Nuclear Dependence of Transverse Single-Spin Asymmetries in Polarized $p + A$ Collisions at RHIC

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[for the PHENIX Collaboration]

SPIN 2018, Ferrara, 10-15 September 2018

Overview

- Transverse Single Spin Asymmetries (TSSAs) in $\vec{p} + p$ Interactions
  - Overview of current understanding

- TSSAs in the nuclear environment $(\vec{p} + A)$ seen in PHENIX
  - π^0 production at <u>central</u> rapidity $(|\eta| < 0.35)$
  - J/ψ production at <u>forward and backward</u> rapidity $(1.2 < |y| < 2.2)$
  - π^+/K^+ production at <u>forward</u> rapidity $(1.4 < \eta < 2.4)$
  - n production at <u>very forward</u> rapidity $(x_F > 0.5\ ;\ 0.3 < \theta < 2.2\ \mathrm{mrad})$

Transverse Single Spin Asymmetries in $\vec{p} + p$ Interactions

- The topic of MANY talks at this conference!!!
- Multi-decades study of this phenomenon led to an understanding of the importance of various spin-momentum correlations
  - Initial state correlations: e.g. Sivers effect correlates the transverse spin of the nucleon with the intrinsic transverse momentum of the resident quark
  - Final state correlations: e.g. Collins effect correlates the transverse spin of the fragmenting quark with the transverse momentum of the produced hadron
- Direct measurements of these functions made in SIDIS and e^+e^- can be applied back to $\vec{p} + p$ interactions to reproduce data with some success
- Fragmentation (Collins) seems to be the main culprit for large asymmetries in $\vec{p} + p \to \pi + X$, at least in the $x_F < 0.3$ region; for $x_F > 0.3$ other mechanisms must be invoked as well
- See Daniel Pitonyak's excellent review (arXiv:1608.05353)
- What happens when these interactions occur in a nuclear environment?

Transverse Single Spin Asymmetries in $\vec{p} + A$ Interactions

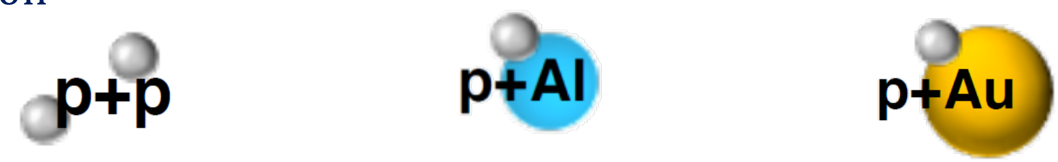
What does the nuclear environment bring?

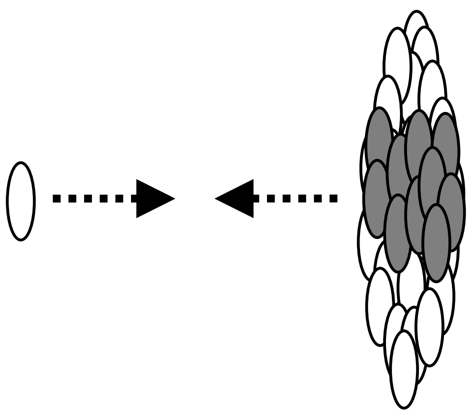
- The nucleon PDFs may change (EMC effect, nuclear shadowing)
  → modification of initial state
- Gluon saturation and/or Color Glass Condensate effects
- Multiple rescatterings
  - Broadening of TMDs → dilute the asymmetry?
  - modification of x_F → enhance the asymmetry?
- Ultra-peripheral collisions
  → strong electromagnetic fields
  → Primakoff effect

Centrality in *p*+A collisions

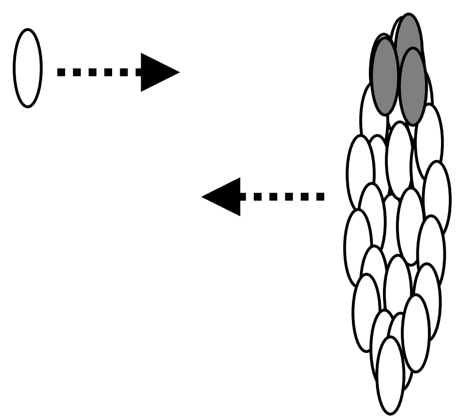
The impact parameter of a *p*+A collision determines the average number of binary *p*+*p* and *p*+*n* collisions that will occur as the proton passes through the nucleus: N_{coll}^{Avg}

The impact parameter cannot be measured directly; instead we observe the charged particle multiplicity at extreme rapidity in a set of "Beam-Beam Counters" and use this to establish a "centrality classification" from 0% to 100%. A model calculation then determines N_{coll}^{Avg}.

