Transverse Spin in PHENIX

Nicole Lewis for the PHENIX Collaboration

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RHIC & AGS Annual User's Meeting

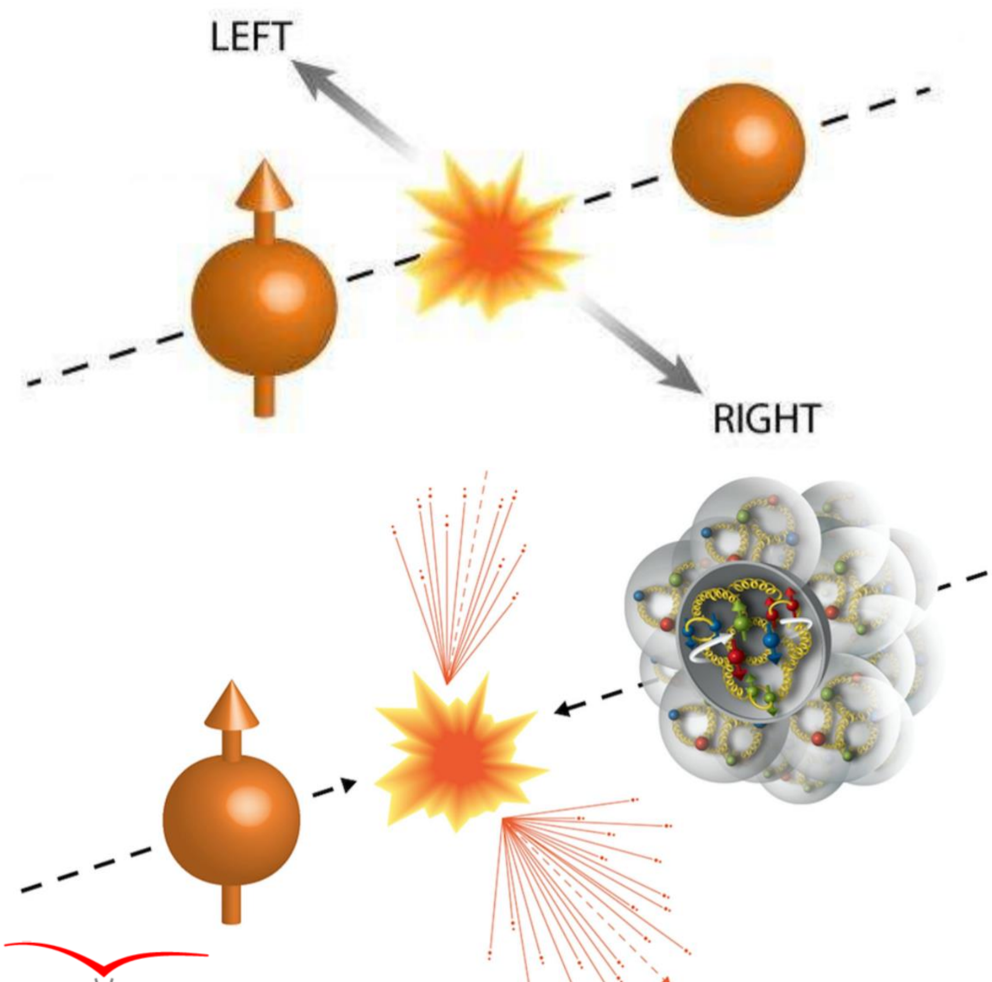
PHENIX

U.S. DEPARTMENT OF ENERGY

Office of Science

UNIVERSITY OF MICHIGAN

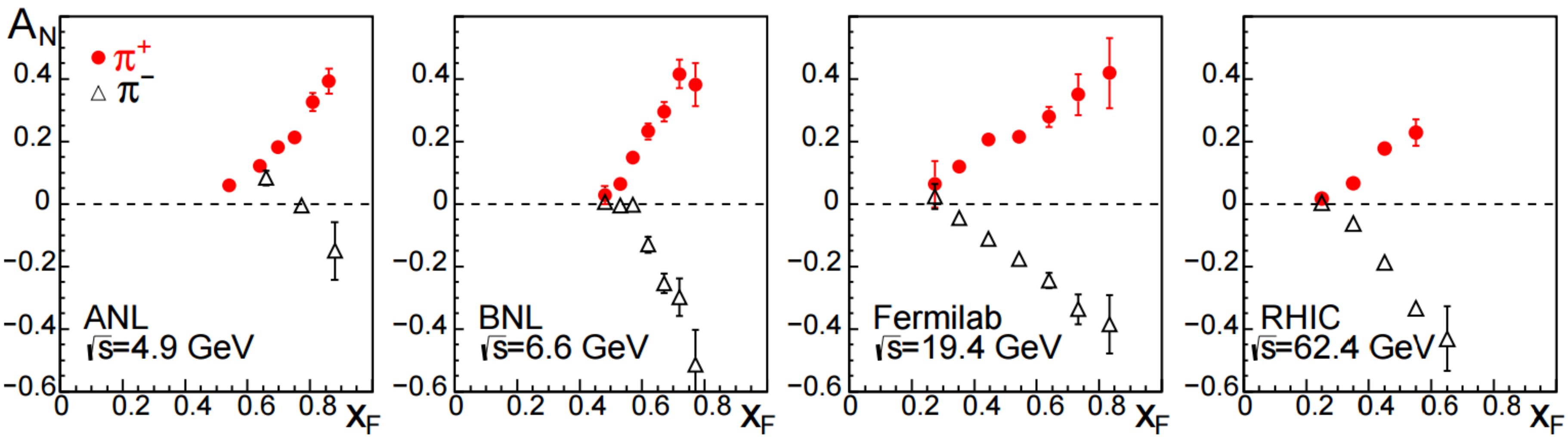
Transverse Single-Spin Asymmetries (TSSAs)



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

G. L. Kane, J. Pumplin, and W. Repko PRL **41**, 1689 (1978) predicted that the perturbative QCD contributions to TSSAs would make them less than 1%.

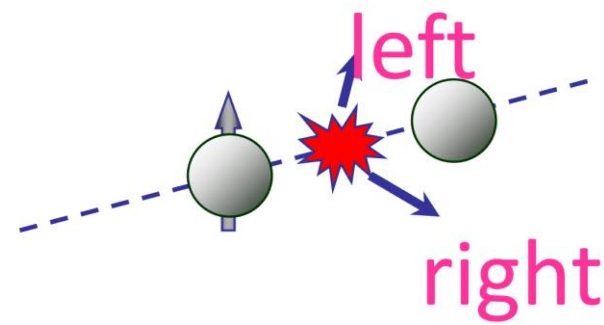
Transverse Single-Spin Asymmetries (TSSAs)



C. A. Aidala, S.D. Bass, D. Hasch, and G. K. Mallot, Rev. Mod. Phys. **85** 655 (2013).

$$x_F = \frac{p_Z}{\sqrt{s}/2}$$

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



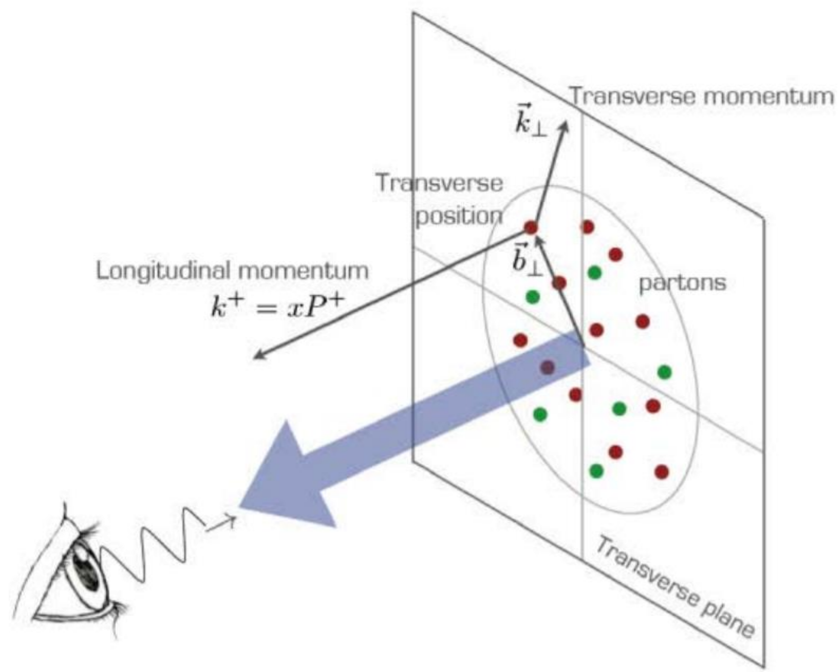
Transverse Momentum Dependent Nonperturbative Functions

Collinear: The parton model integrates over the internal dynamics of the proton

Transverse Momentum Dependent (TMD): functions explicitly depend on the nonperturbative transverse momentum k_T

- In order for TMD factorization to apply $k_T^2 \ll Q^2$.
- Need sensitivity to both k_T and Q to directly measure TMDs

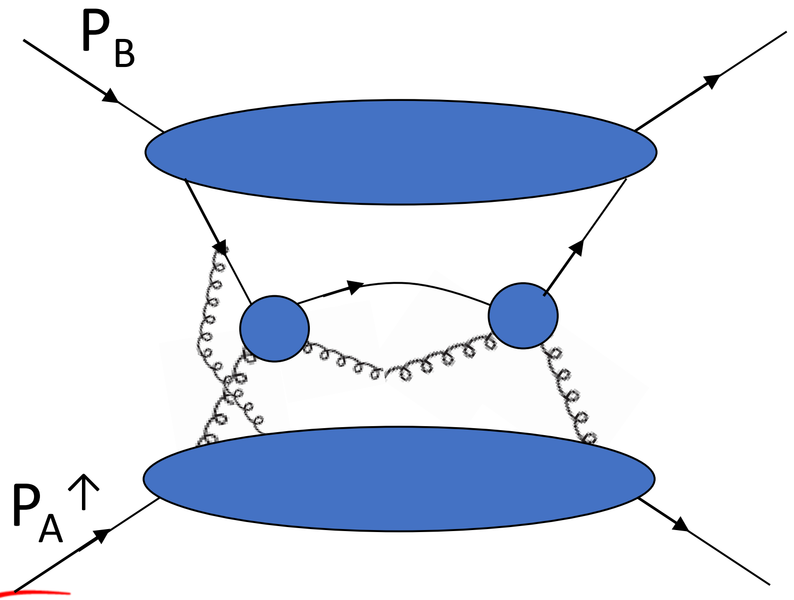
from Alessandro Bacchetta



Higher Twist Functions

Formal definition of twist: “mass dimension minus spin” of the operator in a matrix element within the Operator Product Expansion

Twist-2: traditional PDFs and FFs only consider interactions between one parton in the proton at a time

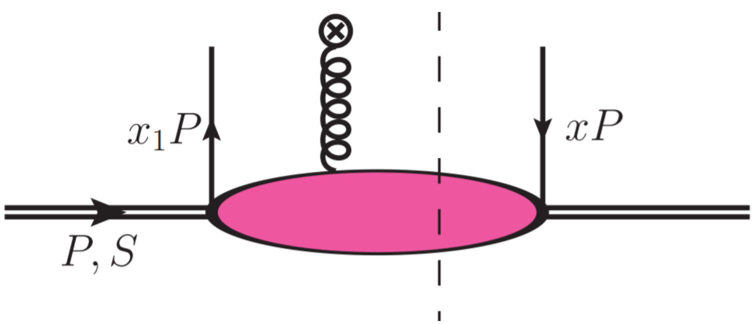


Twist-3: Quantum mechanical interference between one parton versus interacting with two partons at the same relative x

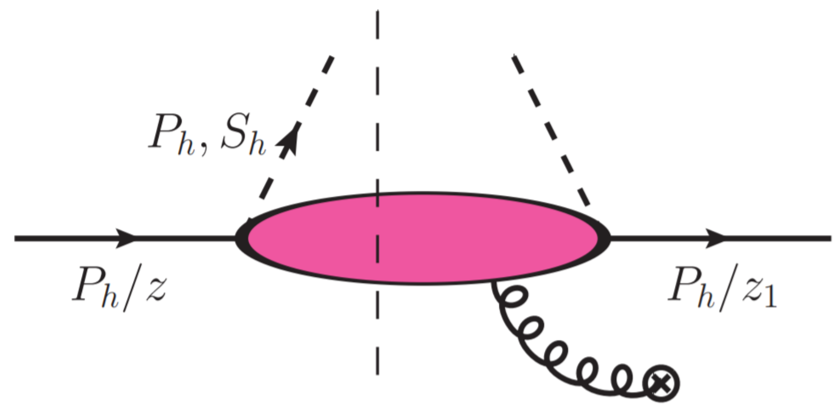
Twist-3 Functions

Multiparton correlations: quantum mechanical interference between scattering off of one versus two partons at the same x

