PHENIX

# Recent Transverse Spin Results in PHENIX

Transversity 2024

3rd June 2024

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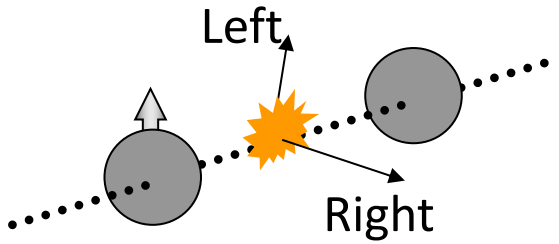
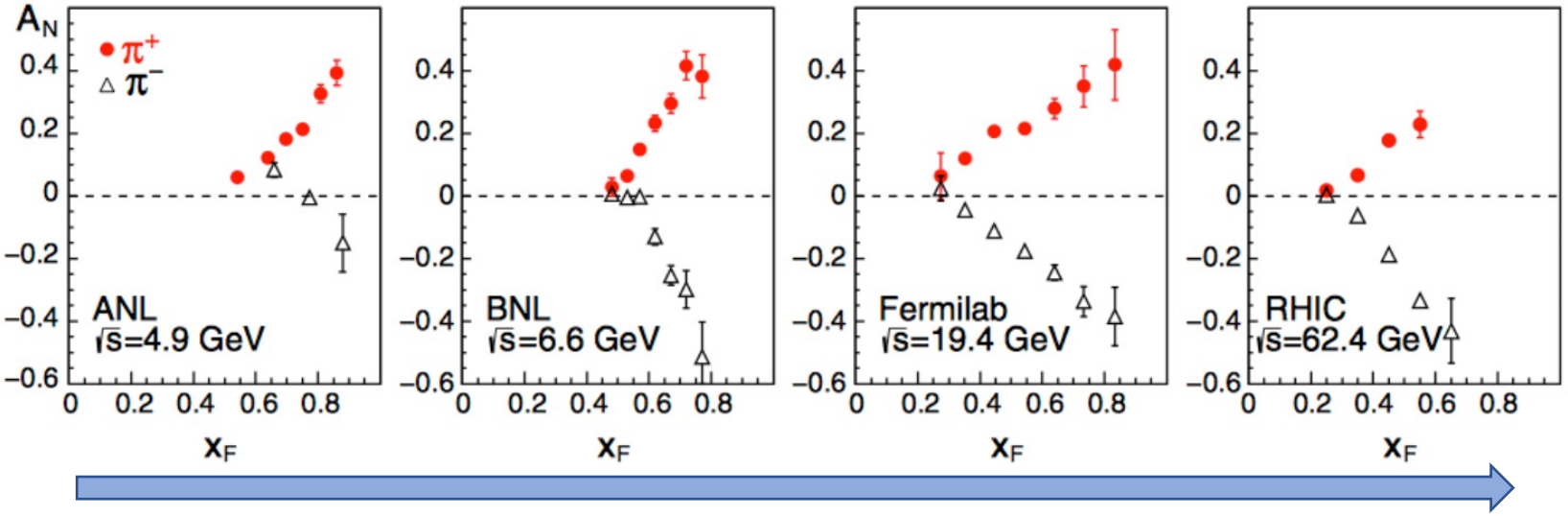
for the PHENIX collaboration

# Transverse Single-Spin Asymmetry ($A_N$)

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

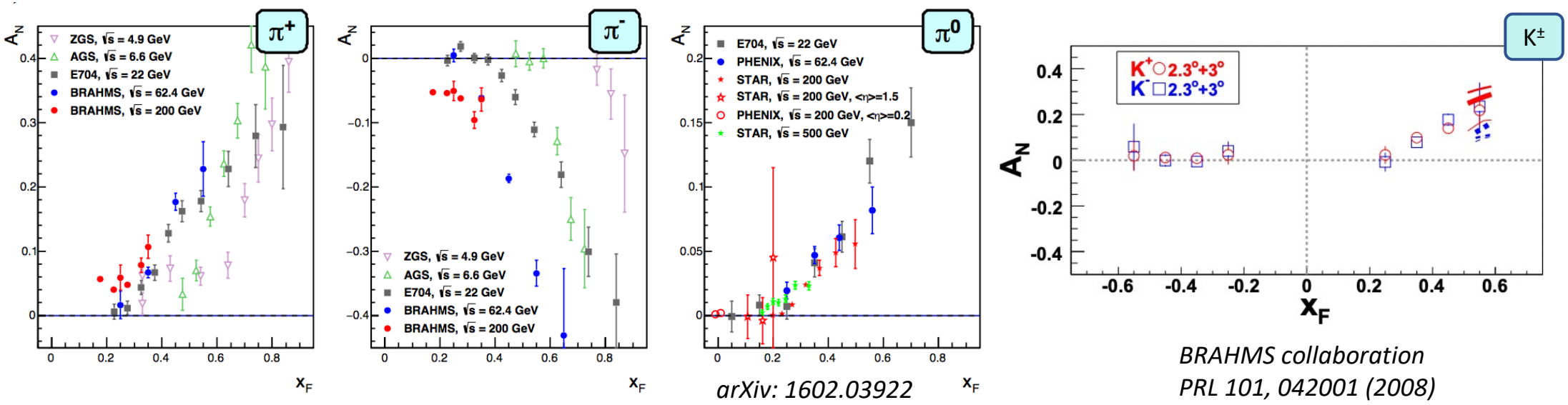



$$x_F = \frac{2p_L}{\sqrt{s}}$$

- Large $A_N$ in single hadron production up to RHIC energies, over 40 years.

# $A_N$ at RHIC energies




*arXiv: 1602.03922*

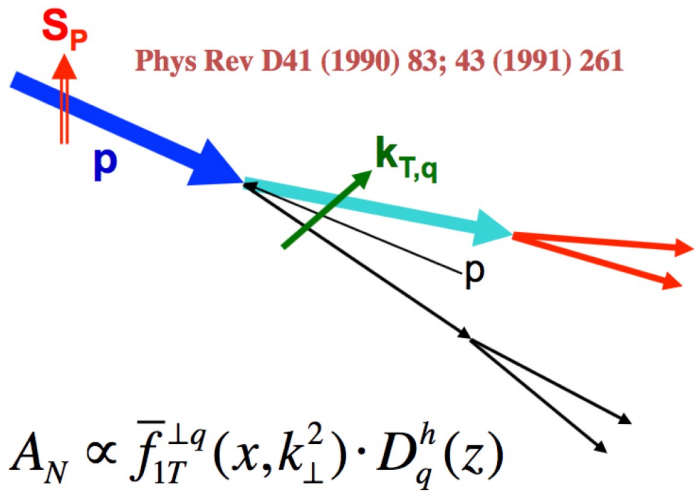
*BRAHMS collaboration*
*PRL 101, 042001 (2008)*

- General features at forward rapidity
  - Striking effects at large $x_F$
  - $A_N$ survives at large energies
  - $A_N(\pi^+)$ and $A_N(\pi^-)$ have roughly same magnitude, opposite sign
  - $A_N(K^+)$ and $A_N(K^-)$ same sign
  - $A_N(\pi^0)$ is positive, smaller than $A_N(\pi^+)$