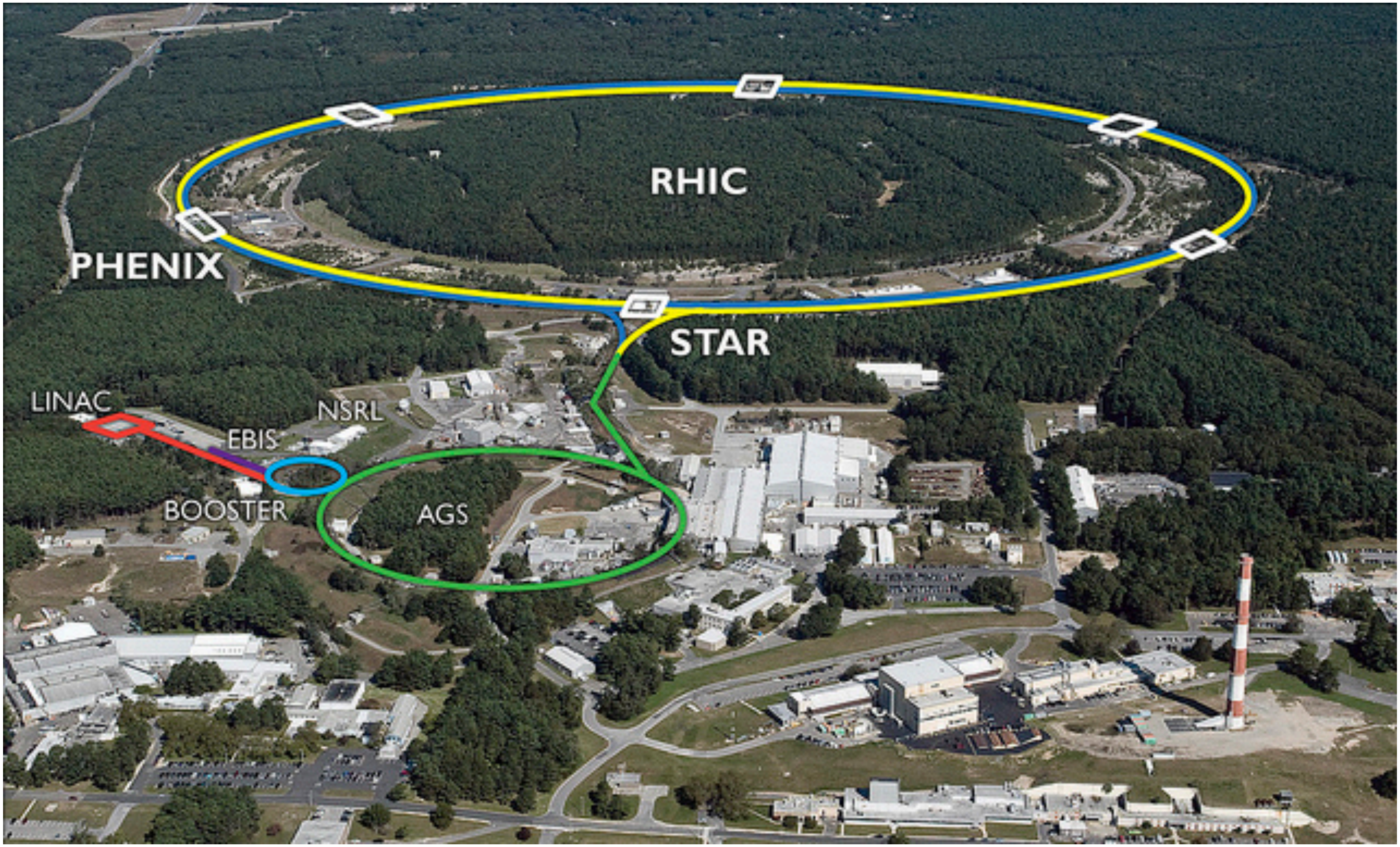




central collision



peripheral collision


RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

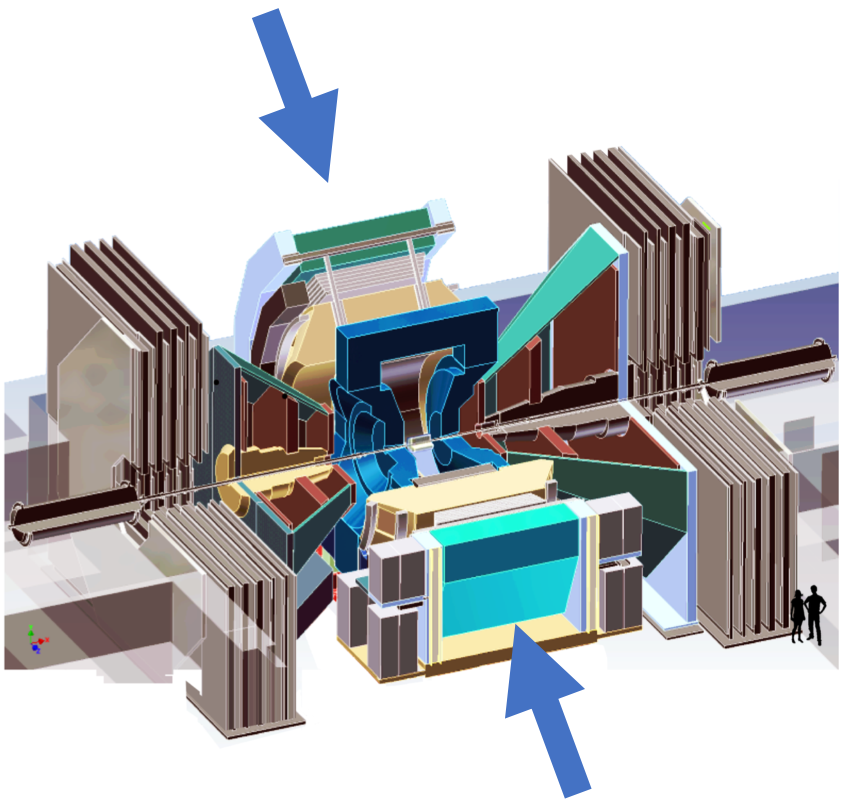
A_N for π^0 production at central rapidity

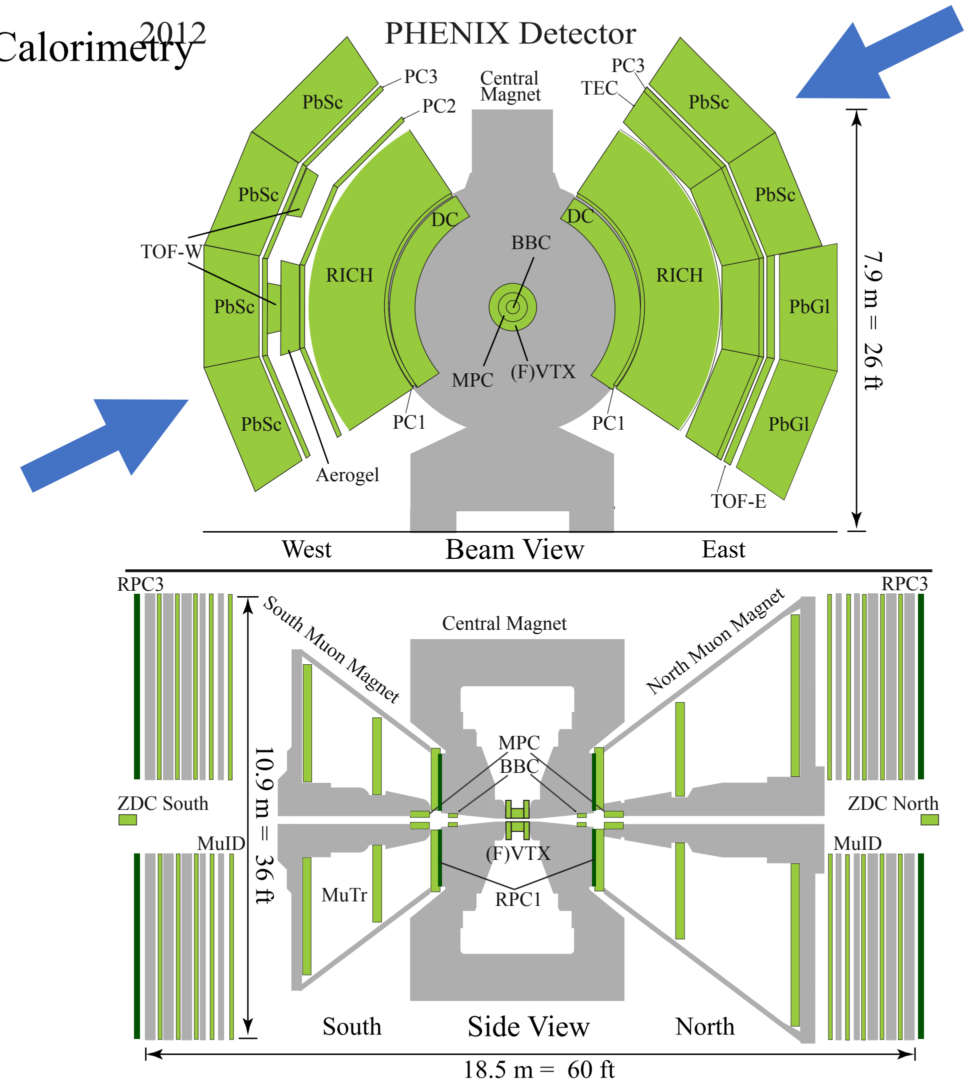
Central Arms $|y| < 0.35$

Vertex Detector – Magnetic Field – Tracking – Particle ID – Calorimetry

Electrons, positrons, photons, charged pions and kaons, $\boxed{\pi^0}$

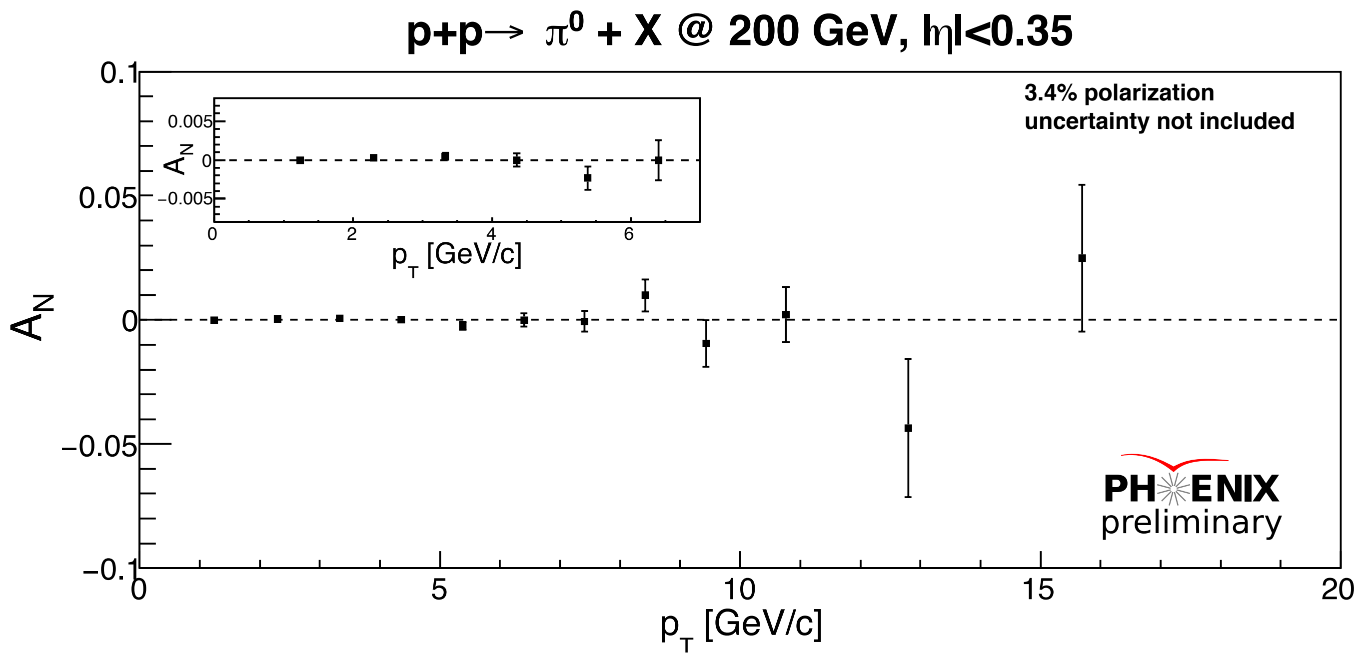
$$\vec{p} + A \rightarrow \pi^0 + X$$





A_N for π^0 production at central rapidity ($|\eta| < 0.35$)

