Transverse Spin in PHENIX

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for the PHENIX Collaboration
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RHIC & AGS Annual User's Meeting

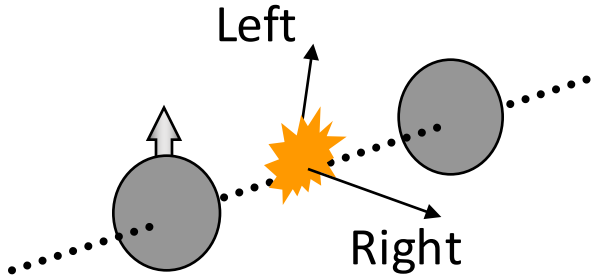
Outline

- Introduction
- PHENIX results
  - mid/forward rapidity π^0, η
  - heavy flavor (J/ψ, D$\rightarrow\mu$)
  - forward neutron
  - charged hadron

Transverse Single Spin Asymmetry A_N

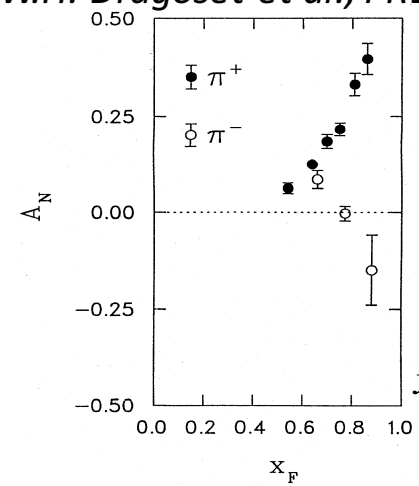
Transverse Single Spin Asymmetries A_N

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



Argonne ZGS, p_{beam} = 12 GeV/c

W.H. Dragoset et al., PRL36, 929 (1976)



$$x_F = \frac{2p_L}{\sqrt{s}}$$

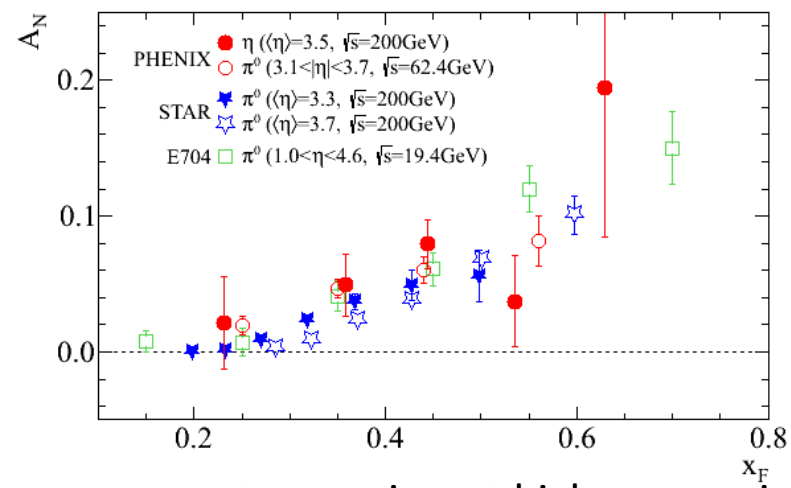
Theory Expectation:

Small asymmetries at high energies

(*Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978)*)

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N ~ O(10^{-4}) theory



Experiments:

ZGS, AGS, FERMILAB to RHIC

A_N ~ O(10^{-1}) observed at forward rapidity

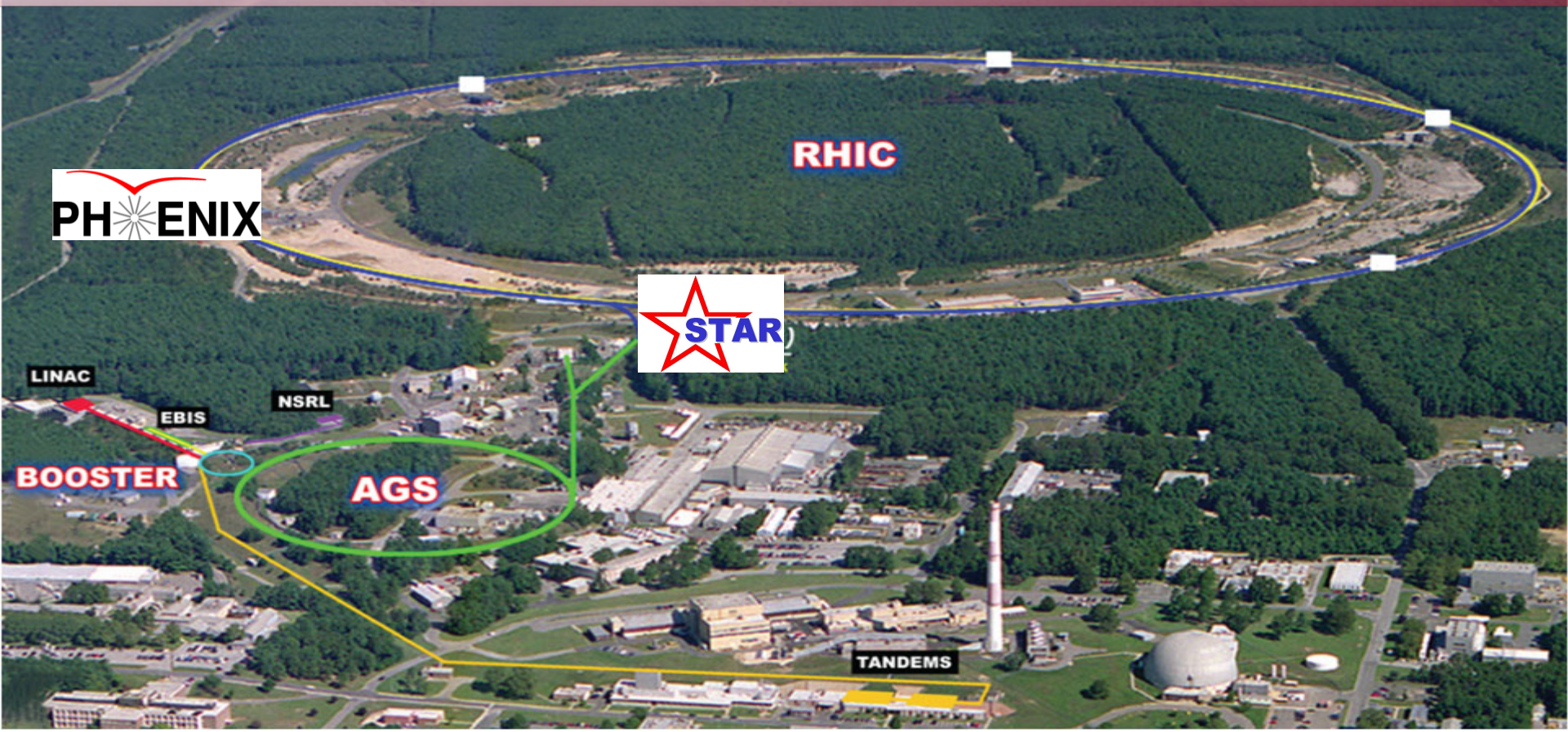
$\sqrt{s} = 5 \sim 500$ GeV

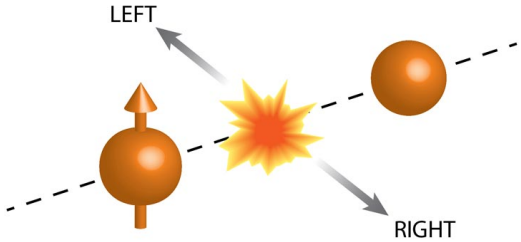
large asymmetry persists at higher energies

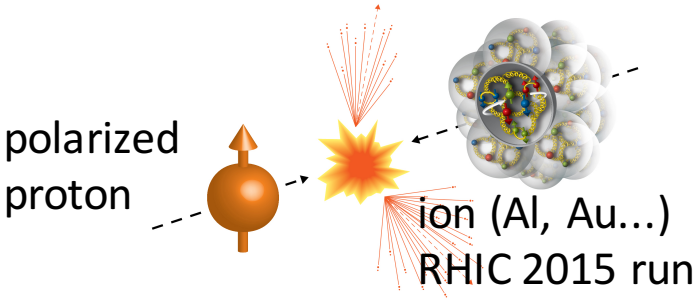
Mechanisms for A_N

	Transverse-momentum-dependent (TMD) Factorization	Collinear Factorization
Applicable	works at $Q \gg p_T \geqq \lambda_{QCD}$ needs 2 scales (Q^2 and p_T)	works at $Q, p_T \gg \lambda_{QCD}$ needs 1 scale (Q^2 or p_T)
p+p observables	*DY, W, Z, Hadron in jet*	π, γ, jet, Heavy Flavor, ...
Initial state	Sivers mechanism – proton spin and quark k_T correlation	Twist-3 multi-parton correlation functions
	related through $T_F^q(x,x) = -\int d^2\mathbf{p}_\perp \frac{\mathbf{p}_\perp^2}{M} f_{1T}^{\perp q}(x,\mathbf{p}_\perp^2)\|_{\mathrm{SIDIS}}$	
Final state	Collins mechanism – proton spin and quark spin correlation, quark spin and hadron k_T correlation	Twist-3 fragmentation functions
	related through $\hat{H}^{h/q}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}(z, z^2\vec{k}_\perp^2)$	