# Possible origin of $A_N$

## Sivers Mechanism

Correlation between proton spin & parton $k_T$

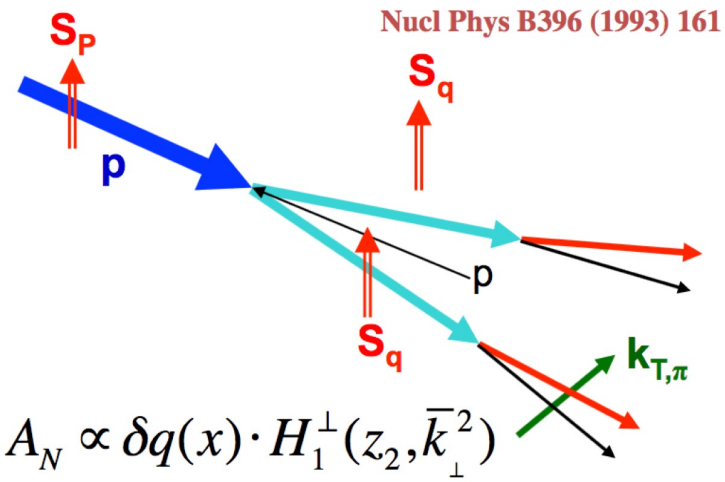



$$A_N \propto \bar{f}_{1T}^{\perp q}(x,k_\perp^2)\cdot D_q^h(z)$$

Jet, direct photon, HF, Z, W, DY, …

## Collins Mechanism

Transversity x spin-dependent fragmentation

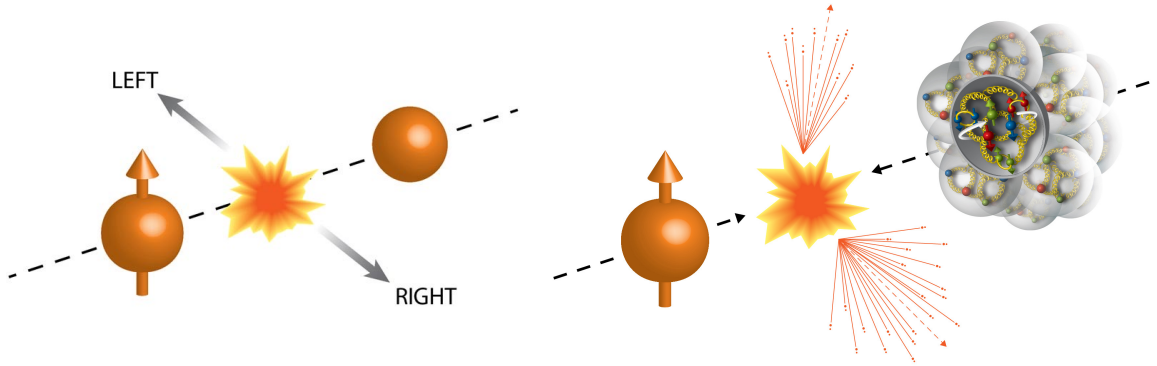



$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$$

Hadron in jet, hadron pair, …

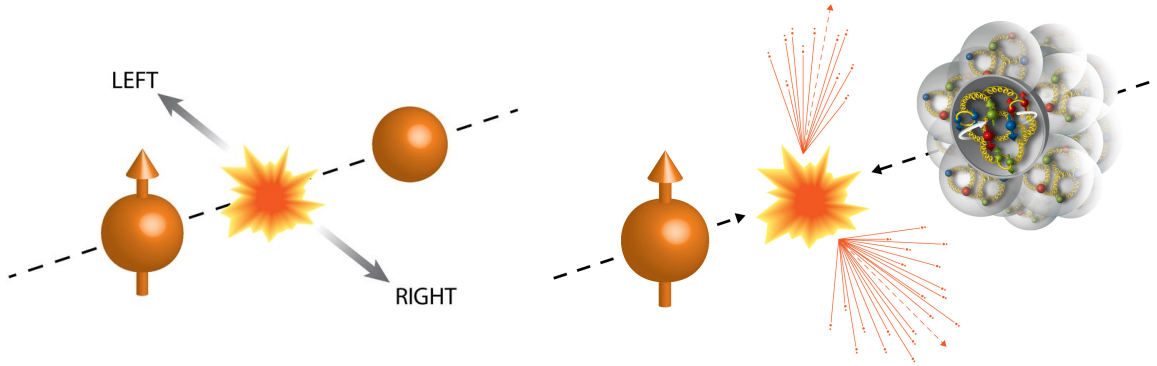
- $p^\uparrow$+p → h+X : collinear factorization approach
  - Twist-3 Multiparton(*qgq, ggg*) correlations and fragmentation functions

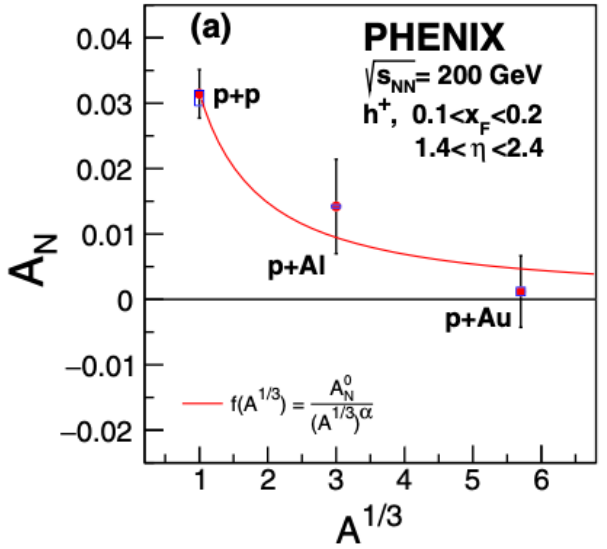
# Inclusive hadron $A_N$ in polarized p+A




- The first polarized p+A collision at RHIC 2015 run
- Interplay of small-x and spin physics
- Help to disentangle differing mechanisms and clarify the origin of the $A_N$.
- A-dependence of $A_N$ can be a probe for the saturation scale in the nucleus.

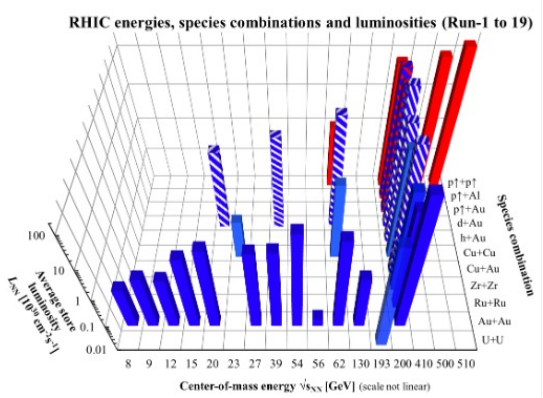
# Inclusive hadron $A_N$ in polarized p+A

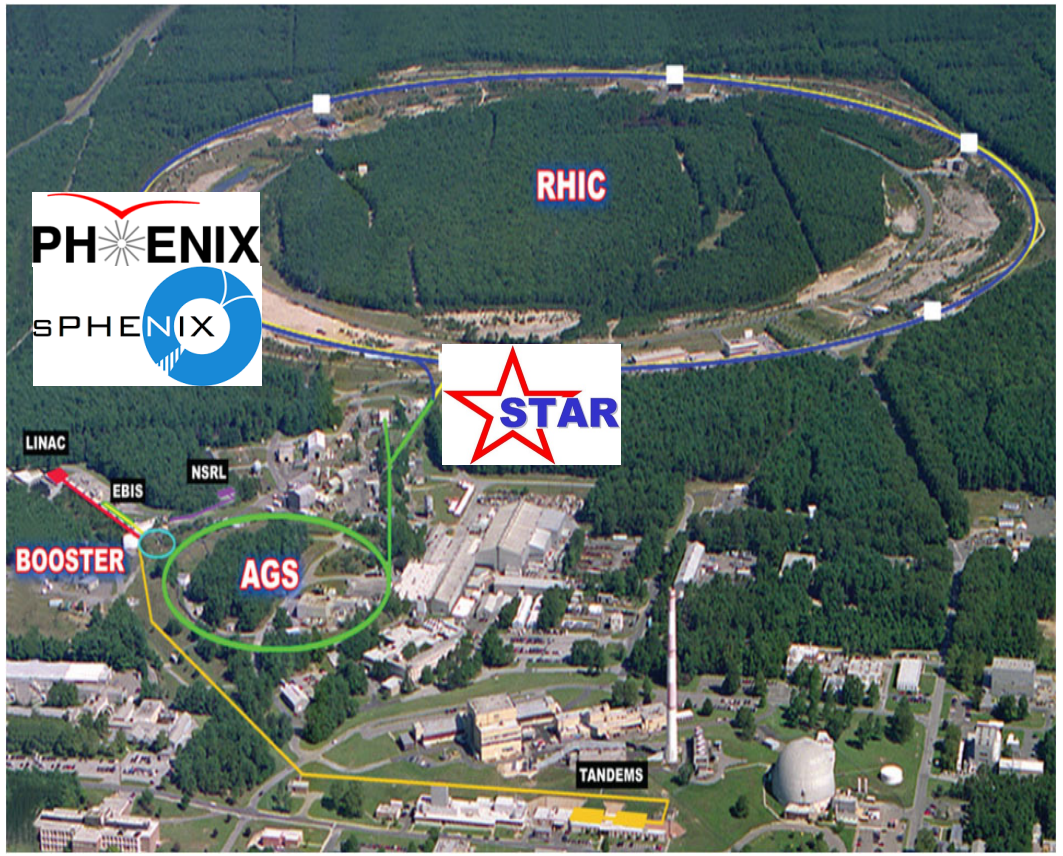


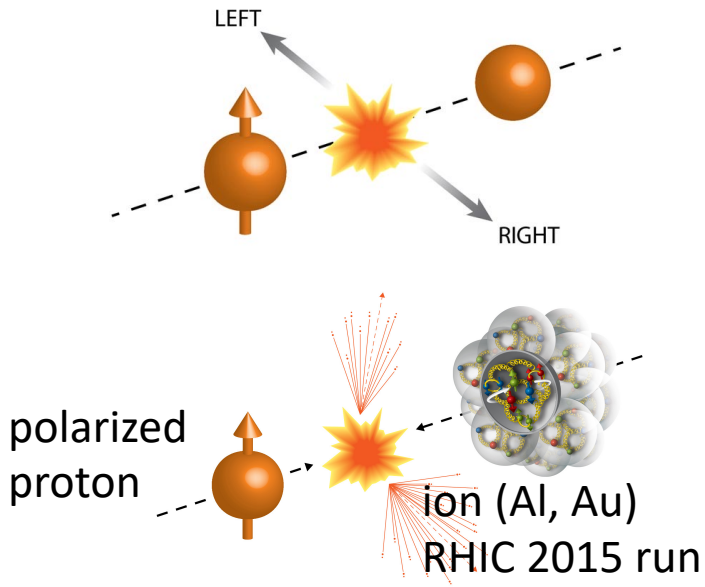

- The first polarized p+A collision at RHIC 2015 run
- Many interesting $A_N$ results in p↑+A collisions
  - neutron, $J/\psi$, $h^+$, $\pi^0$, $\eta$ …
- A-dependence of inclusive hadrons at forward rapidity
  - A-dependence of $A_N(h^+)$ at $0.1<x_F<0.2$ *PHENIX collaboration, PRL 123, 122001 (2019)*
  - Small A-dependence of $A_N(\pi^0)$ in far forward region *STAR collaboration, PRD 103, 072005 (2021)*

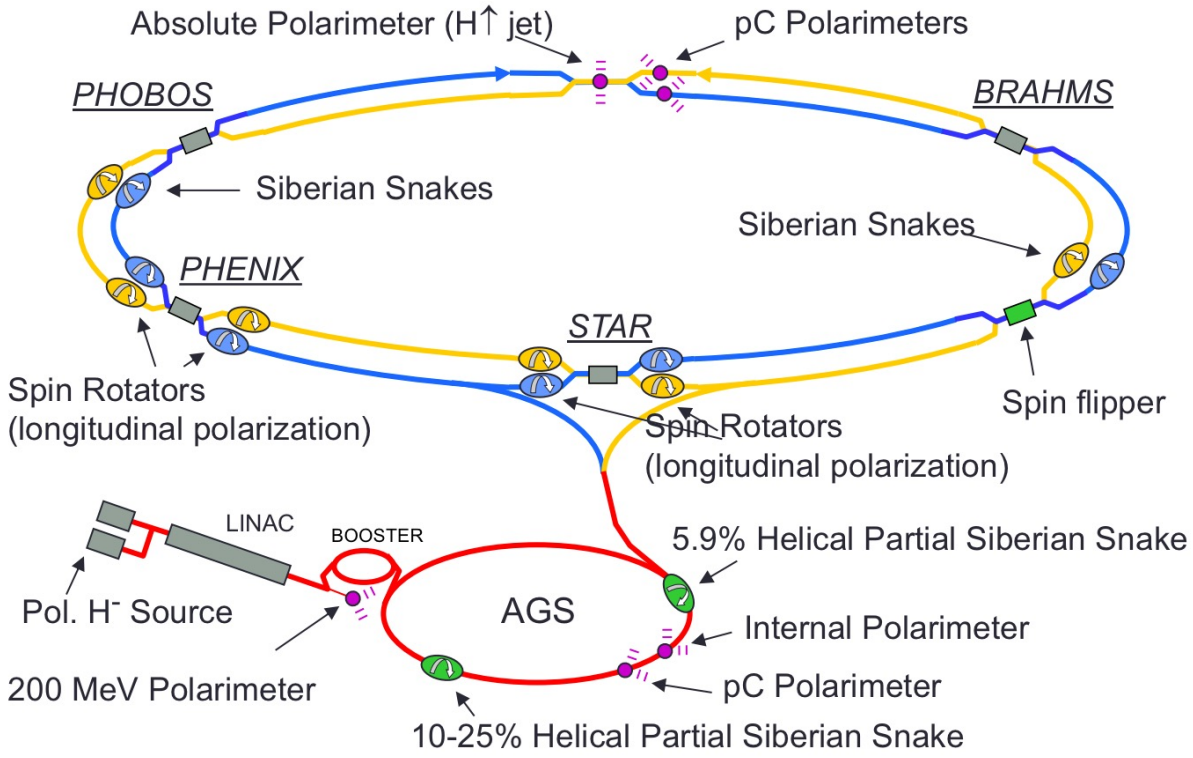
# Relativistic Heavy Ion Collider at BNL



