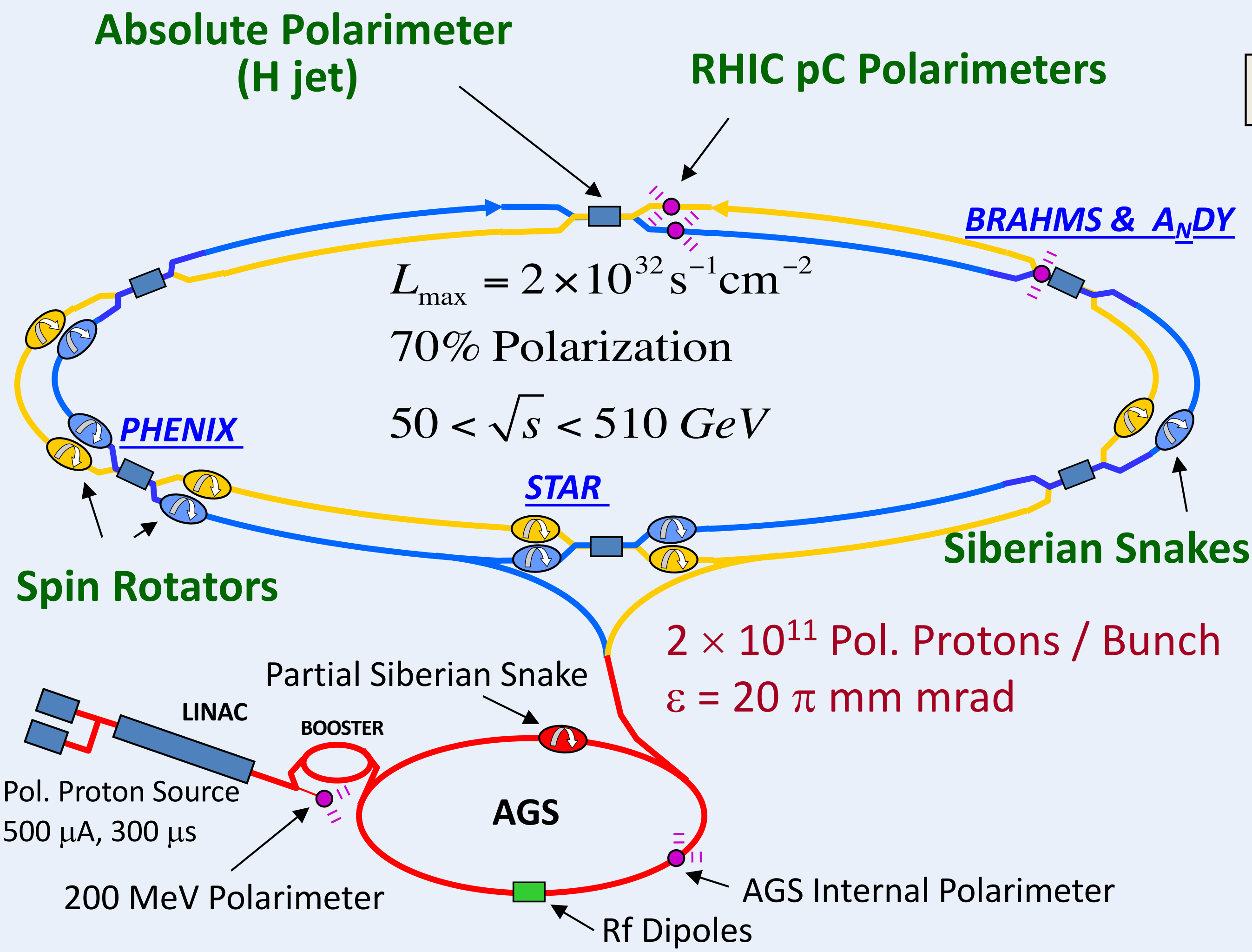
PHENIX Spin Measurements: from pp to pA

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

A.Bazilevsky (BNL)

For PHENIX Collaboration

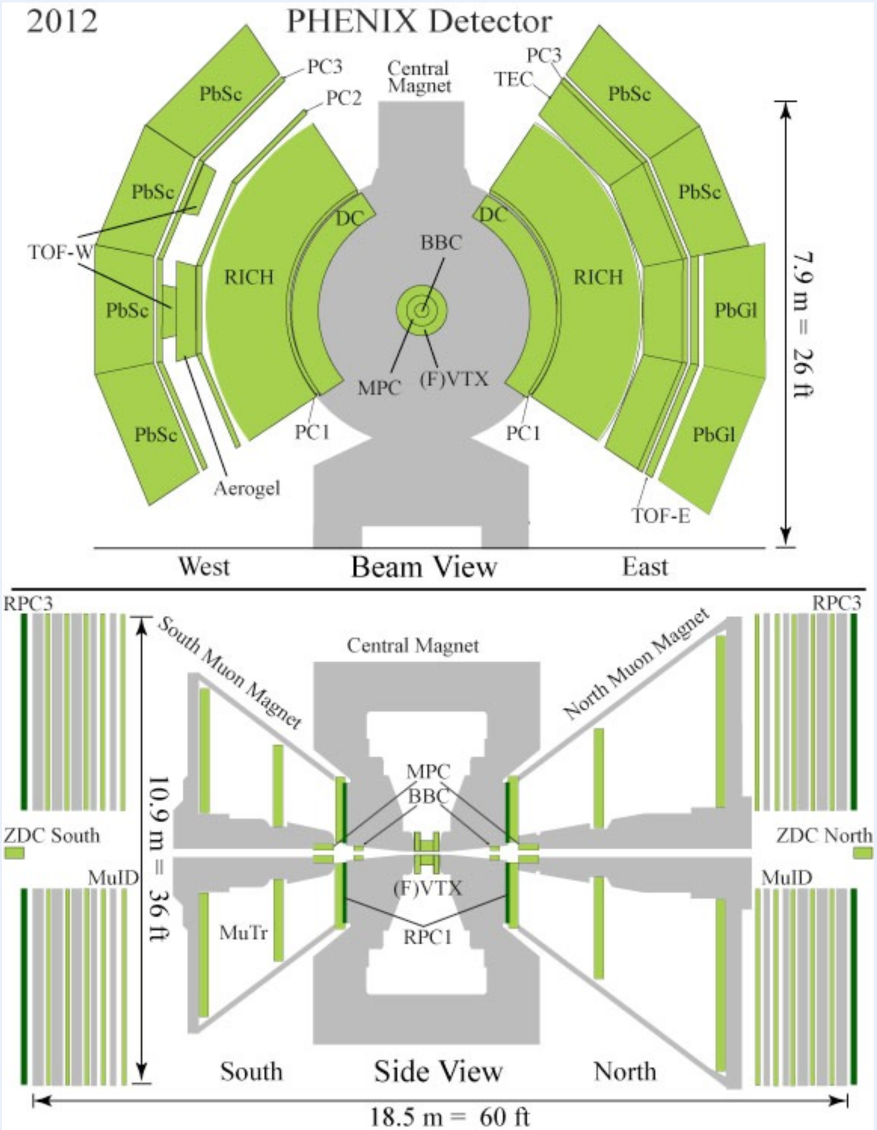
PHENIX Spin @ RHIC



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

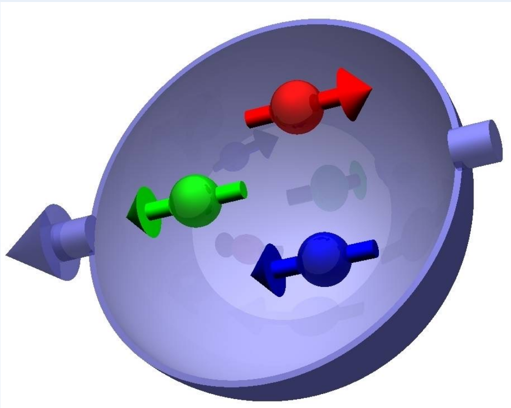
Relative Luminosity

Beam Beam Counter (BBC)
Zero Degree Calorimeter (ZDC)

Local Polarimetry – ZDC & SMD

Spin direction control

Proton Spin Decomposition



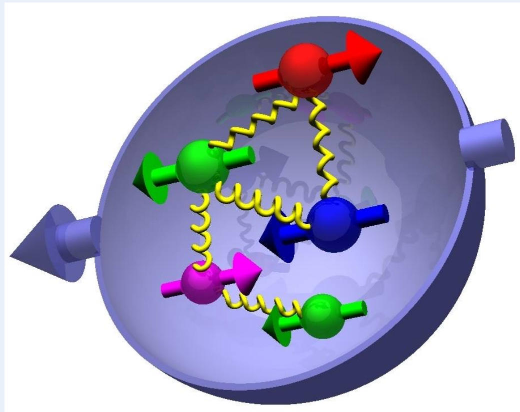
Naïve parton model:

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)$$

1989 EMC (CERN):
ΔΣ=0.12±0.09±0.14

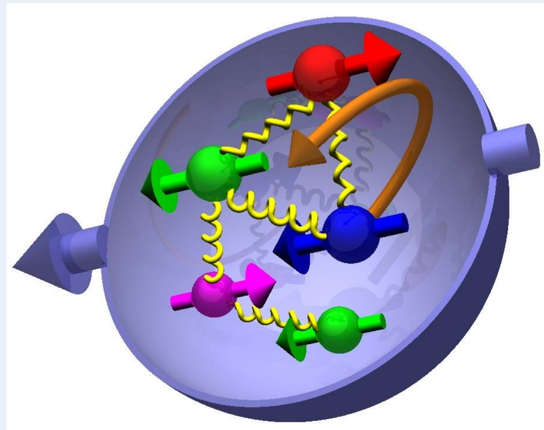
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$$

⇒ Spin Crisis



⇒ Gluons are polarized (ΔG)
⇒ Sea quarks are polarized:

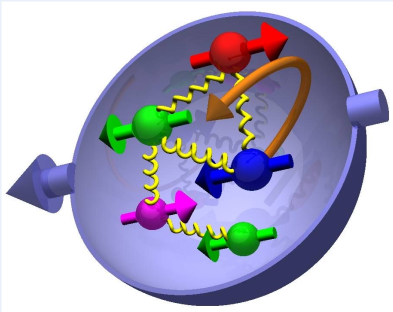
$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G$$



For complete description include parton orbital angular momentum L_Z:

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

Determination of ΔG and Δq-bar has been the main goal of longitudinal spin program at RHIC



ΔG: $\pi 0$ A_{LL}

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

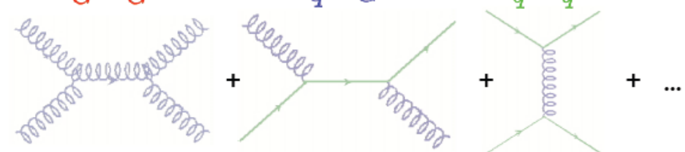
The most abundant probe in PHENIX

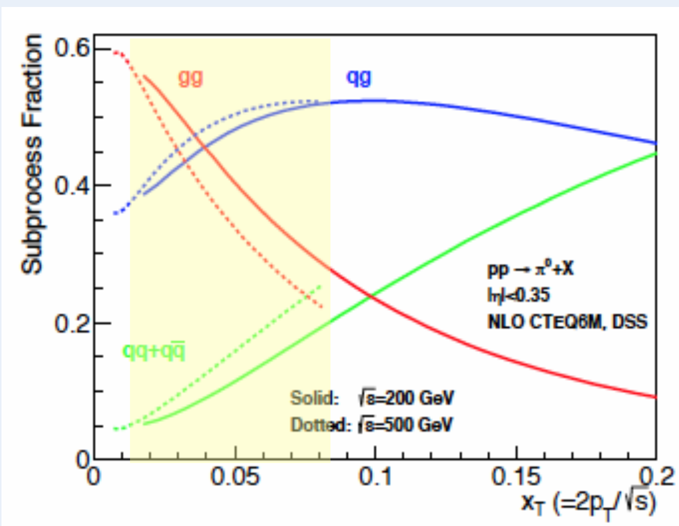
(triggering + identification capability)

