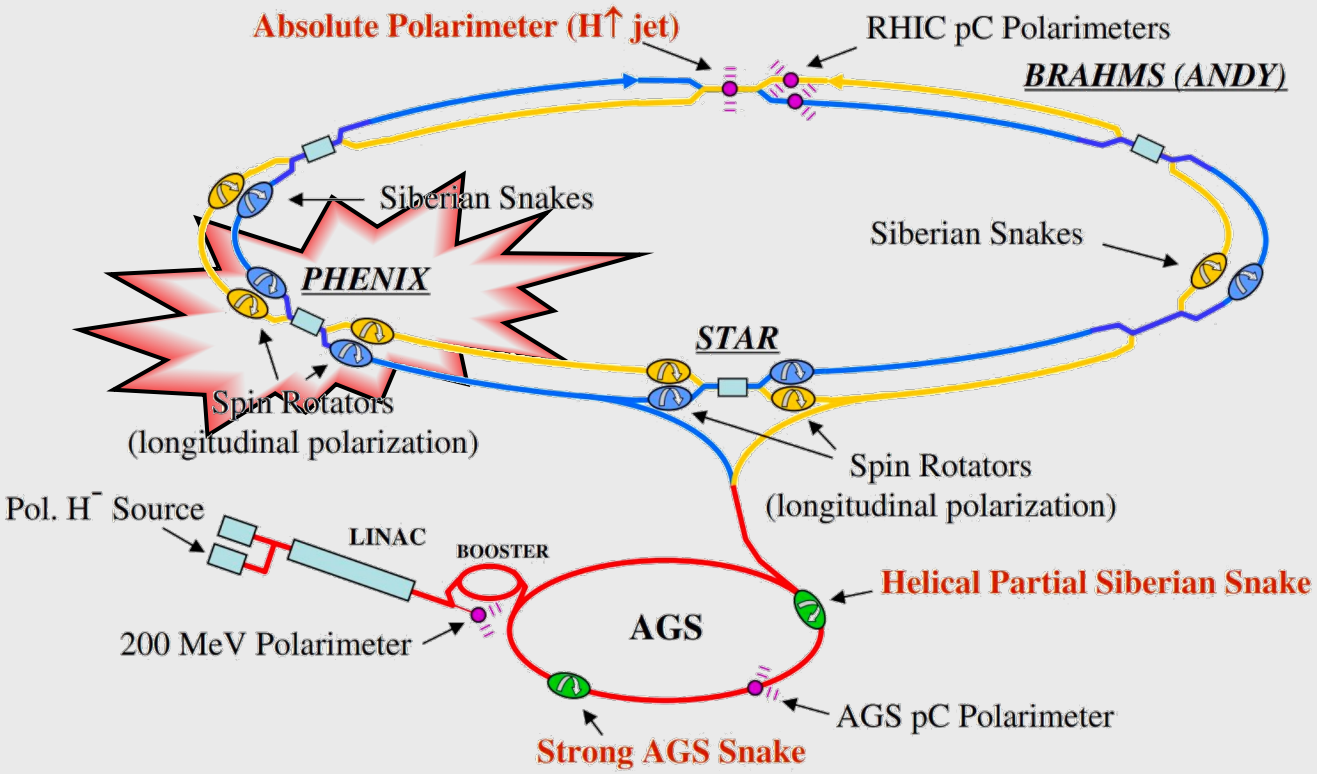
# Highlights from PHENIX Spin

Devon Loomis on behalf of the PHENIX collaboration

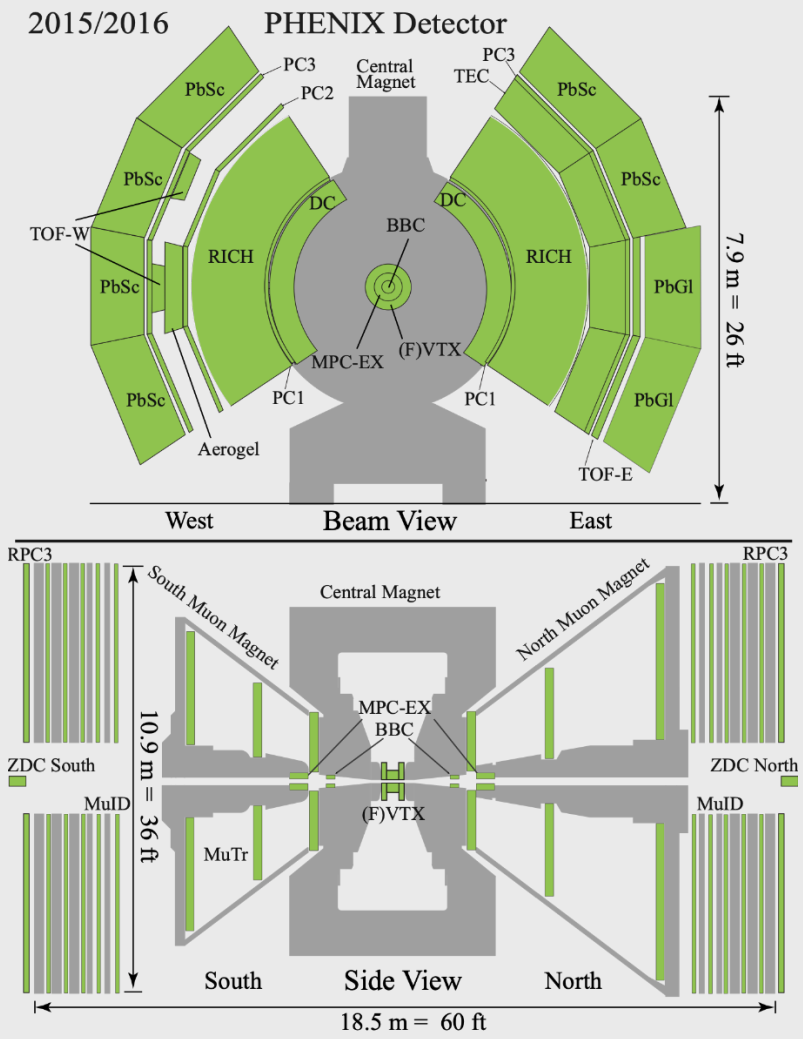


# Polarized physics runs at PHENIX



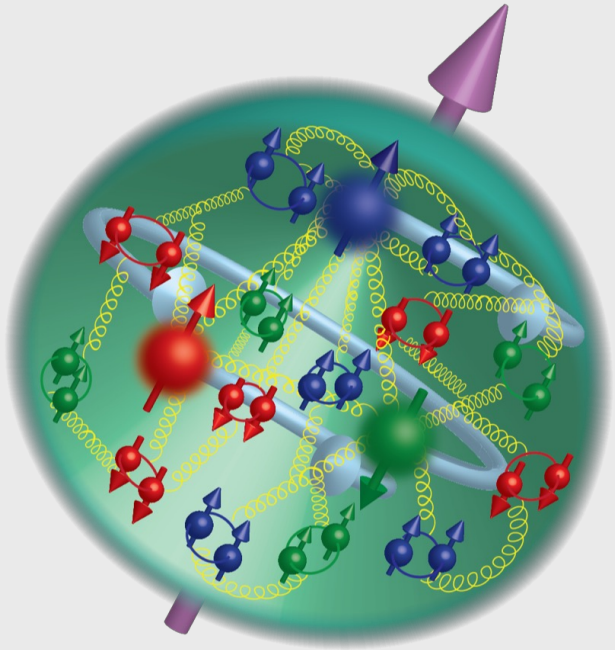

| Year | System | $\sqrt{s}$ (GeV) | Polarization | Recorded Luminosity ($pb^{-1}$) |
|---|---|---|---|---|
| 2006 | p+p | 62.4<br>200 | transverse<br>longitudinal<br>transverse<br>longitudinal | 0.02<br>0.08<br>2.7<br>7.5 |
| 2008 | p+p | 200 | transverse | 5.2 |
| 2009 | p+p | 200<br>500 | longitudinal | 16<br>14 |
| 2011 | p+p | 500 | longitudinal | 18 |
| 2012 | p+p | 200<br>510 | transverse<br>longitudinal | 9.7<br>32 |
| 2013 | p+p | 510 | longitudinal | 155 |
| 2015 | p+p<br>p+Al<br>p+Au | 200 | transverse | 60<br>1.27<br>3.97 |

# PHENIX detector

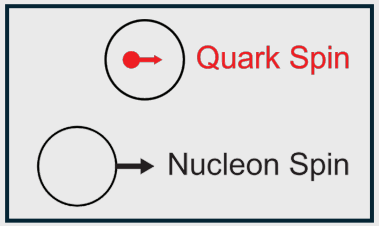



- Central arms - $|\eta| < 0.35$, π/2 azimuthal coverage
  - PbSc and PbGl EMCal (e,$\gamma$)
  - Gas Ring Imaging Cherenkov Detector (RICH) (e,π,K PID)
  - Drift/Pad chambers
- Muon arms - $1.2 < |\eta| < 2.4$
  - Muon ID
  - Muon Tracker
- Forward – $3.1 < |\eta| < 3.9$
  - Beam beam counter (collision/luminosity)
  - Muon Piston Calorimeter – full azimuth forward EMCal (e,$\gamma$)
- Far forward - $|\eta| > 6.8$
  - Zero-degree calorimeter – forward HCal (luminosity,local polarimetry, neutrons)

# Longitudinal Spin

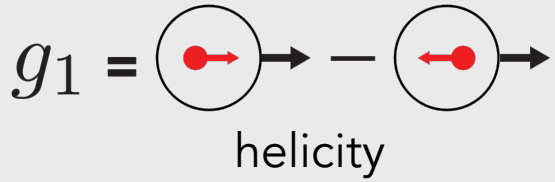


# Accessing gluon helicity




$$\frac{1}{2} = \frac{1}{2}\sum \Delta q + \Delta g + L_q + L_g$$

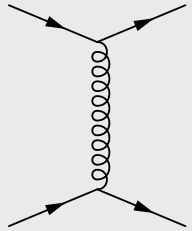
proton spin | quark helicity | gluon helicity | orbital angular momentum

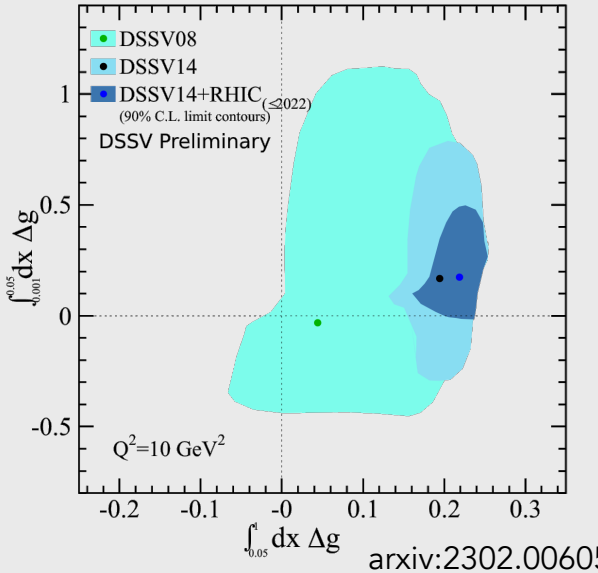



- $\Sigma\Delta$q constrained by polarized DIS ~ 0.3
- $\vec{p}+\vec{p}$ provides leading order access to Δg through longitudinal double spin asymmetries

$$A_{LL} = \frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} \propto \frac{\Delta q}{q}\frac{\Delta q}{q} + \frac{\Delta g}{g}\frac{\Delta q}{q} + \frac{\Delta g}{g}\frac{\Delta g}{g}$$

