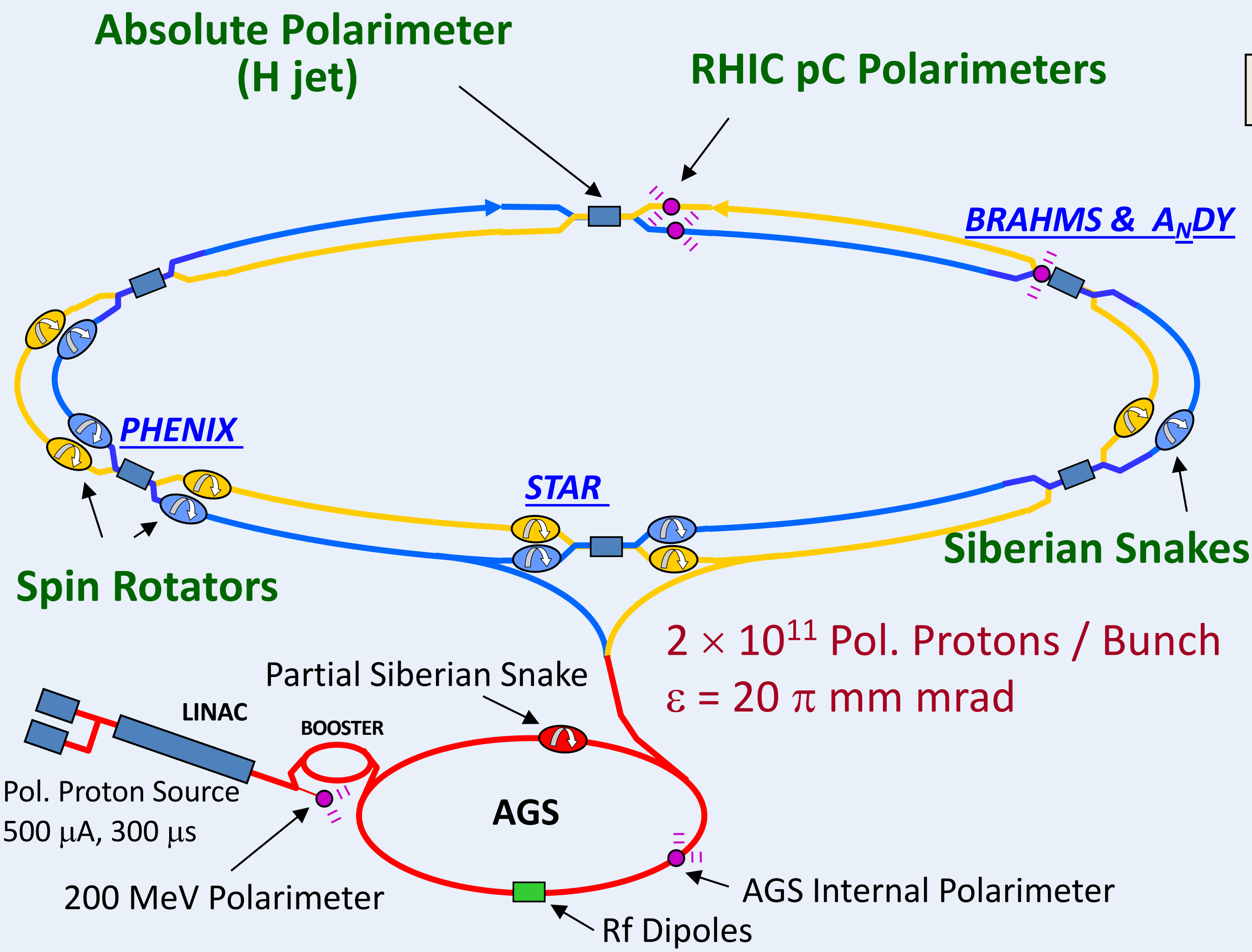
PHENIX Spin Highlights

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

A.Bazilevsky (BNL)

For PHENIX Collaboration

PHENIX Spin @ RHIC

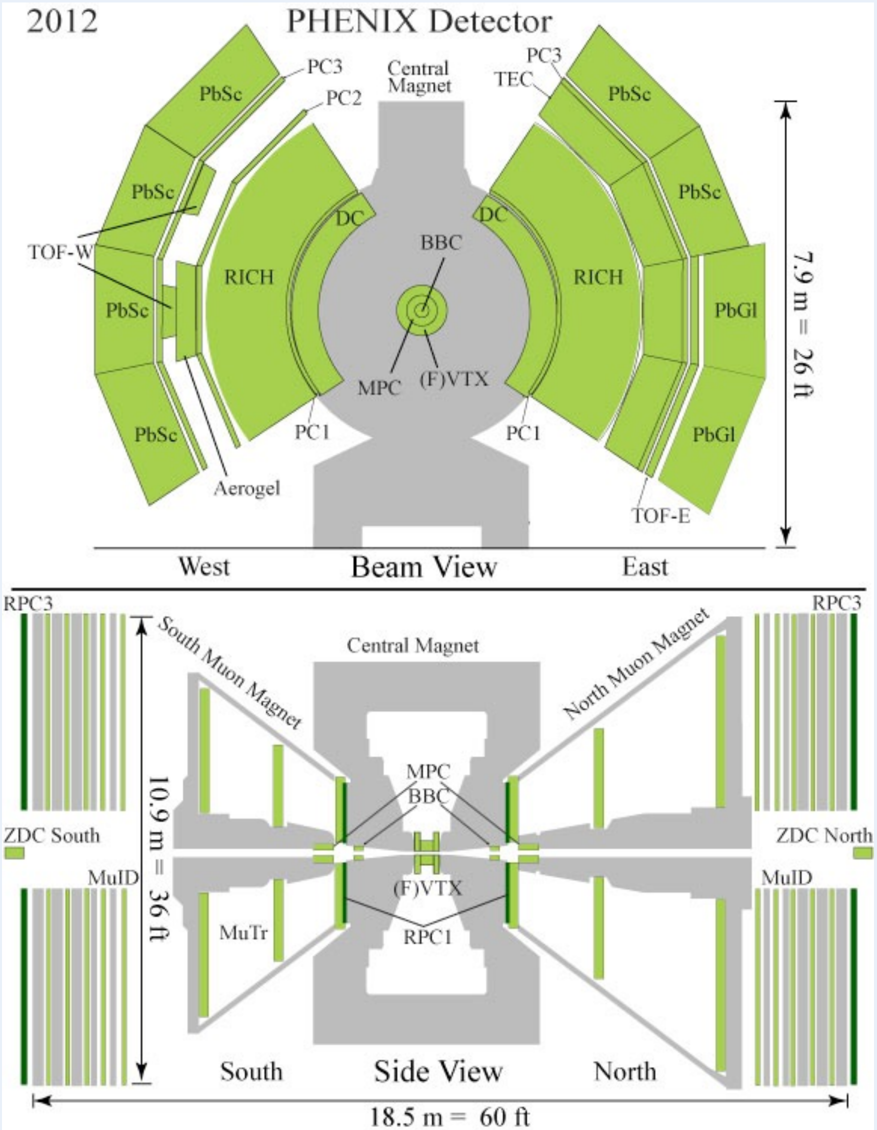


Spin Running in PHENIX, long./trans.

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

A.Bazilevsky, DIS-2024

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

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

Muon Id/Muon Tracker

FVTX

Relative Luminosity

Beam Beam Counter (BBC)

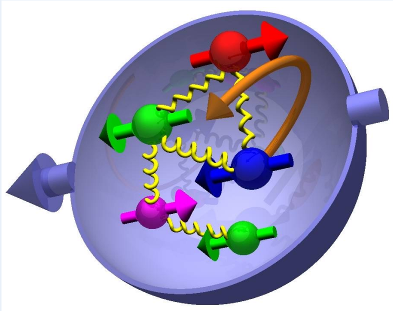
Zero Degree Calorimeter (ZDC)

Local Polarimetry – ZDC & SMD

Spin direction control

ΔG: $\pi 0$ A_{LL}

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



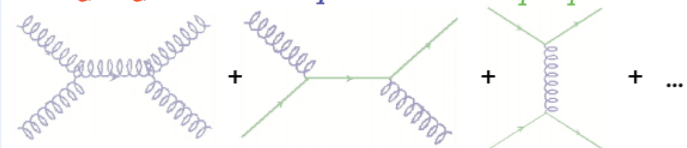
The most abundant probe in PHENIX

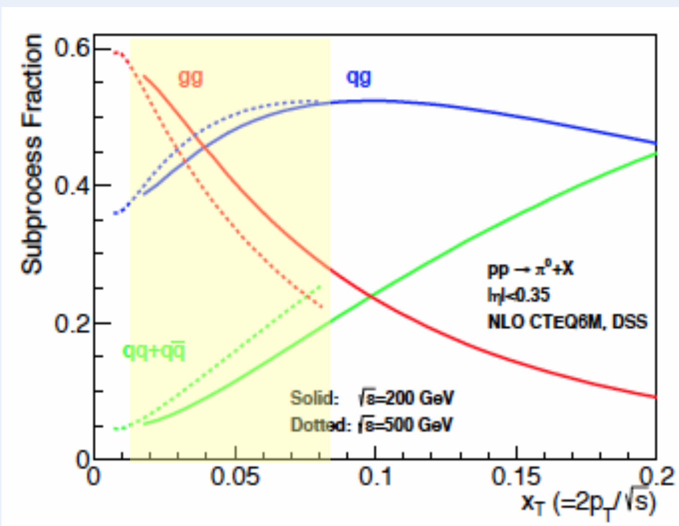
(triggering + identification capability)

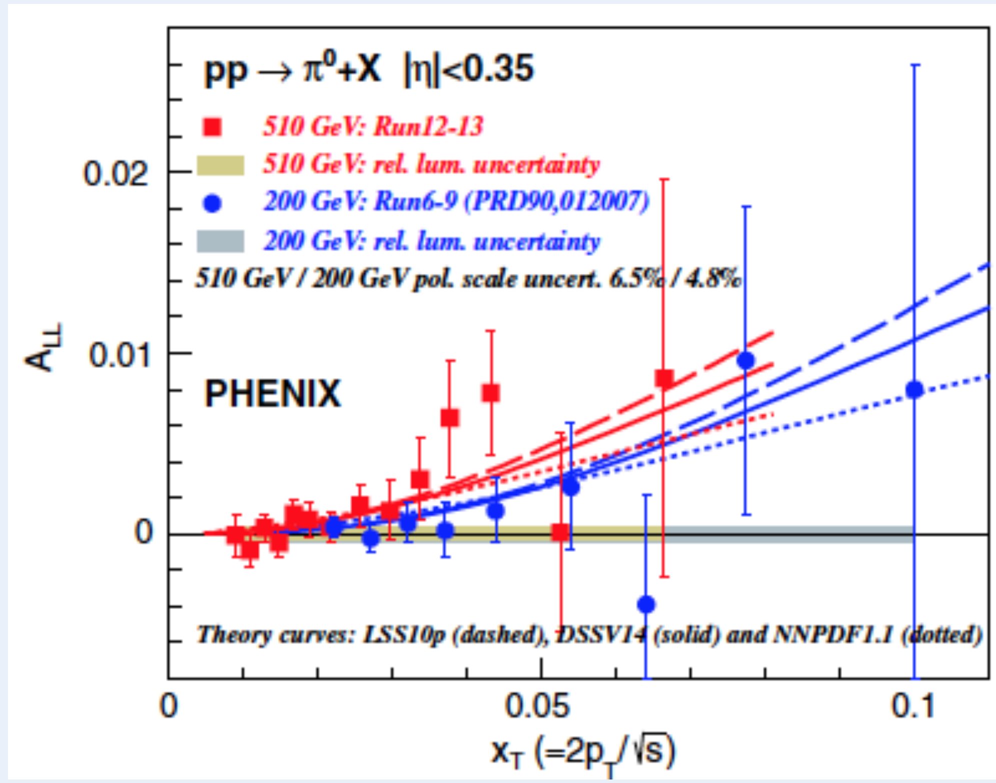
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

