Experimental Review of Nucleon Spin Measurements (since EINN 2019)

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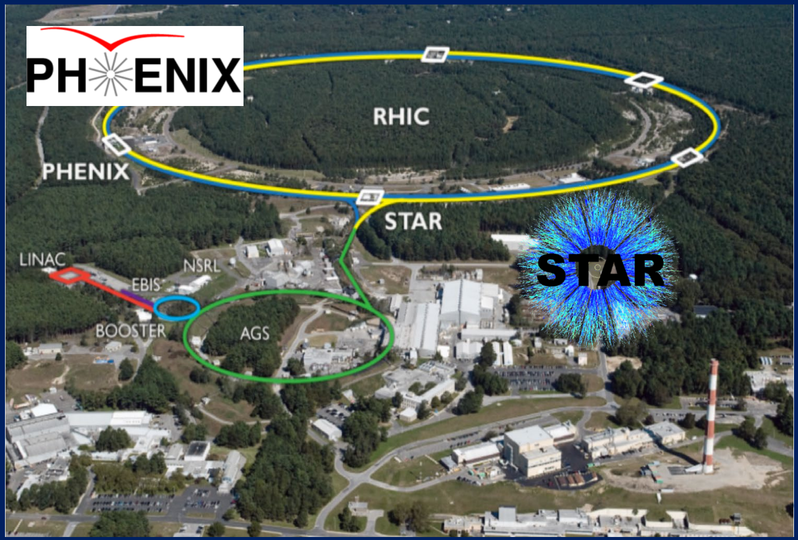
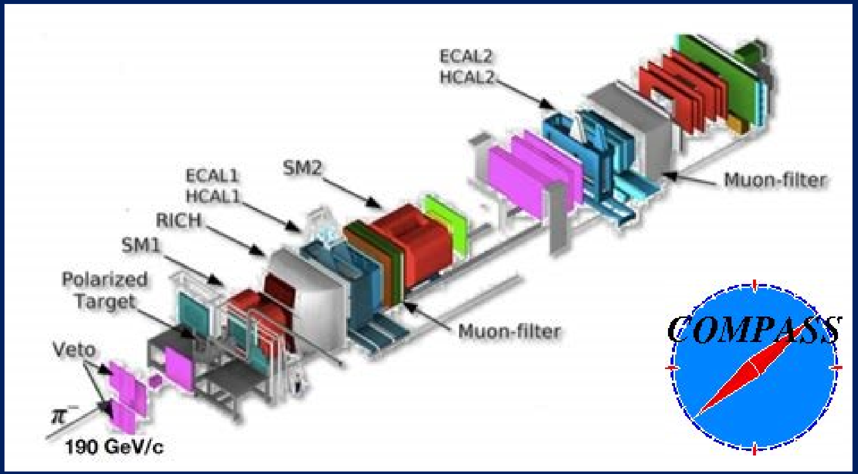
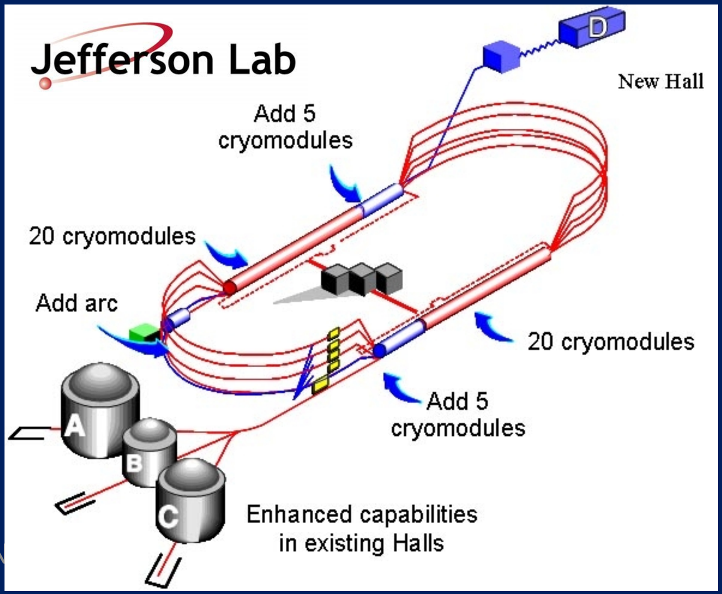
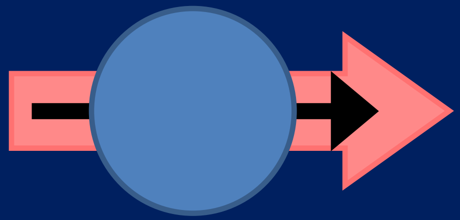
Facilities/Experiments Studying Nucleon Spin Structure



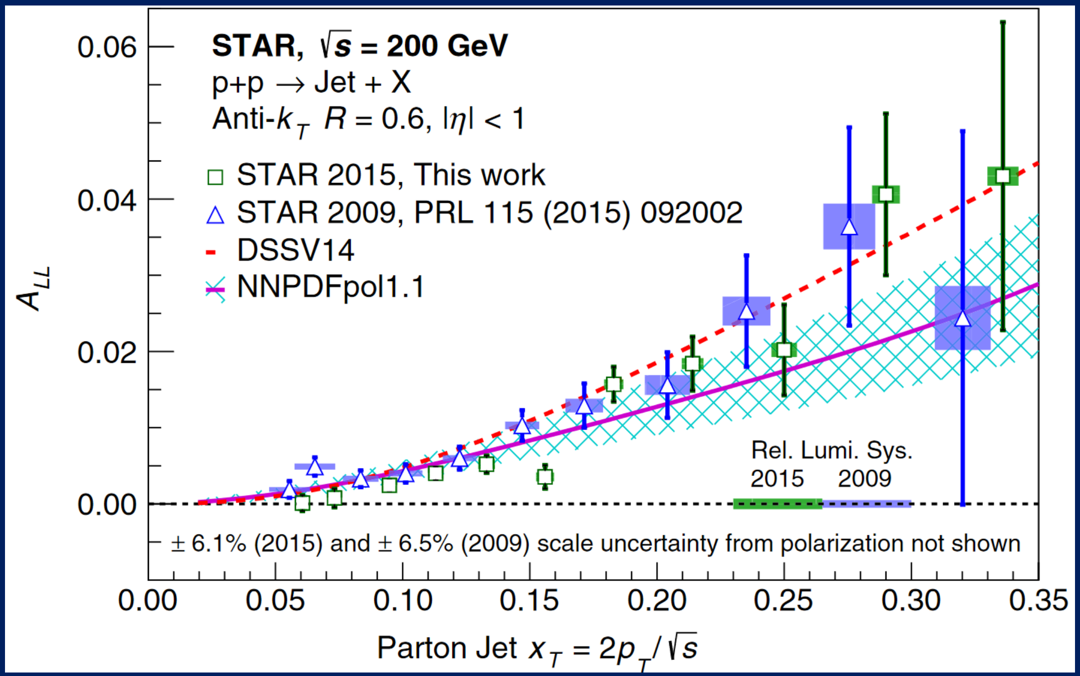


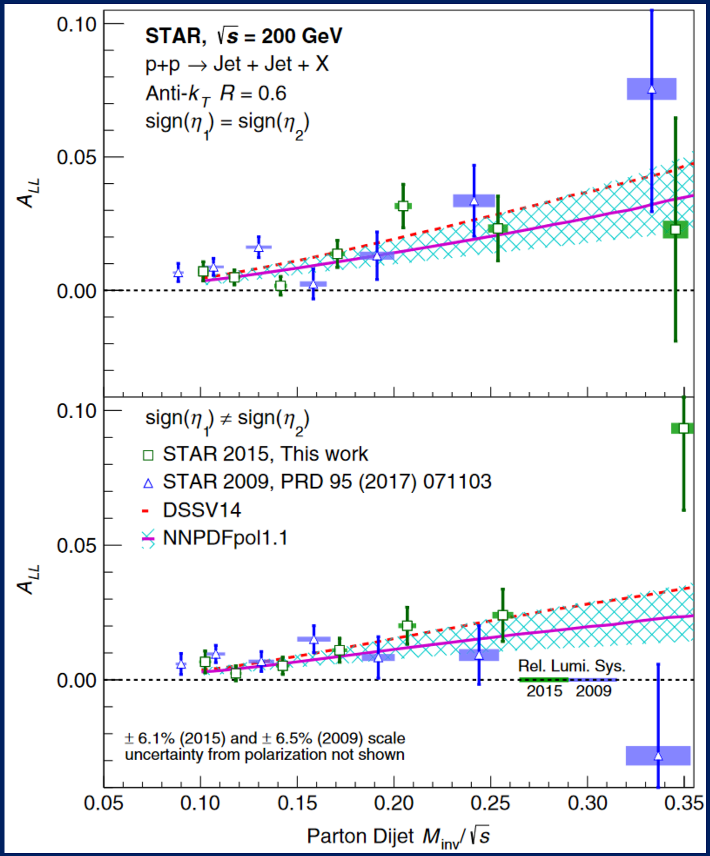




Longitudinally Polarized Measurements

Inclusive Jet and Dijet A_{LL} for $\sqrt{s} = 200$ GeV



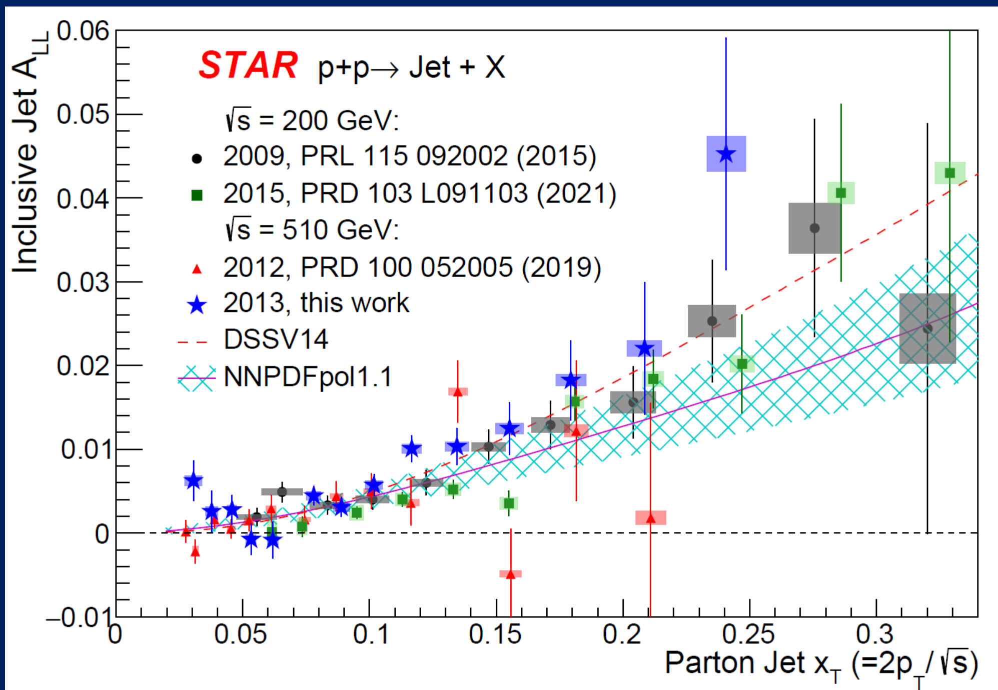


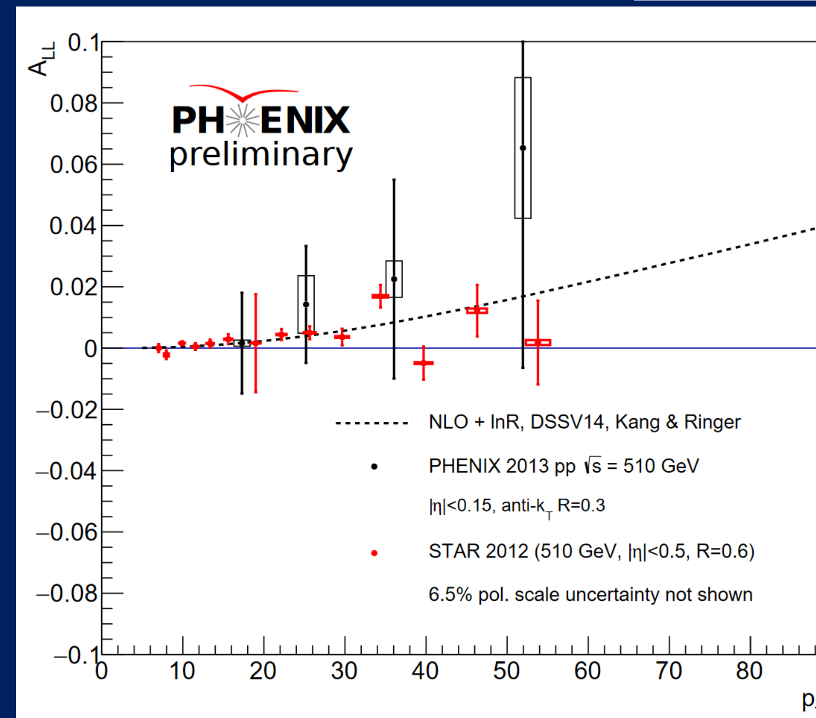
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

STAR, PRD **103,** L091103 (2021)

- Sensitive to gluon polarization at leading order: dominant processes at RHIC gg and qg scattering
- Inclusive result will reduce uncertainty of gluon polarization for $x > 0.05$
- Dijets place stronger constraints on underlying partonic kinematics: $M_{inv} = \sqrt{s x_1 x_2}$

Inclusive Jet A_{LL} for $\sqrt{s}$ = 510 GeV





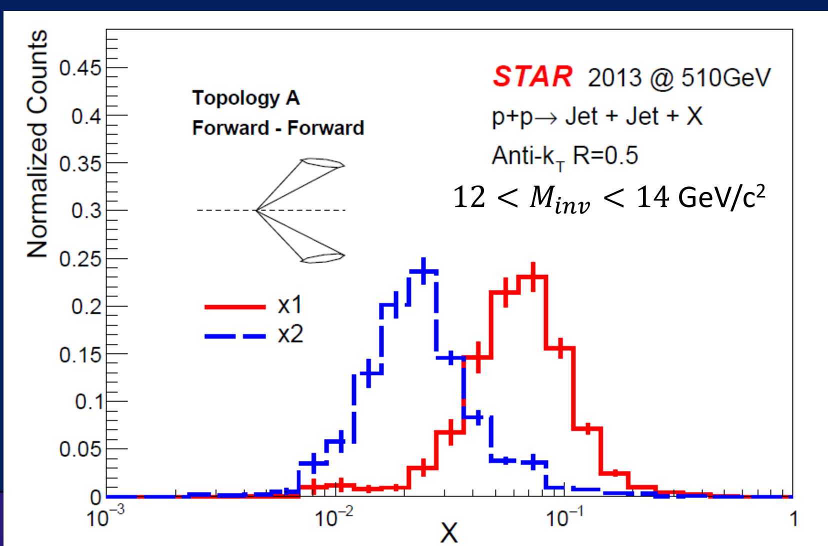
arXiv:2110.11020

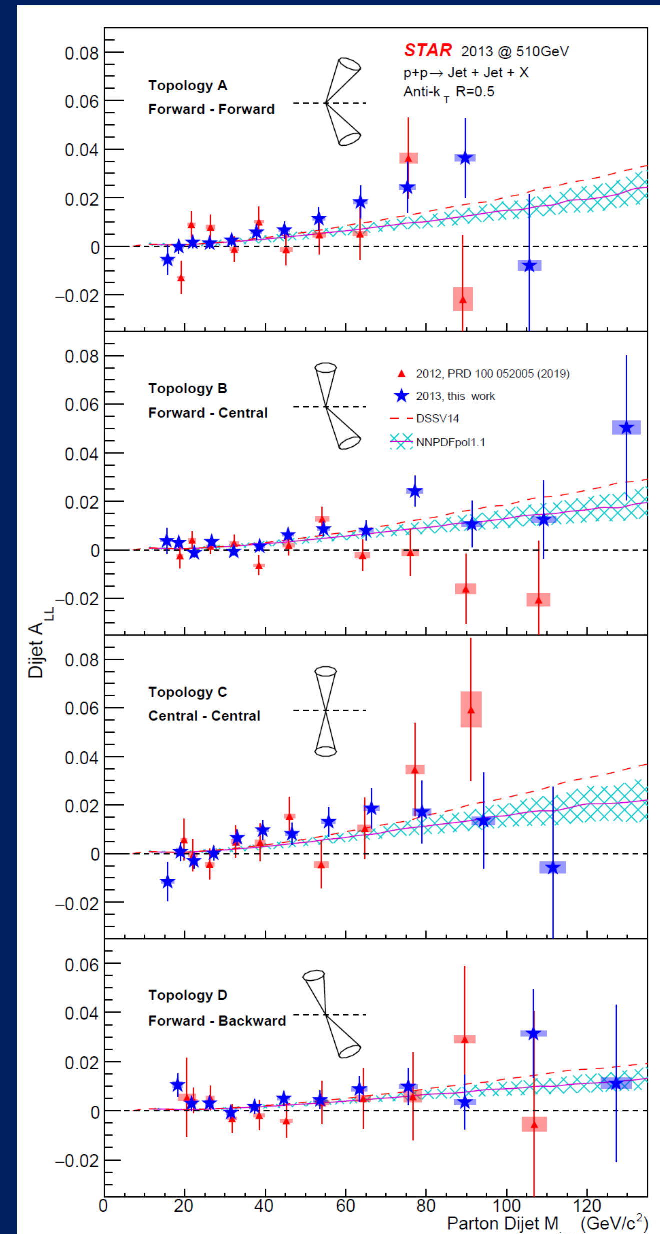
- Higher $\sqrt{s}$ pushes the sensitivity to lower x
- Inclusive jet at 510 GeV provides constraints for $x > 0.015$
- Agreement between $\sqrt{s} = 200$ GeV and 510 GeV and between experiments

Dijet A_{LL} *for* $\sqrt{s} = 510$ GeV

- New dijet results from large 2013 data set
- 4 dijet topologies and range of dijet invariant masses can constrain Δg for different ranges of x_1, x_2

arXiv:2110.11020

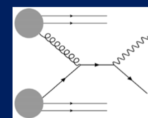


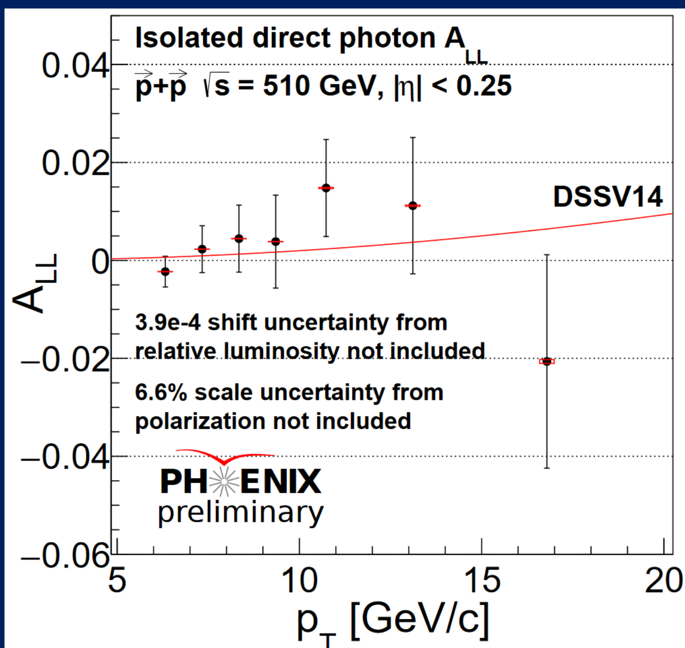


Direct Photon and Charged Pion A_{LL}

Photons that come *directly* from the hard interaction

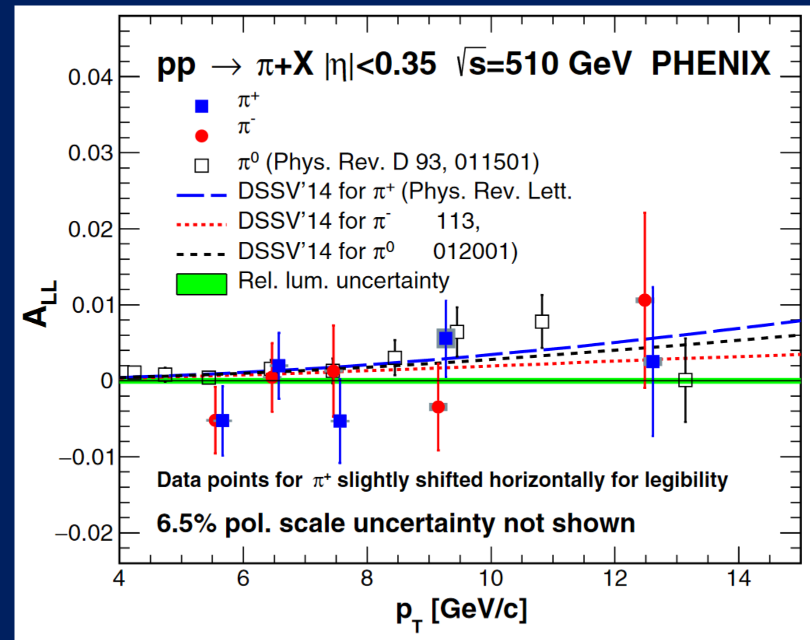
- Only sensitive to initial state effects, no effects from hadronization
- Production dominated by quark-gluon Compton scattering
- Isolation cut reduces contribution of fragmentation and Bremsstrahlung photons



