Spin physics highlights from PHENIX

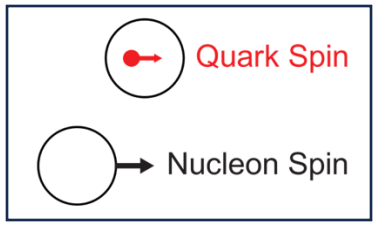
Devon Loomis, for the PHENIX collaboration

The 11th workshop of the APS Topical Group on Hadronic Physics, Anaheim, CA, March 14-16, 2025

Outline

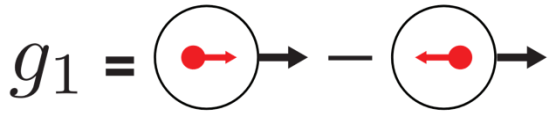
1. **Introduction to longitudinal and transverse spin physics in hadronic collisions**
2. **PHENIX detector overview**
3. **Longitudinal spin results**
4. **Transverse spin results**
5. **Nuclear effects in transverse spin**

Gluon helicity with hadronic collisions



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

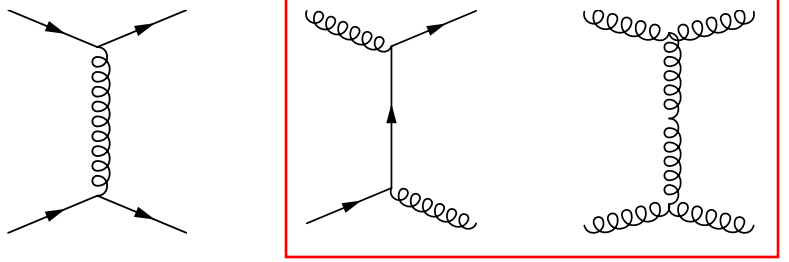
proton spin | quark helicity | gluon helicity | orbital angular momentum

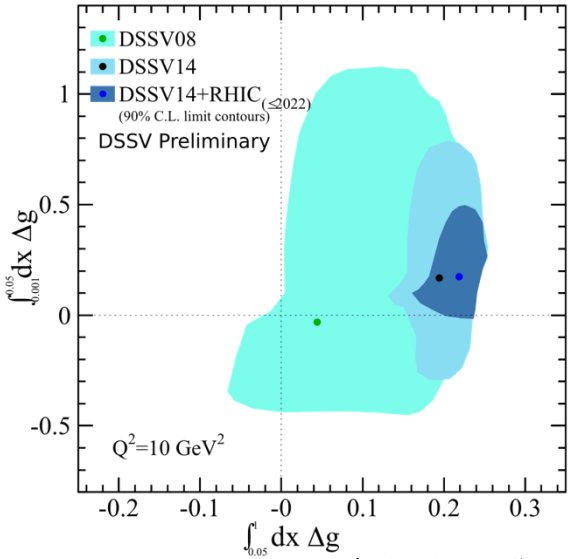


- **Quark helicity contribution constrained by polarized DIS ~ 0.3**
- **Longitudinally-polarized proton collisions provide leading order access to Δg through longitudinal double spin asymmetries**

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

RHIC





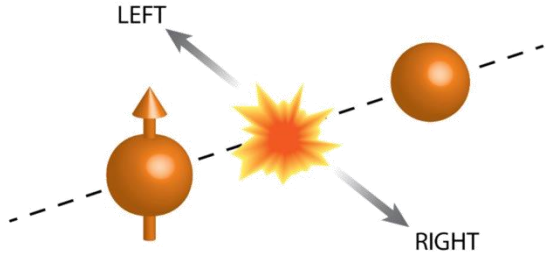
arxiv:2302.00605

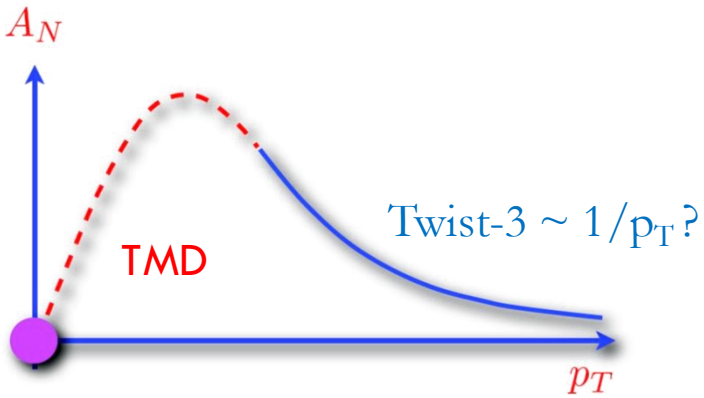
- **Inclusion of PHENIX π^0 and STAR jet A_{LL} → clear evidence of nonzero Δg**

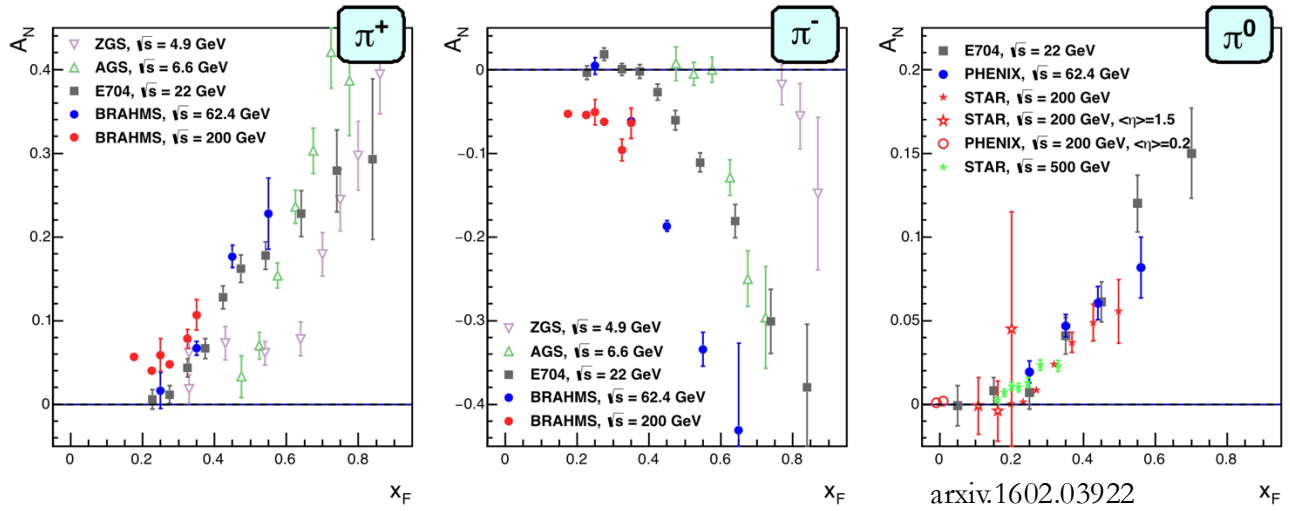
$$\int_{0.05}^{1.0} dx \Delta g(x) = 0.218 \pm 0.027$$

Transverse single spin asymmetries (TSSA)

- 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 the asymmetry $A_N = \alpha_s m_q / \sqrt{s} \sim 0$
- Origin of A_N: Nonperturbative spin-momentum correlations described by
  - Transverse Momentum Dependent (TMD) PDFs/FFs
  - Collinear twist-3 multiparton correlators

