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Exploring the Spin Structure of the Nucleon at STAR

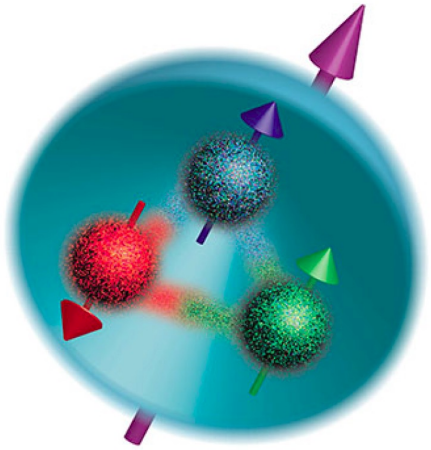
Ting Lin (林挺), for the STAR Collaboration

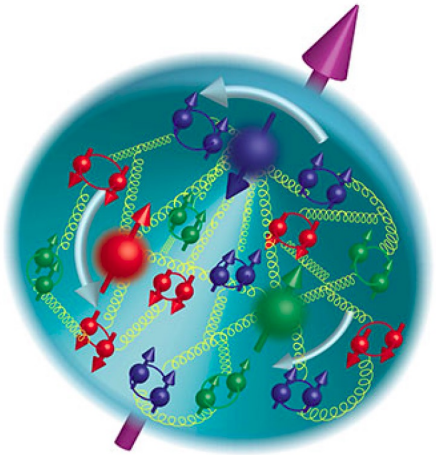
Shandong University (山东大学)

Quark Matter 2023

The 30th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

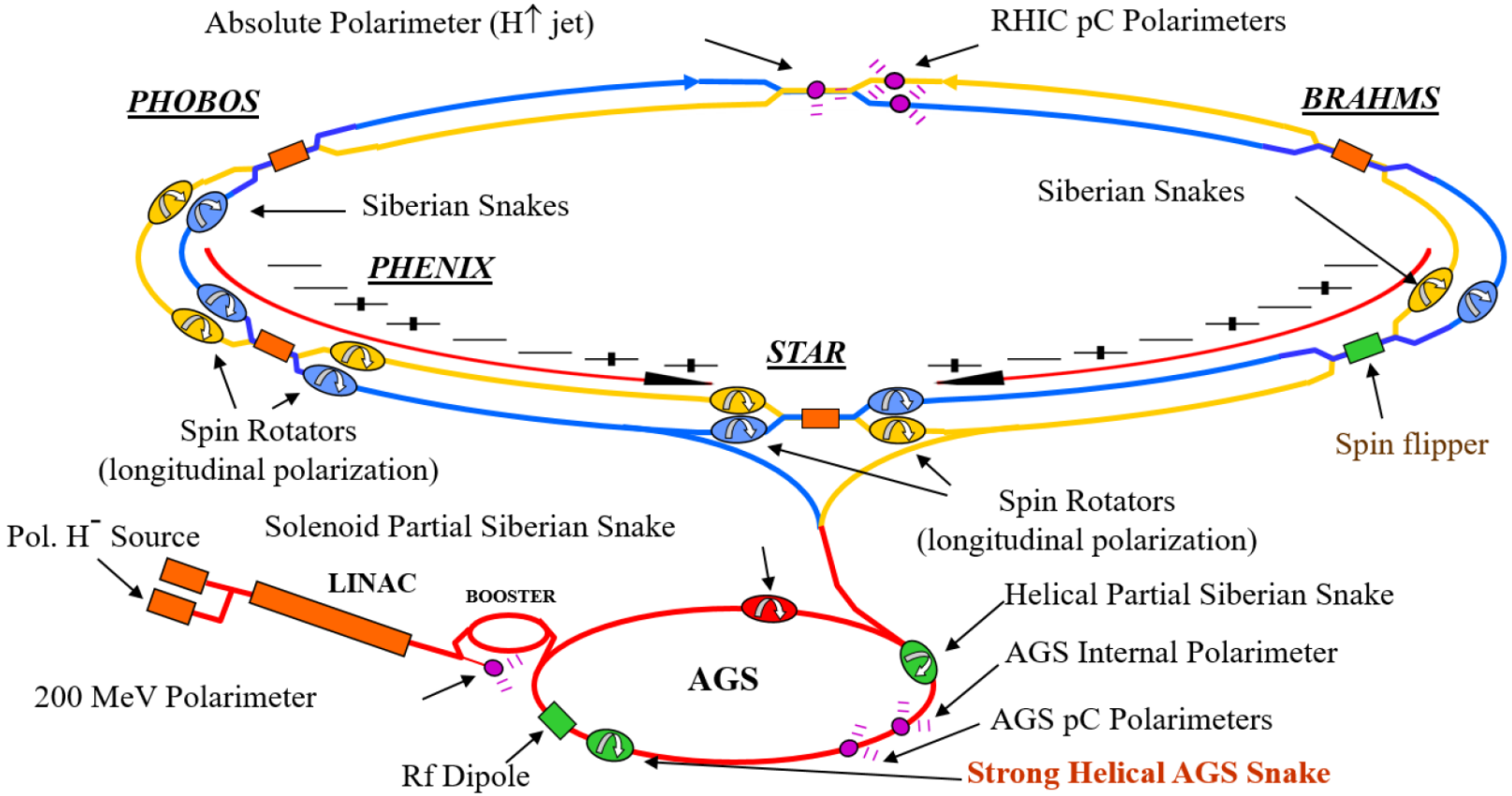
Fundamental Questions Regarding Proton Spin





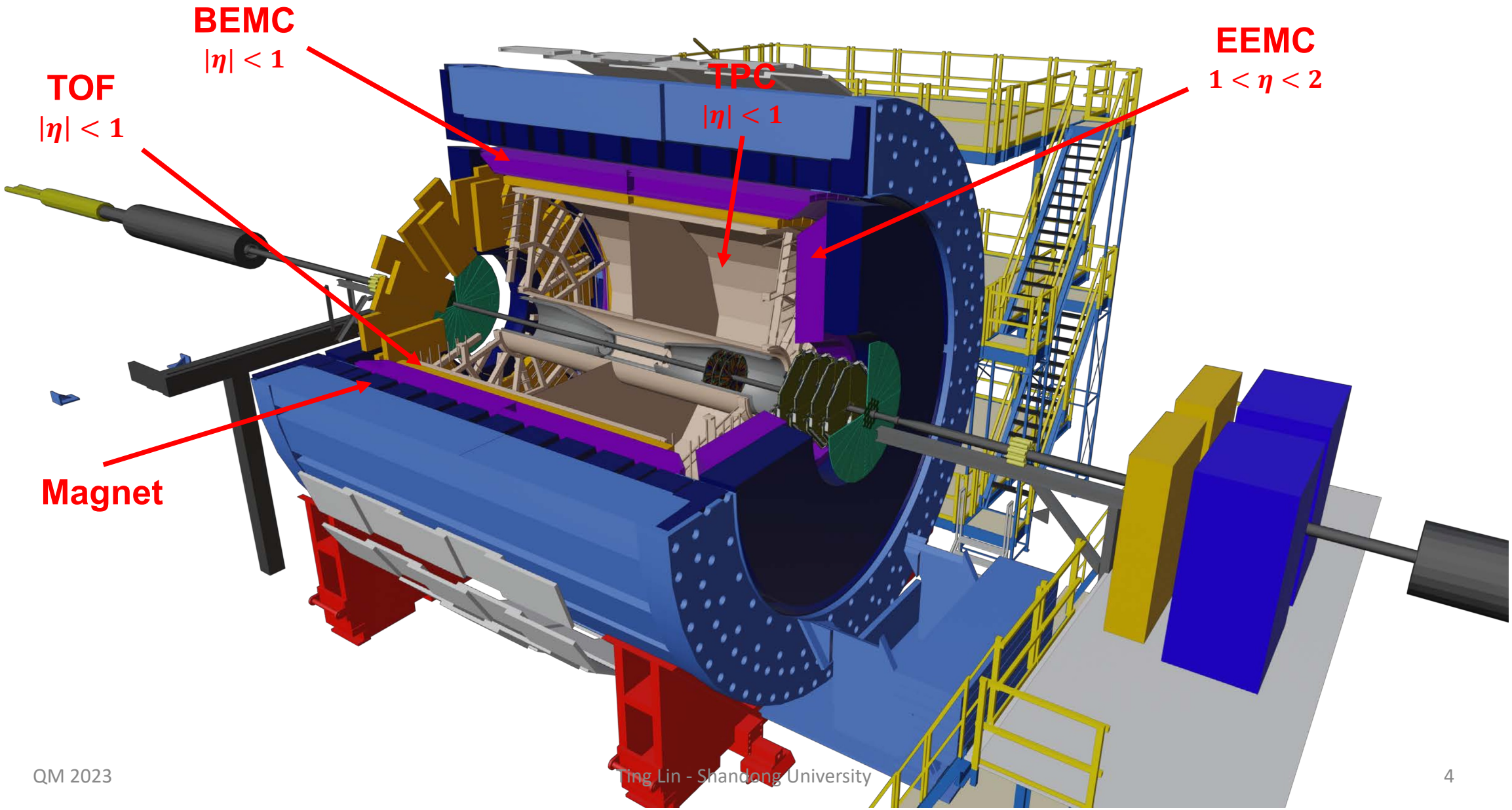
- How do quarks and gluons conspire to provide the proton's spin ½ ?
  - What is the role of gluons and sea quarks?
  - What is the size of the orbital angular momentum?
- What is the dynamic structure of the proton?
  - How do we go beyond longitudinal parton distribution functions to map out the 3D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

Relativistic Heavy Ion Collider (RHIC)



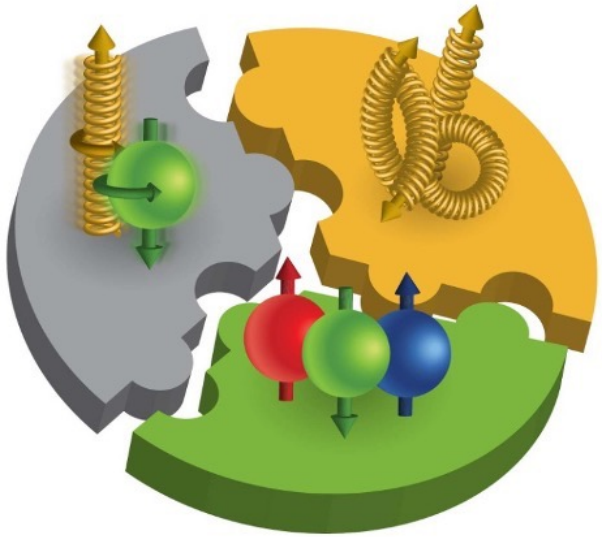
- World's first and only polarized proton+proton collider: Provide polarized proton+proton collisions up to 510 GeV;
- Spin pattern changes from fill to fill with little depolarization: Siberian snakes; Spin rotators; proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet).

