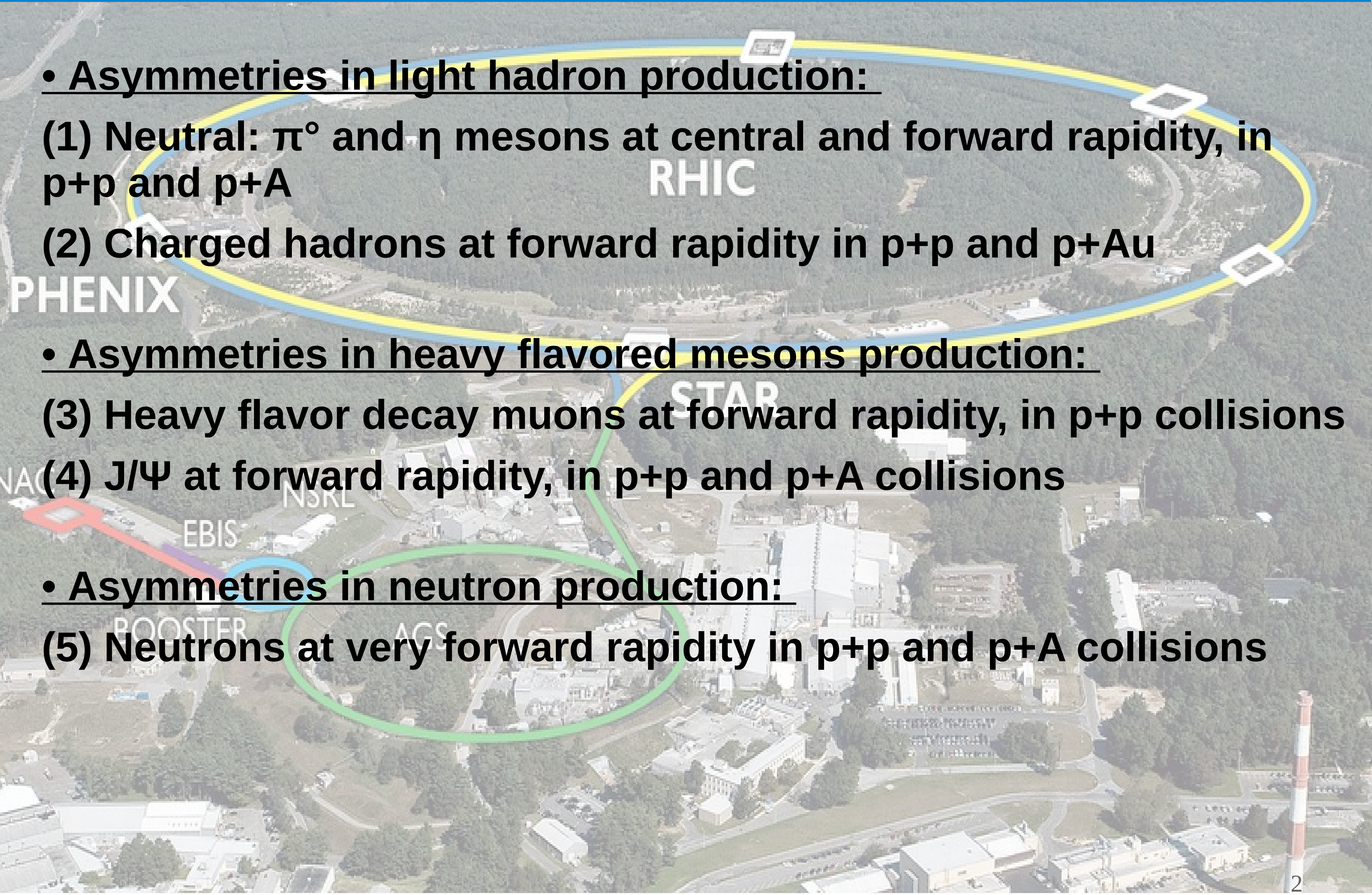
New and future transverse spin physics results at PHENIX

Marie Boër, Catholic University of America,

on behalf of the PHENIX collaboration

Transversity conference, December 11 - 15, 2017, Frascati, Italy.

Outline



• Asymmetries in light hadron production:

(1) Neutral: π° and η mesons at central and forward rapidity, in p+p and p+A

(2) Charged hadrons at forward rapidity in p+p and p+Au

• Asymmetries in heavy flavored mesons production:

(3) Heavy flavor decay muons at forward rapidity, in p+p collisions

(4) J/Ψ at forward rapidity, in p+p and p+A collisions

• Asymmetries in neutron production:

(5) Neutrons at very forward rapidity in p+p and p+A collisions

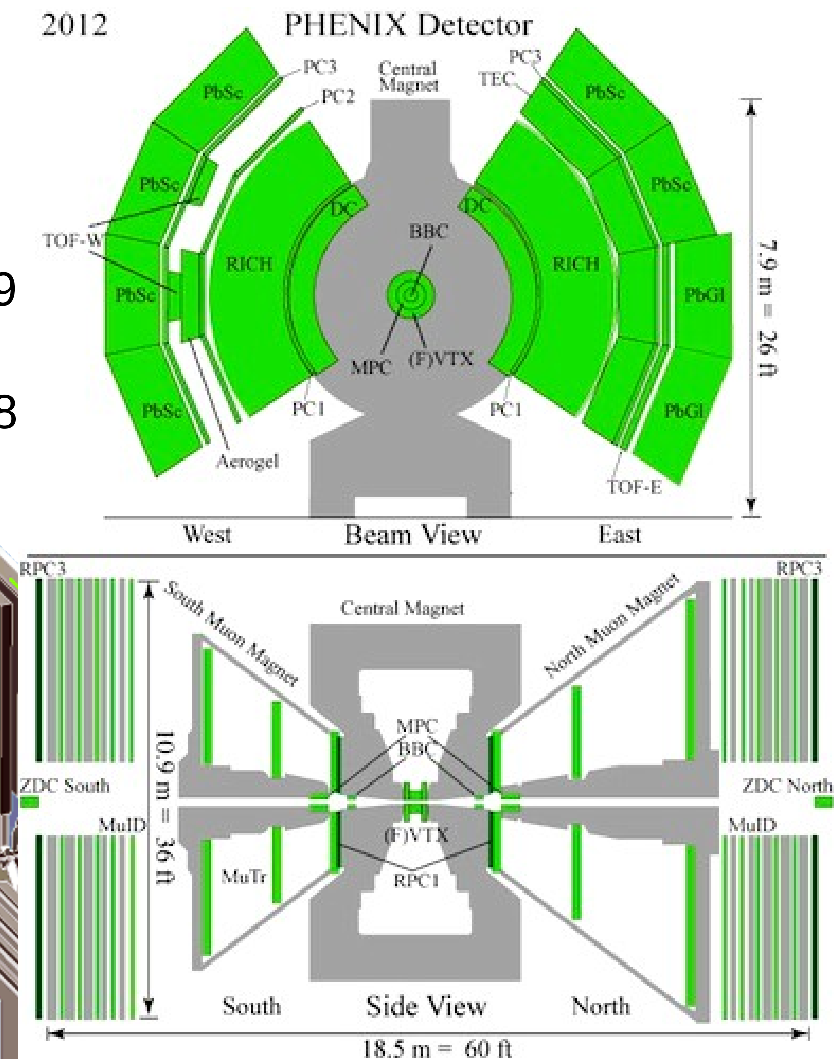
PHENIX spectrometer at RHIC, cut view

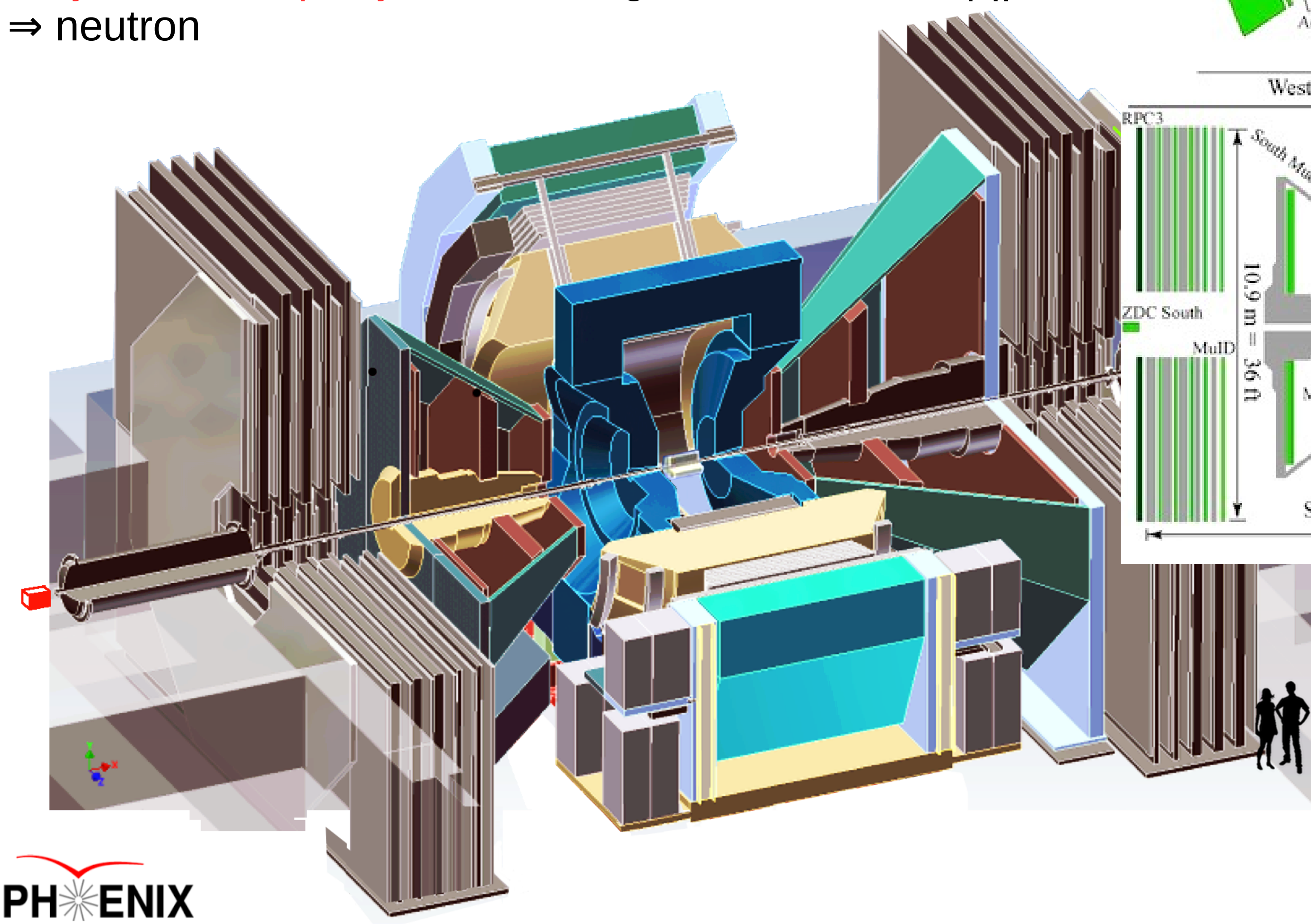
Mid rapidity, central arm: $|\eta| < 0.35$ ⇒ charged hadrons with PID, π°, η...