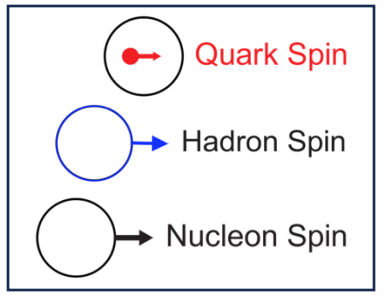






arXiv:1602.03922

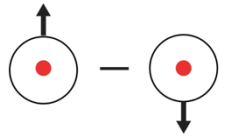
Generation of a TSSA



$$Q >> k_T \gtrsim \Lambda_{QCD}$$

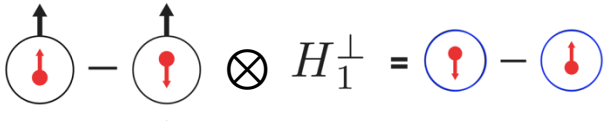
Sivers TMD PDF

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

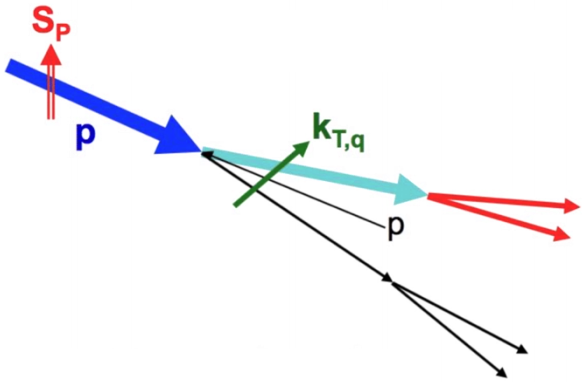


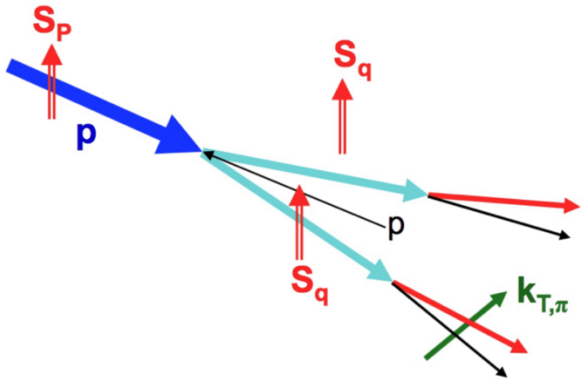
Transversity ⊗ Collins TMD FF

h_1 =



$H_1^{\perp}$ =



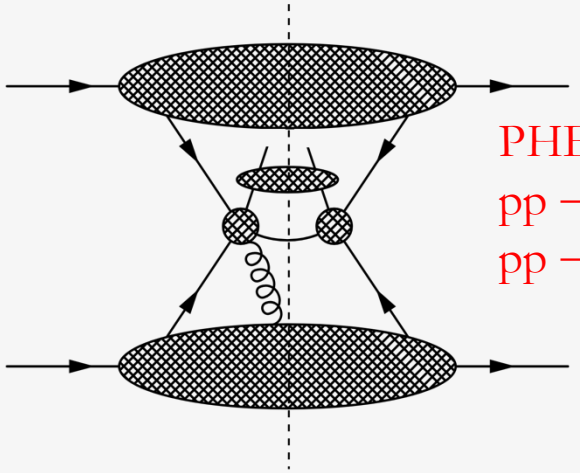


$$A_N \propto f_{1T}^{\perp}(x, k_T^2) \cdot D_q^h(z)$$

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

$$Q, k_T >> \Lambda_{QCD}$$

Twist-3 multiparton correlators



PHENIX

$pp \rightarrow h + X$

$pp \rightarrow \gamma + X$

Sivers-like correlator

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

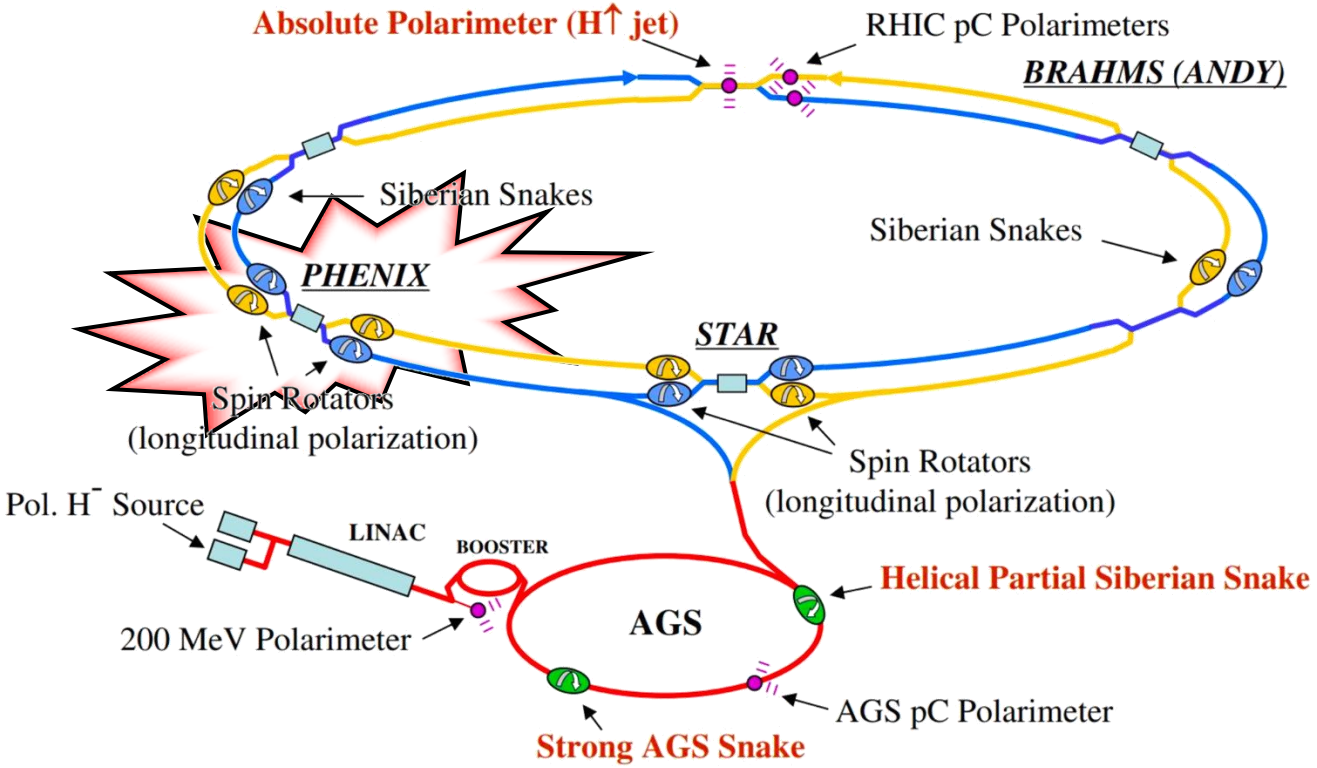
Transversity

Collins-like correlator

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

Polarized physics at PHENIX

Relativistic Heavy Ion Collider (RHIC)

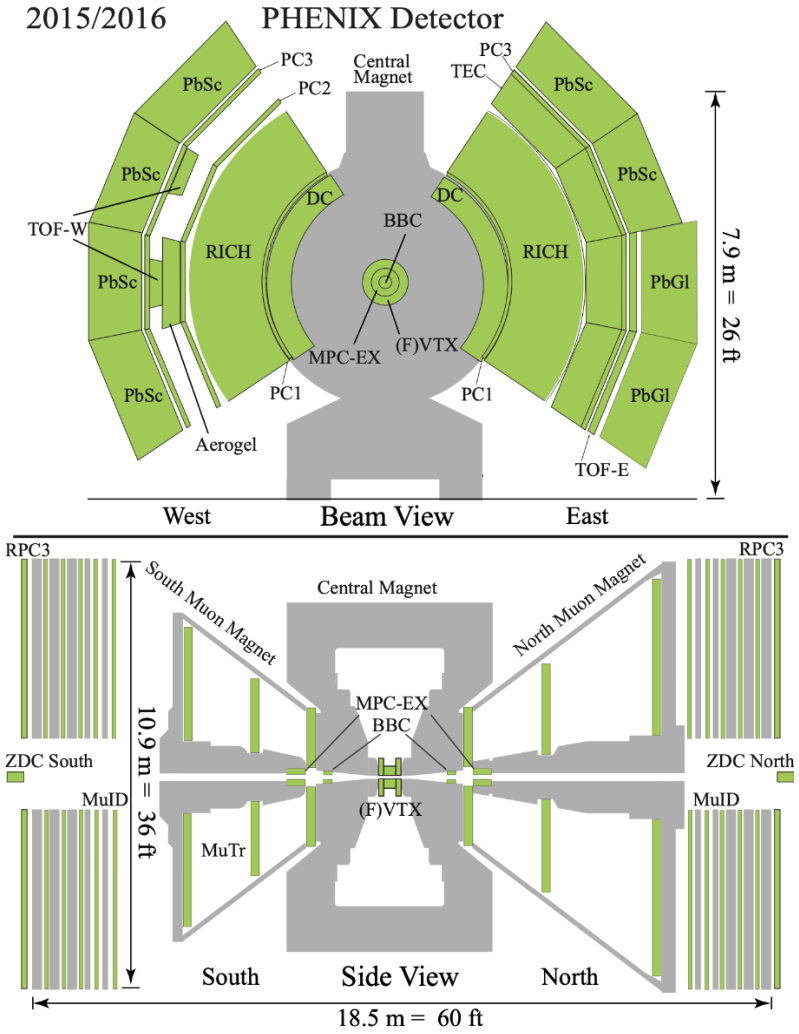


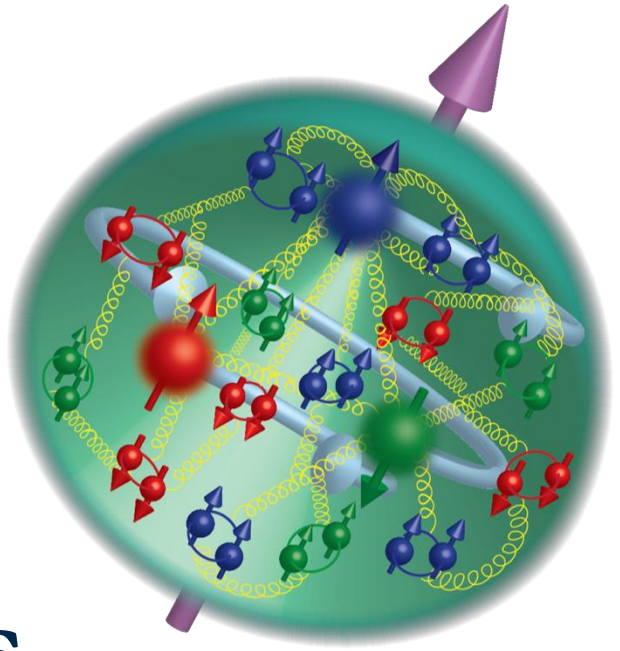
RHIC is the only collider in the world that can provide high energy <u>polarized</u> proton beams

