

Spin asymmetries and cross sections of η mesons at PHENIX

Devon Loomis, for the PHENIX collaboration



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Outline

1. Introduction
2. PHENIX experiment overview
3. Cross section results
4. Transverse single spin asymmetry results
5. Prospects for the longitudinal double spin asymmetry

η meson production at PHENIX

❑ Why η mesons at PHENIX?

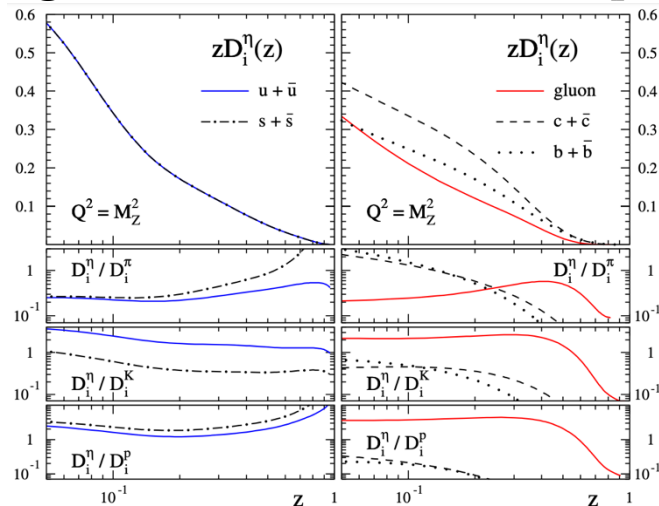
❑ Highest p_T reach of any inclusive measurement at PHENIX

❑ Only reconstructible meson at PHENIX forward rapidity ($\eta > 3$) when $\sqrt{s} \gtrsim 200$ GeV

❑ By comparing to related π^0 observables, natural way to test potential impact of strange quark content on (spin-dependent) fragmentation

❑ Only one available global η meson fragmentation function fit [PRD 83 034002 (2011)]

❑ Large uncertainties on flavor-separated quark (20%) and gluon (15%) fragmentation



New inputs for updated η FF fit

Experiment	Observable	\sqrt{s} (GeV)
PHENIX	$d\sigma_{pp \rightarrow \eta X}$ (Forward)	200
PHENIX	$d\sigma_{pp \rightarrow \eta X}$ (Forward)	500
PHENIX	$d\sigma_{pp \rightarrow \eta X}$	200
PHENIX	$d\sigma_{pp \rightarrow \eta X}$	510
ALICE	$d\sigma_{pp \rightarrow \eta X}$	2760
ALICE	$d\sigma_{pp \rightarrow \eta X}$	7000
ALICE	$d\sigma_{pp \rightarrow \eta X}$	8000
STAR	η/π^0	0.2
BELLE	$d\sigma_{e^+e^- \rightarrow \eta X}$	10.58

PRD 90 072008 (2014)

This analysis

PRD 83 032001 (2011)

This analysis

Eur. Phys. J.C (2017) 77:339

Phys. Lett. B717 (2012) 162

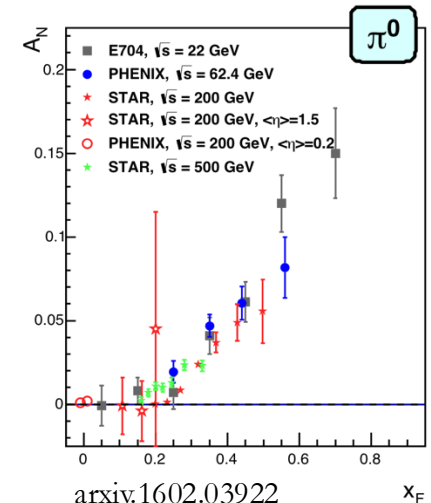
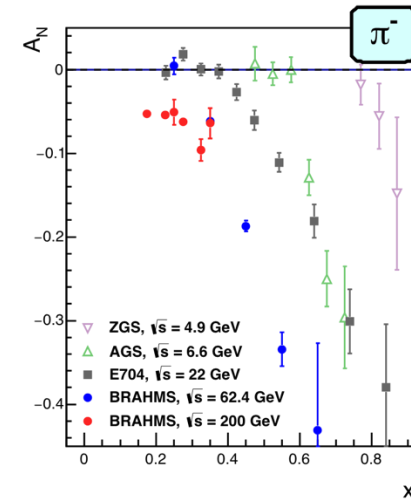
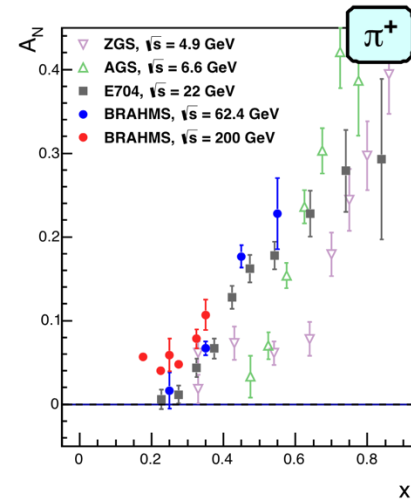
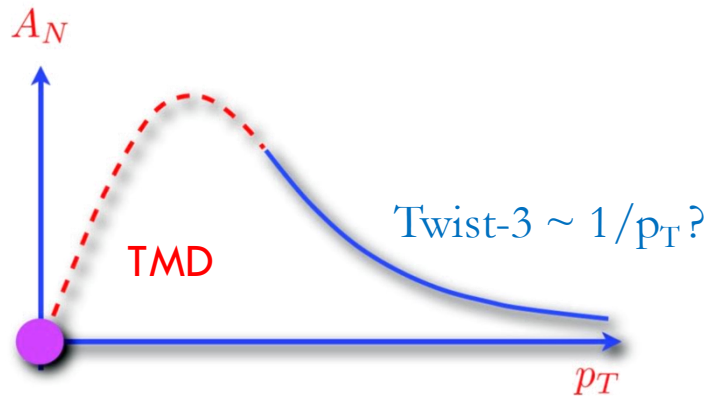
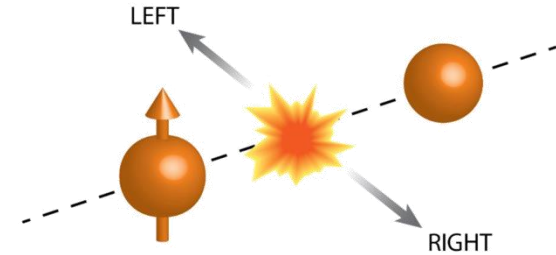
Eur. Phys. J.C (2018) 78:263