PRD93, 011501 (2016)

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





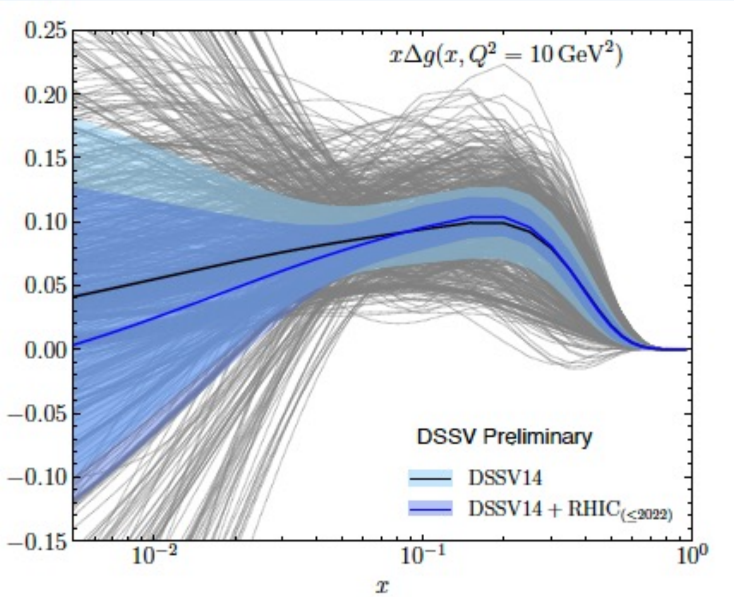


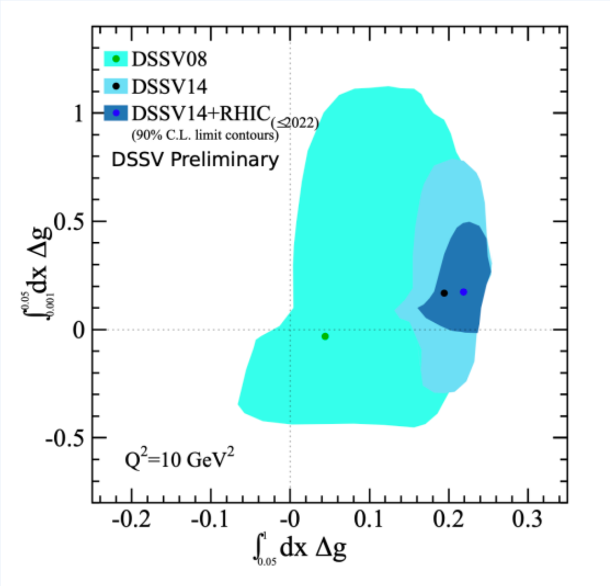
Non-zero A_{LL} associated with non-zero ΔG !

ΔG: DIS+pp global QCD fit

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

pp main contributors: PHENIX π0 + STAR jet





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

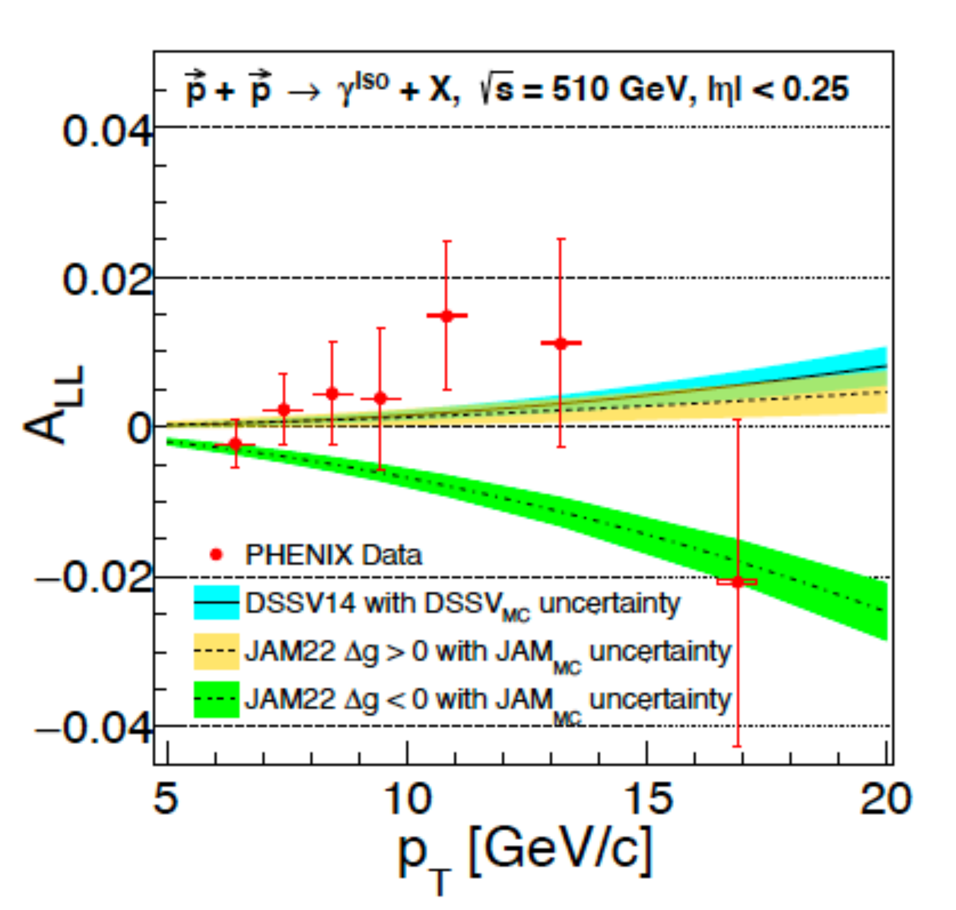
- Significant contribution from gluon spin to proton spin (at x>0.05)
  - Similar conclusion from other global fits: NNPDF, JAM
- More A_{LL} data are published: η, $\pi\pm$, $h\pm$, J/ψ, HF e
- Still huge uncertainty in unmeasured region (x<0.05)
  - => More RHIC results at highest √s and forward rapidity are coming
- Sign needs a confirmation (see next slide)
  - => Need cleaner prob, e.g. direct photons

ΔG: Confirm the Sign

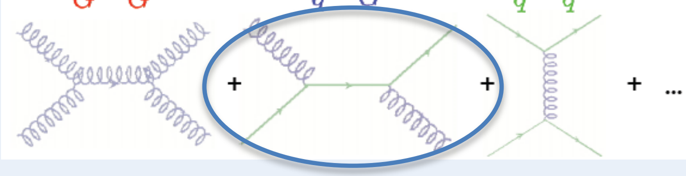
$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G + L_Z$$

Direct photon - a golden channel to probe gluons

PRL130, 251901 (2023)



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



JAM collaboration:

Negative ΔG still allowed

PHENIX:

Clear preference for positive ΔG

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

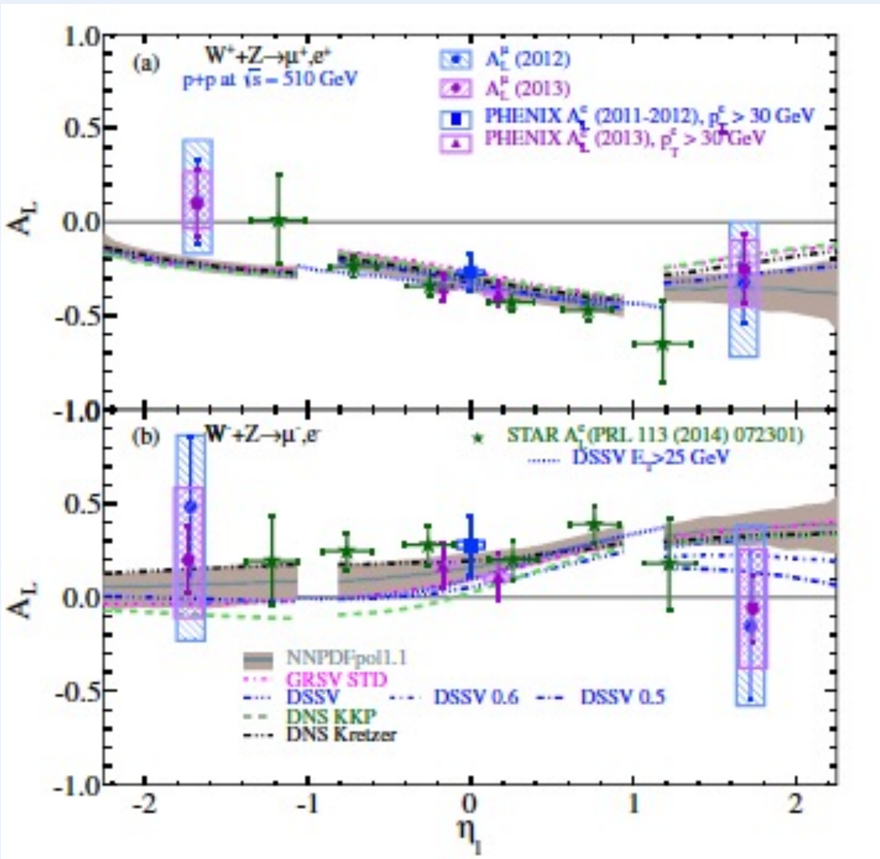
Δq-bar: $W^\pm \to e^\pm, \mu^\pm$

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

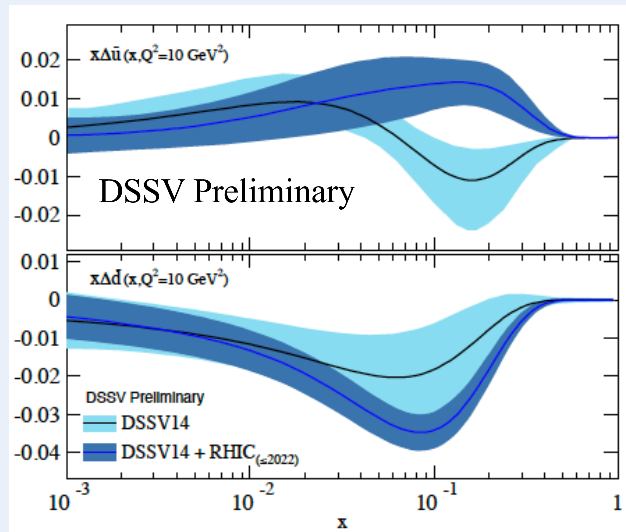
$e^\pm$: $|\eta|<0.35$ $\mu^\pm$: $1.2<|\eta|<2.4$

