第一届强相互作用自旋物理会议

The 1st Conference on Strong-Interaction Spin Physics

STAR Spin Physics Highlight
STAR自旋物理最新进展

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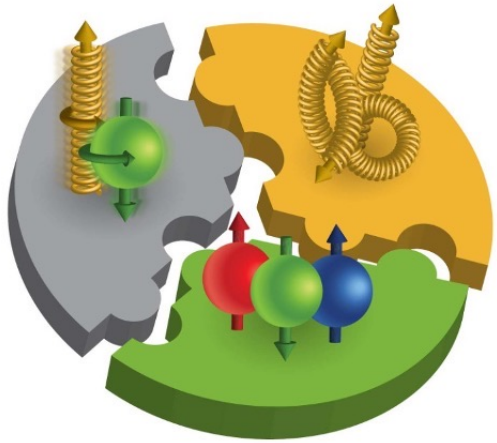
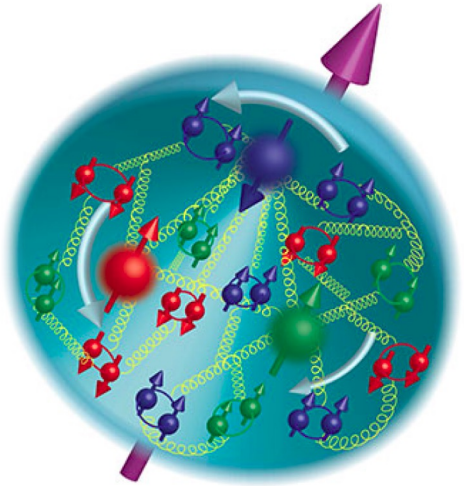
Outline

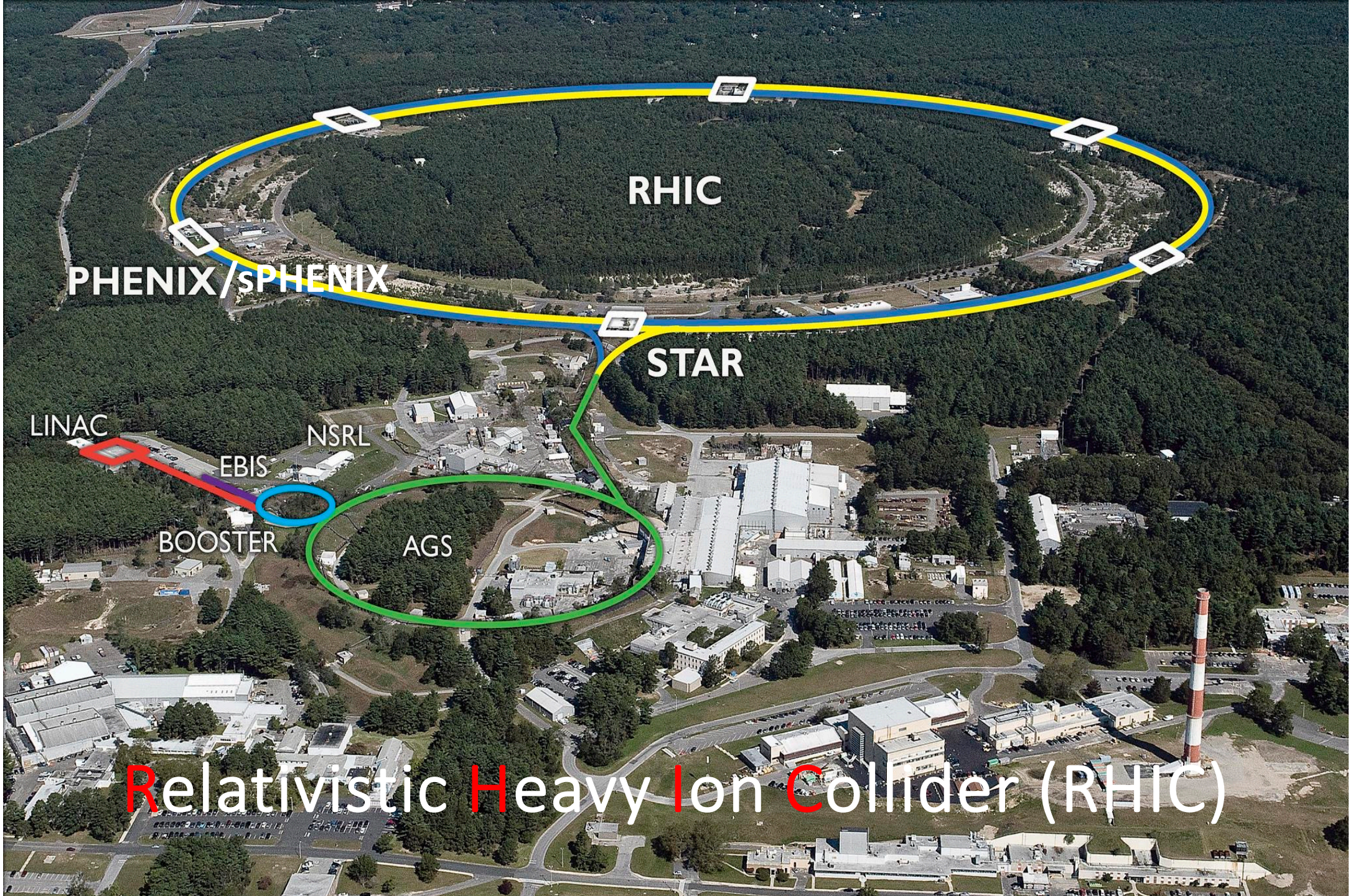
- Motivation
- RHIC Facility and STAR Detector
- Longitudinal Spin Structure
- Transverse Spin Structure
- Summary

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)

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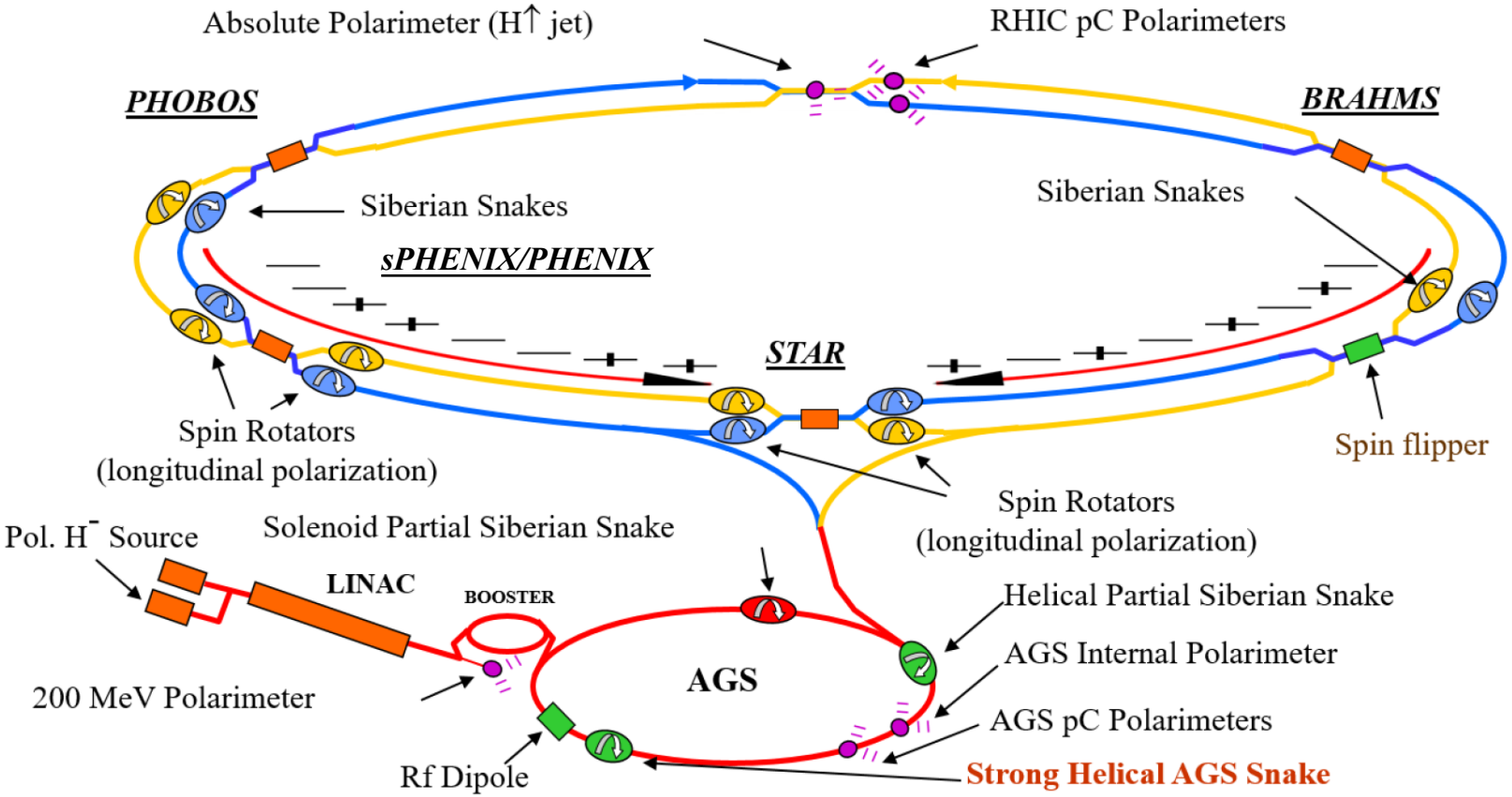
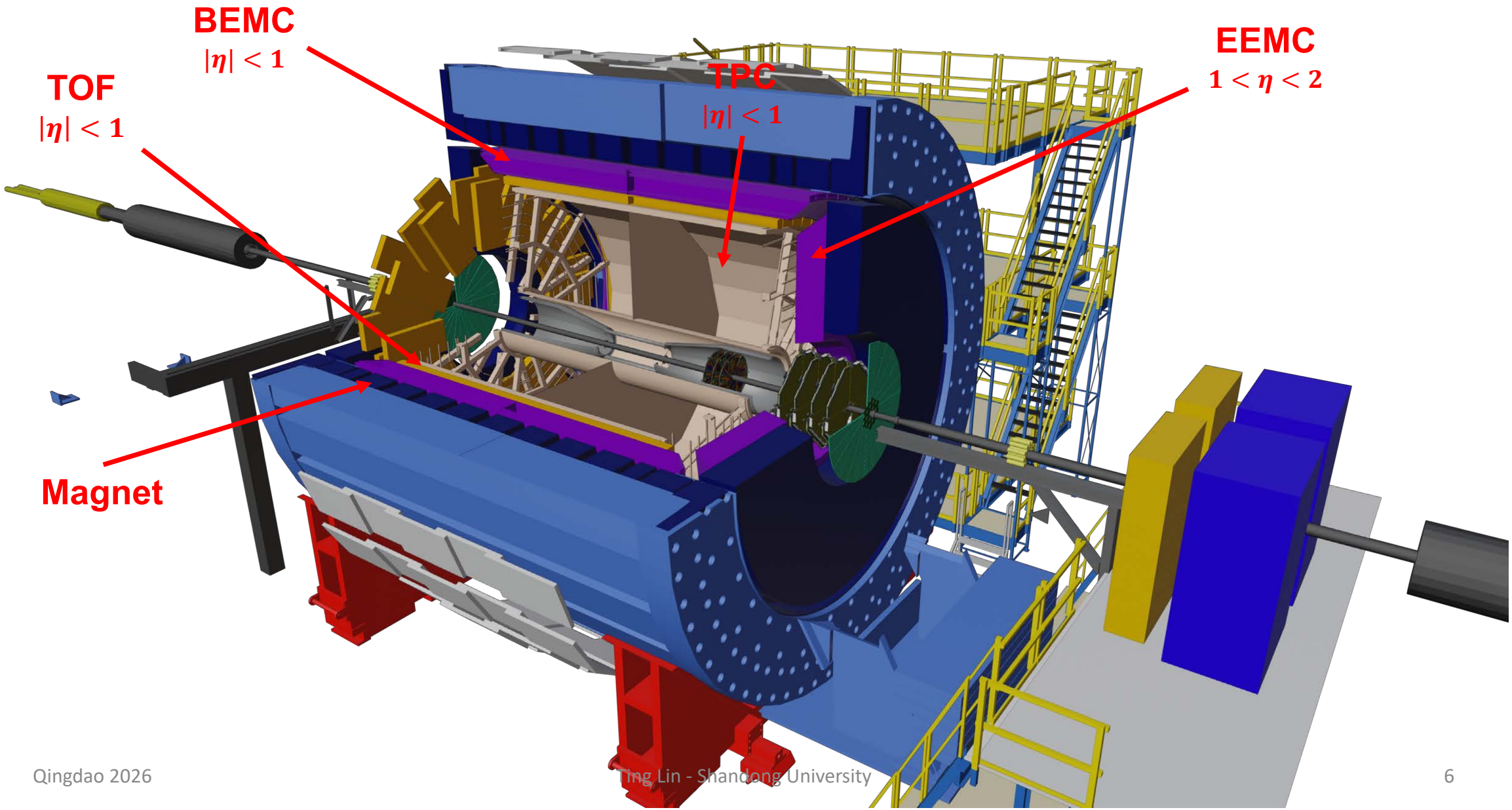


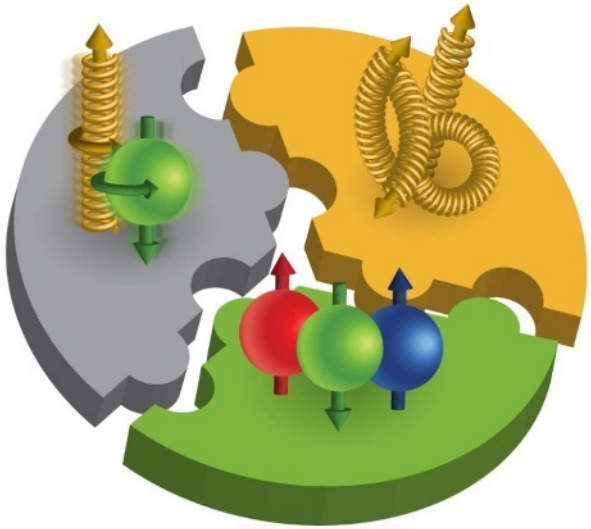
- Spin pattern changes from fill to fill with little depolarization;
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