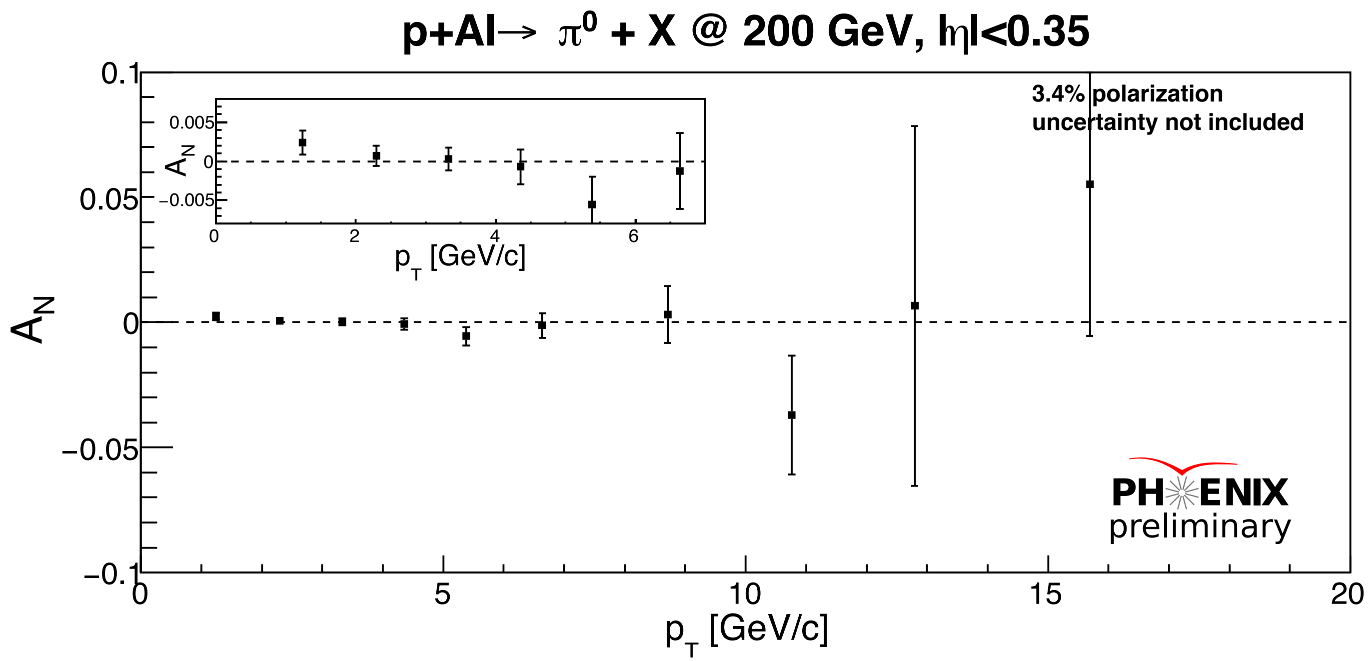
[manuscript in progress]



The transverse single spin asymmetry is consistent with zero over the range $1 < p_T < 16$ GeV in ***p+p***.

A_N for π^0 production at central rapidity ($|\eta| < 0.35$)

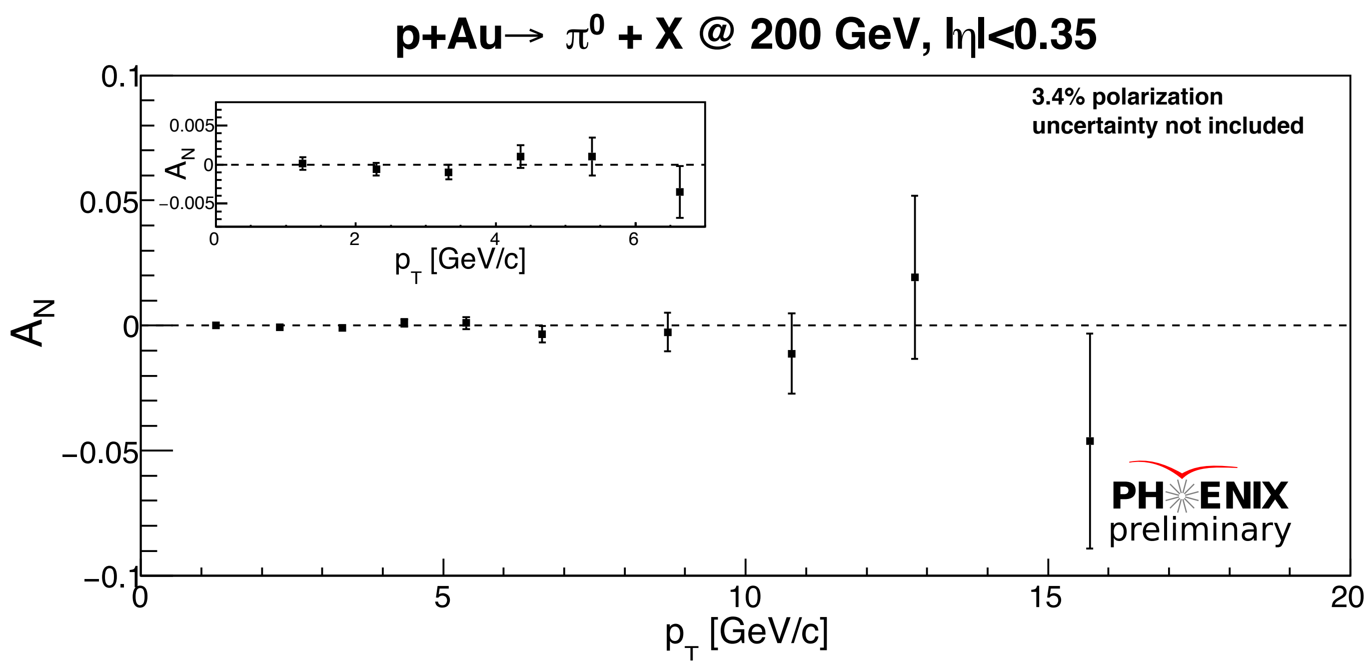
[manuscript in progress]



The transverse single spin asymmetry is consistent with zero over the range $1 < p_T < 16$ GeV in ***p*+Al**.

A_N for π^0 production at central rapidity ($|\eta| < 0.35$)

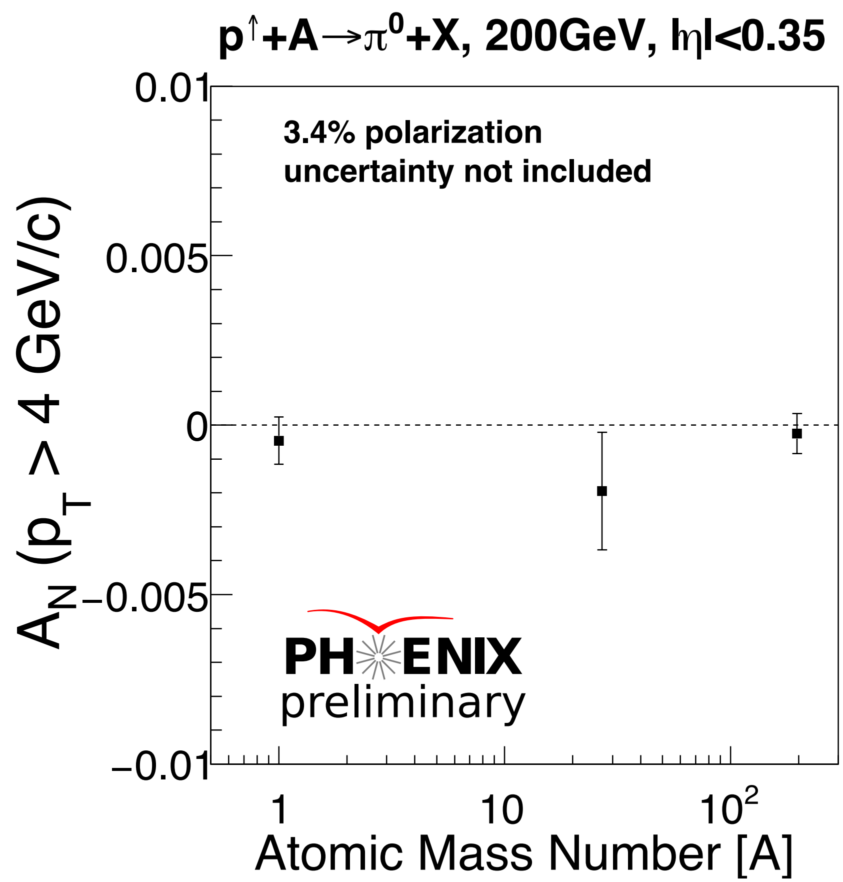
[manuscript in progress]



The transverse single spin asymmetry is consistent with zero over the range $1 < p_T < 16$ GeV in ***p*+Au**.

A_N for π^0 production at central rapidity ($|\eta| < 0.35$)

[manuscript in progress]



We do not observe a nuclear dependence in the transverse single spin asymmetry over the range $1 < p_T < 16$ GeV at central rapidity.