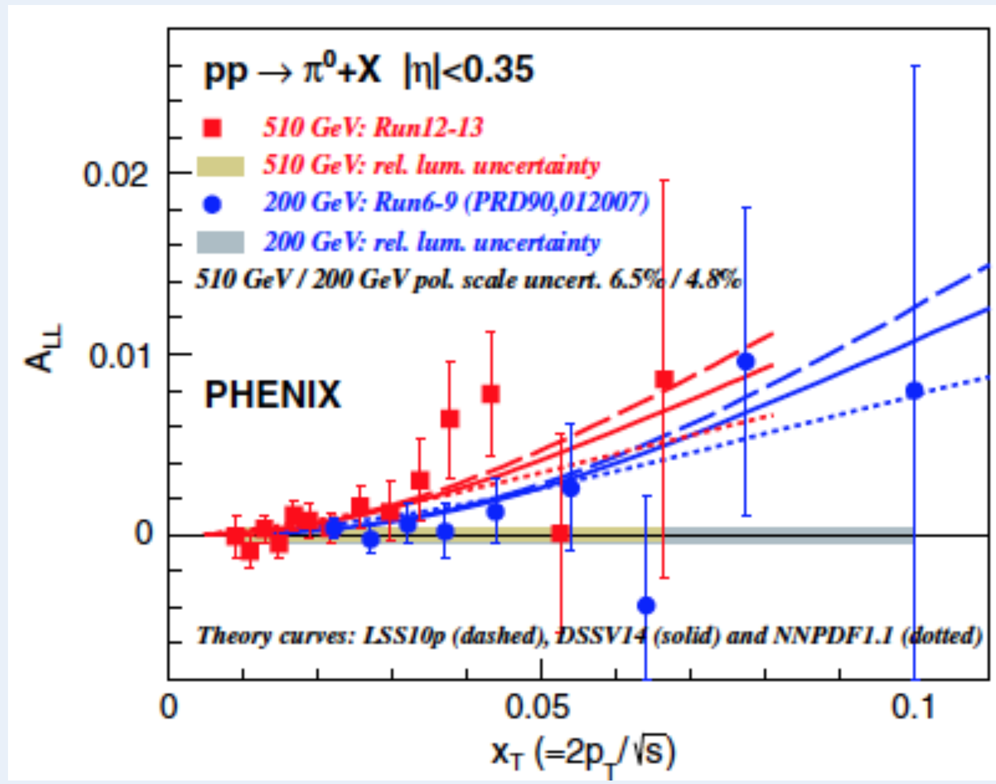
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

PRD93, 011501 (2016)

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



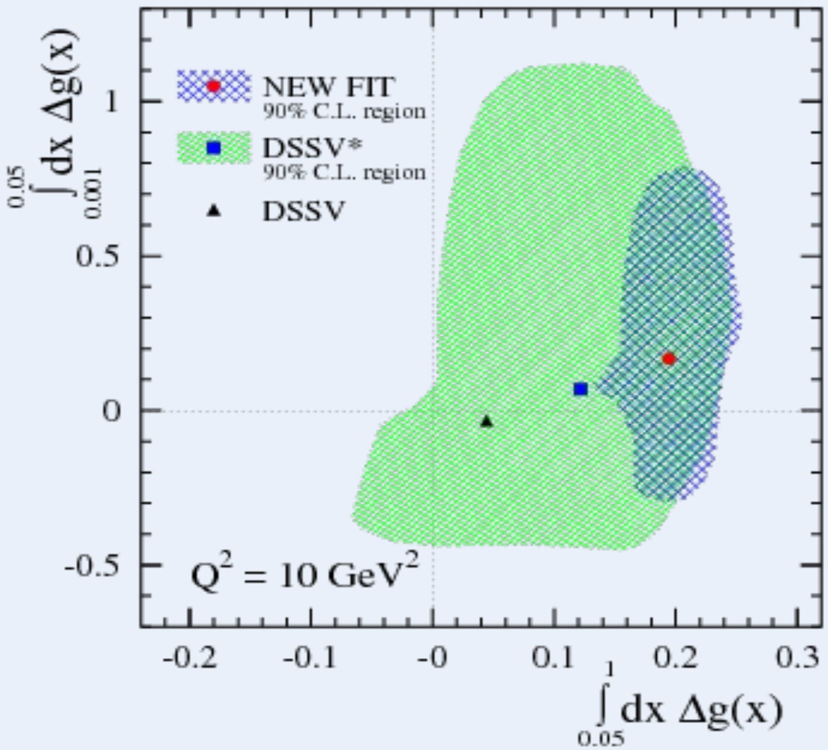




Non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

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



pp: PHENIX π0+ STAR jet

DSSV: Phys Rev Lett, 101, 072001 (2008)

Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)

Data from up to 2009

$$\int_{0.05}^{1} dx\Delta g(x) = 0.2^{+0.06}_{-0.07} \qquad (90\%\ \mathrm{CL})$$

Significant non-zero Δg(x) in the kin. region probed by RHIC

Similar result from another global fit NNPDF

Sign is not yet reliably defined

=> Need cleaner prob, e.g. direct photons

Still huge uncertainty in unmeasured region (x<0.05)

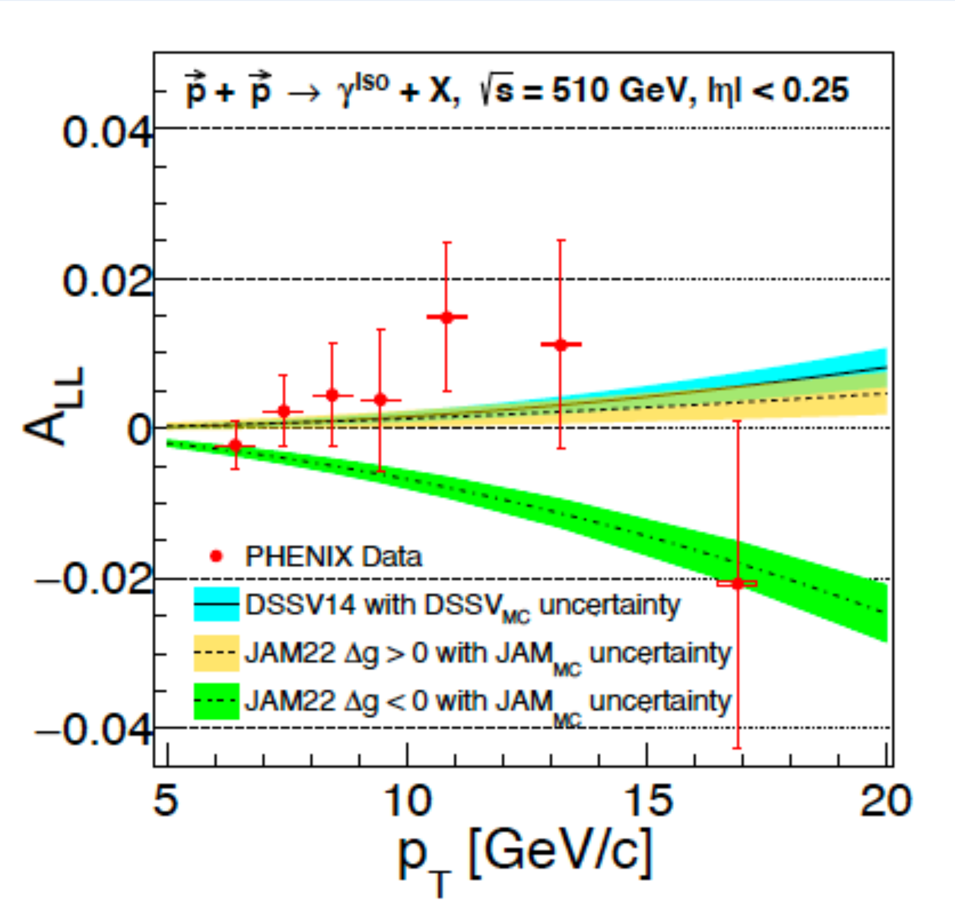
=> Measurements at higher √s and forward rapidity

ΔG: Confirm the Sign

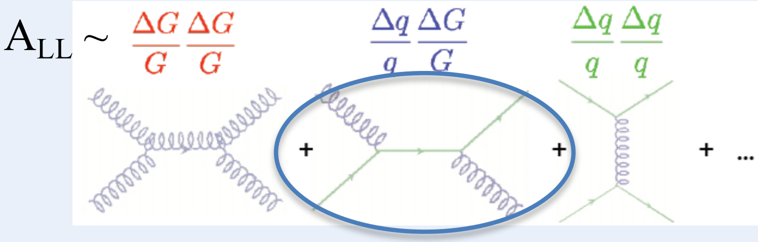
$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta \bar{q}) + \Delta G + L_Z$$

Direct photon - a golden channel to probe gluons

PRL130, 251901 (2023)



See Zhongling Ji talk on July 14



JAM collaboration:

Sign is not defined

PHENIX:

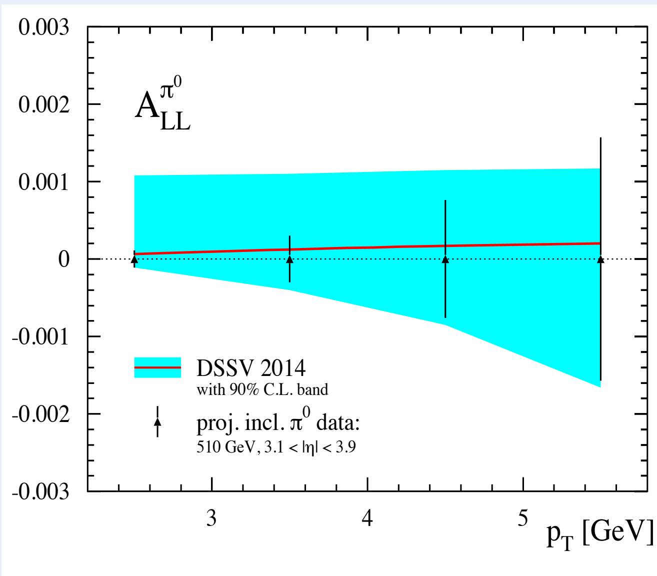
Clear preference for positive ΔG

ΔG: Towards lower x

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

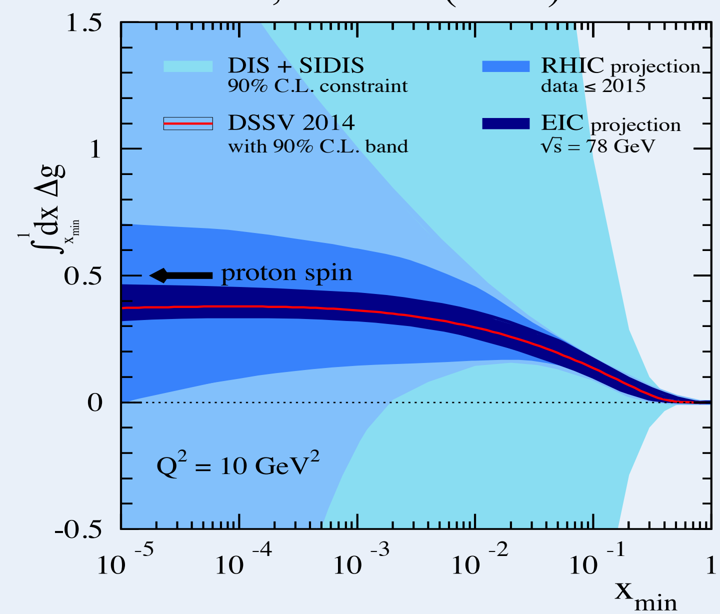
Projection

$\pi 0$: $3.1<|\eta|<3.9$



From available PHENIX+STAR data from 2011-15

Aschenauer, Stratmann,Sassot
PRD 92, 094030 (2015)