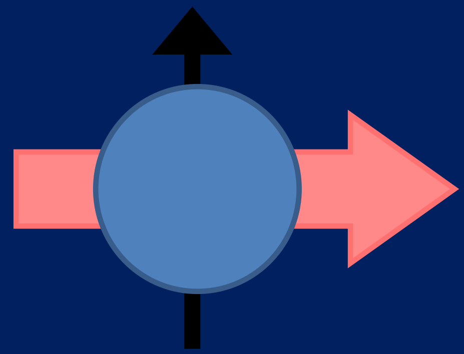


Cleanly sensitive to gluon dynamics, will help constrain Δg for $0.02 < x < 0.08$

PHENIX, PRD **102**, 032001 (2020)

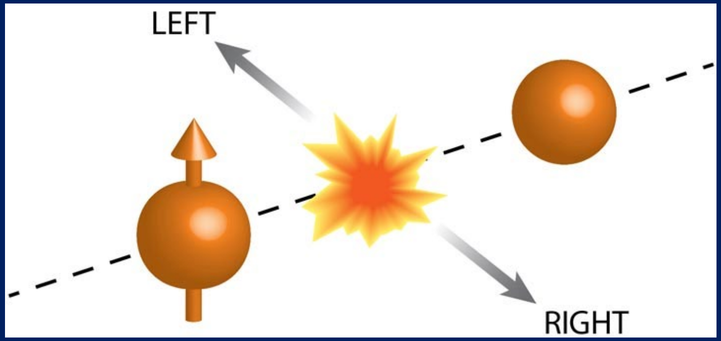


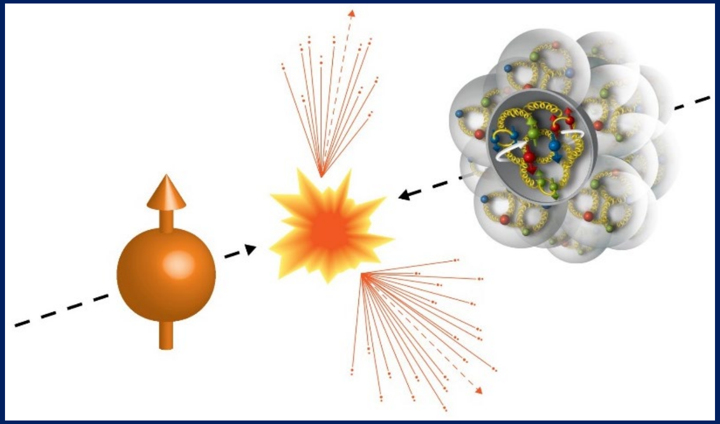
- 510 GeV data probes x down to $\sim 0.04 - 0.09$
- Consistent with DSSV14
- Ordering of positive, neutral, and negative pion asymmetries sensitive to sign of gluon polarization since up and down quark polarizations relatively well known

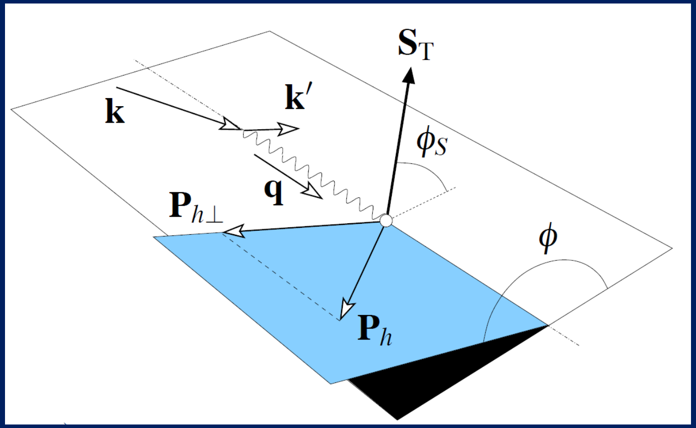


Transversely Polarized Measurements

Transverse Single-Spin Asymmetries

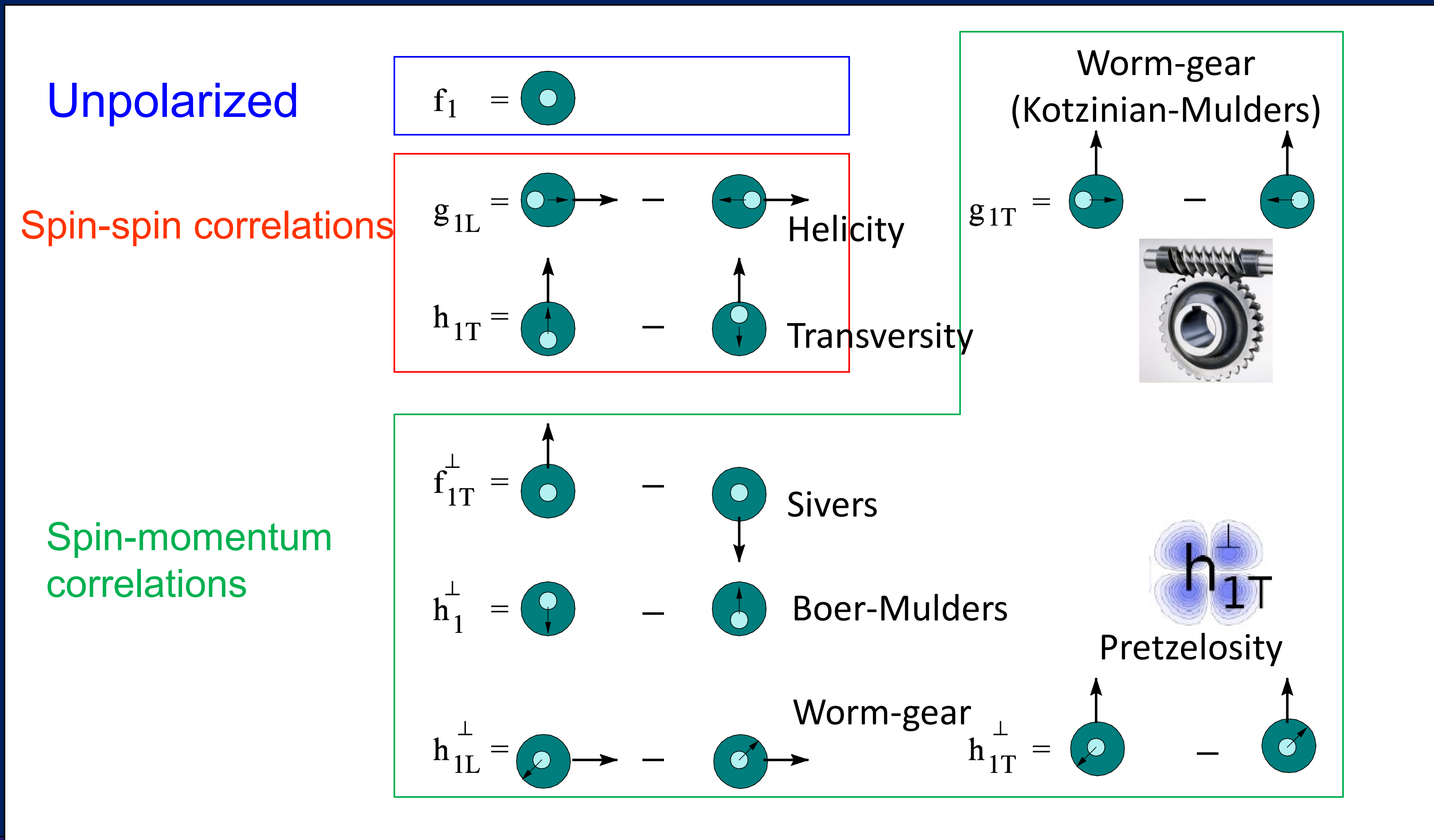




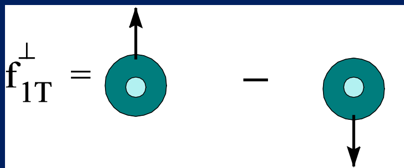


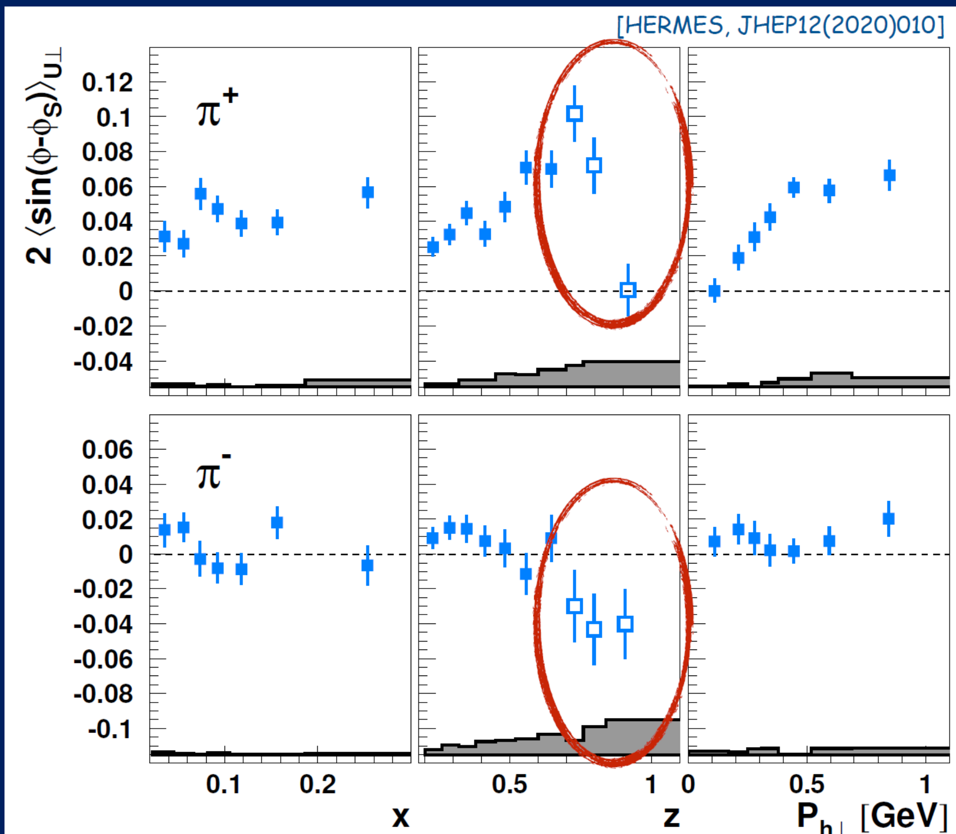
- Transverse Momentum Dependent functions
  - **Initial state effects** from spin-spin and spin-momentum correlations in proton
  - **Final state effects** from spin-momentum correlations in fragmentation
- Multiparton correlation functions: Twist-3 collinear correlation functions
  - Quantum mechanical interference between scattering off of one parton versus two partons

Spin-Spin and Spin-Momentum Correlations in the Nucleon

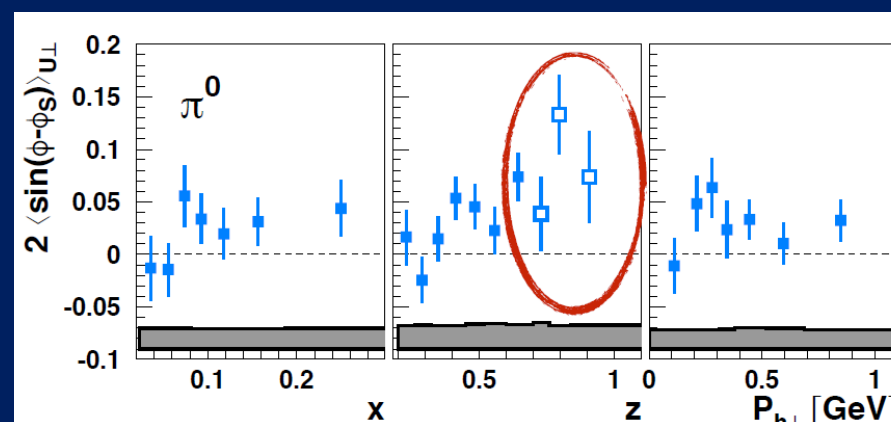


SIDIS Sivers Asymmetries for Pions at High Fragmentation z





- HERMES charged pion Sivers moments extended to high *z*
  - Expect stronger correlation with flavor of struck quark, but also contributions from exclusive ρ production



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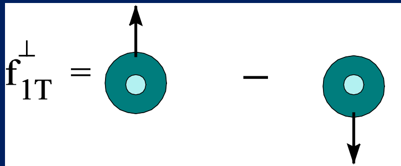
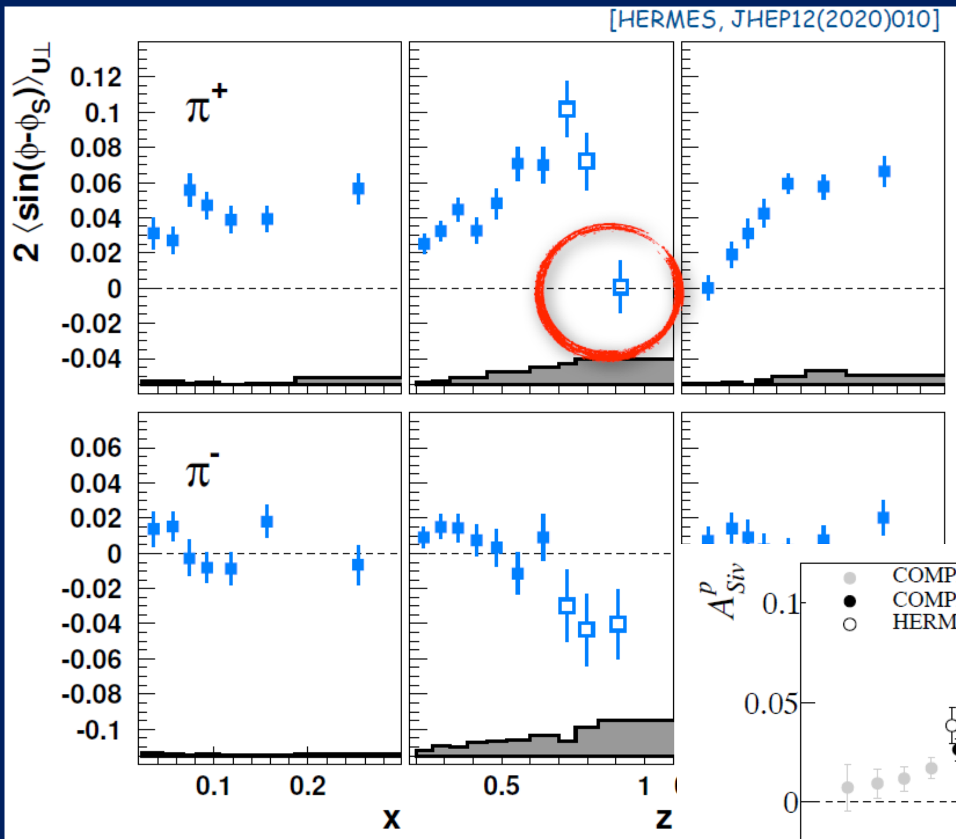
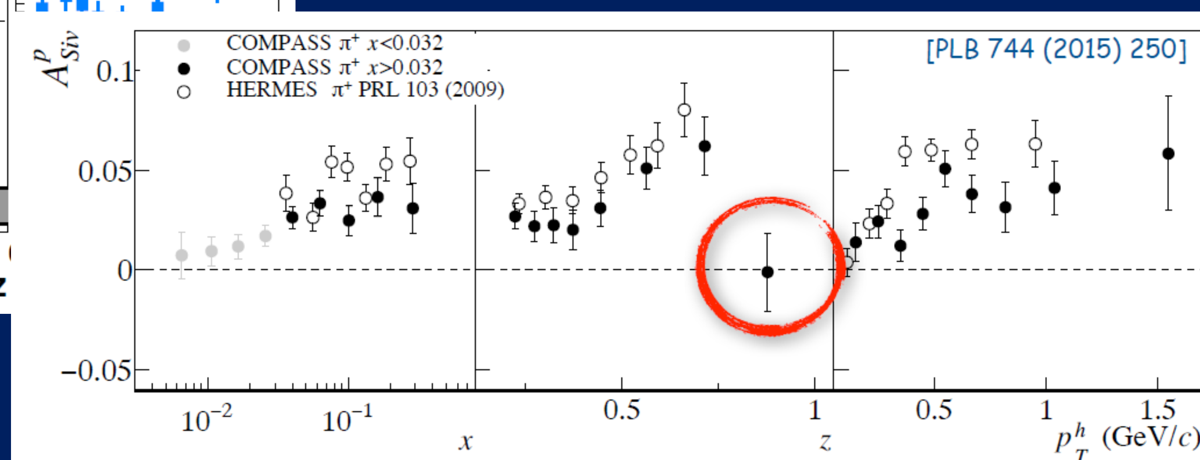
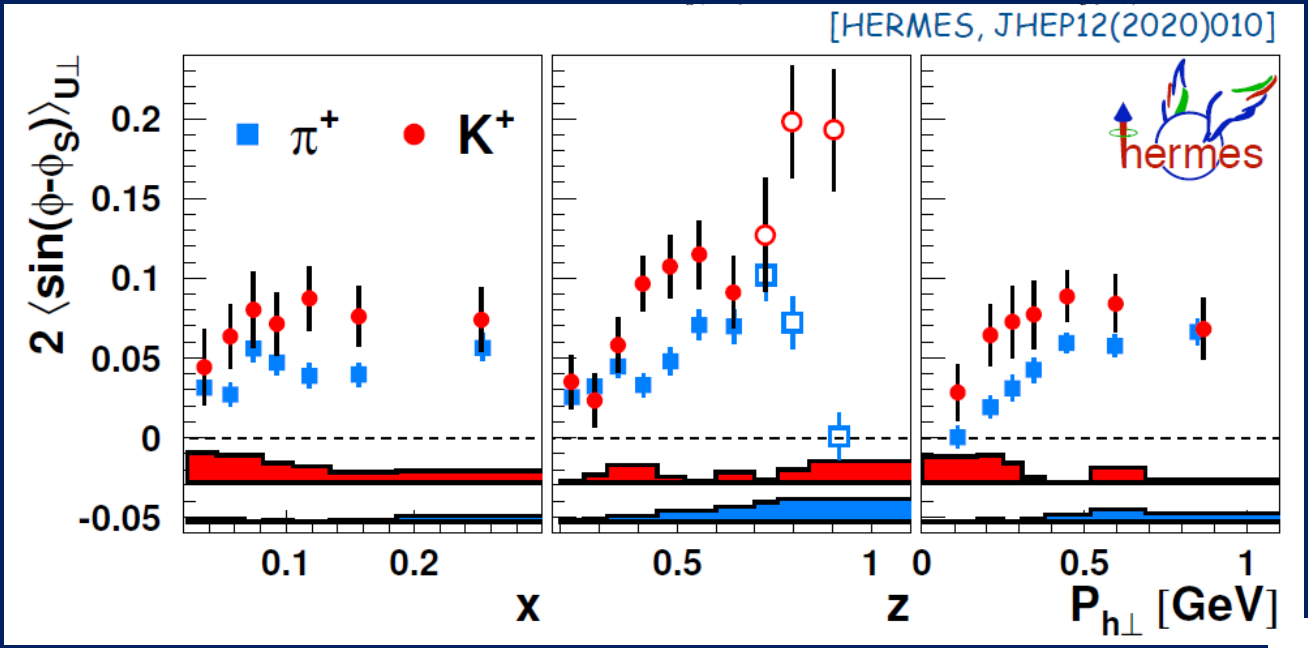