- Quark-Gluon-Quark (qgq) Correlation Function: scattering off of quark and a gluon versus a single quark of the same flavor
- Three-gluon Correlation Function (ggg): two gluons versus one gluon



qgq Twist-3 Initial State

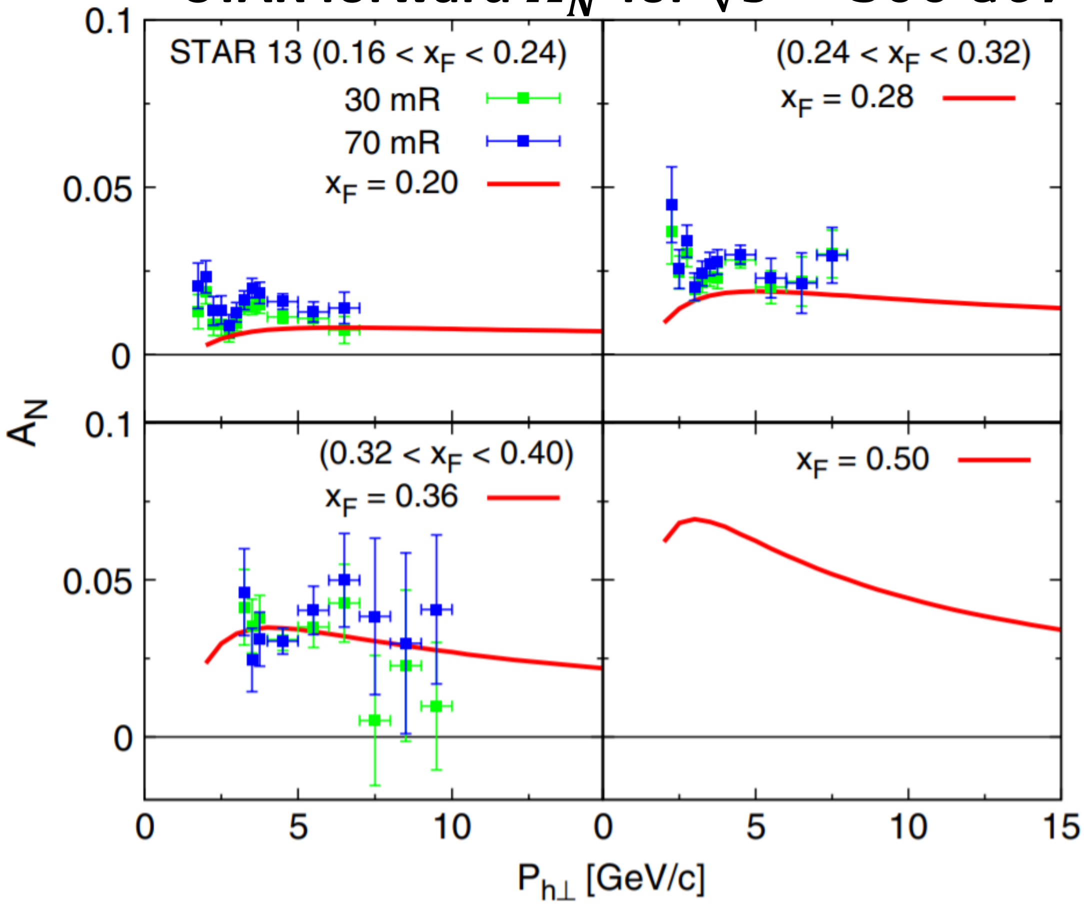


qgq Twist-3 Final State

Daniel Pitonyak, International Journal of Modern Physics A **31**, No. 32, 1630049 (2016)

Twist-3 Functions

STAR forward $A_N^{\pi^0}$ for $\sqrt{s} = 500\ GeV$



K. Kanazawa, *et al,* PRD **89**, 111501(R) (2014)

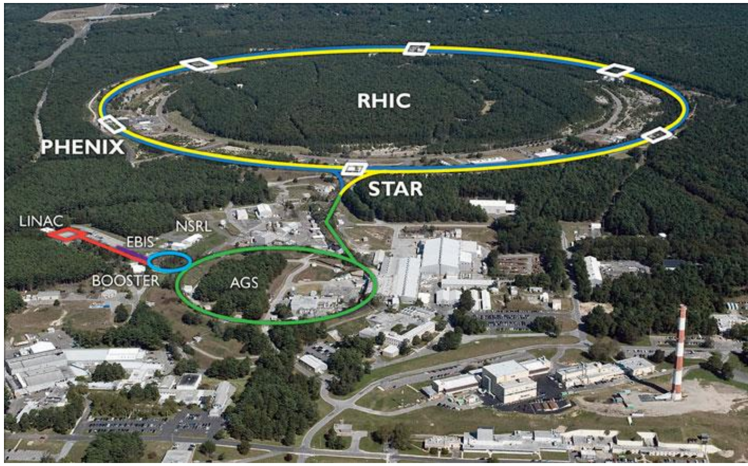
Collinear: No explicit dependence on soft-scale transverse momentum k_T

- Only needs to be sensitive to a single scale: hard scale $Q \sim p_T$
- Can be used to describe spin-momentum correlations in the proton and in hadronization

PHENIX Transverse Spin Runs

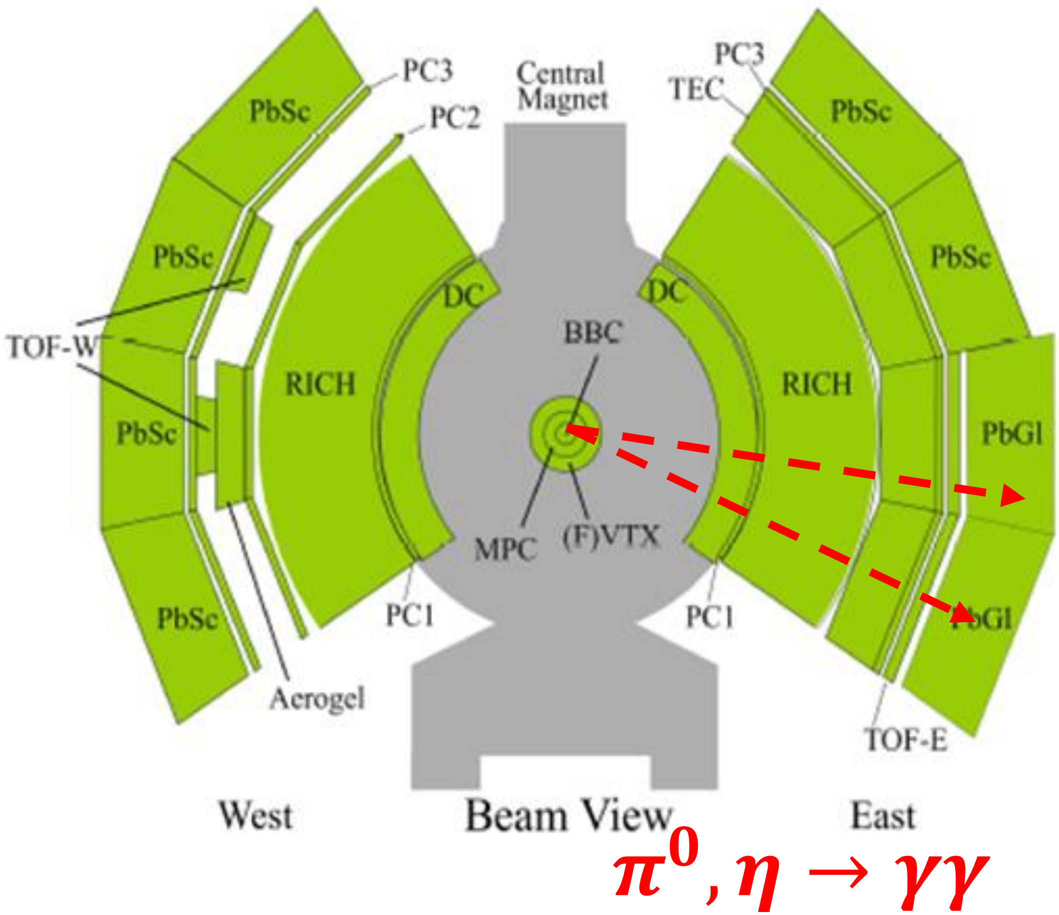
Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4	-- pb^{-1} / 0.2 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1}	48
	200	6.8 pb^{-1} / 8.5 pb^{-1}	7.5 pb^{-1} / 2.7 pb^{-1}	57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200	25 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1}	55
	500	10 pb^{-1} / -- pb^{-1}	14 pb^{-1} / -- pb^{-1}	39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200	-- pb^{-1} / 22 pb^{-1}	-- pb^{-1} / 9.7 pb^{-1}	61/56
	510	82 pb^{-1} / -- pb^{-1}	32 pb^{-1} / -- pb^{-1}	50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57
2015	200 *p* Au	total delivered Luminosity = 1.27 pb^{-1}		60
2015	200 *p* Al	total delivered Luminosity = 3.97 pb^{-1}		54

O : Trasversely polarized



Measuring A_N using 2015 $p^{\uparrow} + A$ gives a unique opportunity to study the nuclear effects of spin-momentum correlations

PHENIX Midrapidity $A_N^{\pi^0}$ and A_N^{η}



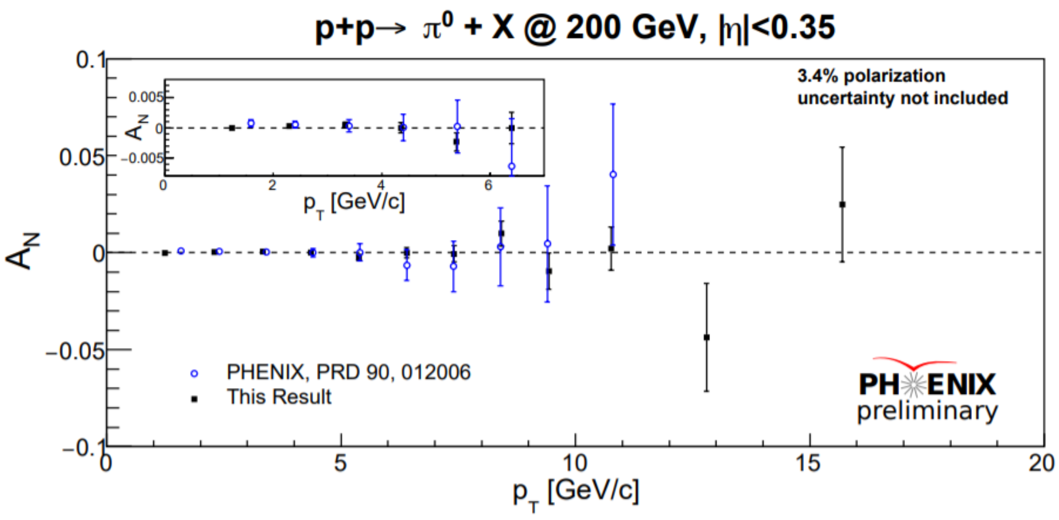
- PHENIX Central Arms
  - $\Delta\phi \sim \pi$
  - $|\eta| < 0.35$
- Central EMCal used for $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ detection
- Nonnegligible contribution of the twist-3 trigluon correlation function from the polarized proton at midrapidity

