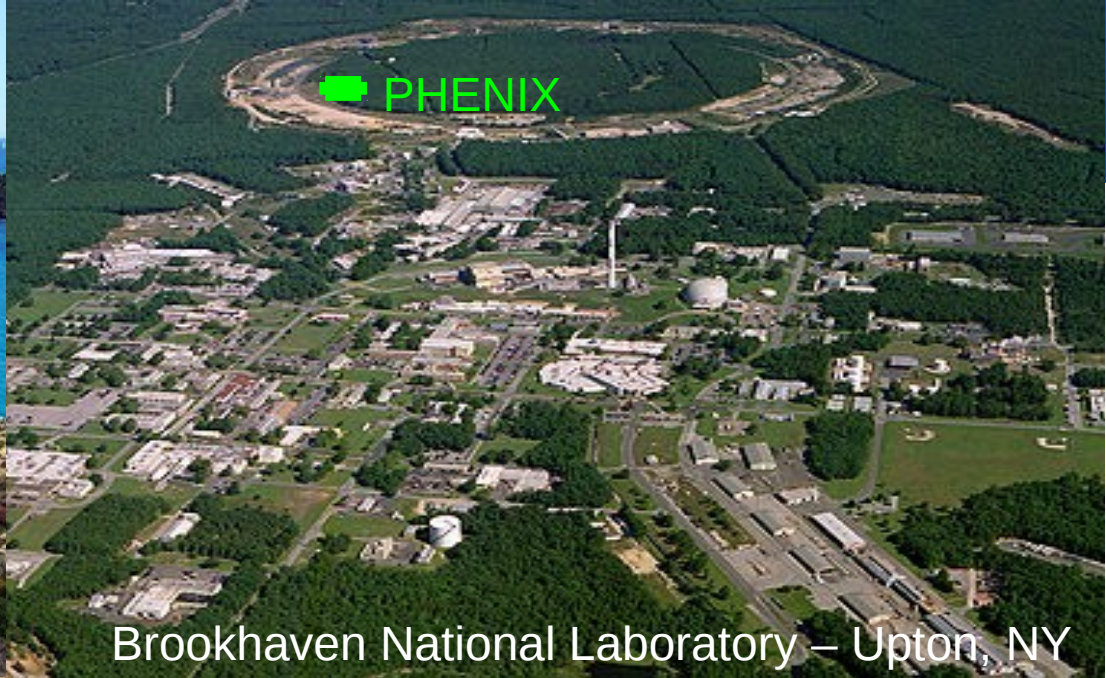




Transversity 2014, Chia, Italy



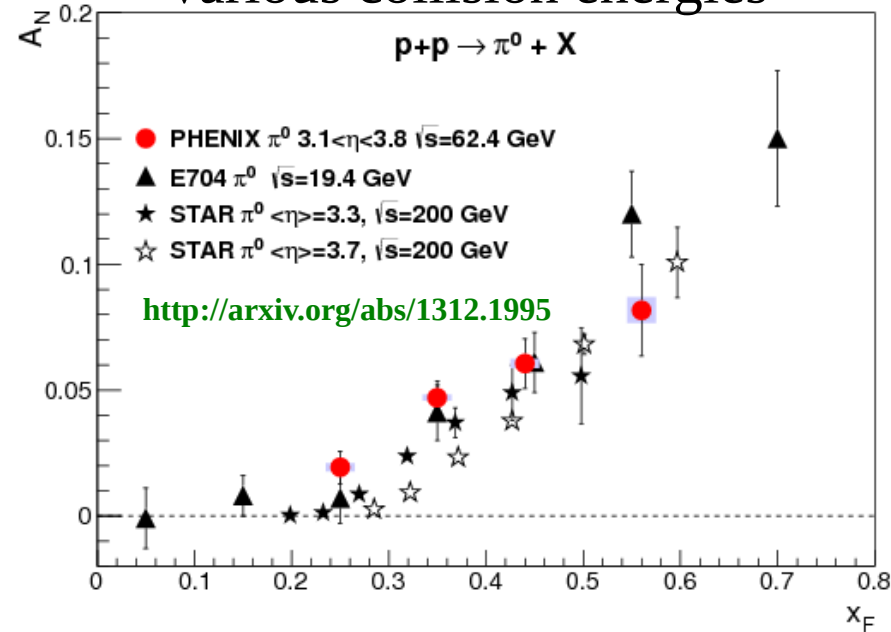
Brookhaven National Laboratory – Upton, NY

Transverse single spin and azimuthal asymmetries in hadronic collisions at PHENIX

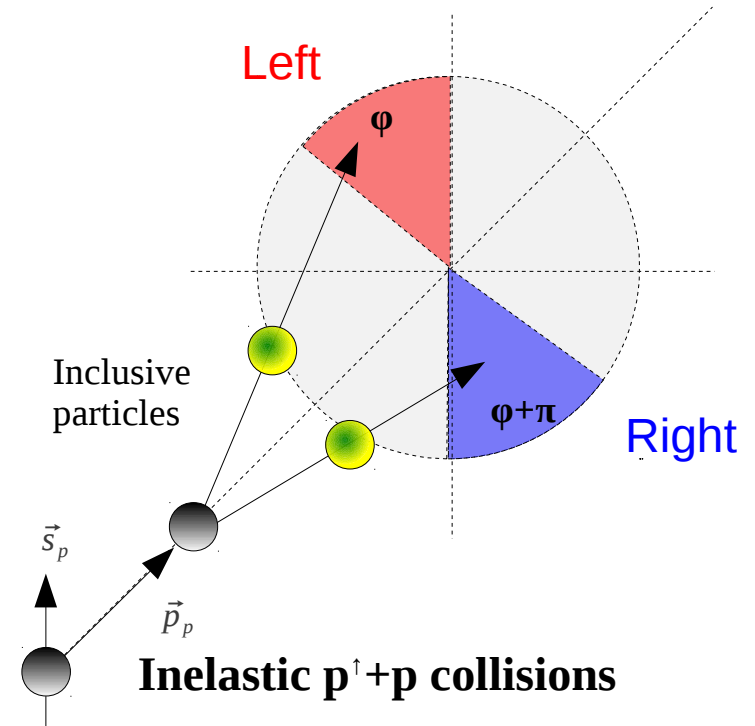
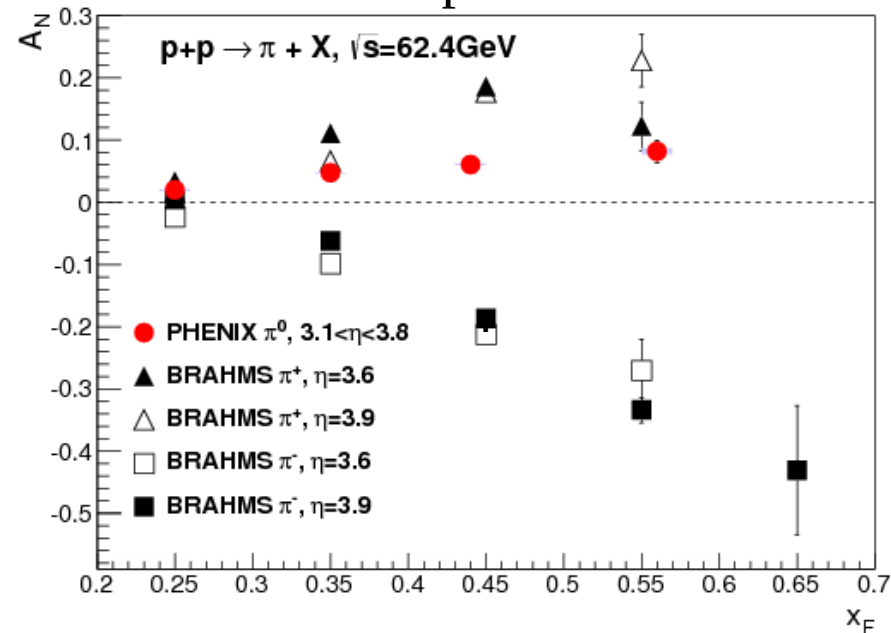
David Kleinjan
University of California, Riverside
For the PHENIX Collaboration

Motivation: A_N non-zero at forward rapidity

Various collision energies



Various particles

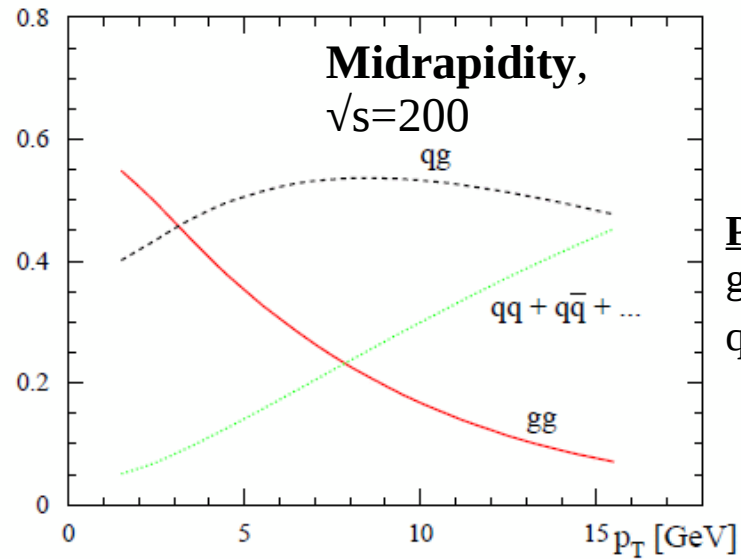
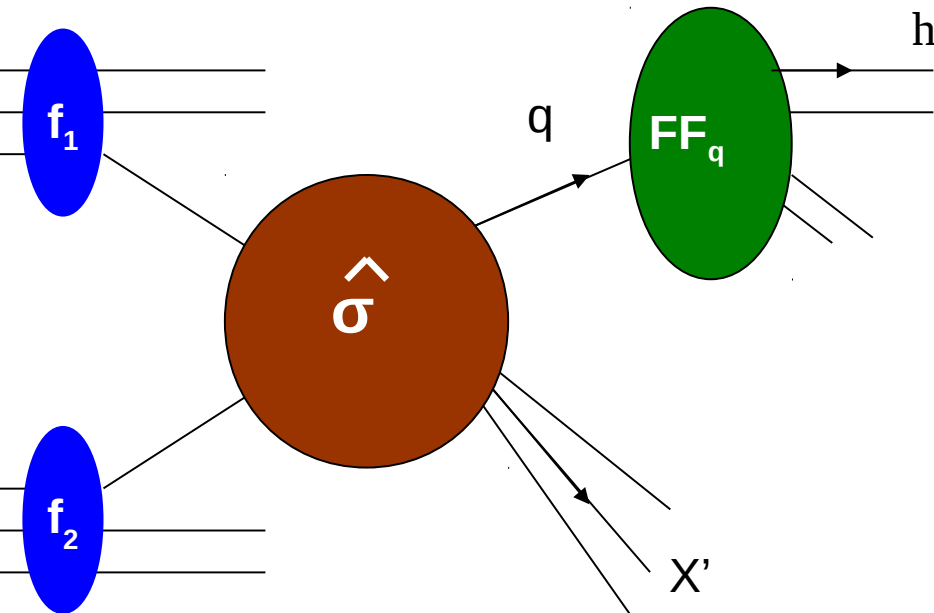


$$A_N = \frac{1}{P} \frac{\sigma^\uparrow(\varphi) - \sigma^\uparrow(\varphi + \pi)}{\sigma^\uparrow(\varphi) + \sigma^\uparrow(\varphi + \pi)}$$

pQCD at leading twist calculation has small spin dependence, i.e. no asymmetry.
 Can initial or final state effects produce a nonzero asymmetry?