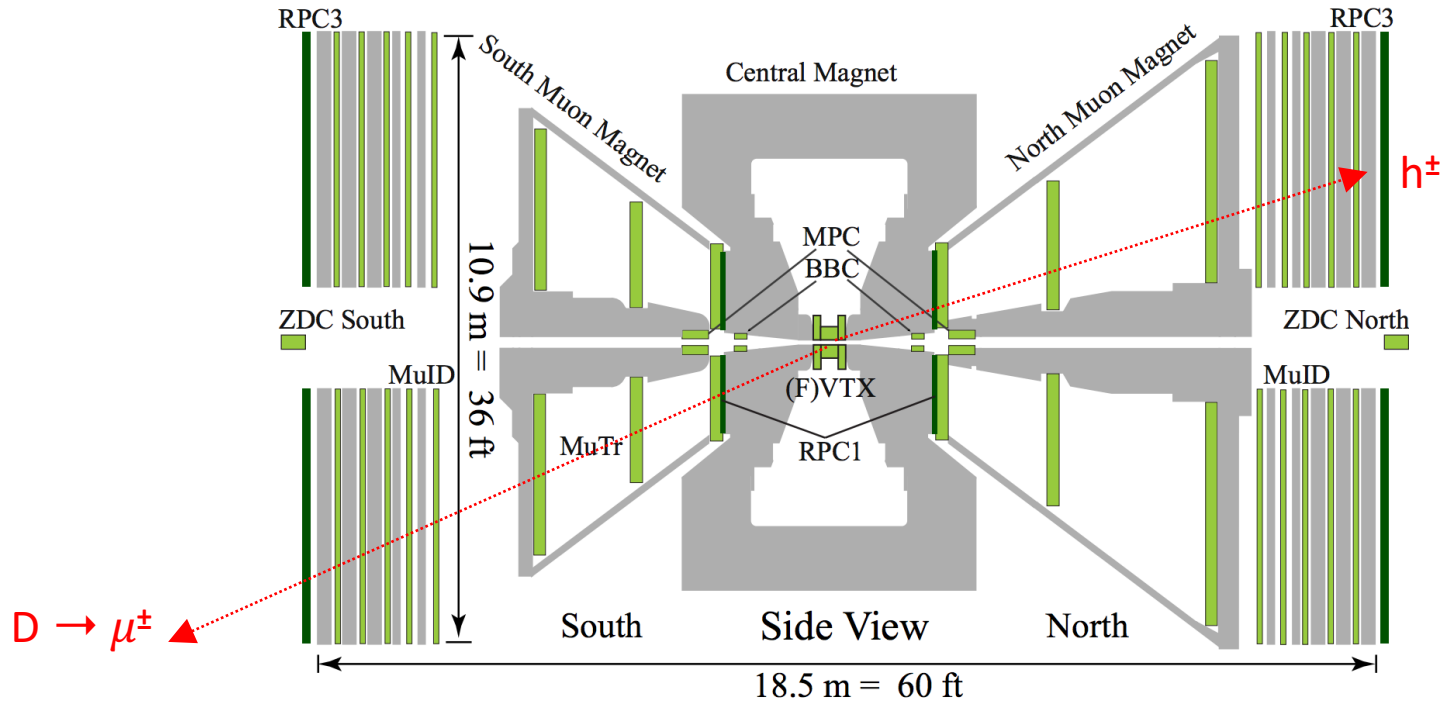
# RHIC as a polarized proton-proton collider




- The only facility: polarized proton collider
- Polarized proton-ion collisions in RUN 2015

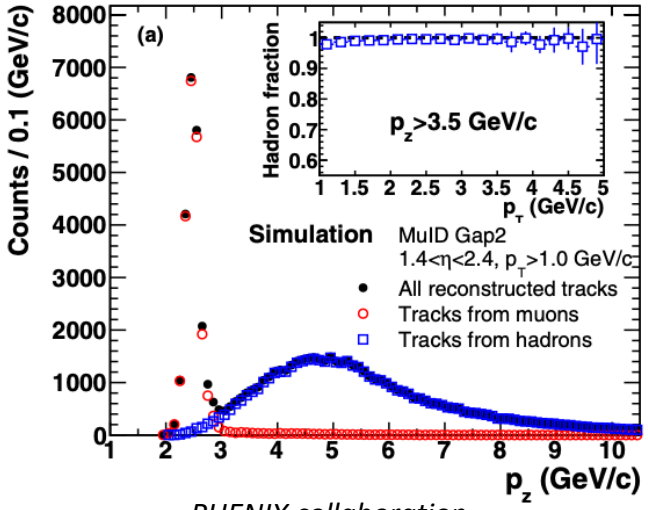
# Apparatus: PHENIX muon spectometer




- Two Muon spectrometers called South arm (-2.2<η<-1.2) and North arm (1.2<η<2.4)
- Muons penetrate whole system while hadrons stop in the middle.