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

PHENIX detector

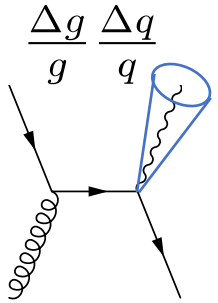
- Central arms - $|\eta| < 0.35$, $\pi/2$ azimuthal coverage per arm
  - PbSc and PbGl EMCal (e,γ)
  - Gas Ring Imaging Cherenkov Detector (RICH) (e,π,K PID)
  - Drift/Pad chambers
- Muon arms - $1.2 < |\eta| < 2.4$
  - Muon ID
  - Muon Tracker
- Forward - $3.1 < |\eta| < 3.9$
  - Beam beam counter (collision/luminosity)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

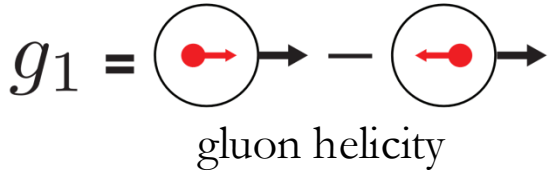




Longitudinal Spin Results

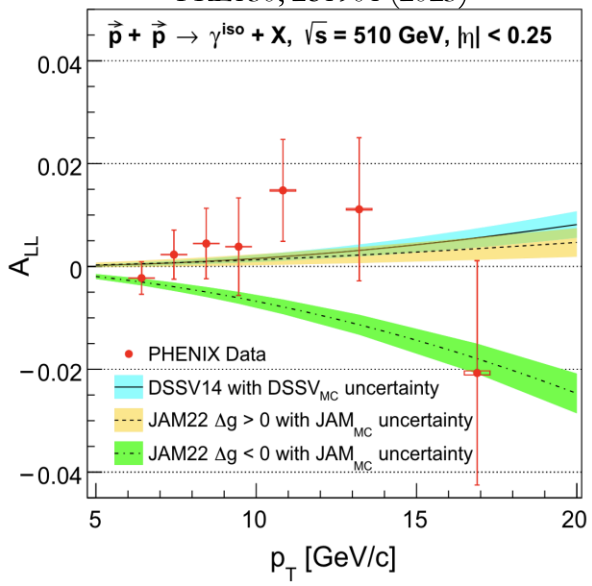
Direct photon A_{LL}

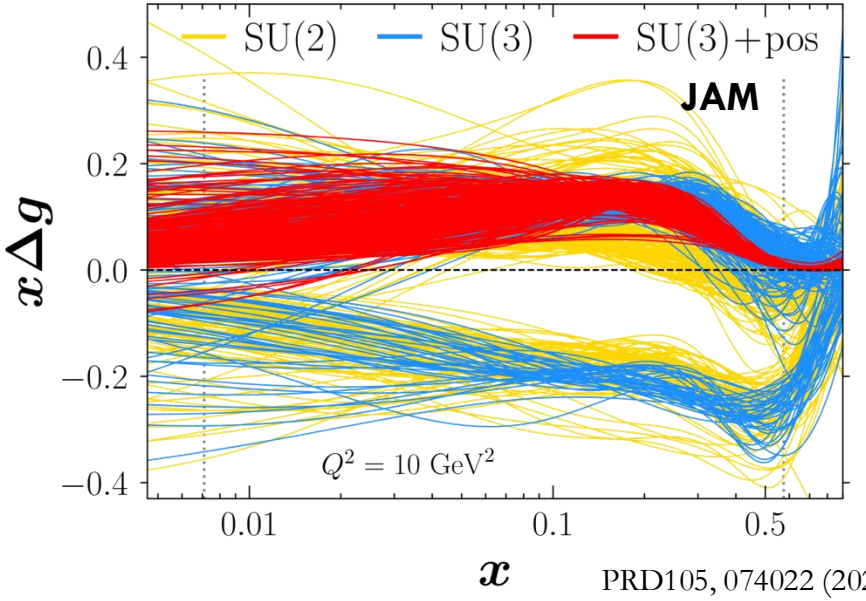




- **JAM collaboration: ambiguity on sign of Δg ?** PRD105, 074022 (2022)
  - **BUT negative Δg leads to negative cross sections** PRD109, 074007 (2024)
- **Direct photons dominated by qg compton scattering**
  - **Sensitive to sign of Δg**
- **Negative solution disfavored at 2.8σ**

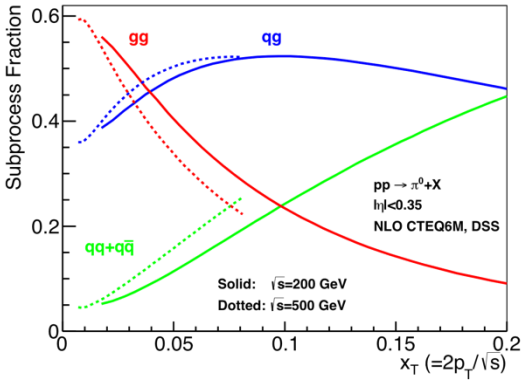
PRL130, 251901 (2023)

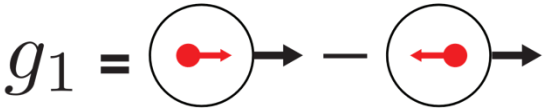




PRD105, 074022 (2022)