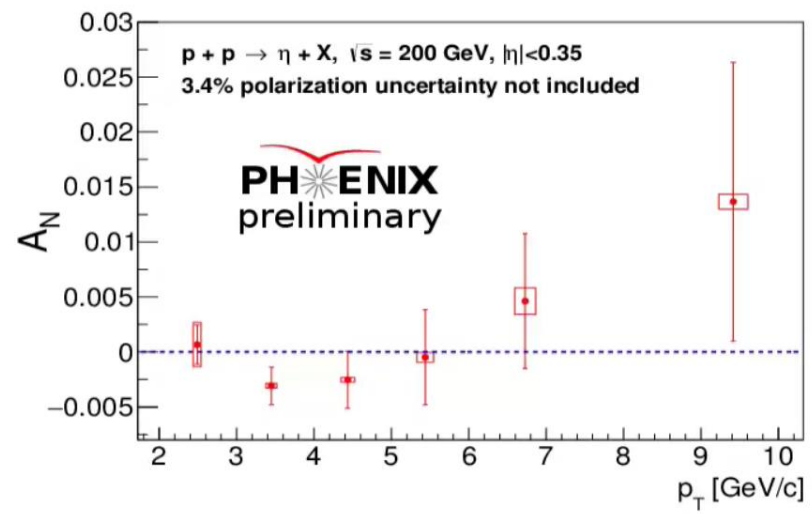
Midrapidity π^0 and η A_N in $p + p$

Run 15 $p + p$ $\sqrt{s} = 200$ GeV

π^0 Asymmetry: Zero to within 10^{-4} at low p_T

η Asymmetry: Consistent with zero to within 0.005 at low p_T

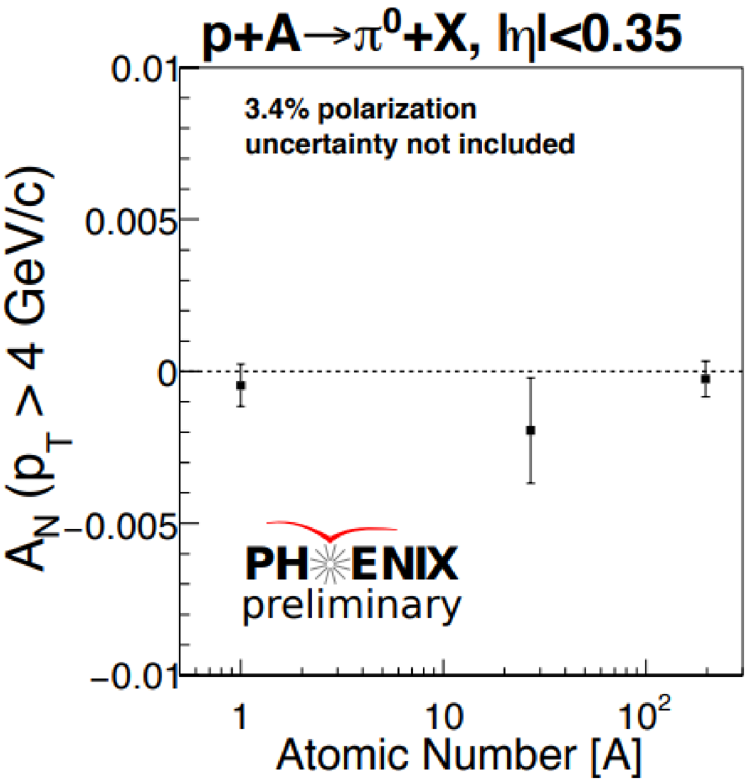


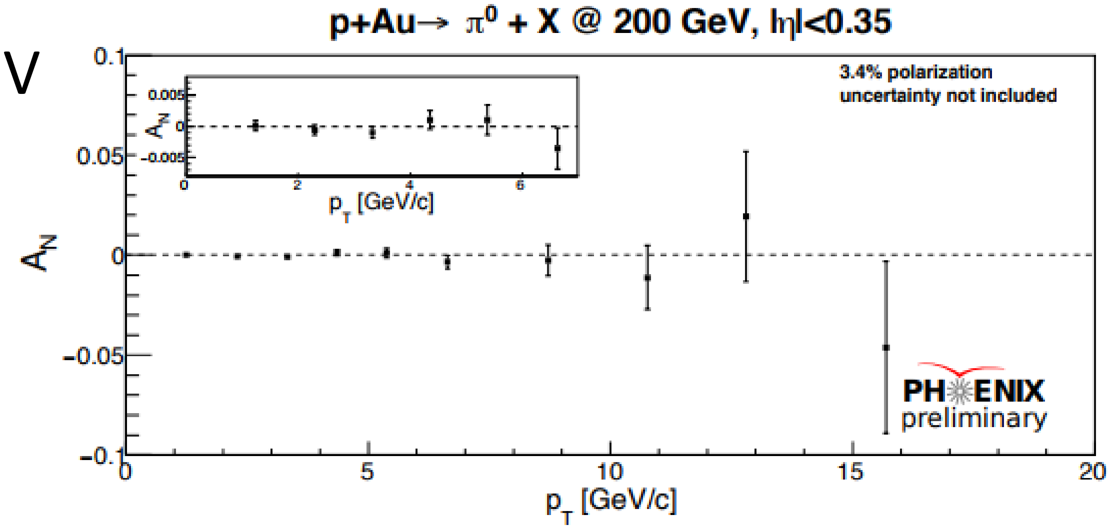


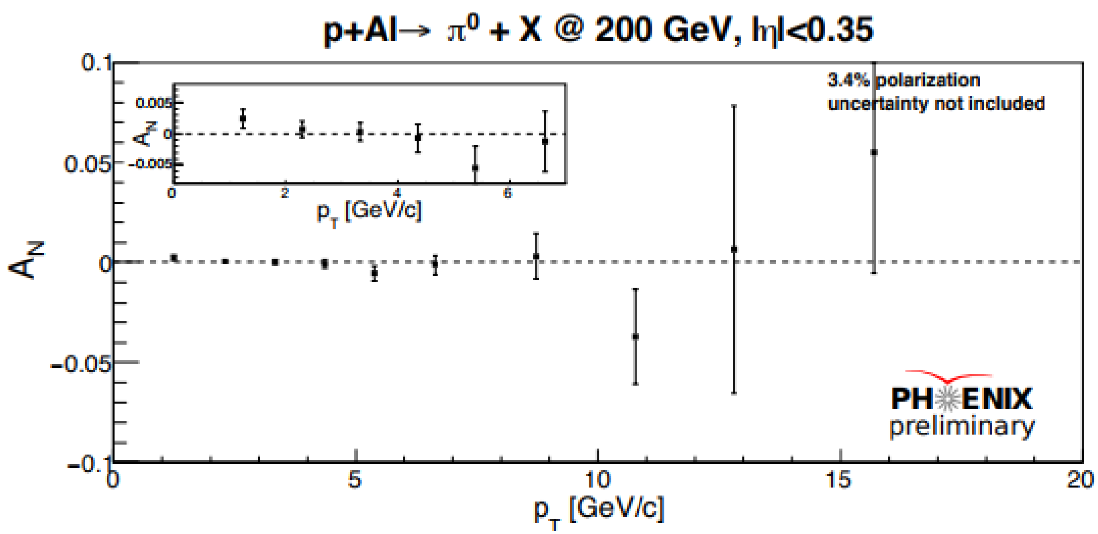
Comparing π^0 to η results may provide insight on effects due to strangeness, isospin, or mass.

Midrapidity π^0 A_N in $p + A$

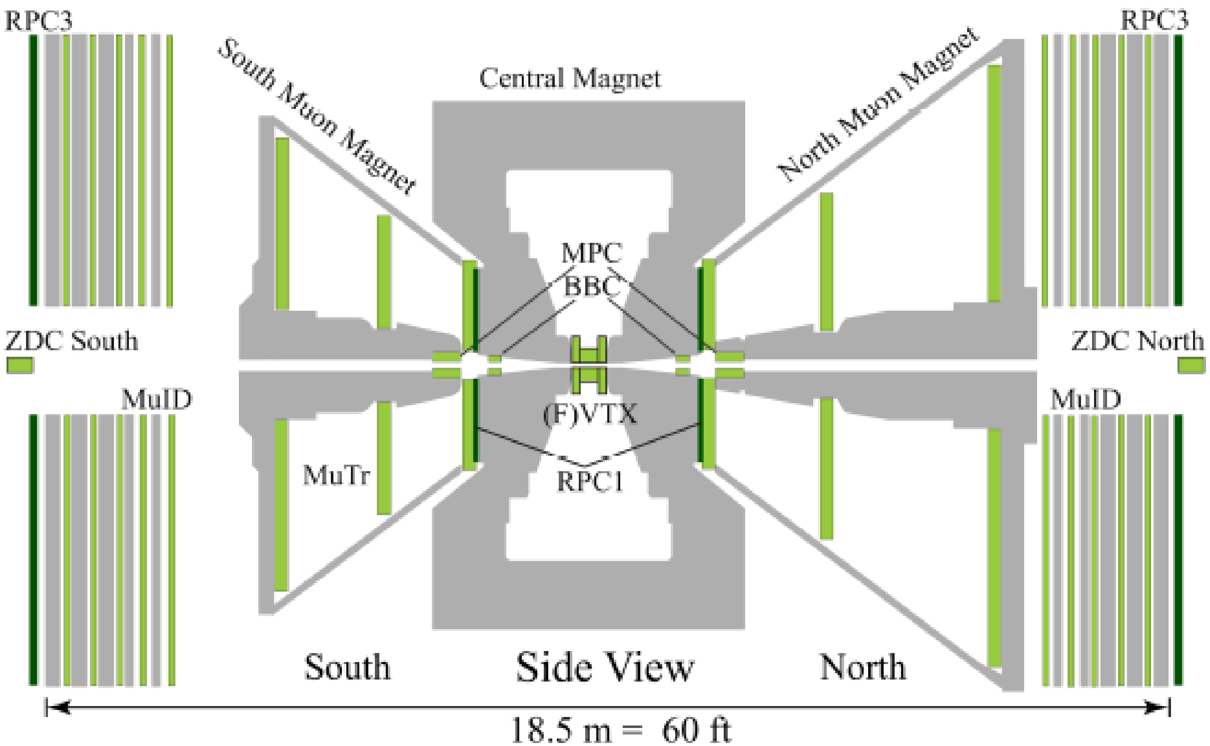
Run 15 $\sqrt{s_{NN}} = 200$ GeV
$p + p, p +$ Al , $p +$ Au





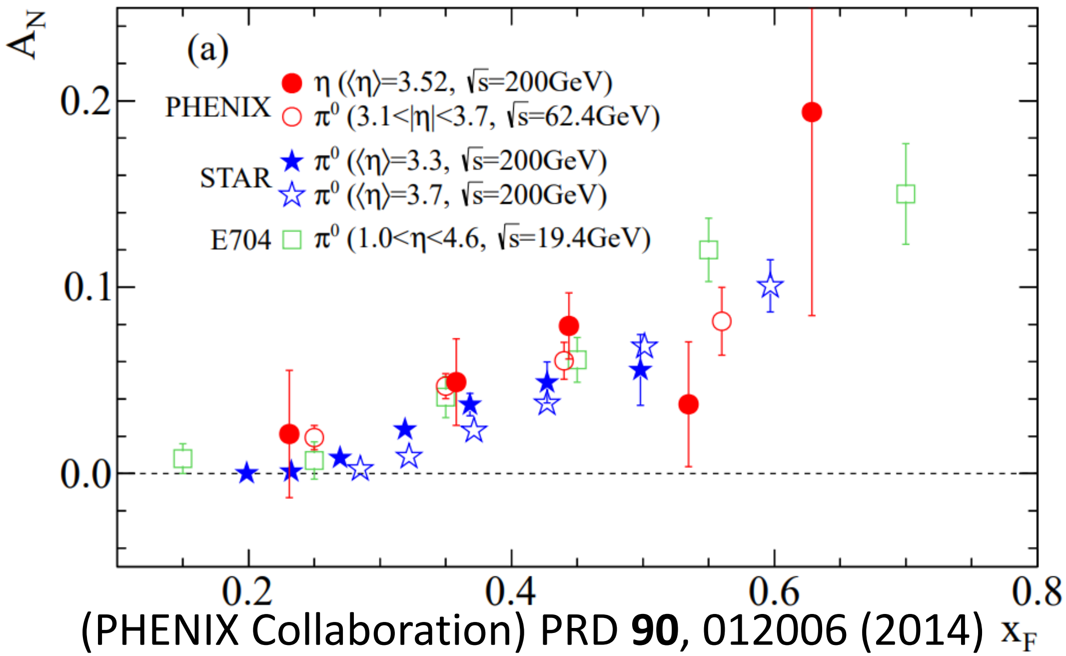


PHENIX forward/backward rapidity

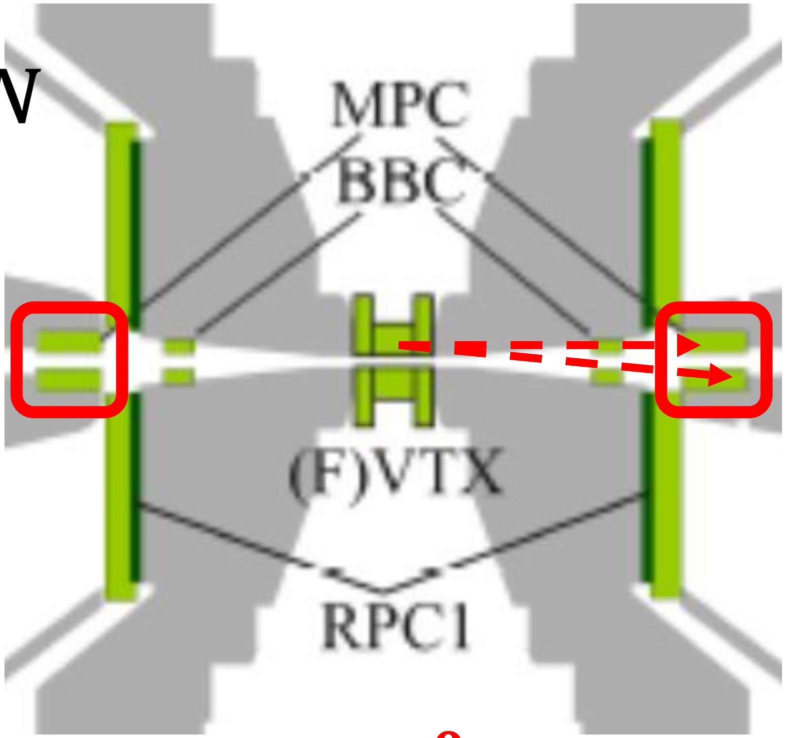


- Muon Piston Calorimeter
  - π^0 and η
- Muon Arms
  - Open heavy flavor
  - J/ψ
  - $h^{\pm}$
- Zero Degree Calorimeter
  - Neutrons

Forward π^0 and η A_N



(PHENIX Collaboration) PRD **90**, 012006 (2014)