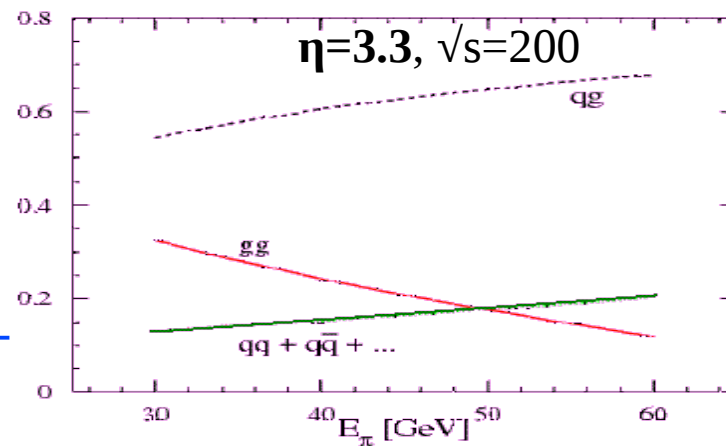
Nucleon-Nucleon collisions: $p + p \rightarrow h + X$

$$\frac{d^3 \sigma(pp \rightarrow hX)}{dx_1 dx_2 dz} \propto \underbrace{q_1(x_1) \cdot q_2(x_2)}_{\text{Proton Structure}} \times \underbrace{\frac{d^3 \hat{\sigma}(q_i q_j \rightarrow q_k q_l)}{dx_1 dx_2}}_{\text{pQCD}} \times \underbrace{FF_{q_k q_l}(z, p_{h,T})}_{\text{Fragmentation Function}}$$



Fragmentation Function

Perpendicular to Coll.
gg dominated at low p_T
qg dominated at high p_T



Near Parrallel to Coll.
qg "valence quark"
dominated

Possible Origins of Non-Zero A_N

$$\frac{d^3 \sigma(pp \rightarrow hX)}{dx_1 dx_2 dz} \propto \underbrace{q_1(x_1) \cdot q_2(x_2)}_{\text{Proton Structure}} \times \underbrace{\frac{d^3 \hat{\sigma}(q_i q_j \rightarrow q_k q_l)}{dx_1 dx_2}}_{\text{pQCD Hard scattering}} \times \underbrace{FF_{q_k q_l}(z, p_{h,T})}_{\text{fragmentation function}}$$

- “Transversity” quark-distributions and Collins TMD fragmentation

- Correlation between proton-spin and quark-spin and spin dependent fragmentation

$$A_N \propto \underbrace{h_1(x)}_{\text{Proton Structure}} \cdot \underbrace{H_1^\perp(z, p_{h,T}^2)}_{\text{fragmentation function}}$$

J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

- Sivers quark distribution

- Correlation between proton spin and transverse quark momentum

$$A_N \propto \underbrace{f_{1T}^{\perp q}(x, k_T^2)}_{\text{Proton Structure}} \cdot D_q^h(z)$$

D. Sivers, Phys. Rev. D **41**, 83 (1990)

- Twist-3 effects

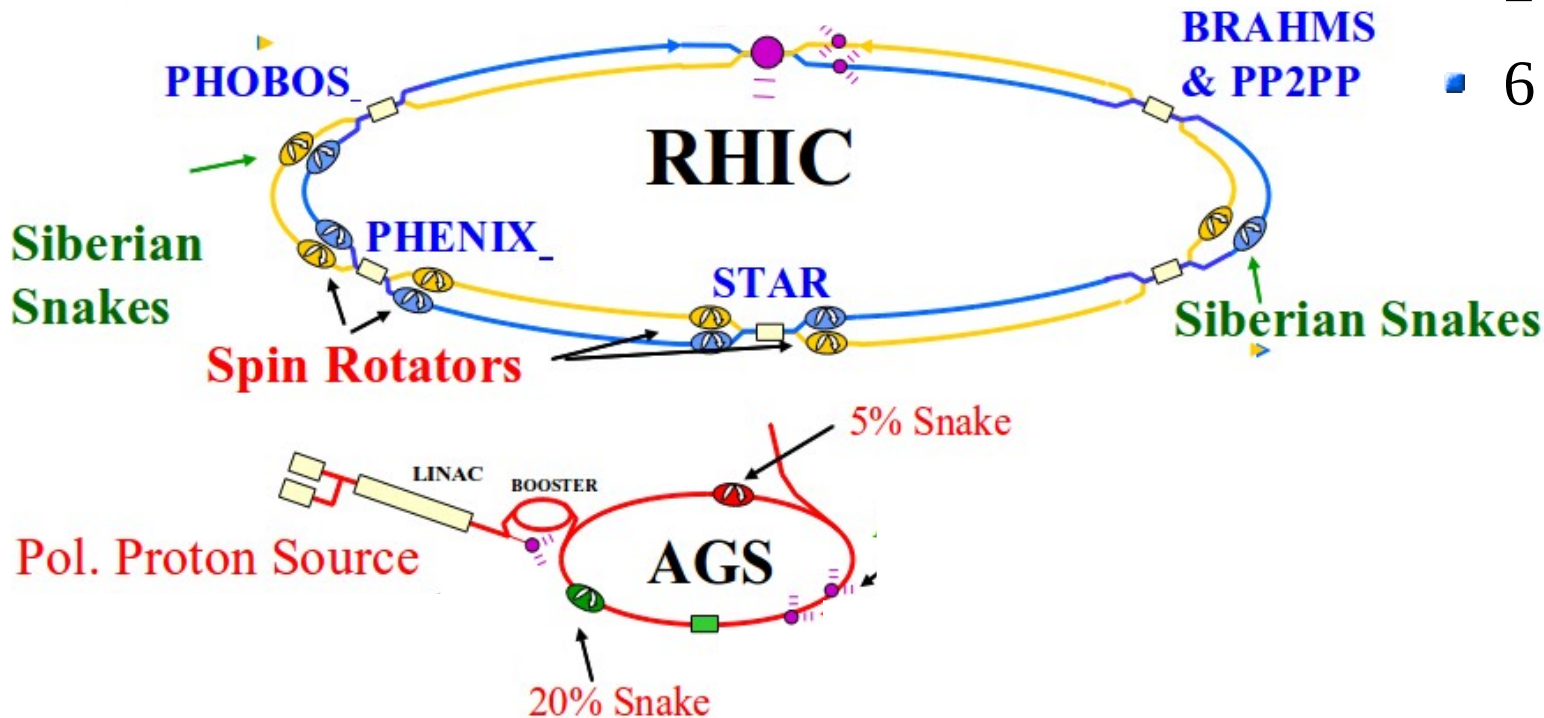
- ggg, qgq correlators

Qiu, Sterman. Phys. Rev D **59**, 014004 (1999)

Kang, Qiu, Zhang.. Phys. Rev D **81**, 114030 (2010)

RHIC & AGS

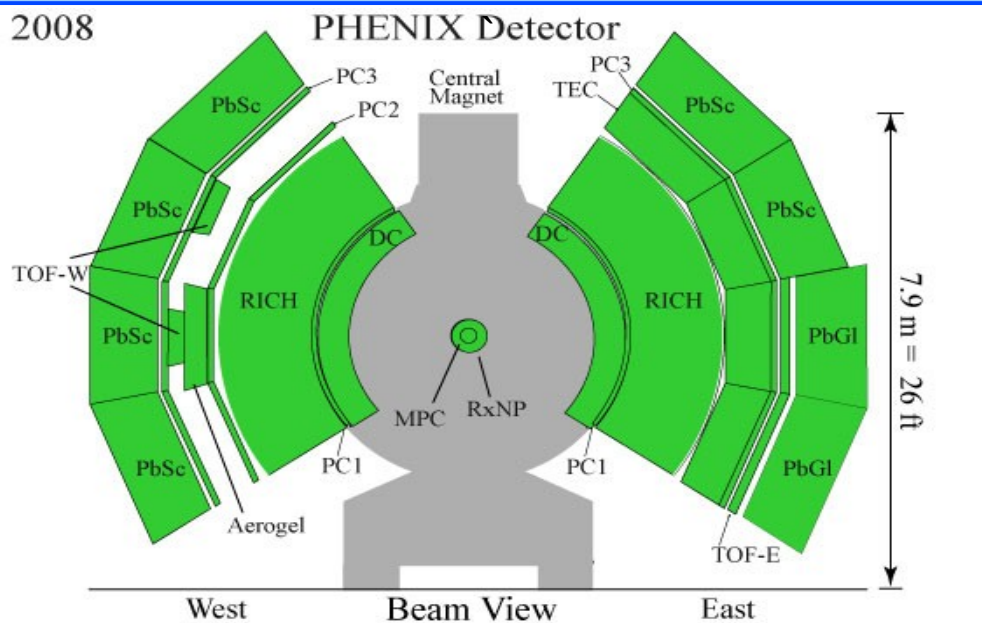
- 3.83 km circumference
- 2 Accelerator Rings
- 6 collision points



- Versatile Polarization Direction: Longitudinal or Transverse
- Energies probed in p+p collisions $\sqrt{s}=62\text{GeV}, 200, 510 \text{ GeV}$

PHENIX Detector (2008 schematic)

2008



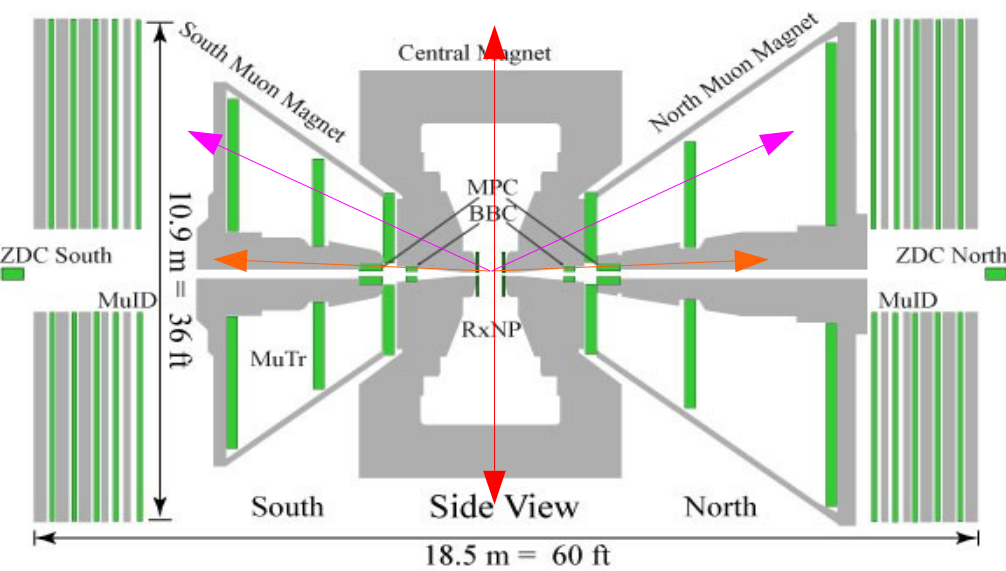
- 2 Central Arms $|\eta| < 0.35$
- Identified charged hadrons
- π^0, η mesons, direct photon
- J/ψ , heavy flavor $\rightarrow e^\pm$

- MPC $3.1 < |\eta| < 3.9$

- π^0, η mesons
- South and North MPC

- 2 Muon Arms $1.2 < |\eta| < 2.4$

- Unidentified charged hadrons
- J/ψ , heavy flavor $\rightarrow \mu^\pm$



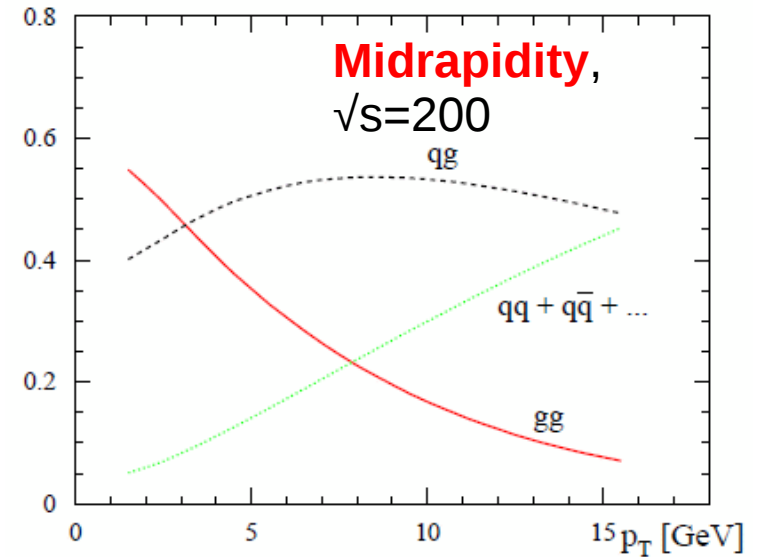
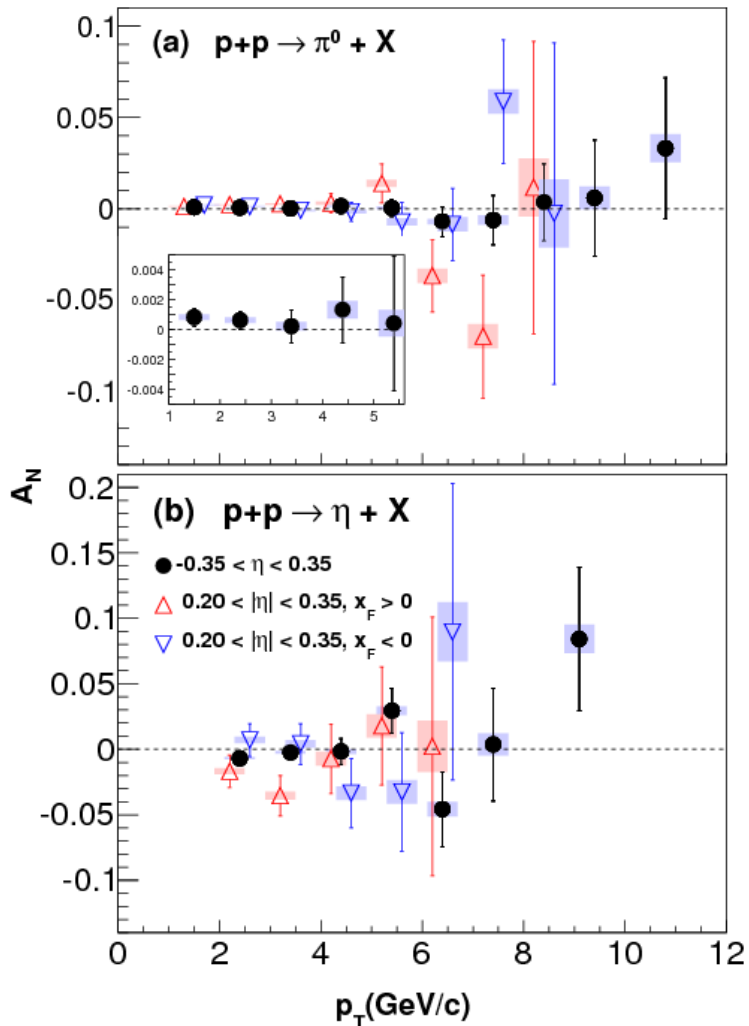
PHENIX measurements today