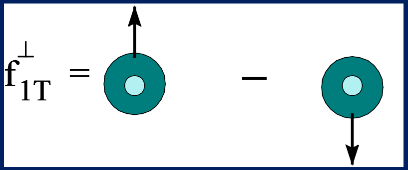
- HERMES charged pion Sivers moments extended to high *z*
  - Expect stronger correlation with flavor of struck quark, but also contributions from exclusive *ρ* production
- Drop in the asymmetry at very high *z* previously observed by COMPASS



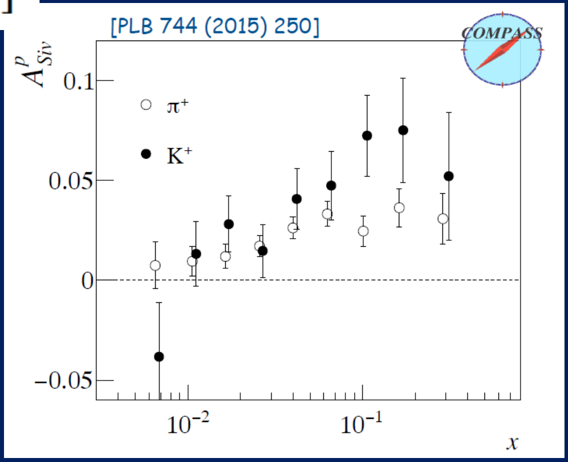
SIDIS Sivers Asymmetries for Kaons at High Fragmentation z



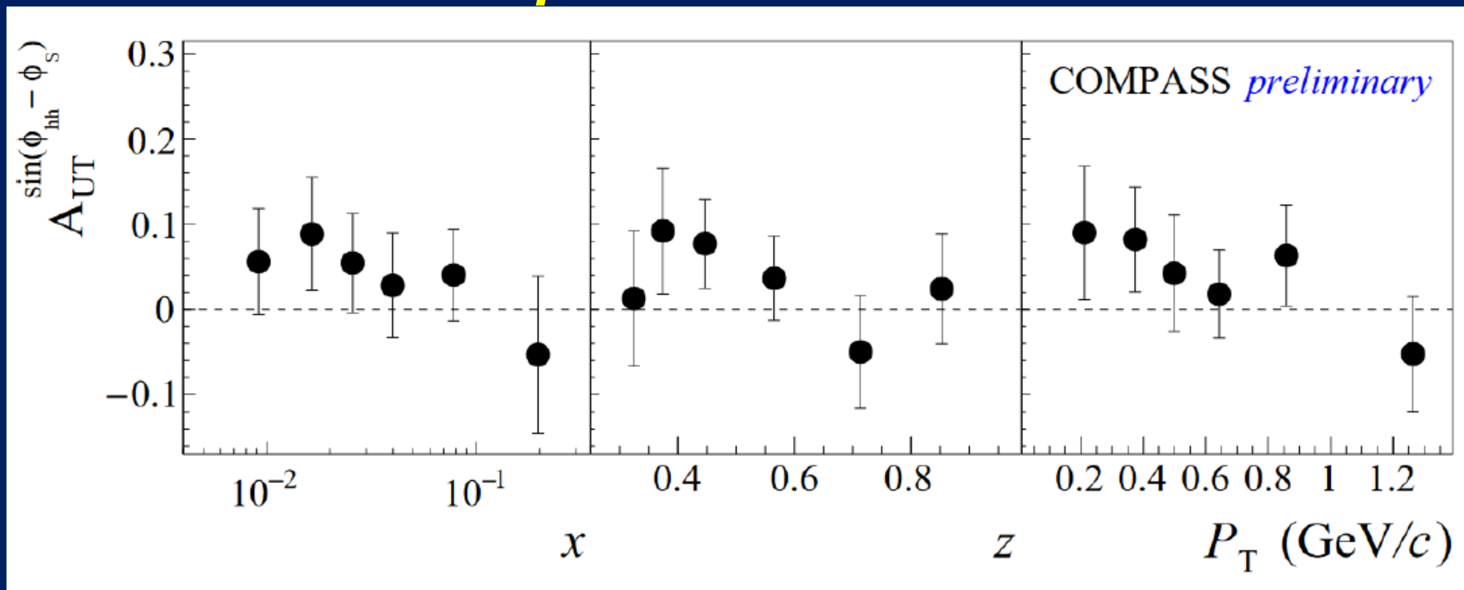
See also extended 3D analysis in $x, z, p_{h\perp}$ for pions in same paper



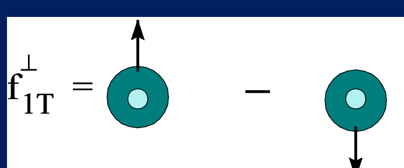
- No drop at high z for kaons
- Larger Sivers asymmetries for K^+ than π^+ – also seen by COMPASS
- Remains puzzling – would expect both to be dominated by hadronization of scattered up quarks. Role of sea?

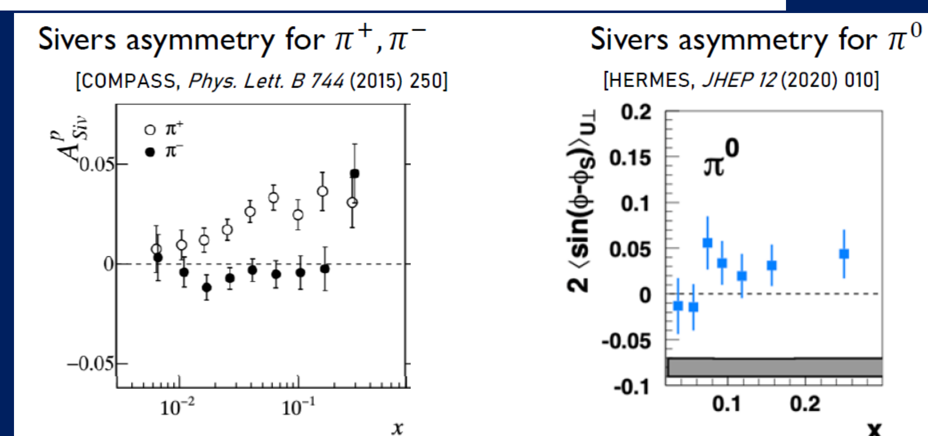


SIDIS Sivers Asymmetries for Inclusive ρ Mesons



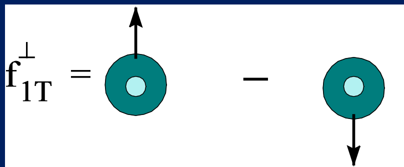
Suggests positive asymmetry, similar to π^0, as expected based on valence quarks of produced hadron

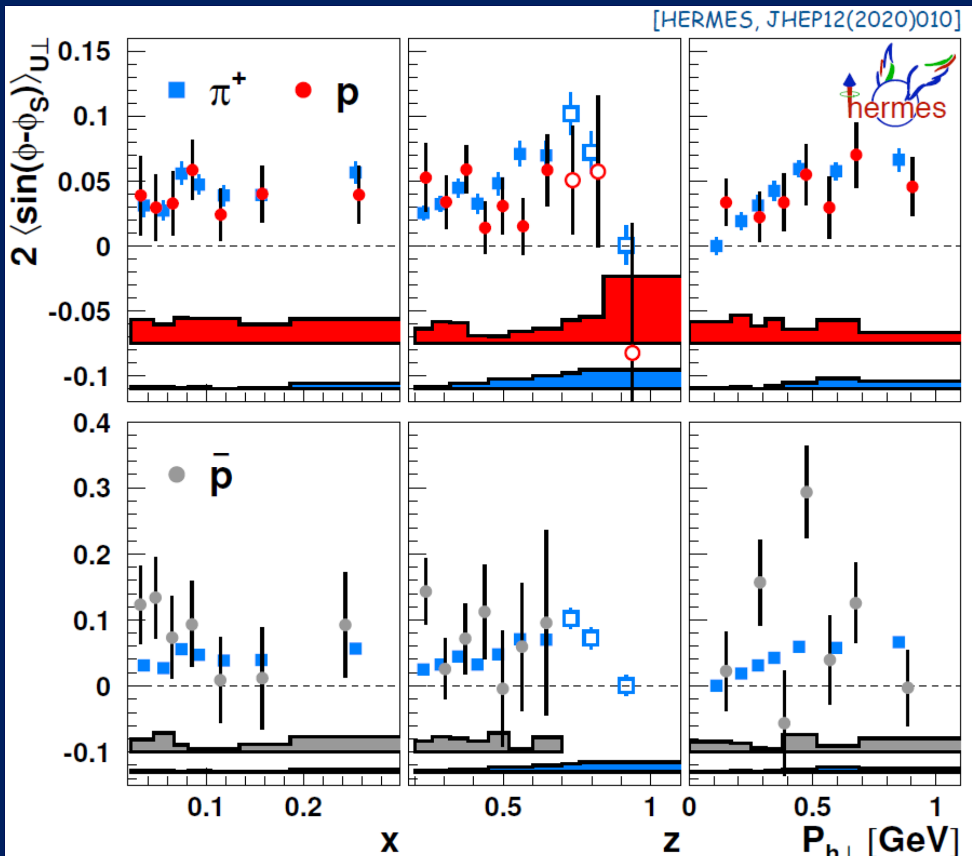




From A. Moretti, Spin 2021

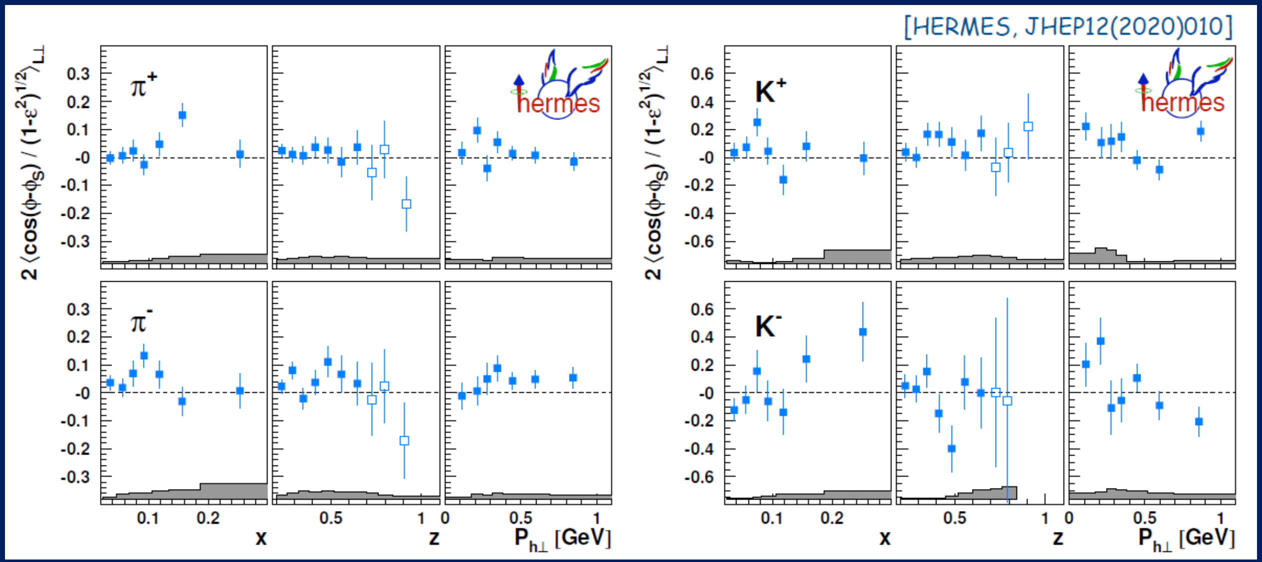
SIDIS Sivers Asymmetries for (Anti-)Protons

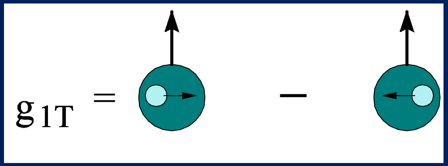




- First measurement of (anti-)proton Sivers asymmetries
- Proton asymmetries positive, similar to π^+
- Antiproton asymmetries also positive? Role of sea important?
- Note: In SIDIS can cleanly separate initial-state effects due to polarized proton structure from final-state effects due to spin-dependent hadronization
  - Different Sivers asymmetries for different produced hadrons must be due to different spin-momentum correlations in the proton for different flavor partons, plus different mix of parton flavors undergoing (unpolarized) fragmentation to the different species

Worm-Gear g_{1T} and Pretzelosity $h_{1T}^{\perp}$ TMD PDFs for Pions and Kaons at Large z



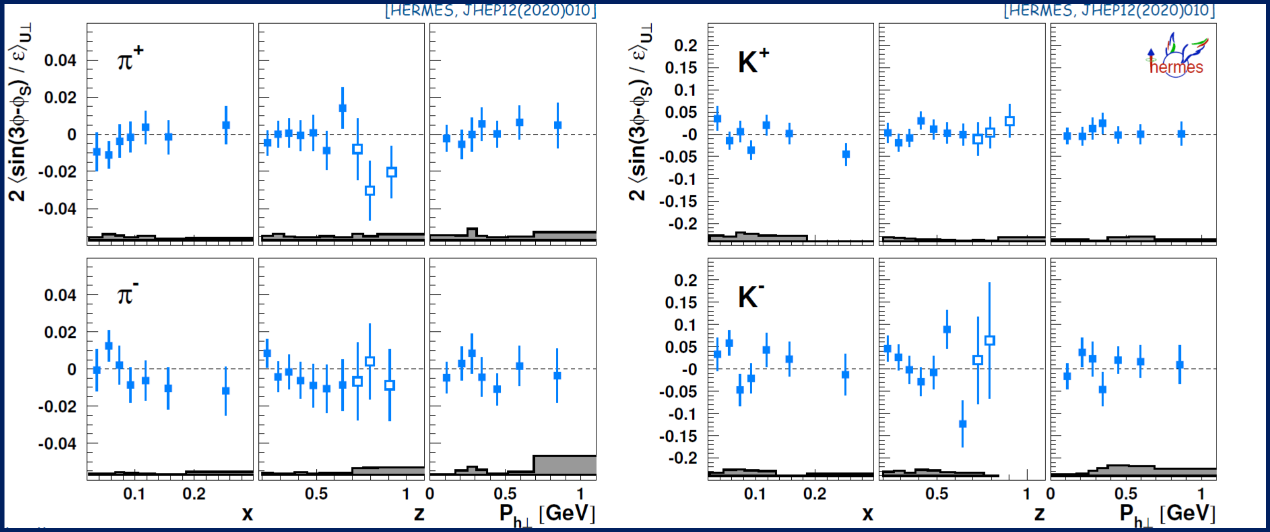


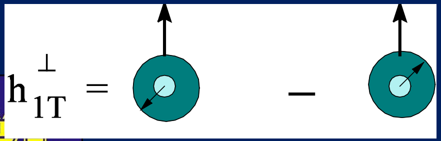
Worm-gear g_{1T} : longitudinally polarized quarks within a transversely polarized proton

Nonzero?

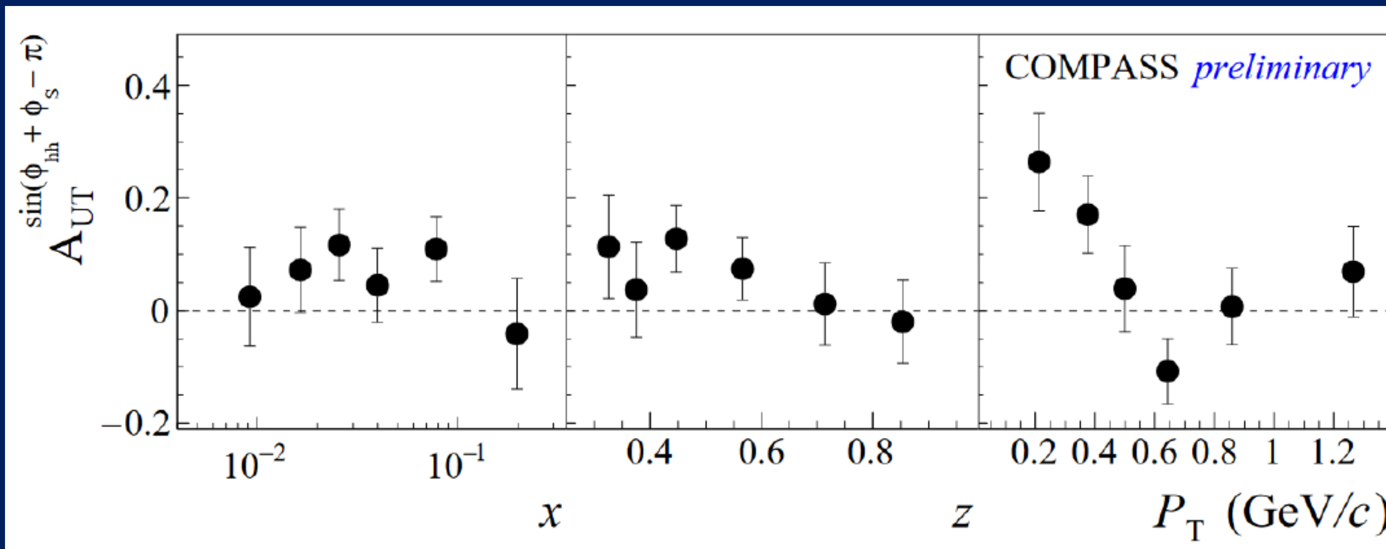
Pretzelosity $h_{1T}^{\perp}$: quadrupole deformation in momentum space