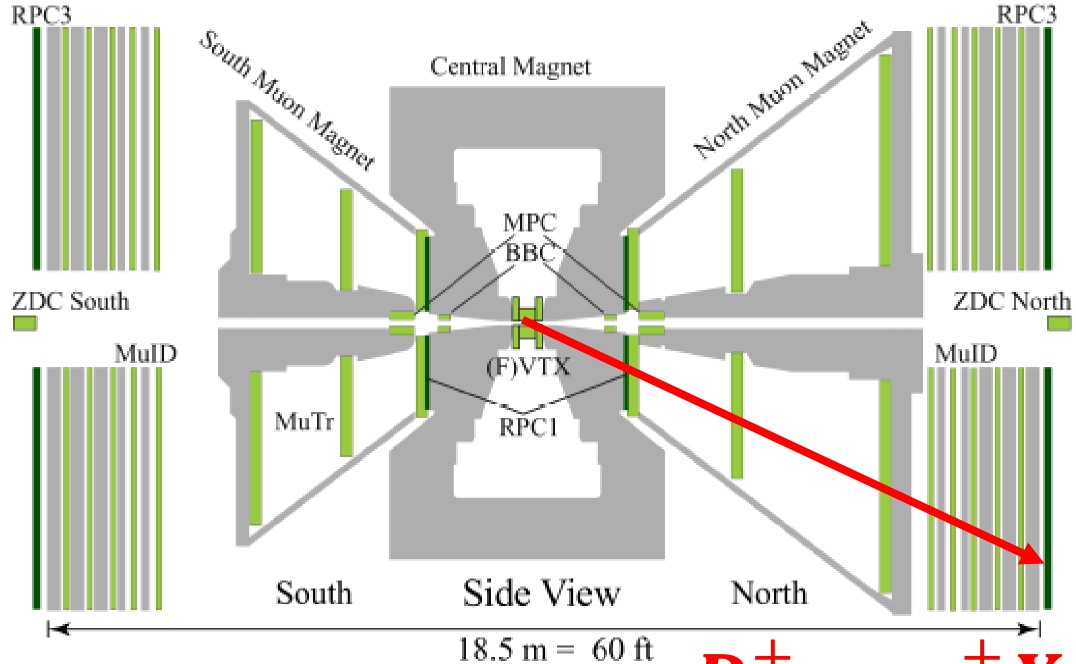


$\pi^0, \eta \rightarrow \gamma\gamma$

- Run 6 ($\sqrt{s}$ =62.4 GeV) and Run 8 ($\sqrt{s}$ = 200 GeV)
- Muon Piston Calorimeter: $3.1 < |\eta| < 3.9$
- Similar A_N for π^0 and η and no clear $\sqrt{s}$ dependence
- Updated forward A_N^η using Run 12 data coming

Forward Open Heavy Flavor A_N

- $\sqrt{s} = 200$ GeV $p + p$ data from Run 12
- Muon Arms $1.2 < |\eta| < 2.4$
- Main contribution to single muons: D-meson decay

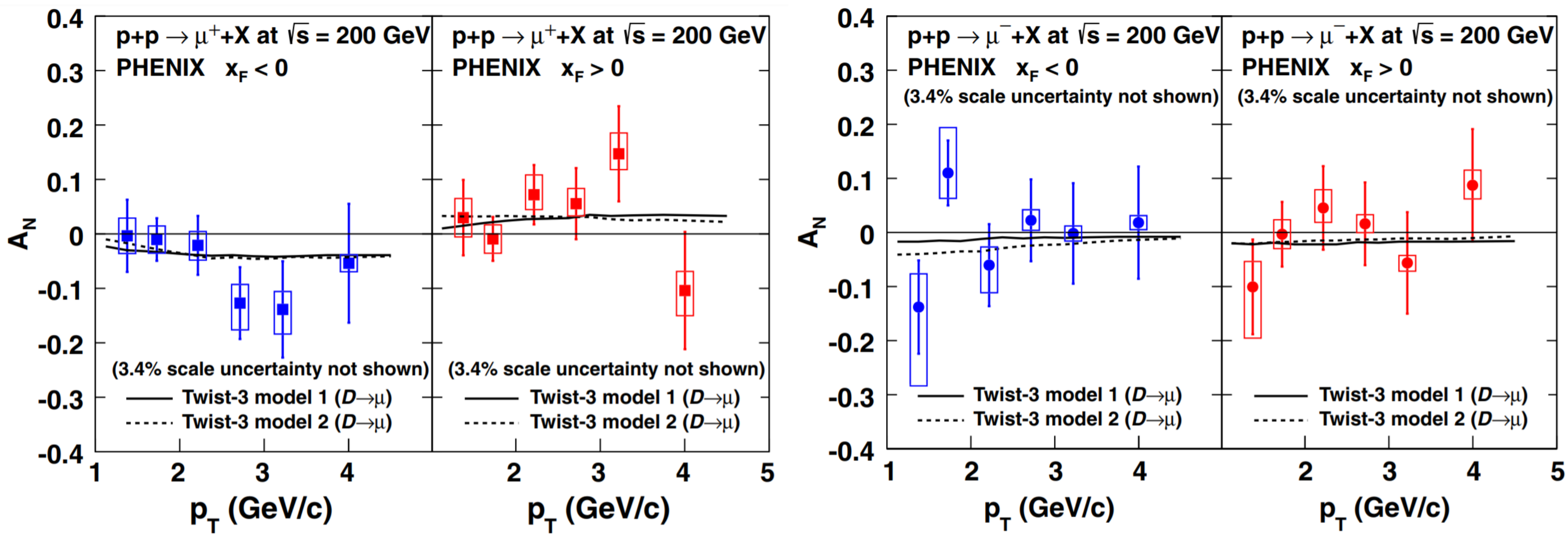


$D^{\pm} \to \mu^{\pm} X$

- AT RHIC energies most heavy flavor production comes from gluon-gluon fusion
- Sensitive to trigluon correlations in the proton in the twist-3 collinear factorization framework
  - Y. Koike and S. Yoshida, Phys. Rev. D **84**, 014026 (2011)

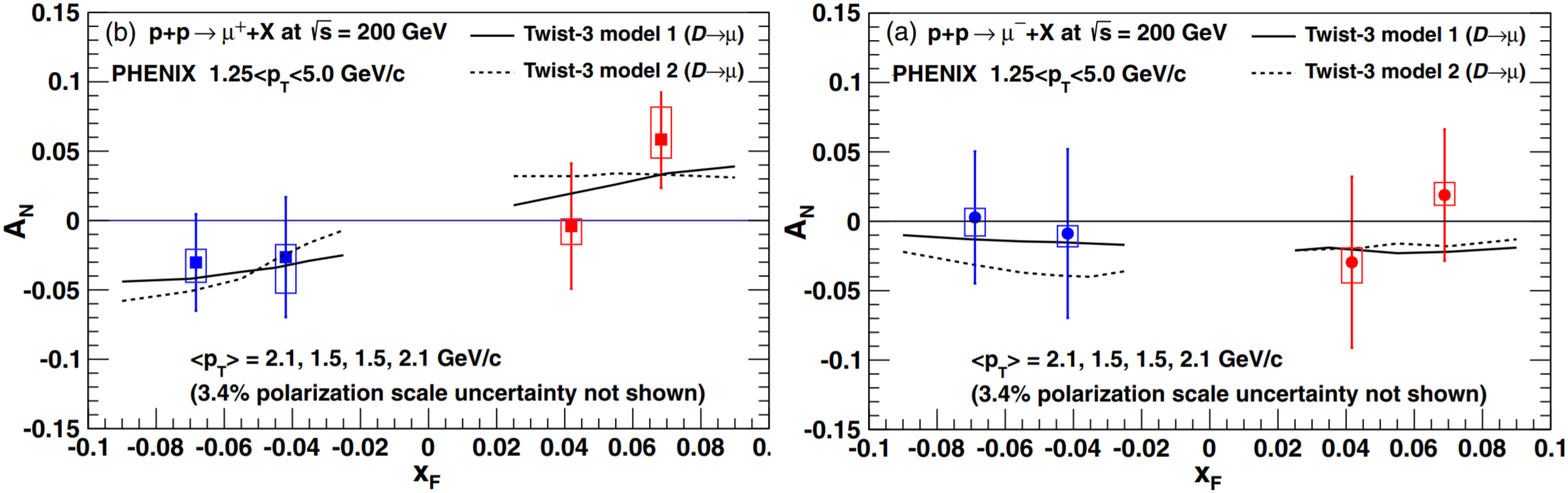
Forward Open Heavy Flavor A_N

- Results consistent with zero within uncertainties
- Consistent with model predictions using twist-3 trigluon correlations
  - Original calculations for D meson translated to single muon



(PHENIX Collaboration) PRD **95**, 112001 (2017)

Forward Open Heavy Flavor A_N

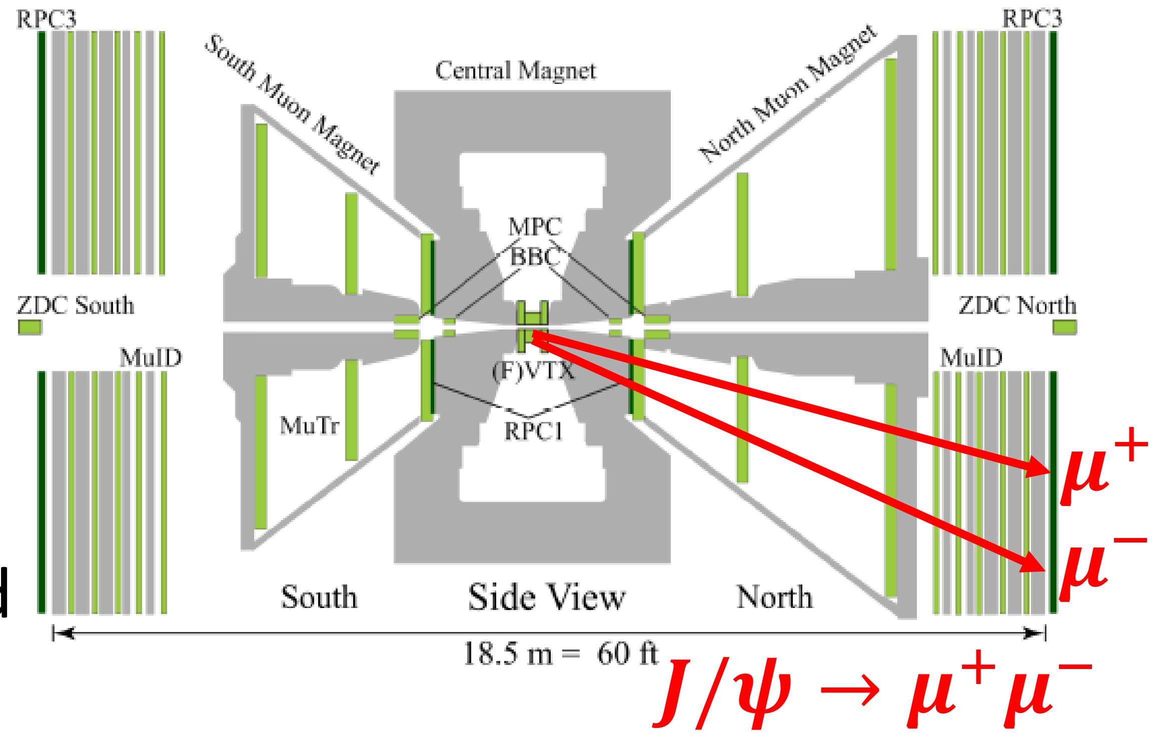


(PHENIX Collaboration) PRD **95**, 112001 (2017)

- Results consistent with zero within uncertainties
- Consistent with model predictions using twist-3 trigluon correlations
  - Original calculations for D meson translated to single muon

Forward J/ψ A_N in $p+p$ vs $p+A$

- Muon Arms
  $1.2 < |\eta| < 2.4$
- Run 15 $\sqrt{s_{NN}} =$ 200 GeV in polarized proton on proton, Al, and Au beam

