



# Nuclear Dependence of Transverse, Single-Spin Asymmetries in Charged-Hadron Production in PHENIX

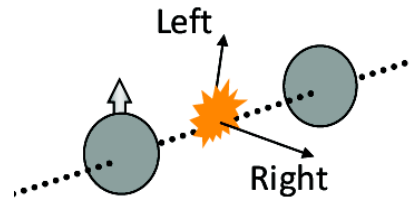
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# Transverse Single-Spin Asymmetries

Represent a puzzle since first observed in 1975

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

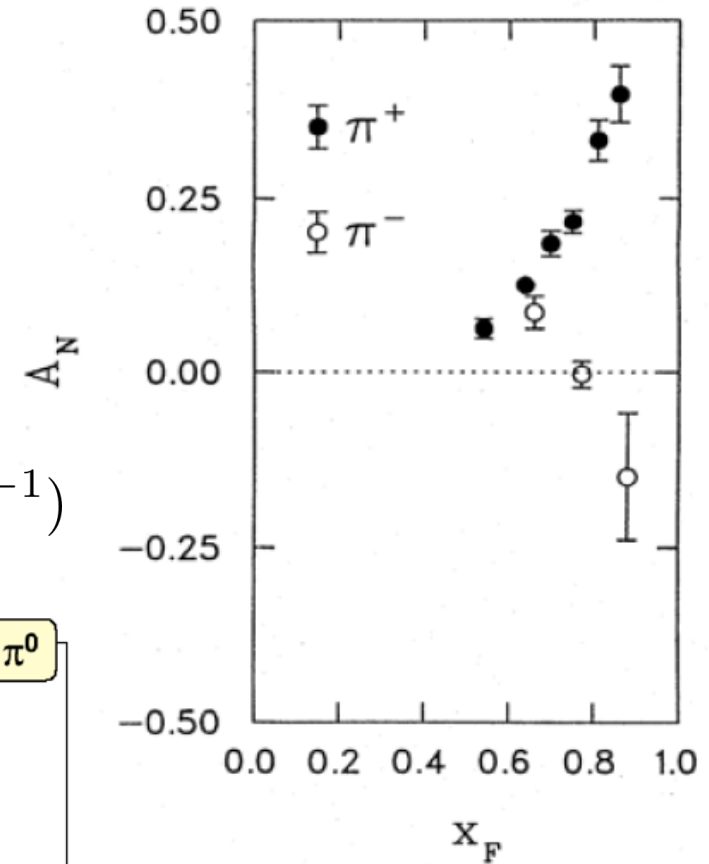
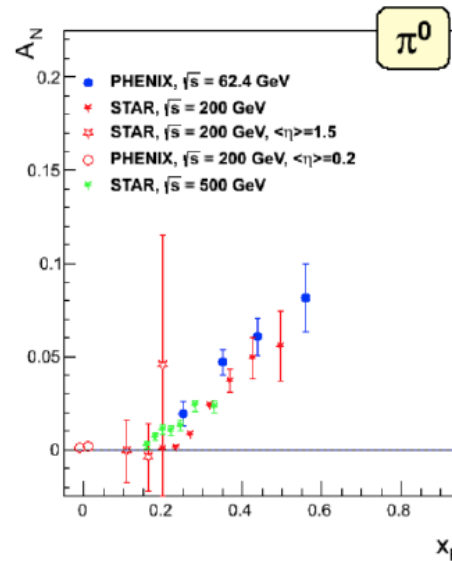
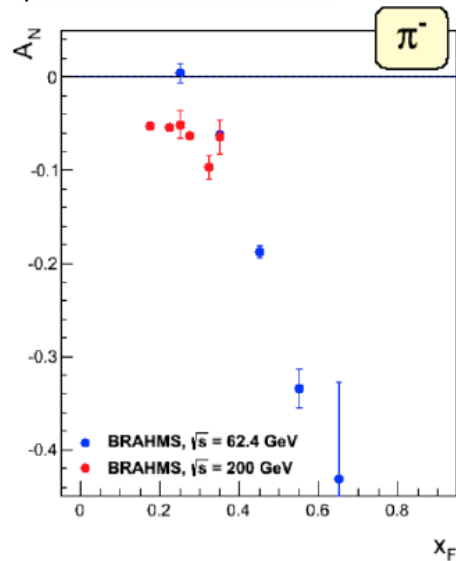
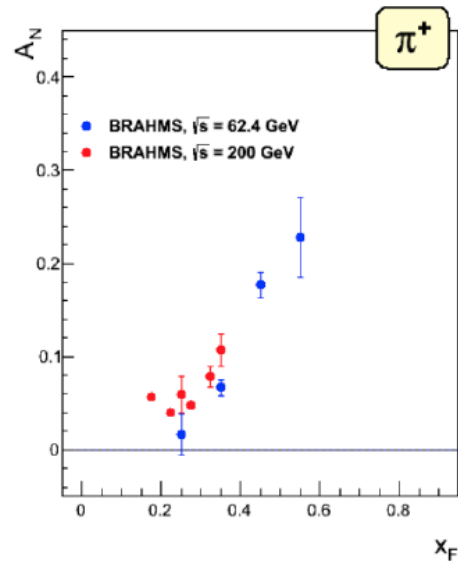


