Highlights of Recent Spin Physics Results from STAR

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for the STAR *Collaboration*

New Trends in High-Energy and Low-x Physics
September 2-5, 2024

Supported in part by
U.S. DEPARTMENT OF ENERGY
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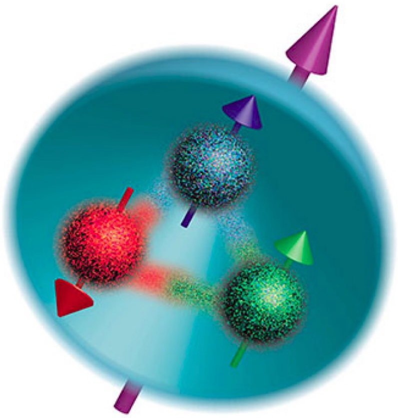
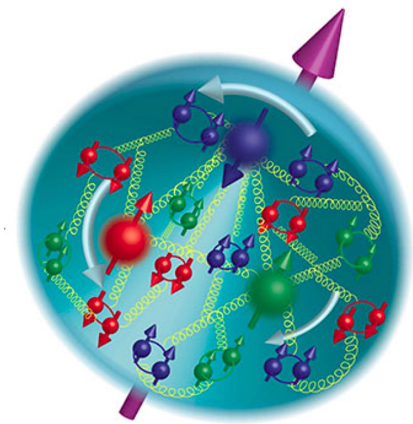
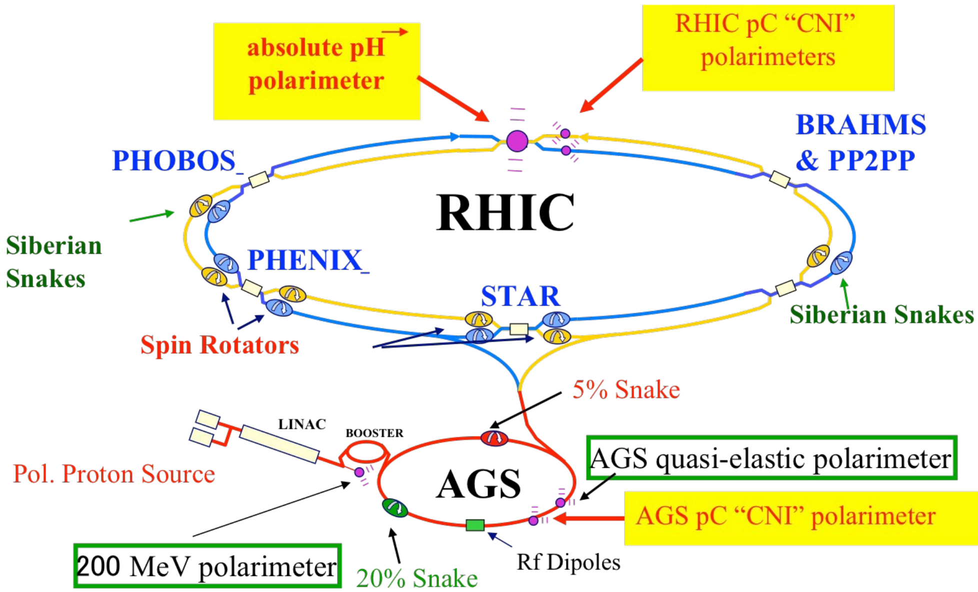
Fundamental Questions Regarding Proton Spin

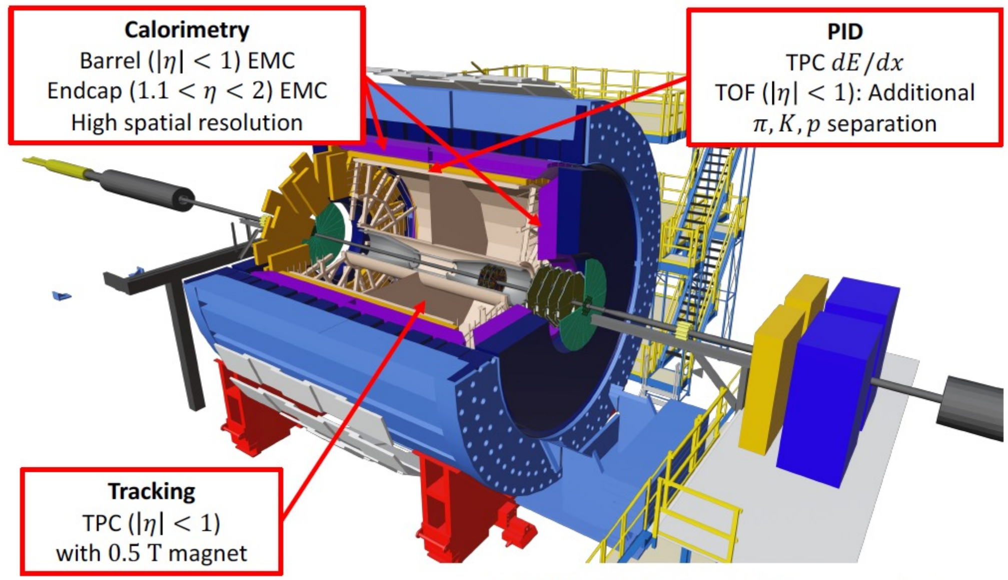




- **How do quarks and gluons conspire to provide the proton's spin ½ ?**
  - What is the role of gluons and sea quarks?
  - What is the size of the orbital angular momentum?
- **What is the dynamic structure of the proton?**
  - How do we go beyond longitudinal parton distribution functions to map out the 3D structure?
  - Can we visualize color interactions in QCD?

The Cold QCD Program at STAR

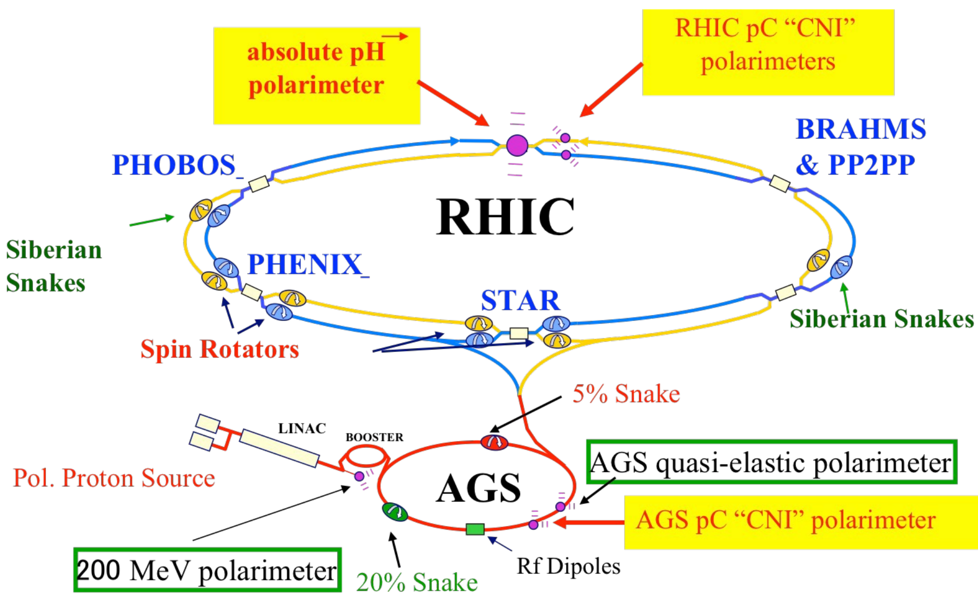


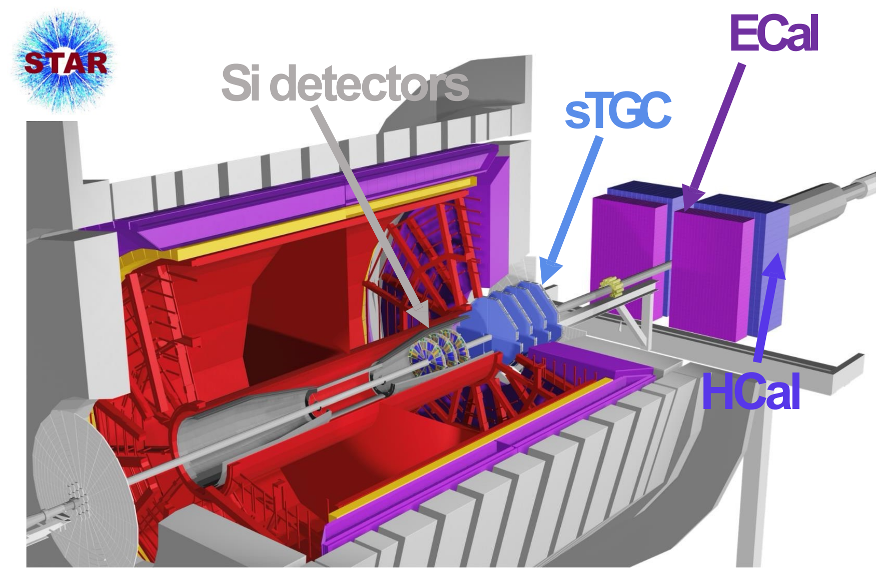


*STAR BEMC, EEMC, TPC, TOF provide full-2π coverage in azimuth.

- RHIC: first and only **(longitudinally and transversely) polarized pp** collider, also capable of colliding AA.
- STAR: has been collecting data with its **forward-upgraded detectors** and will continue data collection until 2025.
- RHIC **Run24: ongoing**, includes **22 weeks of 200 GeV trans. polarized pp** with forward-upgraded detectors.