STAR also does not observe a nuclear dependence in this asymmetry for forward rapidity. (more on that later)

A_N for π^+/K^+ and J/ψ production at forward and backward rapidity

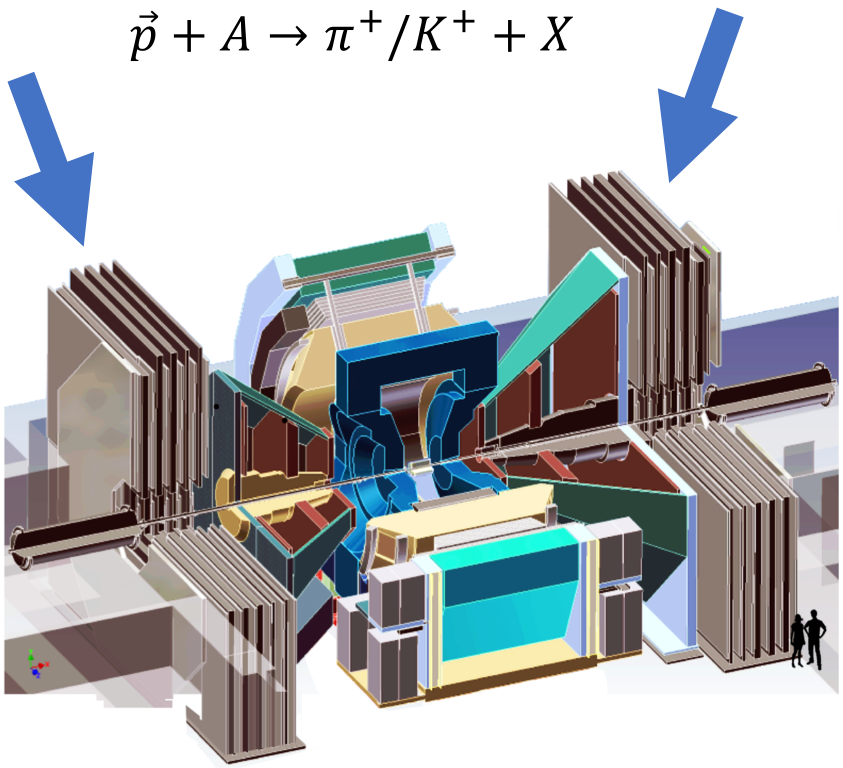
Muon Arms $1.4 < |\eta| < 2.4$

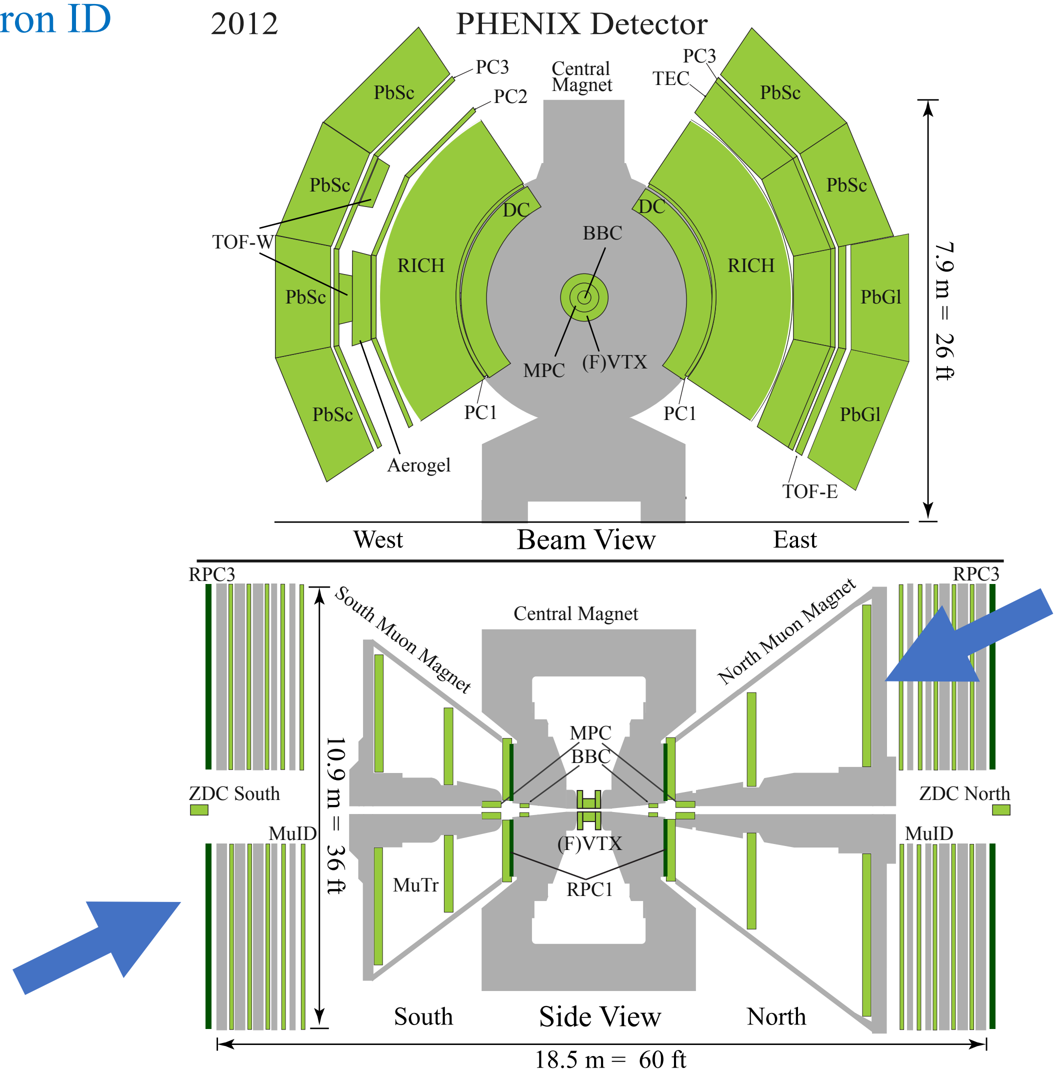
Vertex Detector – Magnetic Field – Tracking – muon/hadron ID

Muons, $\boxed{\text{hadrons } (\pi, K)}$, $\boxed{J/\psi}$, Υ

$$\vec{p} + A \to J/\psi + X$$

$$\vec{p} + A \to \pi^+/K^+ + X$$



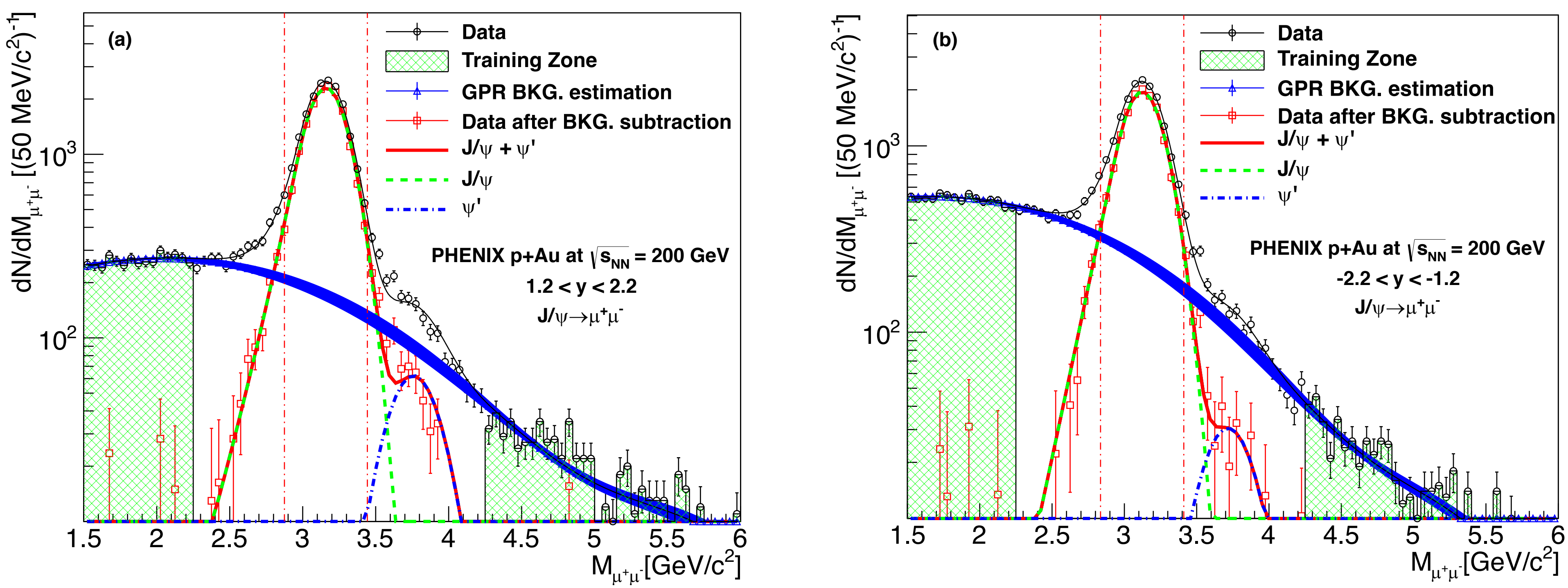


A_N for J/ψ production at forward and backward rapidity

Use GPR for background shape, with training zones above and below the J/ψ and ψ' peaks.