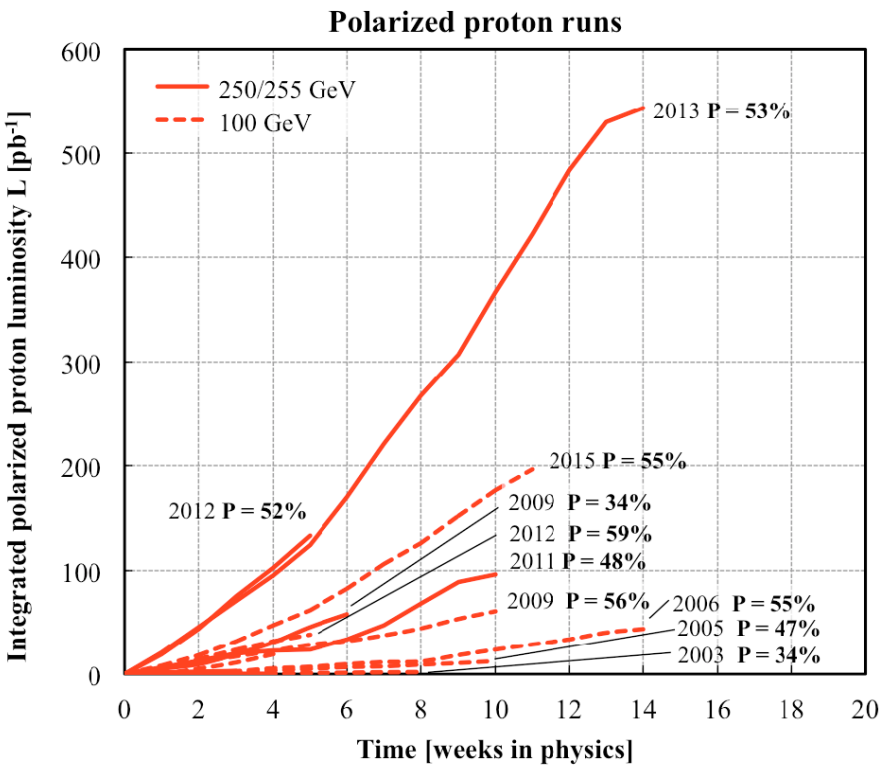
Polarized *p*+*p*(A) collision at RHIC

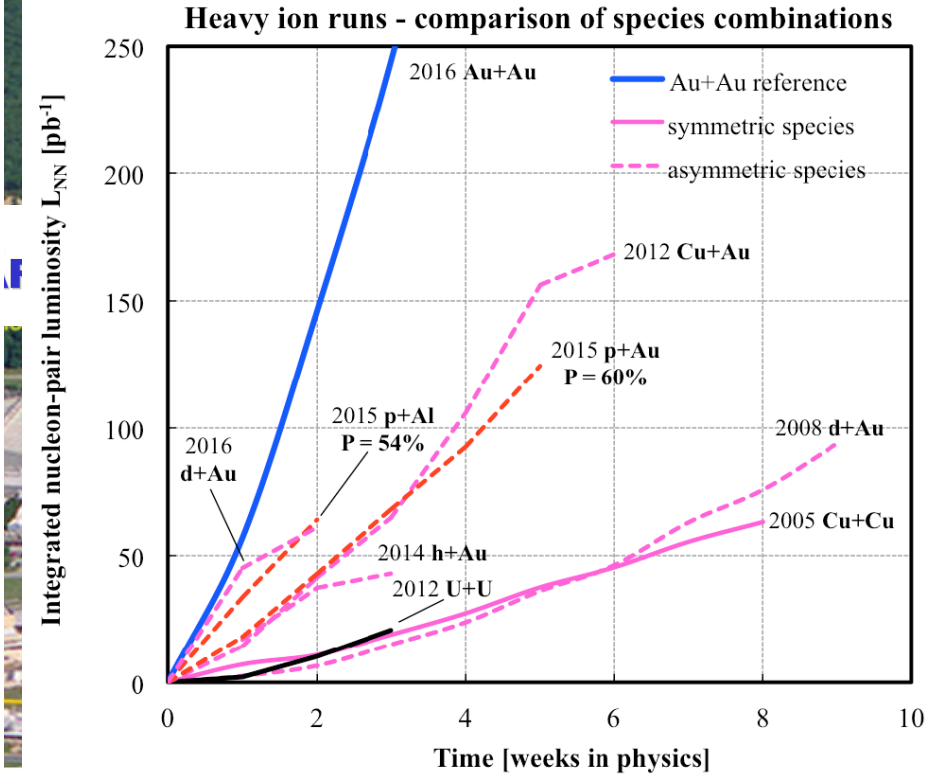


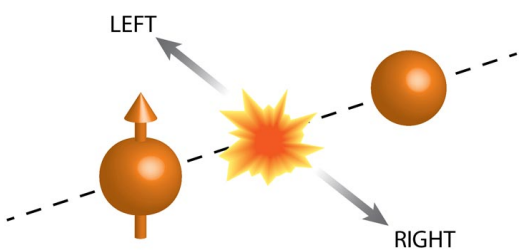


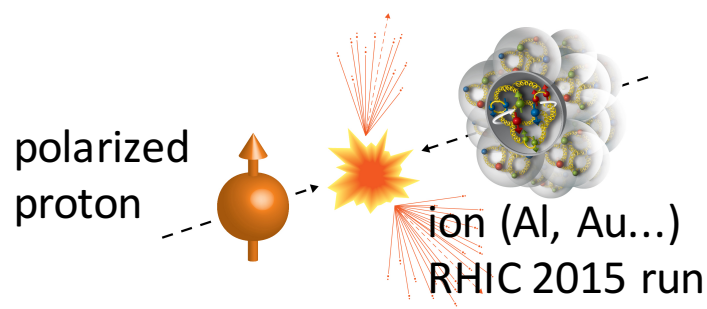


Polarized *p*+*p*(A) collision at RHIC

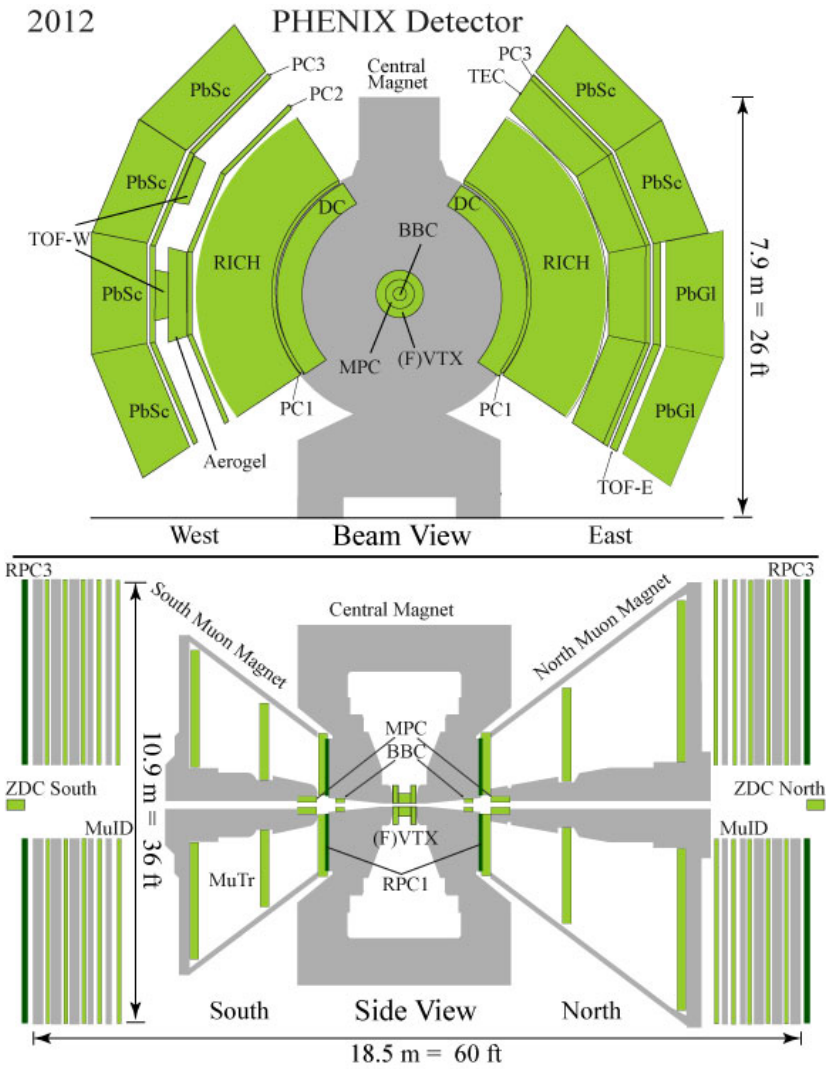






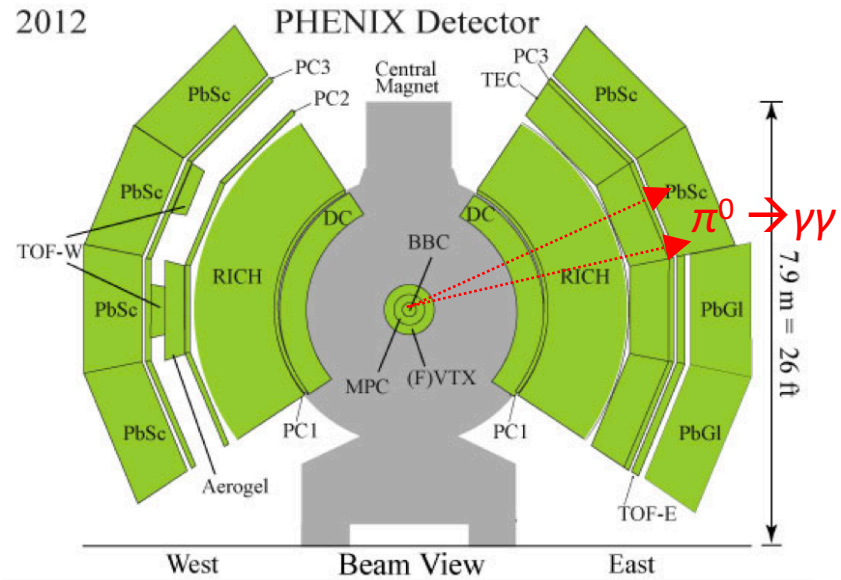


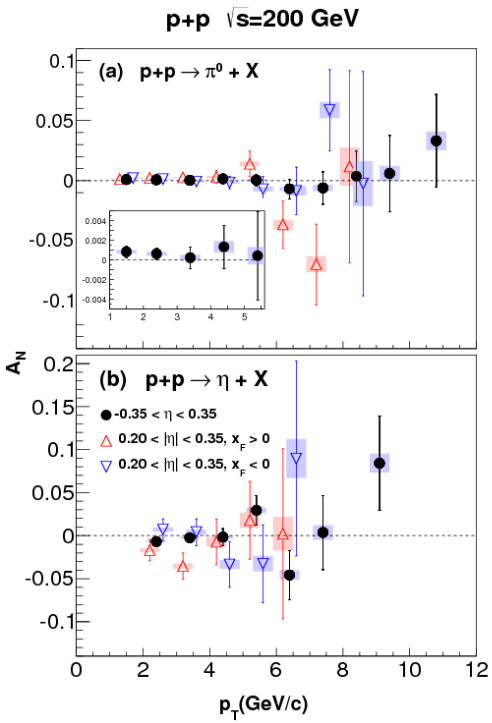
PHENIX Detectors



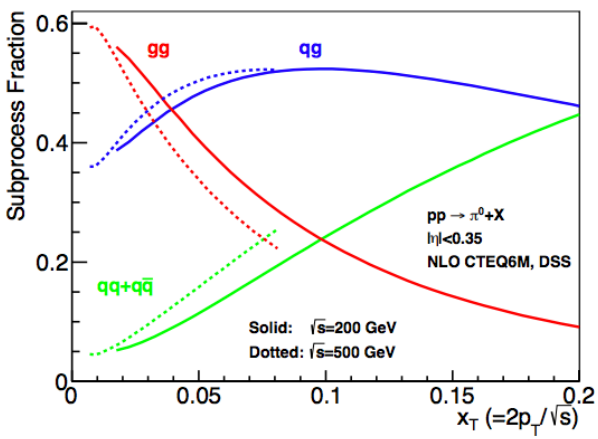
- Philosophy
  - high resolution & high-rate
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35, \Delta\varphi \sim \pi$
  - Momentum, EM Energy
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum
  - High p_T muons, dimuon, charged hadrons
- Muon piston calorimeter
  - $3.1 < |\eta| < 3.9$
  - EM Energy
  - π^0 and η
- Zero Degree Calorimeter
  - $|\eta| > 5.9$