The Cold QCD Program at STAR





STAR Forward Upgrade: 2.5 < η < 4

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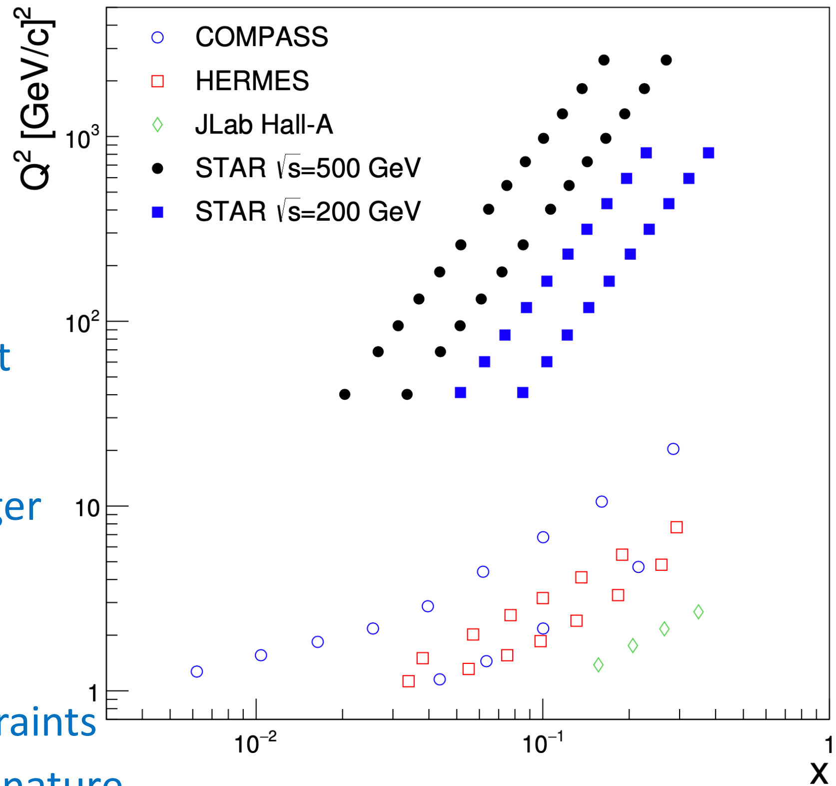
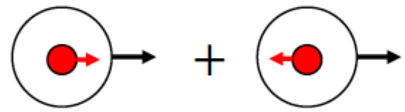
STAR Cold QCD Data and Kinematic Coverage

Year	2011	2012	2015			2017	2022	2024
$\sqrt{s}$ (GeV)	500	200	200			510	508	200
			pp	pAu	pAl			
$L_{int}\ (pb^{-1})$	23	22	52	0.45	1	320	400	TBD
Polarization	53%	57%	57%	60%	54%	55%	53%	TBD



- STAR covers a similar range in momentum fraction to that of SIDIS experiments but at much higher Q^2
- 200 GeV results provide better statistical precision at larger momentum fraction regions while 500 GeV results probe lower *x*-values.
- These two different energies provide experimental constraints on evolution effects and insights into the magnitude and nature of TMD observables that will be measured at EIC.

Cold QCD Program at STAR

Spin Averaged $f(x) =$ 

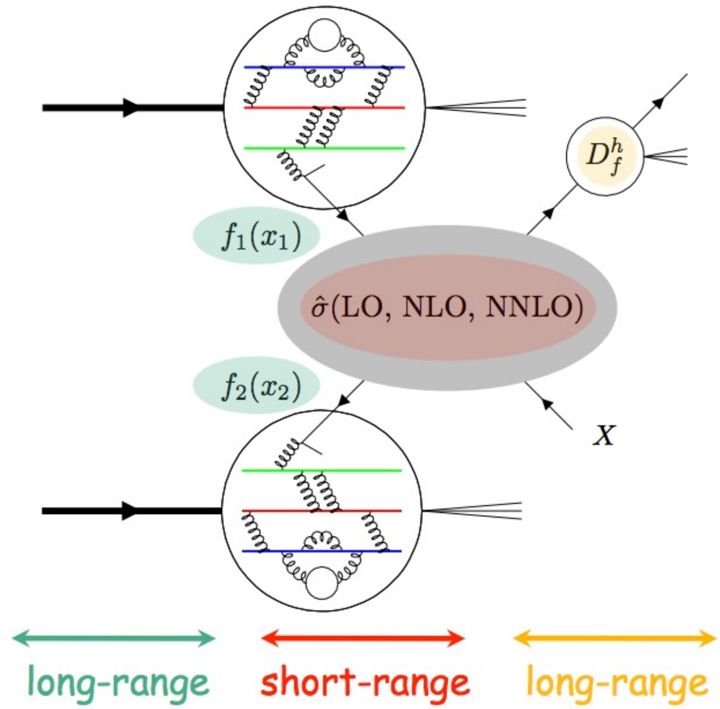
- Gluon density
- Sea quark densities

Longitudinal Spin

- Gluon polarization
- Sea quark polarization

Transverse Spin

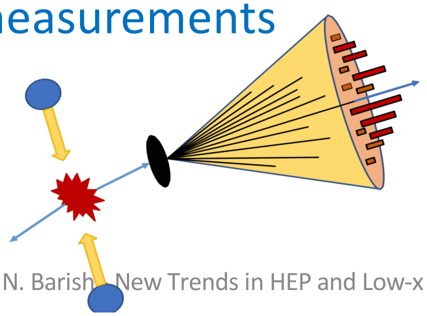
- Sivers effect
- Collins effect
- Transversity

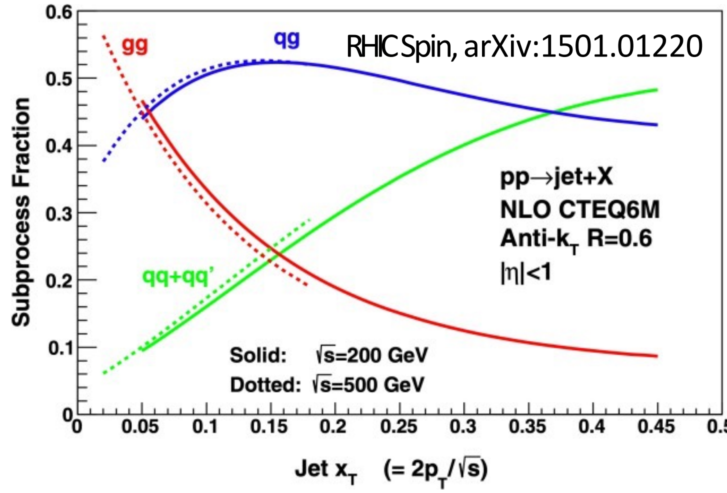


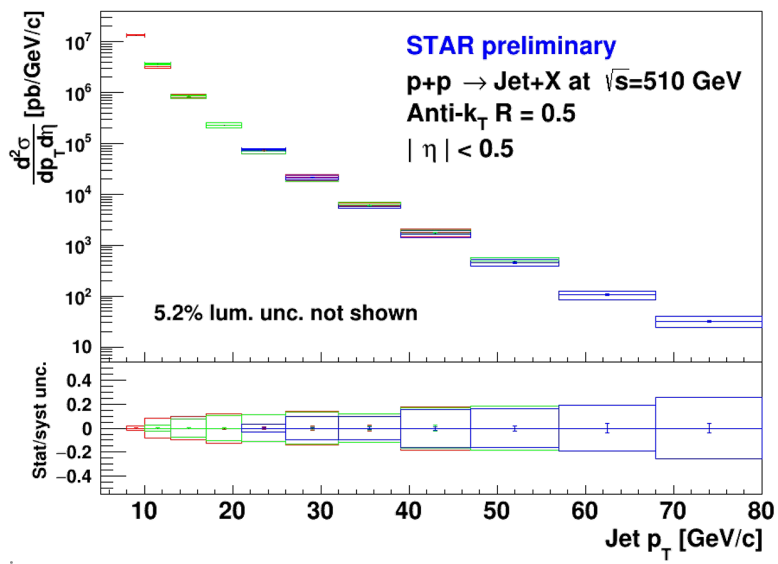
$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

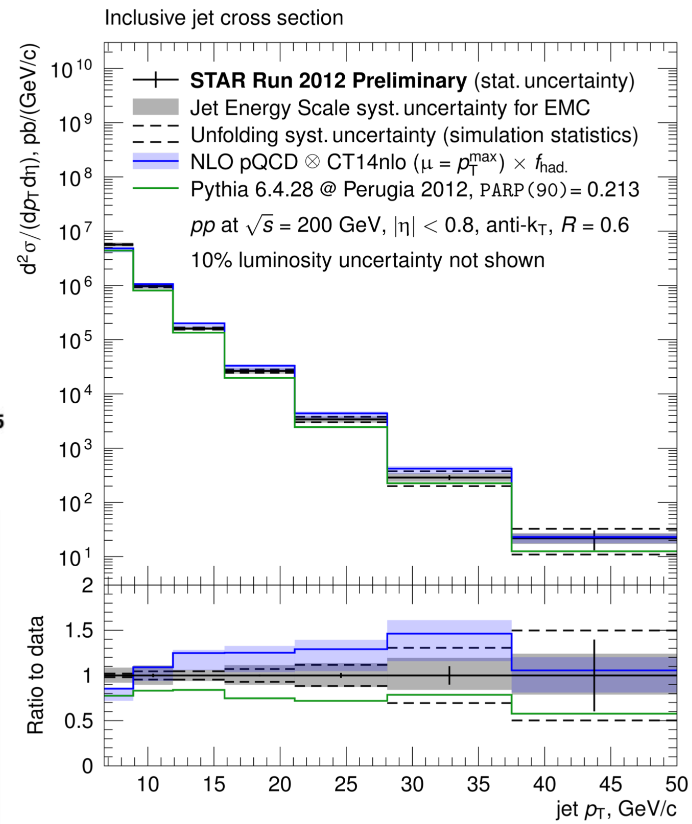
Jets at STAR

- Jets at STAR are sensitive to gluon (gg, qg processes dominate)
- Anti-k_T clustering algorithm with tracking + calorimetry info
- $R = 0.6$ (0.5) for $\sqrt{s}$ = 200 (500/510) GeV, motivated by UE
- Further tuning provided from unpolarized measurements





