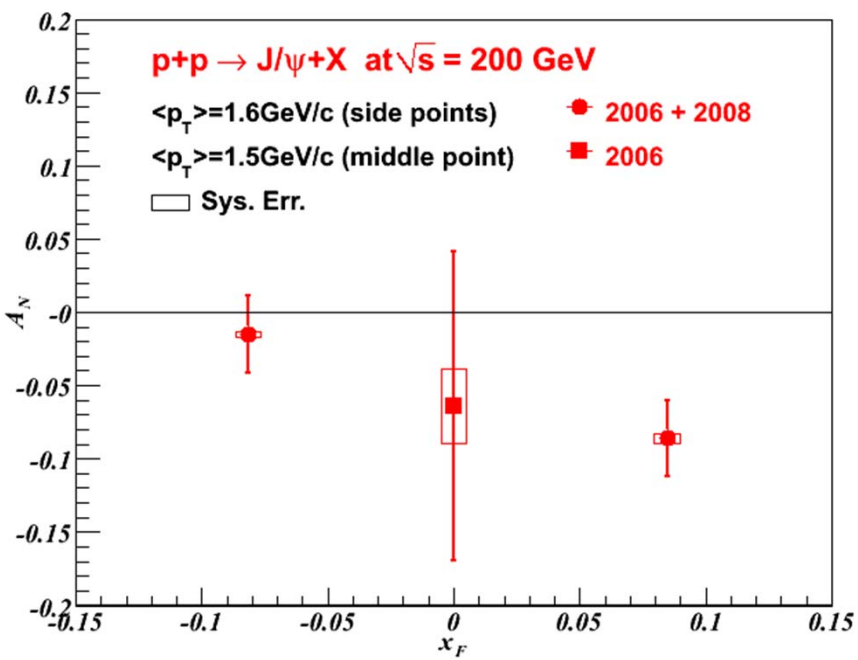
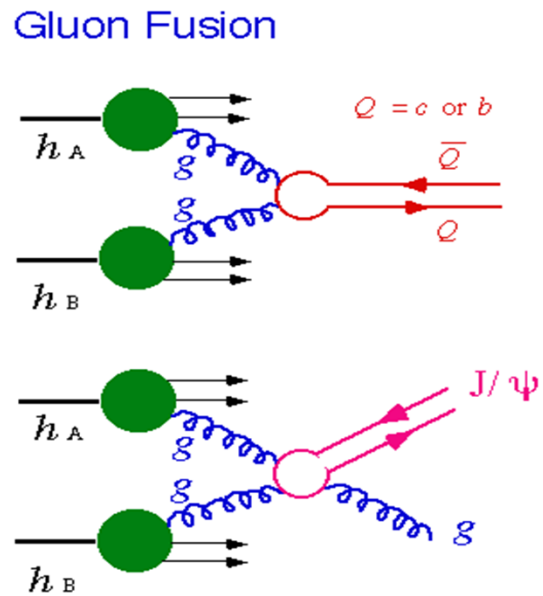


J/Ψ A_N vs. x_F

- J/Ψ production mechanism not well understood
- Single spin asymmetries may shed light on production mechanism (Yuan, PRD78:014024,2008)

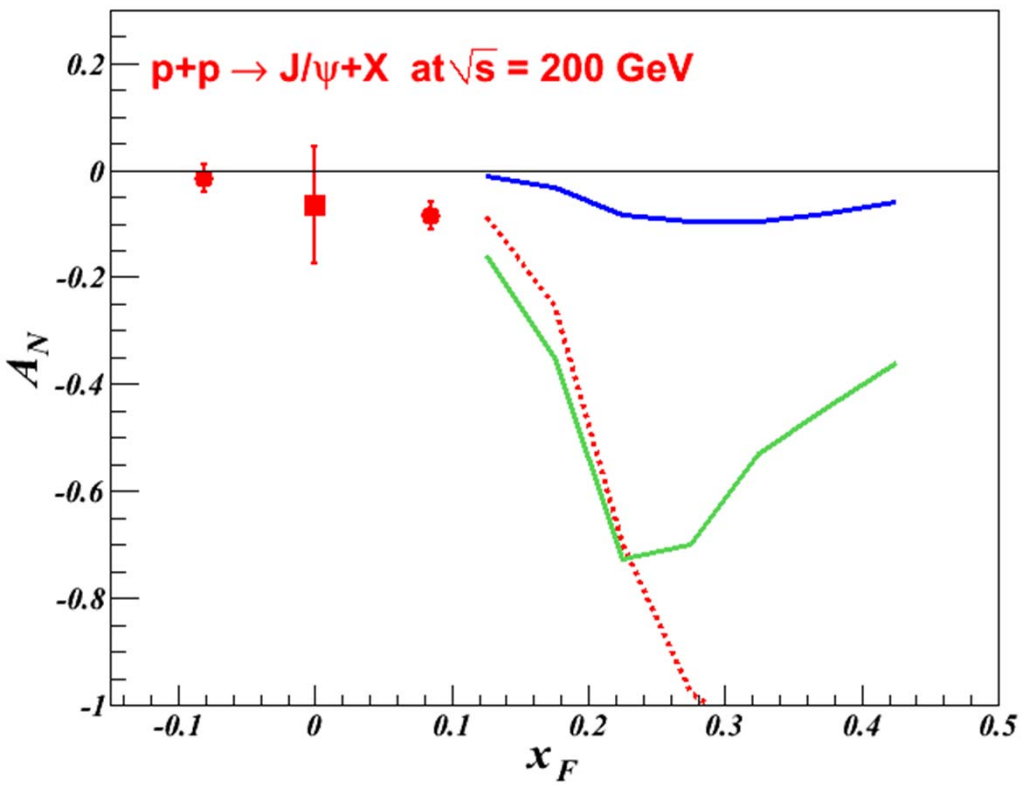




Asymmetry could arise due to TMD correlations in nucleon (Sivers)… but no factorization in p+p collisons!