  - neutron

Mid-rapidity π^0 and η A_N





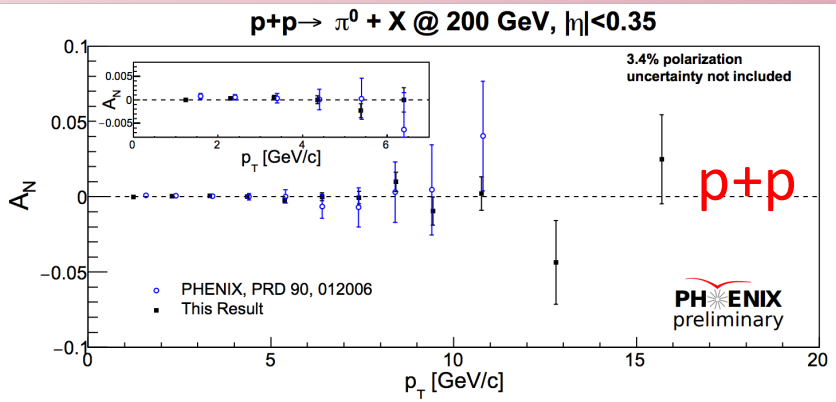
PRD 90, 012006 (2014)
PHENIX Collaboration

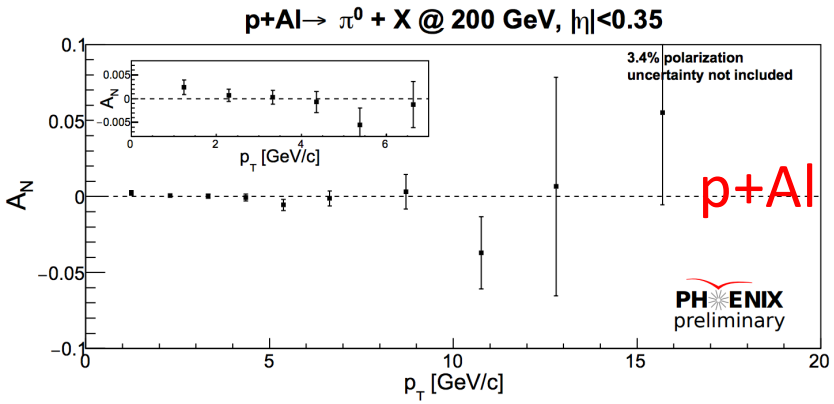


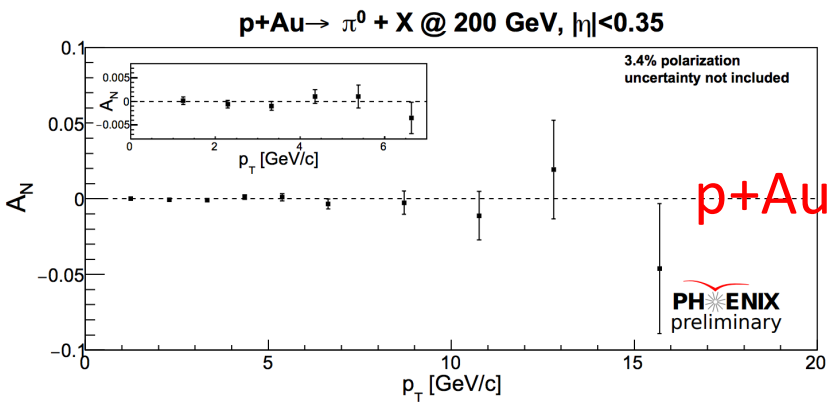
arXiv:1501.01220 (2015)
RHIC Spin Collaboration

- The π^0 and η production is sensitive to *qg* and *gg* process
  - Sivers effect from quark and gluon
- Consistent with zero for both π^0, η

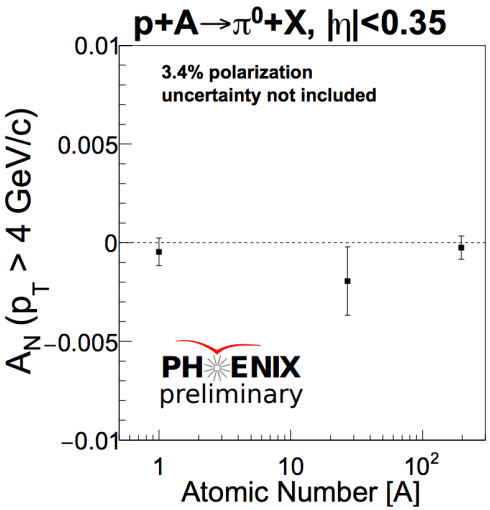
Midrapidity π^0 from p+p, p+A collisions



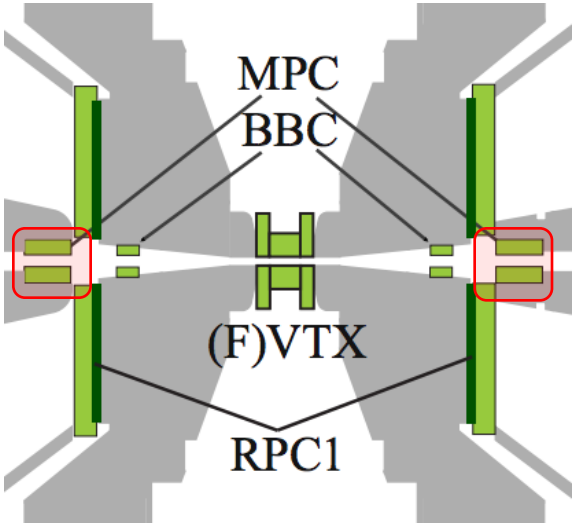


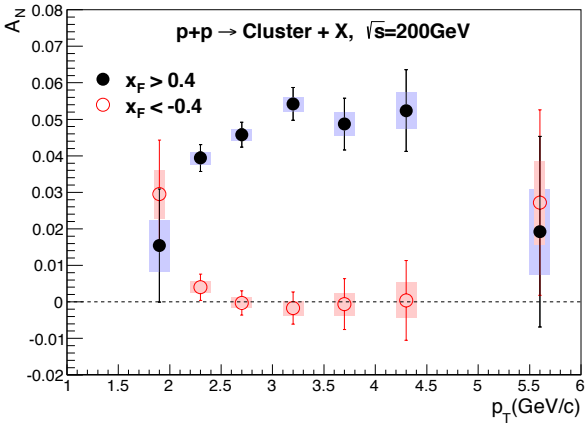


- Run15 results consistent with zero for both p+p, p+A within uncertainty

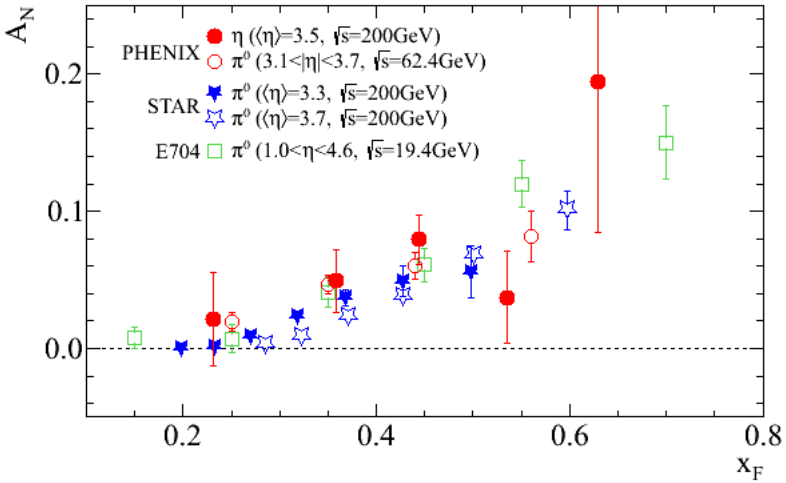


Forward rapidity π^0 and η A_N





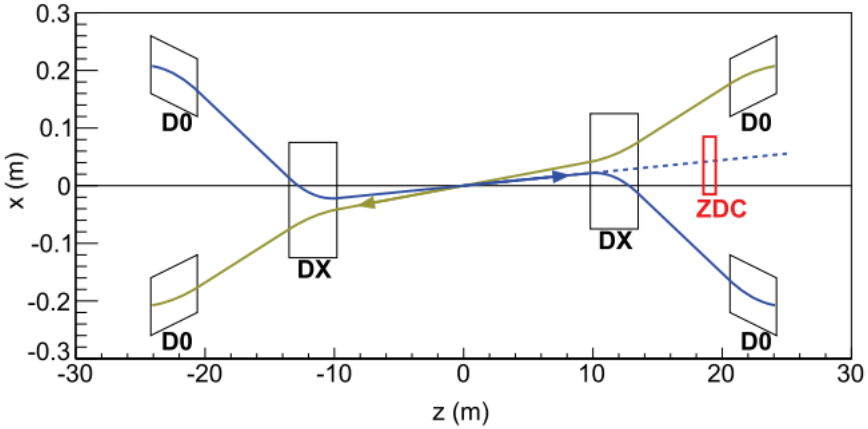
Phys.Rev.D 90, 012006 (2014)
PHENIX Collaboration