Expected to be  $\mathcal{O}(10^{-4})$  in perturbative QCD

Suppressed as  $\frac{\alpha_s m_q}{\sqrt{s}}$  in leading twist

Instead they persist at RHIC energies at  $\mathcal{O}(10^{-1})$

Up to  $\sqrt{s} = 500$  GeV



Higher-twist terms expected to play important role

# Two Possible Mechanisms

In the transverse momentum factorization approach the asymmetry is generated by the Sivers effect and the Collins effect coupled to the transversity distribution

Sivers effect: Correlations between nucleon transverse spin and parton transverse momentum in the polarized nucleon

Initial-state effect

Collins effect: Fragmentation of transversely polarized parton into final-state hadron

Final-state effect

In the twist-3 collinear factorization approach a complete description includes twist-3 functions from

The polarized proton

The unpolarized proton

The parton fragmentation

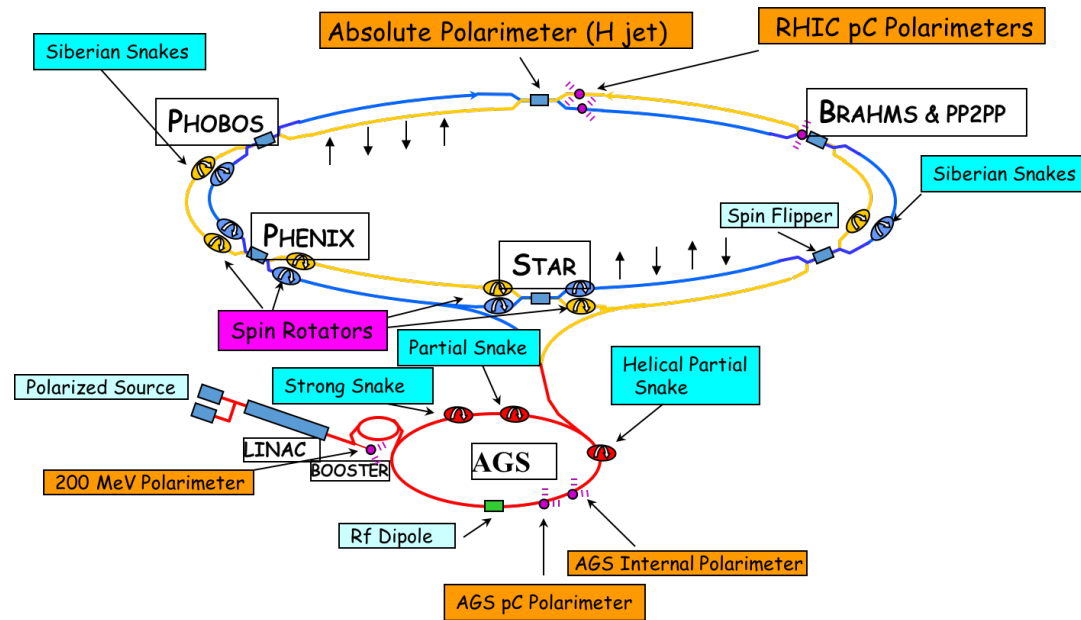
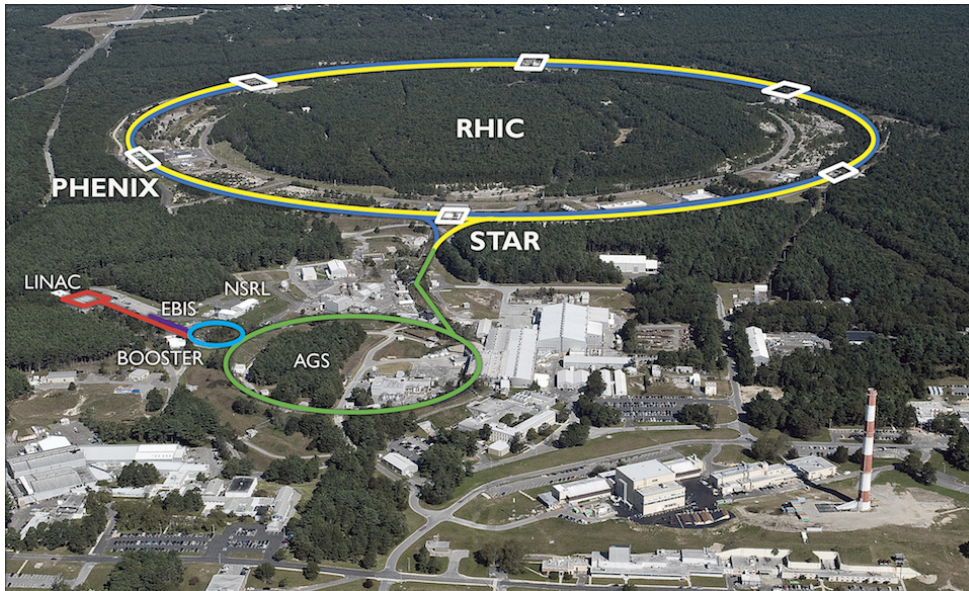
# PHENIX at RHIC

Data taken during the 2015 RHIC run with the PHENIX detector

$p^\uparrow + p$ ,  $p^\uparrow + \text{Al}$ , and  $p^\uparrow + \text{Au}$  at  $\sqrt{s_{NN}} = 200 \text{ GeV}$

Vertical proton polarizations in the range  $57\text{-}61\% \pm 3\%$

Beam bunches every 106 ns, alternating spin patterns





# The PHENIX Detector

Two central multi-detector arms, two muon end-caps (North, South Arm)