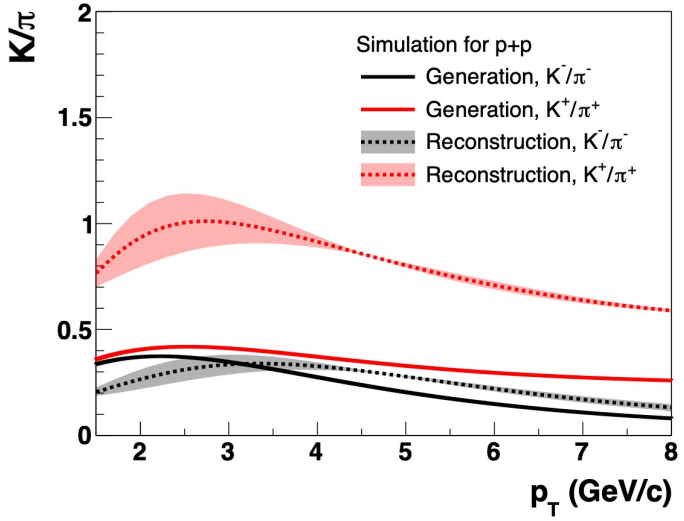
# Charged hadron selection

$p_z$ in simulation

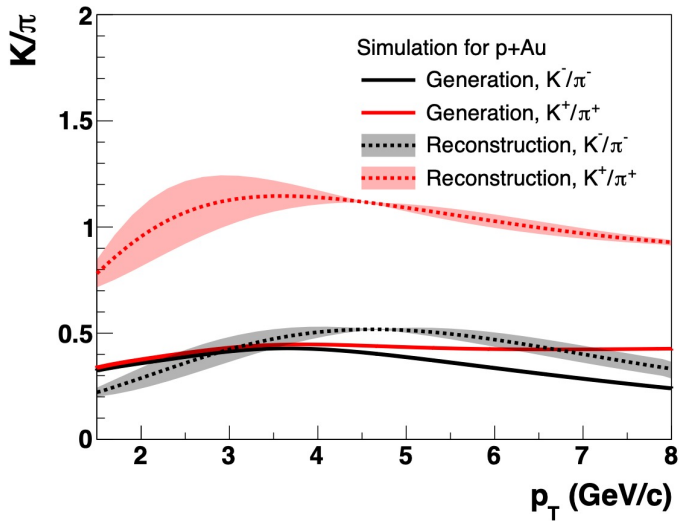



*PHENIX collaboration*
*PRC 101, 034910 (2020)*

K/$\pi$ in p+p



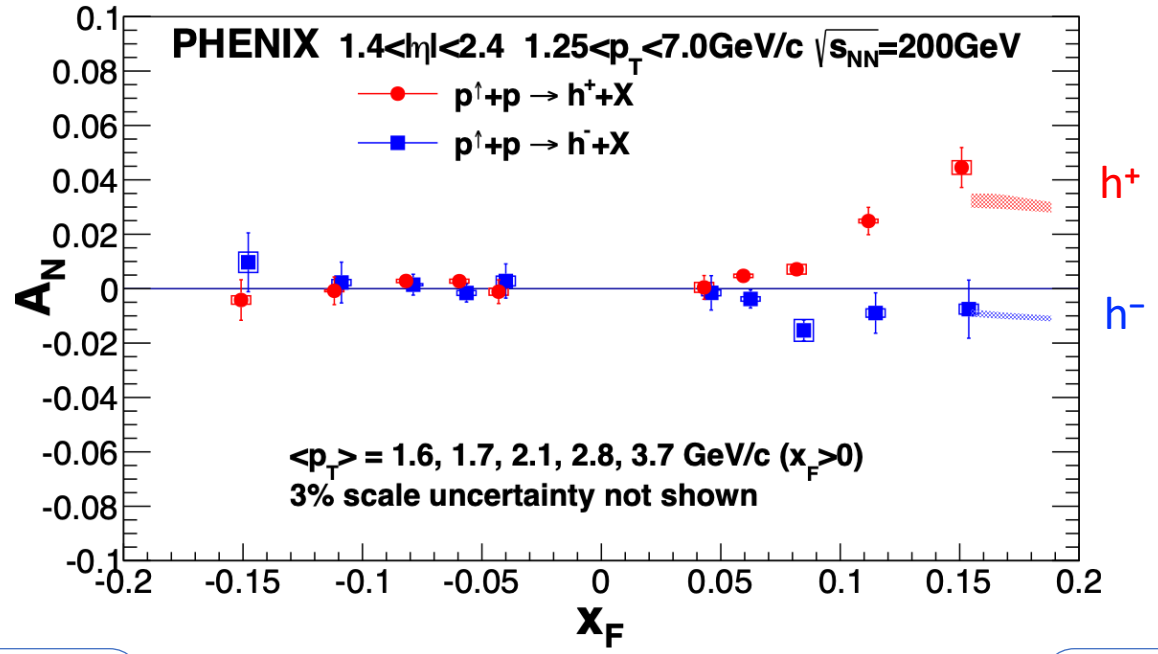

K/$\pi$ in p+Au

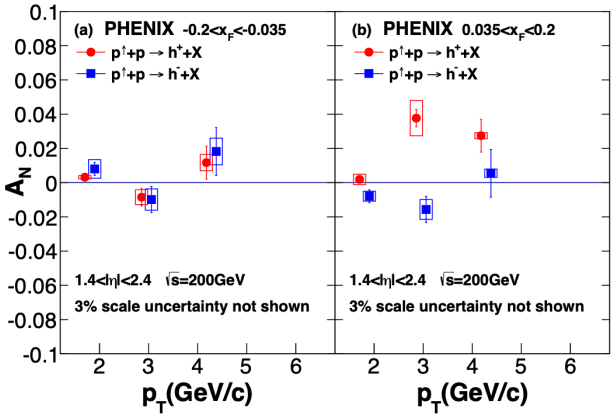


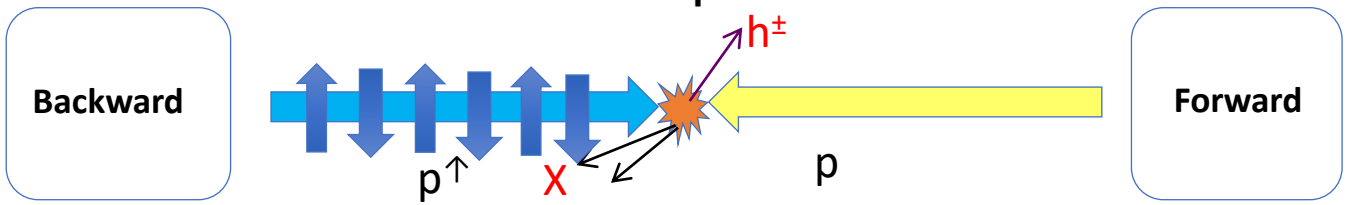

*PHENIX collaboration*
*Phys. Rev. D 108, 072016 (2023)*

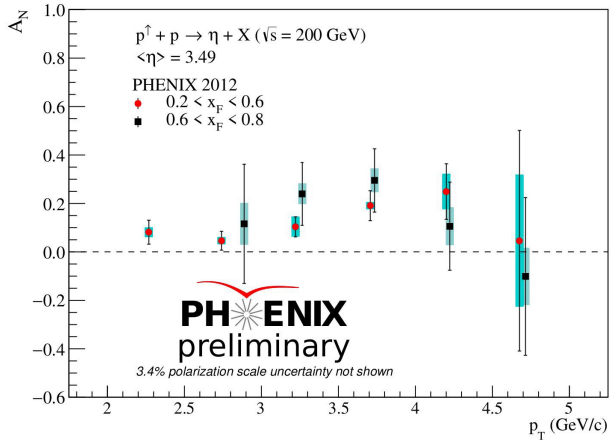
- Charged hadrons are stopped in the middle of Muon Identifier
- Muon background are rejected by $p_z$ cut
- K/$\pi$ modified due to the detector material including the front absorber

# Result: $p^{\uparrow}+p \rightarrow h^{\pm}+X$



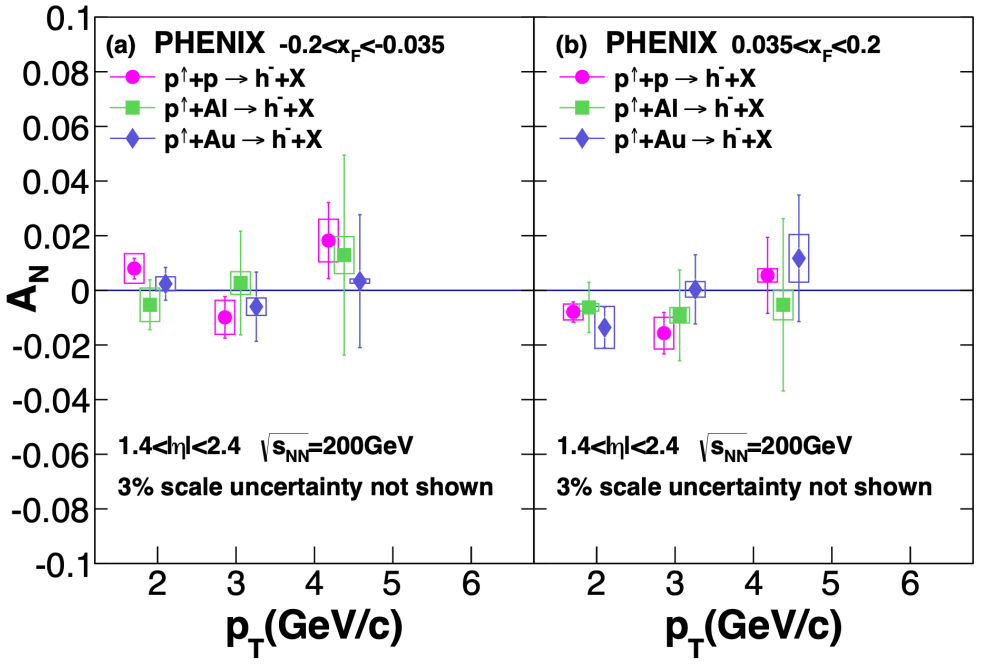




A hint of asymmetry drop at high $p_T$ $\eta$ at high $x_F$ in recent preliminary result

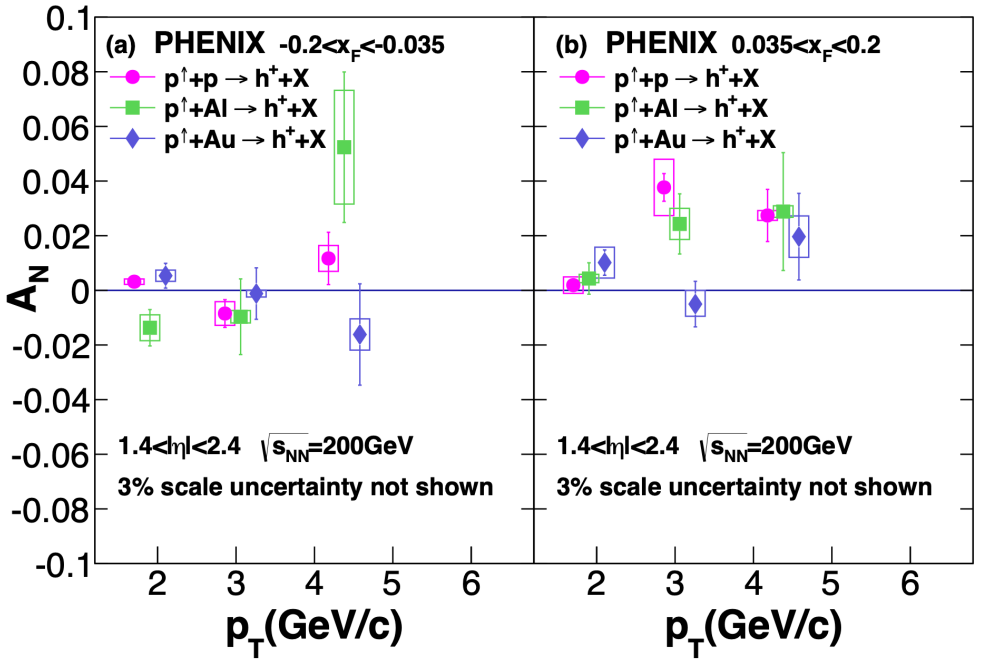
- Charged hadrons at $1.4<|\eta|<2.4$ *Phys. Rev. D 108, 072016 (2023)*
  - $A_N(h^+)$ increases to positive values as $x_F$ increases at $x_F>0$
  - $A_N(h^-)$ small to zero at $x_F>0$ : Opposite sign of $A_N$ for $\pi^-, K^-$ canceled partially
  - Model from *D. Pitonyak, PLB 770, 242 (2017)*