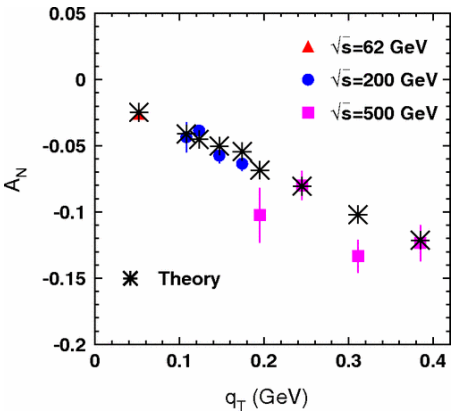


Phys.Rev.D. 90, 072008 (2014)
PHENIX Collaboration

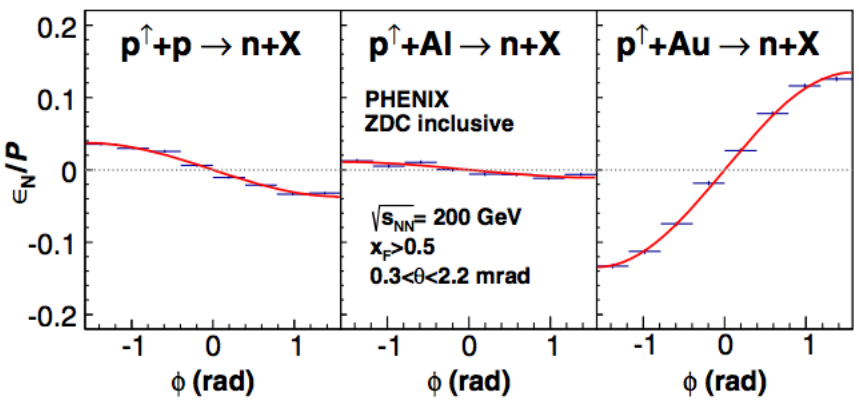
- Similar A_N for π^0 and η
- No obvious p_T or energy dependence

Forward neutron A_N





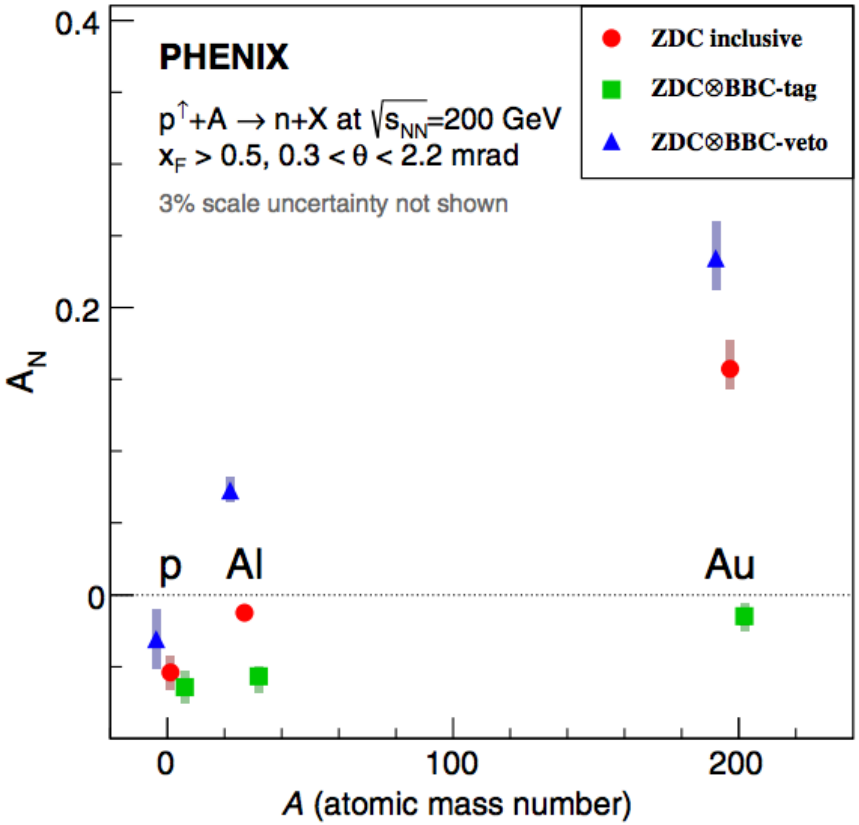
PRD 84, 114012 (2011)
Kopeliovich et al.



Phys.Rev.Lett. 120, 022001 (2018)
PHENIX collaboration

- π-a_1 interference in Reggeon framework explains asymmetry result for *p+p* data well
- small A-dependence was expected
- large A_N observed with opposite sign in p+Au

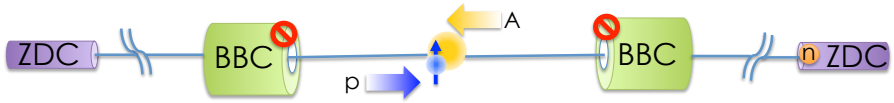
Forward neutron A_N



recently published : *Phys.Rev.Lett. 120, 022001 (2018) PHENIX collaboration*

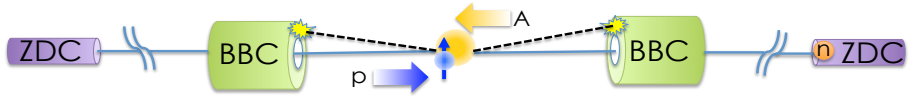
see also :
Eur.Phys.J. C75 (2015) no.12, 614 G.Mitsuka

BBC Vetoing



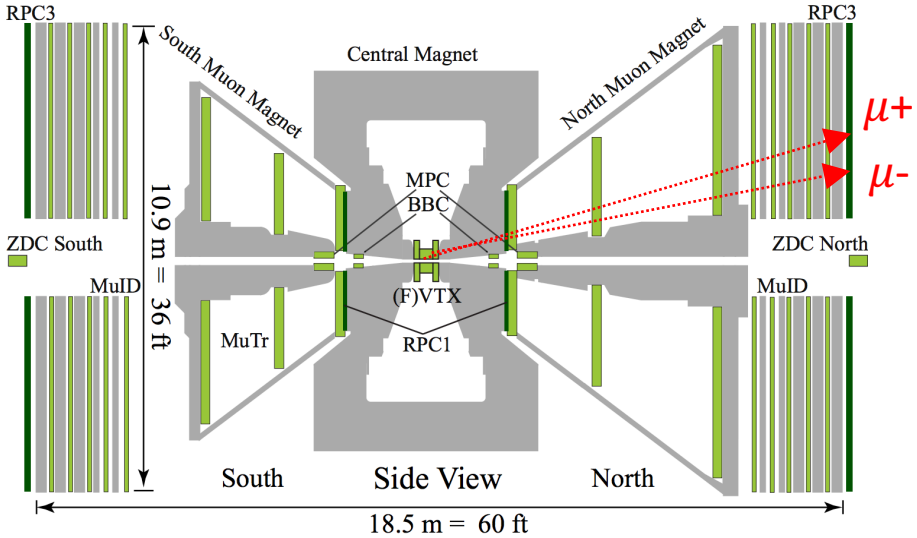
- π^+ boosted toward beam
- enhance EM interactions

BBC Tagging

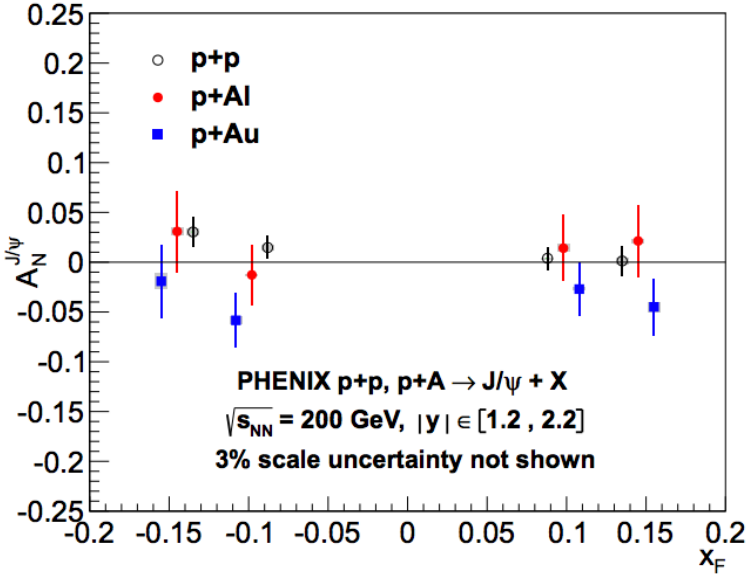


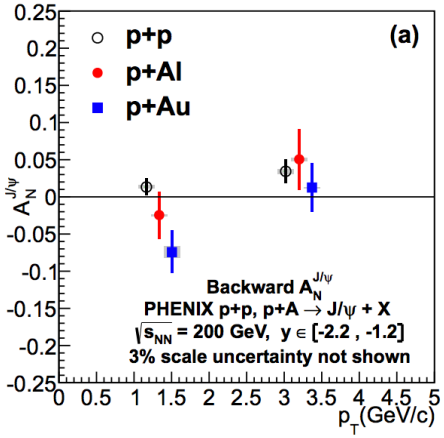
- suppress EM interactions

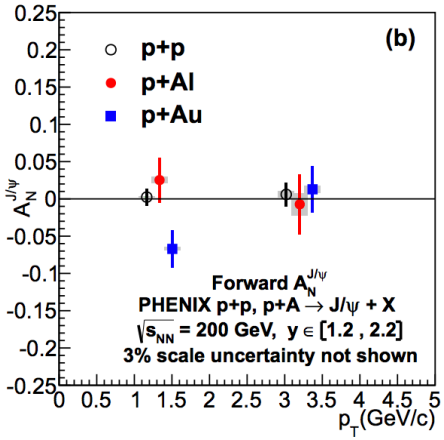
Heavy Flavor - J/ψ



- heavy flavor : ideal tool to investigate the gluon distributions in the nuclei
- A_N of J/ψ is sensitive to the production mechanism
- p+p, p+Al results are consistent with zero
- p+Au result favor negative A_N