J/ψ and ψ' peaks are fit separately.

p+Au forward (*p*-going direction) backward (Au-going direction)



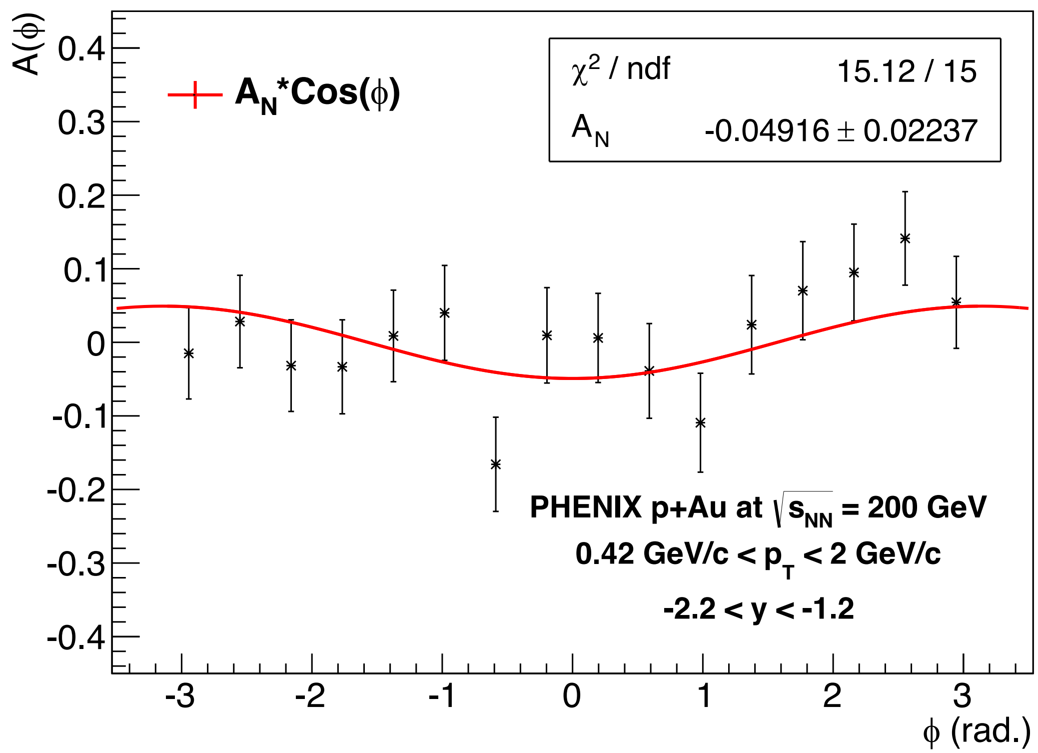
[PRD 98 (2018) 012006]

A_N for J/ψ production at forward and backward rapidity

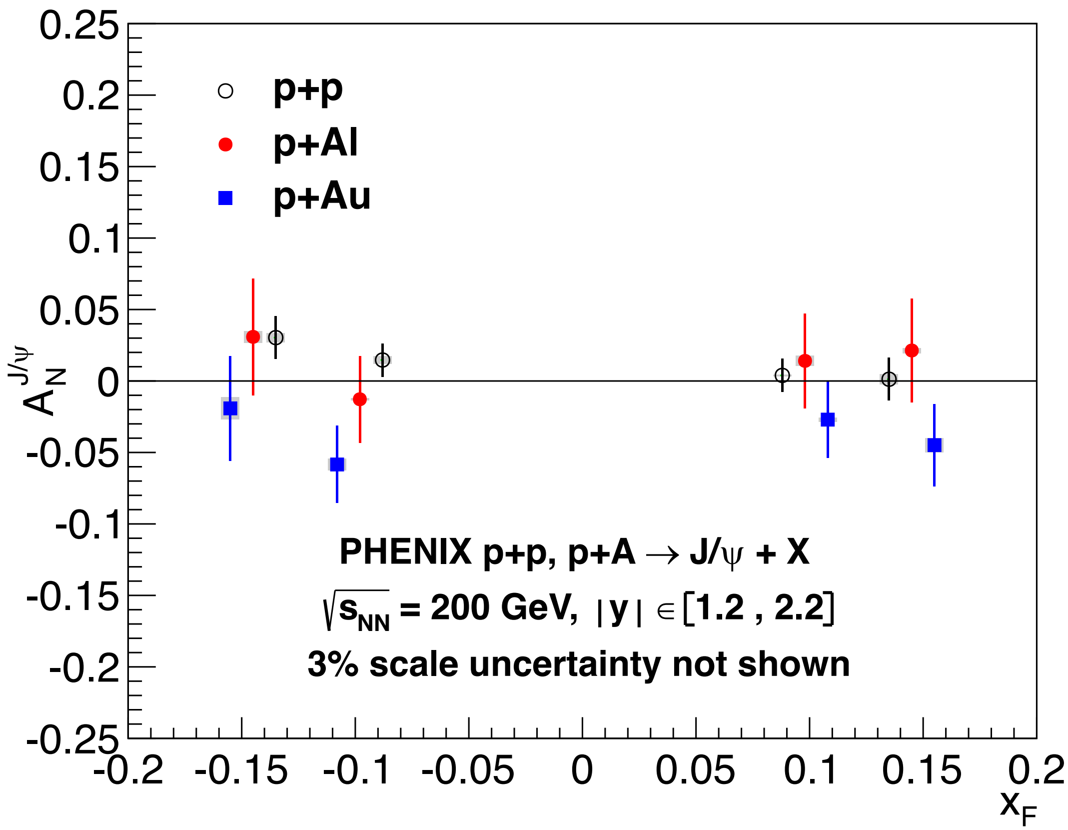
[PRD 98 (2018) 012006]

Azimuthal modulation fit for backward (Au-going) data in *p*+Au collisions.

A 2.2σ signal is observed.



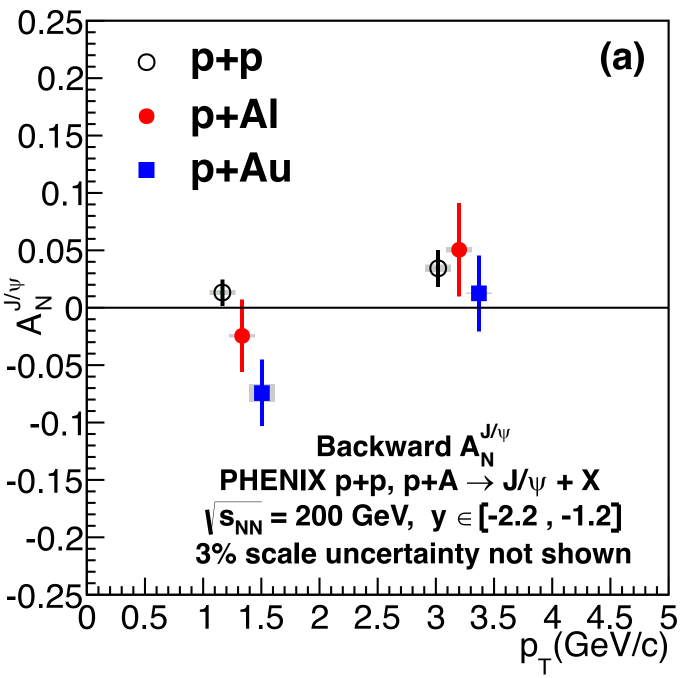
A_N for J/ψ production at forward and backward rapidity

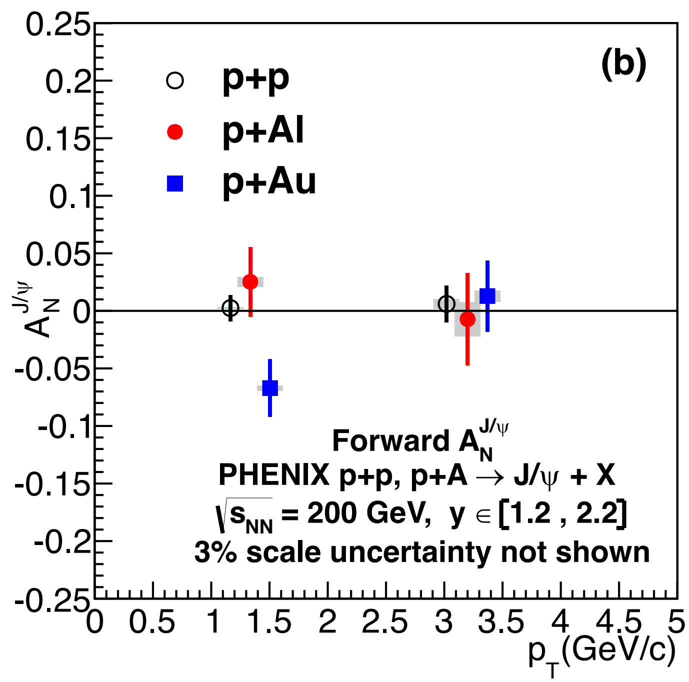


[PRD 98 (2018) 012006]

Results as a function of x_F. We observe a negative asymmetry in p+Au collisions in both forward and backward production; the largest signal is seen for $-0.11 < x_F < -0.05$.