# Results in p↑+p, p↑+Al, p↑+Au → h±+X

p↑+p, p↑+Al, p↑+Au → $h^-$+X



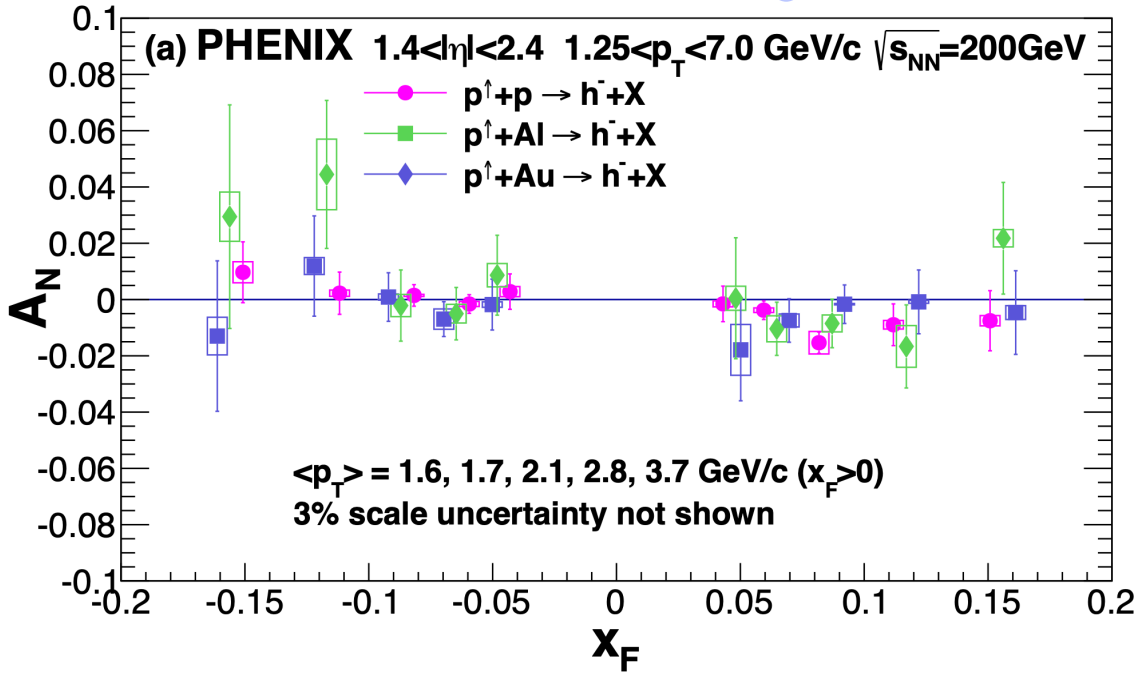

p↑+p, p↑+Al, p↑+Au → $h^+$+X



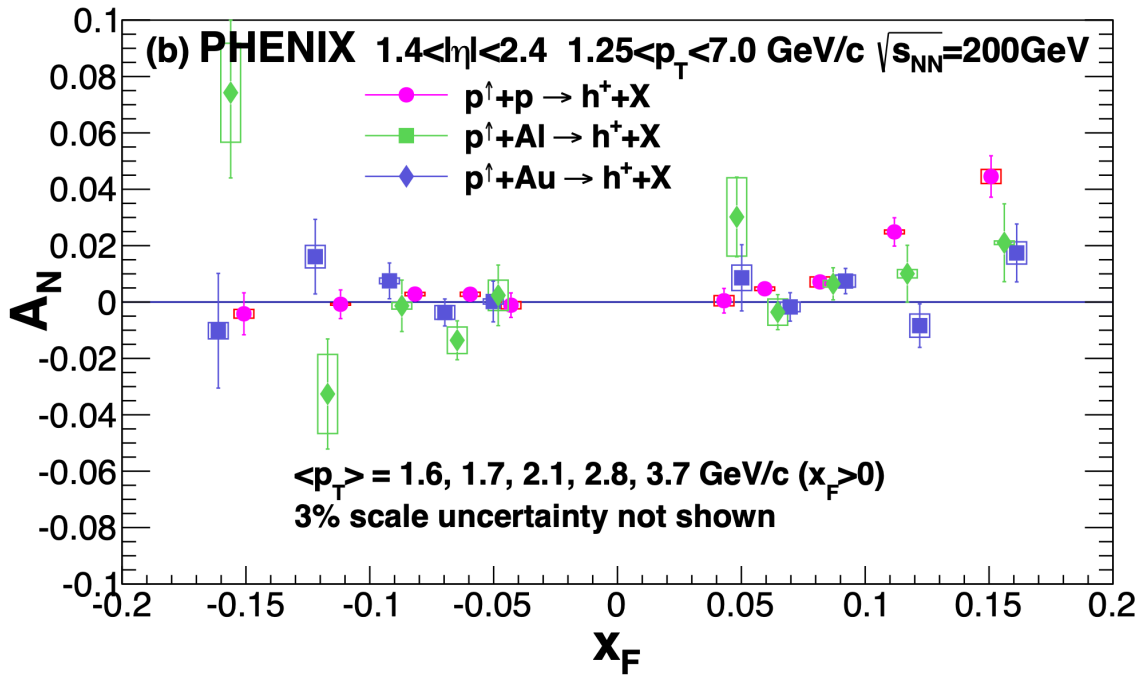

- *PHENIX collaboration Phys. Rev. D 108, 072016 (2023)*
- $1.25 < p_T < 7$ GeV/c

# Results in $p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au \rightarrow h^{\pm}+X$

$p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au \rightarrow h^{-}+X$

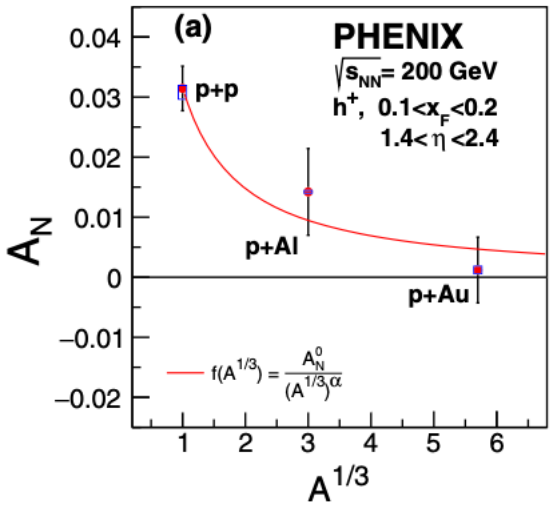



$p^{\uparrow}+p$, $p^{\uparrow}+Al$, $p^{\uparrow}+Au \rightarrow h^{+}+X$

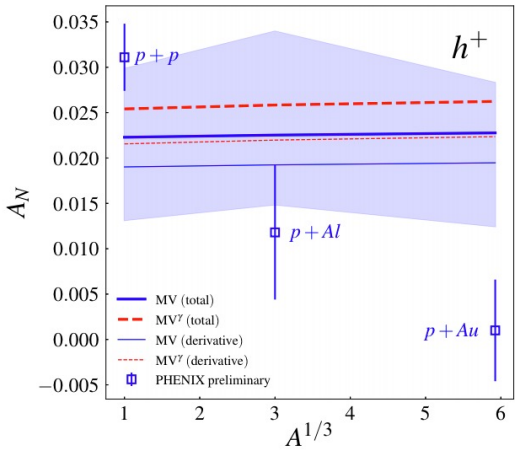



- *PHENIX collaboration Phys. Rev. D 108, 072016 (2023)*
- Smaller $A_N$ for $h^+$ at $0.1<x_F<0.2$ in p+A

# Nuclear dependence of $A_N$

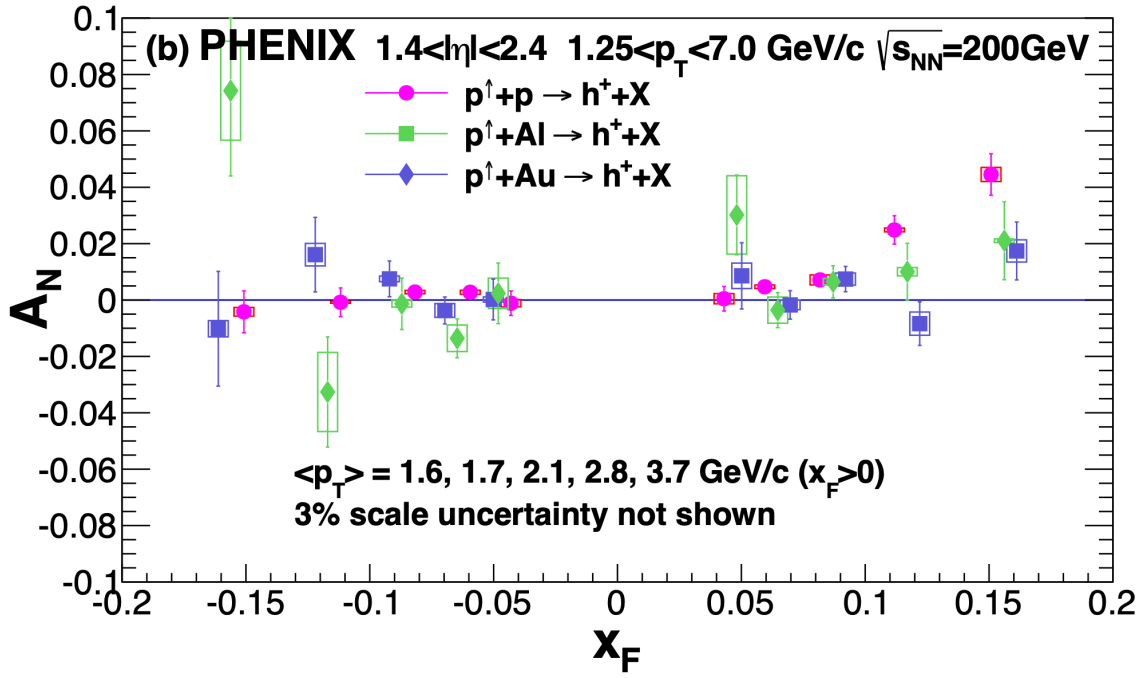



*PHENIX collaboration*
*PRL 123, 122001 (2019)*

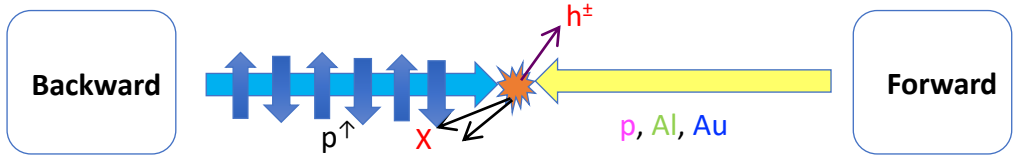



S. Benić and Y. Hatta
*PRD 99, 094012 (2019)*

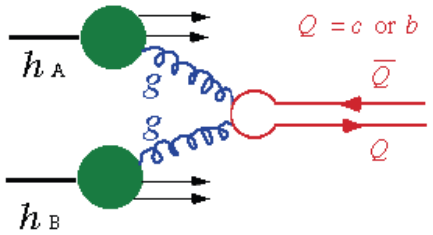
$p^\uparrow$+p, $p^\uparrow$+Al, $p^\uparrow$+Au → $h^+$+X