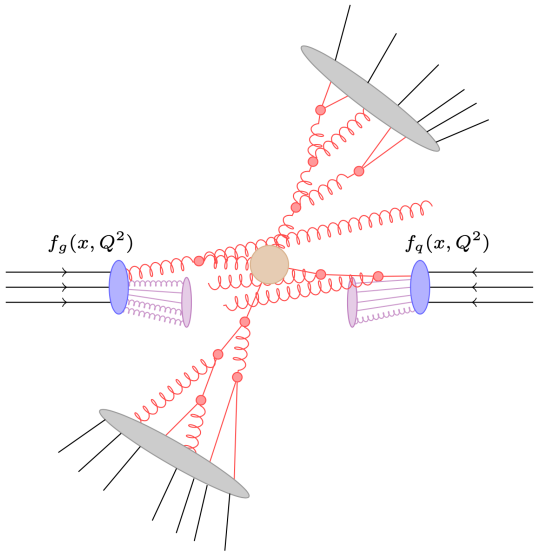
Solenoidal Tracker At RHIC (STAR)



Longitudinal Spin Structure

Spin of the Proton





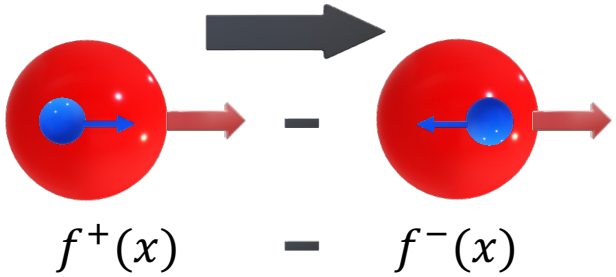
- For helicity distributions (collinear terms) in 'canonical' approach, the proton's spin can be decomposed into:

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

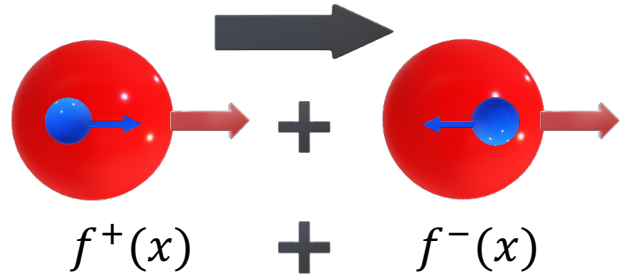
R. L. Jaffe and A. Manohar, NPB 337, 509 (1990)

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

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

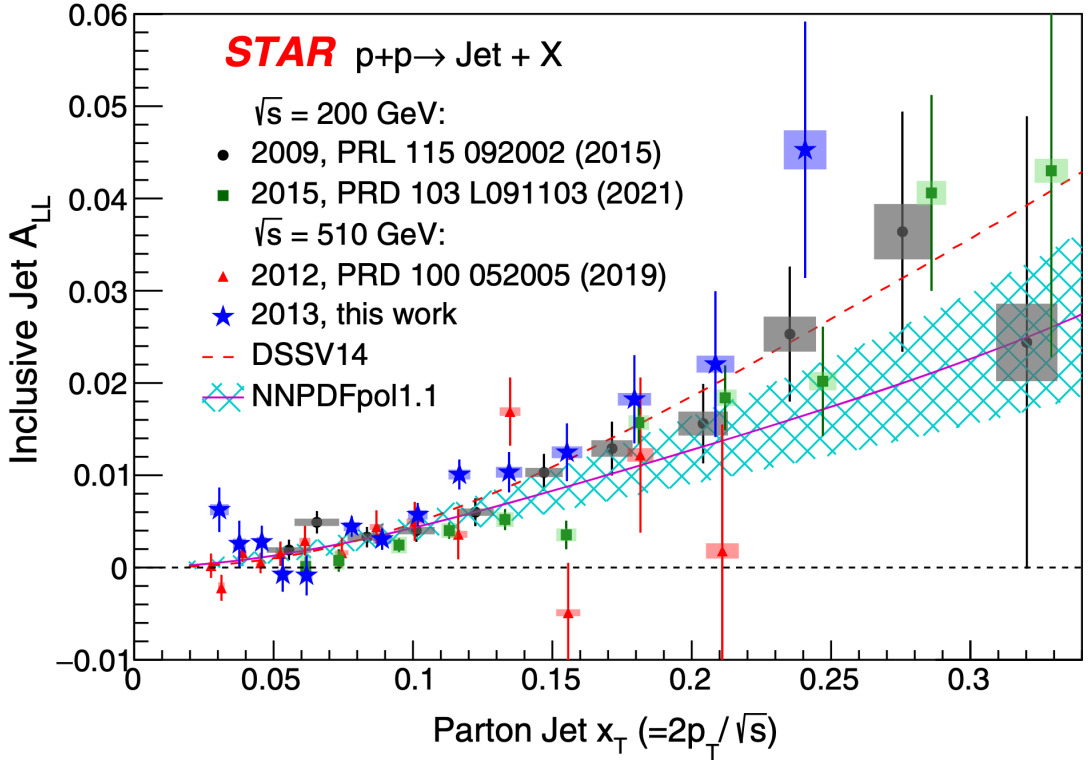


- Unpolarized PDF, $f(x) =$



Probing the Gluon Helicity at STAR

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



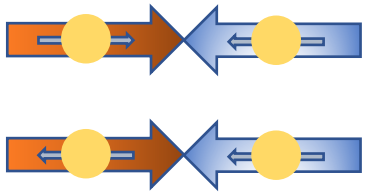
What we measured

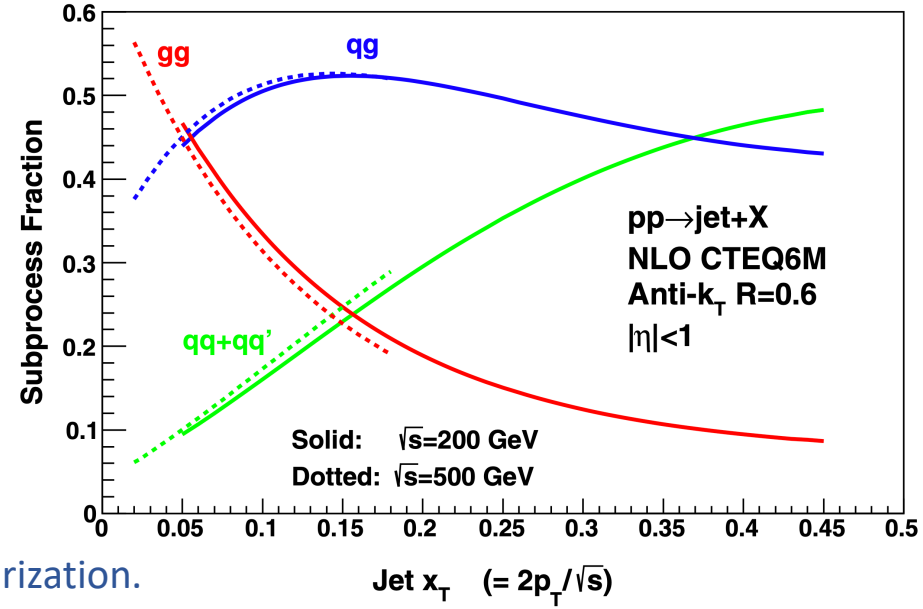
What we hope to learn

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

Measured by others

Calculable

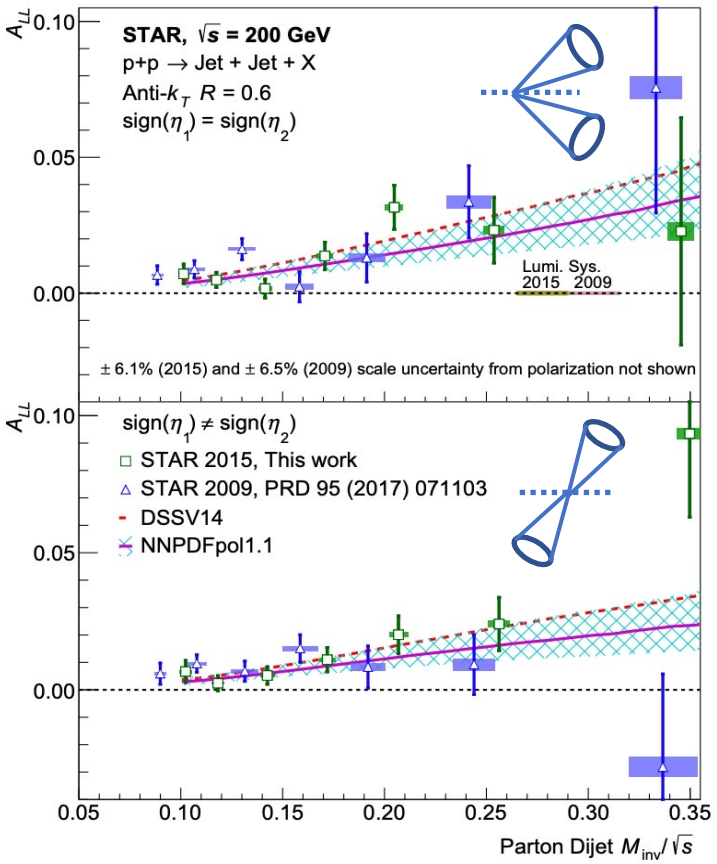




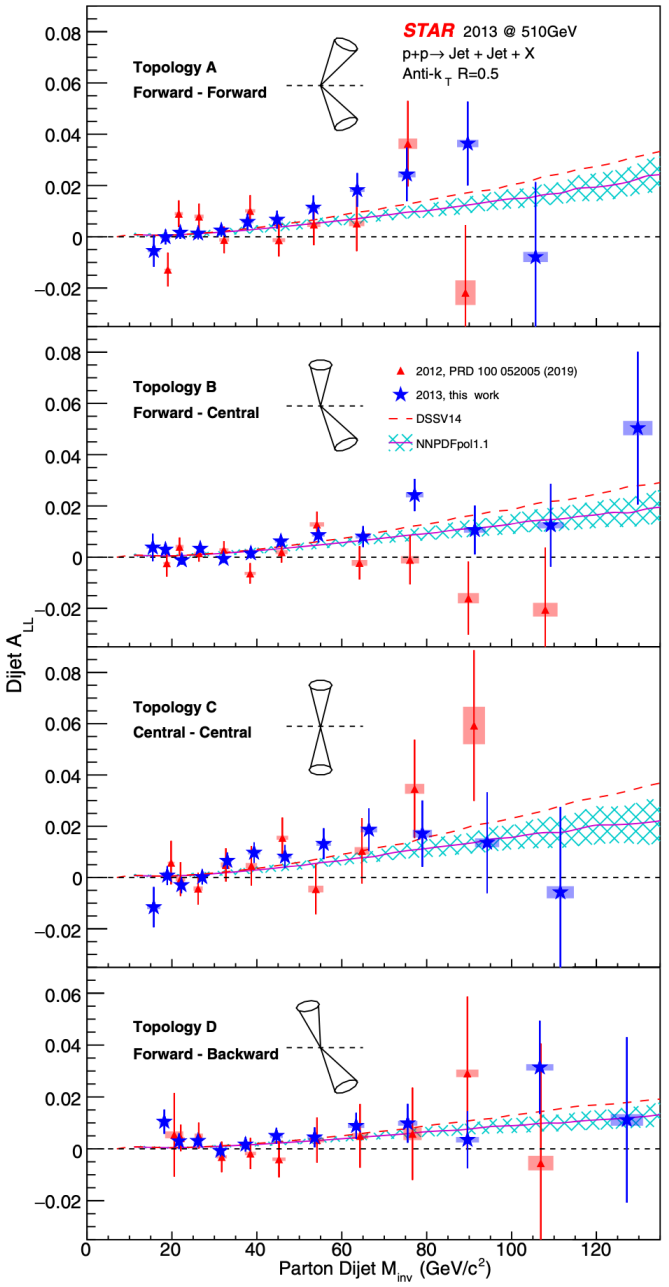
- Quark spin contribute 30% to the total spin of proton;
  - HERMES: $\Delta\Sigma(Q^2 = 3\text{GeV}) = \mathbf{0.330} \pm 0.011\,(\text{theo}) \pm 0.025\,(\text{exp}) \pm 0.028\,(\text{evol})$
  - COMPASS: $\Delta\Sigma(Q^2 = 5\text{GeV}) = \mathbf{0.32} \pm 0.02\,(\text{stat}) \pm 0.04\,(\text{syst}) \pm 0.05\,(\text{evo})$
- At RHIC energy, gg and qg dominate, making A_{LL} for jets sensitive to gluon polarization.