Solenoidal Tracker At RHIC (STAR)



Longitudinal Spin Structure

Spin of the Proton

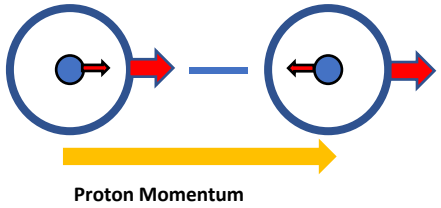


- For helicity distributions (collinear terms) in 'canonical' approach, the proton's spin can be decomposed into:

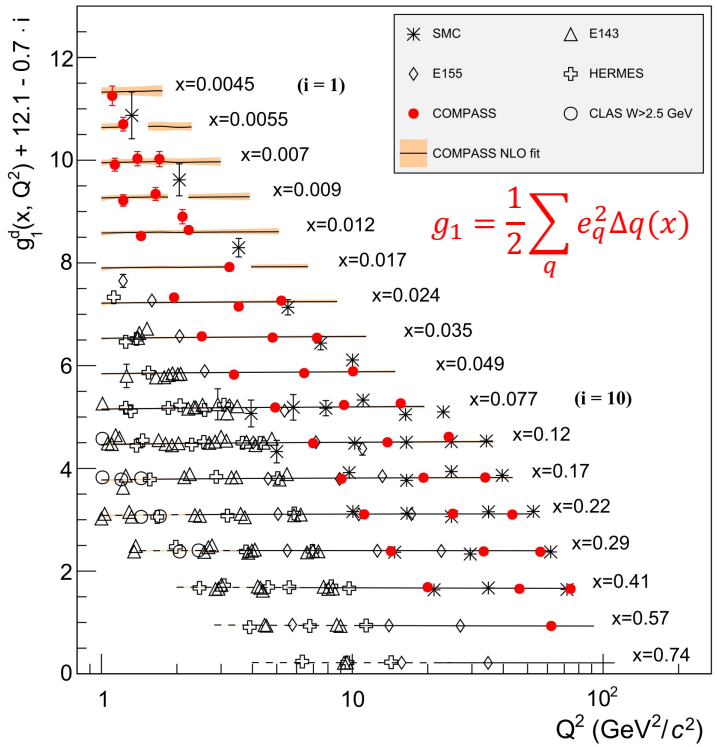
$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

R. L. Jaffe and A. Manohar, NPB 337, 509 (1990)

- Helicity PDF, $\Delta f(x)$:



- $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$
- $\Delta G = \int \Delta g(x)dx$



- HERMES: $\Delta\Sigma(Q^2 = 3\text{GeV}) = 0.330 \pm 0.011\,(\text{theo}) \pm 0.025\,(\text{exp}) \pm 0.028\,(\text{evol})$
- COMPASS: $\Delta\Sigma(Q^2 = 5\text{GeV}) = 0.32 \pm 0.02\,(\text{stat}) \pm 0.04\,(\text{syst}) \pm 0.05\,(\text{evol})$

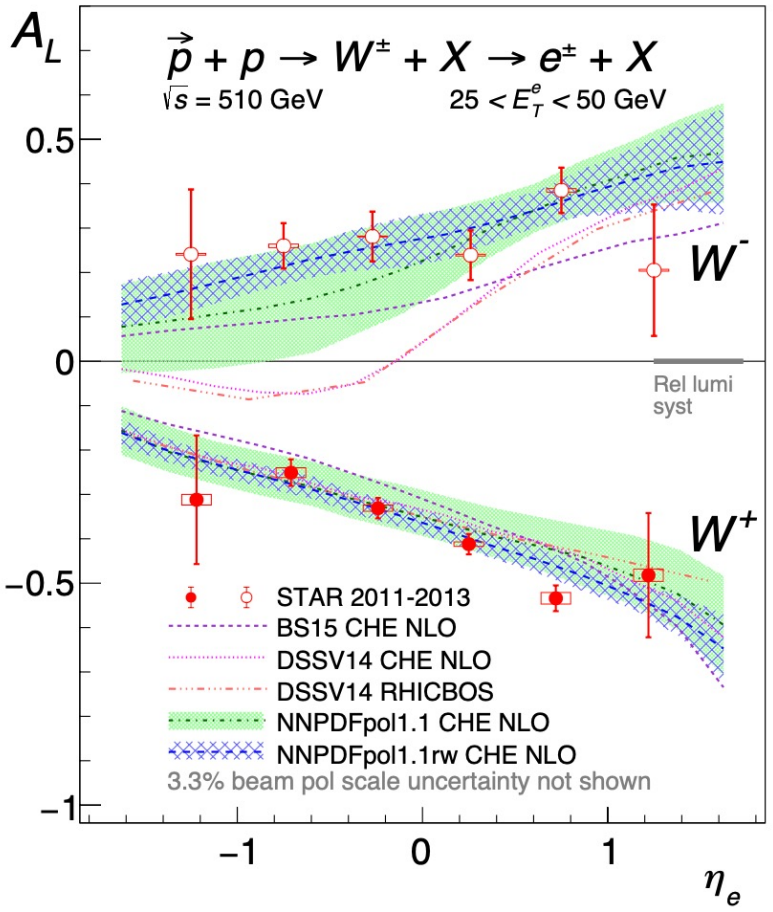
HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 769 34–41 (2017)

Anti-Quark Polarization

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \simeq \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

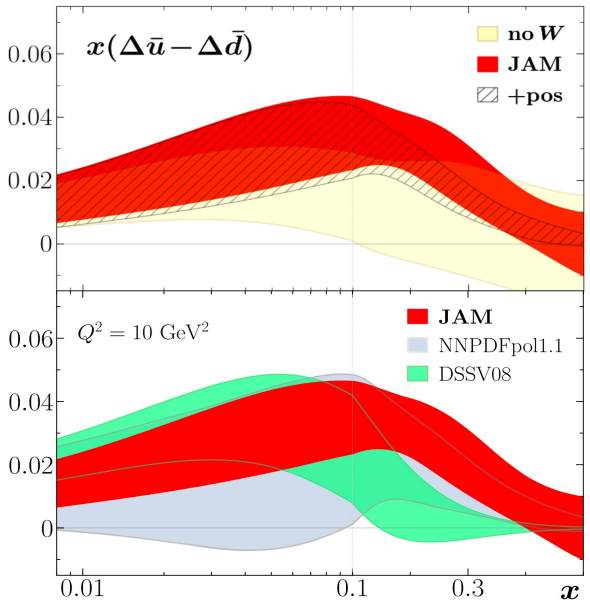
$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \simeq \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_W \gg 0 \ (x_1 \gg x_2) \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

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

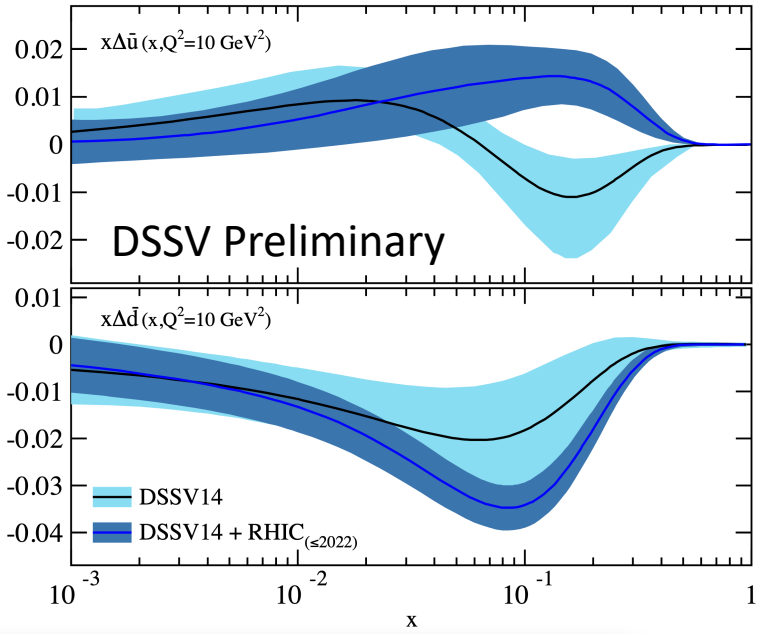


$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

JAM, PRD 106, L031502 (2022)