Forward rapidity, muon arms: $1.2 < |\eta| < 2.4$ ⇒ charged hadrons, muons, J/ψ...

Forward rapidity, muon Piston Calorimeters: $3.1 < |\eta| < 3.9$ ⇒ π°, η

Very forward rapidity, in Zero Degree Calorimeter: $|\eta| > 6.8$ ⇒ neutron





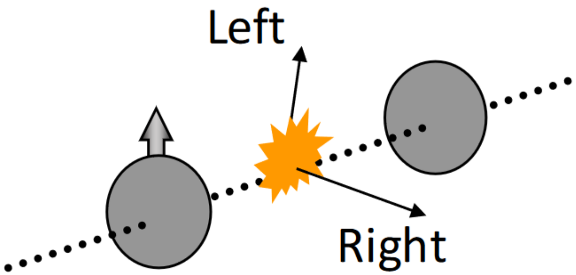
Polarized proton runs at RHIC from 2006 to 2015 and A_N measurement

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

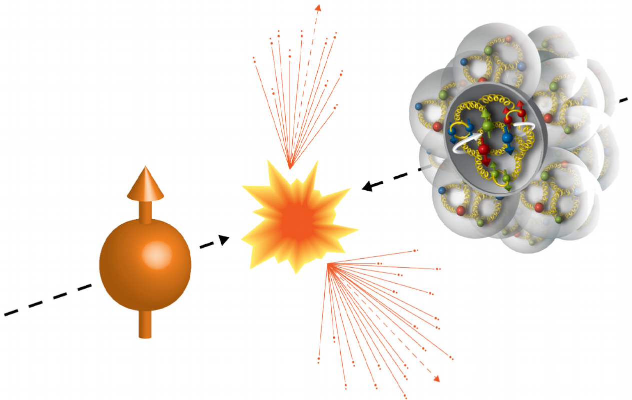
o transversely polarized beam

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

$p^{\uparrow}$+p collisions



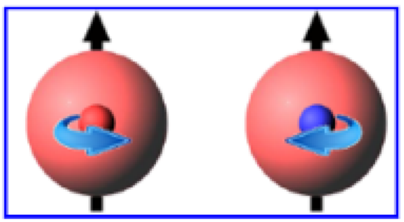
$p^{\uparrow}$+A collisions



Run 2015 : **for the first time polarized $p^{\uparrow}$+A collisions**
5 times luminosity of past transversely polarized runs

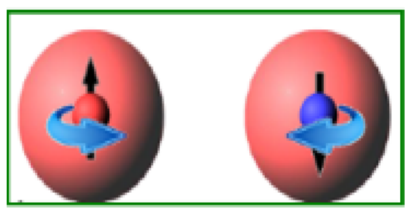
Interpretation of non-zero A_N in hadron collisions, low versus high p_T approach

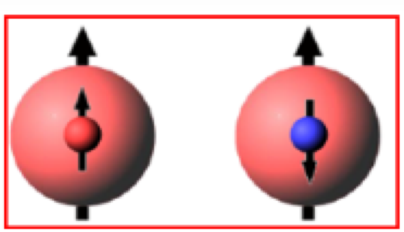
Transverse Momentum Distributions
k_T dependent approach
⇒ need 2 scales: $Q^2 \gg p_T^2$



Sivers $f_{1T}^{\perp}$: correlation of nucleon spin and partons k_T
→ contribute to initial state effects in p+p

Boer-Mulders $h_1^{\perp}$
correlation of partons spin and their k_T

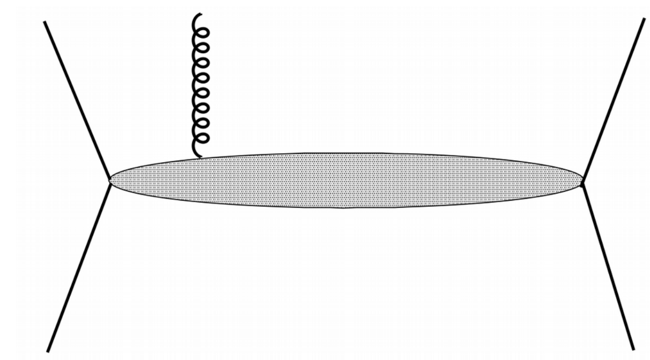




Transversity h_1 correlation of parton and nucleon spins

transversity * Collins fragmentation
correlation of parton spin and hadron k_T
→ contribute to final state effects in p+p

Correlation functions, twist 3 (and >)
integrated over k_T
⇒ need 1 hard scale (large Q^2, large p_T)



gg and qg interactions authorize spin flip...

- Access TMDs through k_T moments
- PHENIX kinematics: this framework to interpret A_N in hadron production

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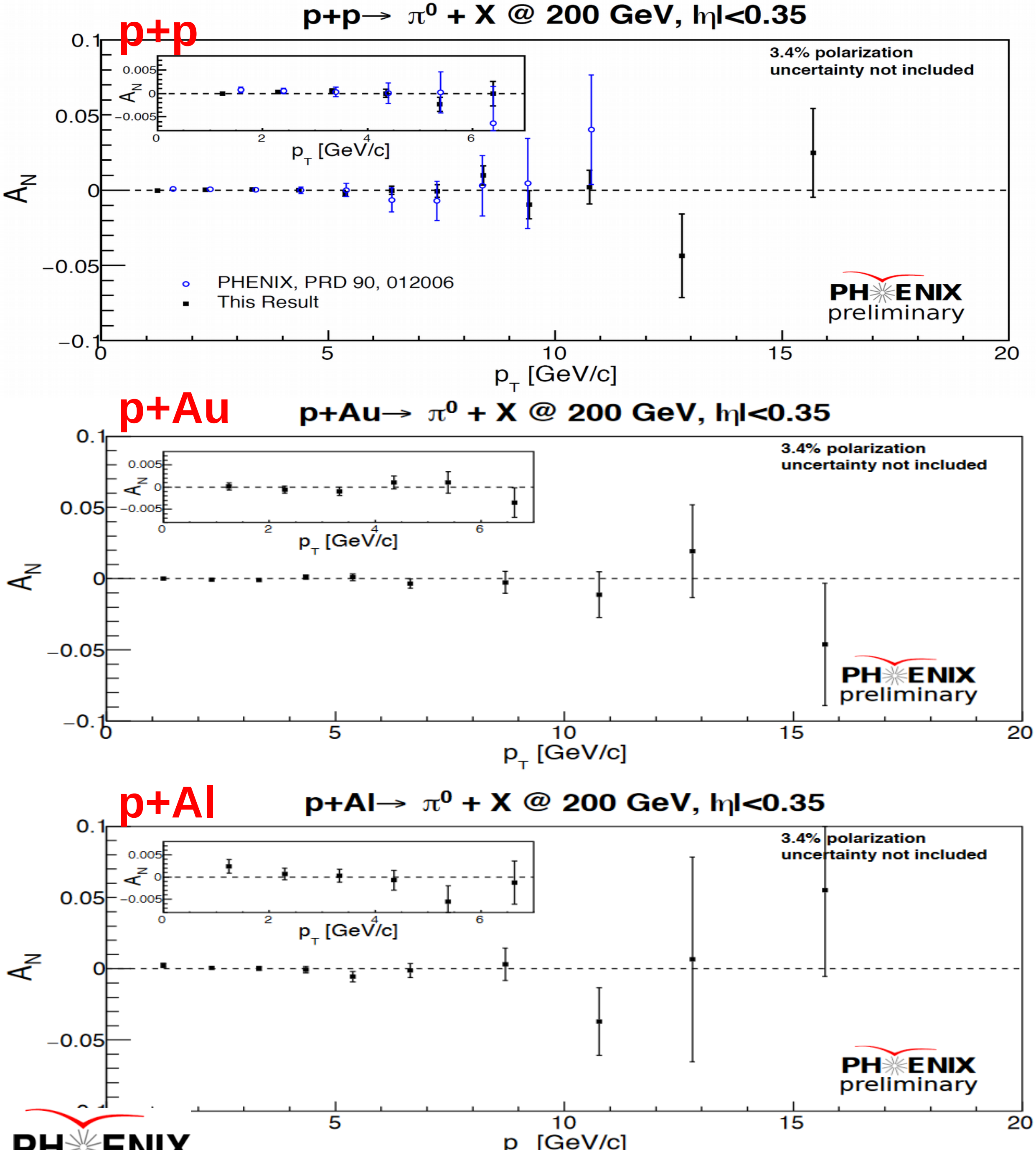
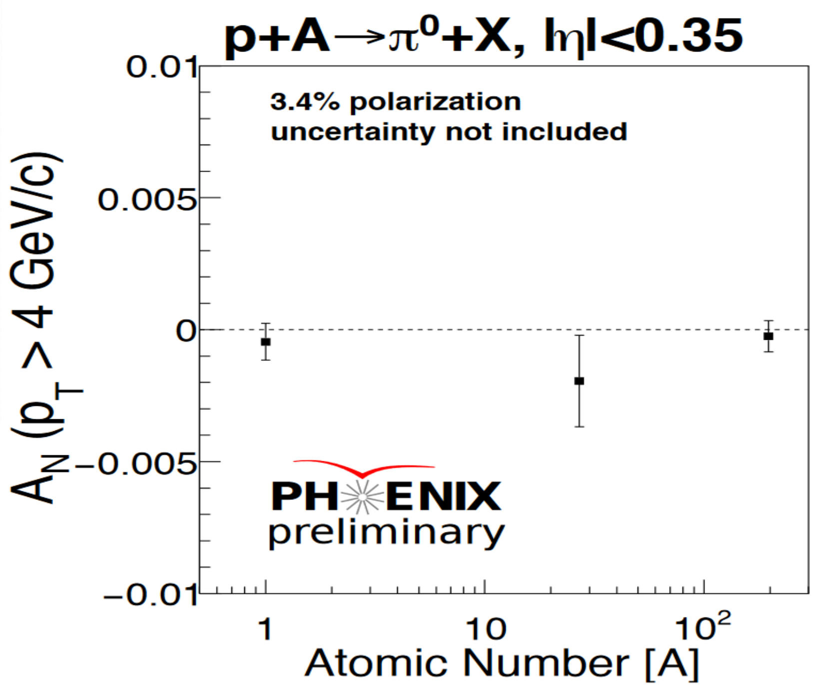
(1) A_N in π° production at central rapidity in p+p and p+A