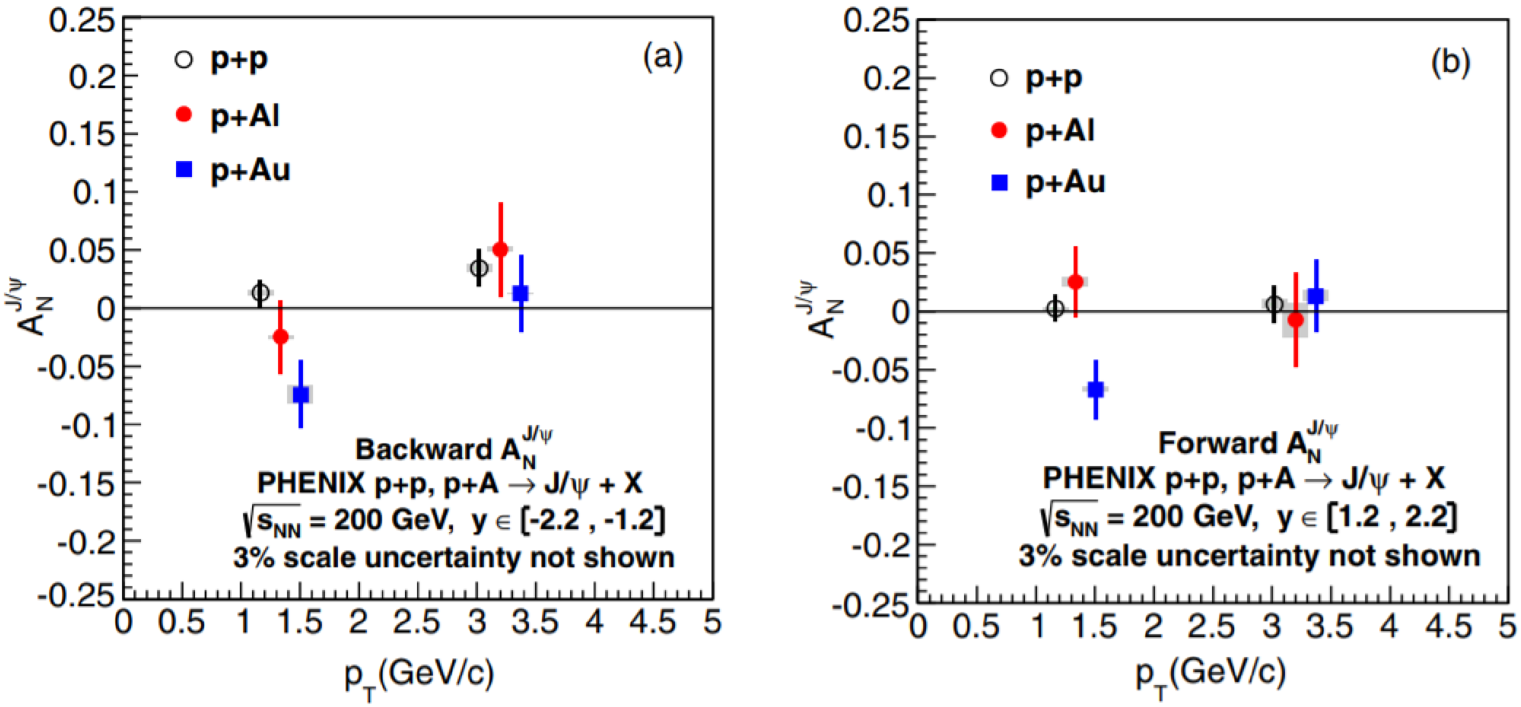


- Most heavy flavor production at RHIC energies comes from gluon-gluon fusion → ideal tool to measure gluon distributions in the nuclei

Forward J/ψ A_N in $p+p$ vs $p+A$

$A_N^{J/\psi}$ in $p+p$ and $p+$Al is consistent with zero, no clear A dependence

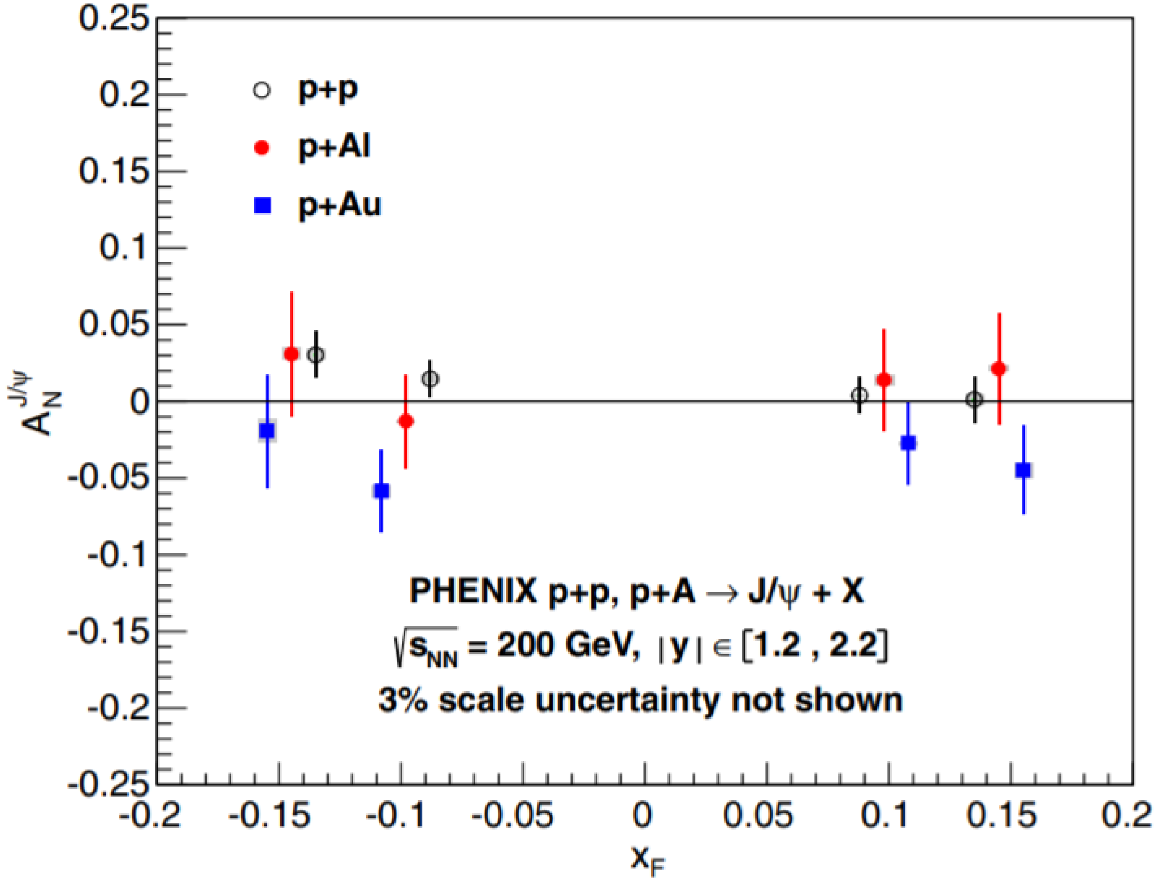
$p+$Au favors a negative $A_N^{J/\psi}$ at low p_T



(PHENIX Collaboration) PRD **98**, 012006 (2018)

PHENIX

Forward $J/\psi\ A_N$ in $p+p$ vs $p+A$



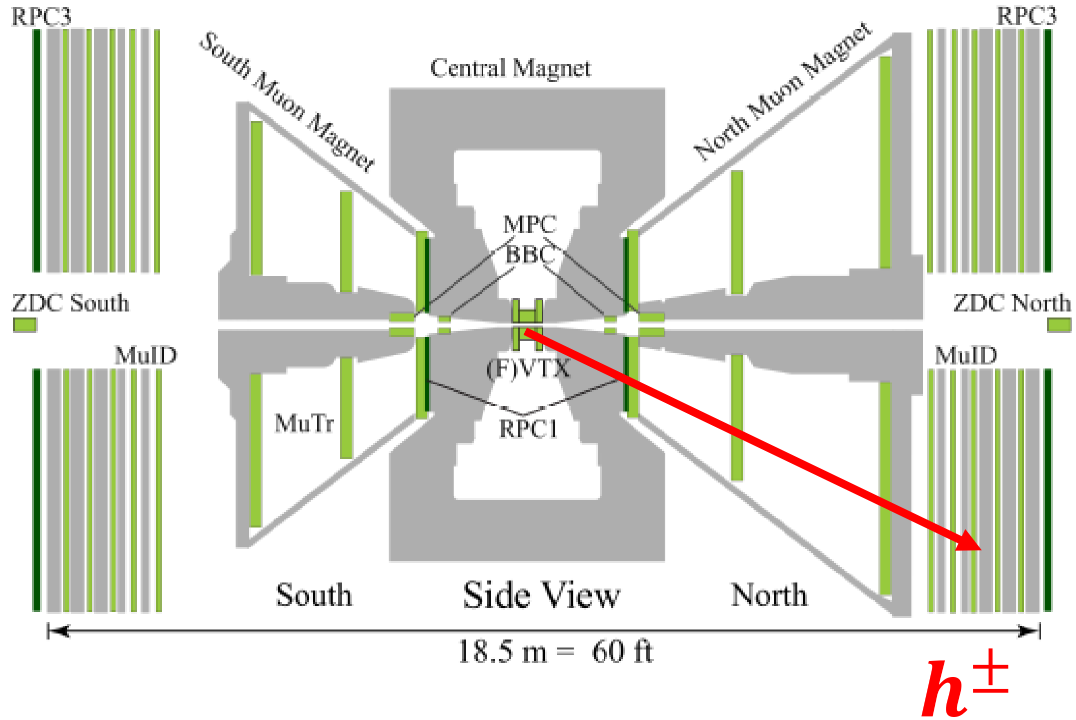
(PHENIX Collaboration) PRD **98**, 012006 (2018)

$A_N^{J/\psi}$ in $p+p$ and $p+$ Al is consistent with zero, no clear A dependence

$p+$ Au favors a negative $A_N^{J/\psi}$

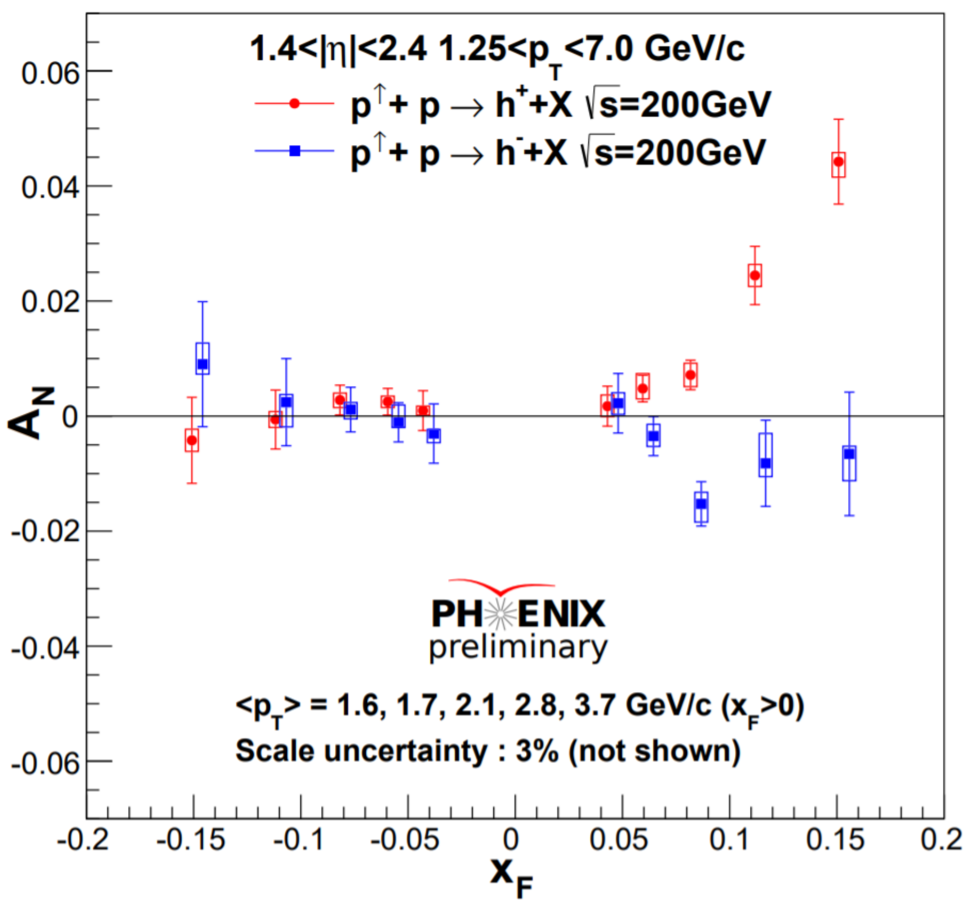
Forward charged hadron A_N

- Muon Arms $1.2 < |\eta| < 2.4$
- Run 15 $\sqrt{s_{NN}} =$ 200 GeV
- Tracks that are stopped by the third and fourth planes of the MuID, out of 5 planes



- $\pi^{\pm}$ - 45%, $K^{\pm}$ - 47%, $p^{\pm}$ - 5%
  - p fraction increases to 7% (9%) for $p+$ Al ($p+$ Au)

Forward Charged Hadron A_N



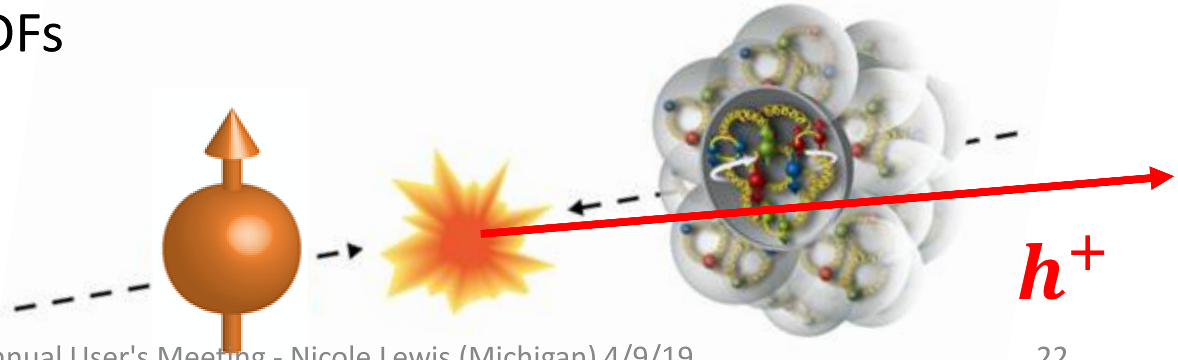
- A_N of $\pi^{\pm}$ and $k^{\pm}$
- $A_N^{\mathrm{h}^+}$ increases a function of x_F for $x_F > 0$
- Partial cancelation of the h^- minus asymmetry due to due to opposite sign of the asymmetry for π^- and k^-