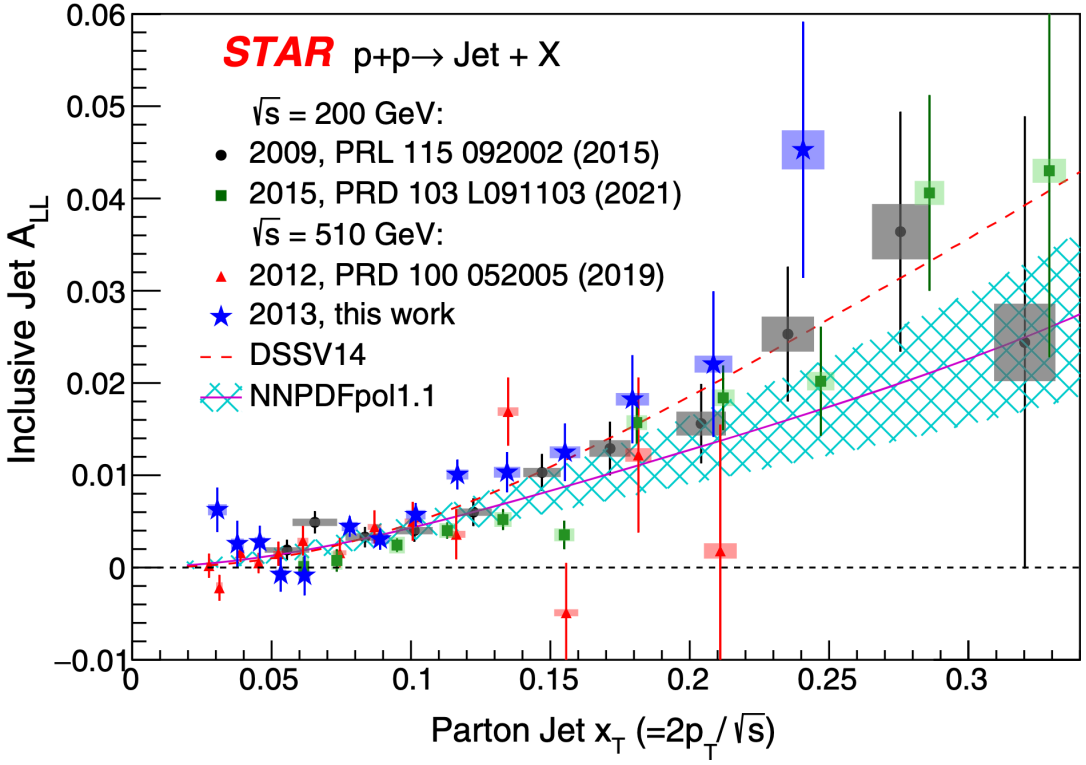
The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



- $W^{\pm}$ measurement at RHIC provides a unique way to delineate the flavor structure of proton spin;
- Clearly demonstrates that $\Delta\bar{u} > \Delta\bar{d}$.

Probing the Gluon Helicity at RHIC

STAR, PRD 103, L091103 (2021)
STAR, PRD 105, 092011 (2022)



What we measured

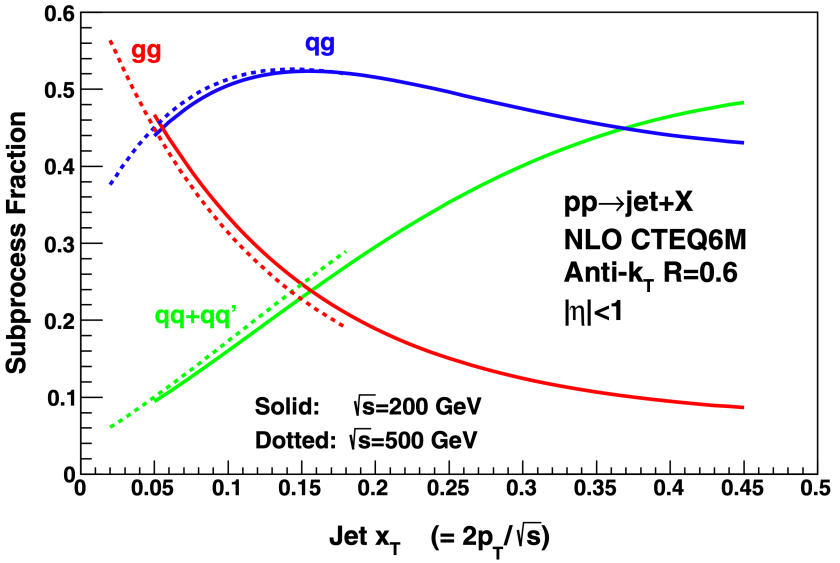
What we hope to learn

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \sim \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Measured by others

Calculable

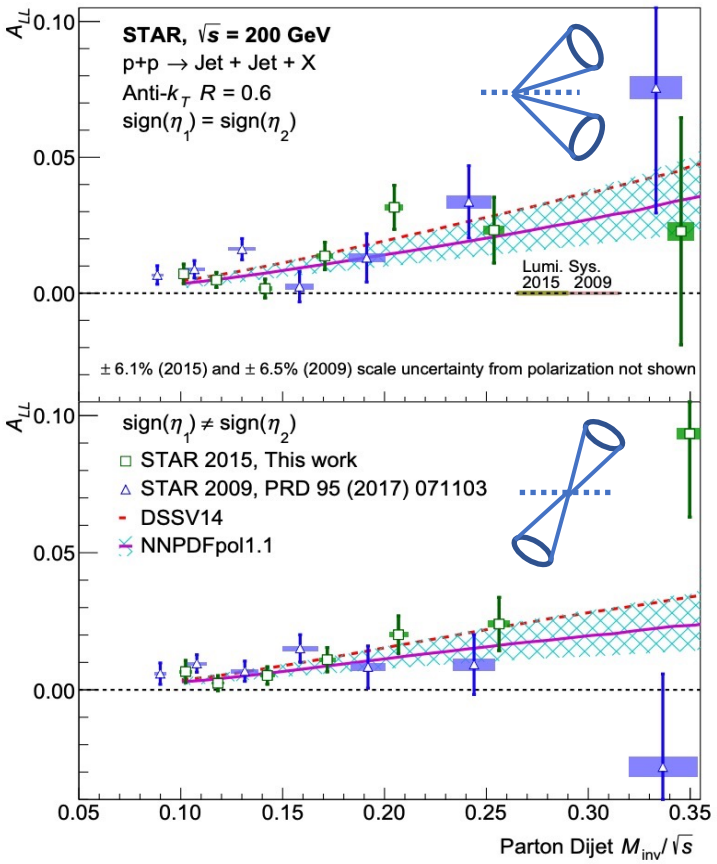
- For most RHIC kinematics, gg and qg dominate, making A_{LL} for jets sensitive to gluon polarization.



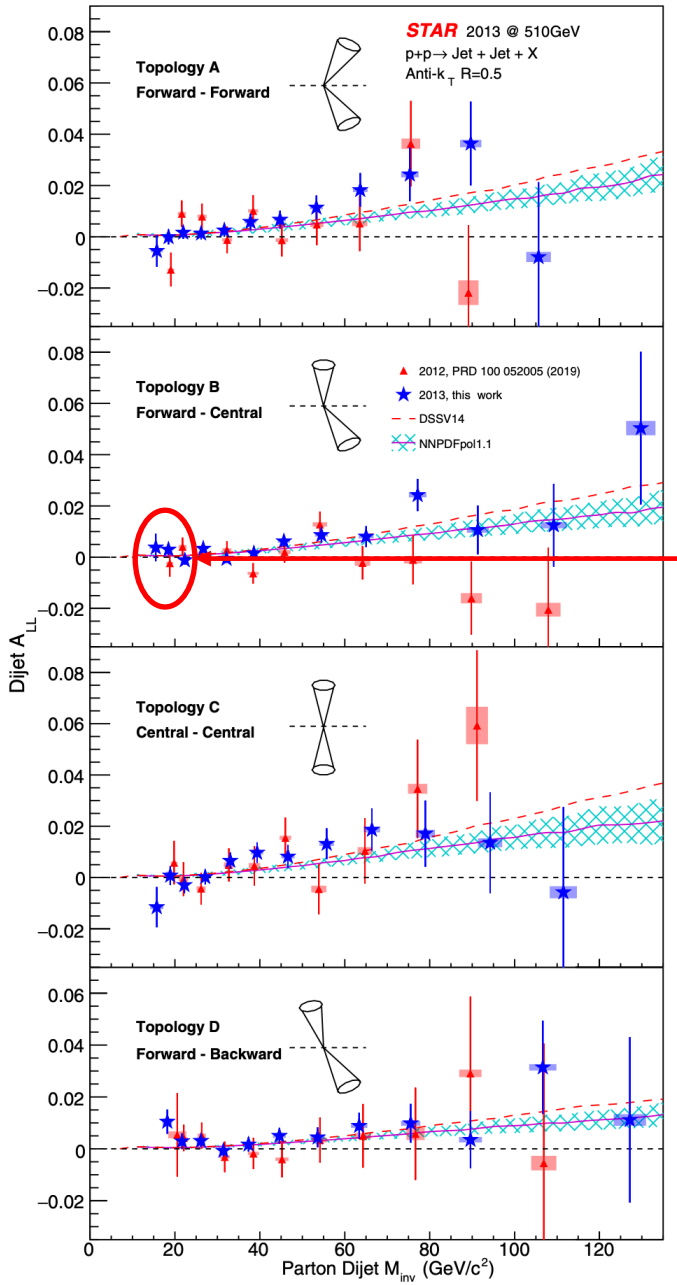
- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05;
- Improved statistical and systematics uncertainties;
- Will significantly reduce uncertainty on gluon polarization once included in global fits.