Only the muon arms are used in this analysis

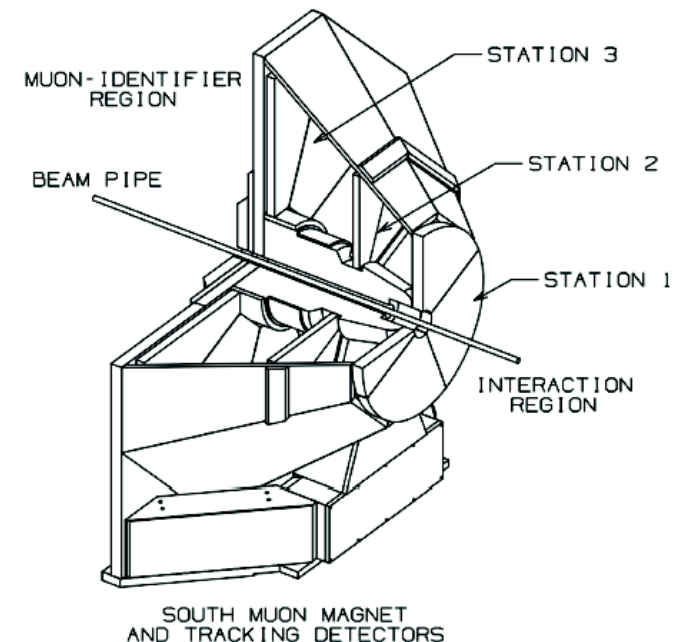
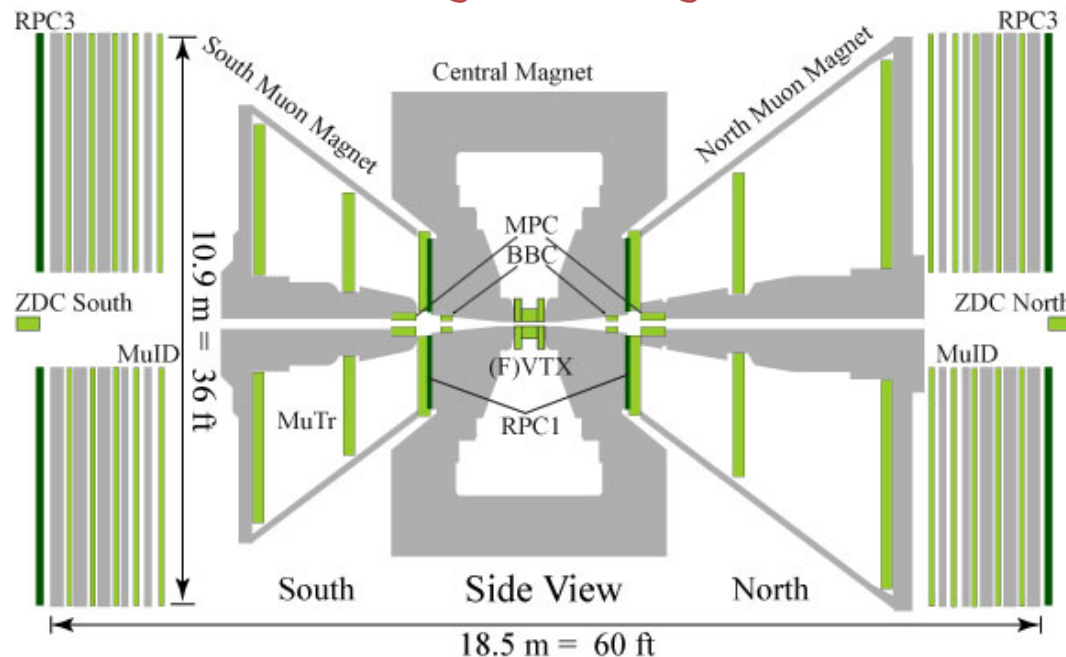
$7.5\lambda_I$  hadron absorber

3 cathode-strip chambers ( $\mu$  tracker) in radial field,  $\int B \cdot dl = 0.72 \text{ T} \cdot \text{m}$

5 planes of larocci tubes and steel absorbers,  $\sim 5\lambda_I$  total ( $\mu$ ID)

Acceptance  $1.2 < \eta < 2.4$  (pol. *p-going*),  $-2.2 < \eta < -1.2$  (*A-going*)

Full azimuthal-angle coverage



# Data Selection

Charged hadrons identified using the muon arms:

Tracks stopping in the third or fourth plane of  $\mu$ ID

Composition:  $\pi^+ / K^+ / p \approx 45\% / 47\% / 5\%$

$p$  fraction increases to 7% (9%) for  $p$ +Al ( $p$ +Au)

Estimated from measured ratios at mid-rapidity and simulations

PYTHIA or HIJING for mid-to-forward-rapidity conversion

GEANT4 for passage through absorber

The Beam-Beam Counters provide z-vertex and min-bias trigger

Also event centrality based on charge distribution in the  $A$ -going side

Coverage:  $3.1 < |\eta| < 3.9$ ; full azimuthal acceptance

Results for positively-charged tracks at forward rapidity presented here

$$1.4 < \eta < 2.4, \quad 0.1 < x_F < 0.2, \quad 1.8 < p_T < 7.0 \text{ GeV}/c$$

Smaller asymmetries expected for negative due to  $K/\pi$  cancellations

# Extraction of TSSA

$A_N$  extracted using an unbinned maximum-likelihood method

$$\log \mathcal{L} = \sum_i \log(1 + P \cdot A_N \sin(\phi_{\text{pol}} - \phi_i))$$