A_N for J/ψ production at forward and backward rapidity





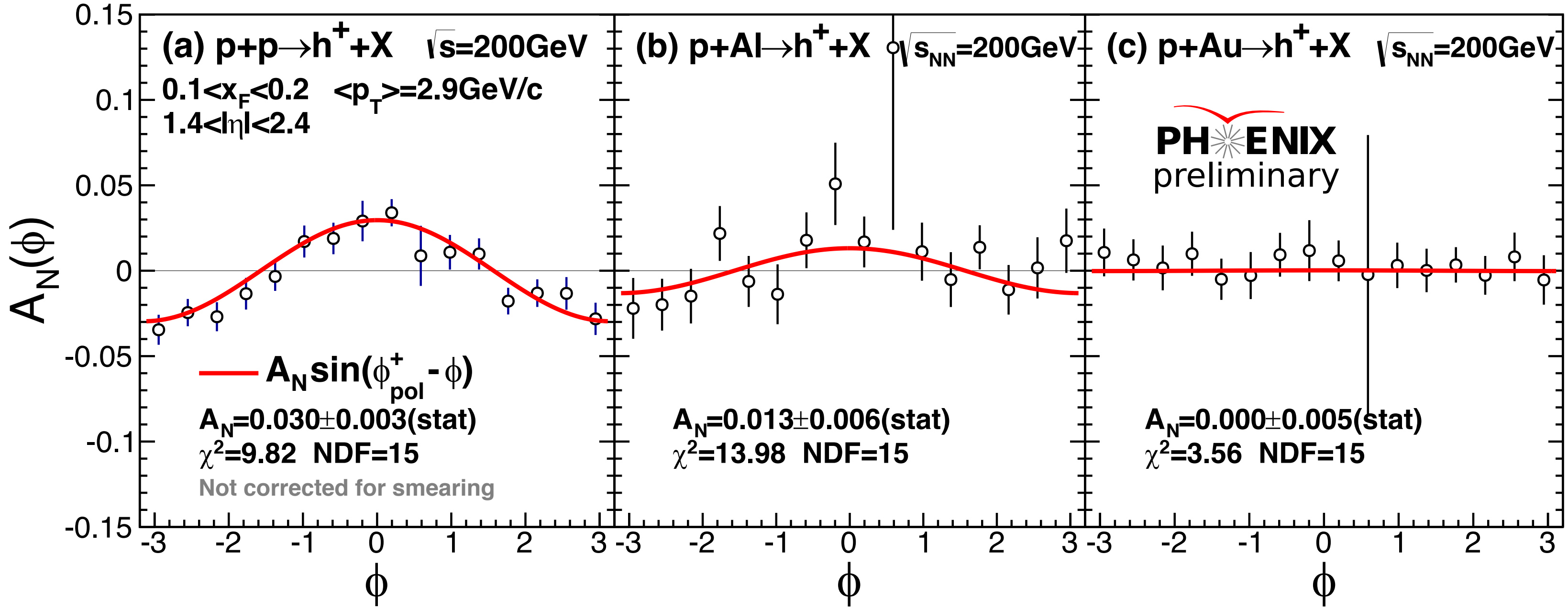
[PRD 98 (2018) 012006]

Results as a function of p_T. We observe a negative asymmetry in p+Au collisions in both forward and backward production for $0.42 < p_T < 2$ GeV.

The nuclear environment has created or enhanced the asymmetry. This could be a new avenue for insight into the J/ψ production mechanism in nuclei, critical for an understanding of J/ψ production modification in A+A collisions.

A_N for π^+/K^+ production at forward rapidity ($1.4 < \eta < 2.4$)

[manuscript in progress]



We reproduce the forward azimuthal asymmetry previously seen in $\vec{p} + p \rightarrow \pi^+/K^+ + X$ (e.g. by BRAHMS [PRL 101 (2008) 042001]).

The amplitude of the azimuthal asymmetry strongly diminishes with increasing mass number.

A_N for π^+/K^+ production at forward rapidity $(1.4 < \eta < 2.4)$

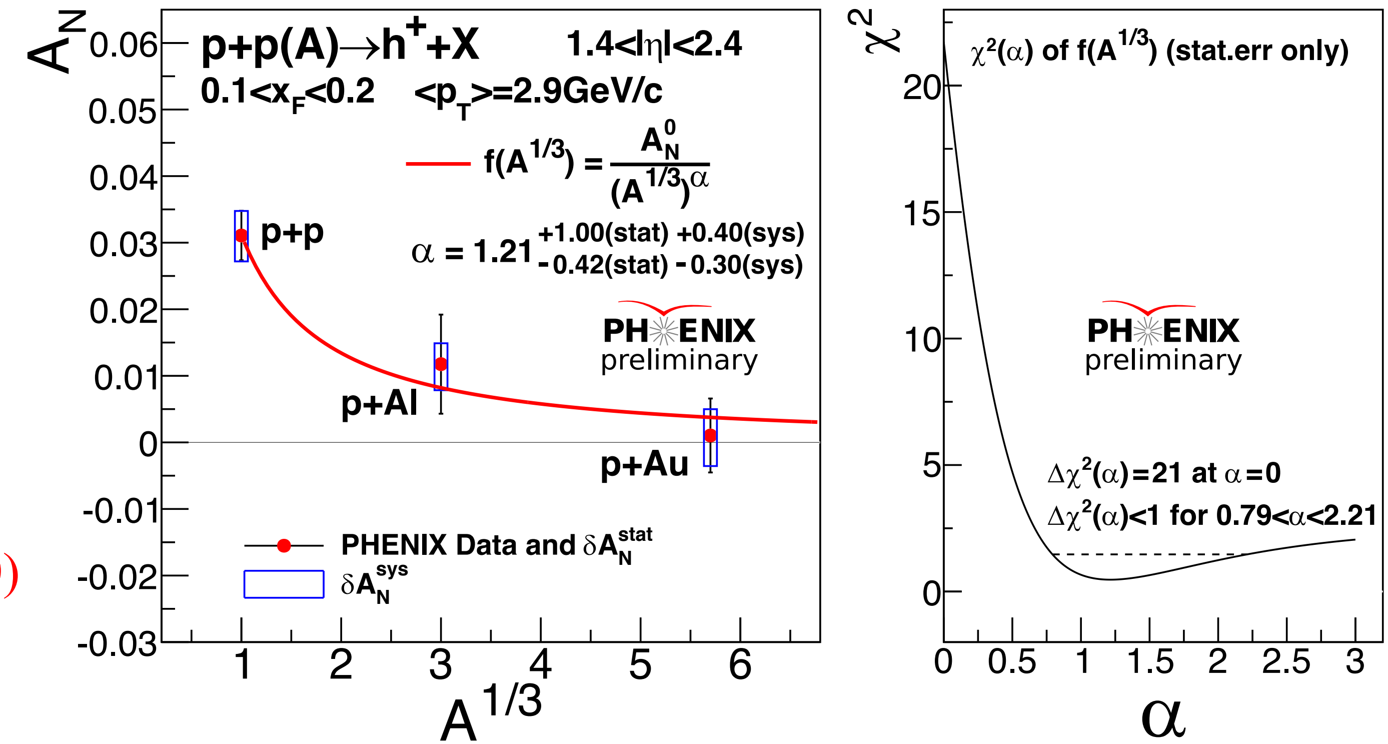
[manuscript in progress]

Mass Number Dependence:

We consider a mass number dependence of the form $\frac{1}{A^{\alpha/3}}$.

Best fit: $\alpha = 1.21^{+1.08}_{-0.52}$

"No mass dependence" ($\alpha = 0$) is ruled out.



The $A^{1/3}$ suppression was anticipated by Hatta et al. [PRD95 (2017) 014008]; gluon saturation in the nucleus suppresses the final-state Collins asymmetry.

Curiously, STAR does not observe a mass number dependence in the $\vec{p} + A \rightarrow \pi^0 + X$ channel.
[slide from Heppelmann, ICTP Workshop, 2015]