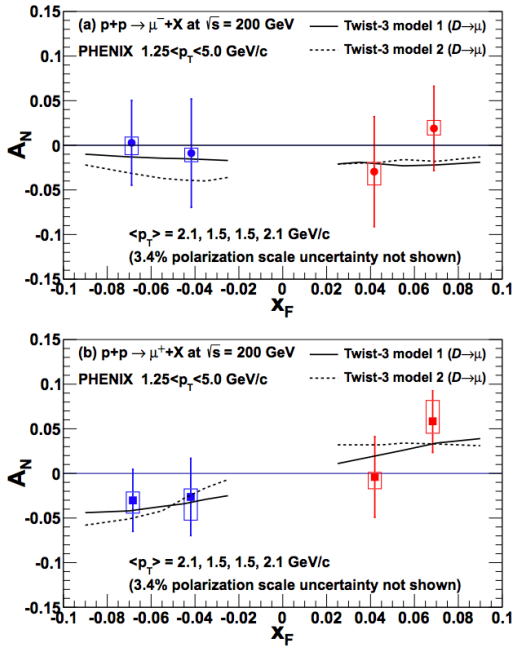

- Smaller $A_N$ for $h^+$ at $0.1<x_F<0.2$ in p+A



# Heavy Flavor $A_N$ in PHENIX

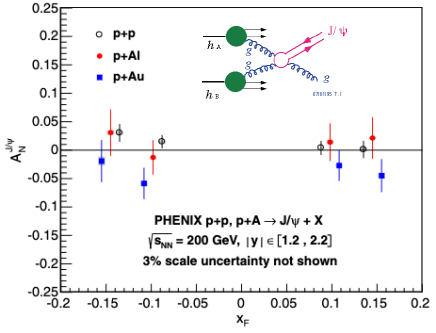



- Dominated by gluon-gluon interaction
- Clean probe for gluon Sivers effect – sensitive to the tri-gluon correlation function in the twist-3 collinear factorization framework.



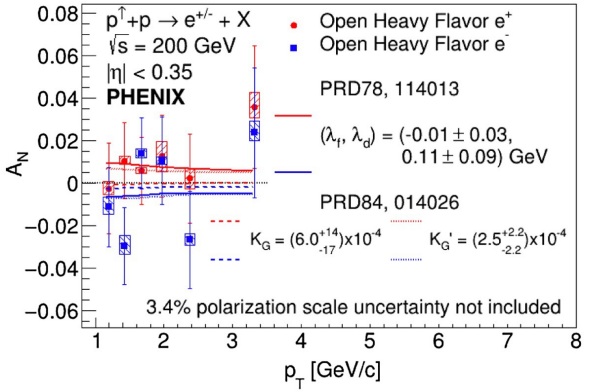

HF→ $\mu^{\pm}$ $1.4 < |\eta| < 2.0$

*Phys. Rev. D 95, 112001 (2017)*




$J/\psi \rightarrow \mu^+\mu^-$ $1.2 < |\eta| < 2.2$

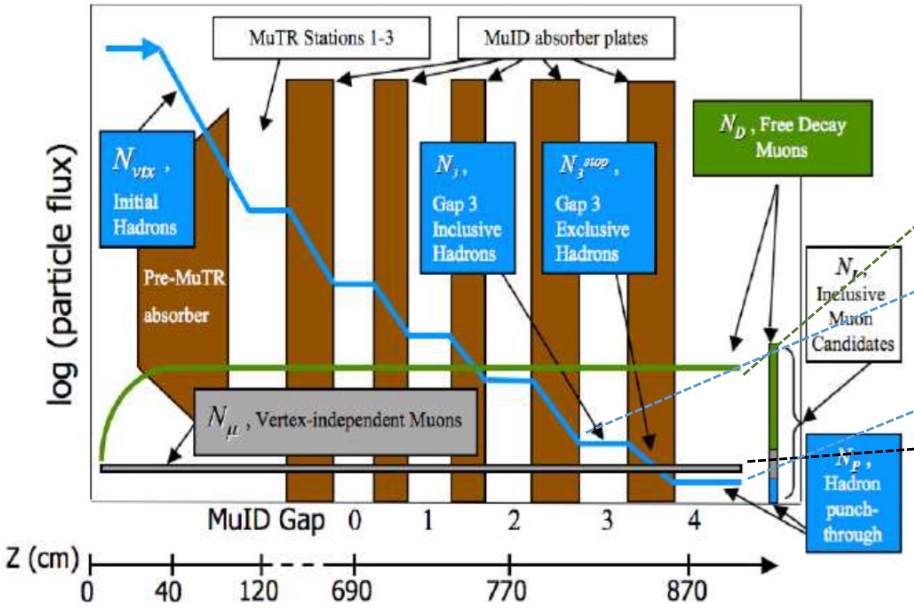
*Phys. Rev. D. 98, 012006 (2018)*




HF→ $e^{\pm}$ $|\eta| < 0.35$

*Phys. Rev. D. 107, 052012 (2023)*

# Open Heavy Flavor $A_N$ with Muon Arm

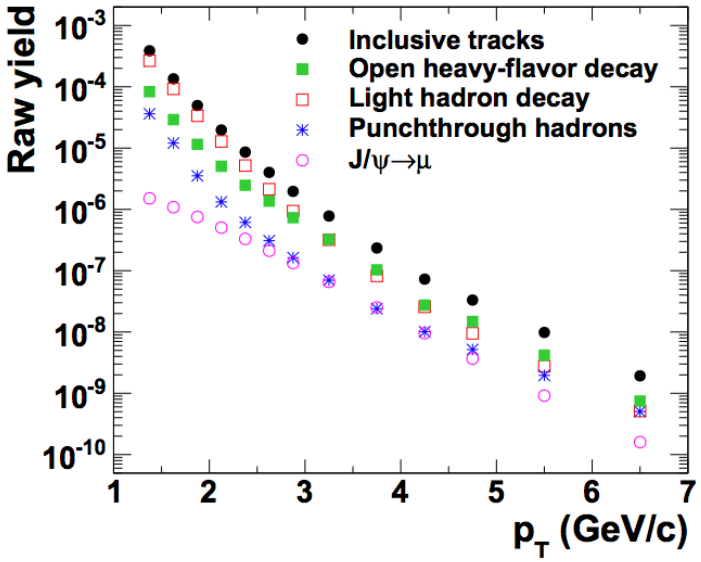



(1) Decay muon background ($\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}$)

(2) Stopped hadron ($\pi^{\pm}, K^{\pm}$)

(3) Punch through ($\pi^{\pm}, K^{\pm}$)

(4) Open Heavy Flavor ($D, B \rightarrow \mu^{\pm}$) and $J/\psi \rightarrow \mu^+\mu^-$

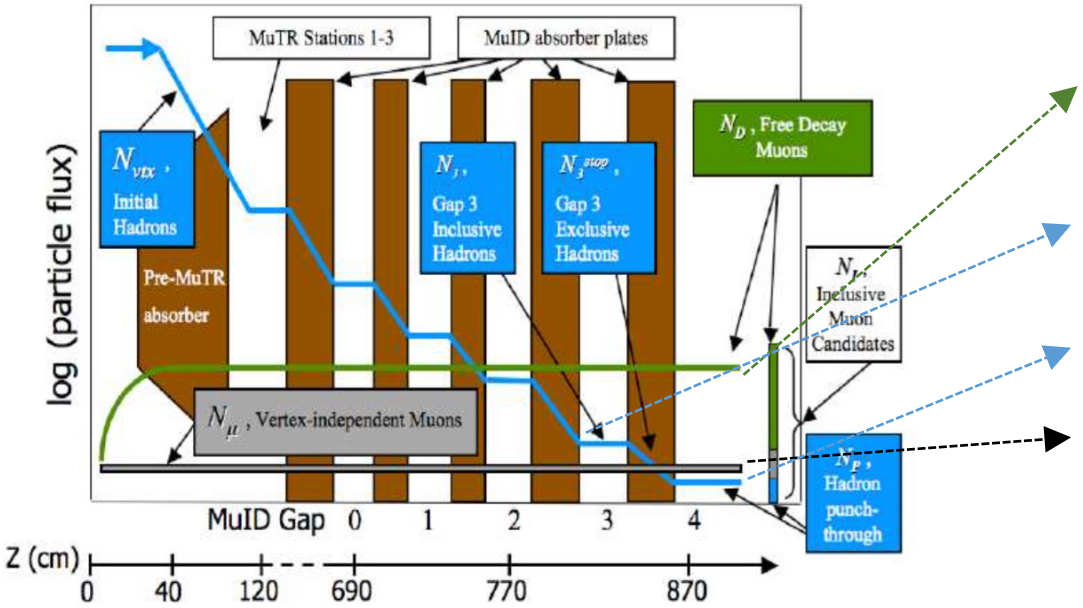



Raw Yield for each contribution

*Phys. Rev. D 95, 112001 (2017)*

- Background $A_N$ : charged hadron sample at MUID Gap3 tracks
- Inclusive $A_N$ : MUID Gap4 tracks
  - Signal : Heavy Flavor → $\mu^{\pm}$
  - Background
    - $\pi^{\pm}, K^{\pm}$ (→ $\mu^{\pm}$) : measured with Gap3 tracks
    - $J/\psi$ : using previous data, systematic uncertainty

# Open Heavy Flavor $A_N$ with Muon Arm




(1) Decay muon background ($\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}$)

(2) Stopped hadron ($\pi^{\pm}, K^{\pm}$)

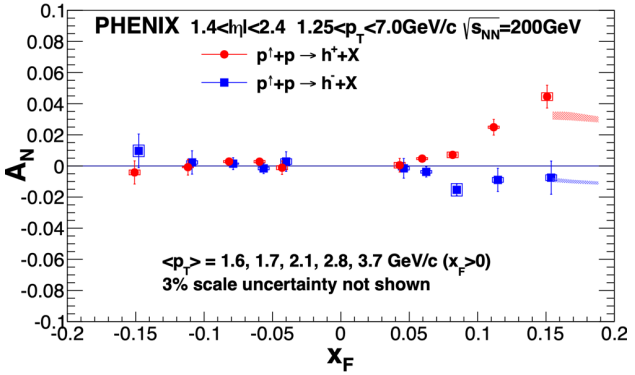
(3) Punch through ($\pi^{\pm}, K^{\pm}$)