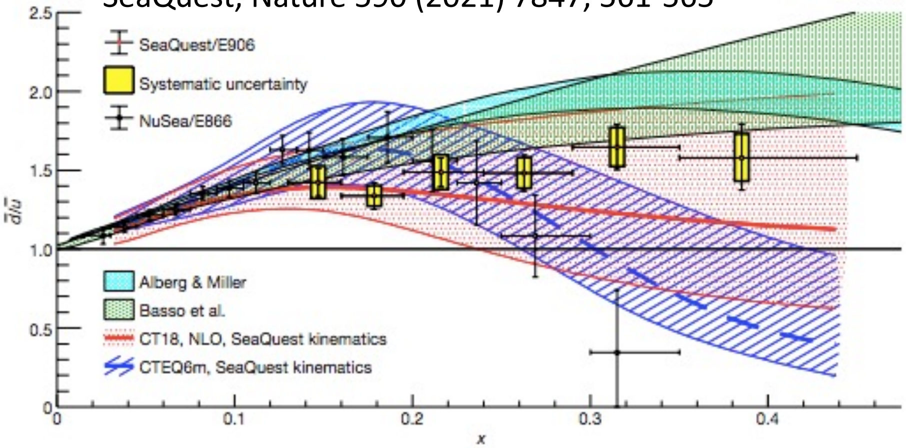


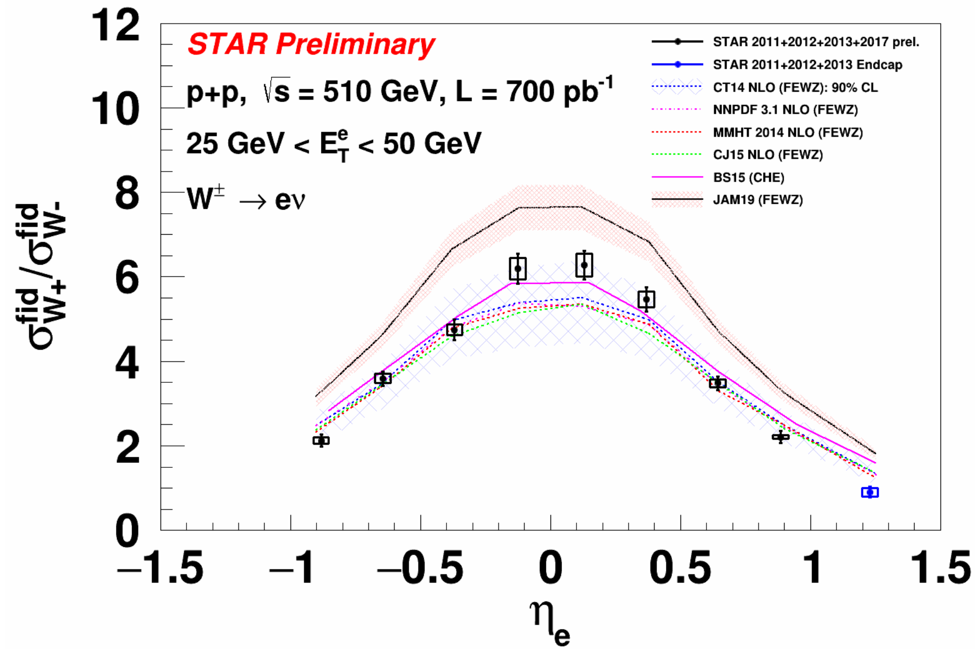


The measured jet cross sections are well described by NLO pQCD predictions.

Sea Quark Densities

SeaQuest, Nature 590 (2021) 7847, 561-565





Unpolarized sea quark ratio $\bar{d}/\bar{u}$

- Predominantly measured via Drell-Yan
- Tension between measurements around the valence region.
- STAR kinematics at the mid-rapidity ($|\eta| < 1$) is sensitive to the $0.1 < x < 0.3$
- Can be further stretched to $0.06 < x < 0.4$ with the EEMC ($0.1 < \eta < 0.3$)

W Production at STAR:

- Sensitive to u $\bar{d}$ (W^+) and $\bar{u}$ d (W^-) at leading order.
- The cross-section ratio is sensitive to $\bar{d}/\bar{u}$

$$\sigma_{W^+}/\sigma_{W^-} \approx \frac{u(x_1)\,\bar{d}(x_2) + u(x_2)\,\bar{d}(x_1)}{\bar{u}(x_1)\,d(x_2) + \bar{u}(x_2)\,d(x_1)}$$

Cold QCD Program at STAR

Spin Averaged

- Gluon density
- Sea quark densities

Longitudinal Spin

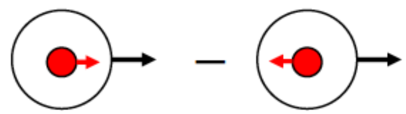
- Gluon polarization
- Sea quark polarization

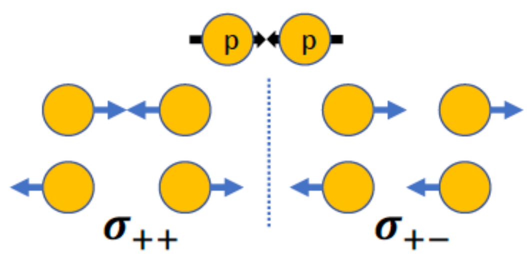
Transverse Spin

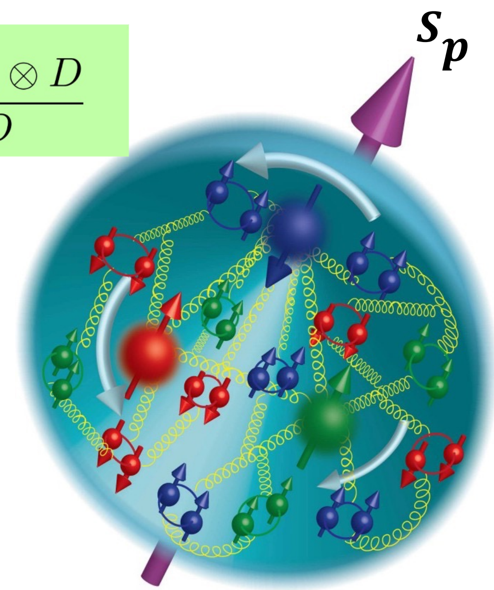
- Sivers effect
- Collins effect
- Transversity

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a_{\hat{L}L} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

Global fit → $\Delta f(x, Q^2)$

$\Delta f(x) =$ 





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

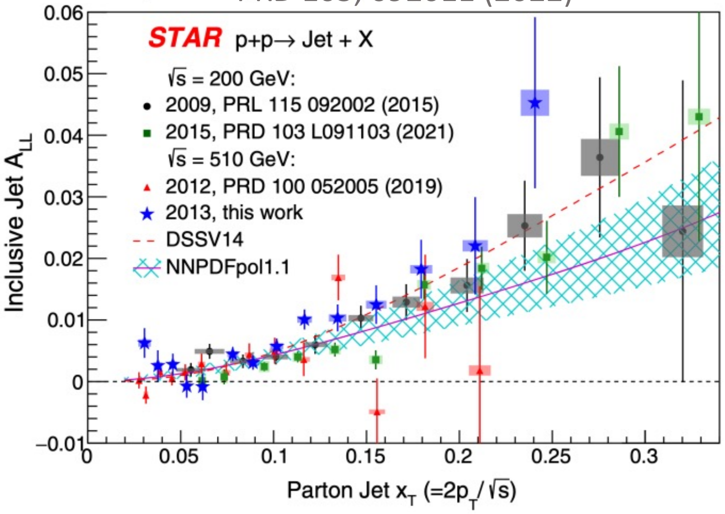
gluon spin (ΔG)

valence + sea quark spin ($\Delta\Sigma$)

quark & gluon orbital motion ($L_q + L_g$)

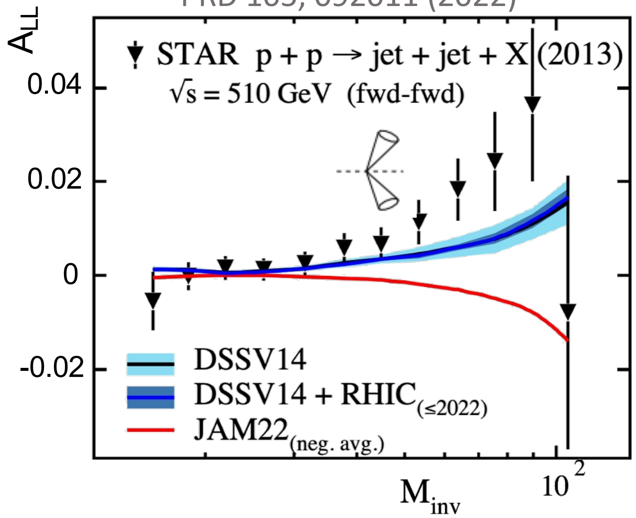
Inclusive, Dijet, and Pion Tagged Jets A_{LL}

PRD 105, 092011 (2022)