STAR RHIC Run 15: (2015)
$\sqrt{s}$=200 GeV

$$p^{\uparrow} p \rightarrow \pi^0 X$$

$$p^{\uparrow} Au \rightarrow \pi^0 X$$

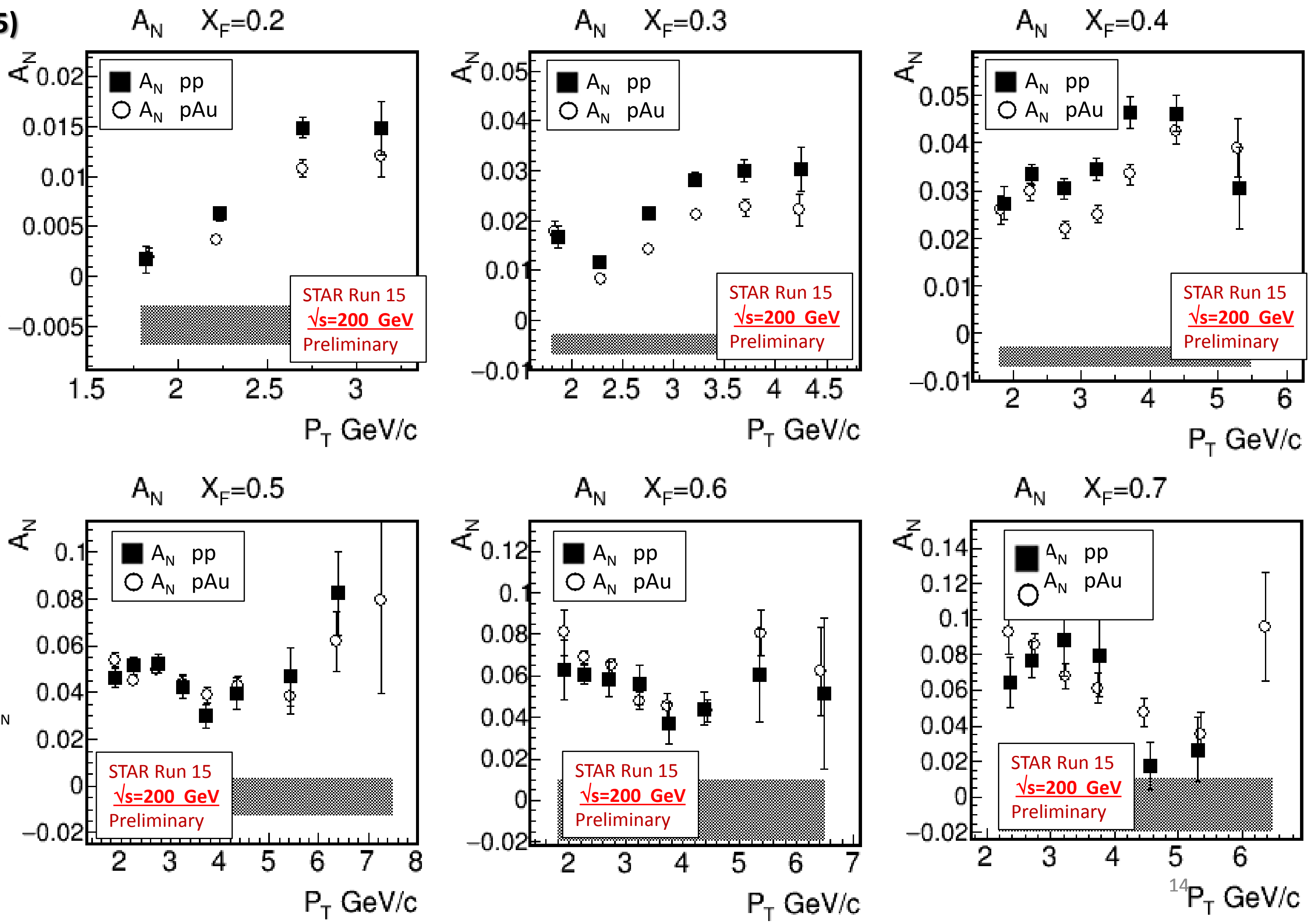
TSSA A_N

Inclusive π^0 event selection described above

Error bars represent statistical errors only.

Luminosity pAu=204.6 nb^{-1}
Luminosity pp=34.8 pb^{-1}
Average Polarization:
pp 55.6±. 2 %
pAu 60.4 ± 2%

Shaded bands represent systematic uncertainty, dominated by dependence of A_N on observed East BBC energy (gold or proton breakup charge multiplicity)



A_N for π^+/K^+ production at forward rapidity $(1.4 < \eta < 2.4)$

[manuscript in progress]

Centrality classes are determined using the multiplicity in the very forward Beam-Beam Counters.

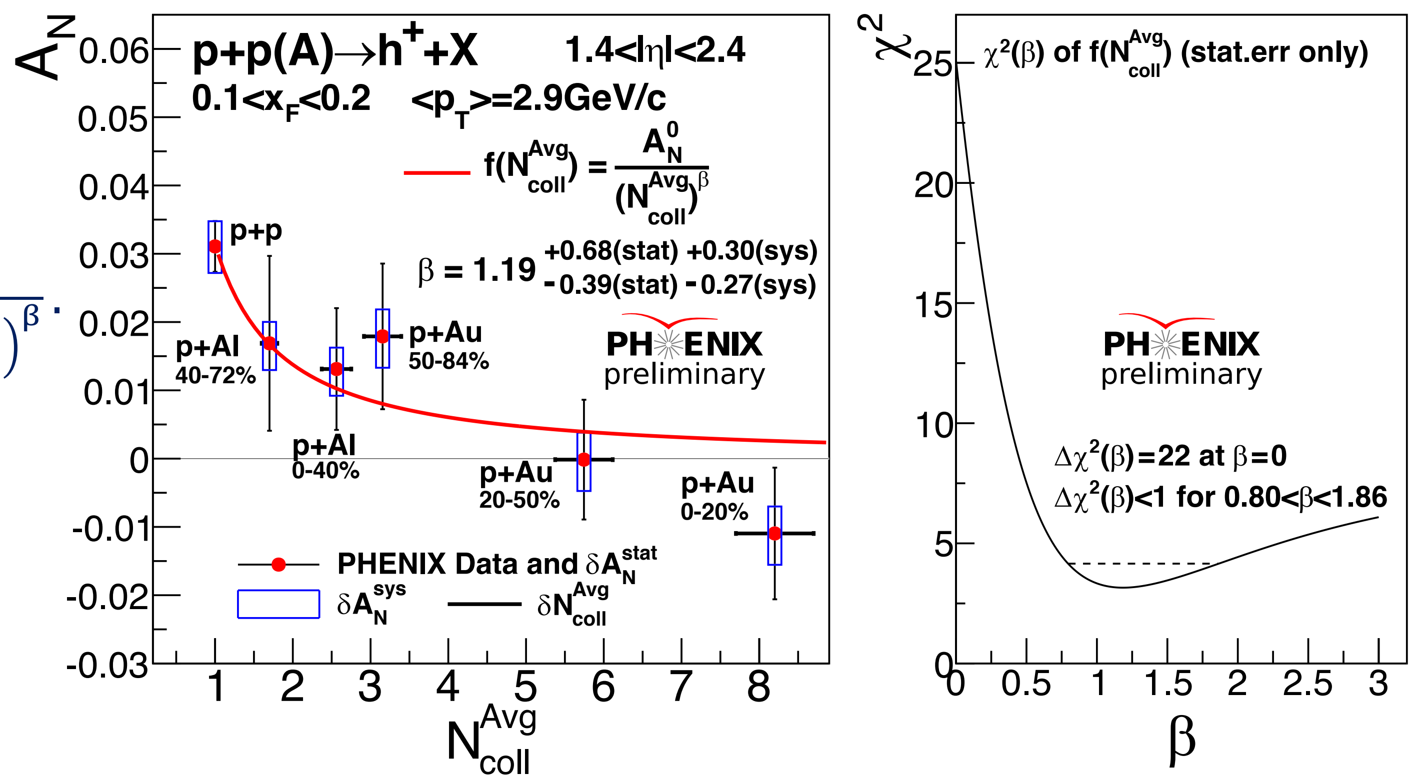
$\Rightarrow$ N_{coll}^{Avg} = average number of binary collisions

Centrality Dependence:

We consider a centrality dependence of the form $\frac{1}{\left(N_{coll}^{Avg}\right)^{\beta}}$.

Best fit: $\beta = 1.19^{+0.74}_{-0.47}$

"No centrality dependence" ($\beta = 0$) is ruled out.

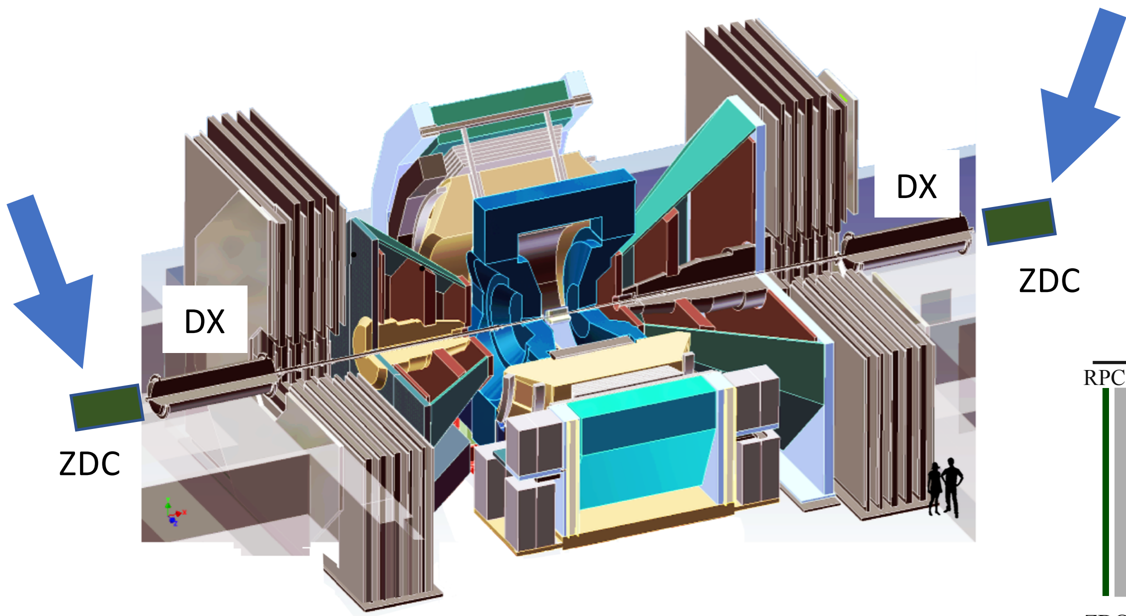


A_N for n production at very forward rapidity ($x_F > 0.5$; $0.3 < \theta < 2.2$ mrad)