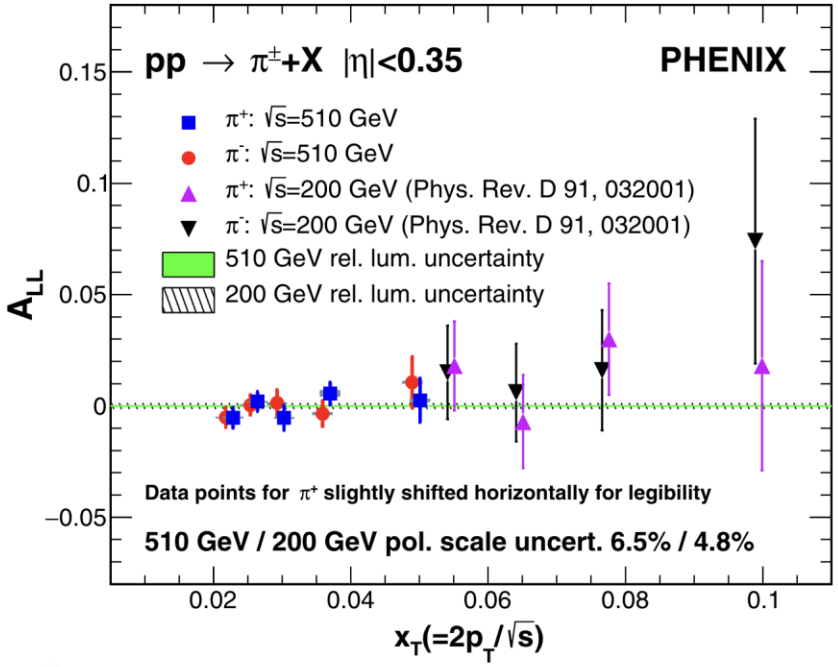
Pion A_{LL}

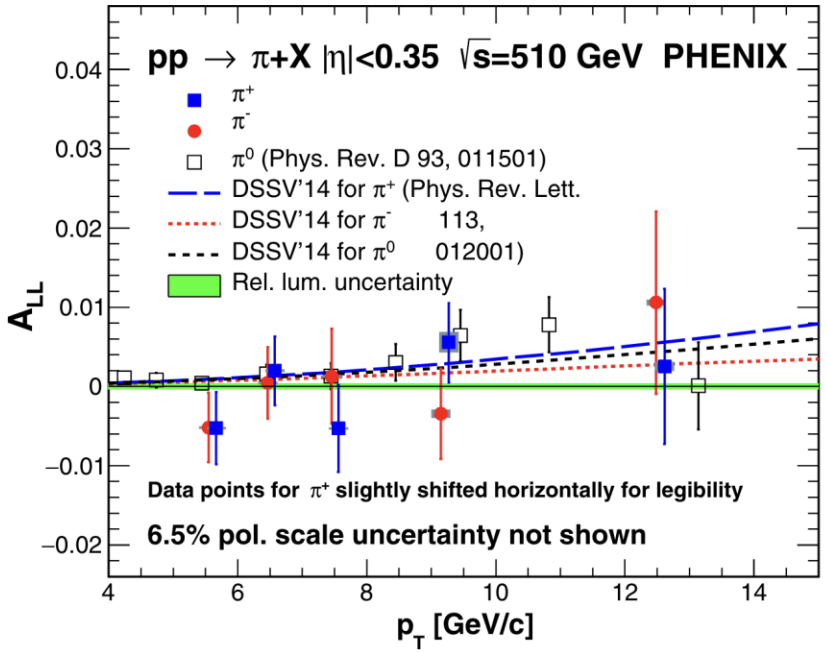


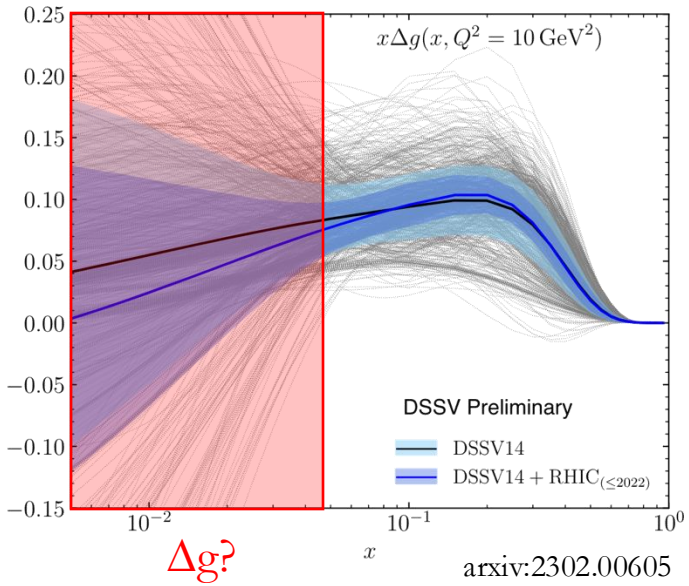


- Δg at x < 0.05 still largely unconstrained
- Charged pion A_{LL} at $\sqrt{s}$ = 510 GeV probes Δg down to low x
  - Consistent with DSSV predictions

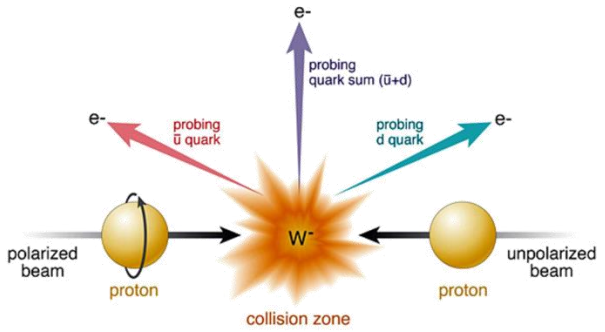
PRD 102, 032001 (2020)







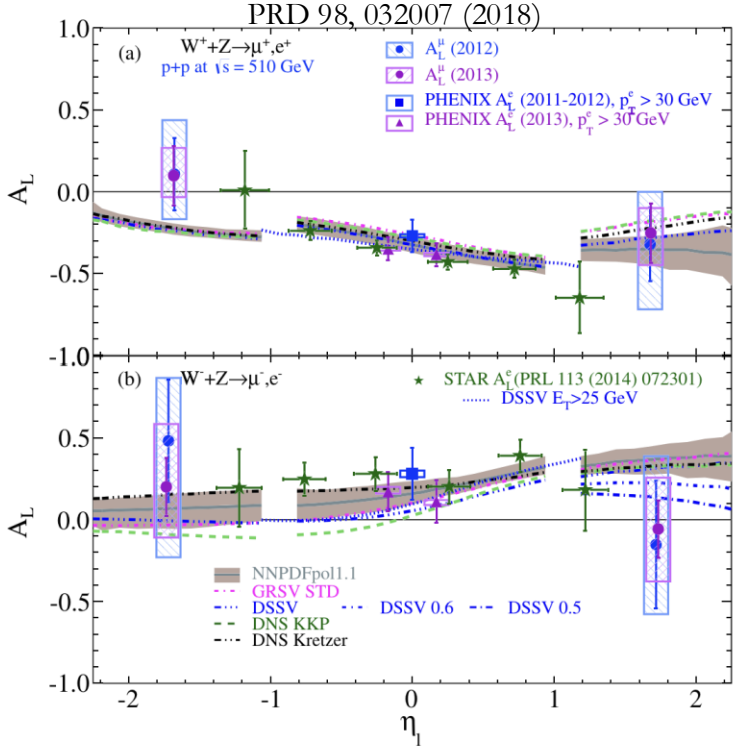
$W^{\pm} \rightarrow e^{\pm}, \mu^{\pm}$ A_L



g_1 = (anti-)quark helicity

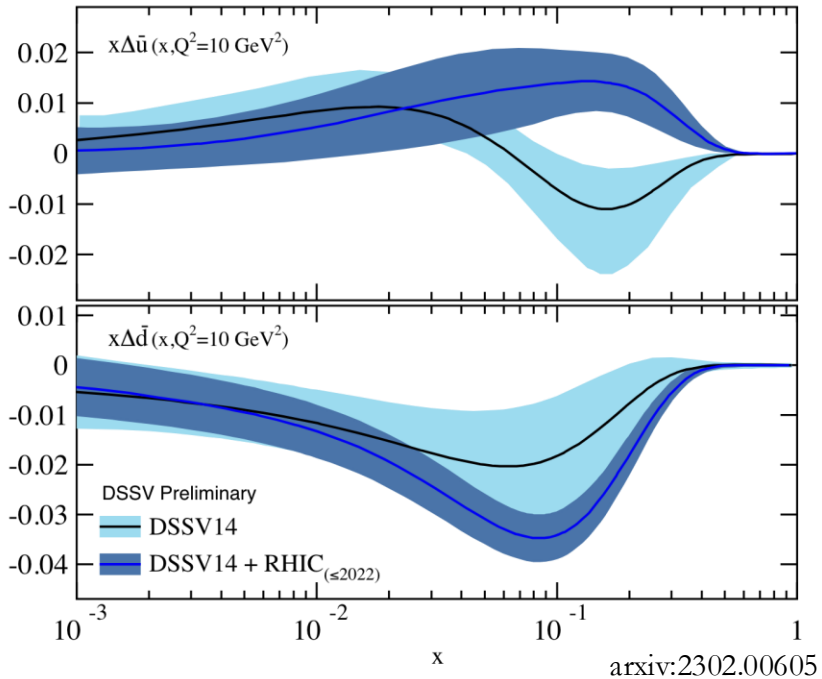
- **Flavor separation of $\Delta\bar{q}$ through parity violating** $u_L \bar{d}_R \rightarrow W^+ \quad d_L \bar{u}_R \rightarrow W^-$
- **Longitudinal *single* spin asymmetry** $A_L^{W^-} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2)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

PRD 98, 032007 (2018)