RHIC



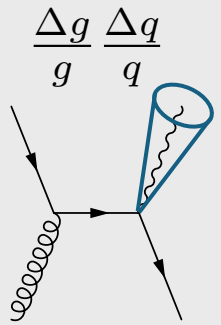


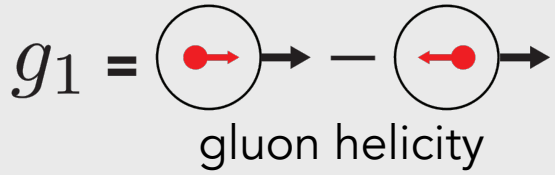

arxiv:2302.00605

- Inclusion of PHENIX $\pi^0$ and STAR jet $A_{LL}$→ clear evidence of nonzero Δg

$$\int_{0.05}^{1.0} dx\Delta g(x) = 0.218 \pm 0.027$$

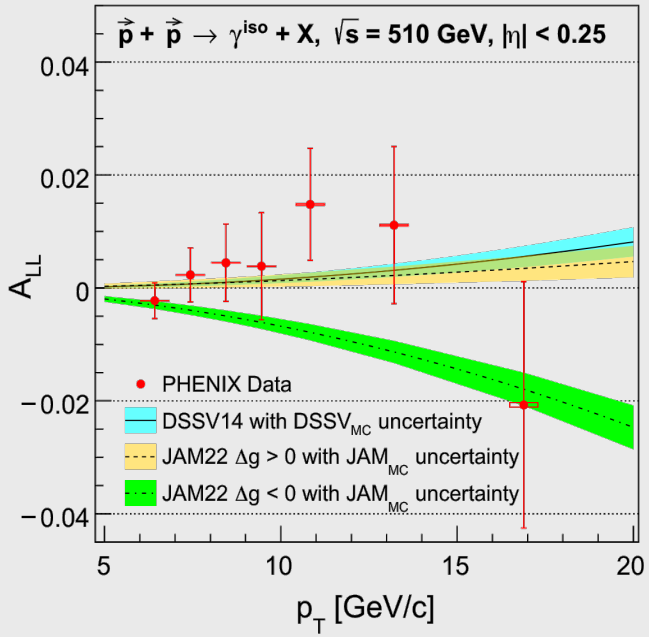
# Direct photon $A_{LL}$

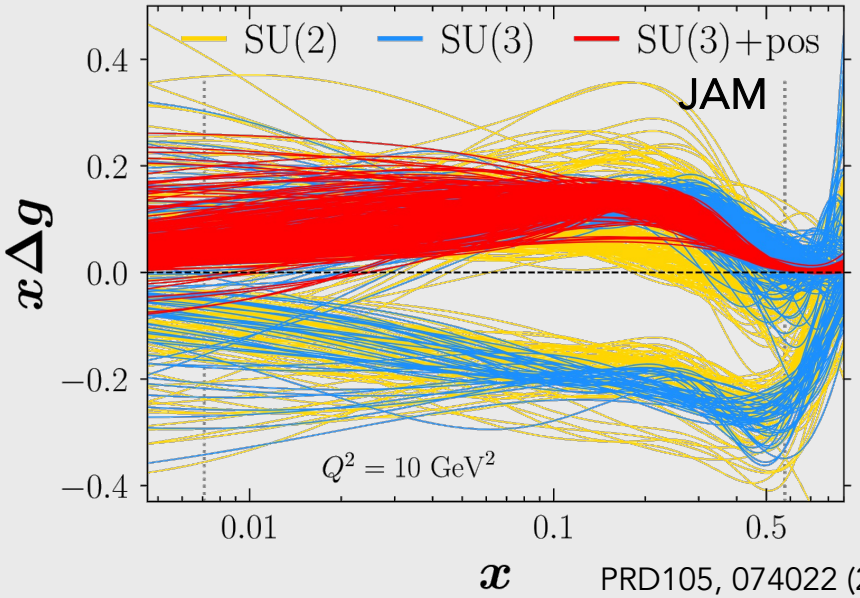



- JAM collaboration: ambiguity on sign of Δg ? PRD105, 074022 (2022)
  - BUT negative Δg leads to negative cross sections PRD109, 074007 (2024)
- Direct photons dominated by qg compton scattering
  - Sensitive to sign of Δg
- Negative solution disfavored at 2.8$\sigma$

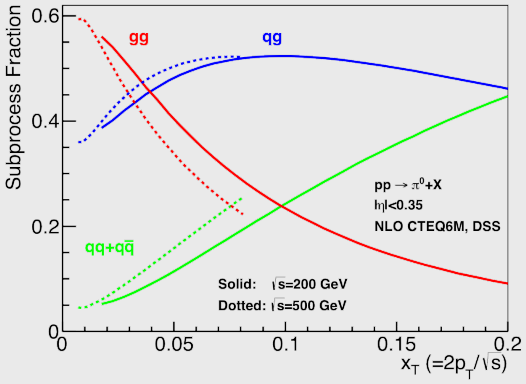
PRL130, 251901 (2023)

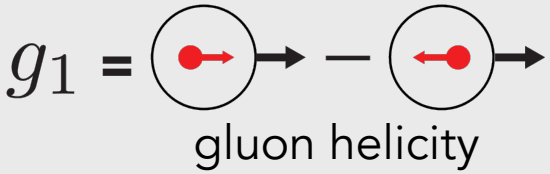



PRD105, 074022 (2022)

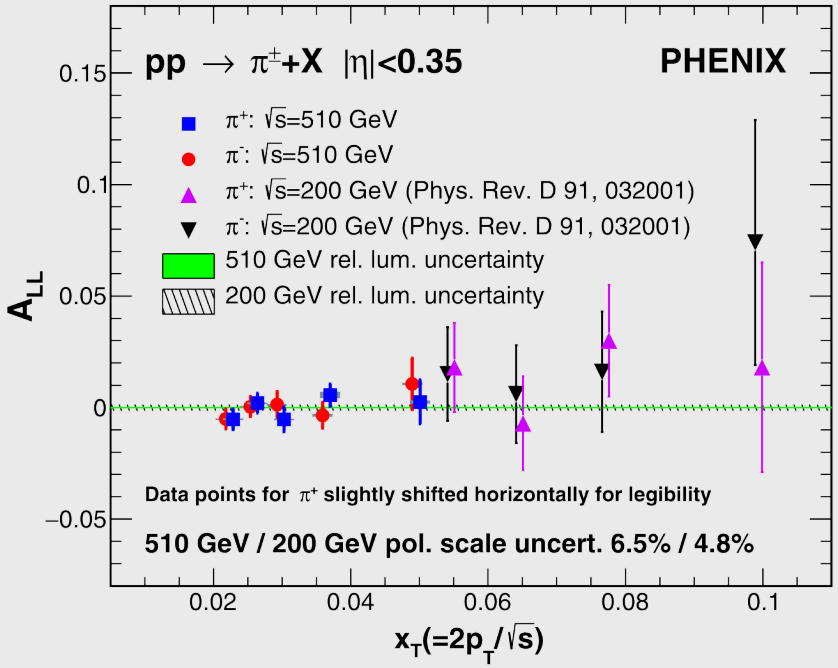
# $\pi^{\pm}$ $A_{LL}$

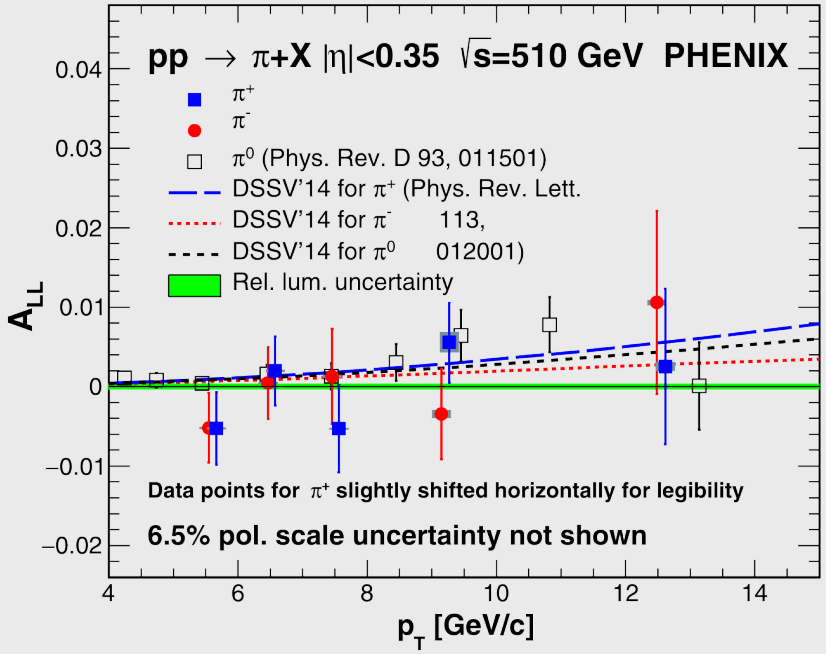


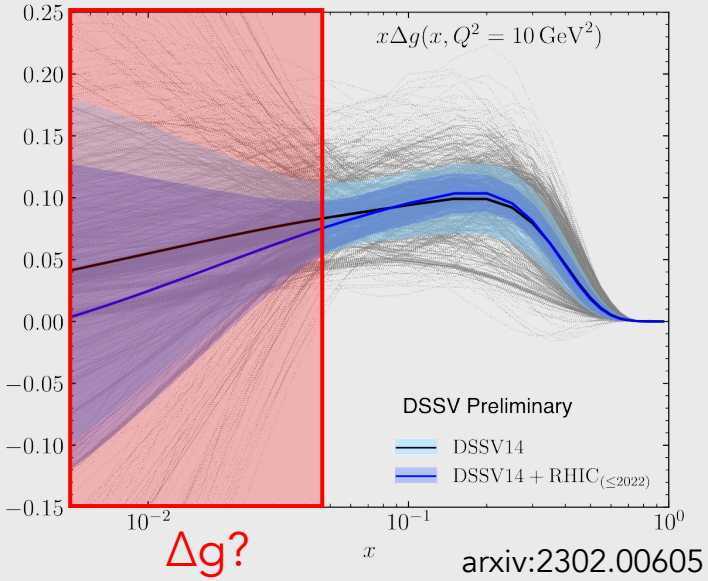




- $\Delta g$ at x < 0.05 still largely unconstrained
- Charged pion $A_{LL}$ at $\sqrt{s}$ = 510 GeV probes $\Delta g$ down to low x
  - Consistent with DSSV predictions

PRD 102, 032001 (2020)



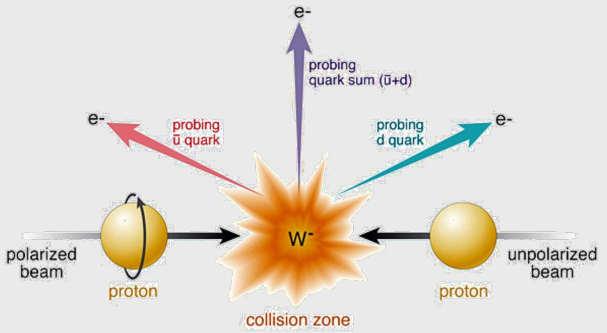



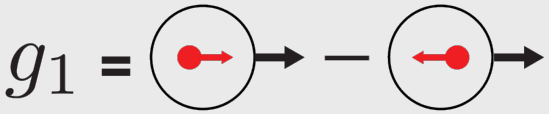




Δg?