PRC 81 064904 (2010)

PRD 111 052003 (2025)

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



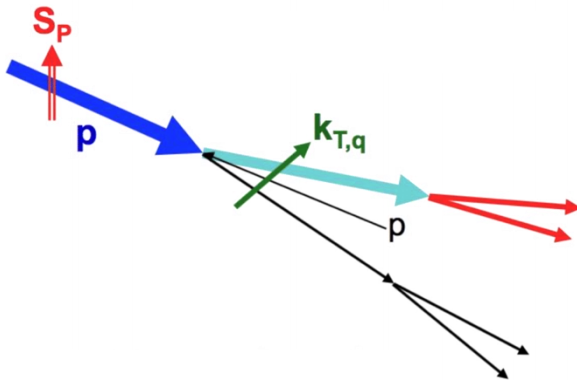
arxiv.1602.03922

Generation of a TSSA

$$Q \gg k_T \gtrsim \Lambda_{\text{QCD}}$$

Sivers TMD PDF

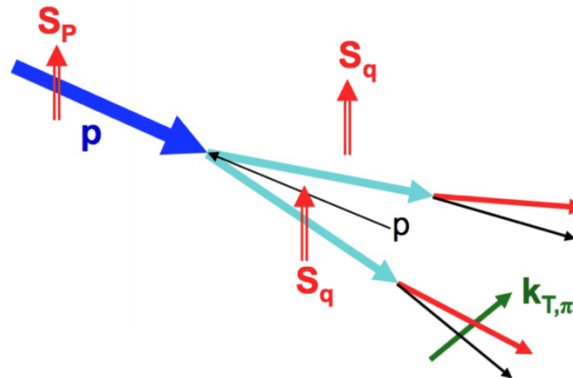
$$f_{1T}^\perp = \begin{array}{c} \uparrow \\ \circ \end{array} - \begin{array}{c} \downarrow \\ \circ \end{array}$$



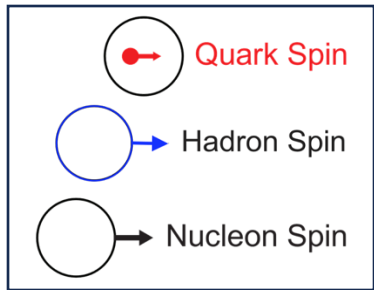
$$A_N \propto f_{1T}^\perp(x, k_T^2) \cdot D_q^h(z)$$

Transversity \otimes Collins TMD FF

$$h_1 = \begin{array}{c} \uparrow \\ \circ \end{array} - \begin{array}{c} \downarrow \\ \circ \end{array} \otimes H_1^\perp = \begin{array}{c} \circ \end{array} - \begin{array}{c} \circ \end{array}$$