Possible contribution from trigluon correlation function.

J/Ψ A_N vs. x_F - Toy Model Predictions



Naive weighted-pythia model using Anselmino extractions from SIDIS data. ArXiv:0805.2677v2 Eur.Phys.J.A39:89-100

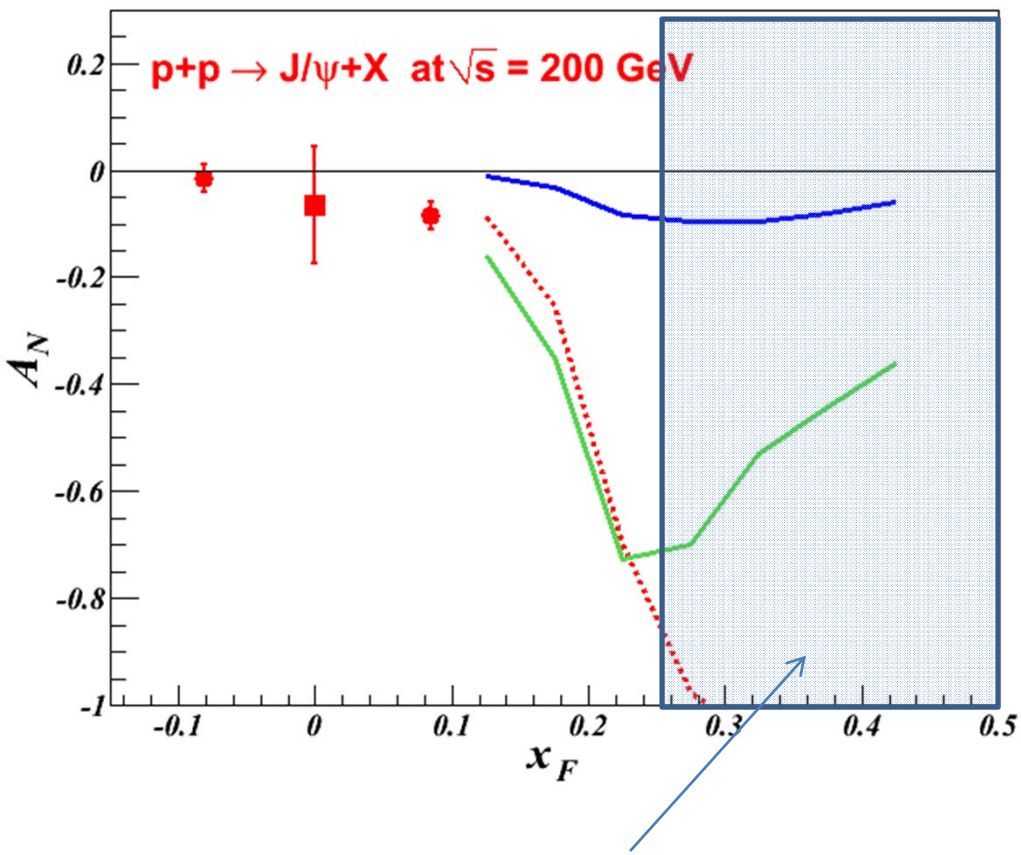
Blue – assumes gluon Sivers is like up quark

Red – assume gluon Sivers is like up quark at up-quark positivity limit (unphysical)

Green – gluon positivity limit

Very interesting to measure J/Ψ A_N at high x_F!