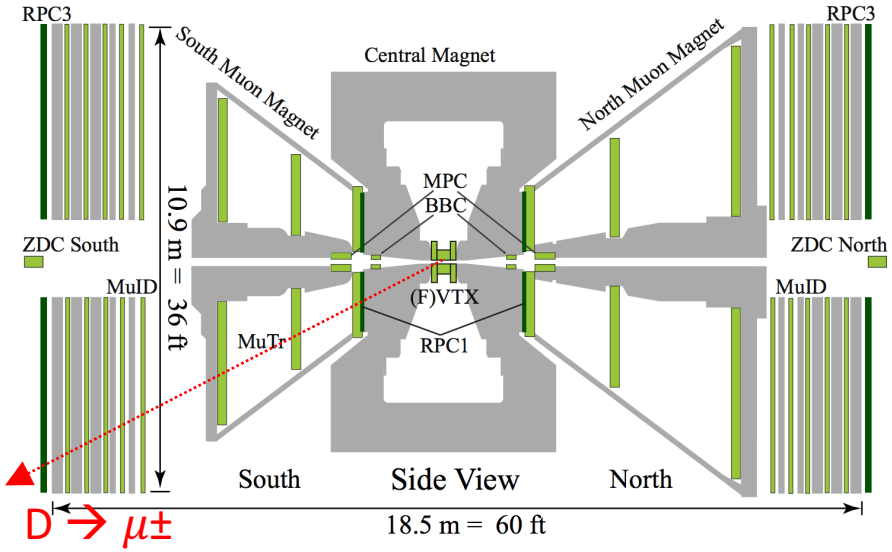






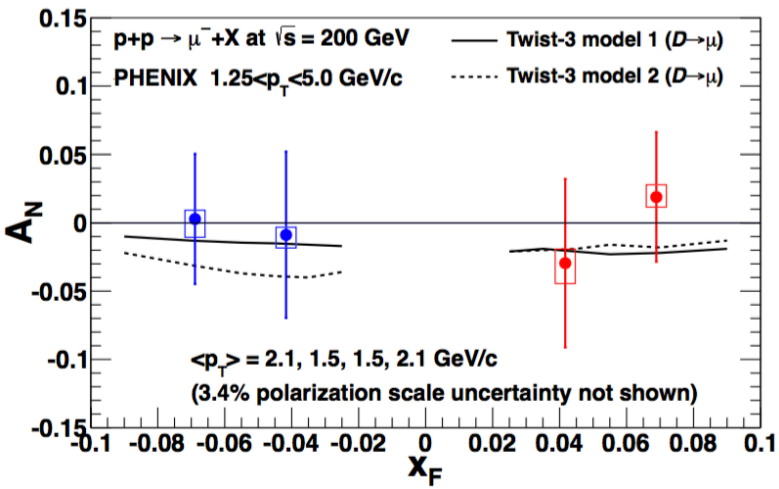
arxiv:1805.01491 PHENIX collaboration

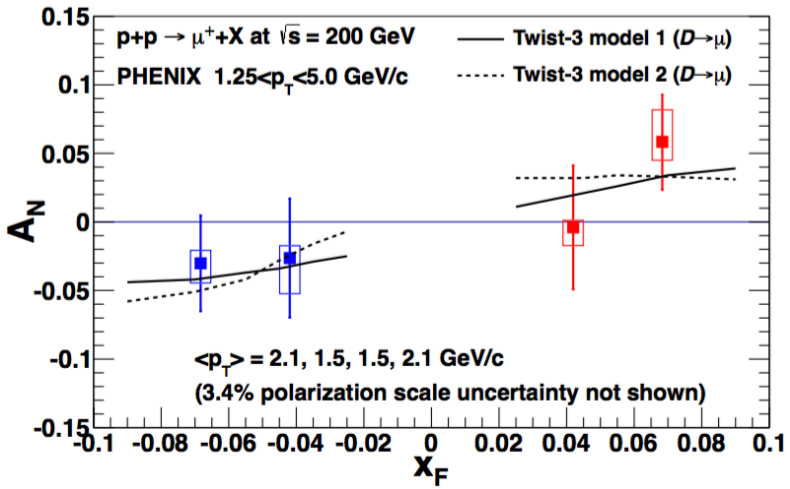
Open Heavy Flavor



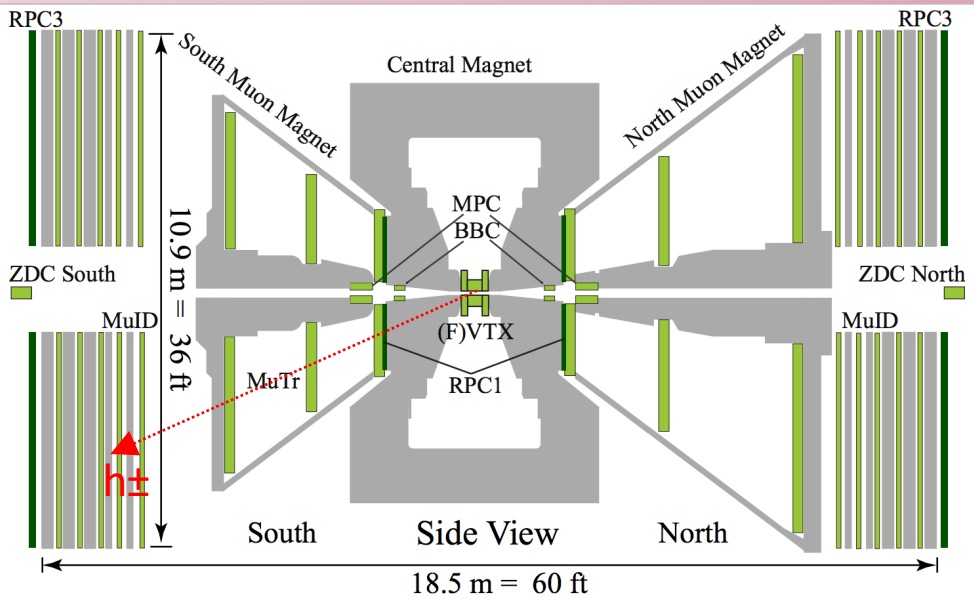
- A_N of μ from open heavy flavor
- sensitive to gluon Sivers-like effect – trigluon correlations in twist-3 collinear factorization.
  - $A_N(D)$ from Y. Koike and S. Yoshida, *Phys. Rev. D84, 014026 (2011)*
- no clear indication of non-zero asymmetry within uncertainty, close to theory expectation.

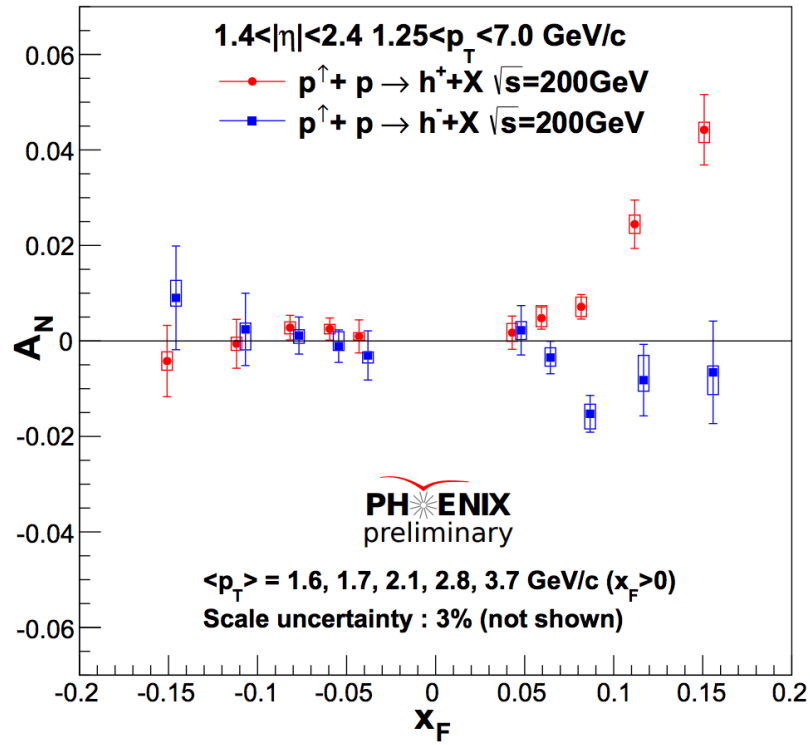
Phys.Rev.D. 95, 112001 (2017) PHENIX collaboration