- Central Arm π^0 and η meson A_N ($|\eta| < 0.35$)
- MPC π^0 , single cluster, and η meson A_N ($3.1 < |\eta| < 3.9$)
- Muon Arm J/ψ , heavy flavor $\rightarrow \mu^\pm A_N$ ($1.2 < |\eta| < 2.4$)
- Others (skipped for time)
 - Di-hadron correlations
 - Interference Fragmentation Functions
 - Jet + π^0 Collins Measurements

Central Arm π^0 and η A_N ($\sqrt{s} = 200$ GeV)

<http://arxiv.org/abs/1312.1995>

p+p $\sqrt{s}=200$ GeV

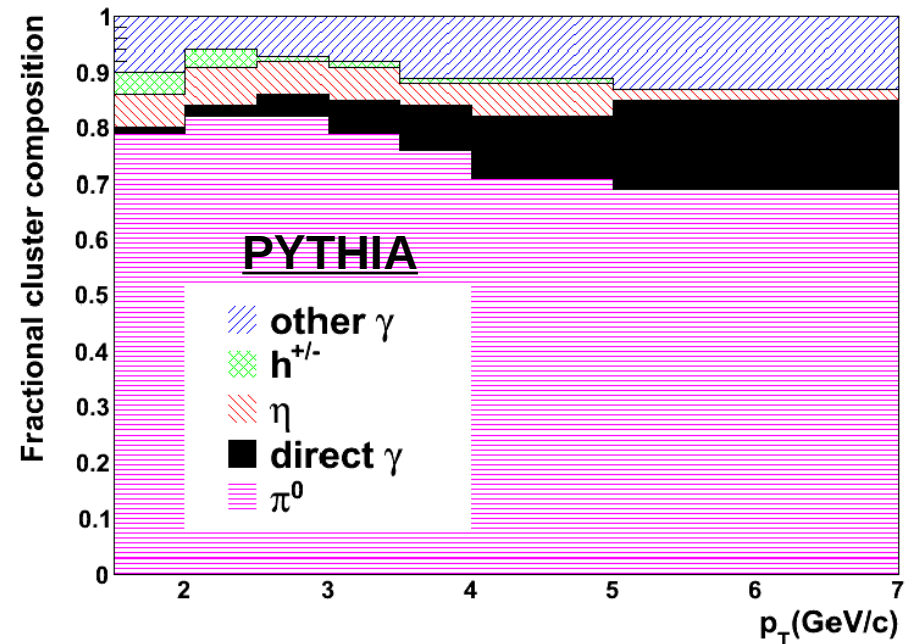
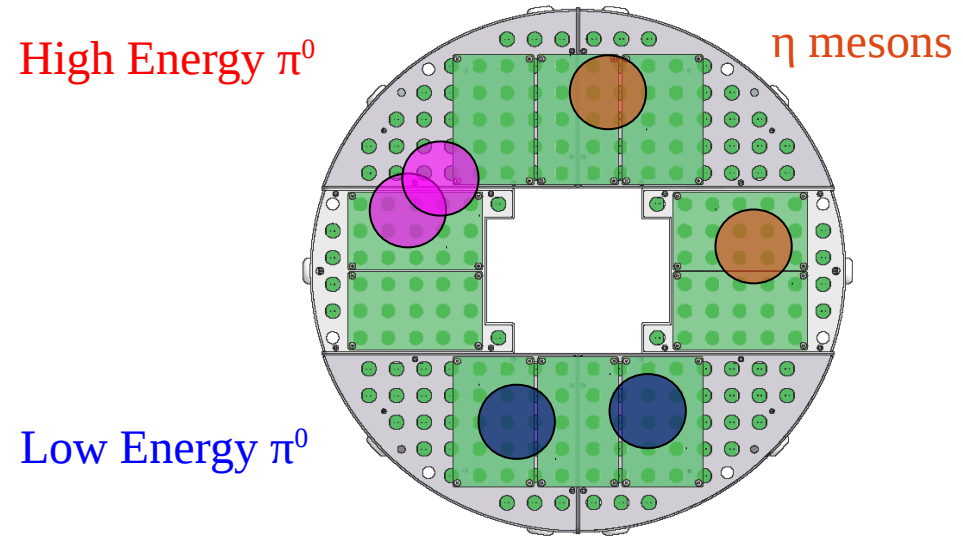


- Consistent with zero for both π^0 and η mesons
- Sensitive to gg , qg scattering
- Exceeds precision of previous result by factor of 20, extends p_T range
 - Phys. Rev. Lett. 95, 202001
- Includes η mesons

MPC detector in PHENIX

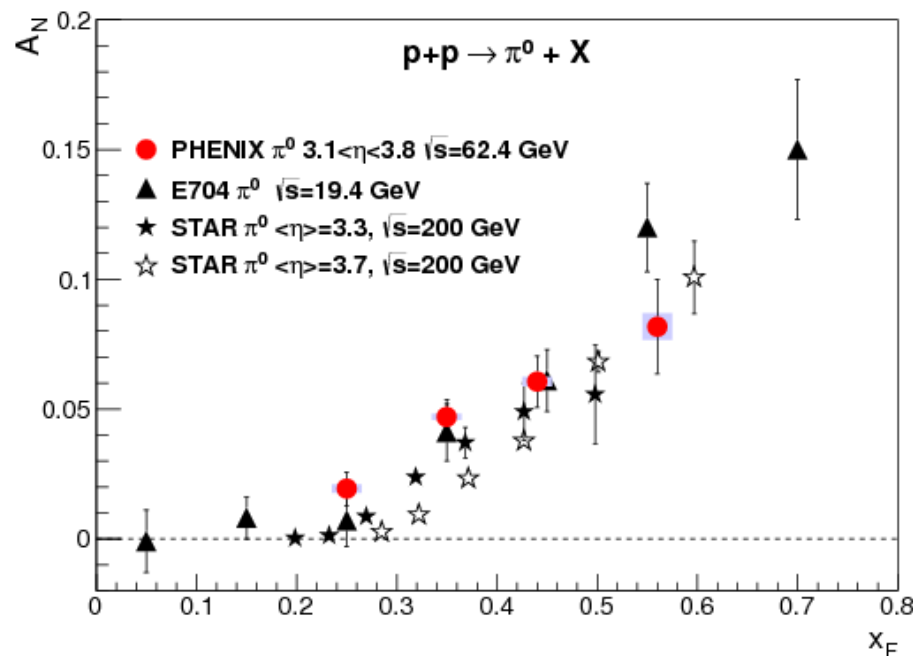
- MPC is forward E.M. Calorimeter
 - 2.2x2.2x18 cm³ PbWO₄ crystal towers
 - 220 cm from nominal interaction point

- Capable of reconstructing
 - η mesons ($\eta \rightarrow \gamma\gamma$, 10 – 70 GeV)
 - Low Energy π^0 ($\pi^0 \rightarrow \gamma\gamma$, 7 - 20 GeV)
 - High Energy π^0 merged clusters ($>\approx 20$ GeV)
 - *PYTHIA study:*
 - *Dominant cluster process at high p_T*



Results for $\pi^0 A_N$ ($\sqrt{s} = 62.4$ GeV)

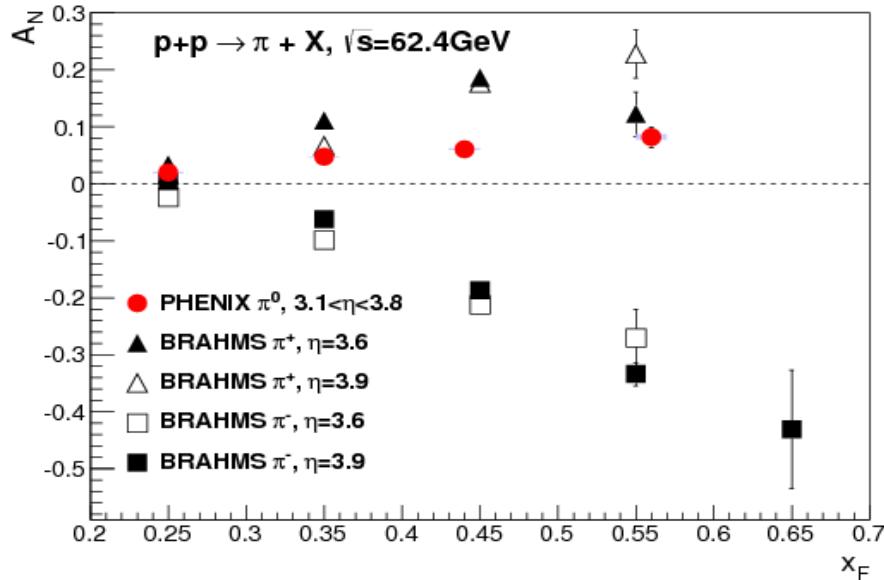
<http://arxiv.org/abs/1312.1995>



- Comparison to other neutral pion A_N measurements
 - A_N for neutral pions consistent across various energies
 - Not strongly dependent on collision energy

Results for $\pi^0 A_N$ ($\sqrt{s} = 62.4$ GeV)