A_N versus p_T for p+p, p+Au, p+Al



A_N integrated over p_T vs A



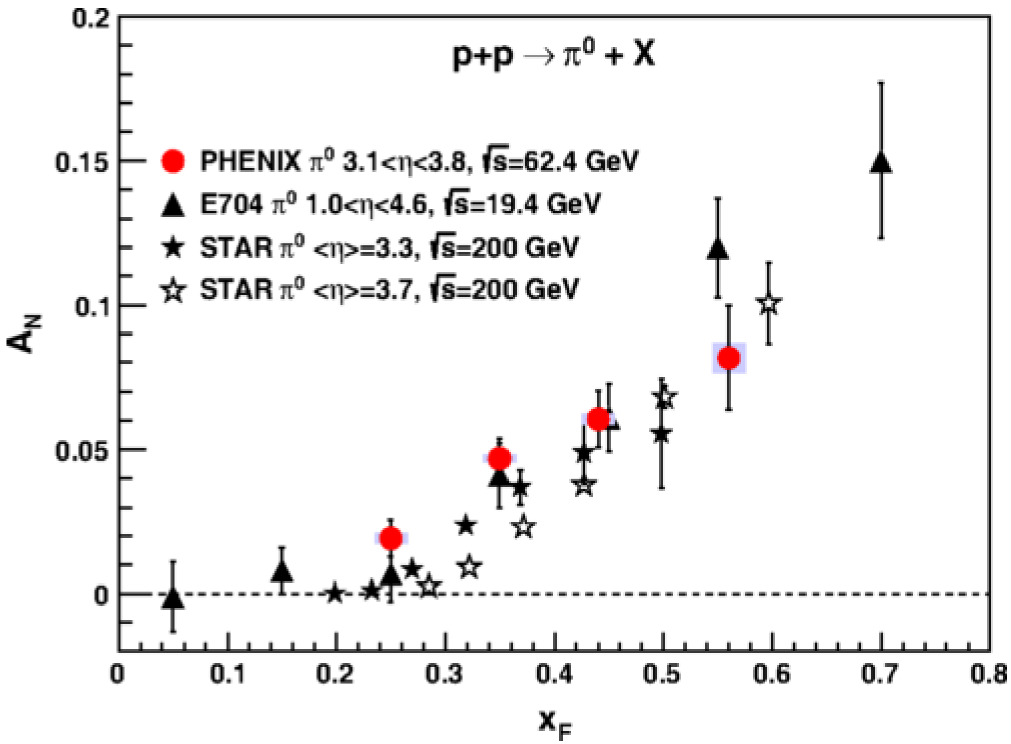
run 2015 p+p, p+Au, p+Al high precision achieved

Mid-rapidity: |η| < 0.35
→ access gluon Sivers through correlation function

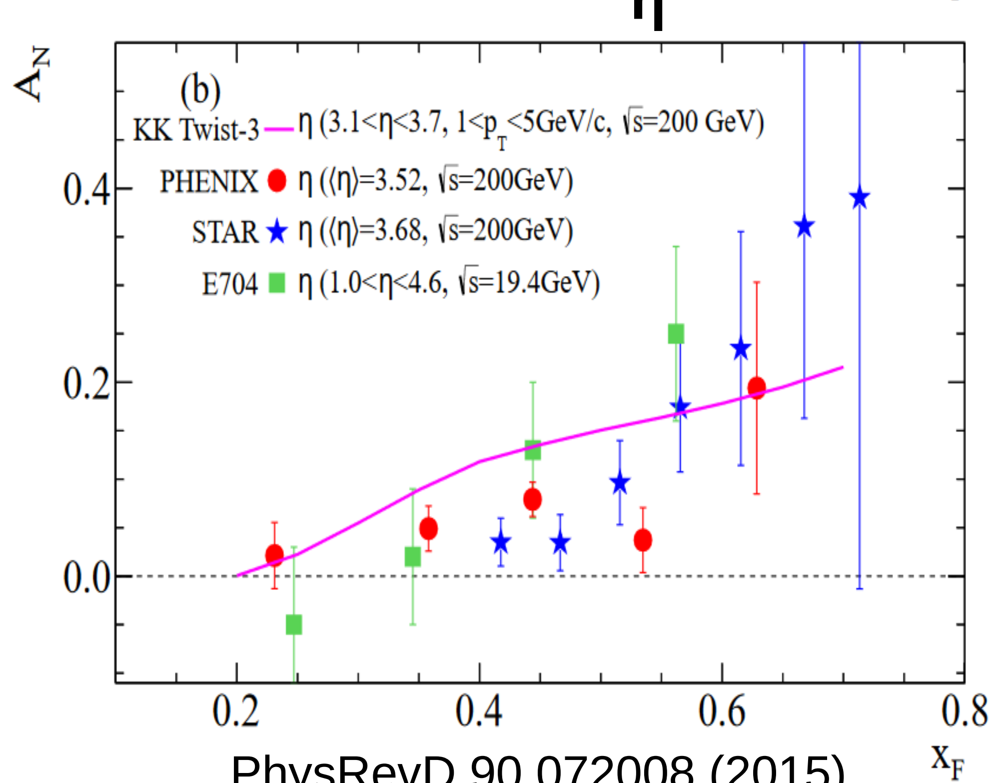
Results consistent with zero for p+p, p+Au and p+Al, no visible nuclear dependence.

(1) A_N in light neutral hadrons production: π° and η at forward rapidity

π° A_N vs x_F various energies, PHENIX, STAR, E704 η



Phys. Rev. D 90, 012006 (2014)

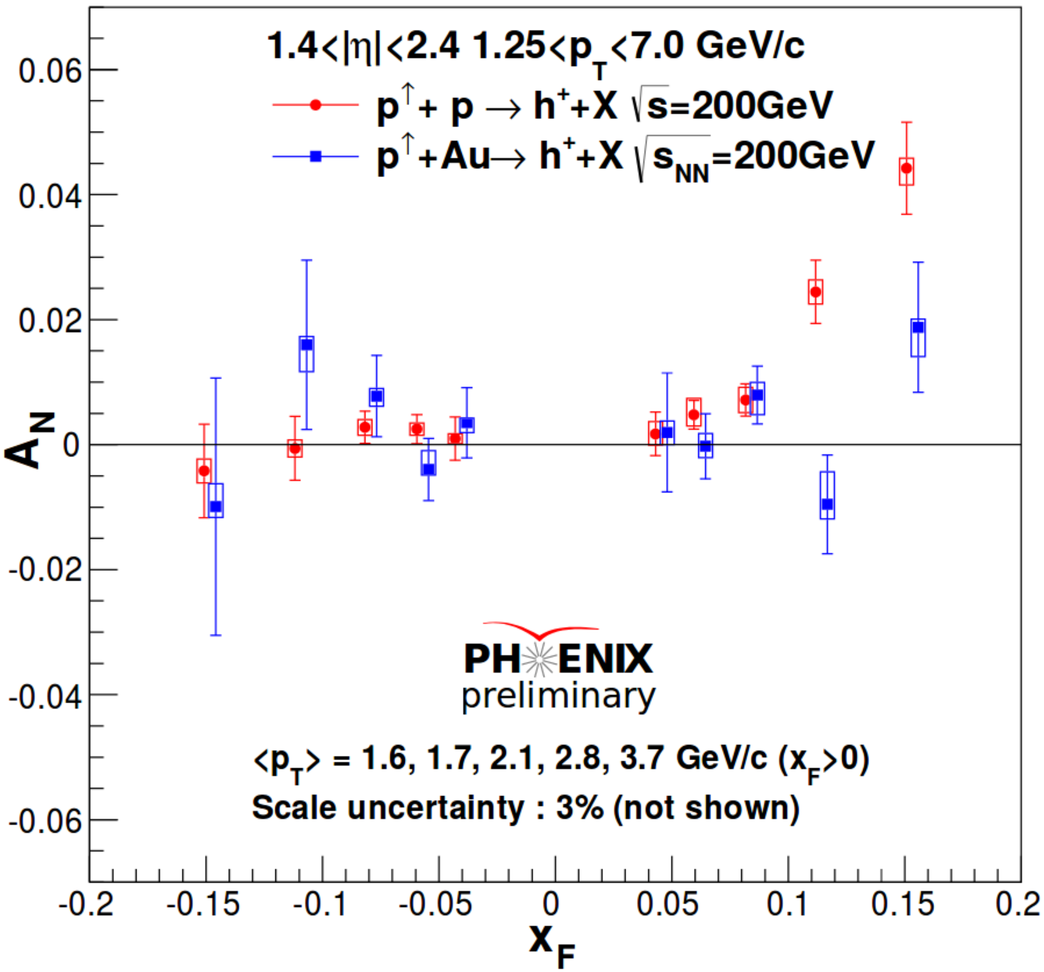


PhysRevD.90.072008 (2015)