J/Ψ A_N vs. x_F - Toy Model Predictions



MPC Acceptance

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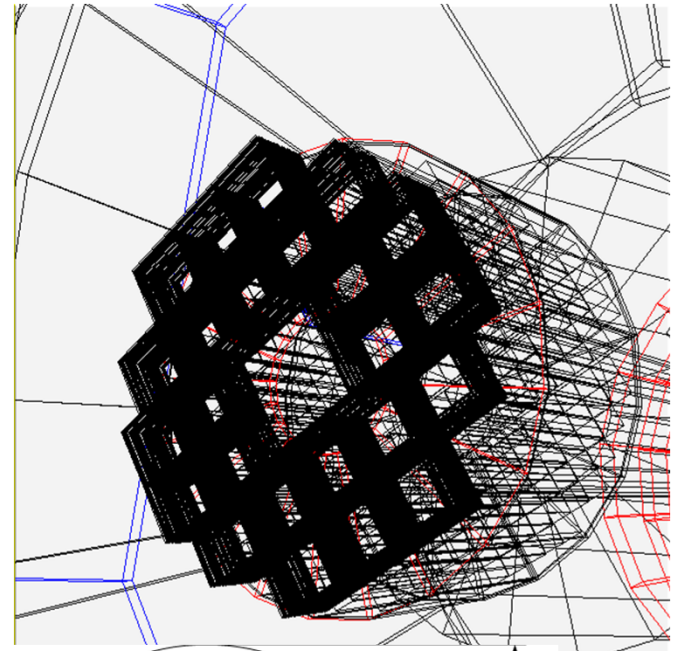
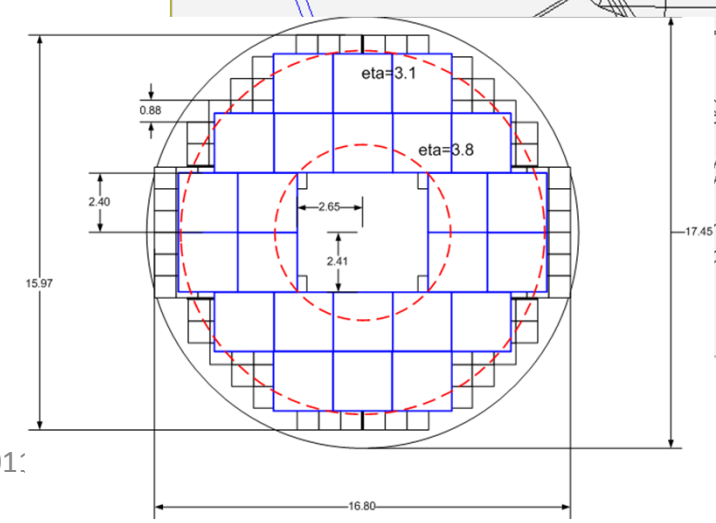
Upgrades – the MPC Extension (EX)

- Enhance the forward direction in PHENIX with a <u>combined</u> preshower and tracking device



- Physics goals:
  - Enable reconstruction of π^0's in the MPC out to high p_T
  - Measurement of direct photons
  - Reconstruction of jet direction with charged hadrons
  - Enable J/Ψ measurements in MPC with low background

- Technology
  - Si detectors (pad and 500 μm strips) plus W absorber



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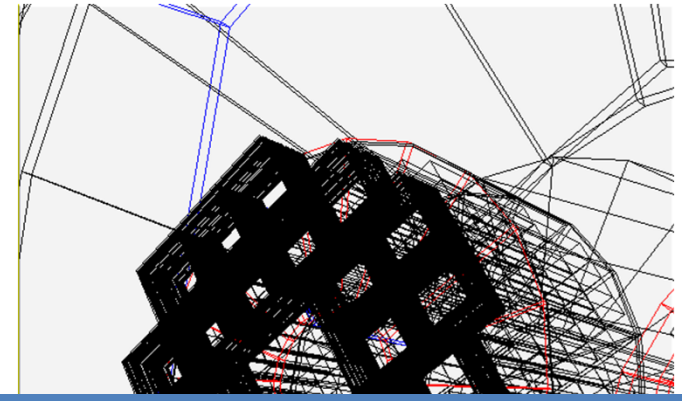
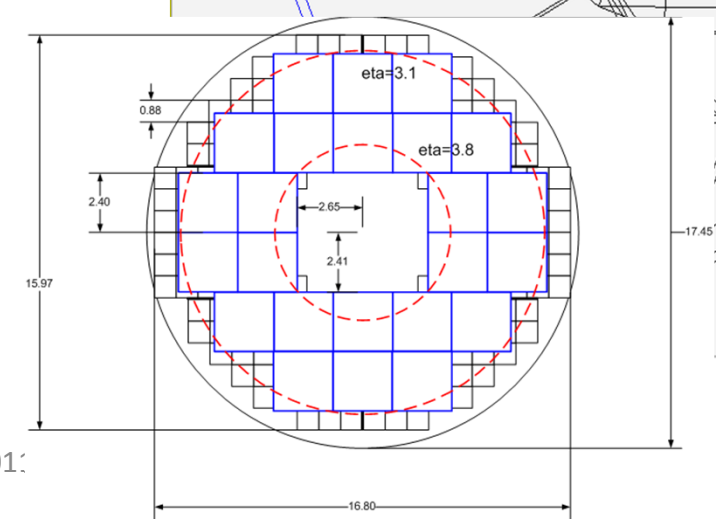


- Physics goals:
  - Enable reconstruction of π^0's in the MPC out to high p_T
  - Measurement of direct photons with low background

Design and MC Studies Underway
Plan to be ready for next d+Au run at RHIC (2014?)