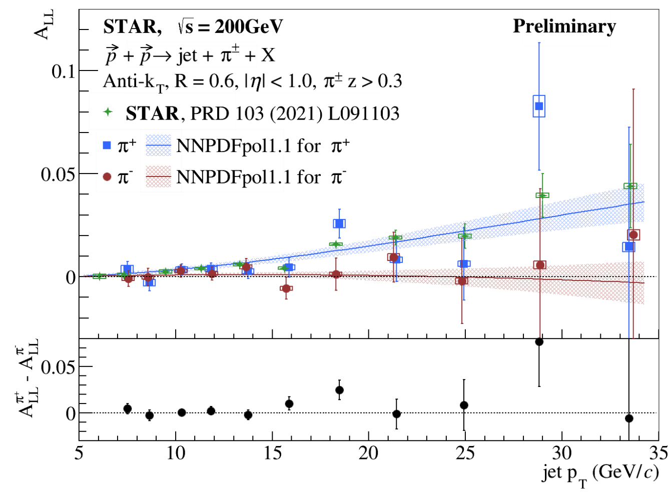


Inclusive Jet A_{LL}

PRD 105, 092011 (2022)



Dijet A_{LL}

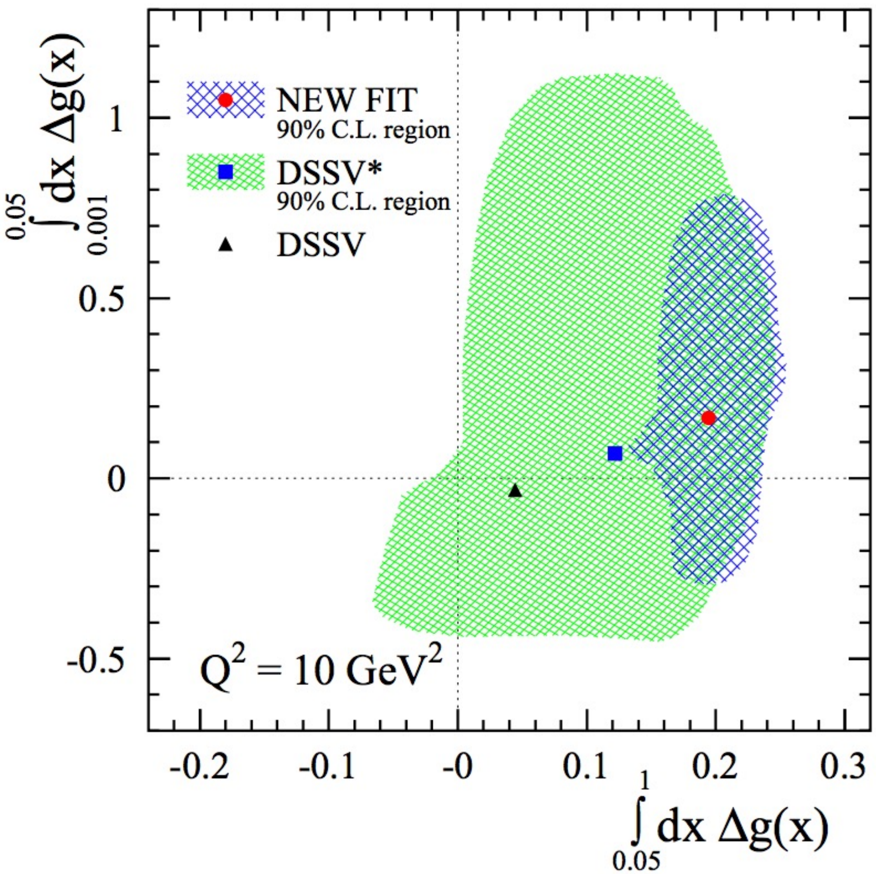


π tagged jet A_{LL}

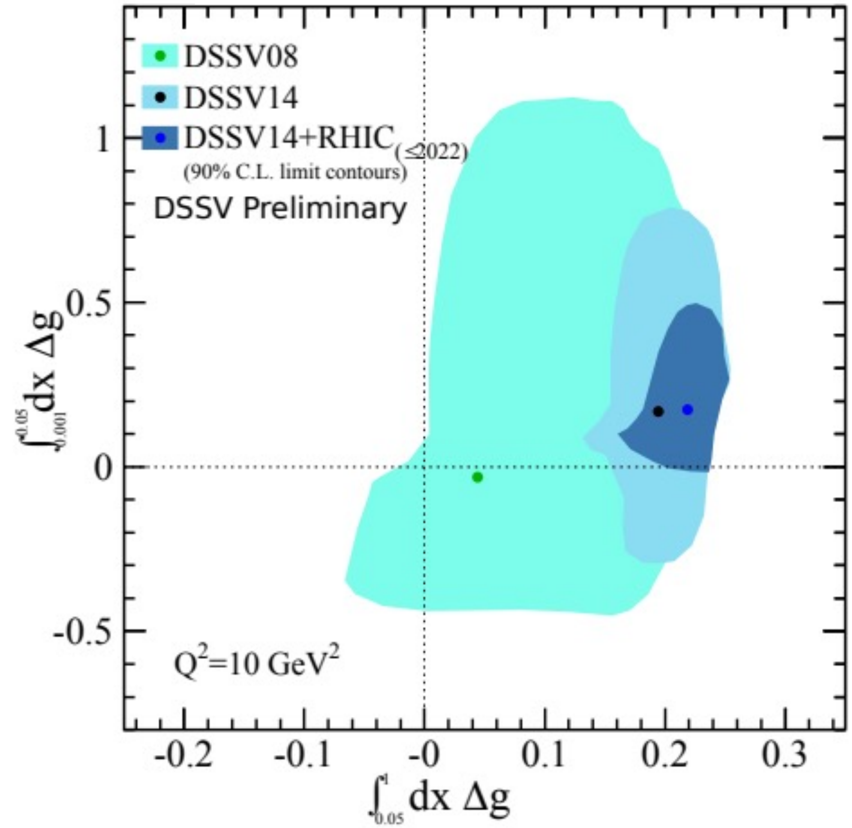
- STAR inclusive jet A_{LL} using 2009 data provided first evidence of positive gluon polarization at $0.05 < x < 0.2$
- STAR inclusive and dijets A_{LL} at 200 and 510 GeV using 2009 to 2015 data:
  - Consistent results from both energies
  - 200 GeV data constrain $\Delta g(x)$ for $x > 0.05$
  - Forward detection and higher collision energy at 510 GeV data push the sensitivity to lower $x \rightarrow 0.02$
- STAR inclusive jets tagged with $\pi^{\pm}$ carrying high z can provide further constraints on $\Delta g(x)$

Inclusive, Dijet, and Pion Tagged Jets A_{LL}

DSSV, PRL 113 (2014) 1, 012001

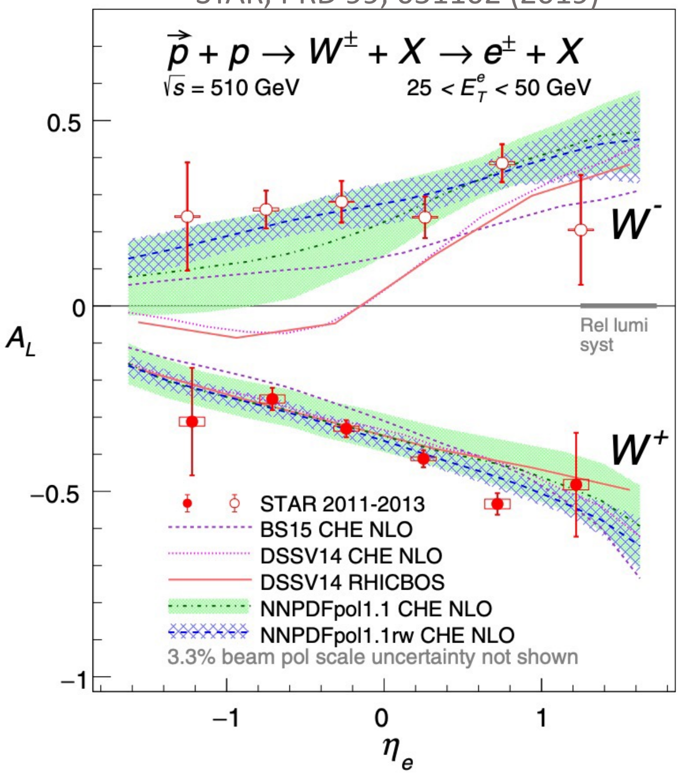


RHIC Spin, arXiv: 2302.00605

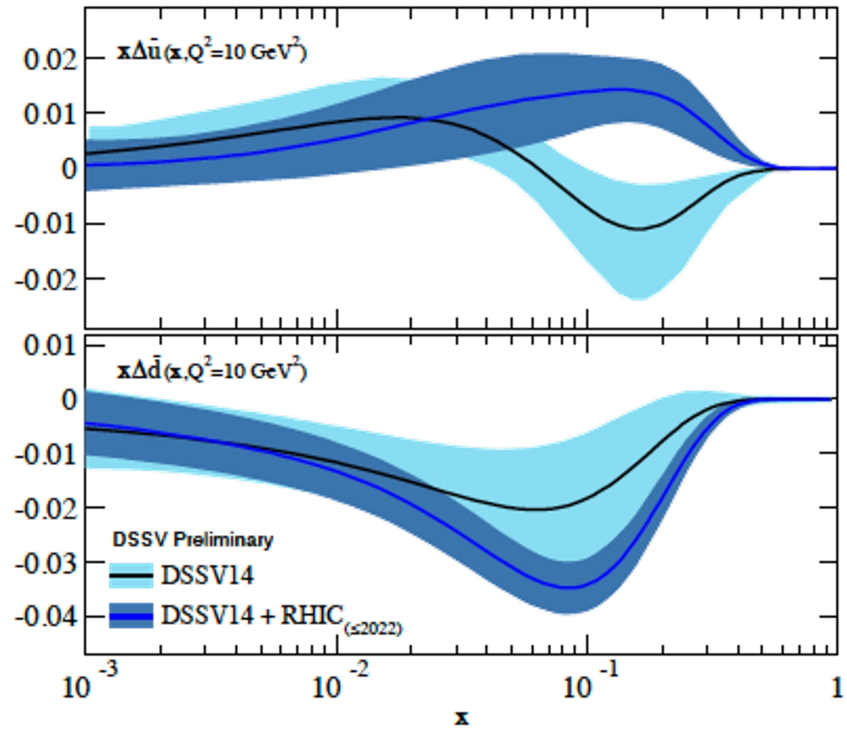


Sea Quark Helicity ($\Delta\bar{u}$, $\Delta\bar{d}$)