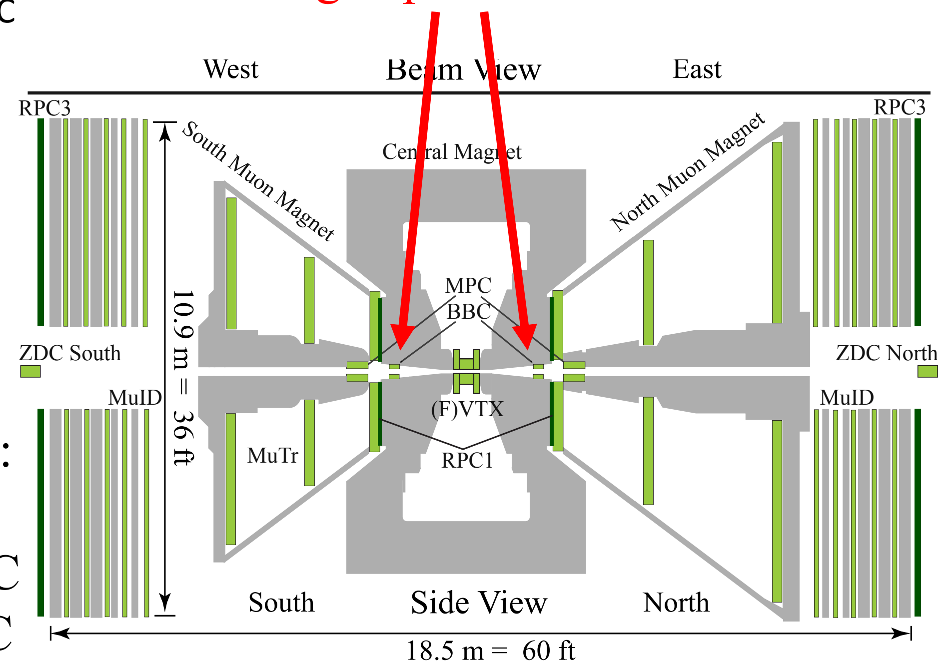
Zero Degree Calorimeters (with Shower Maximum Detectors)

neutrons

$$\vec{p} + A \rightarrow n + X$$



BBC Calorimeters (centrality)
charged particles from collision



Three triggers used to study centrality dependence:

1. ZDC Inclusive: ZDC energy > 15 GeV
2. ZDC⊗BBC-tag: ZDC and ≥1 hit in each BBC
3. ZDC⊗BBC-veto: ZDC and no hit in any BBC

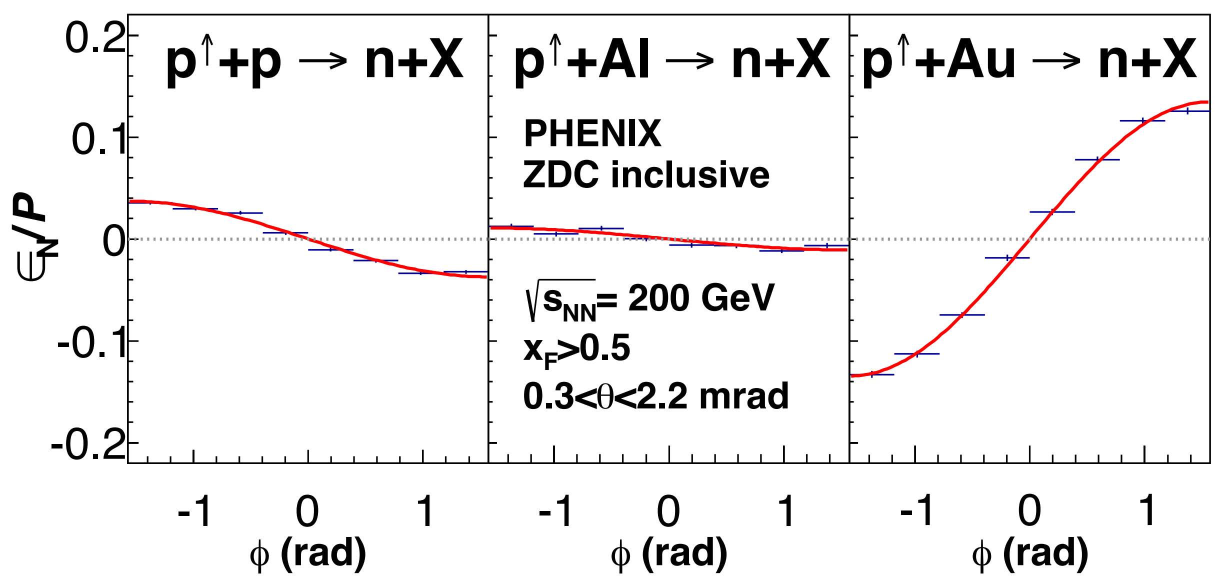
A_N for n production at very forward rapidity ($x_F > 0.5$; $0.3 < \theta < 2.2$ mrad)

$$\epsilon_N(\phi) = PA_N^{\text{fit}} \sin(\phi - \phi_0)$$

ϕ = azimuthal angle of neutron detected in ZDC
ϕ_0 = transverse polarization direction
P = beam polarization magnitude
A_N^{fit} = fitted amplitude of the raw azimuthal asymmetry

"Forward" is defined as the proton-going direction.

Using only the ZDC inclusive trigger, these plots illustrate the rapid change in the observed asymmetry as a function of mass number (p, Al, Au).



[PRL 120 (2018) 022001]

A_N for n production at very forward rapidity ($x_F > 0.5$; $0.3 < \theta < 2.2$ mrad)

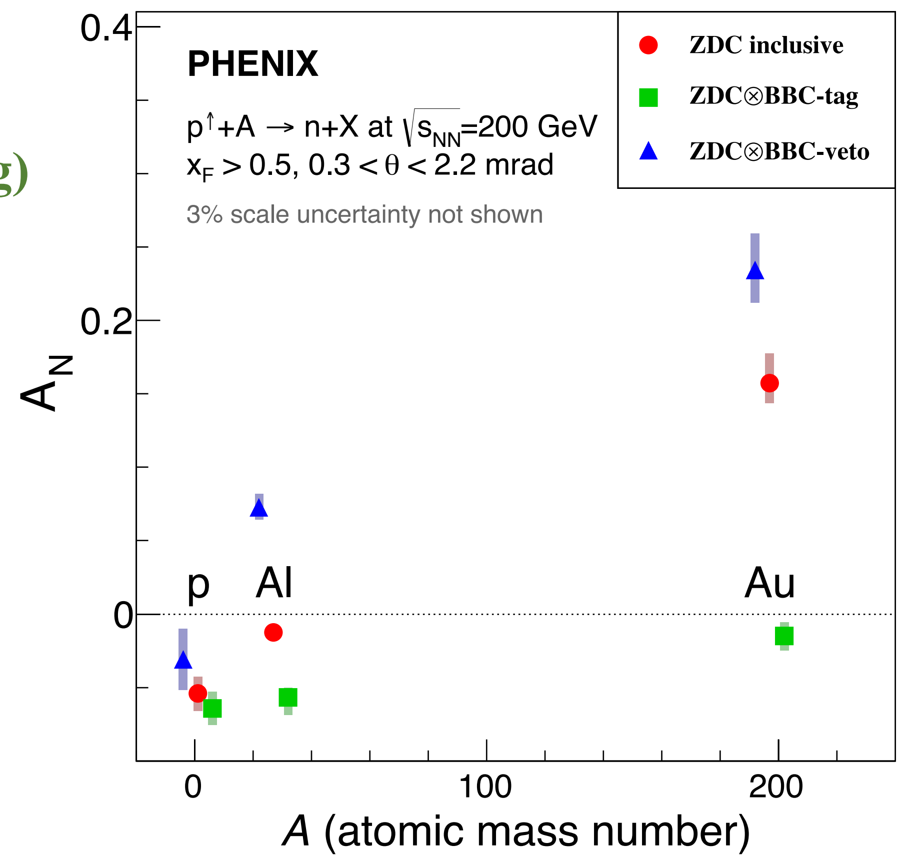
Centrality dependence:
(1) ZDC Inclusive: ZDC energy > 15 GeV
(2) ZDC⊗BBC-tag: ZDC and ≥1 hit in each BBC
(3) ZDC⊗BBC-veto: ZDC and no hit in any BBC

Collisions with small impact parameter (BBC-tag) show a negative asymmetry with a moderate nuclear dependence.

Collisions with a large impact parameter (BBC-veto) show a strong nuclear dependence, indicating the importance of ultra-peripheral collisions.

Mitsuka [PRC 95 (2017) 044908] has shown that in a UPC the photon flux from the unpolarized nucleus can interact with the polarized proton to produce such asymmetries.

[PRL 120 (2018) 022001]



Nuclear Dependence of TSSAs: Summary

- π^0 production at central rapidity
  - A_N very small, independent of nuclear size
- J/ψ production at forward and backward rapidity
  - A_N very small in p+p, becoming negative at low p_T in p+Au
- π^+/K^+ production at forward rapidity
  - A_N very large in p+p, strongly suppressed with increasing nuclear size and centrality → gluon saturation effect
- n production at very forward rapidity
  - Largest effect seen in UPCs; model calculation in agreement

A rich variety of behavior is revealed in this cross between spin-dependent scattering phenomena and the physics of cold nuclear matter.