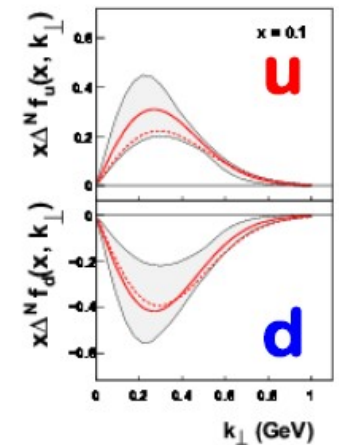
<http://arxiv.org/abs/1312.1995>



- Comparison to BRAHMS charged pion A_N measurements

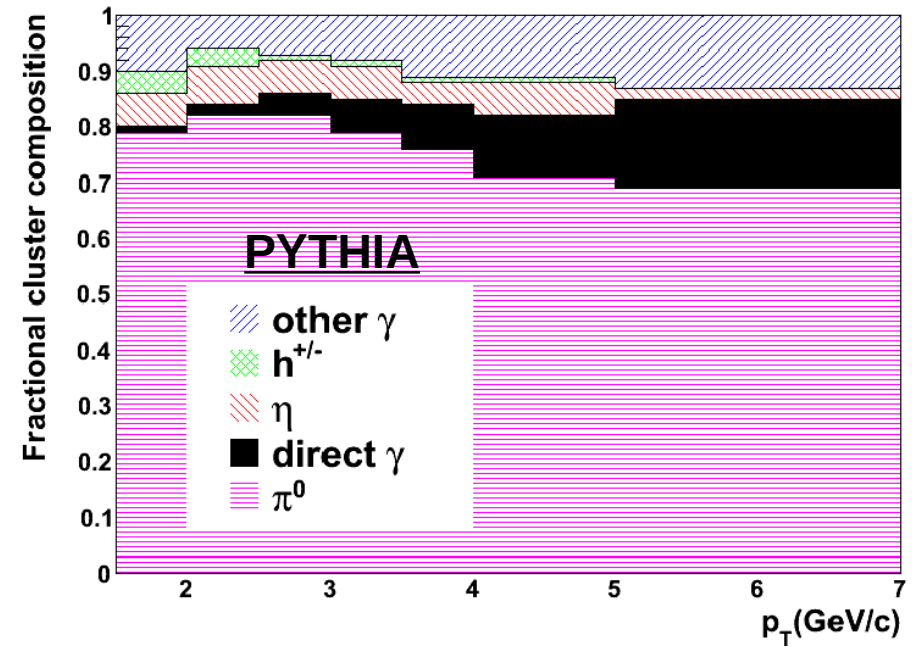
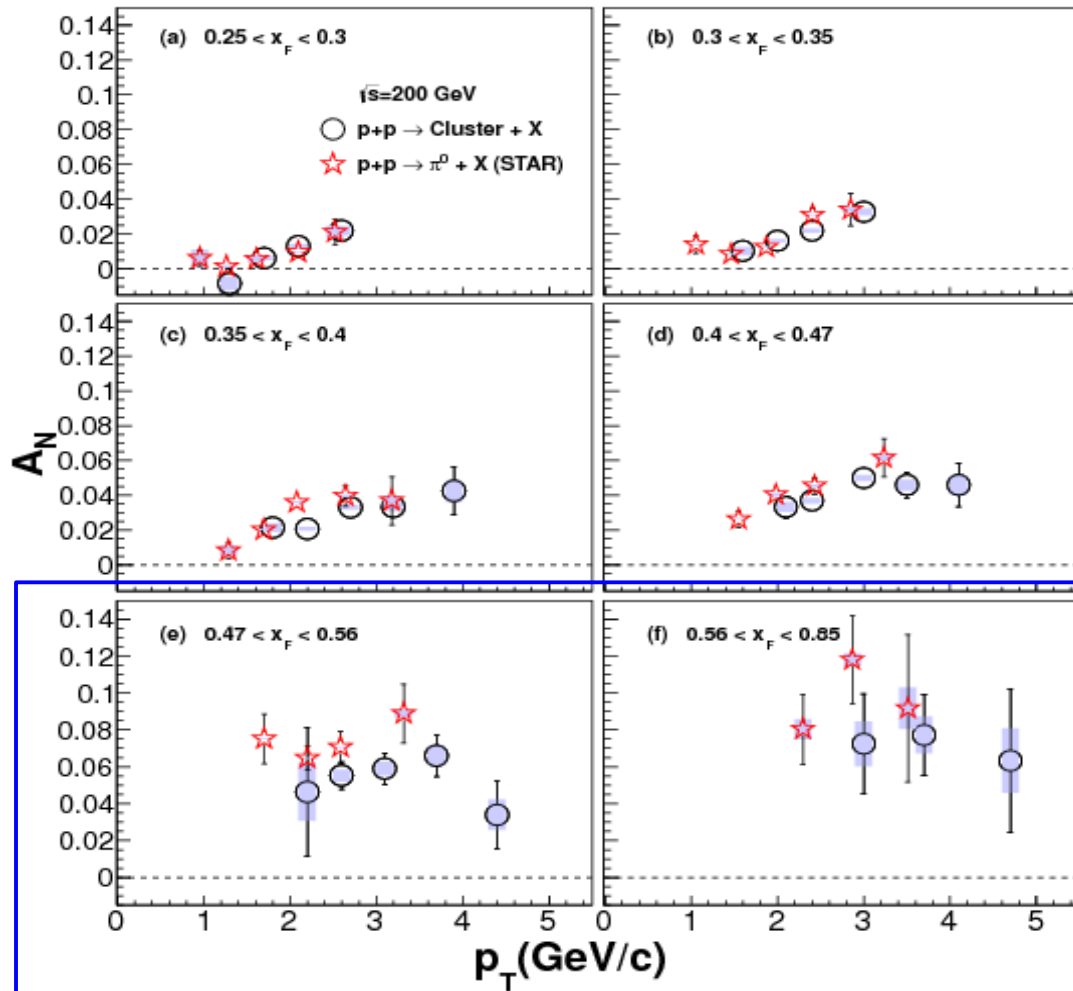
- Pion FF studied in PYTHIA
 - $u \rightarrow \pi^+$, $u \rightarrow \pi^+$ (100/0)
 - $d \rightarrow \pi^-$, $u \rightarrow \pi^-$ (50/50)
 - $d \rightarrow \pi^0$, $u \rightarrow \pi^0$ (75/25)
- Origin of A_N not explained by Sivers alone, assuming:
 - PYTHIA FF holds
 - u-d Sivers from SIDIS s holds in $p^+p \rightarrow \pi + X$

Sivers



Results for Cluster A_N ($\sqrt{s} = 200$ GeV)

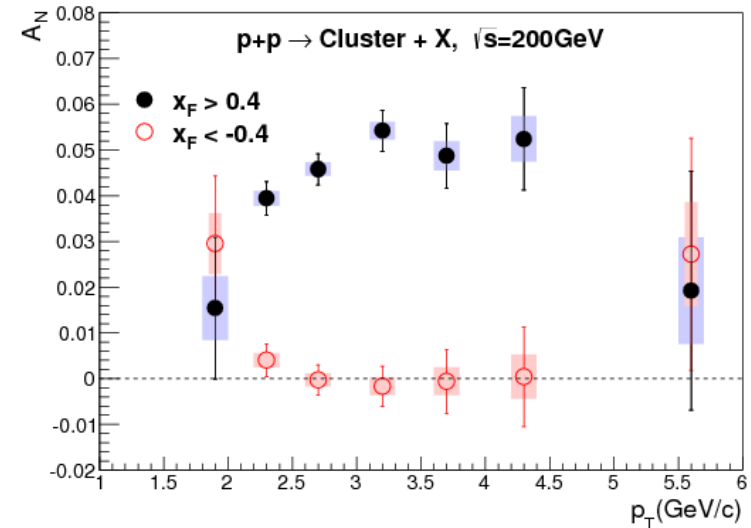
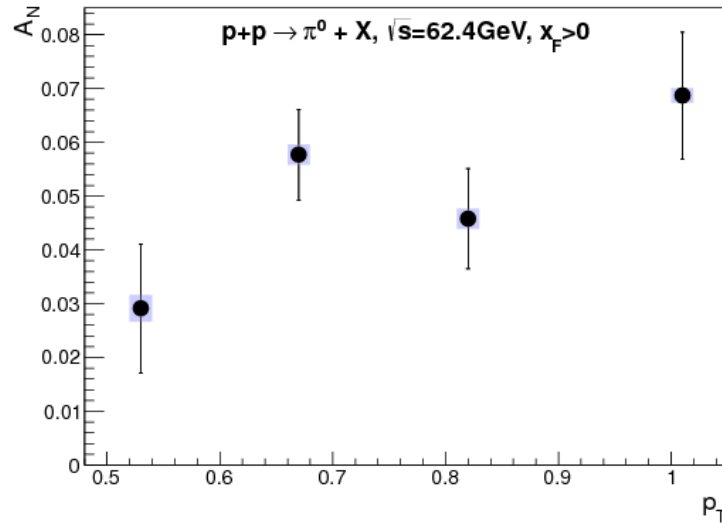
<http://arxiv.org/abs/1312.1995>



- Clear positive A_N at high x_F
 - Dominated by merged π^0 clusters
 - Consistent with STAR π^0 , with exception to highest bins
 - *Isolated direct- γ A_N would be an interesting measurement*

A_N as a function of p_T

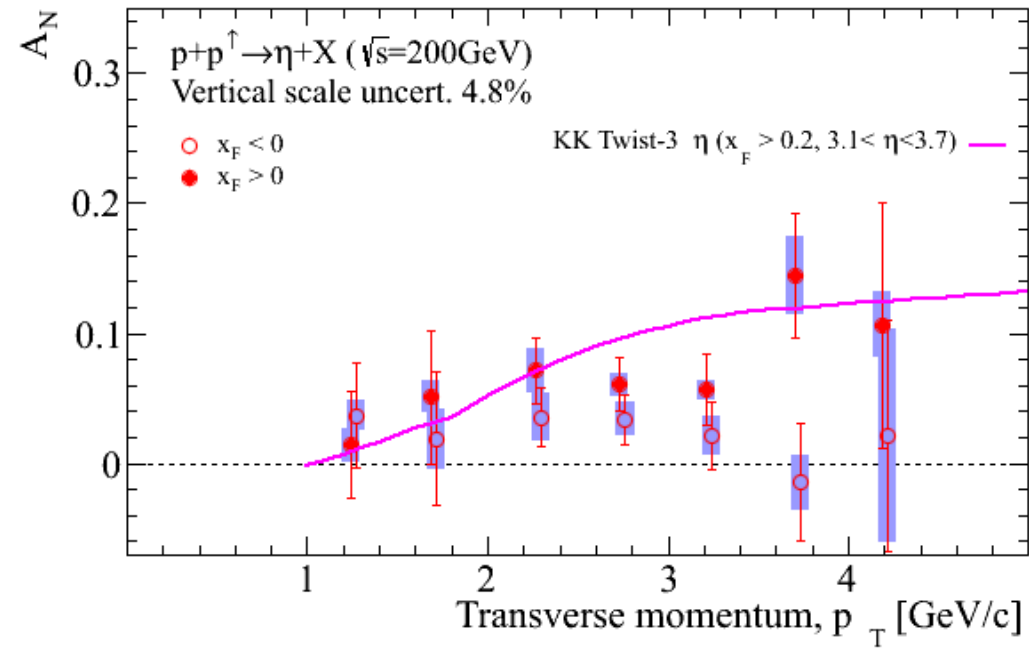
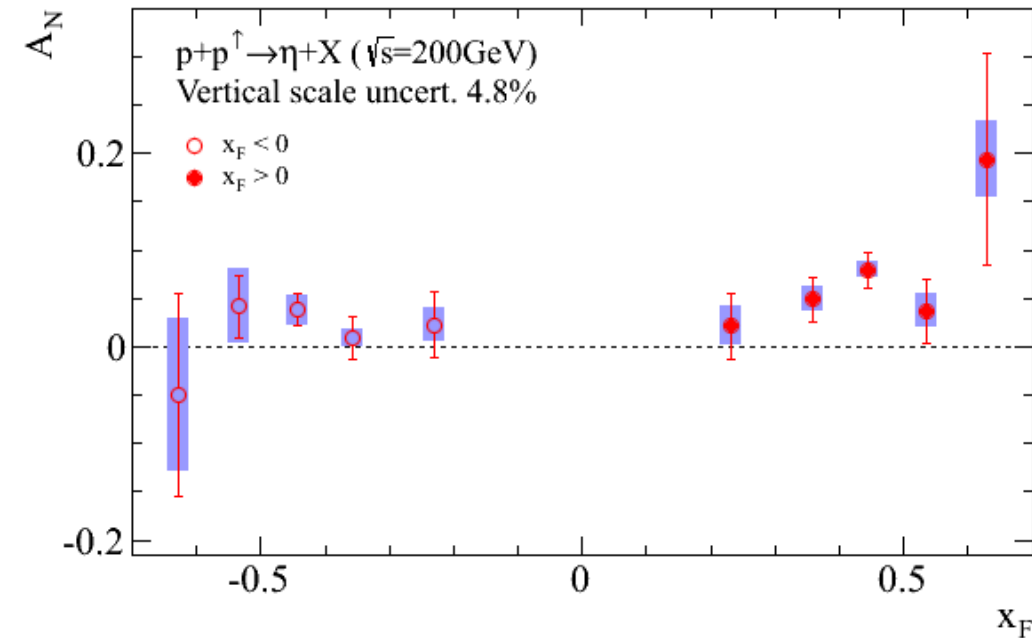
<http://arxiv.org/abs/1312.1995>



- Rises and plateaus at high p_T
- See Pitonyak talk yesterday for twist-3 explanation of A_N vs p_T

Just Submitted: η meson A_N @ $\sqrt{s} = 200$ GeV

<http://arxiv.org/abs/1406.3541>



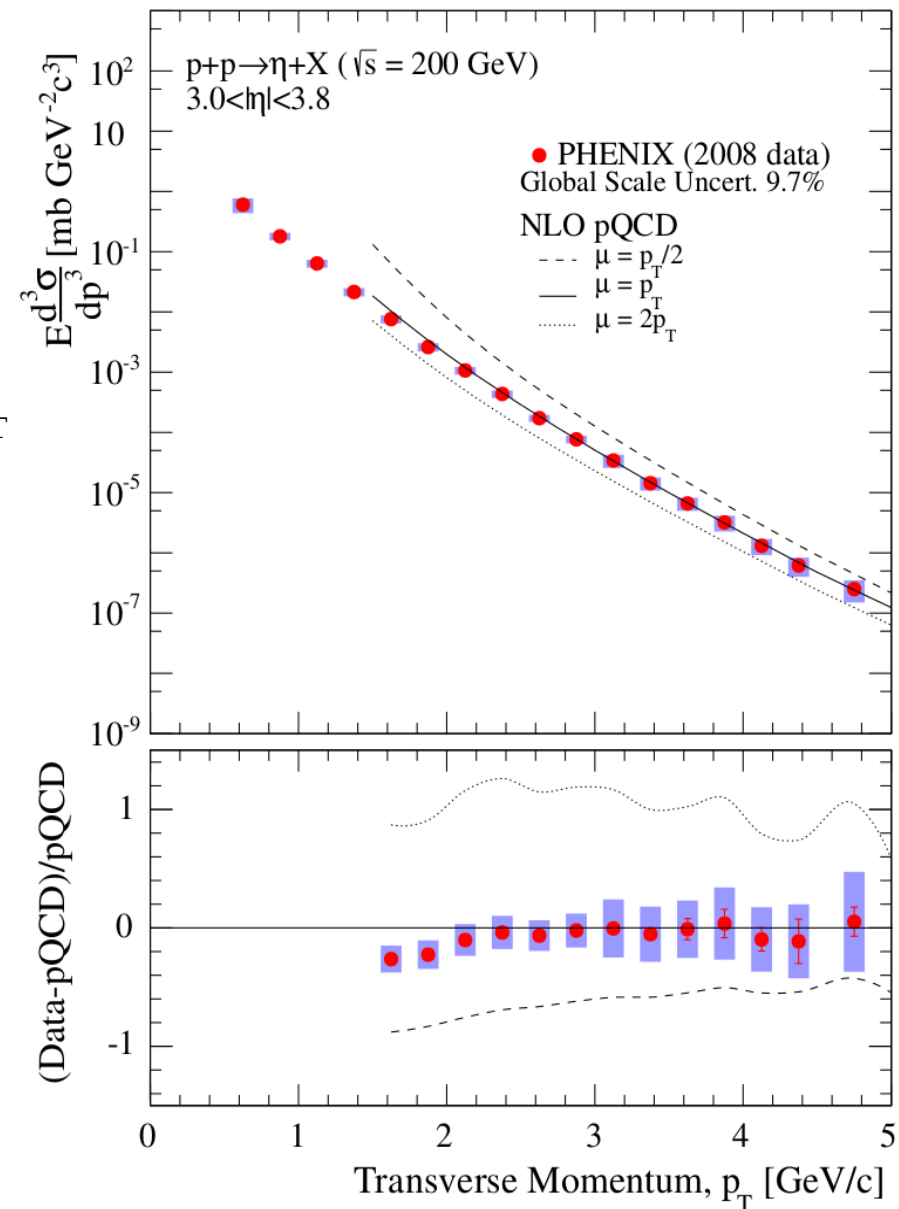
- There is a 3 to 20 percent positive A_N at forward x_F
- Consistent with zero (1.7σ) at negative (backwards) x_F
- Positive p_T dependent A_N for $x_F > 0.2$
 - Increases and plateaus at high p_T

