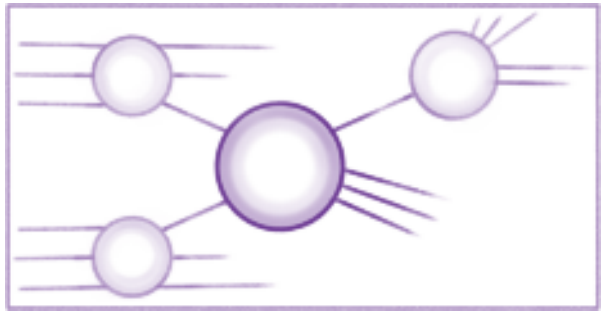
The Cold QCD Program at RHIC



Oleg Eyser

Brookhaven National Laboratory

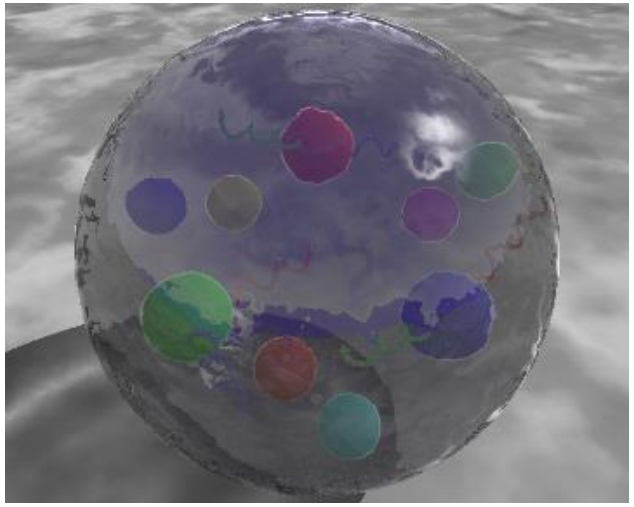
7th International Workshop on
Transverse Phenomena in Hard Processes
and the Transverse Structure of the Proton

June 3-7, 2024

Trieste

Brookhaven National Laboratory

Cold QCD at RHIC



- What is the nature of the spin of the proton?
  - Gluon polarization
  - Sea quark polarization

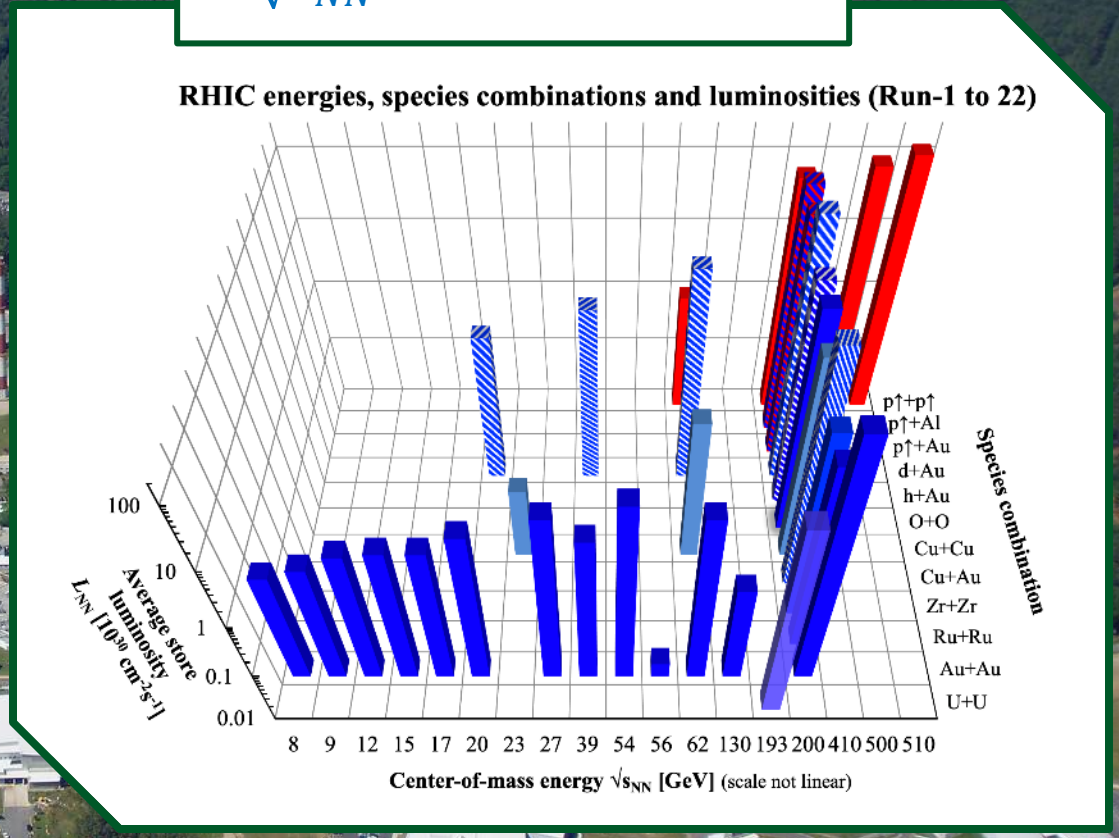
arxiv:1602.03922

- What do transverse spin phenomena teach us about the proton structure?
- How can we describe the multi-dimensional landscape of nucleons and nuclei?
- How do quarks and gluons hadronize into final state particles?

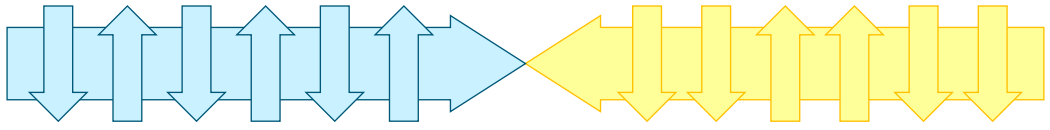
- The RHIC Cold QCD Program, arxiv:2302.00605
- Upcoming RHIC Spin Plan for 2024 to 2028: Completing the RHIC Science Mission

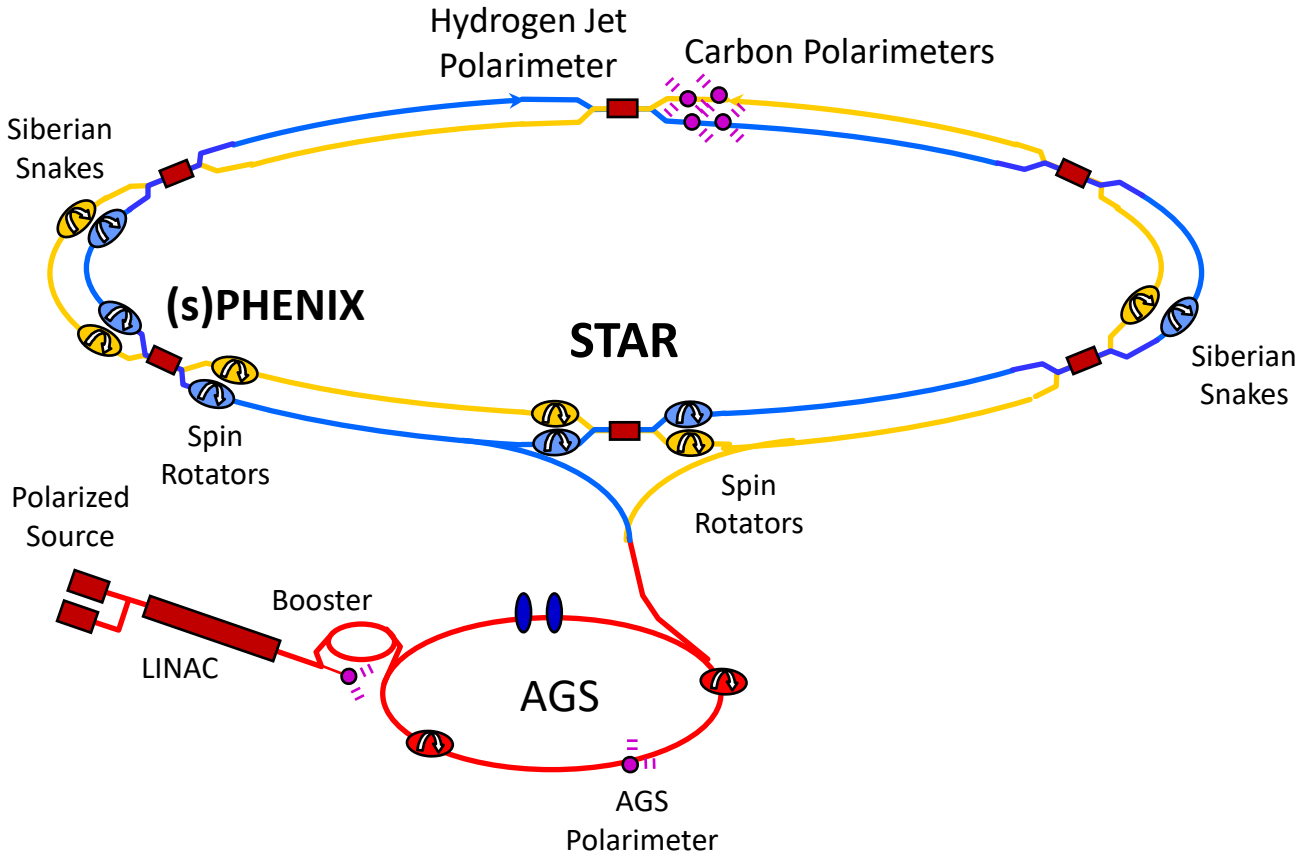
$\vec{p} + \vec{p}$ / $\vec{p} + A$ / $A + A$

