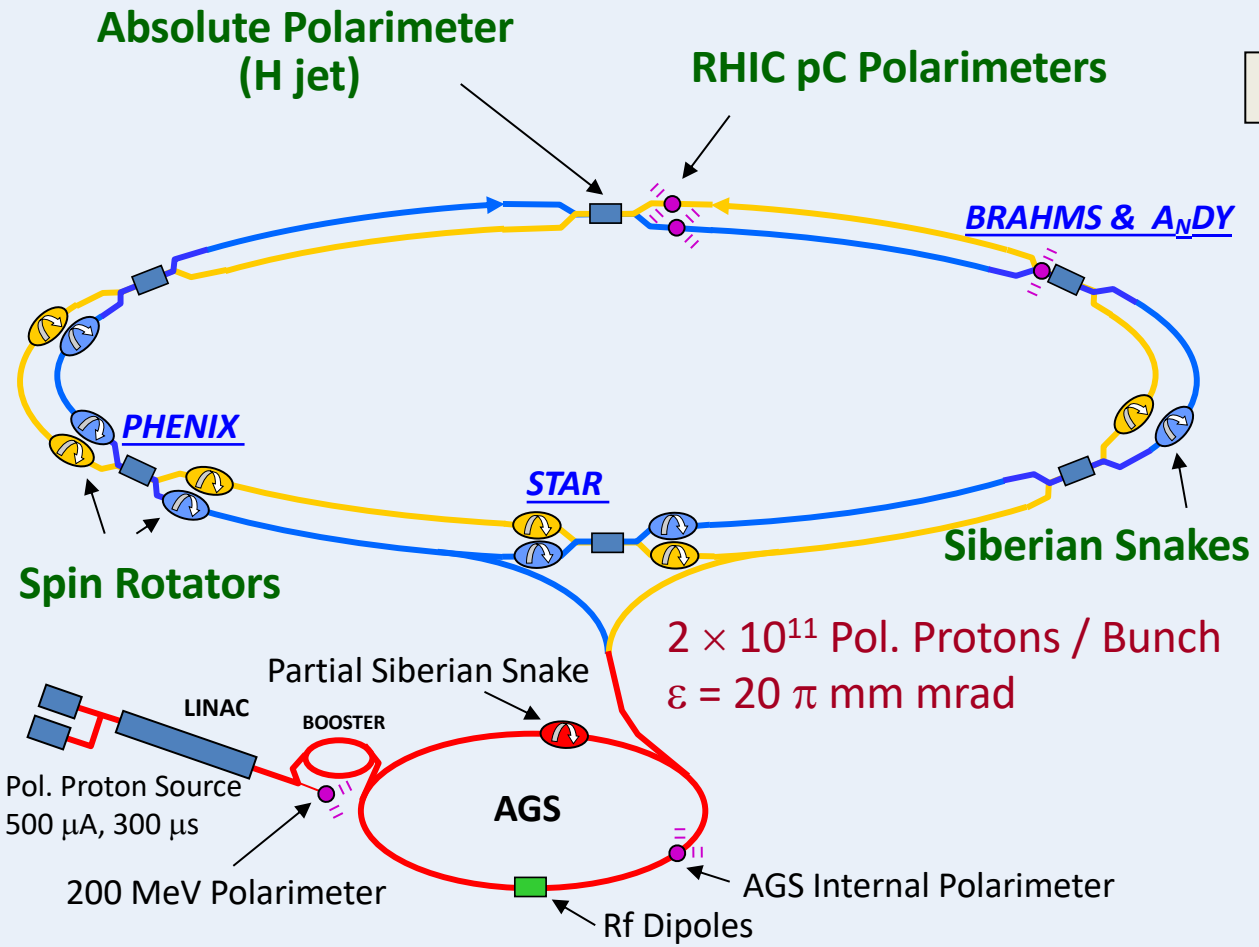
PHENIX Spin Highlights and Recent Results

- ✓ Nucleon helicity structure
- ✓ Transverse spin phenomena in p+p
- ✓ Polarized p + A

A.Bazilevsky (BNL)

For PHENIX Collaboration

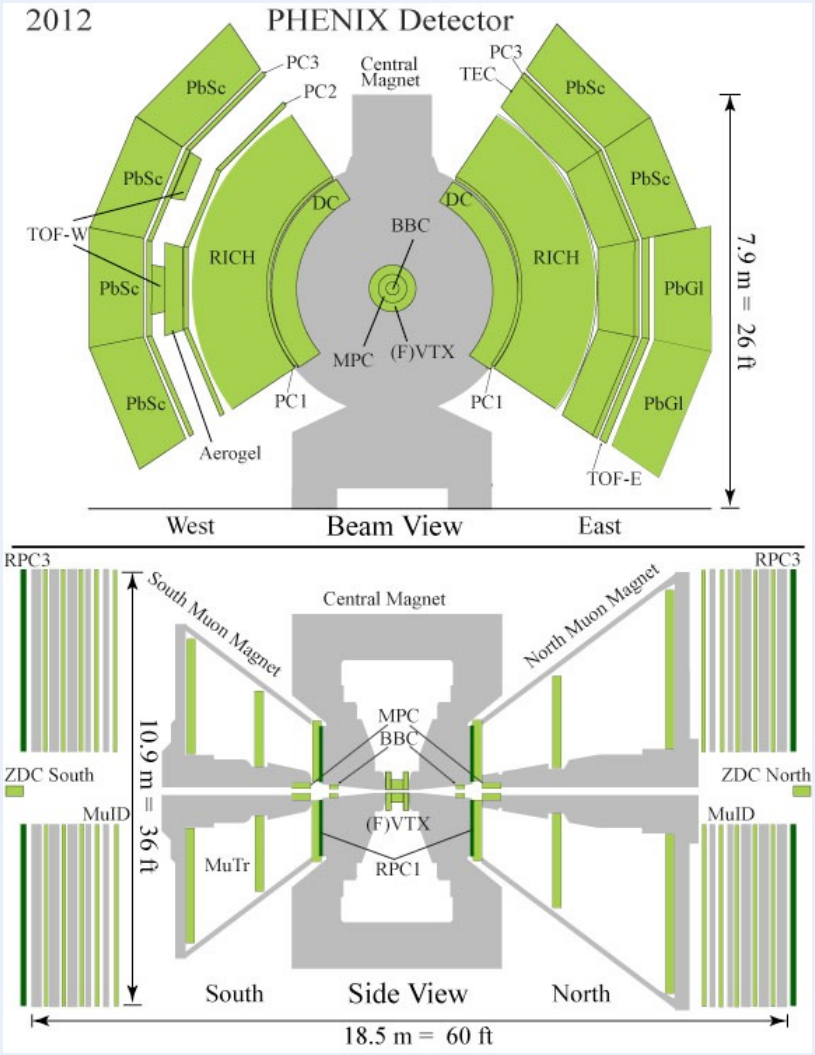
PHENIX Spin @ RHIC



Spin Running in PHENIX, long./trans.

Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2002	200	– / 0.15	15
2003	200	0.35 / –	27
2004	200	0.12 / –	40
2005	200	3.4 / 0.2	49
2006	200	7.5 / 2.7	57
2006	**62.4**	**0.08 / 0.02**	**48**
2008	200	– / 5.2	45
2009	200	16 / –	55
2009	**500**	**14 / –**	**39**
2011	**500**	**18 / –**	**48**
2012	200	– / 10	56
2012	**510**	**32 / –**	**56**
2013	**510**	**155 / –**	**56**
2015	200	– /60	58
2015	pAu@200	– /0.2	61
2015	pAl@200	– /0.5	58

PHENIX Detector



π^0, γ, η

Electromagnetic Calorimeter: **$|\eta|<0.35$**

Muon Piston Calorimeter: **$3.1<|\eta|<3.9$**

$\pi^{\pm}$, e, $J/\psi \rightarrow e^+e^-$, $W \rightarrow e$: **$|\eta|<0.35$**

Drift, Pad Chambers, VTX ($|\eta|<1$)

Ring Imaging Cherenkov Counter, ToF

Electromagnetic Calorimeter

VTX

μ, $h^{\pm}$, $J/\psi \rightarrow \mu^+\mu^-$, $W \rightarrow \mu$: **$1.2<|\eta|<2.4$**

Muon Id/Muon Tracker

FVTX

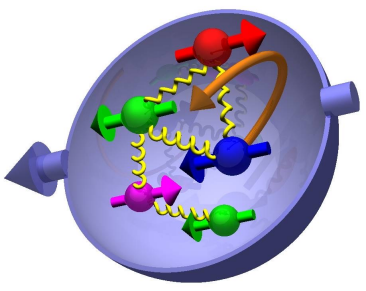
Relative Luminosity

Beam Beam Counter (BBC)

Zero Degree Calorimeter (ZDC)

Local Polarimetry – ZDC & SMD

Spin direction control



ΔG: π0 A_{LL}

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G + L_z$$

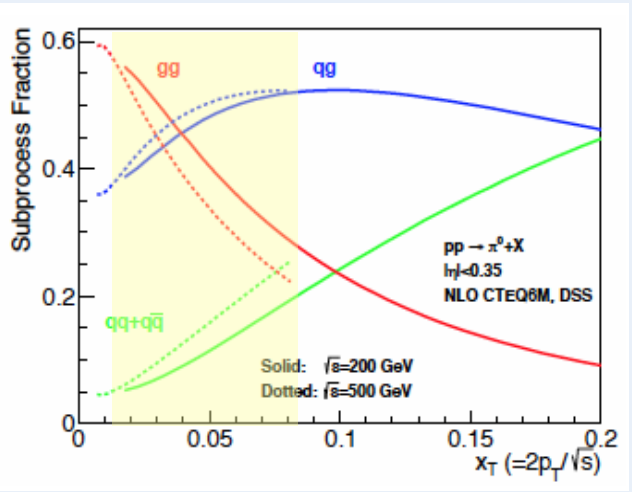
The most abundant probe in PHENIX

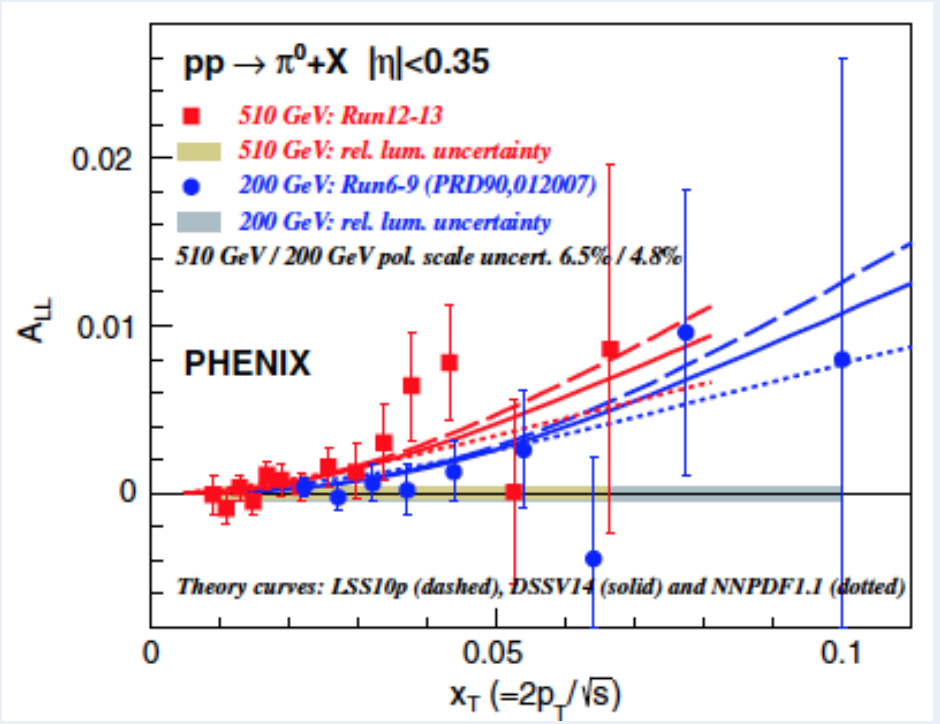
(triggering + identification capability)

