U.S. DEPARTMENT OF ENERGY | Office of Science

UNIVERSITY OF MICHIGAN

PHENIX

Recent spin physics results from PHENIX

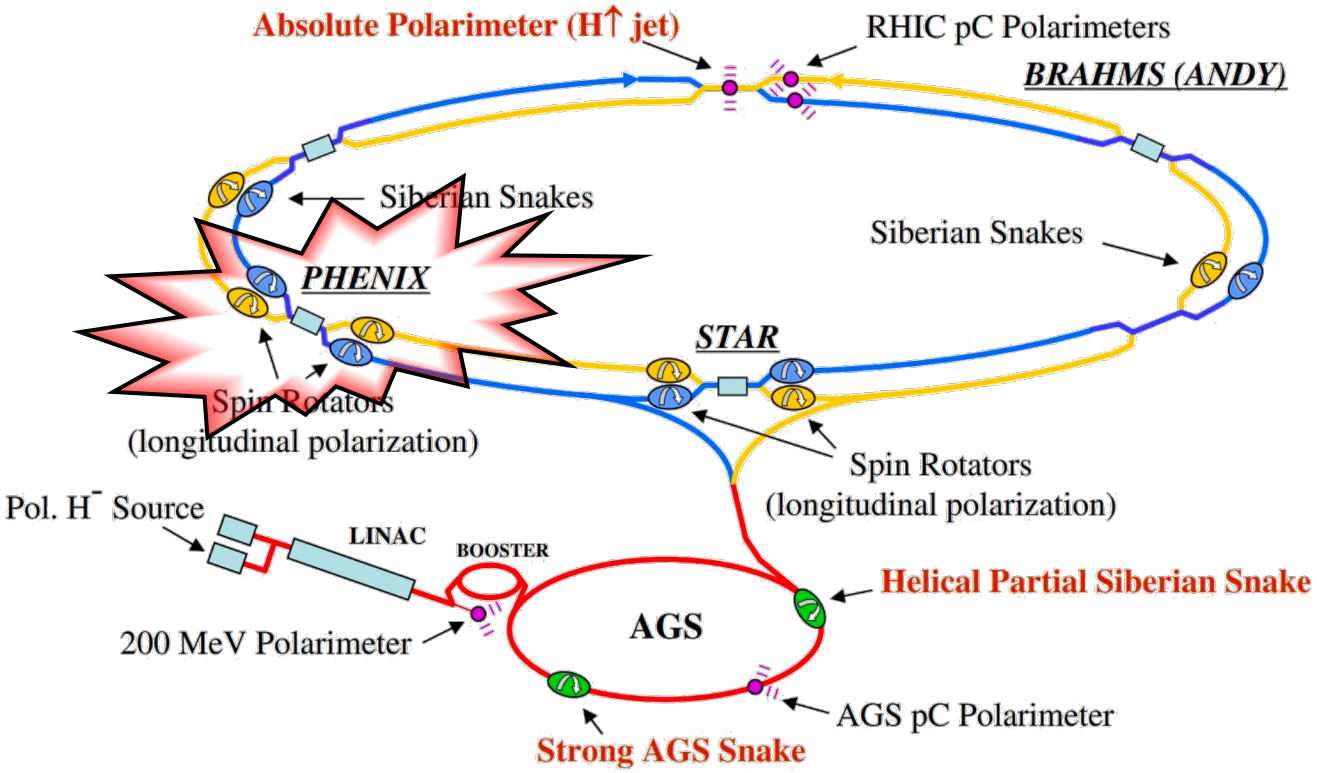
Devon Loomis, for the PHENIX collaboration

XIII International Conference on New Frontiers in Physics

26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

Polarized physics at PHENIX

Relativistic Heavy Ion Collider (RHIC)

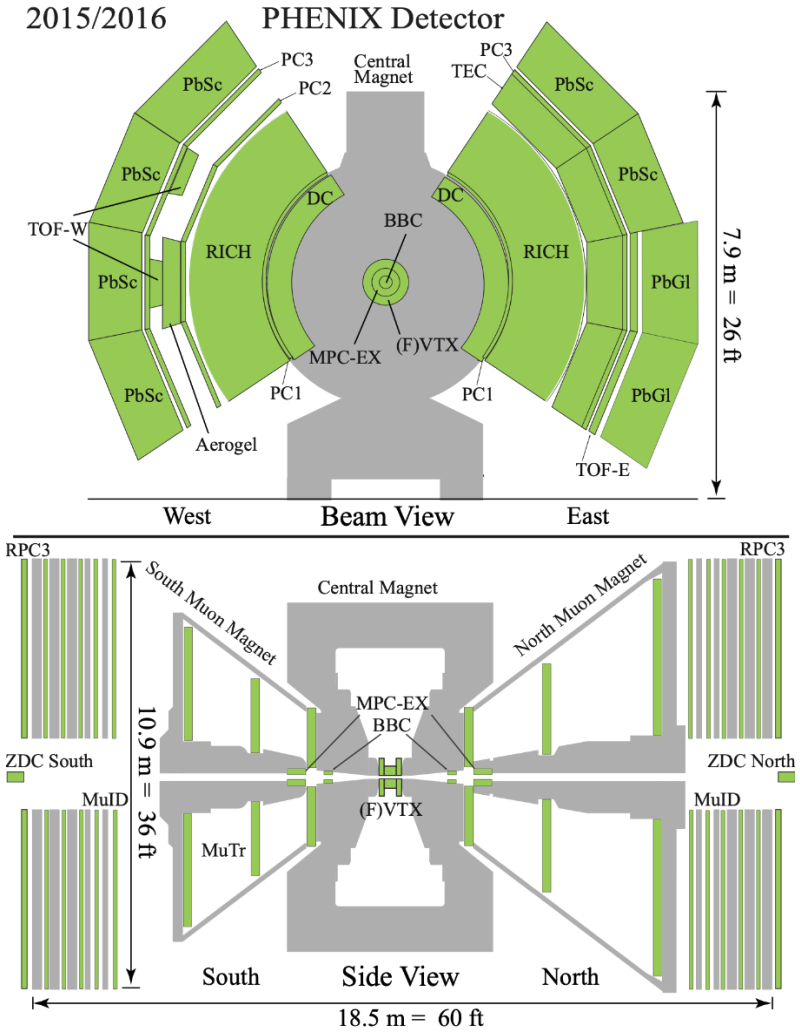


RHIC is the only collider in the world that can provide high energy polarized proton beams

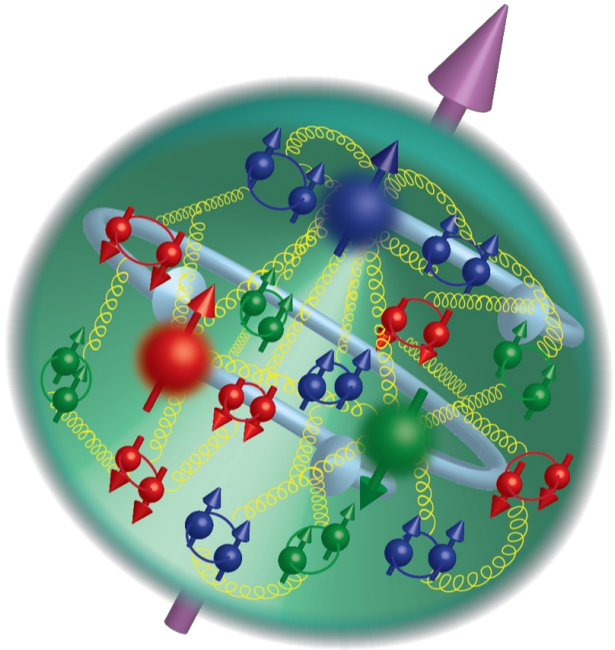
Year	System	$\sqrt{s}$ (GeV)	Polarization	Recorded Luminosity (pb^{-1})
2006	p+p	62.4 200	transverse longitudinal transverse longitudinal	0.02 0.08 2.7 7.5
2008	p+p	200	transverse	5.2
2009	p+p	200 500	longitudinal	16 14
2011	p+p	500	longitudinal	18
2012	p+p	200 510	transverse longitudinal	9.7 32
2013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

PHENIX detector

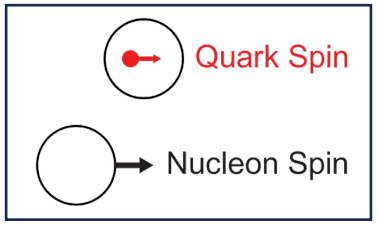
- Central arms - $|\eta| < 0.35$, $\pi/2$ azimuthal coverage per arm
  - PbSc and PbGl EMCal (e,γ)
  - Gas Ring Imaging Cherenkov Detector (RICH) (e,π,K PID)
  - Drift/Pad chambers
- Muon arms - $1.2 < |\eta| < 2.4$
  - Muon ID
  - Muon Tracker
- Forward - $3.1 < |\eta| < 3.9$
  - Beam beam counter (collision/luminosity)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



Longitudinal Spin

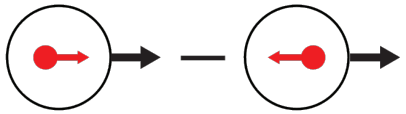


Accessing gluon helicity



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

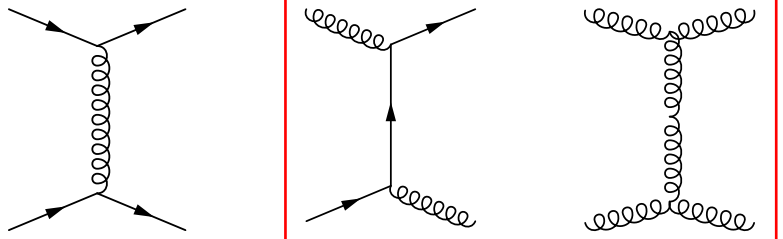
proton spin | quark helicity | gluon helicity | orbital angular momentum

g_1 =  helicity

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

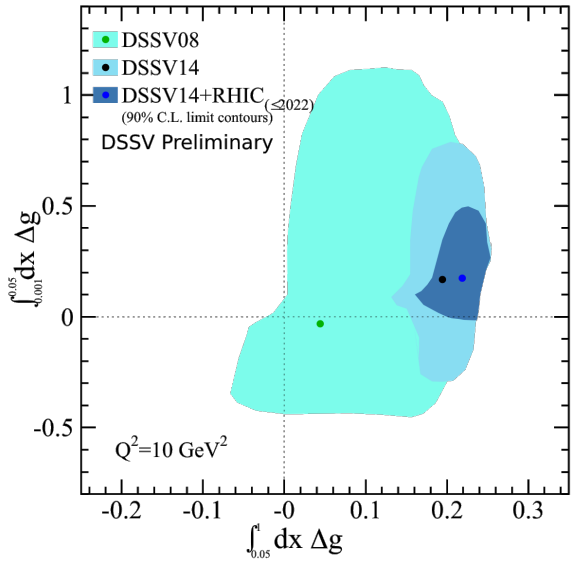
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta q}{q}\frac{\Delta q}{q} + \frac{\Delta g}{g}\frac{\Delta q}{q} + \frac{\Delta g}{g}\frac{\Delta g}{g}$$