arxiv:2302.00605

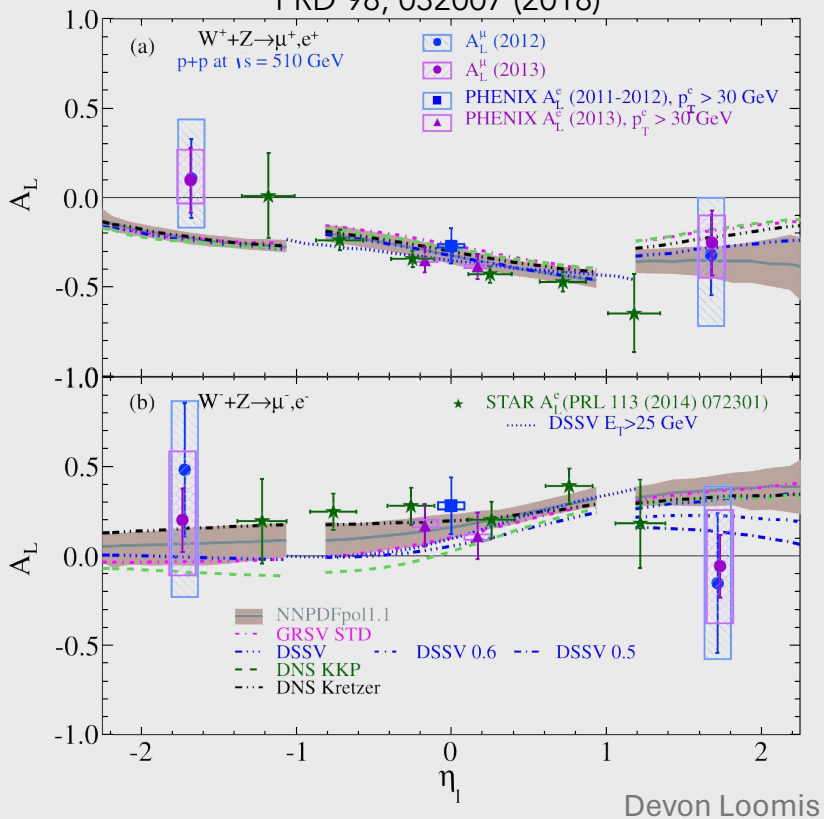
# $W^{\pm} \rightarrow e^{\pm}, \mu^{\pm}$ $A_L$



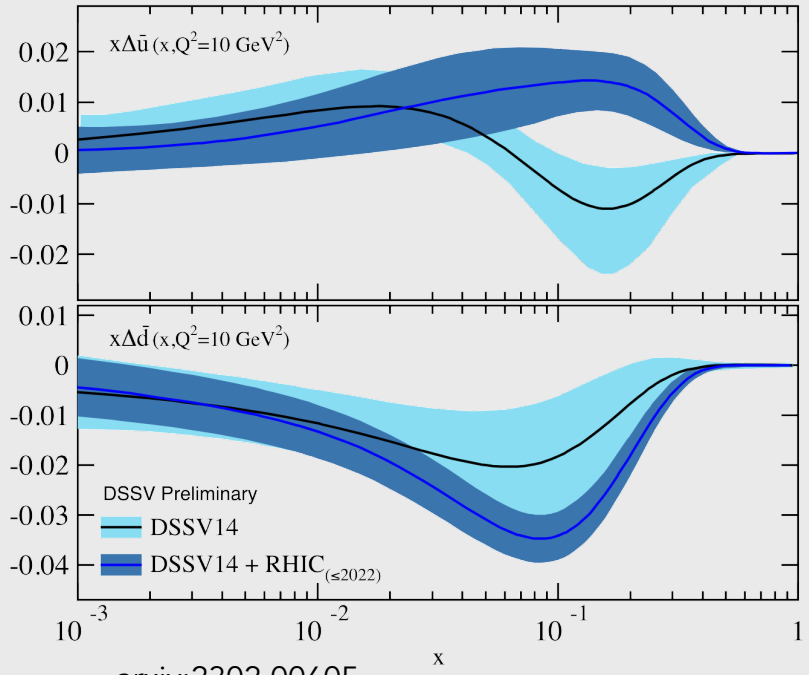

- Flavor separation of $\Delta\bar{q}$ through parity violating $u_L\bar{d}_R \rightarrow W^+ \quad d_L\bar{u}_R \rightarrow W^-$
- Longitudinal *single* spin asymmetry $A_L^{W^-} = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} \approx \frac{\Delta\bar{u}(x_1)d(x_2)-\Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)}$

PRD 98, 032007 (2018)

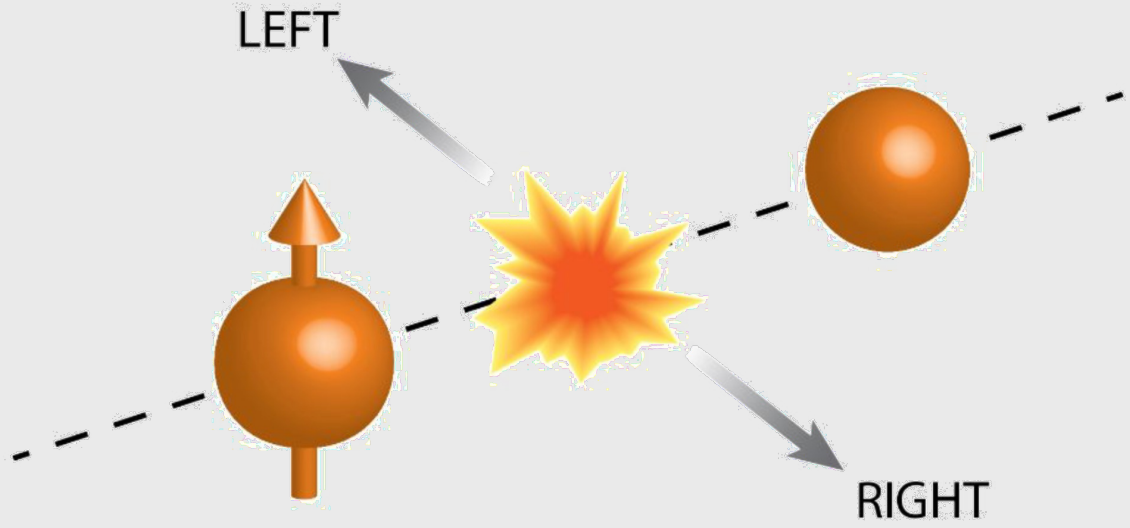



Indication of positive $\bar{u}$ helicity, negative $\bar{d}$ helicity

Polarized sea asymmetry *opposite* sign from unpolarized sea asymmetry



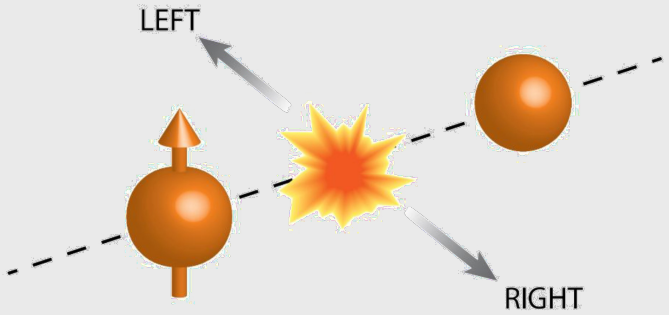

arxiv:2302.00605

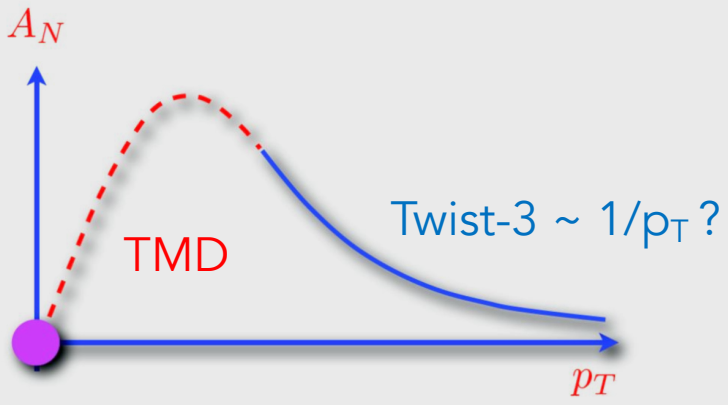


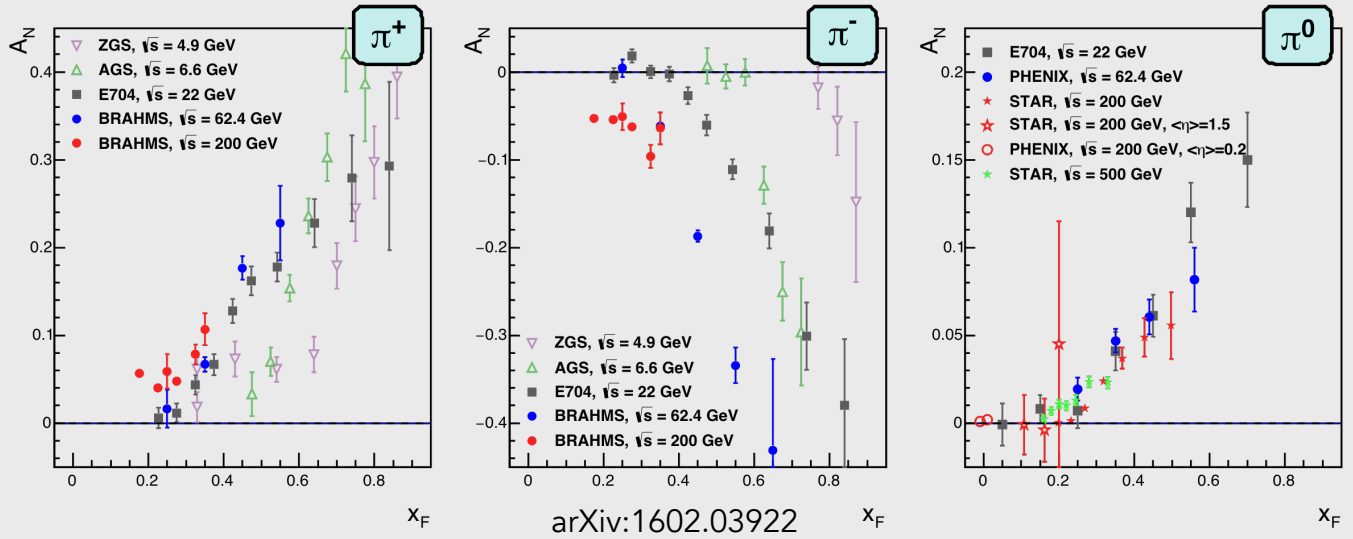

# Transverse Spin

# Transverse single spin asymmetries ($A_N$)

- Transverse single spin asymmetries measure the left-right asymmetry of particle production in $p^{\uparrow}$ + p collisions
- Large asymmetries at high $x_F$ observed up to high $\sqrt{s}$
- Collinear leading twist pQCD predicts $A_N = \alpha_s m_q / \sqrt{s} \sim 0$
- Origin of $A_N$: Nonperturbative spin-momentum correlations described by
  - Transverse Momentum Dependent (TMD) PDFs/FFs
  - Collinear twist-3 multiparton correlators