Dijet A_{LL}

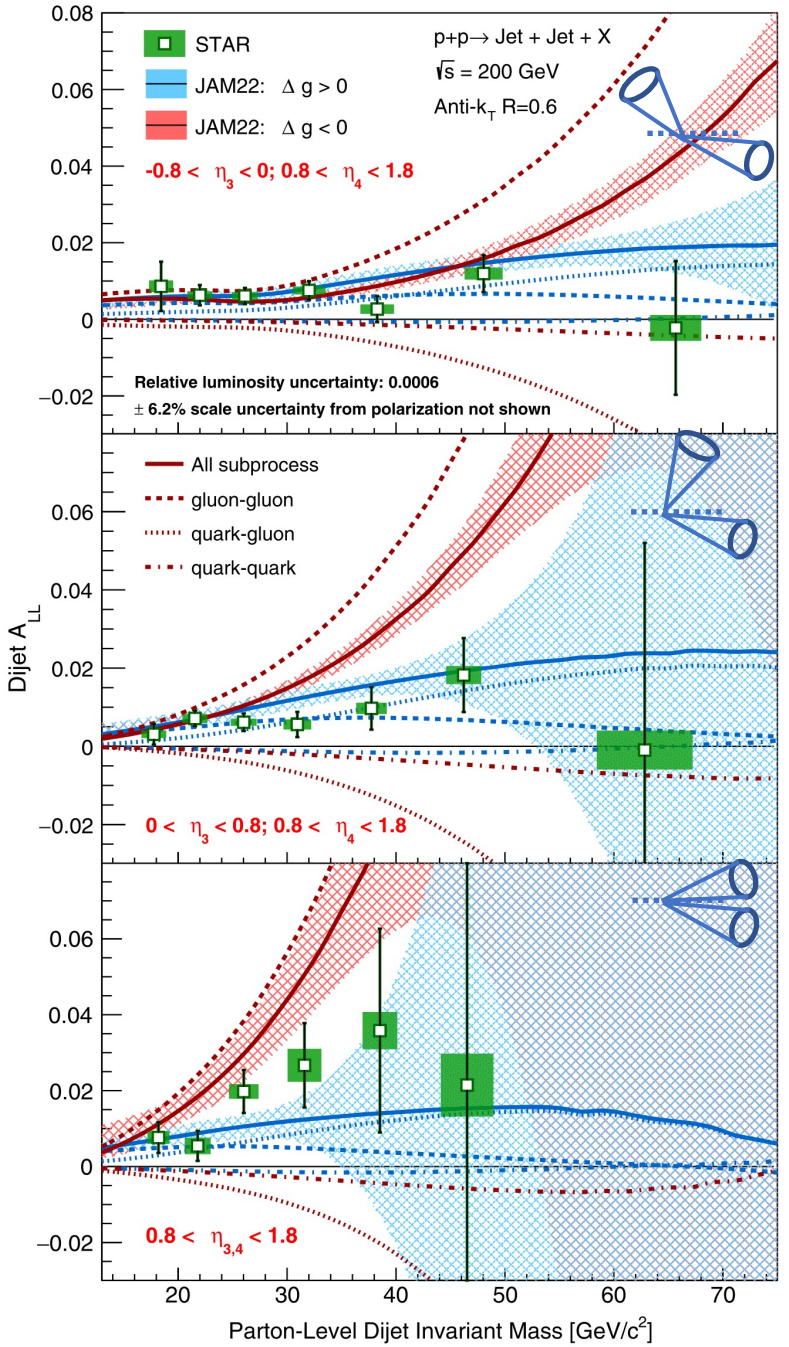
STAR, PRD 103 L091103 (2021)



STAR, PRD 105, 092011 (2022)



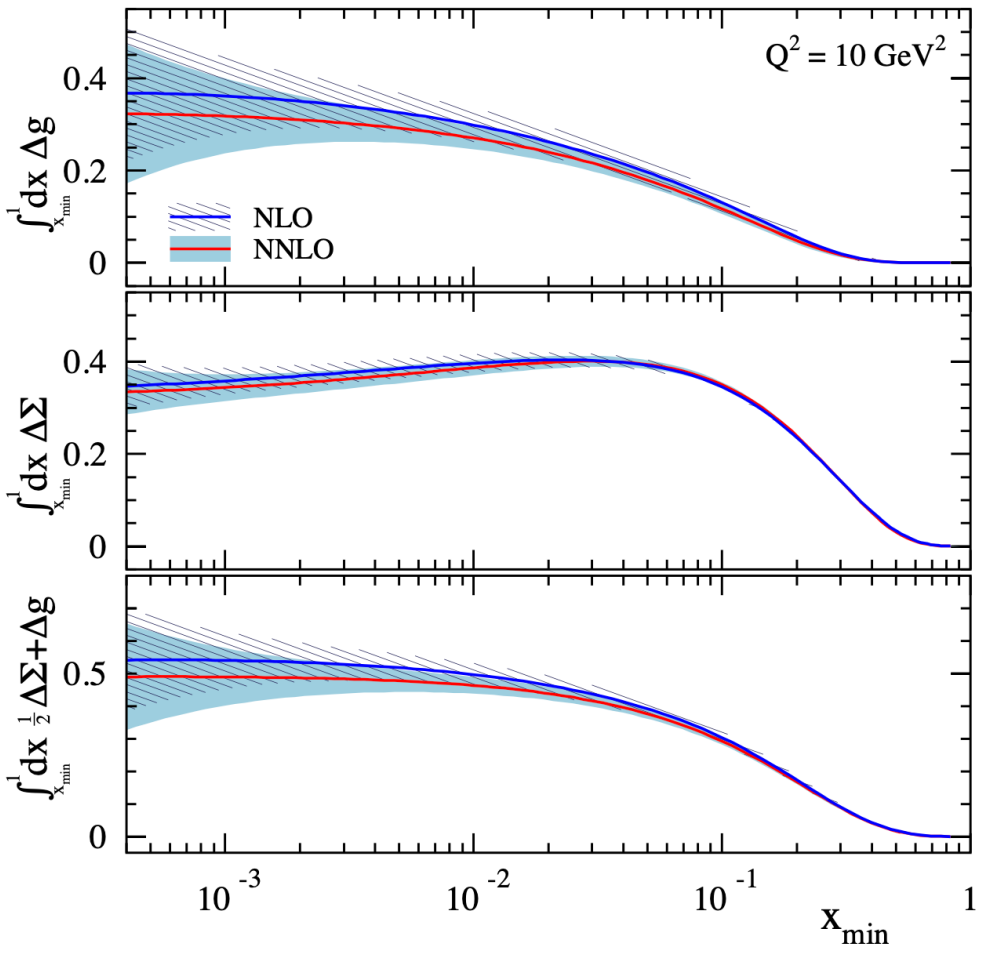
STAR, PRD 112 012003 (2025)



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

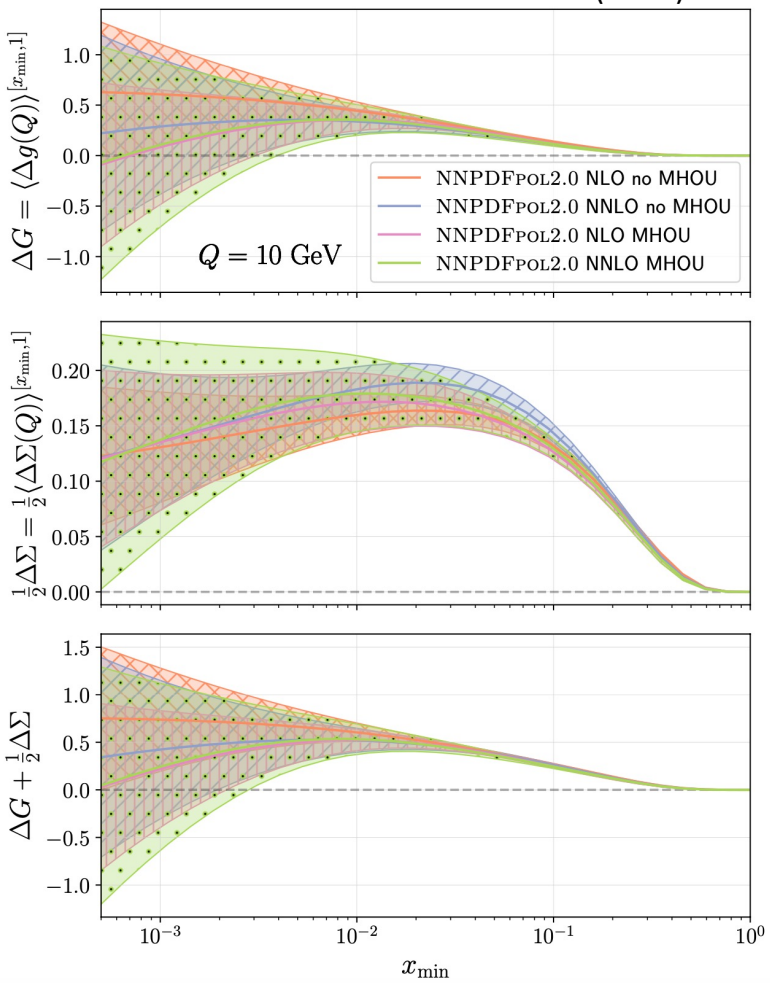
Impact of the New STAR Results

BDSSV PRL 133, 151901 (2024)



- $\Delta G = \int_{0.01}^{1} \Delta g(x) dx = 0.27 \pm 0.03$
- $\Delta\Sigma = \int_{0.01}^{1} \Delta q(x) dx = 0.38 \pm 0.01$
- $\Delta G + \frac{1}{2}\Delta\Sigma = 0.46 \pm 0.03$

NNPDF JHEP 07(2025)168



- When combining the two contributions, one finds a result approaching $1/2$ toward lower x, indication of a small contribution by orbital angular momenta to the proton spin.

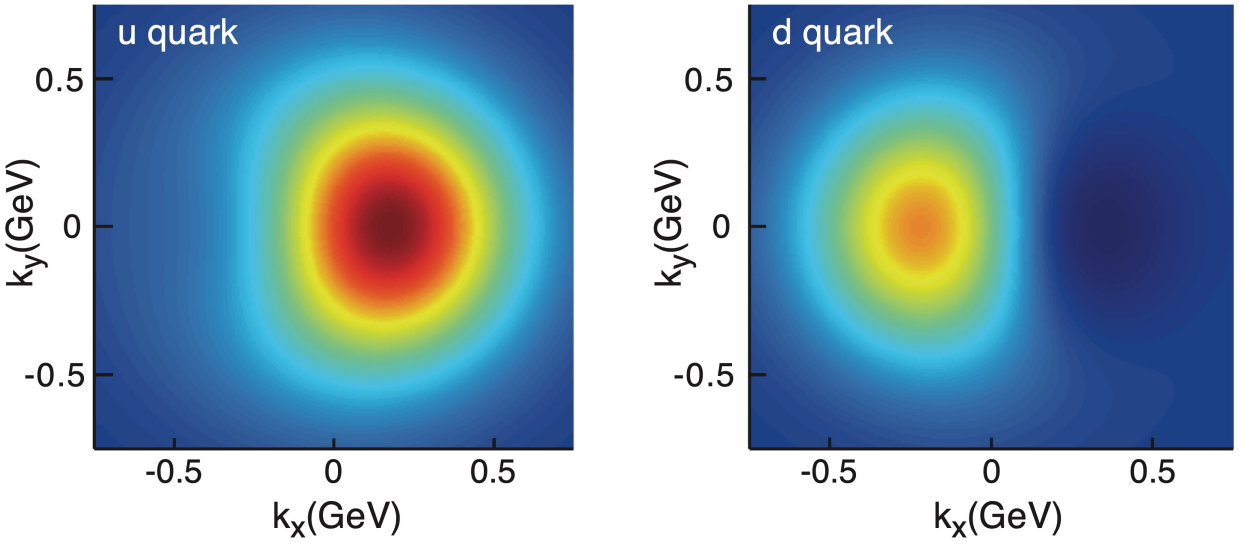
3D Tomography of the Nucleon:

TMD

TMD Parton Distribution Functions

EIC White Paper arXiv:1212.1701

$x\, f_1(x, k_T, S_T)$

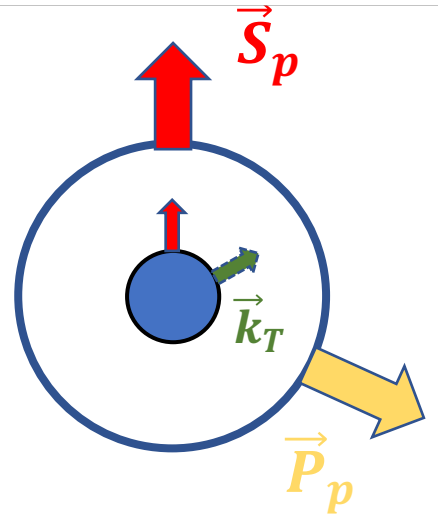


TMD Handbook, arXiv:2304.03302 [hep-ph]

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

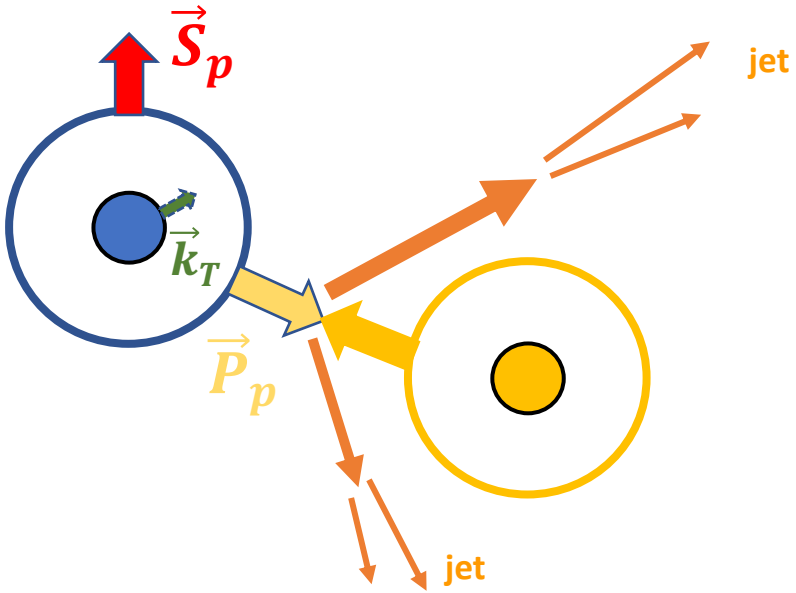
Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity; $h_{1T}^\perp$ = Pretzelosity

- 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.

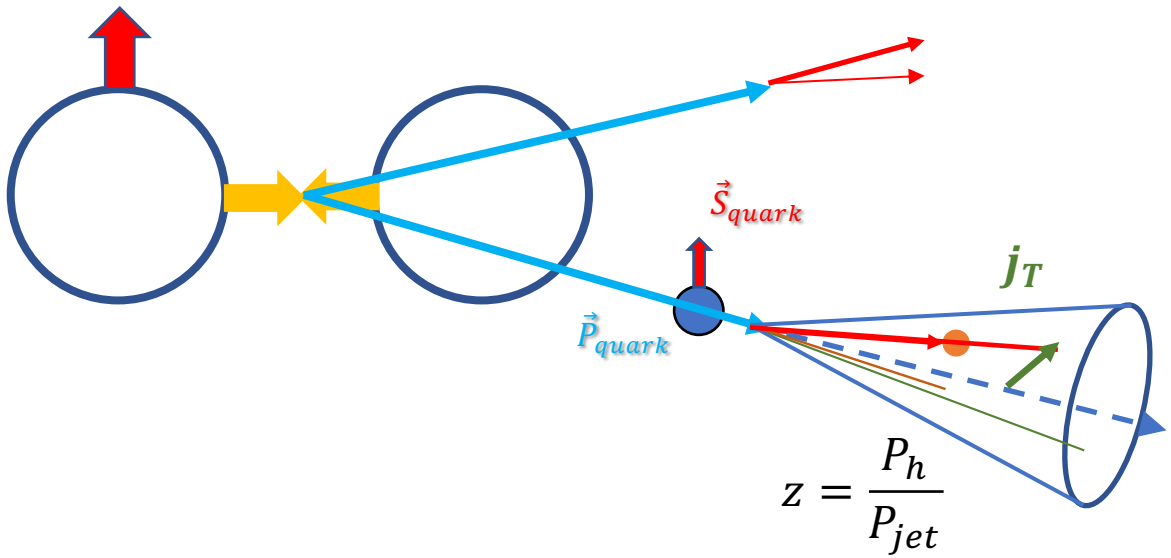


Initial and Final State Effect

Sivers Effect



Collins Effect

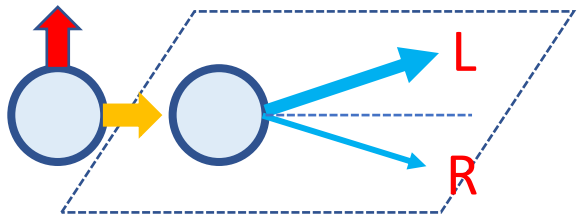


- Correlations of initial-state parton transverse momentum with proton's spin and momentum: $\sim \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T)$
- Non-universality exhibits the process dependence.