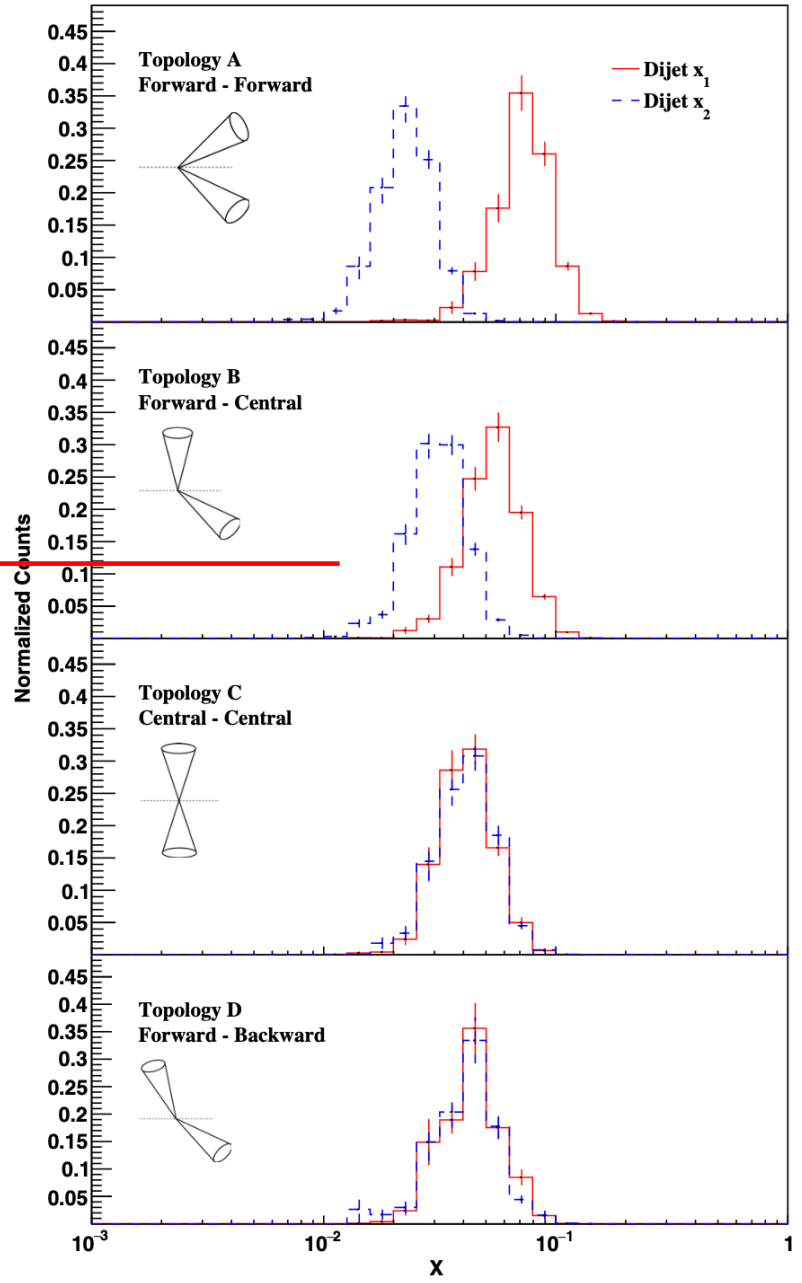
Dijet A_{LL}

STAR, PRD 103 L091103 (2021)



STAR, PRD 105, 092011 (2022)

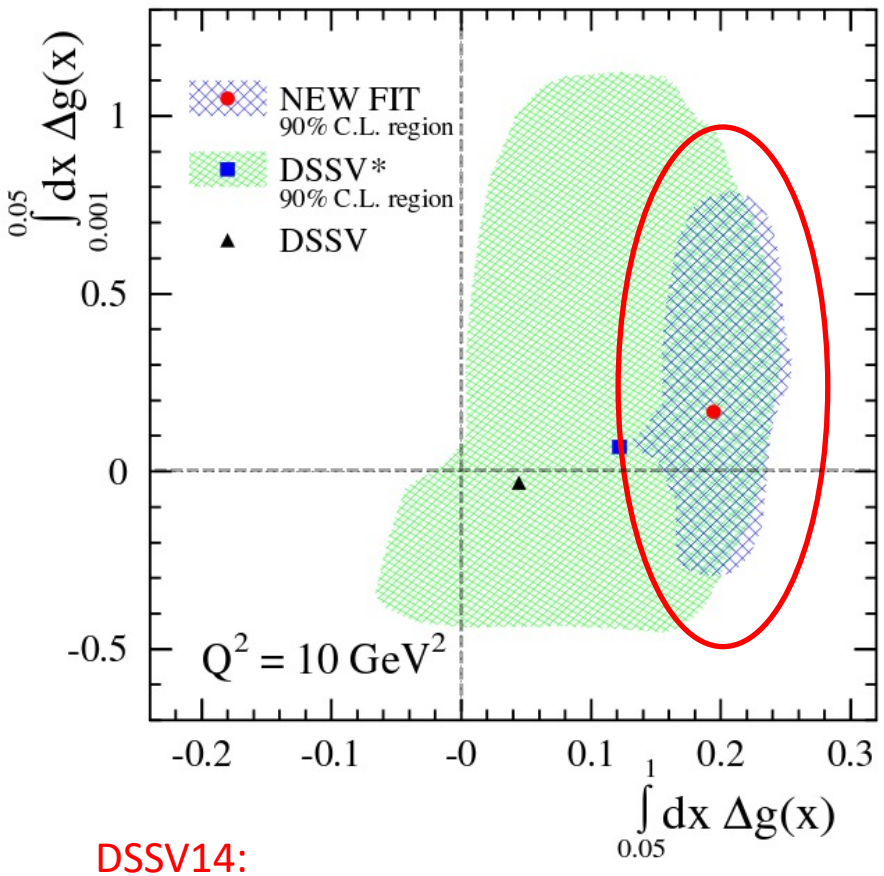




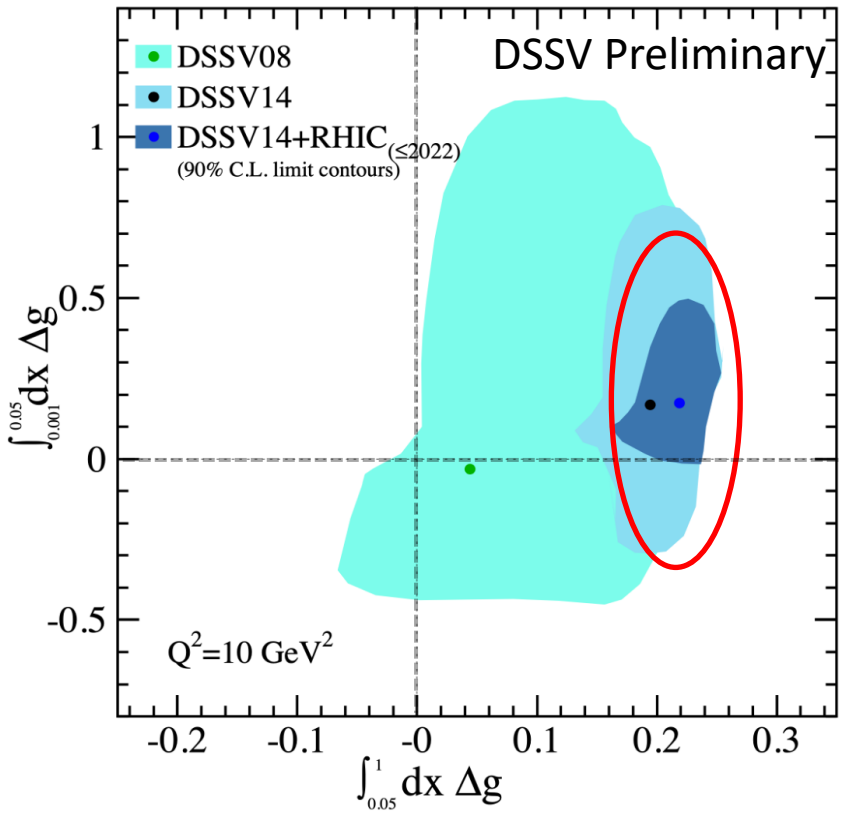
- Dijet captures more information from the hard scattering and provides a more direct link to the initial kinematics than inclusive probes.