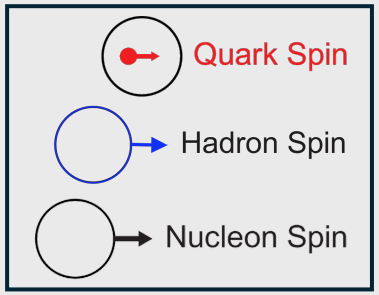


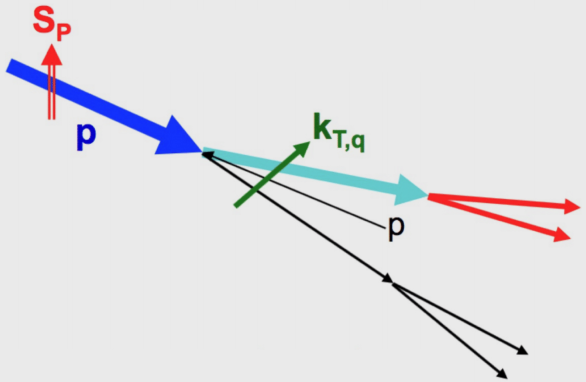

arXiv:1602.03922

# Mechanisms of $A_N$




Sivers TMD PDF

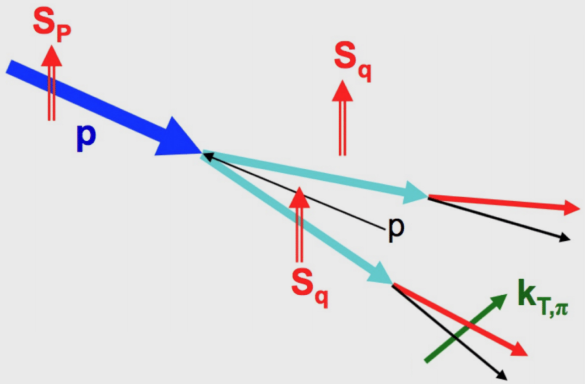
$f_{1T}^{\perp}$ = ● − ●




$A_N \propto f_{1T}^{\perp}(x, k_T^2) \cdot D_q^h(z)$

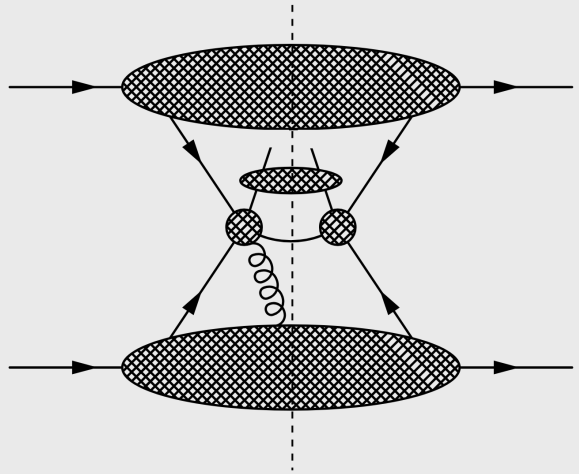
Transversity ⊗ Collins TMD FF

$h_1$ = ↑ − ↑ ⊗ $H_1^{\perp}$ = ↑ − ↓




$A_N \propto h_1(x) \cdot H_1^{\perp}(z, k_T^2)$

Twist-3 multiparton correlators



Sivers-like correlator

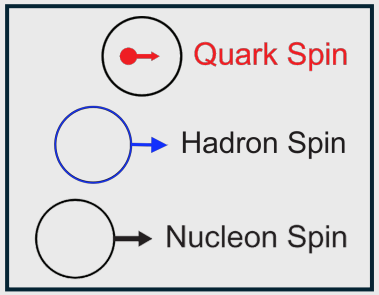
$$A_N \propto \sum_{a,b,c} \boxed{\phi^{(3)}_{a/A}(x_1, x_2, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{q/h}(z)$$

Transversity

$$+ \sum_{a,b,c} \boxed{h_1(x, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma}' \otimes \boxed{D^{(3)}_{q/h}(z_1, z_2)}$$

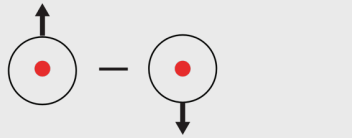
Collins-like correlator

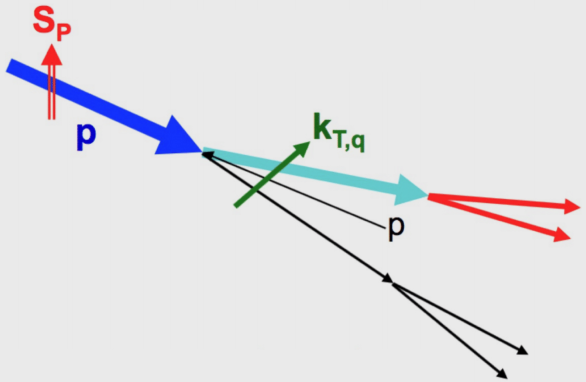
# Mechanisms of $A_N$




Sivers TMD PDF

$f_{1T}^{\perp}$ =

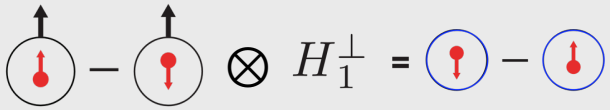





$$A_N \propto f_{1T}^{\perp}(x, k_T^2) \cdot D_q^h(z)$$

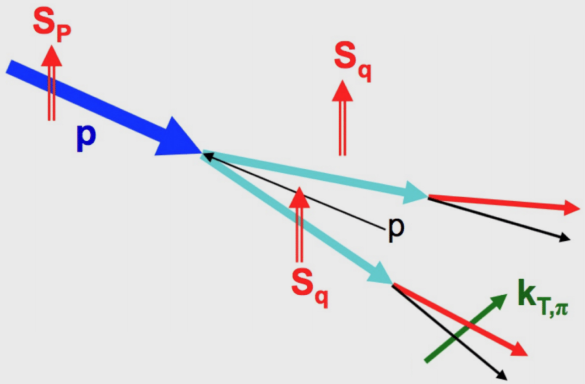
Transversity ⊗ Collins TMD FF

$h_1$ =



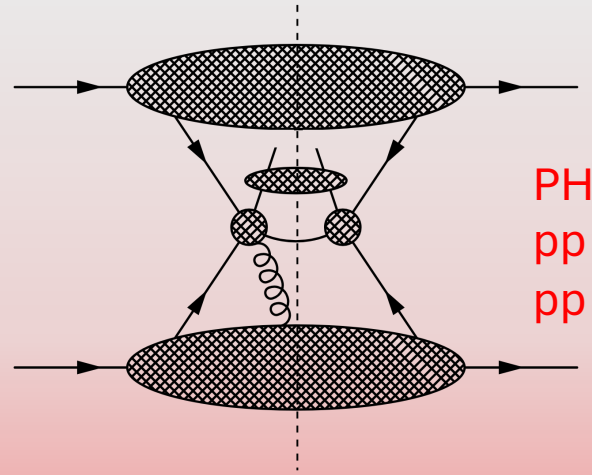
$H_1^{\perp}$ =






$$A_N \propto h_1(x) \cdot H_1^{\perp}(z, k_T^2)$$

Twist-3 multiparton correlators



PHENIX
pp → h + X
pp → γ + X

Sivers-like correlator

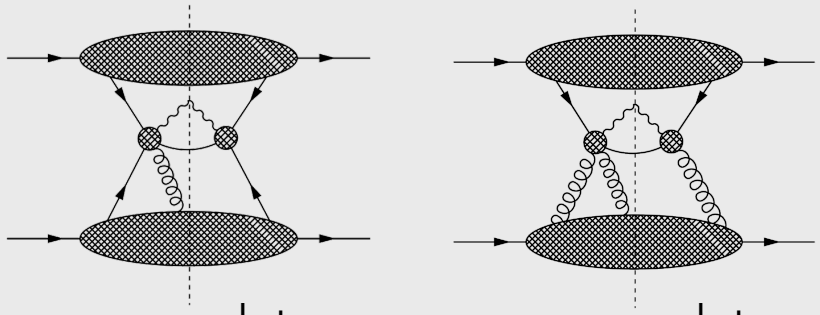
$$A_N \propto \sum_{a,b,c} \boxed{\phi_{a/A}^{(3)}(x_1, x_2, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{q/h}(z)$$

Transversity

Collins-like correlator

$$+ \sum_{a,b,c} \boxed{h_1(x, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma'} \otimes \boxed{D_{q/h}^{(3)}(z_1, z_2)}$$

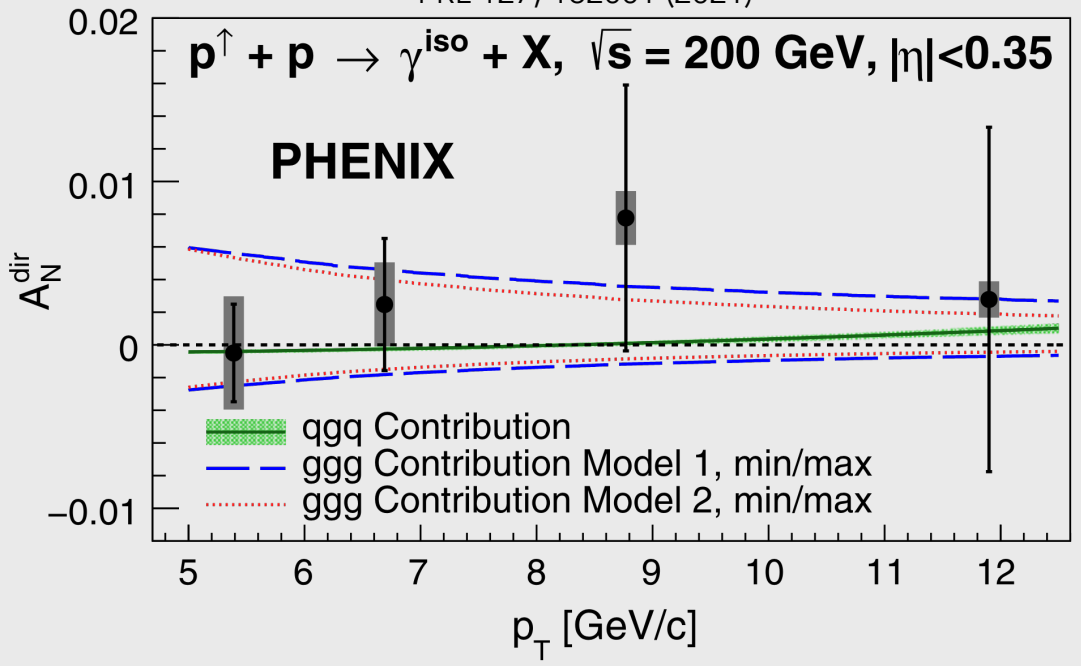
# Direct photon $A_N$



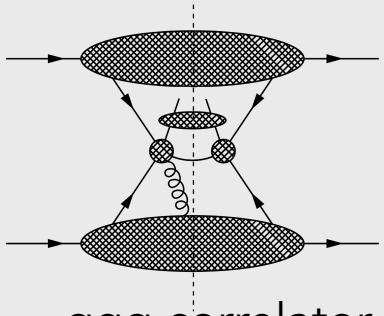

- Photon in final state → no final state effects
  - Clean probe of initial state quark-gluon and trigluon correlation functions
- First direct photon $A_N$ from RHIC → 50 times reduced uncertainties from E704 Fermilab measurement