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

PRD93, 011501 (2016)

$A_{LL} \sim$ $\frac{\Delta G}{G}\frac{\Delta G}{G}$ + $\frac{\Delta q}{q}\frac{\Delta G}{G}$ + $\frac{\Delta q}{q}\frac{\Delta q}{q}$ + ...



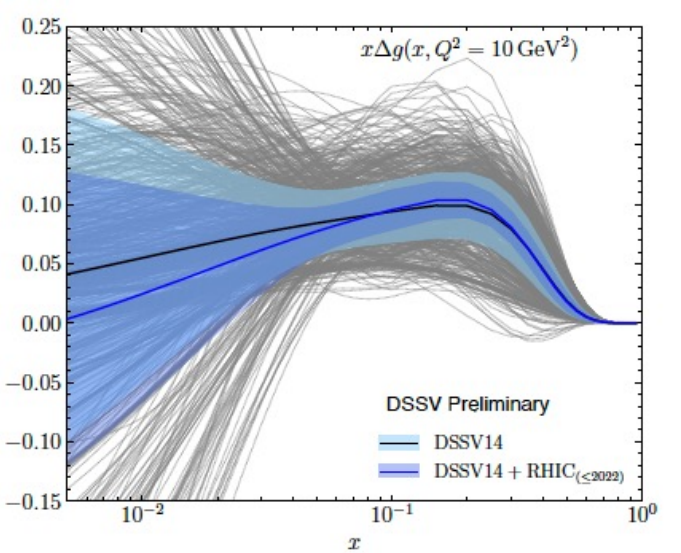


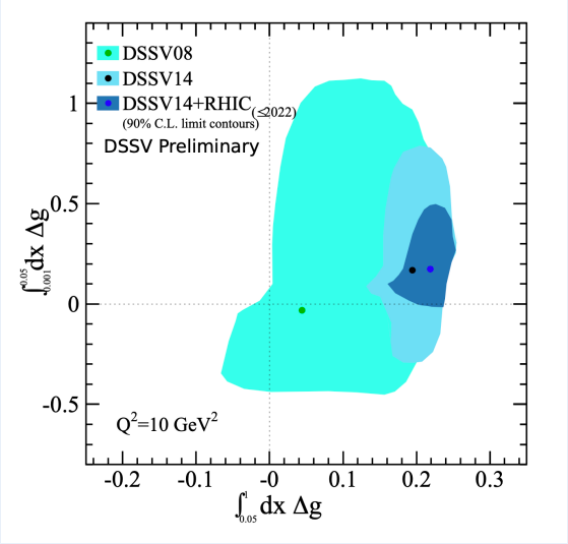
Non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

DSSV:
D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang

pp main contributors: PHENIX π0 + STAR jet





$$\int_{0.05}^{1} dx\Delta g(x) = 0.218 \pm 0.027$$

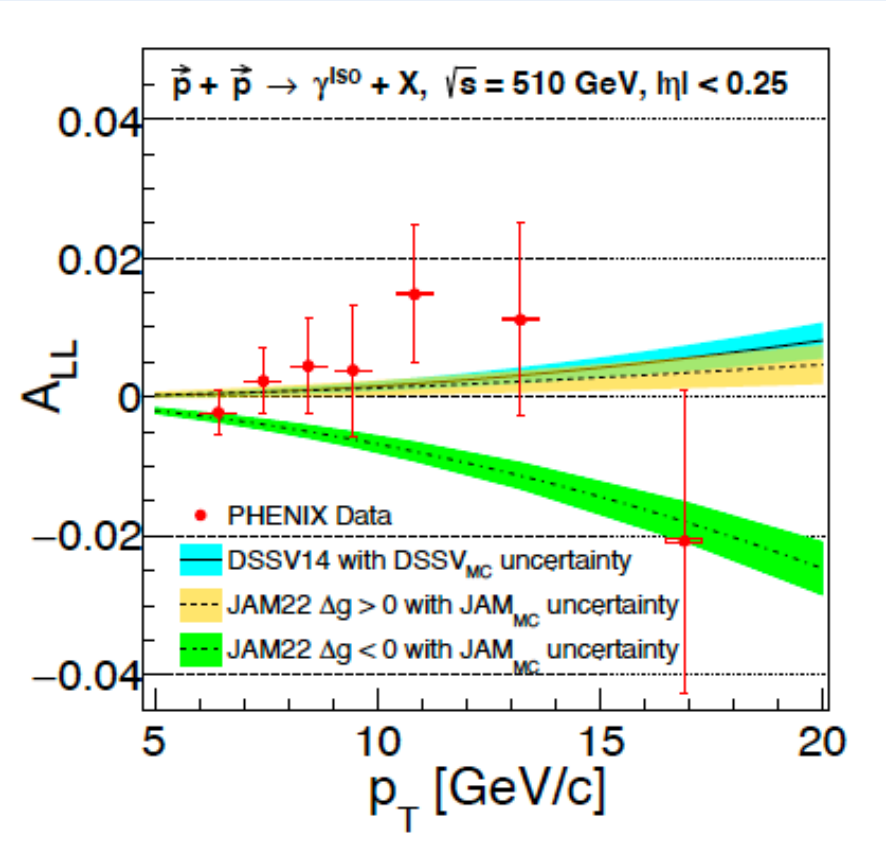
- Significant contribution from gluon spin to proton spin (at x>0.05)
  - Similar conclusion from other global fits: NNPDF, JAM
- More A_{LL} data are published: η, $\pi\pm$, $h\pm$, J/ψ, HF e
- Still large uncertainty in unmeasured region (x<0.05)
  - => Will be fully resolved at EIC
- Sign needs a confirmation (see next slide)
  - => Need cleaner prob, e.g. direct photons

ΔG: Confirm the Sign

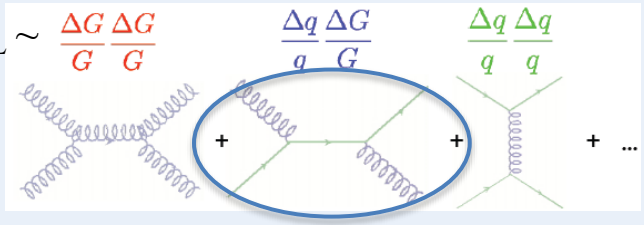
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_z$$

Direct photon - a golden channel to probe gluons

PRL130, 251901 (2023)



$A_{LL} \sim \frac{\Delta G}{G}\frac{\Delta G}{G} + \frac{\Delta q}{q}\frac{\Delta G}{G} + \frac{\Delta q}{q}\frac{\Delta q}{q} + \ldots$



JAM collaboration:

Negative ΔG still allowed

PHENIX:

Clear preference for positive ΔG

$$d_L\bar{u}_R \to W^-$$
$$u_L\bar{d}_R \to W^+$$

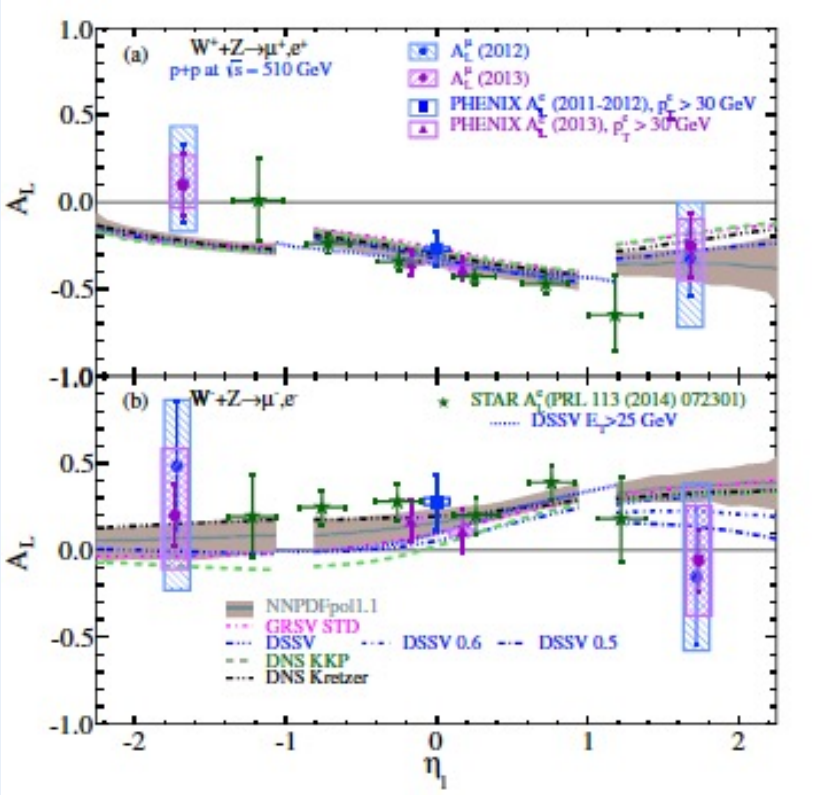
Δq-bar: $W^{\pm} \to e^{\pm}, \mu^{\pm}$