Forward $A_N^{h^+}$ in $p + A$

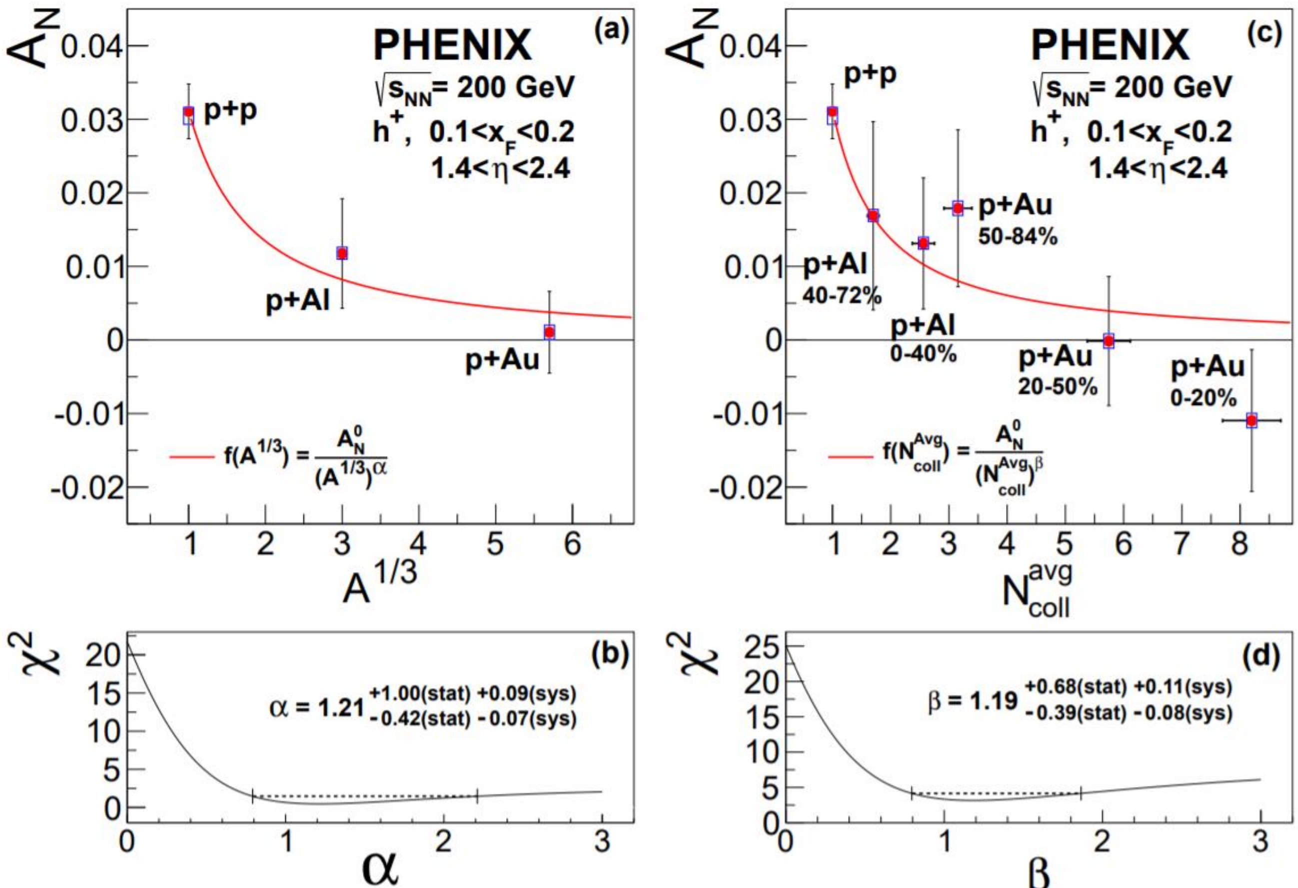
- Forward $A_N^{h^+}$ is nonzero
- High x parton from the polarized proton – likely a valence quark
  - Recent calculations for forward charged pion using twist-3 qgq correlation function in proton and twist-3 fragmentations functions:

    K. Kanazawa *et al*, Phys. Rev. D **89**, 111501(R) (2014)

    L. Gamberg *et al*, Phys.Lett. B **770** (2017) 242-251
- Low x parton from the unpolarized A – likely a gluon
  - Gluon Nuclear PDFs



Forward Charged Hadron A_N in $p + A$

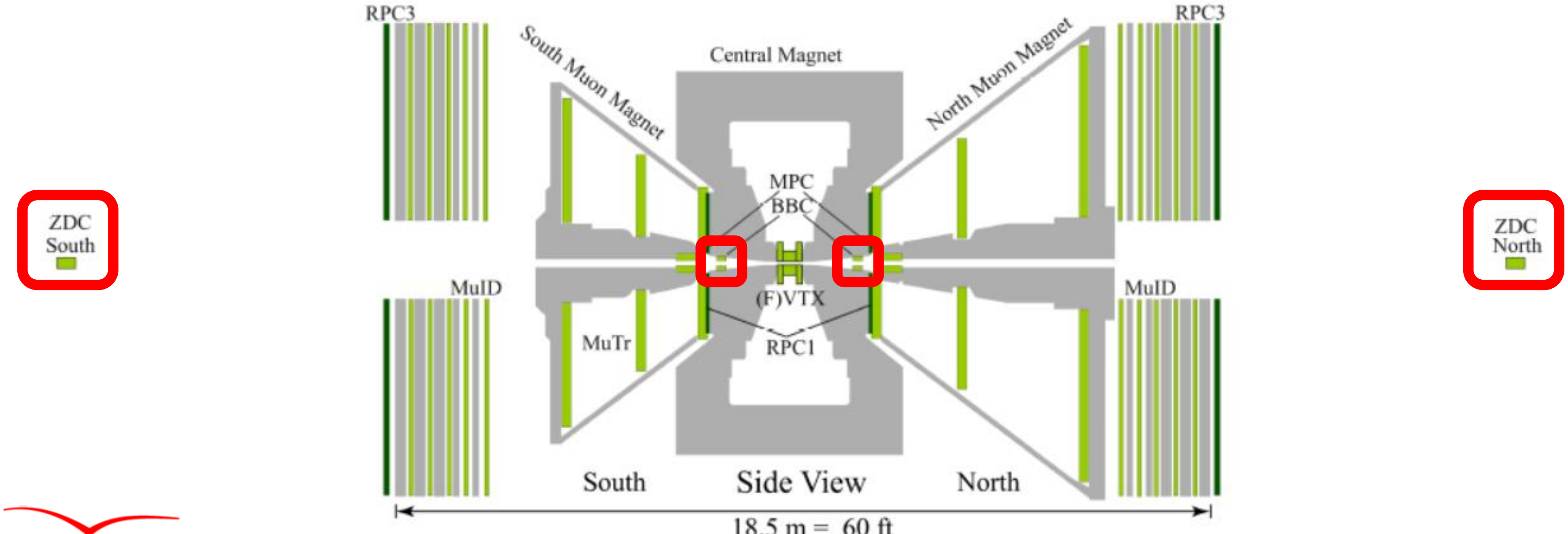


(PHENIX Collaboration) arXiv:1903.07422

- $1.8 < p_T < 7.0$ GeV/c
- Clear decrease of asymmetry as a function of A
- Fit as a function of $A^{1/3}$

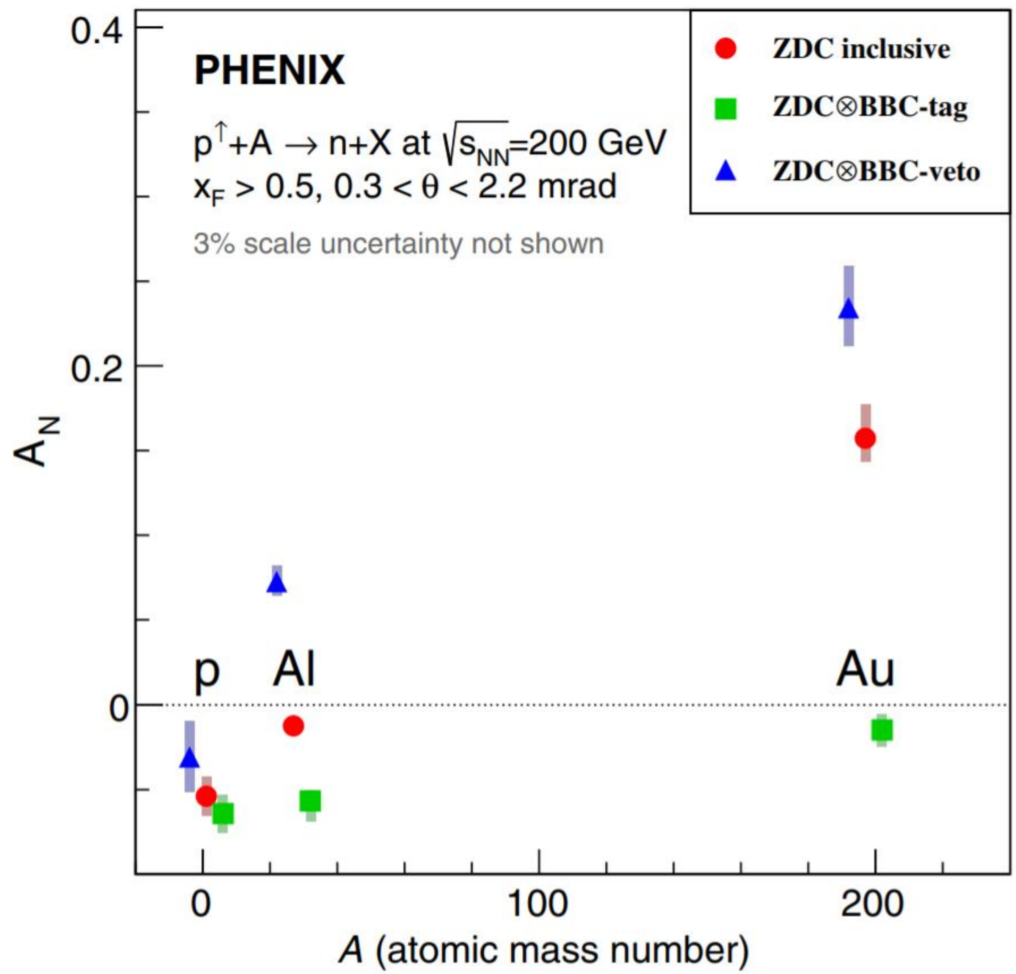
Forward neutron A_N in $p+p$ vs $p+A$

- Run 15 $\sqrt{s_{NN}} = 200$ GeV in polarized proton on proton, Al, and Au beam
- Neutrons measured in Zero Degree Calorimeter $|\eta| > 5.9$
  - Check whether events had activity in the Beam-Beam Counters $3.0 < |\eta| < 3.9$



Forward neutron A_N in $p + p$ vs $p + A$

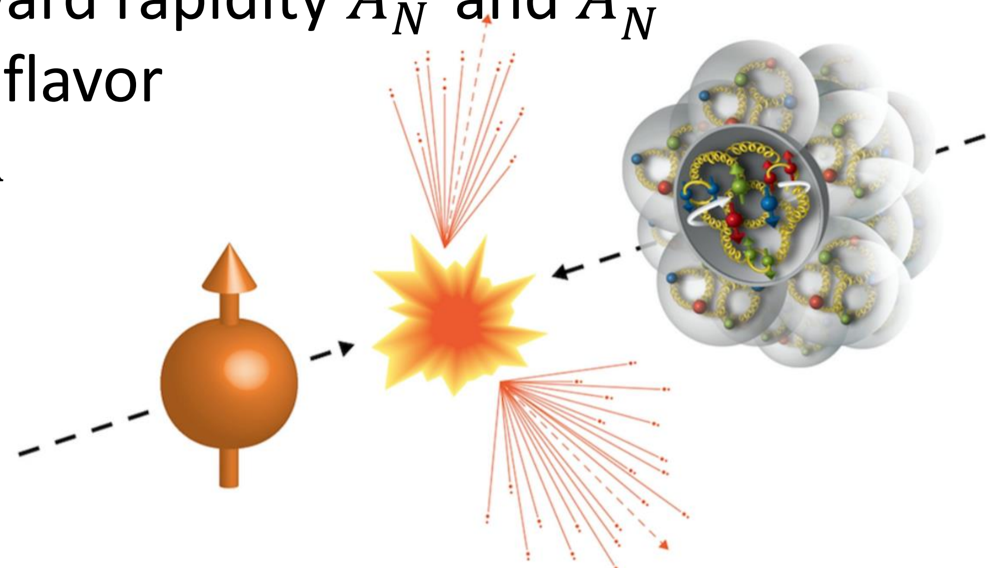
- Clear increase in asymmetry as a function of A
- BBC veto = no hits in either of the Beam-Beam Counters
  - Likely a diffractive event or ultraperipheral collision
  - More dramatic dependence on A, changes sign