Impact of the RHIC Results

DSSV, PRL 113, 012001(2014)



The RHIC Cold QCD Program, arXiv:2302.00605



DSSV14:

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20 \pm 0.06$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15 \pm 0.50$

DSSV14 + RHIC (≤2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22 \pm 0.03$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.17 \pm 0.20$

3D Tomography of the Nucleon:

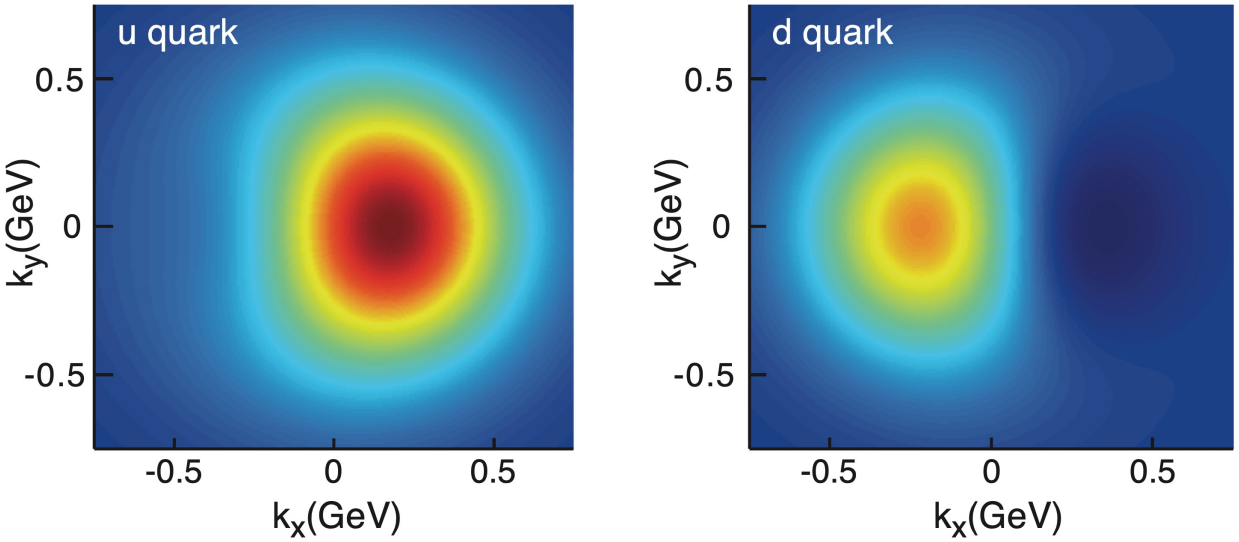
TMD

Nucleon Tomography

EicC, Front. Phys. 16(6), 64701 (2021)

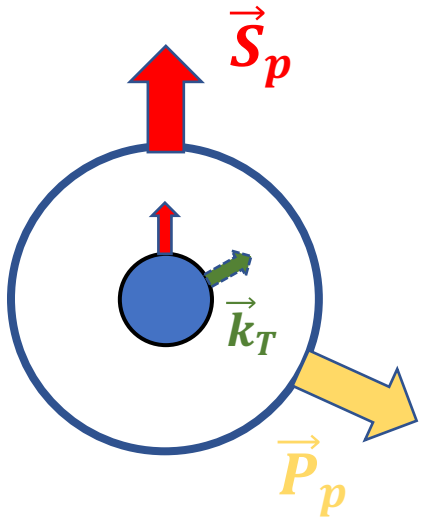
EIC White Paper, arXiv:1212.1701

$x f_1(x, k_T, S_T)$



TMDs		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally polarized (L)	Quark polarization: Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer–Mulders
	L		g_{1L} Helicity	$h_{1L}^\perp$ Longi-transversity
	T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-helicity	h_1 Transversity; $h_{1T}^\perp$ Pretzelosity

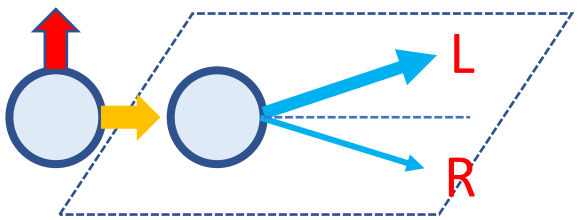
Nucleon spin Quark spin



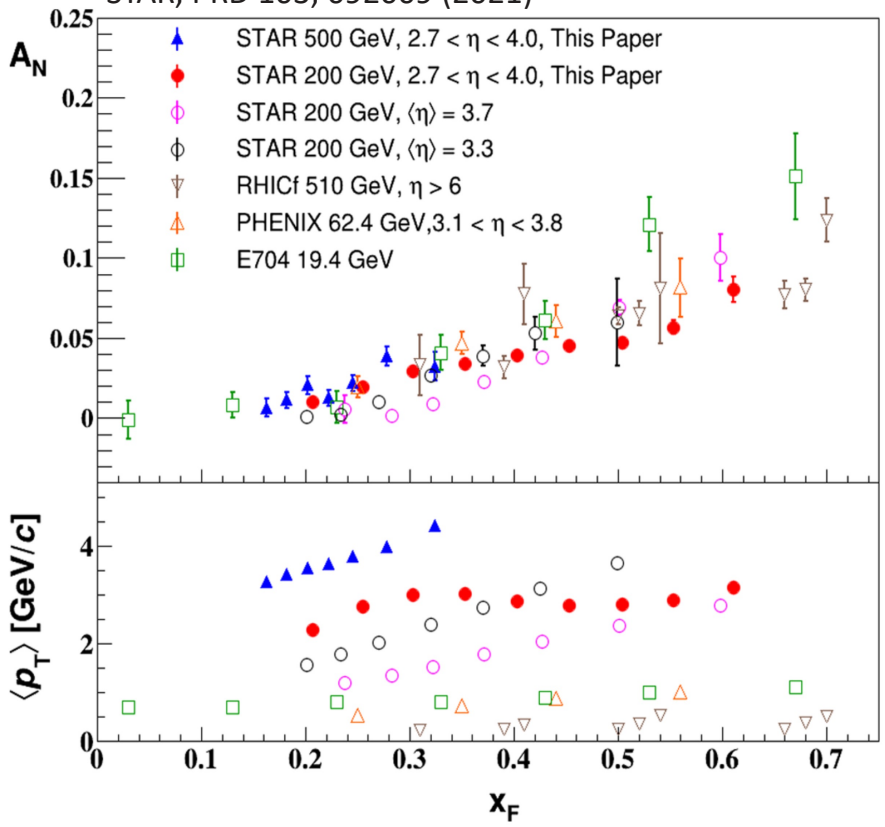
- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

Transverse Single-Spin Asymmetry

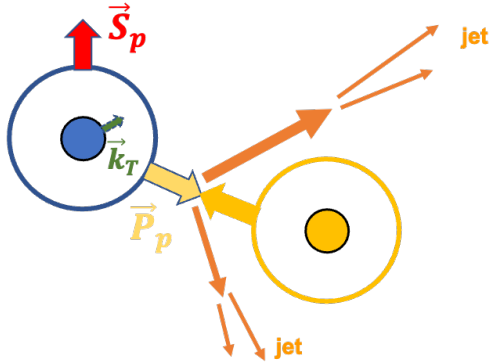
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



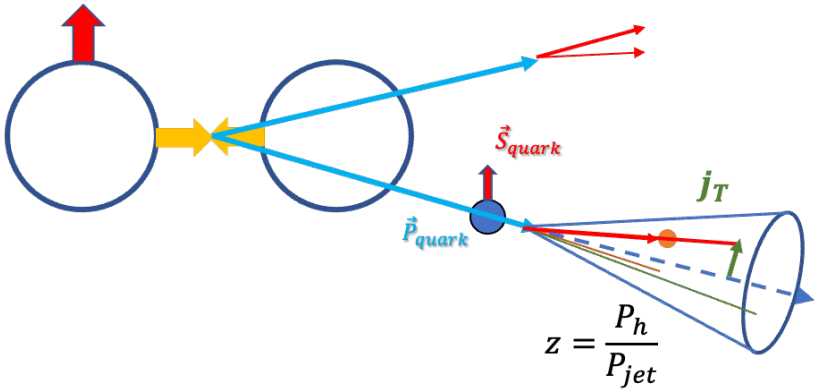
STAR, PRD 103, 092009 (2021)