$\pi 0$ in forward region at $\sqrt{s}$=510 GeV:

Based on collected 2013 data

Probes lower x down to $\sim 10^{-3}$

Other channels also being measured (but with weaker stat. power)

γ, η, π±, h±, heavy flavor through e and μ, h-h, γ-h

$d_L \bar{u}_R \rightarrow W^-$

$u_L \bar{d}_R \rightarrow W^+$

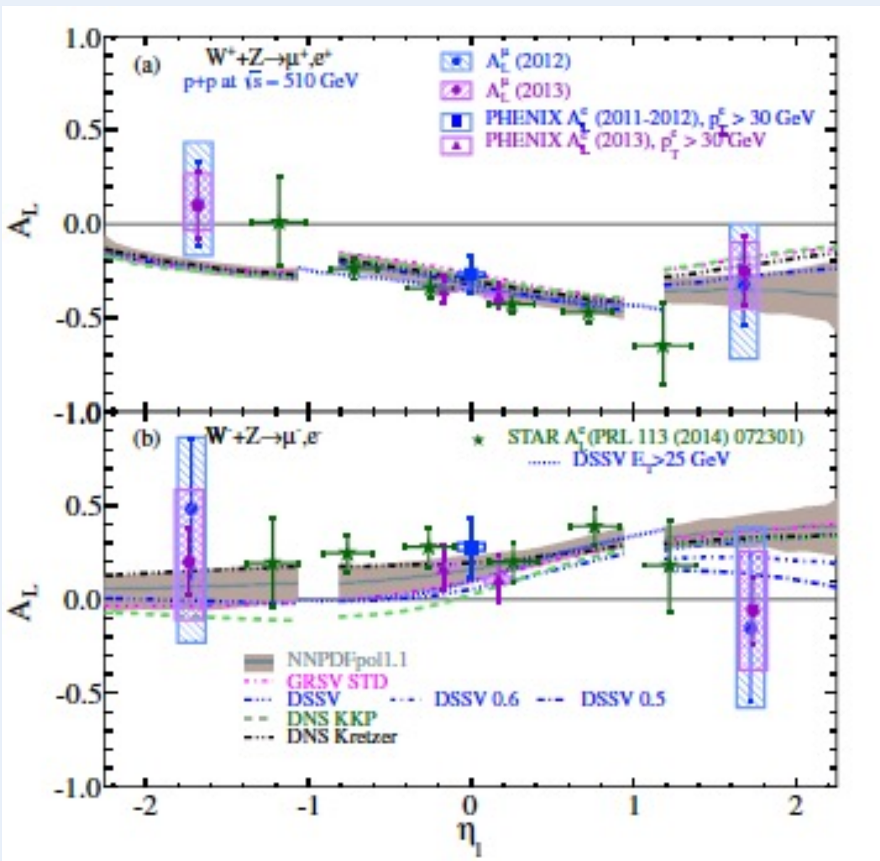
Δq-bar: $W^\pm \rightarrow e^\pm, \mu^\pm$

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

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

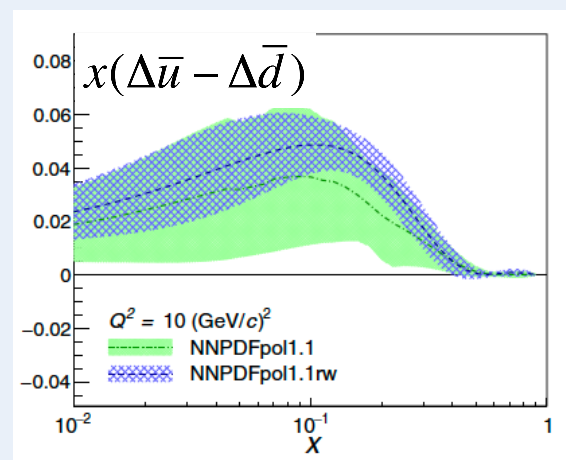
Constrains flavor separated (anti-)quark polarization at high $Q \sim M_W$ at $x>0.05$, with no fragmentation involved (as in SIDIS)

PRD 98, 032007 (2018)



Data generally agree with current theory constraint, with some tension in backward region, leading to a preference of ubar polarization to be more positive and dbar polarization to be more negative

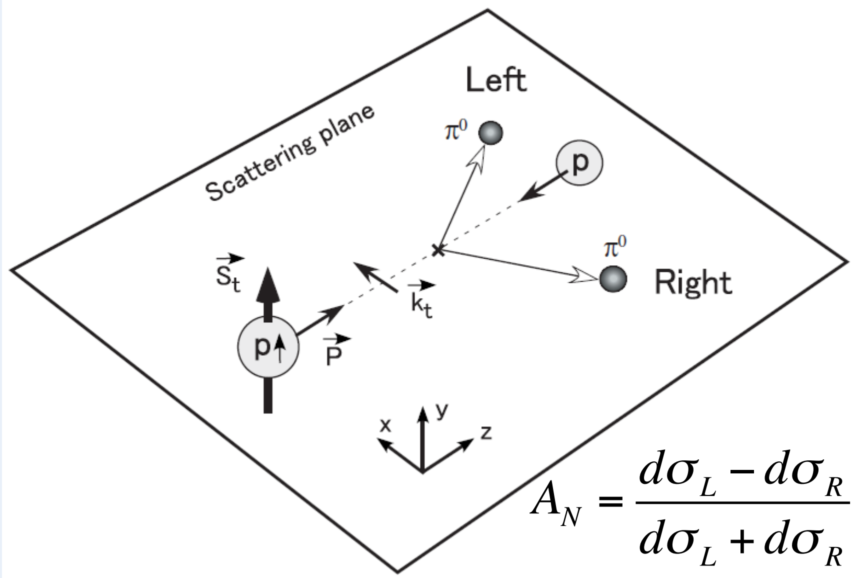
STAR:
PRD99, 051102 (2019)



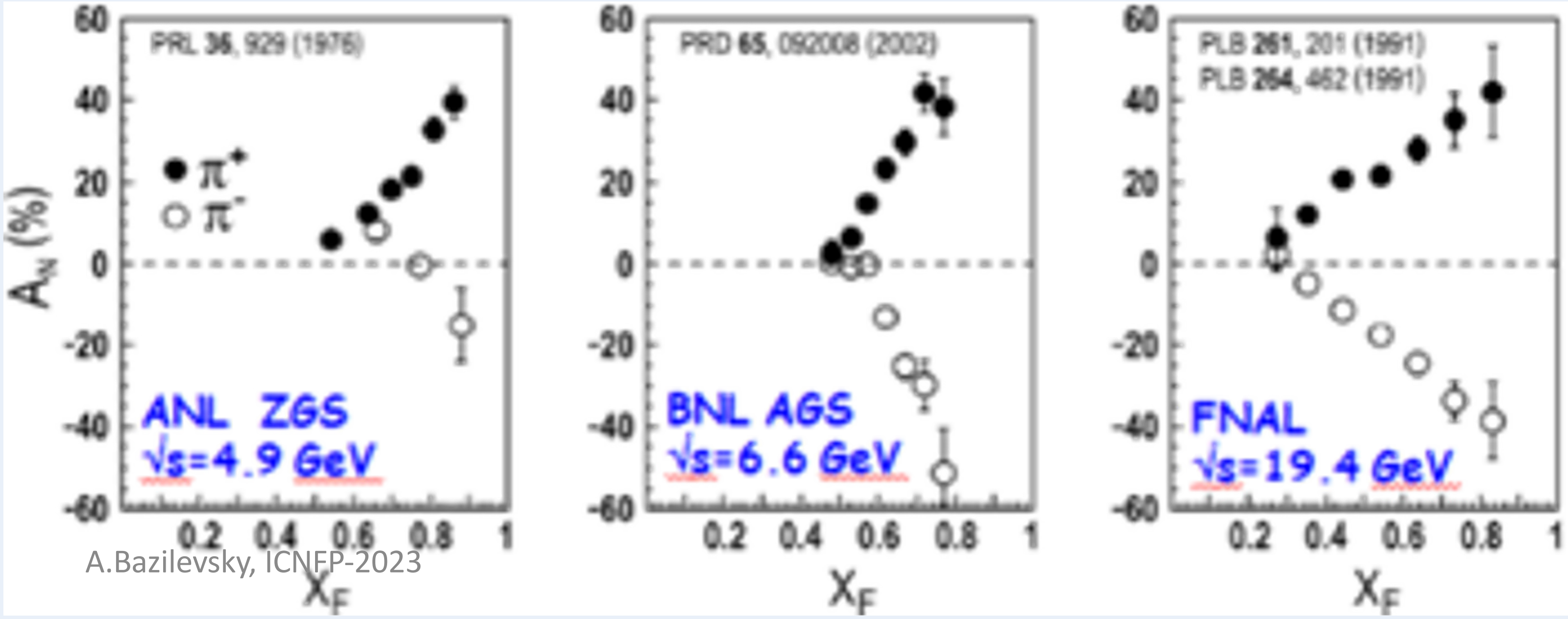
A.Bazilevsky, ICNFP-2023

Transverse Spin Asymmetries

Large Transverse Spin Asymmetries have been observed in $p^{\uparrow}p$

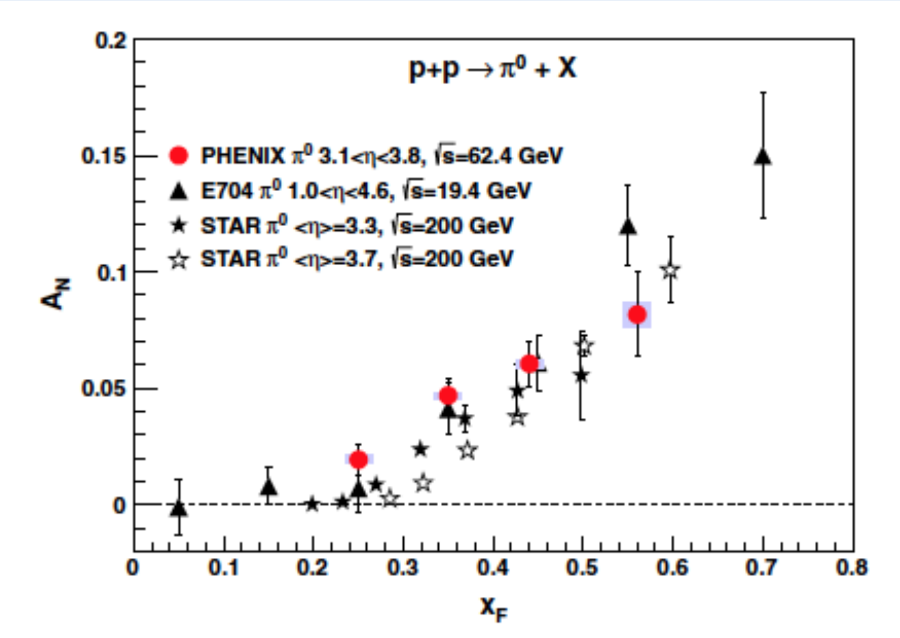


$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



Forward-rapidity π0 A_N

PRD90, 012006 (2014)



Naïve collinear pQCD predicts

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

Asymmetries survive at highest $\sqrt{s}$

Non-perturbative regime!