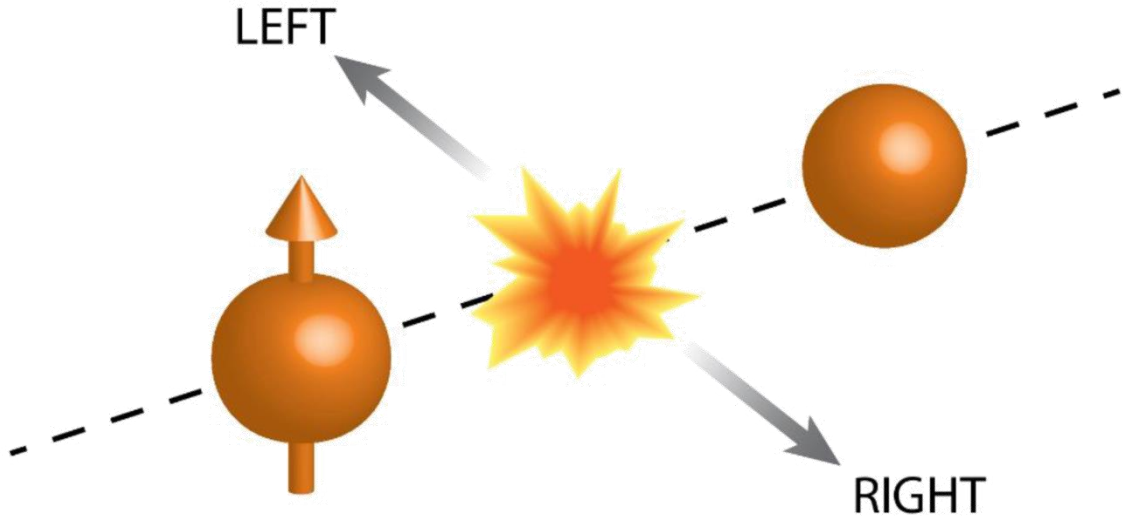


Indication of:
- positive $\bar{u}$ helicity
- negative $\bar{d}$ helicity

Polarized sea asymmetry *opposite* sign from unpolarized sea asymmetry

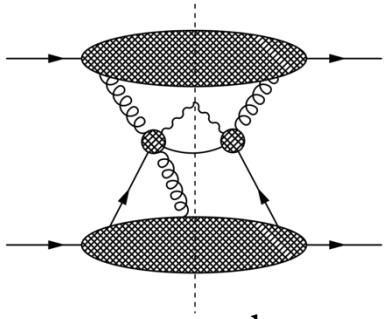


arxiv:2302.00605

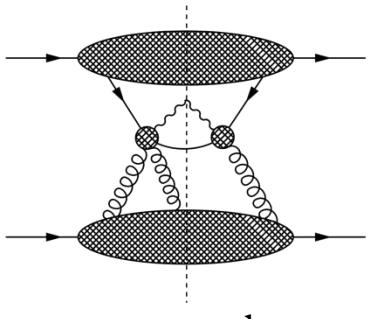


Transverse Spin Results

Direct photon A_N



qgq correlator

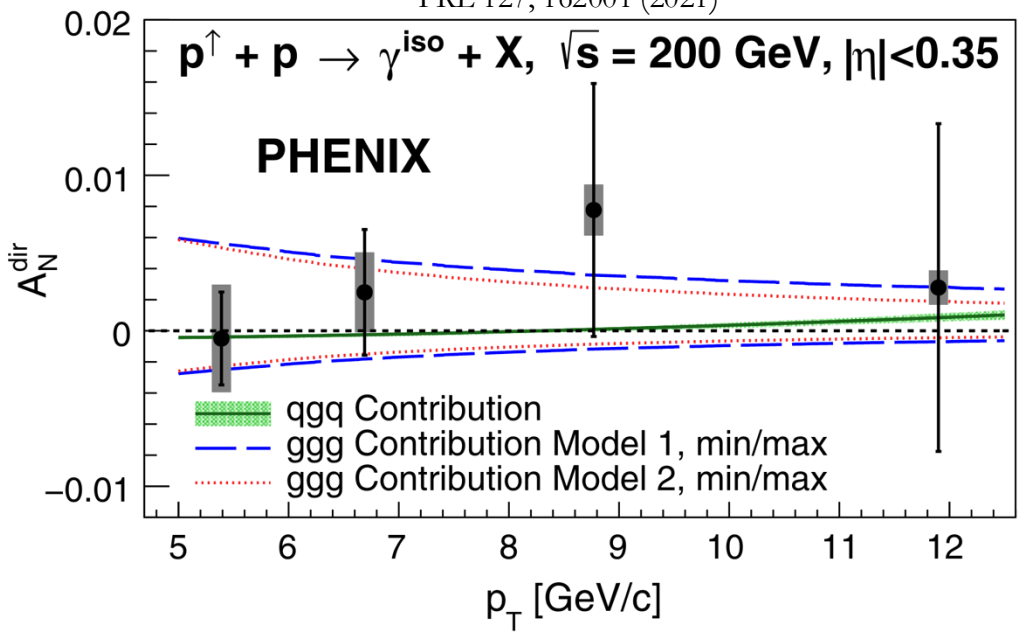


ggg correlator

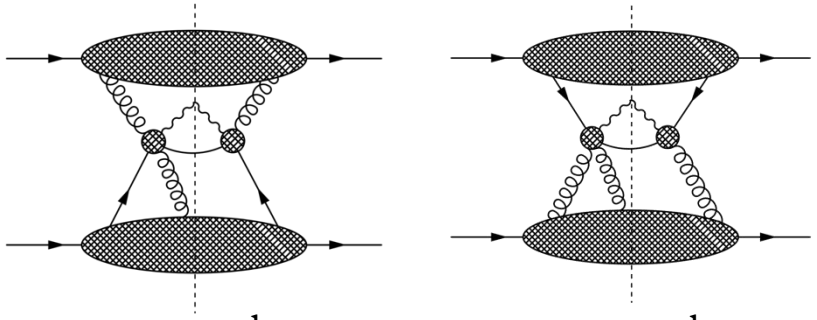
- Photon in final state → no final state color effects
  - Clean probe of initial state quark-gluon and trigluon correlation functions
- First direct photon A_N from RHIC → 50 times reduced uncertainties from Fermilab E704

PRL 127, 162001 (2021)

PLB 345, 569 (1995)

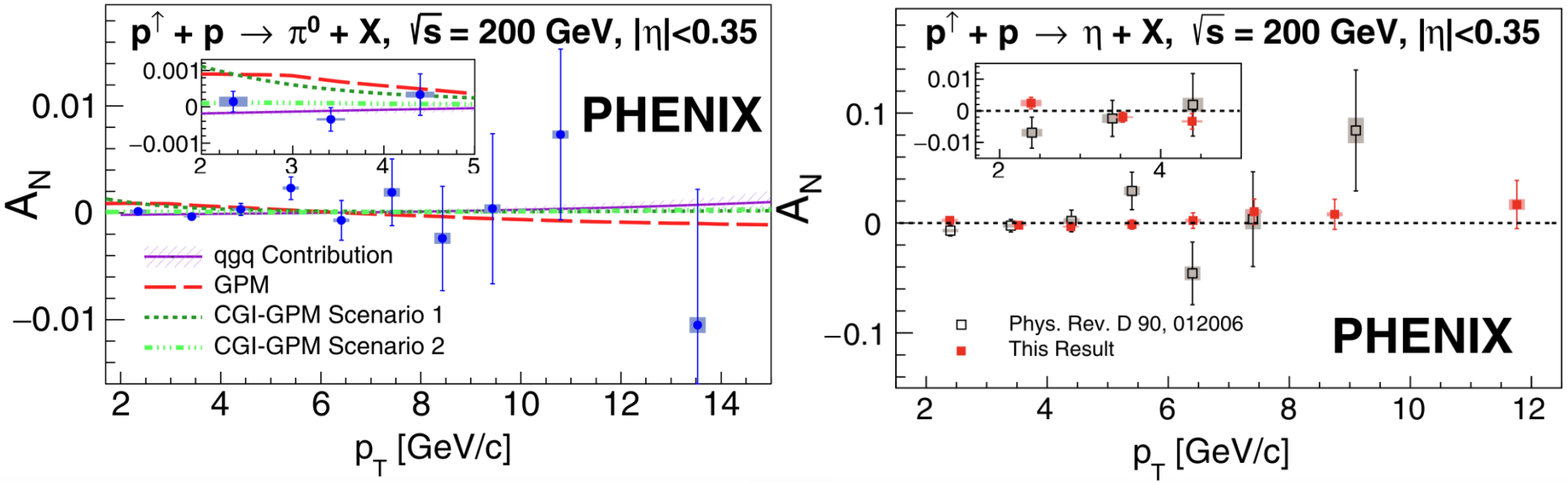


Midrapidity π^0, η A_N

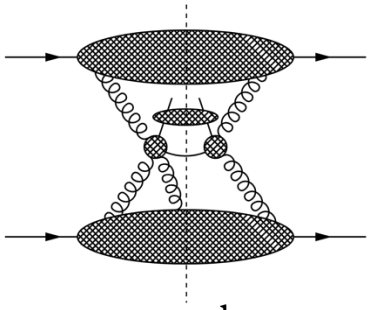


- **Sensitive to gluon dynamics through quark-gluon and trigluon correlation functions**
  - **Used to constrain gluon Sivers TMD** JHEP 1509 (2015), 119
- **High precision measurement: consistent with zero to sub-percent level**

PRD 103, 052009 (2021)