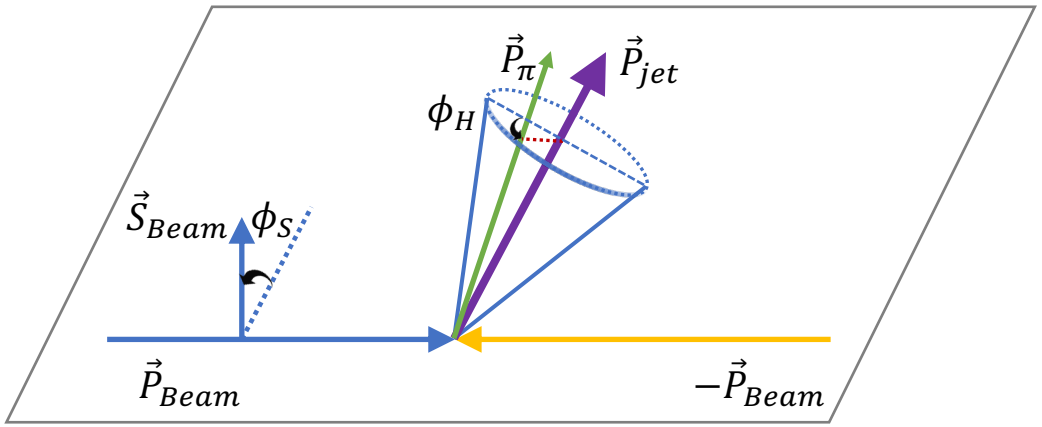
- Correlation between the polarization of a scattered quark and the momentum of hadron fragment transverse to the scattered quark direction: $\sim \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T)$;
- Chiral-odd, should couple with another chiral-odd distributions.

Transverse Single-Spin Asymmetry

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



$$p^{\uparrow} + p \rightarrow \text{Jet} + \pi^{\pm} + \text{X}$$



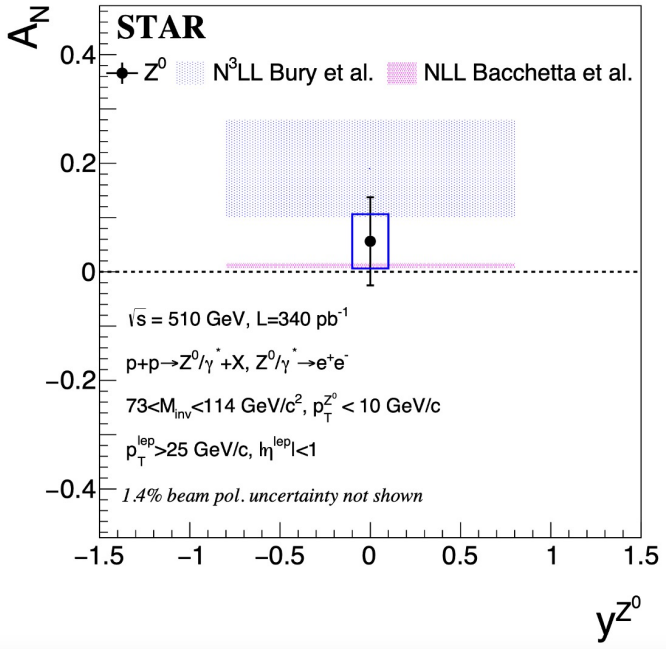
$$A_N = \frac{d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)}{d\sigma^{\uparrow}(\phi_S, \phi_H) + d\sigma^{\downarrow}(\phi_S, \phi_H)} \sim A_{UT}^{Sivers} \sin(\phi_S) + A_{UT}^{Collins} \sin(\phi_S - \phi_H)$$

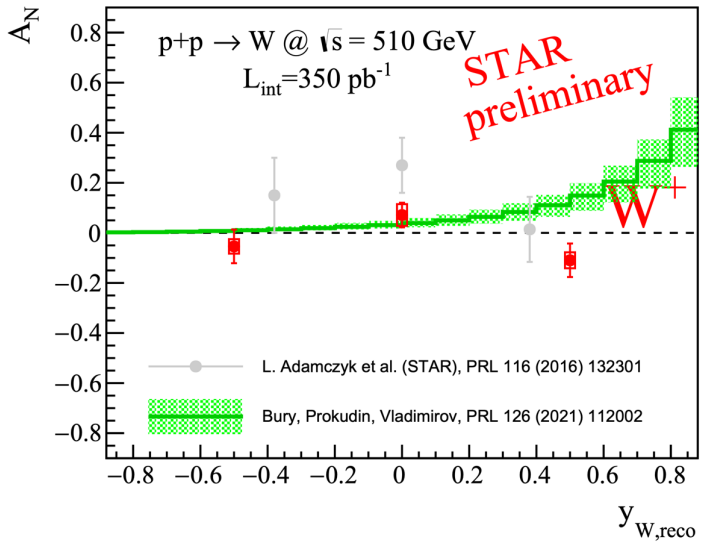
$\sim f_{1T}^{\perp} \otimes D_1$ $\sim h_1 \otimes H_1^{\perp}$

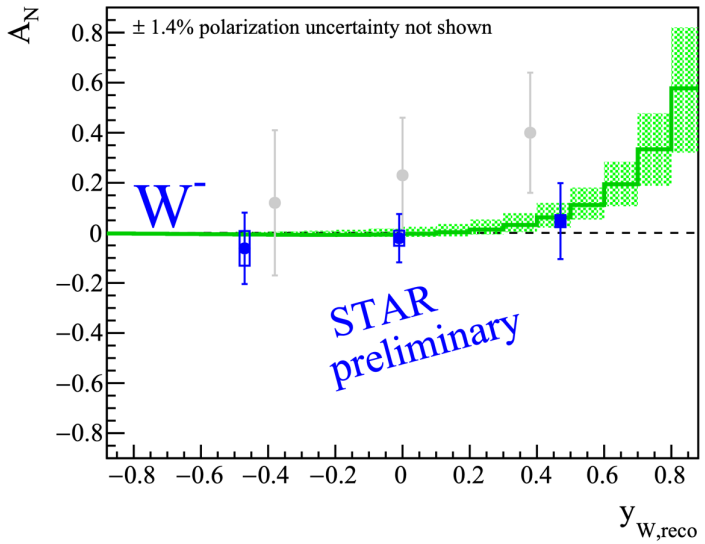
- Each TMD PDF is convoluted with a fragmentation function and appears with a independent harmonic modulations (azimuthal asymmetry amplitudes).

A_N for Z^0 and $W^{\pm}$ Boson Production

STAR, PLB 854 (2024) 138715



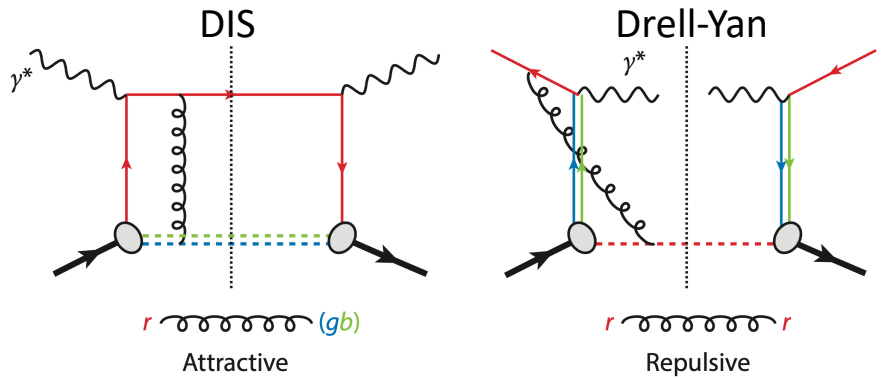




- Test the nonuniversality nature of Sivers function:

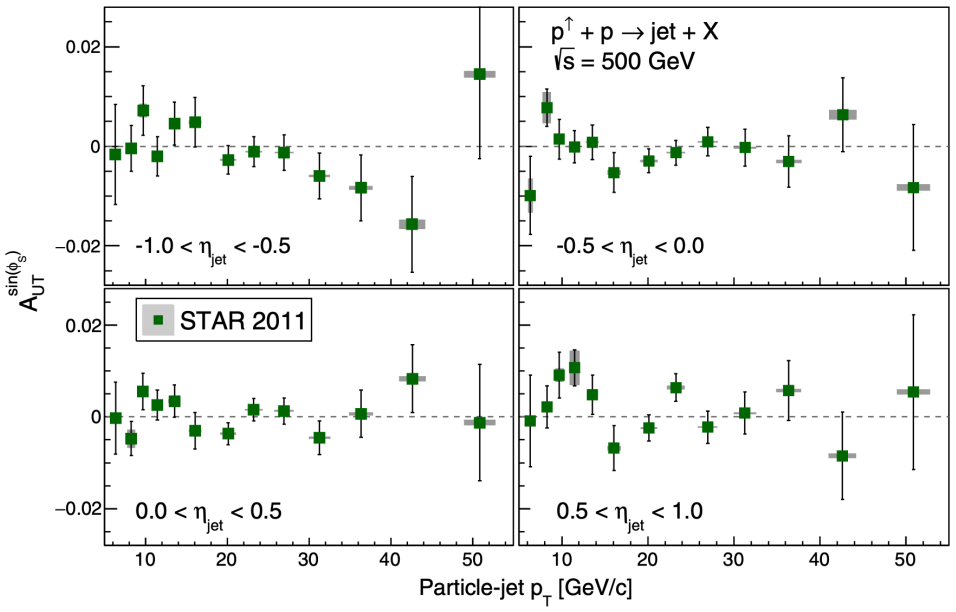
$$\text{Sivers}_{SIDIS} = -\text{Sivers}(\text{Drell} - \text{Yan or } W/Z)$$

- A fundamental prediction from the gauge invariance of QCD.

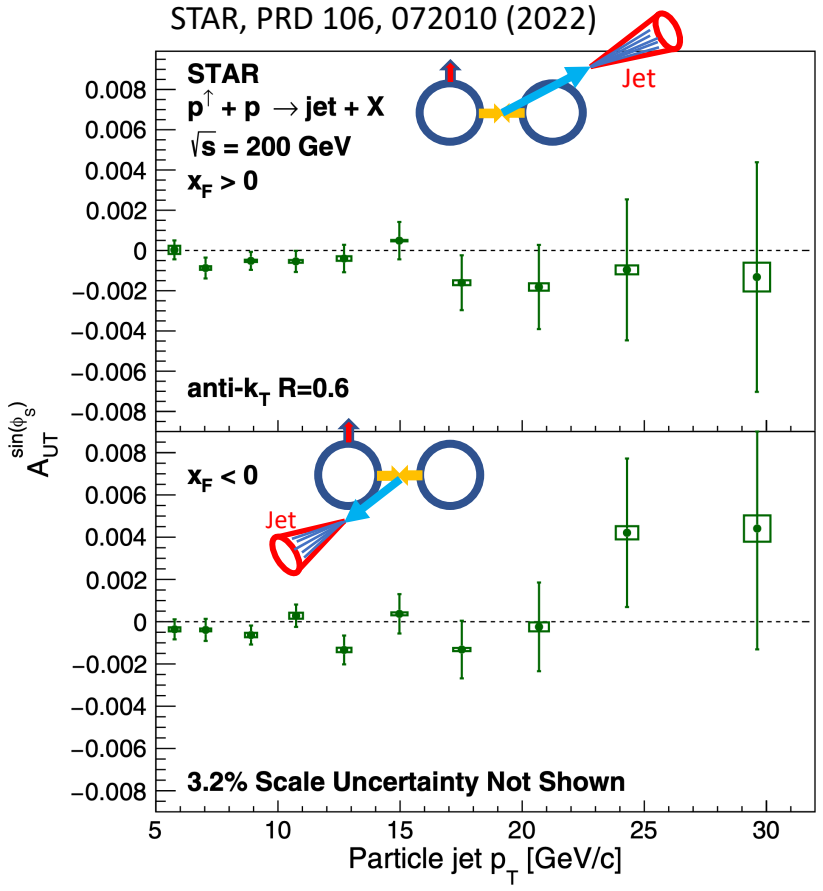


A_N for Inclusive Jet

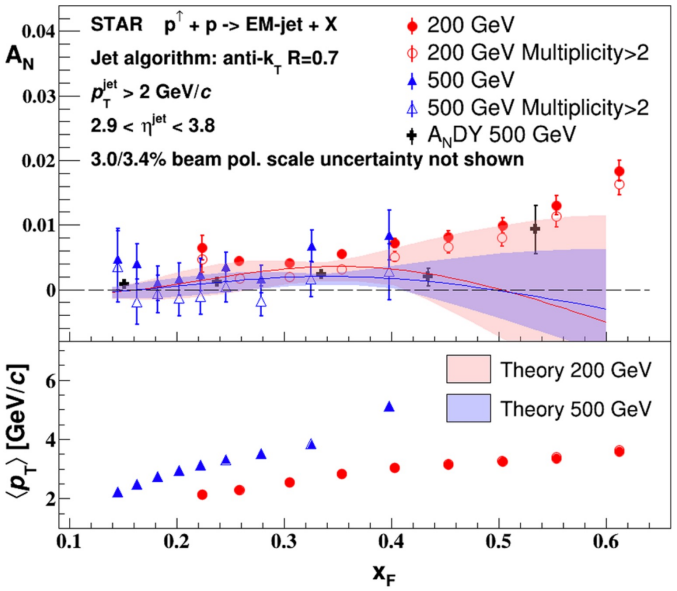
STAR, PRD 97, 032004 (2018)



STAR, PRD 106, 072010 (2022)