RHIC



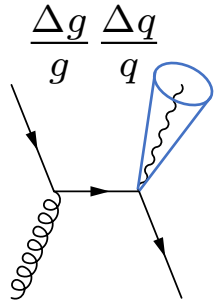
- Inclusion of PHENIX π^0 and STAR jet A_{LL} → clear evidence of nonzero Δg

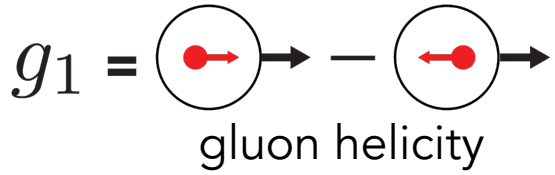
$$\int_{0.05}^{1.0} dx \Delta g(x) = 0.218 \pm 0.027$$



arxiv:2302.00605

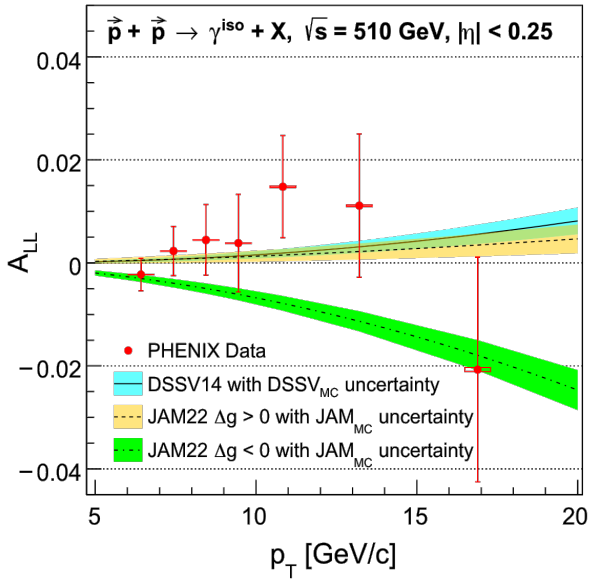
Direct photon A_{LL}

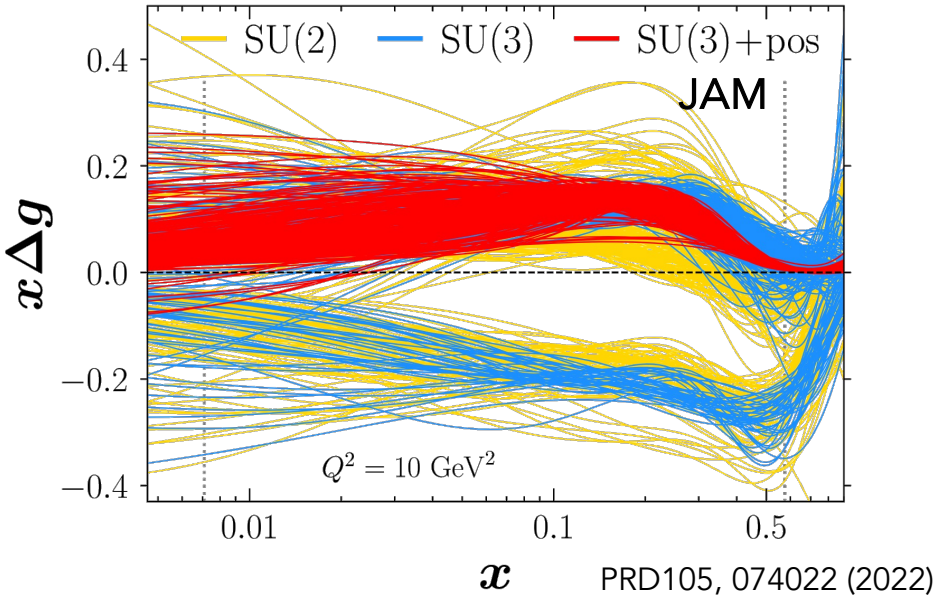




- JAM collaboration: ambiguity on sign of Δg ? PRD105, 074022 (2022)
  - BUT negative Δg leads to negative cross sections PRD109, 074007 (2024)
- Direct photons dominated by qg compton scattering
  - Sensitive to sign of Δg
- Negative solution disfavored at 2.8σ

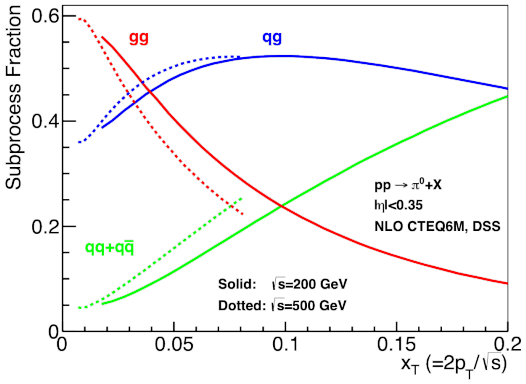
PRL130, 251901 (2023)

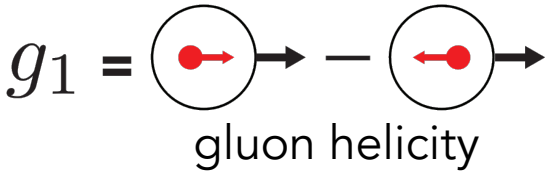




PRD105, 074022 (2022)

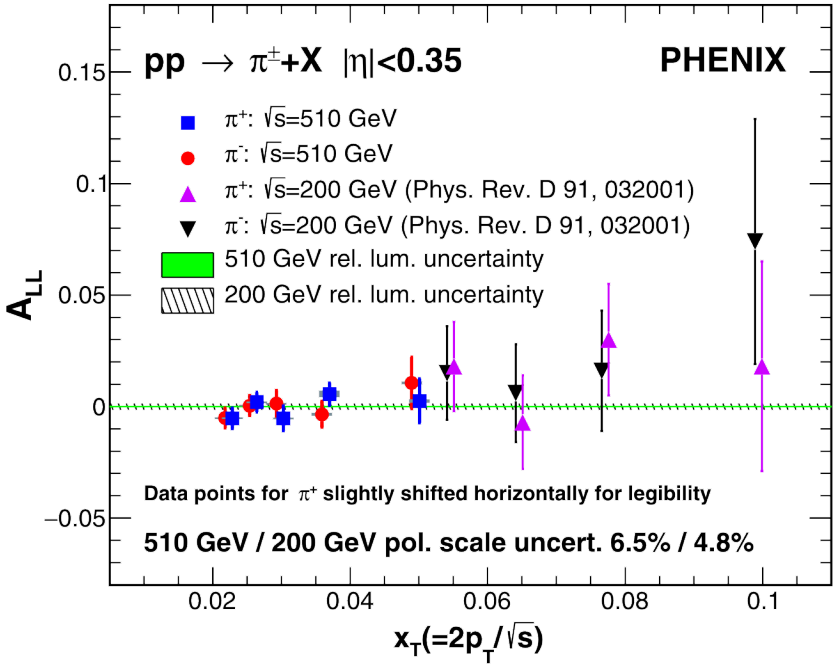
$\pi^{\pm}$ A_{LL}

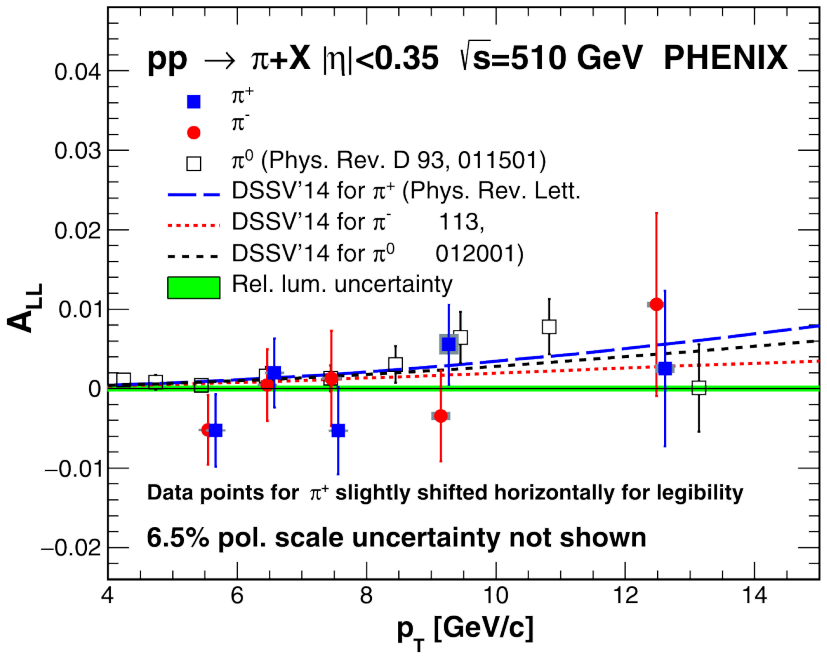


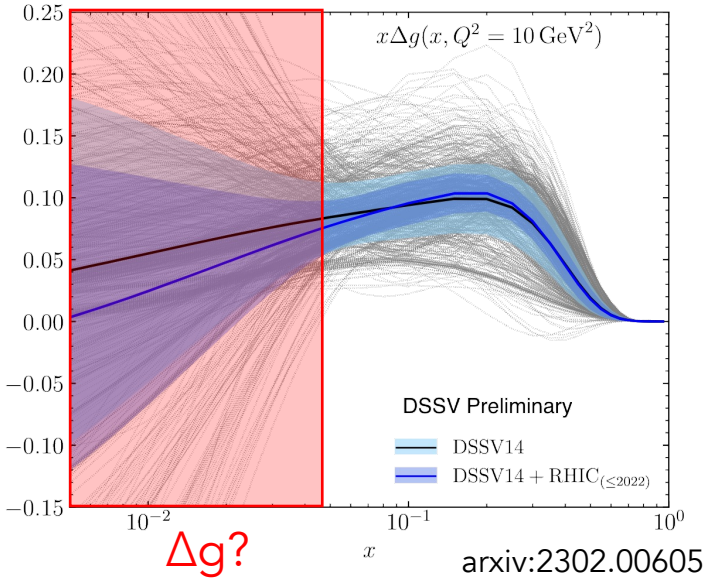


- Δg at x < 0.05 still largely unconstrained
- Charged pion A_{LL} at $\sqrt{s}$ = 510 GeV probes Δg down to low x
  - Consistent with DSSV predictions

PRD 102, 032001 (2020)