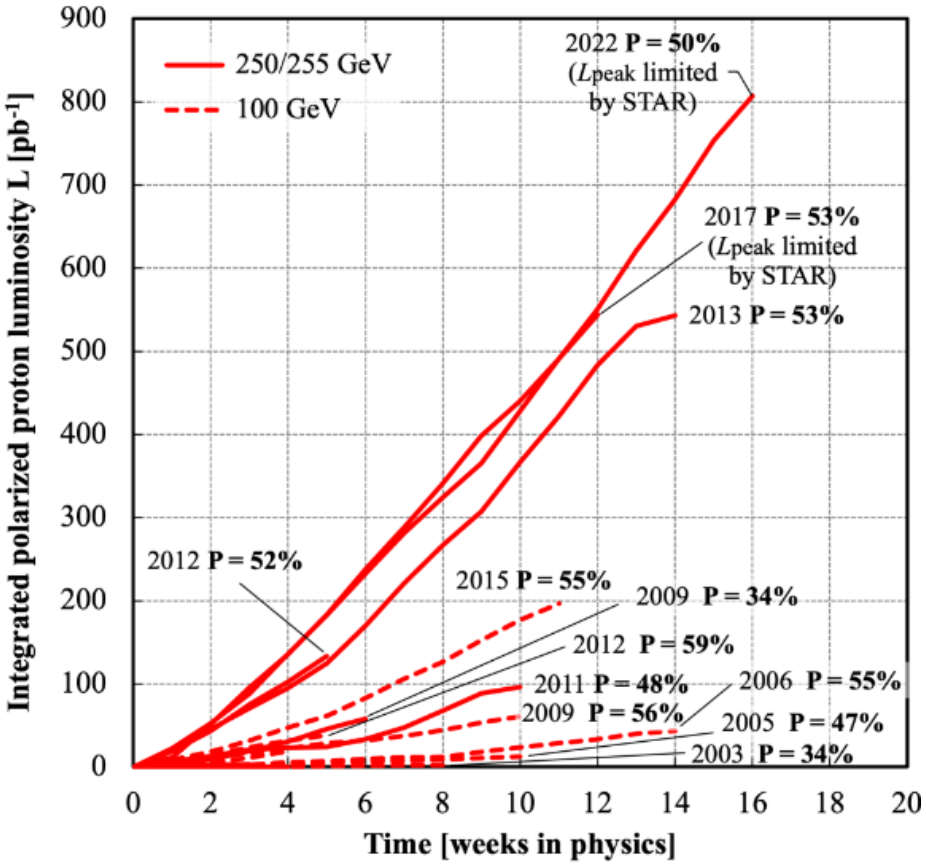
$\sqrt{s_{NN}} = 7.7 - 510$ GeV



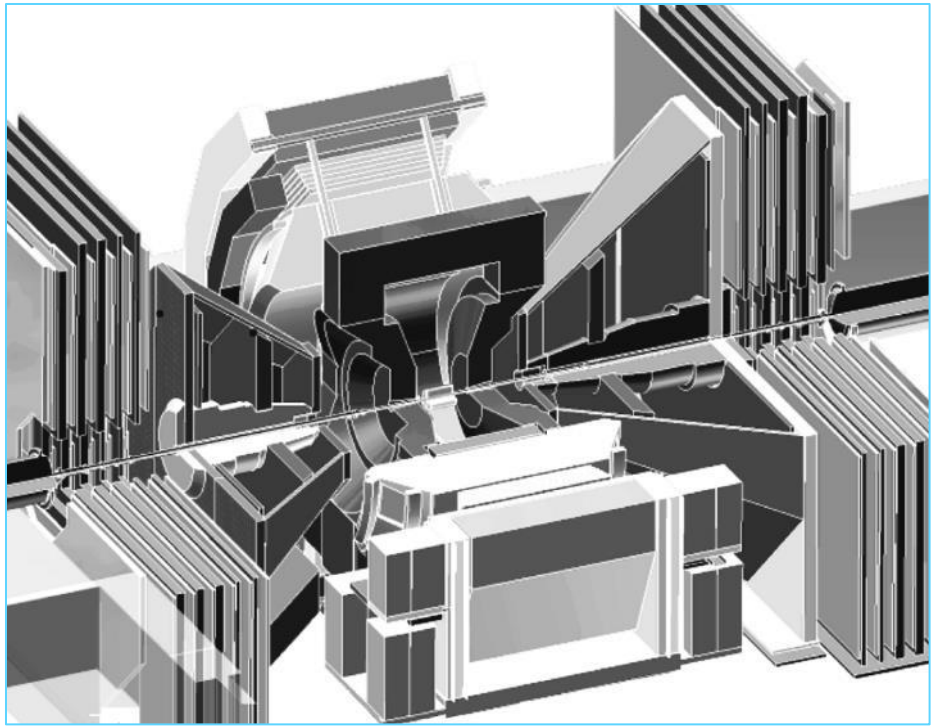
RHIC as a Polarized Proton Collider







RHIC Run 24: p+p at $\sqrt{s} = 200$ GeV



PHENIX

High resolution

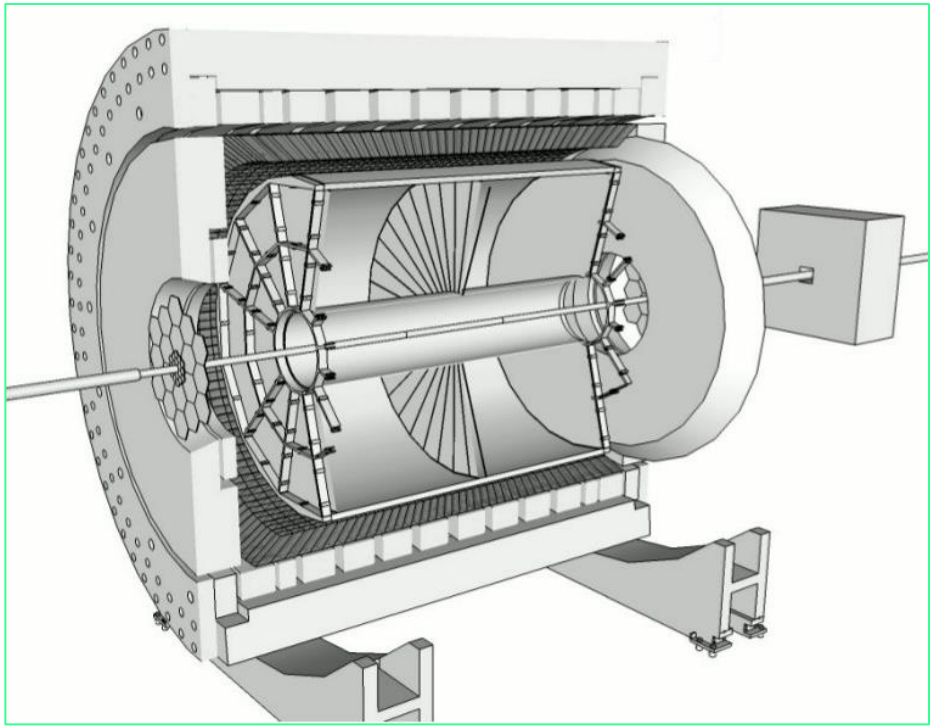
High rate

DC / Pad Chambers / Muon Arms

EMCal

Forward EMCal, $3 < |\eta| < 4$

→ talk by **Jeongsu Bok**



STAR

Large acceptance

$-1 < \eta < 2$

TPC+TOF

EMCal

Forward EMCal, $2.5 < \eta < 4$

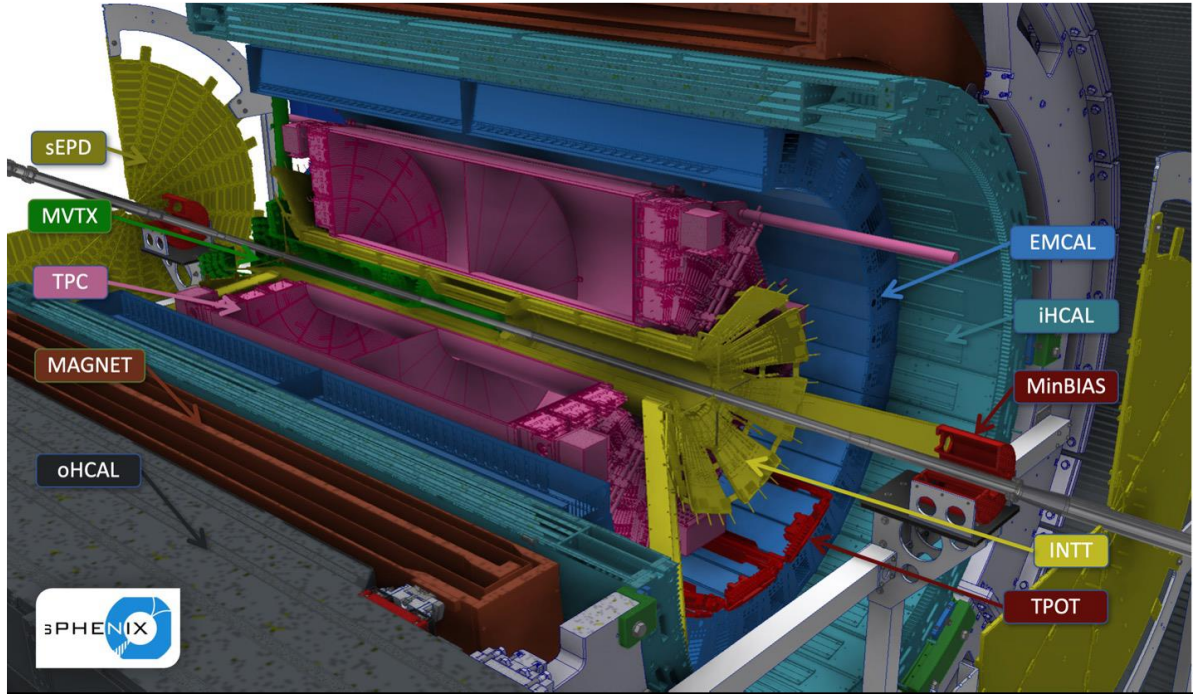
→ talk by **Bassam Aboona**

sPHENIX

$-1.1 < \eta < 1.1$

Precision tracking

Ecal + Hcal



STAR

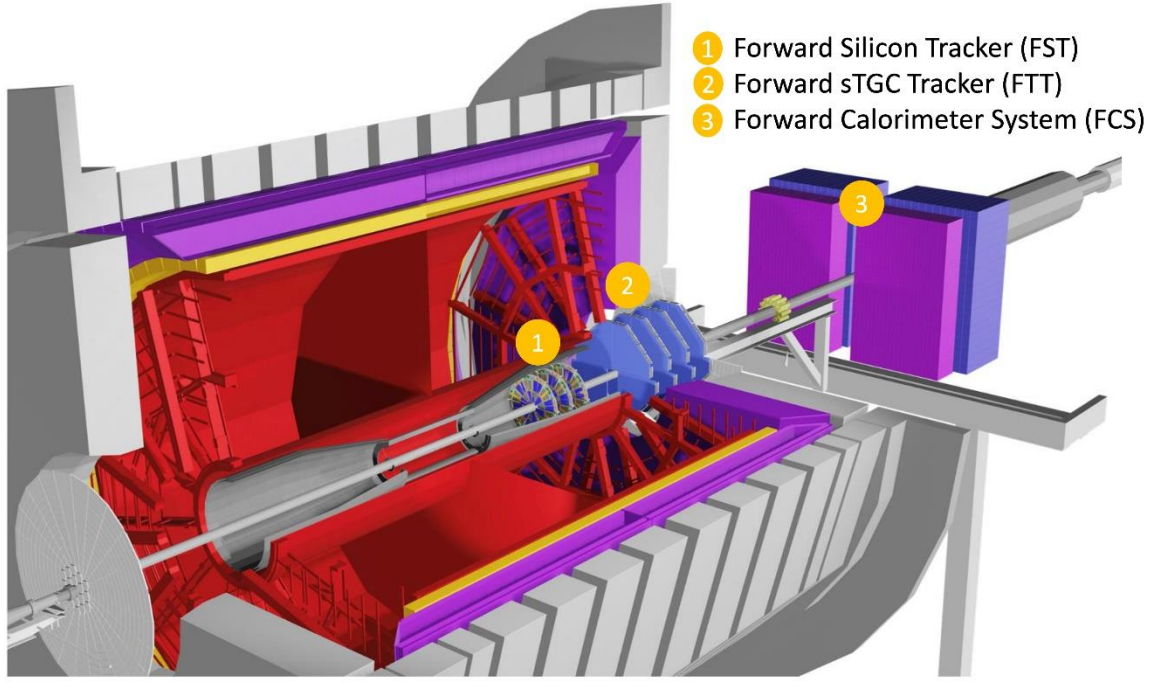
Forward detectors

$2.5 < \eta < 4$

Si & sTGC trackers

Ecal & Hcal

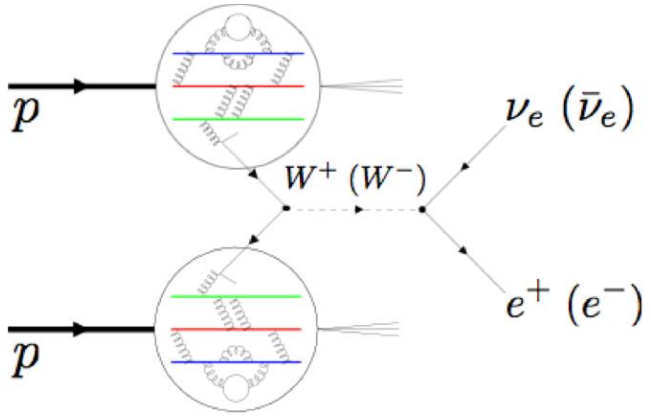
with EPD (preshower)



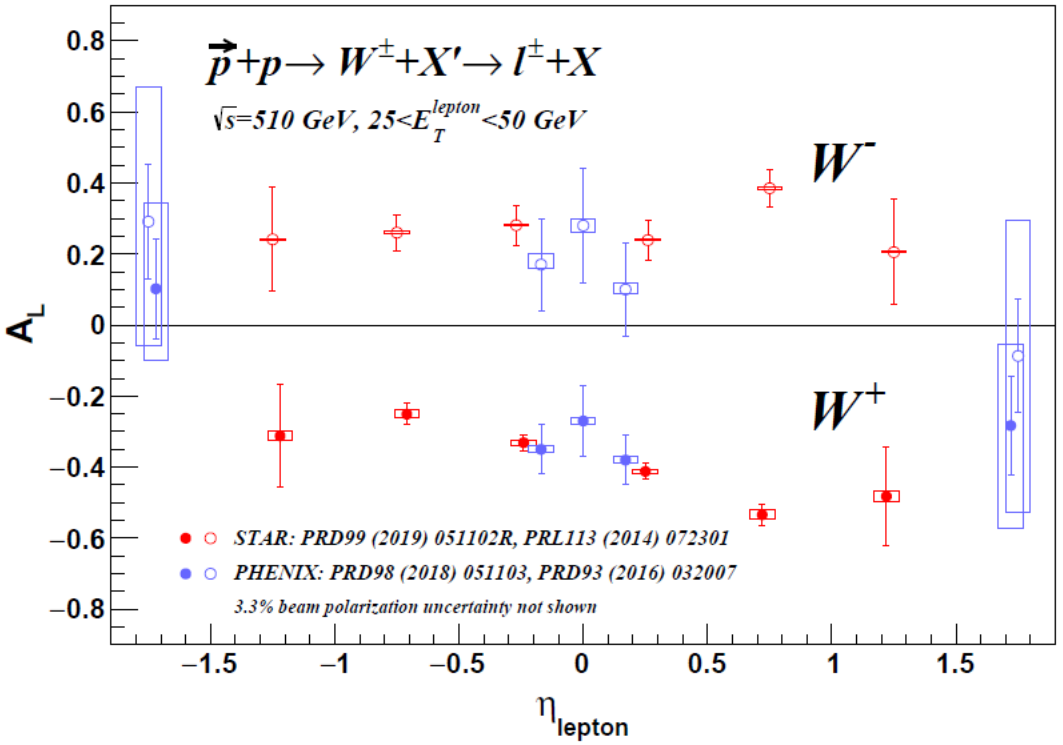
Sea Quark Polarization

- Parity violating single-spin asymmetry

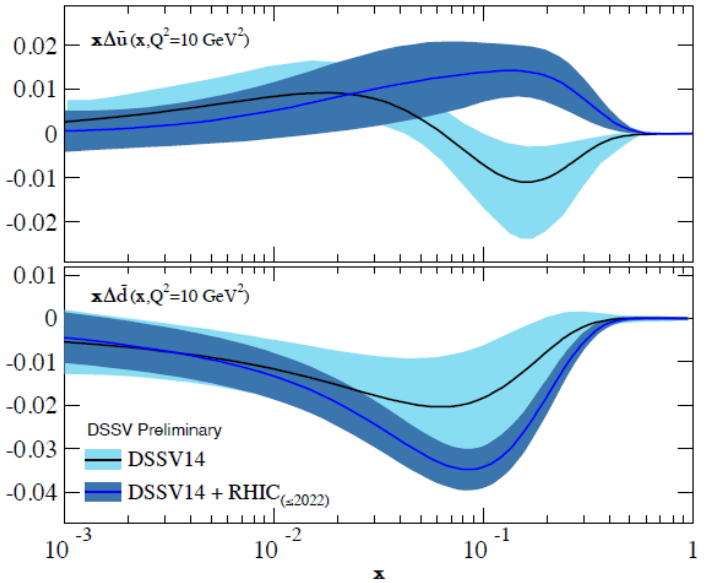
$$A_L = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta\mathrm{d}(\mathrm{x}_1)\bar{\mathrm{u}}(x_2)(1+\cos\theta)^2}{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + \Delta\mathrm{d}(\mathrm{x}_1)\bar{\mathrm{u}}(x_2)(1+\cos\theta)^2}$$



$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}$ $p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm}$

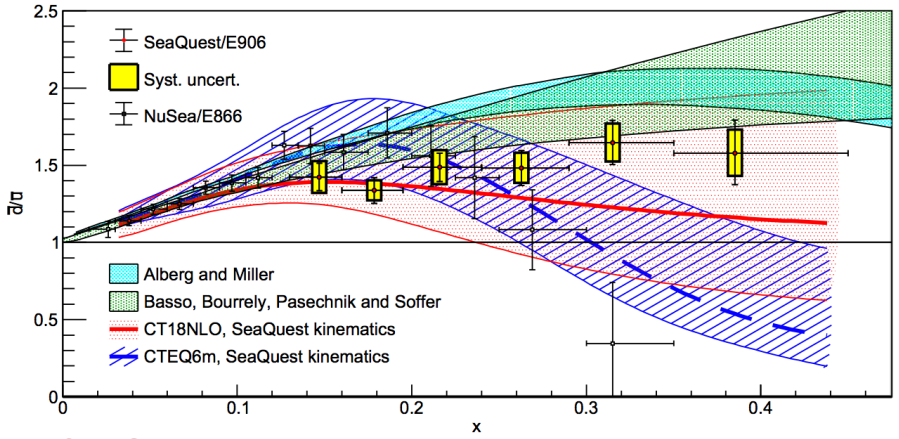


STAR Collaboration, L. Adamczyk et al., Phys. Rev. Lett. 113, 072301 (2014)
PHENIX Collaboration, A. Adare et al., Phys. Rev. D 93, 051103 (2016)
PHENIX Collaboration, A. Adare et al., Phys. Rev. D 98, 032007 (2018)
STAR Collaboration, J. Adam et al., Phys. Rev. D 99, 051102 (2019)



Flavor Composition of the Sea

$$R(x_F) = \frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

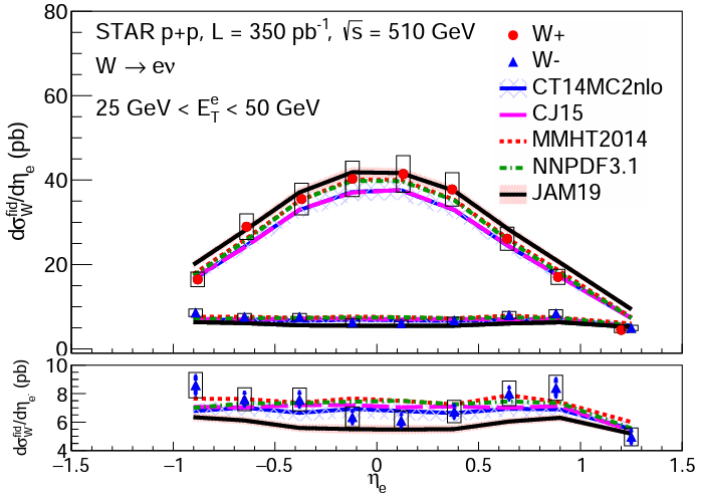


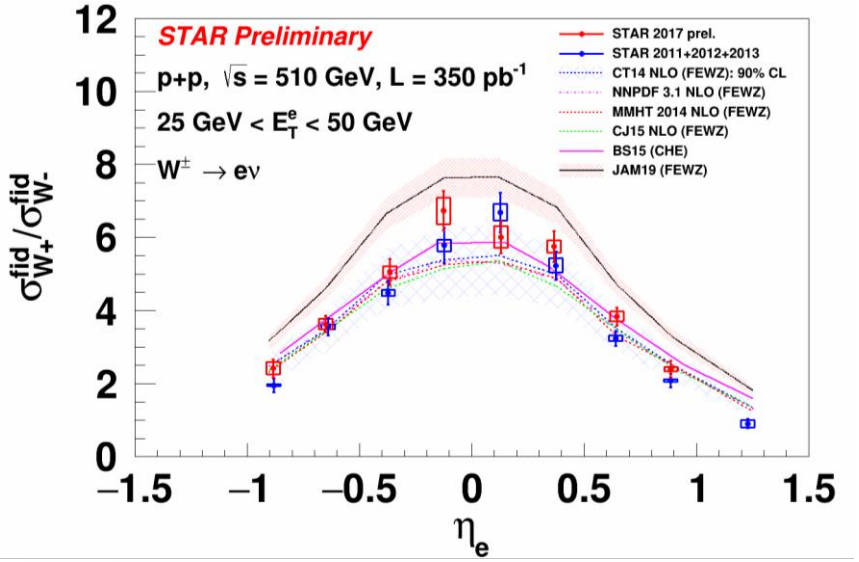
SeaQuest

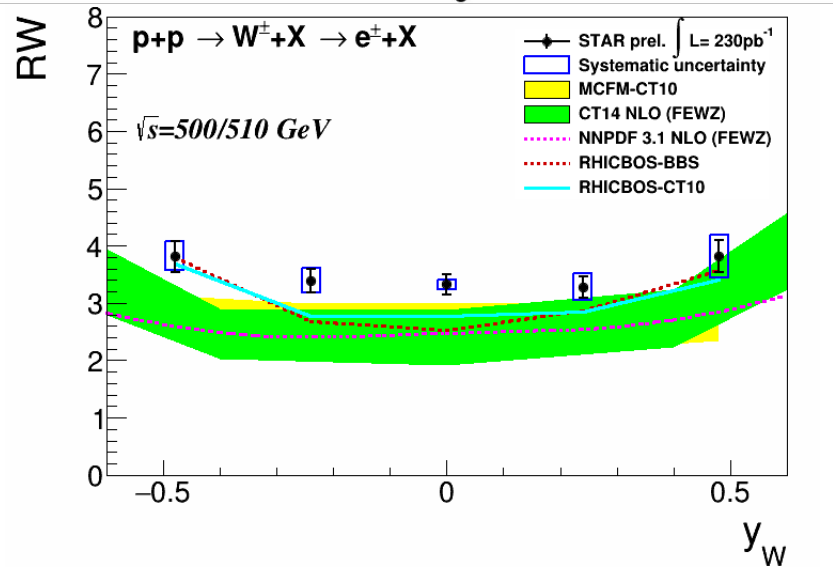
Nature 590 (2021) 7874, 561

$0.1 < x < 0.3$

Phys. Rev. D103 (2021) 12001





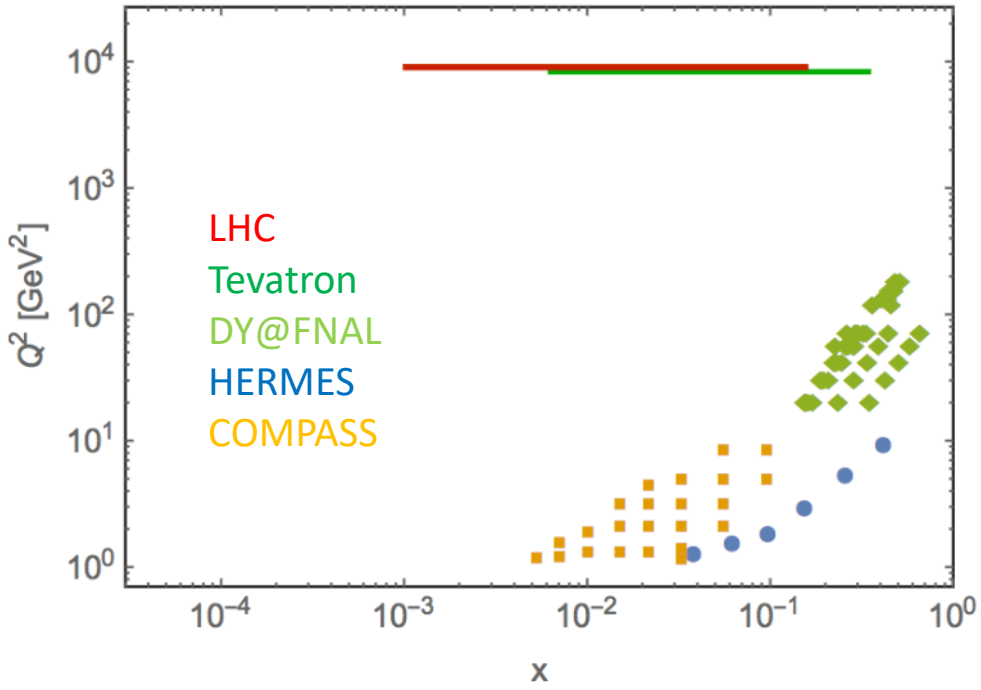


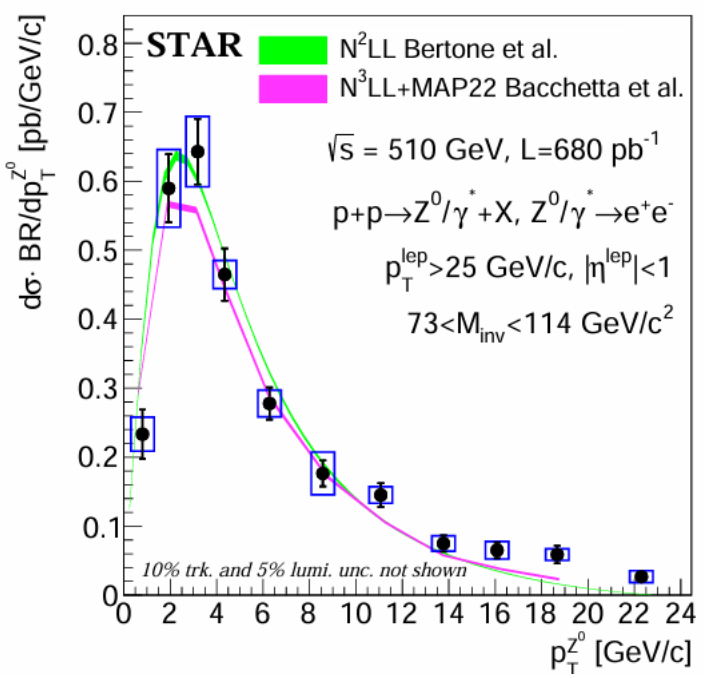
- More data from 2017/2022

Unpolarized TMDs

$$p + p \rightarrow Z^0 \rightarrow e^+ + e^-$$

- Experimentally very clean
- Differential cross section input for global analyses
- STAR: $0.1 < x < 0.3$

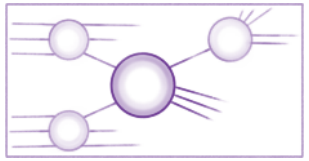




JHEP 06 (2019) 028
JHEP 10 (2022) 127

- Data from 2011-2017
- Unfolded p_T spectrum
- Systematics from energy resolution and electron selection
- Accepted for publication in PLB

Gluon Polarization

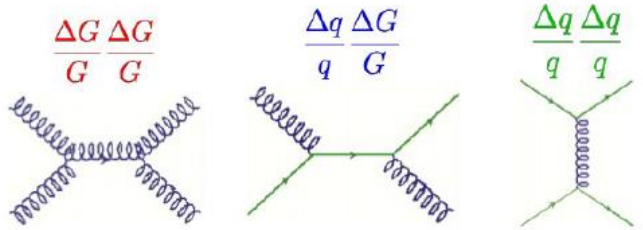


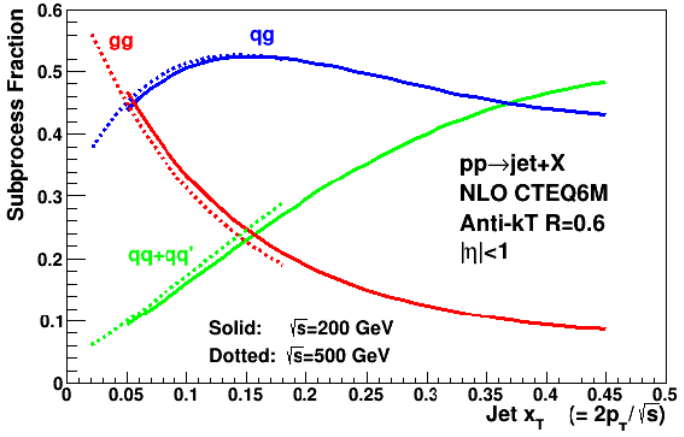
Double helicity asymmetries in proton collisions:

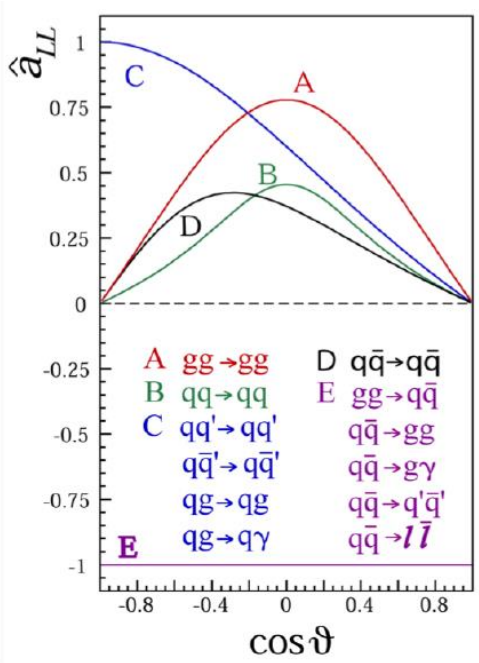
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

$$A_{LL} = \frac{1}{P_1 P_2} \frac{N^{++} - R_3 N^{+-}}{N^{++} + R_3 N^{+-}}$$

$$R_3 = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}}$$

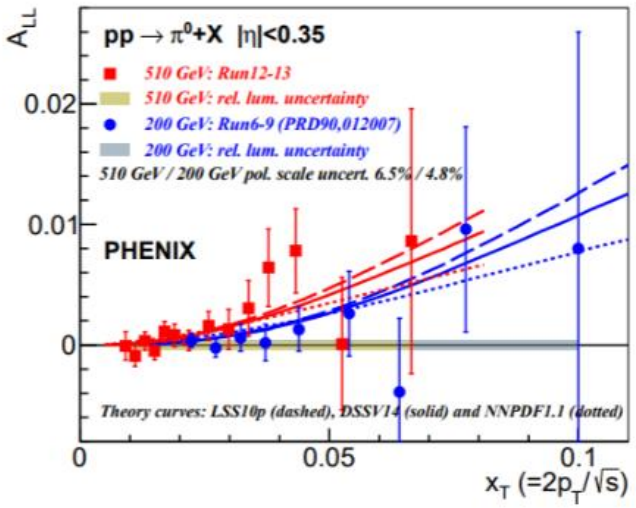






- Beam polarizations
  - $P_{1,2} \approx 55 - 60\%$
  - $\delta P/P \approx 3.5\%$
  - $\delta(P_1P_2)/(P_1P_2) \approx 6\%$
  - Residual transverse polarization
- Relative luminosity
  - Fill-by-fill $\Delta R \approx 4\%$
  - Overall $\Delta R < 5 \cdot 10^{-4}$
  - From rates in different detectors (BBC/VPD/ZDC)

Polarized Gluons in the Proton



- Inclusive jets

$$x \approx x_T e^{\pm\eta}$$

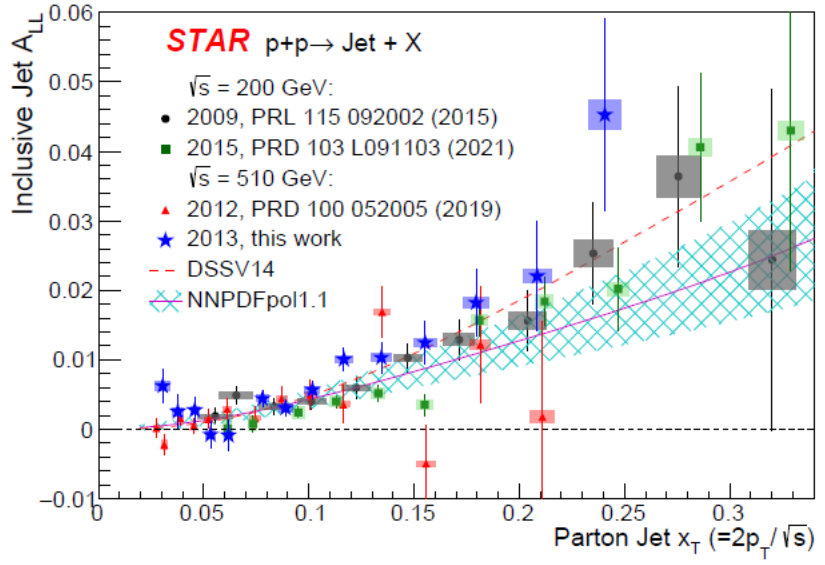
$$x_T = 2p_T/\sqrt{s}$$

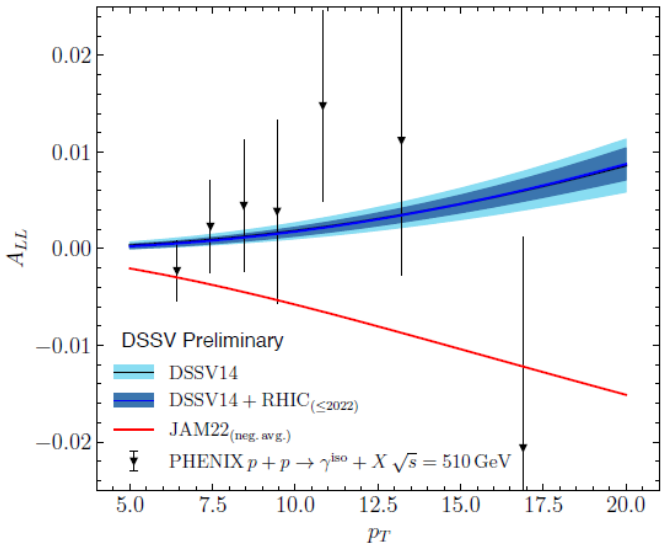
- Dijets

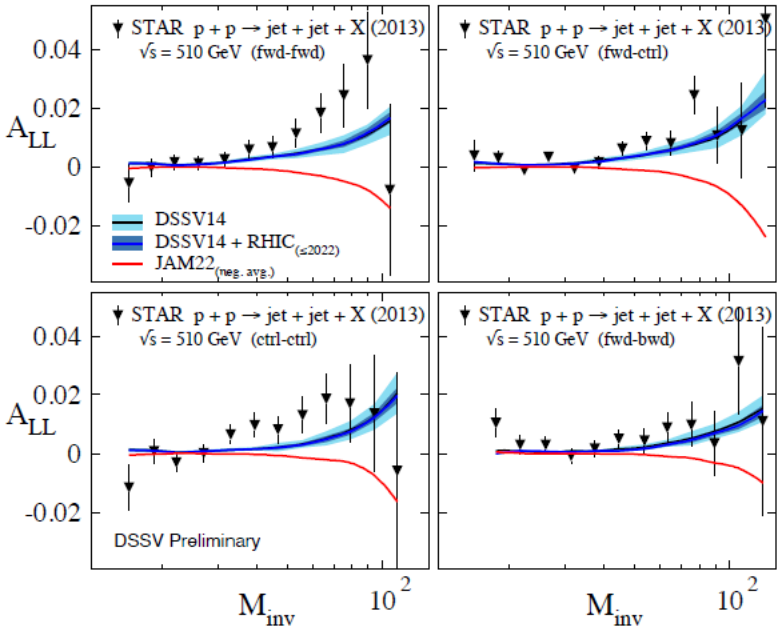
$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

$$M = \sqrt{x_1 x_2 s}$$



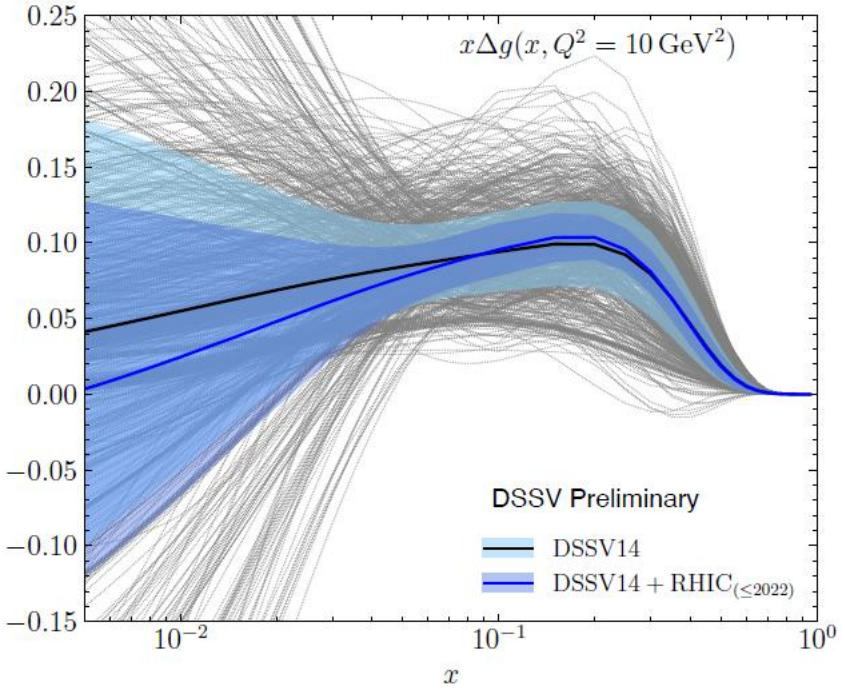


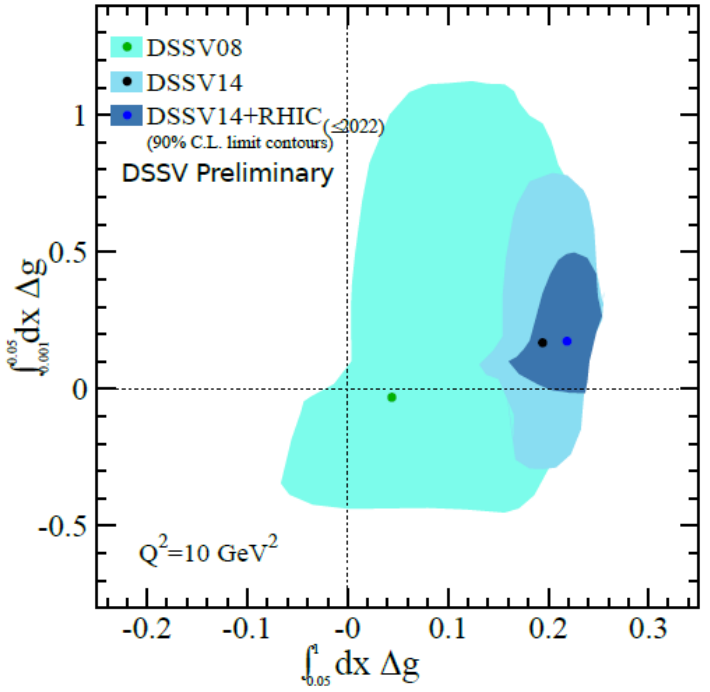


Phys. Rev. D**94** (2016) 112008
Phys. Rev. D**93** (2016) 011501
Phys. Rev. D**102** (2020) 032001
Phys. Rev. Lett. 130 (2023) 251901

Phys. Rev. Lett. 115 (2014) 092002
Phys. Rev. D**95** (2017) 71103
Phys. Rev. D**98** (2018) 032011
Phys. Rev. D**100** (2019) 052005

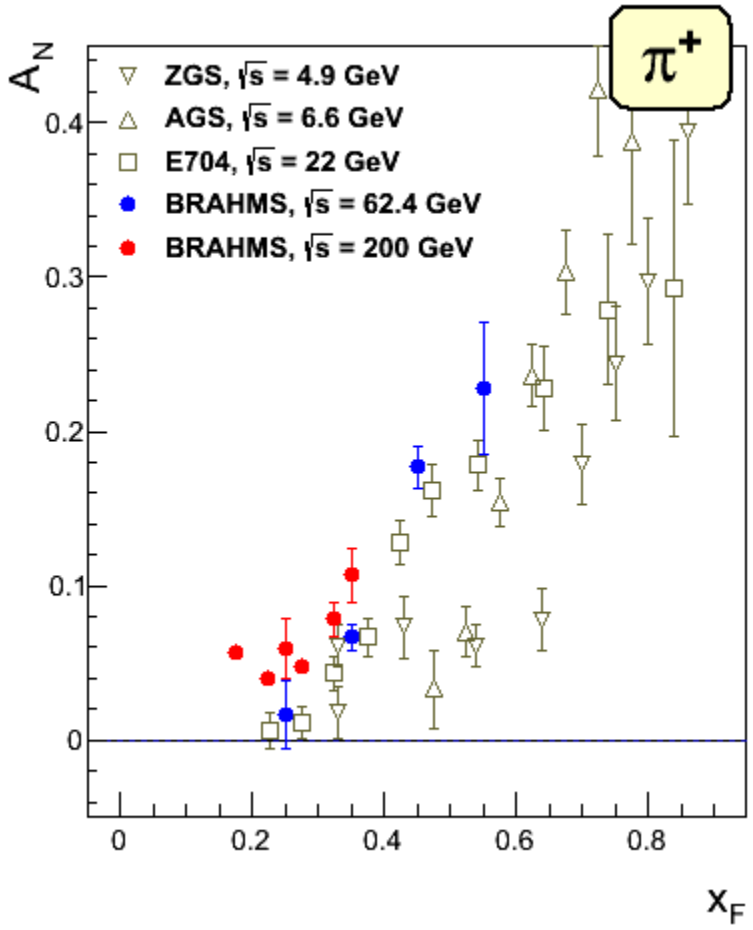
Gluon Helicity at RHIC

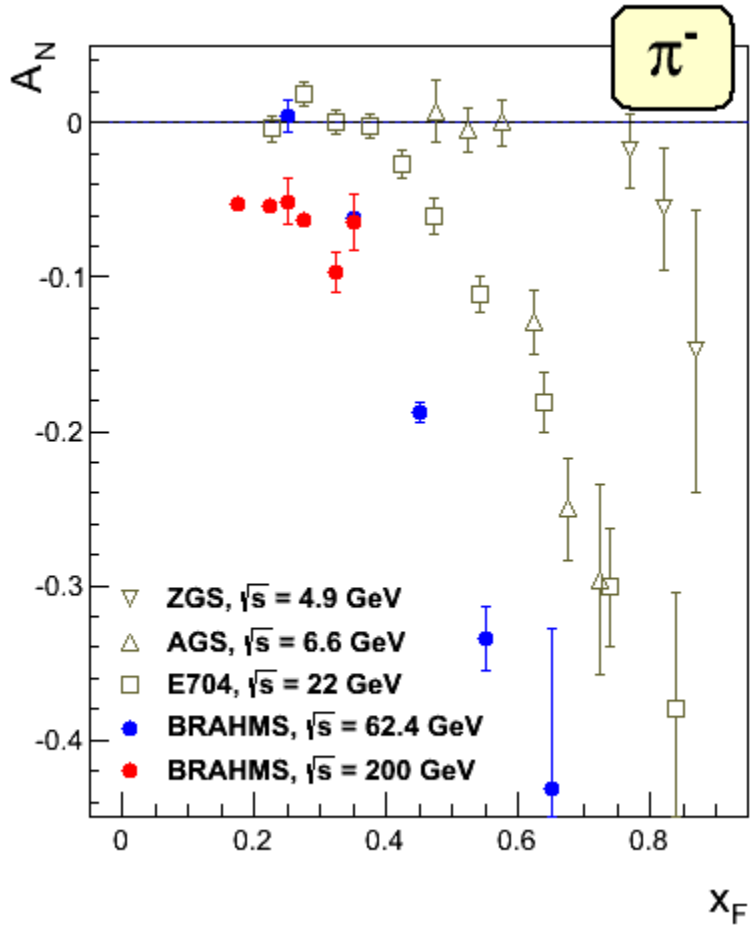


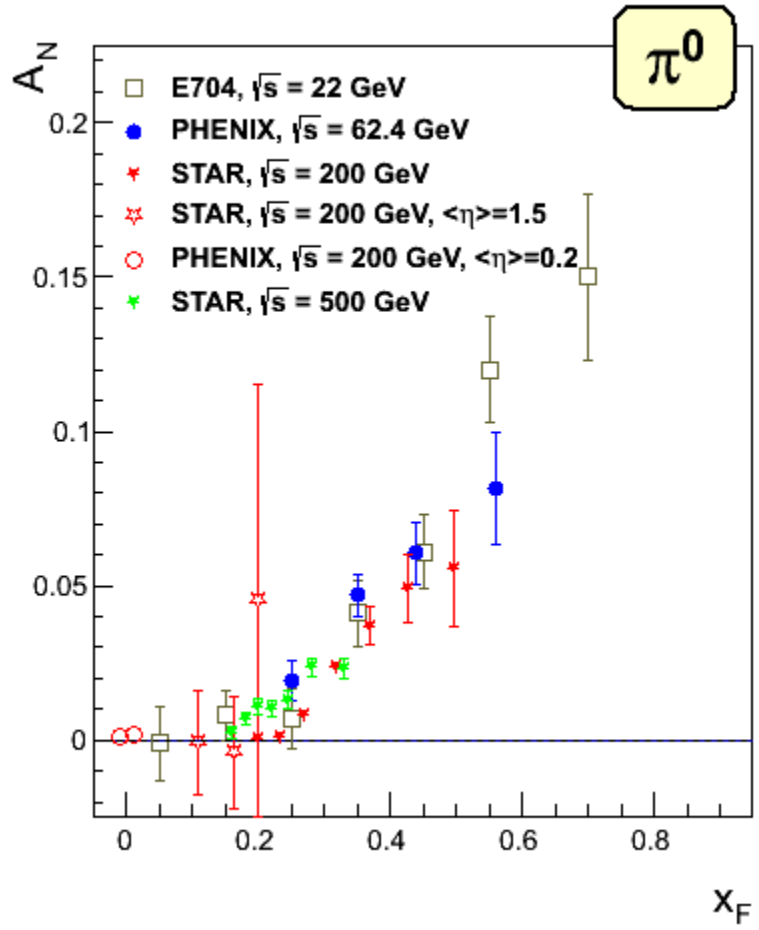


2009 ✓	2011 ✓	2012 ✓	2013 ✓	2015 ✓
200 GeV				200 GeV
500 GeV	500 GeV	510 GeV	510 GeV	