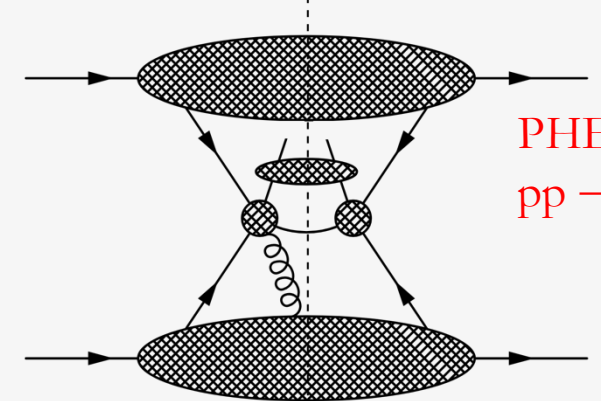


$$A_N \propto h_1(x) \cdot H_1^\perp(z, k_T^2)$$



$$Q, k_T \gg \Lambda_{\text{QCD}}$$

Twist-3 multiparton correlators

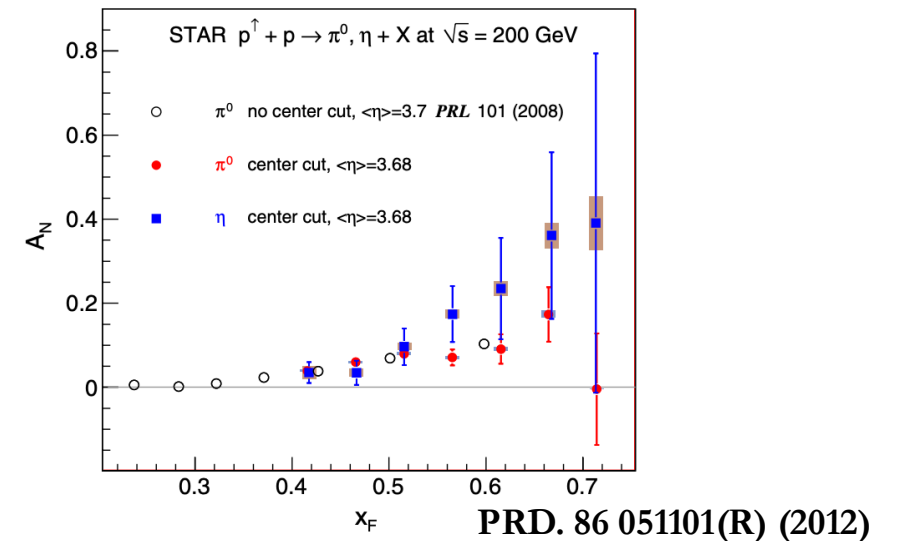
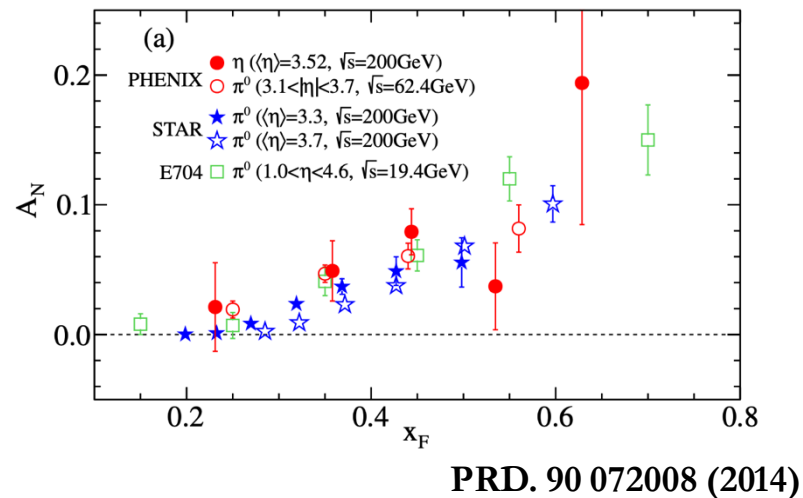


PHENIX
 $pp \rightarrow \eta + X$

$$A_N \propto \sum_{a,b,c} \underbrace{\phi_{a/A}^{(3)}(x_1, x_2, \vec{s}_\perp)}_{\text{Sivers-like correlator}} \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{q/h}(z) + \sum_{a,b,c} \underbrace{h_1(x, \vec{s}_\perp)}_{\text{Transversity}} \otimes \phi_{b/B}(x') \otimes \hat{\sigma}' \otimes \underbrace{D_{q/h}^{(3)}(z_1, z_2)}_{\text{Collins-like correlator}}$$