- Technology
  - Si detectors (pad and 500 μm strips) plus W absorber



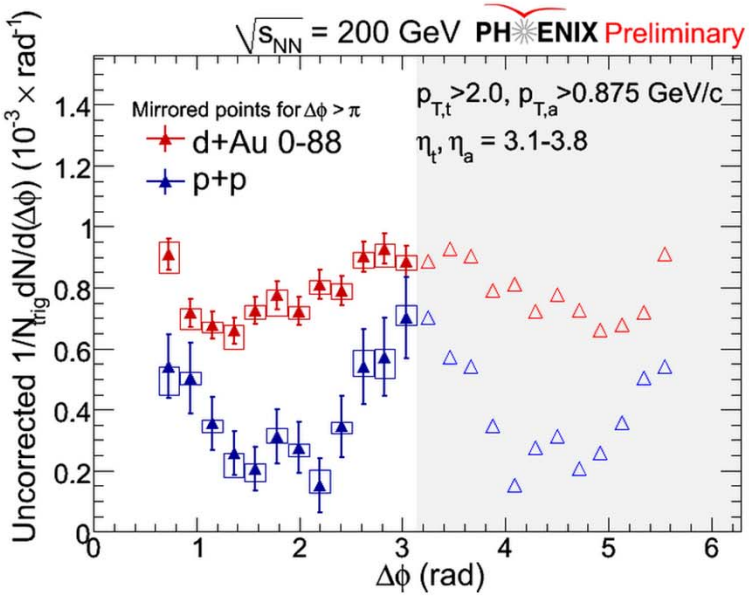
Conclusions

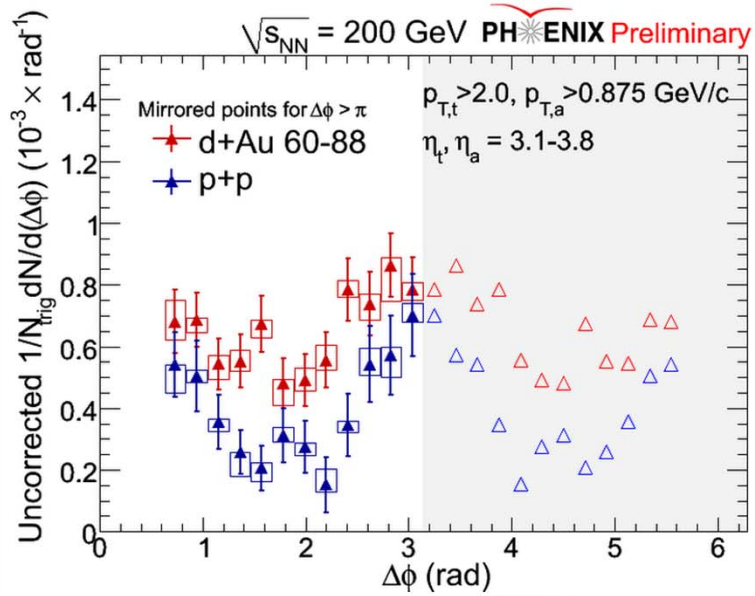
- PHENIX measurements of J/Ψ production at forward rapidity in d+Au collisions cannot be reconciled with a simple picture of cold nuclear matter effects
  - Gluon saturation may play a role, parton energy loss may play a role
- Hadron correlations at small x in d+Au collisions show a striking decorrelation
  - Qualitatively consistent with a CGC picture
- PHENIX has measured a nonzero A_N at forward x_F in J/Ψ production
  - Nonzero Sivers, or tri-gluon correlation?

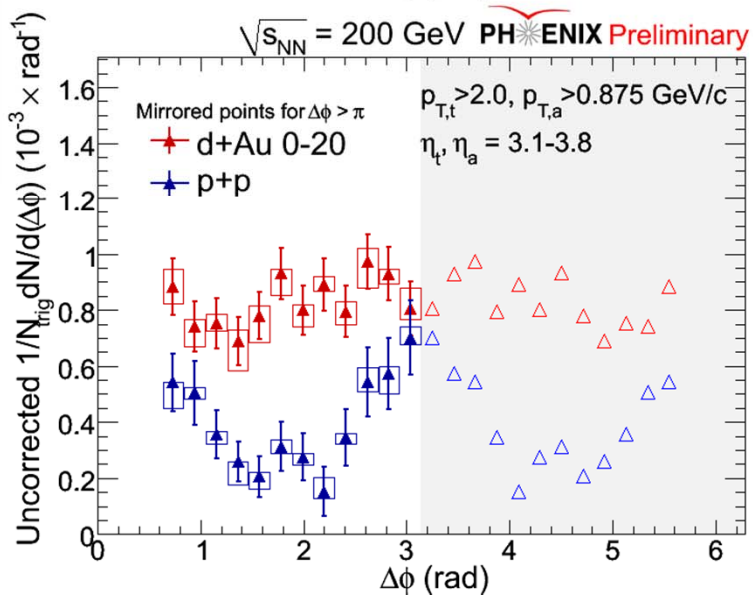
- Future upgrade to emphasize small-x and forward measurments
  - photons, π^0's, jets and J/Ψ