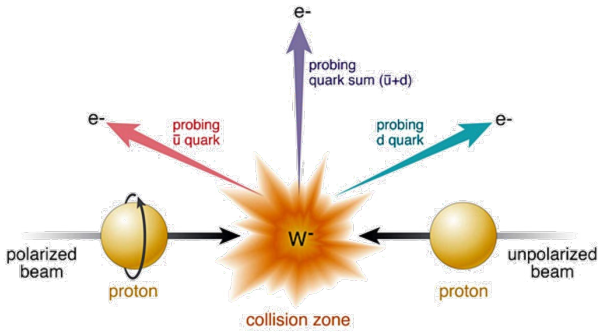






arxiv:2302.00605

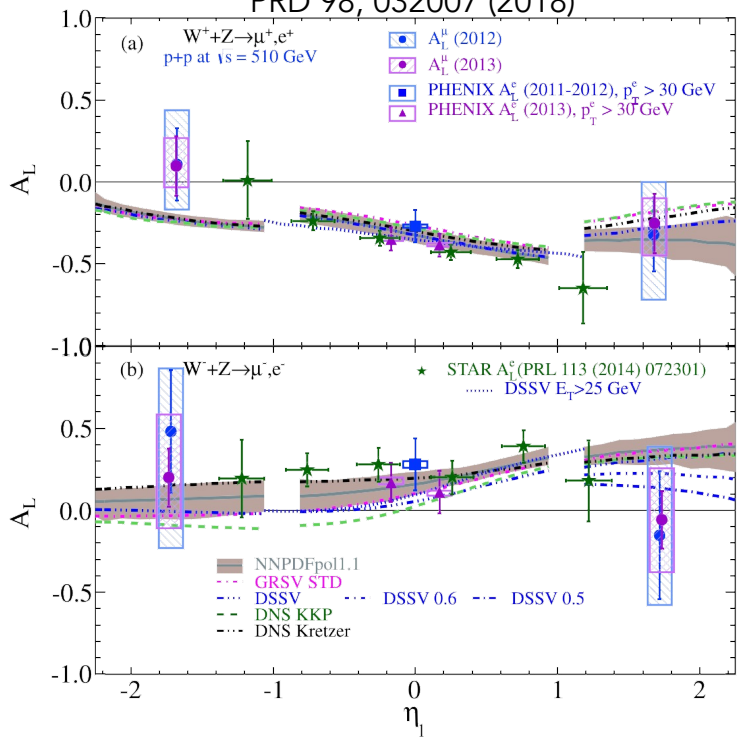
$W^{\pm} \rightarrow e^{\pm}, \mu^{\pm}$ A_L



g_1 = (anti-)quark helicity

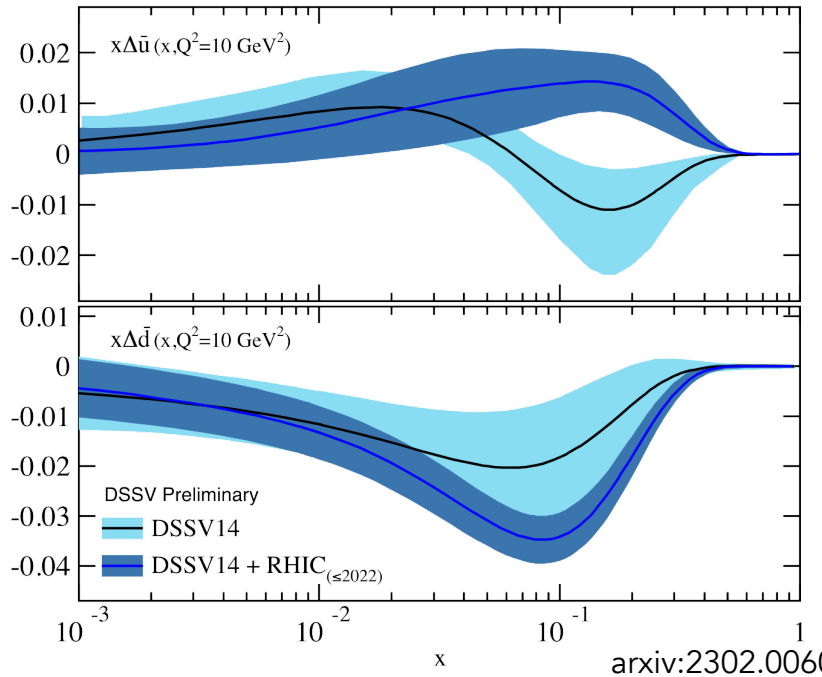
- Flavor separation of $\Delta\bar{q}$ through parity violating $u_L \bar{d}_R \rightarrow W^+ \quad d_L \bar{u}_R \rightarrow W^-$
- Longitudinal *single* spin asymmetry $A_L^{W^-} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2)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

PRD 98, 032007 (2018)



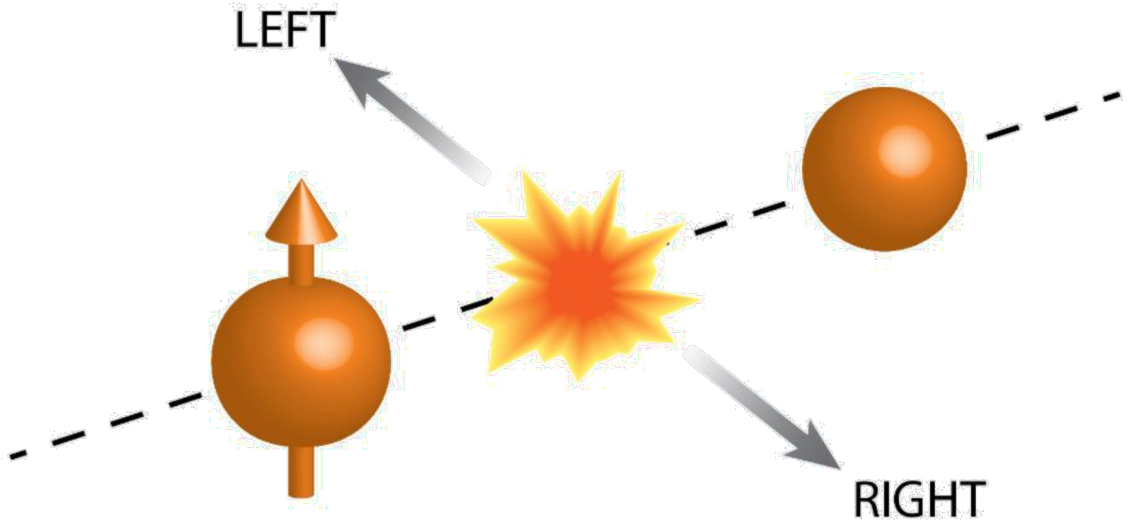
Indication of:
- positive $\bar{u}$ helicity
- negative $\bar{d}$ helicity

Polarized sea asymmetry *opposite* sign from unpolarized sea asymmetry



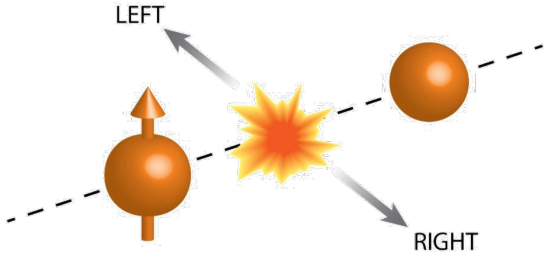
arxiv:2302.00605

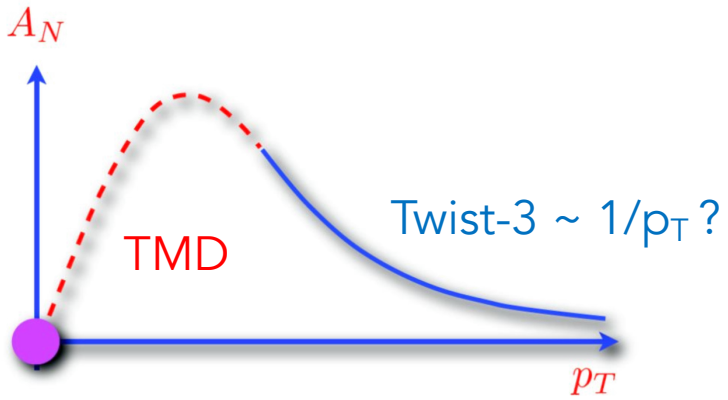
Transverse Spin

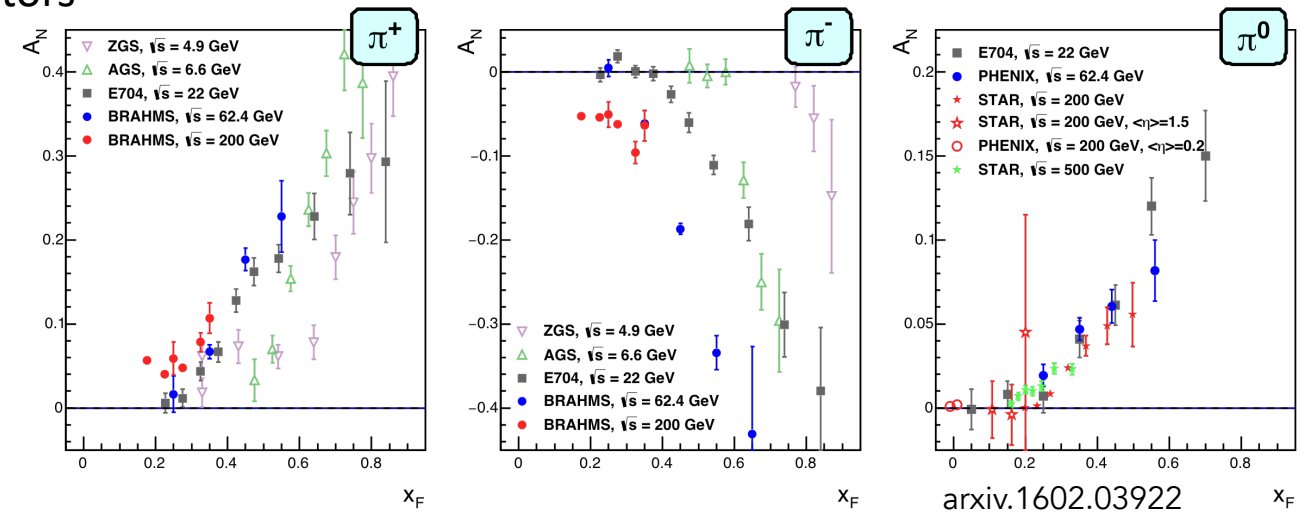


Transverse single spin asymmetries (A_N)