Sivers Effect

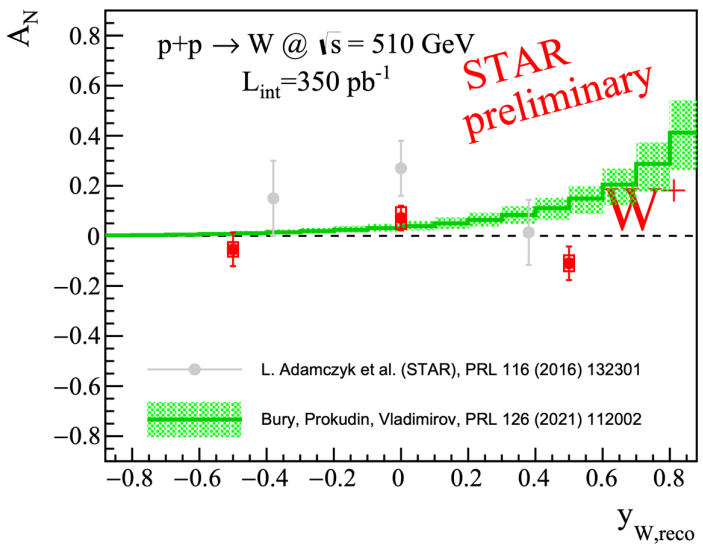


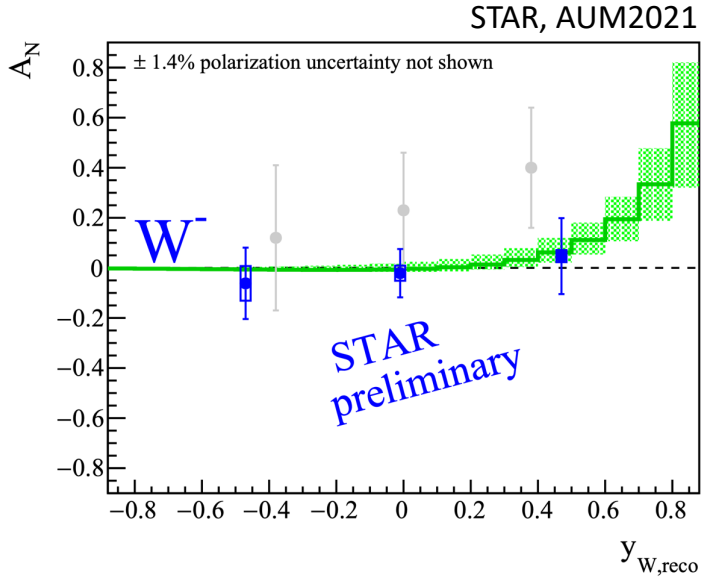
Collins Effect

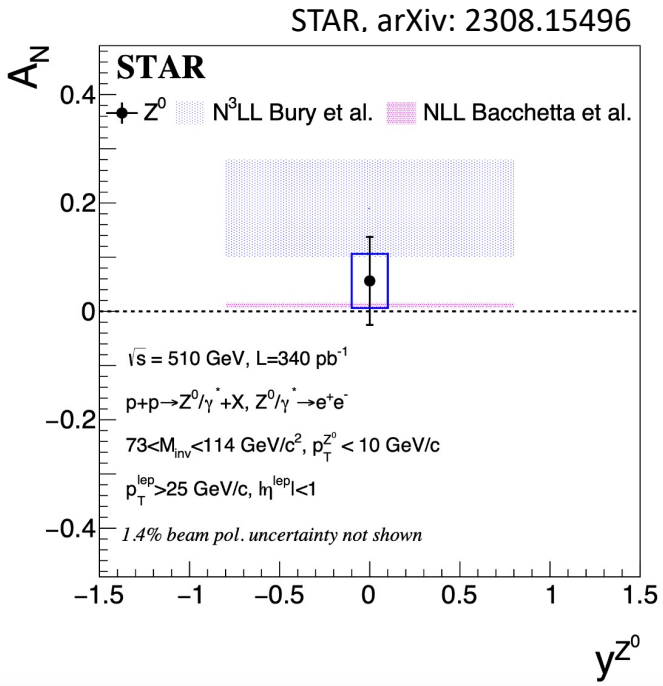


- Large transverse single-spin asymmetry (A_N) has been observed in transversely polarized pp collisions;
- Possible contributions: twist-3 correlators associated with the Sivers functions, Collins FF:
  - Sivers effect: $\sim \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T)$; Non-universality exhibits the process dependence;
  - Collins effect: $\sim \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T)$; Chiral-odd, need to couple with another chiral-odd distributions.

A_N for $W^{\pm}$ and Z Boson Production



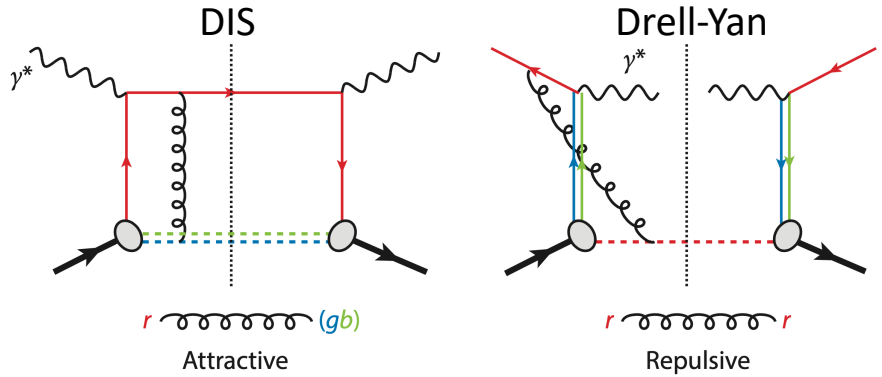




- Test the nonuniversality nature of Sivers function:

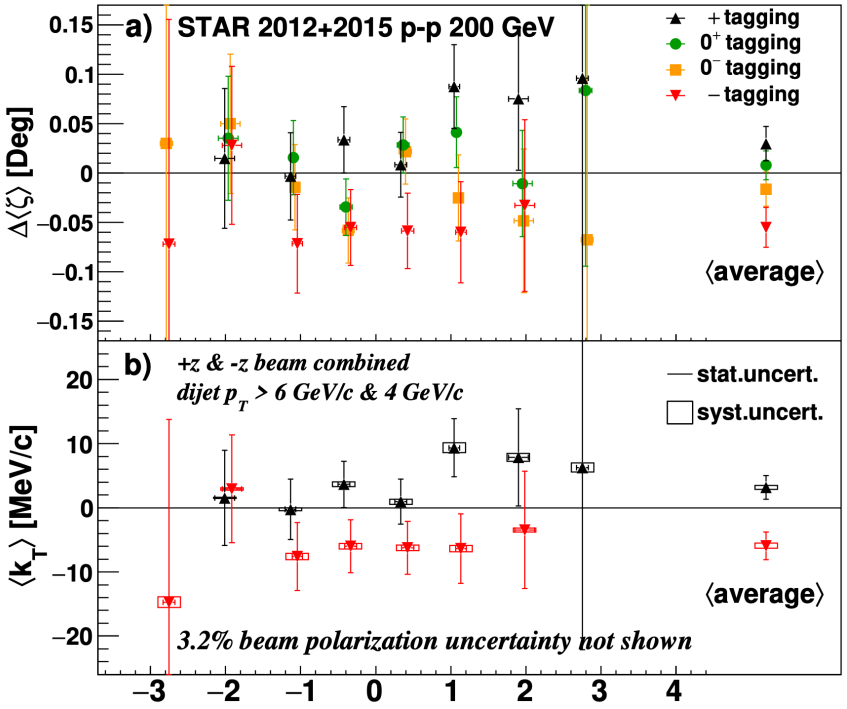
$$\text{Sivers}_{SIDIS} = -\text{Sivers}(\text{Drell} - \text{Yan or } W/Z)$$

- A fundamental prediction from the gauge invariance of QCD.

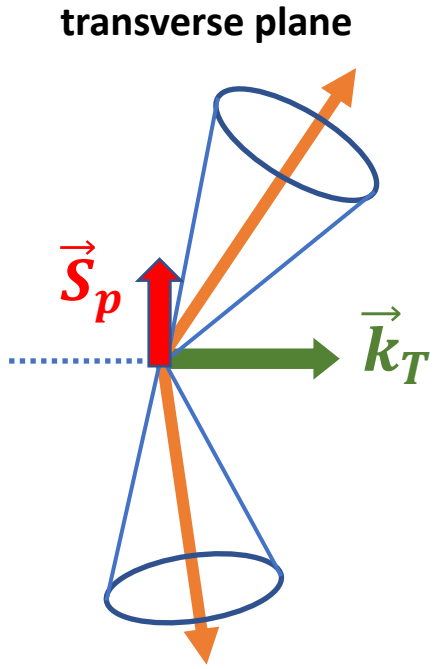


Transverse Single-Spin Asymmetries for Dijet

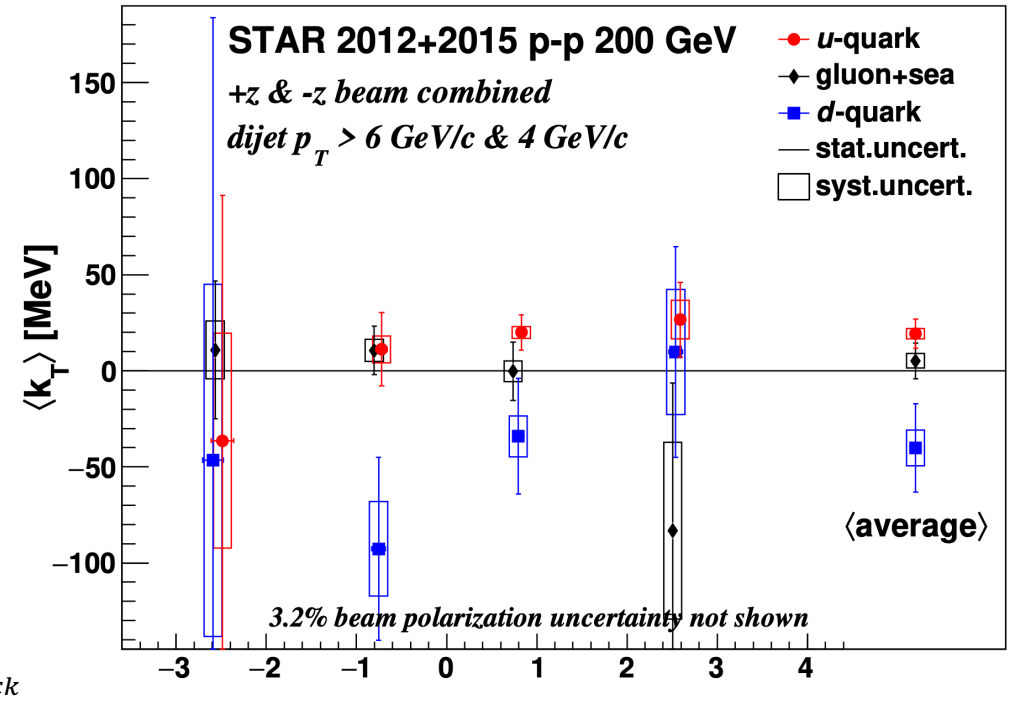
STAR, arXiv:2305.10359



$$\eta^{total} = \ln\frac{x_1}{x_2}$$



Jet Charge tagging: $Q = \sum_{p>0.8\mathrm{GeV}/c} \frac{p^{track}}{p^{jet}} \cdot q$