BACKUP

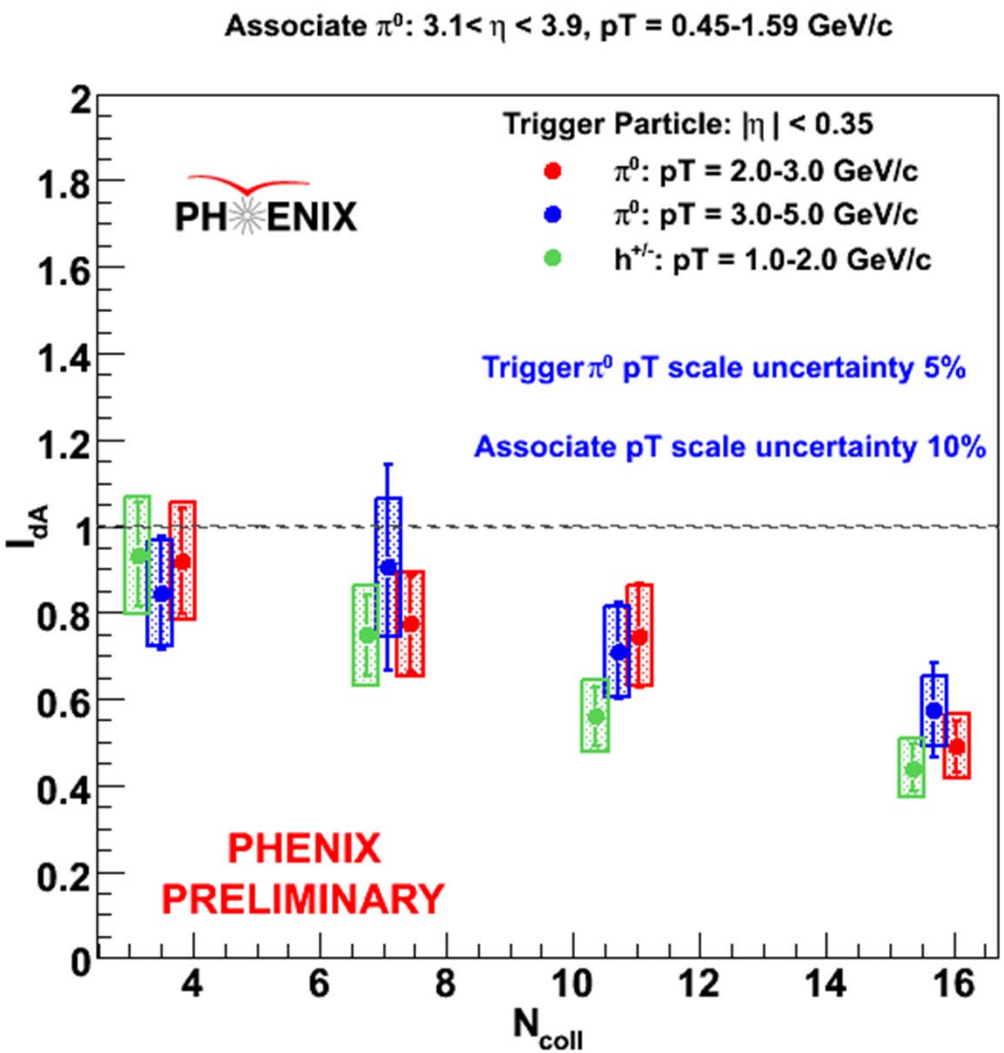
MPC Correlations



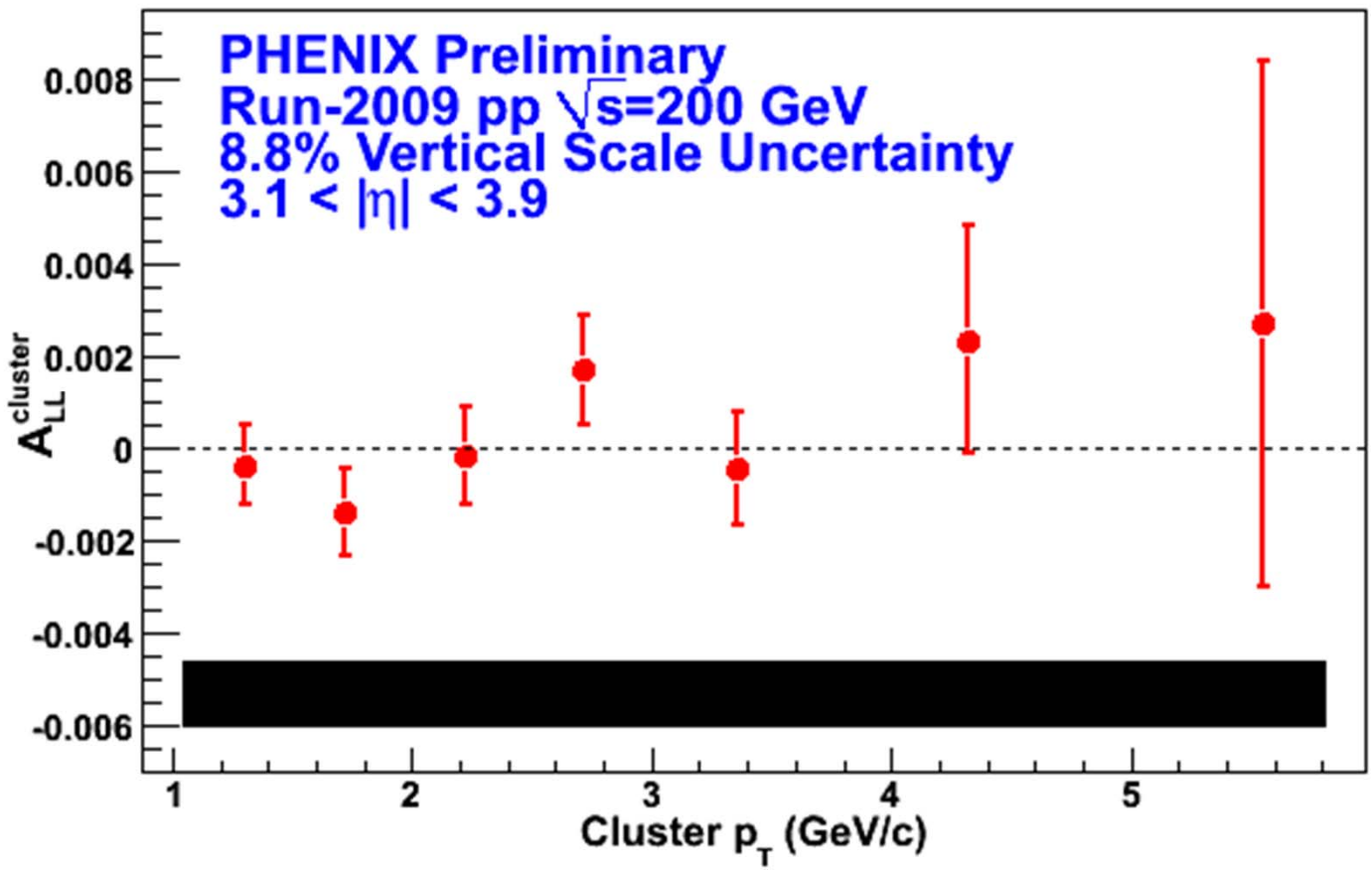




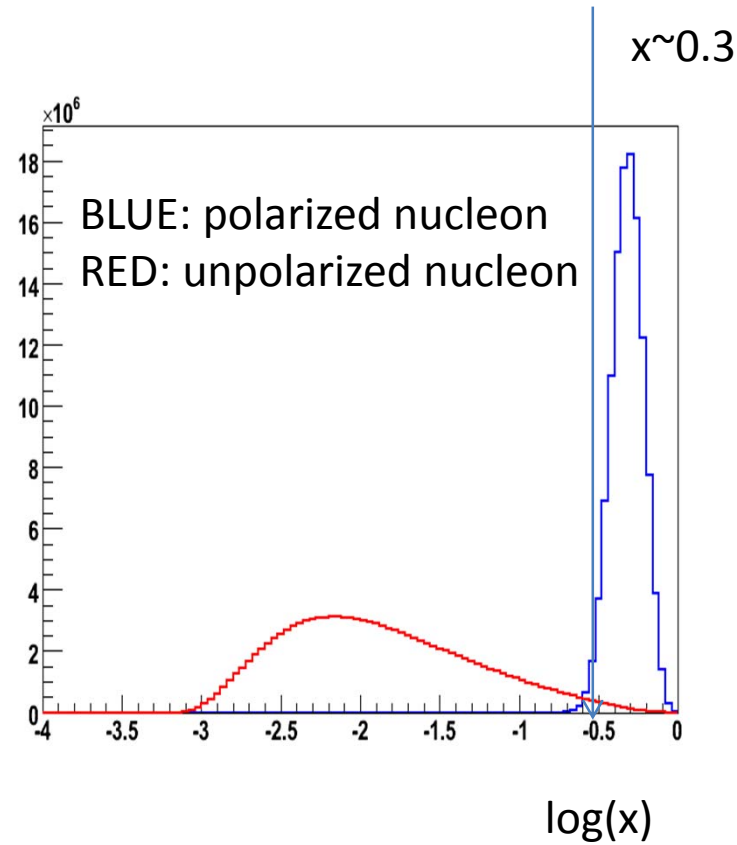
I_{dA}


Associate π⁰: 3.1< η < 3.9, pT = 0.45-1.59 GeV/c
Trigger Particle: |η| < 0.35
π⁰: pT = 2.0-3.0 GeV/c
π⁰: pT = 3.0-5.0 GeV/c
h⁺/⁻: pT = 1.0-2.0 GeV/c
Trigger π⁰ pT scale uncertainty 5%
Associate pT scale uncertainty 10%
PHENIX
PHENIX PRELIMINARY
I_dA
N_coll
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
4
6
8
10
12
14
16