$\phi_i$  Track azimuthal angle relative to polarized-proton direction

$\phi_{\text{pol}}$  Azimuthal angle of beam polarization ( $\pm\pi$ )

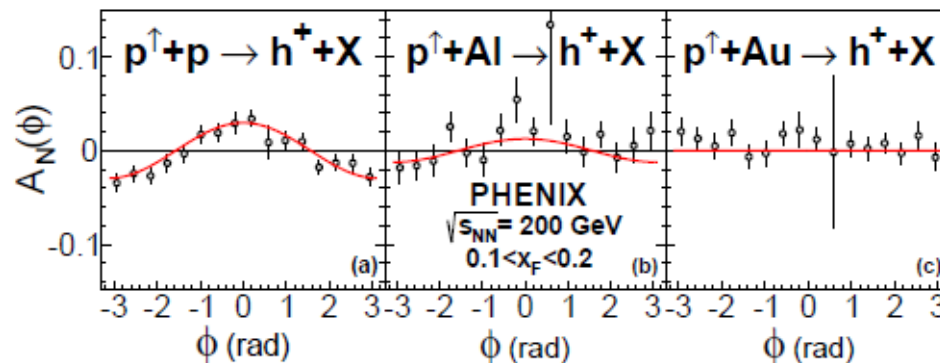
$P$  Beam polarization

$A_N$  Determined by maximizing likelihood

Statistical uncertainty calculated from the 2<sup>nd</sup> derivative

$$\sigma^2(A_N) = \left[ -\frac{\partial^2 \mathcal{L}}{(\partial A_N)^2} \right]^{-1}$$

A systematic uncertainty from comparison with sine-modulation results



# Systematic Uncertainties

Main sources: smearing and method

Smearing: From Monte Carlo truth-vs.-reconstructed-bin matrix

Method: From Comparison of likelihood and modulation results

Other sources are negligible

Total uncertainty: Sum in quadrature

	$p^\uparrow + p$	$p^\uparrow + \text{Al}$	$p^\uparrow + \text{Au}$
$A_N$	$3.11 \times 10^{-2}$	$1.18 \times 10^{-2}$	$0.10 \times 10^{-2}$
$\delta A_N^{\text{stat}}$	$0.37 \times 10^{-2}$	$0.74 \times 10^{-2}$	$0.56 \times 10^{-2}$
$\delta A_N^{\text{syst}}$	$^{+0.05}_{-0.18} \times 10^{-2}$	$^{+0.09}_{-0.08} \times 10^{-2}$	$^{+0.10}_{-0.10} \times 10^{-2}$
$\delta A_N^{\text{method}}$	$^{+0.05}_{-0.05} \times 10^{-2}$	$^{+0.08}_{-0.08} \times 10^{-2}$	$^{+0.10}_{-0.10} \times 10^{-2}$
$\delta A_N^{\text{smear}}$	$^{+0.00}_{-0.17} \times 10^{-2}$	$^{+0.03}_{-0.00} \times 10^{-2}$	$^{+0.01}_{-0.00} \times 10^{-2}$

Statistical errors dominate



# A-Dependence of Asymmetry

Clear A-dependence of  $A_N$  is seen

Decreasing from 3% for  $p+p$  to 1% for  $p+Al$  to consistent with 0 for  $p+Au$