Asymmetries of the ~same size at all $\sqrt{s}$

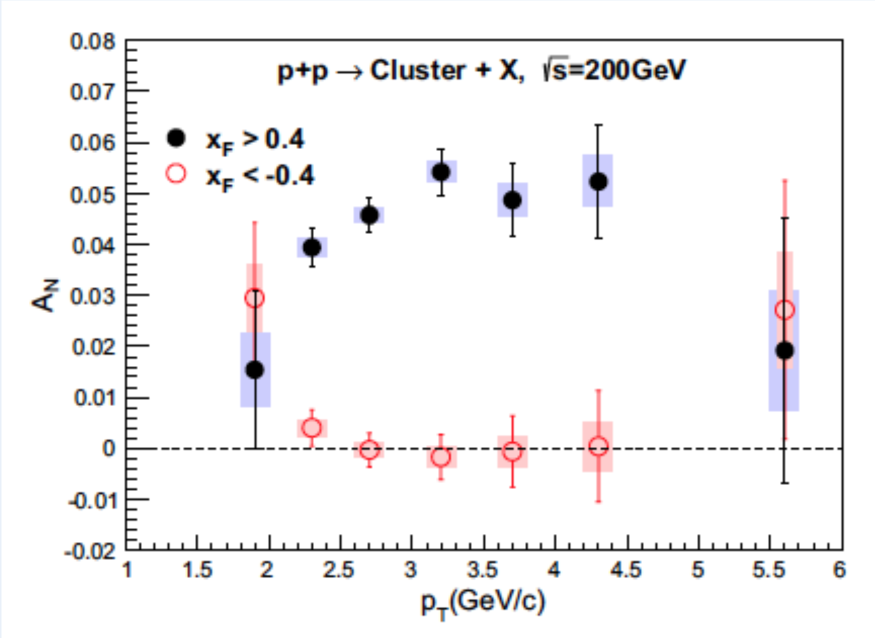
Asymmetries scale with x_F

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



Transverse Spin Physics

Initial State:

Sivers/Twist3 mechanism

- 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:

Collins mechanism

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

Sensitive to
transversity x spin-dependent FF

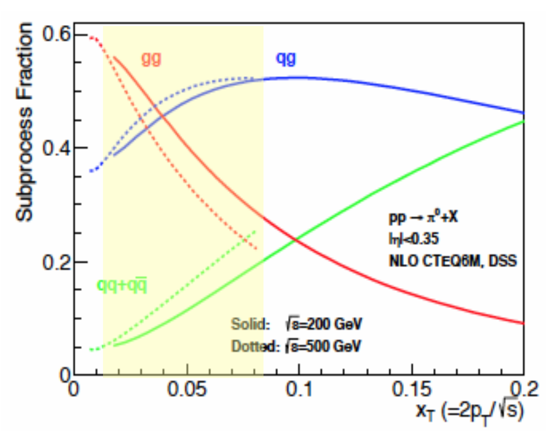
Universal between SIDIS & pp & e+e-

- Quark transversity
- Tensor charge

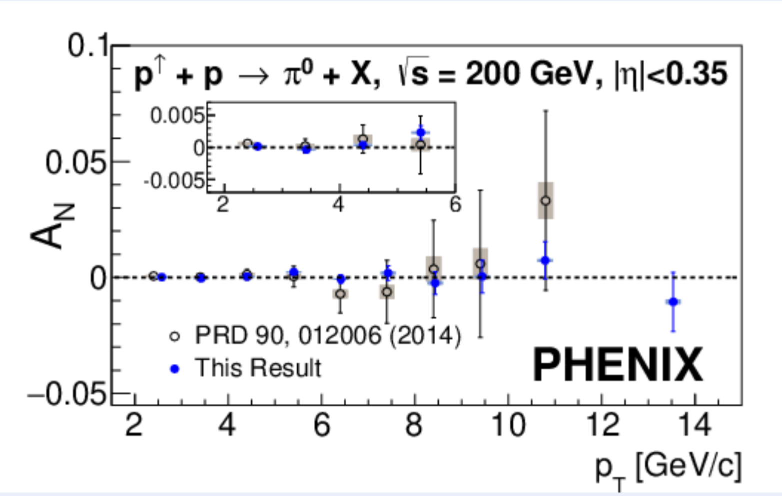
Other mechanisms

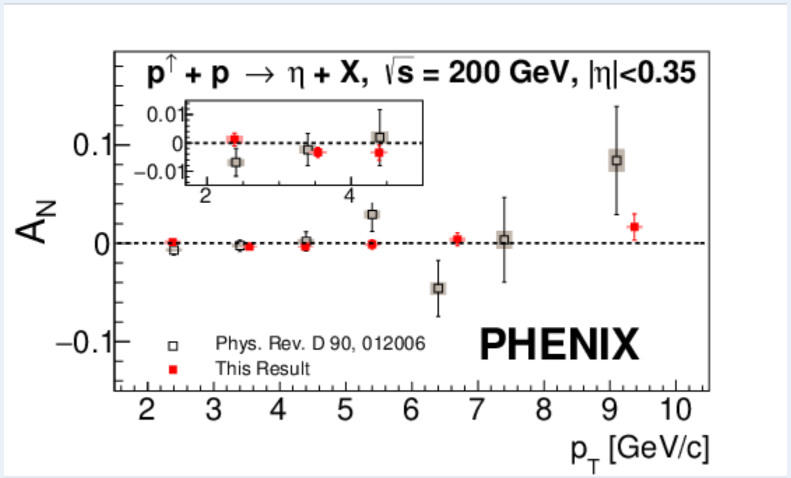
- Diffraction

Mid-rapidity π0 and η A_N



PRD103, 052009 (2021)





Consistent with 0

To ~3×10^{-4} precision level at π0 low p_T

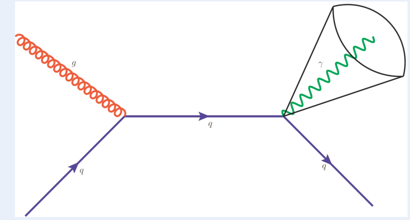
Sensitive to gluon dynamics

Used to constrain gluon Sivers effect:

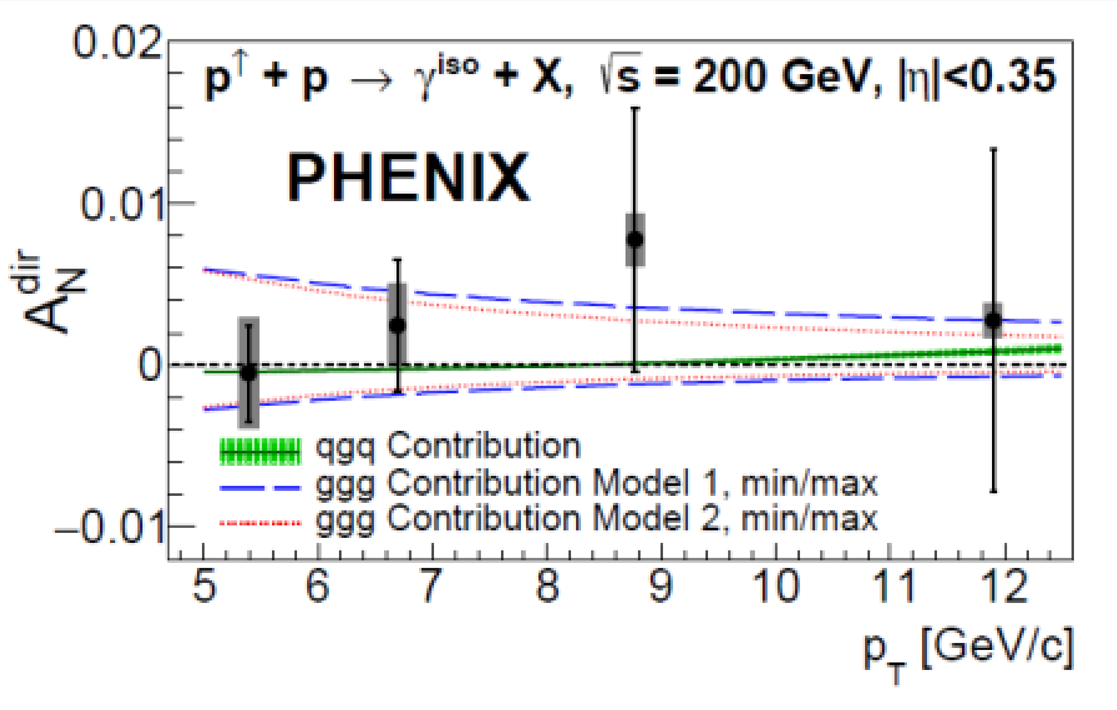
Anselmino et al, PRD 74 (2006), 094011

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

Direct Photon A_N

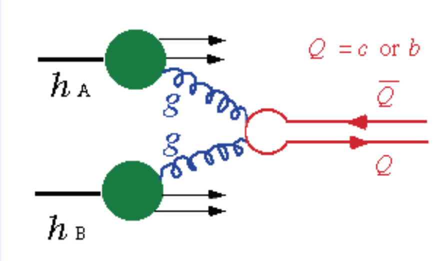


PRL127, 162001 (2021)

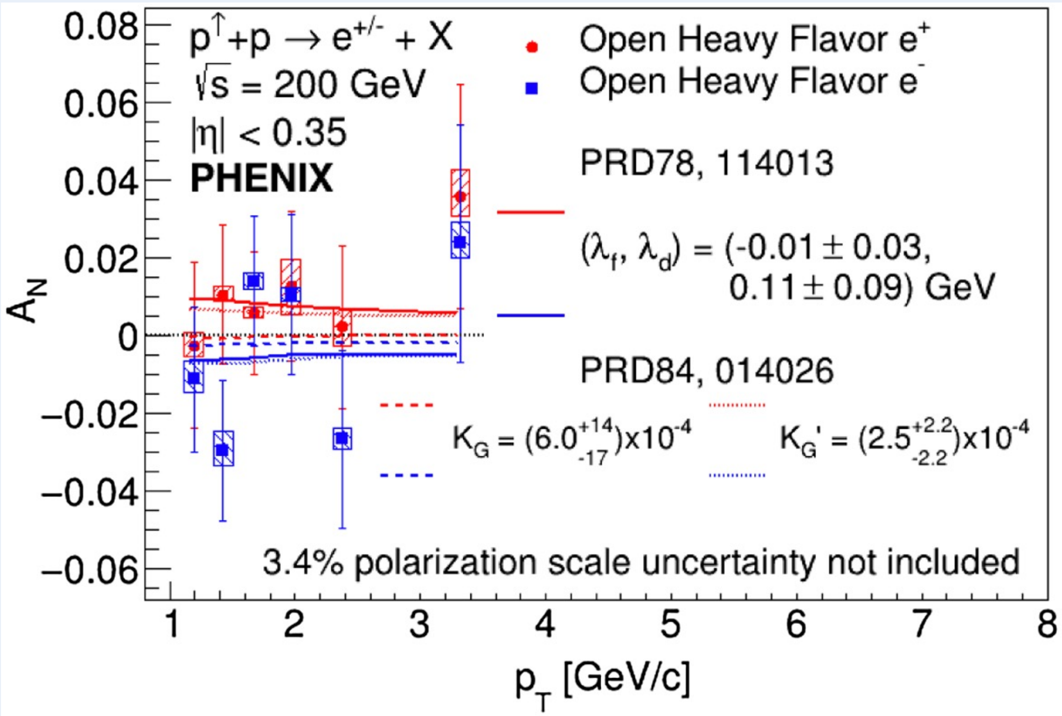


- ✓ First direct $\boldsymbol{\gamma}$ A_N from RHIC
- ✓ ×50 times reduced uncertainty compared to the only prior measurement at E704 (Fermilab)
- ✓ Clean prob of initial state effect (no fragmentation)
- ✓ Constraints gluon dynamics within proton (through gluon-gluon correlation function)