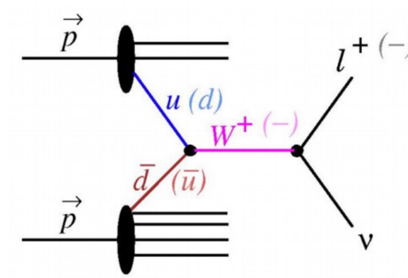
STAR, PRD 99, 051102 (2019)



arXiv:2302.00605



$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



- Measured parity-violating single-spin asymmetry of $W^{+(-)} \propto \Delta\bar{d}$ ($\Delta\bar{u}$)
- For the first time, we can conclude an asymmetry between $\bar{u}$ and $\bar{d}$ polarization: $\Delta\bar{u} - \Delta\bar{d} > \mathbf{0}$ with STAR 2013 $W^{+/-}$ data

Cold QCD Program at STAR

Explore the multidimensional landscape in coordinate and momentum space of nucleons and nuclei

TMD: $f(x, k_{\perp}, Q^2)$

Spin Averaged

Gluon density

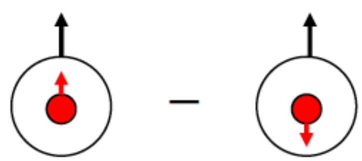
Sea quark densities

Longitudinal Spin

Gluon polarization

Sea quark polarization

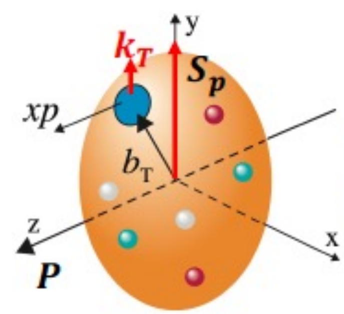
Transverse Spin

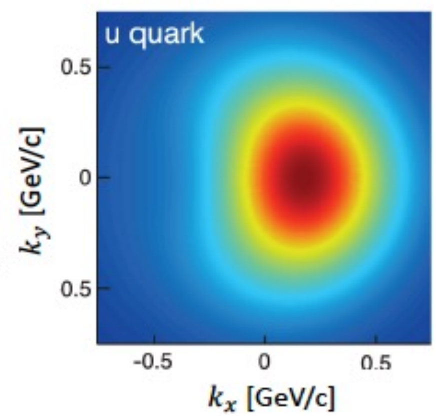
$h_1(x) =$ 

Sivers effect

Collins effect

Transversity





3-dimentional image of the structure of a proton: k_t is the transverse momentum of a parton

Sivers and Collins Functions

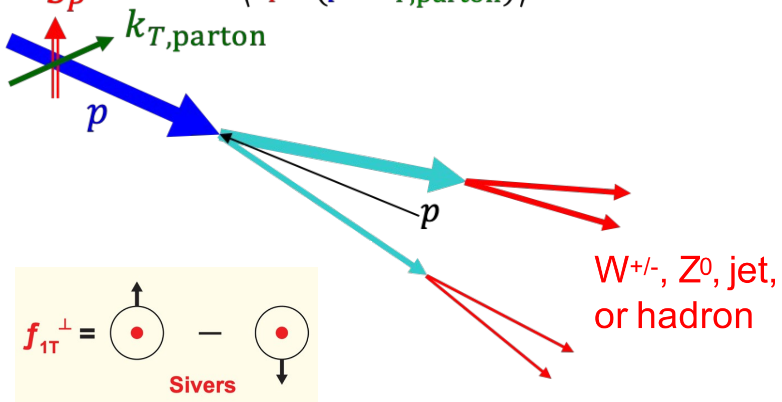
(1) Initial State Effects: “Sivers”

Correlation between proton-spin and intrinsic transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^{2})}_{\text{Sivers distribution (initial state)}} \cdot D_{q}^{h}(z)$$

Sivers distribution (initial state)

$$\langle S_P \cdot (p \times k_{T,\mathrm{parton}}) \rangle \neq 0$$



(II) Final State Effects: “Collins”

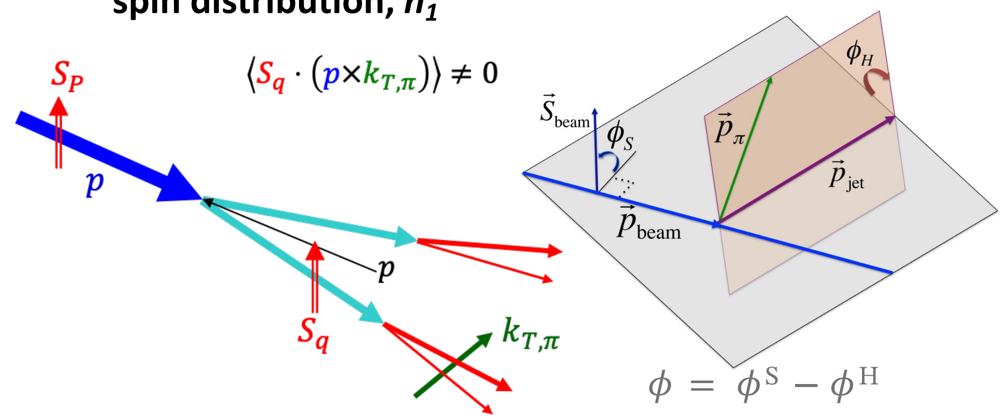
Correlation between proton & quark spin + spin dependant fragmentation function

$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution, } h_1} \cdot \underbrace{H_{1}^{\perp}(z_2, \bar{k}_{\perp}^{2})}_{\text{Collins FF (final state)}}$$

Quark transverse spin distribution, *h₁*

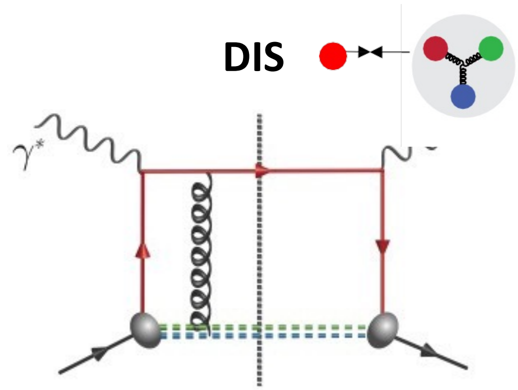
Collins FF (final state)

$$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$$

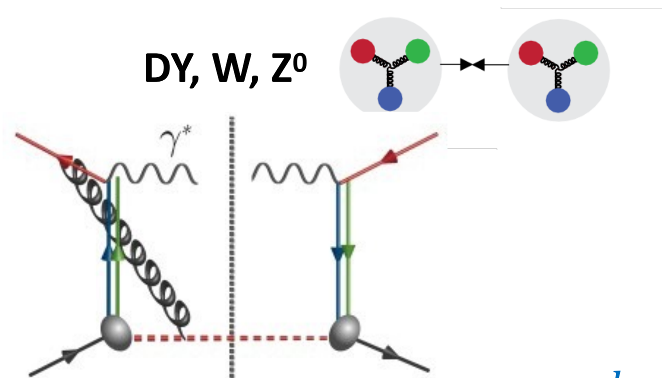


- Observables: $A_{UT}^{\sin(\varphi)}$ for hadrons
- Collins function is predicted to be universal

Sivers Function ($W^{+/-}$ and Z^0)



Final-state interaction

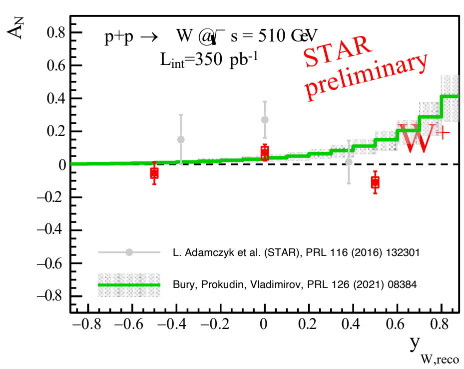


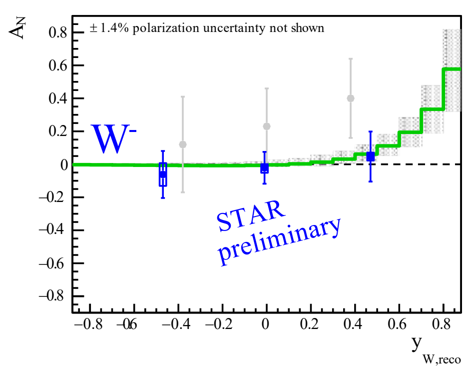
Initial-state interaction

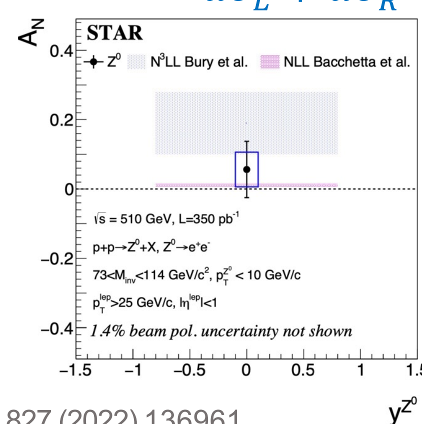
Sivers effect is NOT universal; it is a process-dependent effect:

$\text{Sivers}_{\text{DIS}} = -(\text{Sivers}_{\text{DY}} \text{ or } \text{Sivers}_{W,Z0})$

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



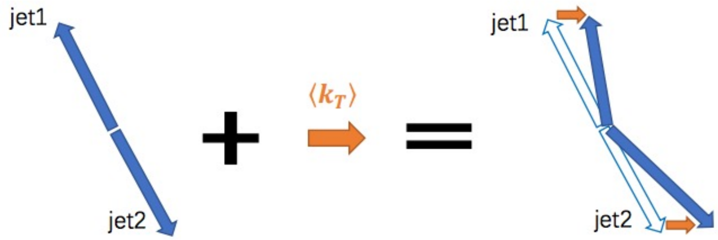


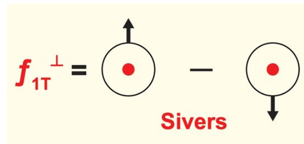


Bury et al., PRL 126 (11) (2021) 112002; Bacchetta et al.,PLB 827 (2022) 136961

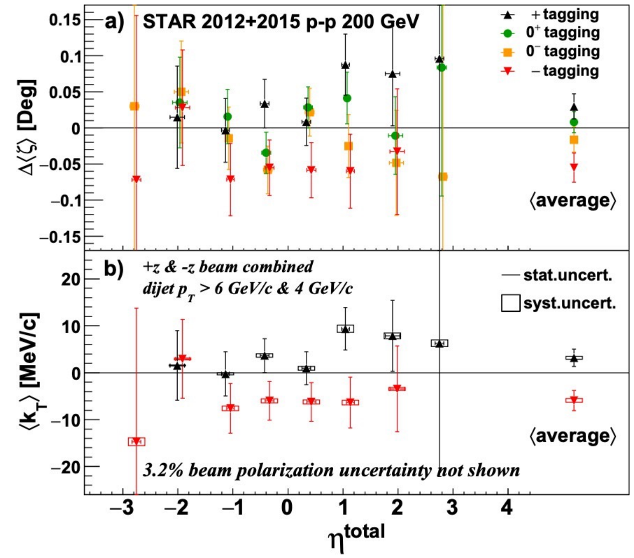
- Mid-rapidity $W^{+/-}$ and Z^0 A_N: statistics much improved with run 2017 compared to run 2011 (25 pb^{-1})
- Additional 400 pb^{-1} data from Run 2022 with Forward Upgrade and η coverage extended by STAR iTPC

Sivers Function (via dijets)

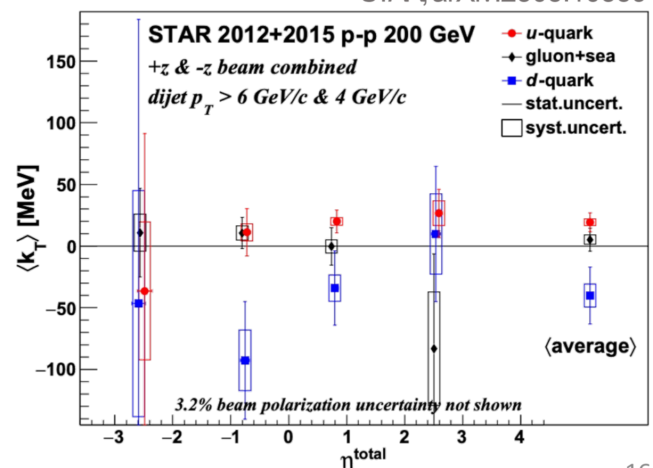




STAR, arXiv:2305.10359



STAR, arXiv:2305.10359



- Azimuthal correlation in p+p dijet a proxy for intrinsic parton k_T
- Jet jet tagged by jet charge

$$Q_{jet} = \Sigma_{trk} \frac{p_{trk}}{p_{jet}} \cdot Q_{trk}$$

$Q_{jet} > +0.25$: u enhanced
$Q_{jet} < -0.25$: d enhanced
$|Q_{jet}| < 0.25$: less u and d enhancement

- **First observation of >2σ Sivers asymmetries in $\vec{p} + p$ collisions**

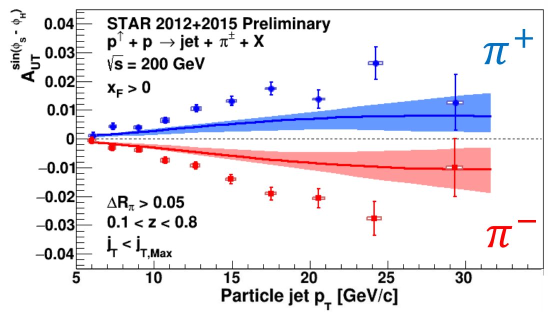
$$\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6 \frac{MeV}{c}, \langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3 \frac{MeV}{c}$$

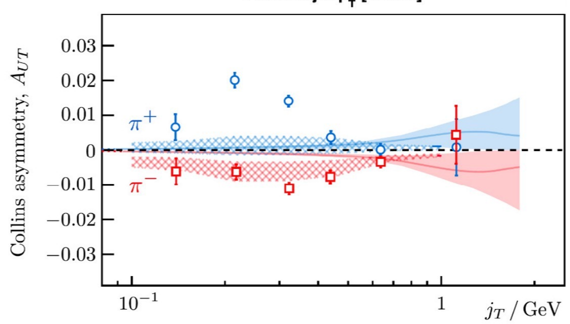
$$\langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8 \frac{MeV}{c}$$

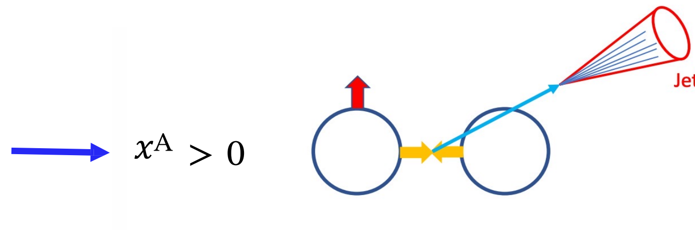
- What's next: x dependence probed by combining with 510/508 GeV data from 2017 and 2022; improved statistics with extended η coverage with STAR iTPC and Forward Upgrade from 2024 run.

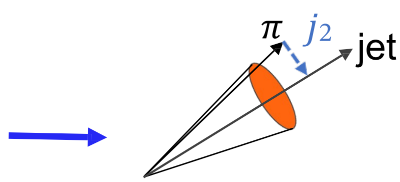
Collins asymmetry for π$^{\pm}$ in jets

STAR, PRD 106, 072010 (2022)

