STAR实验核子自旋结构新进展

Recent Highlights from the STAR Nucleon Spin Measurements

林挺
山东大学

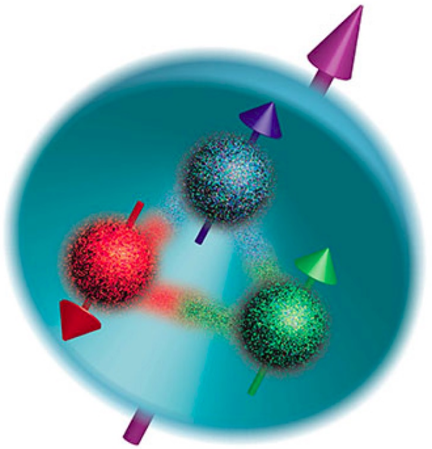
STAR

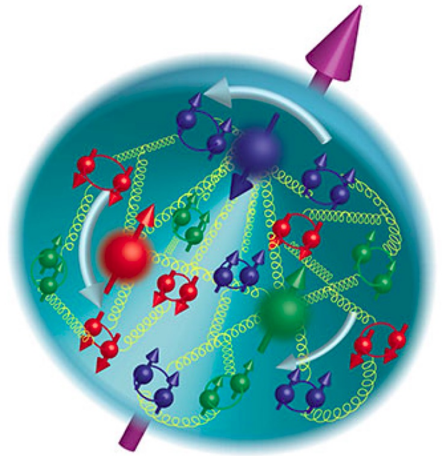
SHANDONG UNIVERSITY

Outline

- Introduction and Motivation
- Longitudinal spin structure: gluon polarization
- Transverse spin structure: TMDs and visualizing color interactions

Fundamental questions regarding proton spin



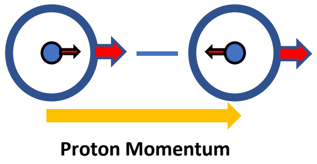


- How do quarks and gluons conspire to provide the proton's spin ½ ?
  - What is the role of gluons and sea quarks?
  - What is the size of the orbital angular momentum?
- What do transverse-spin phenomena teach us about proton structure?
  - How do we go beyond longitudinal parton distribution functions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

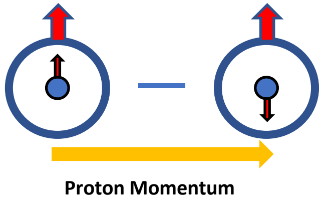
Nucleon Structure

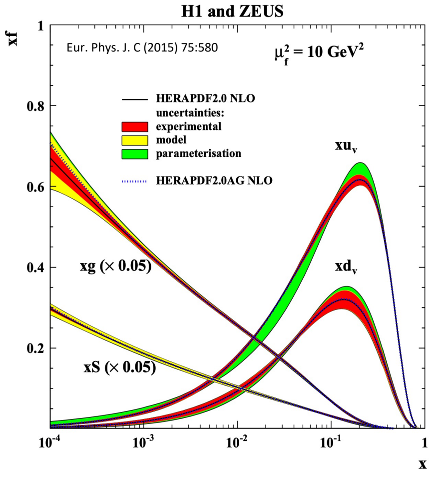
A complete understanding of nucleon structure requires knowledge of

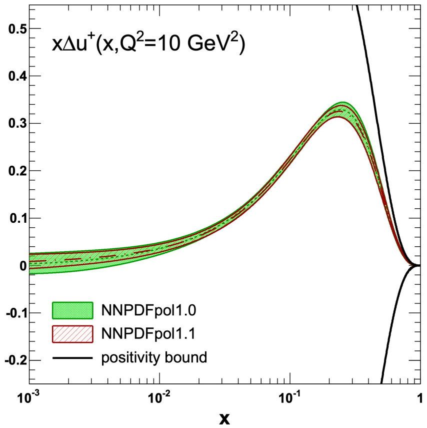
- Unpolarized PDF, $f(x)$;
  - Number density of partons inside proton;
- Helicity PDF, $\Delta f(x)$;
  - Number density of partons with the same spin direction as spin of proton minus the opposite one;

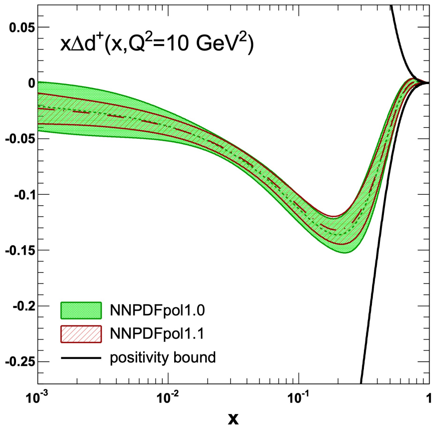


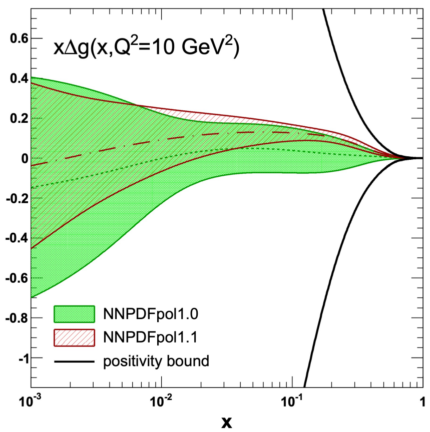
- Transversity, $h_1(x)$;
  - Transverse polarization of quarks in a transversely polarized proton.