Charged hadron A_N in p+p



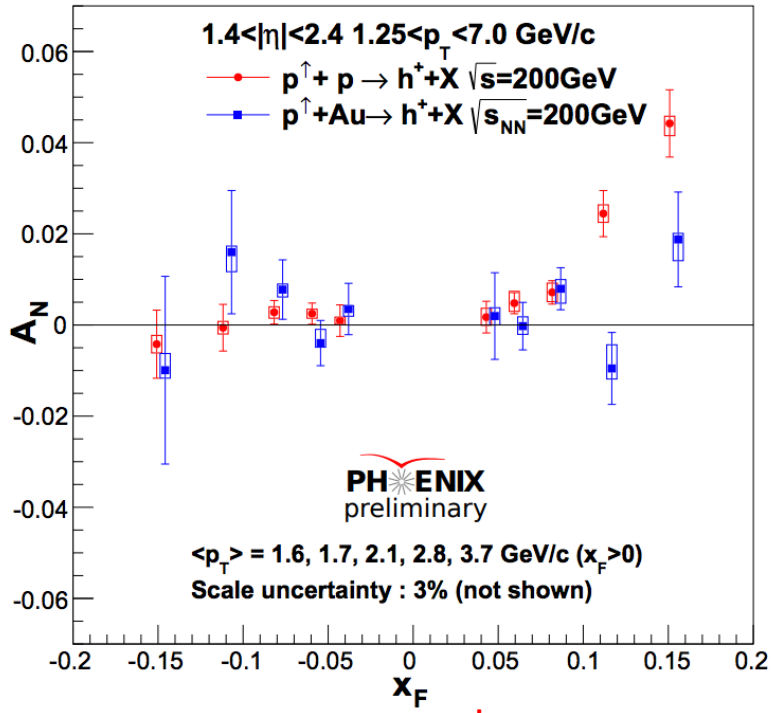


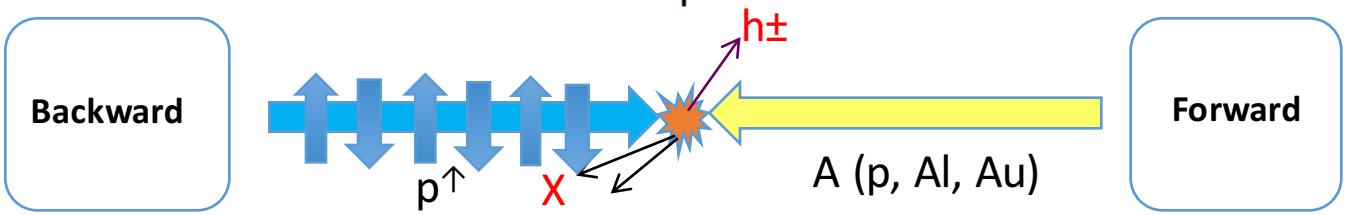
- A_N of (survived) $\pi^{\pm}, K^{\pm}$ mixture
- A_N increases as x_F increases for (+) charged hadron at $x_F>0$
- comparable with BRAHMS results, but not same kinematics.
  - $A_N>0$ for $\pi^+, K^{\pm}$, $A_N<0$ for π^- in BRAHMS result
- recent calculations for charged pion in p+p : *Phys.Rev.D 89 111501 (2014) K.Kanazawa et al, Phys.Lett. B 770 (2017) 242-251 L.Gamberg et al*

Light hadron A_N in p+A

- Helps us to understand
  - underlying mechanisms of A_N
  - small-x saturation of gluon distribution
- Suppression of A_N in $p^{\uparrow}$+A is sensitive to Qs
- ~$A^{1/3}$ suppression by gluon saturation
    - *Phys.Rev.D.84.034019 (2011) Z.Kang, F.Yuan*
    - Odderon exchange : *Phys.Rev.D.86.034028 (2012) Y. Kovchegov, M.Sievert*
  - Hybrid approach of Twist-3 and color glass condensate
    - *Phys.Rev.D.94. 054013 (2016), Phys.Rev.D.95, 014008 (2017) Y.Hattaa, et al*
  - different contributions to A_N have different A-dependence

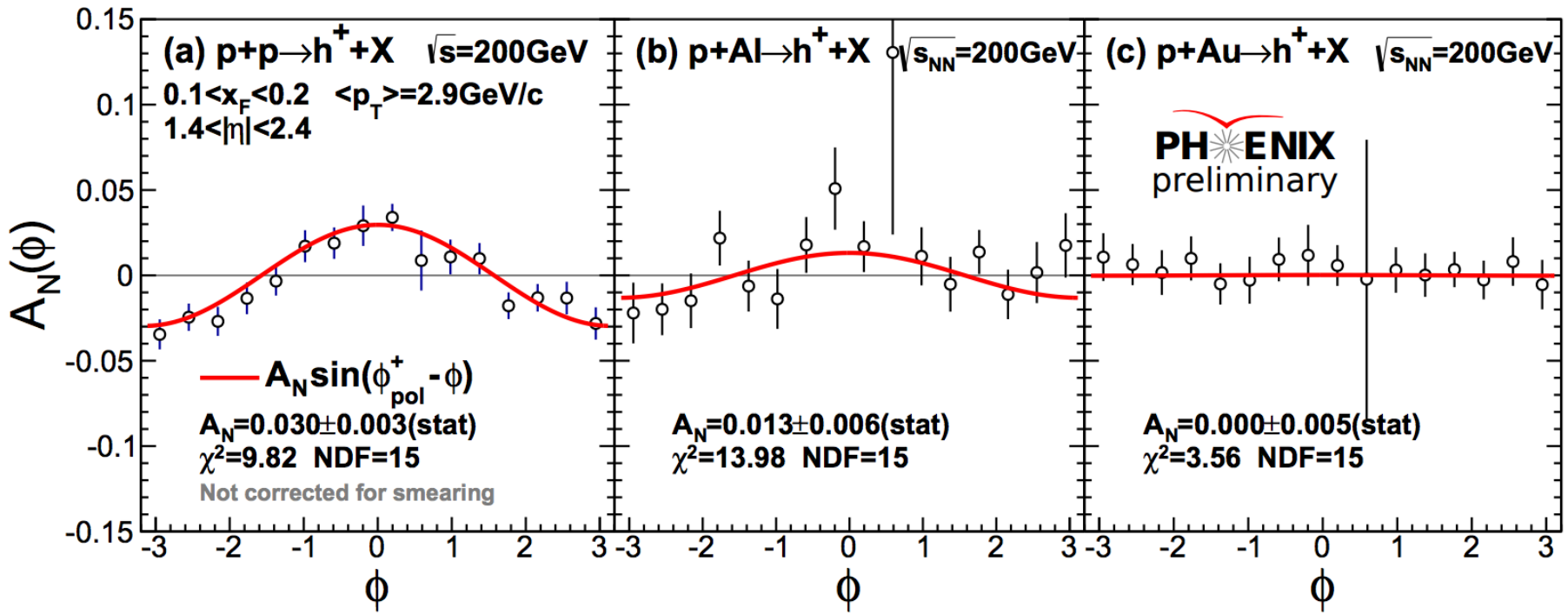
positively charged hadron A_N in p+p, p+Au





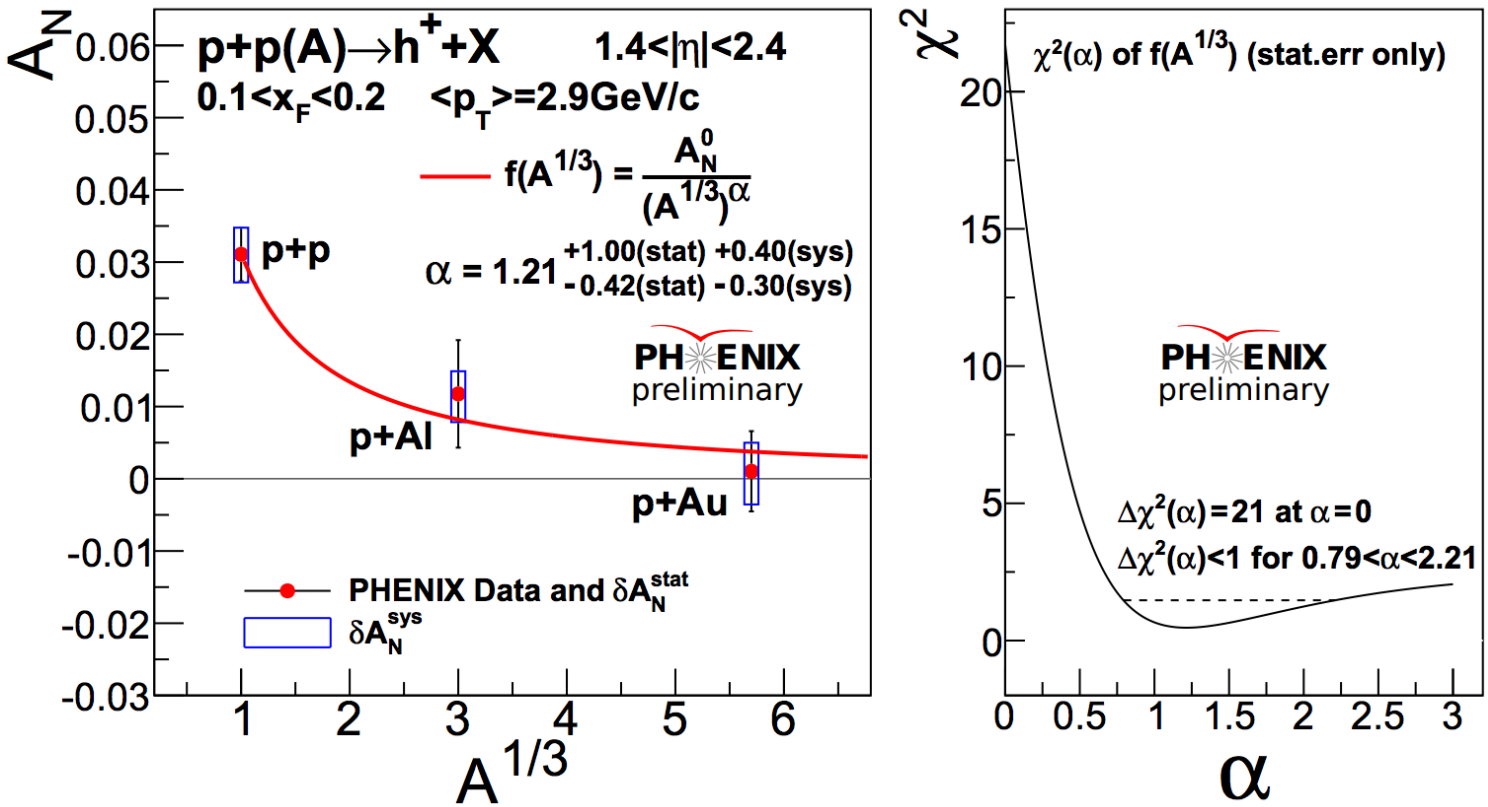
- A_N of (survived) $\pi^{\pm}, K^{\pm}$ mixture.
- p+Au→$h^{(+)}$+X shows suppression of A_N at x_F>0.1