Statistical shown uncertainties as error bars

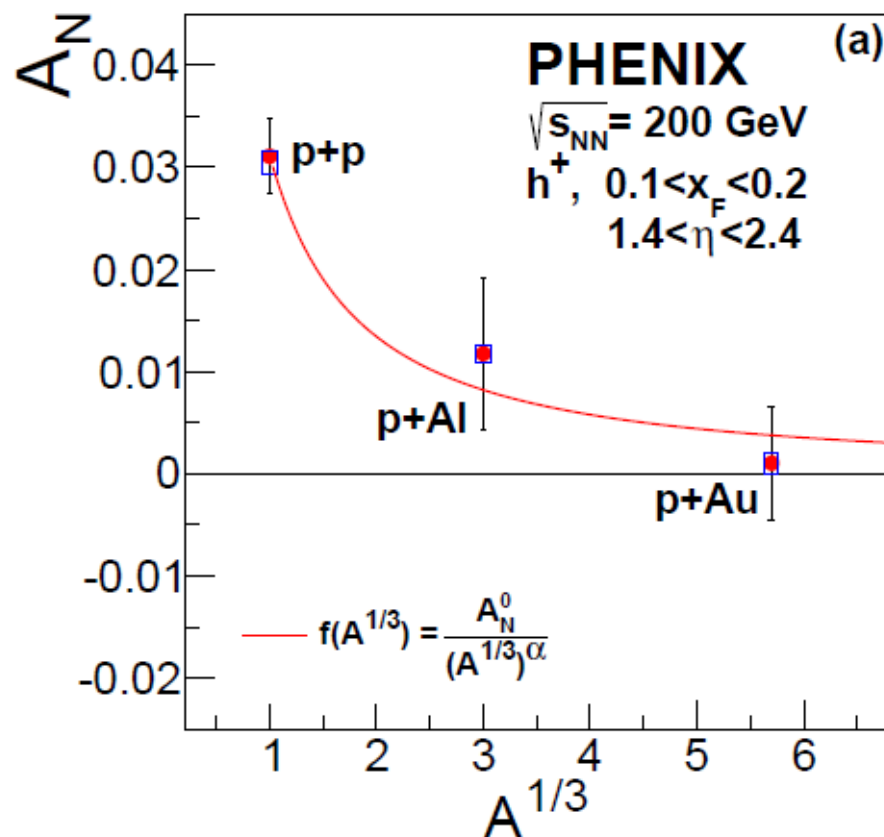
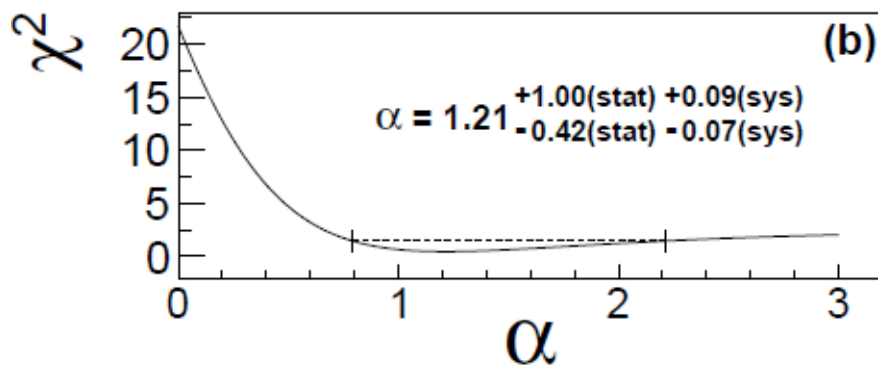
Systematic uncertainties as boxes

Fit function:  $f(A^{1/3}) = \frac{A_N^0}{(A^{1/3})^\alpha}$

Best value:  $\alpha = 1.21$

Result inconsistent with  $\alpha = 0$

Increase in  $\chi^2$  by about 20



# Dependence on Number of Collisions

Also looked at  $A_N$  as a function of average number of  $N$ - $N$  collisions

$N_{\text{coll}}^{\text{Avg}}$  is also related to the effective target thickness