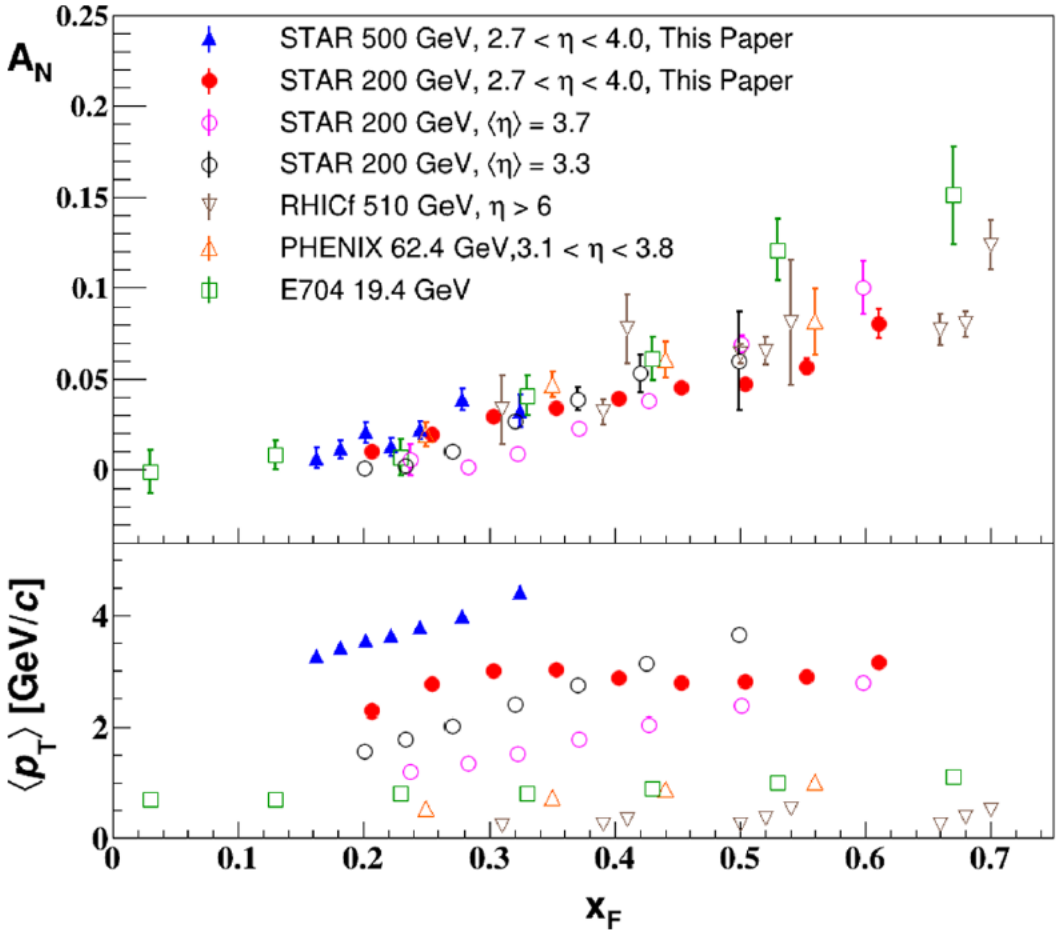
Transverse Spin Effects

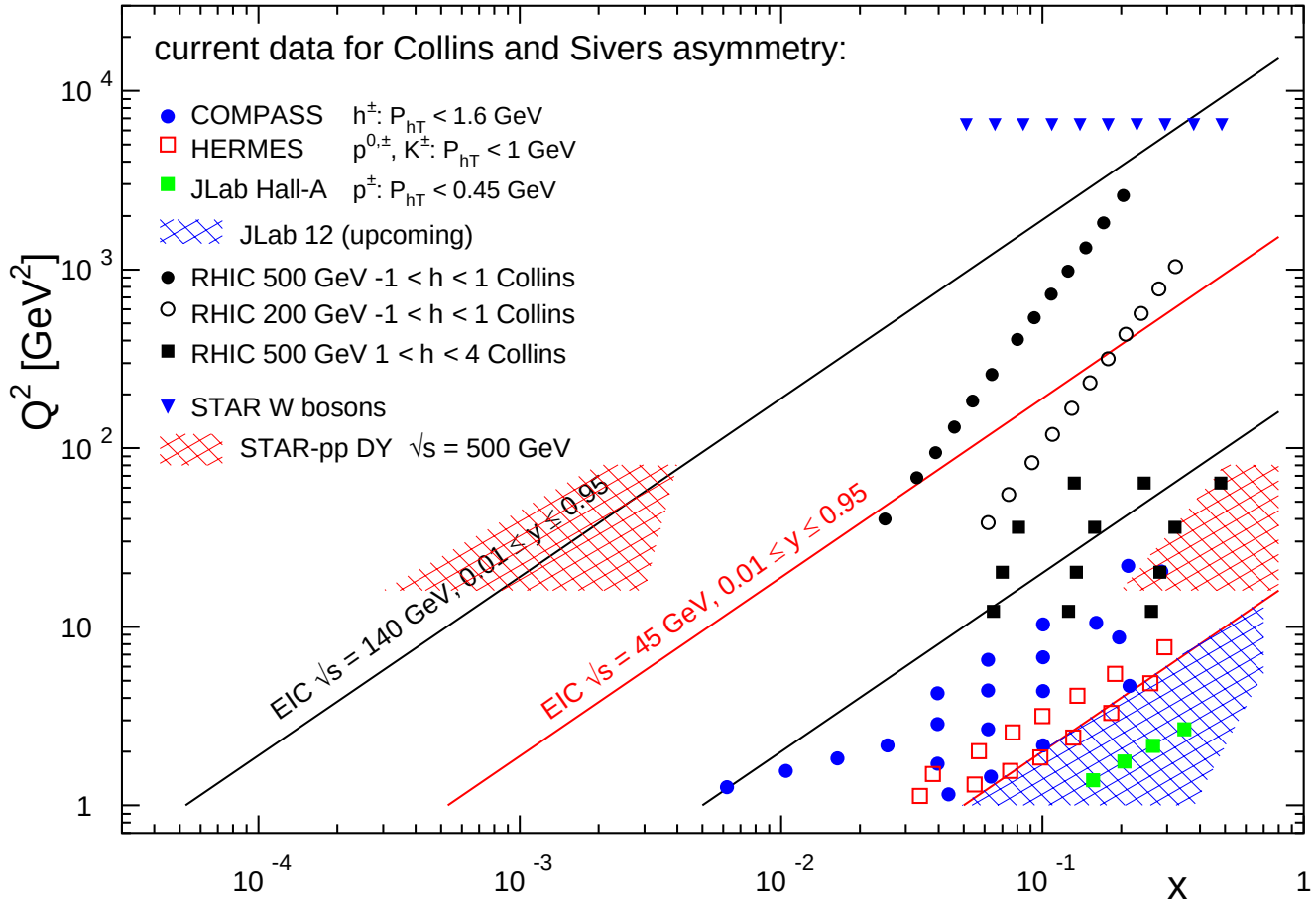




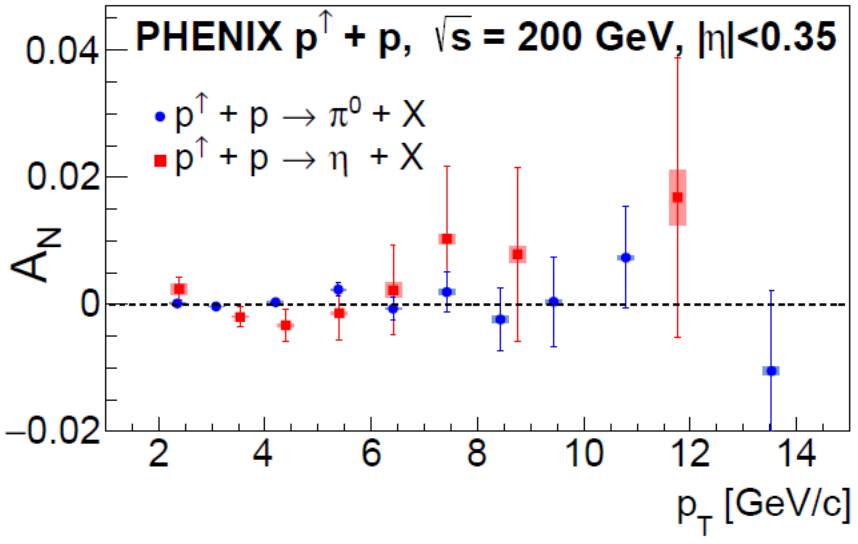


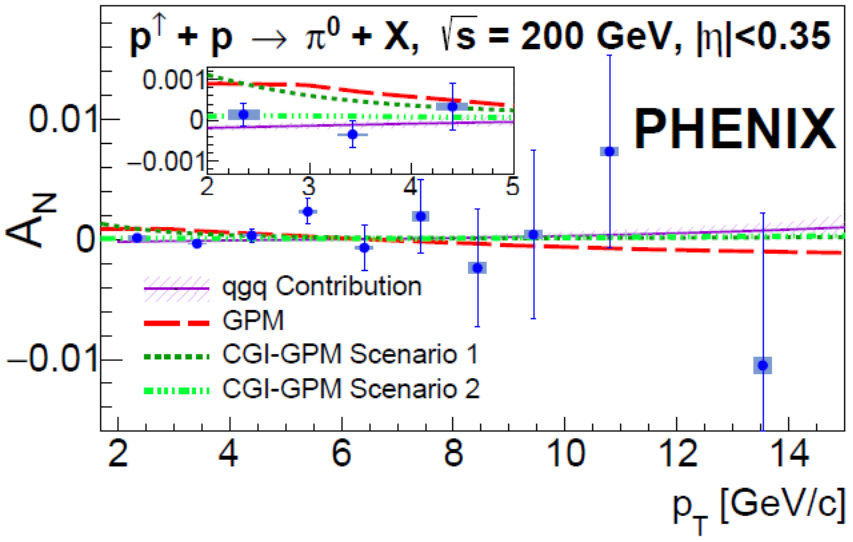
Transverse Spin Effects

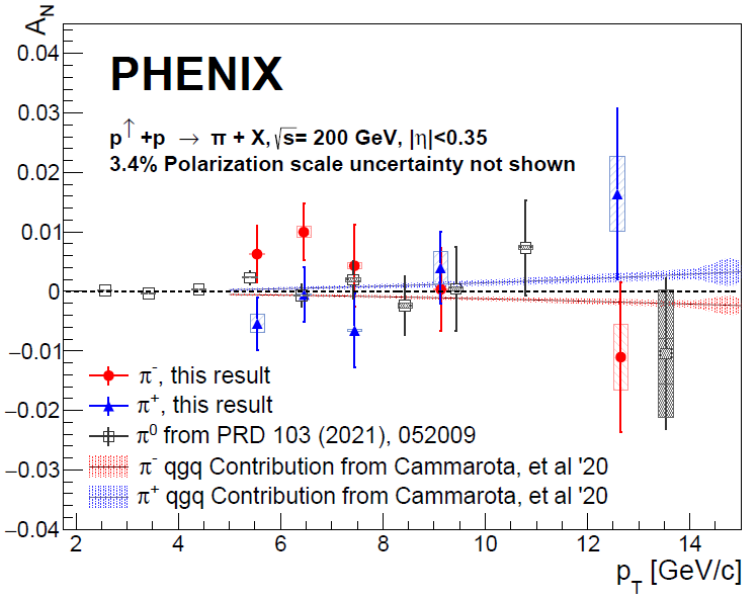




Inclusive Meaurements

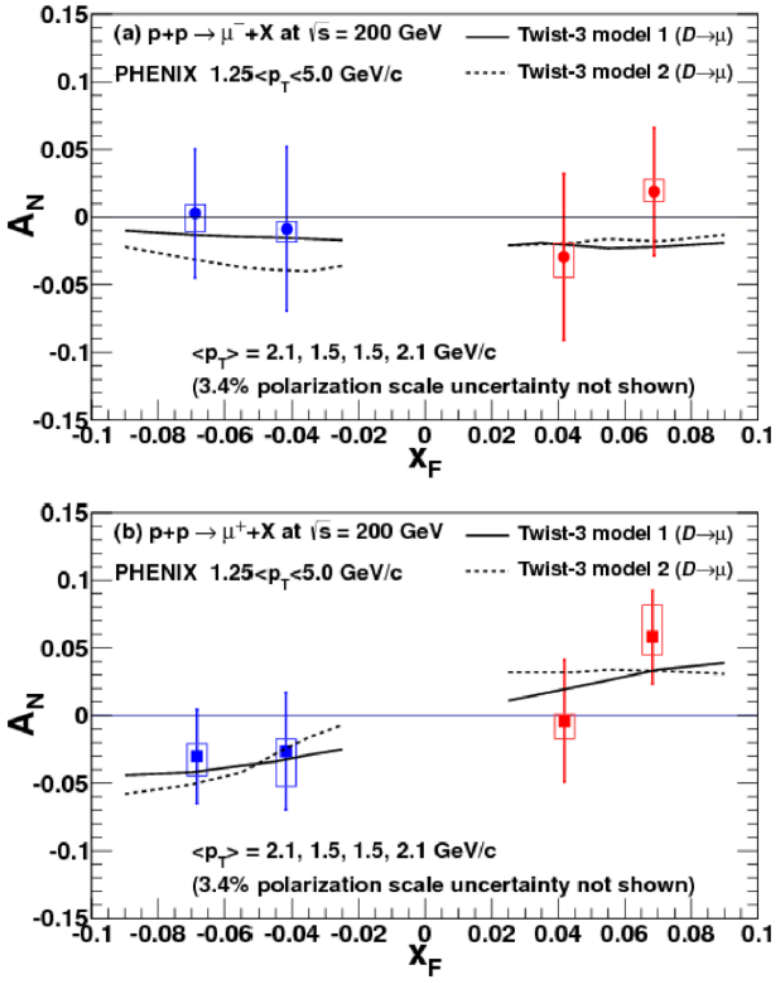


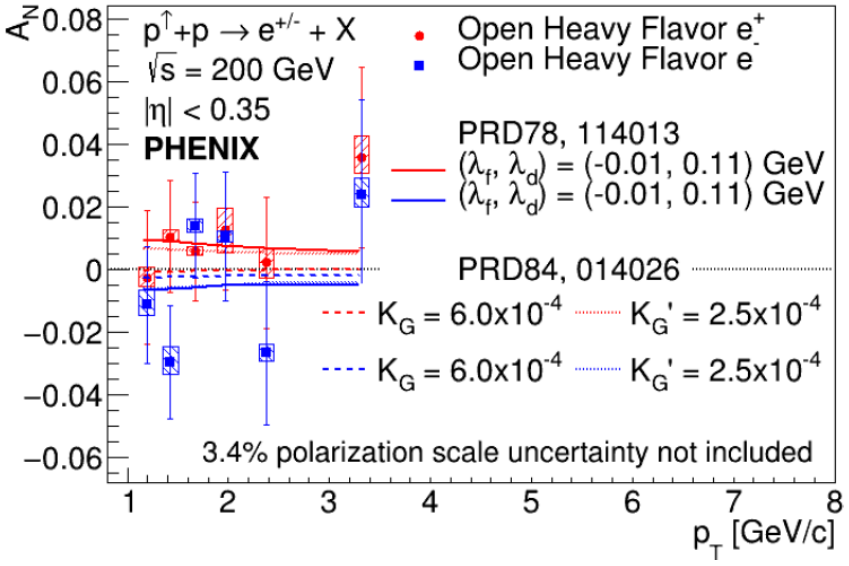




- $\vec{p} + p, \vec{p} + Al, \vec{p} + Au$
- $\sqrt{s_{NN}} = 200 \,/\, 500$ GeV
- Sensitive to gluon T_G
- Very high precision, consistent with zero
- Phys. Rev. D103 (2018) 052009
- Phys. Rev. D105 (2022) 032003
  - Indication of charge dependence
  - Statistics limited by trigger efficiency

Heavy Flavor





- Sensitive to ggg correlators $T_G^{(f,d)}$
- Phys. Rev. D95 (2017)112001
  - Inclusive muons, $1.2 < \eta < 2.2$
- arxiv:2204.12899
  - Electrons
  - Background from meson decays and misidentified $\pi^{\pm}$

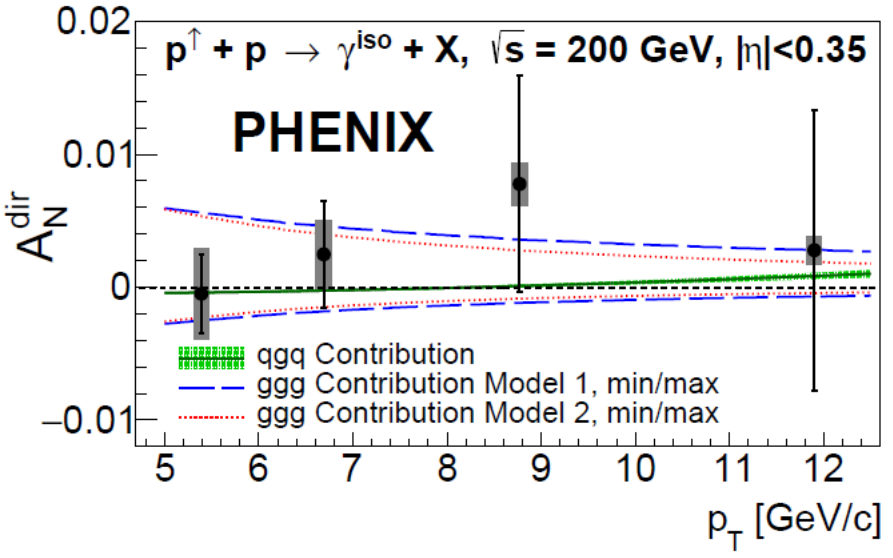
Direct Photons

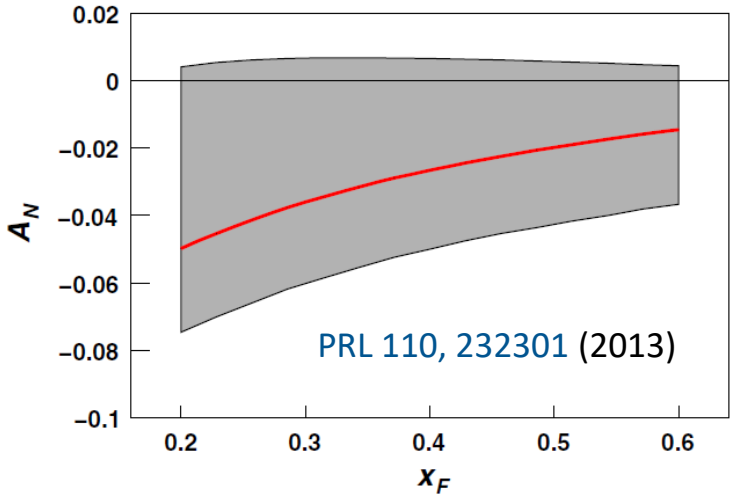
- First measurement from PHENIX
- Constrains twist-3 ETQS function
  - Dominated by ggg correlator
  - Small contribution from qgq correlators
  - Related to Sivers-TMD
- Larger asymmetries expected at forward rapidity

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

$f_{1T}^{\perp q}$: Sivers TMD function
$T_{q,F}$: Efremov-Teryaev-Qiu-Sterman correlator

Phys. Rev. Lett. 127 (2021) 162001





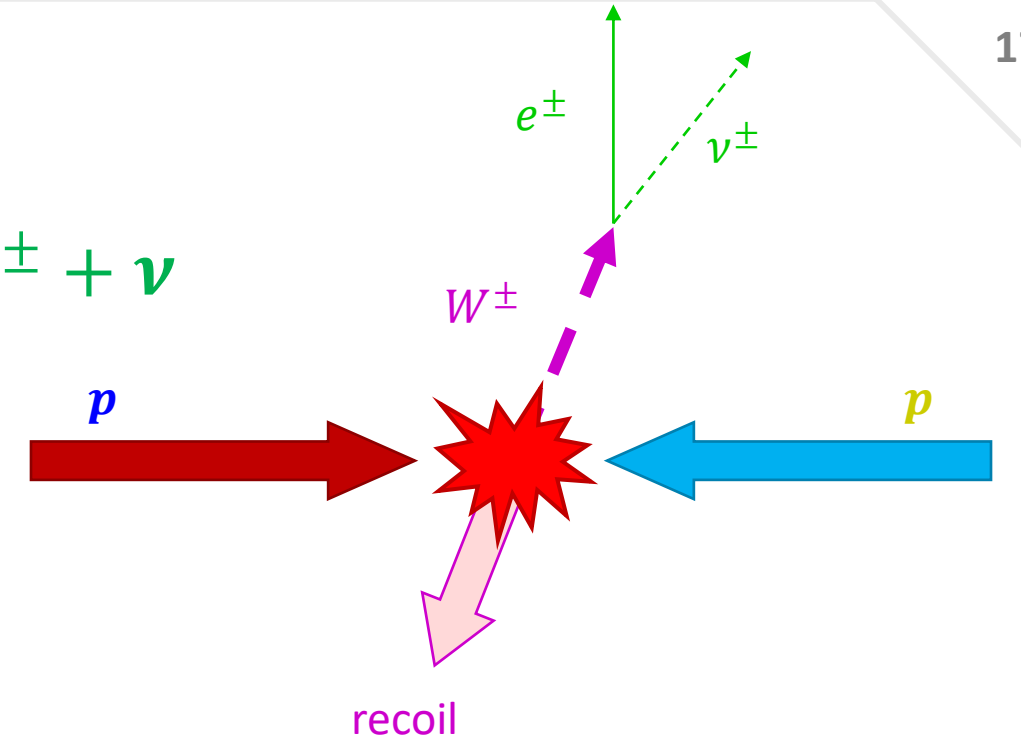
W-Boson Production in $p^{\uparrow} + p$