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G + L_z$$

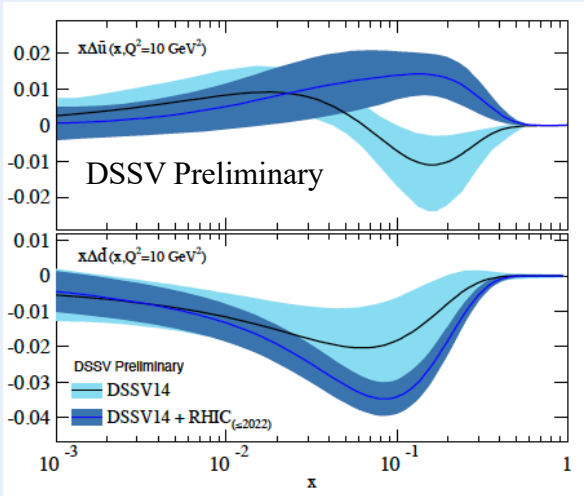
$e^{\pm}$: $|\eta|<0.35$ $\mu^{\pm}$: $1.2<|\eta|<2.4$

Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x>0.05$, with no fragmentation involved (as in SIDIS)

PRD 98, 032007 (2018)



STAR+PHENIX included



Preference of

Positive ubar polarization

Negative dbar polarization

Transverse Spin Physics

Initial State:

- A_N for jets, direct photons
- A_N for heavy flavor ➔ gluon
- A_N for W, Z, DY

Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

- Parton dynamics
- 3D imaging

Final State:

- Hadron azimuthal asymmetry in jet
- Hadron pair azimuthal asymmetry (Interference fragmentation function)

Sensitive to
transversity x spin-dependent FF

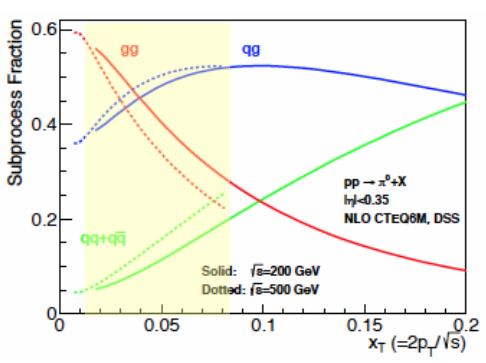
Universal between SIDIS & pp & e+e-

- Quark transversity
- Tensor charge

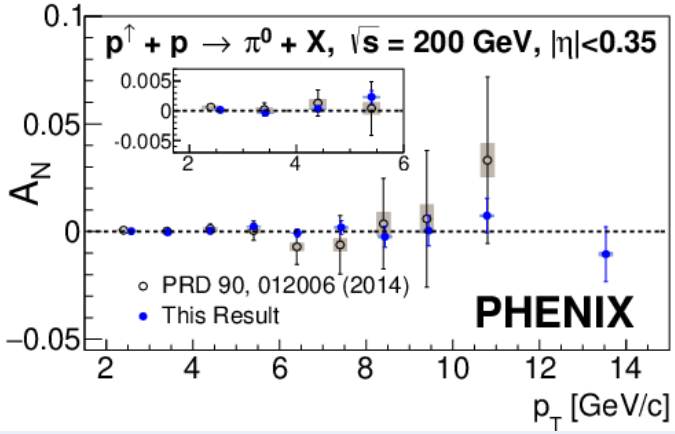
Other mechanisms

- Diffraction

A_N: Mid-rapidity π^0, η, $\pi^{\pm}$



PRD103, 052009 (2021)



Consistent with 0

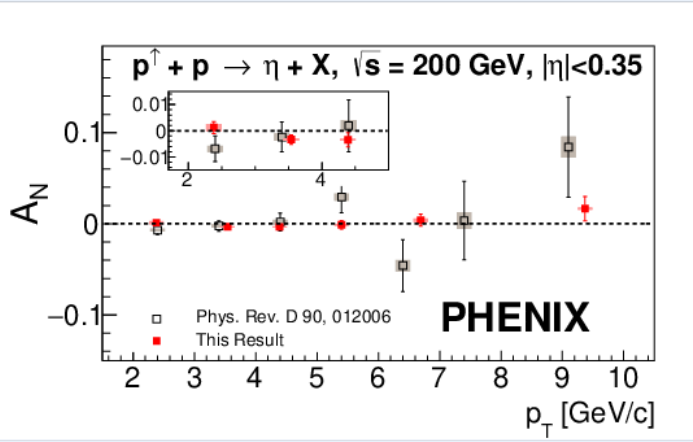
To ~3×10^{-4} precision level at $\pi0$ low p_T

Sensitive to gluon dynamics

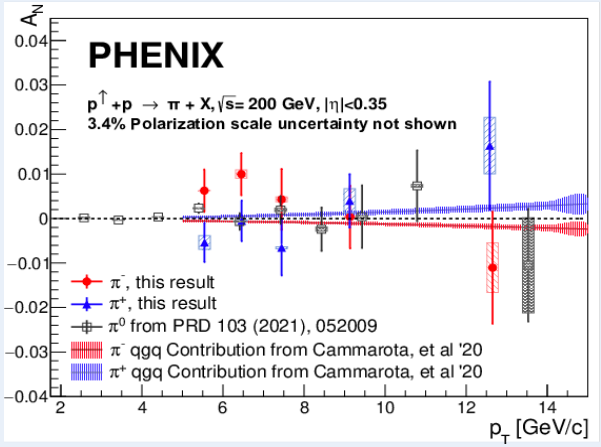
Used to constrain gluon Sivers effect:

Anselmino et al, PRD 74 (2006), 094011

D'Alesio et al, JHEP 1509 (2015), 119

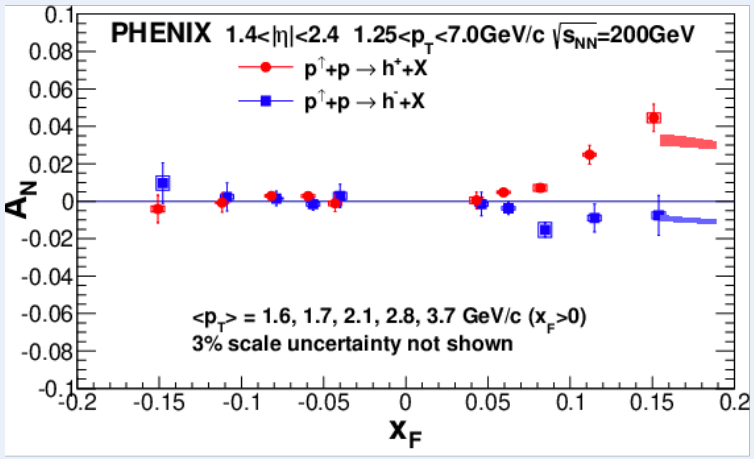


PRD105, 032003 (2022)



A_N: Forward *h*±

PRD108, 072016 (2023)



Sizable positive A_N for h+

Mix of positive A_N from π+ and positive from K+

Slightly negative A_N for h-

Mix of negative A_N from π- and positive from K-

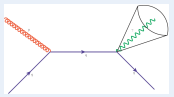
Comparison to Twist-3 model

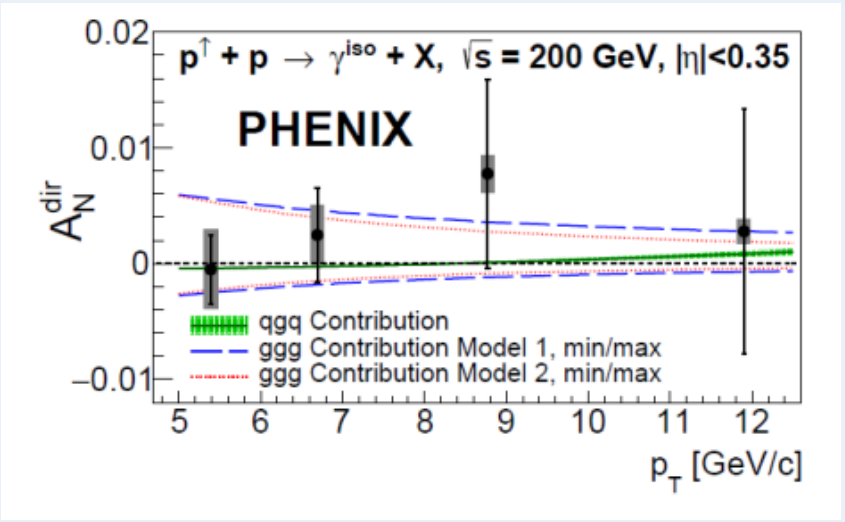
Gamberg, Kang, Pitonyak, Prokudin, Phys.Lett.B 770, 242

A_N: Direct Photon and HF

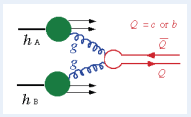
Constraints gluon dynamics within proton (through tri-gluon correlation function)

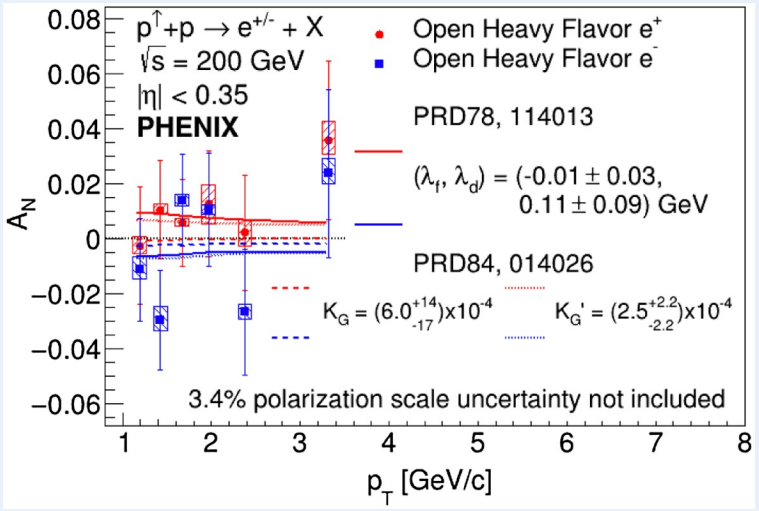
PRL127, 162001 (2021)





PRD107, 052012 (2023)