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



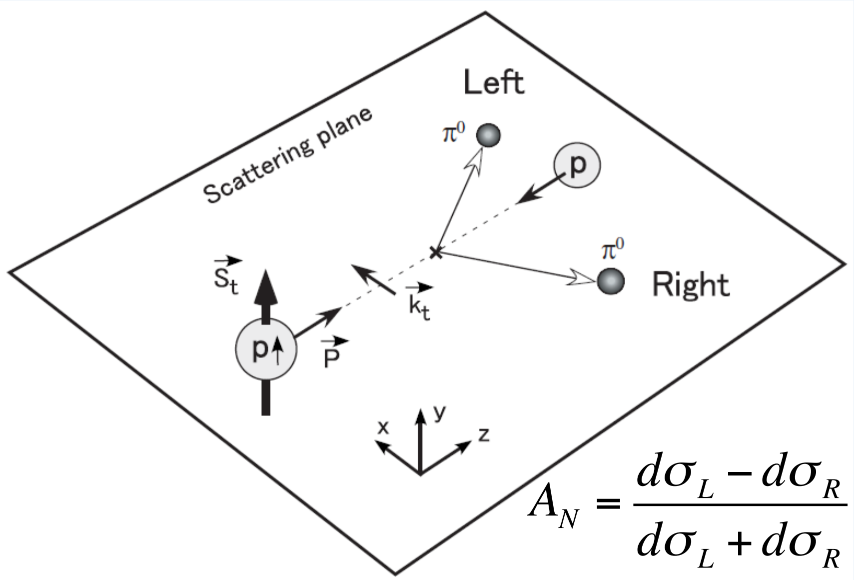
Preference of

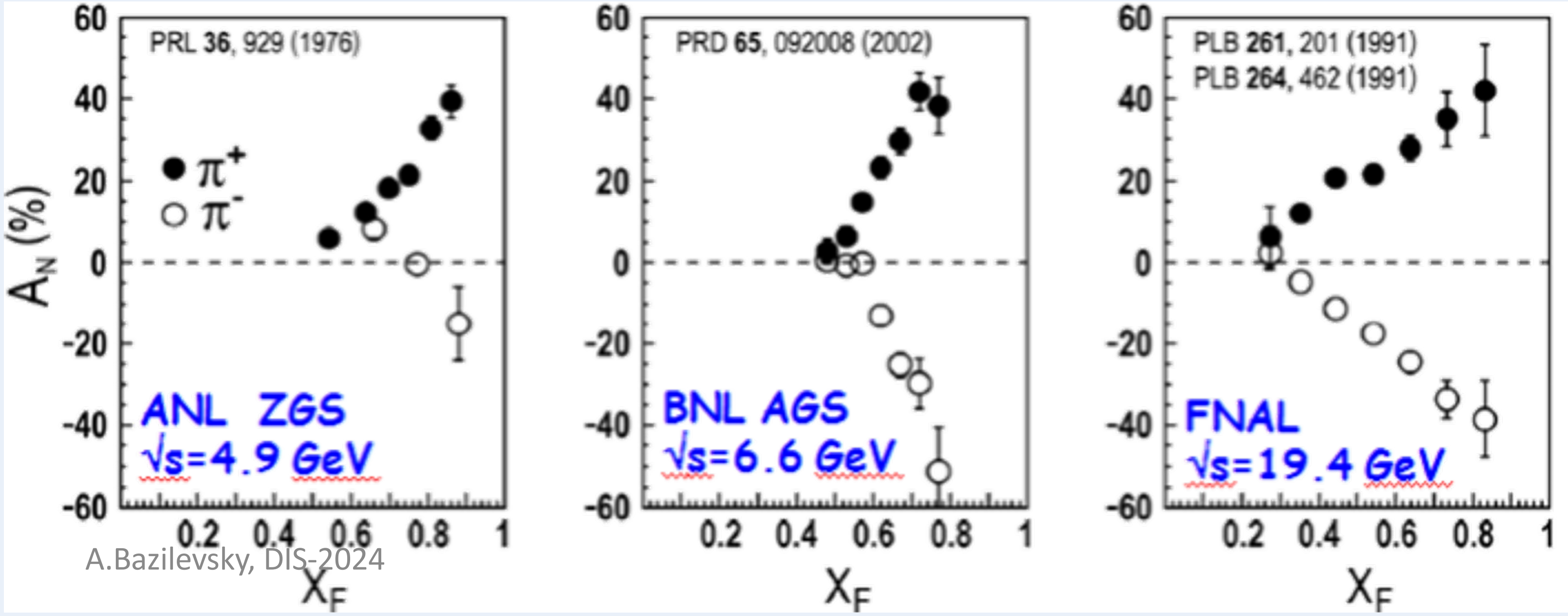
Positive ubar polarization

Negative dbar polarization

Transverse Spin Asymmetries

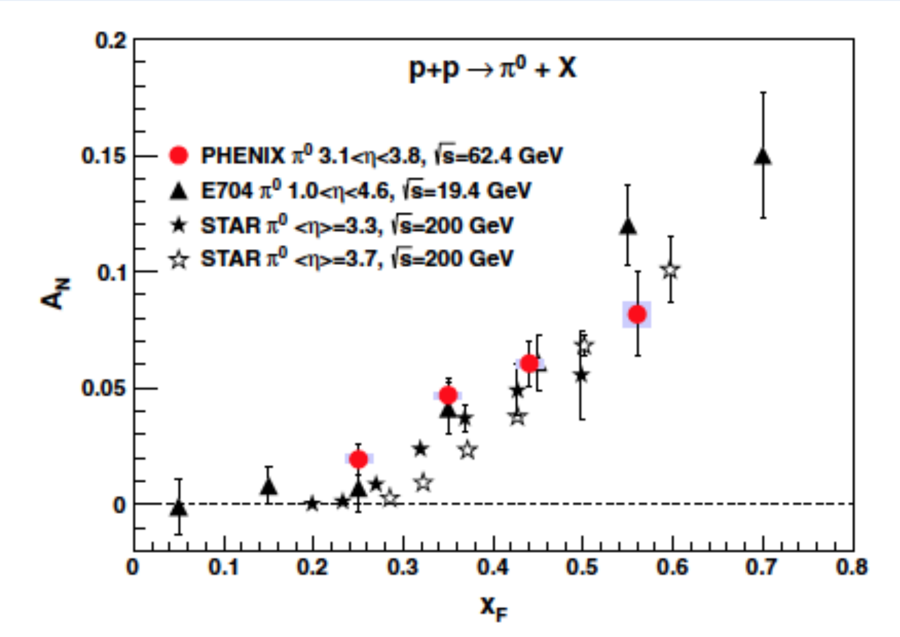
Large Transverse Spin Asymmetries have been observed in $p^{\uparrow}p$





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

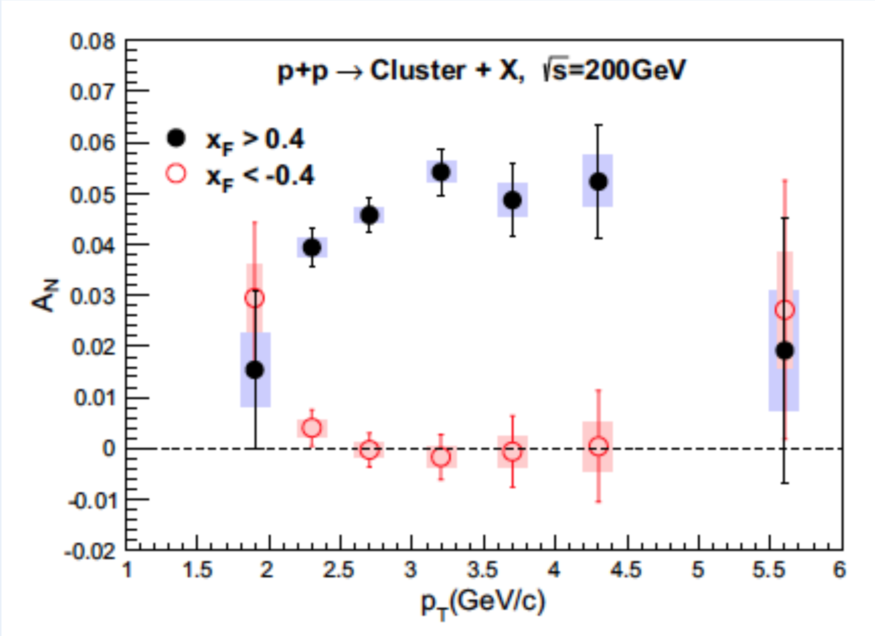
Asymmetries scale with x_F

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



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

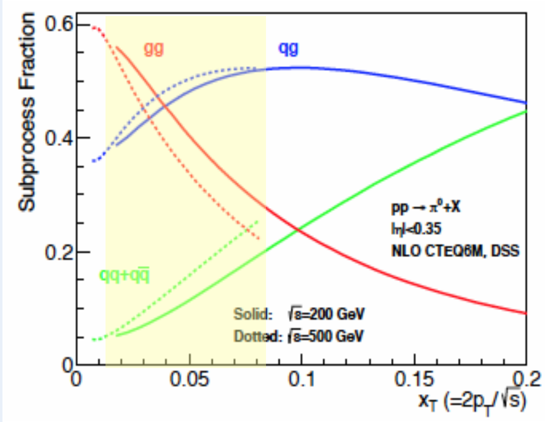
Universal between SIDIS & pp & e+e-

- Quark transversity
- Tensor charge

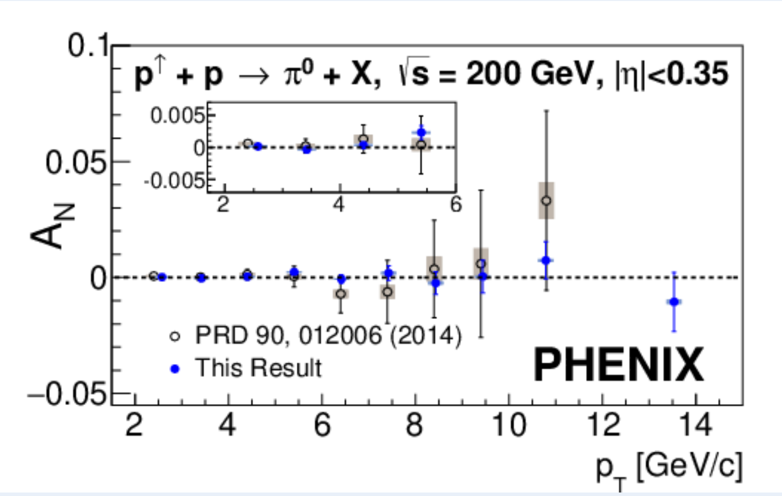
Other mechanisms

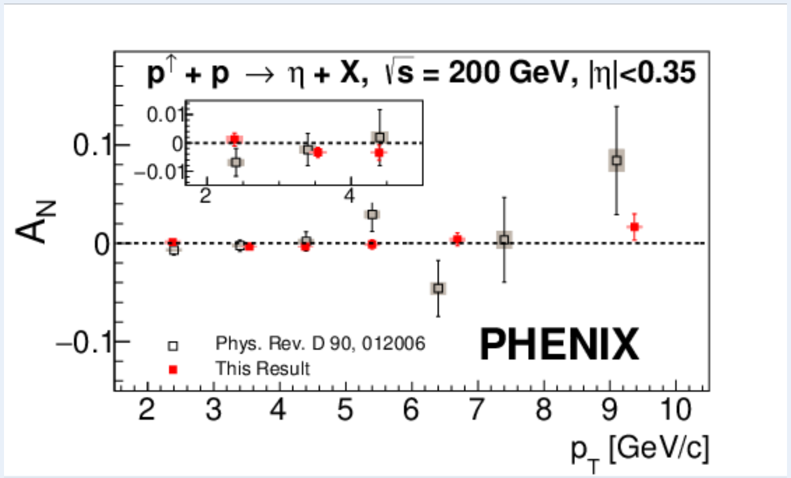
- Diffraction

A_N: Mid-rapidity π0 and η



PRD103, 052009 (2021)