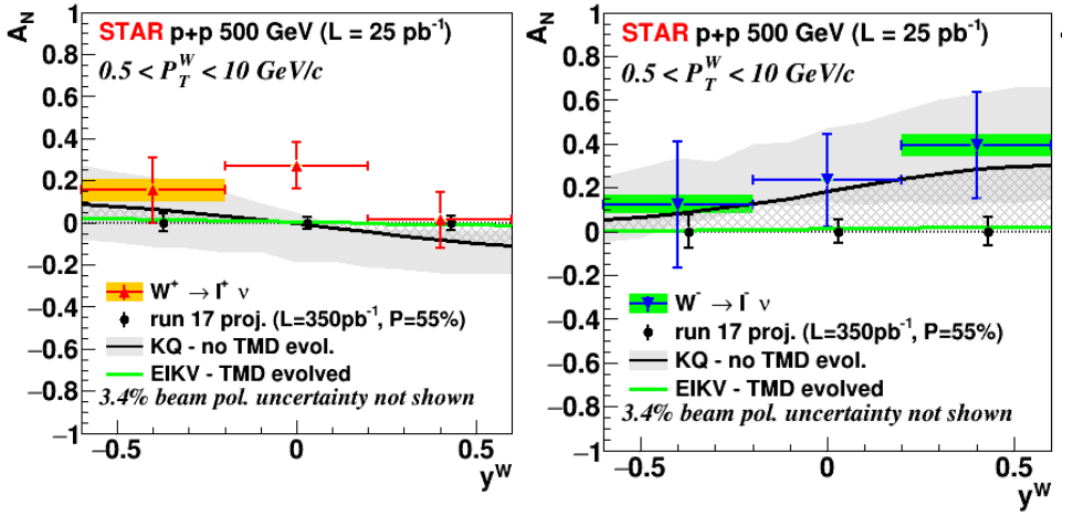
- Test of universality of Sivers effect
- W-boson decay
  - $p_{T,W}$ is lost
  - Almost no azimuthal angle correlation
- Measure recoil from the collision (tracks and EMC)

$$\boldsymbol{p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu}$$

$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

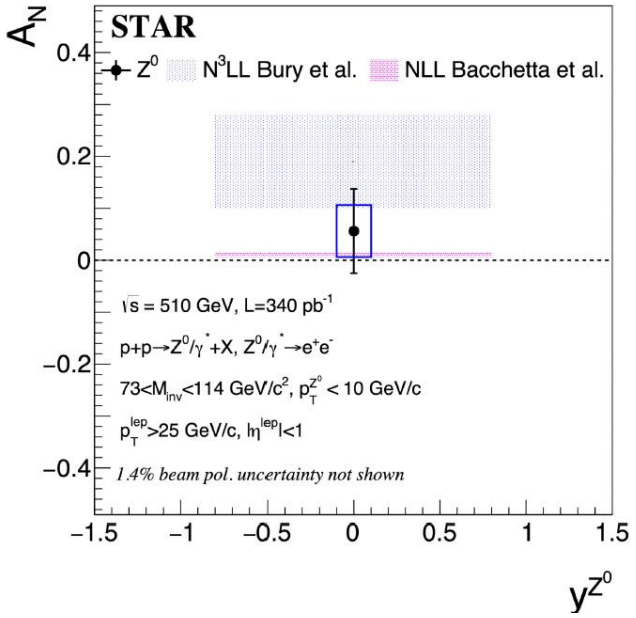
$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$





Phys. Rev. Lett. 116, 132301 (2016)

Comparison with Phys. Rev. Lett. 103, 172001



Z^0-boson

arxiv:2308.15496

accepted for publication in PLB

W-Boson Production in $p^{\uparrow} + p$

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  - $p_{T,W}$ is lost
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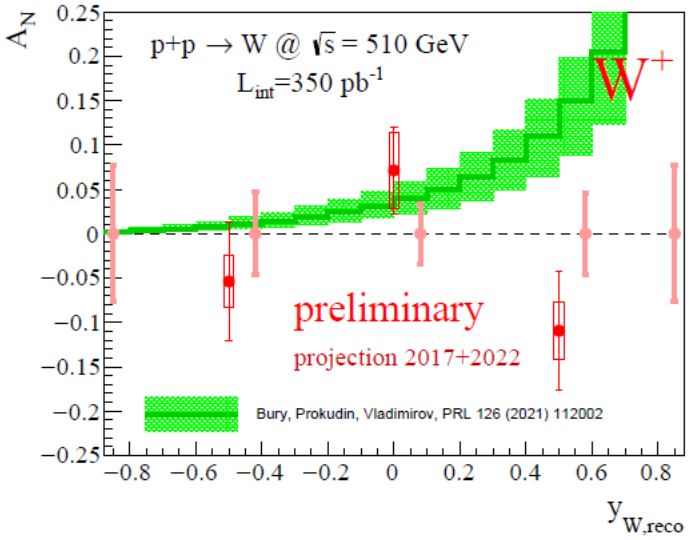
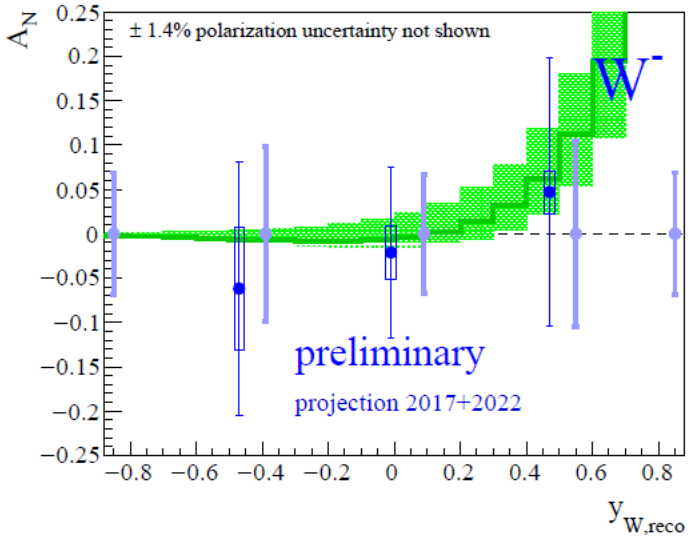
- Measure recoil from the collision (tracks and EMC)

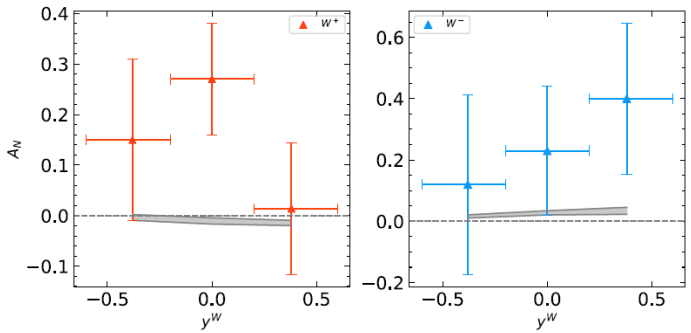
$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$

- Unfolding increases statistical uncertainties
- Projection: forward detectors in 2022 extend kinematic range (and improve recoil reconstruction)







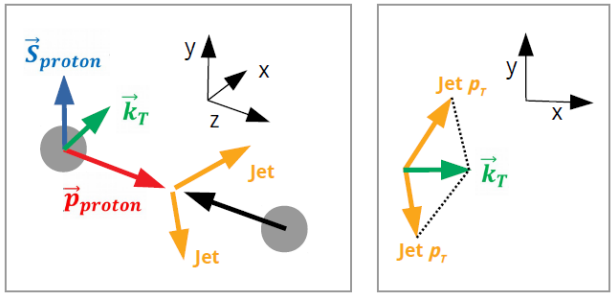
Bacchetta et al.,
Phys. Lett. B 827 (2022) 136961
Comparison with PRL 116 (2016) 13201

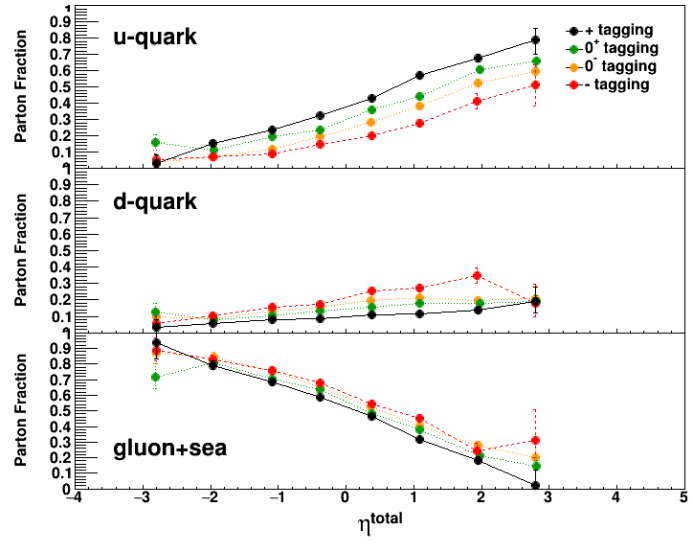
Sivers Asymmetries in Dijets

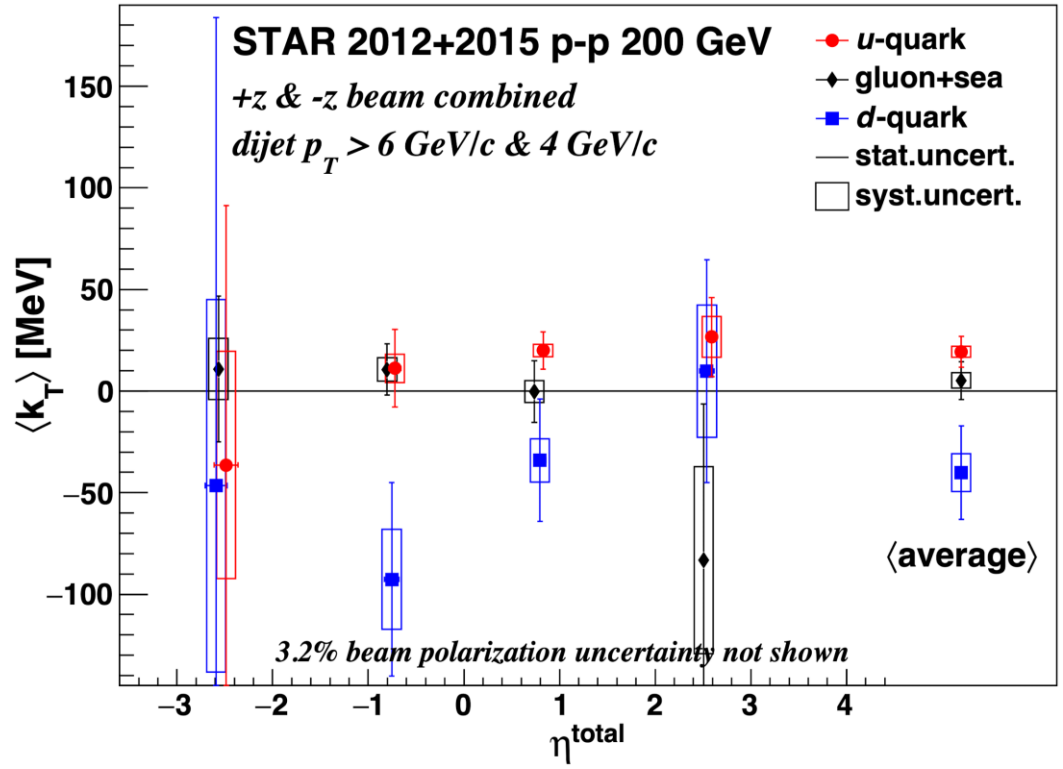
- Correlation between proton spin and parton k_T

$$\left\langle \vec{S} \cdot (\vec{p} \times \vec{k}_T) \right\rangle \neq 0$$

- Enhance quark flavor with charge tagging
  - Track p_T weighted charge
  - Unfolded to parton $\langle k_T \rangle$
- Submitted for publication, arxiv:2305.10359
- More data on disk, $\sqrt{s} = 510$ GeV



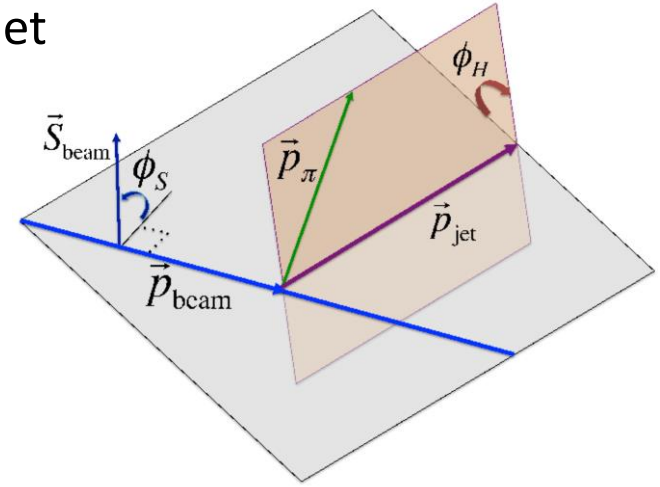




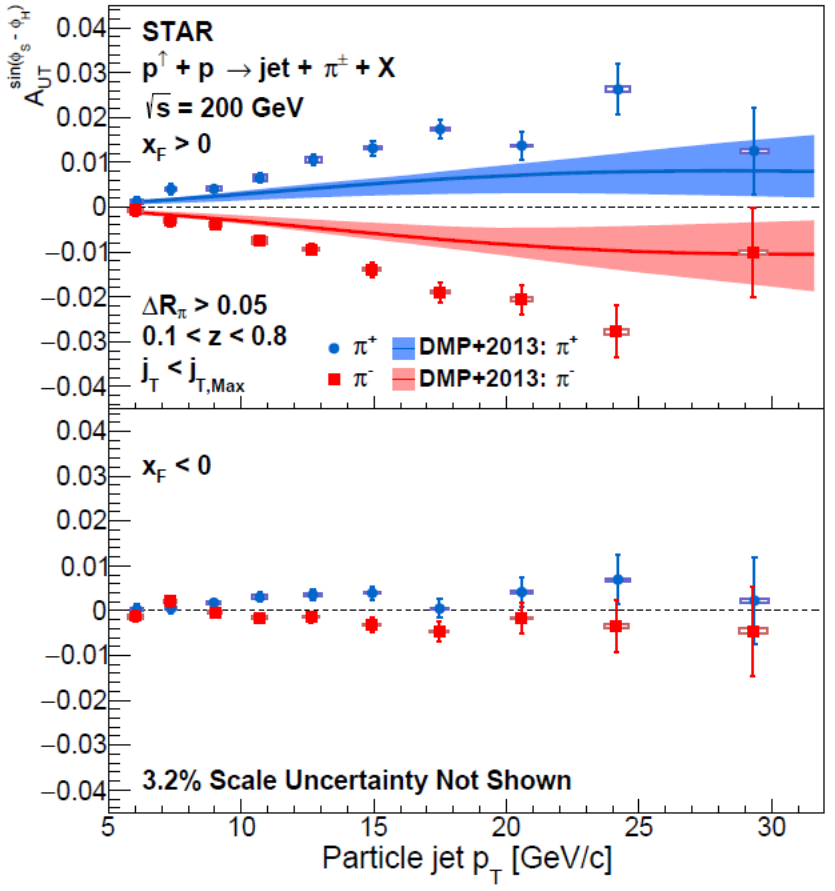
Hadrons in Jets

$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u}) \Delta D_{q_1}^{\pi^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T) \hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z,j_T)}$$

- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet



Phys. Rev. D **106**, 072010 (2022)



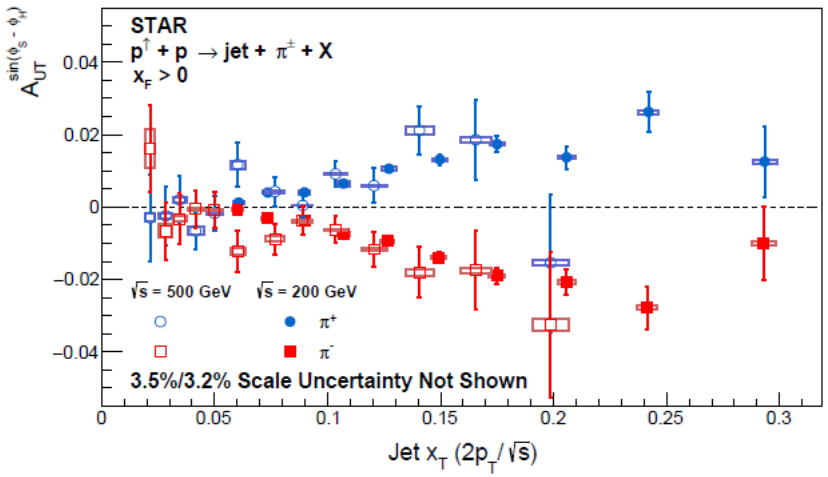
$$d\sigma^\uparrow - d\sigma^\downarrow \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H)$$

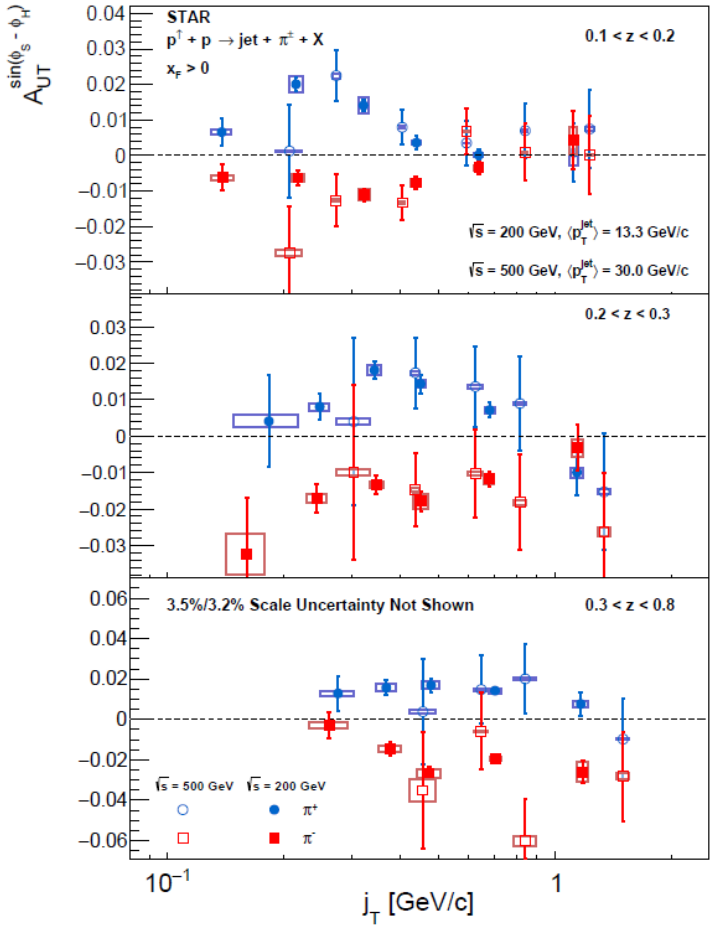
Collins TMD & transversity

Collins-like (linear gluon polarization)

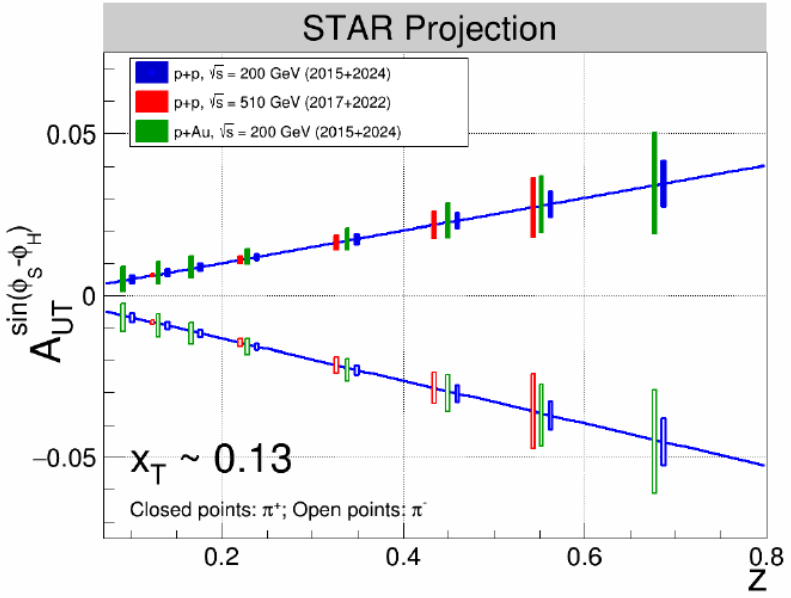
Collins Asymmetries

- Data at $\sqrt{s} = 200$ GeV (from 2012/2015)
- Multidimensional binning p_T, j_T, z
- Separate asymmetries for $\pi^{\pm}, K^{\pm}, p/\bar{p}$
- Phys. Rev. D **106**, 072010 (2022)