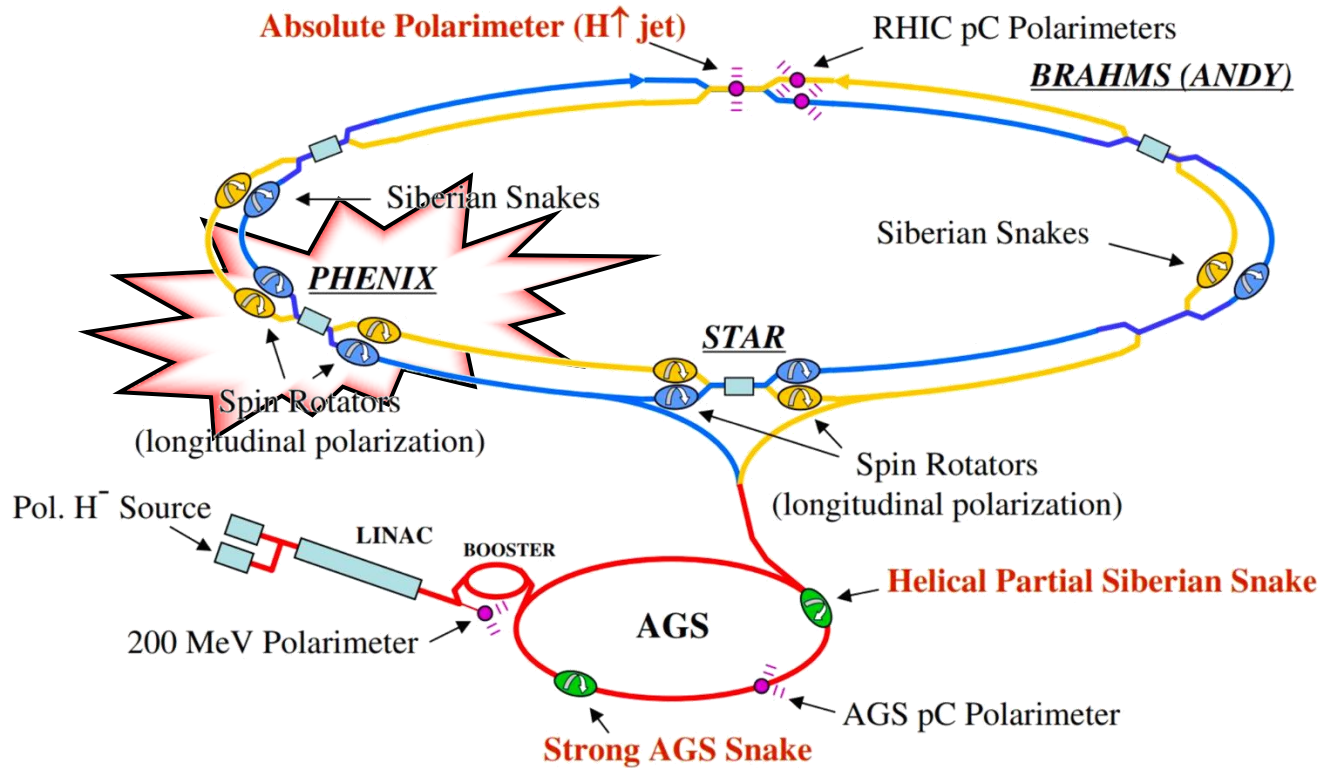
The forward η meson TSSA

- ❑ At forward rapidity, $p^\uparrow + p \rightarrow \eta + X$ accesses high x_F region where large asymmetries have previously been measured
 - ❑ Mostly valence quark interactions \rightarrow probe of twist-3 qgq multiparton correlator
 - ❑ Still trying to disentangle initial- and final-state contributions
 - ❑ Recent phenomenological work suggests the TSSA for inclusive light mesons is dominated by final-state Collins-like correlator [PRD 89, 111501(R) (2014)]
- ❑ Potential hint of difference in TSSA between η and π^0 ?



Polarized physics at PHENIX

Relativistic Heavy Ion Collider (RHIC)

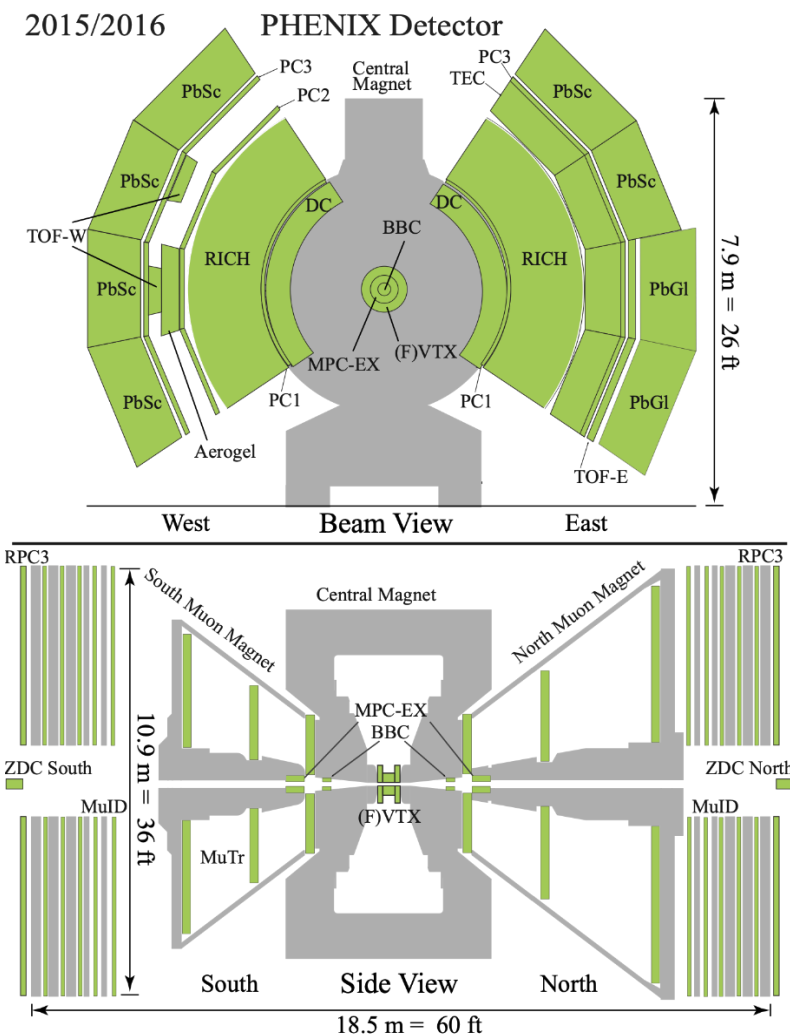


RHIC is the only collider in the world that can provide high energy polarized proton beams