(4) Open Heavy Flavor ($D, B \rightarrow \mu^{\pm}$) and $J/\psi \rightarrow \mu^+\mu^-$

- Background estimation using hadron cocktail
  - initial spectra from data + full GEANT simulation

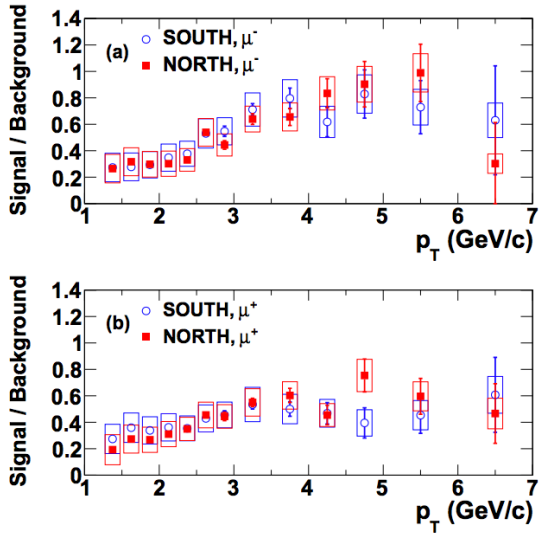
$$A_N^{Phys} = \frac{A_N^{incl} - r \cdot A_N^{BG}}{1 - r}$$

- Analysis ongoing for RUN15 dataset with large statistics




Hadron $A_N$ in previous analysis

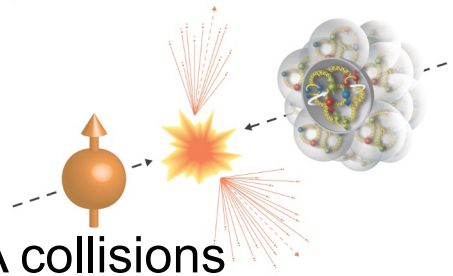
*Phys. Rev. D 108, 072016 (2023)*




S/B in previous analysis

# Summary

- Large Transverse Single Spin Asymmetry ($A_N$) in single hadron production consistently observed up to RHIC energies, over 40 years.
- $A_N$ of charged hadrons at forward and backward rapidity ($1.4<|\eta|<2.4$) from $p^{\uparrow}+p$, $p^{\uparrow}+Al$, and $p^{\uparrow}+Au$ collisions is studied in PHENIX
  - $1.5<p_T<7$ GeV/$c$ , $0.04<|x_F|<0.2$
  - $A_N(h^-)$: small to zero
  - $A_N(h^+)$: increases to positive values as $x_F$ increases in $p^{\uparrow}+p$ , smaller in $p^{\uparrow}+A$ collisions

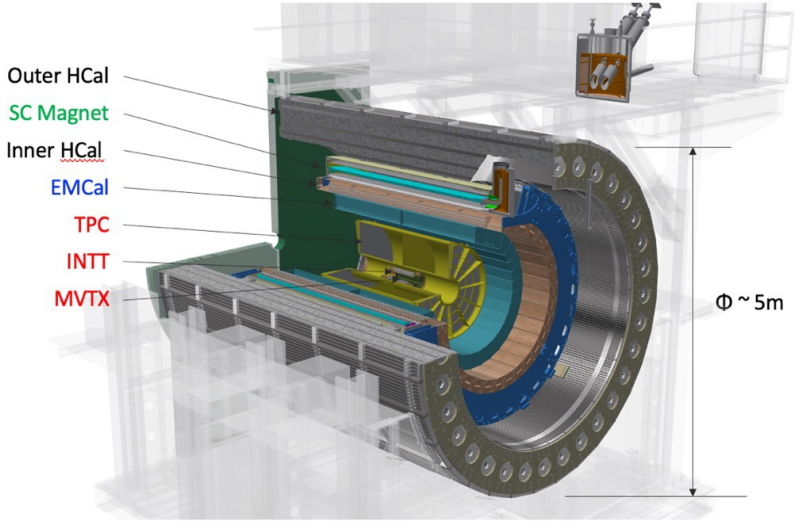


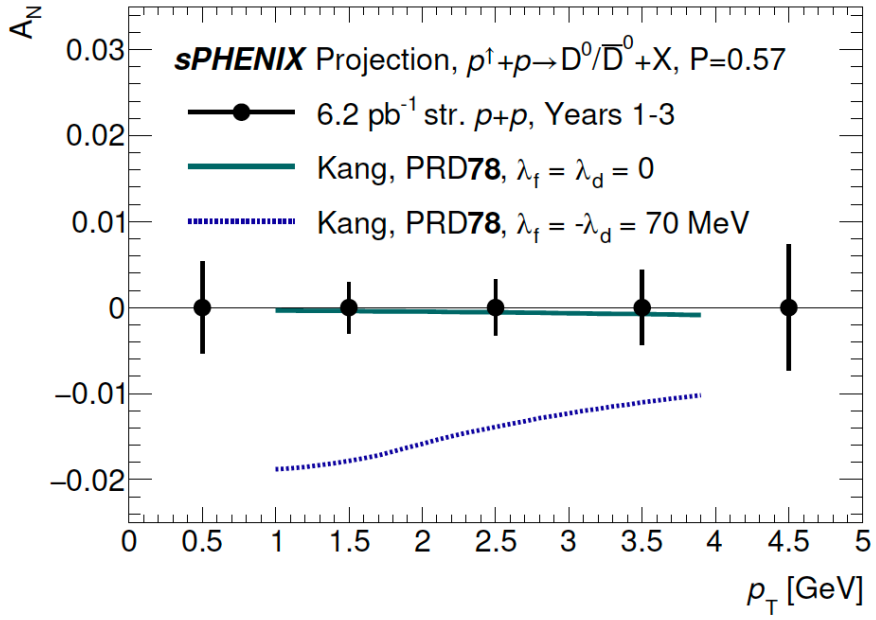
- Heavy Flavor in $A_N$ pp collision is sensitive to tri-gluon correlation function in twist-3 collinear factorization
  - Analysis on open heavy flavor (D,B→ $\mu^{\pm}$ , $1.4 < |\eta| < 2.0$) is ongoing for RUN15 data
  - sPHENIX will measure D meson $A_N$

PHENIX

# Thank You!

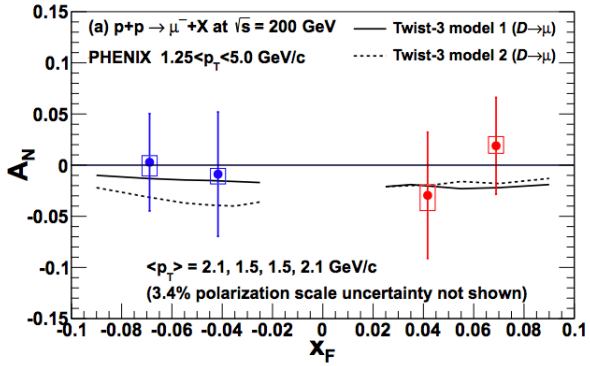
# Future perspective
# D-meson $A_N$ in sPHENIX