Just Submitted: η Cross Section @ $\sqrt{s} = 200$ GeV

<http://arxiv.org/abs/1406.3541>

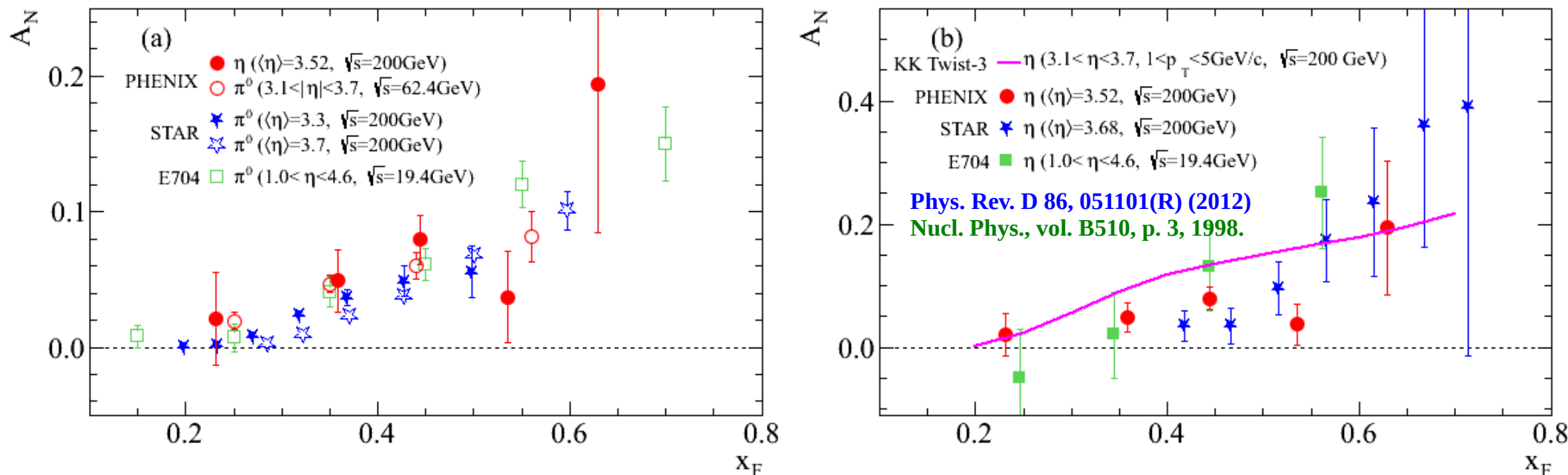
■ η meson Cross Section

- Good agreement with pQCD at a scale of $\mu = p_T$
- Can be used to improve constraints in η FFs
- pQCD calculation by M. Stratmann
 - $p + p \rightarrow h + X$
 - **Phys. Rev. D 67, 054005 (2003)**
 - η meson FF
 - **Phys. Rev. D 83, 034002 (2011)**



Comparison to Other Forward π^0 , η A_N results

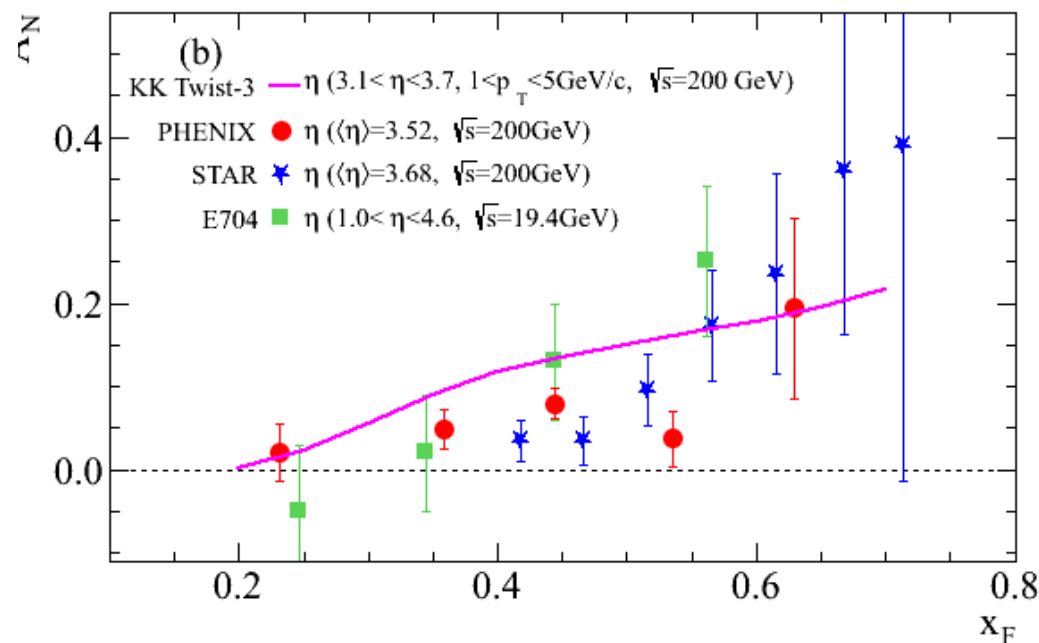
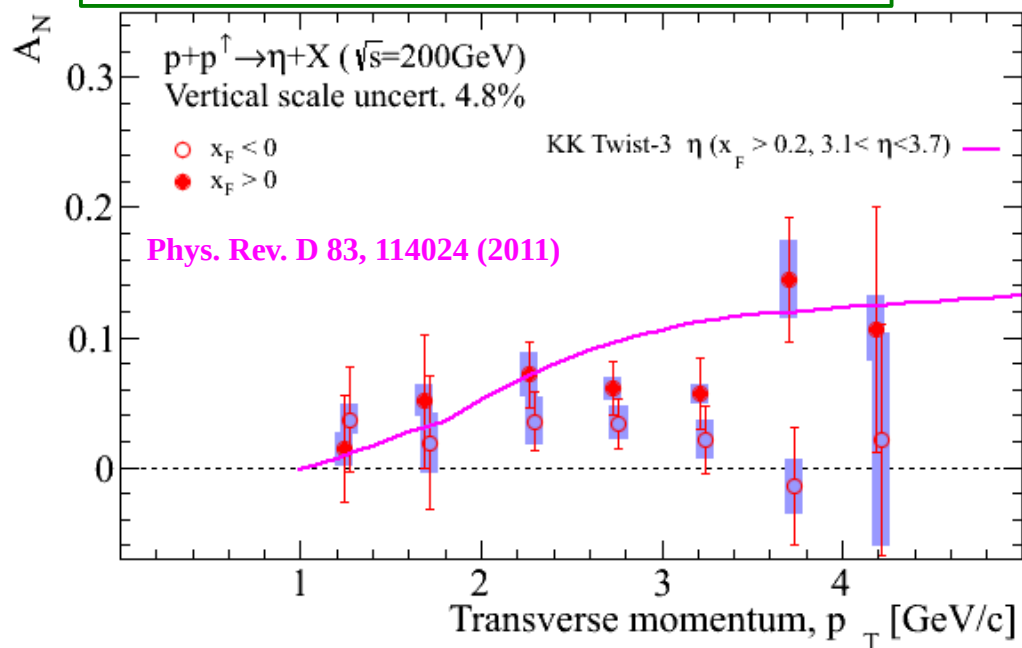
<http://arxiv.org/abs/1406.3541>



- Similar to previous π^0 meson A_N results
 - Differences in isospin, mass, strangeness
 - Potentially different in (polarized) fragmentation
- Consistent with previous STAR η meson A_N result within statistical uncertainty

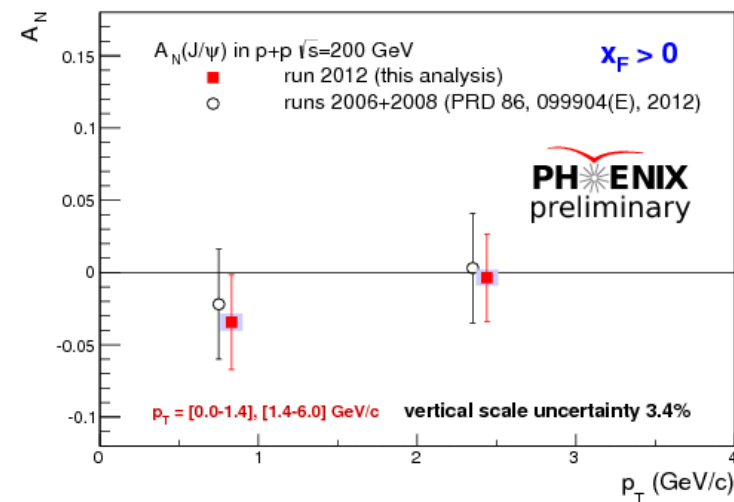
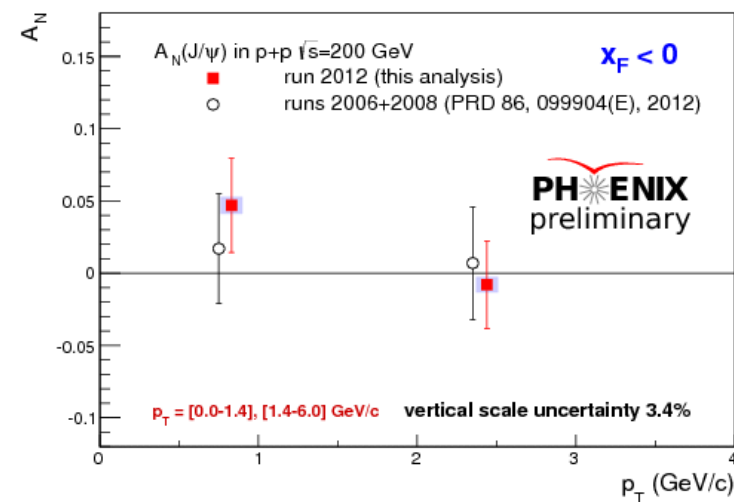
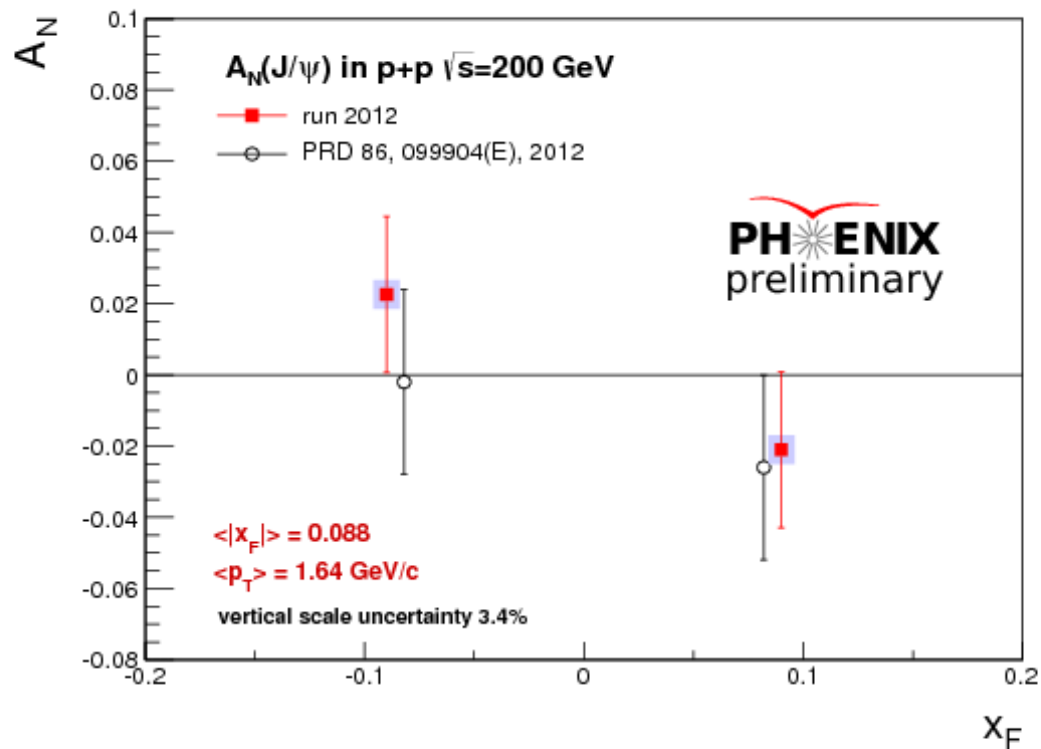
η meson A_N vs Twist-3