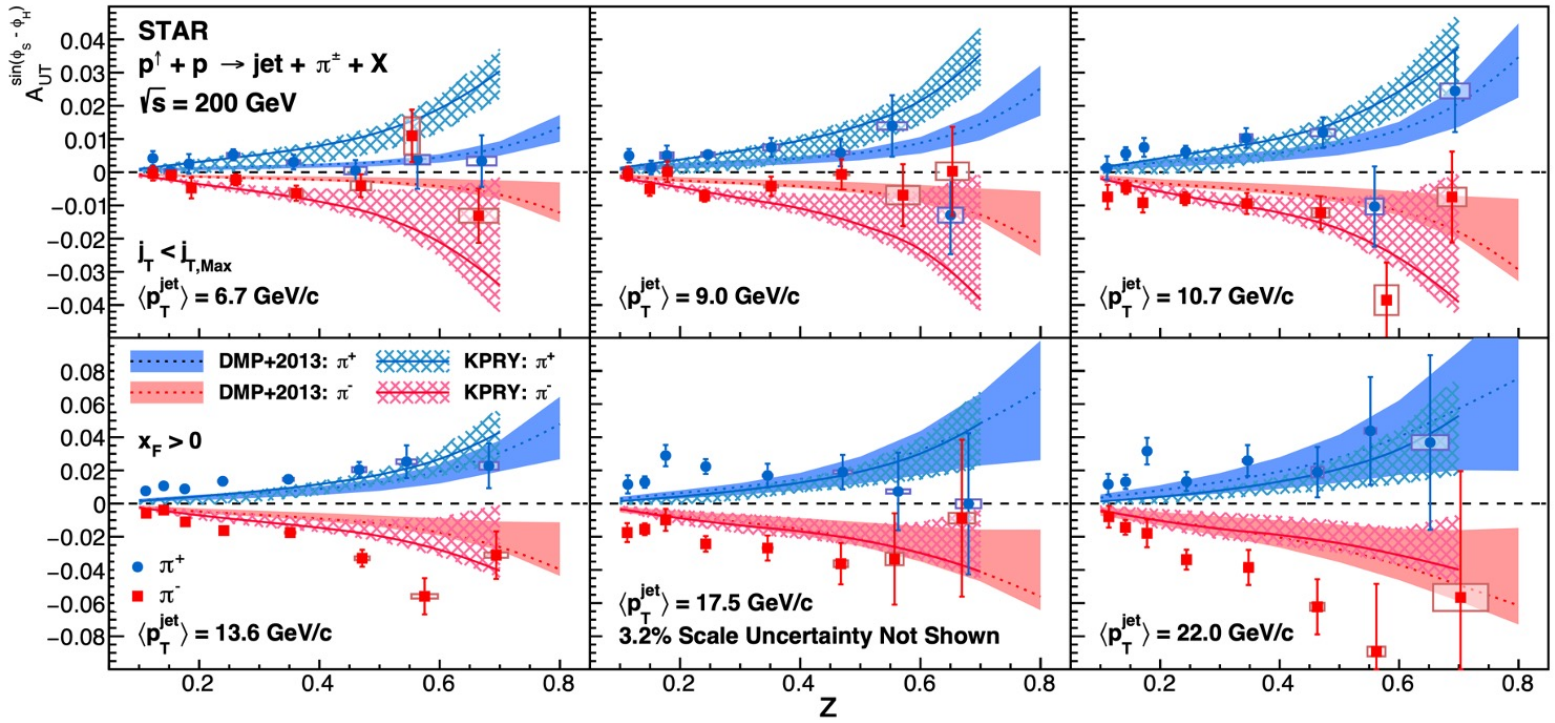
$$\eta^{total} = \ln\frac{x_1}{x_2}$$

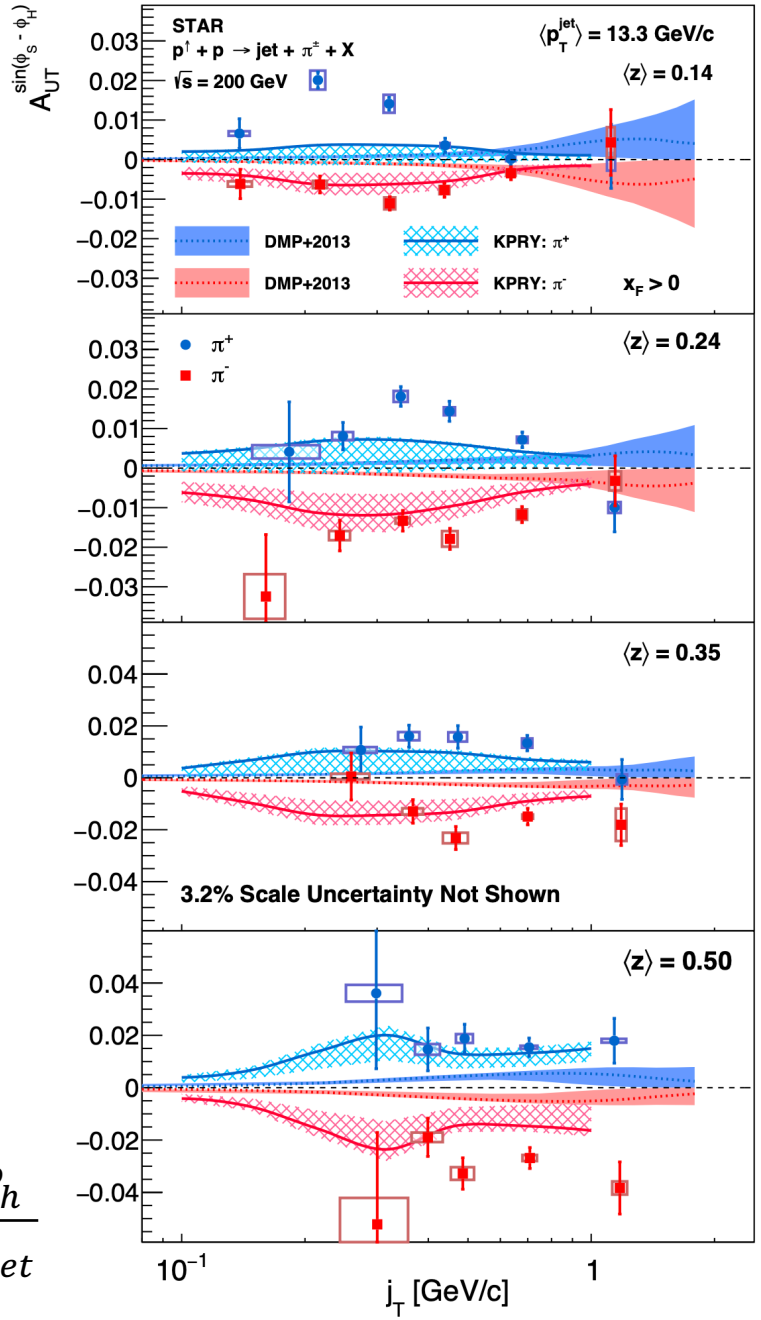
- First observation of non-zero Sivers asymmetries in dijet production in polarized p+p collisions;
- $\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6$ MeV/c, $\langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3$ MeV/c, $\langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8$ MeV/c.

A_N for $\pi^{\pm}$ in Jets

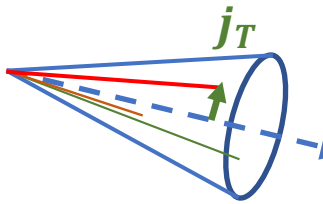
STAR, PRD 106, 072010 (2022)

$A_N \sim h_1 \otimes H_1^{\perp}$





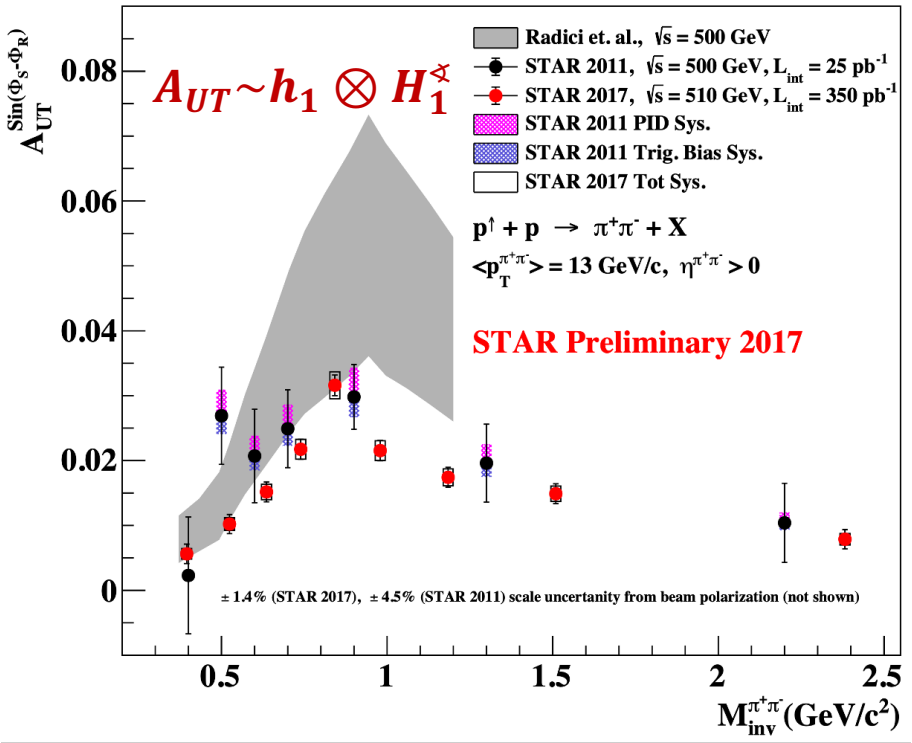
- DMP+2013 model from Umberto D'Alesio *et.al.*, PLB 773, 300 (2017);
- KPRY model from Zhong-Bo Kang *et. al.*,PLB 774, 635 (2017);
- Both assume universality and factorization.