- 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

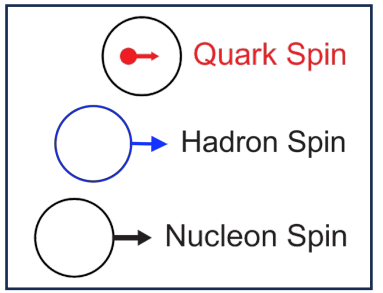






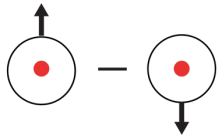
arXiv:1602.03922

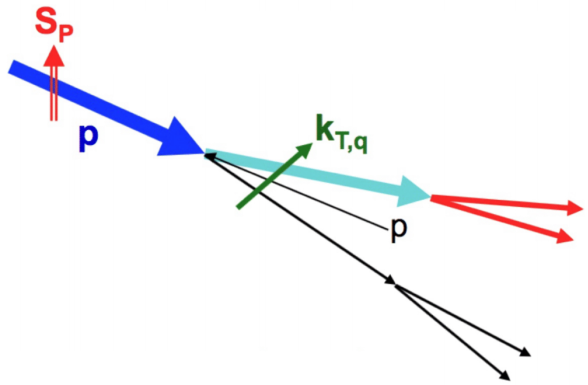
Mechanisms of A_N



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

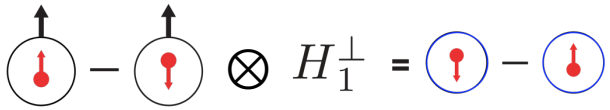
Sivers TMD PDF

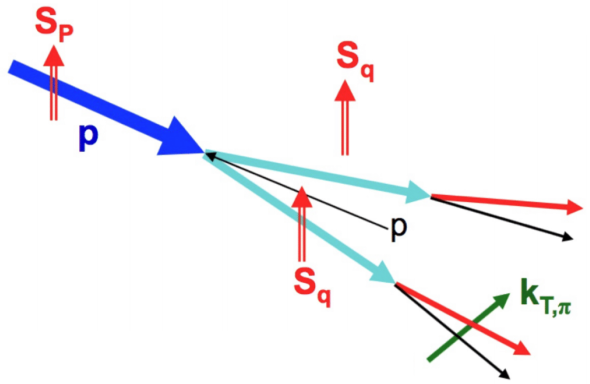
$f_{1T}^{\perp}$ = 



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

Transversity $\otimes$ Collins TMD FF

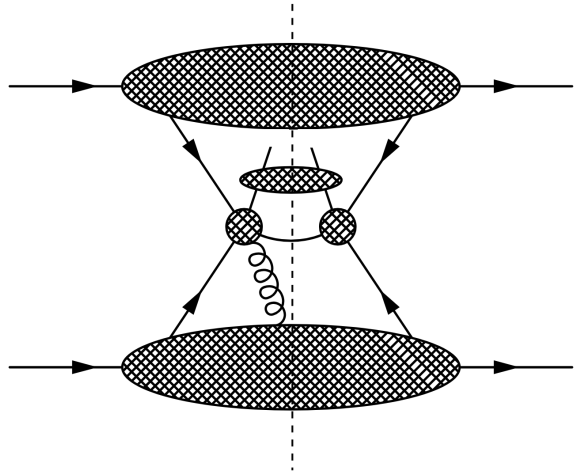
h_1 = 



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

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

Twist-3 multiparton correlators



Sivers-like correlator

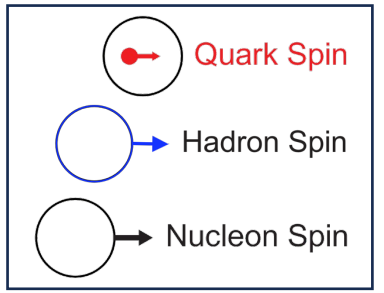
$$A_N \propto \sum_{a,b,c} \boxed{\phi_{a/A}^{(3)}(x_1, x_2, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{q/h}(z)$$

Transversity

Collins-like correlator

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

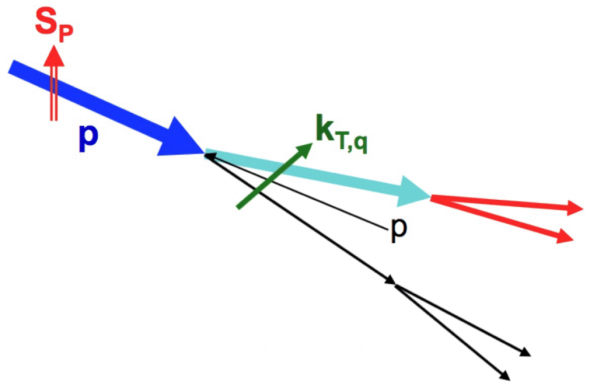
Mechanisms of A_N



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

Sivers TMD PDF

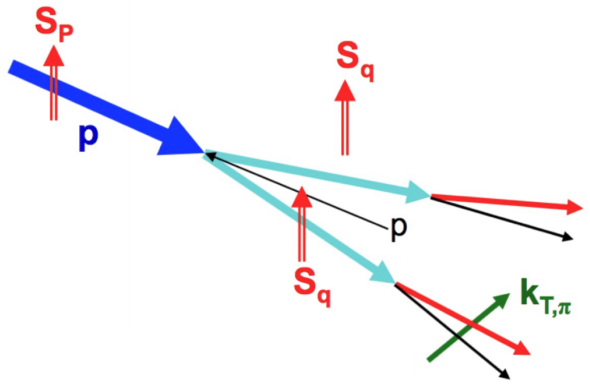
$f_{1T}^{\perp}$ = ⊙ − ⊙



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

Transversity ⊗ Collins TMD FF

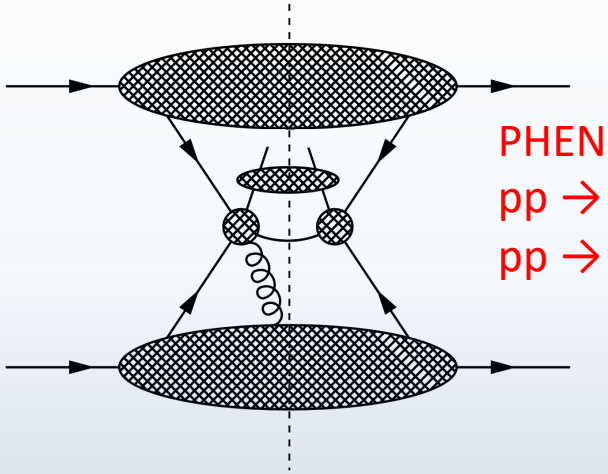
h_1 = ⊙ − ⊙ ⊗ $H_1^{\perp}$ = ⊙ − ⊙



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

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

Twist-3 multiparton correlators



PHENIX
pp → h + X
pp → γ + X

Sivers-like correlator

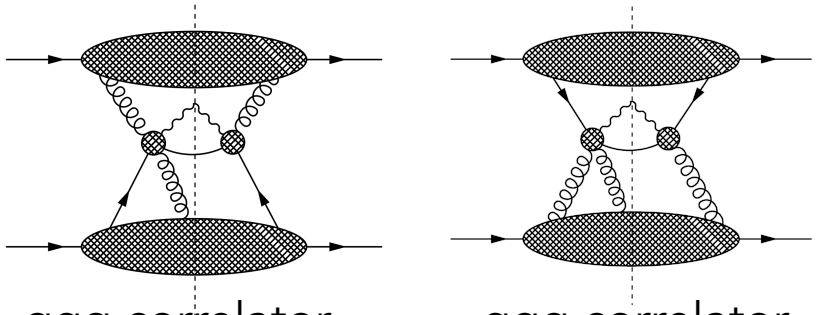
$$A_N \propto \sum_{a,b,c} \boxed{\phi_{a/A}^{(3)}(x_1, x_2, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{q/h}(z)$$

Transversity

Collins-like correlator

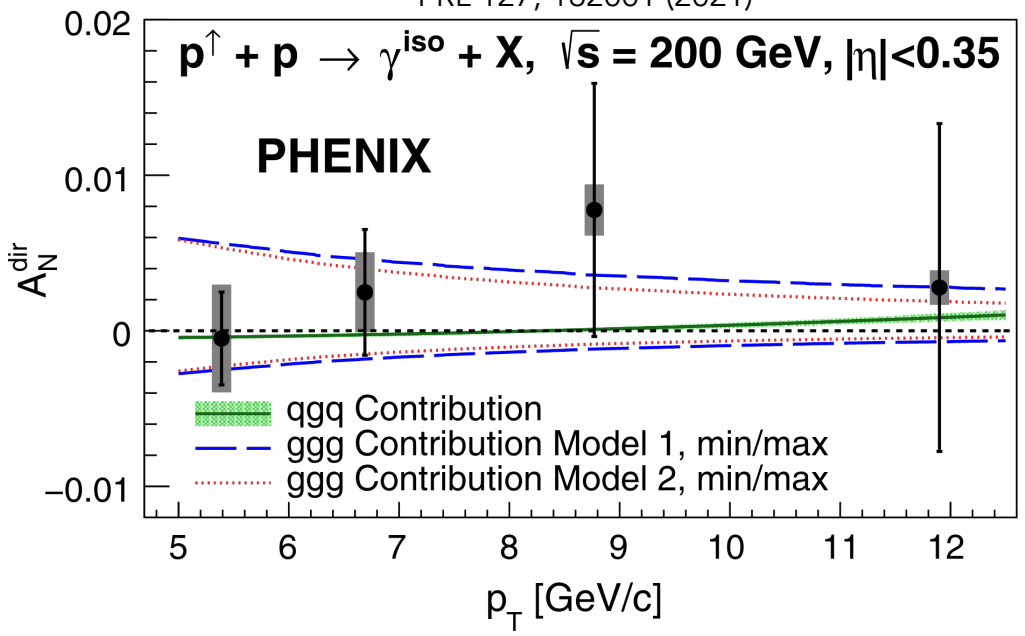
$$+ \sum_{a,b,c} \boxed{h_1(x, \vec{s_\perp})} \otimes \phi_{b/B}(x') \otimes \hat{\sigma'} \otimes \boxed{D_{q/h}^{(3)}(z_1, z_2)}$$

Direct photon A_N

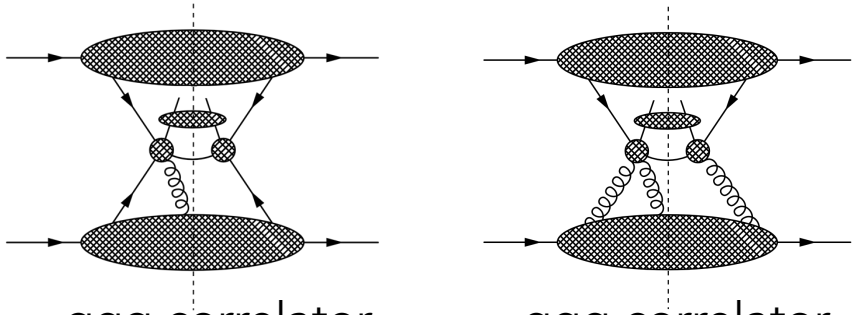


- Photon in final state → no final state color effects
  - Clean probe of initial state quark-gluon and trigluon correlation functions
- First direct photon A_N from RHIC → 50 times reduced uncertainties from Fermilab E704 PLB 345, 569 (1995)