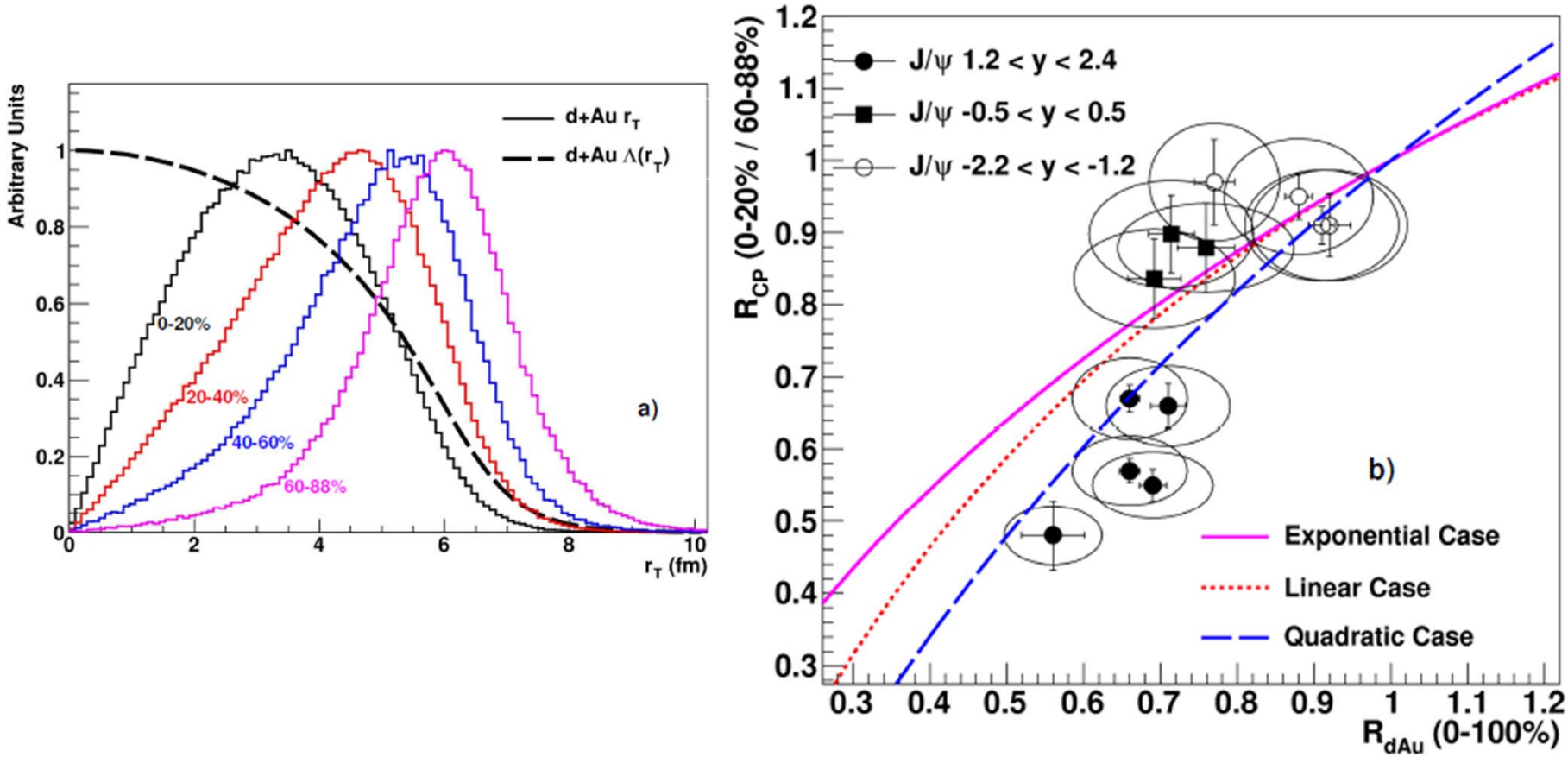
Longitudinal Spin - MPC Cluster A_{LL}



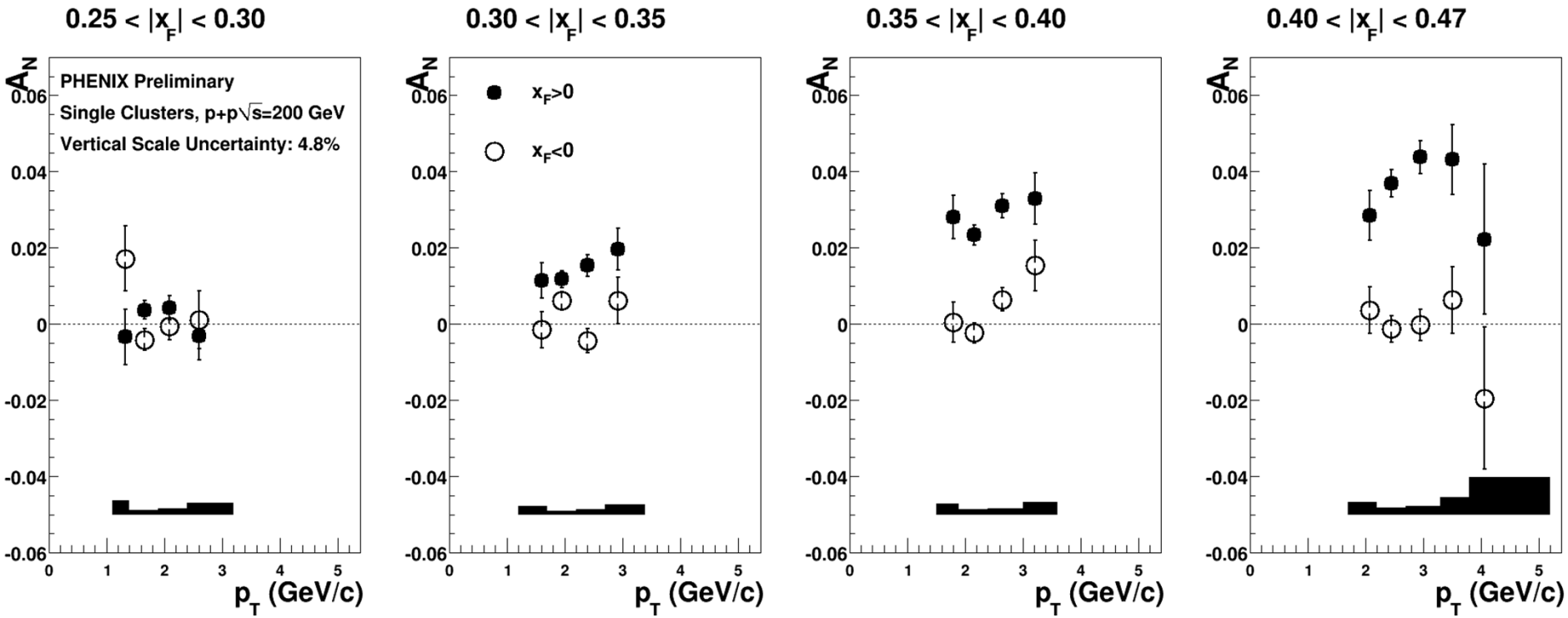
MPC x-coverage (ToyMC)