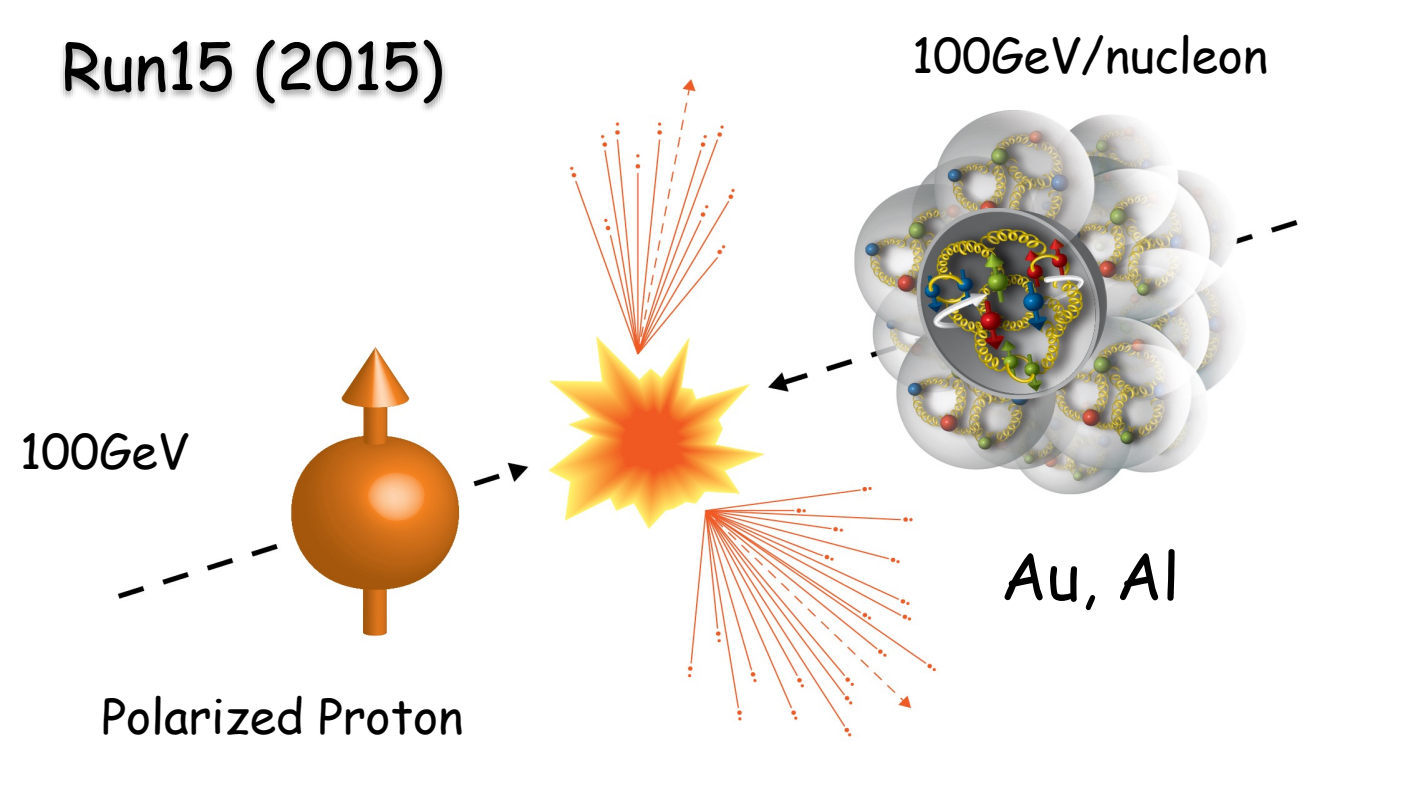
- ✓ Dominated by Gluon Compton
- ✓ ×50 times reduced uncertainty compared to the only prior measurement at E704 (Fermilab)
- ✓ Sensitive to model calculations

Dominated by gluon-gluon fusion

First constrains on tri-gluon parameters

Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013; Y.Koike, S.Yoshida, PRD84,014026

First and the only $p^{\uparrow} + A$ data !!!

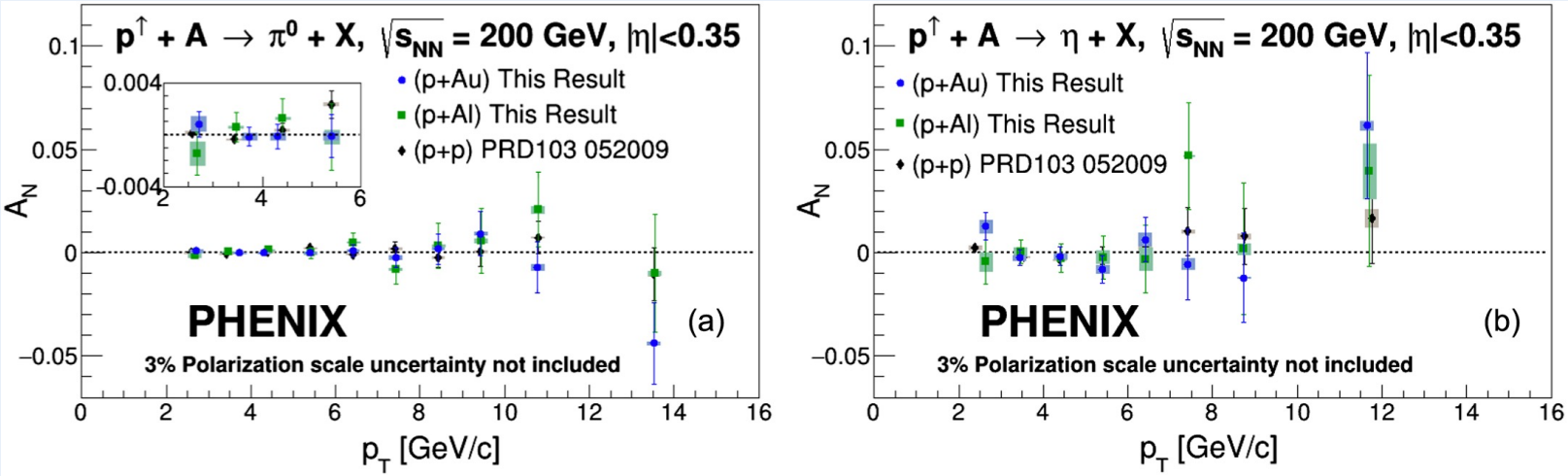


- Pin down the origin of A_N
- Study nuclear effect with a polarized probe!

A_N: Central rapidity

$\pi 0$ at $|\eta|<0.35$

PRD107, 112004 (2023)



Very high precision data

$\sigma_A \sim 3\times10^{-4}$ (10^{-3}) at lowest pT in pp (pA)

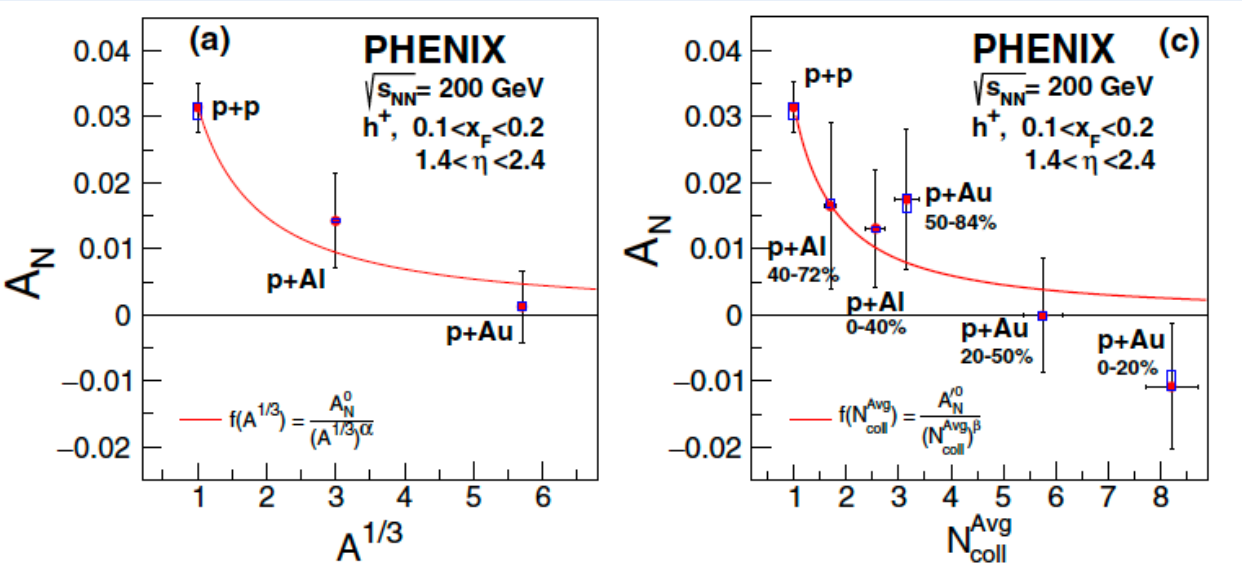
A_N consistent with 0 for all systems

To be used to constrain gluon Sivers fct.

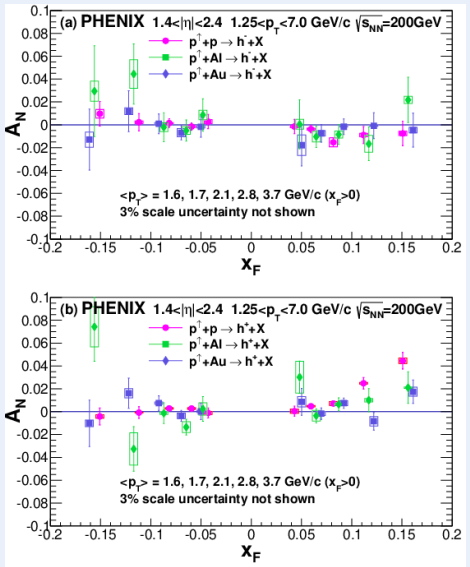
A_N: Forward rapidity

h+ at $1.2<|\eta|<2.4$

PRL123, 122001 (2019)



PRD108, 072016 (2023)



Theory expects $A_N \sim 1/A^{1/3}$ due to gluon saturation

Z.Kang and F.Yuan, PRD 84, 034019 (2011)

Supported by our data

However:

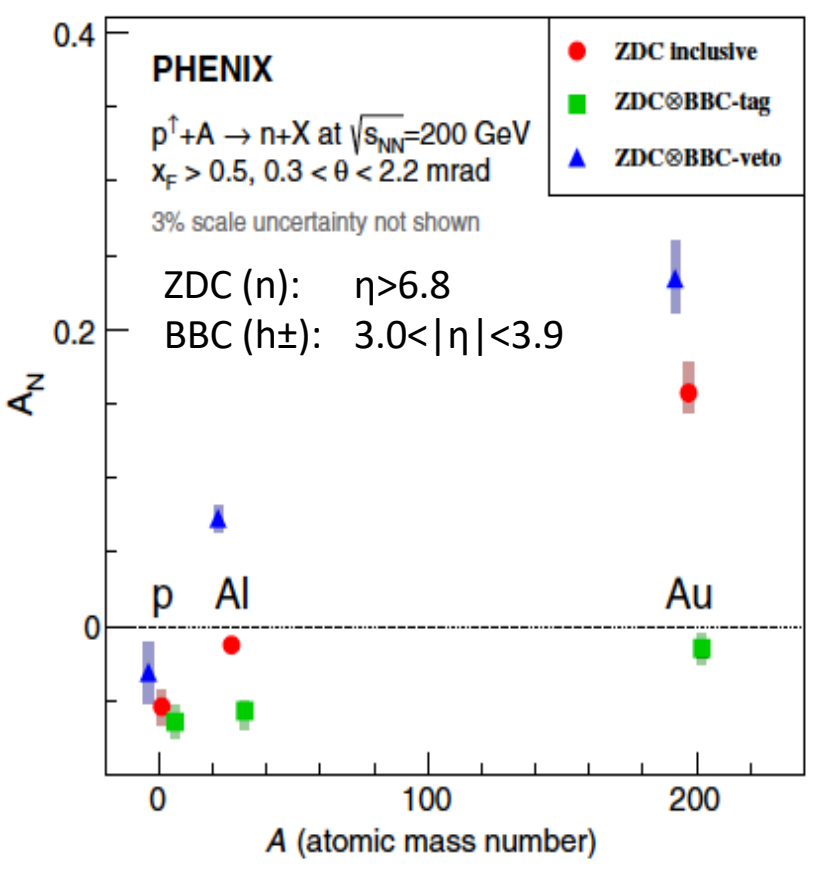
In this kin. region no sensitivity to gluon saturation is expected

Different source of asymmetry? Other nuclear effects?