Heavy Flavor A_N



PRD107, 052012 (2023)



Dominated by gluon-gluon fusion

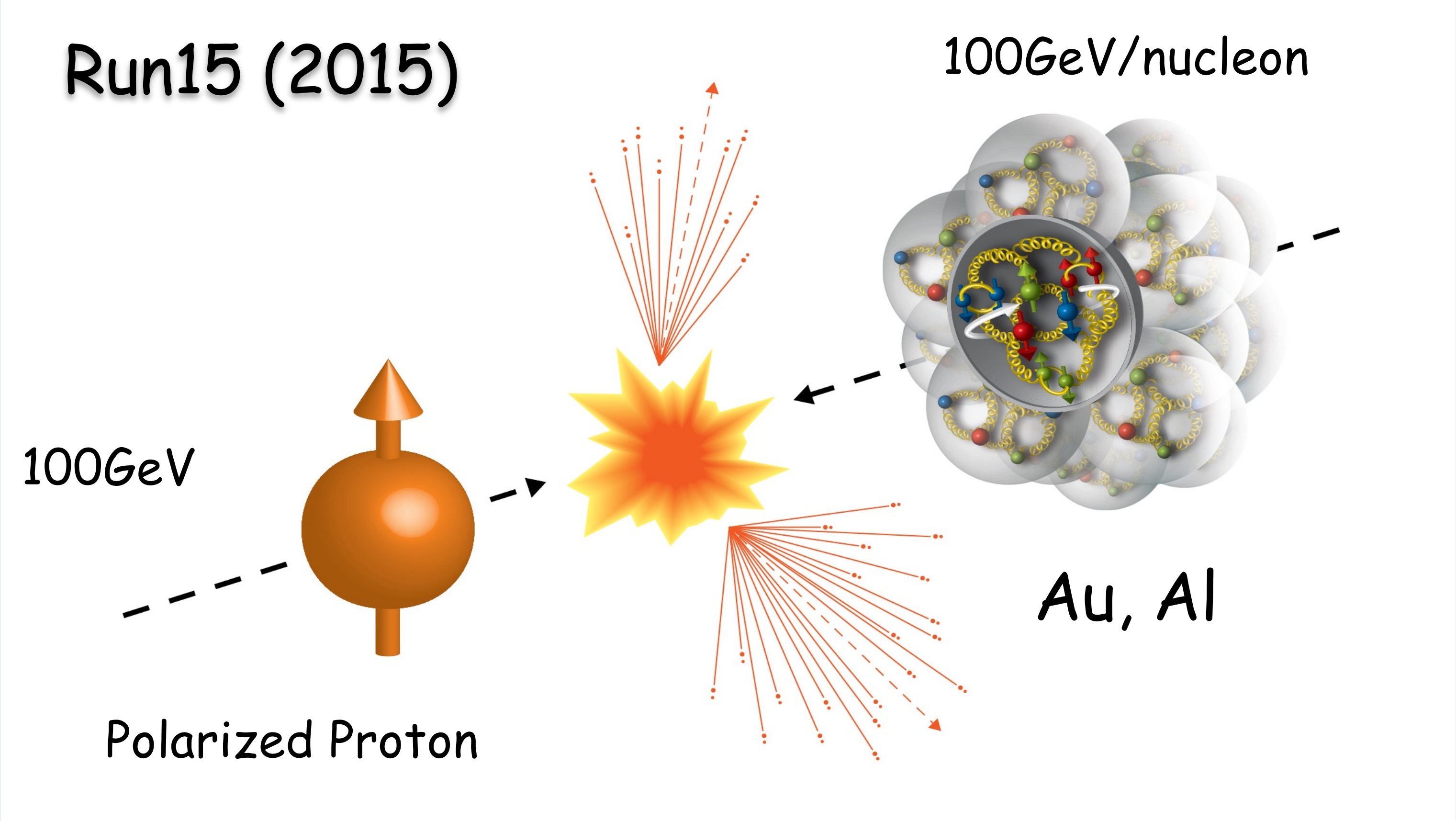
Used to constrain tri-gluon correlation in the Twist-3 collinear framework

Z.Kang, J.Qiu, W.Vogelsang, F.Yuan, PRD78,114013

Y.Koike, S.Yoshida, PRD84,014026

Comparison of charges provides further sensitivities

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

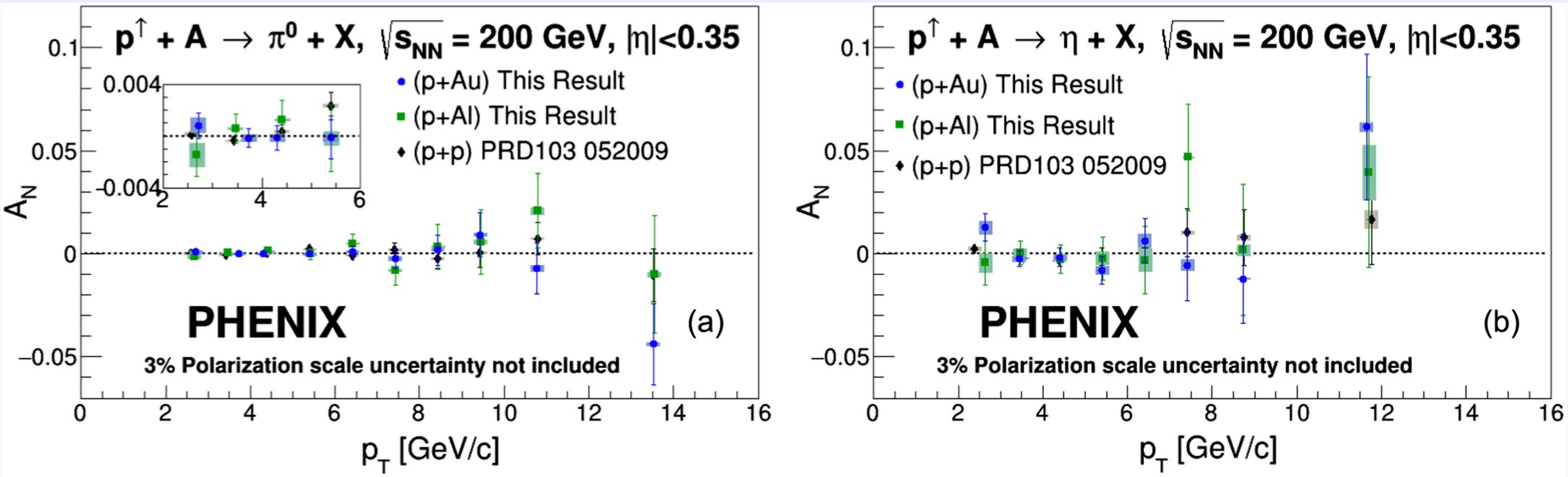


- Pin down the origin of A_N
- Study nuclear effect with a polarized probe!

A_N: Central rapidity

π0 at |η|<0.35

PRD107, 112004 (2023)



Very high precision data

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

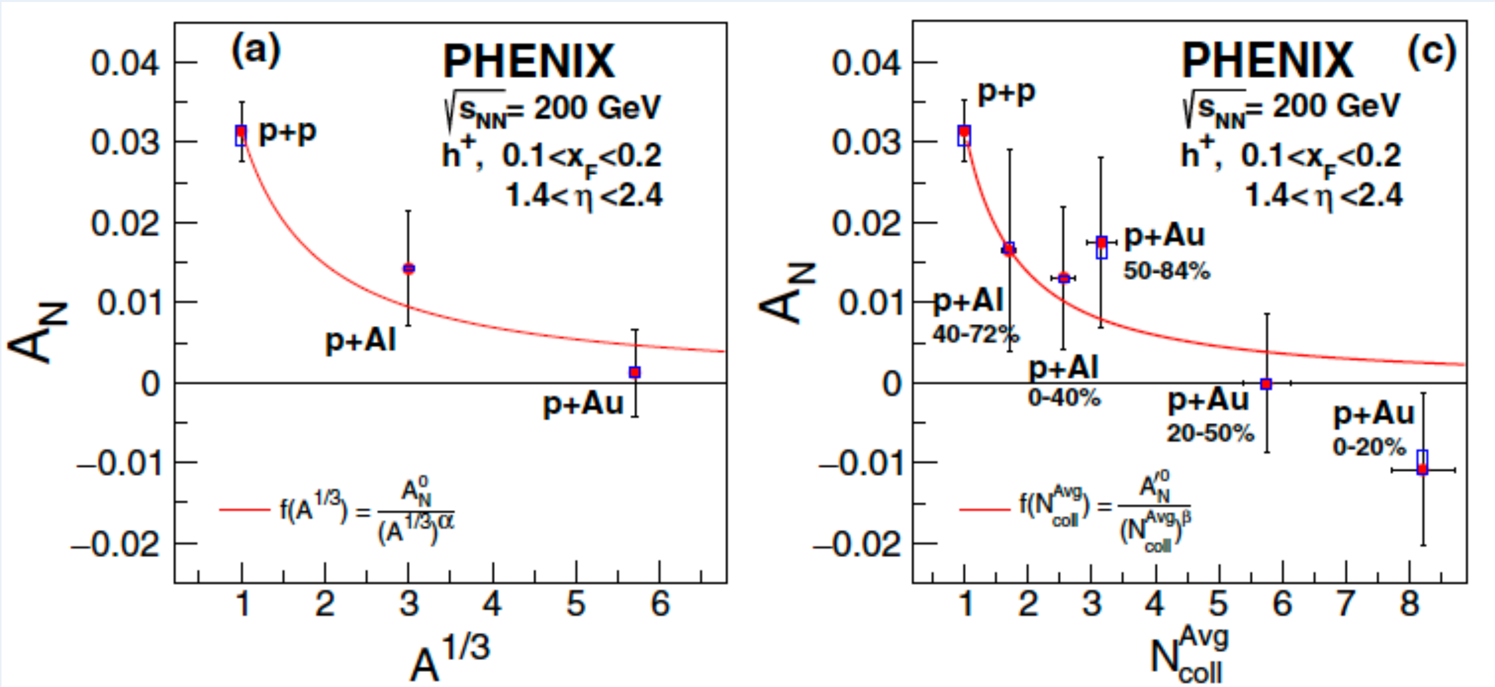
A_N consistent with 0 for all systems

To be used to constrain gluon Sivers fct.