PRL 127, 162001 (2021)

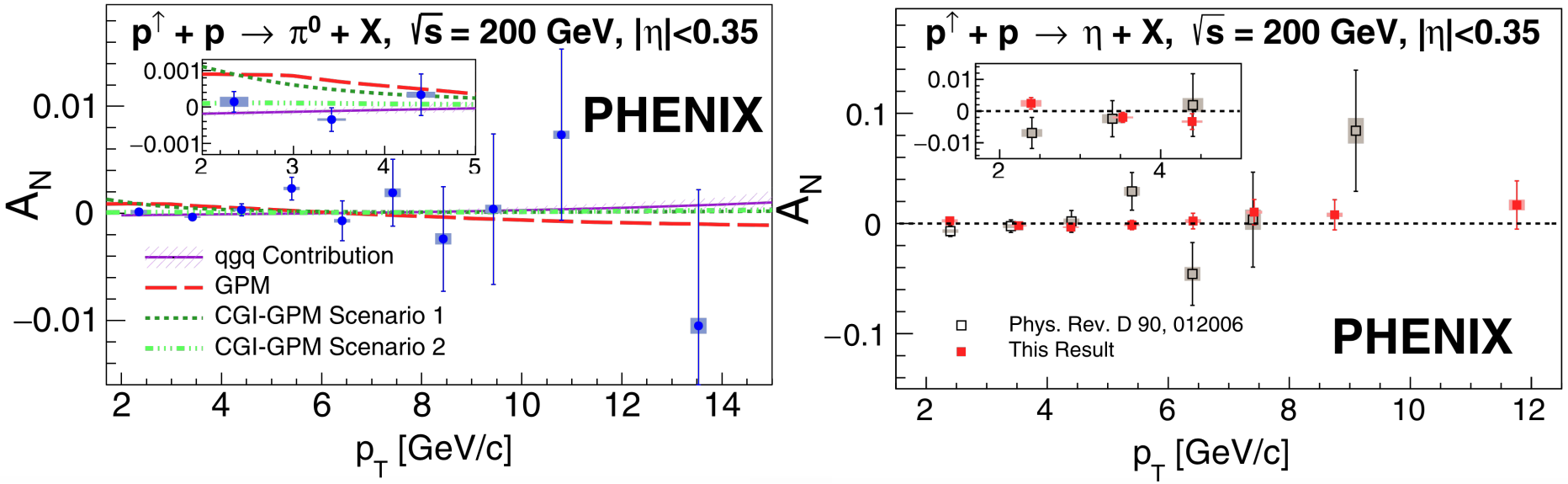


Midrapidity π^0, η A_N

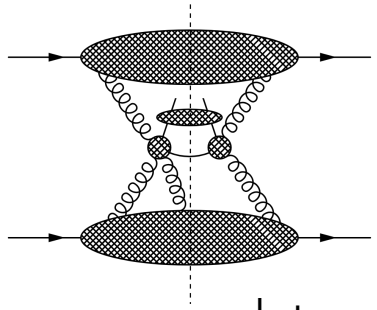


- Sensitive to gluon dynamics through quark-gluon and trigluon correlation functions
  - Used to constrain gluon Sivers TMD JHEP 1509 (2015), 119
- High precision measurement: consistent with zero to sub-percent level

PRD 103, 052009 (2021)



Midrapidity open heavy flavor A_N

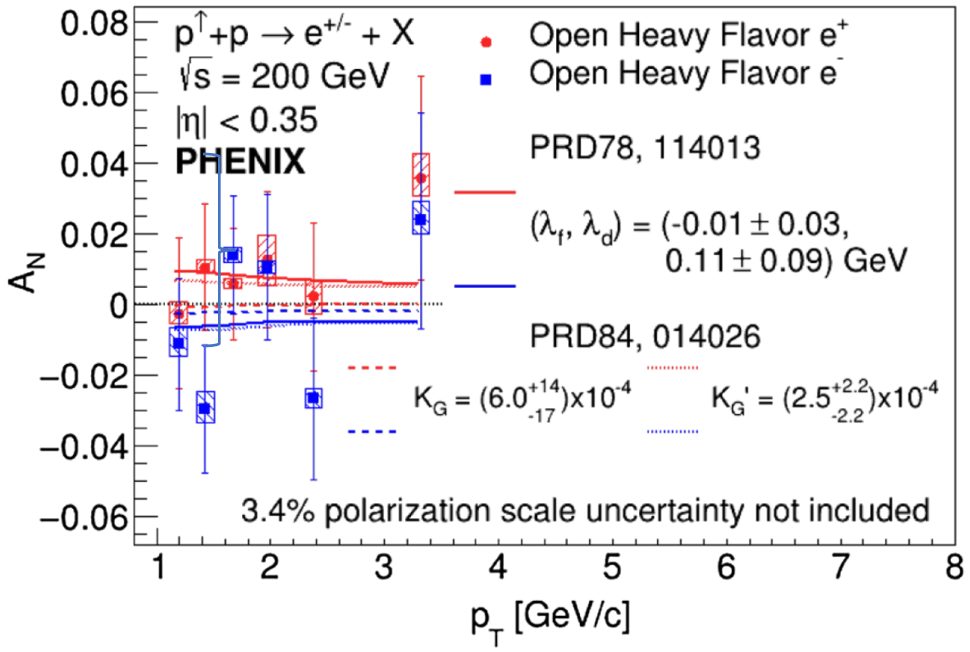


- ❑ Gluon-gluon fusion ✓
- ❑ Zero gluon transversity in spin ½ nucleons ✓

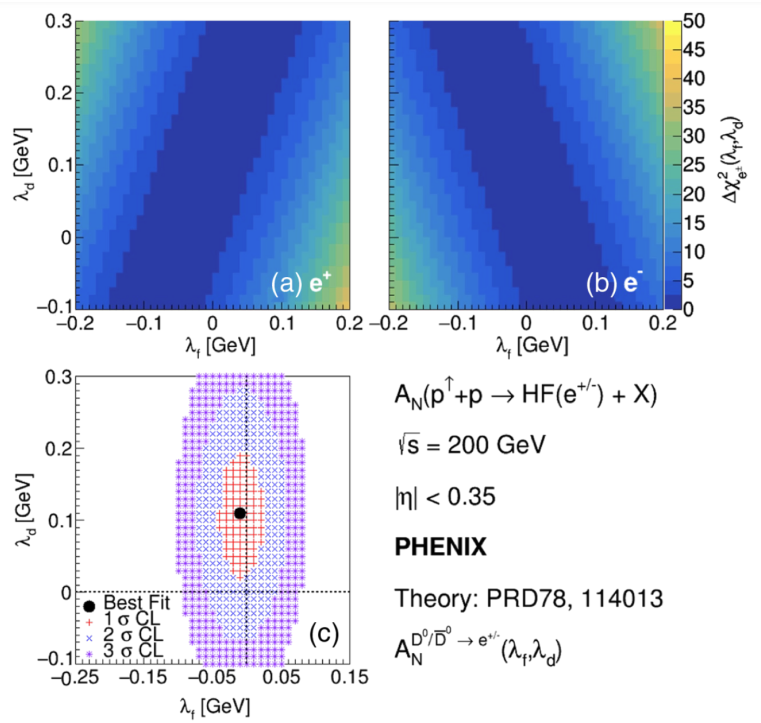
Direct sensitivity to initial-state trigluon correlator

- ❑ First constraints on phenomenological trigluon parameters λ, K_G

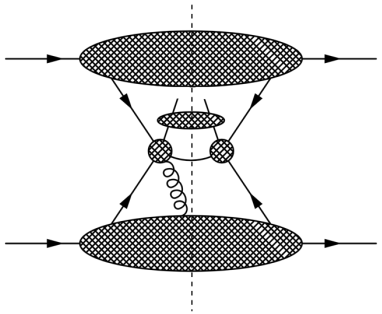
PRD 107, 052012 (2023)



PRD 107, 052012 (2023)



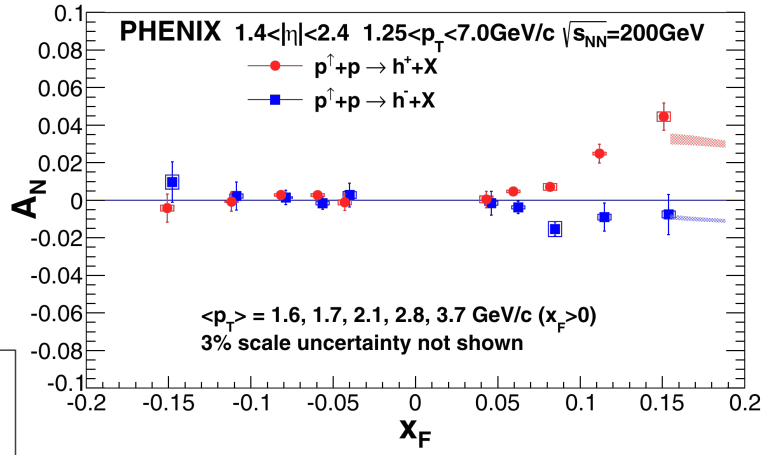
Forward $h^{\pm}$, η A_N

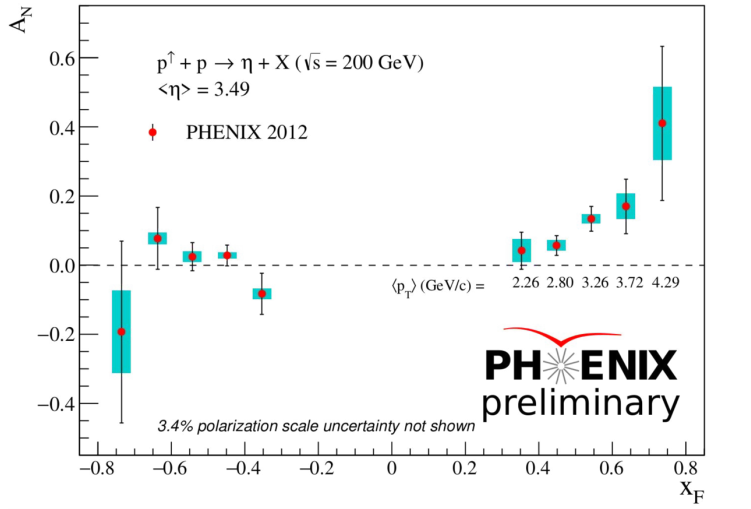


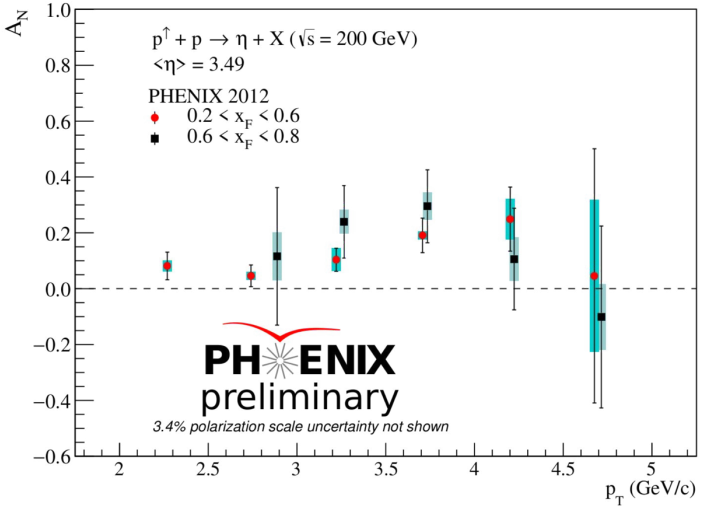
qgq correlator

- 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 $x_F > 0.6$?