<http://arxiv.org/abs/1406.3541>



- Twist-3 calculation based on soft-gluon pole, soft-fermion pole
- Measurement consistent with calculation at low, high x_F (p_T)
- Less agreement at mid x_F (p_T)
- More developments in theoretical framework underway
 - D. Pitonyak, Y. Koike talks yesterday (**ArXiv:1404.1033**)

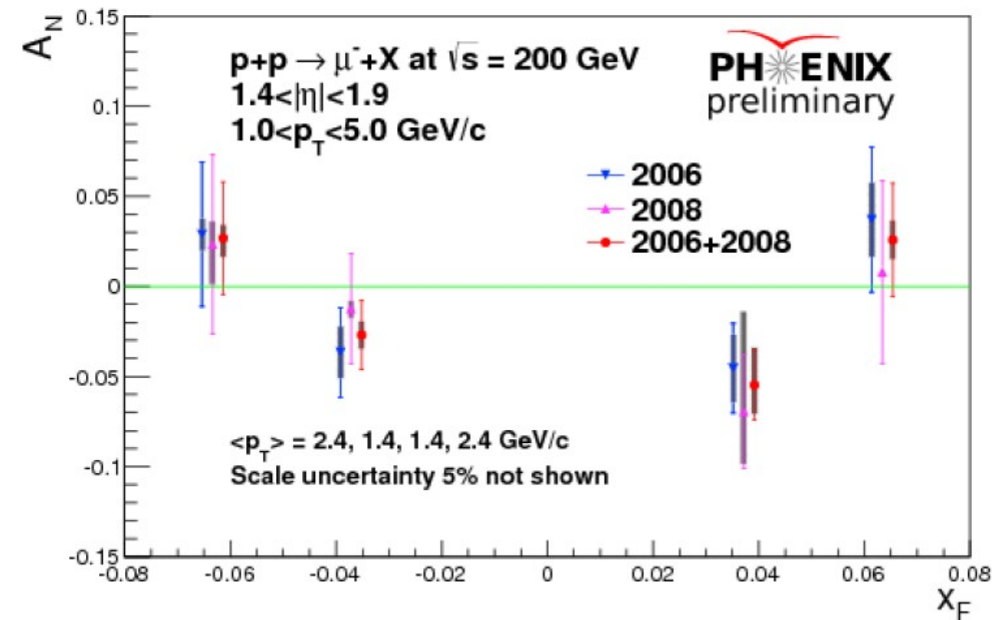
Near Forward Rapidity: J/ψ A_N



- Only color singlet generates SSA
 - Sensitive to production mechanism.
- A_N is consistent with zero.

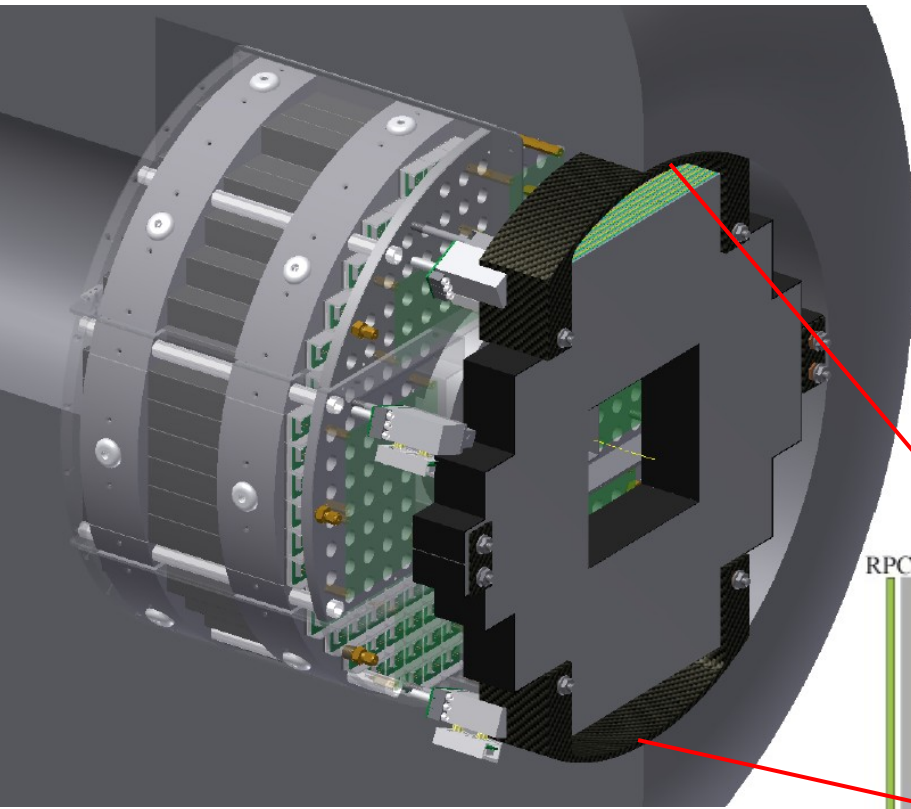
Near Forward Rapidity: Heavy Flavor A_N

- D meson A_N
 - Dominated by gluon-gluon fusion
 - Probes Tri-Gluon correlation Function
 - Koike, Yoshida, Phys Rev. D84 014026 (2011)



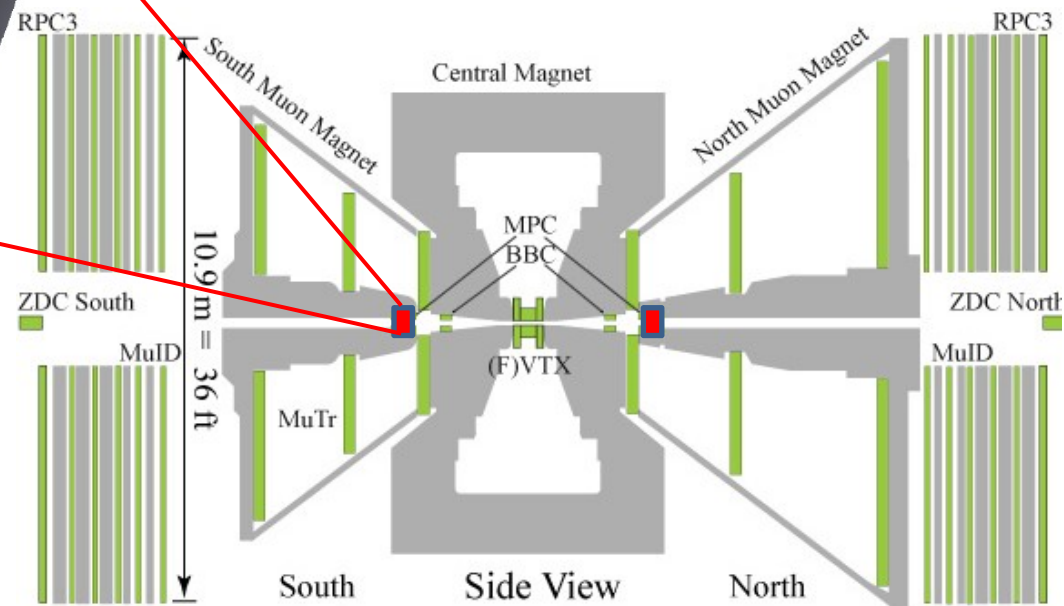
- PHENIX: no pure D-meson reconstruction (yet)
 - Single muon measurements are a probe
- $p^\uparrow + p$ @ $\sqrt{s}=200$ GeV taken in 2012 (9.1 pb^{-1}) with new PHENIX Silicon detectors
 - Help reject background
 - Analyses underway

Future: Direct γ with MPC-EX



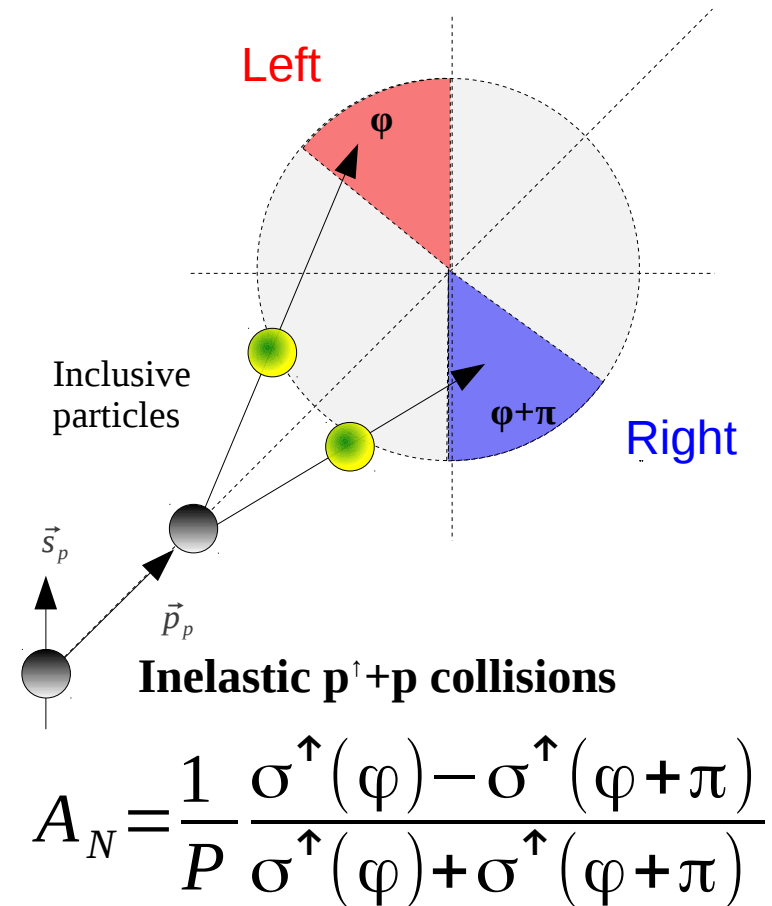
- A combined charged particle tracker and detector
 - Merged π^0 cluster rejection
 - Future Direct photon A_N and Cross-Section measurements

- Commissioned in 2014
- First Physics in 2015
 - p^+ + Au, p^+ +p run



Conclusions

- PHENIX has measured several Transverse single spin asymmetries
 - Mid-Rapidity π^0 and η A_N consistent with zero
 - Non-zero x_F , p_T dependence of A_N for forward π^0 and η mesons
 - π^0 A_N : Comparison to other pion A_N
 - η A_N : Consistent with other π^0 and η measurements (**submitted today** [arXiv:1406.3541](https://arxiv.org/abs/1406.3541))
 - Comparison of different particle species will help disentangle origin of non-zero A_N
 - Measurement of J/ψ , Heavy flavor A_N
 - Can help constrain tri-gluon correlations