Consistent with 0

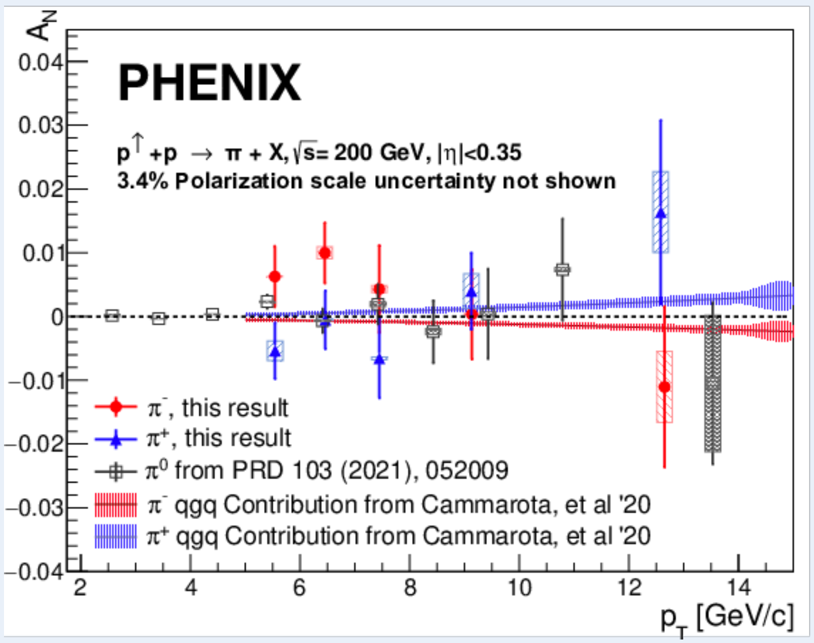
To ~3×10^{-4} precision level at π0 low p_T

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

A_N: Mid-rapidity π±

PRD105, 032003 (2022)



Flavor sensitivity in initial and final effects

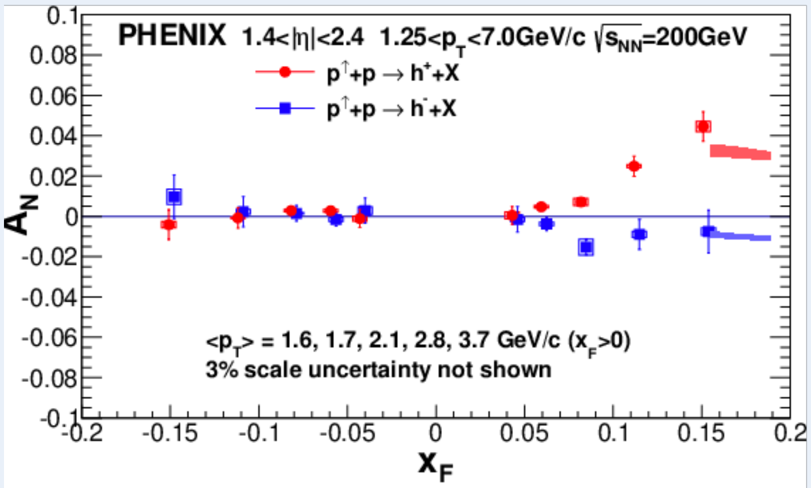
u→π+ vs d→π-

Consistent with zero (as π0 results)

A hint for a charge dependence?

A_N: Forward *h*± and *η*

PRD108, 072016 (2023)



Sizable positive A_N for h+

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

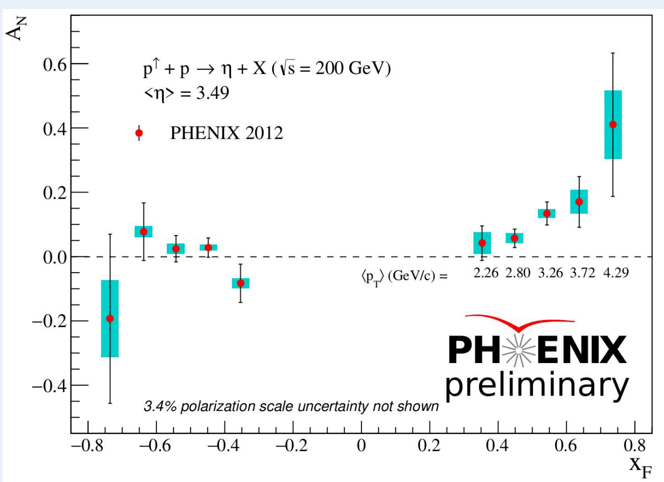
Slightly negative A_N for h-

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

Comparison to Twist-3 model

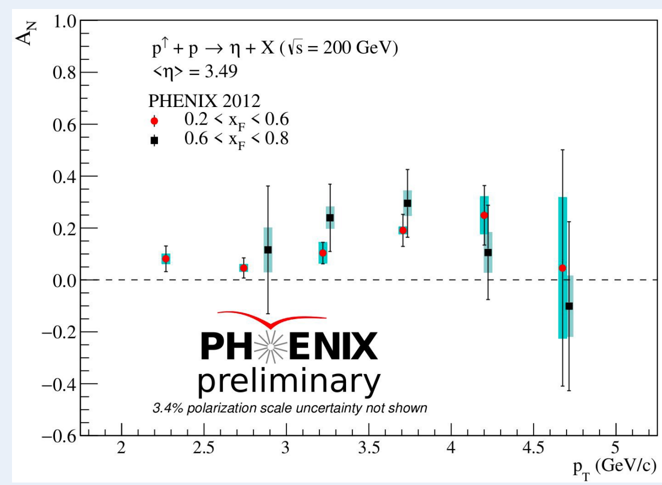
Gamberg, Kang, Pitonyak, Prokudin, Phys.Lett.B 770, 242

See D. Loomis talk, WG5

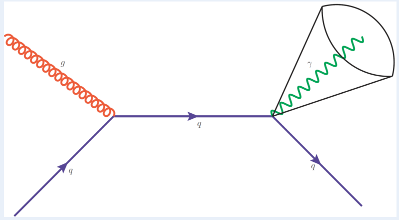


~0 at negative xF
Increasing with positive xF
Similar to π0

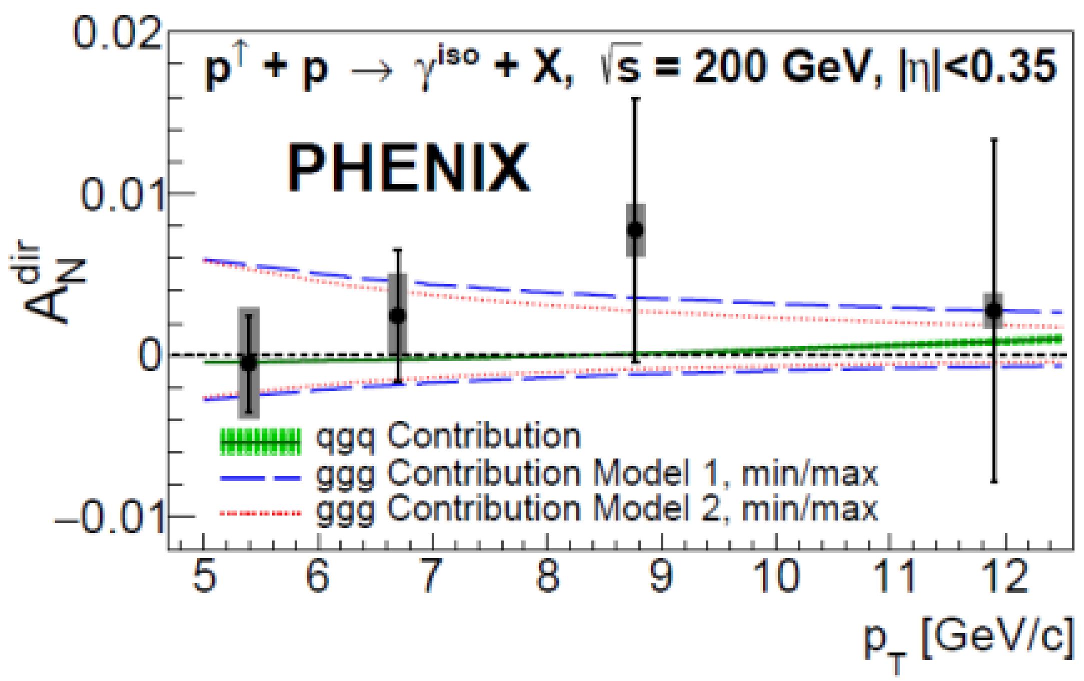
A hint of asymmetry drop at high pT



A_N: Direct Photon

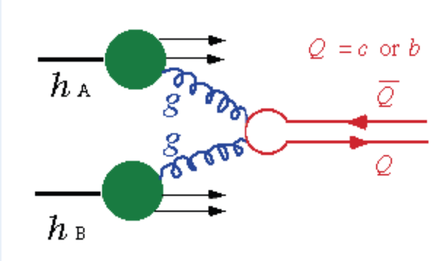


PRL127, 162001 (2021)