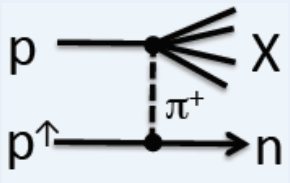
A_N: Very forward rapidity

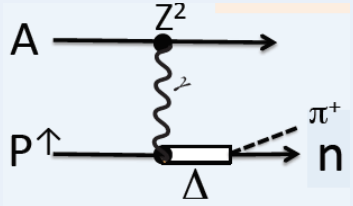
n at $|\eta|>6.8$

PRL 120, 022001 (2018)



- Strong dependence on A and particle production in other rapidity regions
- Likely multiple mechanisms contribute





One pion exchange (OPE): B.Kopeliovich et al PRD 84, 114012

Electromagnetic interaction (UPC): G.Mitsuka, PRC95 044908

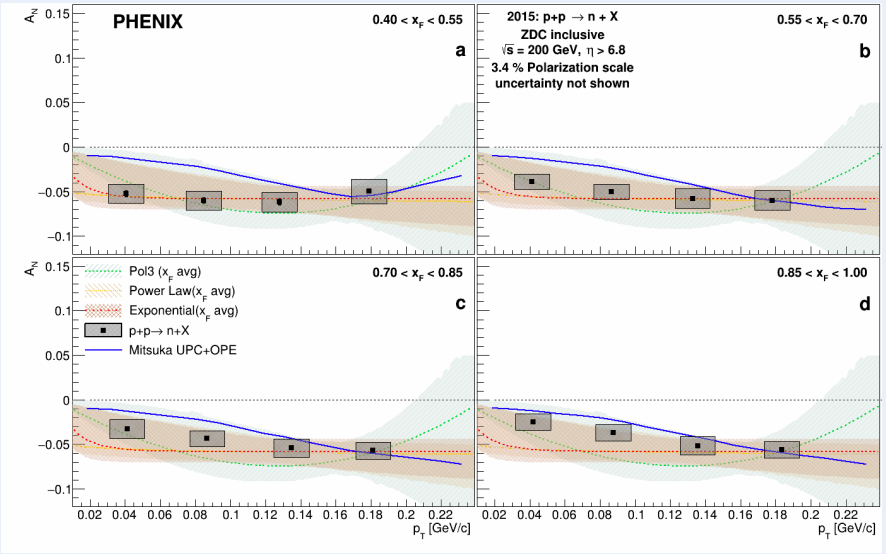
- Correlation with particle production in other rapidities, and different A and √s will help to isolate different channels

A_N: Very forward rapidity

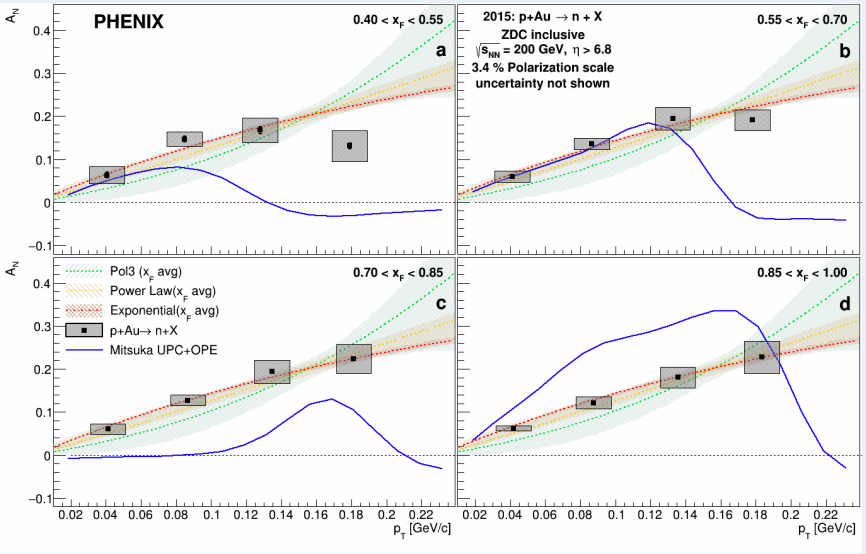
n at $|\eta|>6.8$

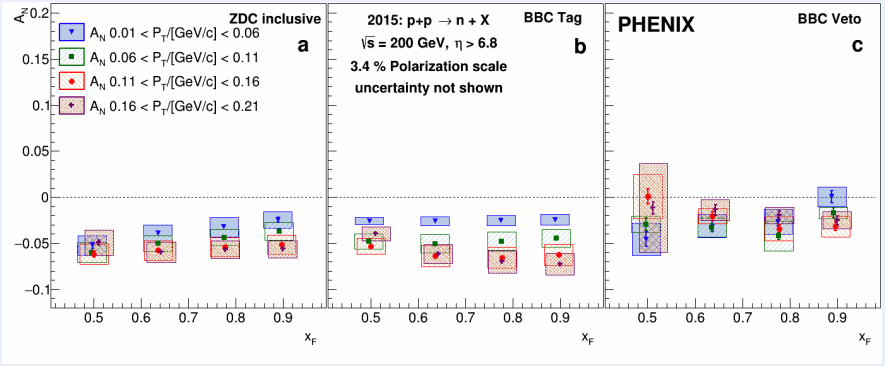
PRD 105, 032004 (2022)

pp



pAu





Magnitude increasing with pT

Weak xF dependence

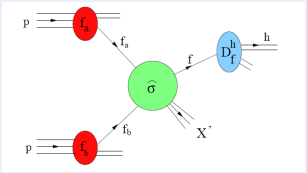
Model: UPC+OPE

- OPE dominates in pp
- UPC dominates in pAu

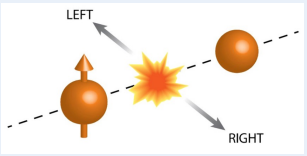
Very Recent Results

p+p: η cross section (forward/central) and A_N (forward)

Cross sections of η mesons in p+p collisions at forward rapidity at √s = 500 GeV and central rapidity at √s = 510 GeV,
arXiv:2507.04896, accepted by Phys.Rev.D



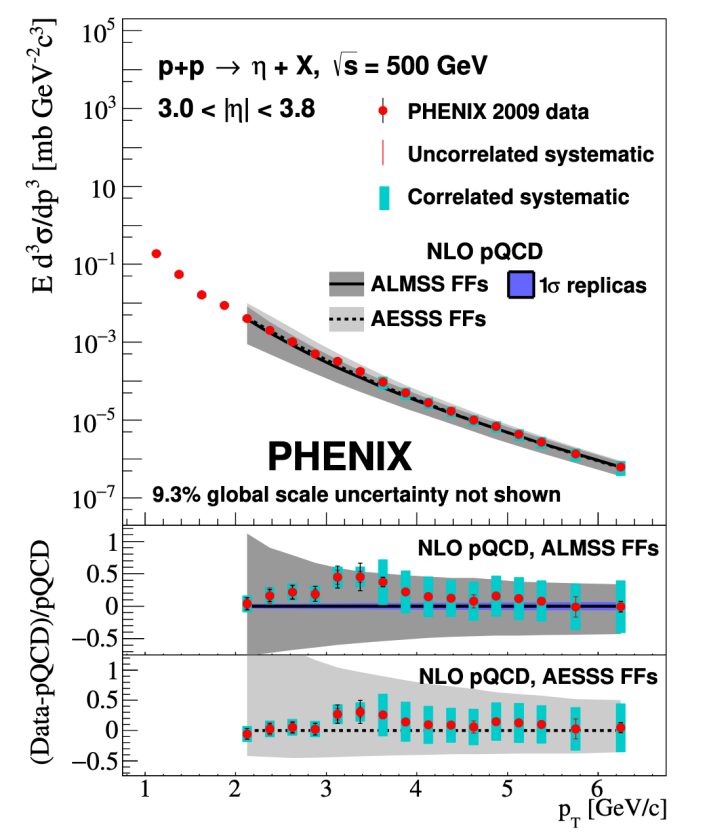
Transverse single-spin asymmetry of forward η mesons in p↑+p collisions at √s = 200 GeV,
PRD 113, 071006 (2026)