(PHENIX Collaboration) PRL **120**, 022001 (2018)

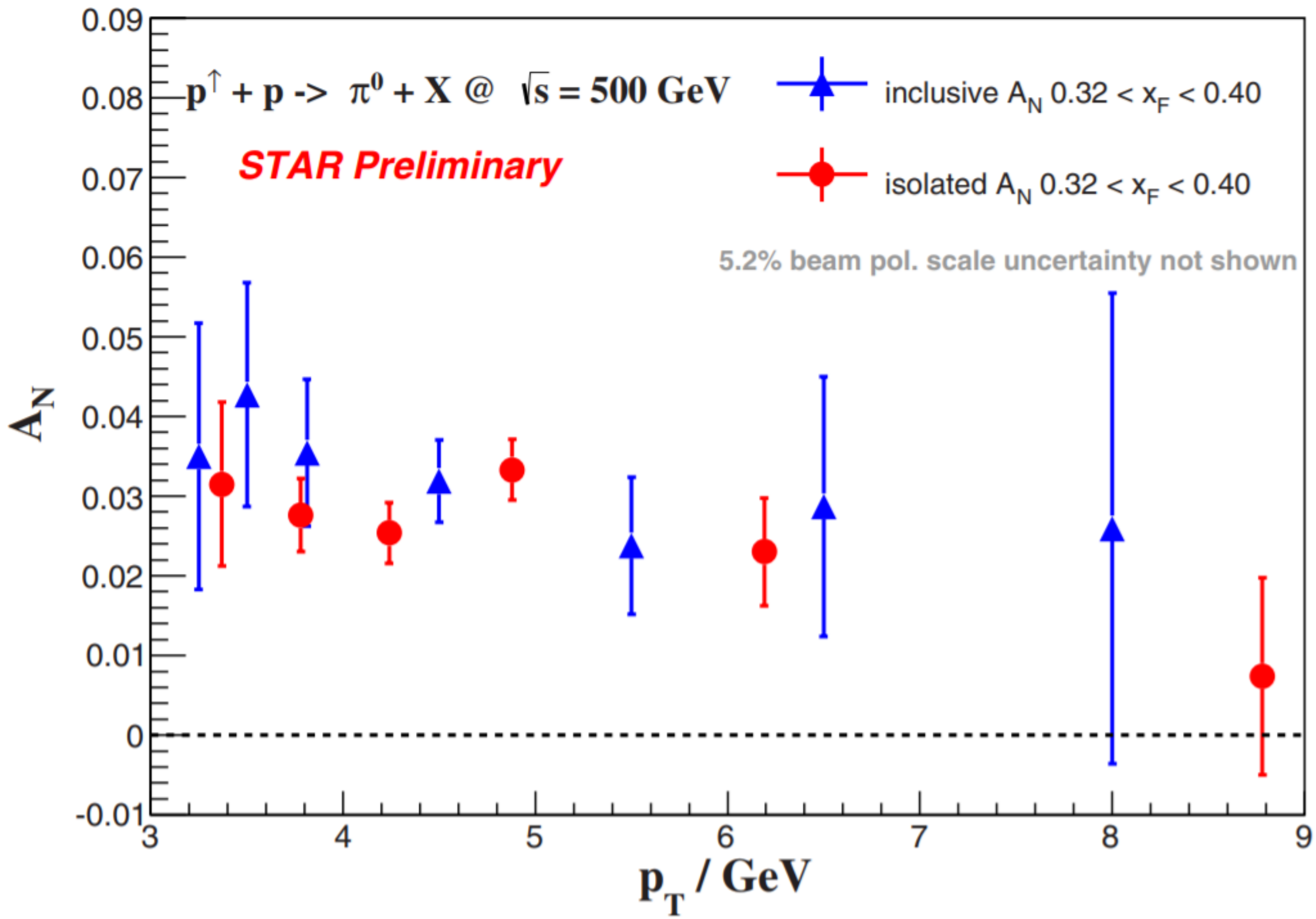
Conclusion

- A_N at RHIC provides a unique probe into parton dynamics in the proton and hadronization and remain a long standing puzzle
  - Twist-3 colinear correlation functions
  - Measuring A_N as a function of A probes nuclear effects on parton spin-momentum correlations
- Midrapidity and forward rapidity $A_N^{\pi^0}$ and A_N^{η}
- Forward open heavy flavor
- A_N as a function of A
  - J/ψ
  - Charged hadrons
  - Neutron
  - Midrapidity π^0



Back Up

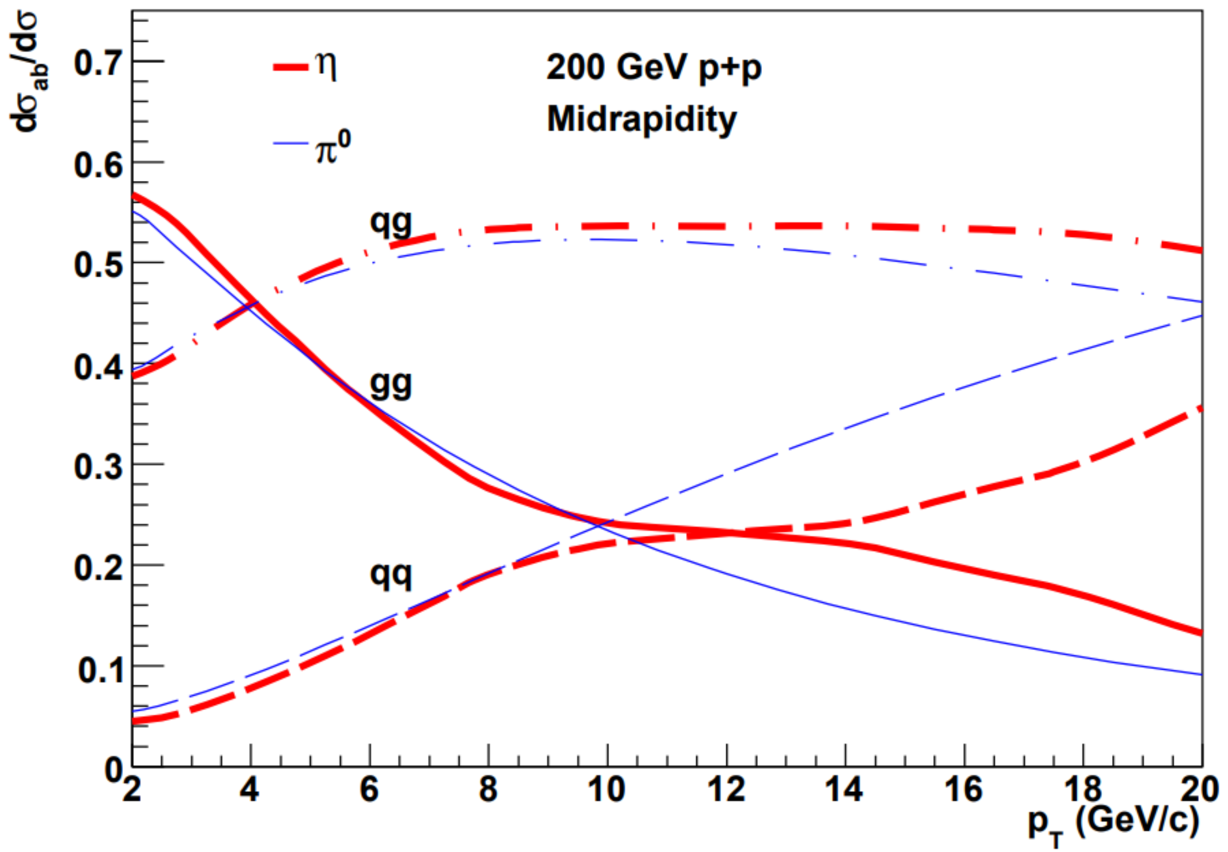
TSSAs at Higher Energies



Yuxi Pan for the STAR Collaboration, International Journal of Modern Physics: Conference Series **40**, 1660037 (2016)

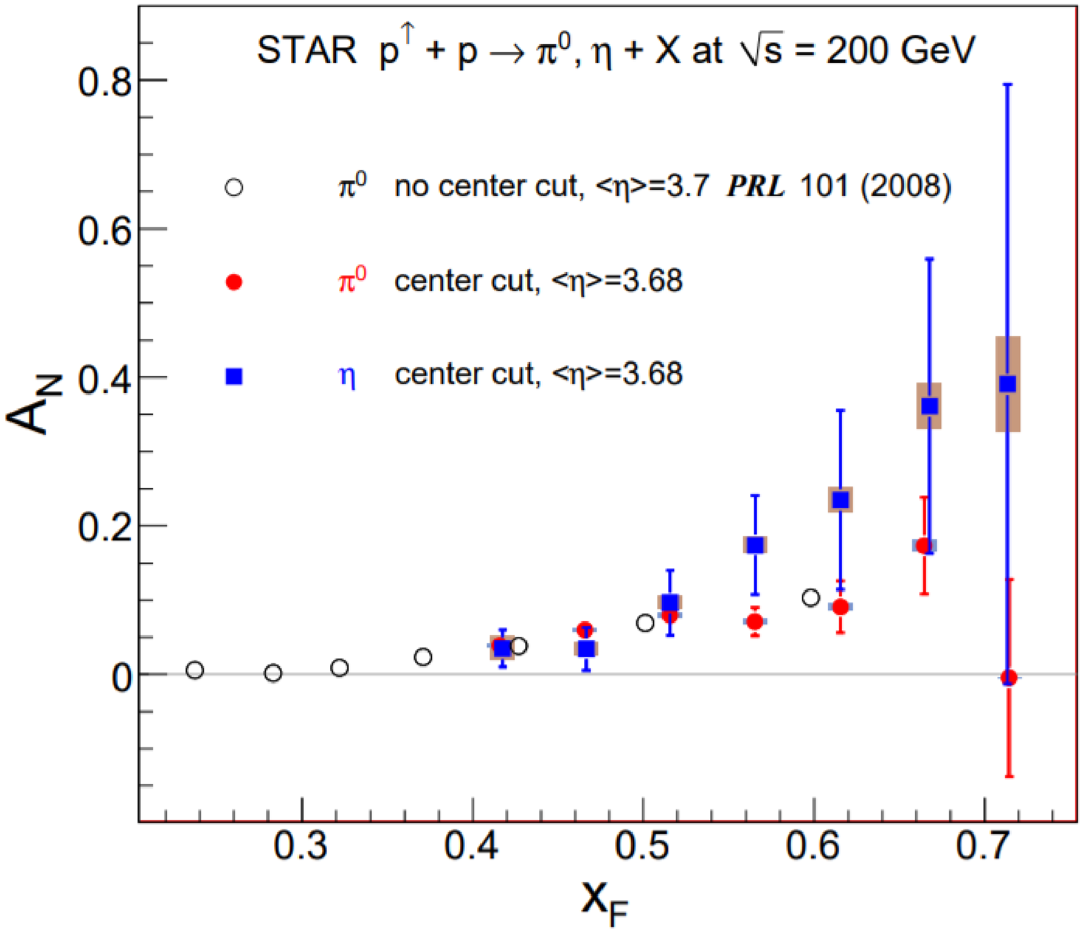
Partonic Contributions to midrapidity π^0 and η

- At low p_T dominated by $gg \rightarrow gg$ and $gg \rightarrow q\bar{q}$
- $qg \rightarrow qg$ fraction increases with p_T
- $q\bar{q} \rightarrow q\bar{q}$ dominates at very high p_T, but that is beyond the scope of this measurement