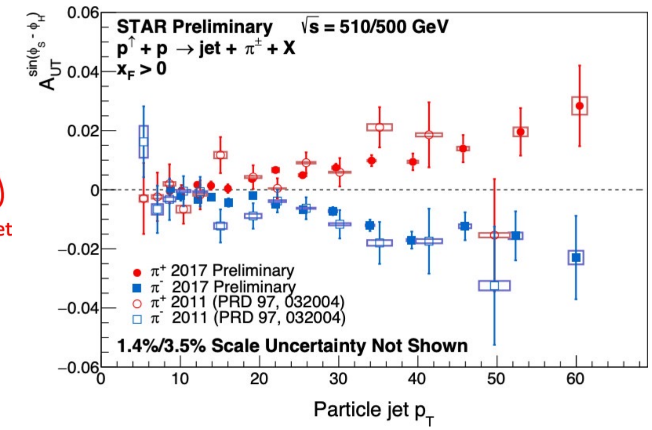


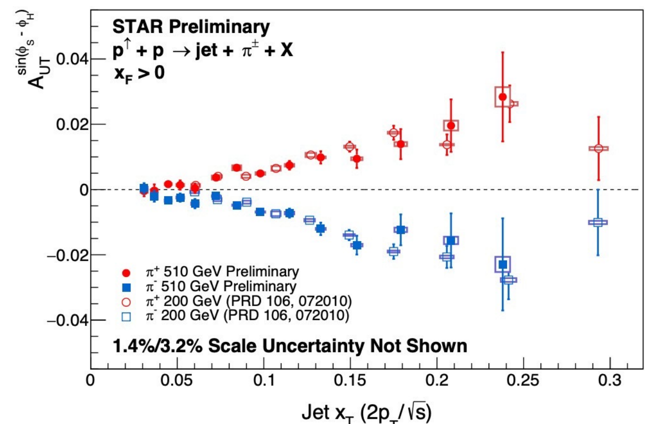






j_T: pion's momentum transverse to the jet axis

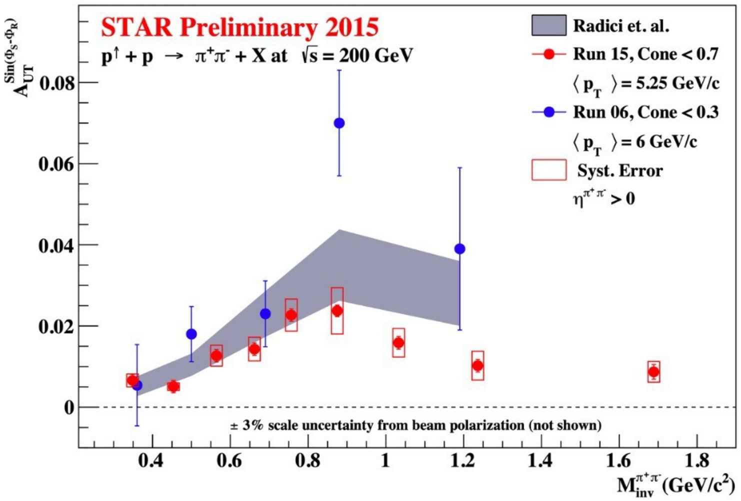


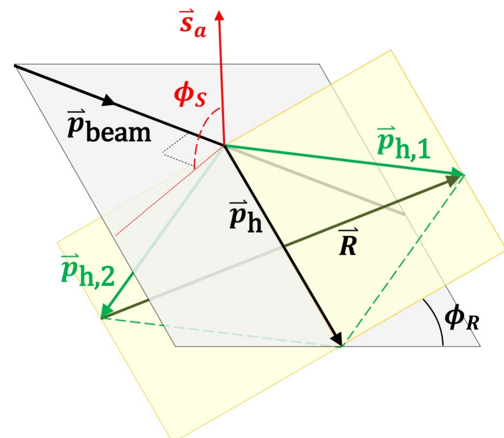


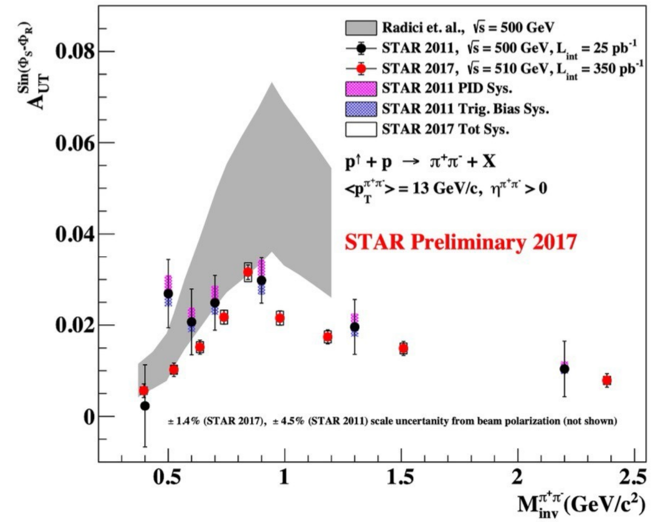
Spin-dependent modulation of $\pi^{\pm}$ in jets at mid-rapidity ($|\eta_{jet}| < 1$):

- Significant Collins asymmetries for $\pi^{\pm}$ measured with high precision
- Stringent constraints on theoretical calculations of transversity and Collins FF
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Interference FF (from di-hadrons)







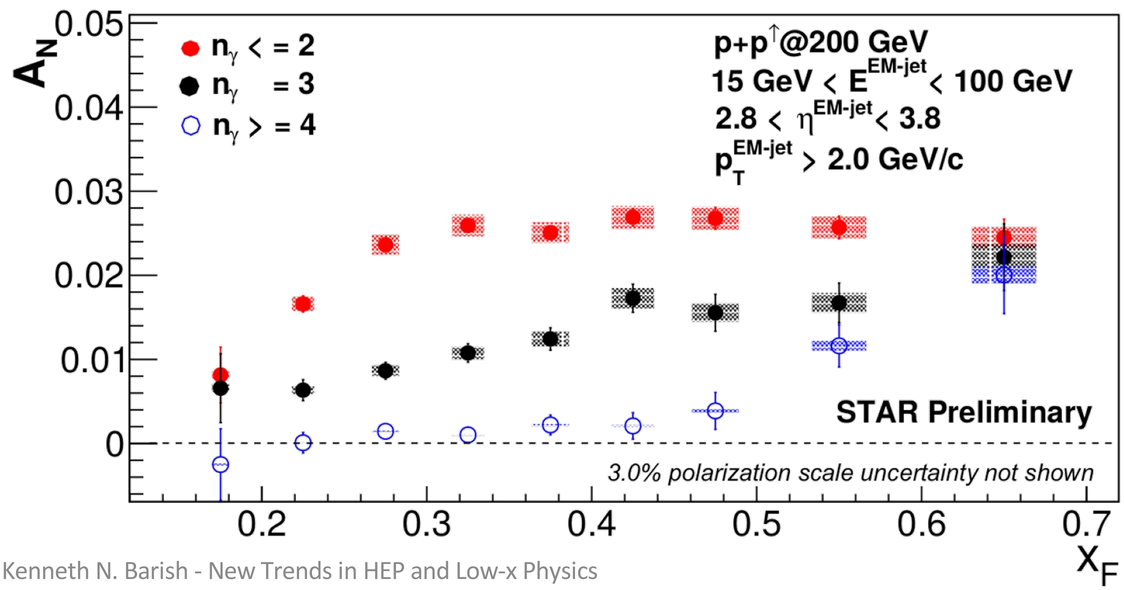
$$d\sigma_{UT} \propto \int dx_a dx_b h_1(x_a) f_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

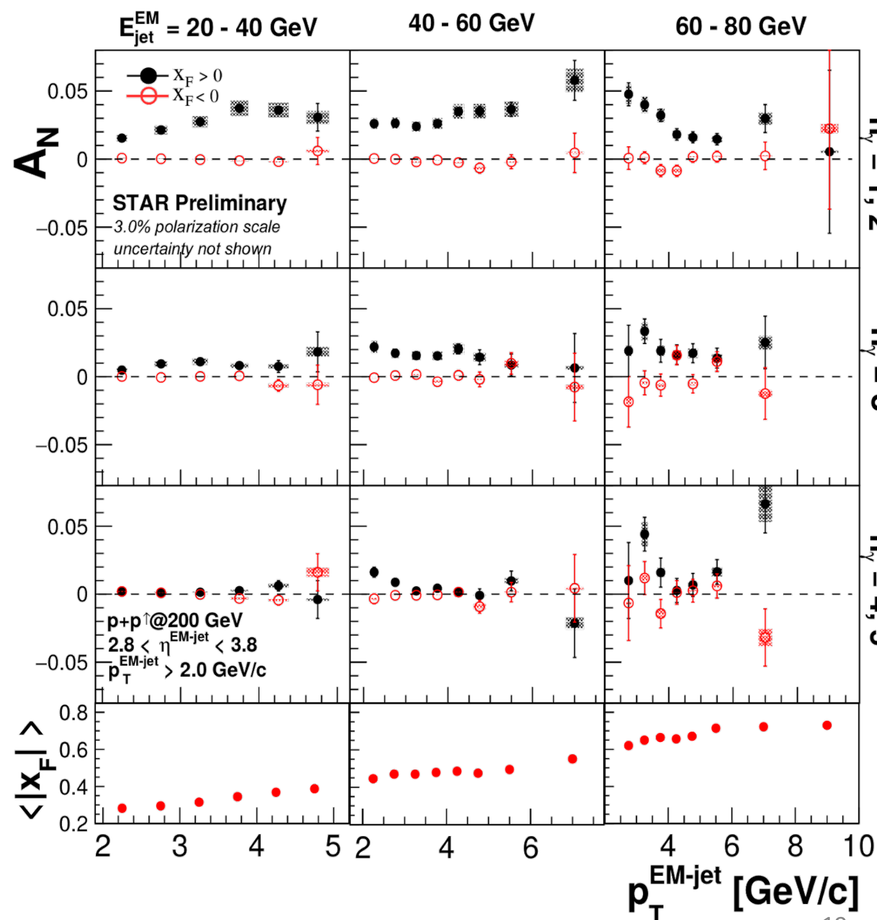
- Spin dependent di-hadron correlations probe collinear quark transversity coupled to the interference fragmentation function (IFF) at higher Q^2 region compared to SIDIS
- The results can test the universality property of IFF from e^+e^-, SIDIS and p+p data
- Planning for precision measurement of IFF asymmetries for pion/kaon from 2022+2024 dataset

Inclusive EM-jet A_N

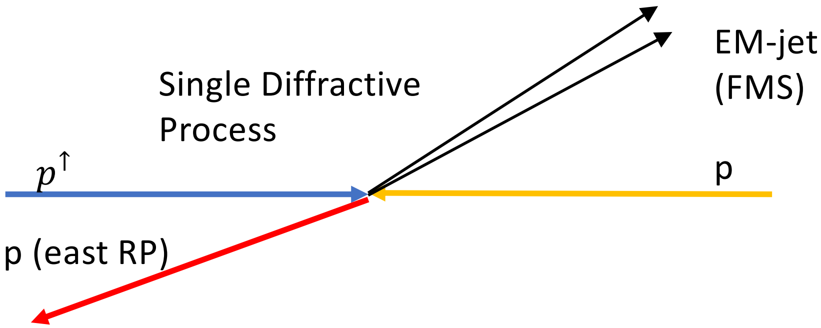
Electromagnetic jets (EM-jets) are the jets reconstructed using only photons

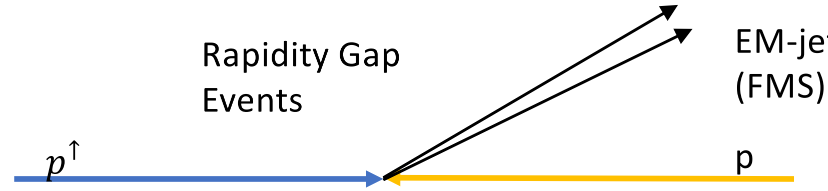
- EM-jet A_N decreases with increasing photon multiplicity for $x_F > 0$
  - A_N is larger for the EM-jets consisting of 1 or 2 photons
- A_N increases with x_F for all the cases of photon multiplicity