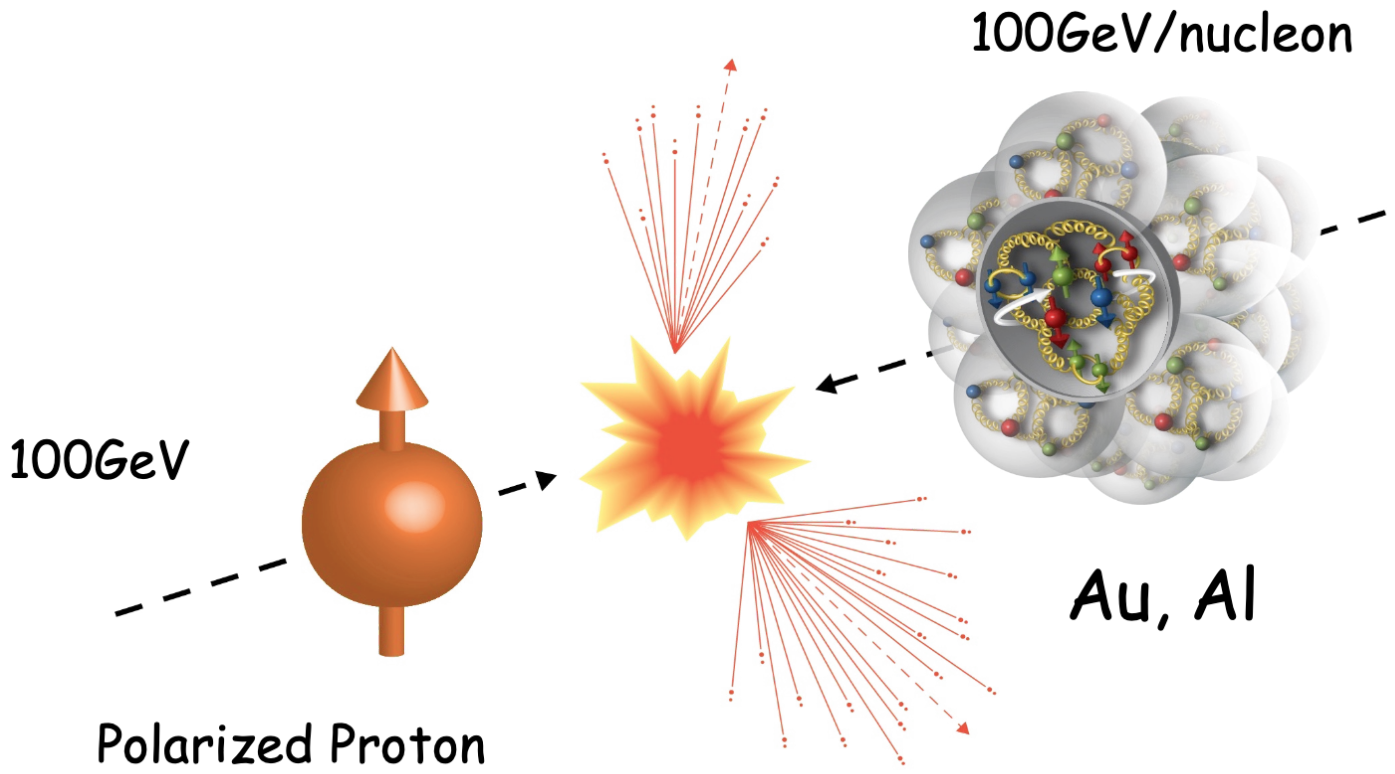
PRD 108, 072016 (2023)





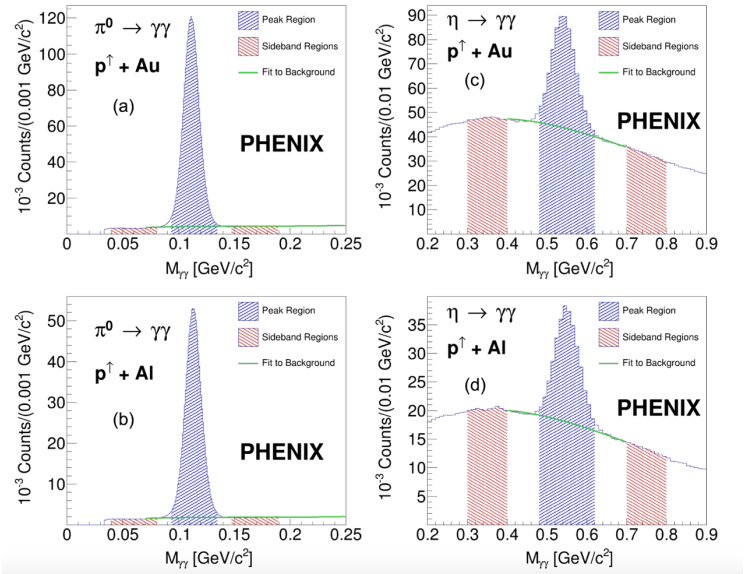


$p^{\uparrow} + A$

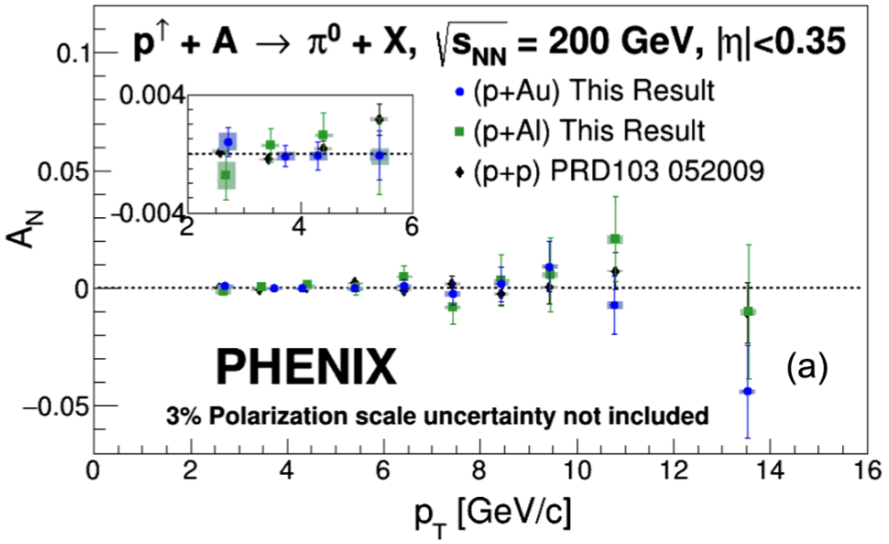


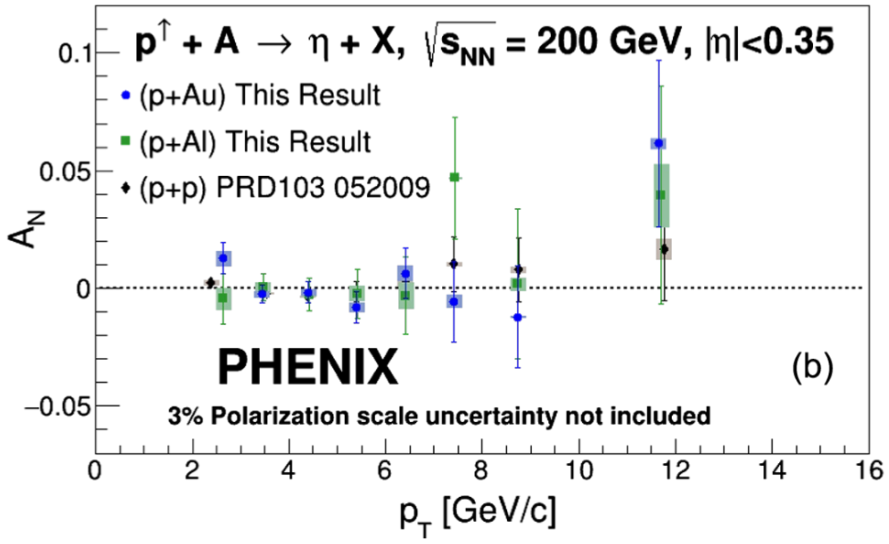
Midrapidity π^0, η A_N

- 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)