Nuclear dependence of A_N



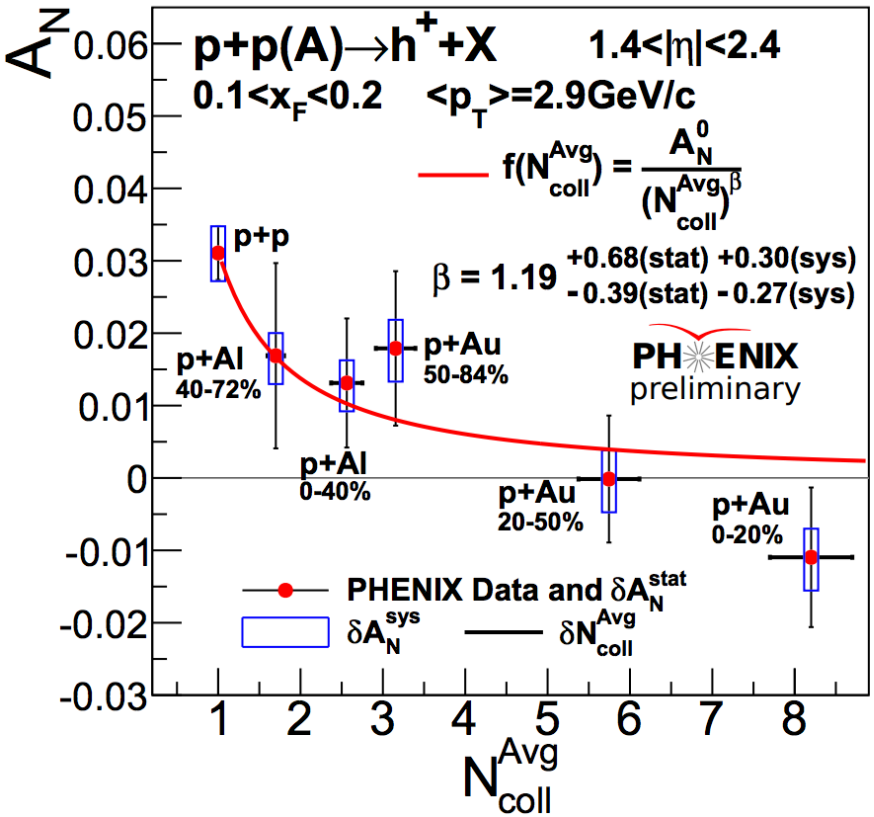
- sine modulations for positively charged hadron at $0.1<x_F<0.2$
- nonzero modulation in p+p, suppressed in p+Au

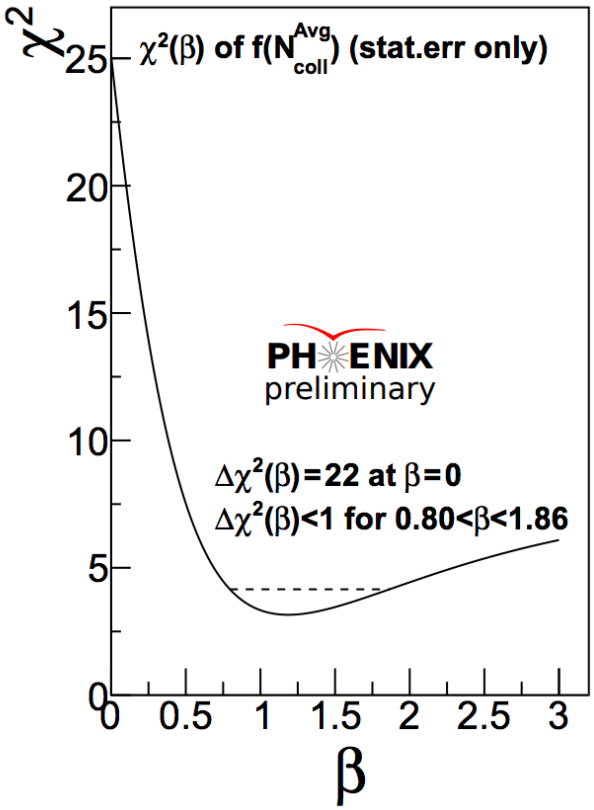
Nuclear dependence of A_N



- Nuclear dependence of A_N for positively charged hadron at $0.1<x_F<0.2$
  - quantifying A-dependence, α =1 corresponds to $1/A^{(1/3)}$ dependence
  - Right panel is χ^2 for wide range of power parameter α
  - $\Delta\chi^2$=21 at α=0 (NO A-dependence)

Avg.N_{coll} dependence of A_N





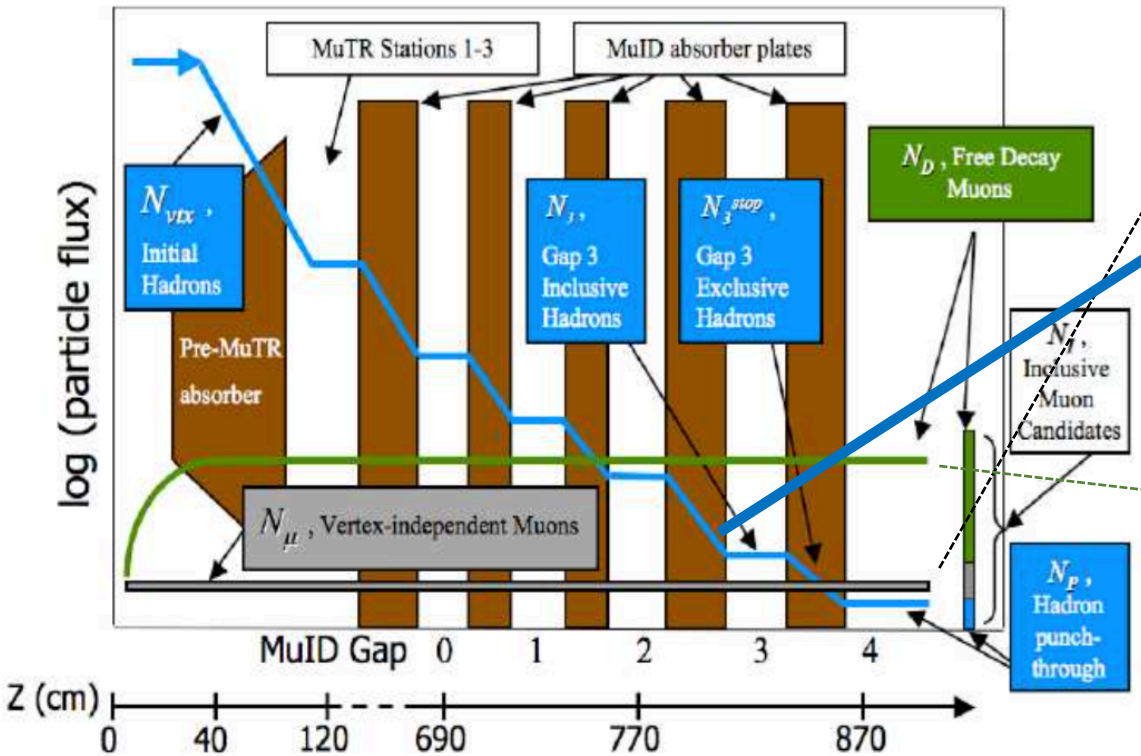
- Avg.N_{coll} dependence of A_N for positively charged hadron at $0.1<x_F<0.2$
  - x-axis is averaged-N_{coll}, related to the path length in a nucleus in p+A collisions
  - Right panel is χ^2 for wide range of power parameter β
  - $\Delta\chi^2$=22 at β=0

Summary and Outlook

- PHENIX has measured A_N in many different processes in an attempt to solve a long-standing puzzle
  - π^0, η
  - heavy flavor
- PHENIX p+A results
  - midrapidity π^0 consistent with zero
  - surprising A_N in neutron production in p+Au from other processes
  - indication of large A_N in J/ψ in pAu
  - positively charged hadron at forward rapidity showed obvious suppression of A_N in p+Au comparing with p+p
    - information on the underlying mechanism of A_N
    - small-x saturation of gluon distribution in large nuclei

backup slides

Tracks in the PHENIX Muon Arm



(1) Open Heavy Flavor ($D,B\rightarrow\mu\pm$), $J/\psi\rightarrow\mu+\mu-$

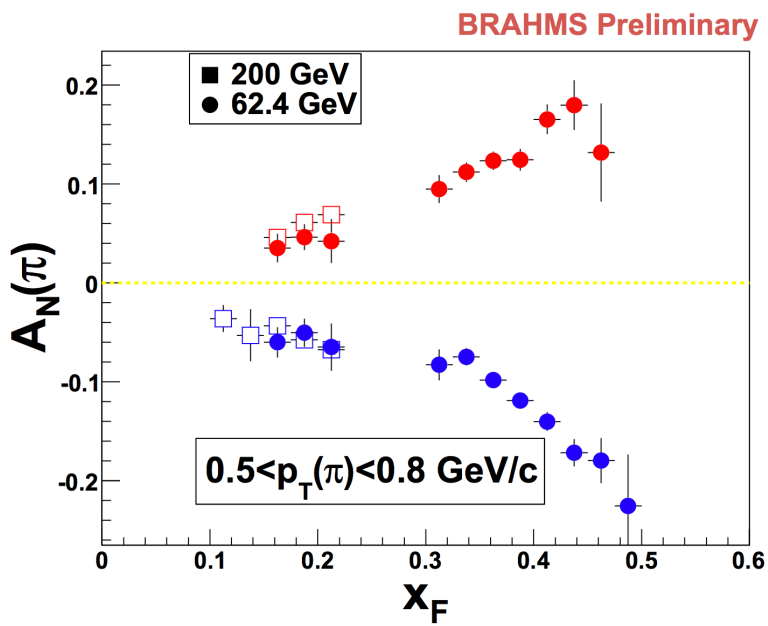
(2) Stopped hadron ($\pi\pm, K\pm$)