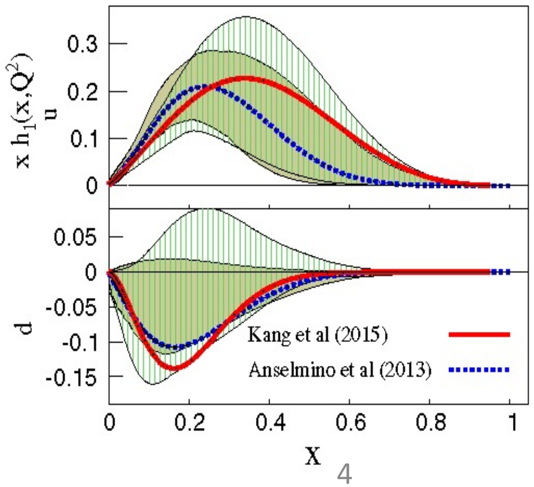




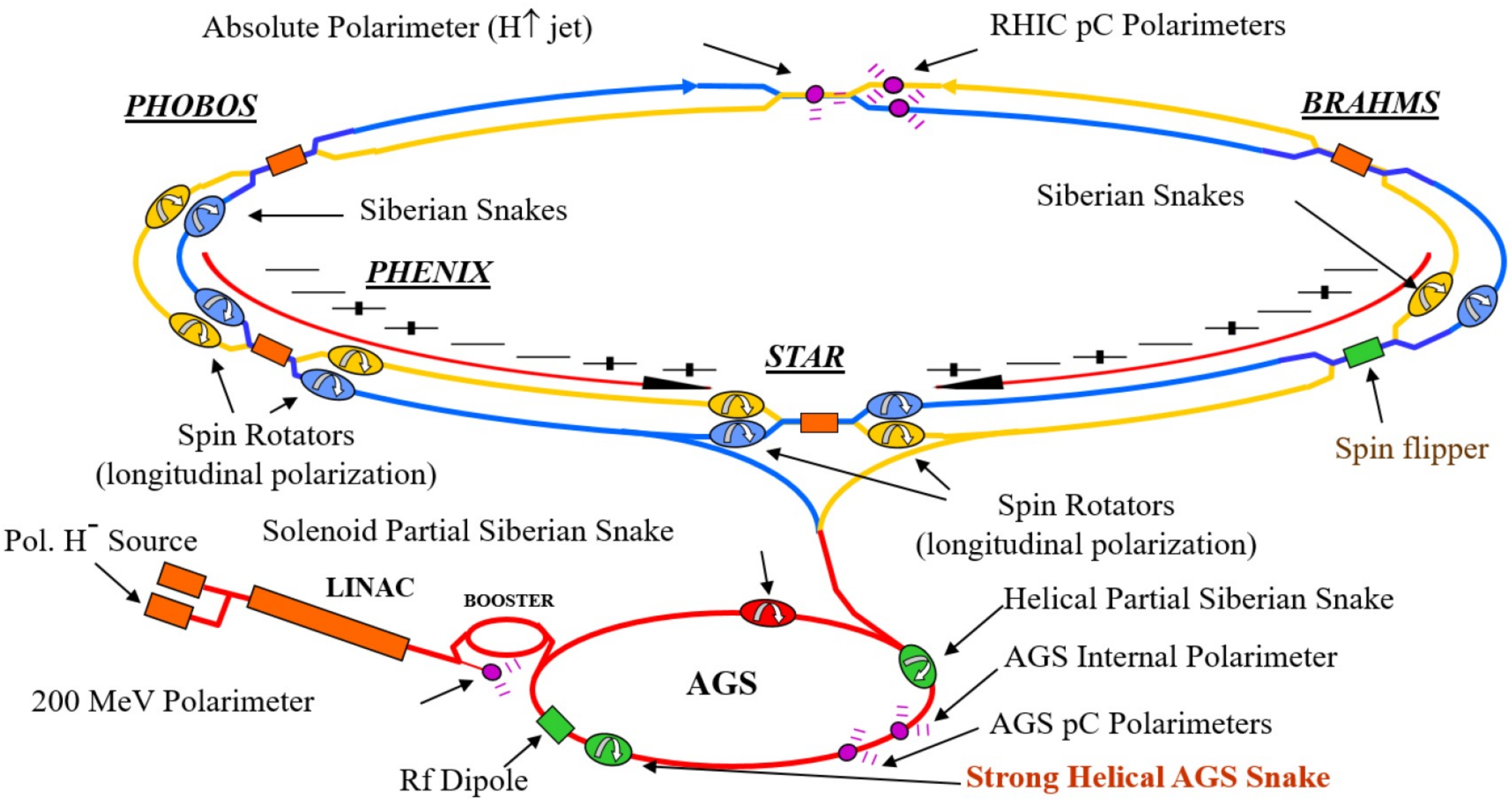




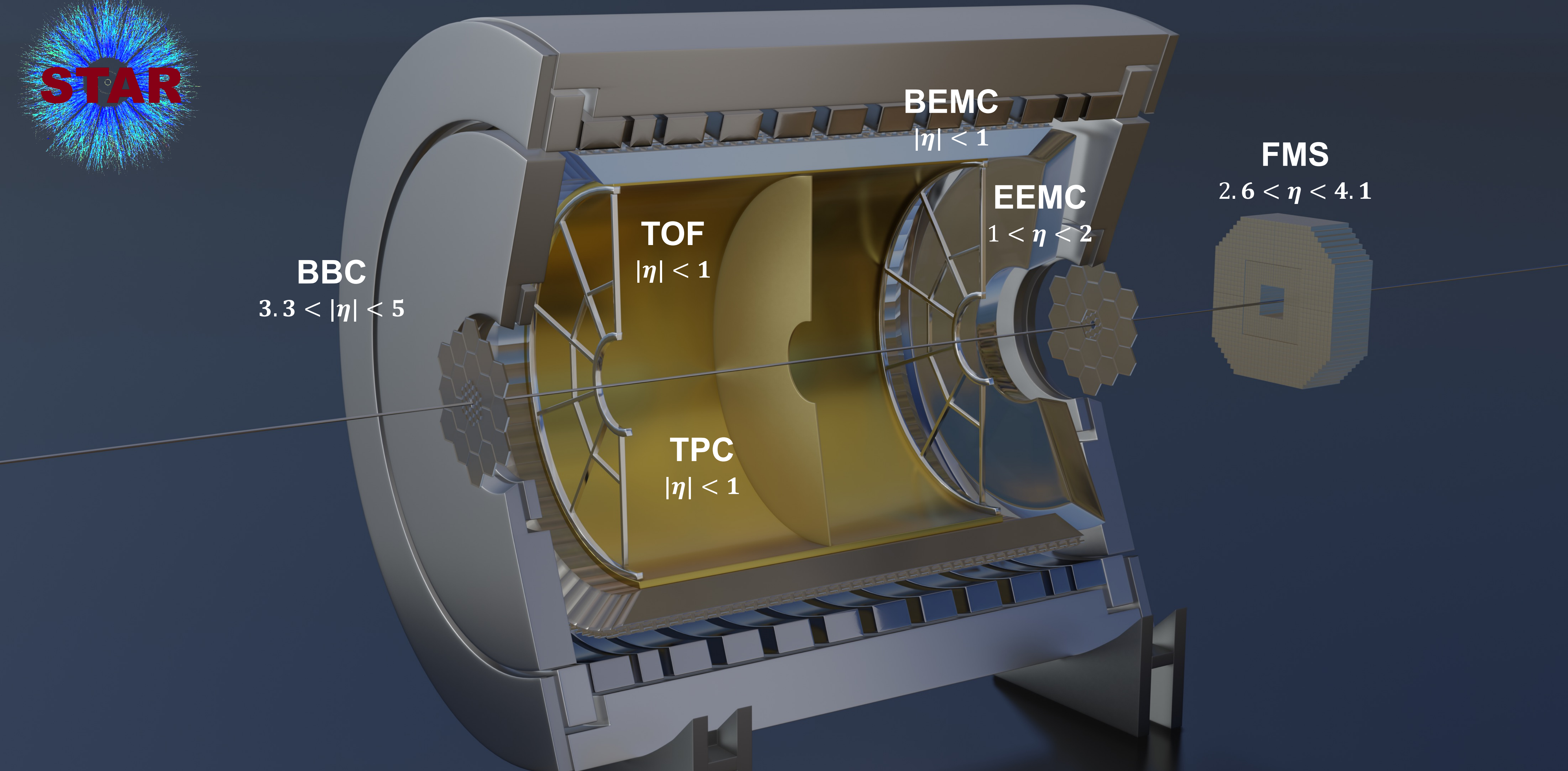




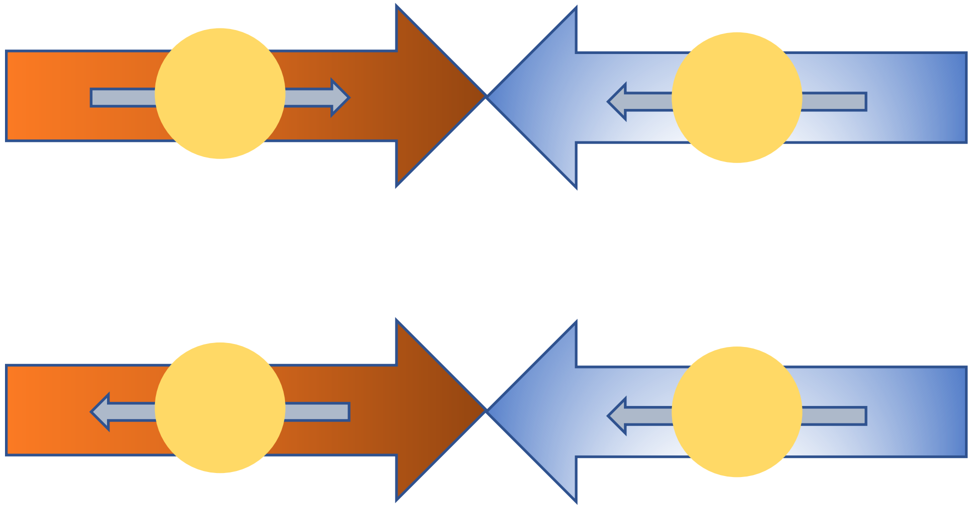
Relativistic Heavy Ion Collider (RHIC)



- World's first and only polarized proton+proton collider;
- Provide polarized proton+proton collisions up to 510 GeV.

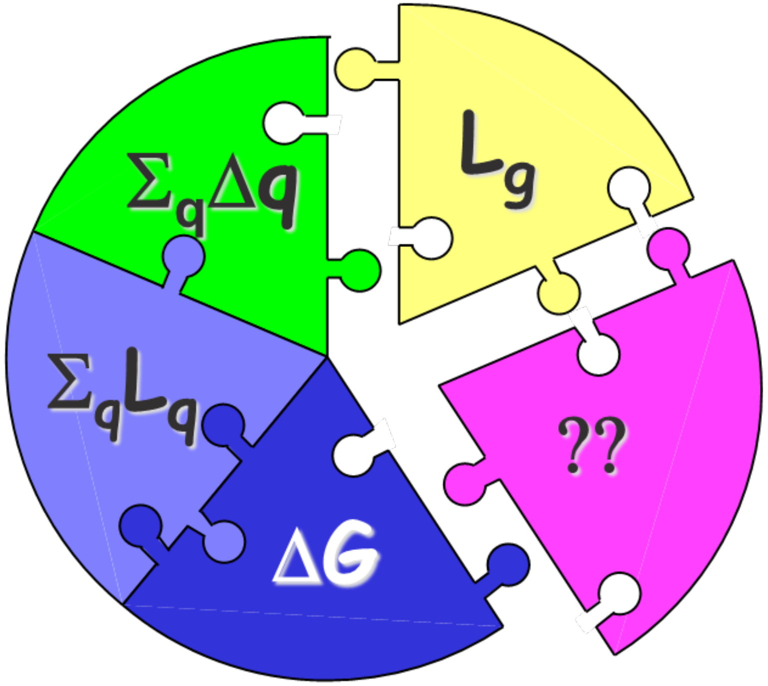


The Solenoidal Tracker At RHIC (STAR)



Longitudinal Spin Structure

Spin of the Proton

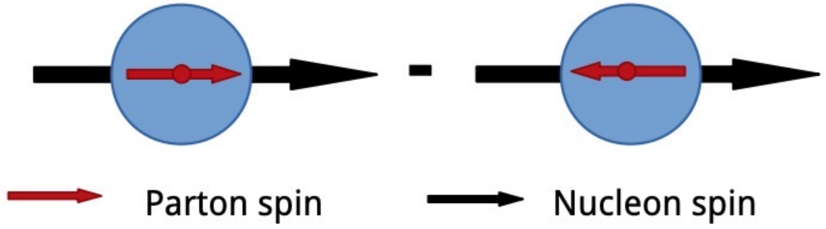


$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- The proton's spin arises from combination of intrinsic and orbital angular momenta of these components;
- Polarized DIS data gives $\Delta\Sigma \approx 30\%$;
- Scaling violations of structure functions in polarized DIS gives information on gluon polarization but limited kinematic coverage leaves ΔG poorly constrained.

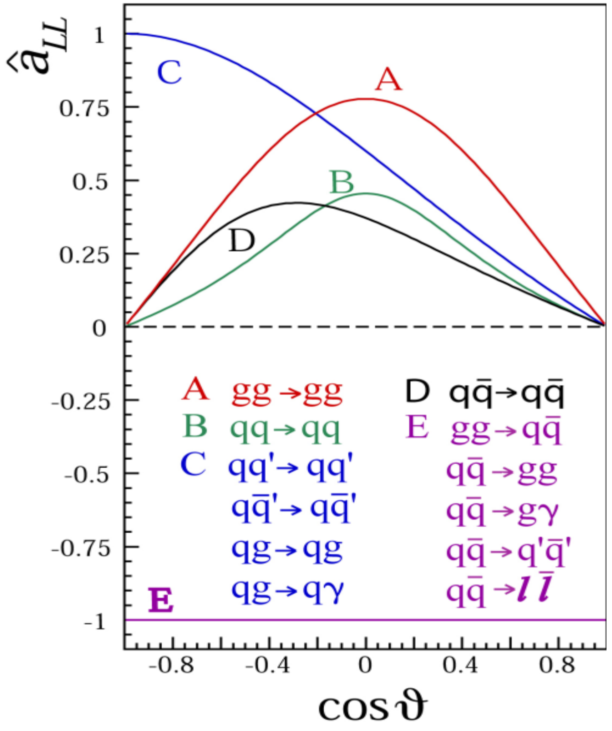
$$\Delta\Sigma = \int \left(\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}\right) dx$$