PLB 345, 569 (1995)

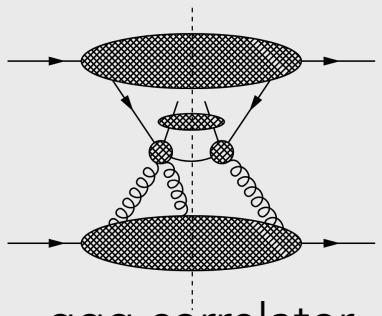
PRL 127, 162001 (2021)



# Midrapidity $\pi^0$, $\eta$ $A_N$



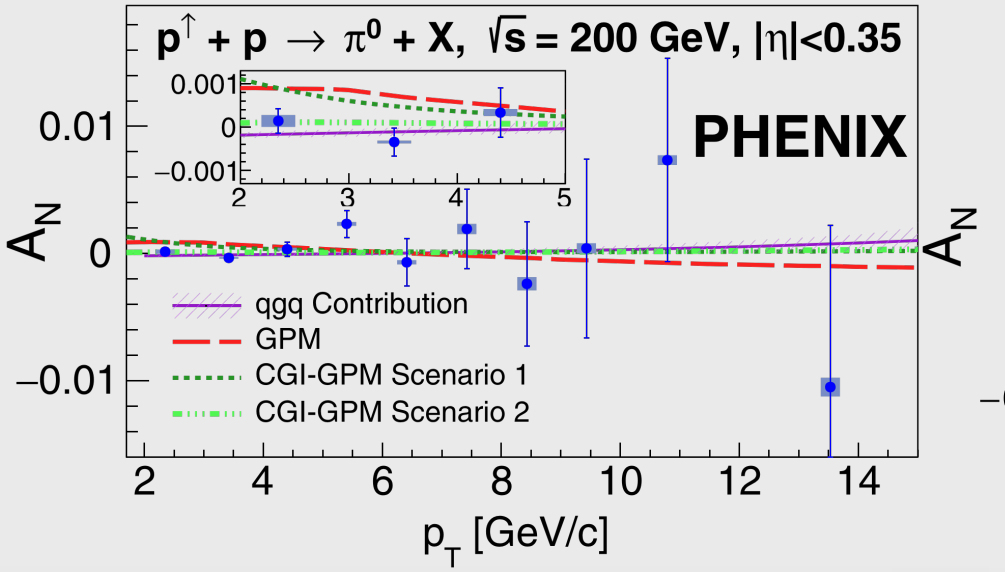
qgq correlator

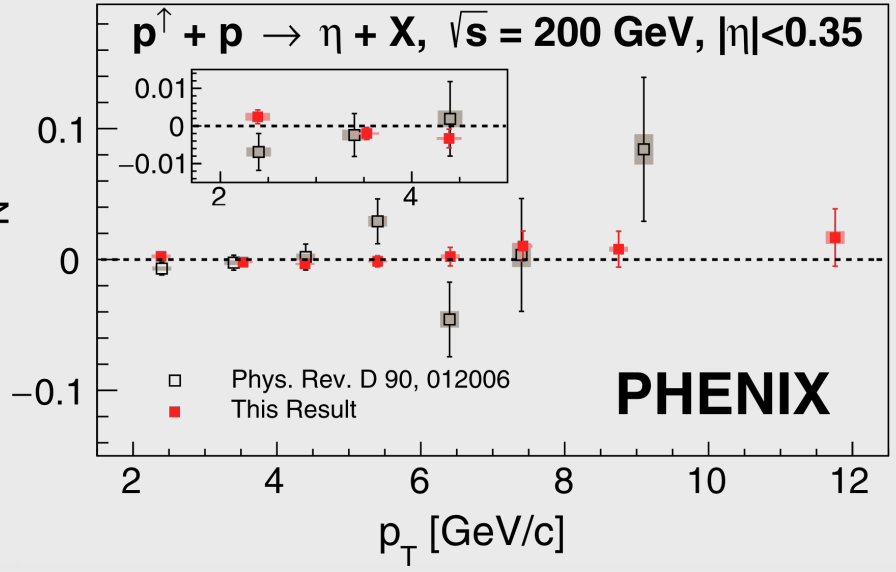


ggg correlator

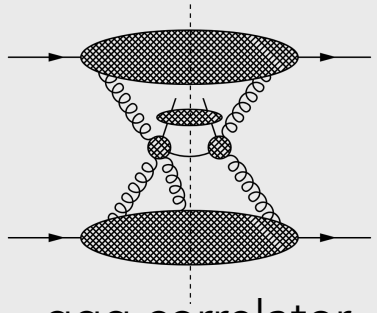
- Sensitive to gluon dynamics through quark-gluon and trigluon correlation functions
  - Used to constrain gluon Sivers TMD JHEP 1509 (2015), 119
- High precision measurement: consistent with zero to sub-percent level

PRD 103, 052009 (2021)



# Midrapidity open heavy flavor $A_N$



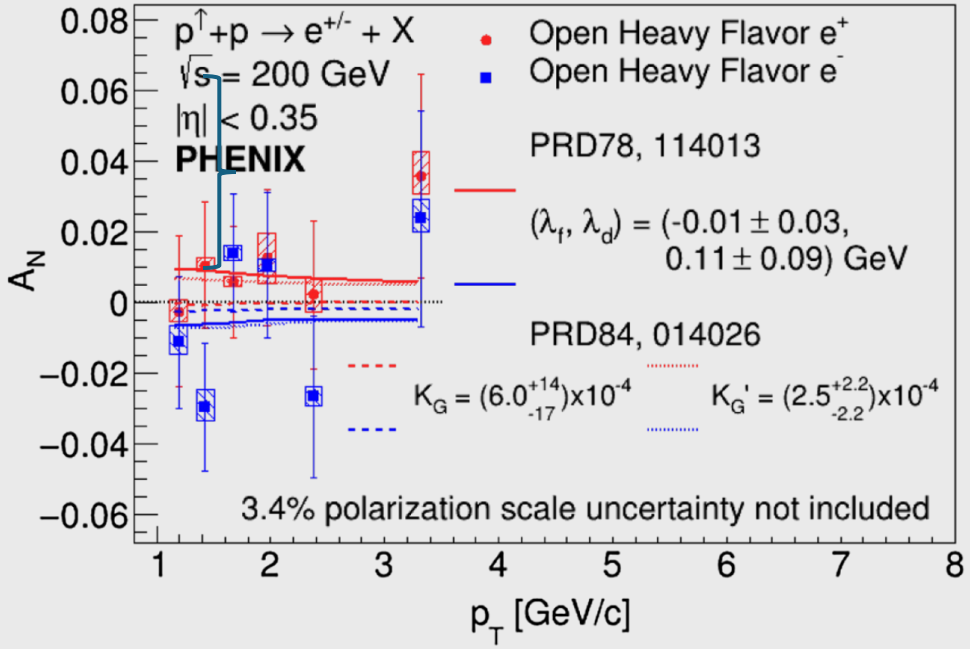
ggg correlator

- Gluon-gluon fusion ✓
- Gluon transversity = zero ✓

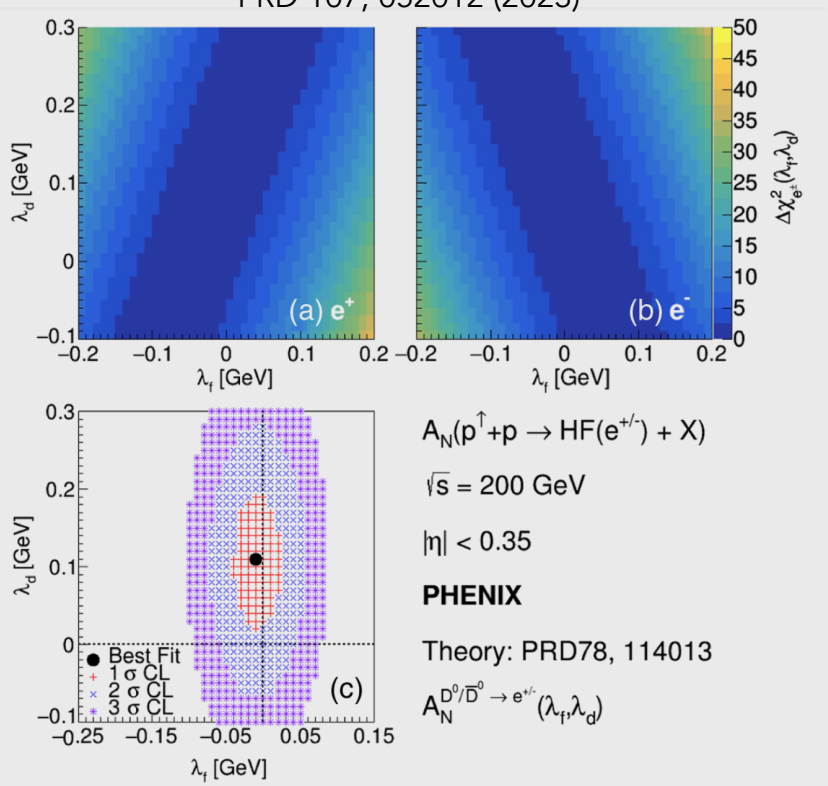
} Direct sensitivity to initial-state trigluon correlator

- First constraints on phenomenological trigluon parameters $\lambda$, $K_G$

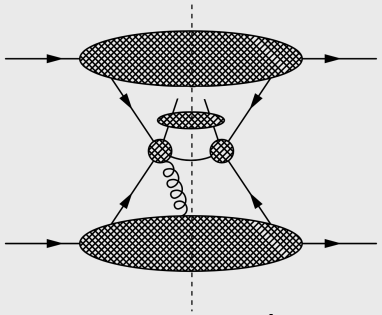
PRD 107, 052012 (2023)




PRD 107, 052012 (2023)