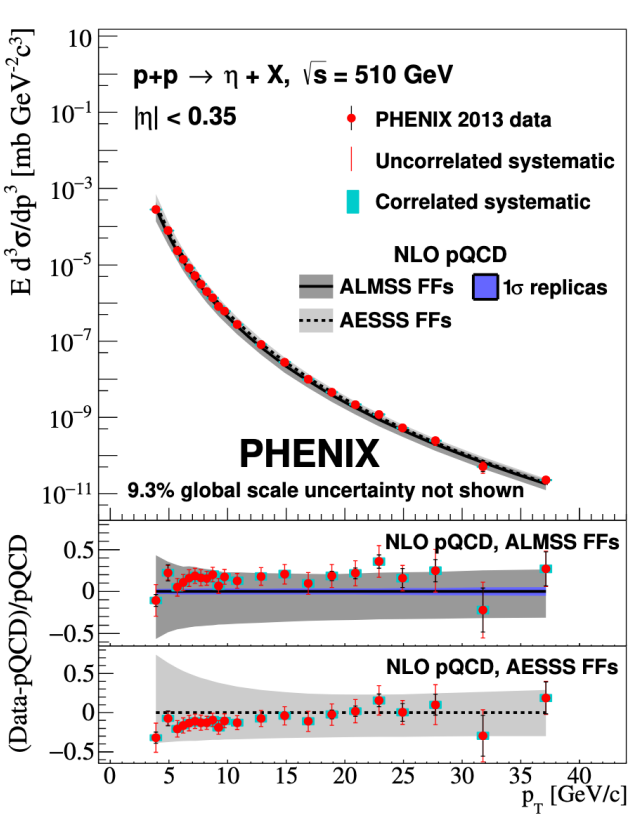
η cross section

arXiv:2507.04896

Forward



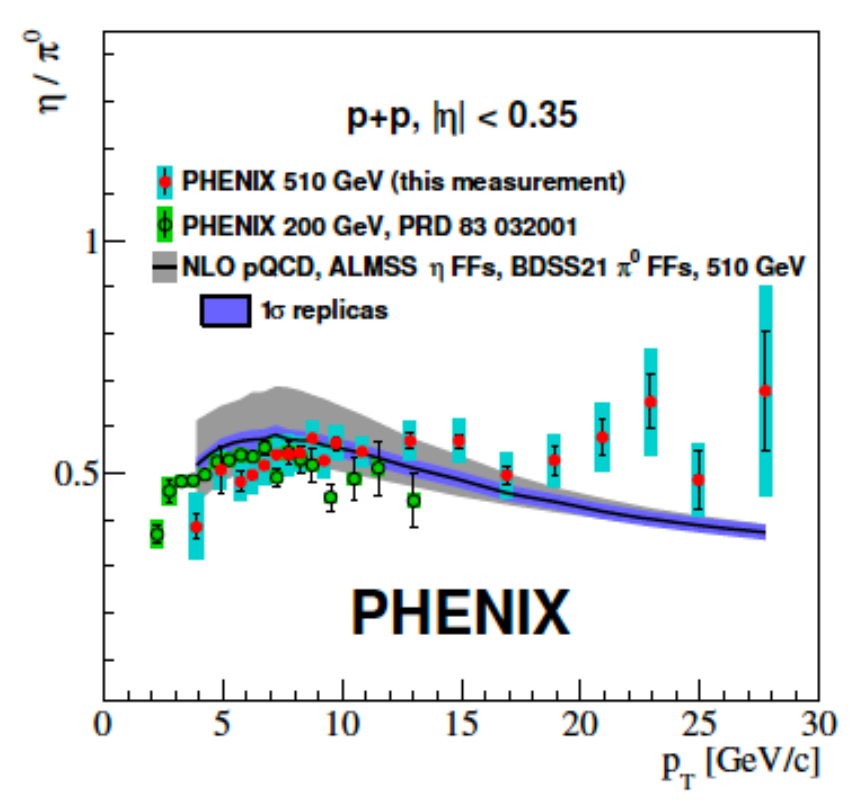
Central



Input to η FF: Aidala, Loomis, Martinez, Sassot, Stratmann (ALMSS), arXiv: 2507.04887

η/π^0 ratio at √s=510 GeV

arXiv:2507.04896



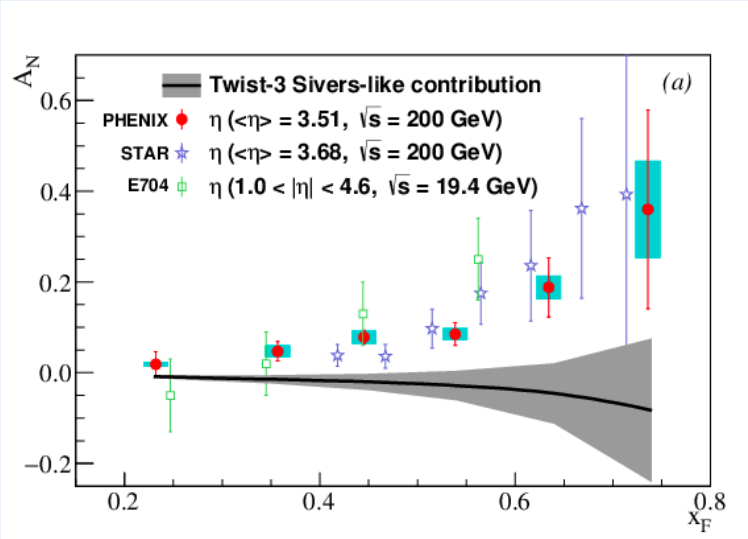
Powerful input to fragmentation functions as many experimental systematics cancel (not used in global fit yet)

NLO pQCD looks underestimates the ratio at higher pT

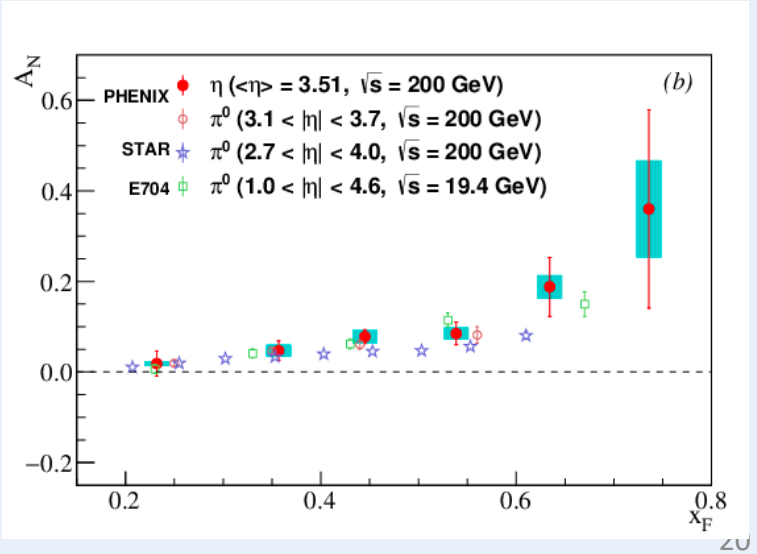
ALMSS (2507.04887): This discrepancy as well as some tension between RHIC (√s=200-510 GeV) and LHC (√s=2.76-13 TeV) in the global fit may be resolved by future NNLO analysis

Forward η $A_N(x_F)$

PRD 113, 071006 (2026)



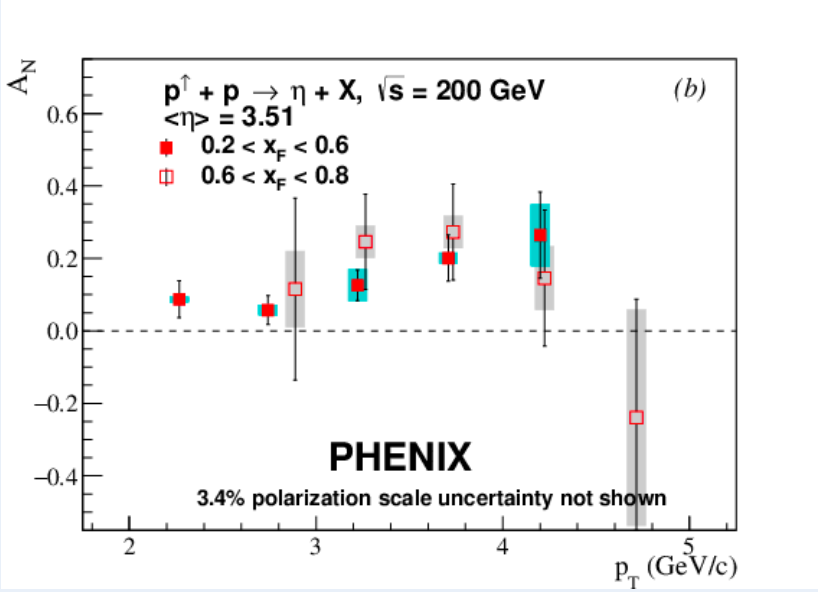
- Most precise measurement to date of the forward meson A_N
- A_N=0 in backward; positive and increasing with xF in forward – up to 35%!
- Calculations of the initial-state twist-3 contribution to the asymmetry appear insufficient to describe the large observed asymmetry
- Suggests a significant component of the asymmetry is carried by spin-dependent hadronization



- Similarity between η and $\pi 0$ A_N
- Suggests a limited impact from mass, isospin, strange quark content on spin-dependent hadronization

Forward η $A_N(p_T)$

PRD 113, 071006 (2026)



$A_N(p_T)$ flattening with hint on suppression at >4 GeV/c

Consistent with expectation from Twist-3

Summary

- How do gluon contribute to the proton Spin
  - Non-zero positive (in the limited x-range) and comparable to (or larger than) quark contribution
  - Direct photons removed the sign uncertainty

Proton spin decomposition

- What is the flavor structure of polarized sea in the proton
  - A_L(W) contributes to $\Delta\bar{u}$ and $\Delta\bar{d}$

Parton dynamics 3D imaging

- What are the origins of transverse spin phenomena in QCD
  - $A_N(\pi^0, \eta, \pi^{\pm}, h^{\pm}, \boldsymbol{\gamma}$, Heavy Flavor) => qg and ggg correlations

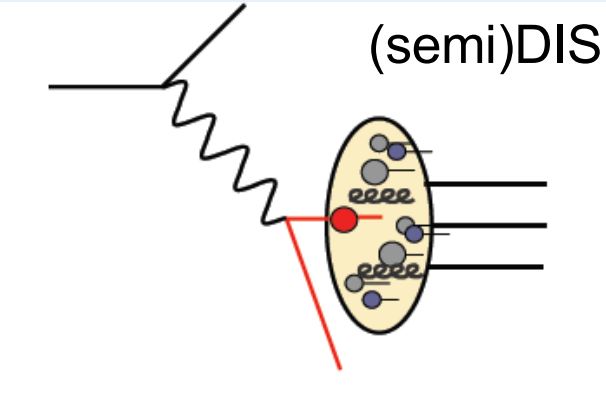
- First (and the only) $p^{\uparrow}A$ data
  - A wealth of exciting results awaiting for theoretical interpretation

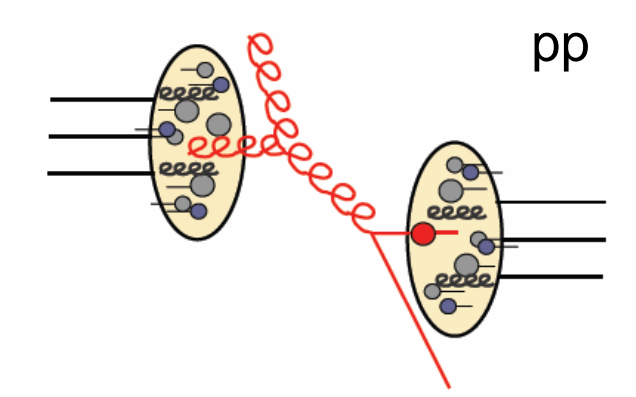
Probing nuclear matter effects

After decommissioning in 2016, PHENIX keeps producing significant results

Backup

From DIS to pp:





Probes ΔG:

Q^2 dependence of structure fct

Photon-gluon fusion

(Anti-)quark flavor separation:

Through fragmentation processes

Probes ΔG:

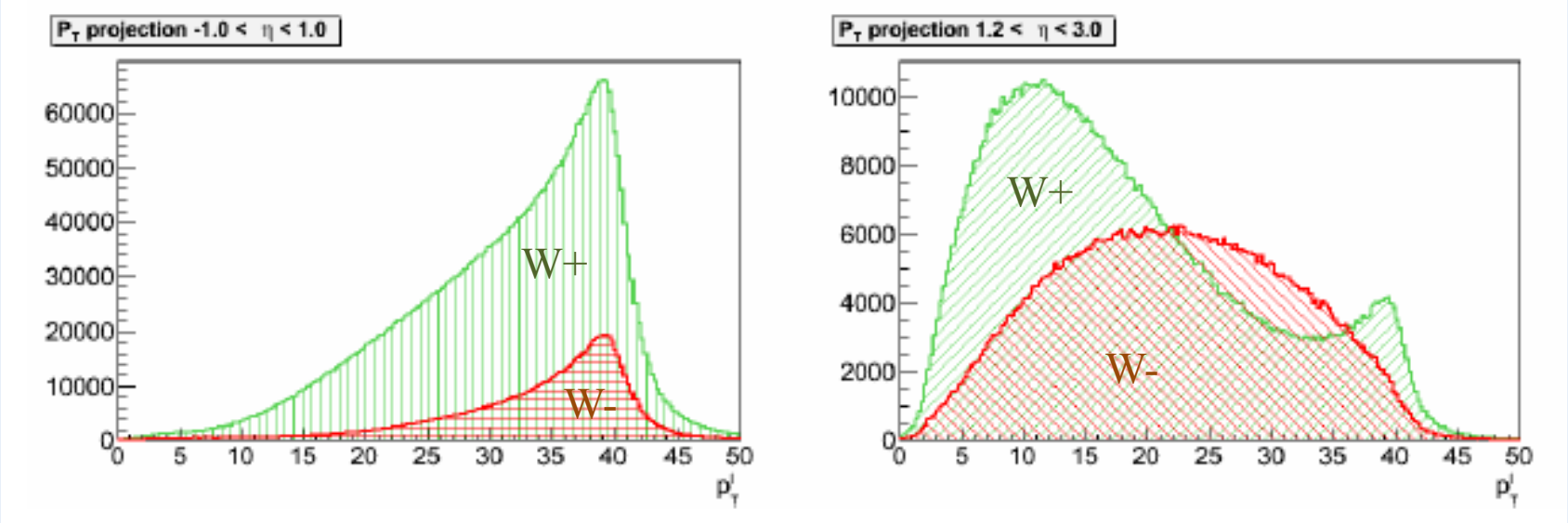
Directly from *gg* and *qg* scattering

(Anti-)quark flavor separation:

Through $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$

Complementary approaches

W: Central vs Forward region

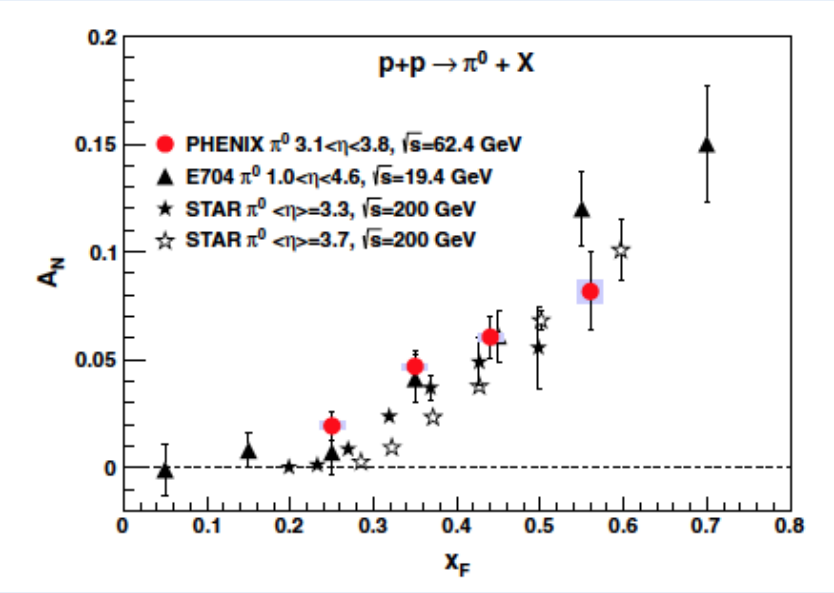


Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

A_N: Highest √s and pT

PRD90, 012006 (2014)



Naïve collinear pQCD predicts

$A_N \sim \alpha_s m_q / p_T \sim 0$

Asymmetries survive at highest √s

Non-perturbative regime!

Asymmetries of the ~same size at all √s

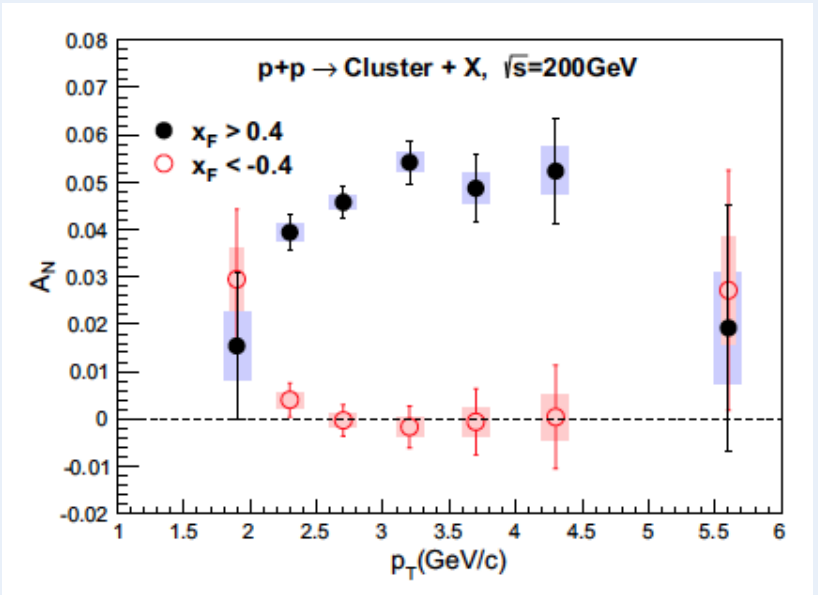
Asymmetries scale with x_F

Collinear (higher twist) pQCD predicts

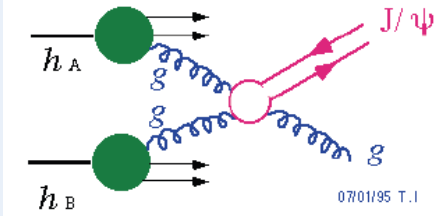
$A_N \sim 1/p_T$?

No fall off is observed out to p_T ~5 GeV/c

STAR showed no fall off up to ~7 GeV/c

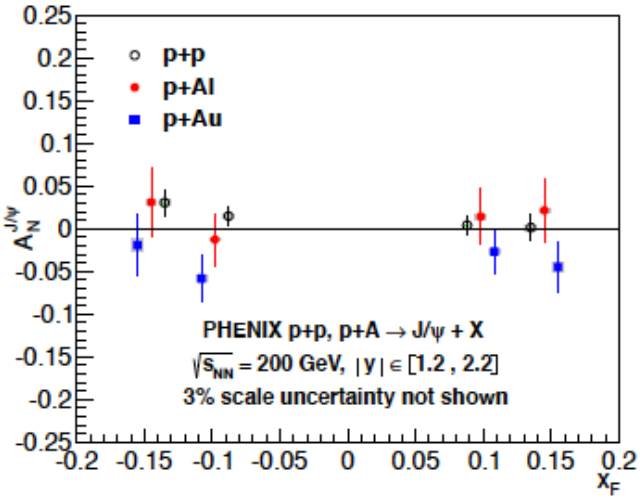


A_N: Forward rapidity



J/ψ at 1.2<|η|<2.4

PRD 98, 012006 (2018)



J/ψ production sensitive to gluon distribution

A_N sensitive to J/ψ production mechanism

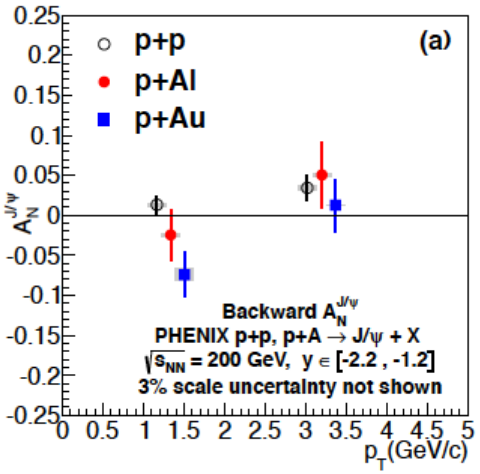
F.Yuan, PRD78, 014024:

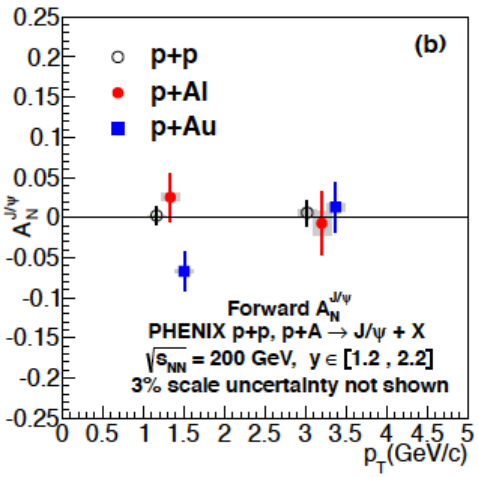
For non-zero gluon Sivers, A_N vanishes in color octet model, but survives in color singlet model

In p+p and p+Al: $A_N \sim 0$

In p+Au: trends to $A_N < 0$

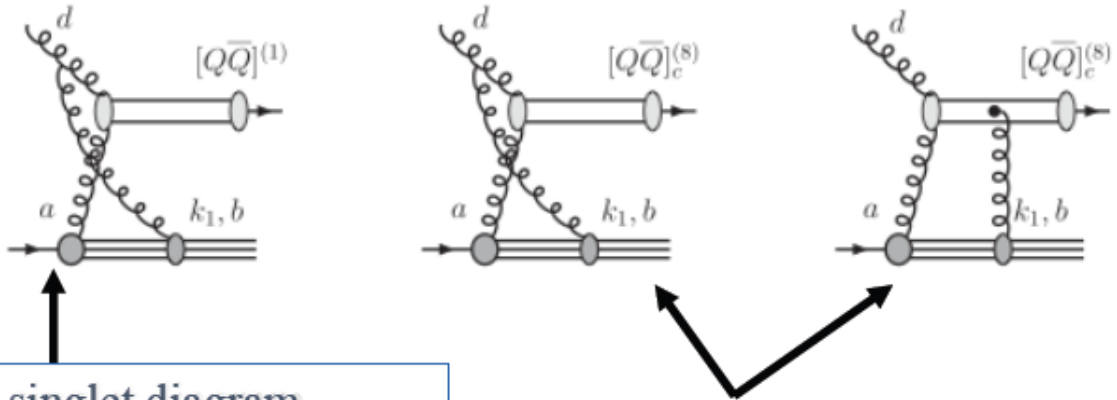
??