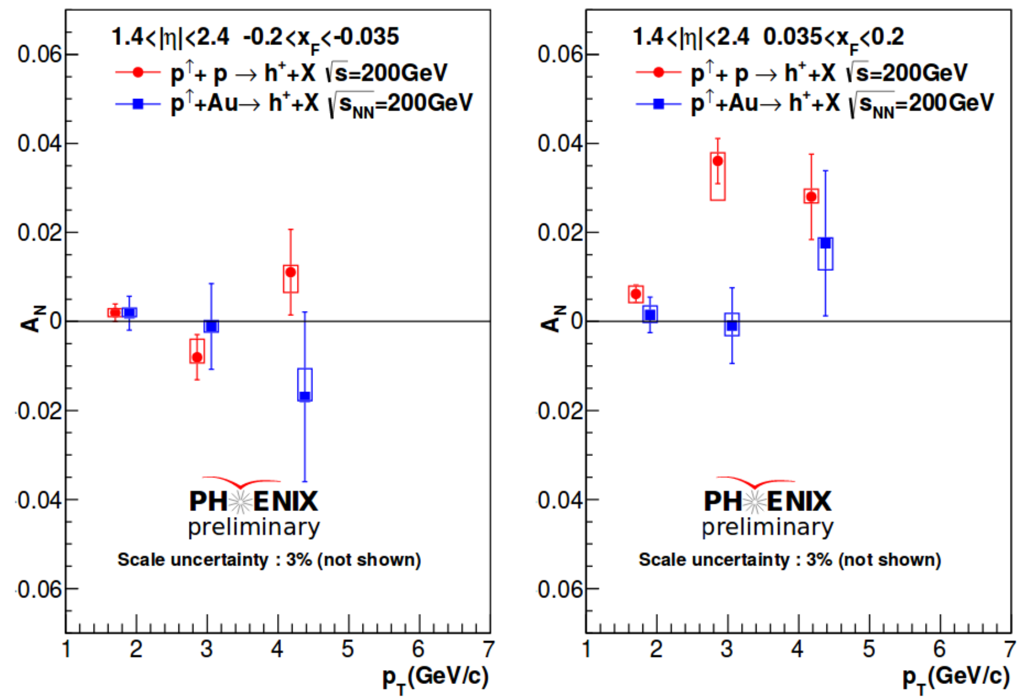
Unexpected large A_N found by all experiments in both π° and η production, at same level

- Large asymmetries measured at forward rapidity (∝ x_F), while compatible with zero at mid- (previous slide) and backward rapidity.
- Weak energy dependence
- Pink fit: twist-3 calculations using quark-gluon correlation functions
- A_N origin may be: gluon correlation at initial state, final state effect with twist 3 fragmentation...

(2) Transverse spin asymmetries in charged light hadrons production



x_F and p_T dependence for positive hadrons (π^+, K^+...)



- non zero asymmetry for h^+ at forward rapidity in p+p, increasing as a function of X_F.
- comparable with BRAHMS result (not same kinematic)
- suppression of the asymmetry in p+A

⇒ A suppression coming from saturation effect is predicted in:
Kang, Yuan, Phys.RevD. 84, 034019(2011); Kovchegov, Sievert, Phys.RevD.86, 034028(2012); Yoshitaka Hatta et al, Phys.RevD.95, 014008(2017)

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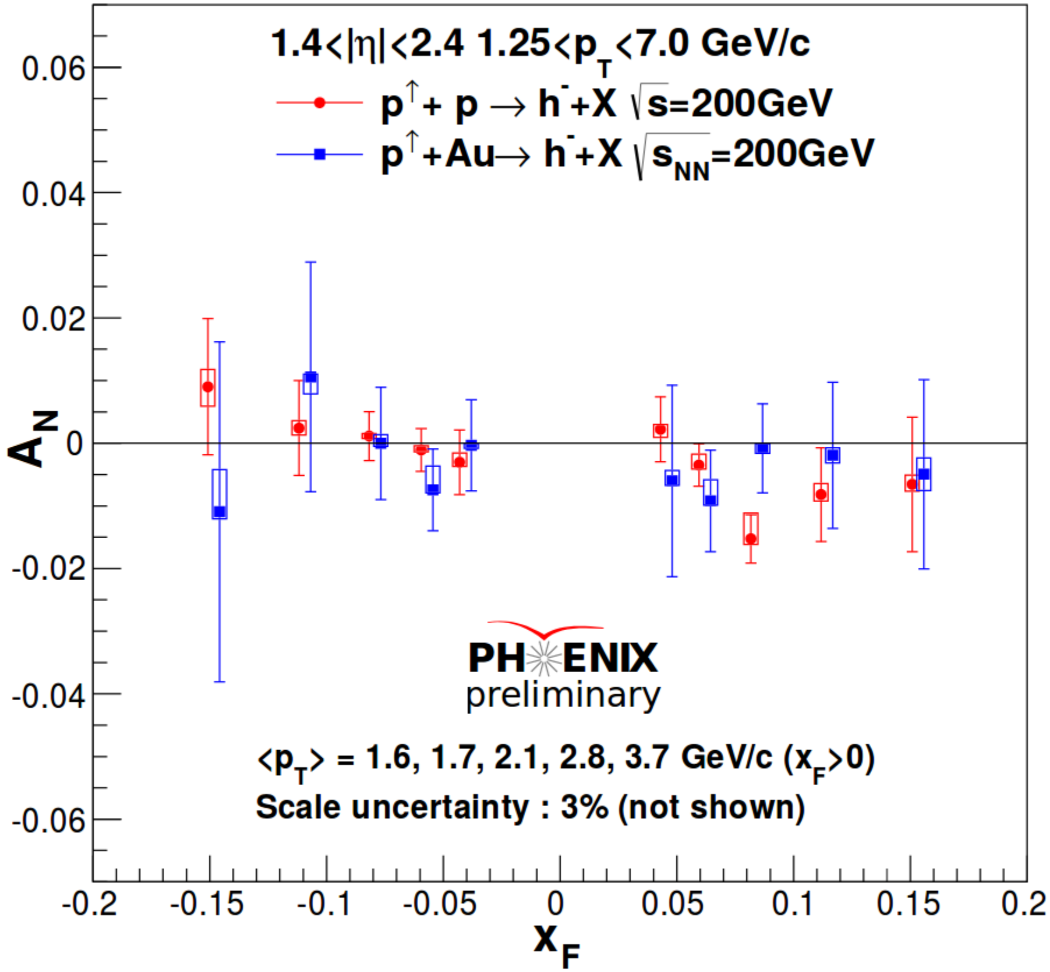
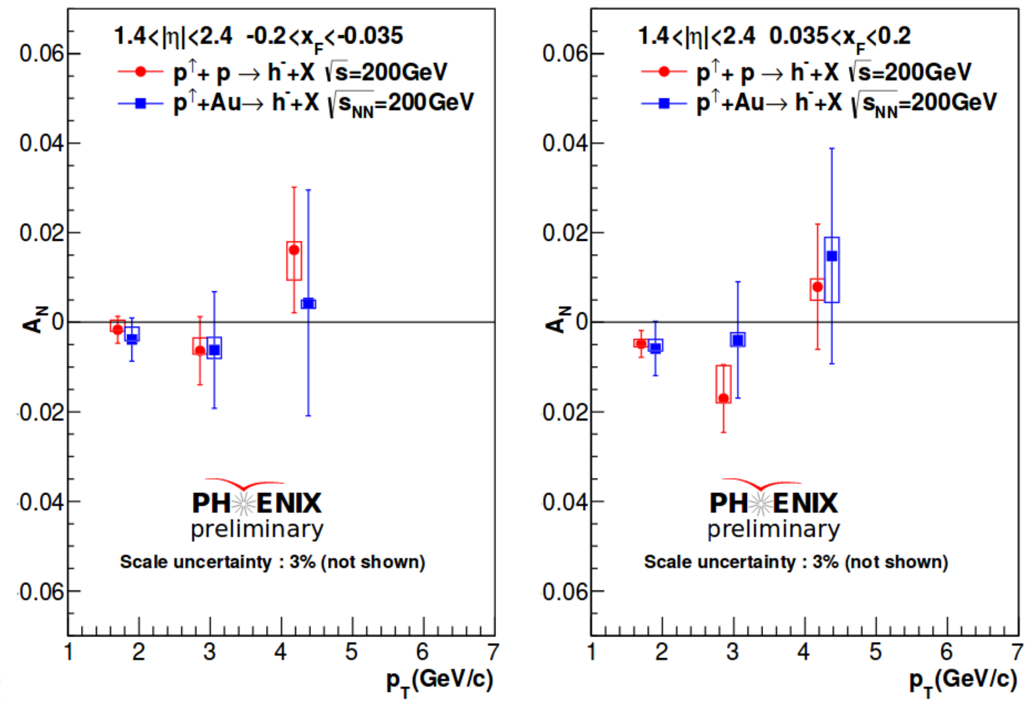


x_F and p_T dependence for negative hadrons (π^-, K^-...)



- A_N compatible with 0 for negative hadrons

⇒ small A_N anticipated from BRAHMS results with π/K separation:

positive $A_N(K^-)$, negative $A_N(\pi^-)$ in BRAHMS

For positive hadrons: positive $A_N(K^+)$ and $A_N(\pi^+)$ in BRAHMS PRL101,042001(2008), arXiv:0908.4551

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(3) Open heavy flavor transverse spin asymmetry

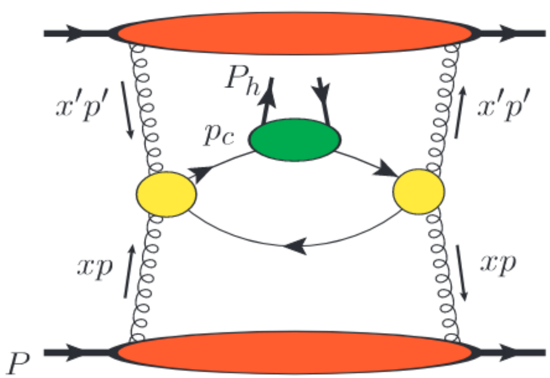
- Sensitive to gluon Sivers function, as moment related to correlation function
(see Kang et al, Phys.Rev.D83:094001,2011)

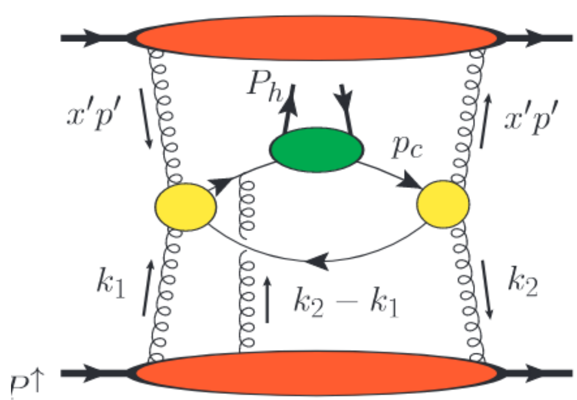
- Production is dominated by tri-gluon correlation in collinear factorization approach.