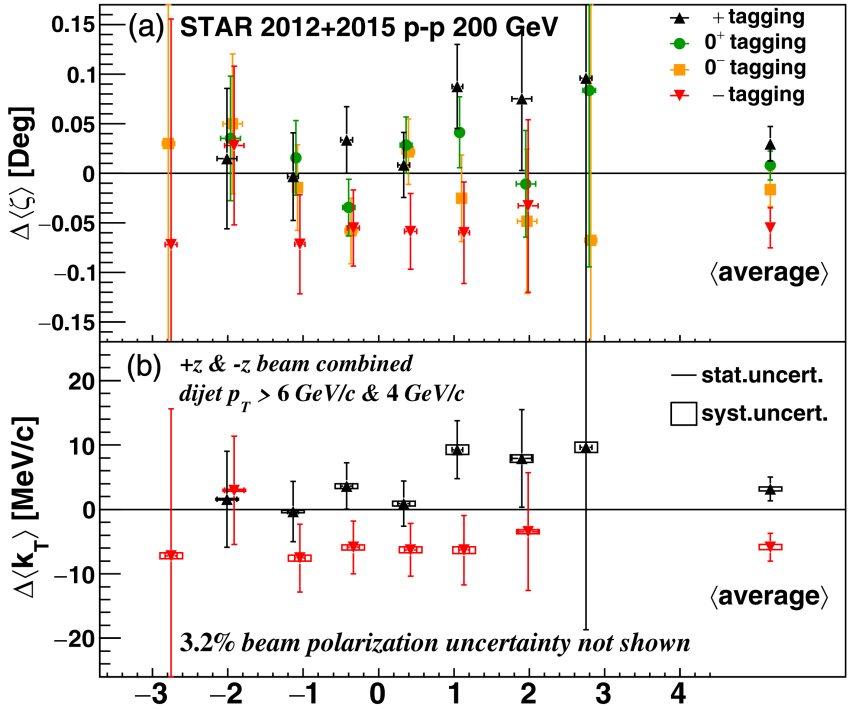
STAR, PRD 103, 092009 (2021)



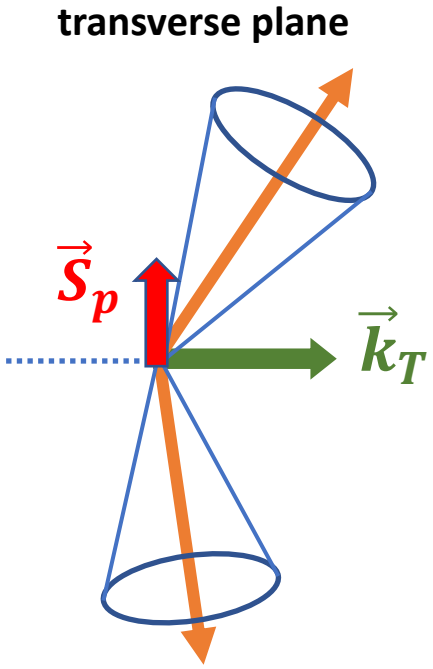
- Inclusive jet A_N are sensitive to the Sivers function via the twist-3 correlators;
- Free of final-state contributions.

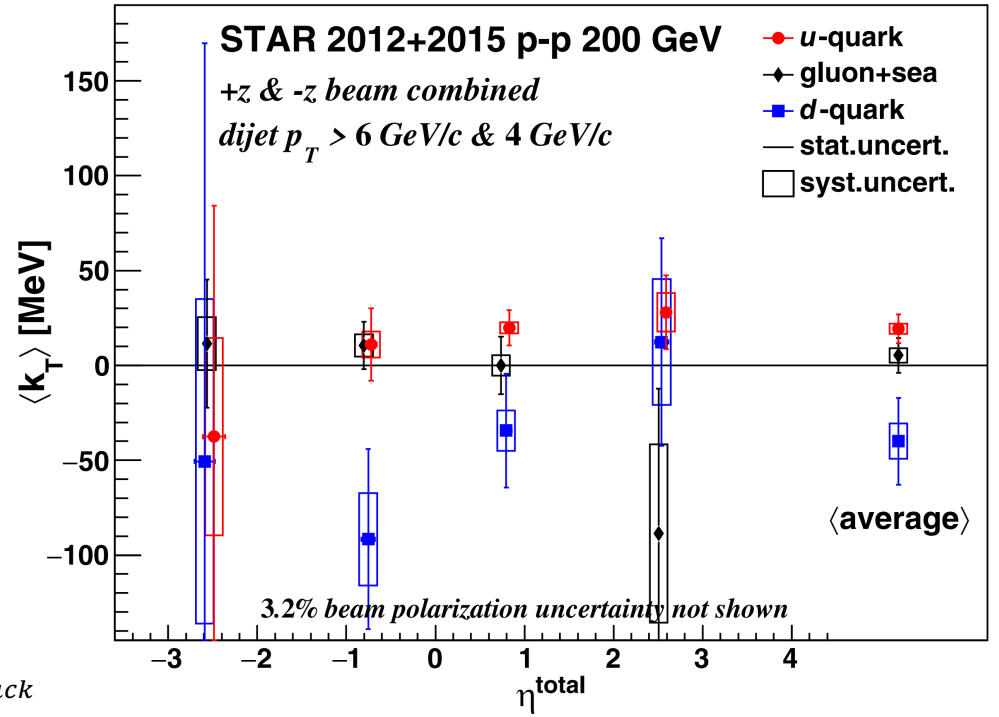
Transverse Single-Spin Asymmetries for Dijet

STAR, PRD 114, L011504 (2026)



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





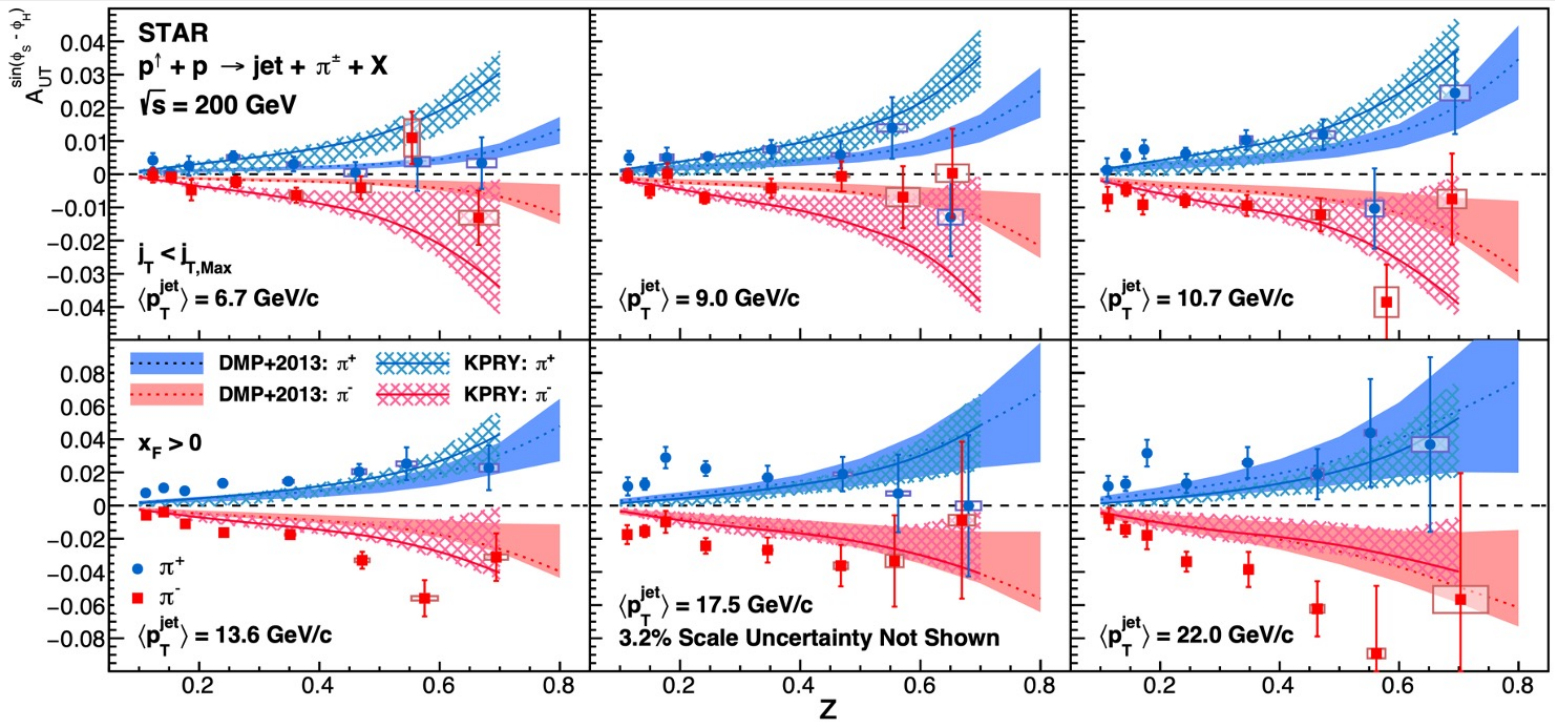
Jet Charge tagging: $Q = \sum_{p>0.8\mathrm{GeV}/c} \frac{p^{track}}{p^{jet}} \cdot q$

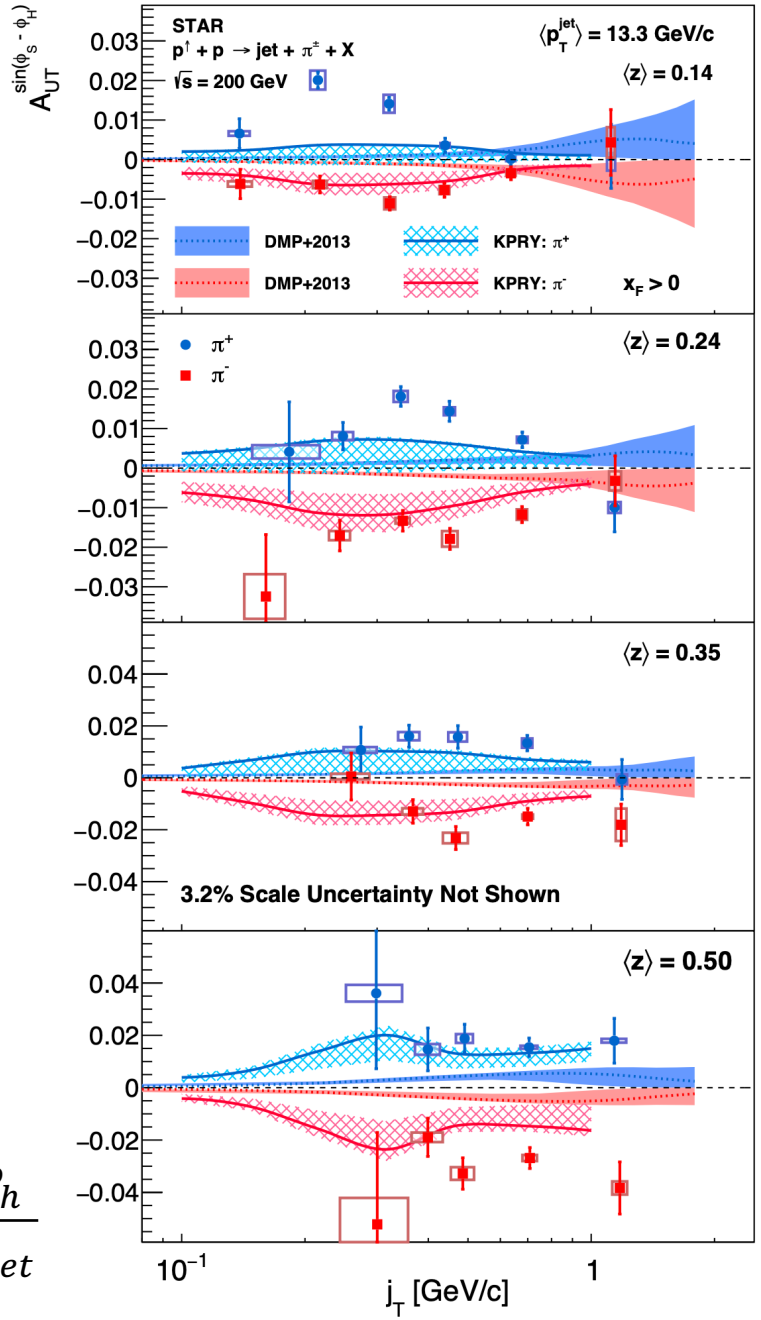
- First observation of non-zero Sivers asymmetries in dijet production in polarized p+p collisions;
- $\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6$ MeV/c, $\langle k_T^d \rangle = -40.0 \pm 22.9 \pm 9.3$ MeV/c, $\langle k_T^{g+sea} \rangle = 5.3 \pm 9.2 \pm 3.8$ MeV/c.

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

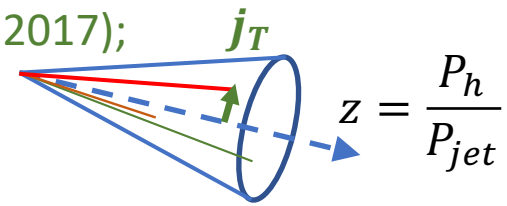
STAR, PRD 106, 072010 (2022)

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





- 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.