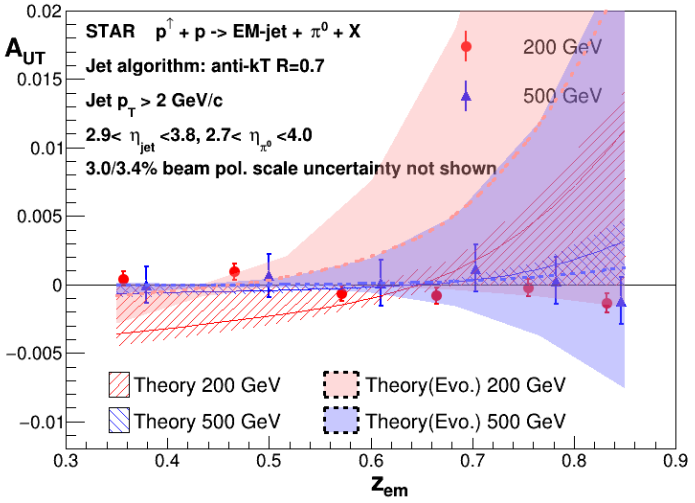


- Projections for p+p 200/500 GeV
- p+A at 200 GeV (possibly 2024/25)

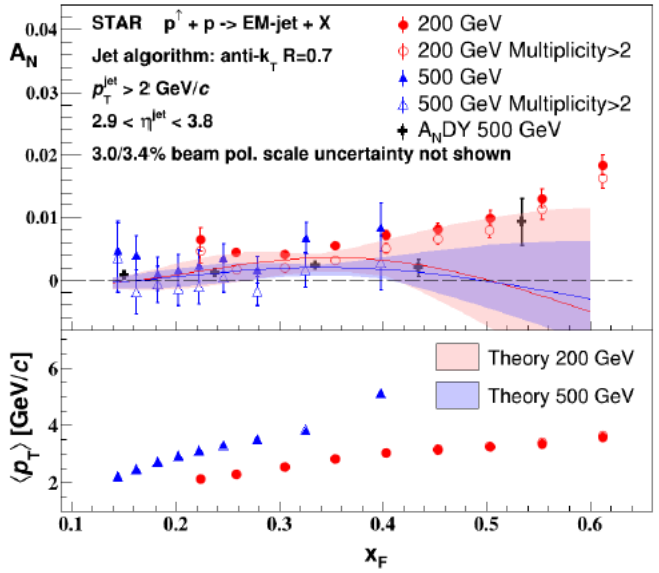


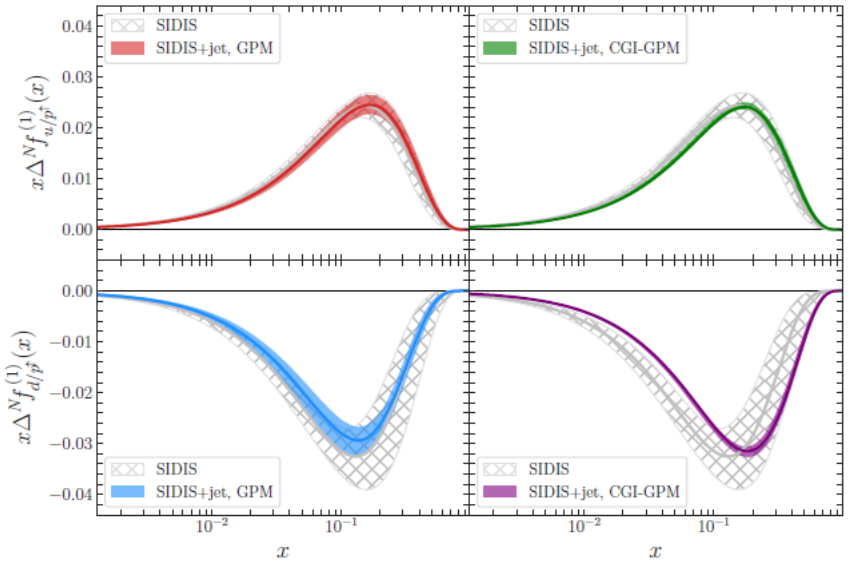
Forward Rapidities

- Electromagnetic jets with forward calorimeter
  - π^0 in jet
- $2.8 < \eta < 4.0$
- Phys. Rev. D103 (2021) 92009
- Collins asymmetries are very small.
- Jet asymmetries are small and consistent with previous results
- Significant impact on Sivers function in global fit:
  Phys. Lett. B 815, 136135 (2021)
- Studies of possible diffractive contributions to transverse spin asymmetries (→ Bassam's talk)



Comparison with
Z. Kang et al., PLB 774, 635 (2017)
L. Gamberg et al., PRL 110, 232301 (2013)
J. Cammarota et al., arxiv:2002.08384

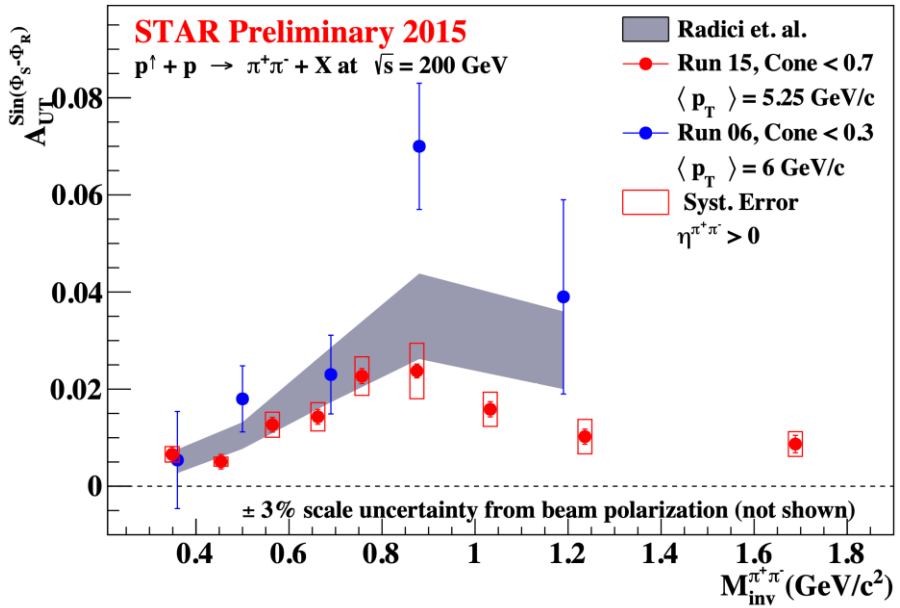


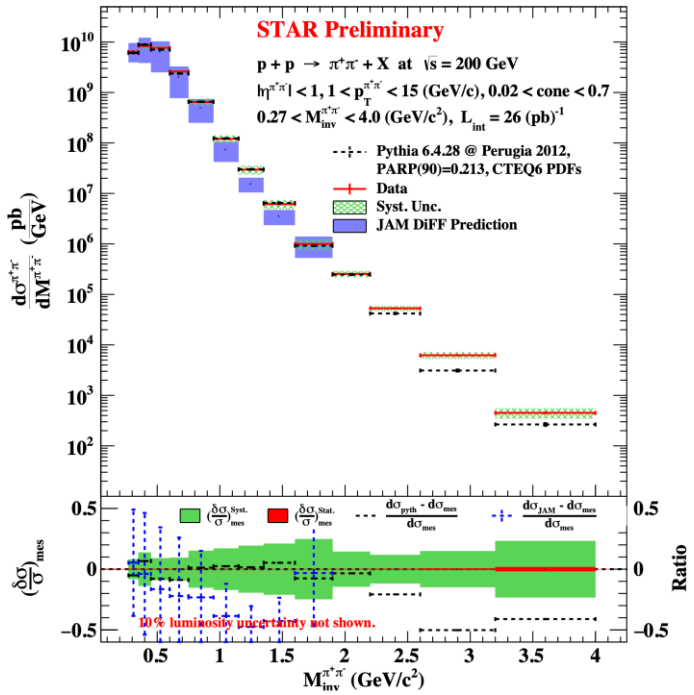


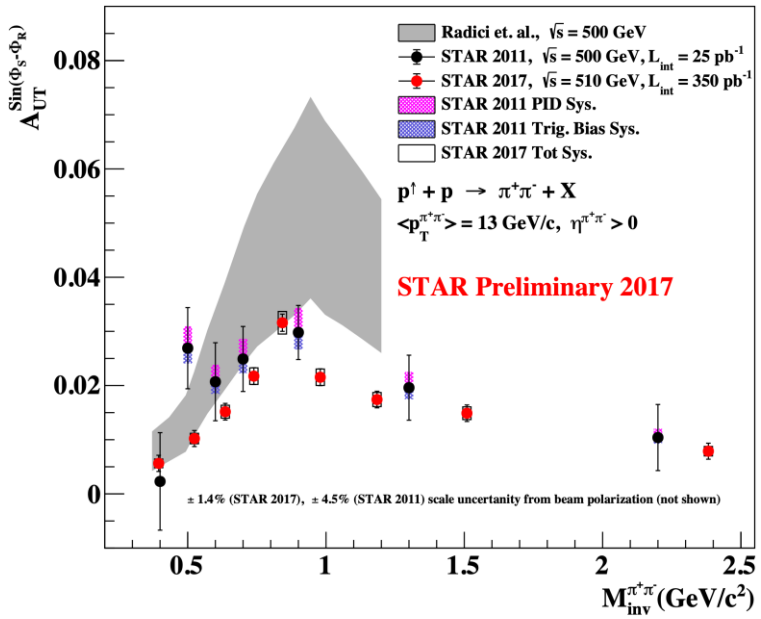
Interference Fragmentation Functions

- Dipion correlation at mid-rapidity
- Improved statistics at 200 and 510 GeV
- Measurement of cross section (200 GeV) for model-independent extraction of transversity

$$A_{UT} \propto \frac{h_1^a(x)H \otimes H_1^{\sphericalangle}(z, M_h^2)}{f_1^a \otimes D_1}$$



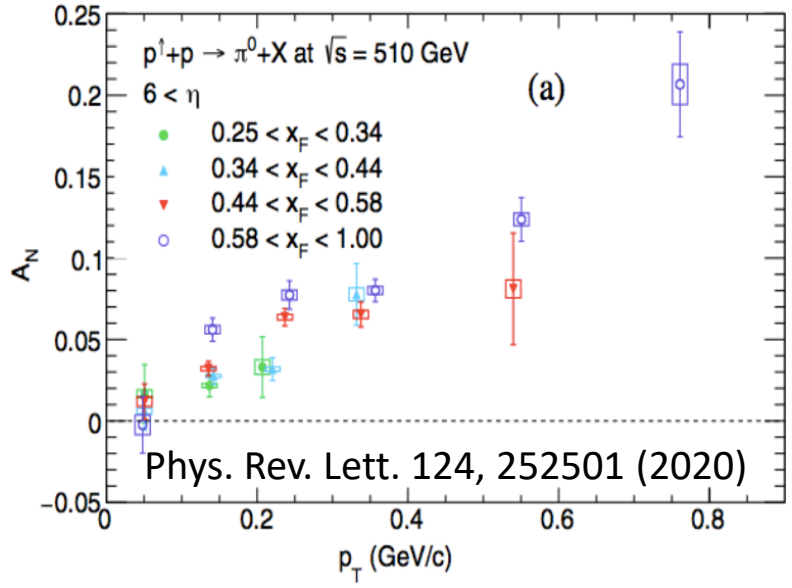


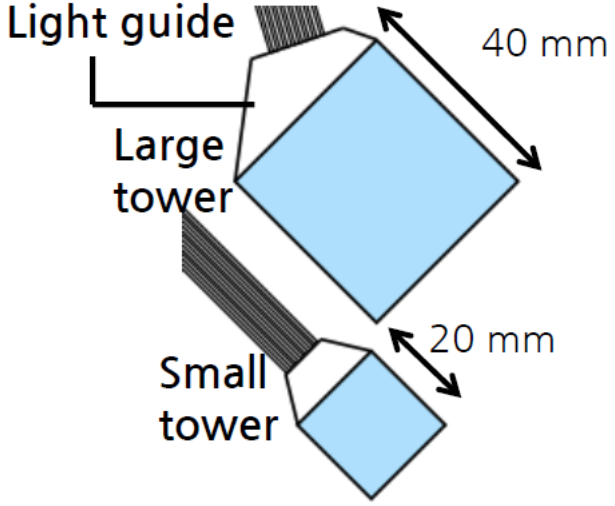


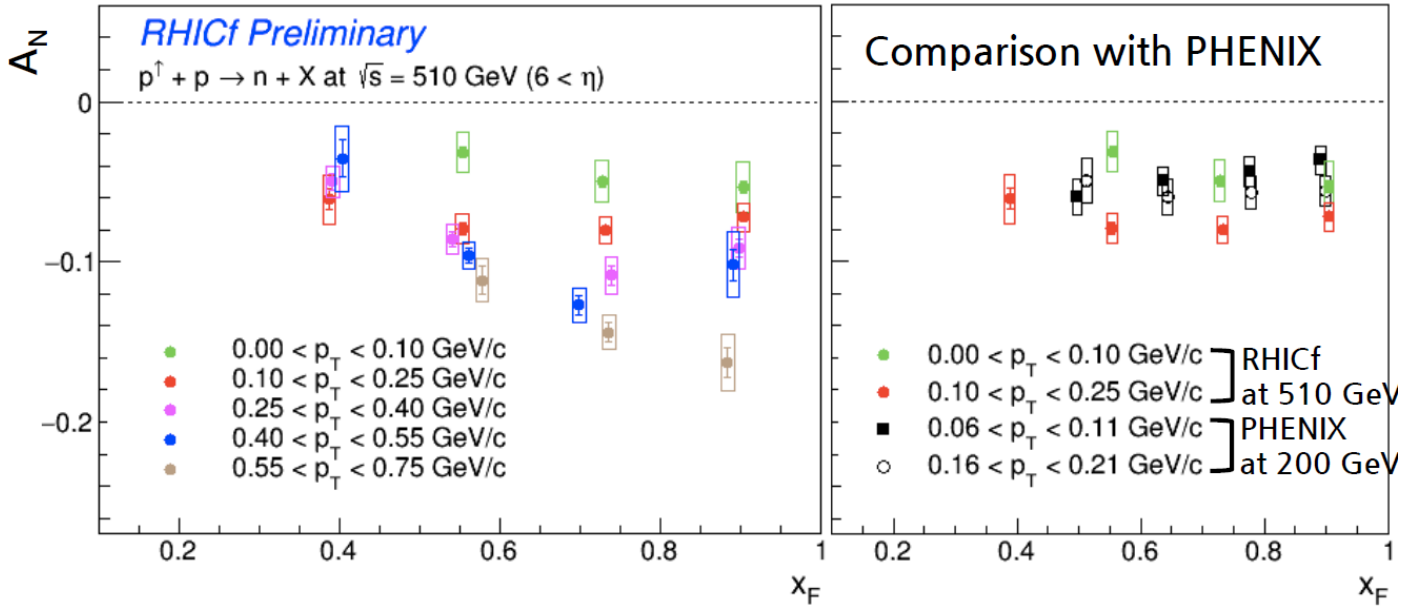
→ dedicated talk by **Bernd Surrow**

RHICf Experiment

- Longitudinally segmented calorimeter for n, γ, and π^0 reconstruction
- $\eta > 6.0$
- Required special beam conditions in 2017
- $\sqrt{s} = 510$ GeV
- On-going analysis in combination with other STAR detectors





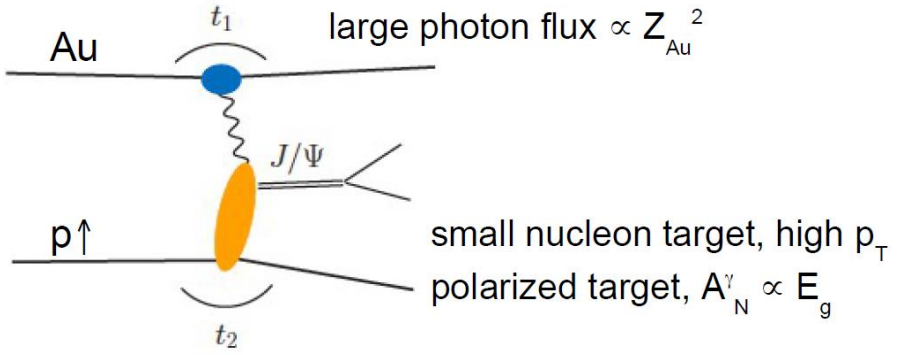


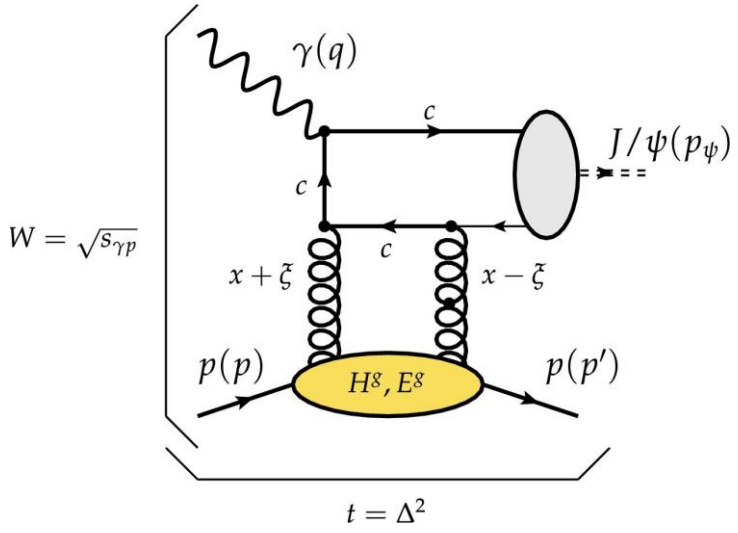
J/psi Production in UPC

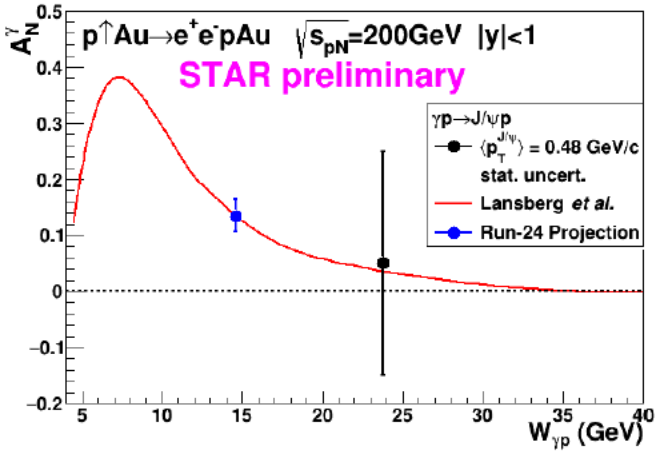
- Photoproduction with polarized protons