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

PHENIX detector

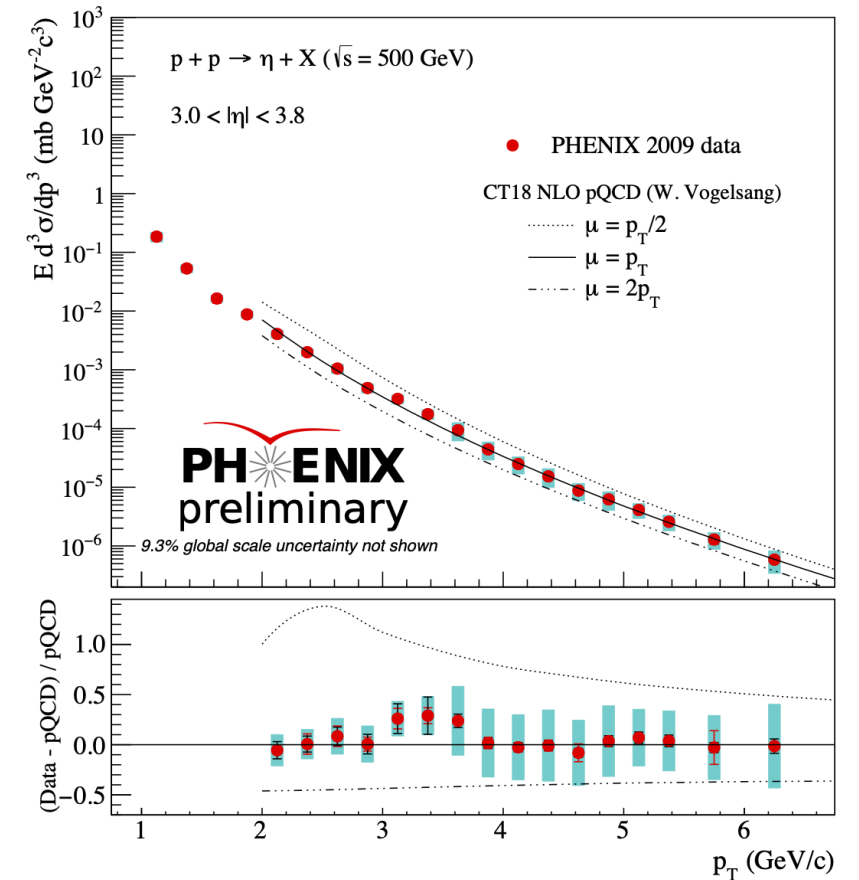
- ❑ Central arms - $|\eta| < 0.35$, $\pi/2$ azimuthal coverage per arm
 - ❑ Highly segmented PbSc and PbGl EMCal (e, γ)
 - ❑ Gas Ring Imaging Cherenkov Detector (RICH) (e, π, K PID)
 - ❑ Drift/Pad chambers
- ❑ Muon arms - $1.2 < |\eta| < 2.4$
 - ❑ Muon ID
 - ❑ Muon Tracker
- ❑ Forward - $3.1 < |\eta| < 3.9$
 - ❑ 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)



The η meson cross section

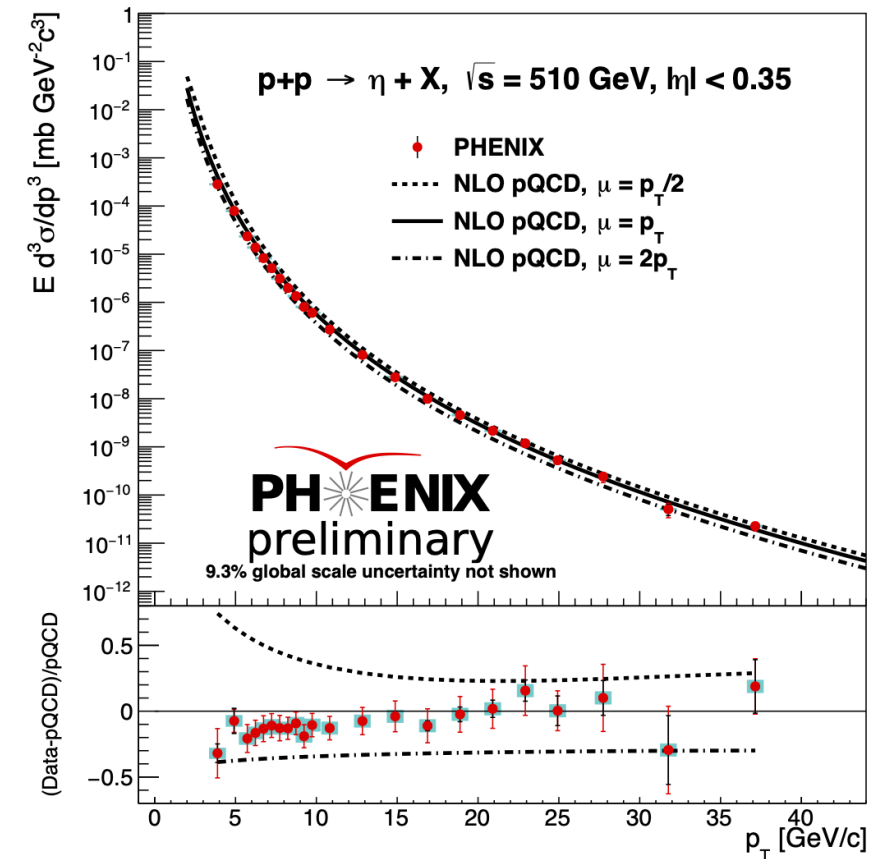
The forward η meson cross section at 500 GeV

- ❑ First forward ($3.0 < |\eta| < 3.8$) η meson cross section at 500 GeV
- ❑ Reconstructed $\eta \rightarrow \gamma\gamma$ through photon energy deposition in the forward Muon Piston Calorimeter
- ❑ Minimum bias conditions for low- p_T η mesons
- ❑ Dedicated high energy photon trigger for high- p_T η production ($p_T > 3.5$ GeV)
- ❑ Sampled integrated luminosity $\mathcal{L} = 9.26 \text{ pb}^{-1}$
- ❑ NLO pQCD calculations using CT18 PDFs and AESSS η meson fragmentation functions consistent with data