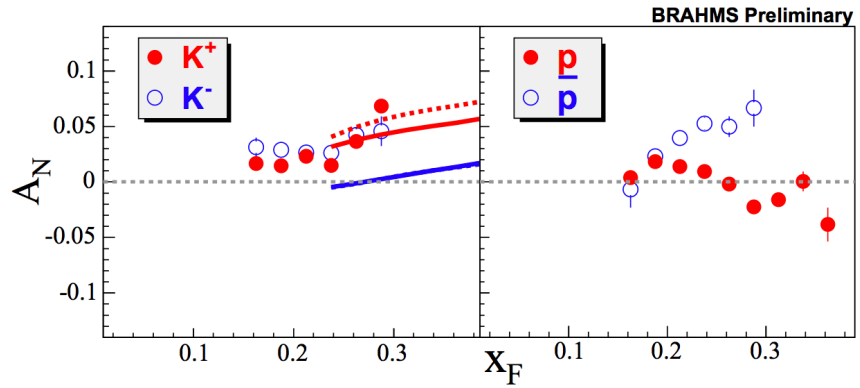
(3) Decay muon ($\pi\pm, K\pm\rightarrow\mu\pm$)

(4) Punch through ($\pi\pm, K\pm$)

- discriminate charged hadrons and muons
  - charged hadrons stop at MUID gap2,3 while muon reach to the last gap of MUID(gap4)
- $\pi\pm, K\pm$ are background in open heavy flavor study($D,B\rightarrow\mu\pm$)
- $\pi\pm, K\pm$ are signal in charged hadron study.
- dimuon pairs are candidates of J/ψ etc.

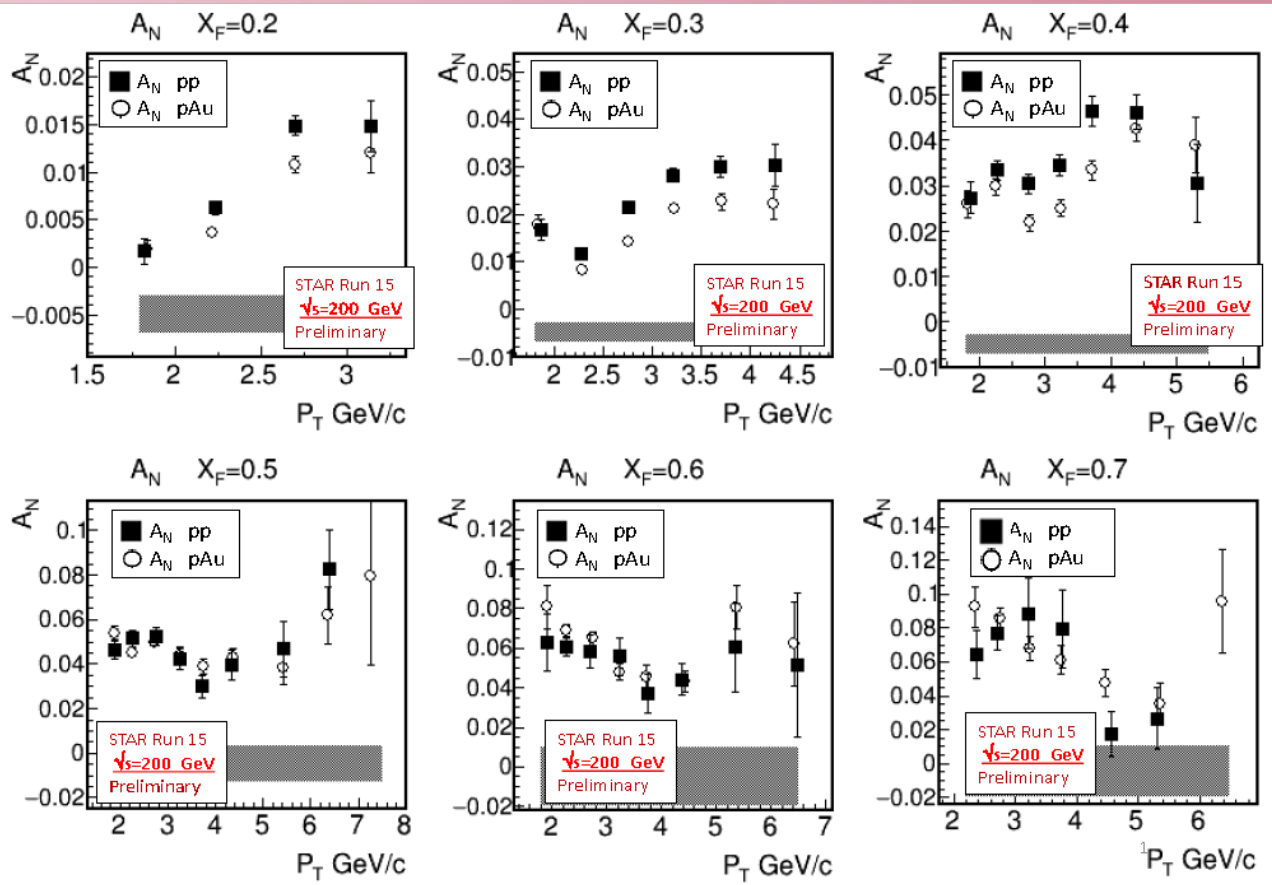
backup : charged hadron A_N in BRAHMS





- PRL101 042001(2008) at 62.4GeV
- BRAHMS preliminary for 200GeV from DIS09 (arXiv:0908.4551)
- increasing trend of A_N as x_F increases
- opposite sign of A_N in charged pions, same sign of A_N in charged Kaons
- different kinematics

backup : recent STAR π^0 in p+A



- taken from QM 2017, SPIN 2016
- small to no suppression within systematic uncertainty
- different kinematic region

light hadron A_N

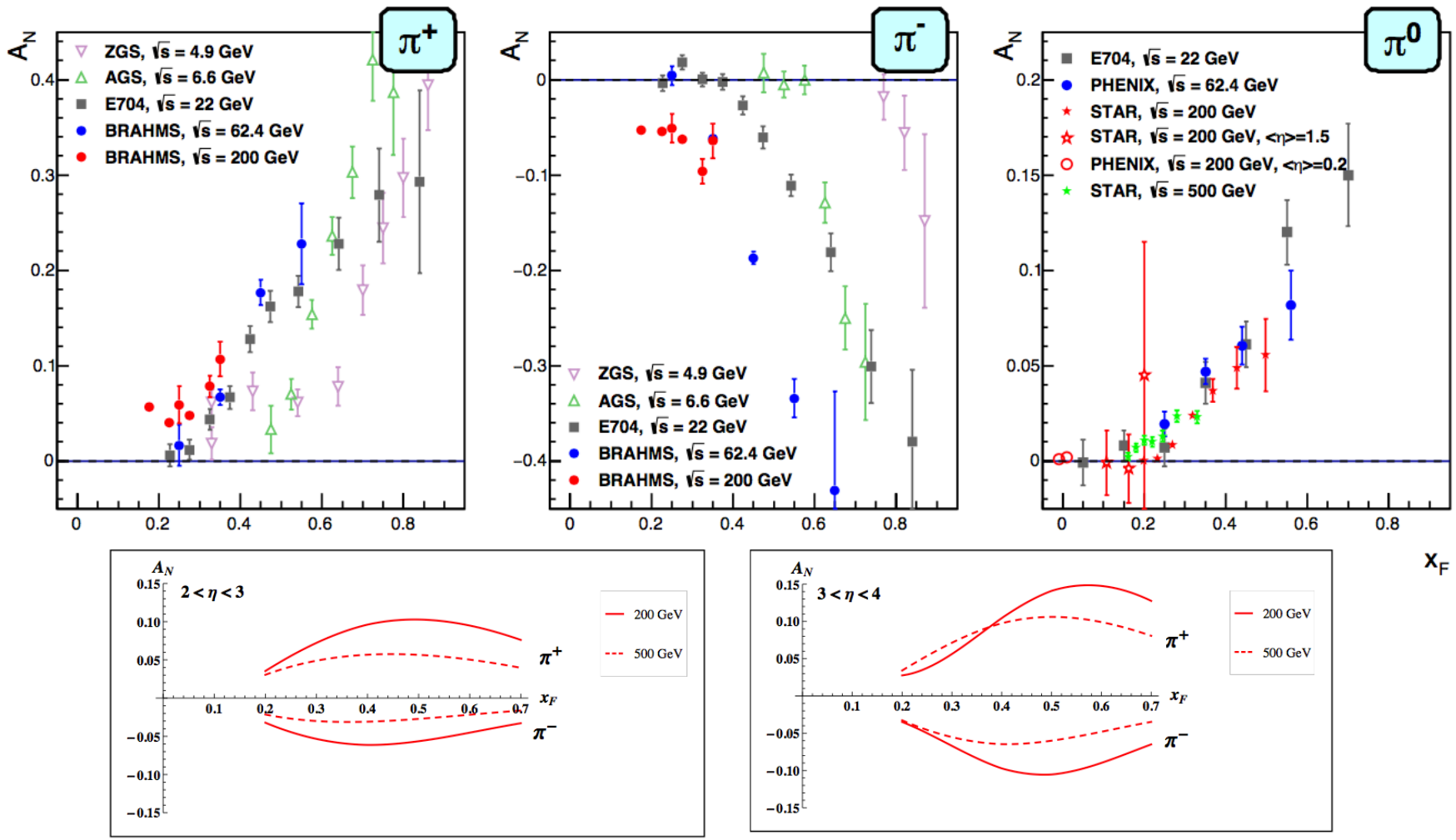


Figure 2-10: Predictions, based on the work in Ref. [51], for A_N for π^+ and π^- production at STAR for $2 < \eta < 3$ (left) and $3 < \eta < 4$ (right) at 200 GeV (solid lines) and 500 GeV (dashed lines).

from RHIC Cold QCD Plan document *arXiv:1602.03922 E.C.Aschenauer et al*