Outlook

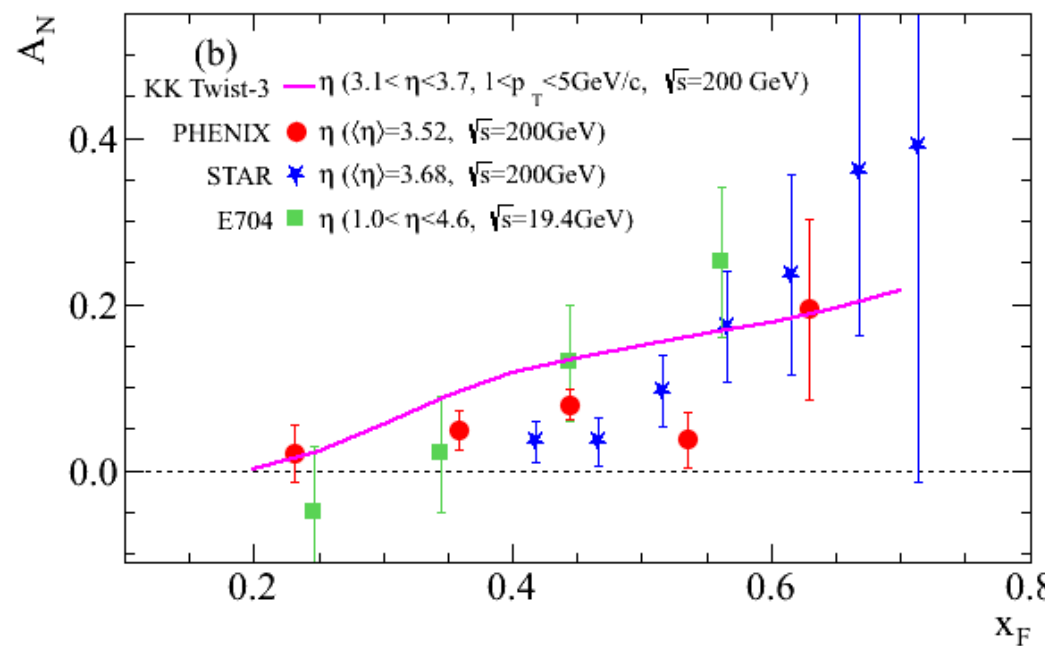
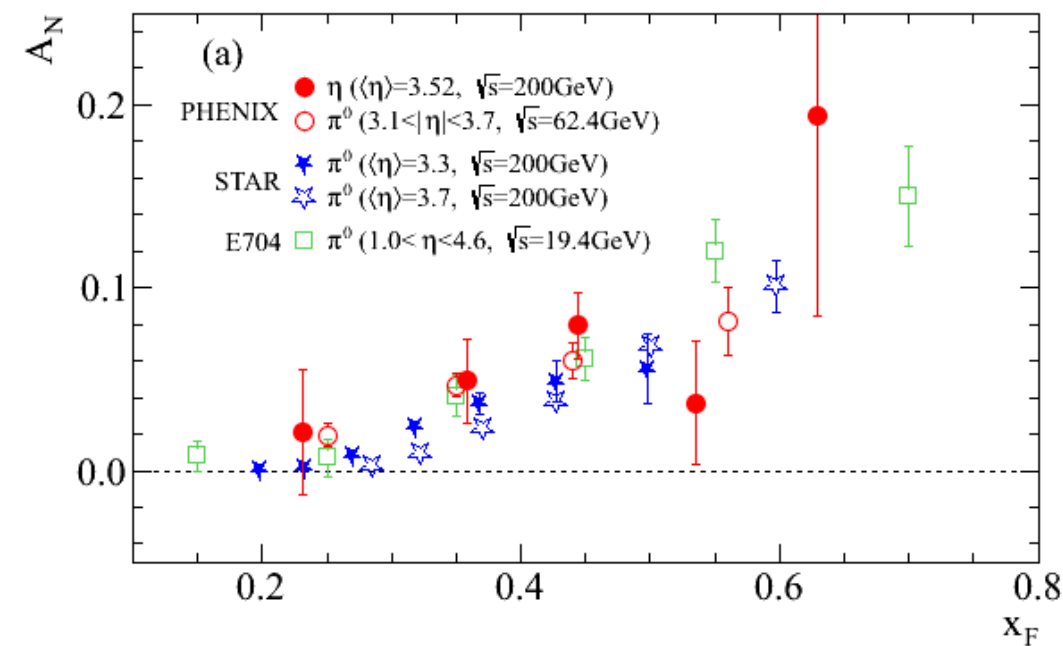
Year	\sqrt{s} (GeV)	L (pb ⁻¹)	Polarization	FoM (P ² L)
2008	200	5.2	46%	1.1
2012	200	9.1	58%	3.3

- 2012 Transverse Spin Data
 - New MPC electronics and trigger
 - Improved trigger purity, energy range (very high energy clusters)
 - Silicon detector heavy flavor separation for near forward muon A_N measurements ($D \rightarrow \mu, J/\psi$)
- Upcoming 2015 Transverse RHIC Run
 - MPC-EX to measure direct- γ A_N
 - More Silicon detector heavy flavor separation
- Beyond: sPHENIX F-Spectrometer for jets, DY



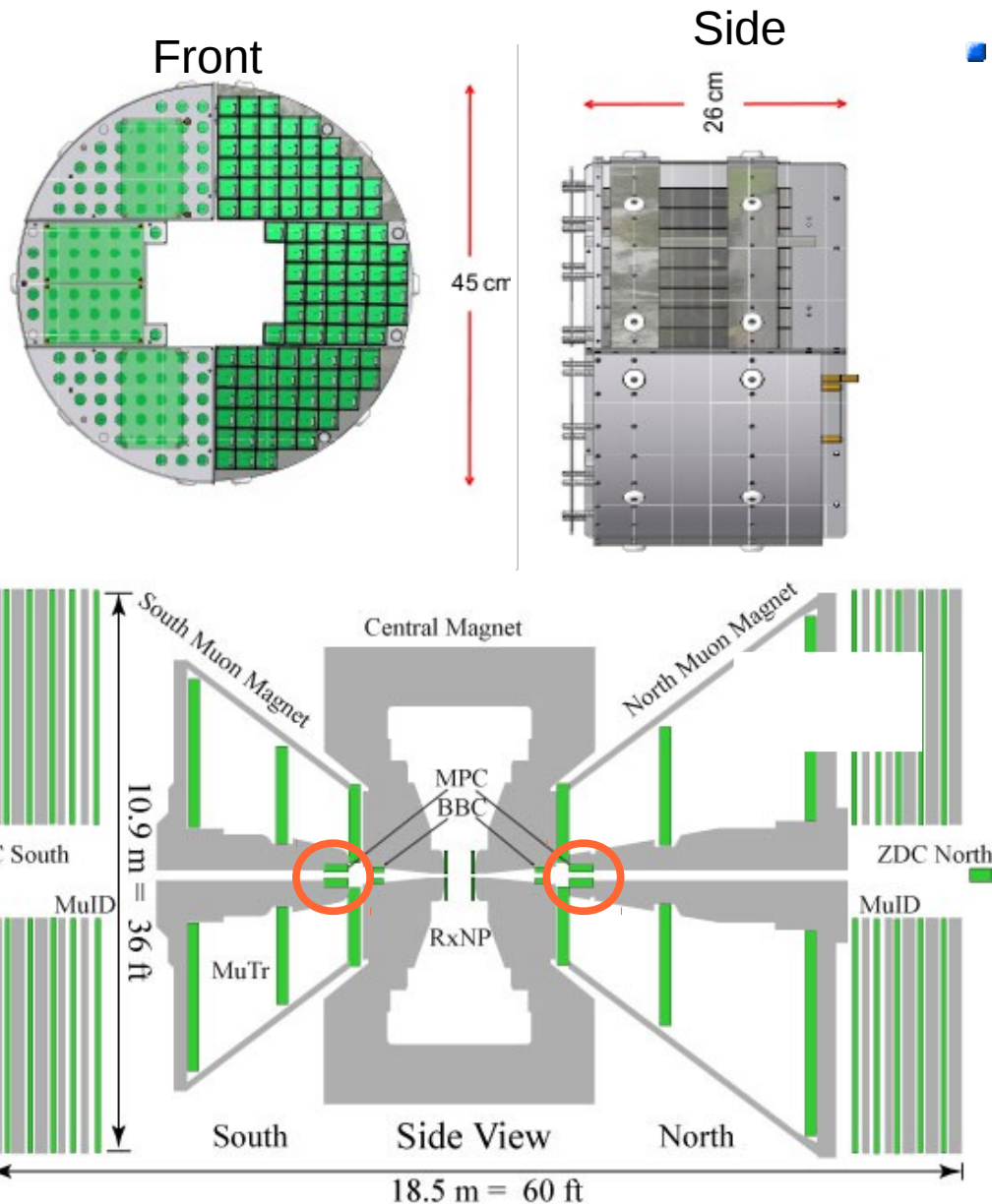
Transversity 2014, Chia, Italy

Thank You!

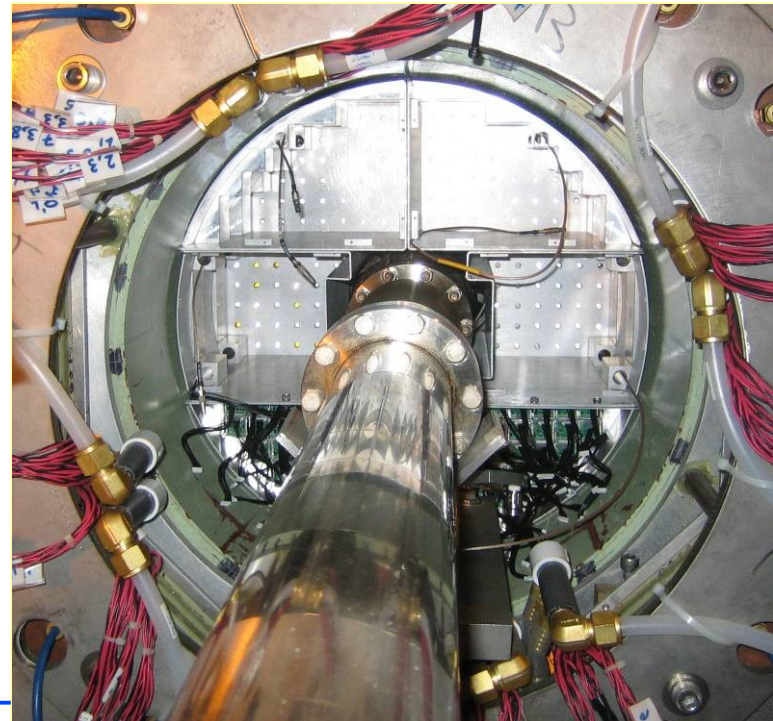


backup

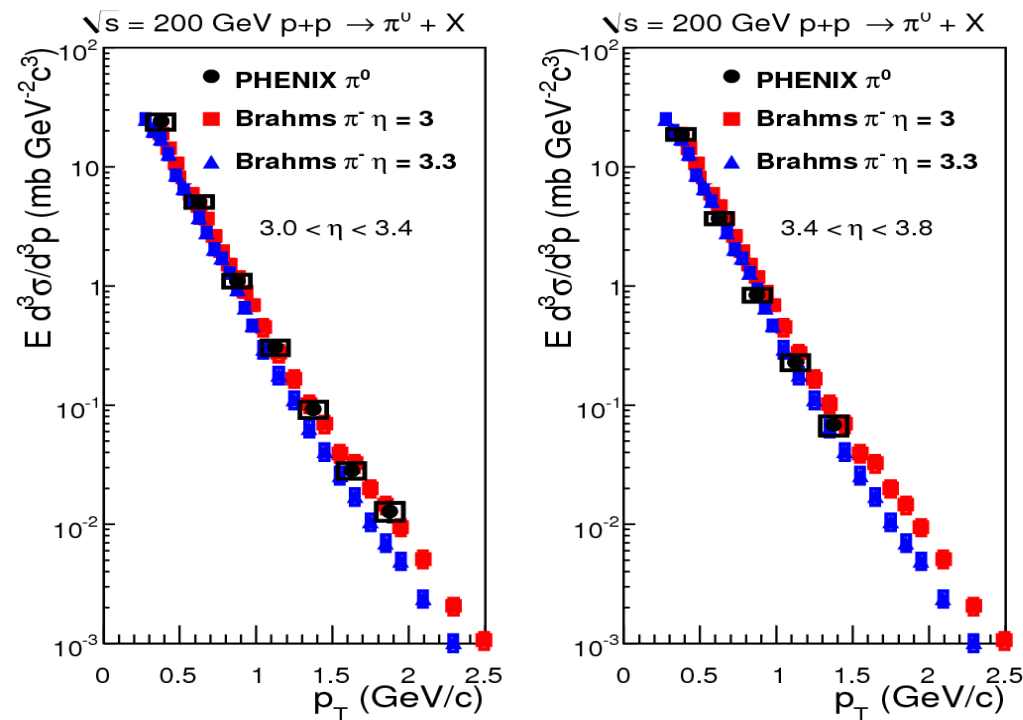
MPC detector in PHENIX



- MPC is forward E.M. Calorimeter
 - $2.2 \times 2.2 \times 18 \text{ cm}^3$ PbWO_4 crystal towers
 - 220 cm from nominal interaction point
 - $|3.1| < \eta < |3.9|$
 - 196(220) crystals in south(north) MPC