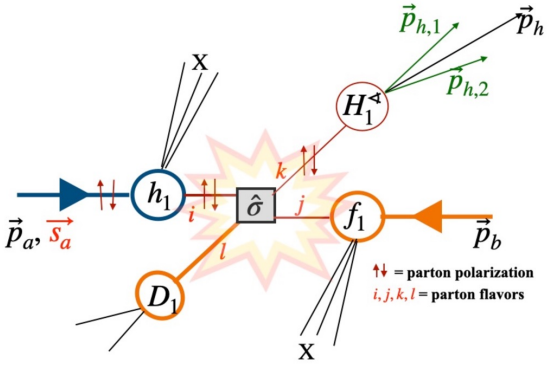


$$z = \frac{P_h}{P_{jet}}$$

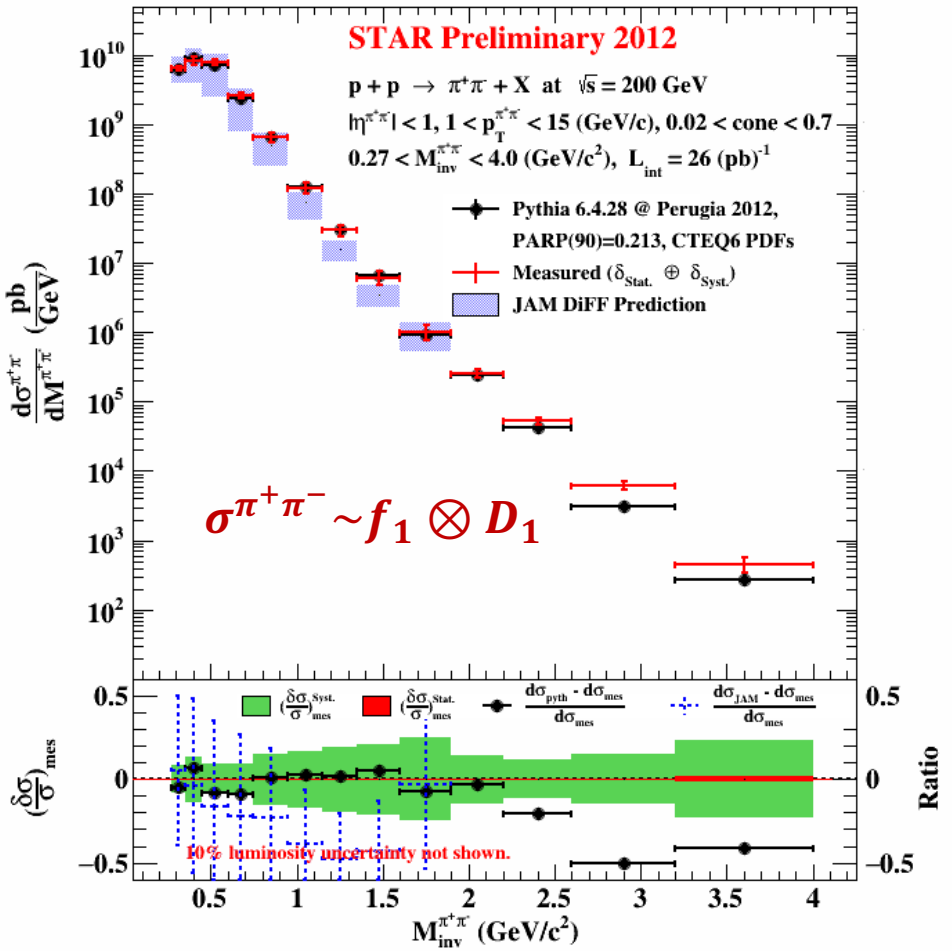
Di-hadron Measurement

STAR, AUM2023





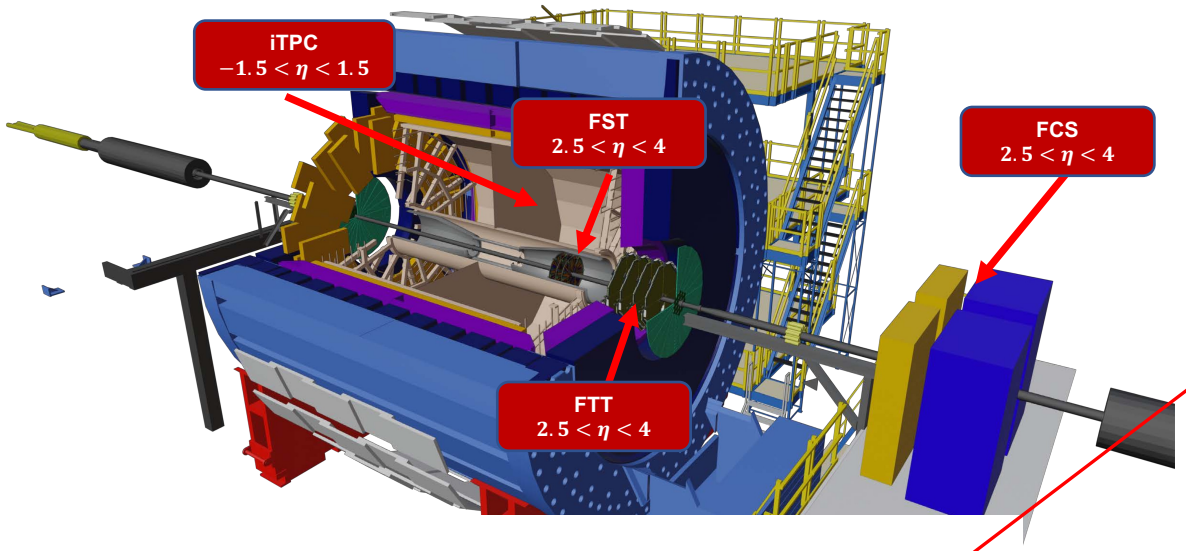
STAR, AUM2023

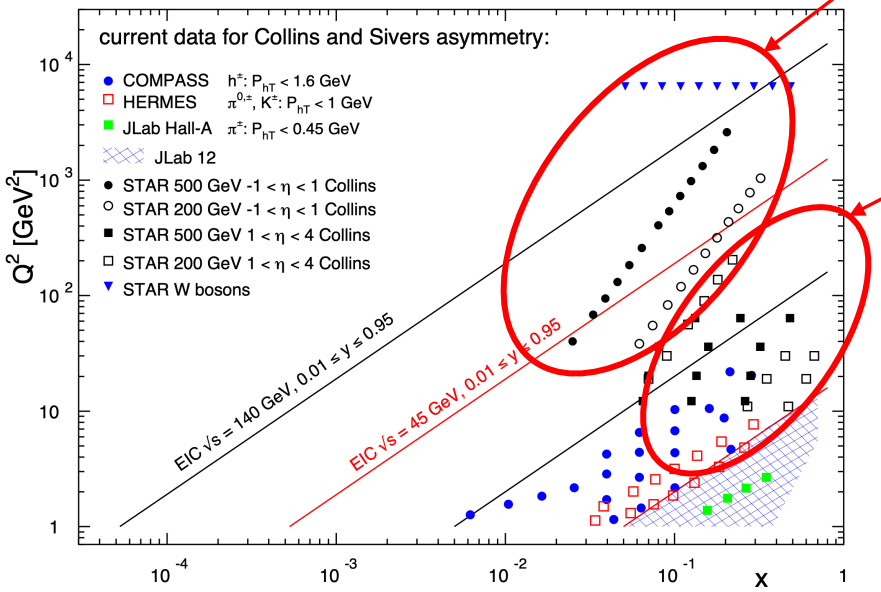


- Spin dependent di-hadron correlations probe collinear quark transversity coupled to the interference fragmentation function;
- First measurement of unpolarized $\pi^+\pi^-$ cross sections provides constrains to gluon fragmentation functions.

Outlook

See: Zhen Wang's talk





Mid Rapidity → **Forward 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.

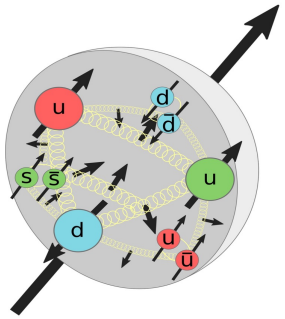
$2.5 < \eta < 4$

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.

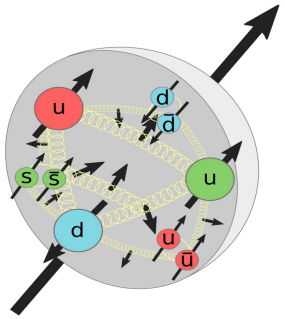
All of these measurements are critical to the scientific success of EIC to test universality and factorization.

Summary



- STAR has concluded the longitudinal polarized data taking;
  - Found evidence of an asymmetry in the polarized anti-quark sea ($\Delta\bar{u} > \Delta\bar{d}$);
  - Found evidence for positive gluon polarization in the region $x > 0.05$;
- Many new impactful results from transverse spin measurements;
  - Made the first observation of transversity, Sivers and Collins effect in pp collisions;
- Unique forward and midrapidity physics with recent upgrades;
  - Overlap kinematic coverage with EIC;
  - Establish the validity and limits of factorization and universality.

Summary



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Thanks!