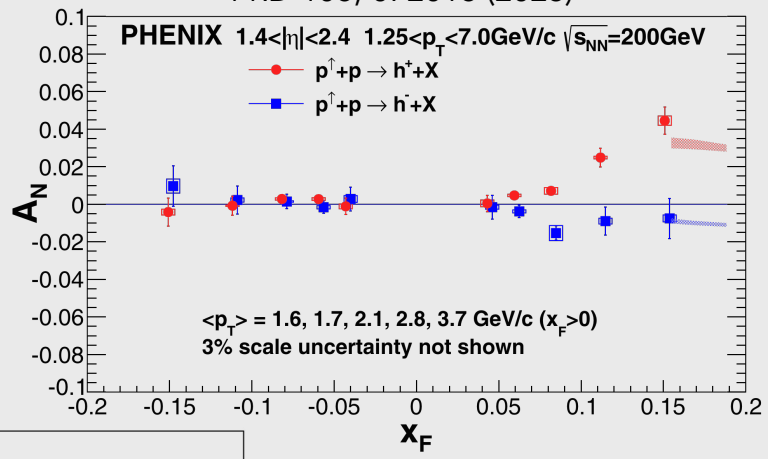
# Forward $h^{\pm}$, $\eta$ $A_N$

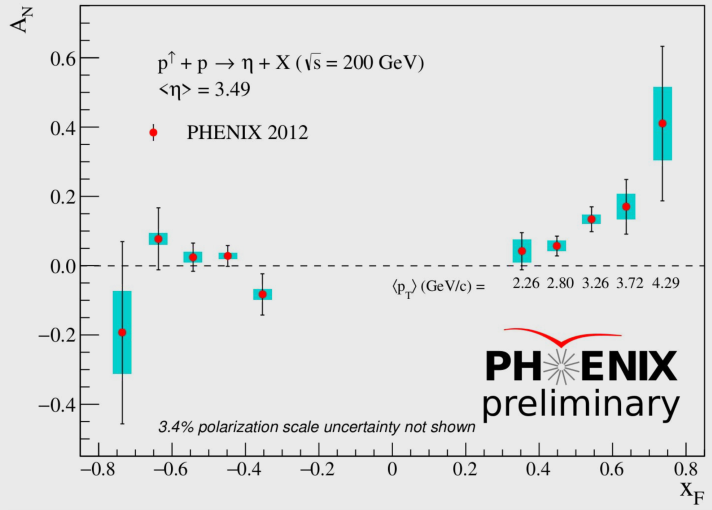


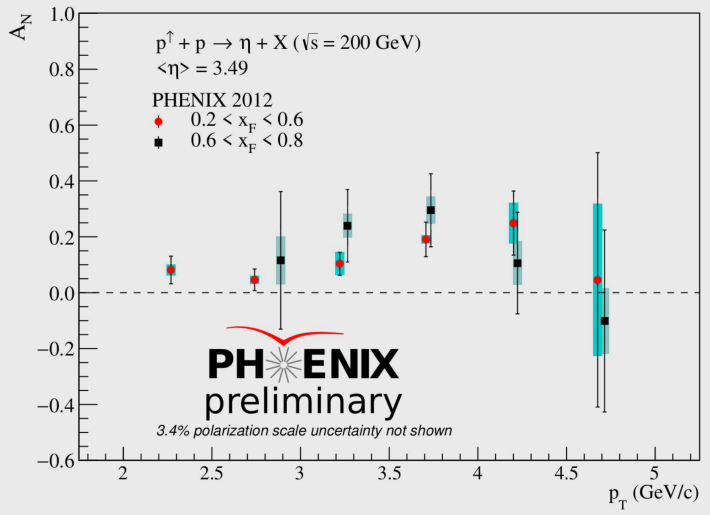
qgq correlator

- Forward production of hadrons at high $x_F$ dominated by valence quark interactions → probe of quark-gluon correlator
- $h^+$: large positive asymmetries
- $h^-$: mix of negative π and positive K asymmetries
- $\eta$: large (~20-40%) asymmetries at high $x_F$
  - Potential first hint of suppression at high $p_T$ in $x_F > 0.6$?

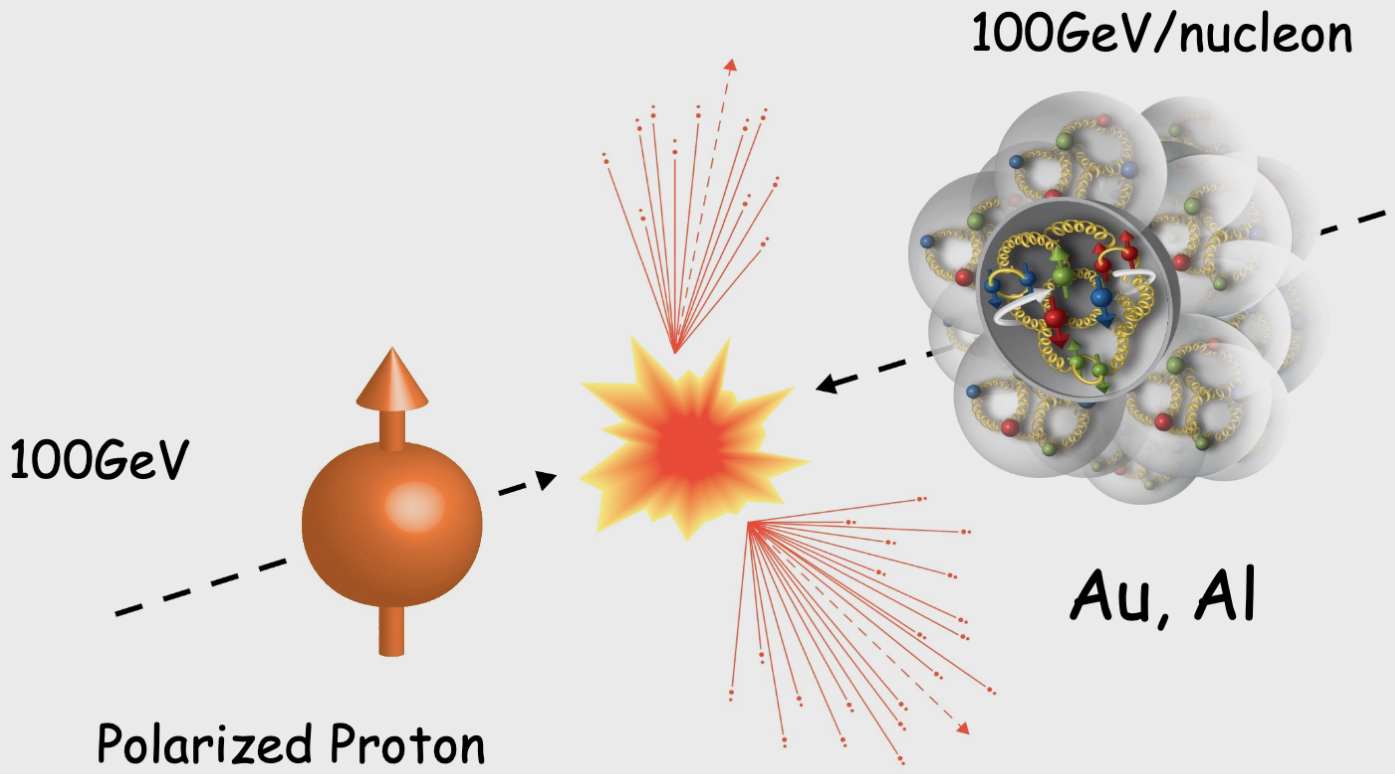
PRD 108, 072016 (2023)



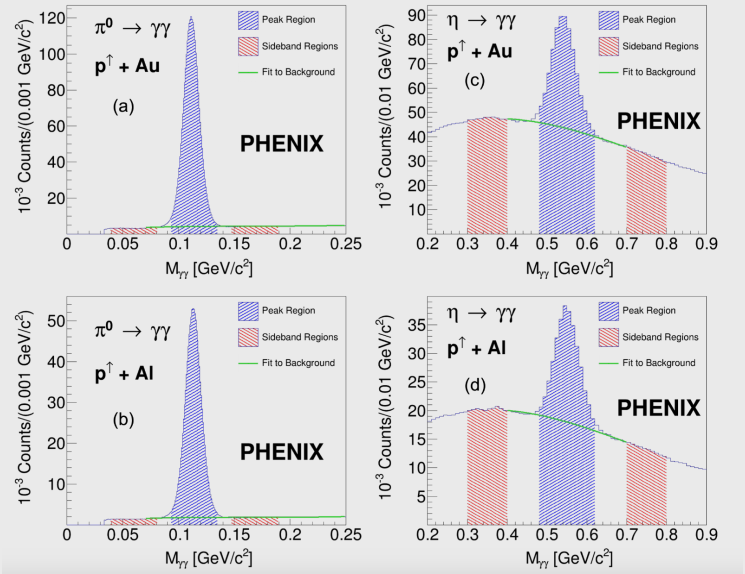



# $p^{\uparrow}$+ A

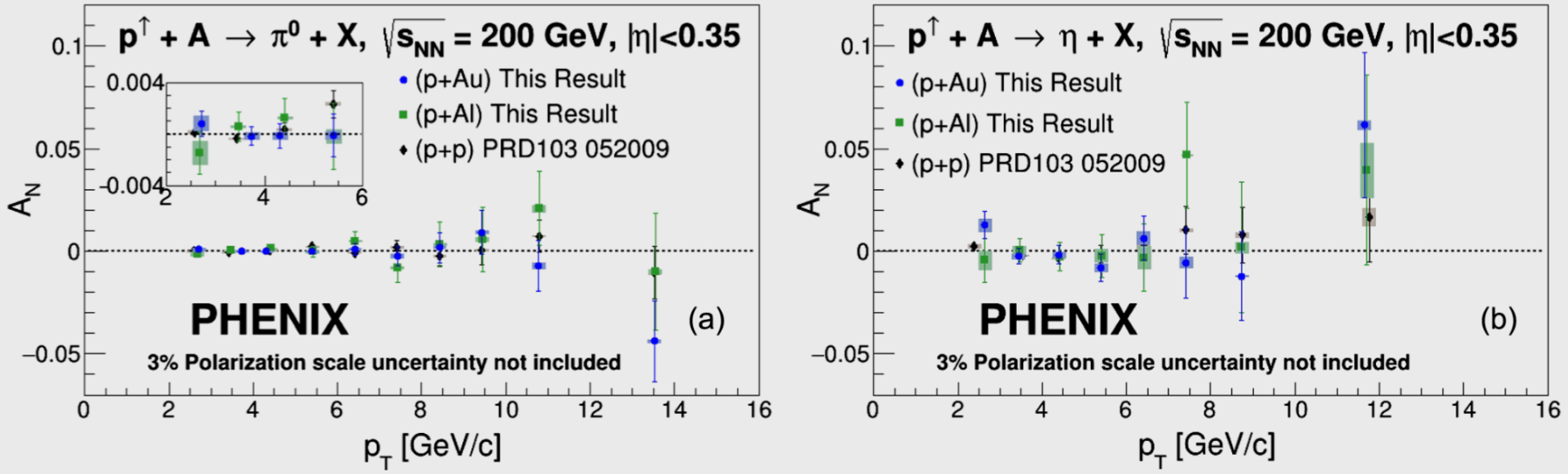


# Midrapidity $\pi^0$, $\eta$ $A_N$

- Dependence on *A* consistent with zero
- High precision measurements of p↑+p, p↑+Al, p↑+Au all consistent with zero