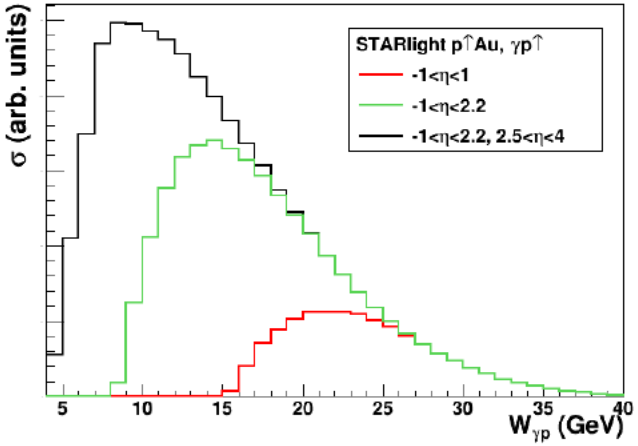
$$d\sigma/d\phi \propto 1 + A_N^{\gamma} \cos\phi$$

$$A_N^{\gamma} \propto p_T \frac{\mathrm{Im} H^g E^{g*}}{|H^g|^2}$$









Phys.Lett. B793 (2019) 33-40

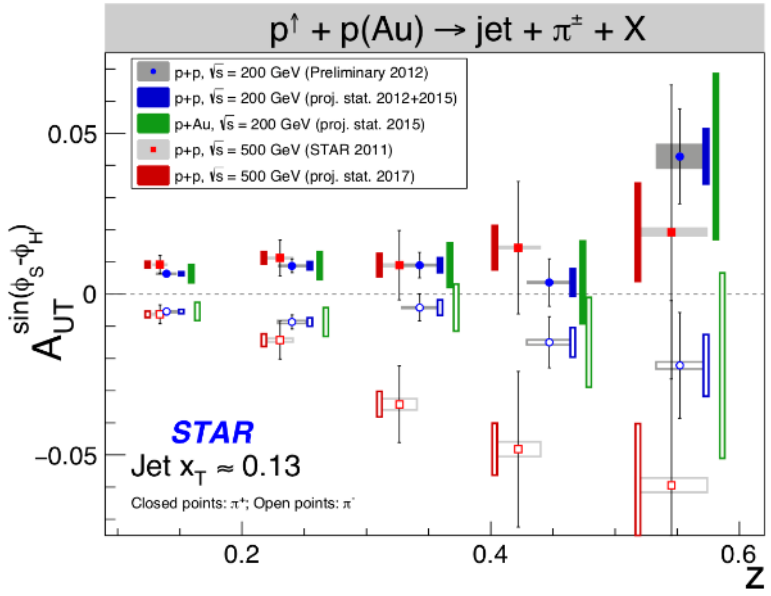
- Expect larger asymmetry at low $W_{\gamma p}$
- Expect results from p+p at 510 GeV soon

Future Measurements

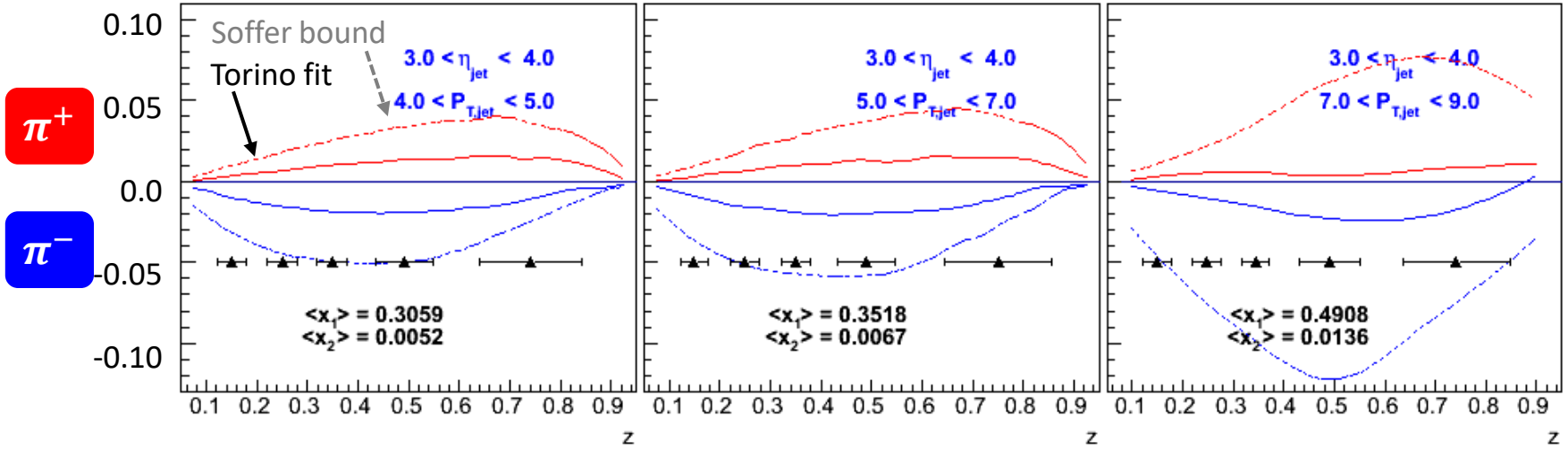
- Hadron in jet
  - STAR measured at midrapidity, 200 – 500 GeV
  - Move to higher x

$$\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$$

  - Multi-dimensional binning



$\sqrt{s} = 500$ GeV, 268 pb^{-1}sampled



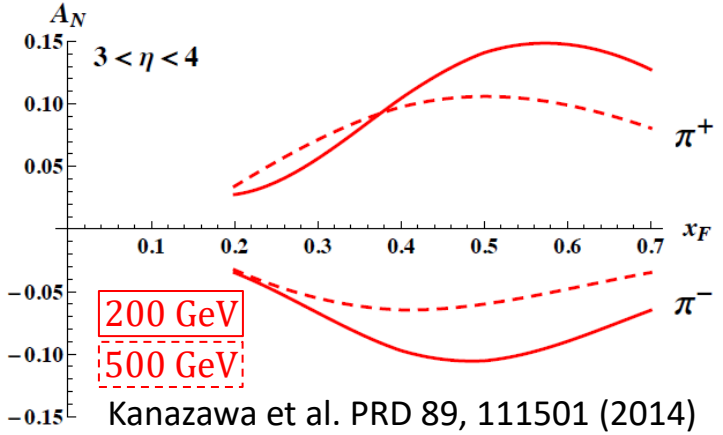
Torino: Phys. Rev. D87 (2013) 094019 Soffer bound&transversity: Phys. Rev. Lett. 74 (1995) 1292

Future Measurements

- Suggested large spin dependent effects in quark fragmentation
  - Collinear quark-gluon-quark correlators

$$\widehat{H}_{FU}^{\Im}(z, z_z)$$

  - Flavor dependence
  - Evolution effects of ETQS distribution functions

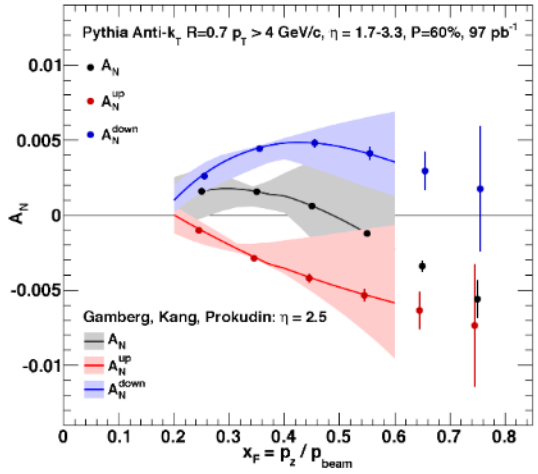


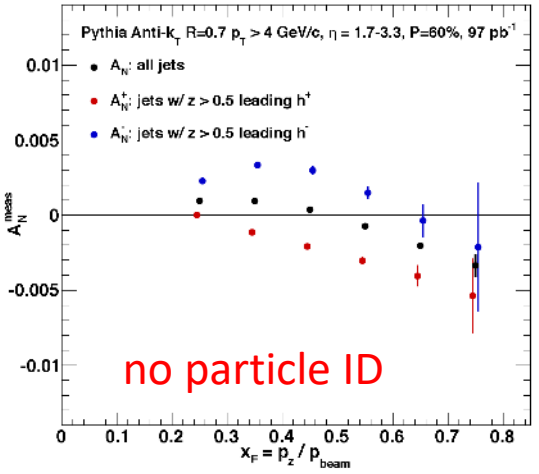
Kanazawa et al. PRD 89, 111501 (2014)

- Test origin of large transverse asymmetries
  - Compare direct photons and jets

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

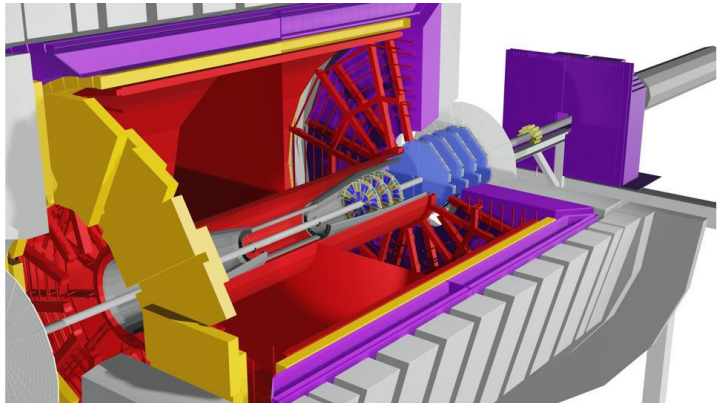
  - Cancellation of u & d quark Sivers
  - Bias from high-z charged pion

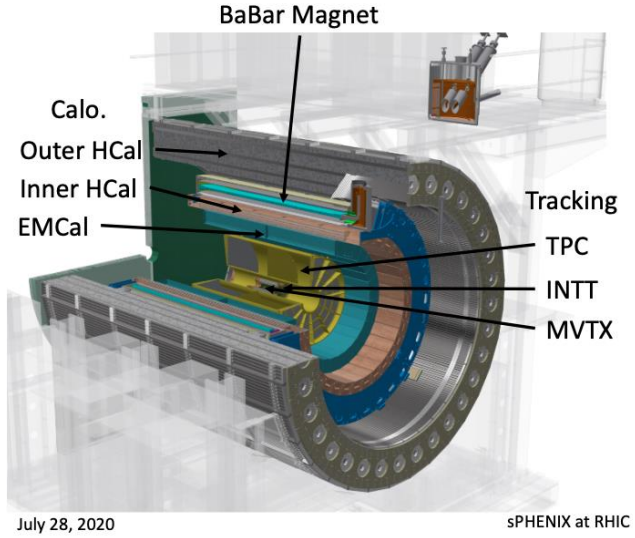




Summary

- RHIC data at mid- and forward rapidity has made significant impact on our understanding of
  - the gluon polarization,
  - the sea quark polarization, and
  - transverse spin effects.
- The STAR Forward Upgrade and sPHENIX still have exciting years ahead.
  - 2022 $\vec{p}+p$ at $\sqrt{s}=508$ GeV
  - 2024 $\vec{p}+p/A$ at $\sqrt{s}=200$ GeV
- Measurements are complementary to and will inform experimental requirements for the future electron-ion collider.

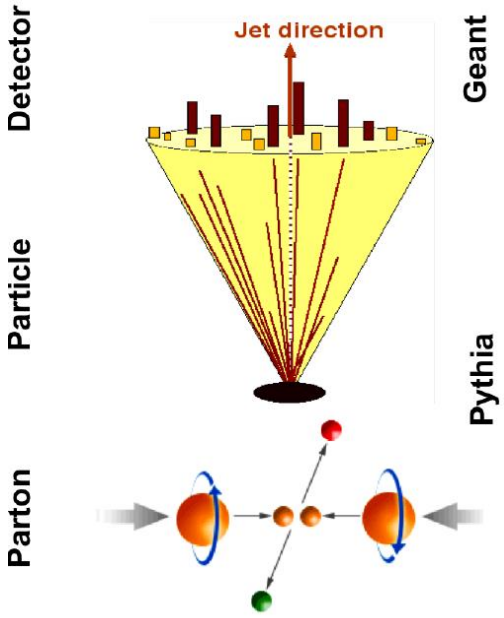


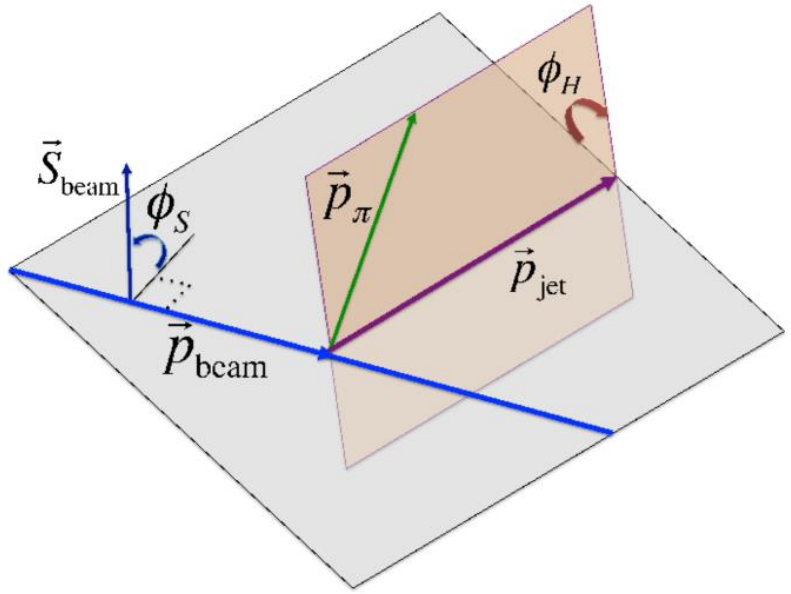


BACK-UP

Hadrons in Jets

- Two scales for TMD measurement
  - p_T of jet
  - j_T of hadron in jet
- Jet reconstruction (anti-k_T)
  - PYTHIA + GEANT
  - Kinematics corrected to particle level and parton level matching
  - Trigger bias
- Pion purities / hadron contamination
- Leak through from other asymmetries





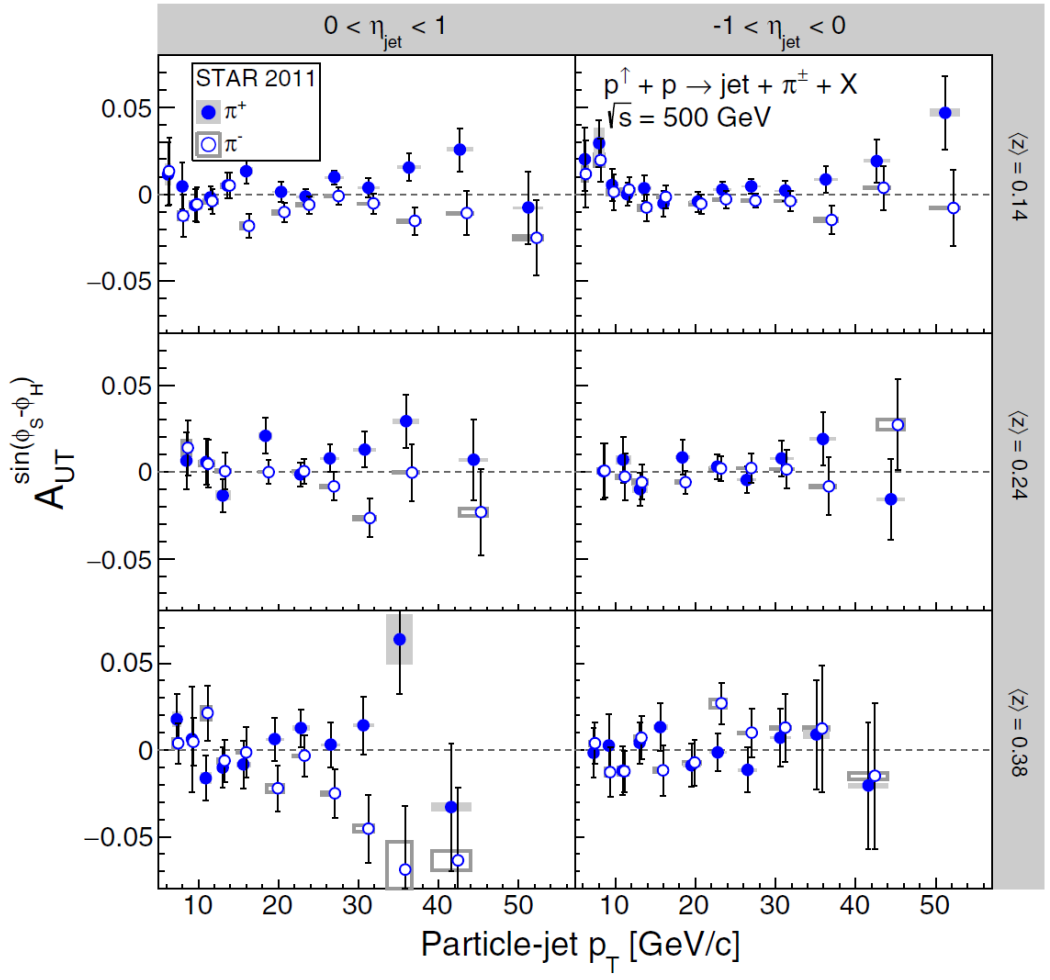
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H) + d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

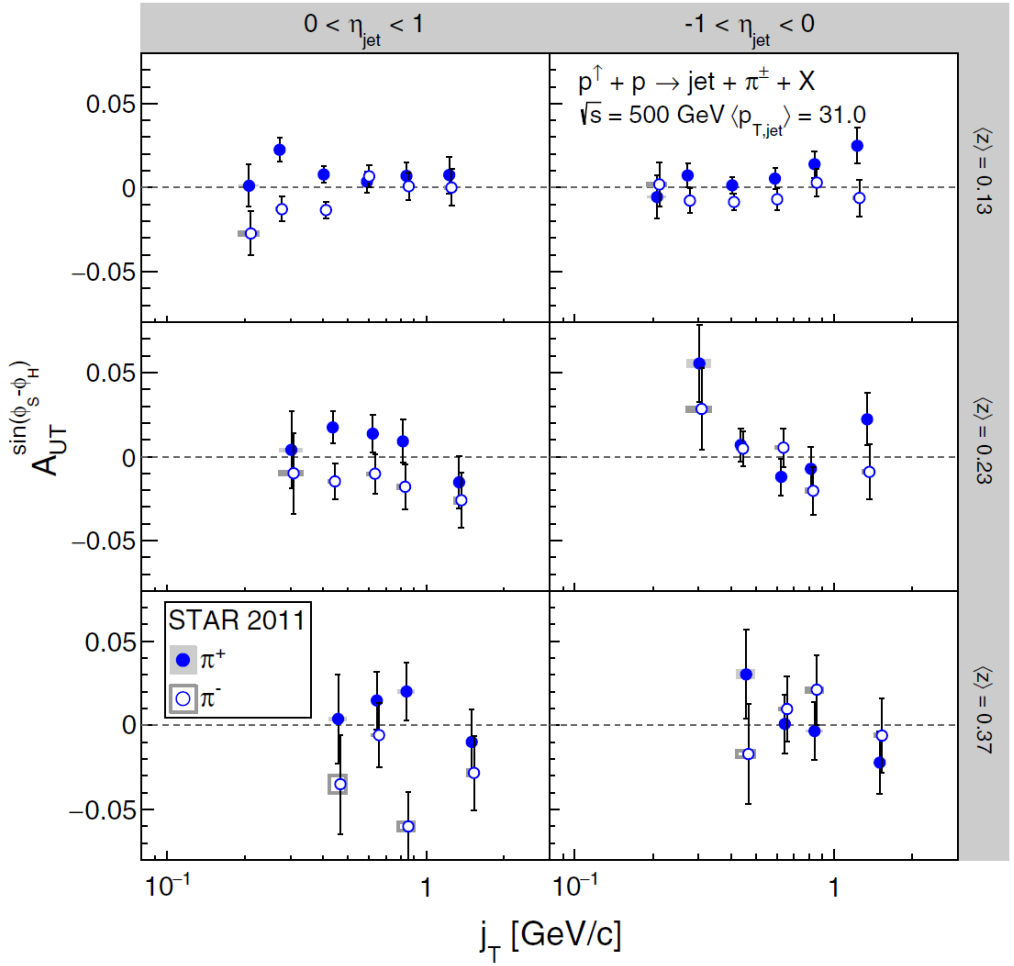
Collins TMD & transversity

Collins-like (linear gluon polarization)