Consistent with zero

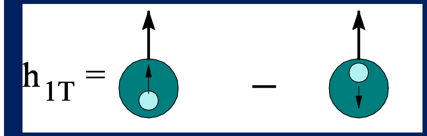




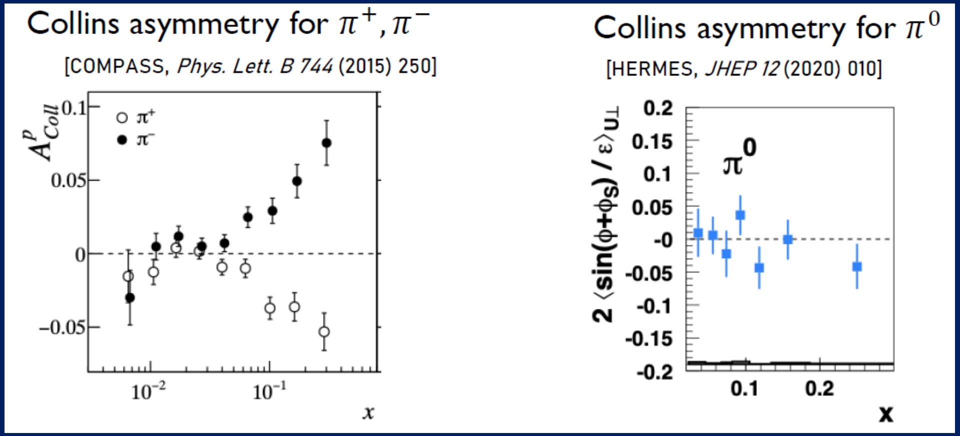
SIDIS Transversity PDF × Collins FF Asymmetries for Inclusive ρ Mesons



Large at small p_T



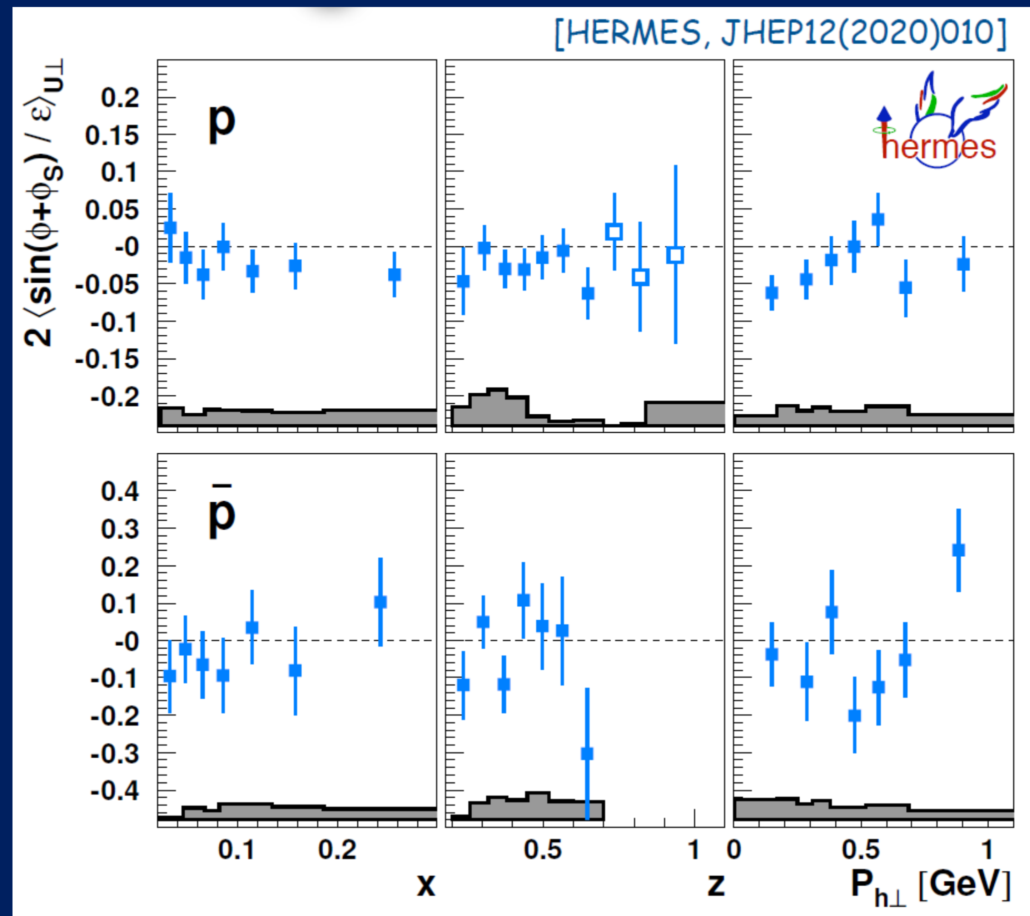
- First measurement of Collins TMD FF for a spin-1 vector meson
- Suggests positive asymmetry, opposite π^+, as expected from models



From A. Moretti, Spin 2021

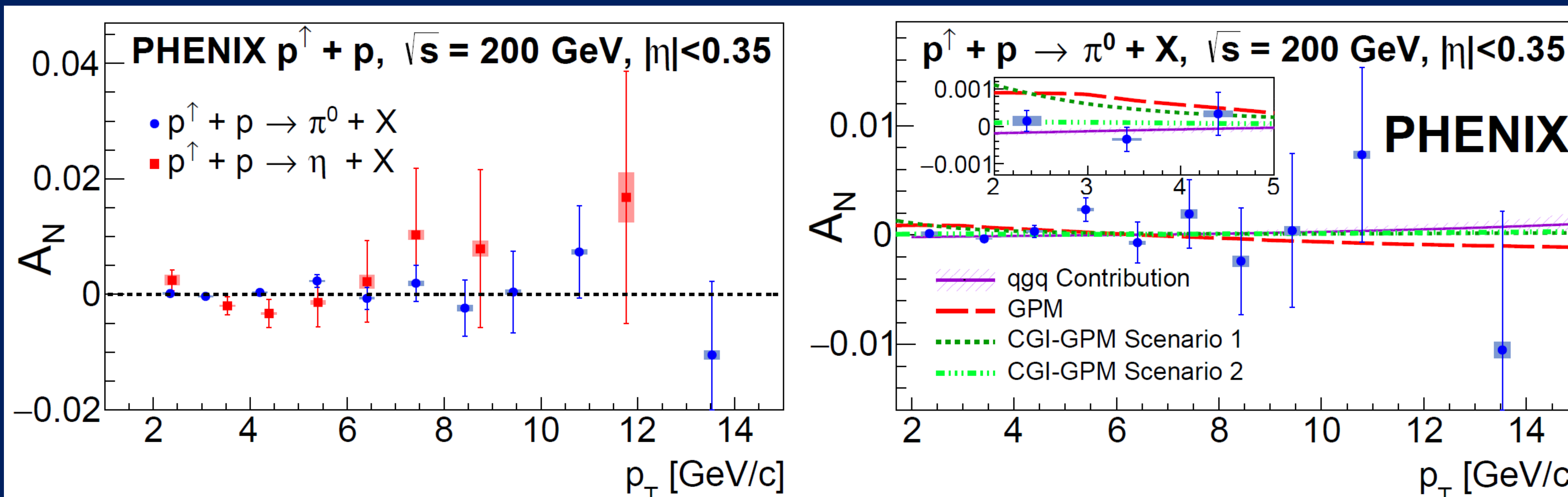
SIDIS Transversity PDF × Collins FF Asymmetries for (Anti-)Protons

- Consistent with zero
- Collins TMD FF zero for spin-1/2 baryon production in general?



Midrapidity π^0 and η Transverse Single-Spin Asymmetry A_N in p+p

PHENIX, PRD **103**, 052009 (2021)

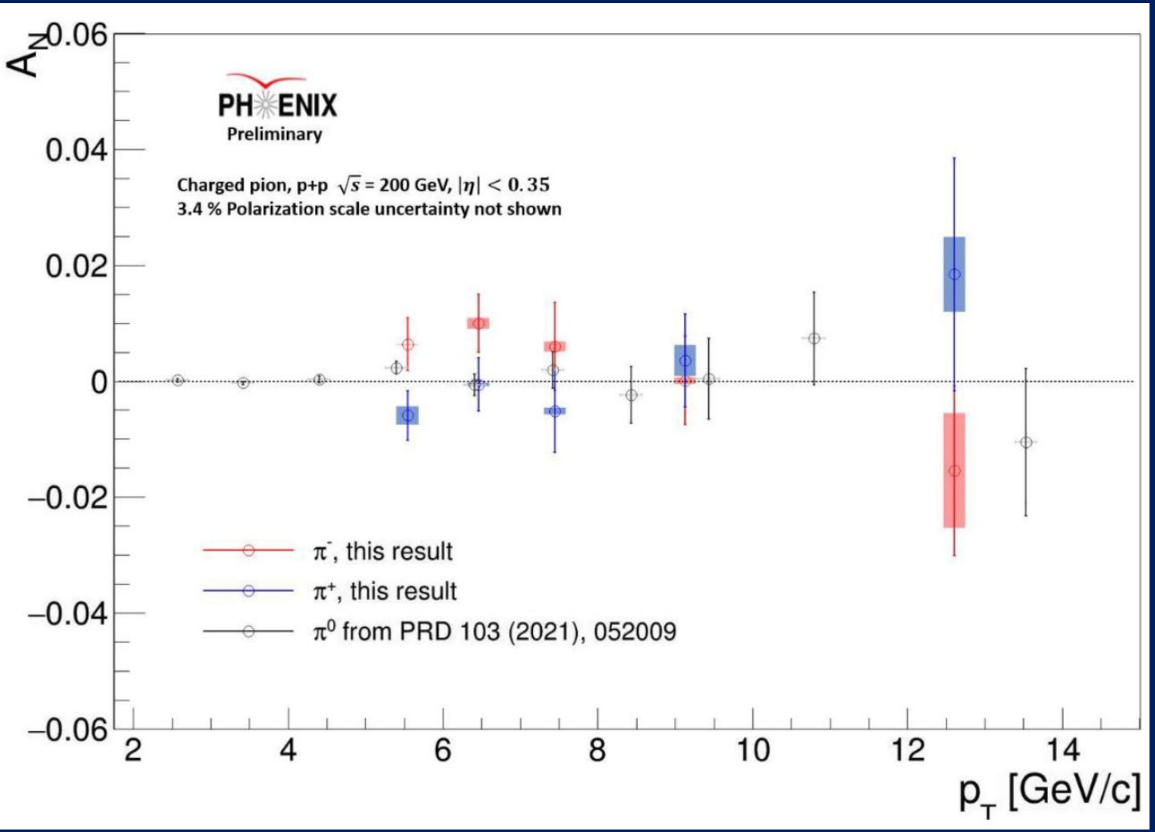


- Consistent with zero
- Factor of three increase in precision compared to previously published results and higher reach in p_T
- Sensitive to spin-momentum correlations in the proton and in hadronization for quarks and gluons

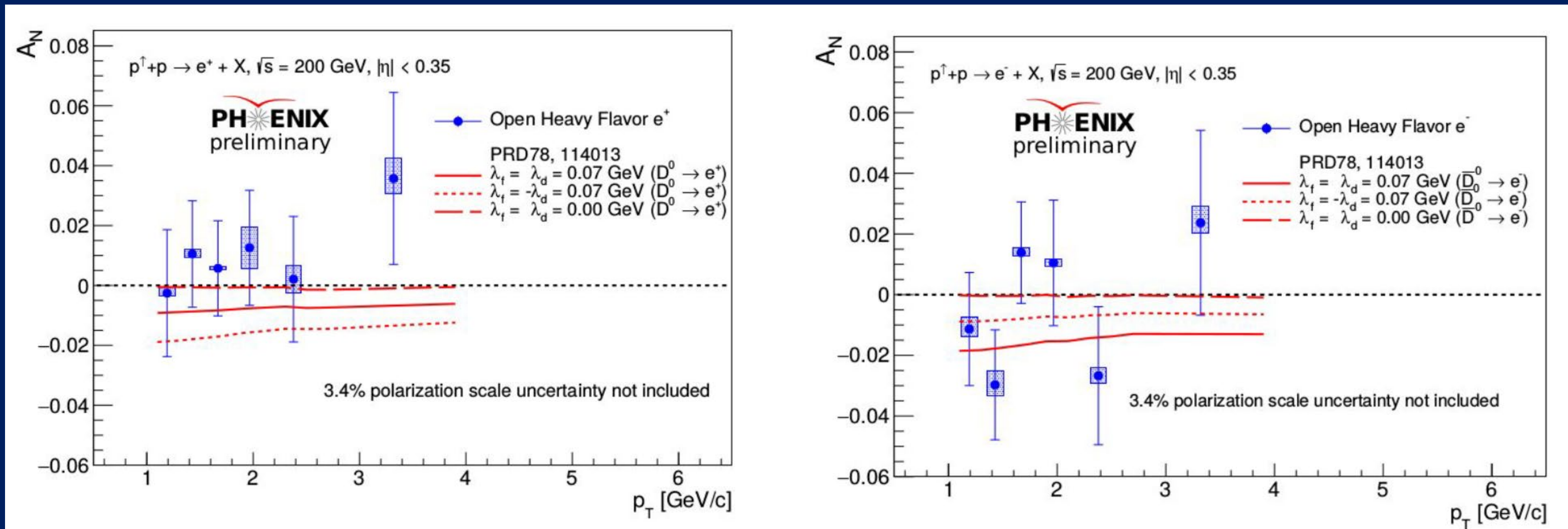
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Midrapidity Charged Pion A_N in $p+p$

- Midrapidity $\pi^{\pm}$ A_N consistent with zero and with the π^0 asymmetry
- Hint that $\pi^{\pm}$ might behave differently (potential flavor dependence)

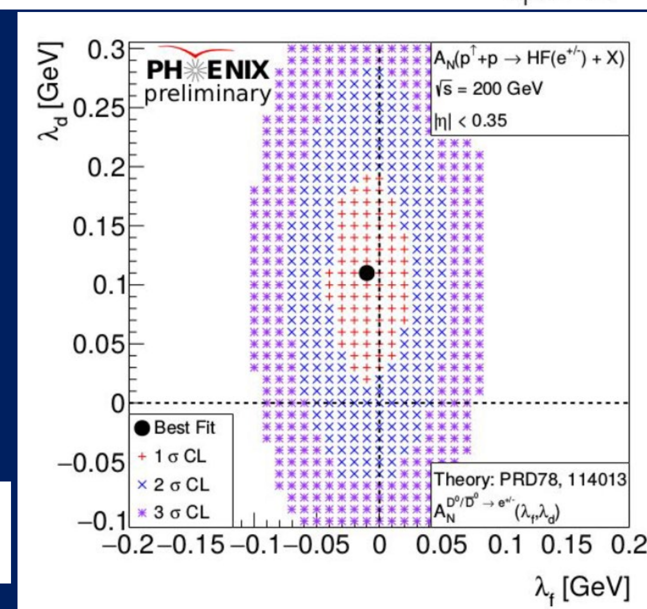


Midrapidity Open Heavy Flavor A_N in p+p



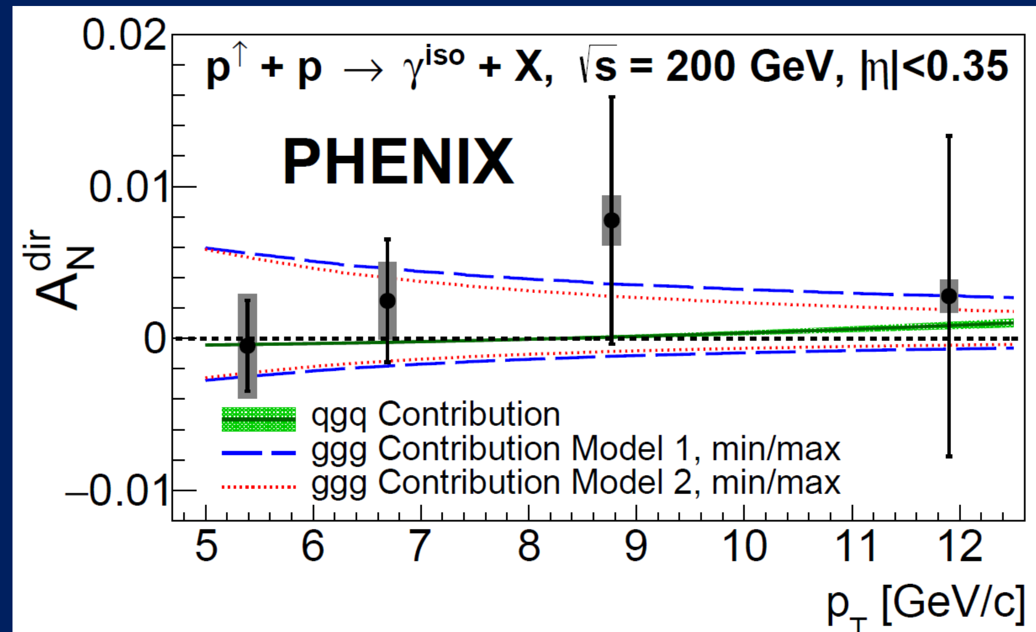
- Cleanly sensitive to gluon spin-momentum correlations in the proton
  - Dominant process gg fusion
- Provide constraints on the twist-3 collinear trigluon correlation functions
  - Calculations for D mesons from PRD78, 114013

$$\phi^{(3),f}_{g}(x,x) = \lambda_f\, g(x), \quad \phi^{(3),d}_{g}(x,x) = \lambda_d\, g(x)$$

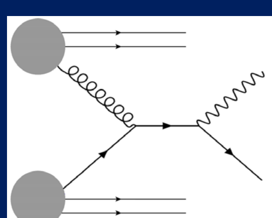


Midrapidity Direct Photon A_N in p+p

- Measured for the first time at RHIC
- Cleanly sensitive to gluon spin-momentum correlations in proton
  - Dominant process quark-gluon Compton scattering
- Consistent with zero to within $\sim 2 \times 10^{-2}$
- Will help constrain the trigluon correlators
  - In particular in conjunction with new PHENIX midrapidity open heavy flavor electron results



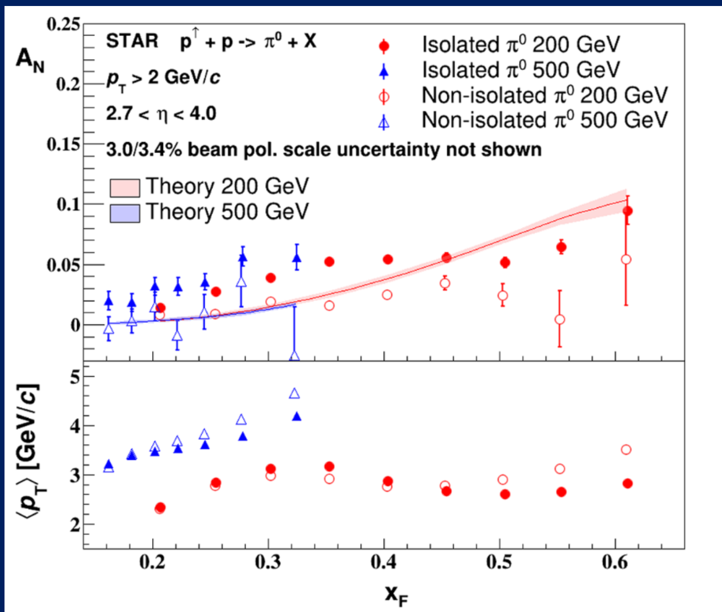
PRL 127, 162001 (2021)



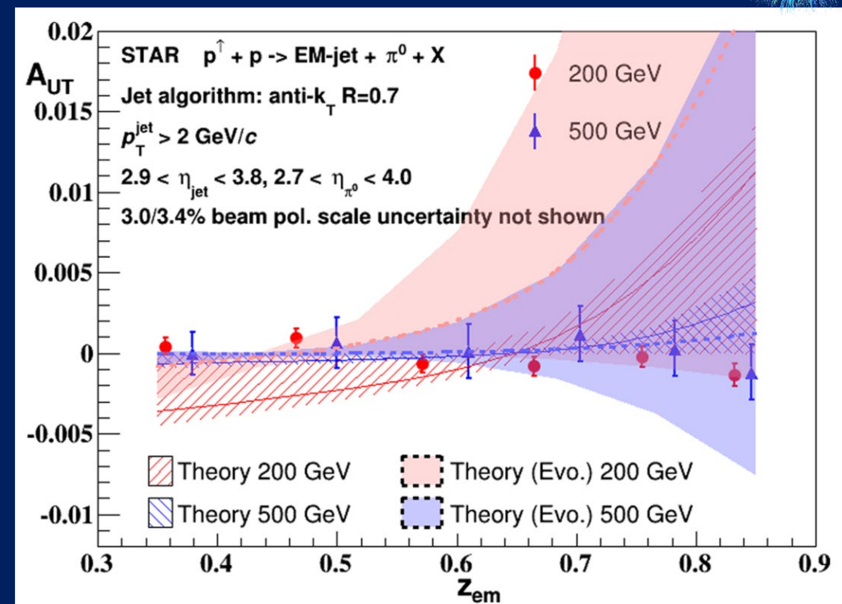
- *qgq* contribution – Kanazawa, Koike, Metz, Pitonyak, PRD 91, 014013 (2015)
  - Already constrained by other measurements to be very small
- *ggg* contribution – Koike and Yoshida, PRD 85, 034030 (2012)

Exploring Origin of Large Forward Asymmetries in p+p: Isolated π^0 and π^0-in-Jet A_N

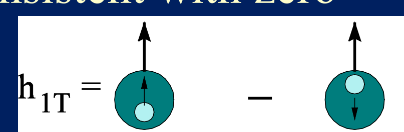
STAR, PRD **103,** 92009 (2021)



Note axis ranges!