A_N: Forward rapidity

h+ at 1.2<|η|<2.4

PRL123, 122001 (2019)



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:

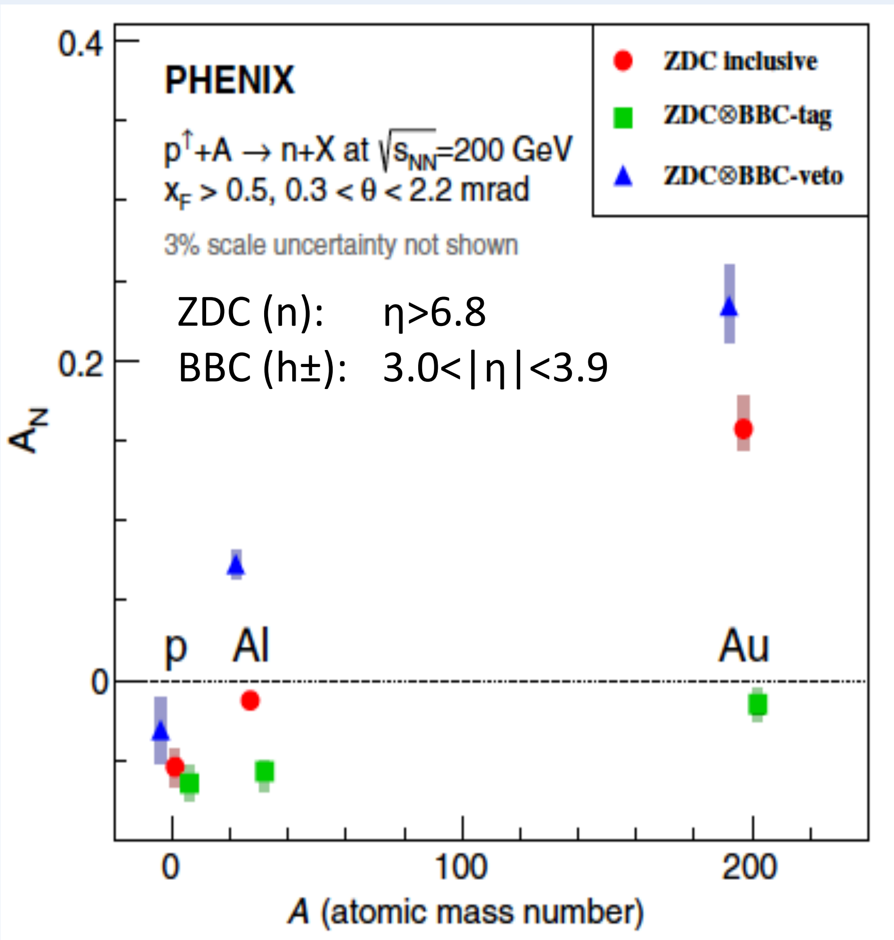
In this kin. region no sensitivity to gluon saturation is expected

Different source of asymmetry? Other nuclear effects?

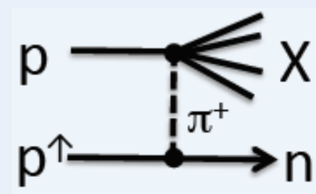
A_N: Very forward rapidity

n at |η|>6.8

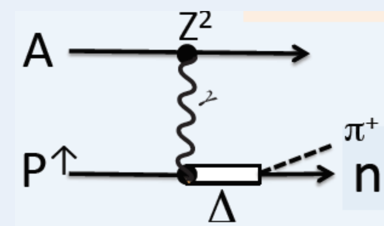
PRL 120, 022001 (2018)



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



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



Electromagnetic interaction:
G.Mitsuka, PRC95 044908

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

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
  Data at lower x coming
- What is the flavor structure of polarized sea in the proton
  $A_L(W)$ will contribute to $\Delta\bar{u}$ and $\Delta\bar{d}$
- What are the origins of transverse spin phenomena in QCD
  $A_N(\pi^0,\eta)$, central and forw; A_N(Heavy Flavor, J/ψ) => gluon Sivers
- First $p^{\uparrow}A$ data !
  A wealth of exciting results awaiting for theoretical interpretation

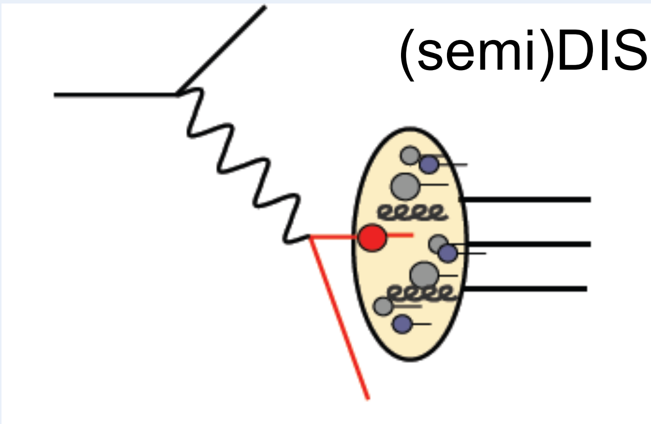
Proton spin decomposition

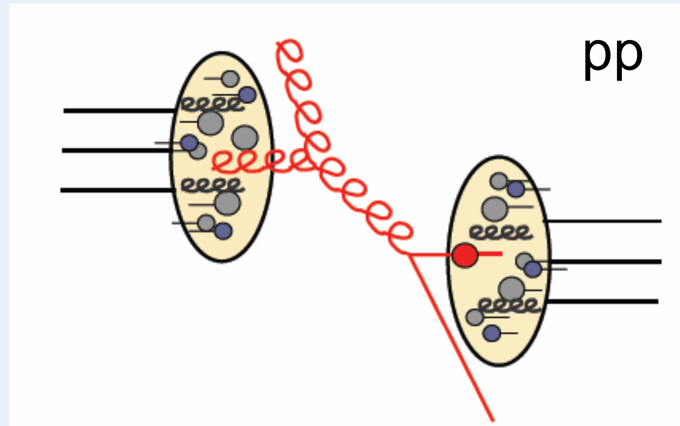
Parton dynamics 3D imaging

Probing nuclear matter effects

Backup

From DIS to pp:





Probes ΔG:

Q² dependence of structure fct

Photon-gluon fusion

(Anti-)quark flavor separation:

Through fragmentation processes

Probes ΔG:

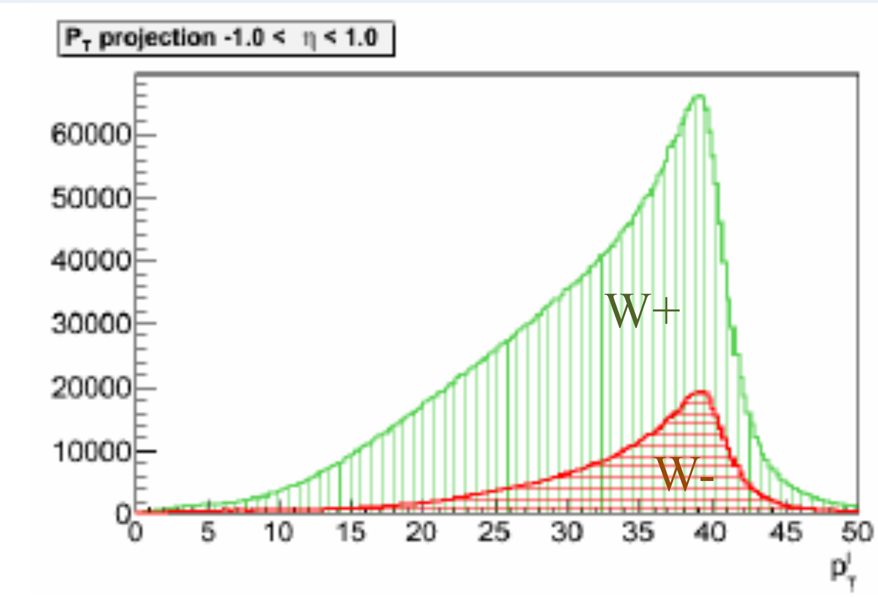
Directly from *gg* and *qg* scattering

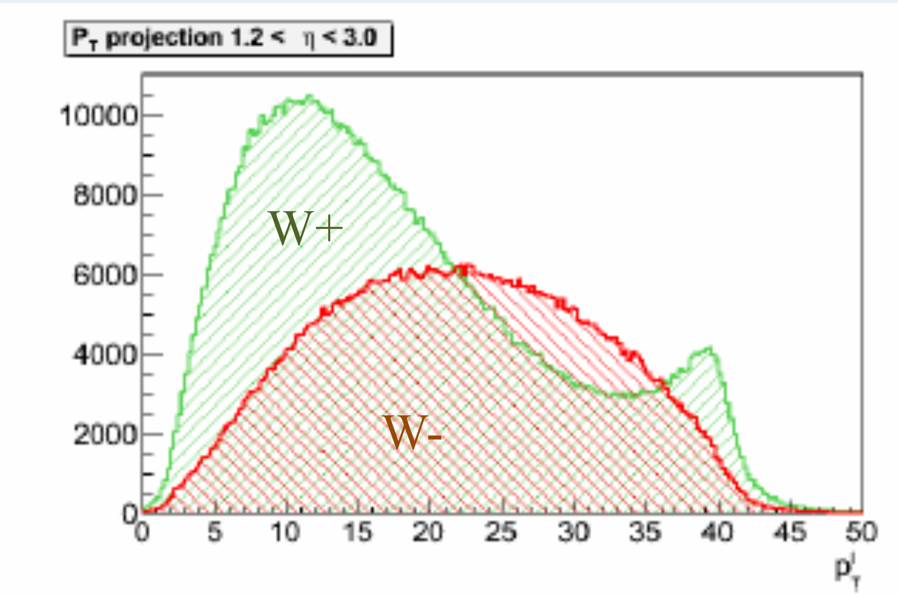
(Anti-)quark flavor separation:

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

Complementary approaches

W: Central vs Forward region





Clear Jacobian peak
at central rapidities

Suppressed/No Jacobean peak
at forward rapidities

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

Δq-bar: W± → e±

|η|<0.35

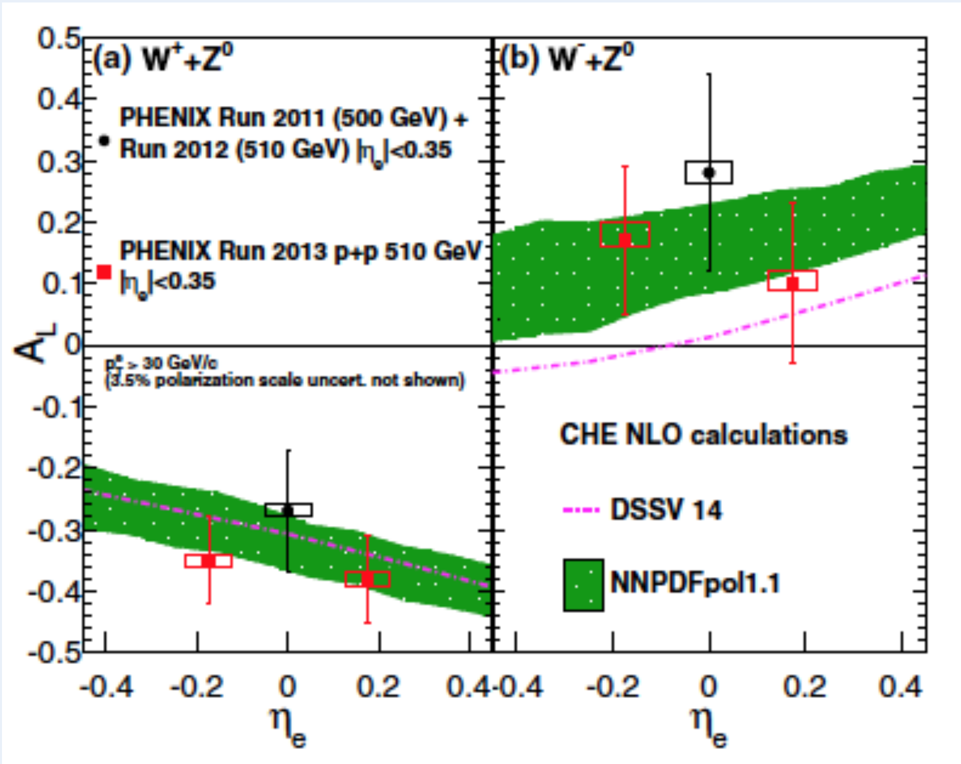
$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta \bar{q}\right) + \Delta G + L_Z$$