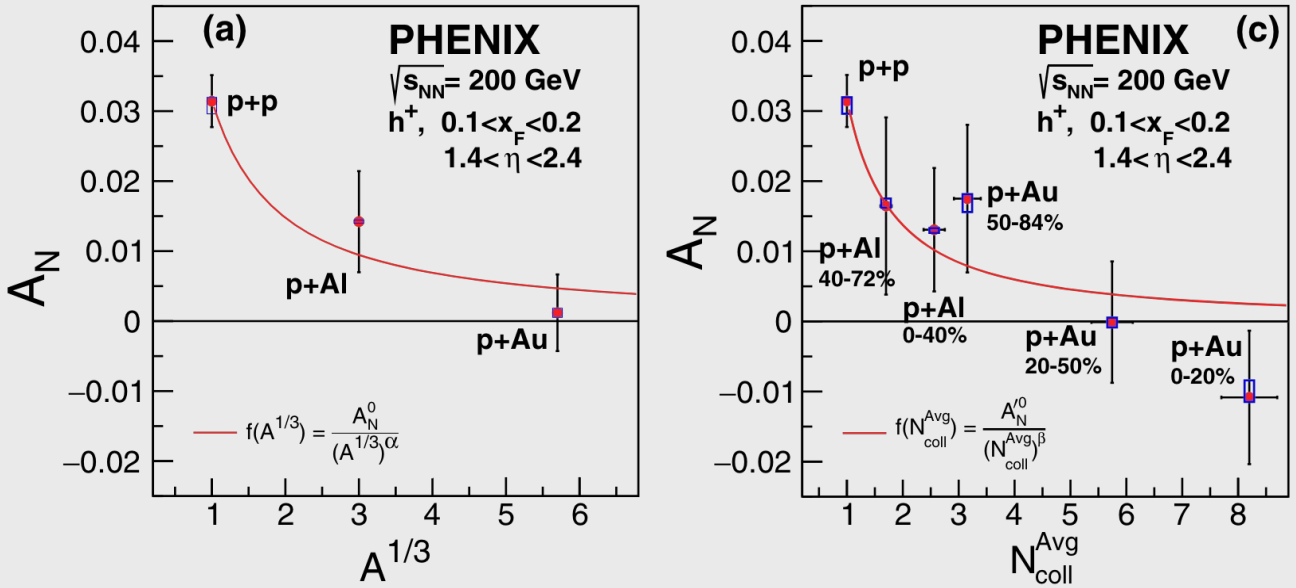



PRD 107, 112004 (2023)

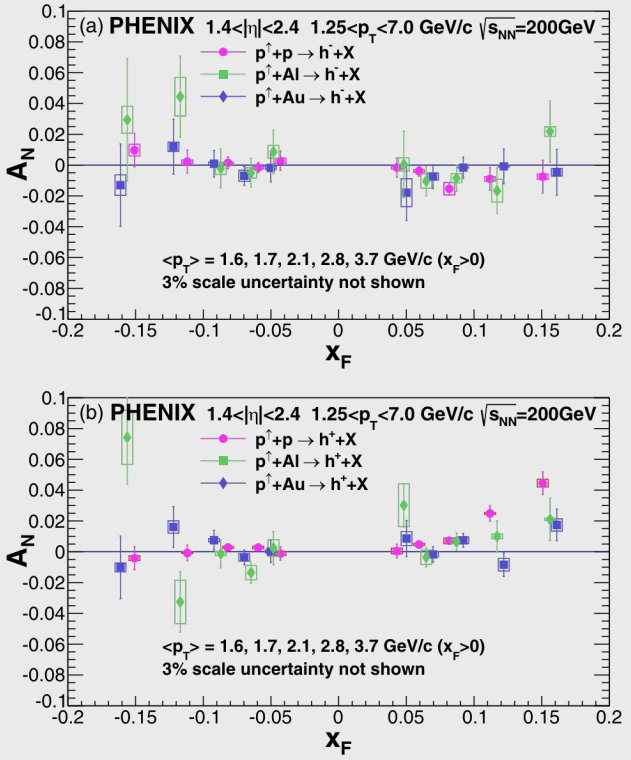


# Forward $h^{\pm}$ $A_N$

- Striking dependence of $A_N$ on $A$
  - Models predict $A^{-1/3}$ dependence <u>but only relevant in color glass condensate regime</u> PRD 84, 034019 (2011)
  - Higher twist calculations in SIDIS predict ~$A^{-1/3}$ dependence PRC 81, 065211 (2011)
- Dependence on $A$ still apparent in forward $h^+$ $A_N$ vs. $x_F$ PRL 123, 122001 (2019)




PRD 108, 072016 (2023)

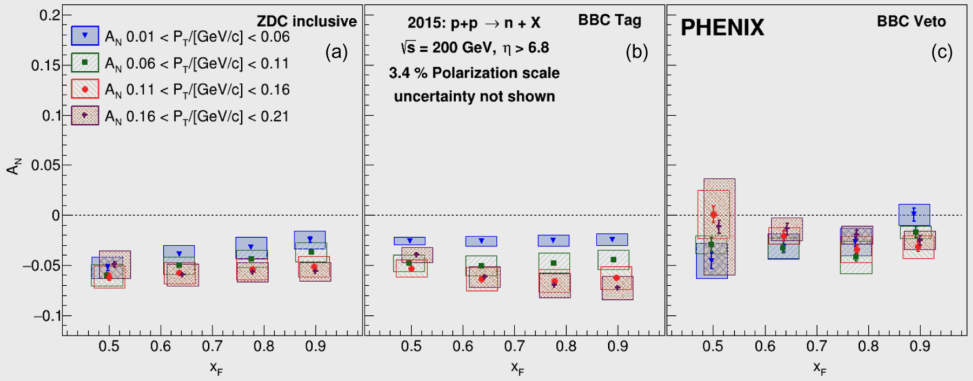


# Far forward neutron $A_N$

- Negative $A_N$ in far forward neutrons from p+p reasonably well described by one pion exchange (OPE) model
- Initially unexpected large dependence (+ sign change) on *A*
  - Additional contribution from ultra-peripheral collisions (UPC) qualitatively describes data

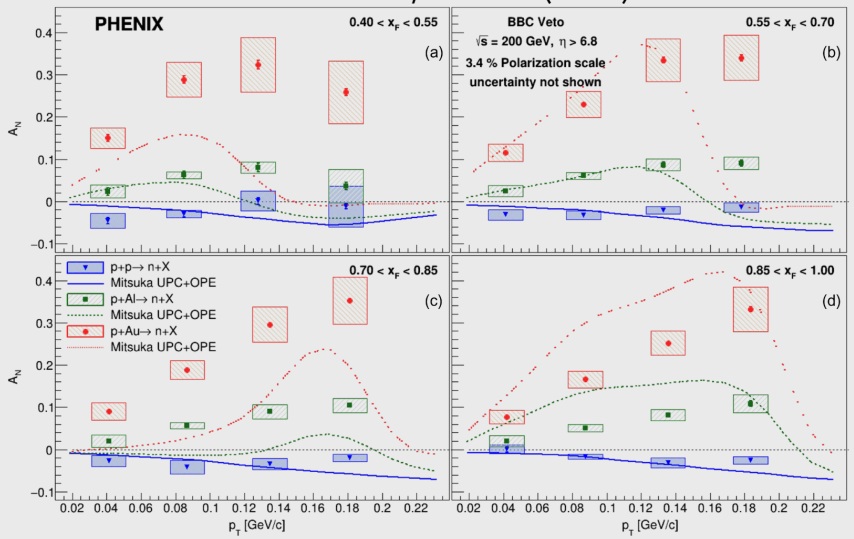
Weak $x_F$ dependence

PRD 105, 032004 (2022)

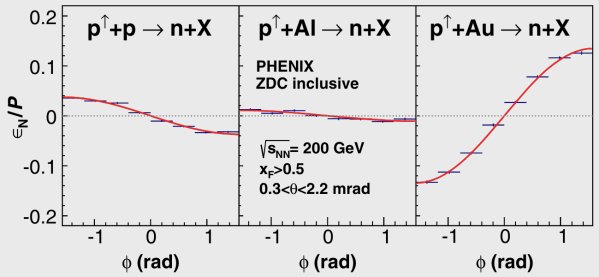


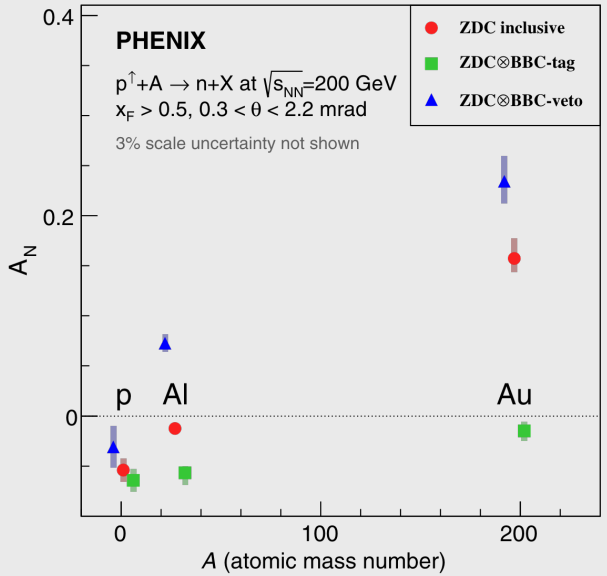

Increasing with $p_T$

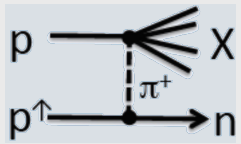
PRD 105, 032004 (2022)



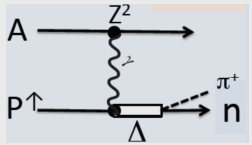

PRL 120, 022001 (2018)




OPE




UPC

# Summary

- After 20 years of at the forefront of spin physics, PHENIX is winding down its final analyses
  - Exploration of longitudinal and transverse spin asymmetries has advanced our understanding of hadronic spin structure and dynamics
  - Final measurements on deck will investigate $\Delta g$ at low-x:
    - Midrapidity $\eta$ $A_{LL}$ 510 GeV
    - Forward rapidity cluster $A_{LL}$ 510 GeV
- More interesting RHIC spin physics on the way in Run24
  - STAR Forward Upgrade
  - First sPHENIX spin data

# Backup

# Transverse Momentum Dependent Distributions

- Transverse Momentum Dependent (TMD) PDFs encode spin-spin and spin-momentum correlations between an initial state proton and a constituent parton
- TMD FFs encode encode spin-spin and spin-momentum correlations between a final state hadron and its fragmenting parton

TMD PDFs

| Nucleon Polarization | Quark Polarization: Un-Polarized (U) | Quark Polarization: Longitudinally Polarized (L) | Quark Polarization: Transversely Polarized (T) |
|---|---|---|---|
| U | $f_1$ = Unpolarized | | $h_1^\perp$ = Boer-Mulders |
| L | | $g_1$ = Helicity | $h_{1L}^\perp$ = Worm-gear |
| T | $f_{1T}^\perp$ = Sivers | $g_{1T}^\perp$ = Worm-gear | $h_1$ = Transversity; $h_{1T}^\perp$ = Pretzelosity |