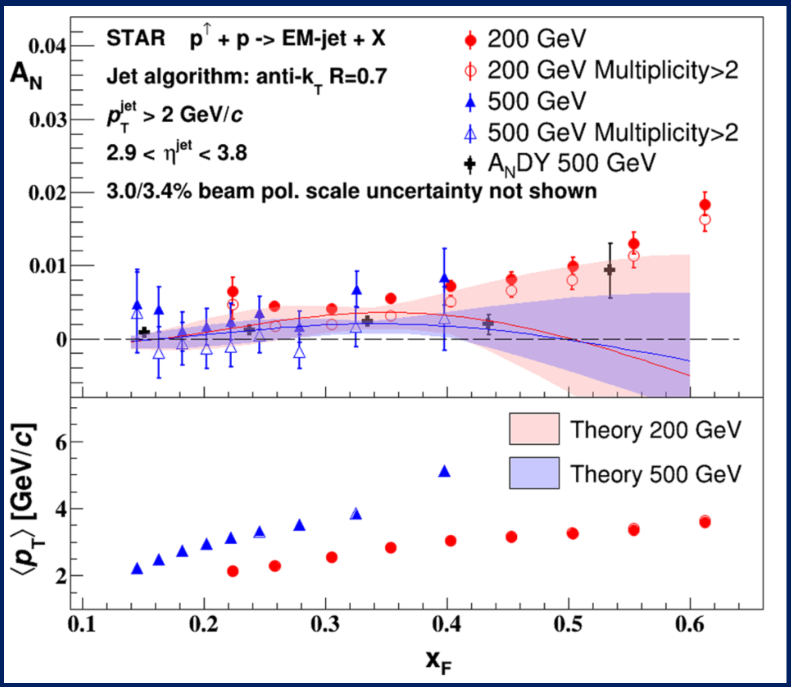


- Large forward π^0 asymmetry is larger for isolated π^0 (left; filled points)
  - Larger contribution from diffractive processes?
  - Nonisolated π^0s considered to be part of a jet
- Forward π^0-in-jet transversity × Collins asymmetry consistent with zero within ~0.002 (right)



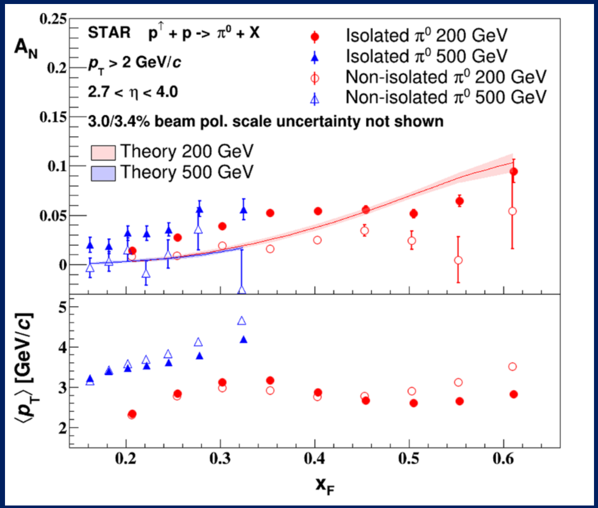
Exploring Origin of Large Forward Asymmetries in p+p: Electromagnetic-Jet A_N

A_N slightly smaller for EM-jets with higher multiplicity

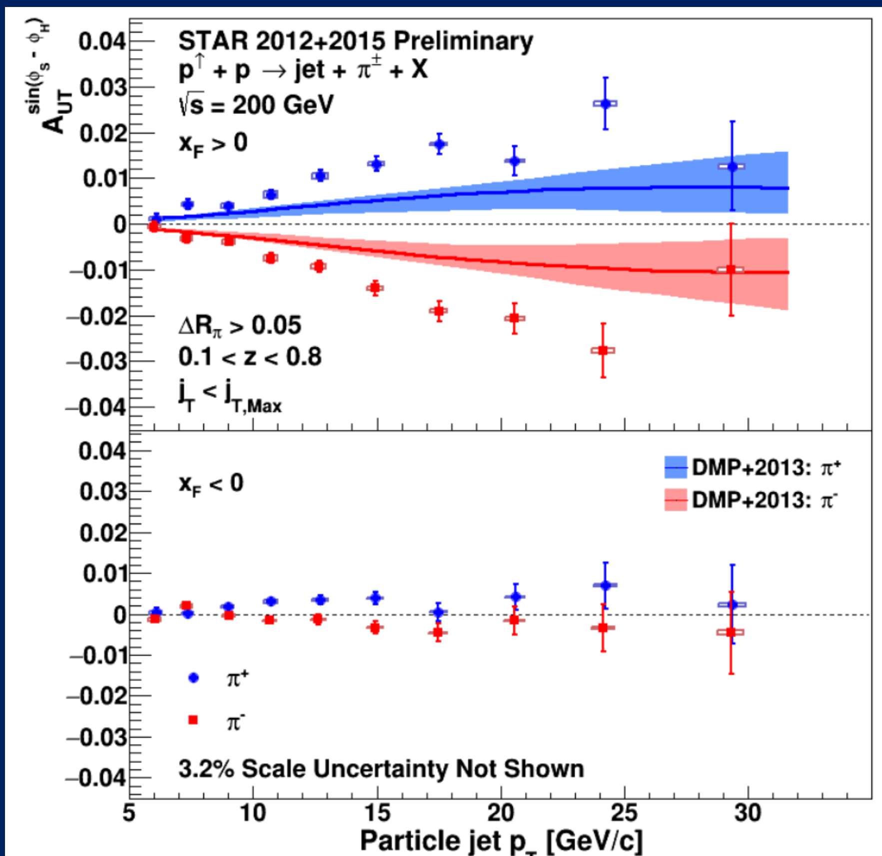


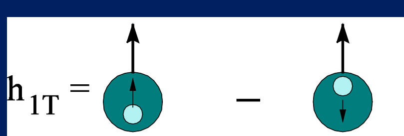
STAR, PRD **103,** 92009 (2021)

- Inclusive forward jet asymmetries reach ~0.02
  - Sensitive primarily to initial-state effects from proton structure
- Compare to ~0.10 for isolated π^0 in same pseudorapidity

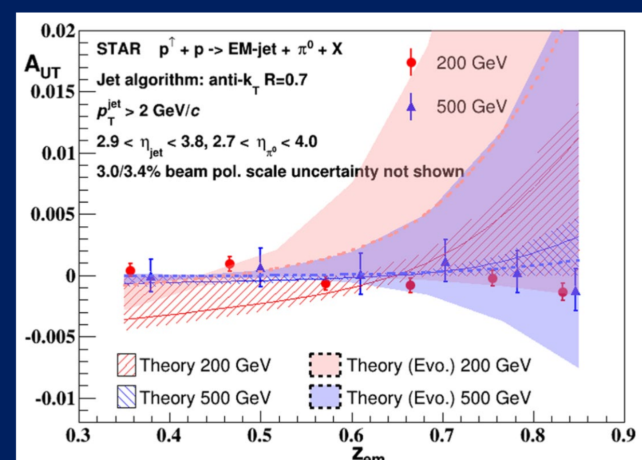


Exploring Origin of Large Forward Asymmetries in p+p: $\pi^{\pm}$-in-Jet A_N





- Forward $\pi^{\pm}$-in-jet transversity × Collins asymmetries reach magnitudes of ~0.03
  - Opposite sign for π^+, π^-
- Compare to ~0.002 for π^0-in-jet in same pseudorapidity

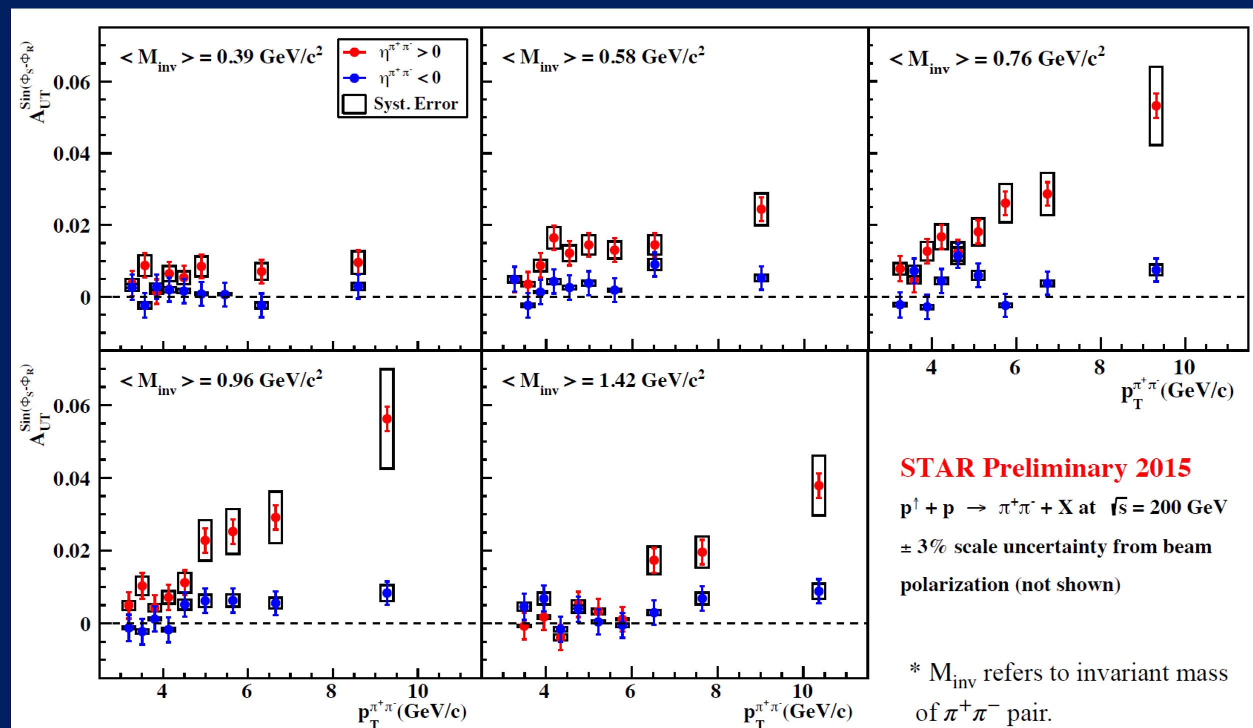


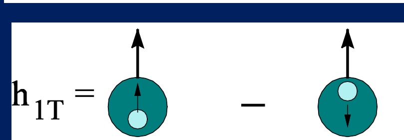
Transversity PDF × Dihadron Interference Fragmentation Function (IFF) Asymmetry in p+p

Dihadron interference FF

- Twist-2 collinear framework
- Correlation of transverse spin of fragmenting quark and momentum cross-product of hadron pair

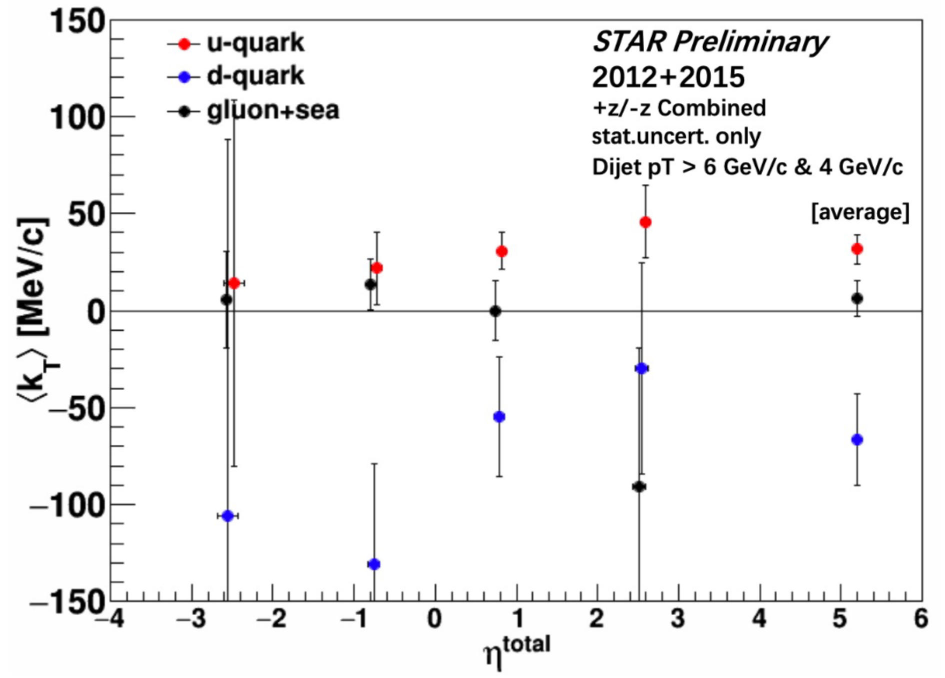
- Measured in p_T and invariant mass of the pair
- Larger asymmetry for $M_{inv} \approx M_\rho$
- Can further constrain the transversity spin-spin correlation in the proton



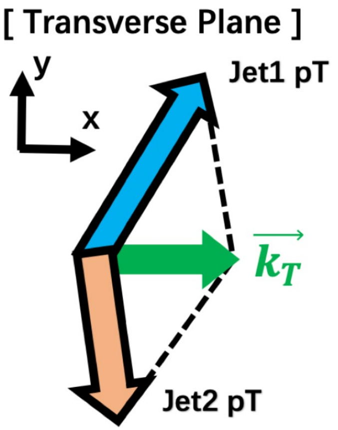


Dijet Sivers Asymmetry in p+p

$$p^{\uparrow} + p \rightarrow \text{Jet} + \text{Jet} + X, \sqrt{s} = 200 \text{ GeV}$$



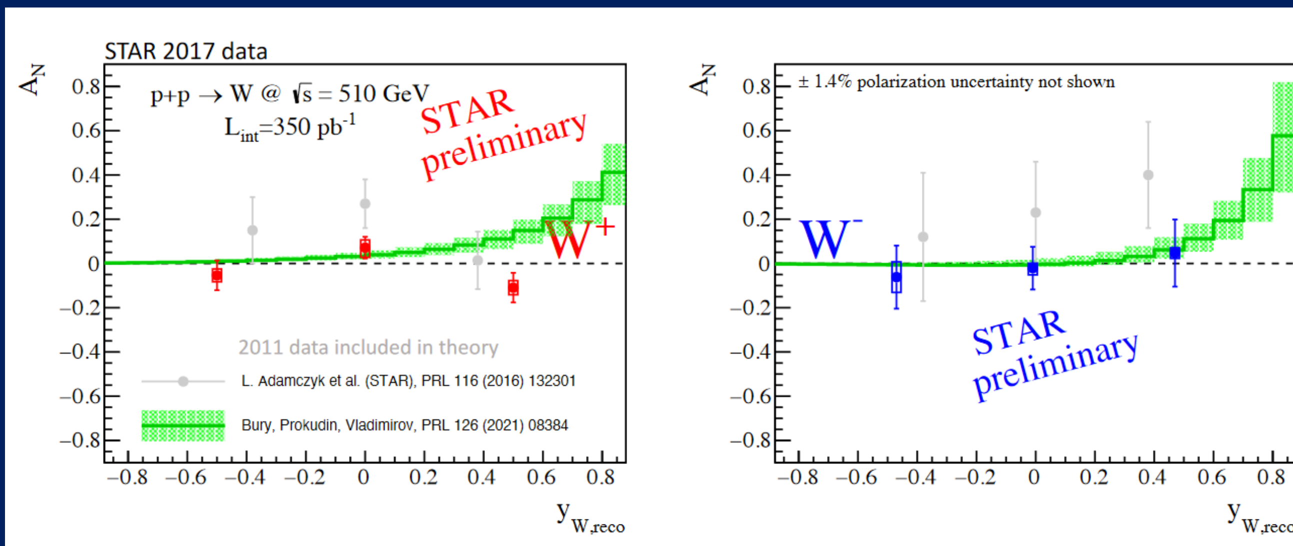
$$\eta^{\text{total}} = \eta_1 + \eta_2 \propto \ln\left(\frac{x_1}{x_2}\right)$$

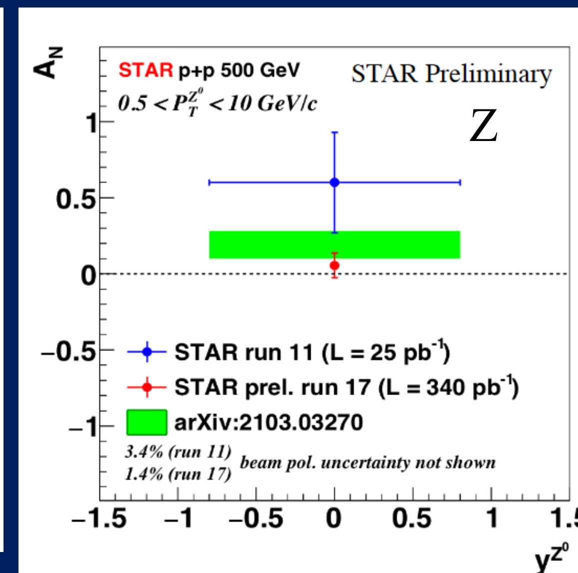


Non-zero k_T leads to spin-dependent tilt of di-jet opening angle in transverse plane

- First non-zero Sivers asymmetries in di-jet production in polarized pp collisions
  - Expect no effect on average: enhance contribution of u or d quarks by sorting jets by their net charge
  - $\langle k_T \rangle$ for d opposite in sign, twice as large as average $\langle k_T \rangle$ for u quarks
- Constraints for the Sivers function at a high Q^2 scale ($Q^2 > 160$ GeV^2)

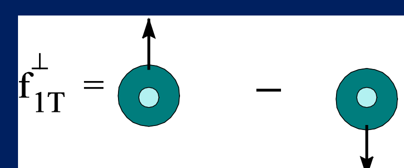
Sivers Asymmetries for $W^{\pm}$ and Z in p+p





- A_N of weak bosons sensitive to Sivers sign-change and TMD evolution effects, complementary to Drell-Yan (DY)
- Test of nonuniversality of Sivers function

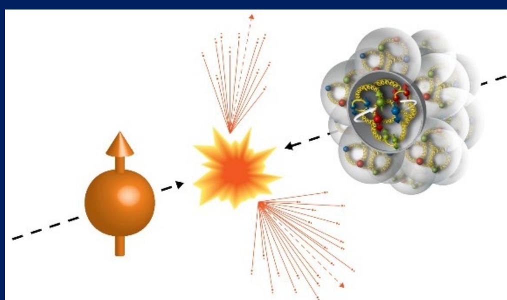
$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{SIDIS}$$