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

$$A_L = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$

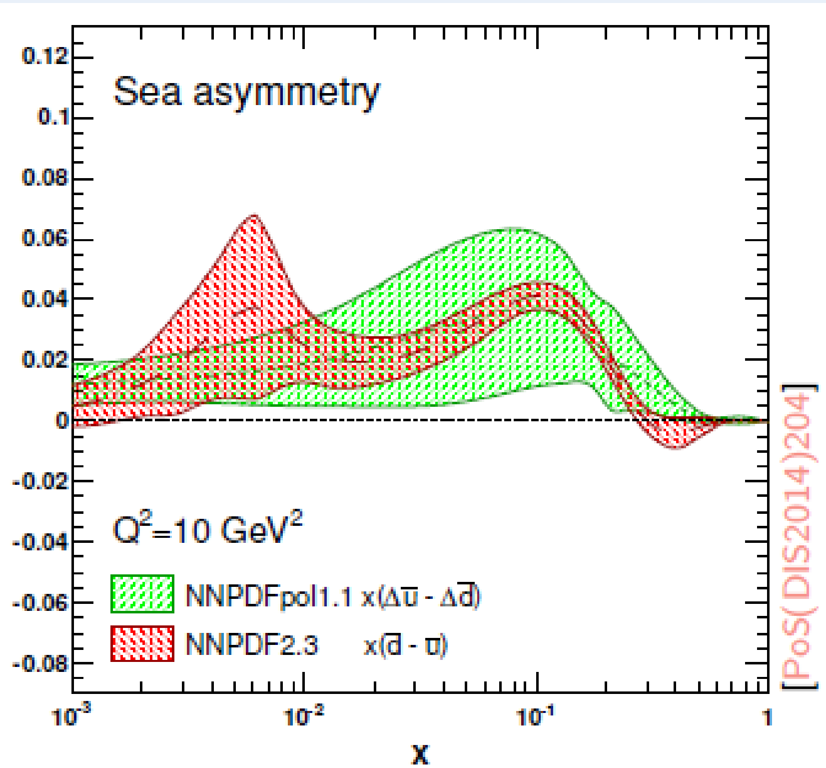
$$A_L^{W^+} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

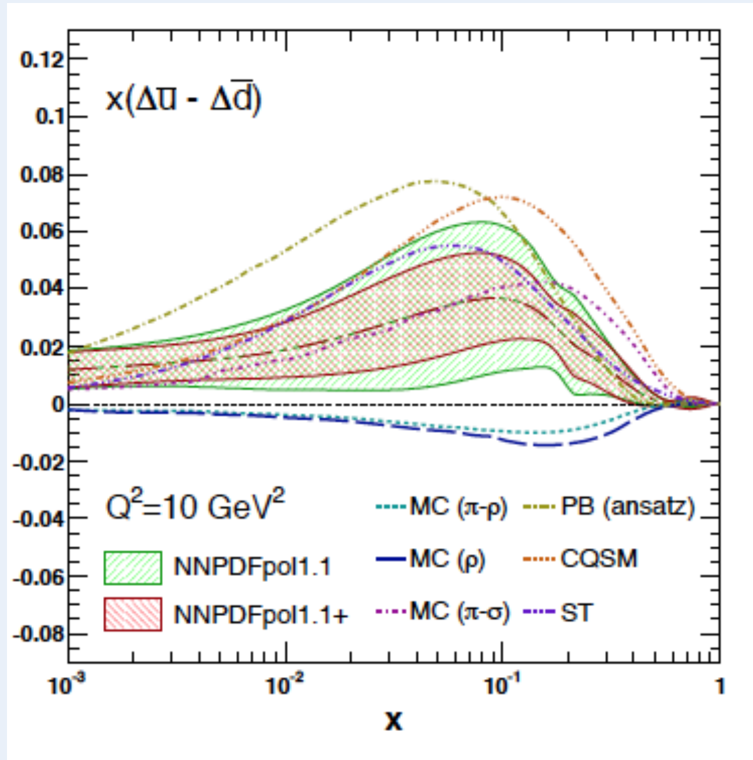
PRD93, 051103 (2016)



Symmetry breaking in polarized sea?

Unpolarized sea is not symmetric

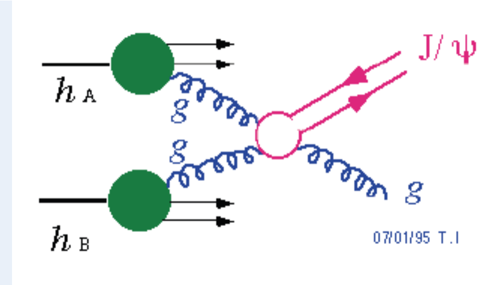




Polarized sea symmetric may be broken too!

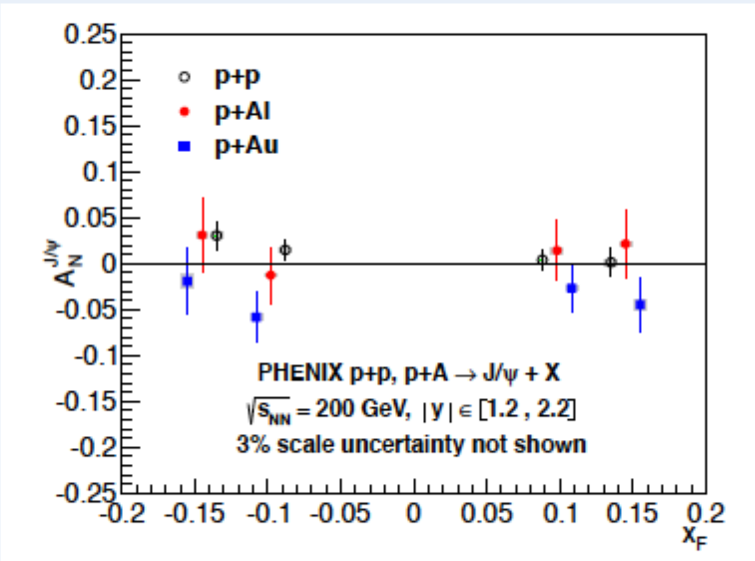
Already available data (Run13) will improve the measurement further

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

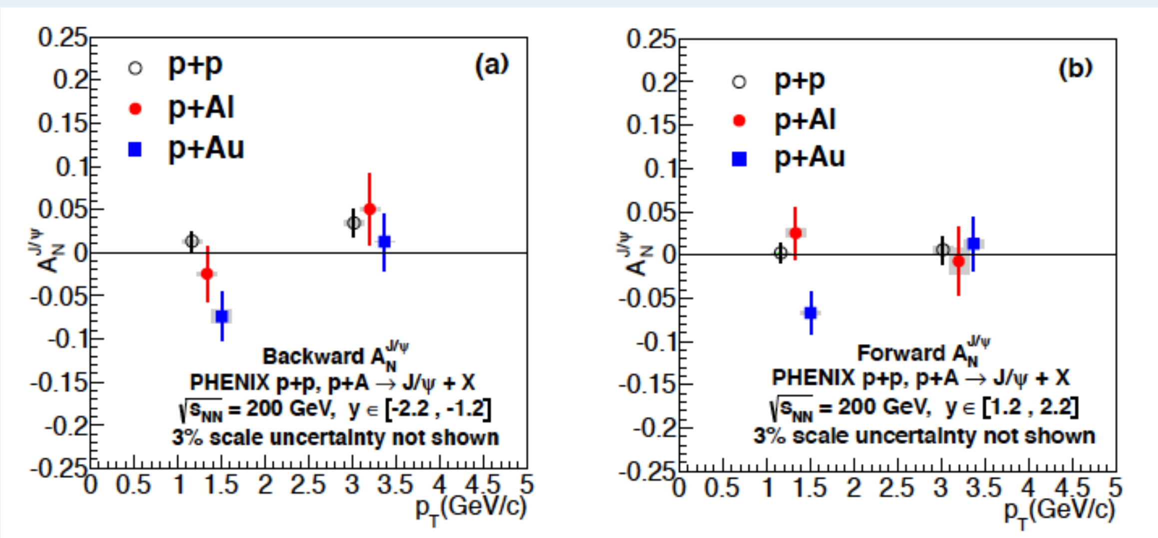
F.Yuan, PRD78, 014024:

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

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

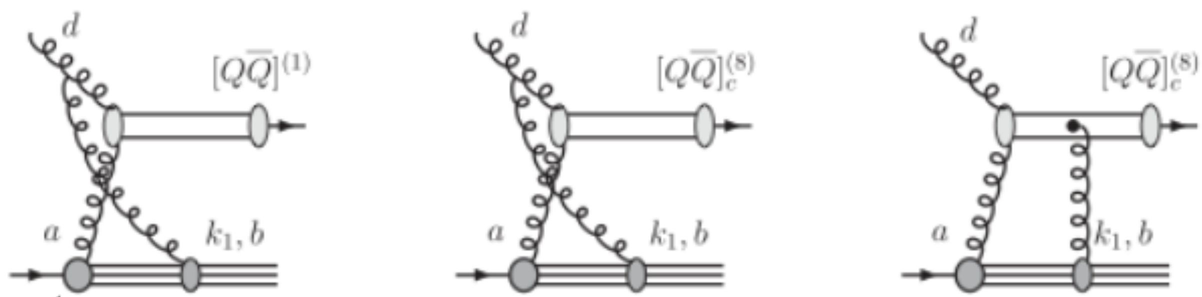
In p+Au: trends to $A_N < 0$

??