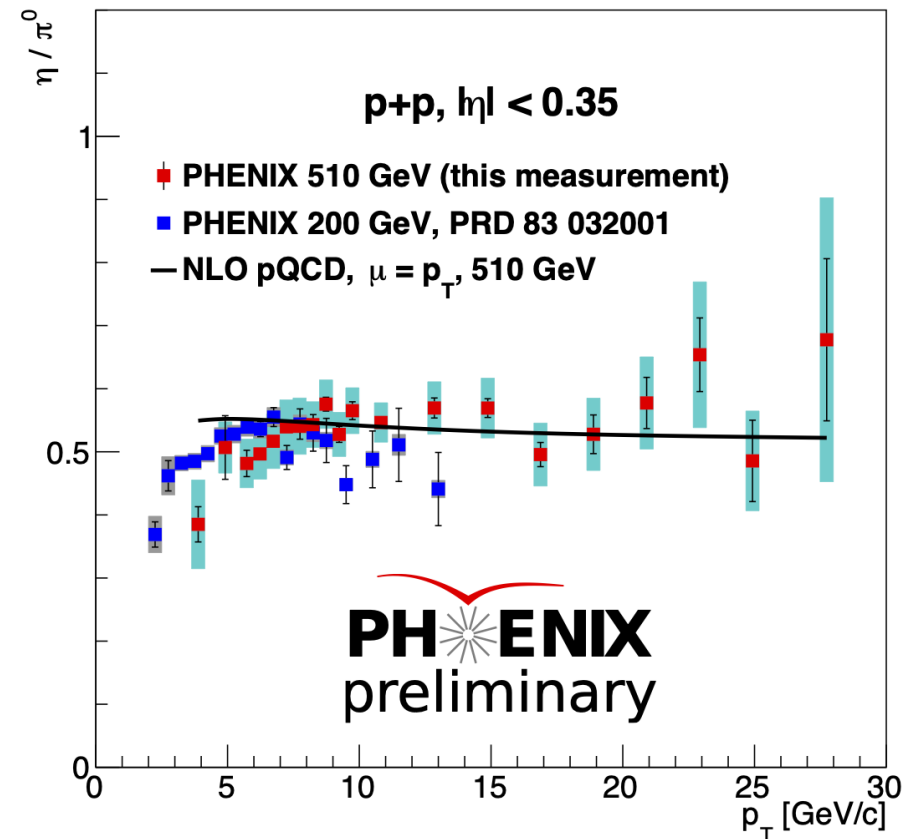
The central η meson cross section at 510 GeV

- ❑ First central ($|\eta| < 0.35$) η meson cross section at 510 GeV
- ❑ Reconstructed $\eta \rightarrow \gamma\gamma$ through photon energy deposition in central EMCal
- ❑ Sampled integrated luminosity $\mathcal{L} = 114 \text{ pb}^{-1}$
- ❑ NLO pQCD calculations using CT18 PDFs and AESSS η meson fragmentation functions consistent with data at high $p_T > 12 \text{ GeV}/c$
- ❑ Theory appears to systematically overestimate the cross section at low p_T by 10-20%



The η/π^0 ratio at 510 GeV

- ❑ Powerful input to fragmentation functions as many experimental systematics cancel
- ❑ Theoretically calculated ratio is largely independent of factorization scale
- ❑ NLO pQCD calculations describe reasonably well the high p_T behavior of the ratio
- ❑ Below 8 GeV/c, the theory prediction does not capture the shape of the ratio, in particular failing to describe the decrease seen in both the 510 GeV and 200 GeV results
- ❑ Interesting to note that the theory calculations of the η cross section begin to show disagreement at $p_T < 12$ GeV/c while ratio agrees down to $p_T \sim 8$ GeV/c



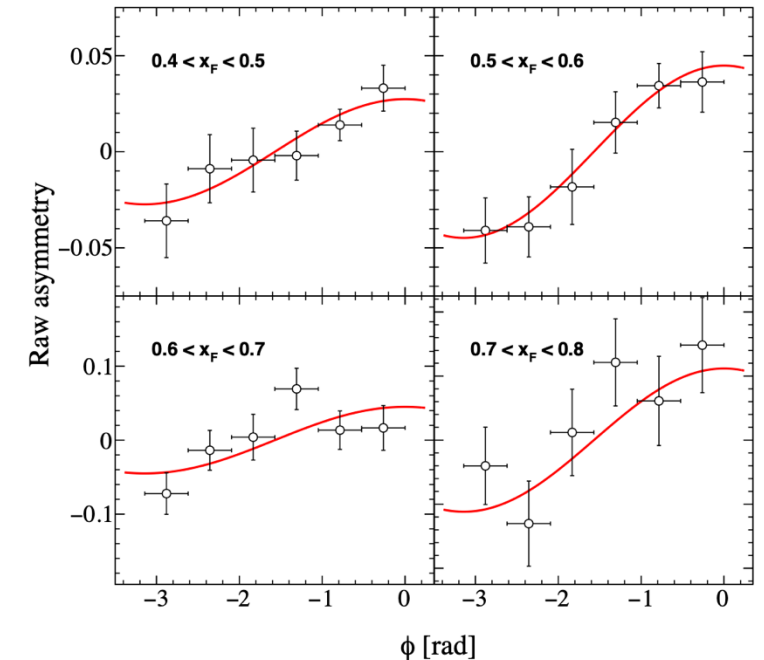
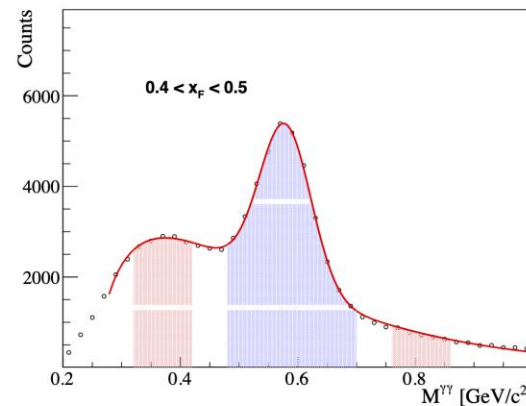
The η meson TSSA