- Greatly improved uncertainties using STAR 2017 data

Nuclear Dependence of A_N for Forward Hadrons

In 2015 RHIC took transversely polarized data for $p^{\uparrow}p$, $p^{\uparrow}$Al and $p^{\uparrow}$Au

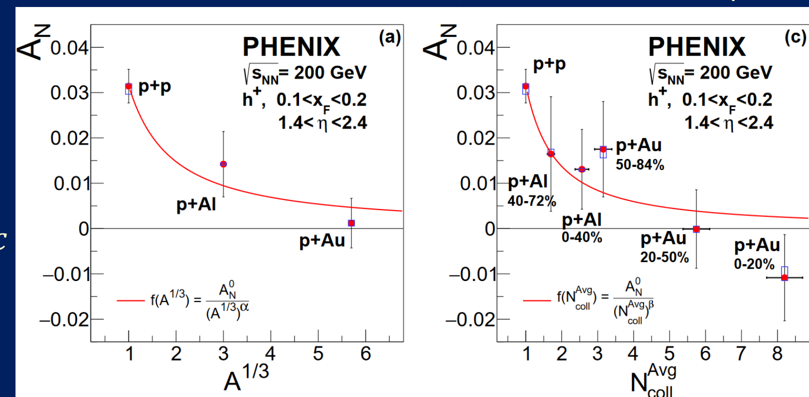


PHENIX, PRL **123**, 122001 (2019)

PHENIX forward charged hadron A_N

$1.4 < \eta < 2.4$
$0.1 < x_F < 0.2$
$1.8 < p_T < 7$ GeV/c

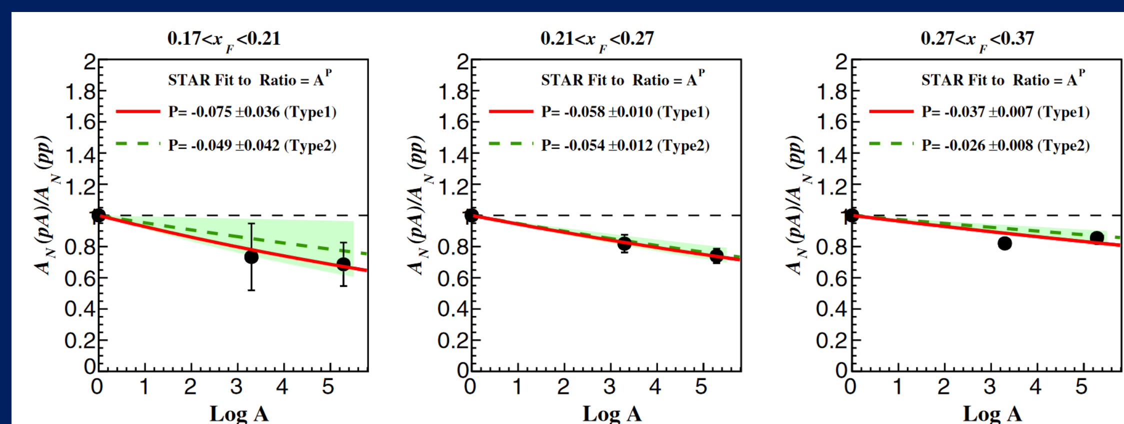
Noticeable A_N suppression in pA collision



STAR forward π^0 A_N

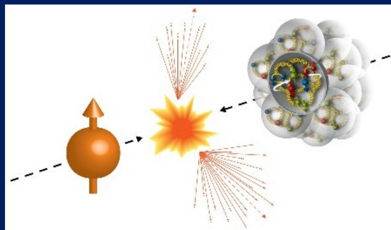
$2.6 < \eta < 4.0$
$0.2 < x_F < 0.7$
$1.5 < p_T < 7$ GeV/c

Less striking A dependence



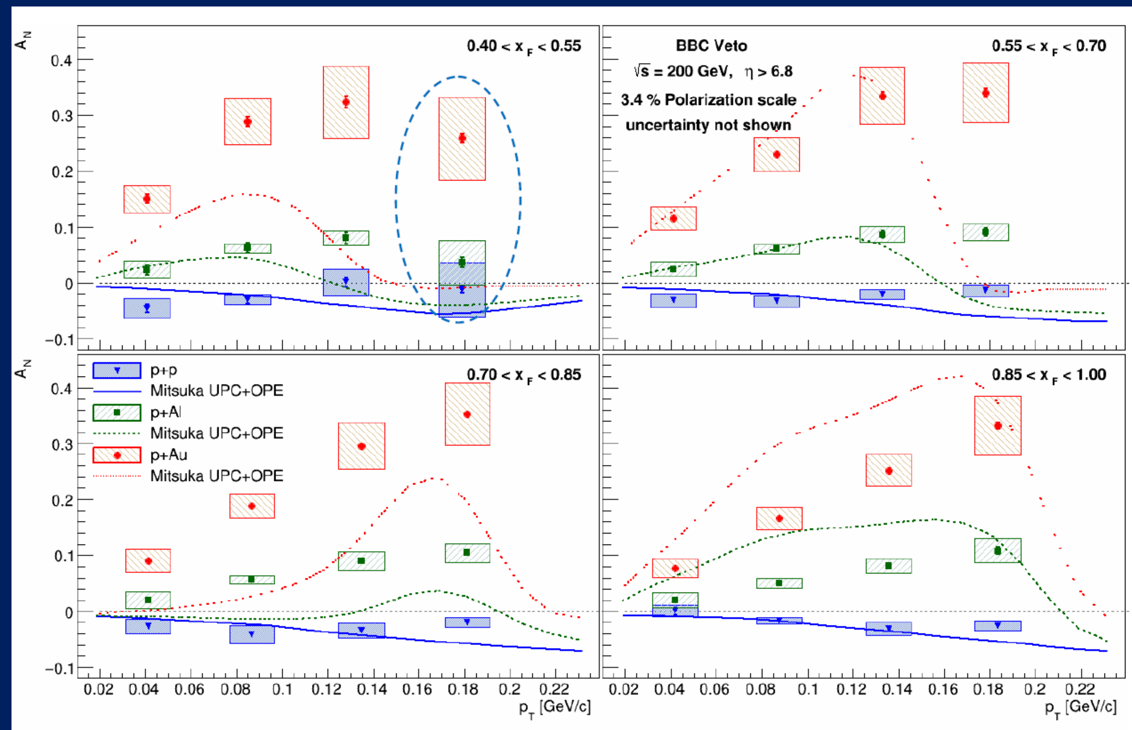
STAR, PRD **103,** 072005 (2021)

Nuclear Dependence of A_N for Forward Neutrons



- Large nuclear dependence previously measured in *pp*, *p*Al and *p*Au
  - PHENX, PRL **120**, 022001 (2018)
- Now measured in *pA* as a function of p_T and x_F
- Enhancement of contributions from ultraperipheral collisions (UPC) over one-pion exchange (OPE) as charge of the nucleus increases
  - Leads to sign flip in asymmetries for *pp* vs. *pA*
  - Generally described by calculations qualitatively

arXiv:2110.07504



See also PRD **103**, 032007 (2021)

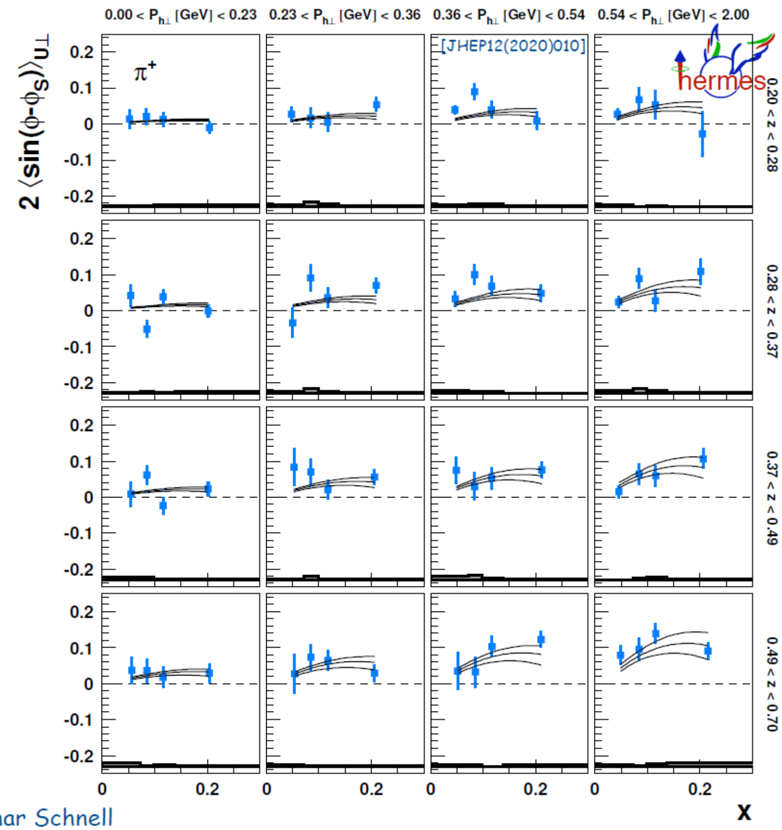
Summary

- Lots of measurements of proton spin structure in the past two years!
- Complementary collision systems and observables allow us to probe and disentangle different aspects of nucleon structure
- Still plenty to learn about spin-spin and spin-momentum correlations within longitudinally and transversely polarized protons
- See the following talks today and the Imaging & 3D Structure session on Friday for more information

Backup

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes
multi-dimensional analysis



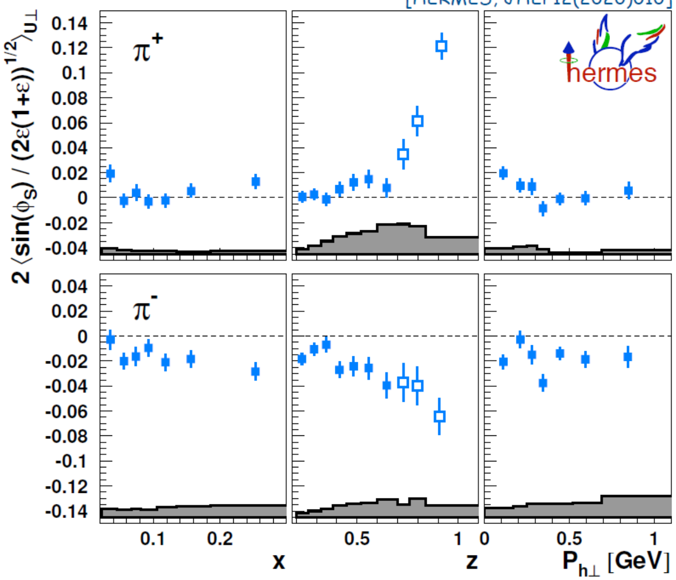
- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
  - reduced systematics
  - disentangle correlations
  - isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distributions to guide phenomenology*)

*) see, e.g., backup slides or supplemental material of JHEP12(2020)0210

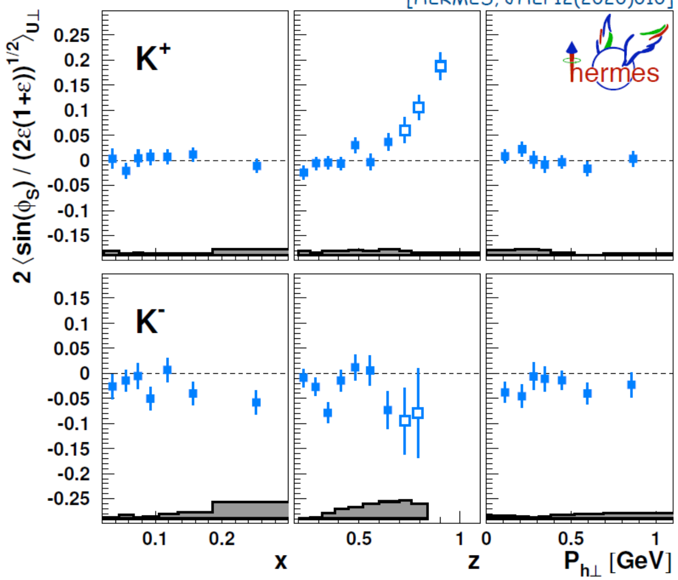
Gunar Schnell 14 SPIN 2021

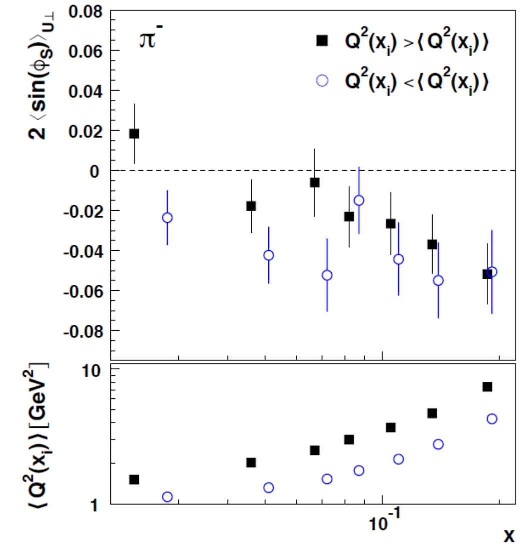
subleading twist — $\langle \sin(\phi_S) \rangle_{UT}$

[HERMES, JHEP12(2020)010]

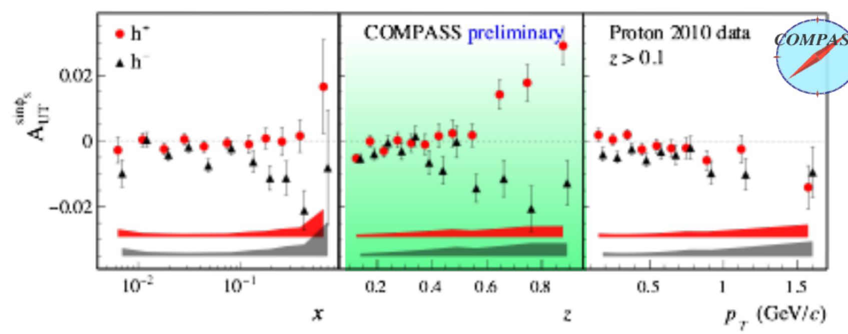


[HERMES, JHEP12(2020)010]





- clearly non-zero asymmetries with opposite sign for charged pions (Collins-like behaviour)
- striking z dependence and in particular magnitude
- hint of Q suppression
- similar z behaviour seen at COMPASS



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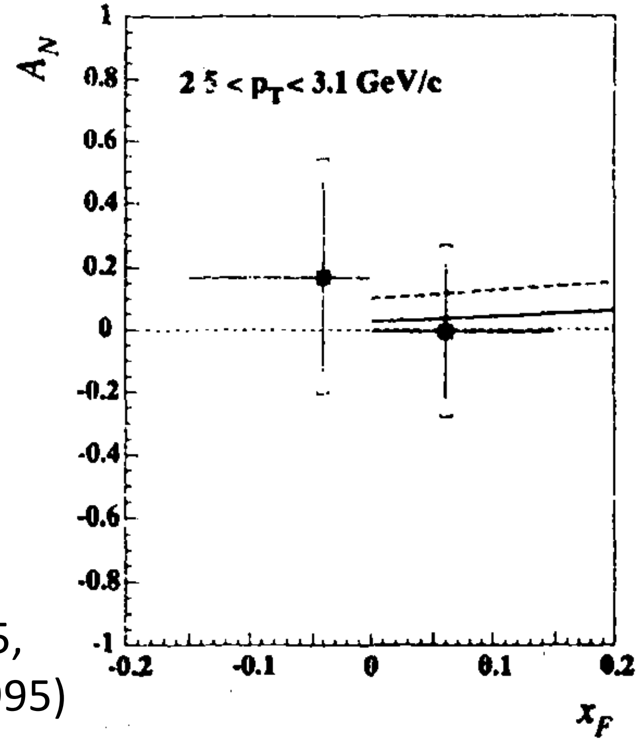
Inclusive direct photon A_N from Fermilab E704

- $\sqrt{s} = 19.4$ GeV

x_F	x_F^{avg}	A_N (%)
−0.15–0.00	−0.04	16.7±30.0±7.4
0.00–0.15	0.06	−0.6±21.6±5.7



E704, PLB 345, 569 (1995)

Fig. 5. Single transverse spin asymmetry, A_N, for direct photon production in pp collisions at 200 GeV/c as a function of x_F. Statistical errors are indicated as error bars and systematic errors are indicated as squared brackets. Solid and dashed curves show theoretical predictions at $\sqrt{s}$ = 30 GeV and p_T = 4.0 GeV/c assuming two types of the quark-gluon correlation strength [5].

Direct photon background:
Hadron decay photons with missing partner

Sometimes only one of the photons from a $h \to \gamma\gamma$ decay is measured and the second photon is missed

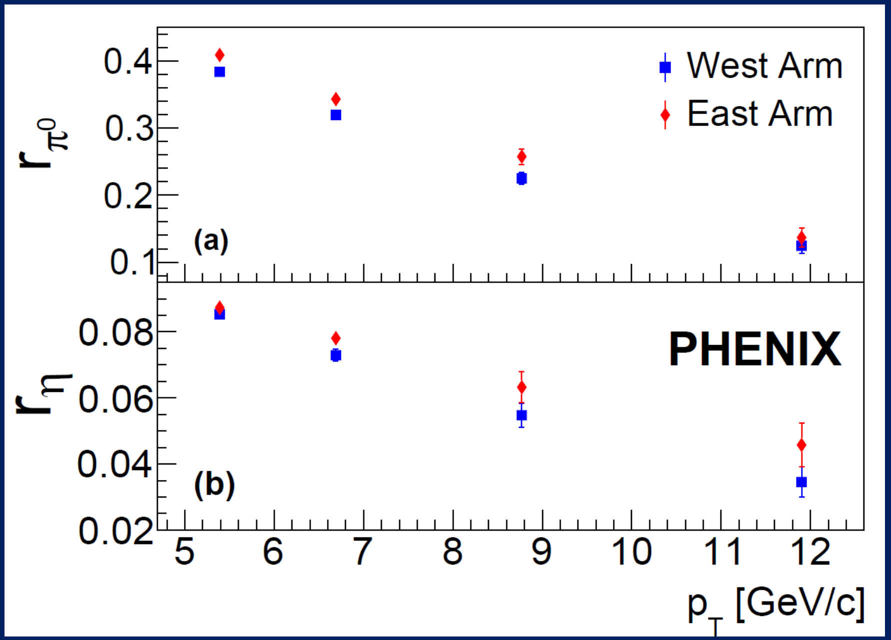
- η decays tend to be more asymmetric because they are ~4 times heavier than π^0s

Estimate number missed using ones that were tagged:

From data: Ratio of number isolated decay photons to direct photon candidate sample

$$r_{miss} = \frac{N_{bg}}{N_{sig} + N_{bg}} = R\,\frac{N_{tag}^{iso,h}}{N^{iso}}$$

From simulation: Converts between tagged decay photons to missed decay photons



PRL 127, 162001 (2021)

Direct photon background: *Merging of π^0 decay photons*

Photon merging - sometimes the two photons from a $\pi^0 \rightarrow \gamma\gamma$ decay are so close together that the EMCal cannot resolve them as separate photons

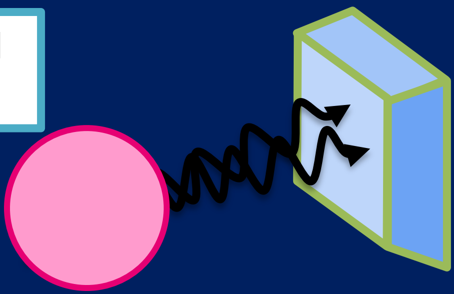
Similar to the background fraction due to missing one of the decay photons

From Data: Ratio of number isolated decay photons to direct photon sample

$$r_{merge} = \frac{N_{bg}}{N_{sig} + N_{bg}} = \frac{N_{merge}}{N_{tag}} \frac{N_{tag}^{iso,h}}{N^{iso}}$$