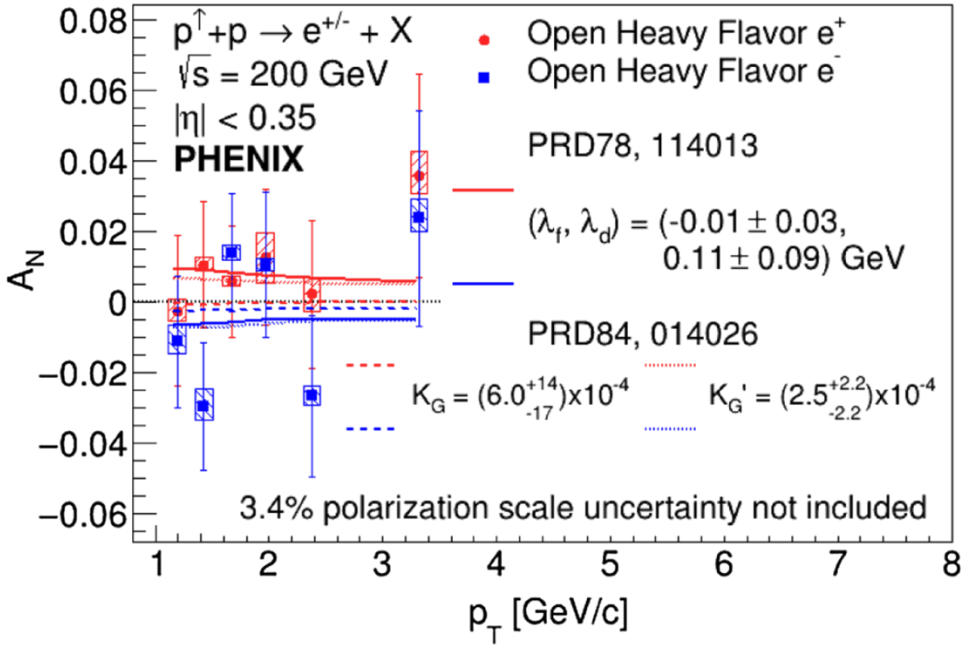
Midrapidity open heavy flavor A_N



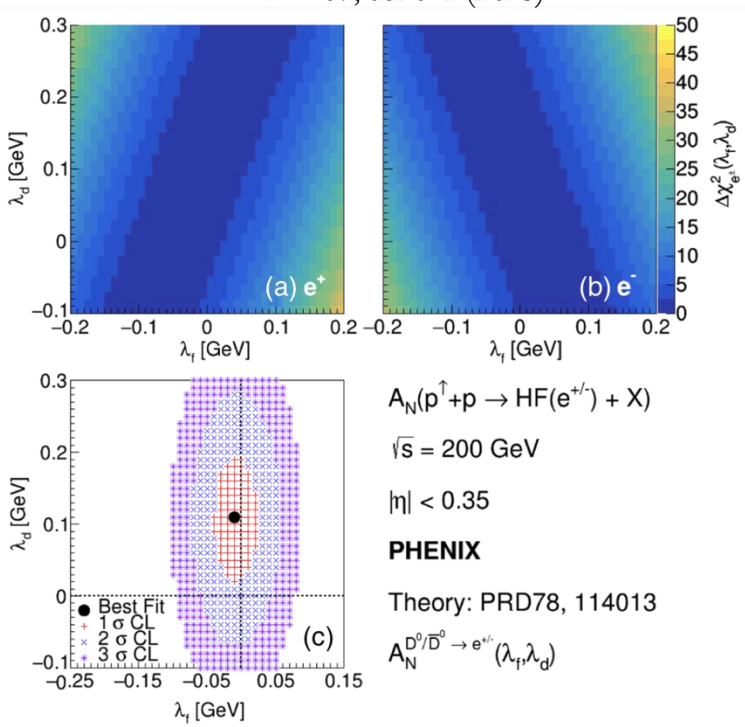
ggg correlator

- **Direct sensitivity to initial-state trigluon correlator**
  - **Gluon-gluon fusion**
  - **Zero gluon transversity in spin ½ nucleons**
- **First constraints on phenomenological trigluon parameters λ, K_G**

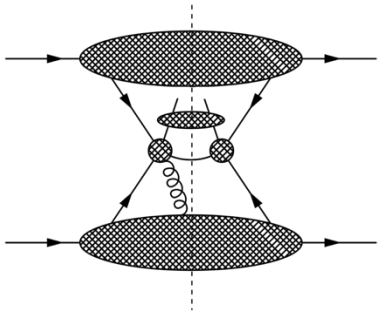
PRD 107, 052012 (2023)



PRD 107, 052012 (2023)