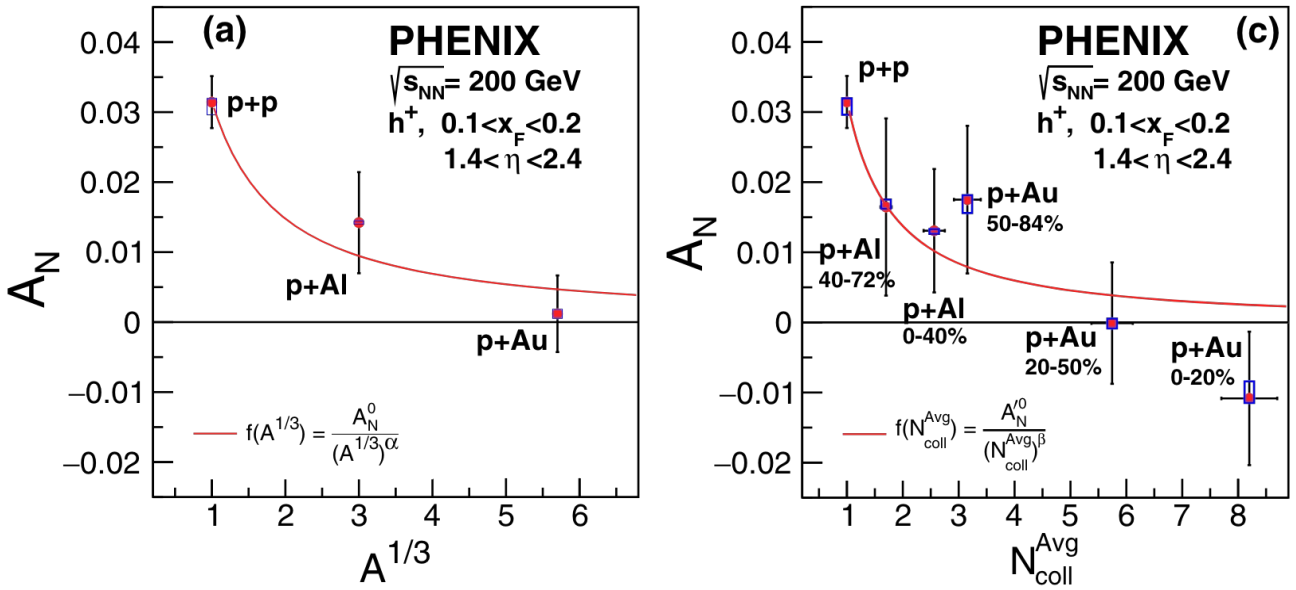




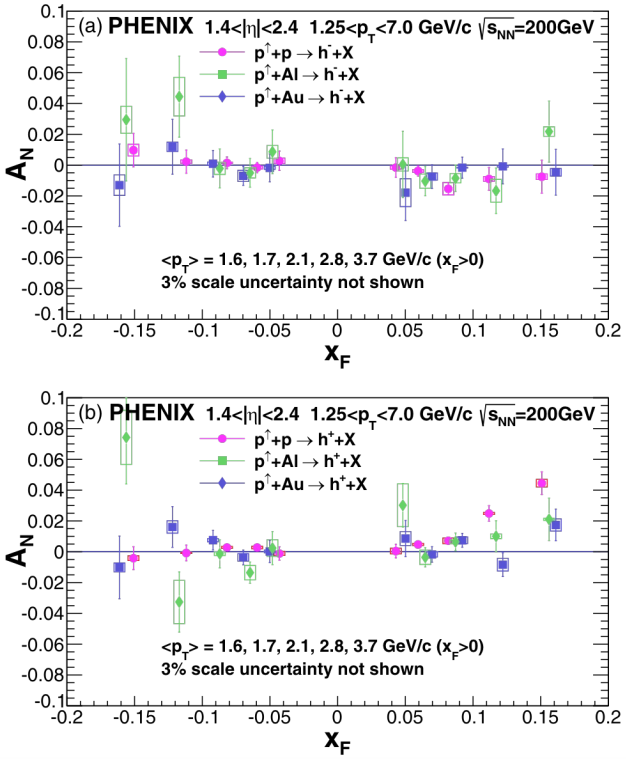
Forward $h^{\pm}$ A_N

- Striking dependence of A_N on 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)



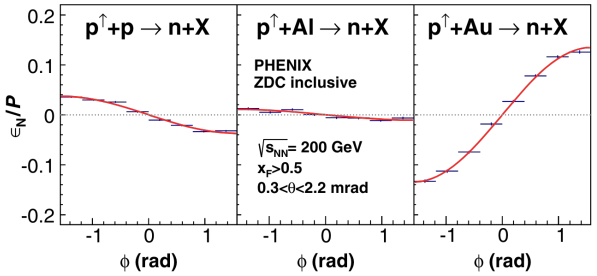
PRD 108, 072016 (2023)

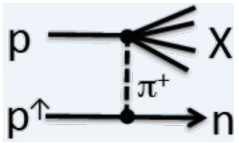


Far forward neutron A_N

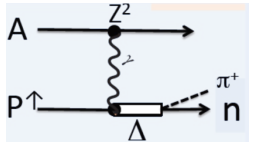
- Negative A_N in far forward neutrons from p+p well described by one pion exchange (OPE) model
- Initially unexpected large dependence on *A* (+ sign change)
  - Additional contribution from ultra-peripheral collisions (UPC) qualitatively describes data

PRL 120, 022001 (2018)

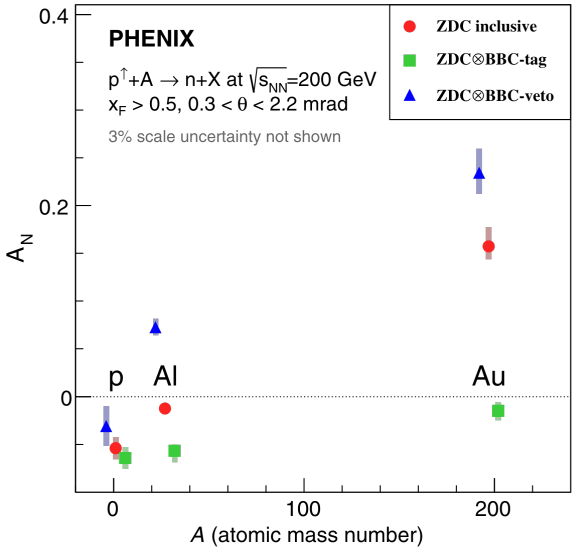




OPE

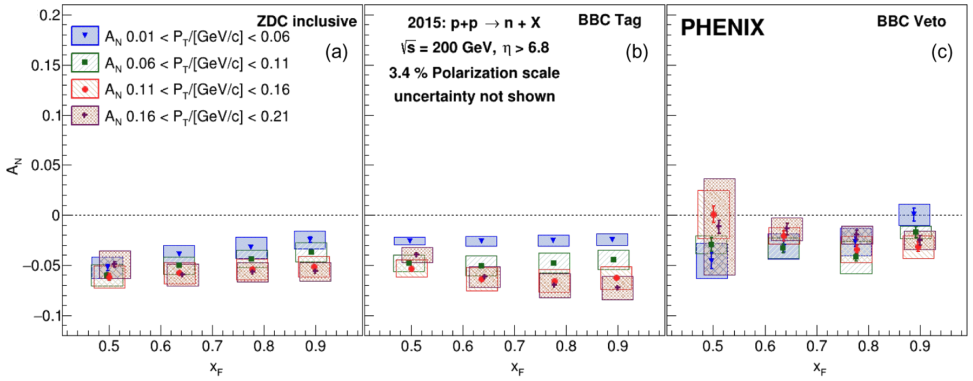


UPC



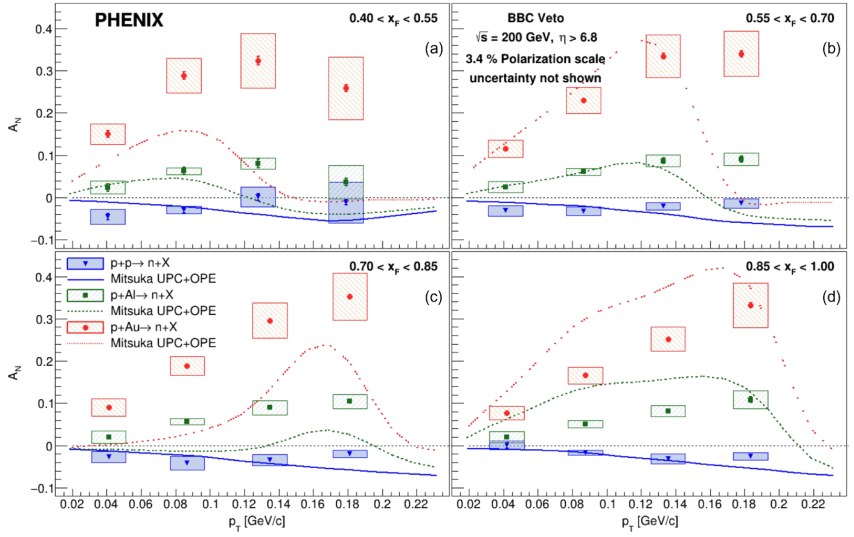
Weak x_F dependence

PRD 105, 032004 (2022)



Increasing with p_T

PRD 105, 032004 (2022)



Summary

- After 20 years 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 will investigate Δg at low-x:
    - Midrapidity η A_{LL} 510 GeV
    - Forward rapidity cluster A_{LL} 510 GeV
- More interesting RHIC spin physics on the way
  - STAR Forward Upgrade
  - First sPHENIX spin data

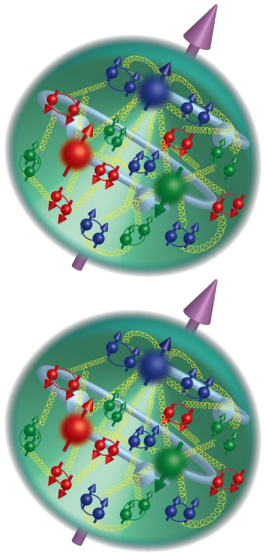
Backup

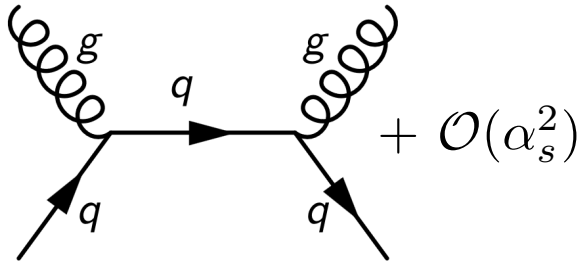
Collinear QCD Factorization

- Mechanism needed to split the non-perturbative long-distance physics from the perturbative short-distance physics
- QCD factorization proven to hold for a vast array of processes in collinear, leading twist limit

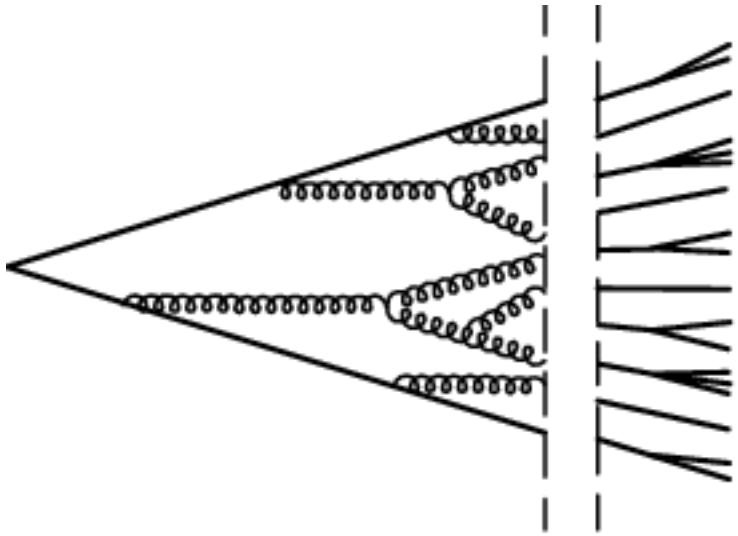
$$d\sigma \propto \sum f_a(x_a) \otimes f_b(x_b) \otimes d\sigma^{ab\to cX} \otimes D_c^h(z_c)$$