From Simulation: Converts between tagged decay photons and merged π^0 photons

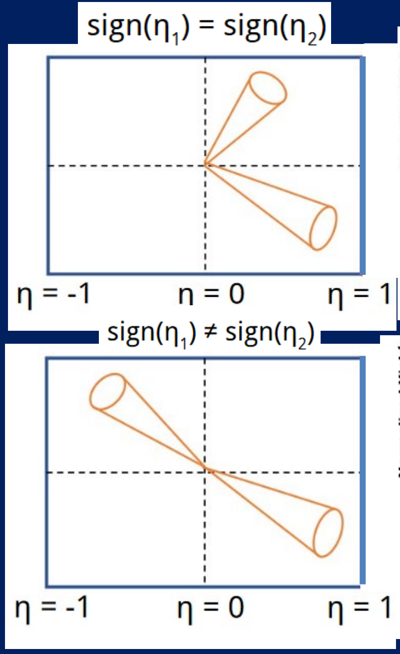
Found to be negligible after a cluster shower shape cut

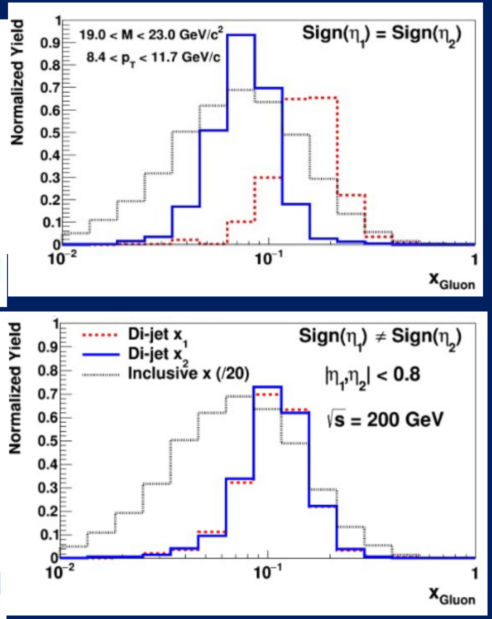


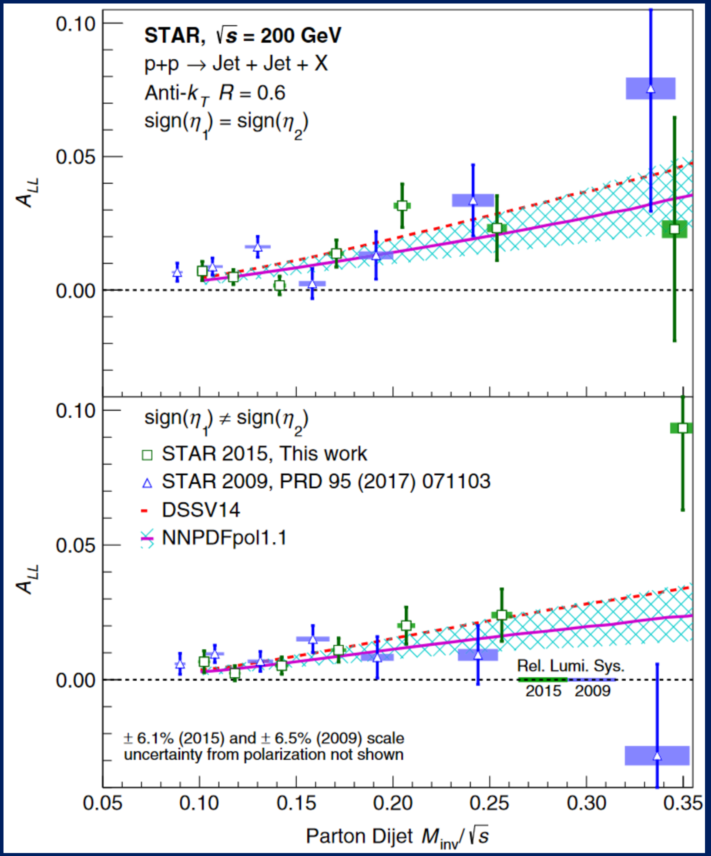
Dijet A_{LL}

Di-jets give stricter constraints to underlying partonic kinematics

May place better constraints on the x-dependences of $\Delta g(x, Q^2)$





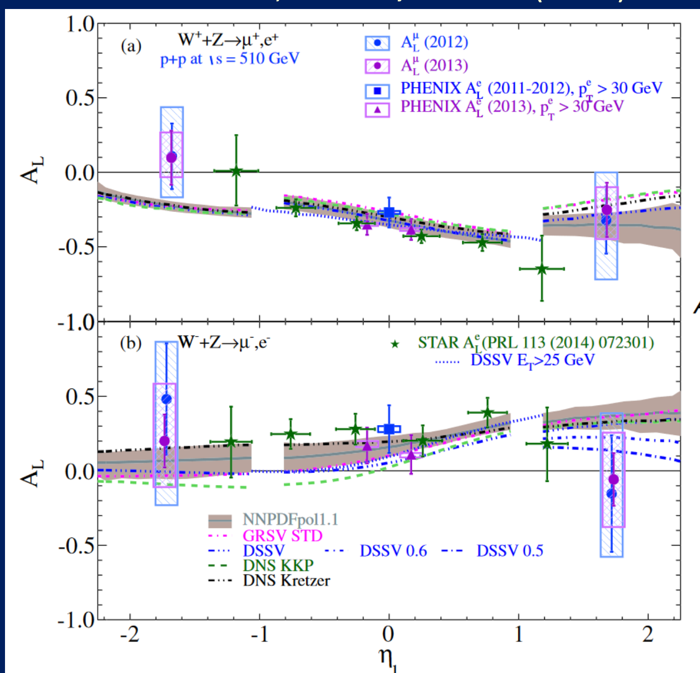


STAR, **PRD** 103, L091103 (2021)

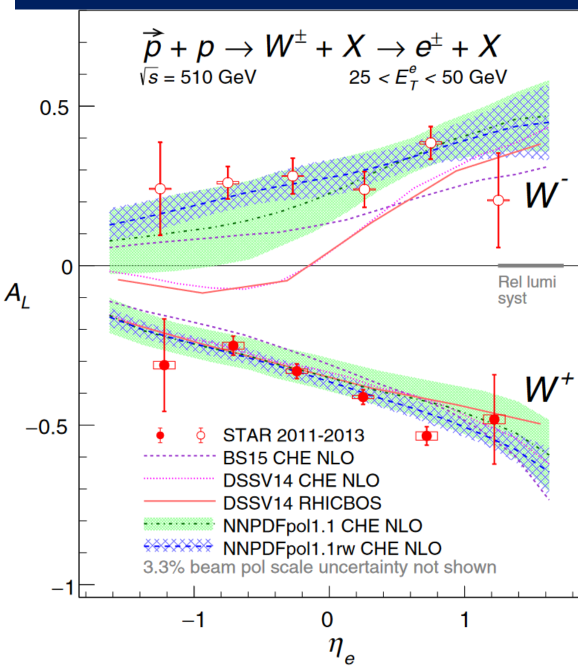
Single-Spin Asymmetry for W Production

Sensitive to antiquark helicities

PHENIX, PRD **98,** 032007 (2018)

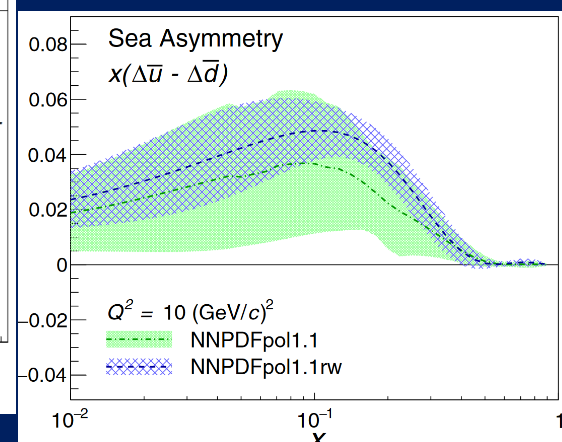


STAR, PRD **99**, 051102(R) (2019)



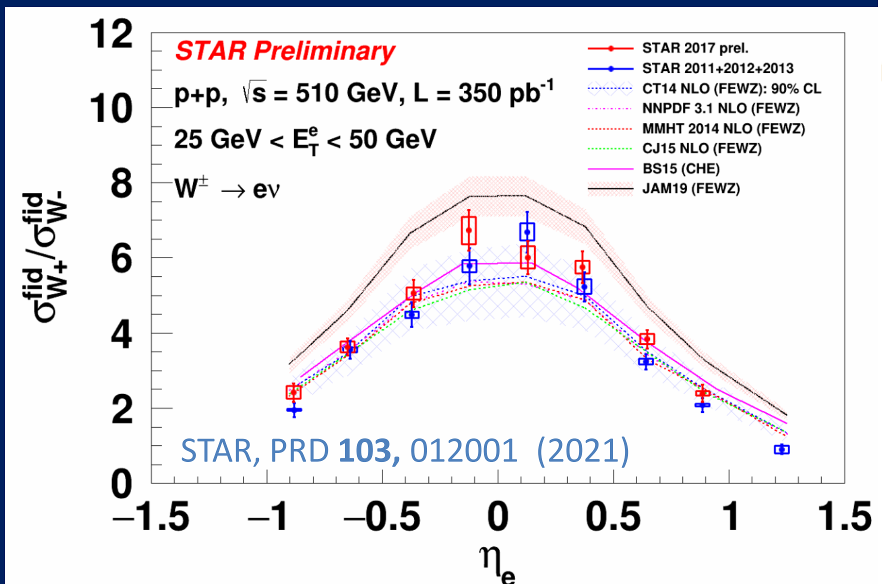
Clear evidence for a polarized flavor asymmetry of the quark sea

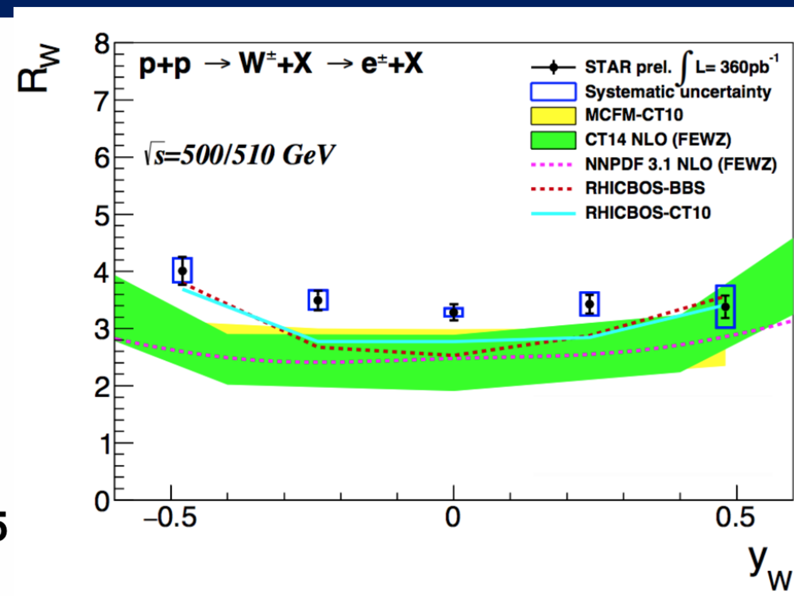
Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$



Cross Section Ratio for W Production

Sensitive to the unpolarized $\bar{d}(x)/\bar{u}(x)$ quark distribution



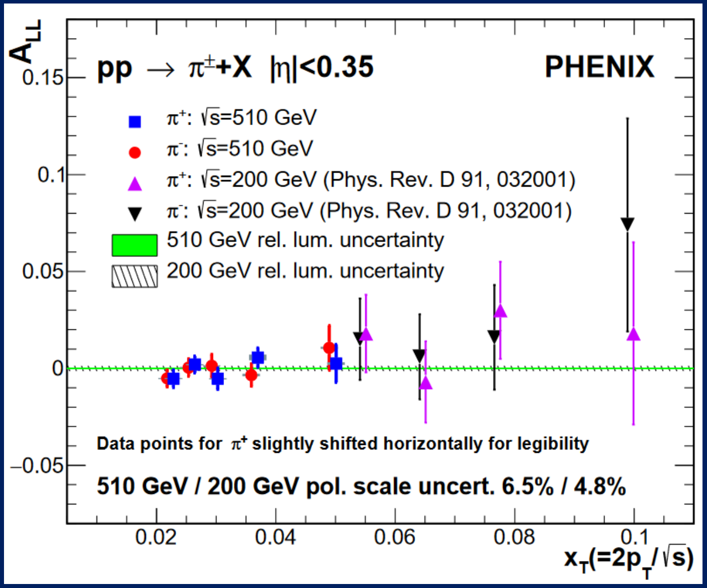


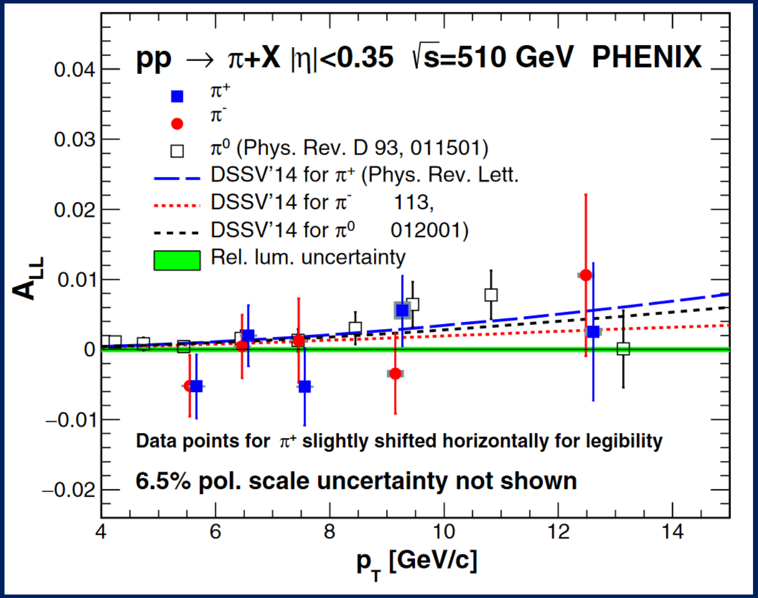
W^+/W^- cross section ratio at STAR complementary to the Drell-Yan data

- Data cover overlapping region of $0.1 \lesssim x \lesssim 0.3$

Charged Pion A_{LL}

PHENIX, PRD **102**, 032001 (2020)





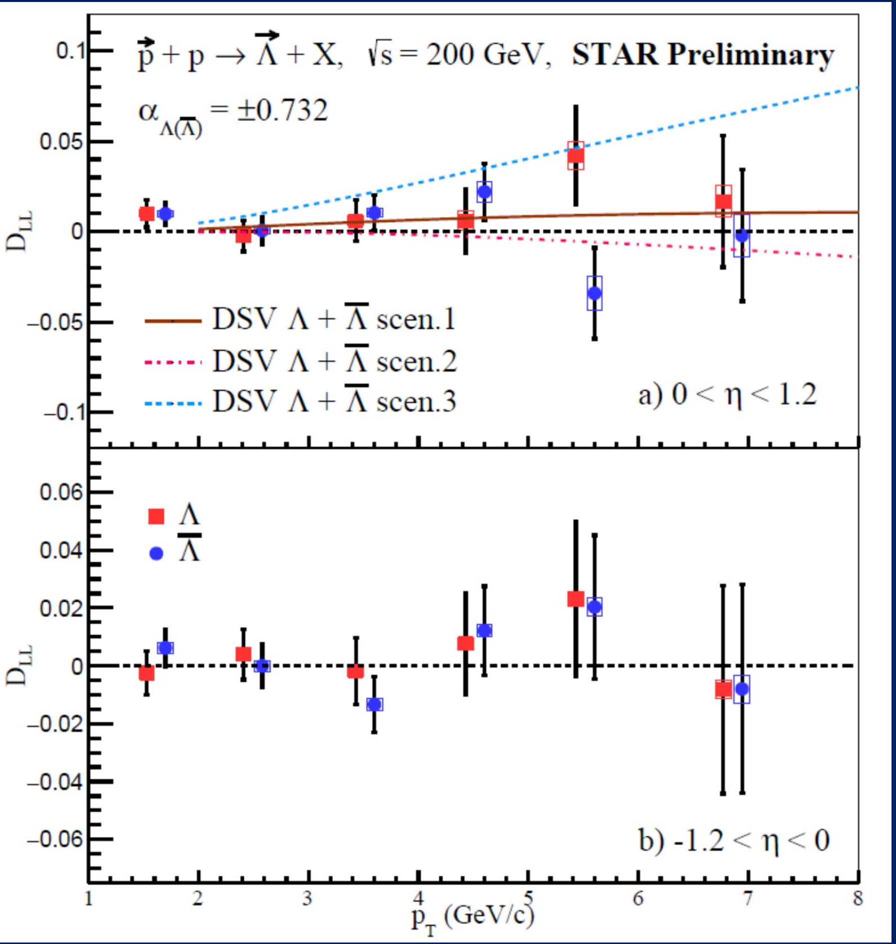
- 510 GeV data probes low x range, down to $x \approx 0.04 - 0.09$
- Consistent with DSSV14
- Ordering of the positive, neutral, and negative pion asymmetries is sensitive to the sign of the gluon polarization since the up and down quark polarizations are relatively well known

Longitudinal Spin Transfer to Lambda Hyperons

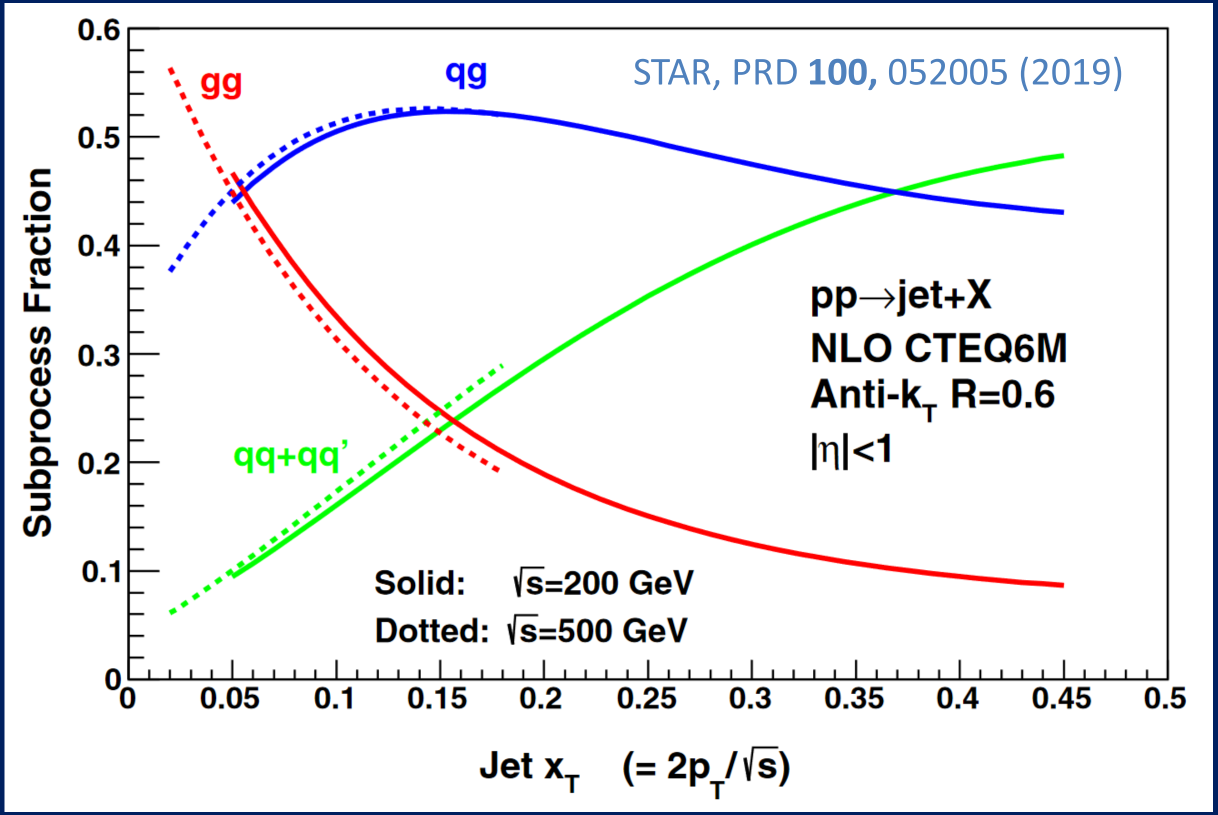
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