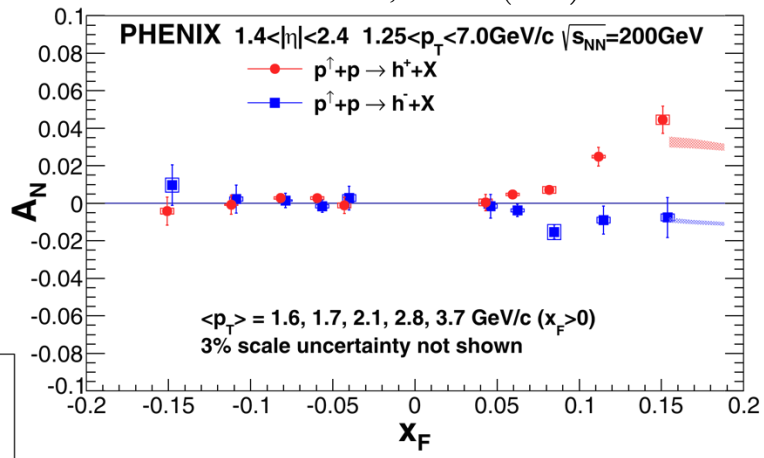
Forward $h^{\pm}$, η A_N

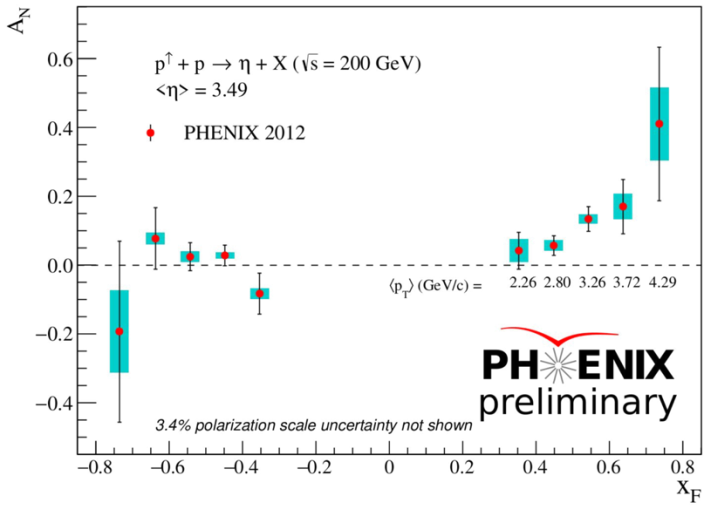


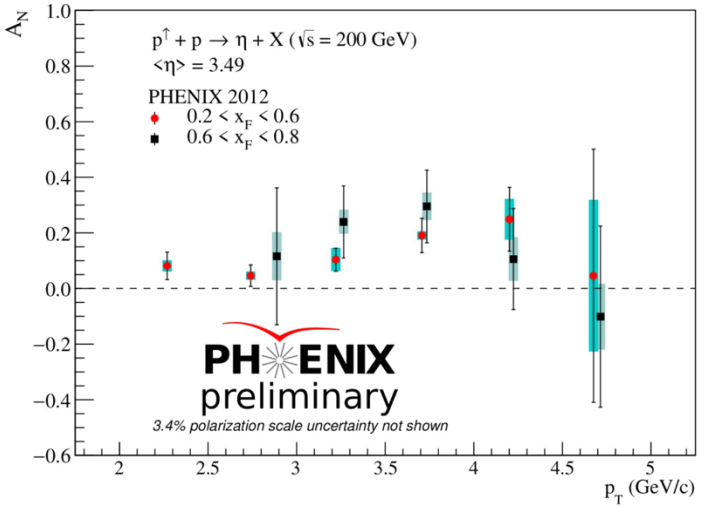
qgq correlator

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

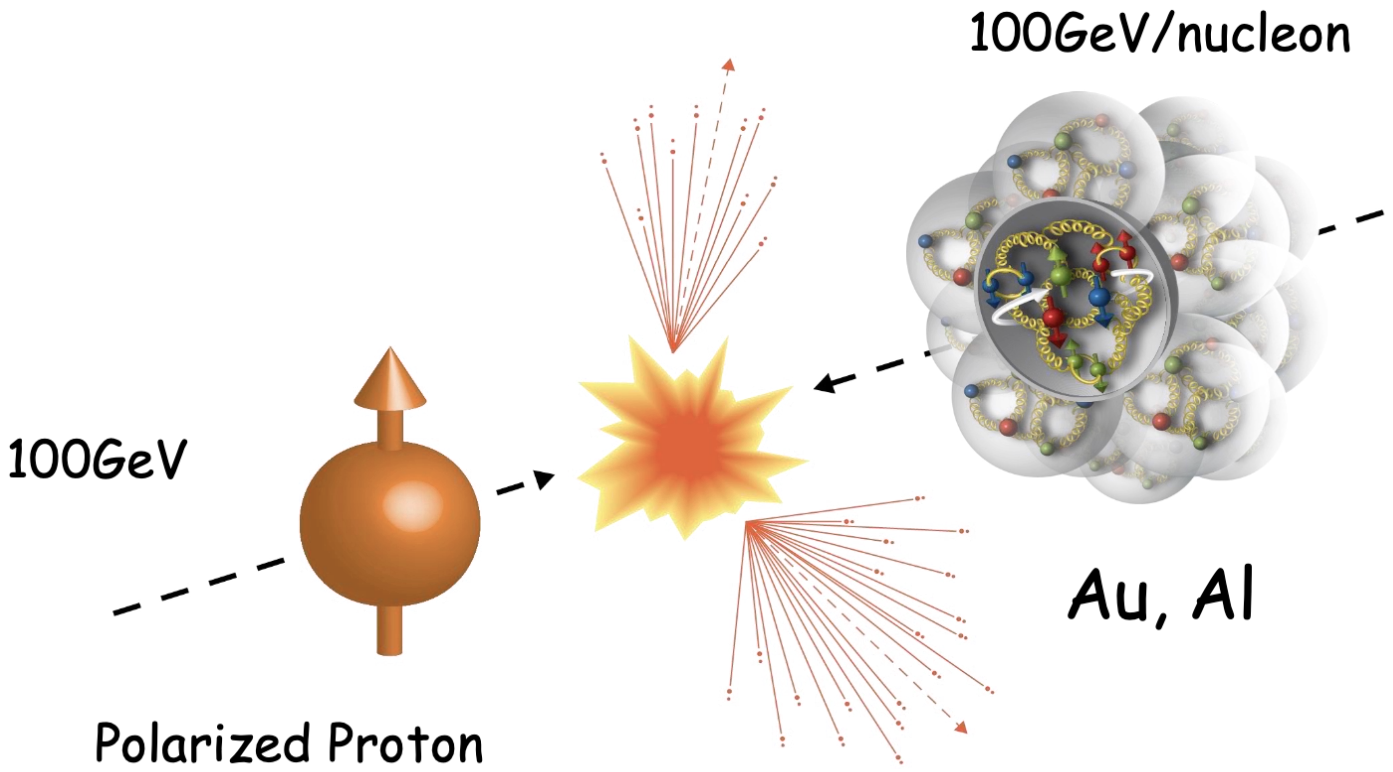
PRD 108, 072016 (2023)





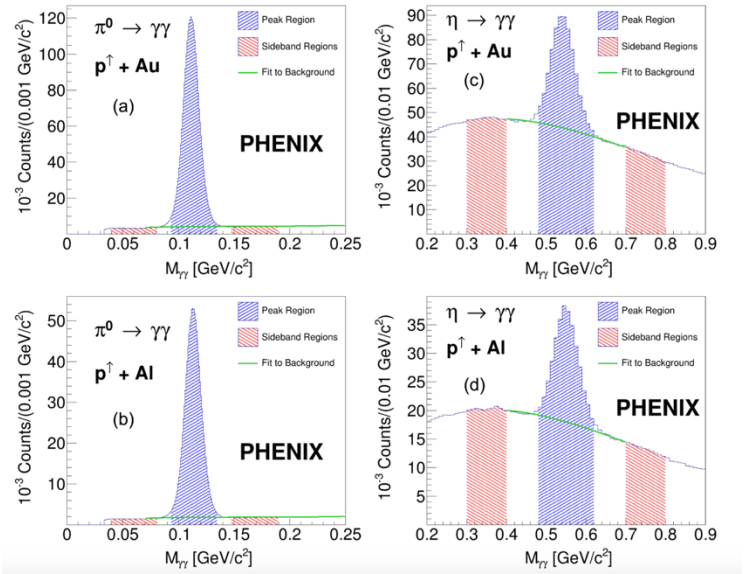


$p^{\uparrow} + A$

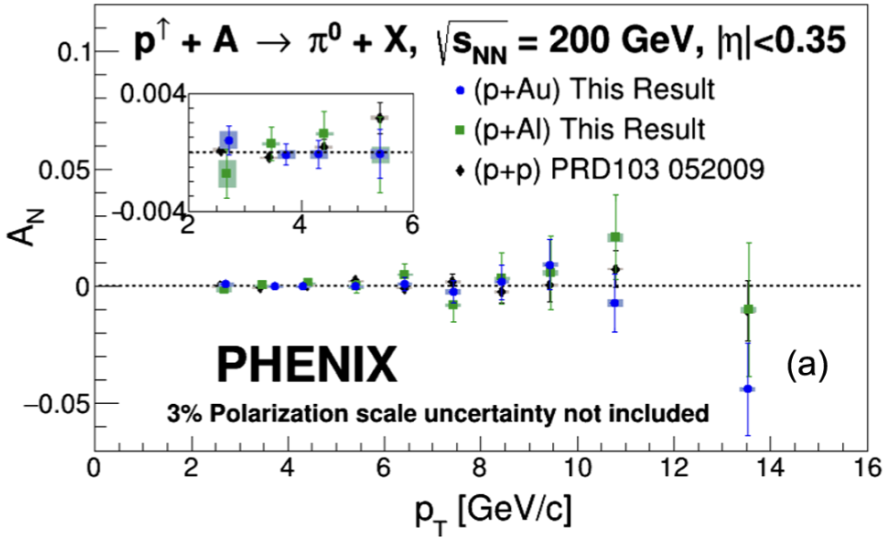


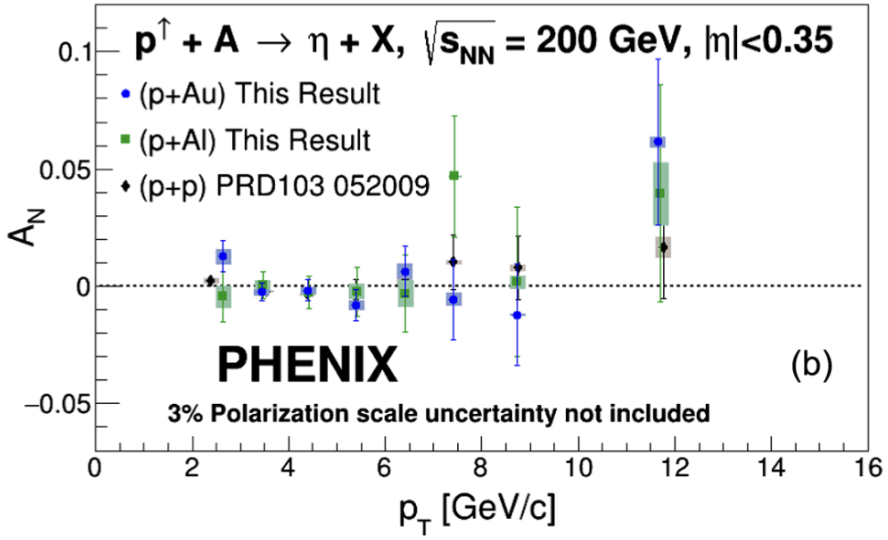
Midrapidity π^0, η A_N

- Consistent results in all collision systems
- High precision measurements of $p^{\uparrow}$+p, $p^{\uparrow}$+Al, $p^{\uparrow}$+Au
  - all consistent with zero



PRD 107, 112004 (2023)