The forward η meson TSSA

- ❑ The forward TSSA is measured through the azimuthal modulation of $\eta \rightarrow \gamma\gamma$ yields in the Muon Piston Calorimeter when one of the colliding protons is transversely polarized

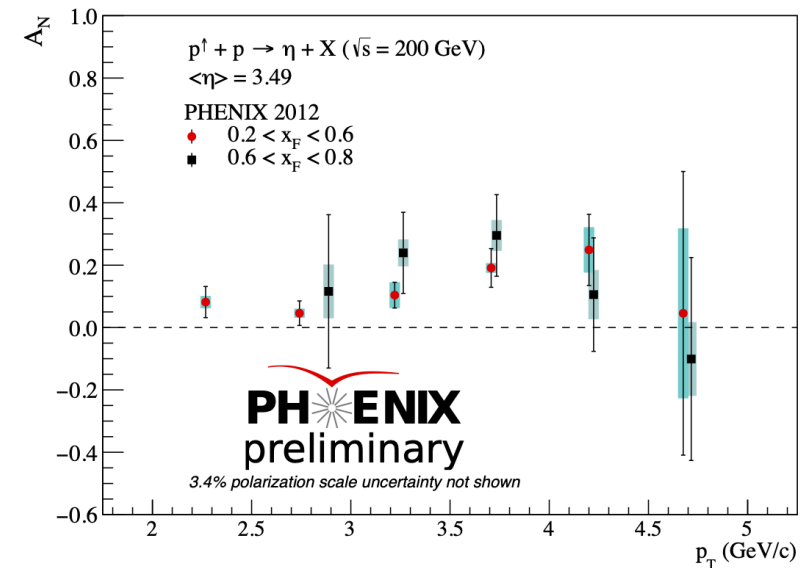
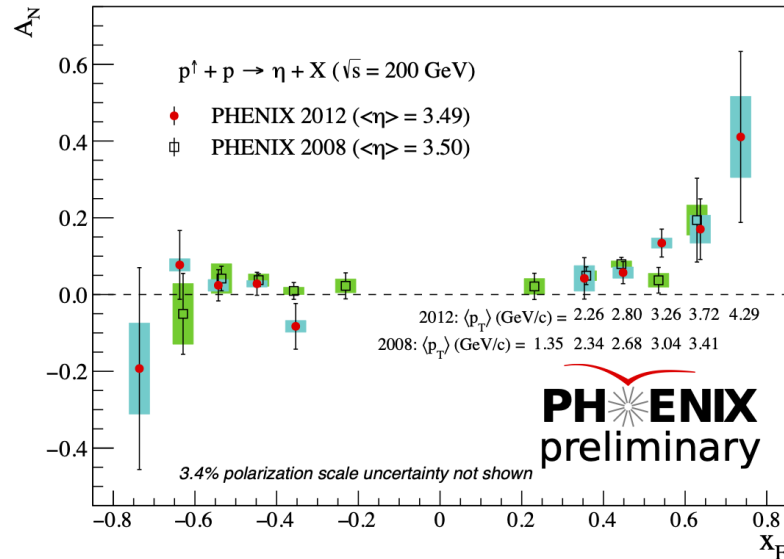
$$d\sigma = (d\sigma)_0 [1 + \epsilon(\phi)], \quad \epsilon(\phi) = P_Y A_N \cos \phi$$

- ❑ Raw asymmetries $\epsilon(\phi)$ binned independently in x_F and p_T
- ❑ Asymmetries are corrected for potential background contributions by subtracting the asymmetry measured in the invariant mass sidebands weighted by the background fraction in the η signal region



The forward η meson TSSA

- ❑ Large positive asymmetry - consistent with previous PHENIX TSSA with higher x_F reach
- ❑ Consistent within statistical and systematic uncertainties with the π^0 TSSA
- ❑ At high x_F , first potential hint of a decrease in the asymmetry at increasing p_T
 - ❑ Predicted in twist-3 phenomenology of the light meson A_N [PRD 83, 114024 (2011), PRD 89, 111501(R) (2014)]