- non zero asymmetry would be expected from initial state effect

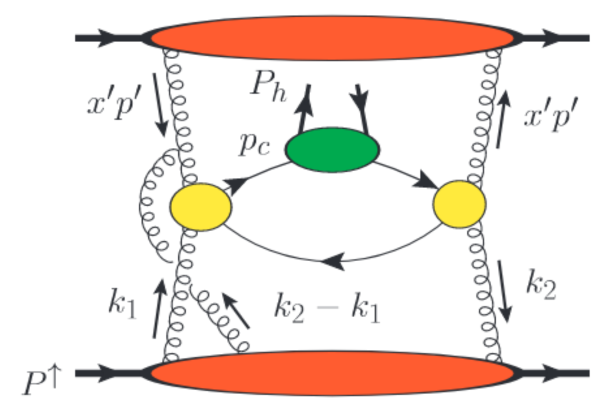
twist 2 "generic" diagrams for p+p → D X

twist 3 "generic" diagrams for p+p → D X





initial state interaction



final state interaction

Koike, Yoshida,
Phys.Rev.D84:014026,2011

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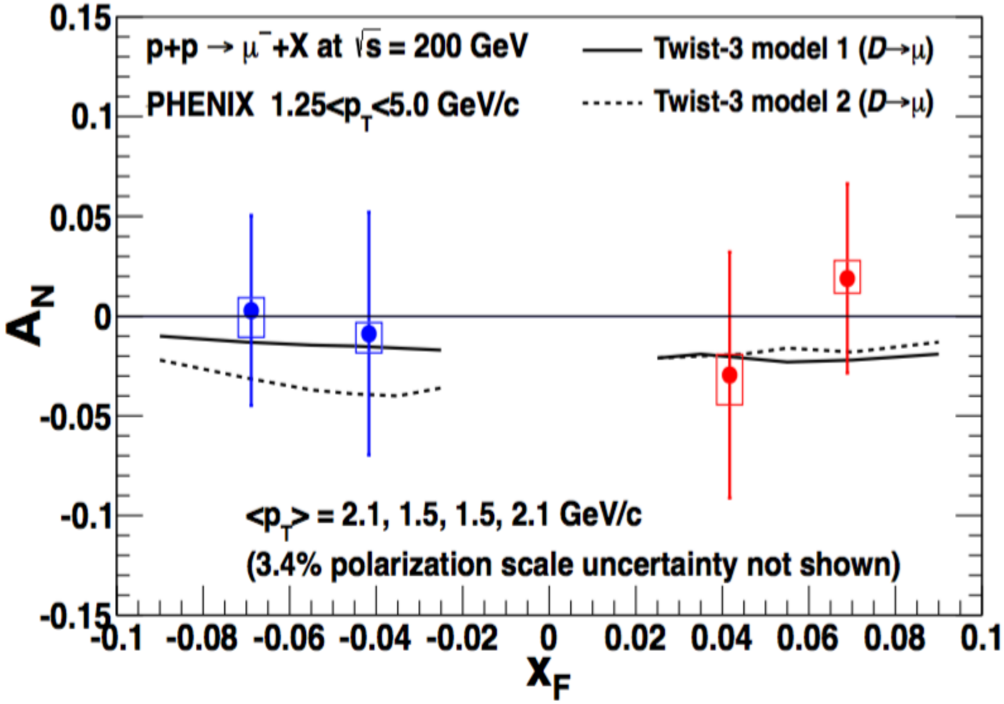
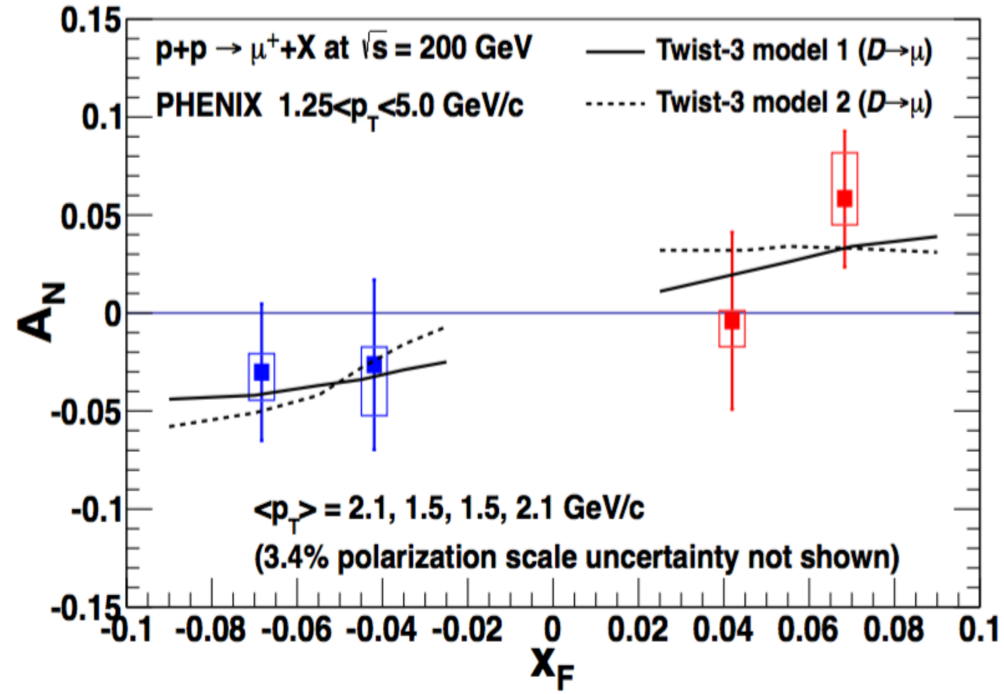
(3) Open heavy flavor transverse spin asymmetry (vs xF)

decay into μ-



decay into μ+



- **Main contribution to single muons: D-meson decay (~ 60% to 92% at lower p_T)**
- **Results consistent with zero within uncertainties, for μ+ and μ–**
- **Model predictions at twist 3 within collinear factorization framework consistent with measurement. Original calculations for D meson translated to single μ decay.**

Twist 3 model: Y. Koike, S. Yoshida, PRD84:014021 (2011)

AN calculations for D mesons provided by S. Yoshida.

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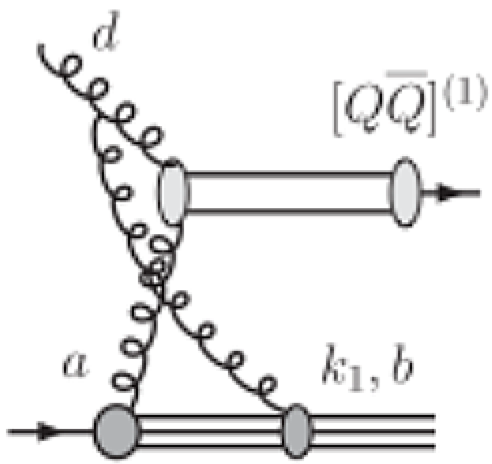
Recently published: Phys. Rev. D 95, 112001 (2017)

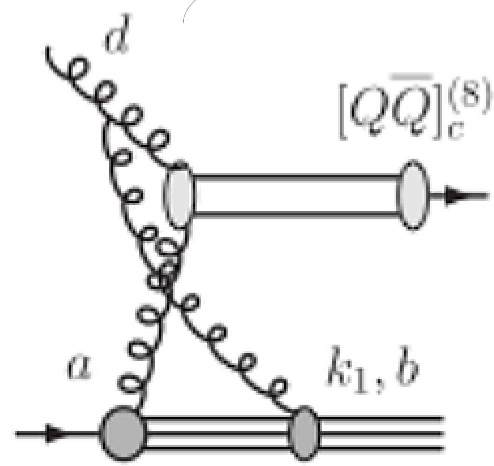
(4) Transverse spin asymmetry in inclusive J/ψ production

Sensitive to production mechanism: only color singlet can produce non zero A_N

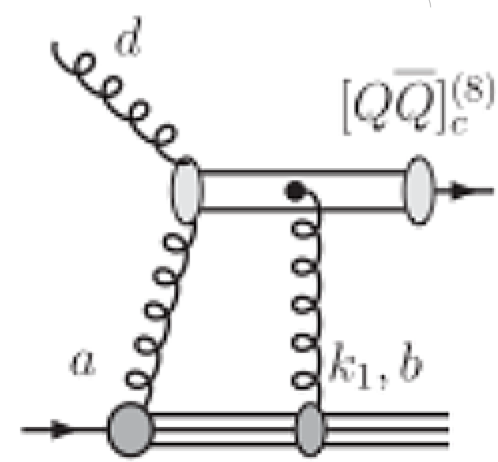
Color singlet | **Color octet**



Initial state interaction



Initial state interaction



Final state interaction

Comparison :

4 data sets, last one in 2015 with *5 improved luminosity and first time transversely polarized p+A

Run	Luminosity	Pol
Run6	1.8 pb^{-1}	53%
Run8	4.5 pb^{-1}	45%
Run12	9.2 pb^{-1}	60%
Run15	50 pb^{-1}	60%

Interpretation: F. Yuan et al, Phys.Rev. D56 (1997) 321-328, fig from F. Yuan talk