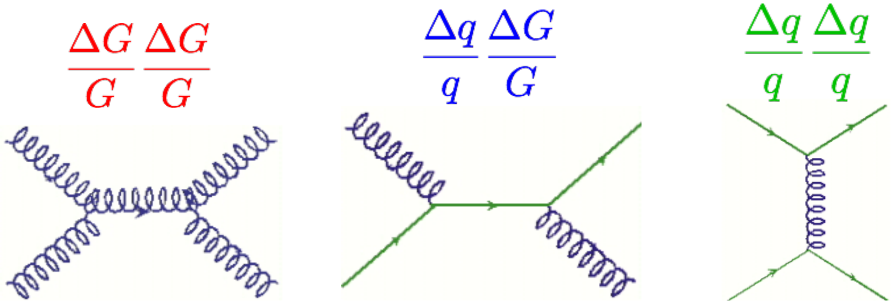
$$\Delta G = \int \Delta g(x) dx$$

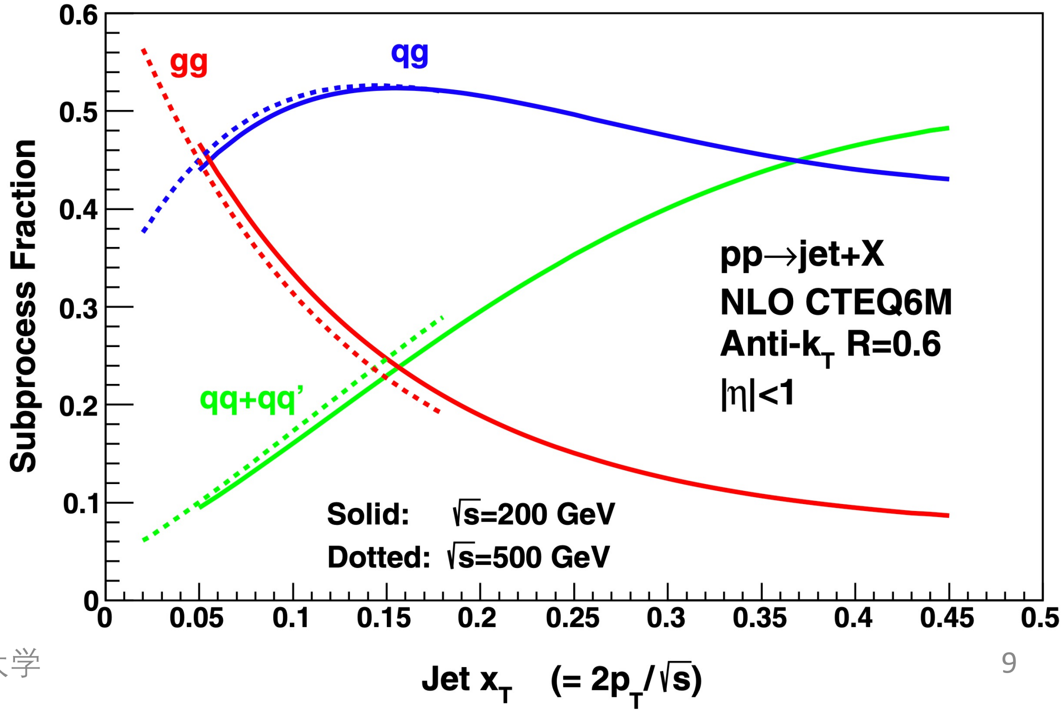


Exploring Gluon Polarization at RHIC

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



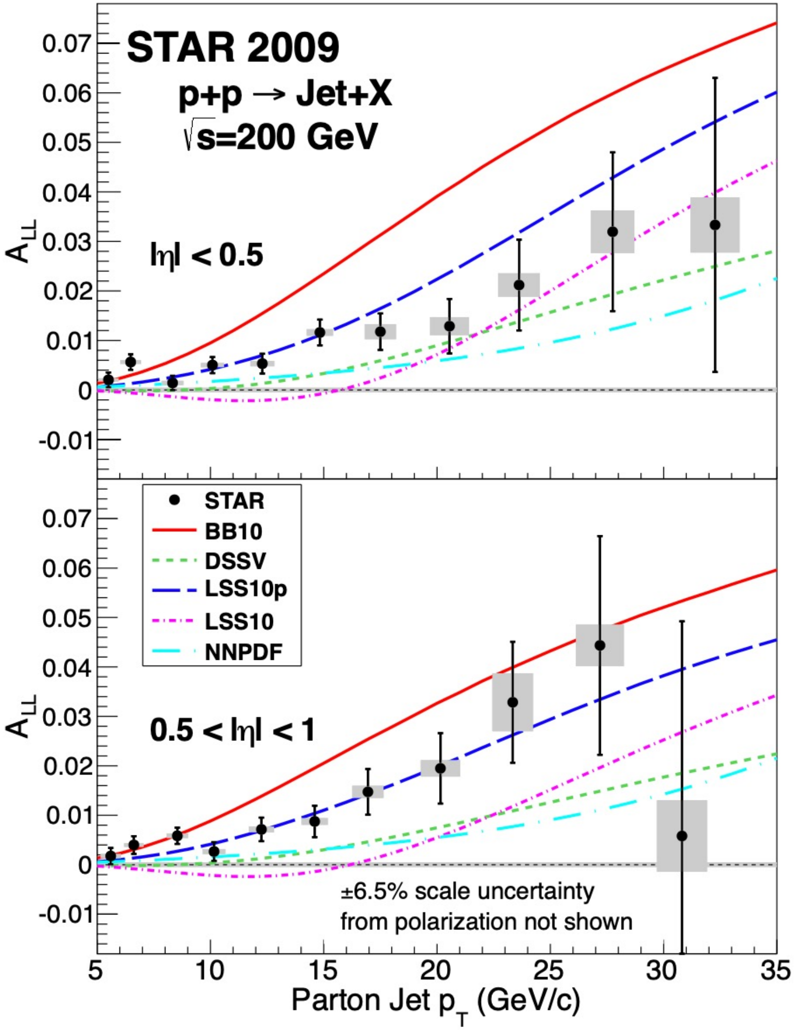




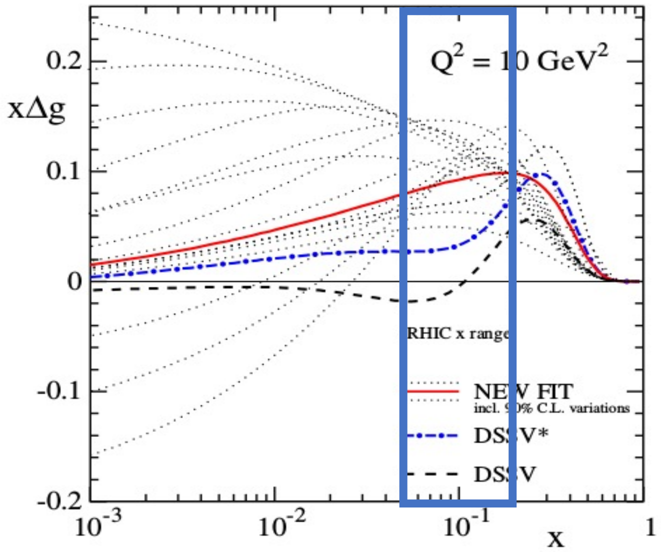
- At the parton level, helicity correlations are very large in leading-order QCD
- For most RHIC kinematics, gg and qg dominate, making A_{LL} for jets sensitive to gluon polarization.

Evidence of positive ΔG

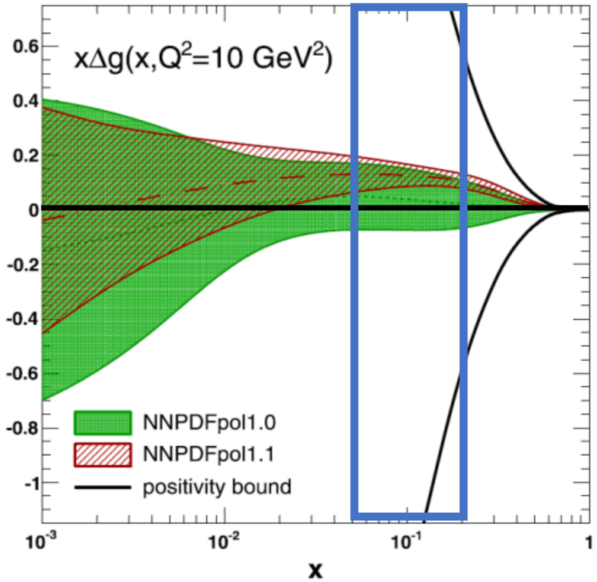
STAR, PRL **115**, 092002 (2015)



DSSV, PRL 113, 012001(2014)



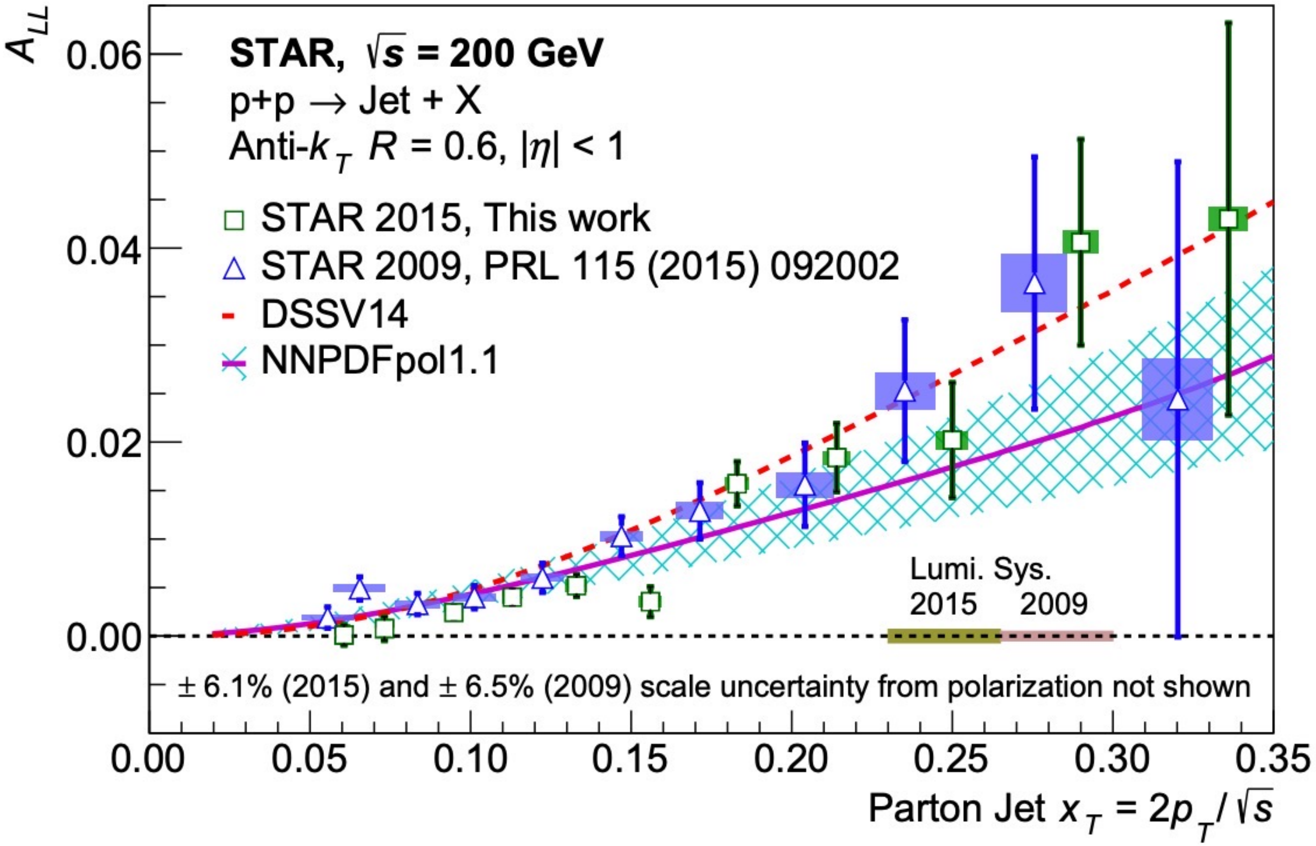
NNPDF, Nucl. Phys. B 887, 276 (2014)