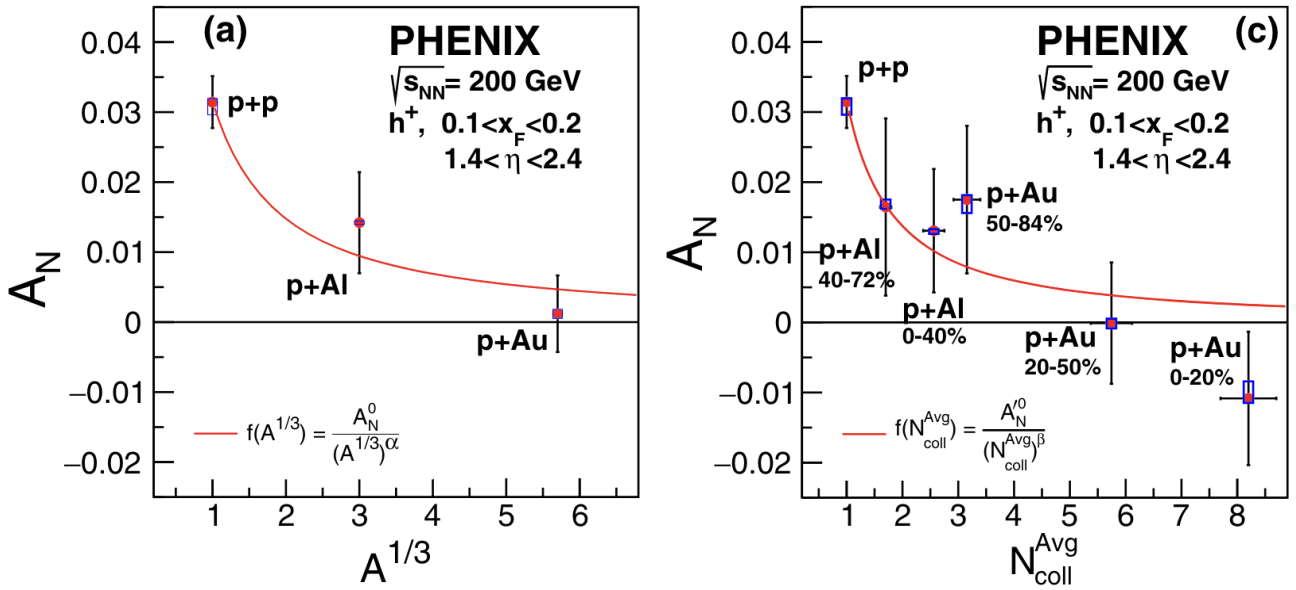




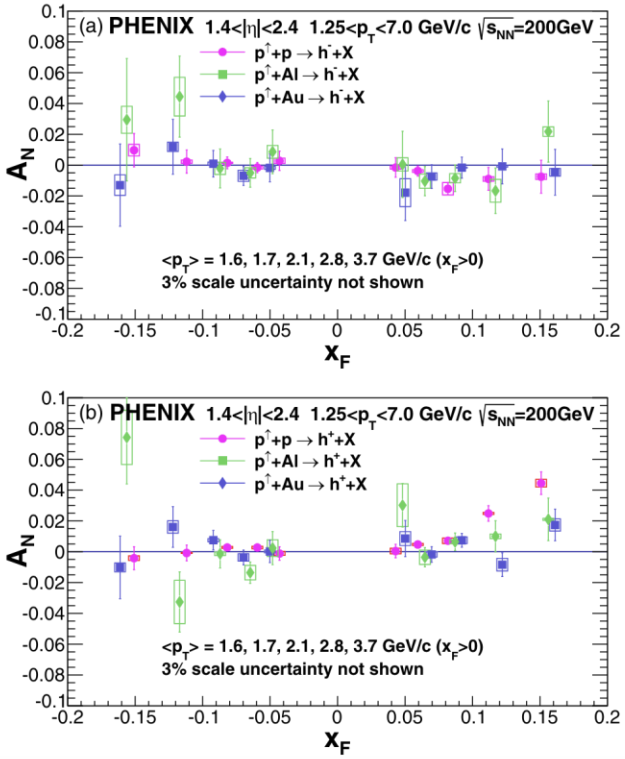
Forward $h^{\pm}$ A_N

- Striking dependence of A_N on atomic mass number *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)



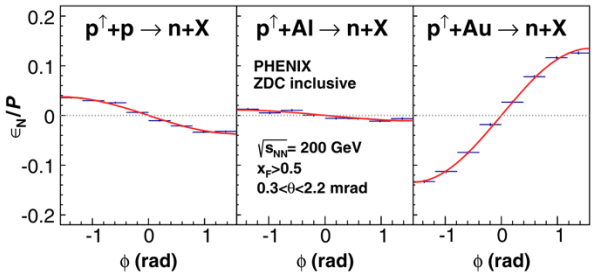
PRD 108, 072016 (2023)

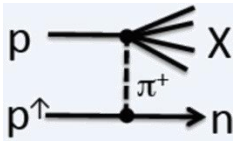


Far forward neutron A_N

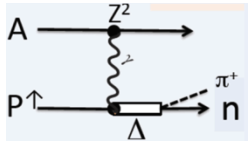
- Negative A_N in far forward neutrons from p+p well described by one pion exchange (OPE) model
- Initially unexpected large dependence on *A* (+ sign change)
  - Additional contribution from ultra-peripheral collisions (UPC) qualitatively describes data

PRL 120, 022001 (2018)

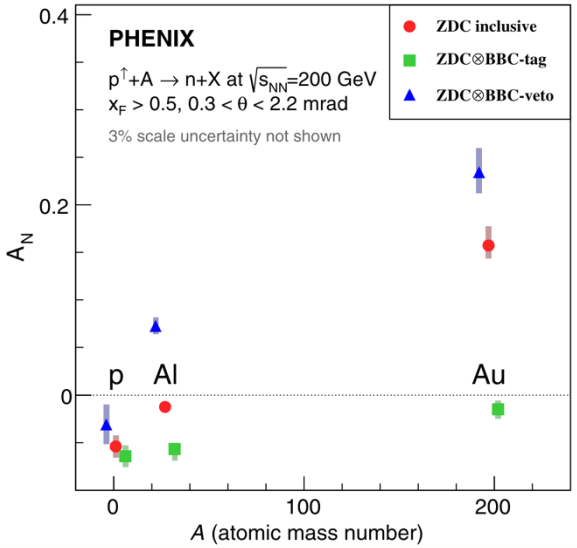




OPE

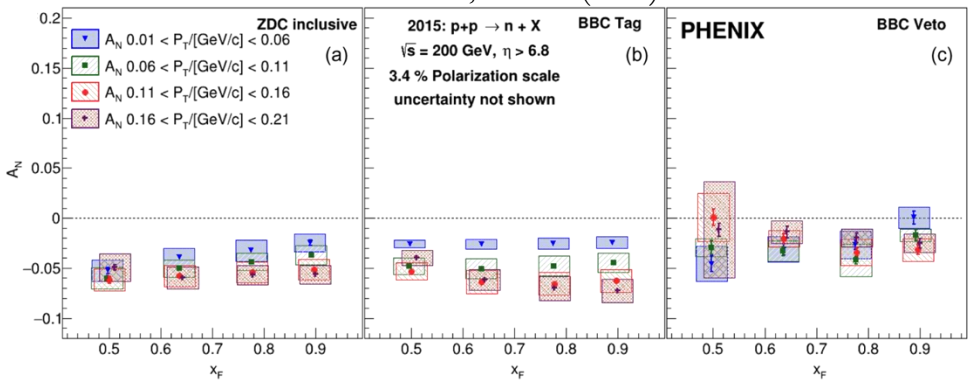


UPC



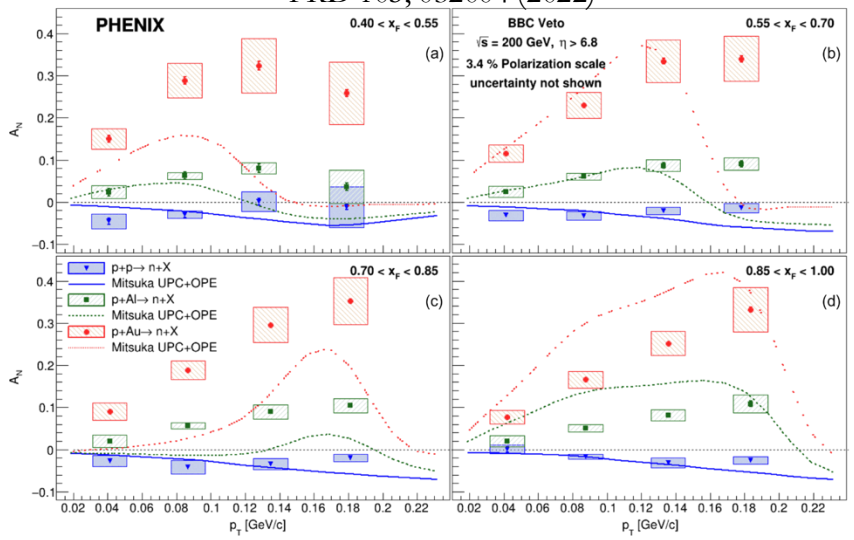
Weak x_F dependence

PRD 105, 032004 (2022)



Increasing with p_T

PRD 105, 032004 (2022)



Summary

- **PHENIX has had a long and successful spin physics program**
  - **20 years of exploration into longitudinal and transverse spin asymmetries has advanced our understanding of hadronic spin structure and dynamics**
  - **Final measurements will investigate Δg at low-x:**
    - **Midrapidity η A_{LL} 510 GeV**
    - **Forward rapidity cluster A_{LL} 510 GeV**
- **Additional interesting RHIC spin physics on the way**
  - **STAR Forward Upgrade**
  - **First sPHENIX spin data**