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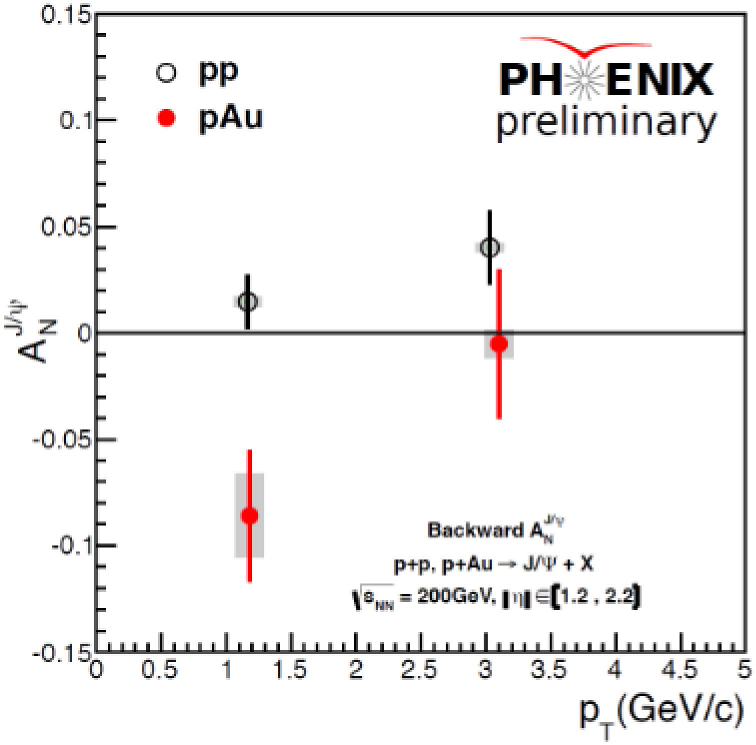
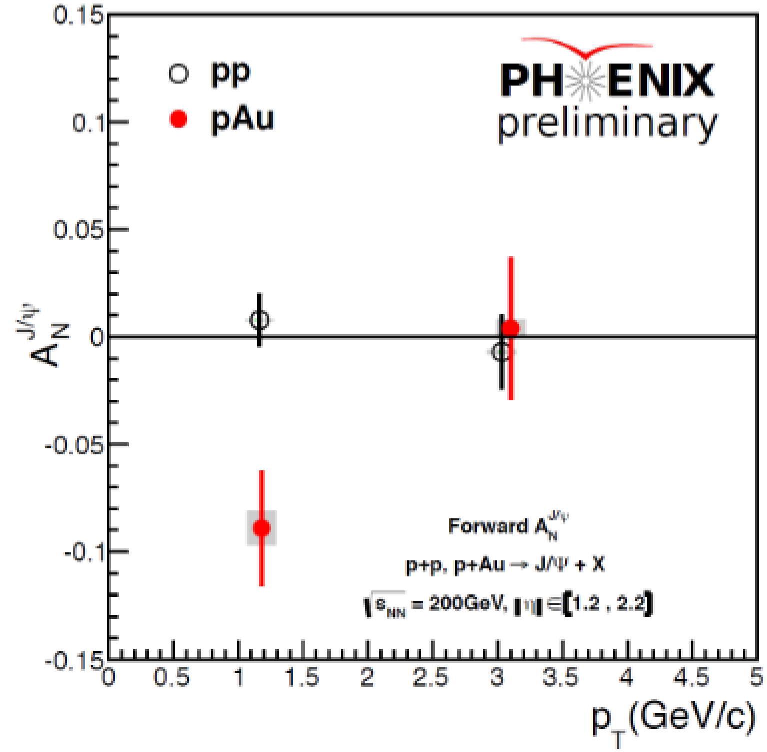
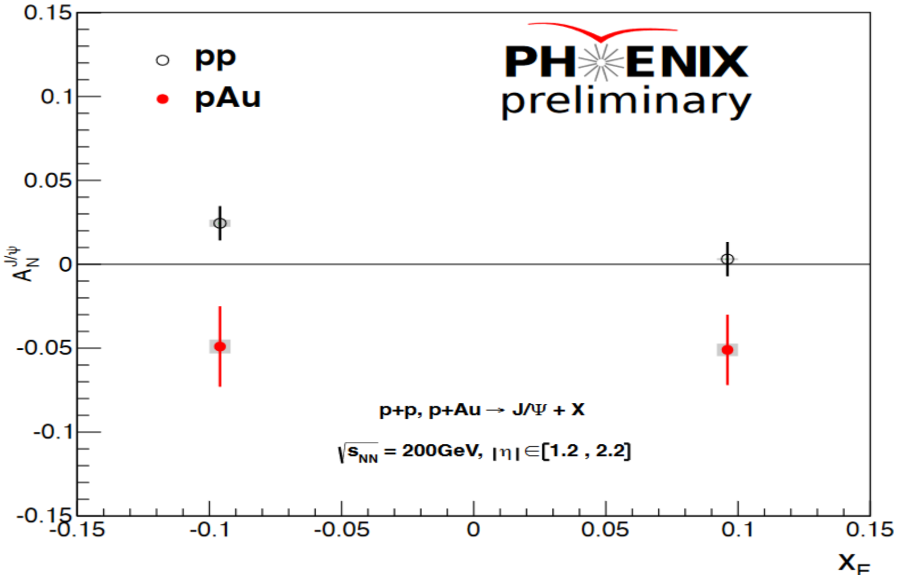
(4) A_N for inclusive J/ψ production: p+p and p+A





run 2015

A_N vs p_T (top) and x_F (bottom)



Run 2015: *5 statistics compared to all other sets

A_N consistent with zero for p+p

2 σ level negative asymmetry observed at low pT for p+Au

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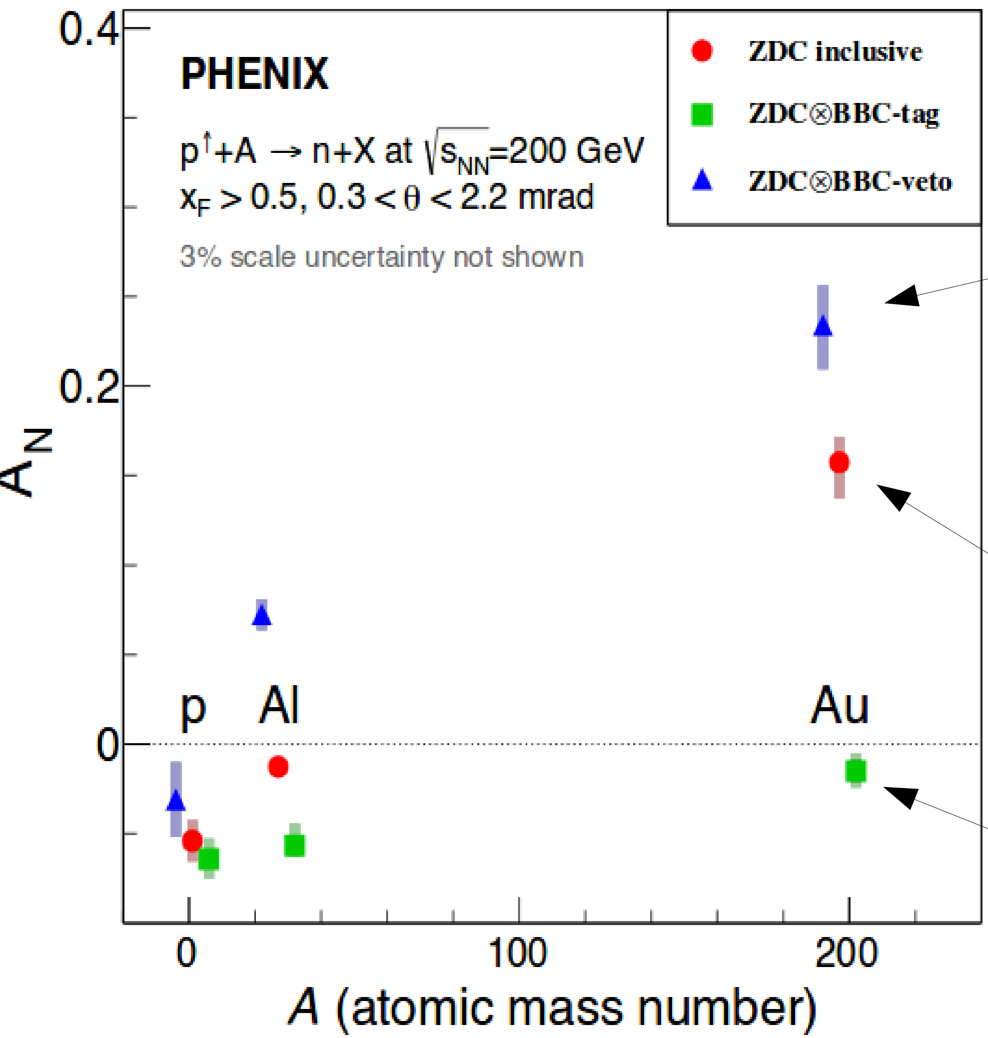
article in preparation, includes p+p, p+Au and p+Al

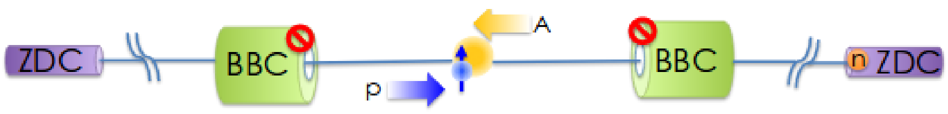
(5) A_N in very forward neutron production

A_N measured in p+p, p+Al, p+Au for neutron, $|\eta| > 6.8$, "very forward"



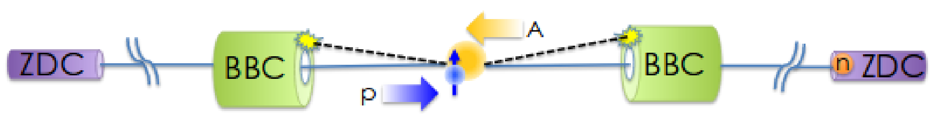
trigger configuration

particles veto at lower rapidity (no BBC hits)
⇒ less activity around the neutron
⇒ larger fraction of Ultra-Peripheral Collisions
⇒ stronger A dependence and large A_N



measurement in Zero Degree Calorimeter

particle hits at lower rapidity (2 BBC hits)
⇒ more activity around the neutron
⇒ larger fraction of hard collisions
⇒ weaker A dependence



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arXiv:1703.10941

(5) Interpretation of the neutron asymmetries and A dependence

- **Unpolarized neutron production cross section in p+p:** can be described with π exchange

- **Non zero A_N in p+p** [Fukao et al, Phys.Lett.B650:325-330,2007]

can be explained by interference between π exchange (spin flip) and a_1 Reggeon (non spin flip) [Kopeliovich et al, Phys. Rev. D 84, 114012 (2011)].