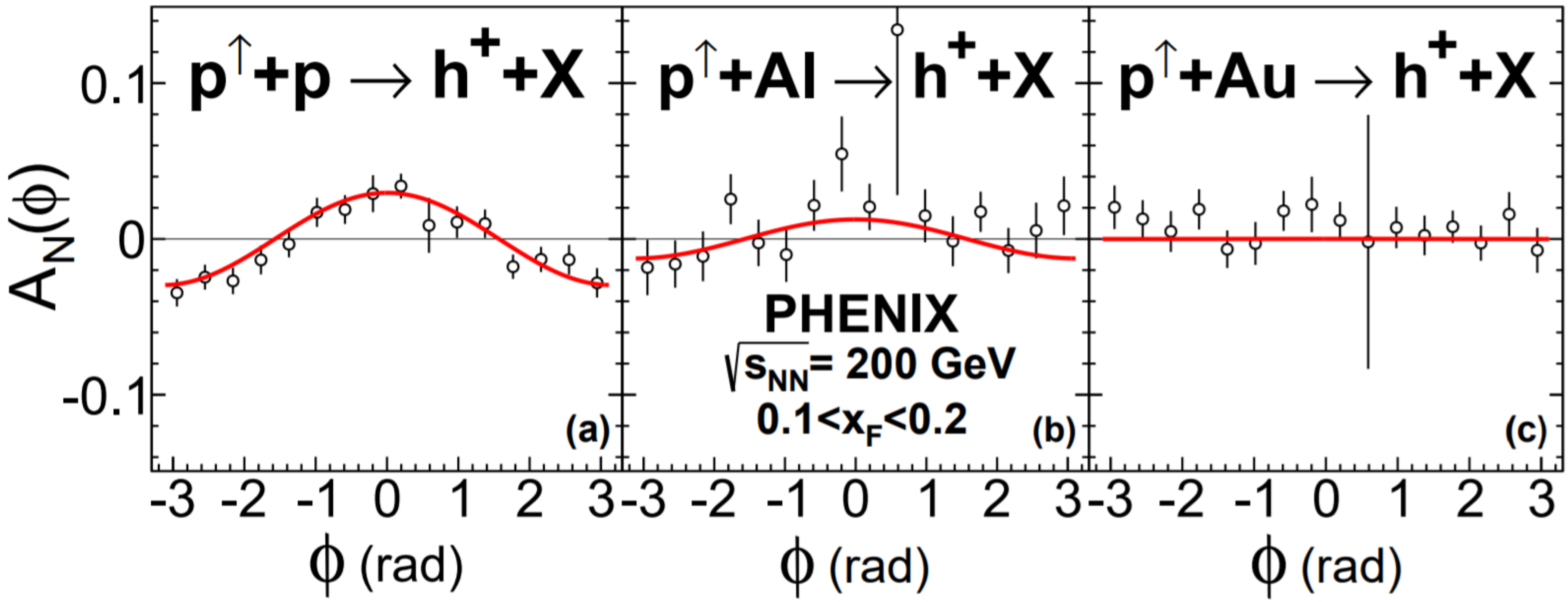
(PHENIX Collaboration) PRD **83**, 032001 (2011)

STAR forward $A_N^{\pi^0}$ and A_N^{η}



(STAR Collaboration) PRD **86**, 051101(R) (2012)

Forward charged hadron A_N in $p + p$ vs $p + A$



(PHENIX Collaboration) arXiv:1903.07422

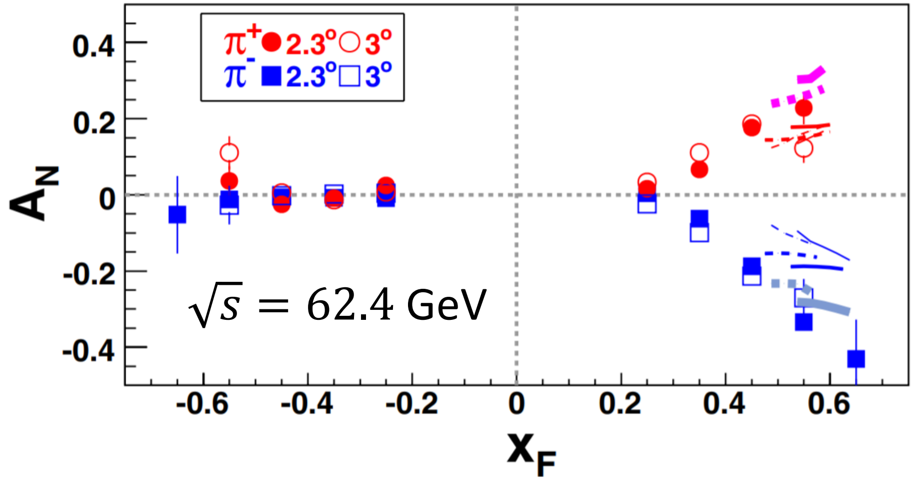
For $1.4 < \eta < 2.4$ and $1.8 < p_T < 7.0$ GeV/c

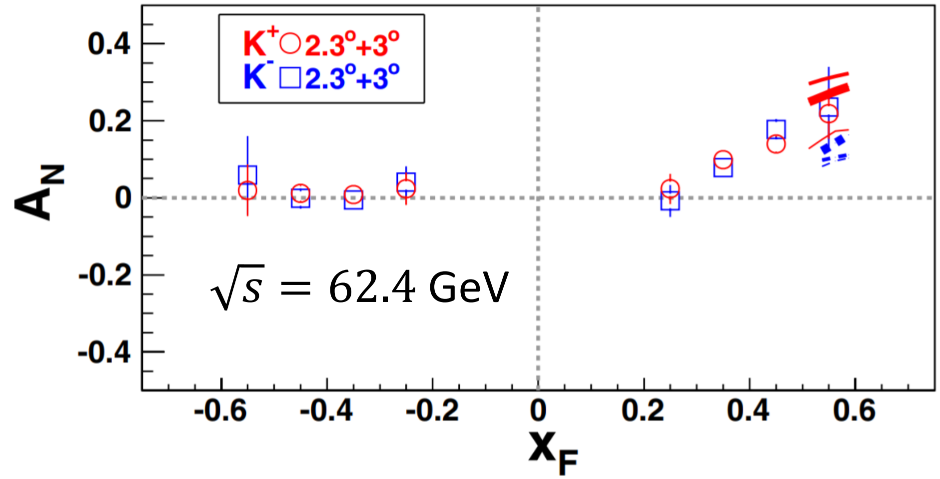
BRAHMS $A_N^{\pi^\pm}$ and $A_N^{K^\pm}$

2.3° and 3° are different angles of the Forward Spectrometer

- Solid theory curve lines are caudated for 2.3° and dotted are for 3°
- Thick lines – initial-state twist 3
- Medium lines – final state twist 3
- Thin lines – Sivers function calculations

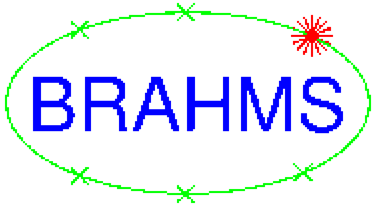
- Thick lines: Twist-3 with sea quark contrib.
- Medium lines: Twist-3 without sea quarks
- Thin lines: Sivers



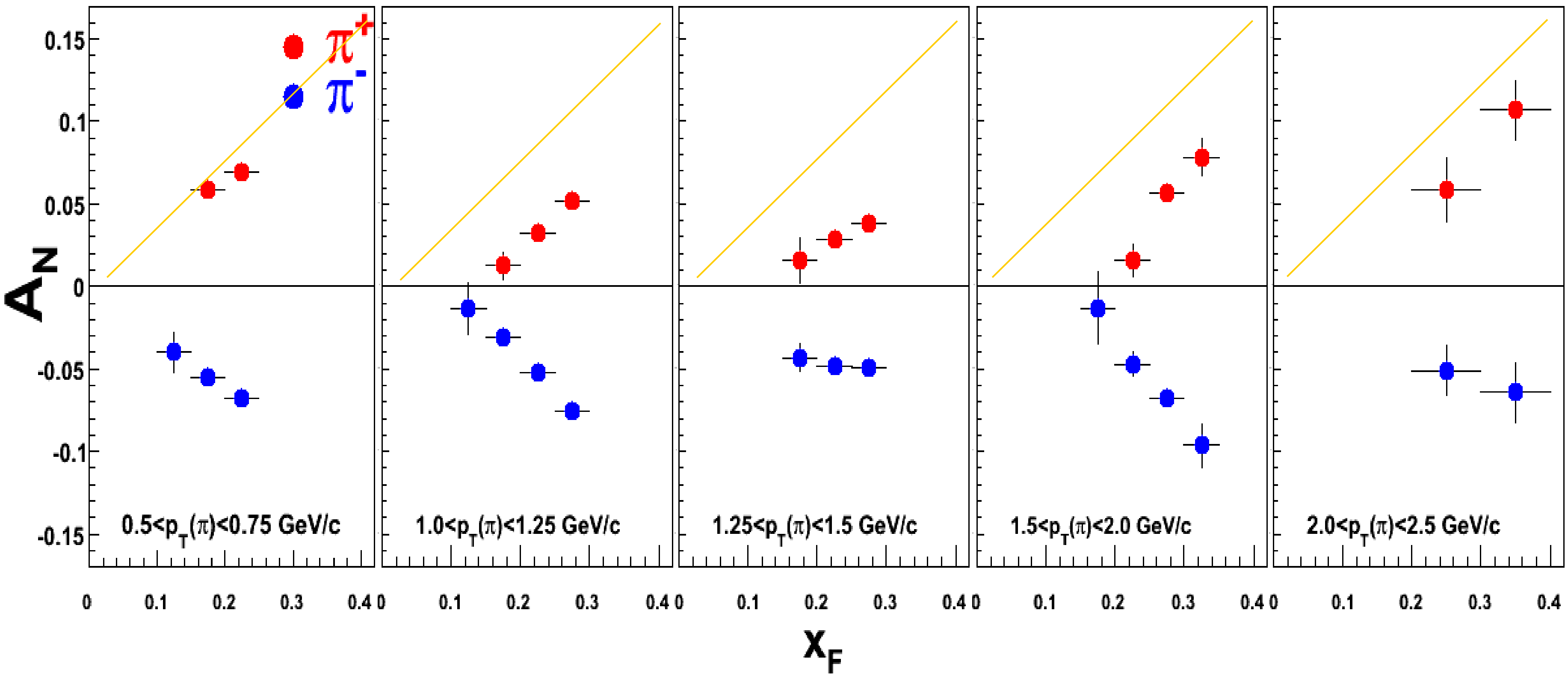


(BRAHMS Collaboration) PRL **101**, 042001 (2008)

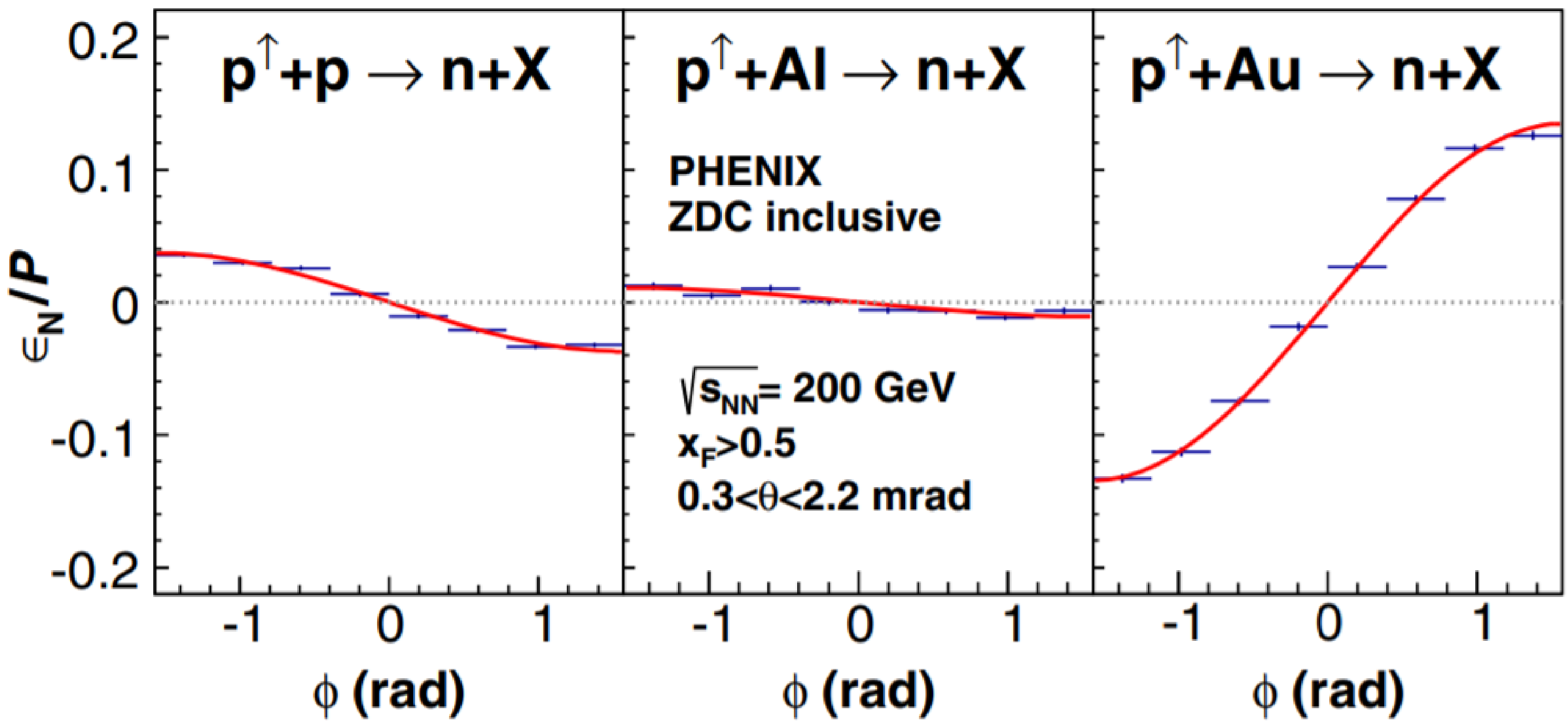
BRAHMS forward $A_N^{\pi^\pm}$ and $A_N^{K^\pm}$



Preliminary $\sqrt{s} = 200$ GeV



Forward neutron A_N in $p+p$ vs $p+A$



(PHENIX Collaboration) PRL **120**, 022001 (2018)