$J/\psi\ A_N$

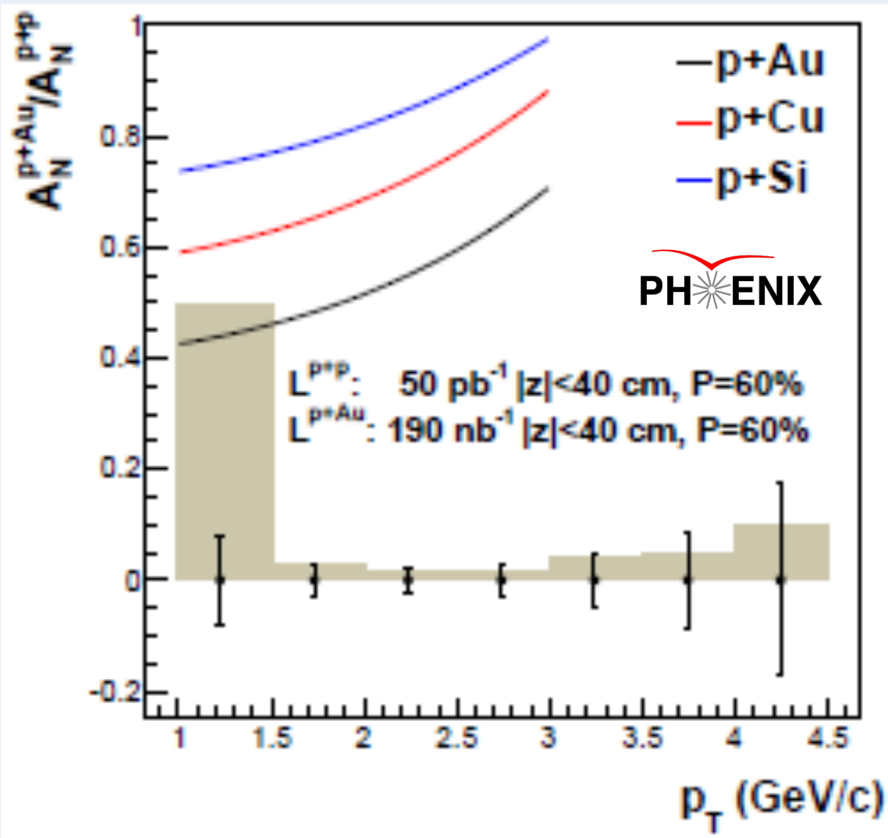
- ❑ J/ψ A_N is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, J/ψ A_N vanishes if the pair are produced in a color-octet model but survives in the color-singlet model
  - *Feng Yuan, Phys. Rev D78, 014024(2008)*



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



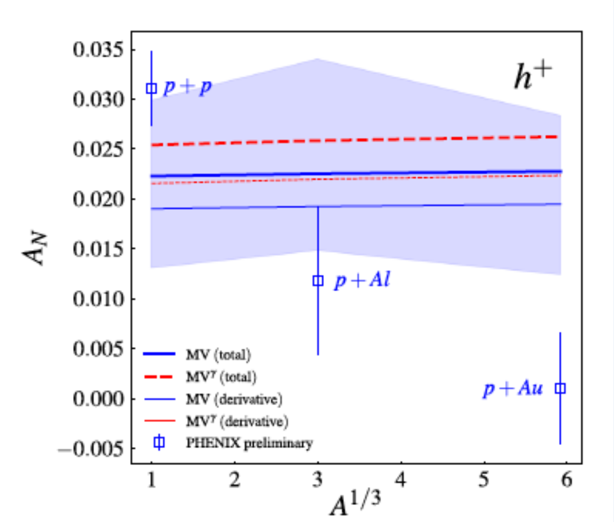
Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

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

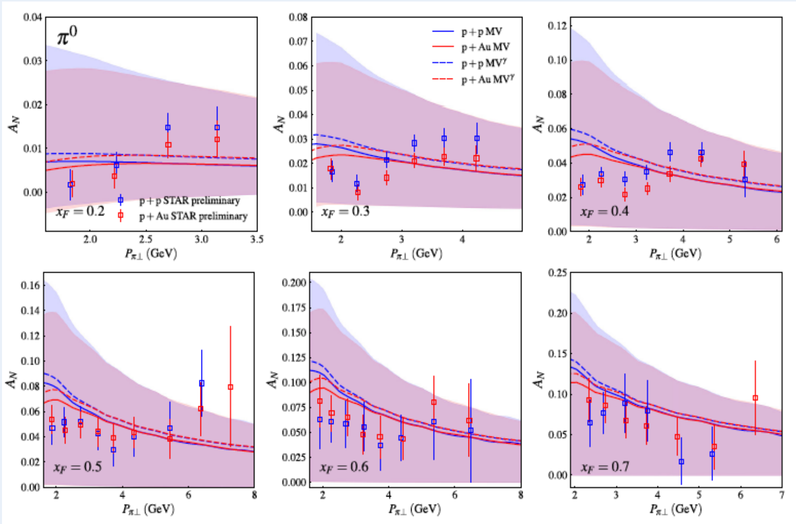
- Unique RHIC possibility $p^{\uparrow}A$
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in $p^{\uparrow}A$ provides sensitivity to Q_s
- Data already collected in Run-2015!

A_N: Forward rapidity

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



PHENIX (Preliminary)	STAR (Preliminary)
h+	$\pi 0$
$1.4<\eta<2.4$	$2.6<\eta<4.0$
$0.1<x_F<0.2$	$0.2<x_F<0.7$
$1.8<p_T<7$	$1.5<p_T<7$
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?

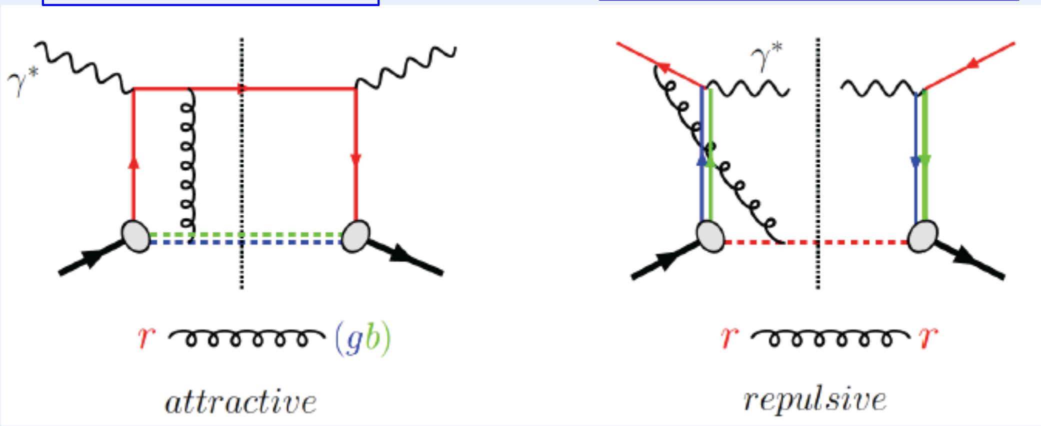
Any connection with QGP formation in pA?

Color Interaction in QCD

Controlled non-universality of Sivers function

QCD:

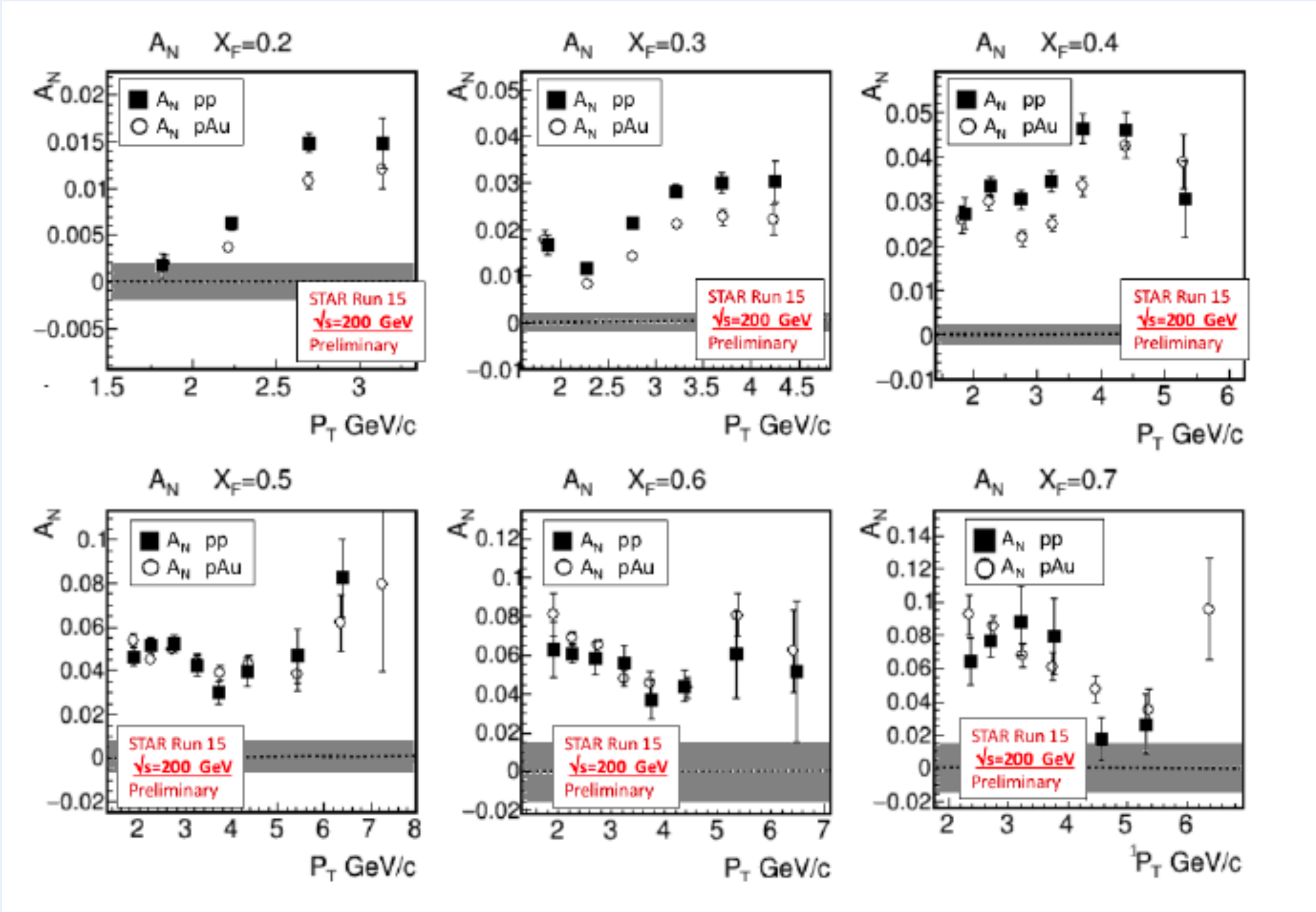
DIS Attractive FSI	Drell-Yan, W or Z Repulsive ISI



$$\text{Sivers}_{\text{DIS}} = -(\text{Sivers}_{\text{DY}} \text{ or Sivers}_{\text{W}} \text{ or Sivers}_{\text{Z}})$$

A_N(dir. γ) has related sign change in Twist-3

Critical test of TMD factorization
All observables can be explored at RHIC

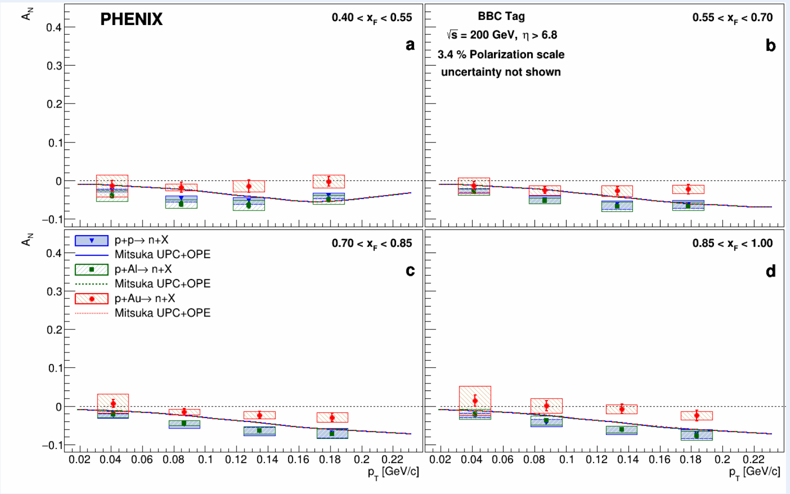

A_N X_F=0.2
A_N X_F=0.3
A_N X_F=0.4
A_N X_F=0.5
A_N X_F=0.6
A_N X_F=0.7
A_N pp
A_N pAu
STAR Run 15
√s=200 GeV
Preliminary
P_T GeV/c

A_N: Very forward rapidity

n at |η|>6.8

PRD 105, 032004 (2022)

BBC correlated



BBC veto