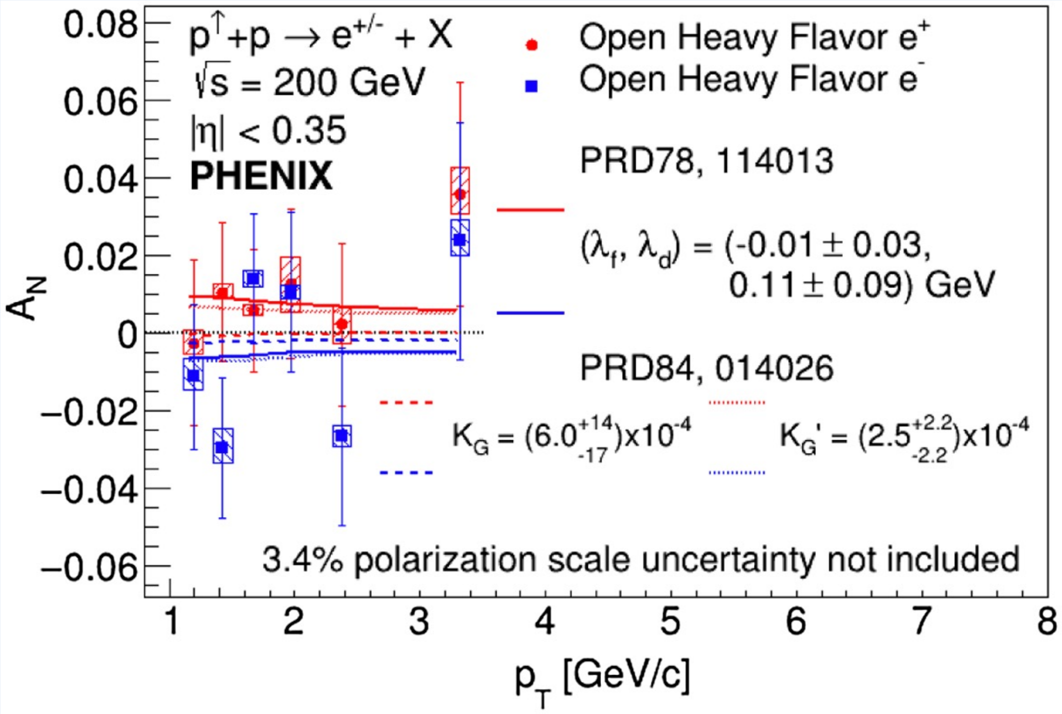


- ✓ First direct γ A_N from RHIC
- ✓ ×50 times reduced uncertainty compared to the only prior measurement at E704 (Fermilab)
- ✓ Clean prob of initial state effect (no fragmentation)
- ✓ Constraints gluon dynamics within proton (through gluon-gluon correlation function)

A_N: Heavy Flavor



PRD107, 052012 (2023)



Dominated by gluon-gluon fusion

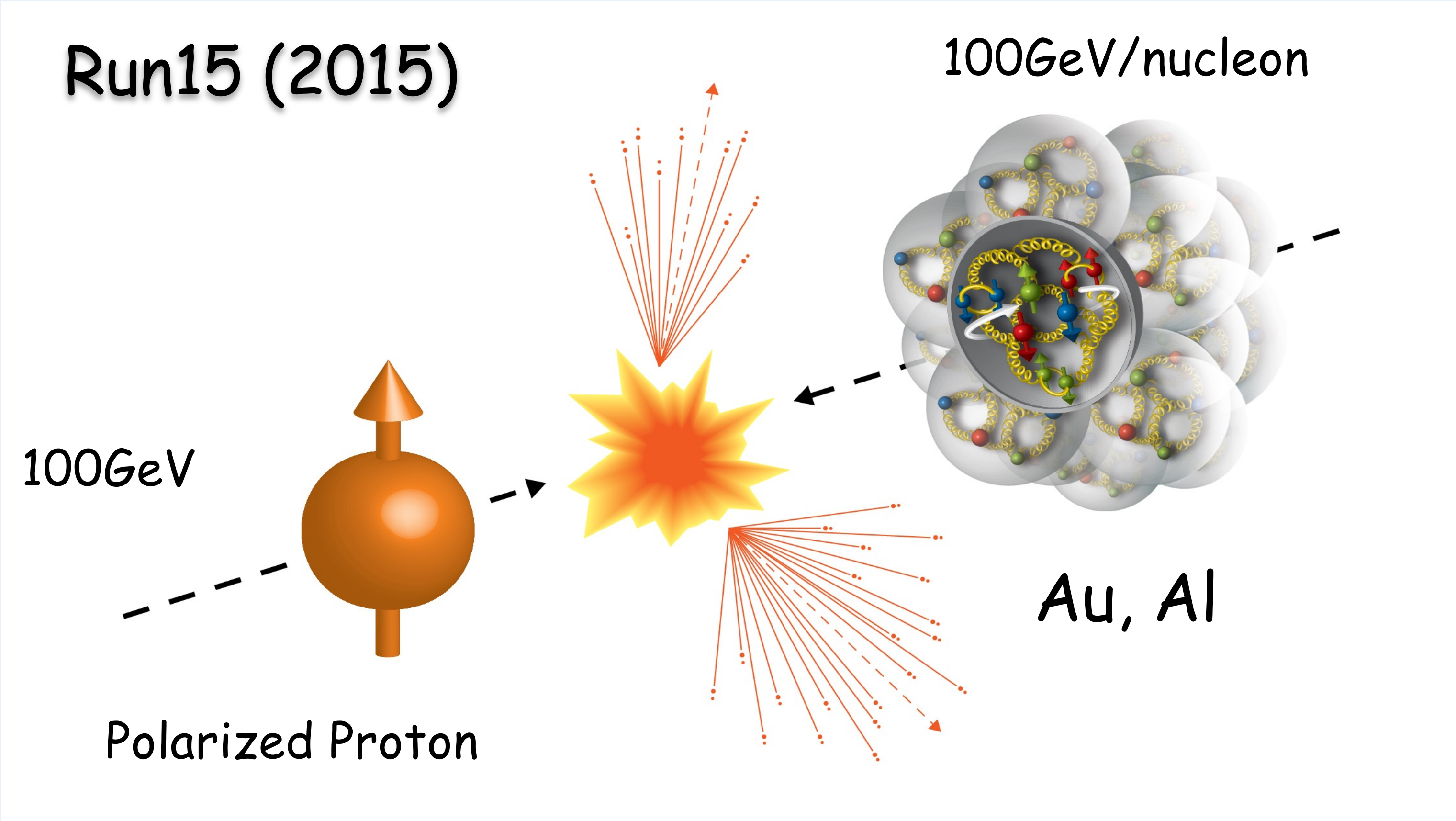
Used to constrain tri-gluon correlation in the Twist-3 collinear framework

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 !!!

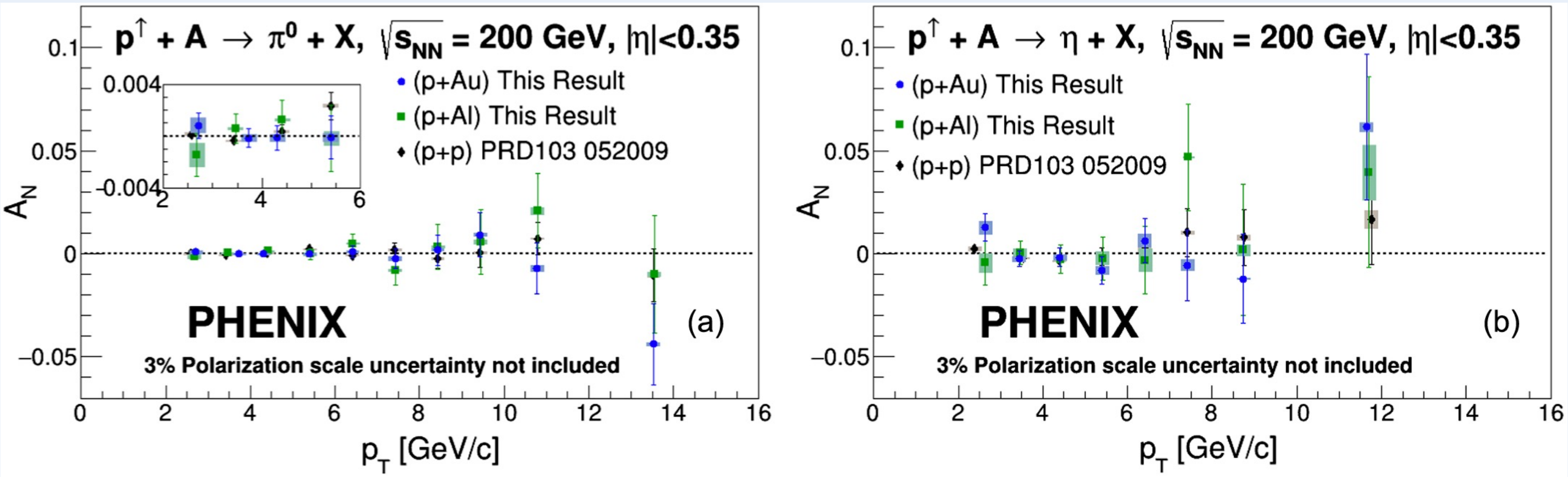


- Pin down the origin of A_N
- Study nuclear effect with a polarized probe!

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

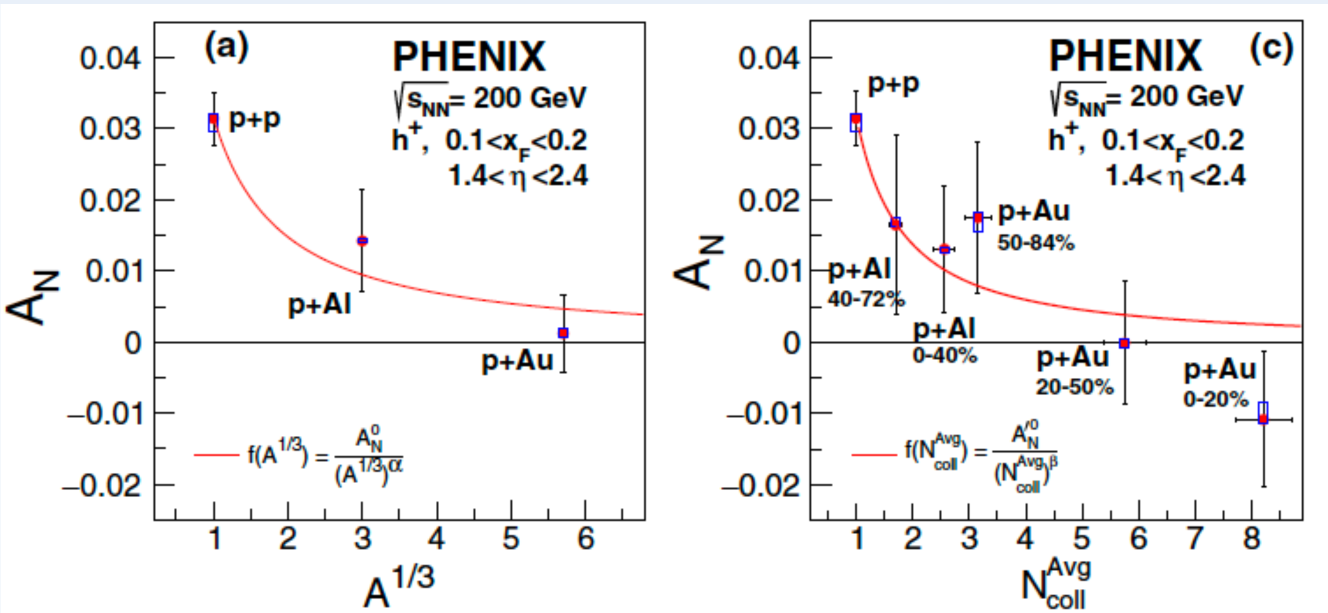
To be used to constrain gluon Sivers fct.