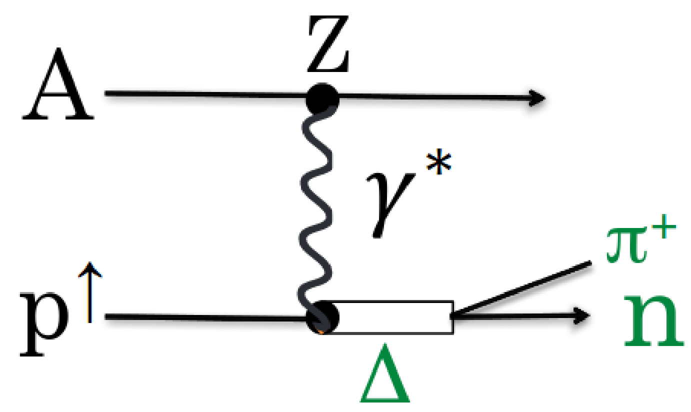
But: predicted weak nuclear dependence

- **New PHENIX results with large nuclear dependence**

- observation of larger asymmetry and sign change when there are less interactions around the neutron

⇒ Ultra Peripheral Collisions with γ* exchange ($\gamma^* p^{\uparrow} \to \pi^+ [\Delta^* ... \to N]$) can explain it

⇒ virtual photon flux increase in Z^2 can explain the nuclear dependence



- **Model and simulations mixing "hadronic" collisions + UPC reproduce PHENIX results**

- simulations predict an average of small negative asymmetries as expected for only hadronic collisions and large positive asymmetries expected for only electromagnetic process [Mitsuka, Eur.Phys.J.C75:614,2015]

- ongoing studies of p_T and x_F dependence

arXiv:1703.10941

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Summary

(1) Large asymmetries in light hadron production at forward rapidity, while found compatible with zero at central and backward rapidity.
Results can be reproduced with some models including twist 3 correlation functions.

(2) Large asymmetries in positive hadron production at forward rapidity in p+p.
Effect tend to be suppressed in p+Au, some models explain it from saturation.
Asymmetry compatible with zero for negative inclusive light hadrons (π^-, K^-...).
Compatible with BRAHMS results.

(3) Asymmetries found compatible with zero for inclusive heavy flavored mesons production (dominated by D). Can be reproduced with some twist 3 parameterizations

(4) J/ψ asymmetry in p+p compatible with zero, unexplained asymmetry found in p+Au

(5) Large asymmetry and strong nuclear dependence in very forward neutron production.
Interpreted by contribution of $\gamma^* p \rightarrow \pi^+ n$ in UPC, results can be reproduced with model including UPC.

- Near future:

Heavy flavor muons A_N with high precision data at forward rapidity, direct photon A_N at mid-rapidity, DY A_N

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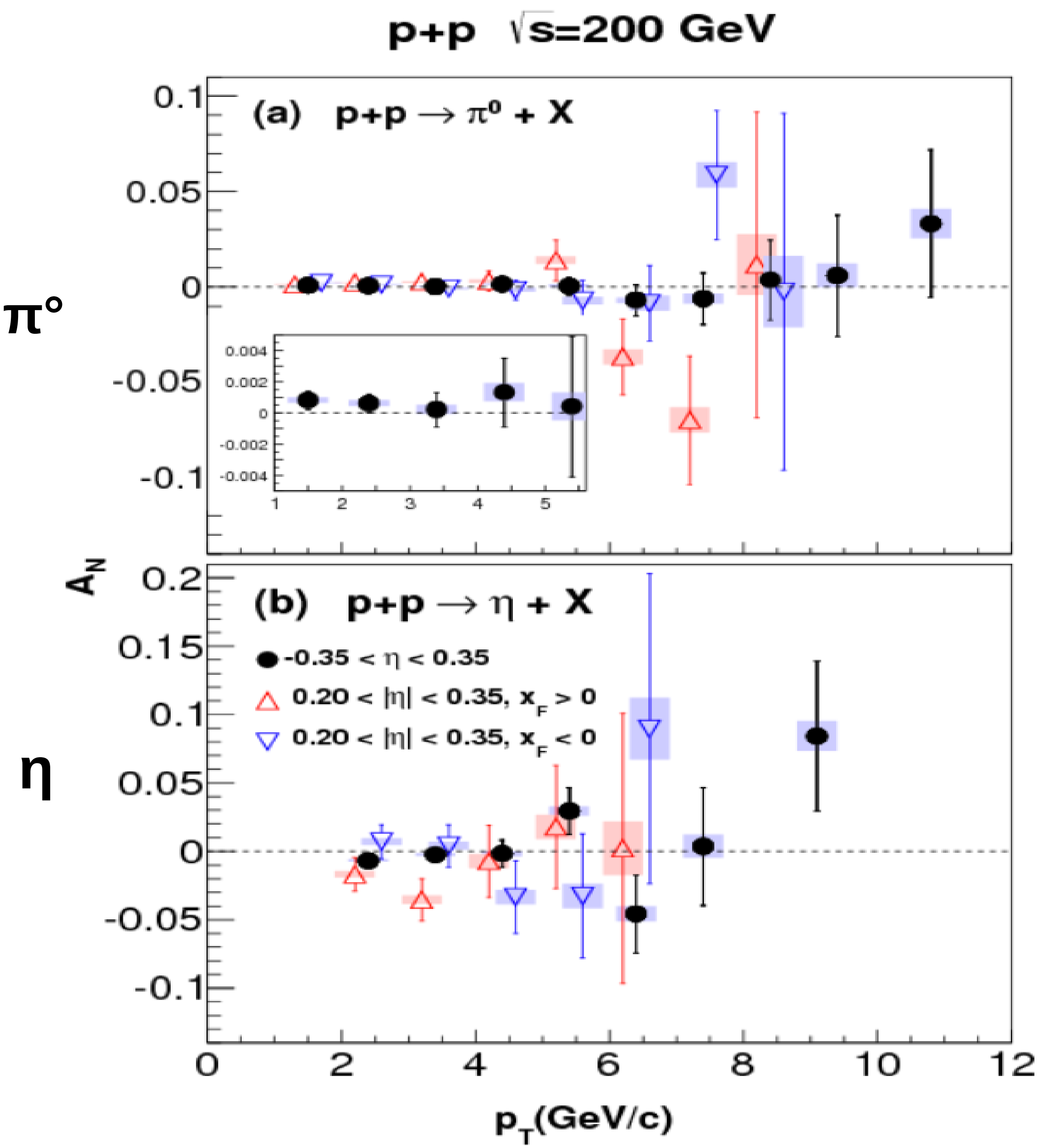
(1) A_N in light neutral hadrons production: π° and η at central rapidity



A. Adare et al. (PHENIX Collaboration) PRD 90, 012006 (2014)

π° and η A_N in p+p at 200 GeV
→ access gluon Sivers function through correlation function

Mid-rapidity: |η| < 0.35

A_N found consistent with zero for the whole p_T range in p+p collisions, within statistic uncertainties.

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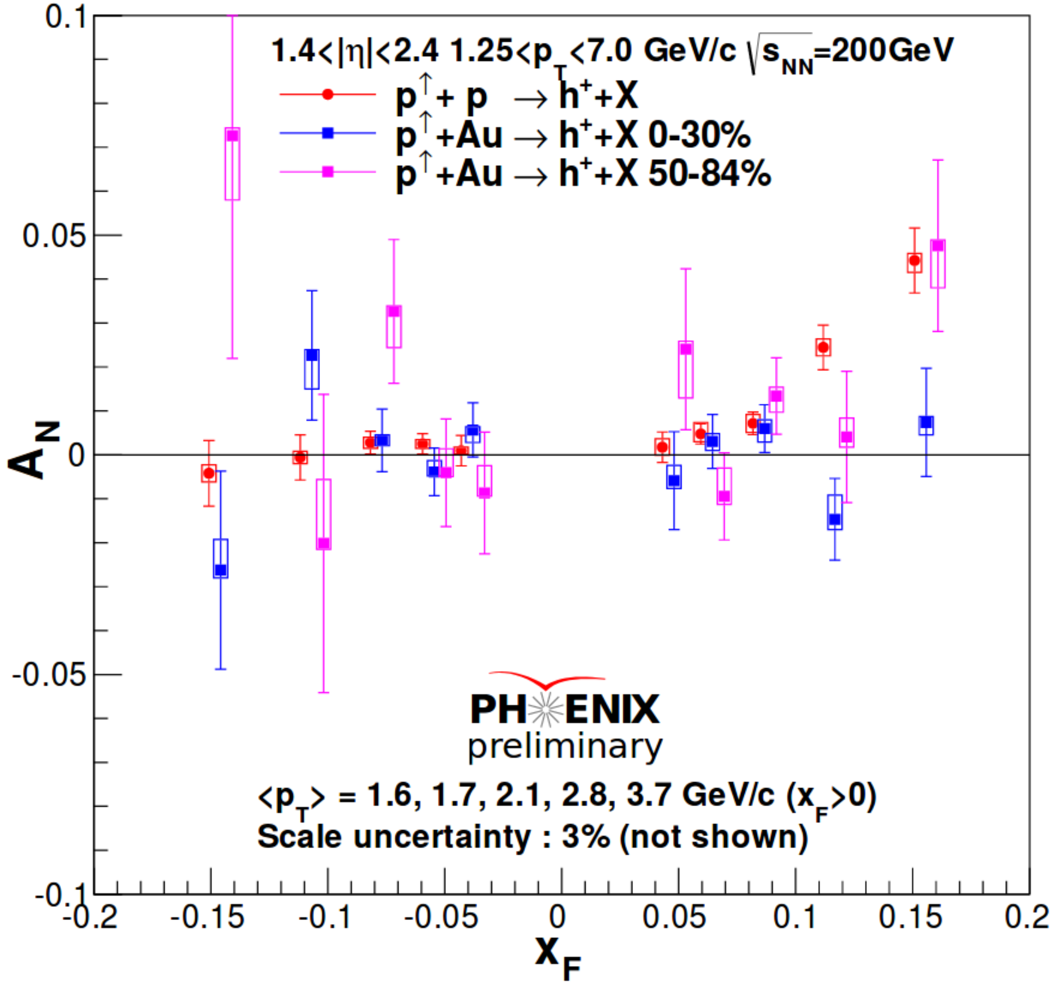
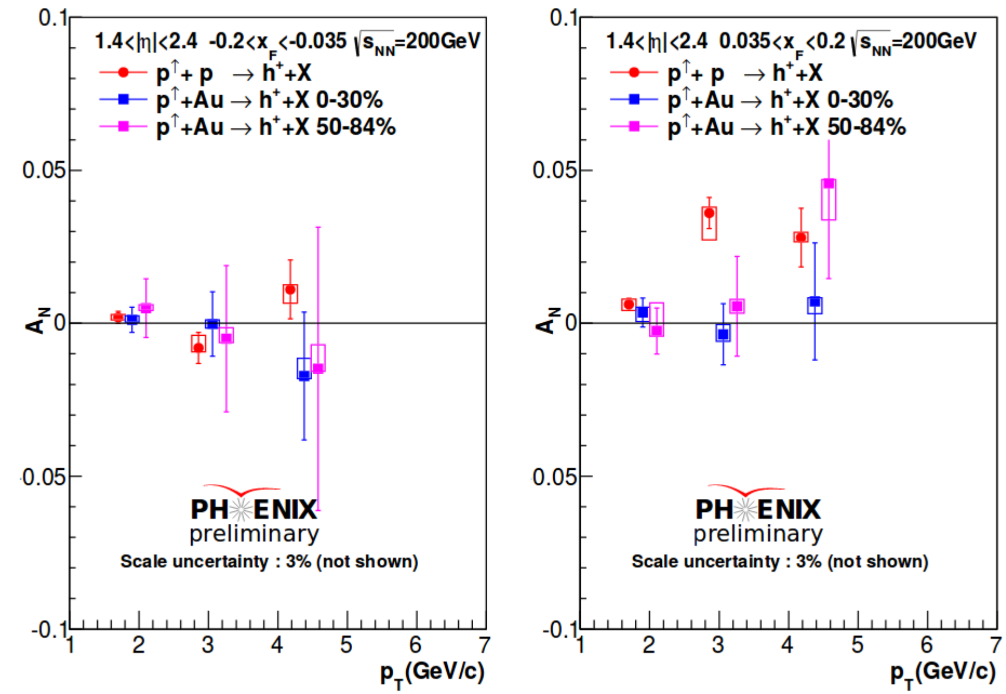
(2) Transverse spin asymmetries in charged light hadrons production