Parton distribution functions





Fragmentation functions



Beyond leading twist collinear factorization

Transverse Momentum Dependent factorization

- Transverse momentum dependent (TMD) distributions
  - Nonperturbative transverse momentum dependence in the leading twist PDFs or FFs
  - TMD PDFs: spin-momentum correlation of initial-state proton and constituent parton
  - TMD FFs: spin-momentum correlation of final-state hadron and fragmenting parton

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

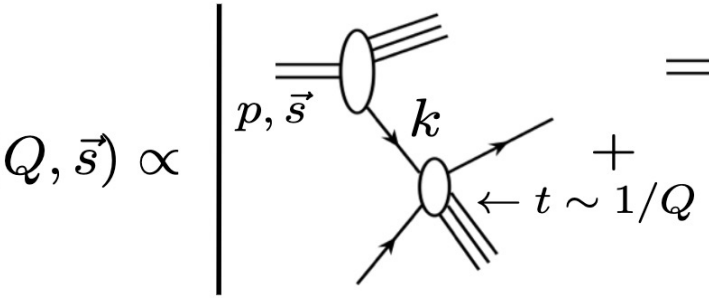
	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons	D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons: L		G_1 = Helicity	$H_{1L}^\perp$
Polarized Hadrons: T	$D_{1T}^\perp$ = Polarizing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

Beyond leading twist collinear factorization

Higher twist collinear factorization

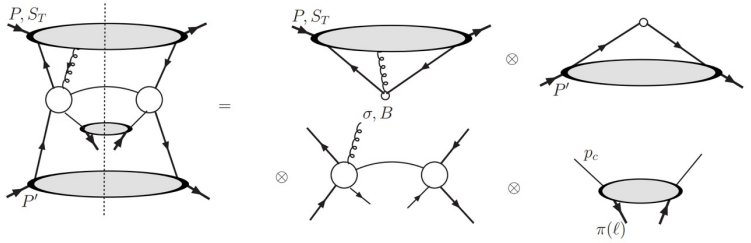
- Twist 3 collinear multiparton correlators
  - Higher order term in the 1/Q expansion of the cross section
  - Interpretation: interference between a single parton state and a two-parton composite state

$$\sigma(Q,\vec{s}) \propto \left| \quad + \quad + \quad + \cdots \right|^2$$



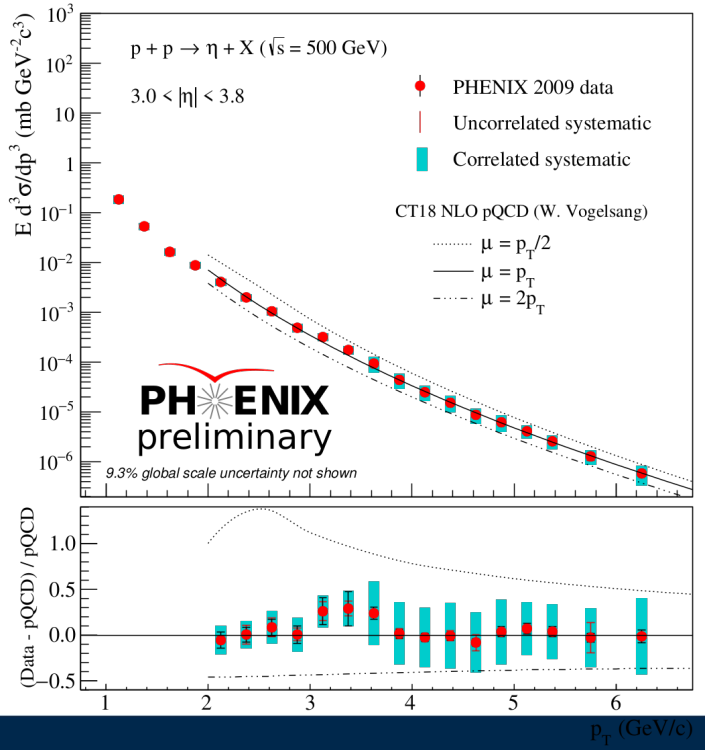
$$\sigma(Q,\vec{s}) = \sigma_0 \otimes f_2 \otimes f_2 + (1/Q)\sigma_1 \otimes f_2 \otimes f_3 + (1/Q^2)$$

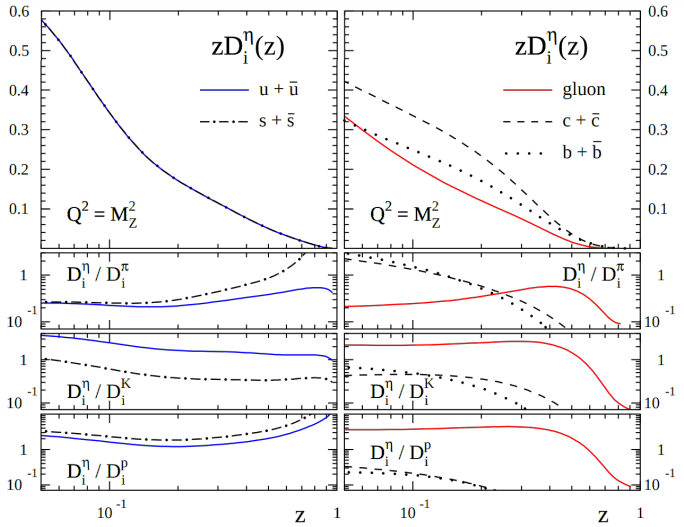
Twist-3 ETQS (qgq) function



Preliminary forward η meson cross section 500 GeV

- First measurement of η 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 η meson fragmentation functions





PRD. 83 034002 (2011)

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

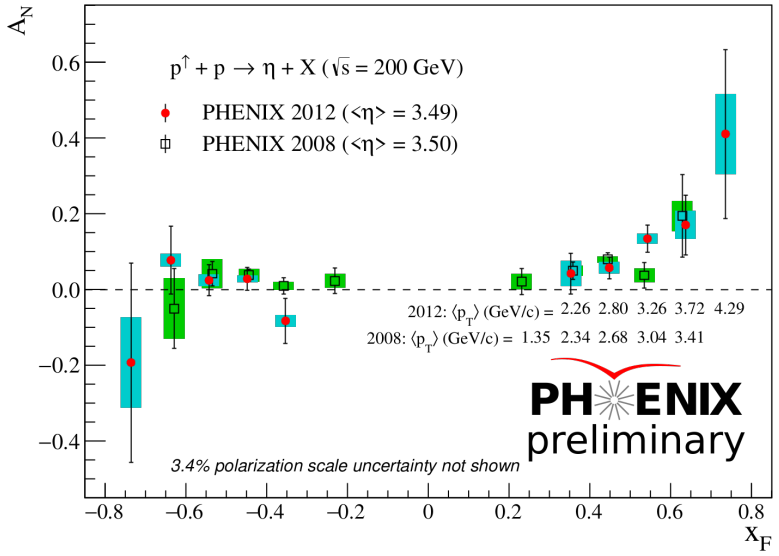
$$\delta D^{\eta}_{g} = \pm 15\%$$

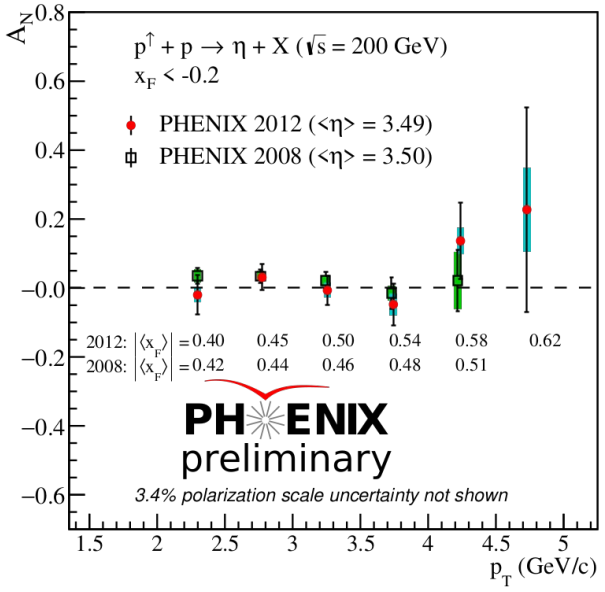
Potential inputs for an updated η analysis

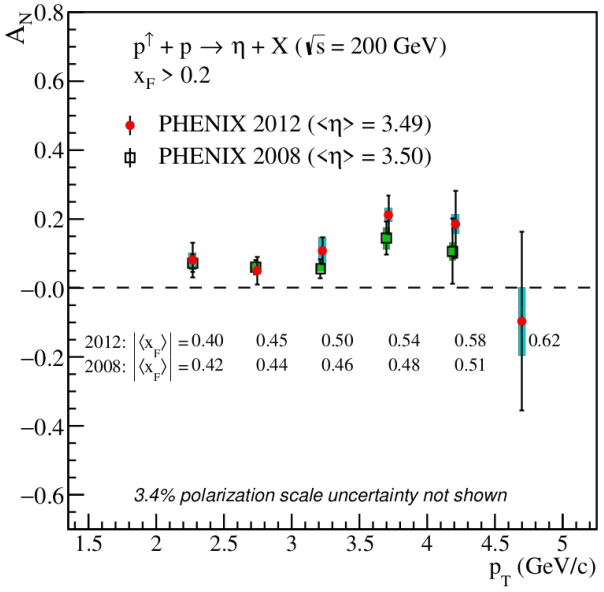
Experiment	*Observable*	$\sqrt{s}$ *(TeV)*	*Pseudorapidity*	
PHENIX	$d\sigma_{pp\to\eta X}$	0.2	Forward	PRD 90 072008 (2014)
PHENIX	$d\sigma_{pp\to\eta X}$	0.5	Forward	
PHENIX	$d\sigma_{pp\to\eta X}$	0.2	Midrapidity	PRD 83 032001 (2011)
PHENIX	$d\sigma_{pp\to\eta X}$	0.51	Midrapidity	In progress
ALICE	$d\sigma_{pp\to\eta X}$	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	η/π^0	0.2	Midrapidity	PRC 81 064904 (2010)

Preliminary Run12 forward η 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







History of forward η meson TSSA

- $p^{\uparrow} + p \rightarrow h + X$ at forward rapidity accesses high x_F region where large nonzero asymmetries have been measured → probe of twist-3 ETQS qgq correlator
- Recent phenomenological work suggests that A_N for inclusive pions mostly due to Collins-like twist-3 fragmentation term [PRD 89, 111501(R) (2014)]
- Comparing to forward π^0 A_N can highlight potential contribution from strange quarks