- Both DSSV and NNPDF have performed new polarized PDF fits;
- Both find the **2009 RHIC results provide significantly tighter constraints on gluon polarization;**
- Both find **evidence for positive gluon polarization** in the region $x > 0.05$:
  - New NNPDF: 0.23 ± 0.06
  - New DSSV: $0.20^{+0.06}_{-0.07}$

New Inclusive jet A_{LL} at 200 GeV

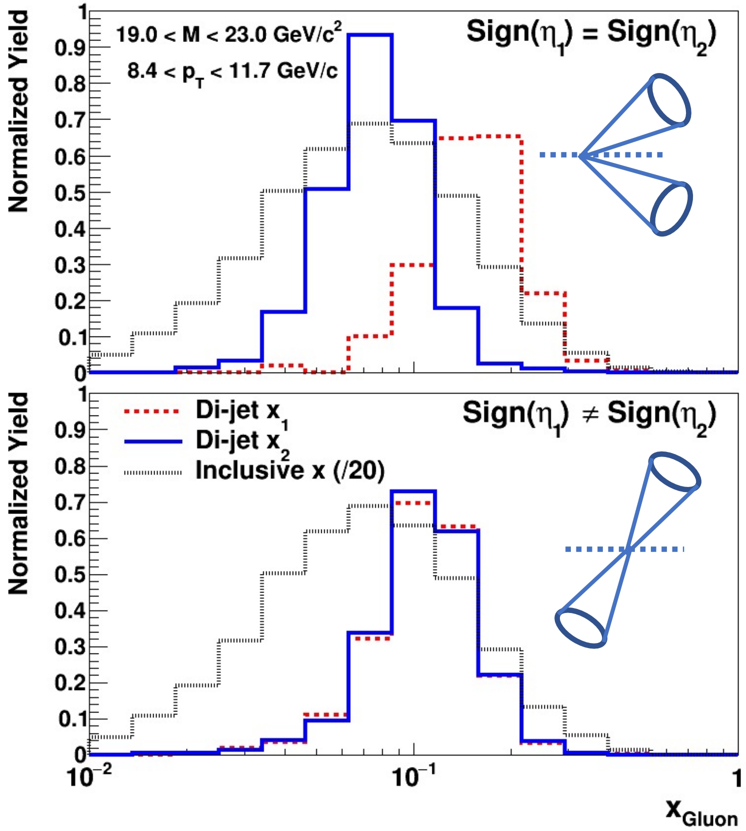
STAR, PRD 103 (2021) L091103

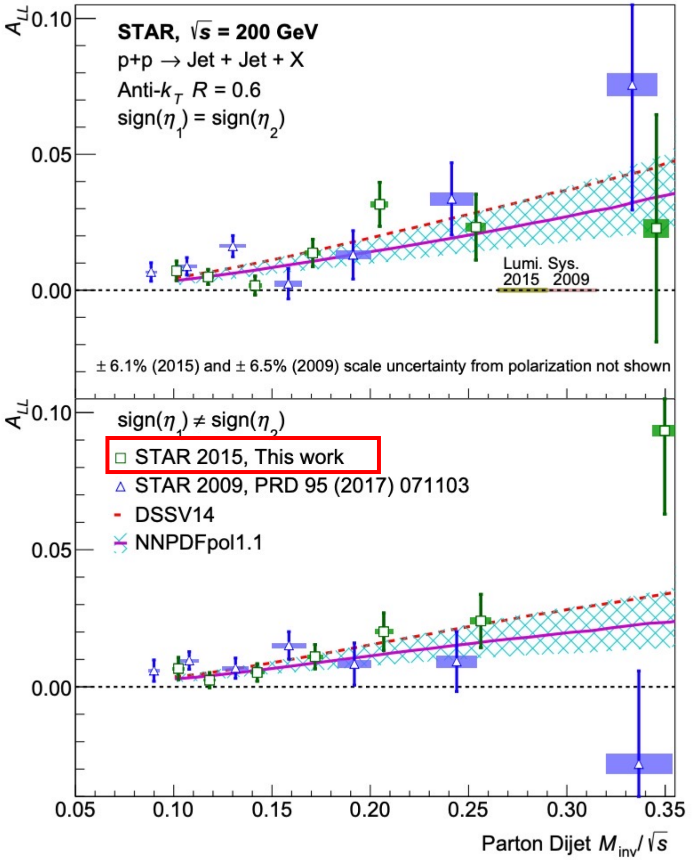


- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05;
- Improved statistical and systematics uncertainties;
- Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits.

Dijet A_{LL} at 200 GeV

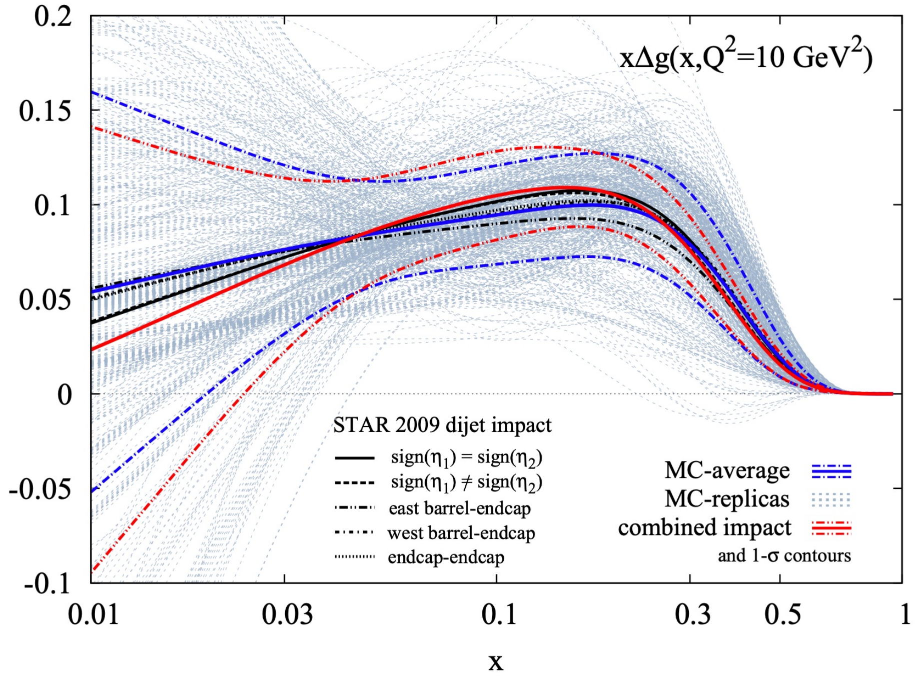
STAR, PRD 103 (2021) L091103



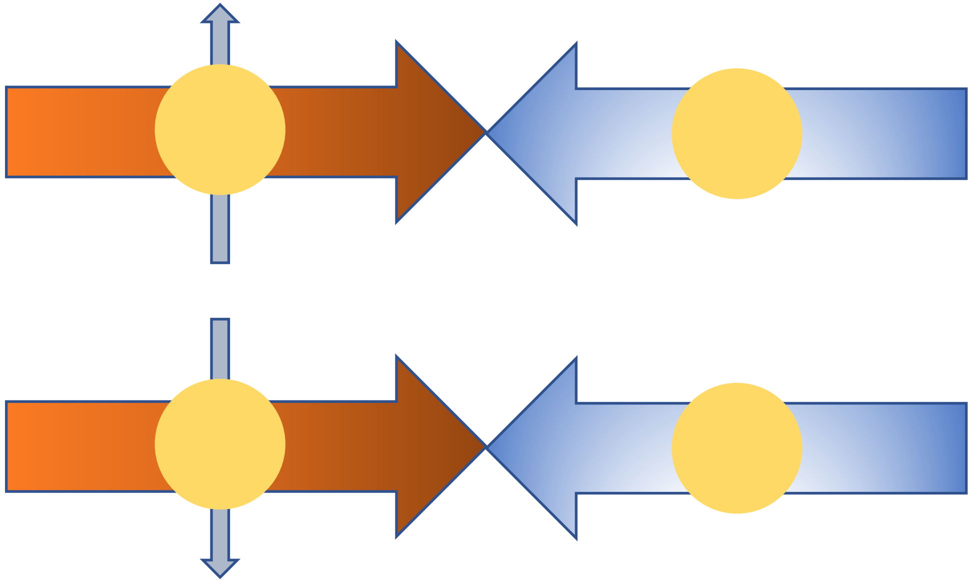


Impact of 2009 di-jet data:
STAR, PRD 95 (2017) 071103
STAR, PRD 98 (2018) 032011

DSSV, Phys. Rev. D 100, 114027 (2019)