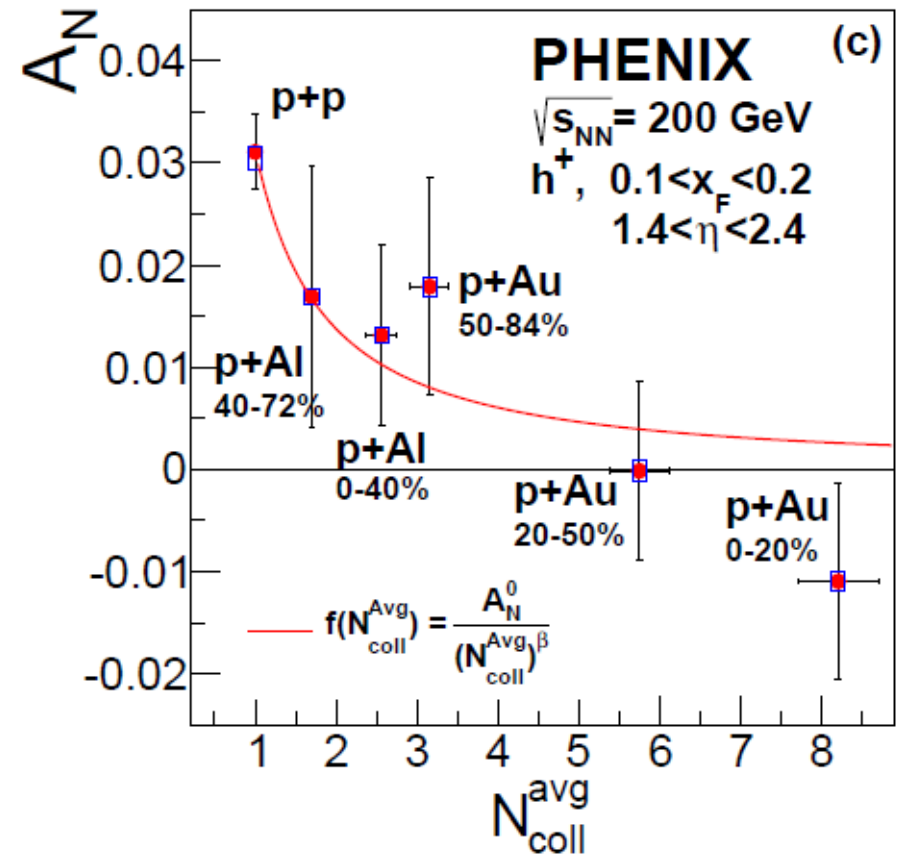
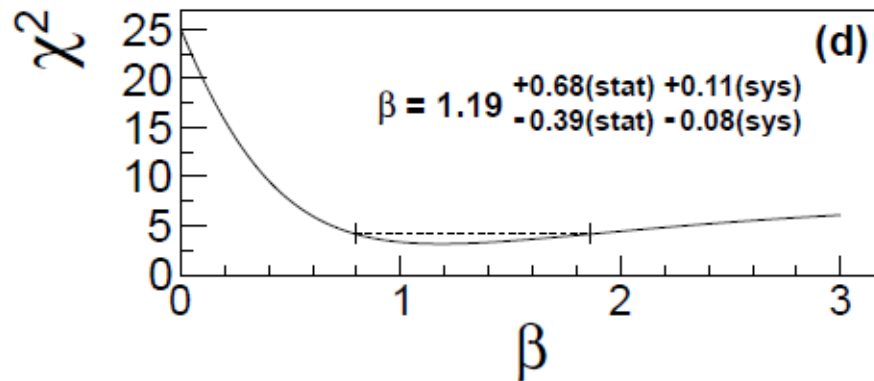
Calculated for each centrality class using the Glauber model

A decrease of  $A_N$  with the number of collisions is seen

Fit function: 
$$f(N_{\text{coll}}^{\text{Avg}}) = \frac{A_N^0}{(N_{\text{coll}}^{\text{Avg}})^\beta}$$

Best value:  $\beta = 1.19$

Again excluding  $\beta = 0$



# Discussion

First observation of nuclear dependence of transverse single-spin asymmetry

Observed in positive-hadron production at forward rapidities

Disfavors  $A$ -independent scenarios for explaining TSSA in hadron production at similar kinematics

Also observed dependence on number of collisions

Suggests that the suppression of  $A_N$  is related to the density of nuclear matter traversed by the proton

May be related to novel effects in  $p+A$  scattering, such as multiple parton scattering

Or interaction of the parton with hot QCD matter

Results should provide new insights into the origins of  $A_N$

May also provide new tools for studying small-system collisions