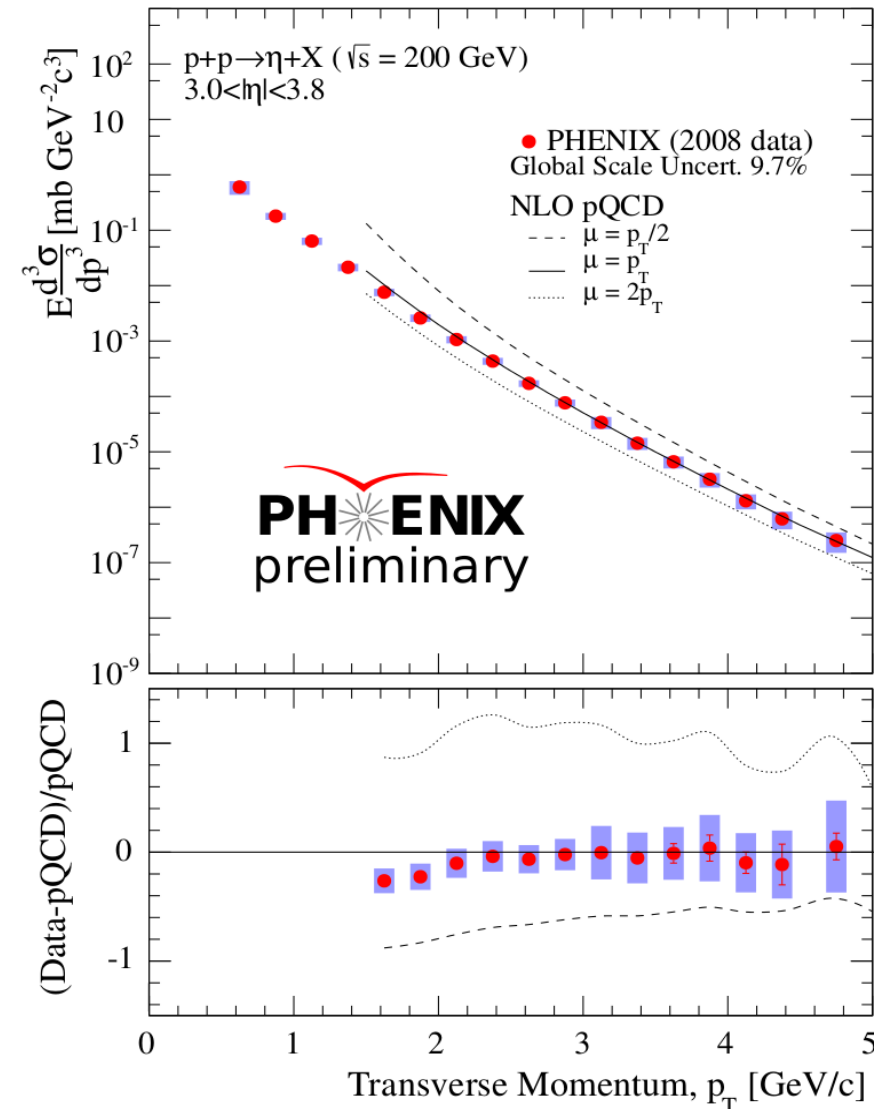


MPC π^0 and η Cross Section @ $\sqrt{s}=200$ GeV

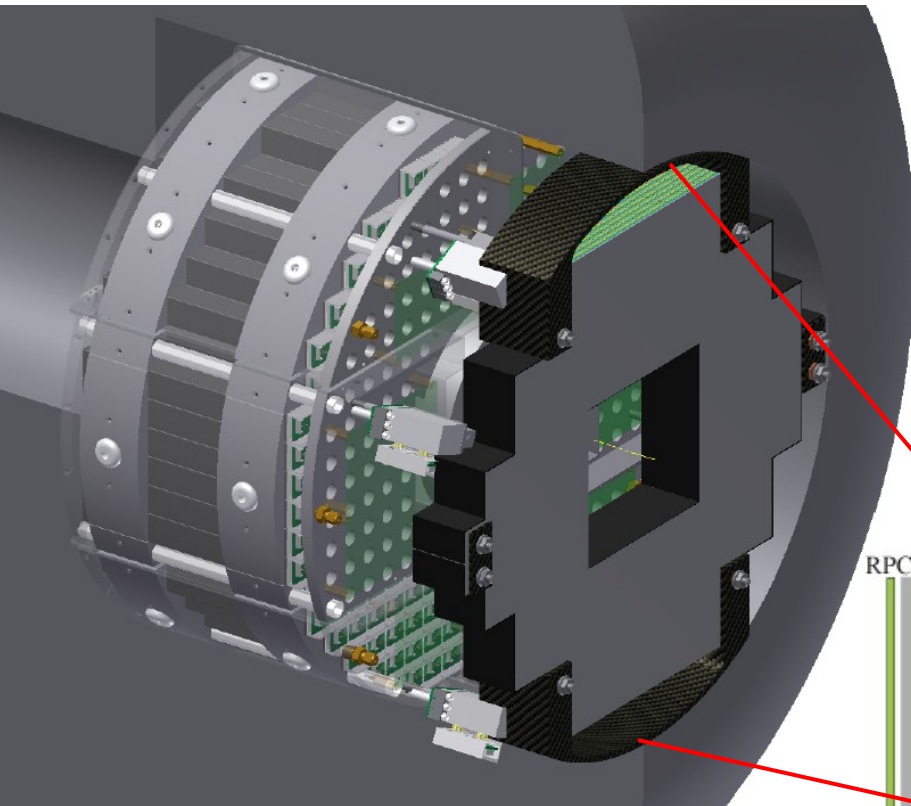


PHENIX: Phys. Rev. Lett. 107, 172301
 BRAHMS:

- π^0 Cross Section
 - Close agreement with BRAHMS π^\pm
- η meson Cross Section
 - Good agreement with pQCD

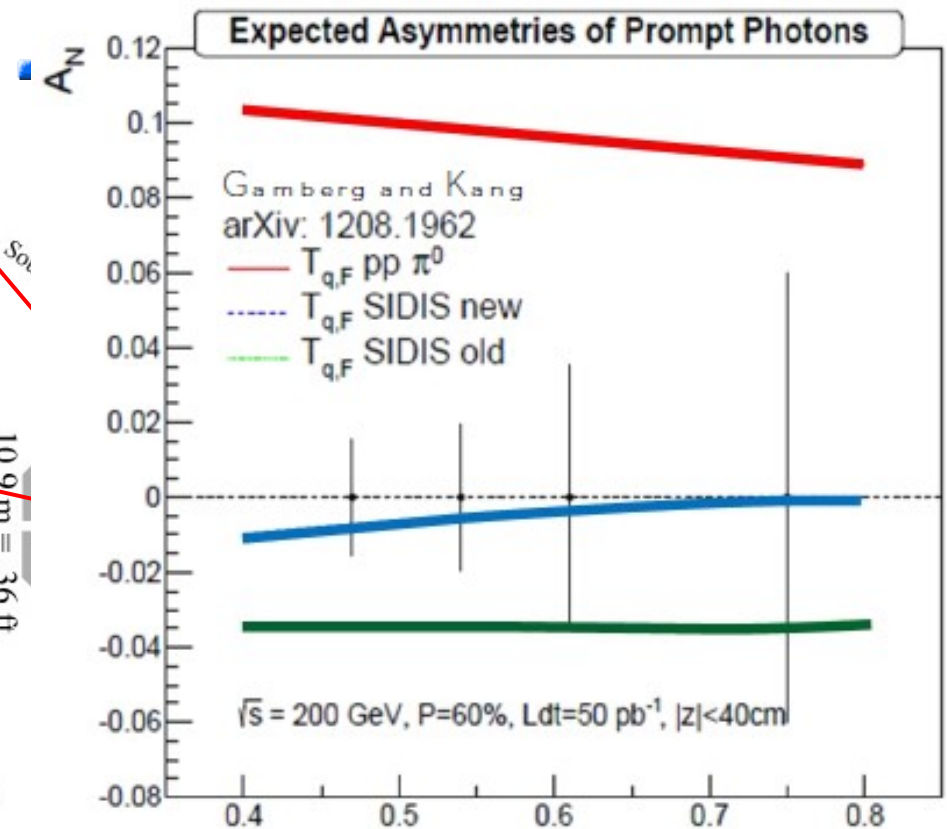
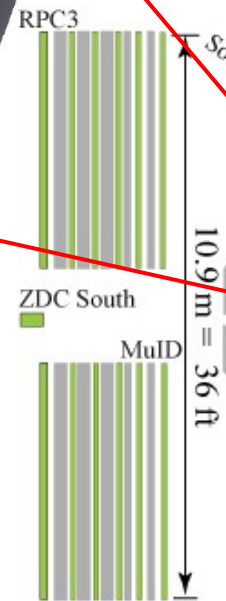


Future: Direct γ with MPC-EX



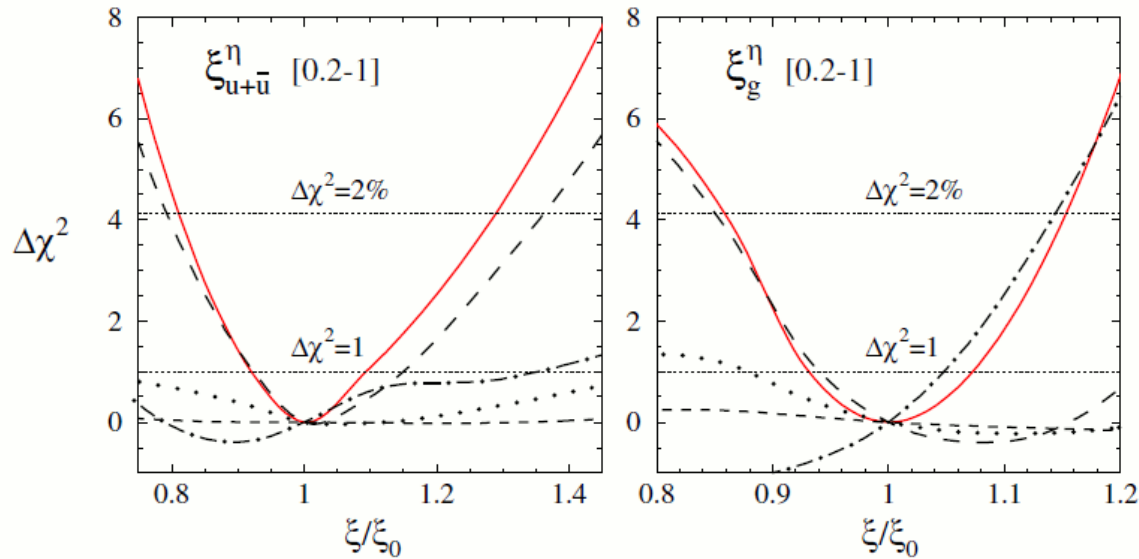
- A combined charged particle tracker and detector
- Merged π^0 cluster rejection

- Commissioned in 2014
- First Physics in 2015
 - p^+ + Au, p^+ + p run



X_F

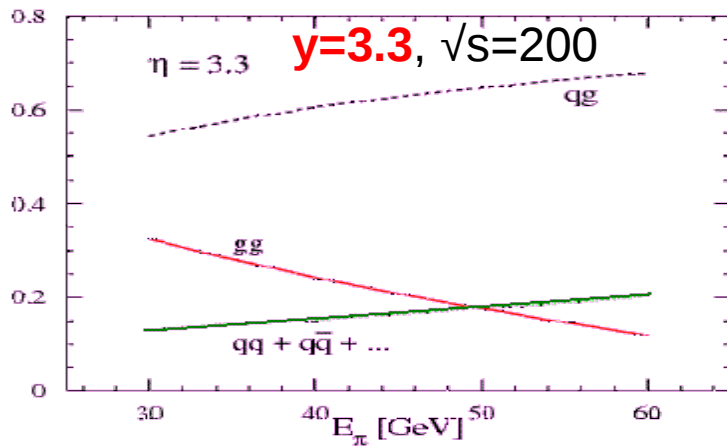
Global Analysis of η Meson FFs



$$\delta D_u^\eta \approx \frac{-20\%}{+30\%}$$

$$\delta D_g^\eta = \frac{-15\%}{+15\%}$$

Phys. Rev. D 83, 034002 (2011)

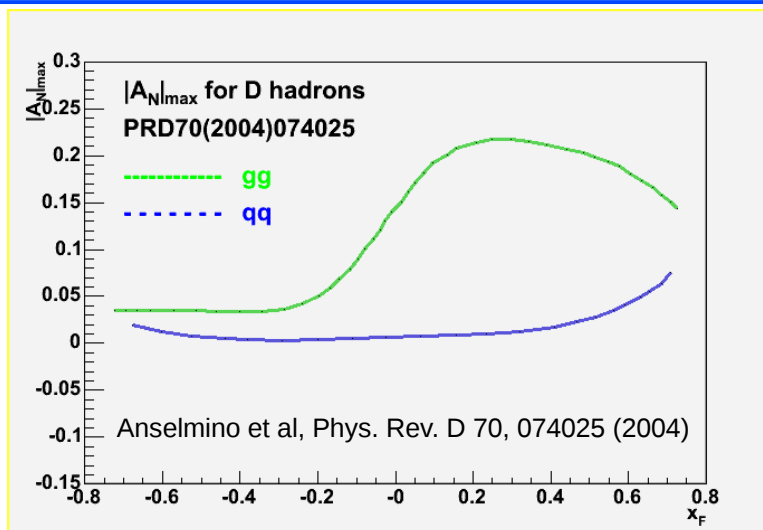
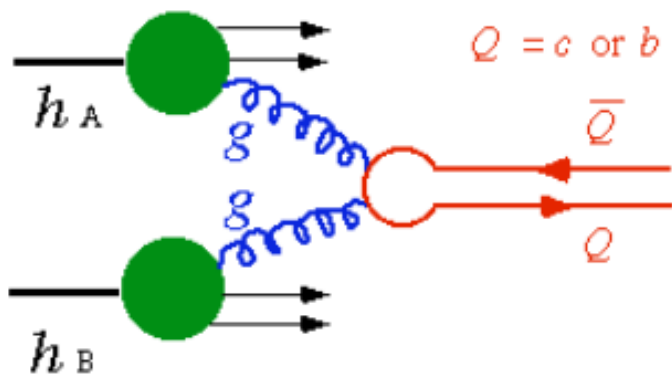


- Cross section measurement will Improve uncertainty η meson flavor dependent FFs

Sivers function constraints: Heavy Flavor A_N

D meson A_N

- Dominated by gluon-gluon fusion
- Gluon Transversity is zero due to chiral-odd effects
- Probes GLuo
-



Gluon Sivers=Max
 Quark Sivers=0
 Gluon Sivers=0
 Quark Sivers=Max

- PHENIX: no pure D-meson reconstruction (ye
 - Single muon measurements are a probe
- $p^\uparrow + p$ @ $\sqrt{s}=200$ GeV taken in 2012 (9.1 pb^{-1}) v new PHENIX FVTX detectors
 - Analyses underway