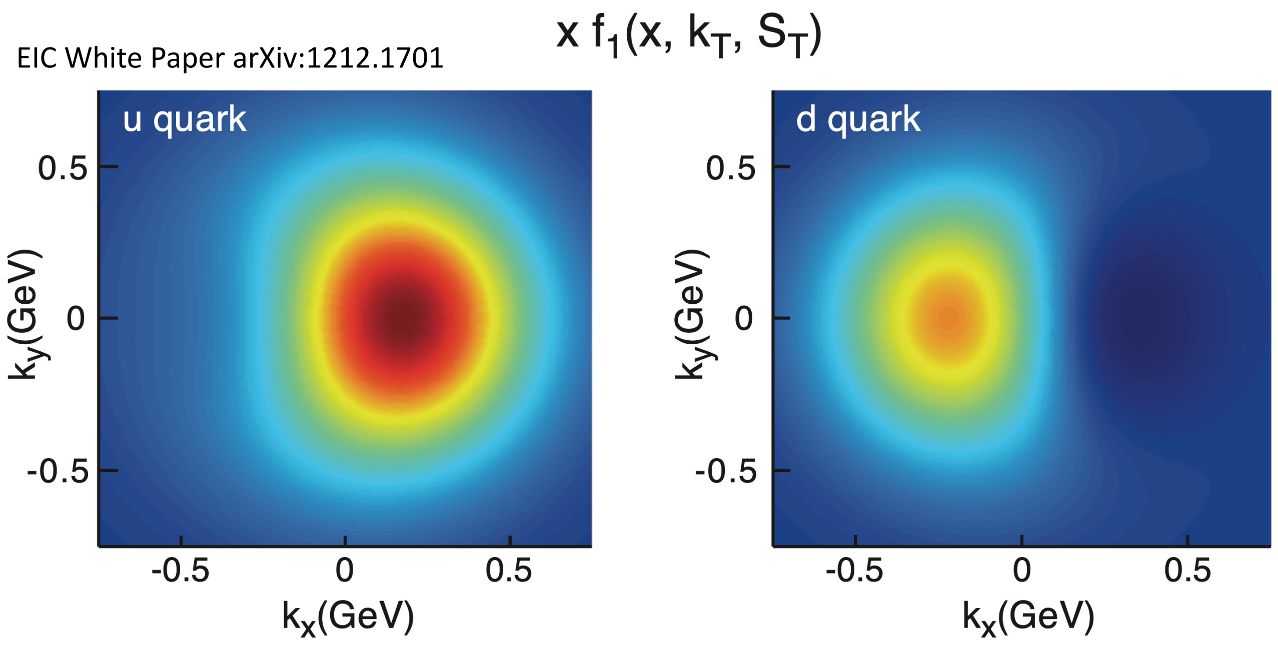


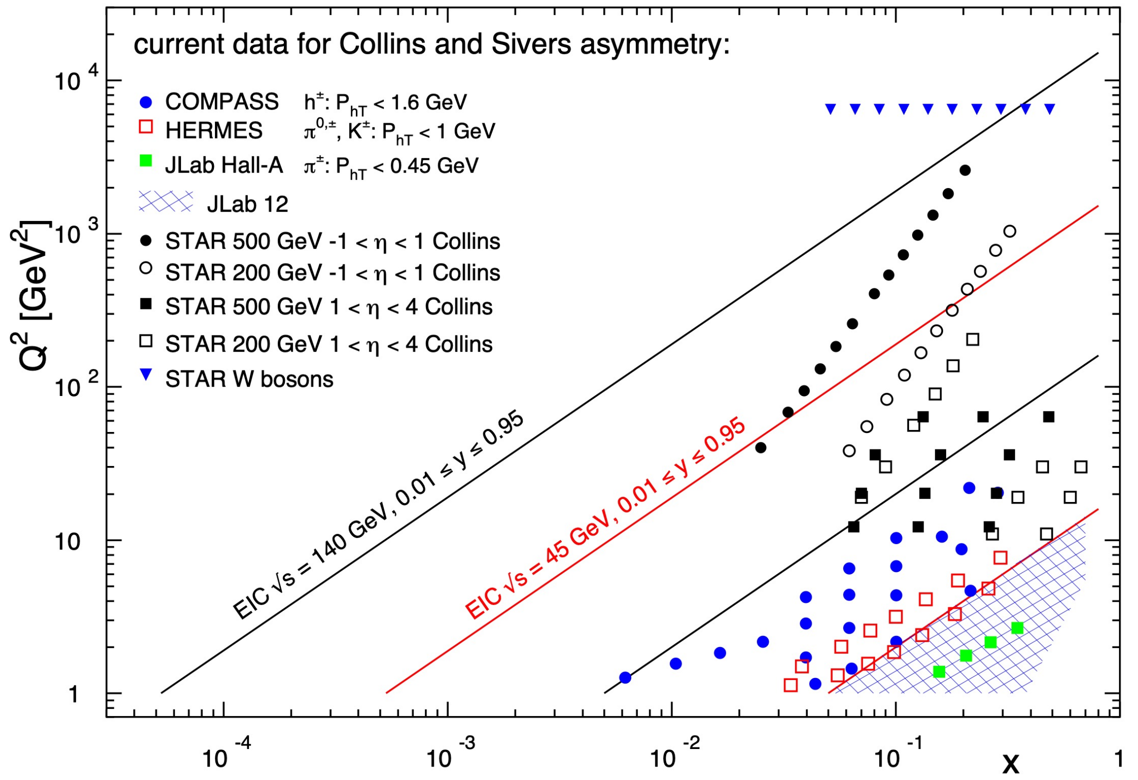
- Di-jets: probe narrower ranges of partonic momentum fraction;
- Gluon polarization in the region $x > 0.1$:
  - before: 0.133 ± 0.035;
  - after reweighting: 0.126 ± 0.023



Transverse Spin Structure

Nucleon Tomography



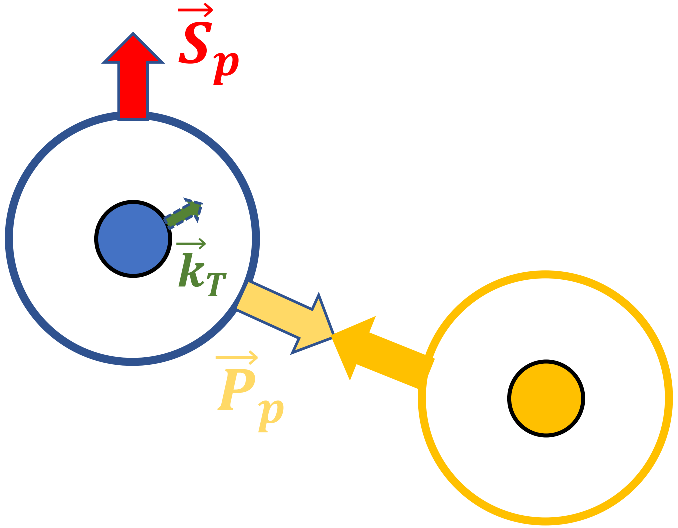


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

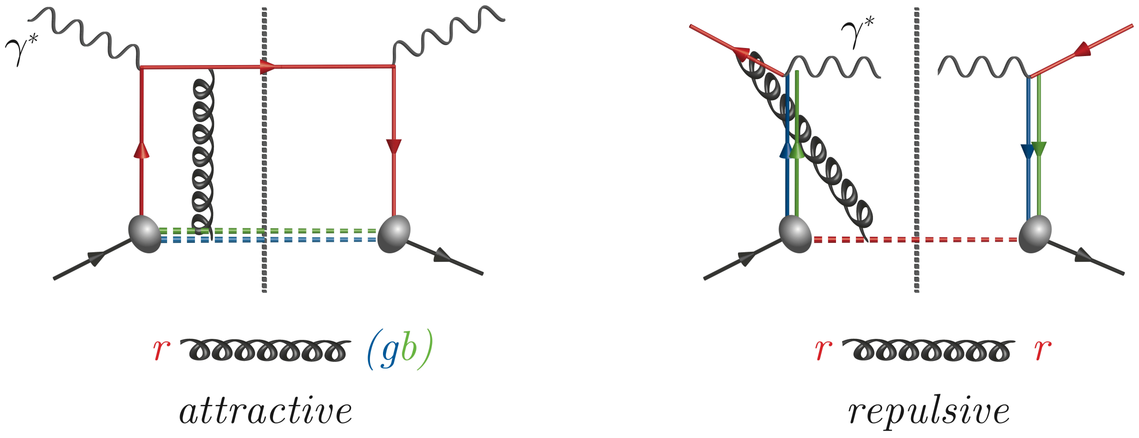
- Before STAR, TMDs came only from fixed target e+p;
  - high x @ low Q^2;
- RHIC provide unique kinematics for wide x at high Q^2;
  - Evolution, factorization and universality of TMDs.

Sivers Effect

- It encapsulates the correlations of initial-state parton transverse momentum with proton's spin and momentum;
  - $f_{q/p^{\uparrow}}(x,k_T) = f_{q/p}\,(x,k_T) - \frac{1}{M} f_{1T}^{\perp q}(x,k_T)\vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T)$
  - Non-universality exhibits the process dependence, attractive color force in SIDIS turns into repulsive force in p+p.

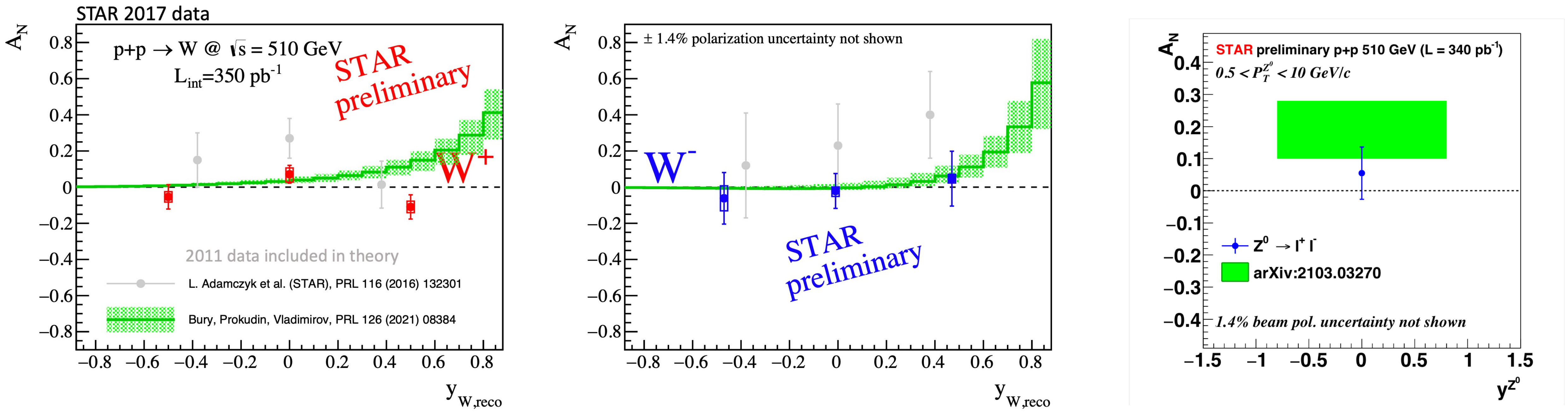


$$f_{1T}^{\perp q}(x,k_T)|_{SIDIS} = -f_{1T}^{\perp q}(x,k_T)|_{DY}$$



- $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \frac{\sum_{a,b} f_{1T}^{\perp a}(x_a,k_T^a)\, f_b(x_b,k_T^b)\,\sigma_{ab}^{\text{pol}}}{\sum_{a,b} f_a(x_a,k_T^a)\, f_b(x_b,k_T^b)\,\sigma_{ab}^{\text{unpol}}}$