Dependence on Nuclear Thickness

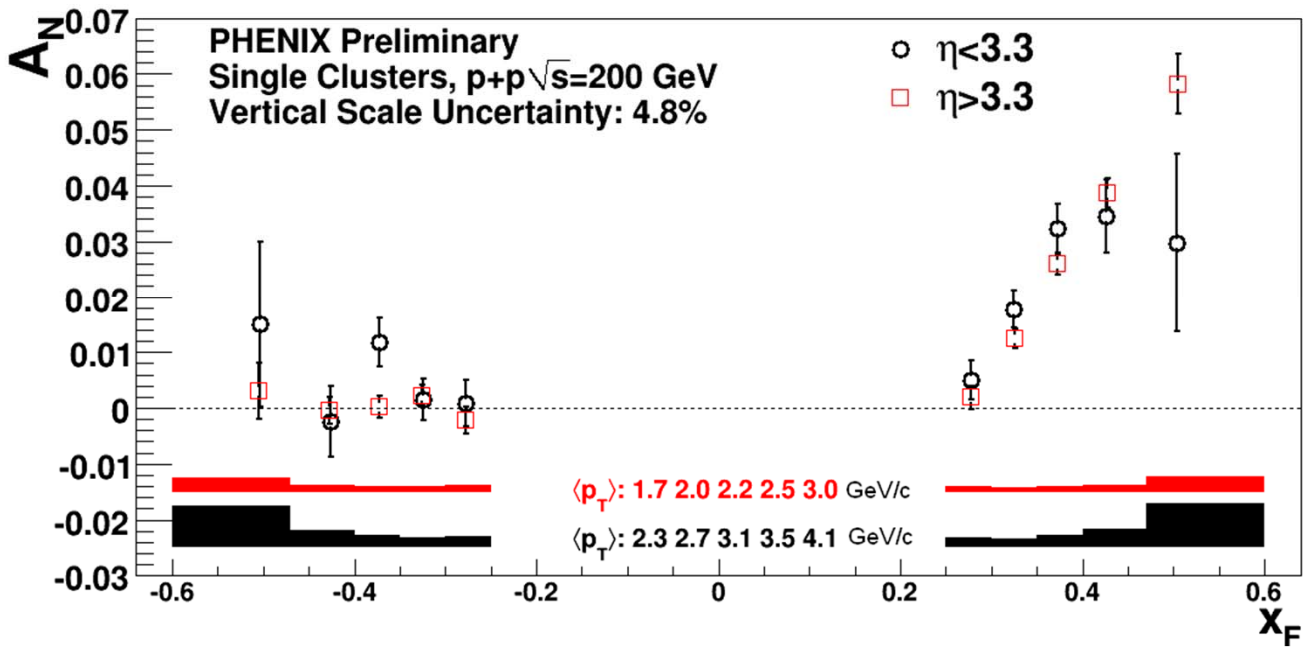


xF and pT binning

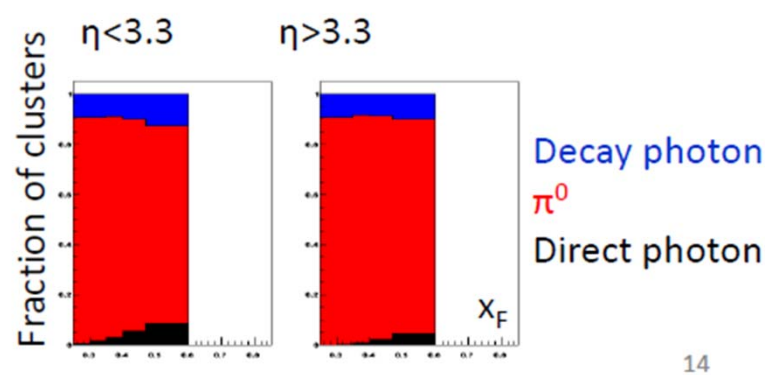


MPC Cluster A_N

- New PHENIX measurement showing single spin asymmetry at large x_F:



Need new measurements to disentangle sources of these asymmetries.

Asymmetries at forward x_F -> valence quark effect

See Also WG6S1: Feng Wei