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

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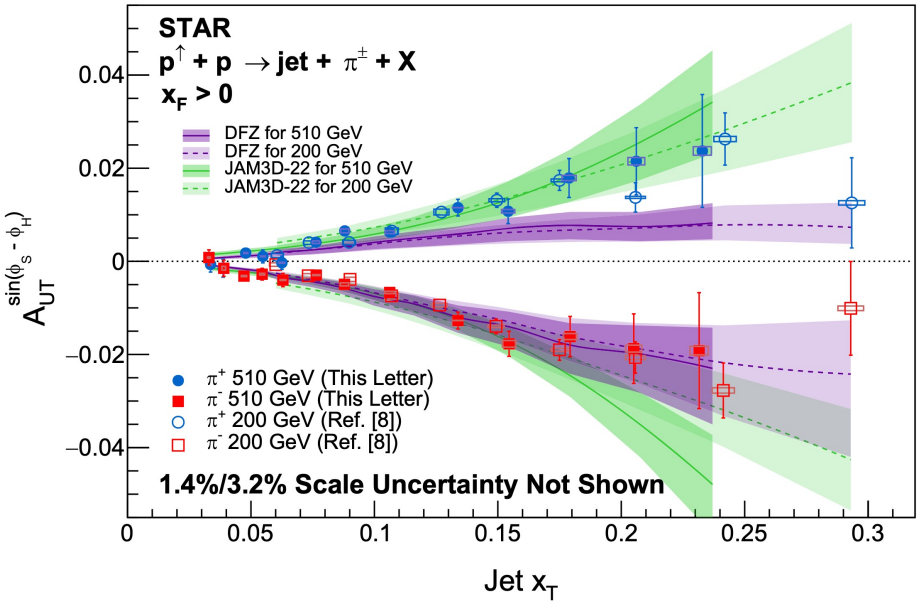
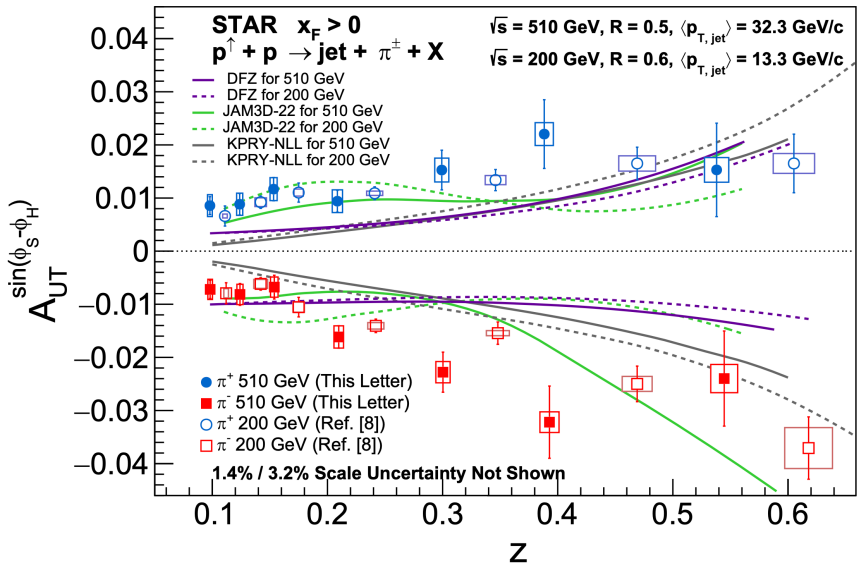
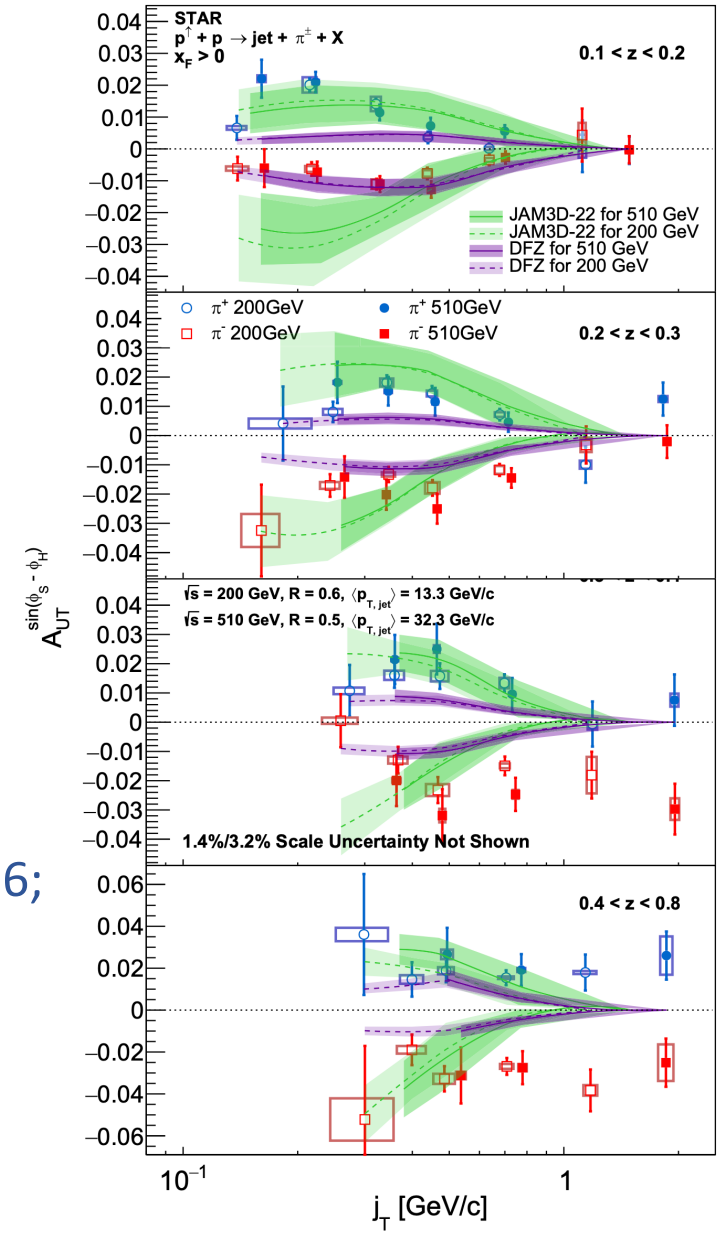
Comparison with pp 510 GeV

STAR, PRL 135 261902 (2025)





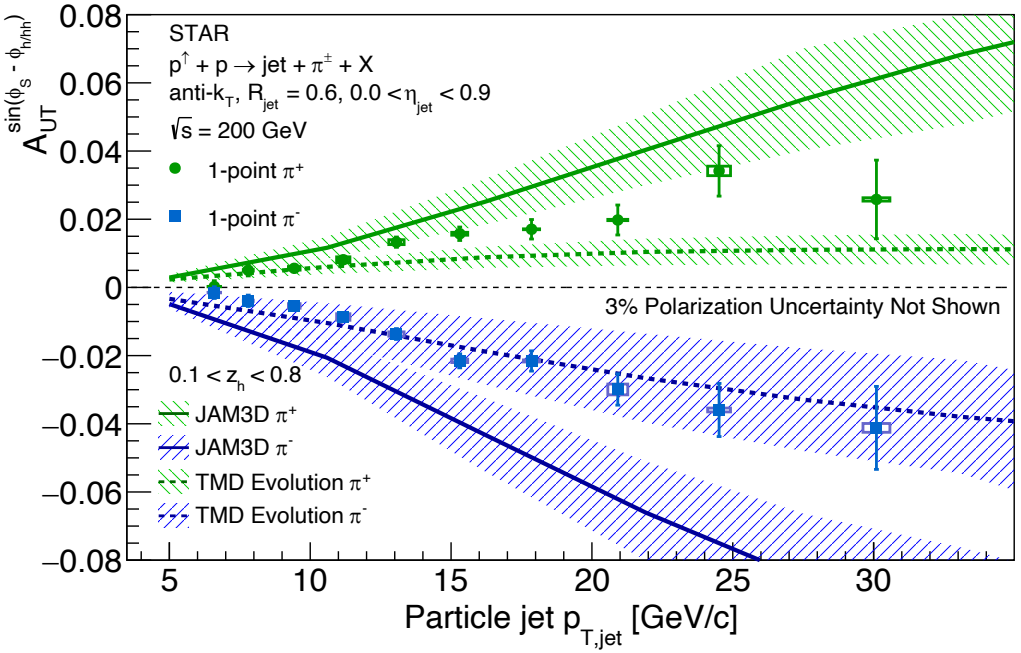


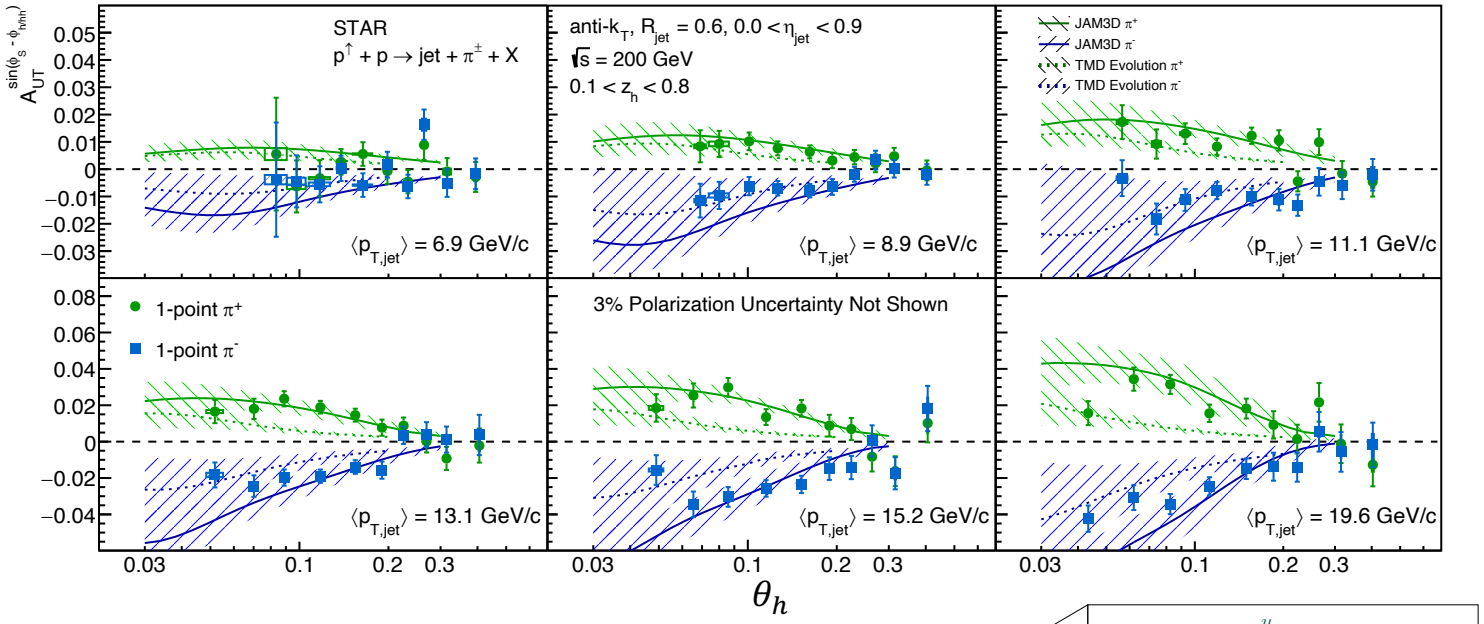
- The asymmetries agree at $0.06 < x_T = \frac{2p_{\mathrm{T,jet}}}{\sqrt{s}} < 0.2$, Q^2 differ by a factor of 6;
- Collins asymmetry has a weak energy dependence in hadronic collisions;
- z and j_T dependences of the Collins FF are closely related.

One-Point Energy Correlator

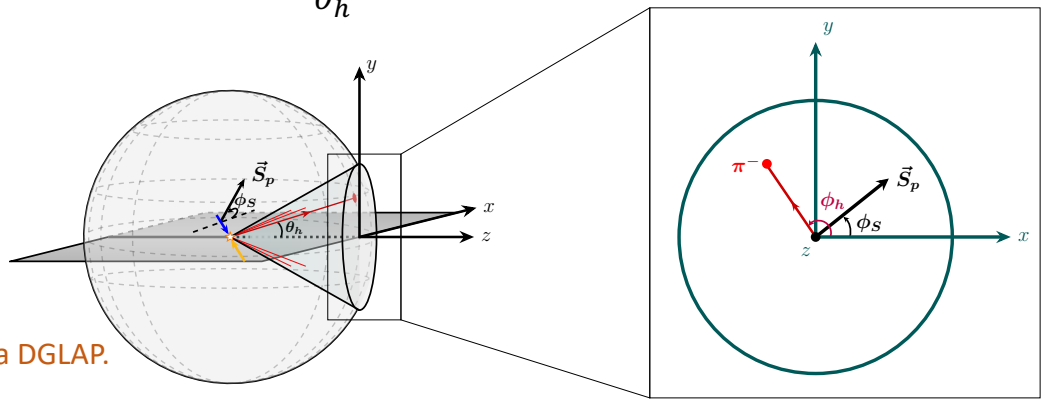
Theory predictions from: Mei-Sen Gao , Zhong-Bo Kang, Wanchen Li, and Ding Yu Shao PRL 136, 151902 (2026)

STAR, arXiv: 2604.15543 [hep-ex]