Collins Asymmetries

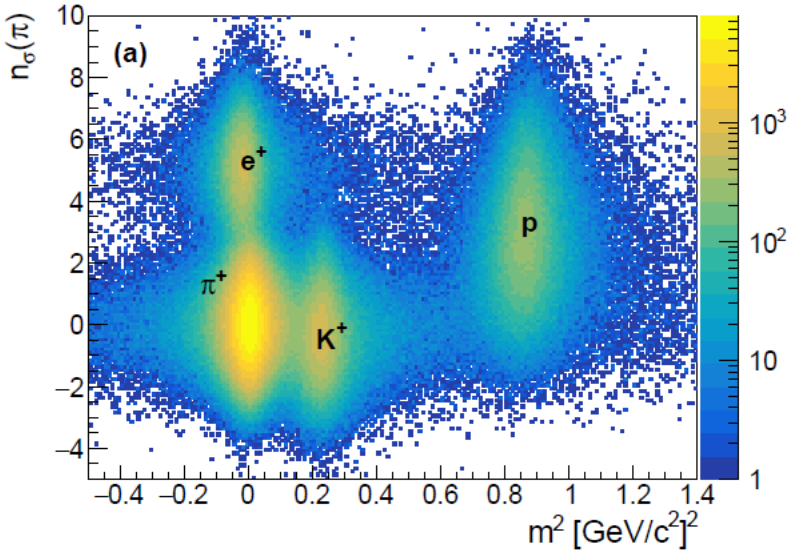
Phys. Rev. D97 (2018) 032004





$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$
$$+ d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$

Collins Asymmetries



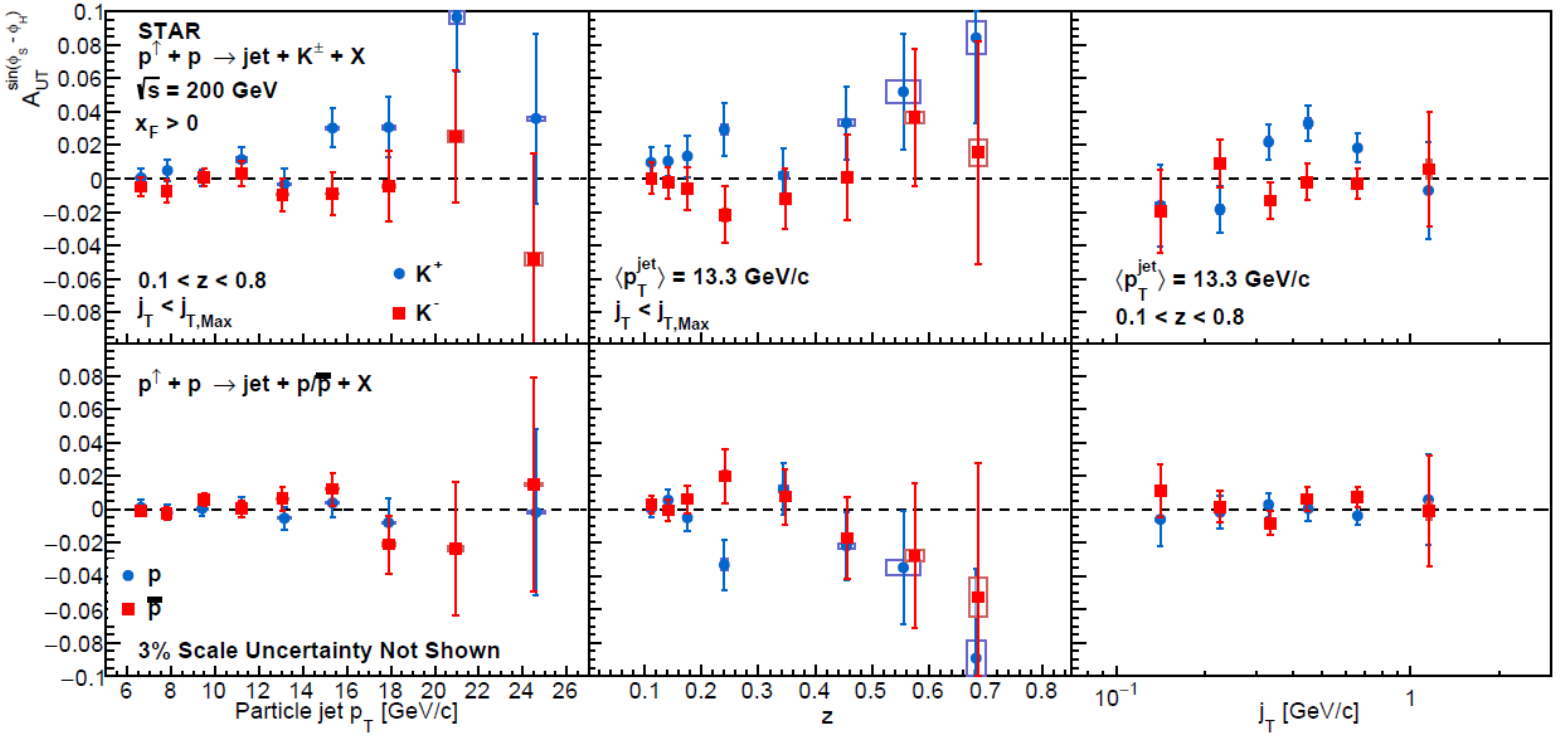
$$A_N = (A_{\pi_{rich}}, A_{K_{rich}}, A_{p_{rich}})$$

$$A_{N,pure} = (A_\pi, A_K, A_p)$$

$$A_{N,pure} = A_N M^{-1}$$

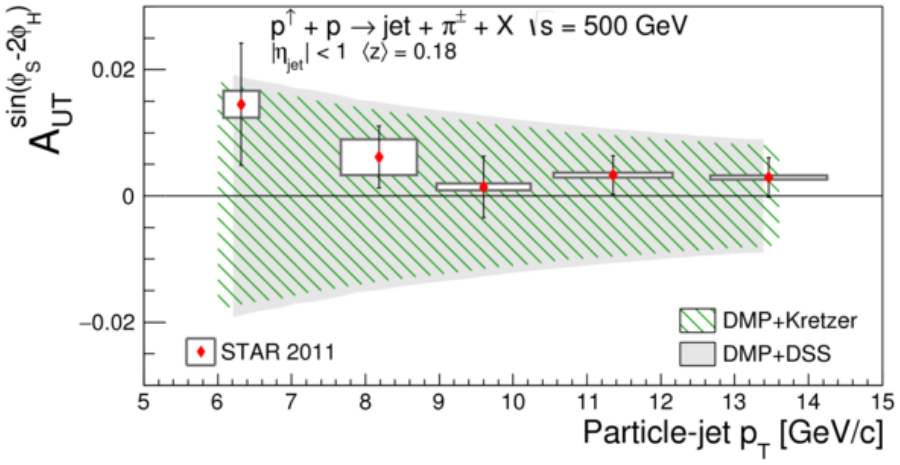
$$M = \begin{pmatrix} f^\pi_{\pi_{rich}} & f^\pi_{K_{rich}} & f^\pi_{p_{rich}} \\ f^K_{\pi_{rich}} & f^K_{K_{rich}} & f^K_{p_{rich}} \\ f^p_{\pi_{rich}} & f^p_{K_{rich}} & f^p_{p_{rich}} \end{pmatrix}$$

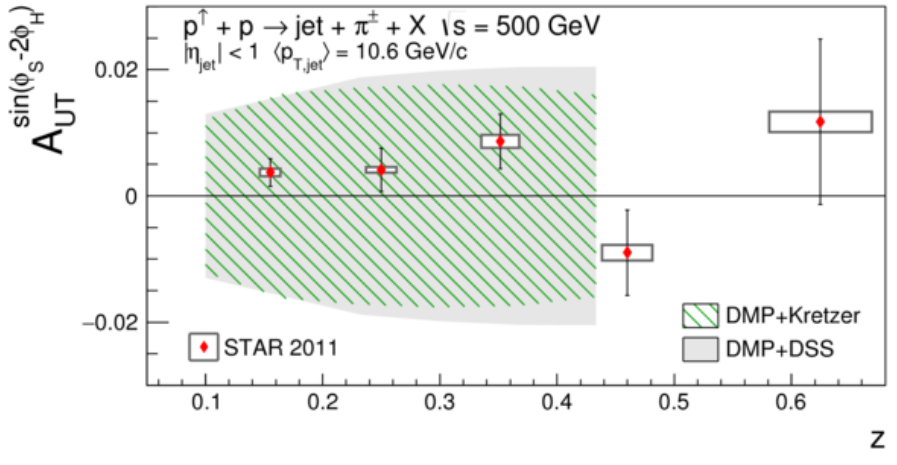
arxiv:2205.11800



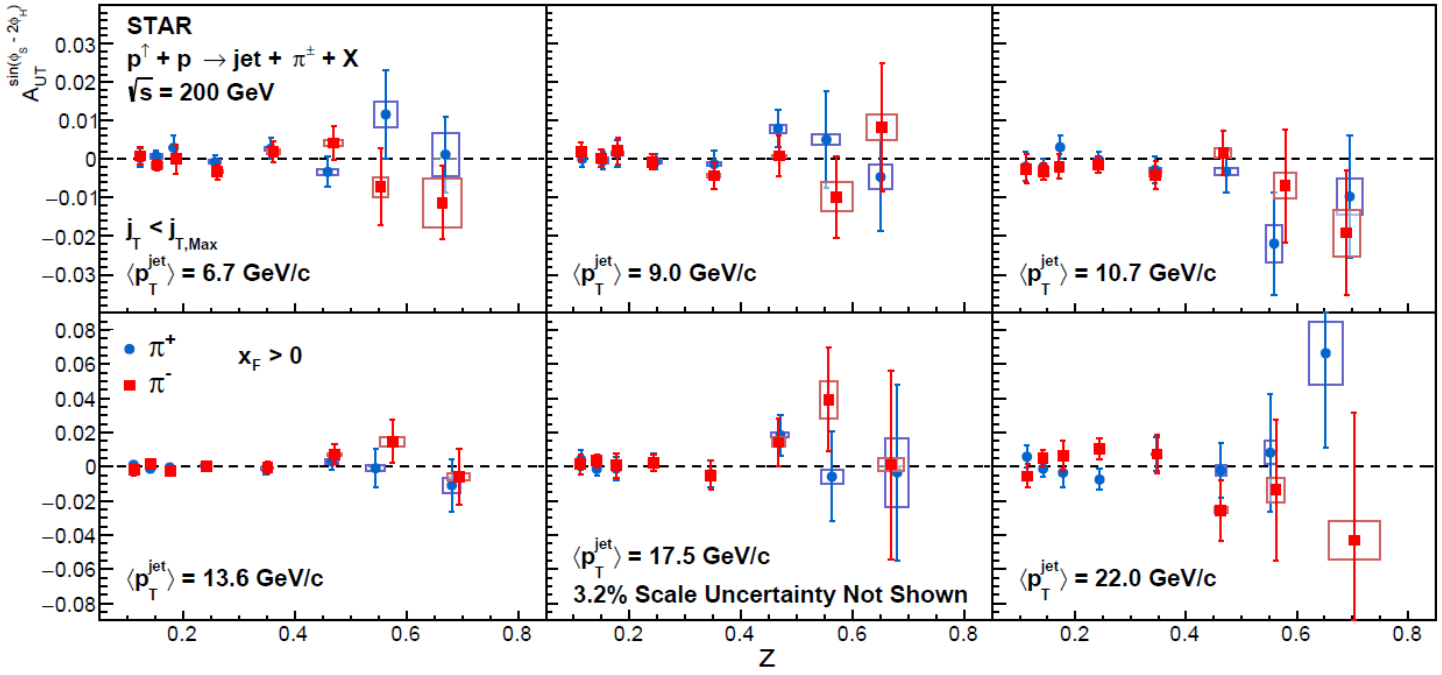
Collins-Like Asymmetries

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H)$$





Phys. Rev. D97 (2018) 032004



arxiv:2205.11800

W-Boson Reconstruction

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

- W-boson decay
  - $p_{T,W}$ is lost
  - Almost no azimuthal angle correlation
- Measure recoil from the collision (tracks and EMC)

$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$

- Limited barrel acceptance
  - Comparison with simulation
  - Recoil p_T correction
  - $p_{z,\nu}$ is more problematic

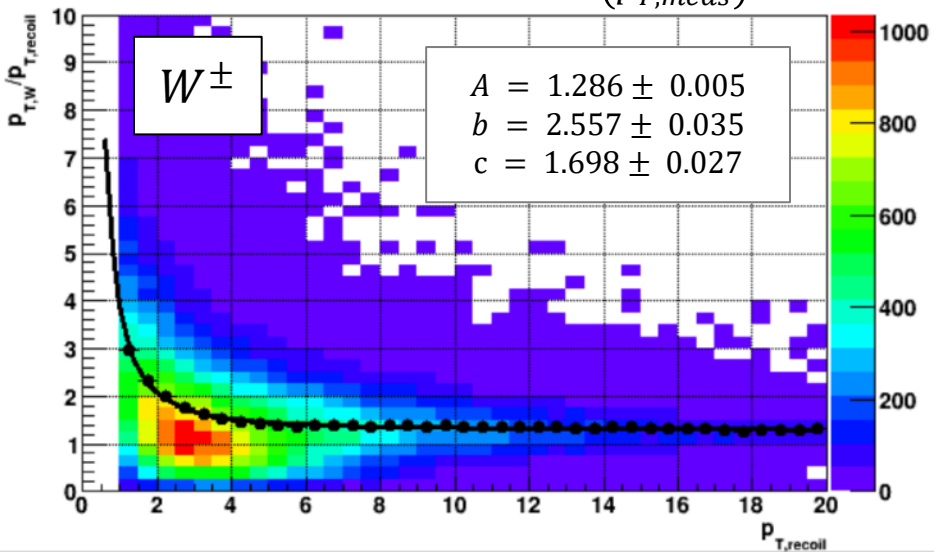
$$M_W^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$

$$p_{\nu,z} = \frac{A}{p_{e,T}^2}\left[p_{e,z} \pm p_e \cdot \sqrt{1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}}\right]$$

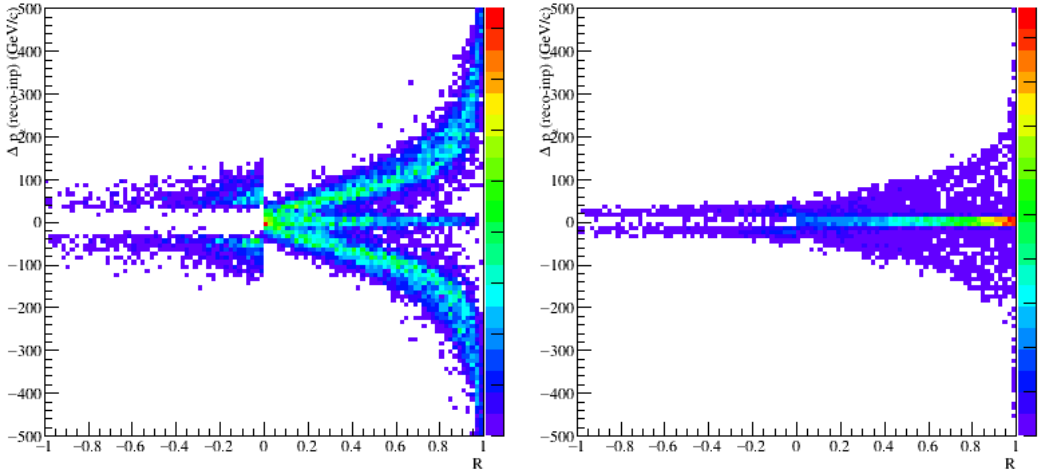
$$A = M_W^2/2 + \vec{p}_{e,T} \cdot \vec{p}_{\nu,T}$$

$$R = 1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}$$

$$p_{T,W} = f(p_{T,meas}) = A + \frac{b}{(p_{T,meas})^c}$$



W^-



Azimuthal Angle Smearing

- Transverse spin asymmetries are measured through azimuthal modulations:

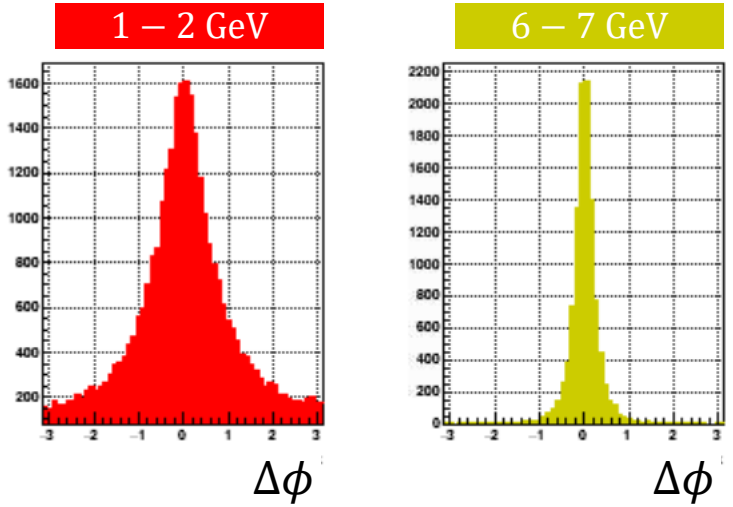
$$d\sigma(\phi) = \sigma_0[1 + PA_N \cos(\phi)]$$

$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi+\pi)}{d\sigma(\phi) + d\sigma(\phi+\pi)} \qquad A_N = \frac{1}{P}\frac{N_\phi - N_{\phi+\pi}}{N_\phi + N_{\phi+\pi}}$$

- Toy Monte Carlo study → determine asymmetry dilution
  - 100k MC samples based on input distribution from embedding (per η-bin)

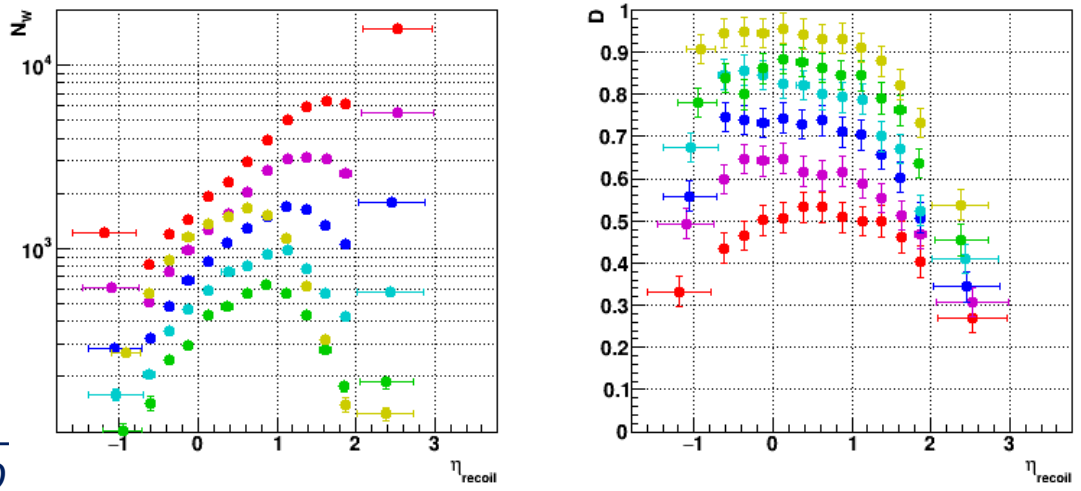
$$D = A_{N,meas}/A_{N,input}$$

$p_{T,recoil}$



$$\Delta\phi = \phi_W - \phi_{recoil}$$

$$\sigma_{A_N} \propto \frac{1}{\sqrt{N}D}$$



Asymmetry correction: $A_N = A_{N,meas}/D$

Transverse Spin Asymmetries in $\vec{p} + A / \vec{p} + p$

- Neutral pions at $\sqrt{s_{NN}} = 200$ GeV
- $2.8 < \eta < 4.0$
- $0.17 < \eta < 0.81$
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