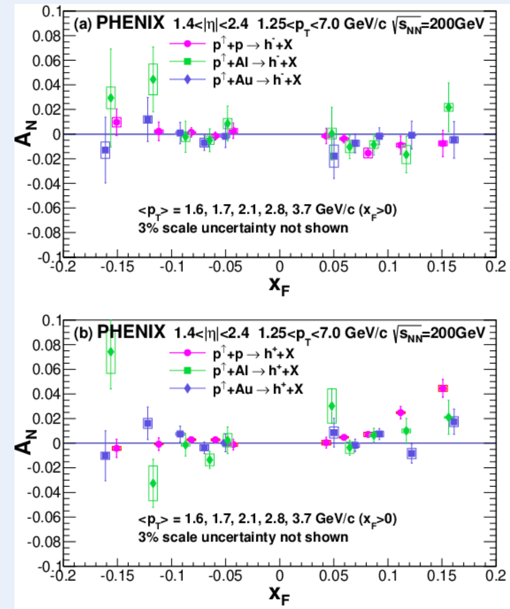
A_N: Forward rapidity

h+ at 1.2<|η|<2.4

PRL123, 122001 (2019)

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

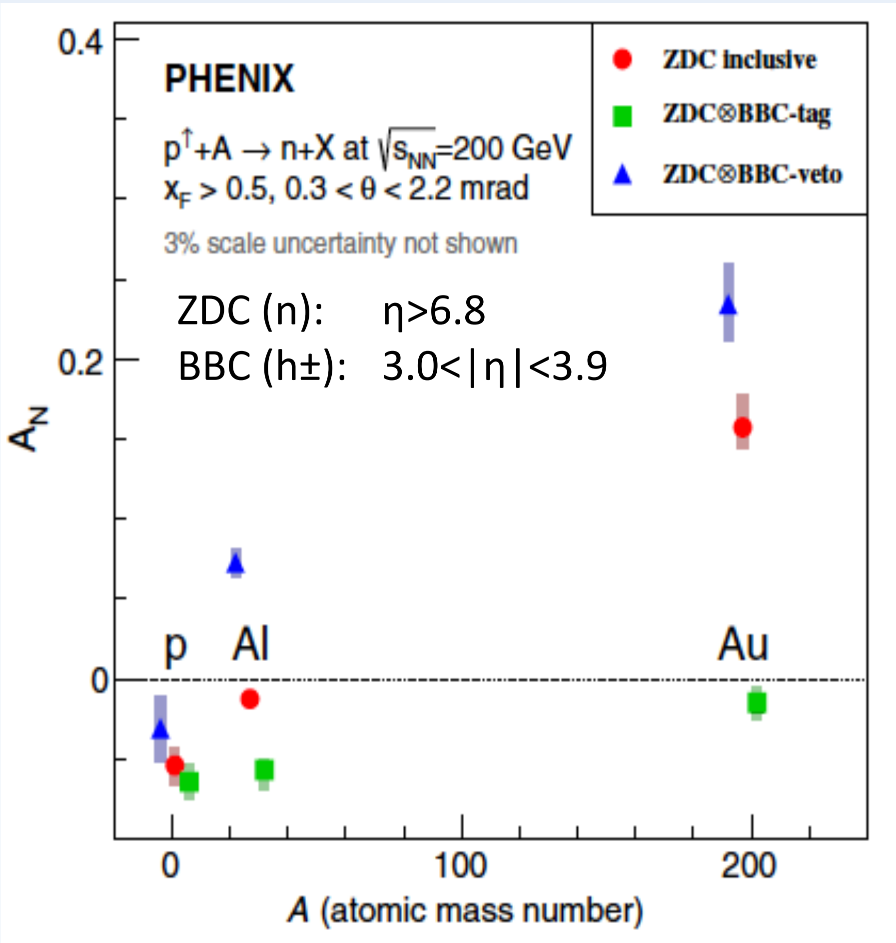
However:

- In this kin. region no sensitivity to gluon saturation is expected
- Different source of asymmetry? Other nuclear effects?

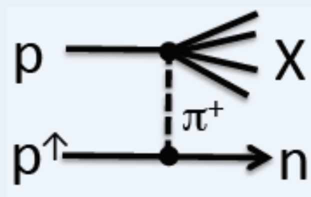
A_N: Very forward rapidity

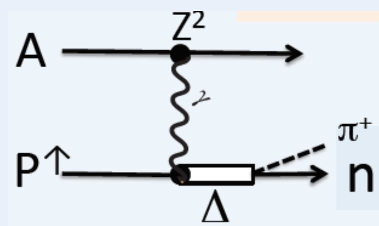
n at |η|>6.8

PRL 120, 022001 (2018)



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





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

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

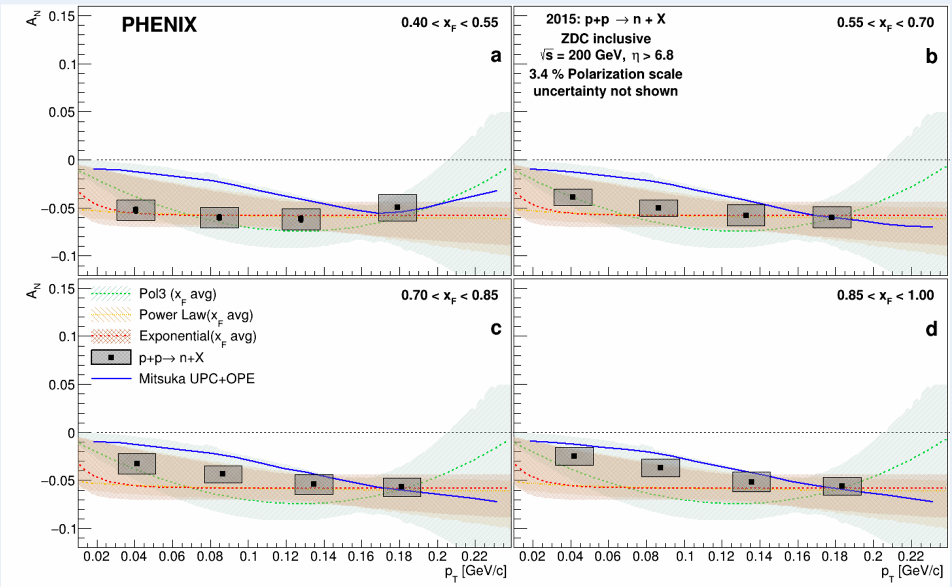
- Correlation with particle production in other rapidities, and different A and √s will help to isolate different channels

A_N: Very forward rapidity

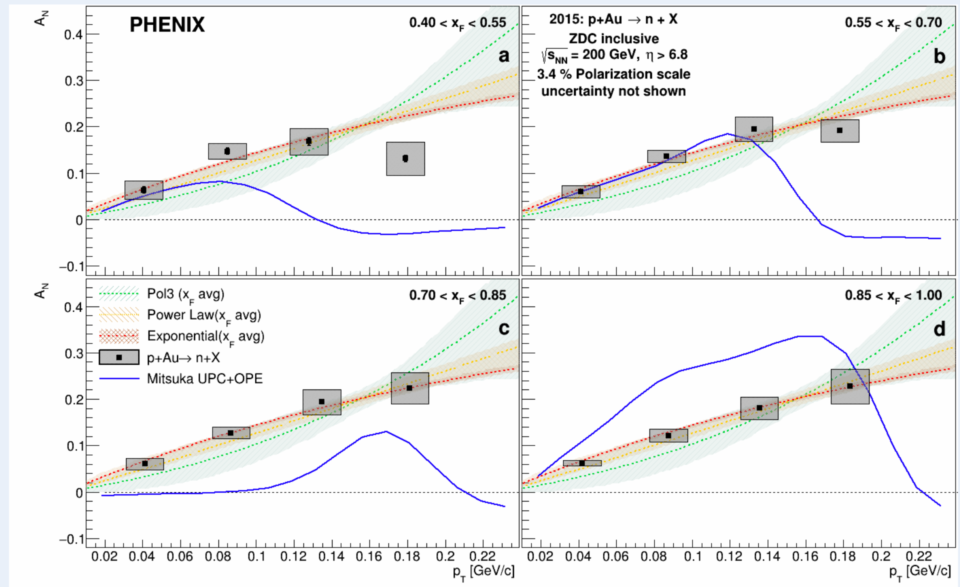
n at |η|>6.8

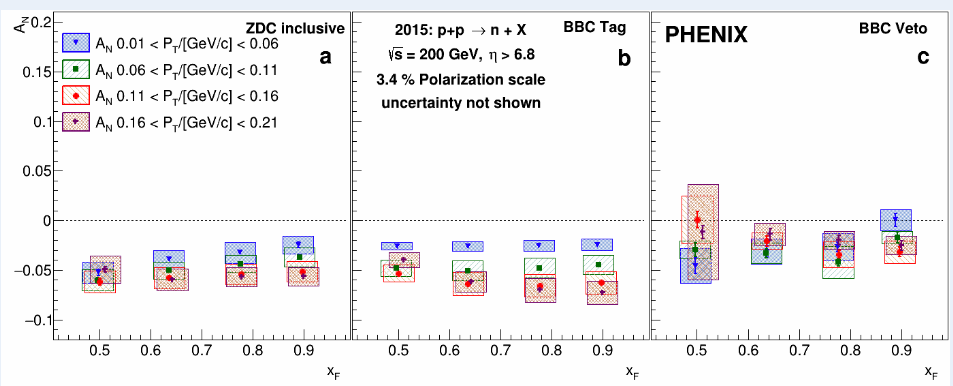
PRD 105, 032004 (2022)

pp



pAu





Magnitude increasing with pT

Weak xF dependence

Model: UPC+OPE

OPE dominates in pp

UPC dominates in pAu

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

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

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

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

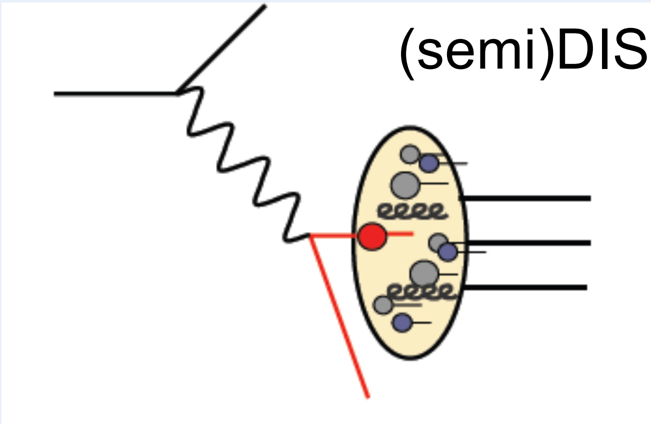
Proton spin decomposition

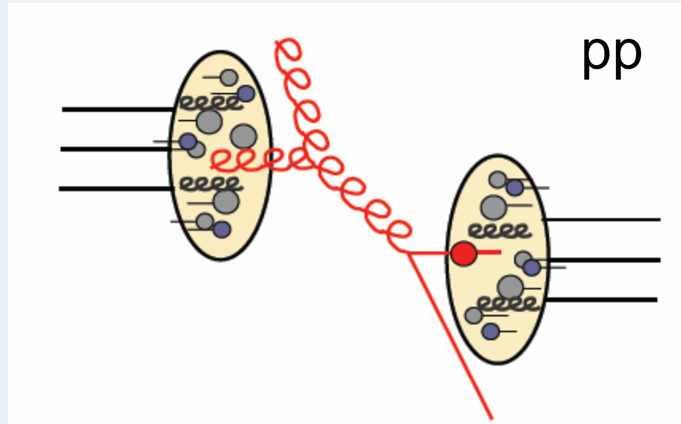
Parton dynamics 3D imaging

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 $\bar{u}d \rightarrow W^{-}$