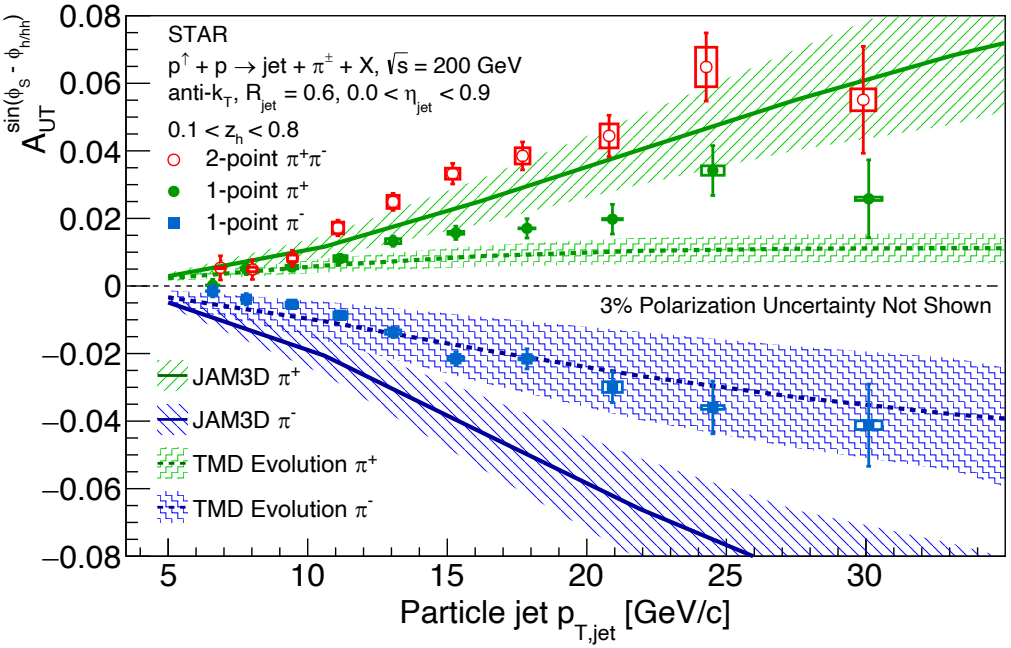


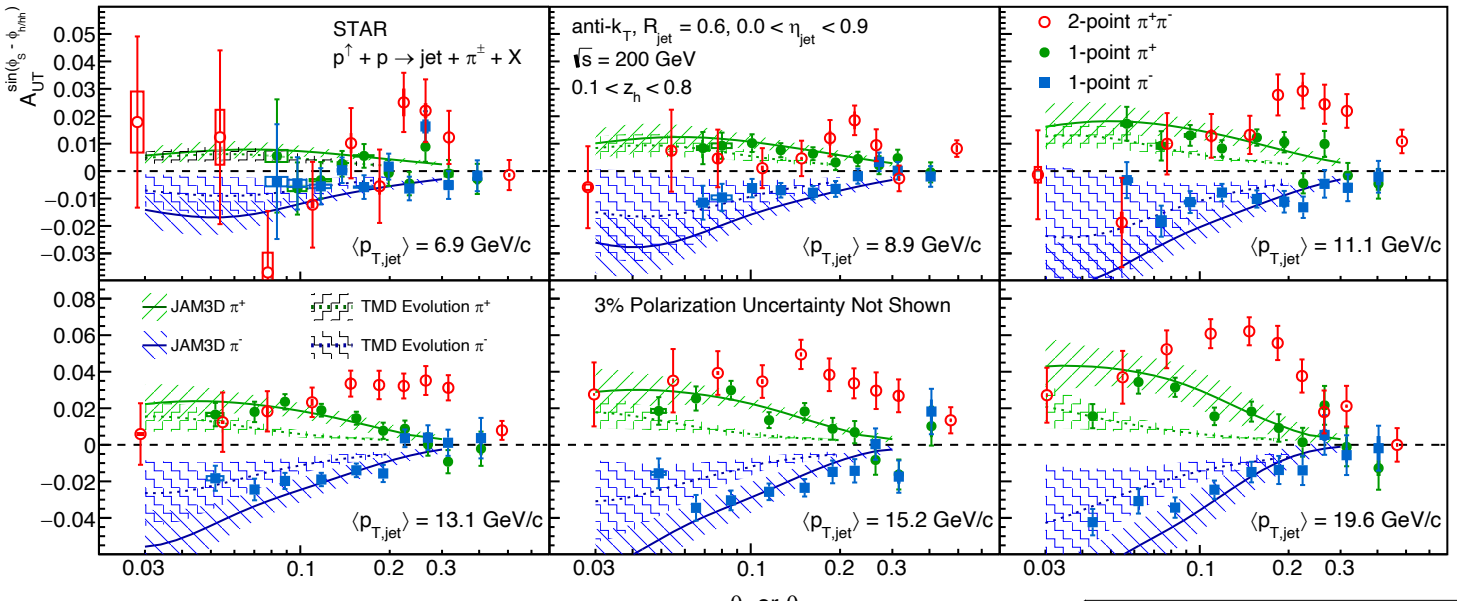
- A novel probe of the nucleon's transversity distribution using EEC
  - $\mathrm{OPEC}(\theta_h, \phi_h) = \frac{d(\sum_{jet} \sum_i z_{h,i})}{d\theta_h d\phi_h}$
- Reduces model dependence by integrating over z_h into Mellin moment;
  - TMD evolution: full TMD evolution using rigorous Sudakov exponentiation;
  - JAM3D: Omits full TMD evolution, relying on a simple Gaussian model; collinear parts via DGLAP.



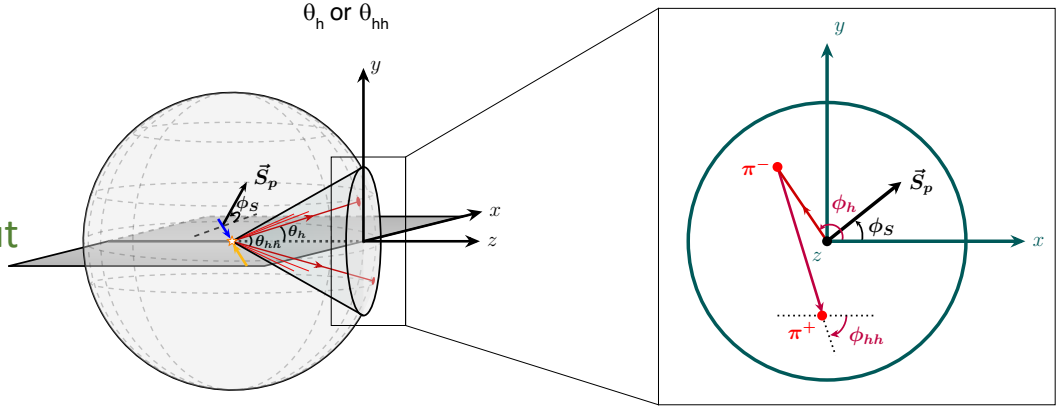
Two-Point Energy Energy Correlators

STAR, arXiv: 2604.15543 [hep-ex]



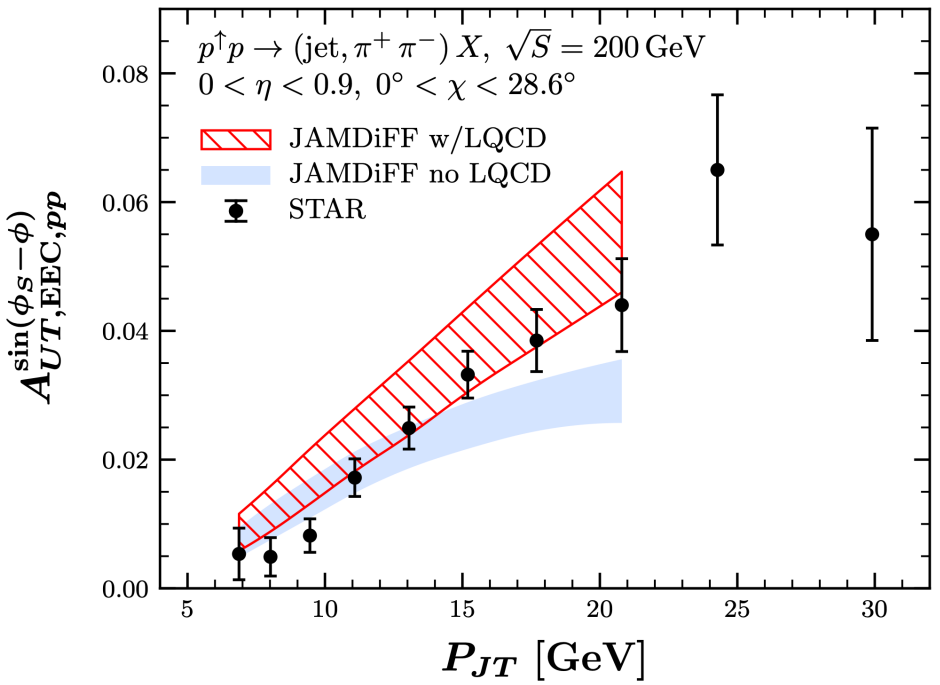


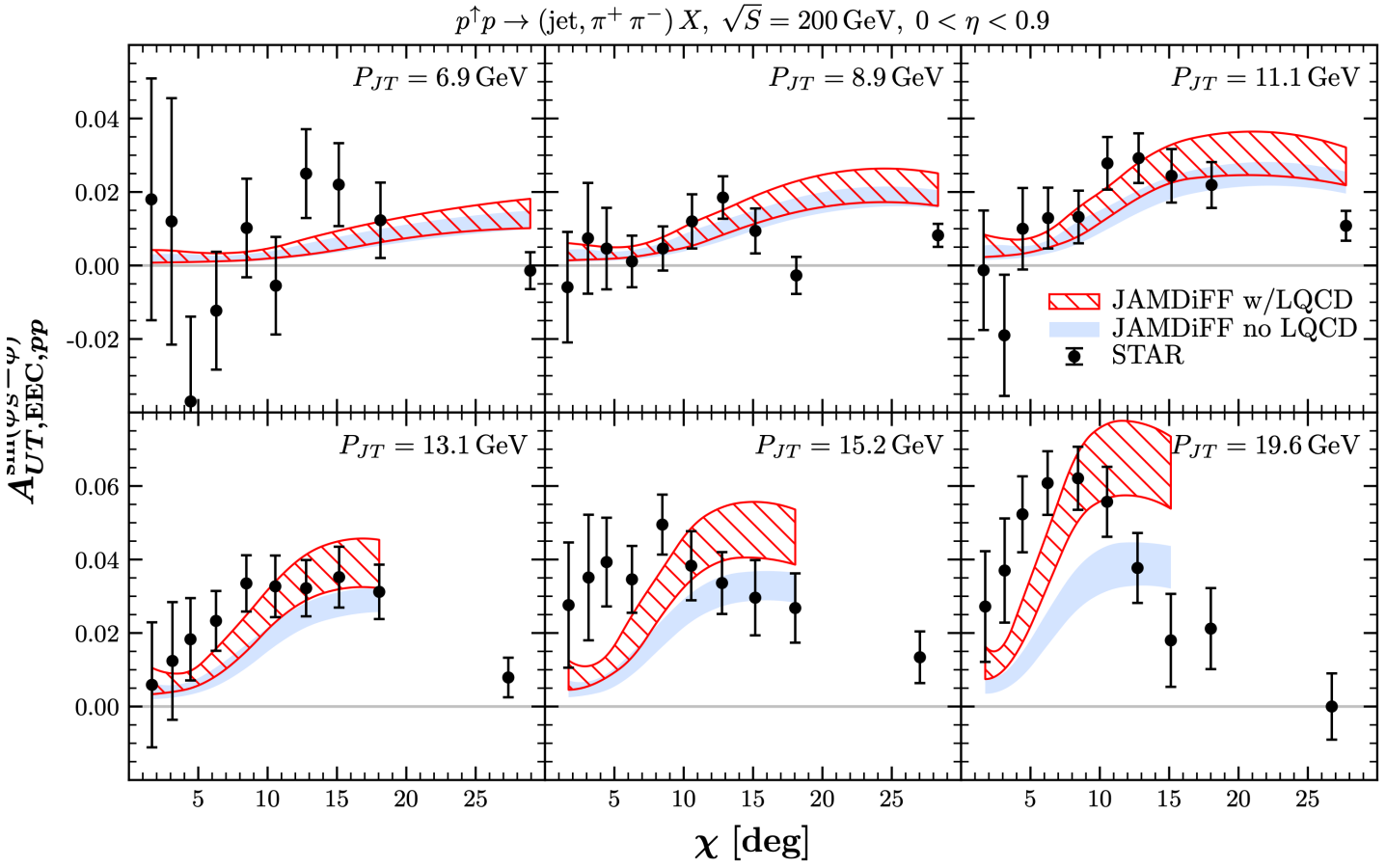
- Asymmetries can be as larger as about 6% at this kinematic region;
- Two-point asymmetries align with one-point π^+ at low jet p_T, and are about twice at high jet p_T.



Theory Calculations on Two Point EEC

July 2nd: arXiv:2607.02441 [hep-ph]
Zhong-Bo Kang, Andreas Metz, Daniel Pitonyak
Congyue Zhang

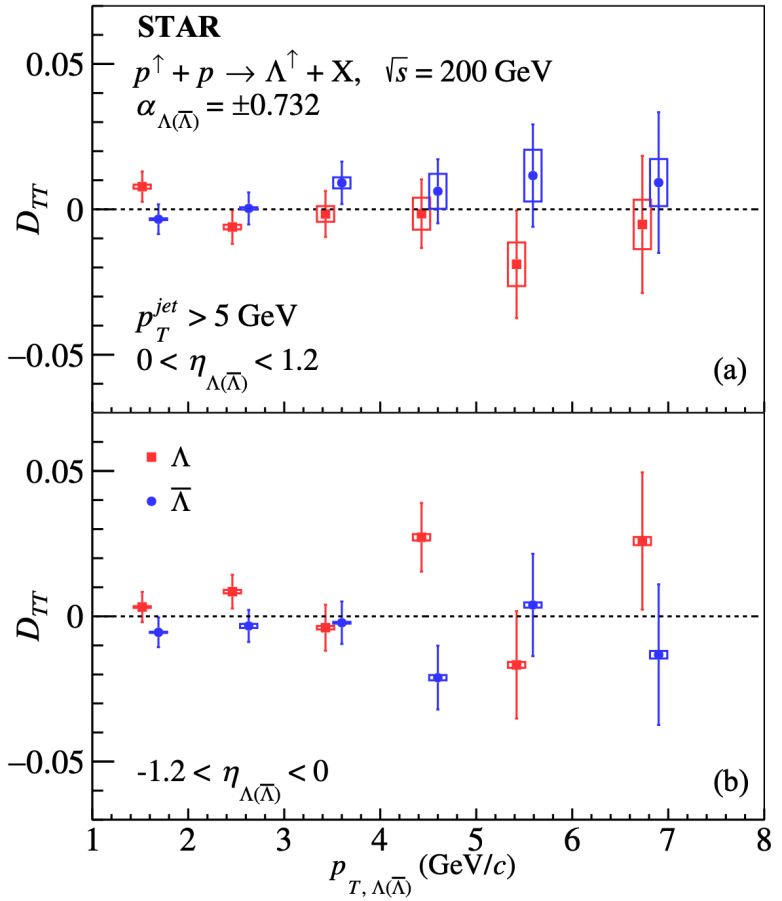


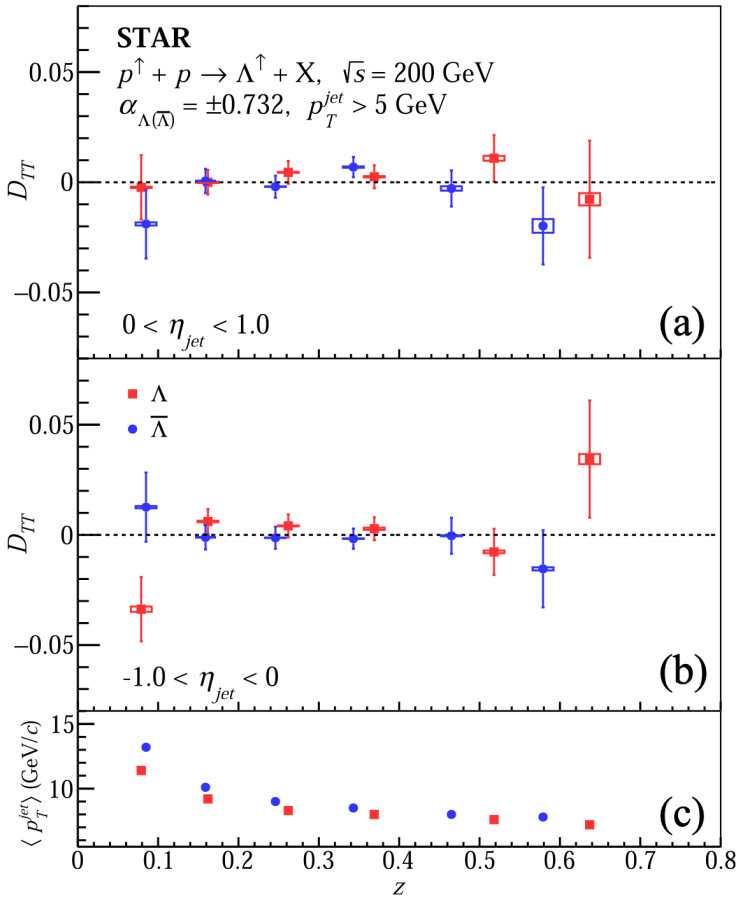


- New theory calculation on the polarized EEC within the dihadron fragmentation framework;
- Data favor the predictions with transversity extractions consistent with Lattice QCD tensor charges.