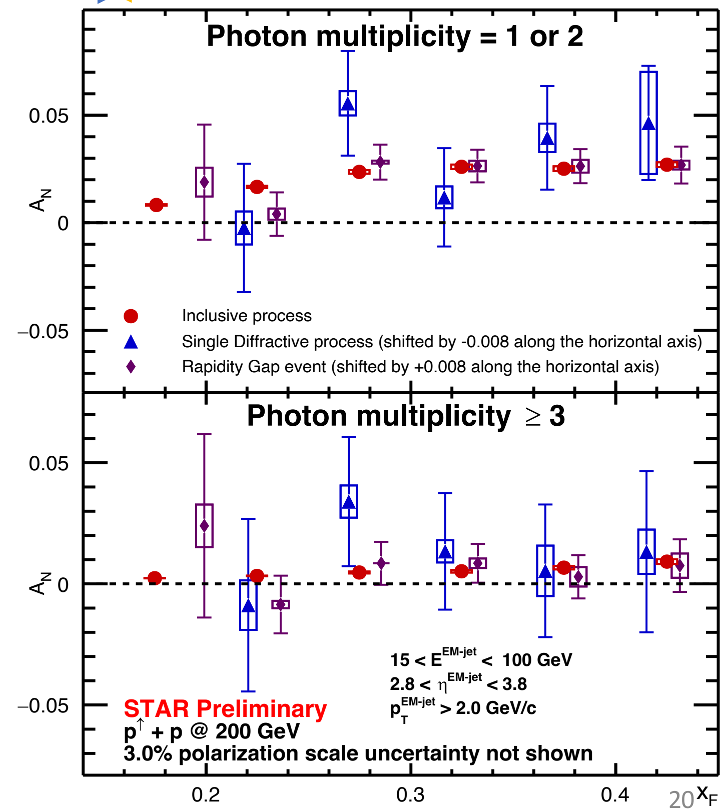


Single Diffractive EM-jet A_N at 200 GeV



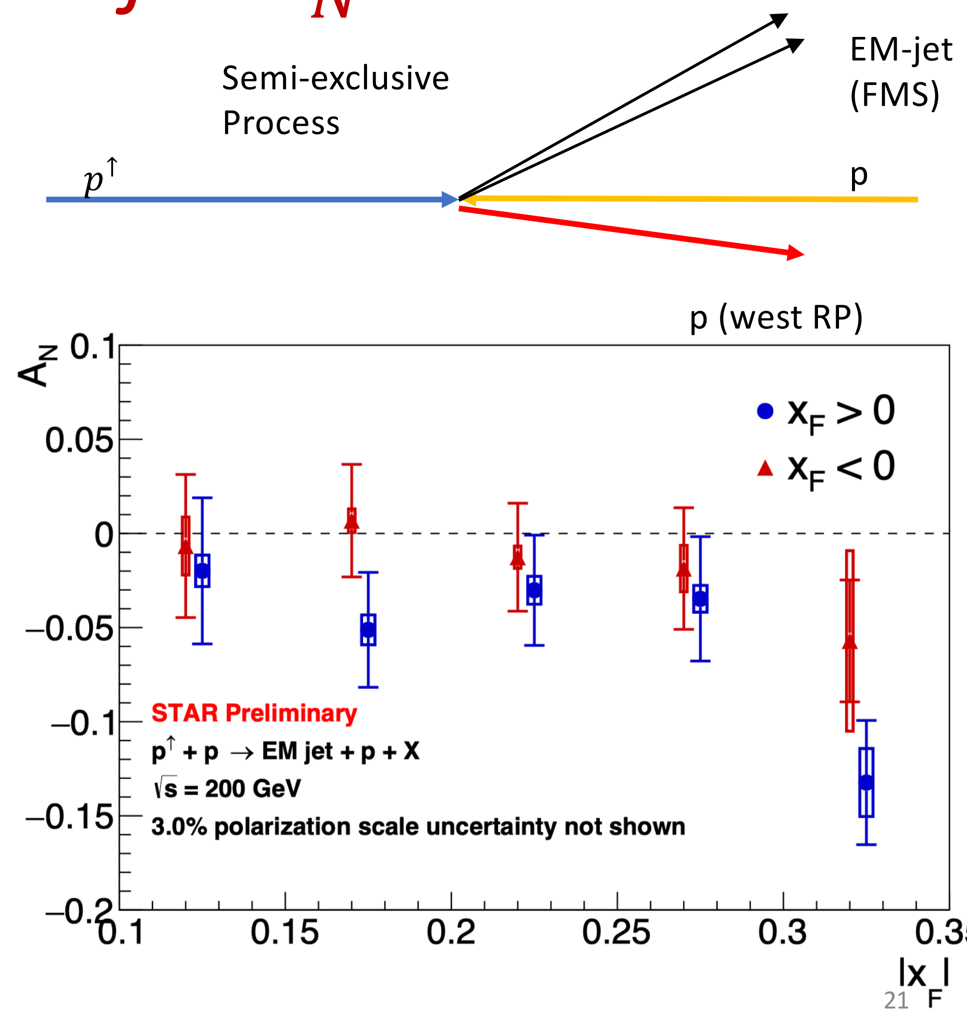


- The EM-jet A_N for $x_F > 0$ (> 2 σ significance of non-zero) is observed for 1 or 2 photon multiplicity EM-jets in the single diffractive process
- A_N for the three processes consistent with each other within uncertainty
- The single diffractive processes fail to provide evidence for its significant contribution to large A_N in the inclusive processes



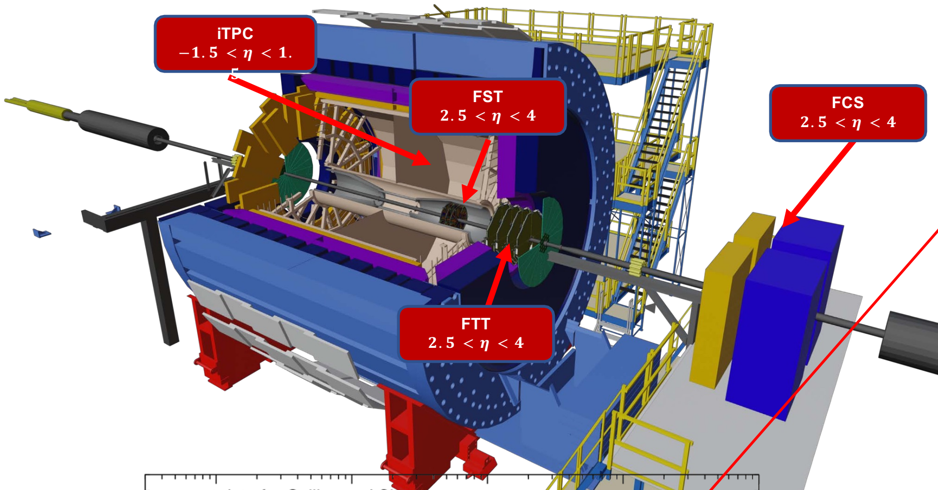
“Semi-exclusive” Process EM-jet A_N at 200 GeV

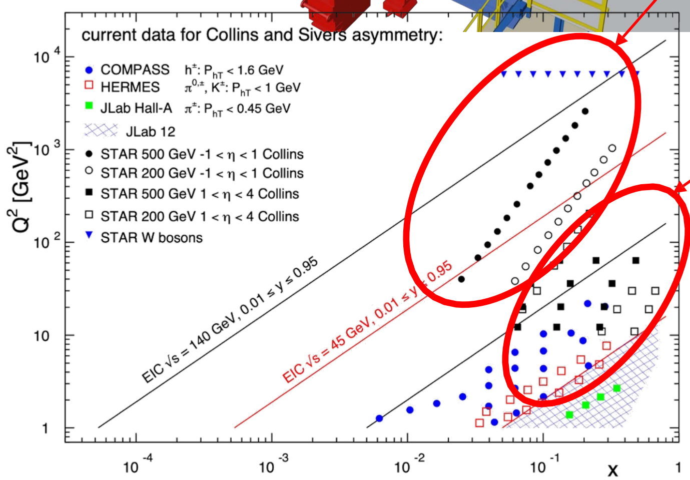
“Semi-exclusive” process: Polarized proton intact; constrain the energy of EM-jet at FMS and west side proton to less than beam energy



- A non-zero A_N for $x_F > 0$ is observed with 3.3 σ significance for semi-exclusive process
- Sign of A_N is negative. Theoretical input are needed to understand the different sign

Outlook





Mid Rapidity	Forward Rapidity
$-1.5 < \eta < 1.5$	$2.5 < \eta < 4$

Mid Rapidity: $-1.5 < \eta < 1.5$

Physics Topics:

Improve statistical precision:

- ▶ Sivers effect in dijet and W/Z production;
- ▶ Collins effect for hadrons in jets;
- ▶ Transversity and IFF;
- ▶ Diffractive studies for spatial imaging of nucleon;
- ▶ GPD E_g through UPC J/Ψ;
- ▶ Nuclear PDF and fragmentation function.

Forward Rapidity: $2.5 < \eta < 4$

Physics Topics:

- ▶ TMD measurements at high x
  - Transversity, Collins;
  - Sivers through DY and jets
- ▶ UPC J/Ψ GPD at forward rapidity;
- ▶ Nuclear PDFs and FF;
- ▶ R_{pA} for direct photons and DY;
- ▶ Gluon Saturation through di-hadrons, γ-Jets, di-jets.

All of these measurements are critical to the scientific success of EIC to test universality and factorization.

- Large p+p 508 GeV sample from 2022 currently under analyses (w/ forward upgrades);
- Ongoing p+p in 2024 and possibly p+Au in 2025.

Extra Slides