J/ψ A_N

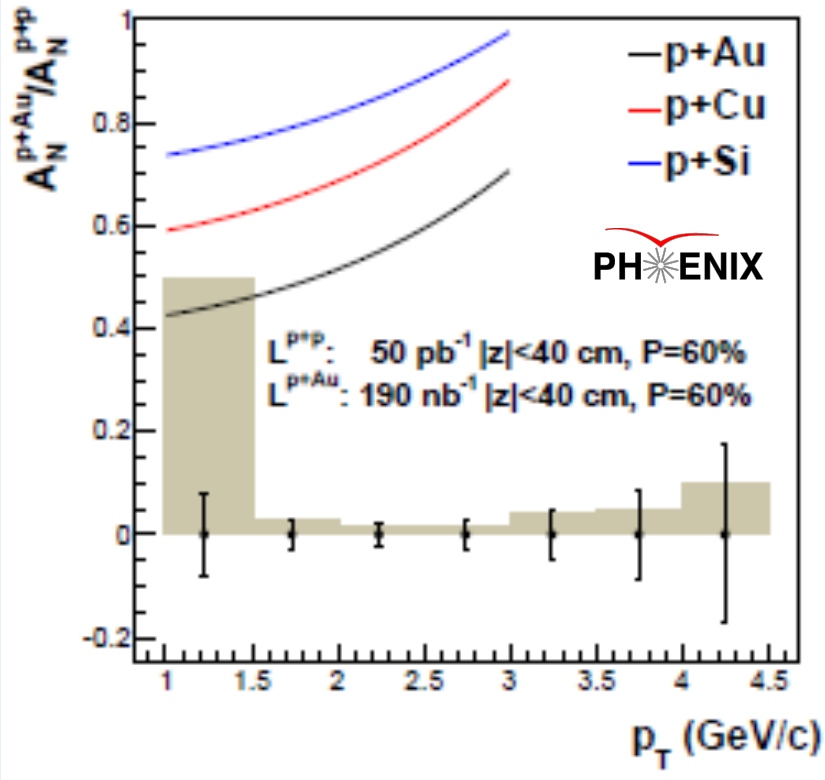
- J/ψ A_N is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, J/ψ A_N vanishes if the pair are produced in a color-octet model but survives in the color-singlet model
  - *Feng Yuan, Phys. Rev D78, 014024(2008)*



One color-singlet diagram
— no cancellation, asymmetry generated by the initial state interaction, $A_N \neq 0$

Two color-octet diagrams
— cancellation between initial and final state interactions, no asymmetry $A_N = 0$

π0 A_N in pA



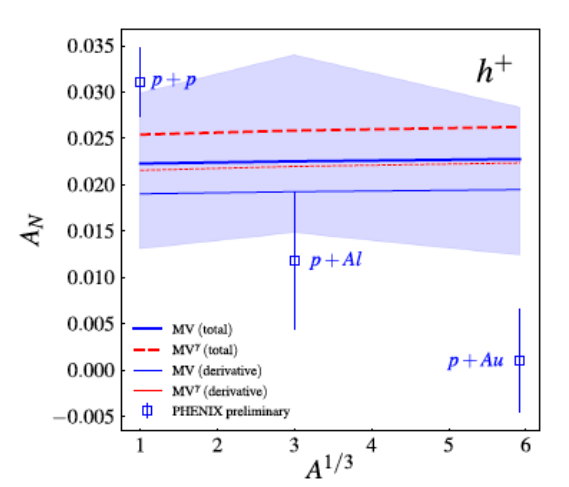
Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

Kang, Yuan: PRD84, 034019
Kovchegov, Sievert: PRD86, 034028

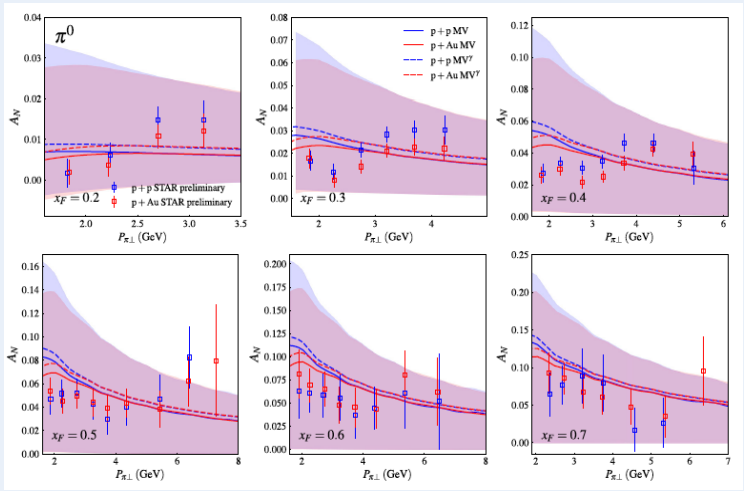
- Unique RHIC possibility p$^{\uparrow}$A
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in p$^{\uparrow}$A provides sensitivity to Q_s
- Data already collected in Run-2015!

A_N: Forward rapidity

S.Benic and Y.Hatta, PRD99, 094012
(Twist-3 fragmentation + gluon saturation)



PHENIX (Preliminary)	STAR (Preliminary)
h+	π0
1.4<η<2.4	2.6<η<4.0
0.1<x_F<0.2	0.2<x_F<0.7
1.8<p_T<7	1.5<p_T<7
A_N suppressed	A_N (almost) not modified

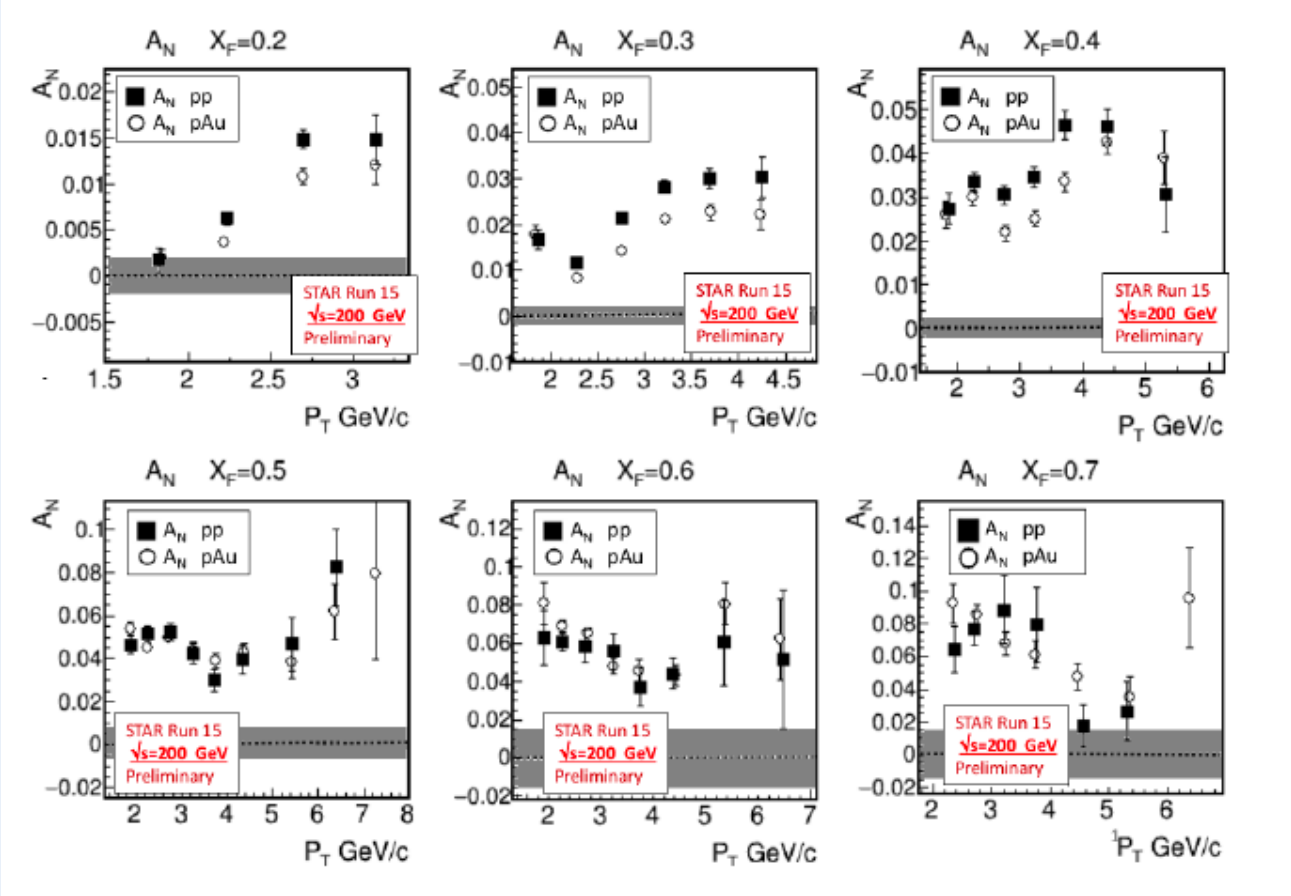


"<p_T>~2.9 GeV/c is too hard to be sensitive to the saturation scale Q_S^{Au} ~ 0.9 GeV. … This makes the PHENIX result even more striking."

Different source of hadron A_N?

Other nuclear effects?

Any connection with QGP formation in pA?


A_N X_F=0.2
A_N X_F=0.3
A_N X_F=0.4
A_N X_F=0.5
A_N X_F=0.6
A_N X_F=0.7
A_N pp
A_N pAu
STAR Run 15
√s=200 GeV
Preliminary
P_T GeV/c