Lambda Polarization in Transversely Polarized Proton

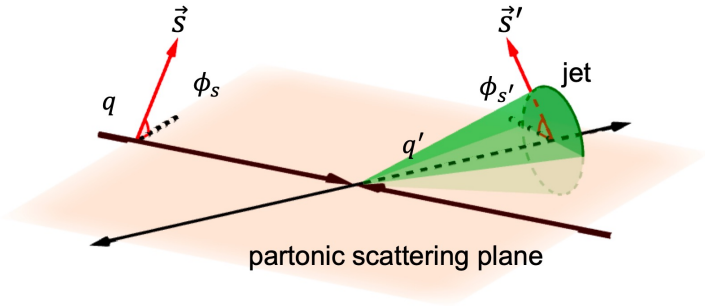
STAR, PRD 109 012004 (2024)





$$D_{TT} = \frac{d\sigma^{(p^{\uparrow}p \to \Lambda^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p \to \Lambda^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p \to \Lambda^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p \to \Lambda^{\downarrow}X)}}$$

$$\frac{dN}{d\cos\theta^*} \propto A(1 + \alpha_\Lambda P_\Lambda \cos\theta^*)$$

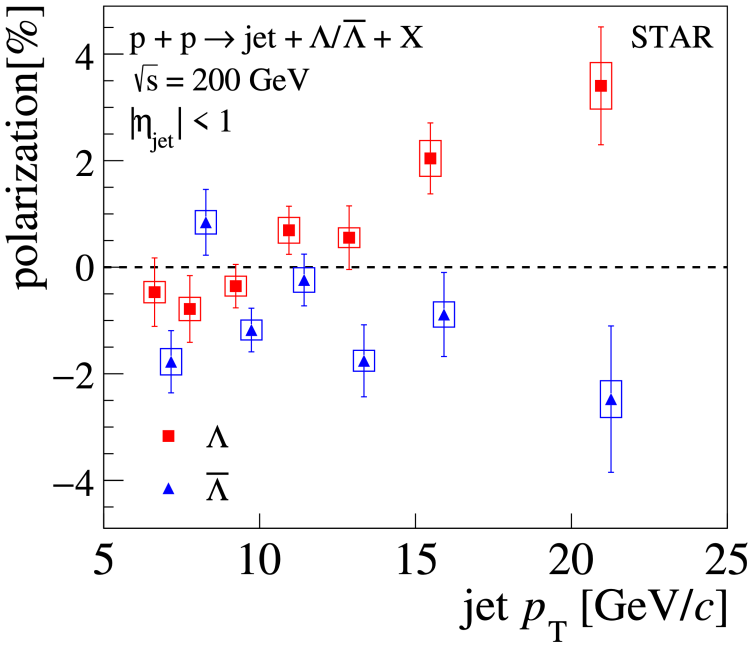


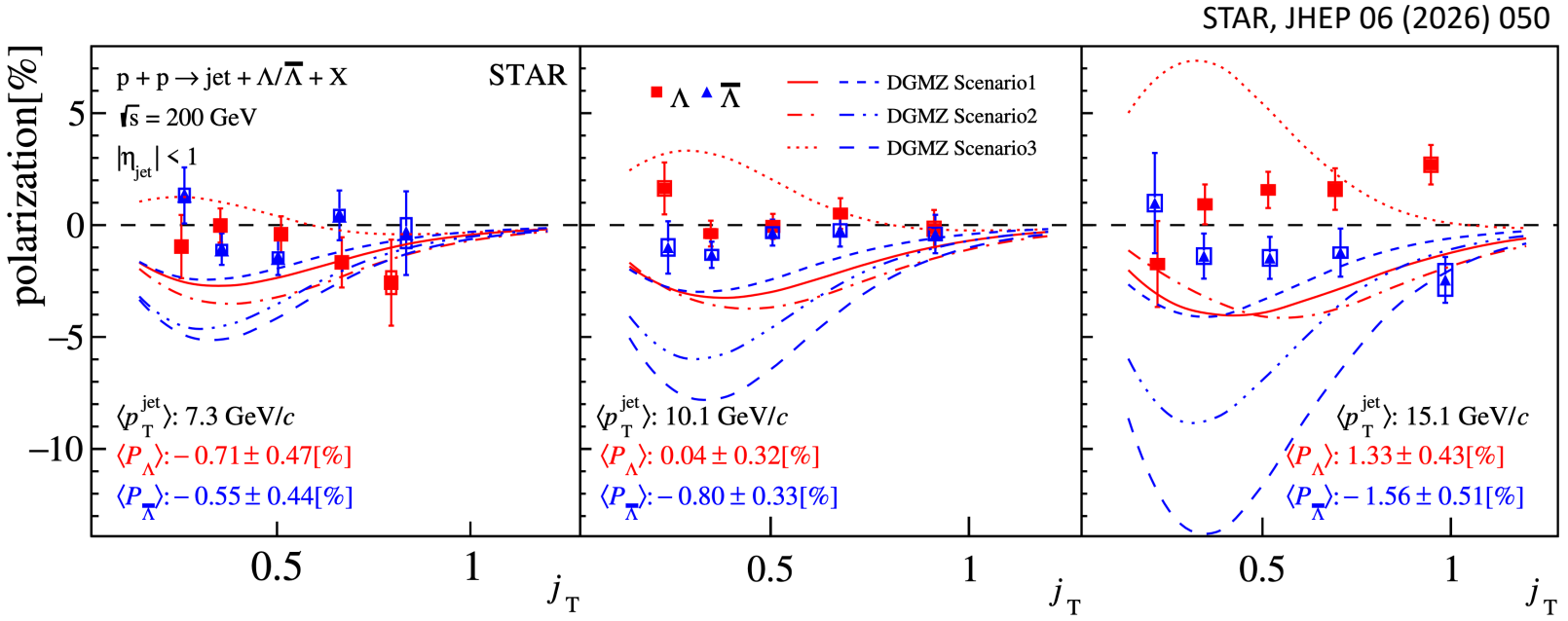
- These results provide insights into the strange quark and anti-quark transversity in the proton;
- The first measurement of the D_{TT} $vs.z$ directly probes the polarized fragmentation functions.

高涛亚的报告
周三下午17:20

Lambda Polarization in Un-Polarized Proton

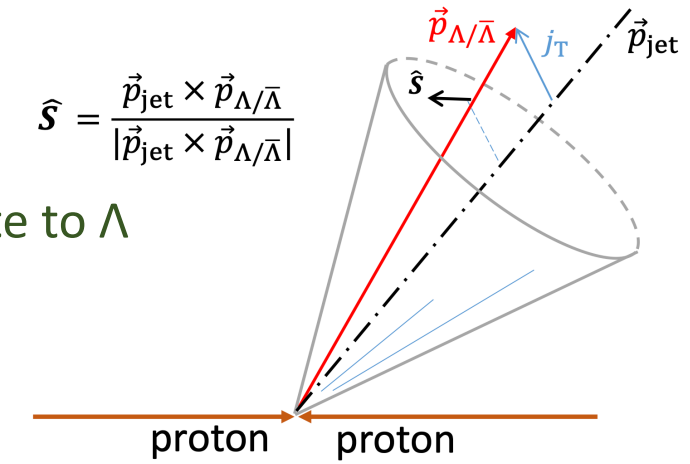
STAR, JHEP 06 (2026) 050



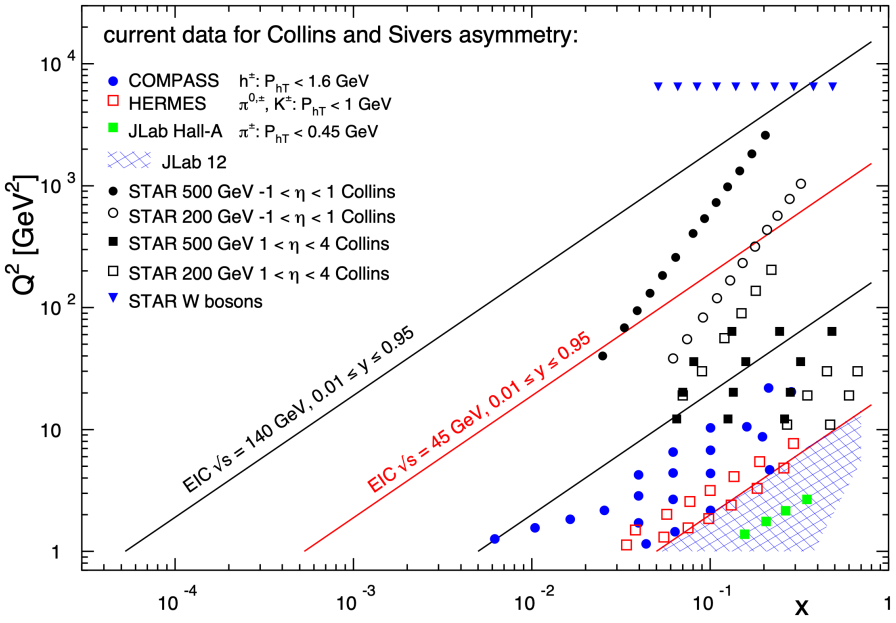


- First measurement of transverse polarization of Λ-in-jet at pp 200 GeV;
- These results probe polarizing fragmentation function which might contribute to Λ spontaneous polarization.

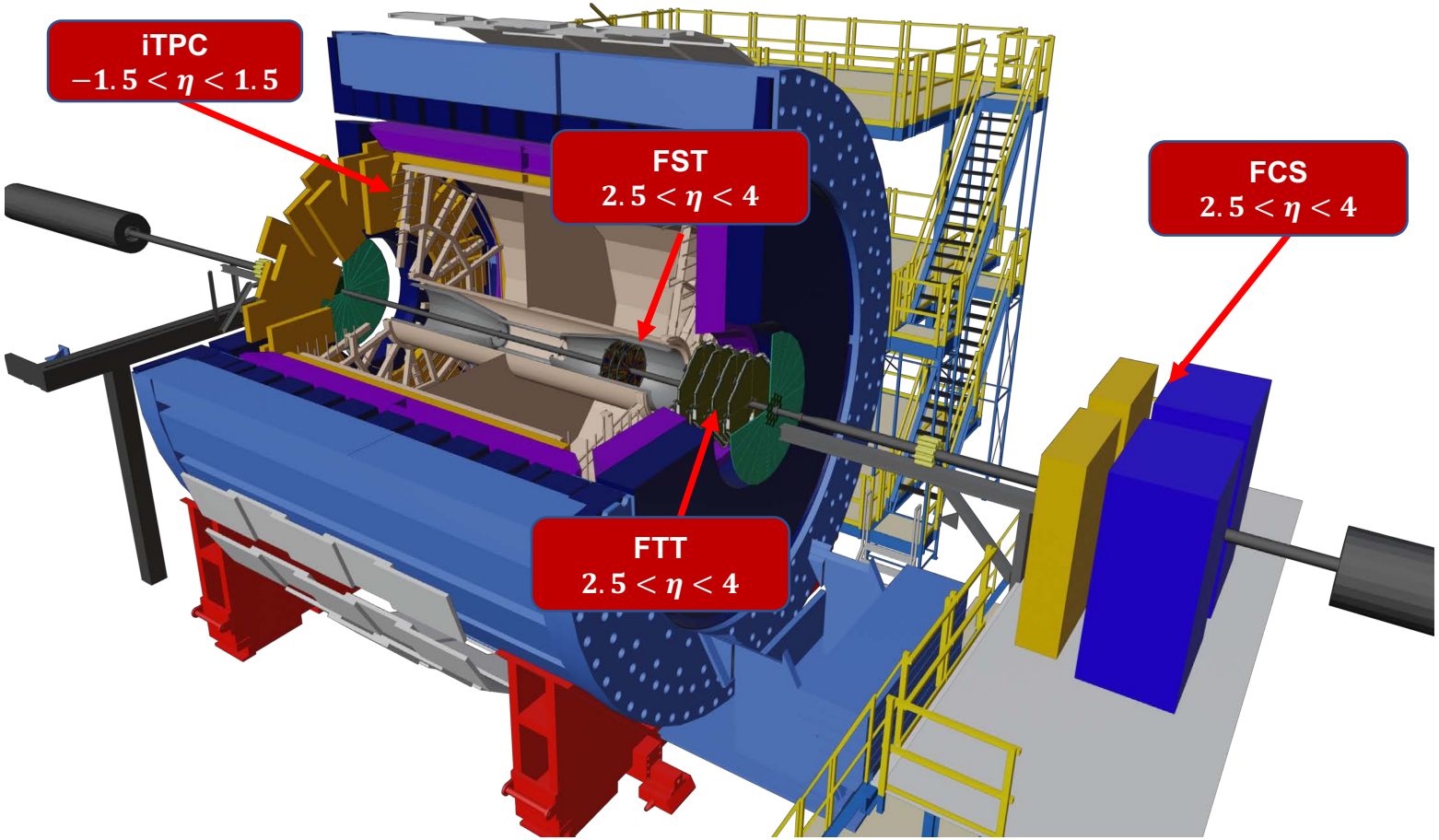
$$\hat{s} = \frac{\vec{p}_{\text{jet}} \times \vec{p}_{\Lambda/\bar{\Lambda}}}{|\vec{p}_{\text{jet}} \times \vec{p}_{\Lambda/\bar{\Lambda}}|}$$



Outlook



Year	2022	2024
$\sqrt{s}$ (GeV)	508	200
L_{int} (pb^{-1})	432	164
Polarization	51%	55%



- Important detector upgrade in the last few years;
- Large data sample from 2022 and 2024 under analysis.

Summary

- Significant progress towards understanding the internal spin structure of nucleon at STAR:
  - Confirm previous finding of positive gluon polarization inside proton;
  - New insights into transversity, Sivers and Collins effect in pp collisions;
- RHIC has conclude its polarized pp and heavy ion collisions:
  - Unique transverse spin physics program with recent upgrades is ongoing;
  - More results are on the way!!!

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Thank You!