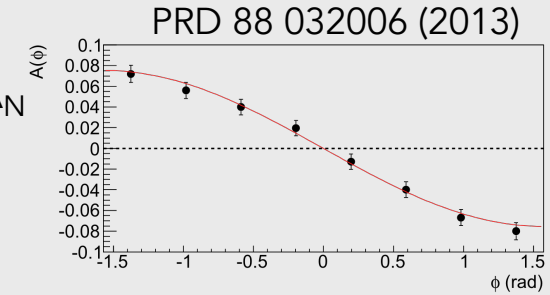
TMD FFs

| | Quark Polarization: Un-Polarized (U) | Quark Polarization: Longitudinally Polarized (L) | Quark Polarization: Transversely Polarized (T) |
|---|---|---|---|
| Unpolarized (or Spin 0) Hadrons | $D_1$ = Unpolarized | | $H_1^\perp$ = Collins |
| Polarized Hadrons: L | | $G_1$ = Helicity | $H_{1L}^\perp$ = |
| Polarized Hadrons: T | $D_{1T}^\perp$ = Polarizing FF | $G_{1T}^\perp$ = | $H_1$ = Transversity; $H_{1T}^\perp$ = |

arxiv:2304.03302

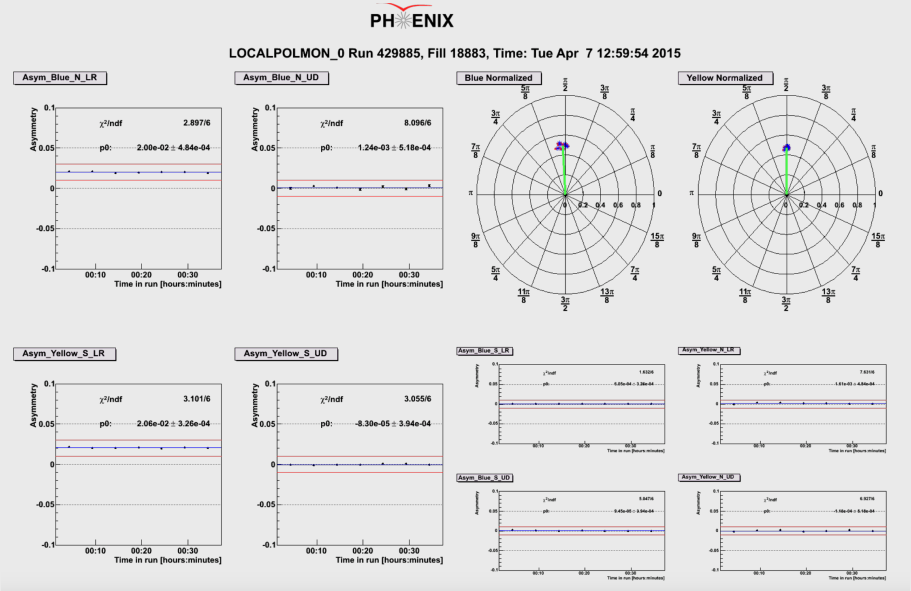
# PHENIX Local Polarimetry

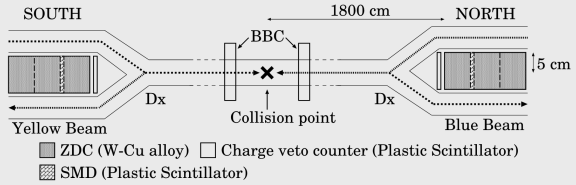
Neutron $A_N$




- Zero-degree calorimeter (ZDC) and Shower Maximum Detector (SMD) used to measure well-known neutron transverse single spin asymmetries in the far forward region
- With vertical polarization:
  - Left-right forward neutron asymmetries nonzero
  - Up-down forward neutron asymmetries zero
- Any nonzero up-down asymmetry → offset from vertical polarization

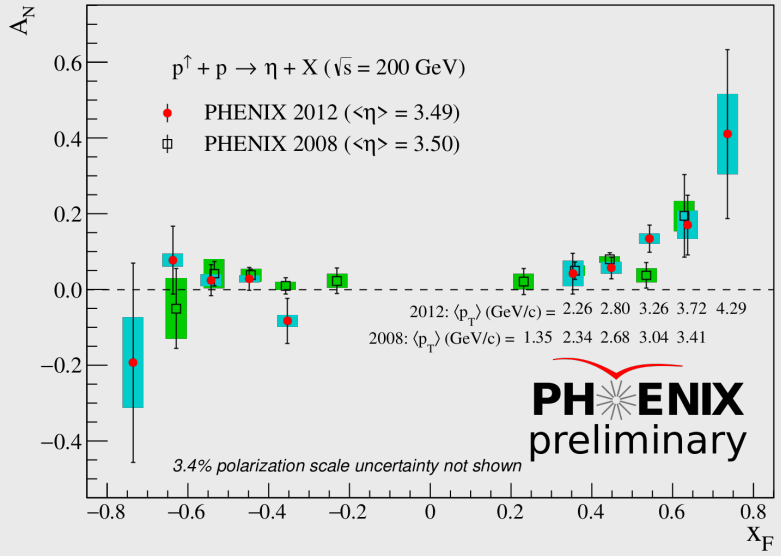
Forward = polarized proton going direction
South ZDC/SMD: Yellow beam
North ZDC/SMD: Blue beam

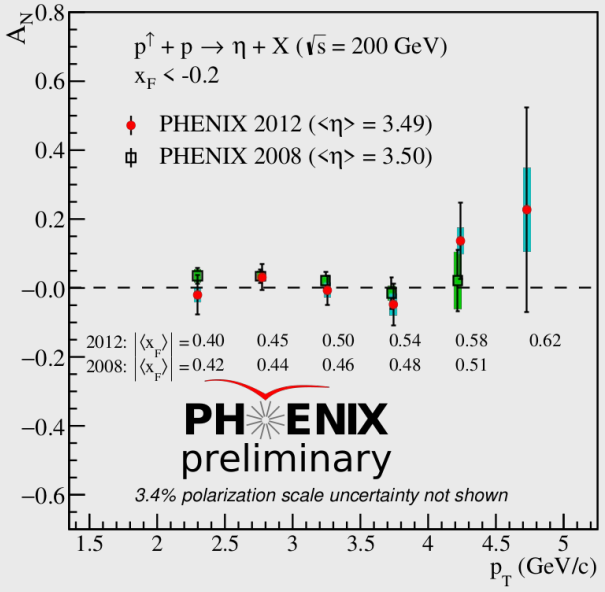


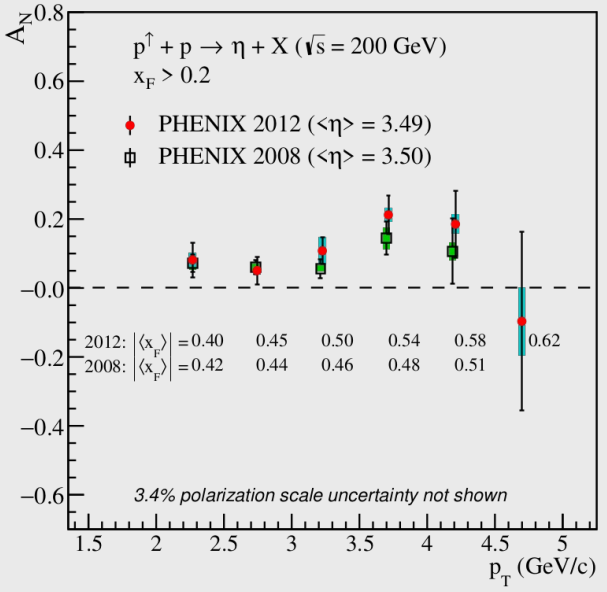




# Preliminary Run12 forward $\eta$ meson $A_N$

- Good agreement within uncertainties to previous published PHENIX results from 2008 with greater reach to higher $x_F$
- Future inclusion of minimum bias data will extend results to lower $x_F$

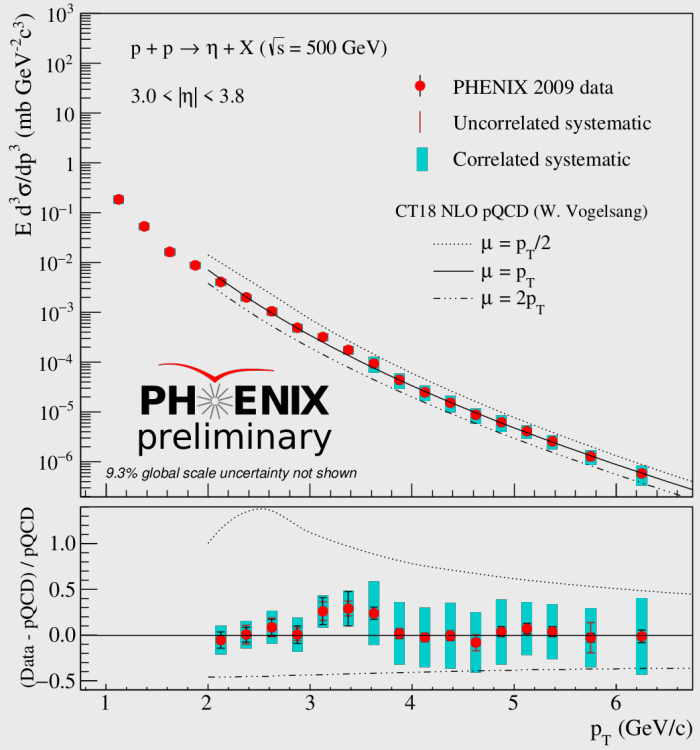


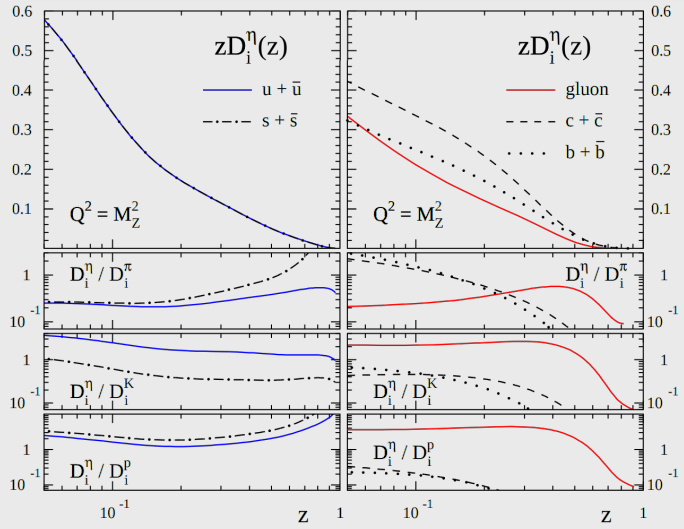



# Forward $\eta$ meson cross section 500 GeV

- First measurement of $\eta$ meson cross section at forward rapidity in 500 GeV pp collisions
- Good agreement with NLO pQCD predictions
- Will be used in an update to the only global set of $\eta$ meson fragmentation functions




PRD. 83 034002 (2011)

$$\delta D^{\eta}_{u,d} = ^{+30\%}_{-20\%}$$

$$\delta D^{\eta}_{g} = \pm 15\%$$

Potential inputs for an updated $\eta$ analysis

| *Experiment* | *Observable* | $\sqrt{s}$ *(TeV)* | *Pseudorapidity* | |
|---|---|---|---|---|
| PHENIX | $d\sigma_{pp\to\eta X}$ | 0.2 | Forward | PRD 90 072008 (2014) |
| PHENIX | $d\sigma_{pp\to\eta X}$ | 0.5 | Forward | |
| PHENIX | $d\sigma_{pp\to\eta X}$ | 0.2 | Midrapidity | PRD 83 032001 (2011) |
| PHENIX | $d\sigma_{pp\to\eta X}$ | 0.51 | Midrapidity | In progress |
| ALICE | $d\sigma_{pp\to\eta X}$ | 2.76 | Midrapidity | EPJ.C (2017) 77:339 |
| ALICE | $d\sigma_{pp\to\eta X}$ | 7 | Midrapidity | PLB 717 (2012) 162 |
| ALICE | $d\sigma_{pp\to\eta X}$ | 8 | Midrapidity | EPJ.C (2018) 78:263 |
| STAR | $\eta/\pi^0$ | 0.2 | Midrapidity | PRC 81 064904 (2010) |