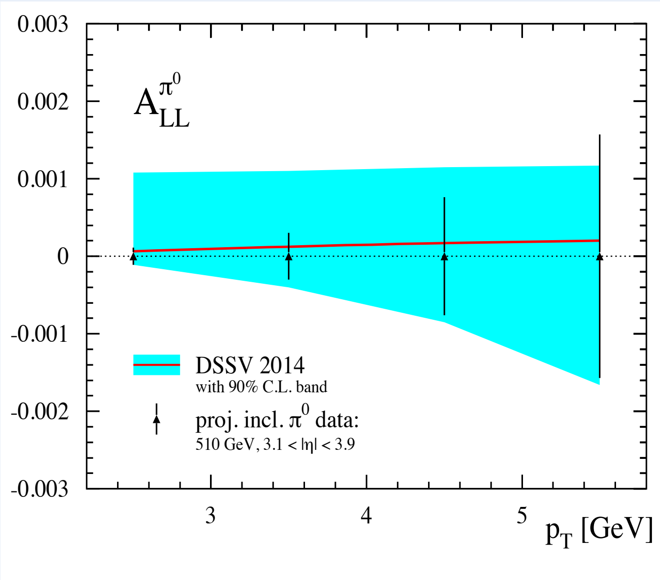
Complementary approaches

ΔG: Towards lower x

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

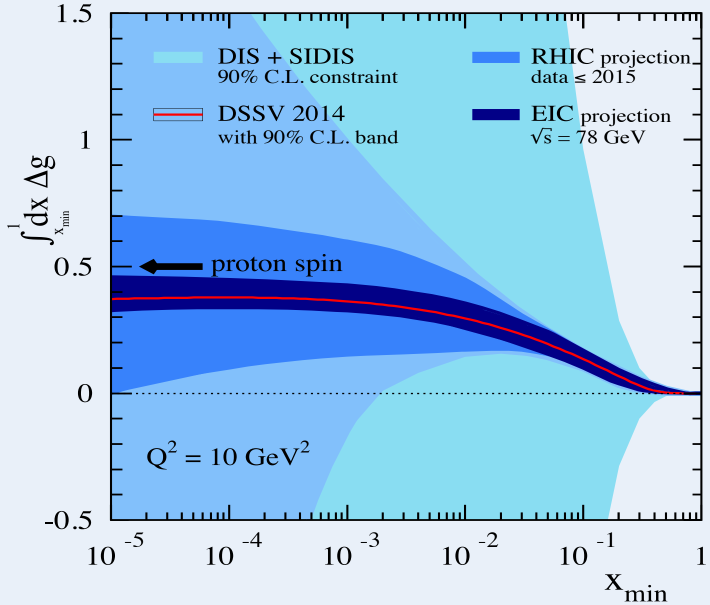
Projection

π0: 3.1<|η|<3.9



From available PHENIX+STAR data from 2011-15

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



π0 in forward region at √s=510 GeV:

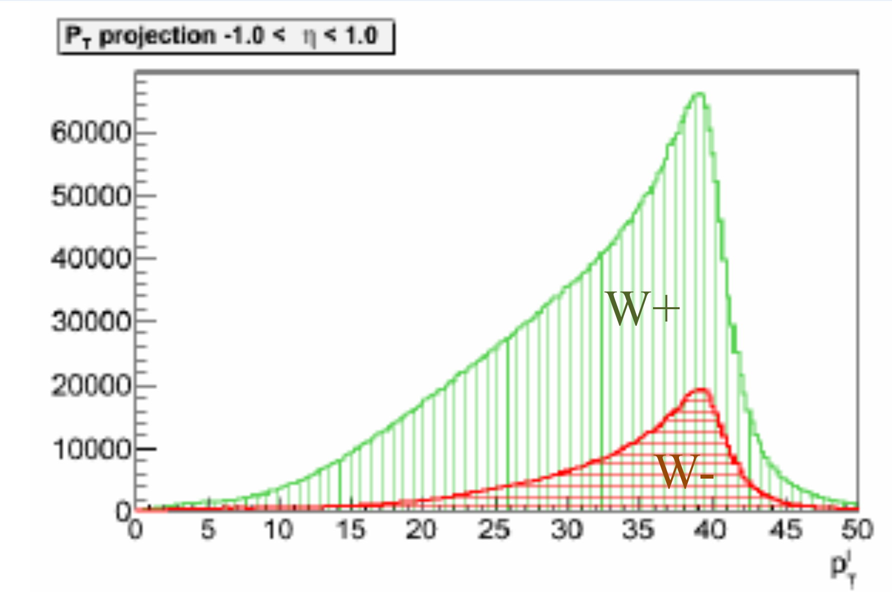
Based on collected 2013 data

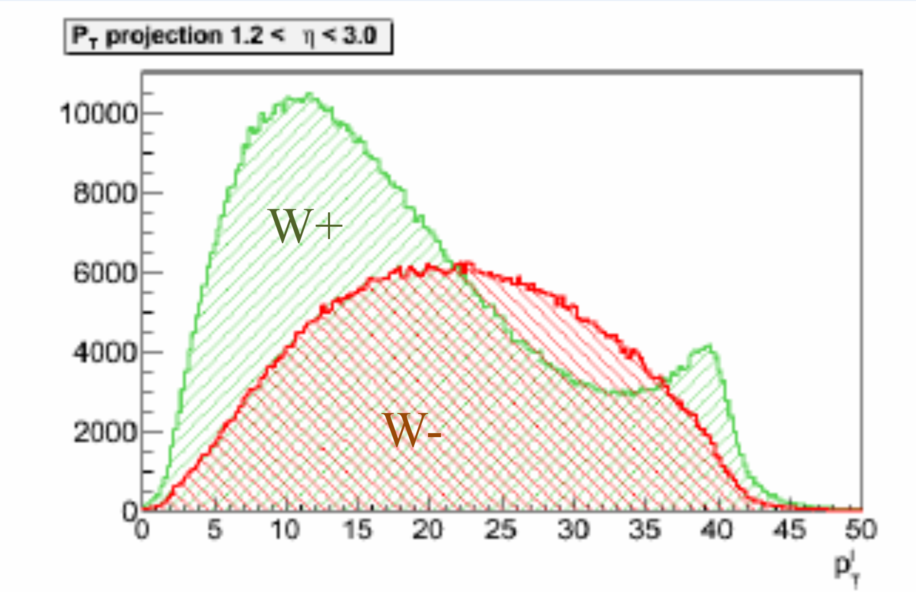
Probes lower x down to $\sim 10^{-3}$

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

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

W: Central vs Forward region

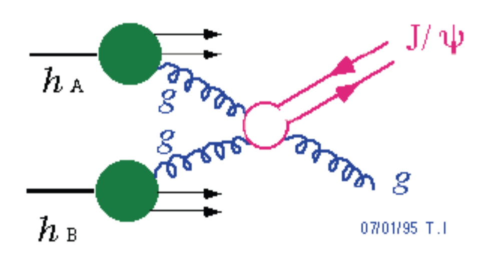




Clear Jacobian peak
at central rapidities

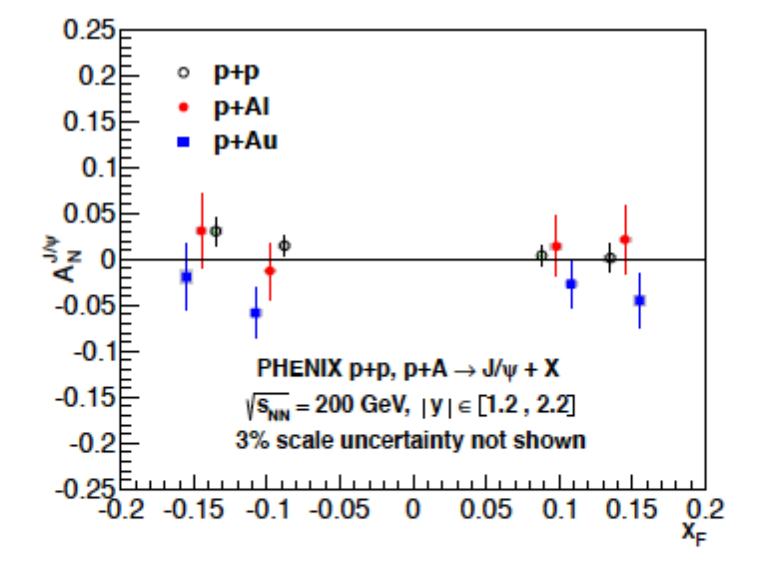
Suppressed/No Jacobean peak
at forward rapidities

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

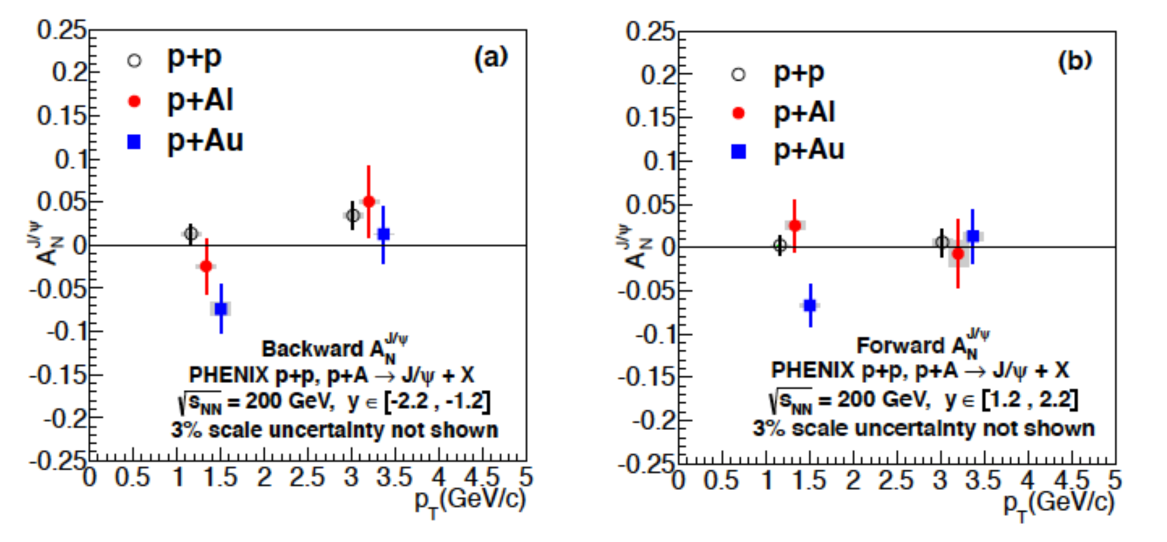
F.Yuan, PRD78, 014024:

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

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

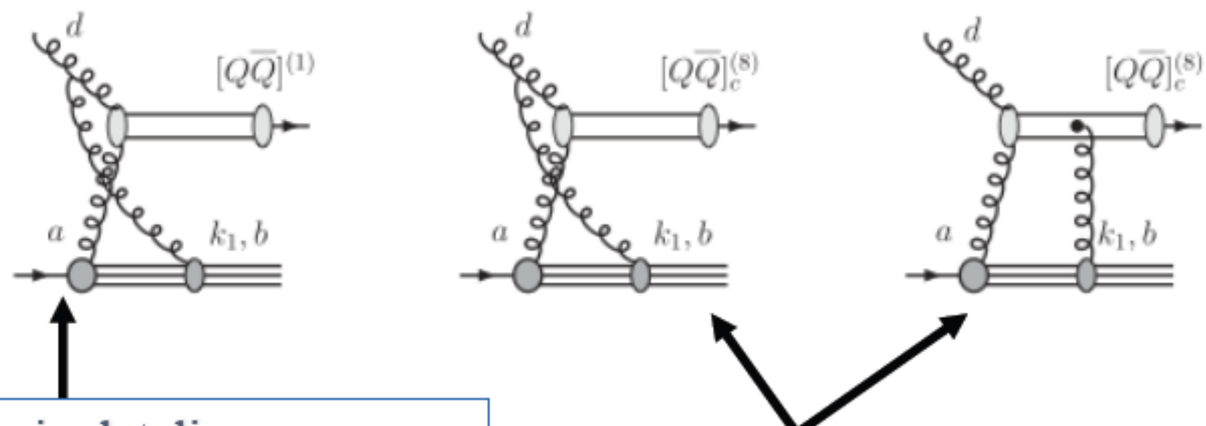
In p+Au: trends to $A_N < 0$

??



J/ψ A_N

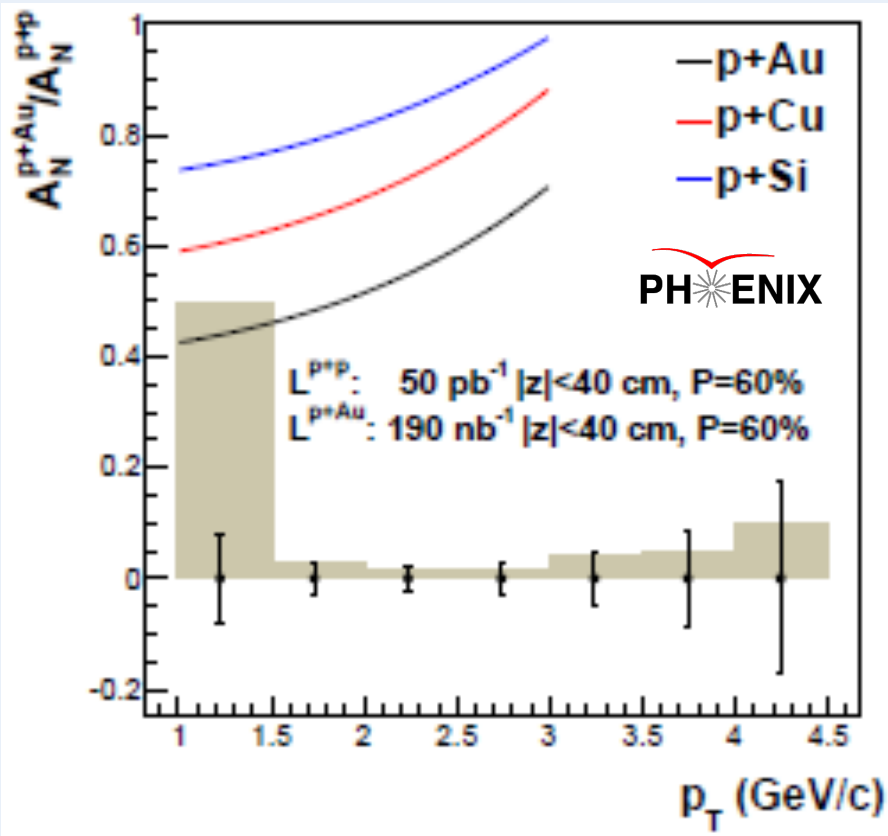
- J/ψ A_N is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, J/ψ A_N vanishes if the pair are produced in a color-octet model but survives in the color-singlet model
  - *Feng Yuan, Phys. Rev D78, 014024(2008)*



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



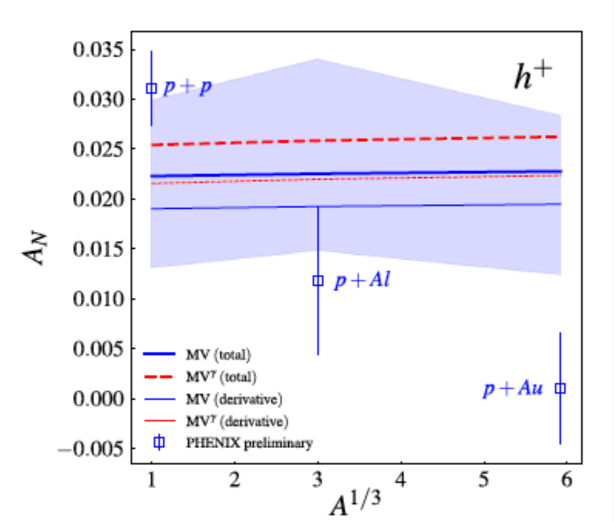
Probing gluon saturated matter, Color Glass Condensate (CGC) with polarized protons

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

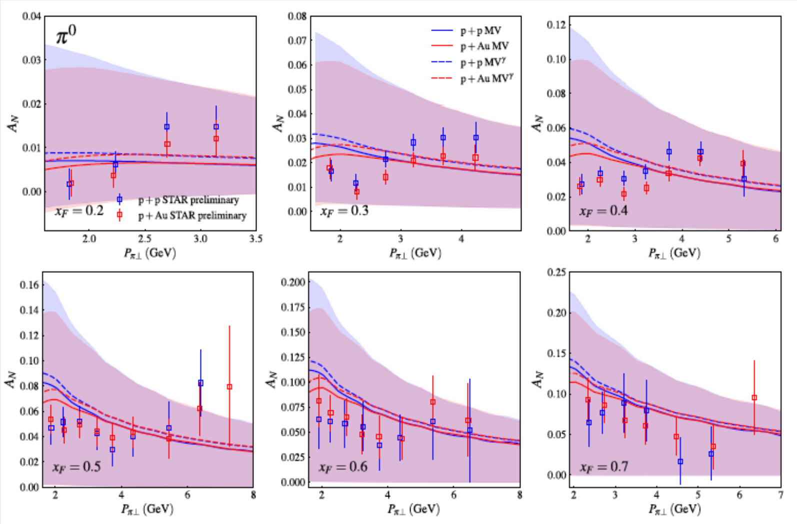
- Unique RHIC possibility $p^{\uparrow}A$
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in $p^{\uparrow}A$ provides sensitivity to Q_s
- Data already collected in Run-2015!

A_N: Forward rapidity

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



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

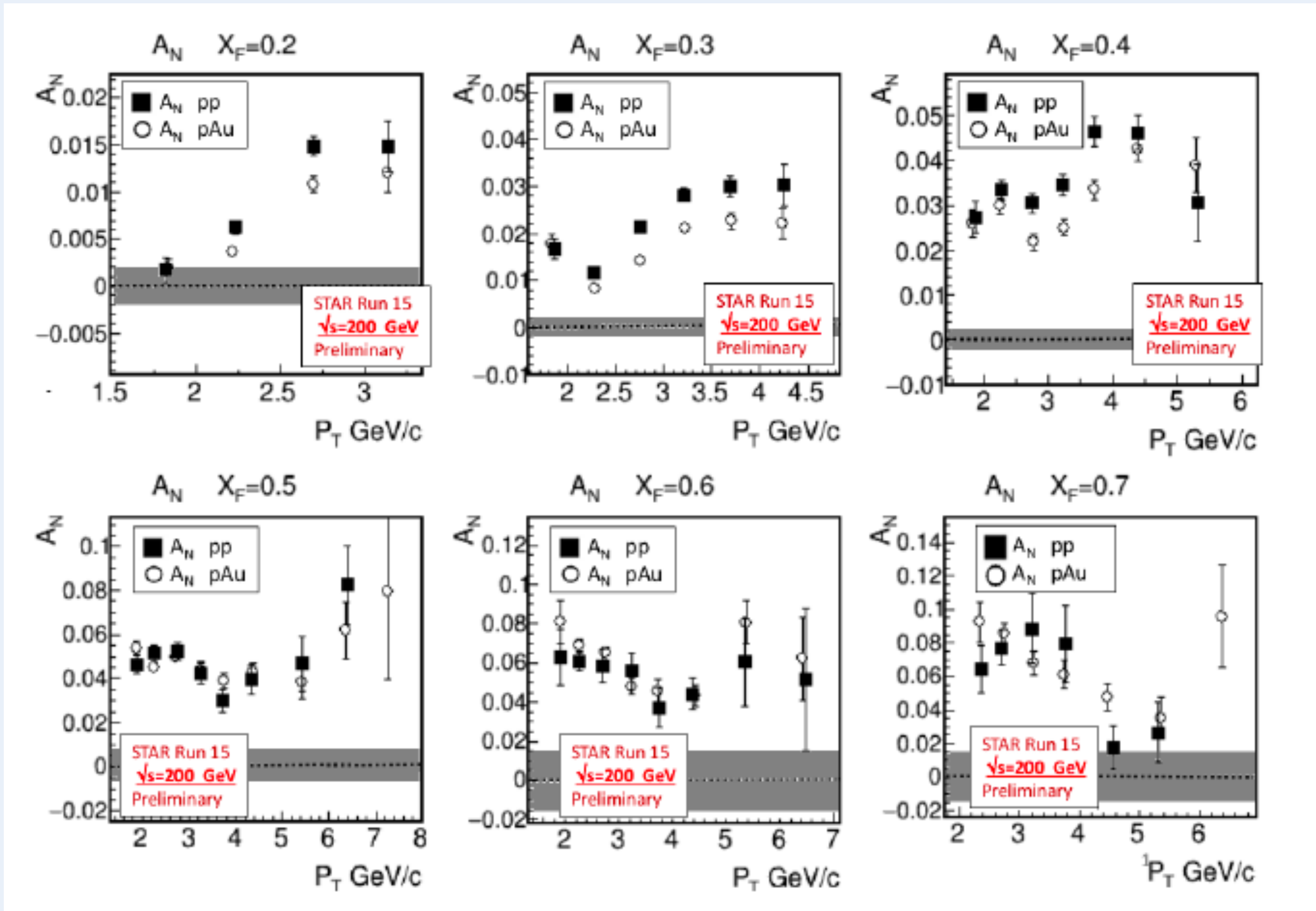


"$<p_T>\sim 2.9$ GeV/c is too hard to be sensitive to the saturation scale $Q_S^{Au} \sim 0.9$ GeV. ... This makes the PHENIX result even more striking."

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