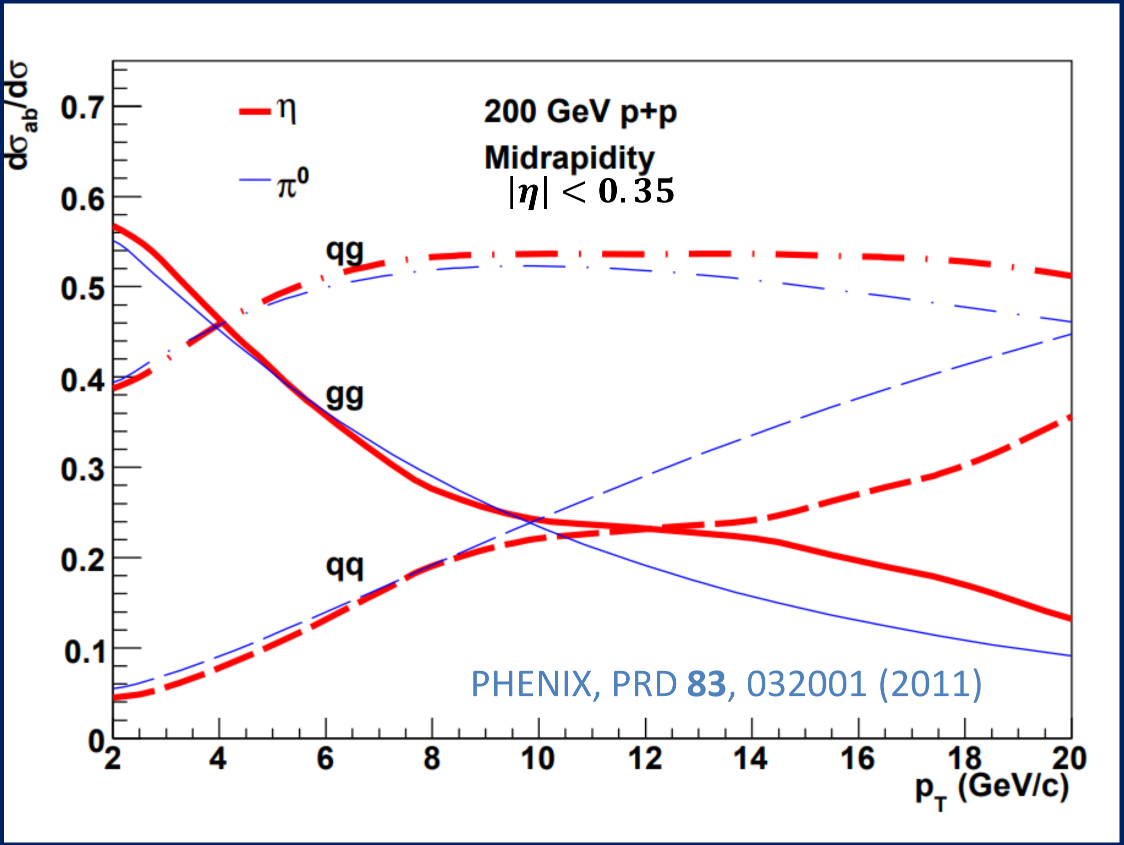
- Sensitivity to strange helicity distributions and polarized fragmentation



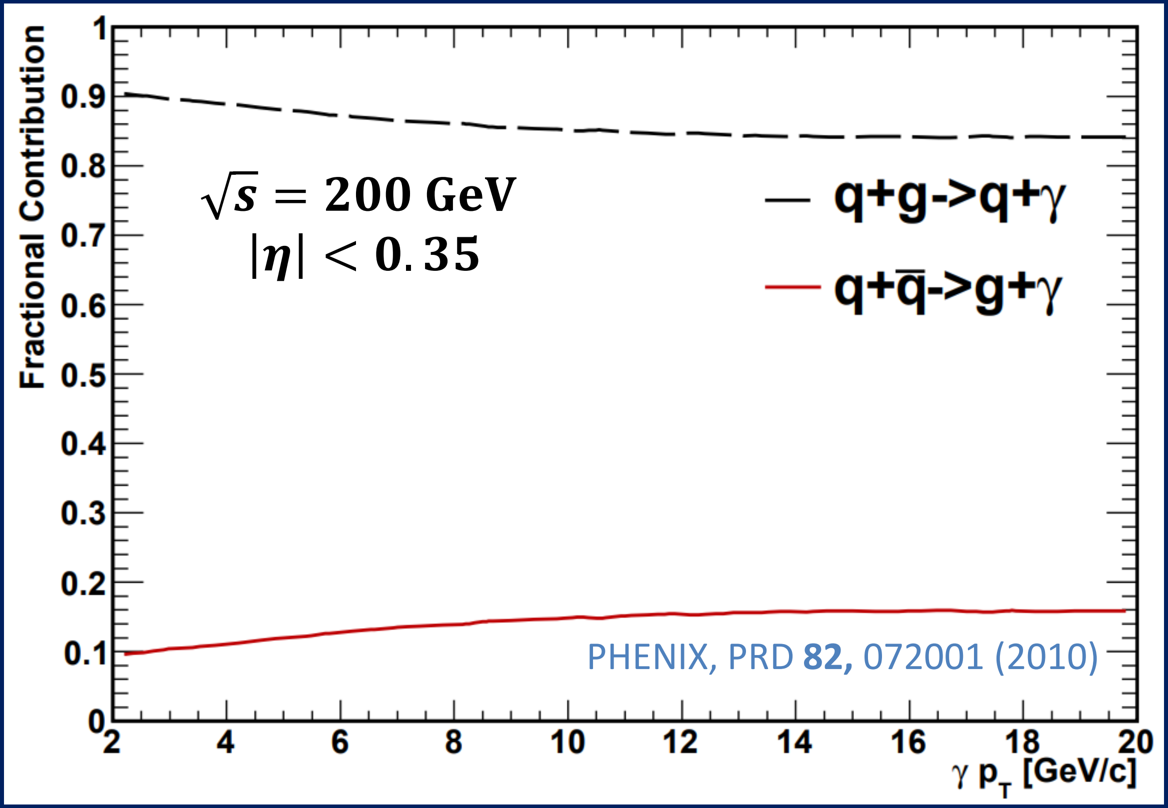
Partonic Fractional Contributions to Central Jets at STAR



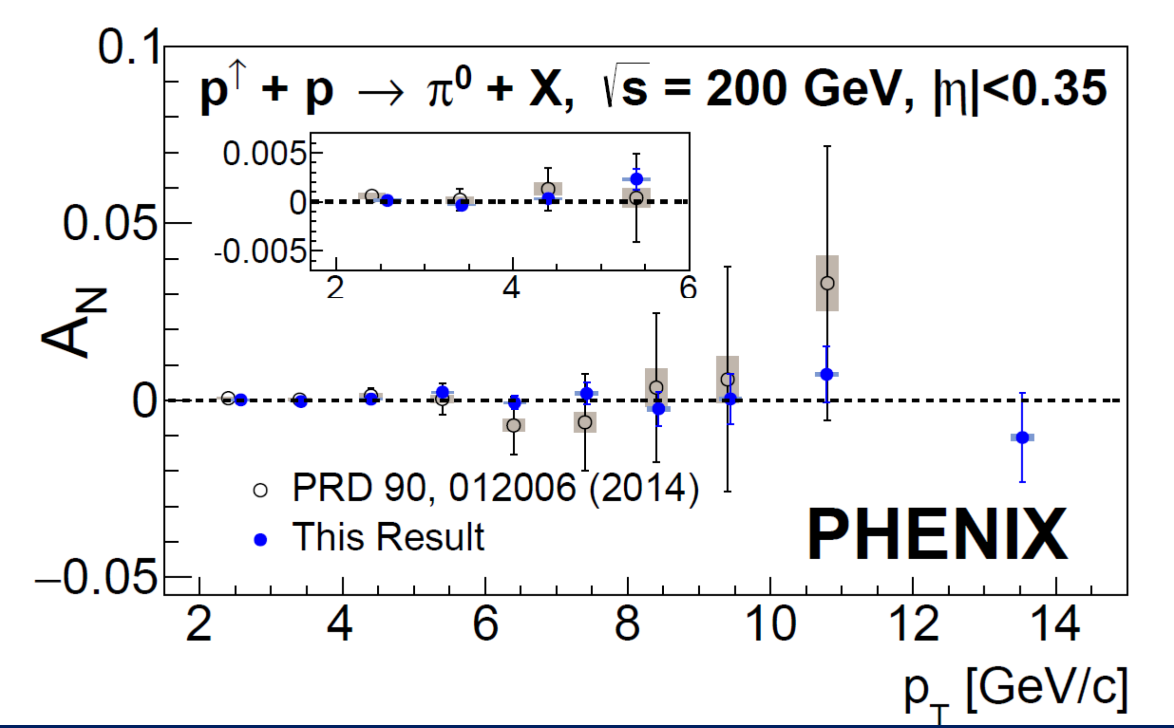
Partonic Fractional Contributions to Midrapidity π^0 and η Mesons at PHENIX



Partonic Fractional Contributions to Midrapidity Direct Photons at PHENIX



Midrapidity neutral pion A_N



PRD103, 052009 (2021)

- Consistent with zero to within 10^{-4} at low p_T
- Definitive results from PHENIX, from final $p^{\uparrow} + p$ data taken in 2015
- Factor of 3 improvement in statistical uncertainty with respect to previous result, and higher reach in p_T

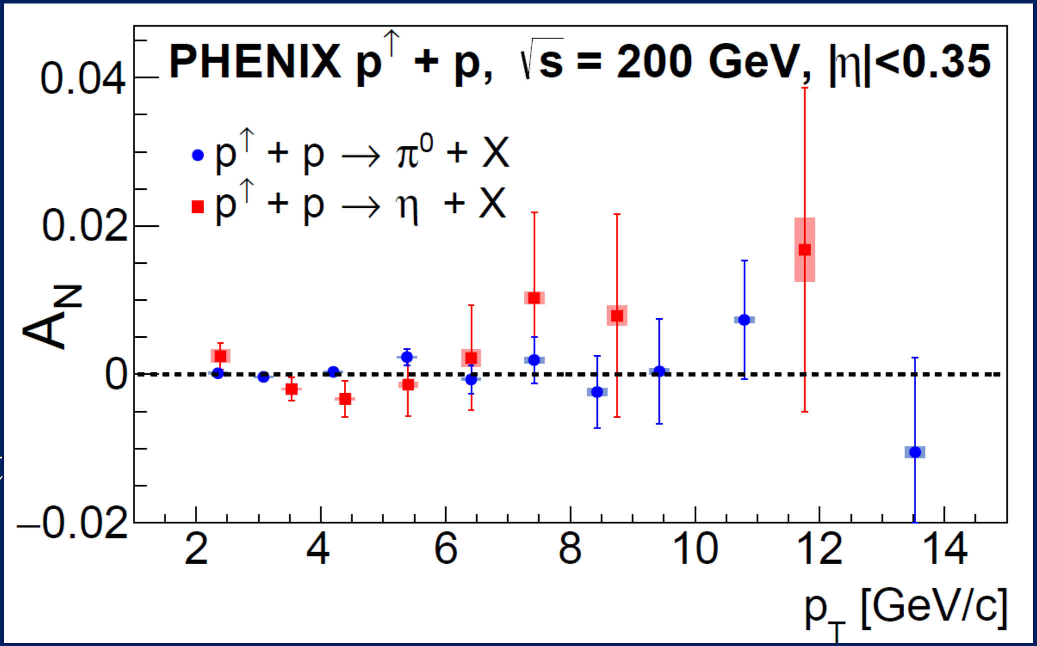
Midrapidity π^0 and η A_N in p+p

- π^0: Consistent with zero to within 10^{-4} at low p_T
- η: Consistent with zero to within 5×10^{-3} at low p_T
- Any differences in π^0 and η A_N could be due to effects of strangeness or isospin in hadronizat

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

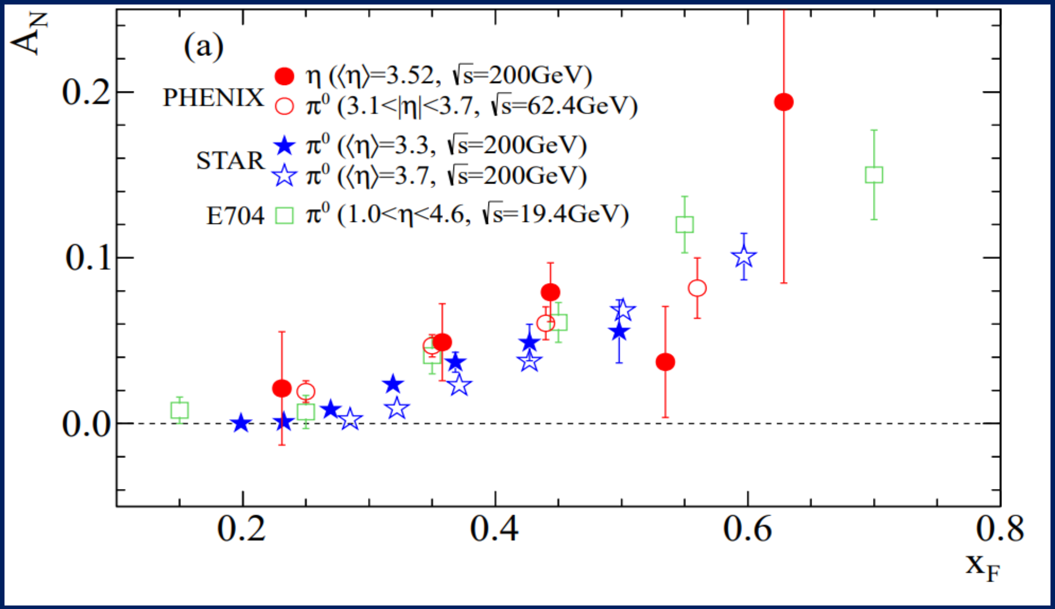
$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

- Or to mass effects in hadronization: $m_{\pi^0} \approx 135$ MeV/c^2 $m_\eta \approx 548$ MeV/c^2

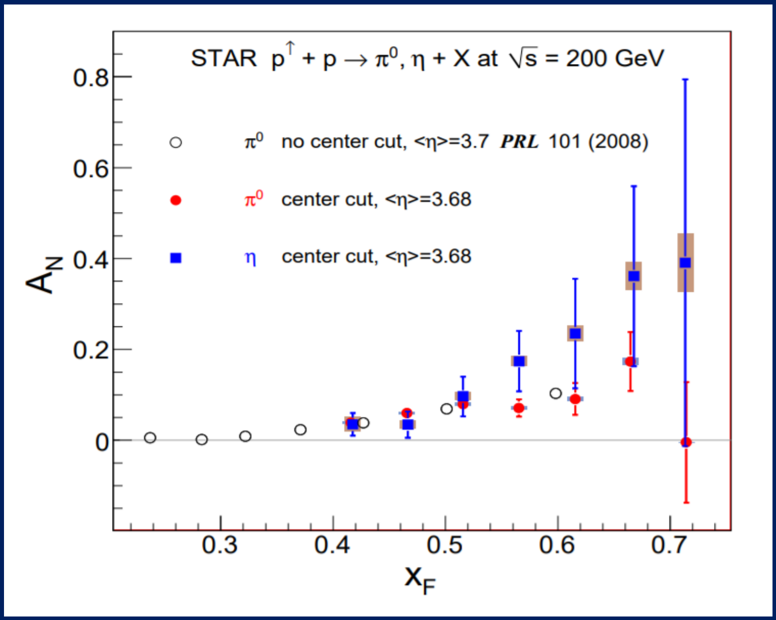


PRD103, 052009 (2021)

Comparing forward π^0 and η results



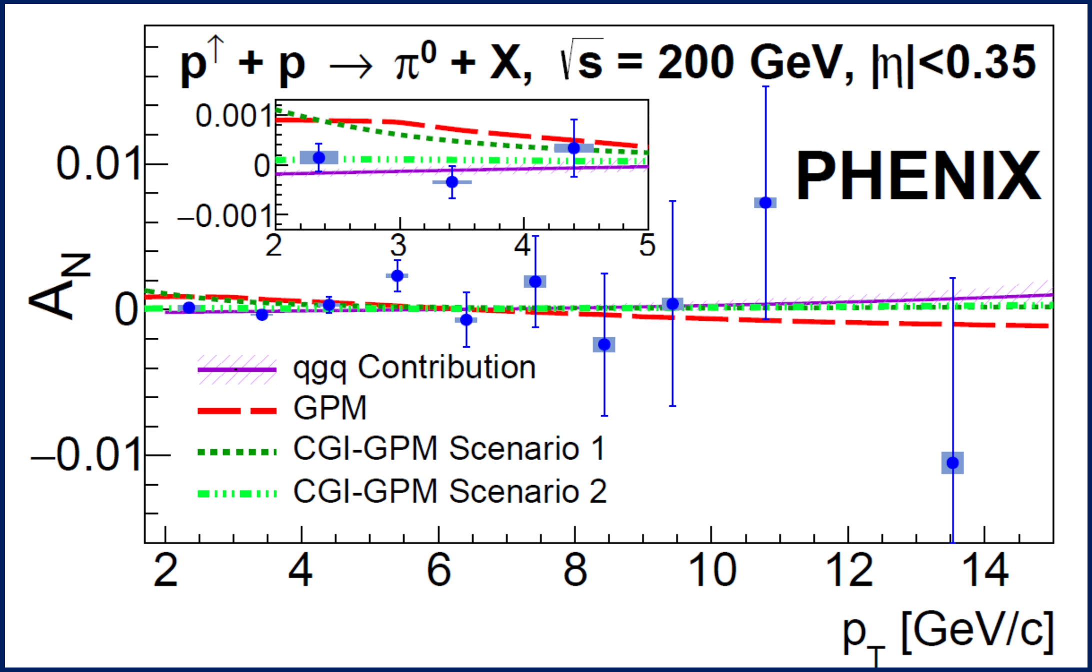
PHENIX, PRD 90, 072008 (2014)



STAR, PRD 86, 051101(R) (2012)

- Forward rapidity: Large contribution of quarks coming from the polarized proton
- Results hint that A_N^{η} may be larger than $A_N^{\pi^0}$ at forward rapidity. Further studies required.

Midrapidity $A_N^{\pi^0}$: Theoretical predictions



PRD103, 052009 (2021)

- Very small qgq correlator contribution predicted
  - JAM Collaboration, PRD 102, 054002 (2020)
- Results can help constrain gluon spin-momentum correlations
  - Twist-3 trigluon correlators (Beppu, Kanazawa, Koike, Yoshida, PRD 89, 034029 (2014))
  - Gluon Sivers function – in the Generalized Parton Model (GPM) (D'Alesio Flore, Murgia, Pisano, Taels, PRD 99, 036013 (2019))

Transversity PDF × Interference Fragmentation Function (IFF) Asymmetry in p+p

Dihadron Interference FF