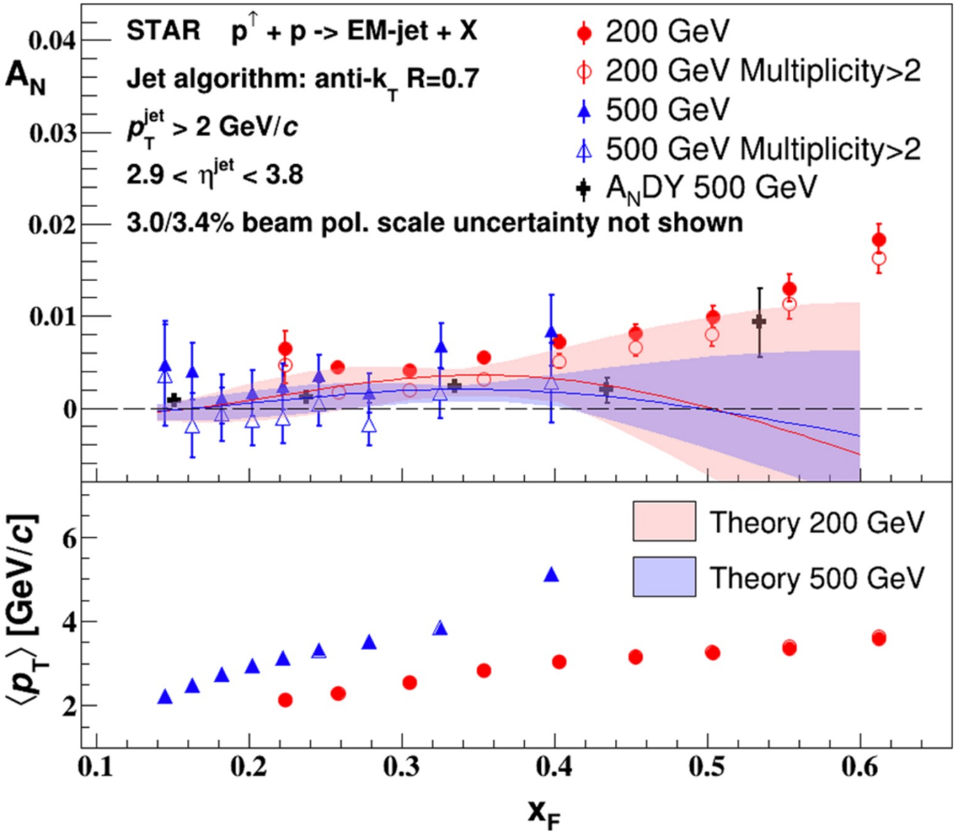
A_N for $W^{\pm}$ and Z



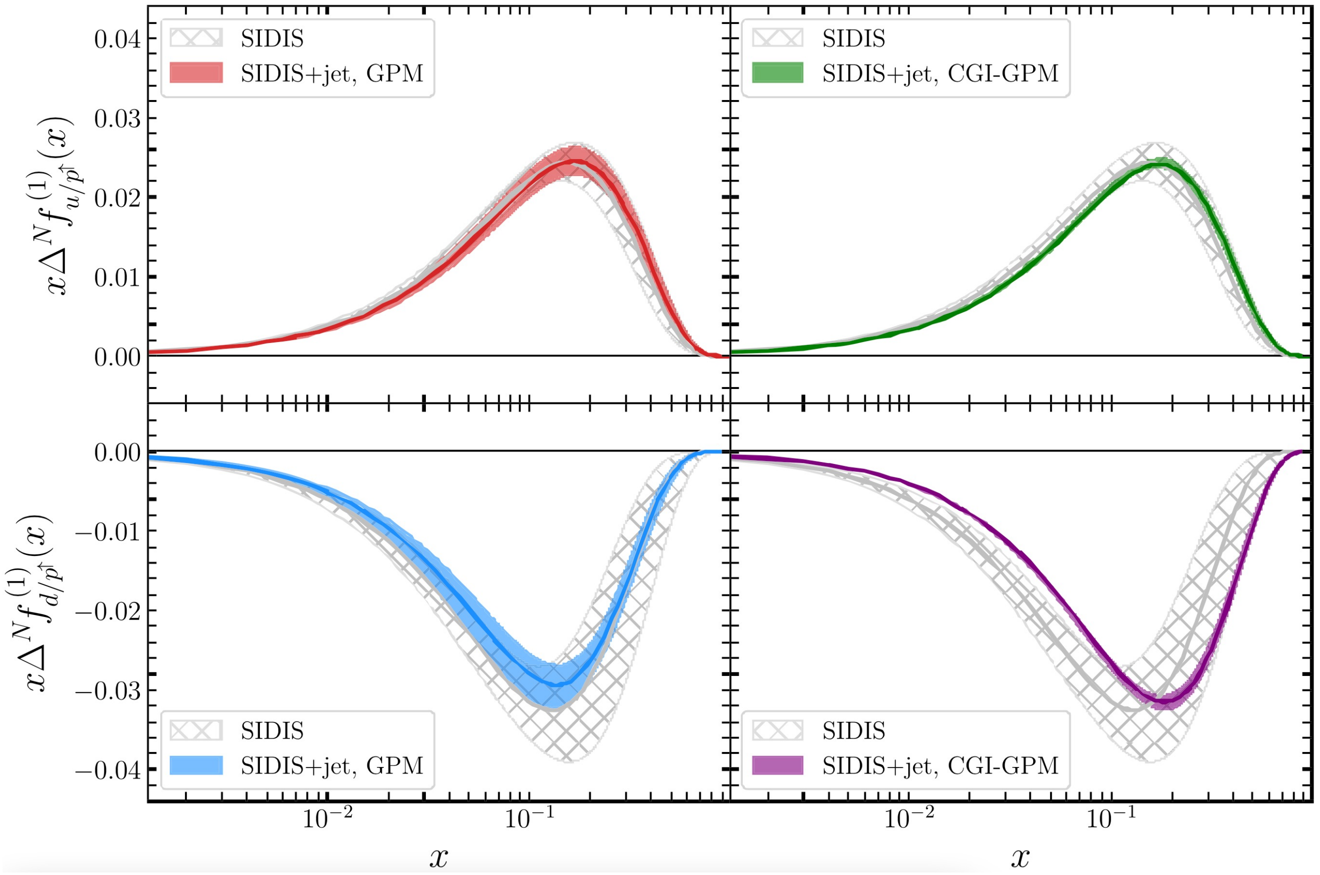
- Improved uncertainties from run 2017 preliminary results;
- Bury, Prokudin, and Vladimirov PRL 126, 08384 (2021) – extraction includes SIDIS, DY and 2011 STAR data with N^3LO and NNLO accuracy of the TMD evolution assuming sign-change.

A_N for Forward Jet

STAR, Phys. Rev. D 103, 092009 (2021)

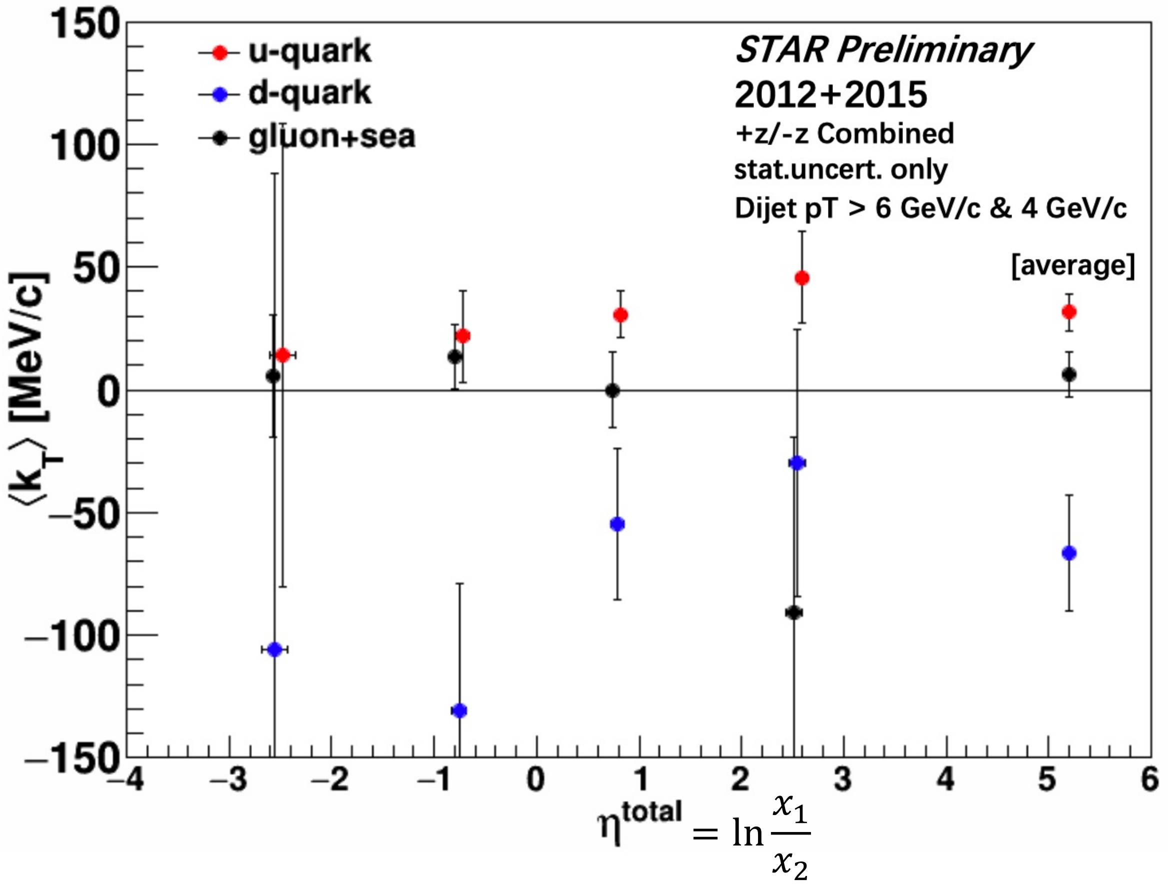


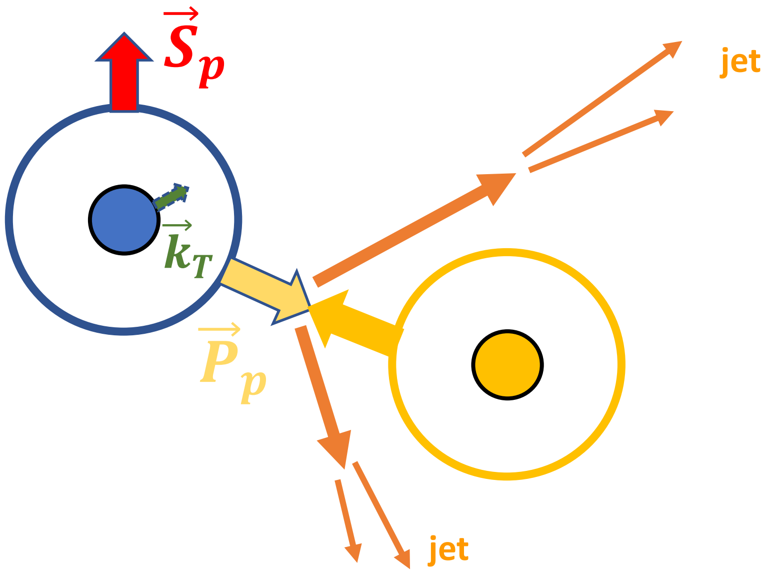
M.Boglione et.al., PLB 815, 136135 (2021)

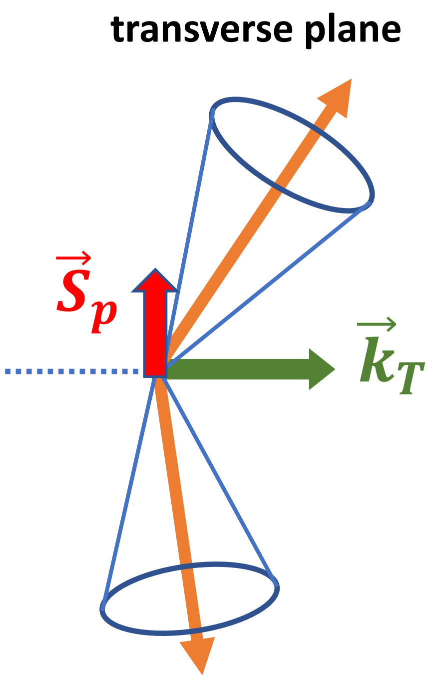


- Inclusive jet A_N is sensitive to the Sivers function via the twist-3 correlators;
- This result significantly reduces the uncertainty of the quark Sivers function extracted from SIDIS at x > 0.2.