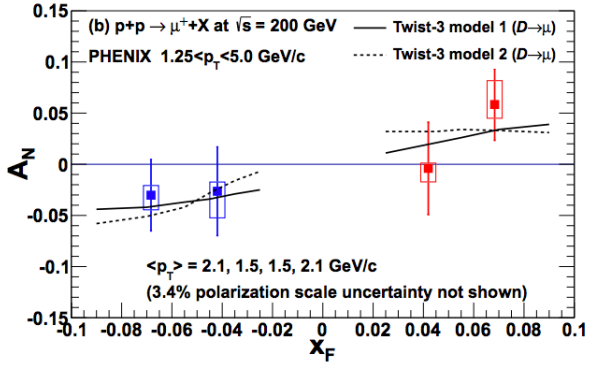


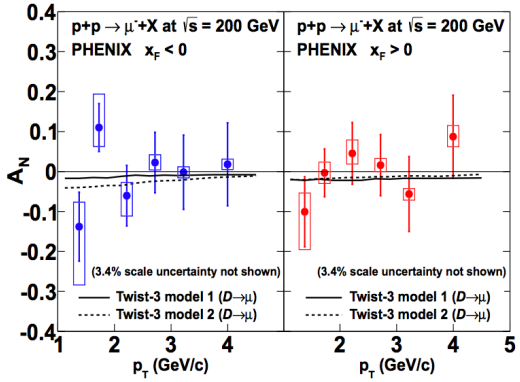



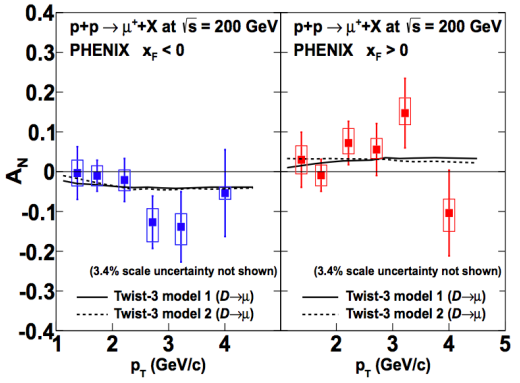

- sPHENIX is taking data from transversely-polarized p+p collision

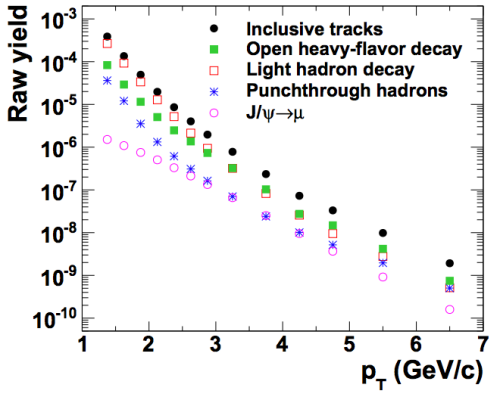
# Previous open HF $A_N$ with Muon Arm

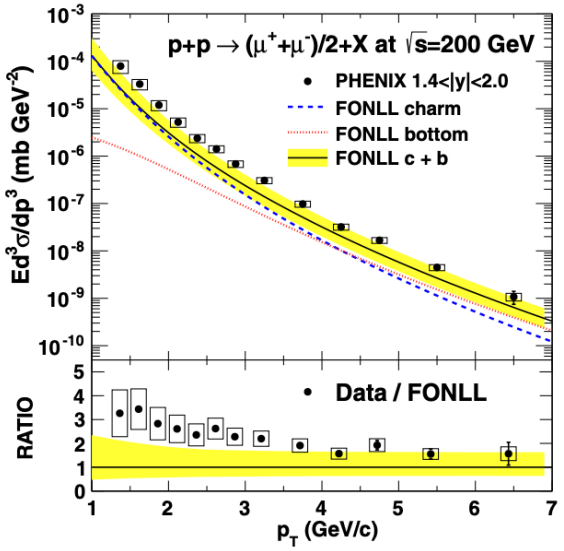


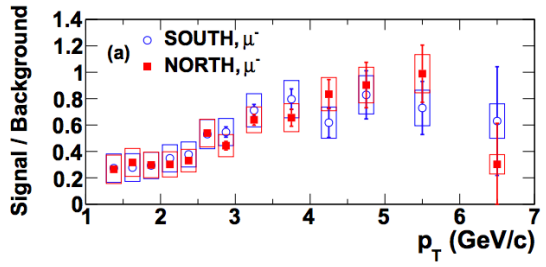



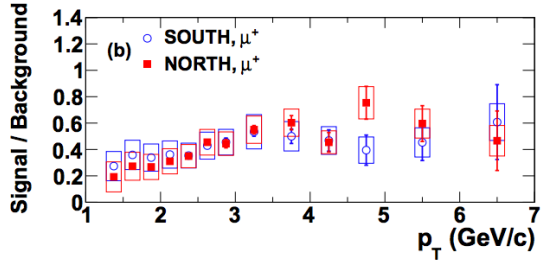



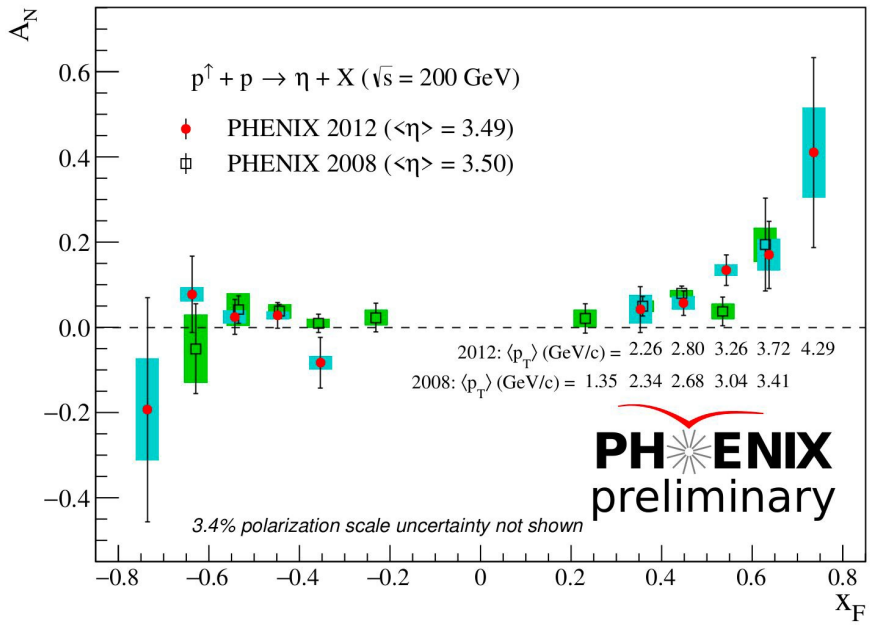



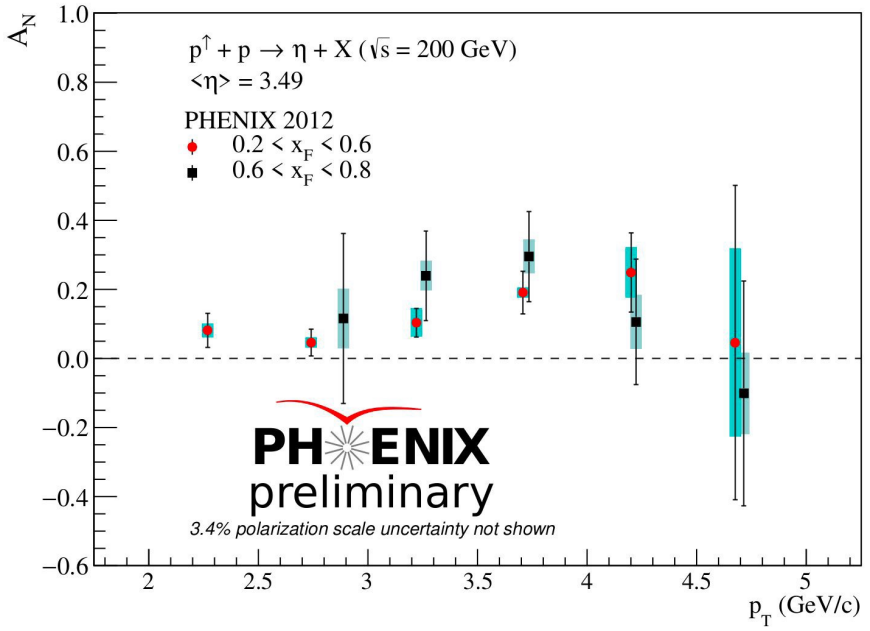



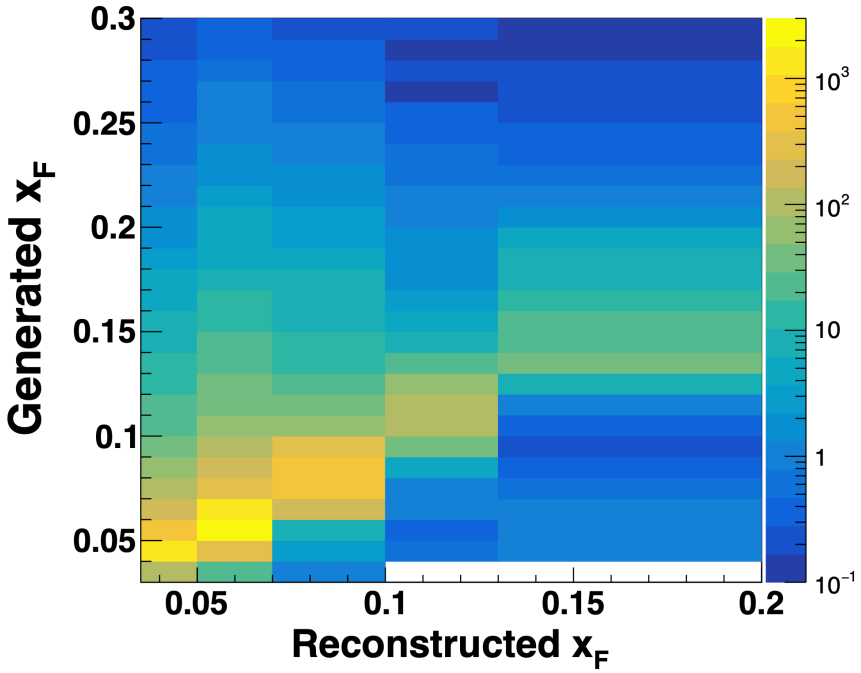

*Phys. Rev. D 95, 112001 (2017)*
Model from *Y. Koike and S. Yoshida*
*Phys. Rev. D 84, 014026 (2011)*

# Recent PHENIX result : forward $\eta$ $A_N$

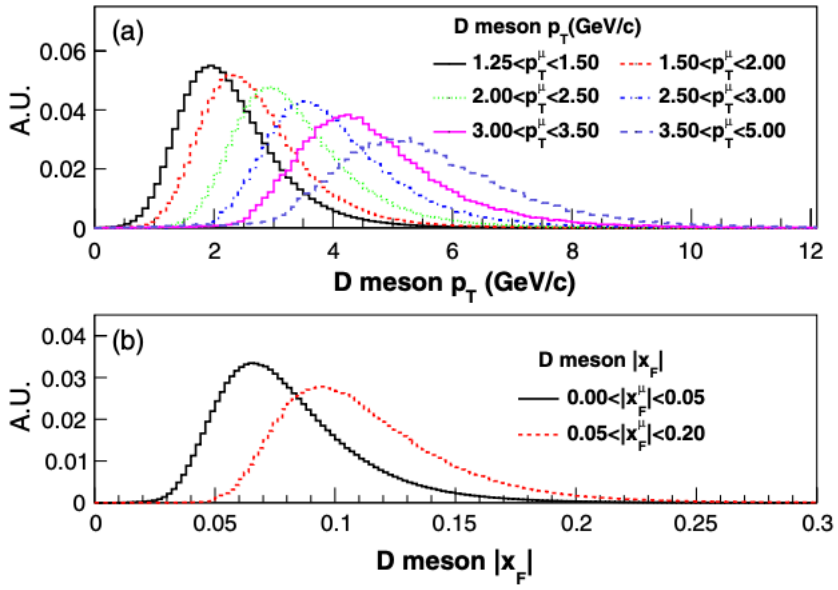


# Backup




Charged hadron




D meson decay

# Abstract

- Title: Recent Transverse Spin Results in PHENIX
- Abstract
  - Studying transverse single-spin asymmetries (TSSAs) in transversely polarized proton-proton collisions allows us to understand the spin structure of the proton and parton dynamics within the proton. The Relativistic Heavy Ion Collider (RHIC) is a unique apparatus for exploring the nucleon spin structure by colliding polarized protons and protons on ions. The measurement of TSSA of light hadrons in polarized pp and polarized pA collisions can provide insight into the underlying mechanism of the TSSA. Also, measuring TSSA of open heavy flavor offers a unique opportunity to get information on the trigluon correlation function in the collinear factorization framework. In this presentation, recent results of TSSAs for positively and negatively charged hadrons at forward and backward rapidity will be presented. In addition, we will report the status and prospects of open heavy-flavor TSSAs in the PHENIX experiment.