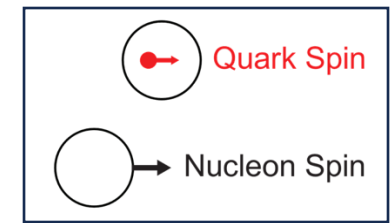


Prospects for the η meson A_{LL}

Gluon helicity at RHIC

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

proton spin
quark helicity
gluon helicity
orbital angular momentum

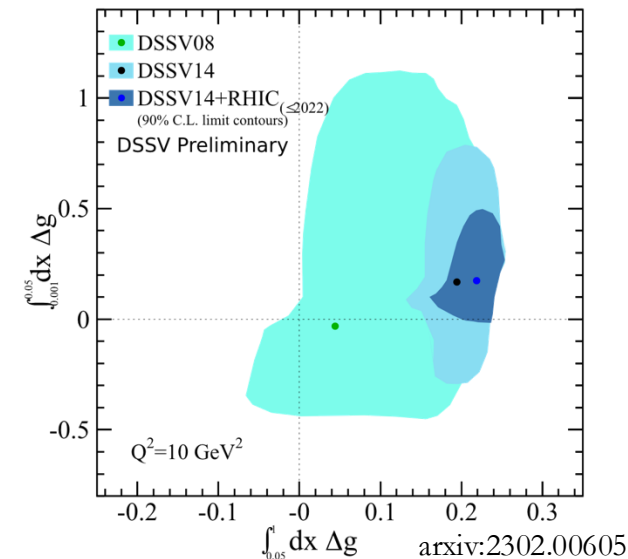
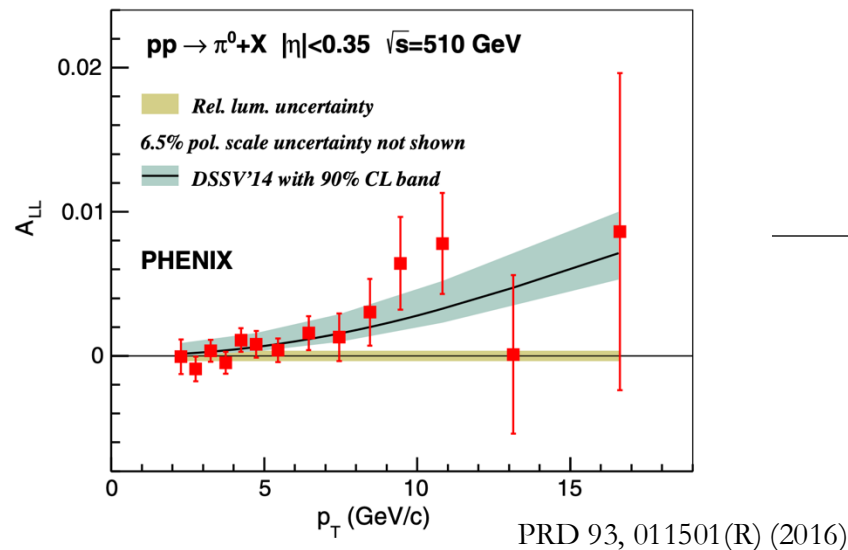


$$g_1 = \text{Nucleon Spin} - \text{Quark Spin} = \text{helicity}$$

□ Longitudinally-polarized proton collisions provide leading order access to ΔG through longitudinal double spin asymmetries, $A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$

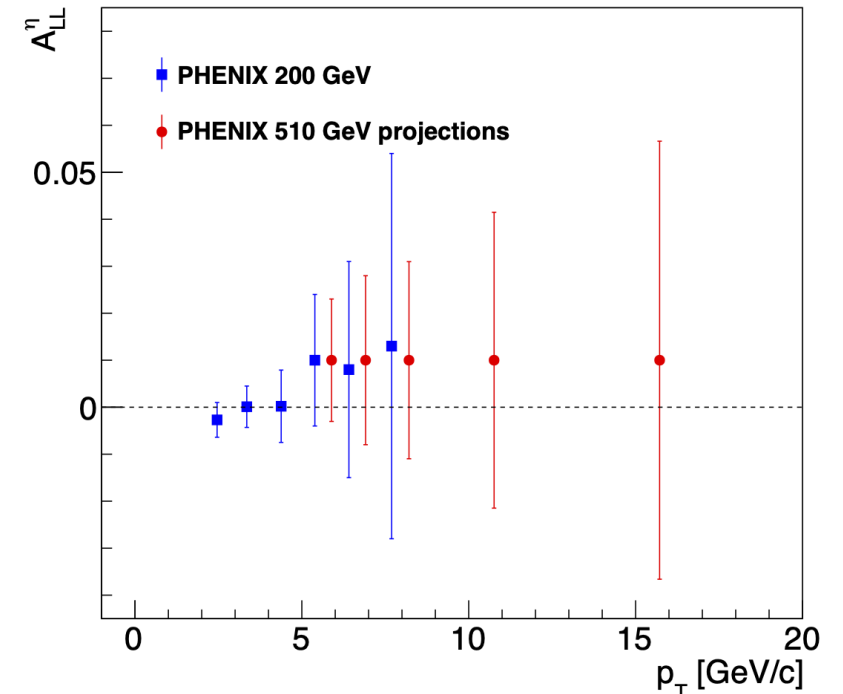
□ PHENIX π^0 and STAR jet $A_{LL} \rightarrow$ clear evidence of nonzero ΔG : $\int_{0.05}^{1.0} dx \Delta g(x) = 0.218 \pm 0.027$

arxiv:2302.00605



Projections for the η meson A_{LL} at 510 GeV

- ❑ The η meson A_{LL} has never been included in Δg extractions
 - ❑ Impact of η A_{LL} on Δg has suffered from imprecision of fragmentation functions
 - ❑ New global fit should improve situation!
- ❑ Measurements of η A_{LL} thus far at lower p_T in 200 GeV where the asymmetry is known to be small
- ❑ A 510 GeV A_{LL} will complement previous 200 GeV PHENIX result with extended reach to higher p_T



Summary

- ❑ Cross sections of η mesons at forward rapidity at 500 GeV and at midrapidity at 510 GeV have been measured
 - ❑ Important data relevant for new global fragmentation fit
- ❑ Updated forward η meson transverse single spin asymmetry with higher p_T and x_F reach
 - ❑ Large asymmetries $\sim 40\%$ observed at high x_F
 - ❑ Potential hint of $1/p_T$ like behavior at high p_T and x_F
- ❑ First longitudinal double spin asymmetry of η mesons at 510 GeV still to come
 - ❑ High p_T complement to earlier 200 GeV results

Backup

The central π^0 cross section at 510 GeV

- 510 GeV π^0 cross section measured in high luminosity 2013 dataset
 - Input to η/π^0 ratio
- Excellent agreement with NLO pQCD calculations using MSTW PDFs and DSS14 FFs