Sivers Effect from Dijet Measurement



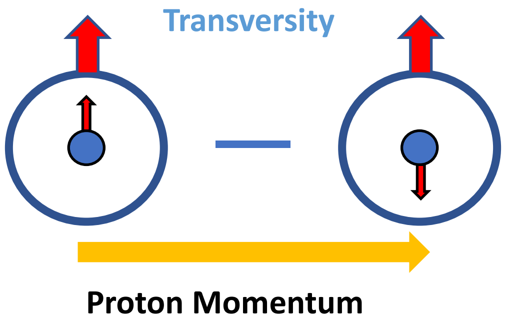


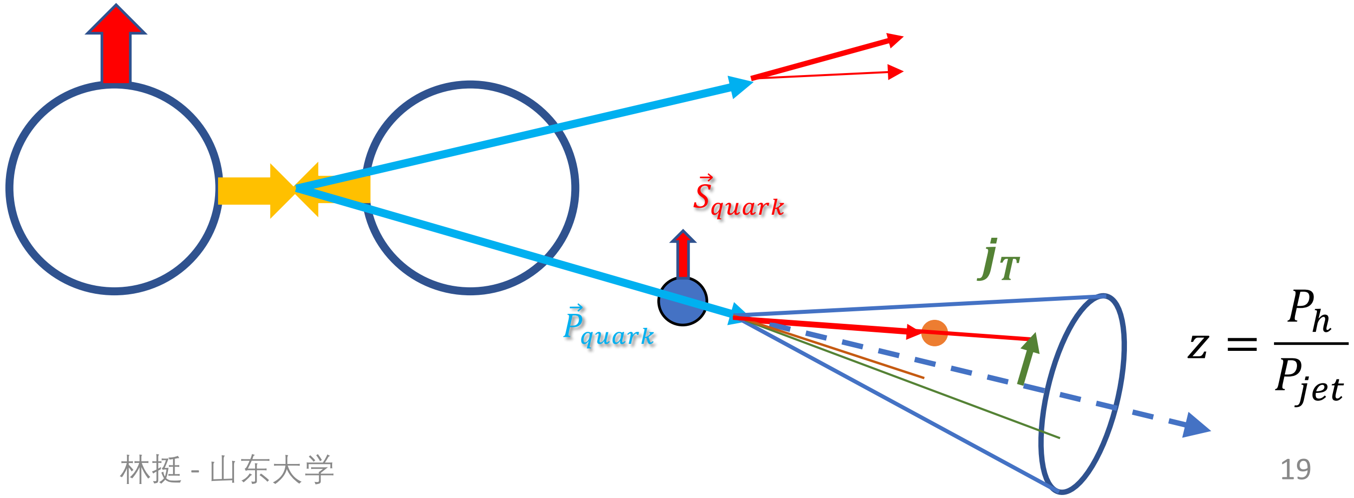


- First observation of non-zero Sivers asymmetries in dijet production in polarized p+p collisions;
- $\langle k_T^u \rangle$ ≈ 31 MeV/c, $\langle k_T^d \rangle$ ≈ -55 MeV/c, $\langle k_T^{g+sea} \rangle$ ≈ 0 MeV/c.

Collins Effect

- Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction;
  - Collins effect combines the quark transversity in the proton with the spin-dependent Collins fragmentation function;
  - $D_{h/q,S_q}(z,\boldsymbol{j_T}) = D_{h/q}(z,\boldsymbol{j_T}) + \frac{\mathbf{1}}{zM_h} H_1^{\perp q}(z,\boldsymbol{j_T})\vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T);$



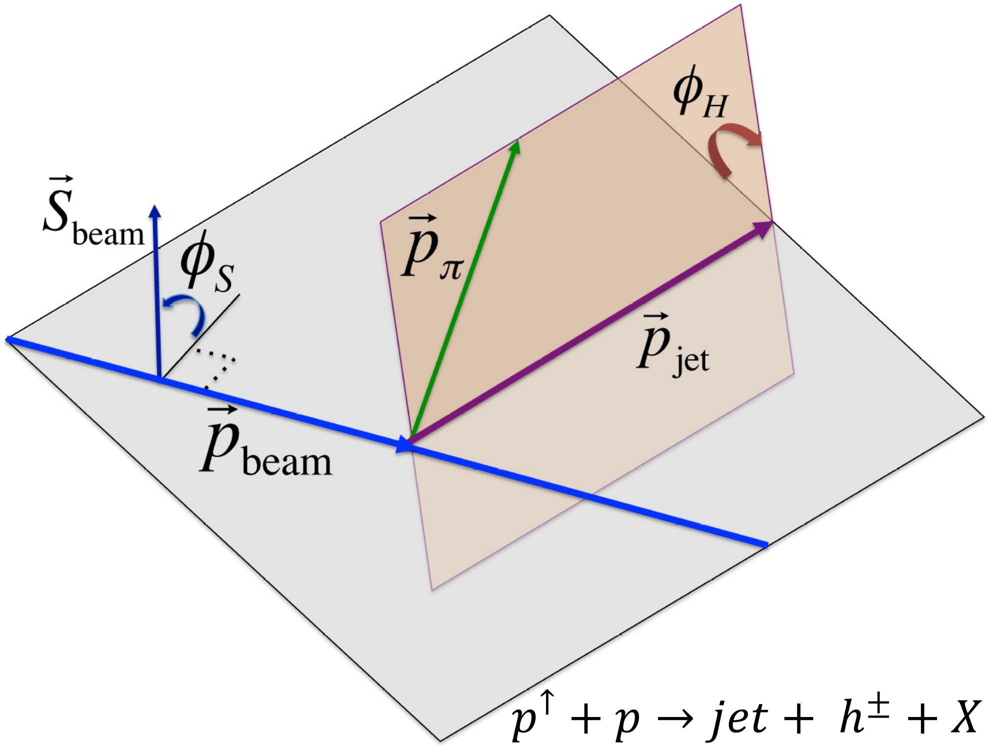


Transverse Single-Spin Asymmetry

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)} \xrightarrow[\phi=\phi_S-\phi_H]{} \frac{\sum_{a,b,c} \boldsymbol{h_1^a(x_1,\mu)}\, f_b(x_2,\mu)\, \sigma_{ab\to c}^{\text{Collins}}\, \boldsymbol{H_{1,h/c}^{\perp}(z_h, j_T; Q)}}{\sum_{a,b,c} f_a(x_1,\mu)\, f_b(x_2,\mu)\, \sigma_{ab\to c}^{\text{unpol}}\, D_{h/c}(z_h, j_T; Q)}$$

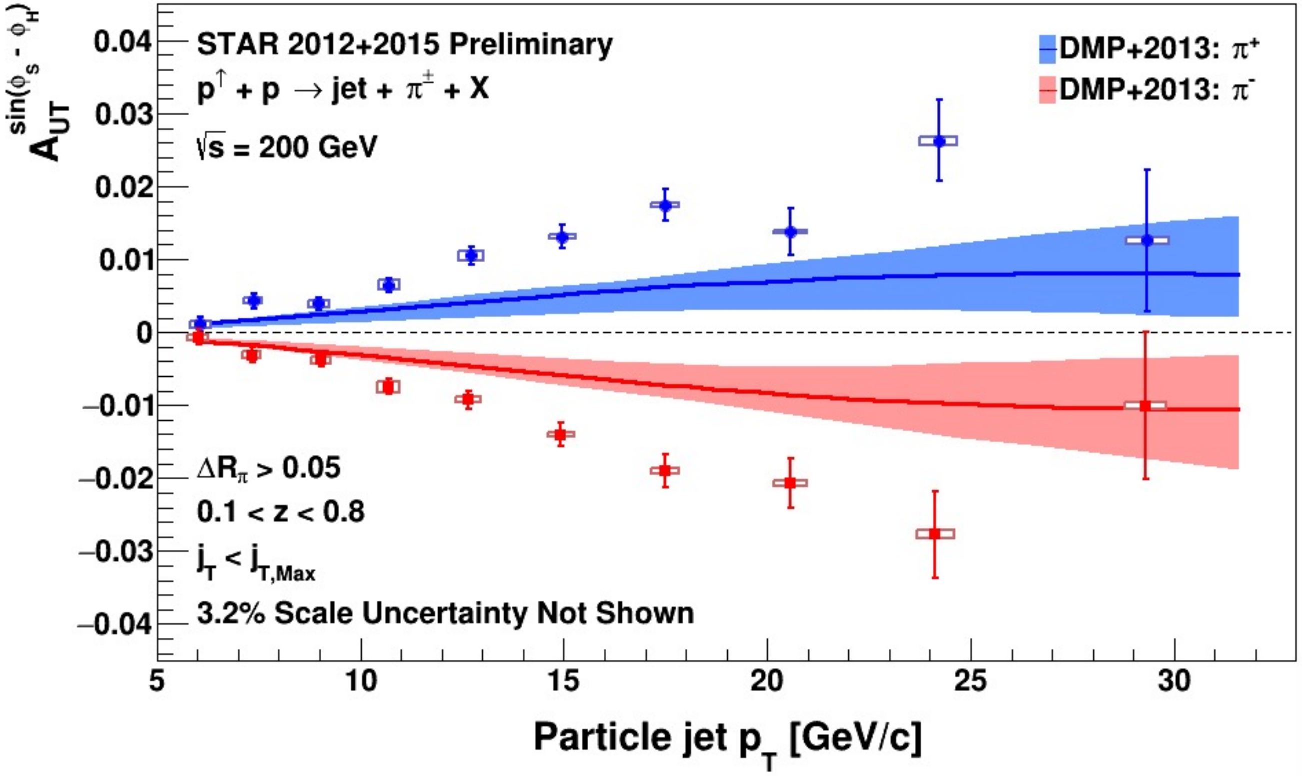
Zhong-Bo Kang *et al.*, JHEP 11, 068 (2017) and PLB 774, 635 (2017)