x_F and p_T dependence for positive hadrons (π^+, K^+...)

CENTRALITY DEPENDENCE



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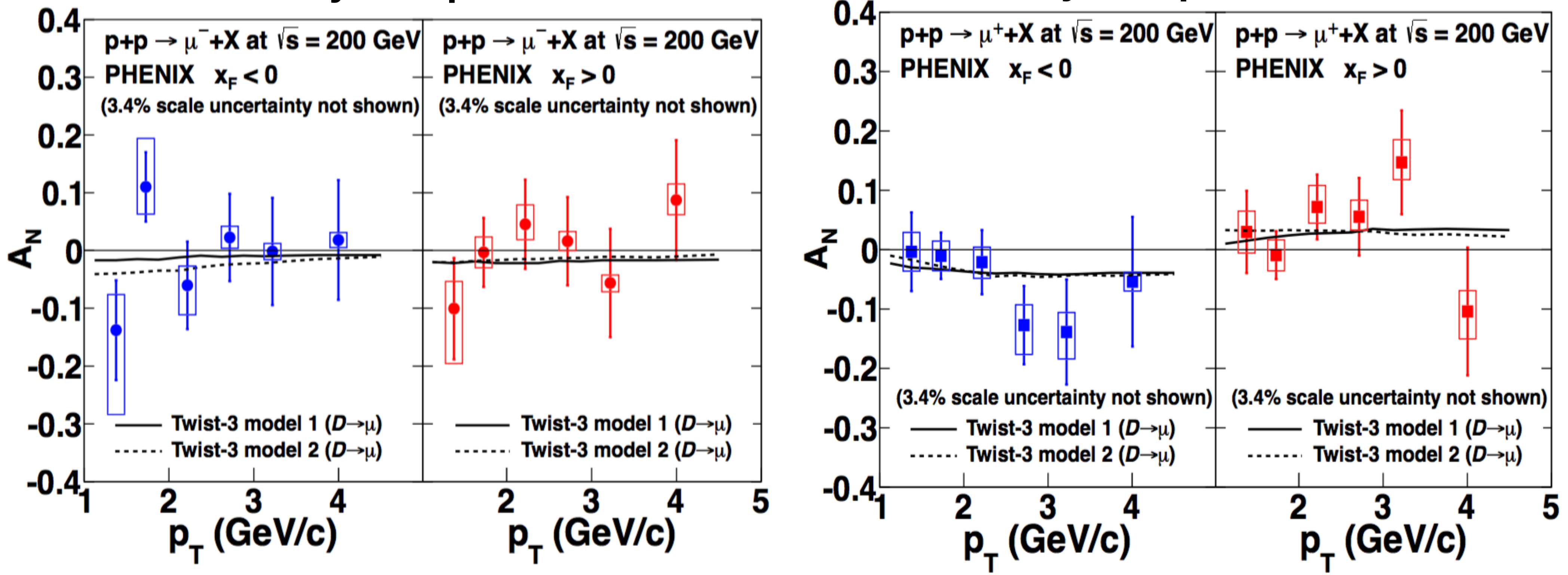
(3) Open heavy flavor transverse spin asymmetry (vs pT)

decay into μ- | decay into μ+



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- **Results consistent with zero within uncertainties, for μ+ and μ–**
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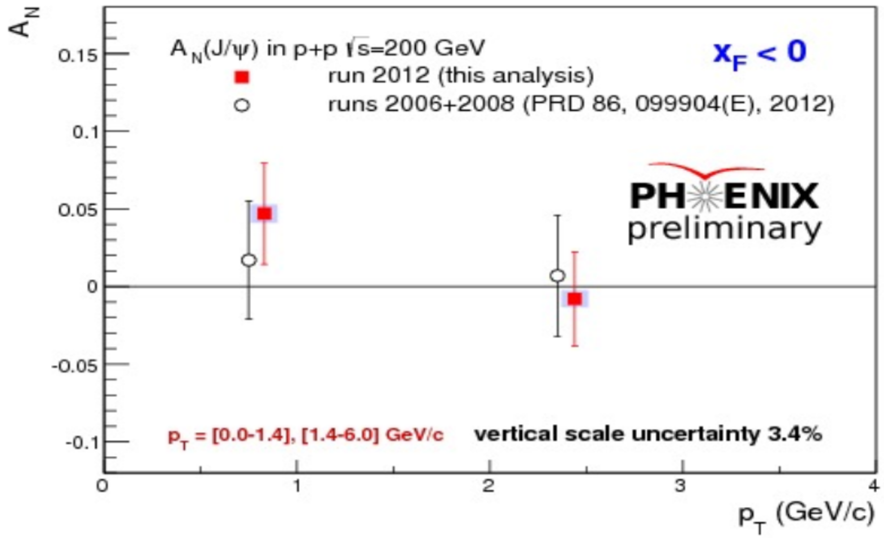
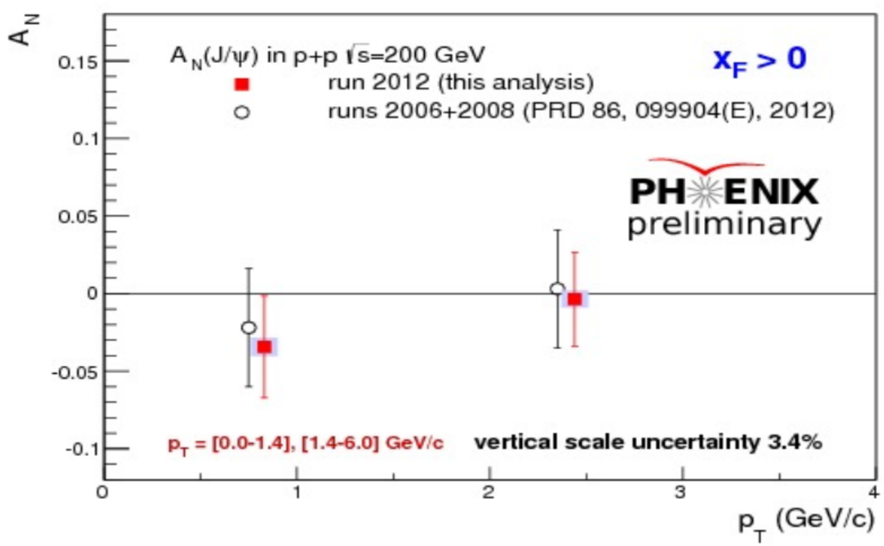
Recently published: Phys. Rev. D 95, 112001 (2017)

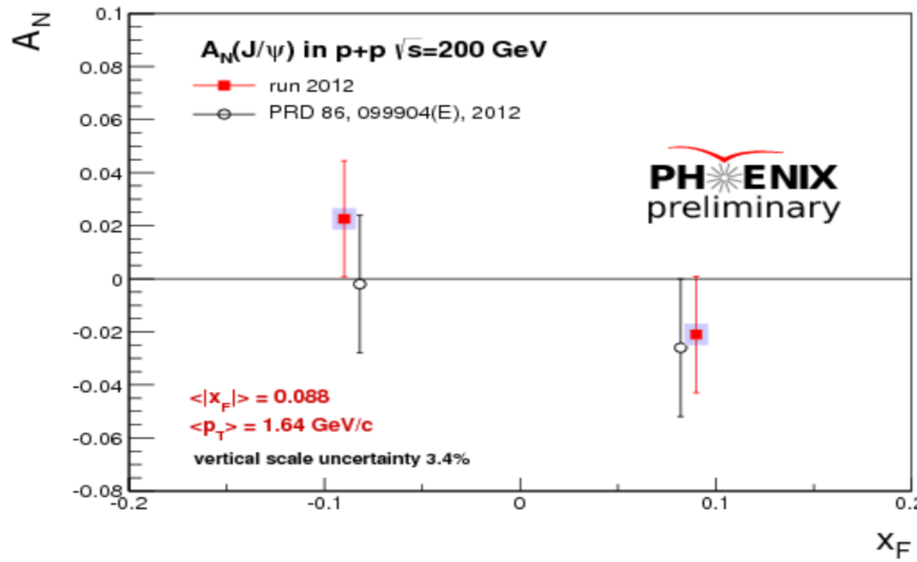
(4) A_N for inclusive J/ψ production: p+p and p+A

A_N versus pT, 2006+2008 and 2012 data





A_N vs xF, 2006+2008, 2012



Results from 2006 to 2012:

- AN compatible with zero for p+p
- Confirmed with more statistics (next slide)

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Phys. Rev. D 82, 112008 (2010)