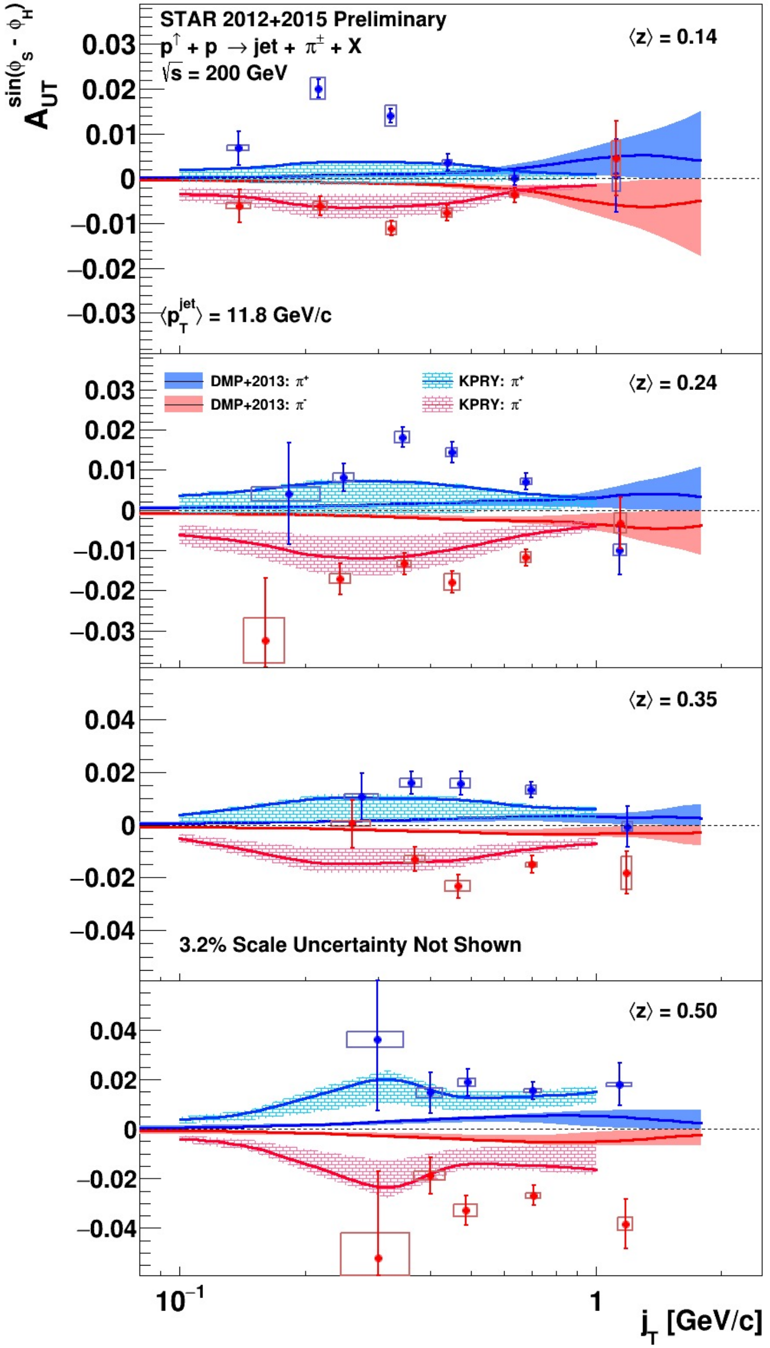
- Collins effect in pp involves a mixture of collinear and TMD factorization:
  - Initial jet production involves the collinear transversity $\boldsymbol{h_1^a}$;
  - Polarized quark then fragments according to the TMD Collins fragmentation function $\boldsymbol{H_{1,h/c}^{\perp}}$;
- Cleaner kinematic separation of transversity and TMD physics than SIDIS, which convolutes the TMD transversity with the Collins FF;
- At EIC, full jet reconstruction will enable similar kinematic separation.



$p^{\uparrow} + p \to jet + h^{\pm} + X$

Collins Asymmetry for $\pi^{\pm}$ in Jets

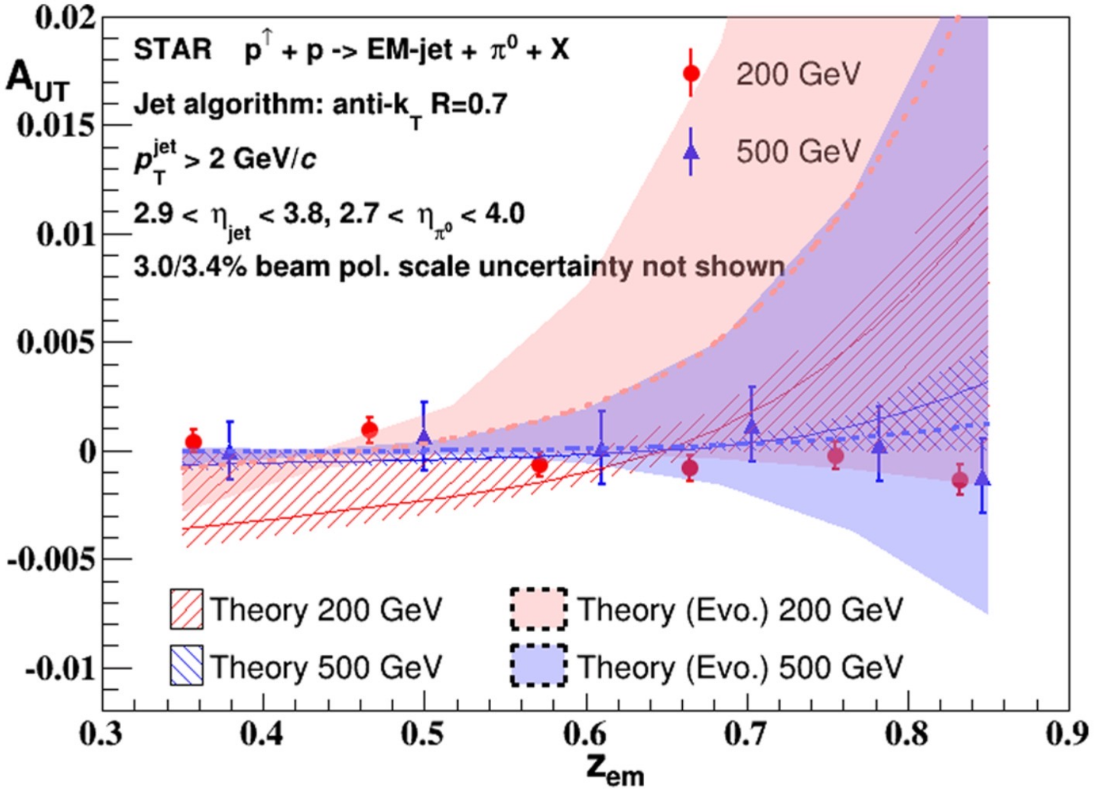


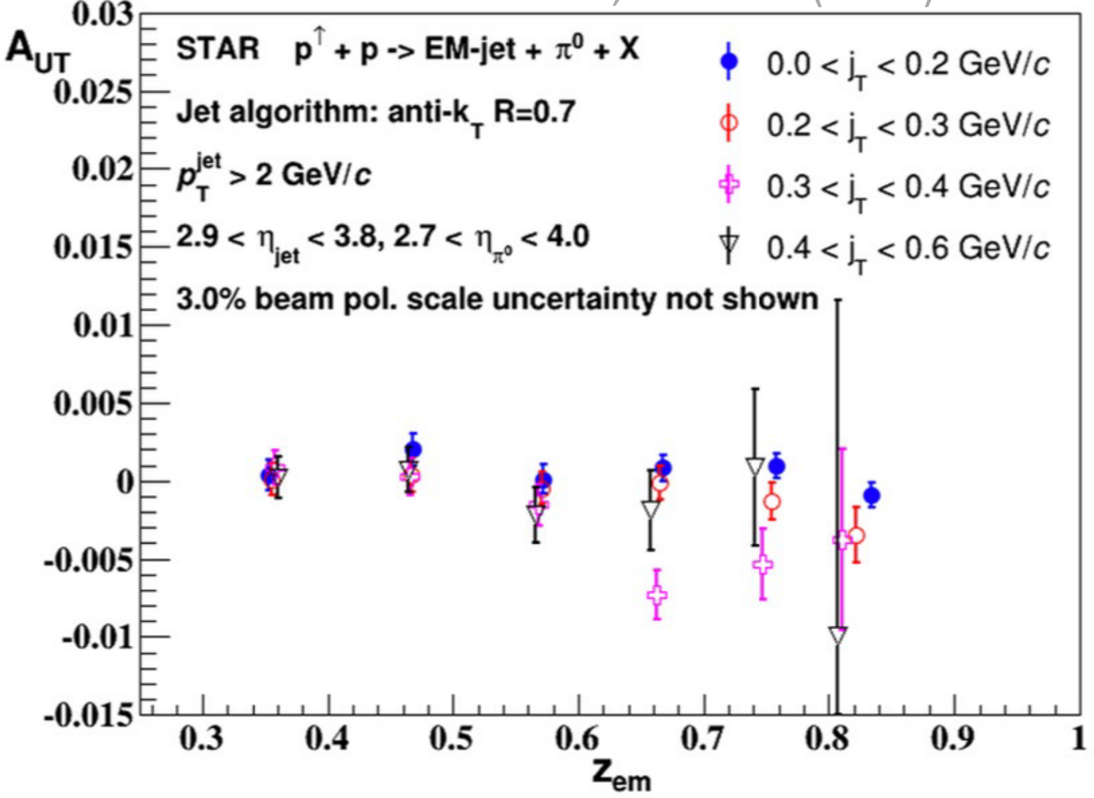


- Significant Collins asymmetries have been observed from 200 GeV measurement:
  - Collinear transversity is probed most directly in the jet p_T dependence;
  - Collins TMD FF is sensitive to the (j_T, z) dependence.

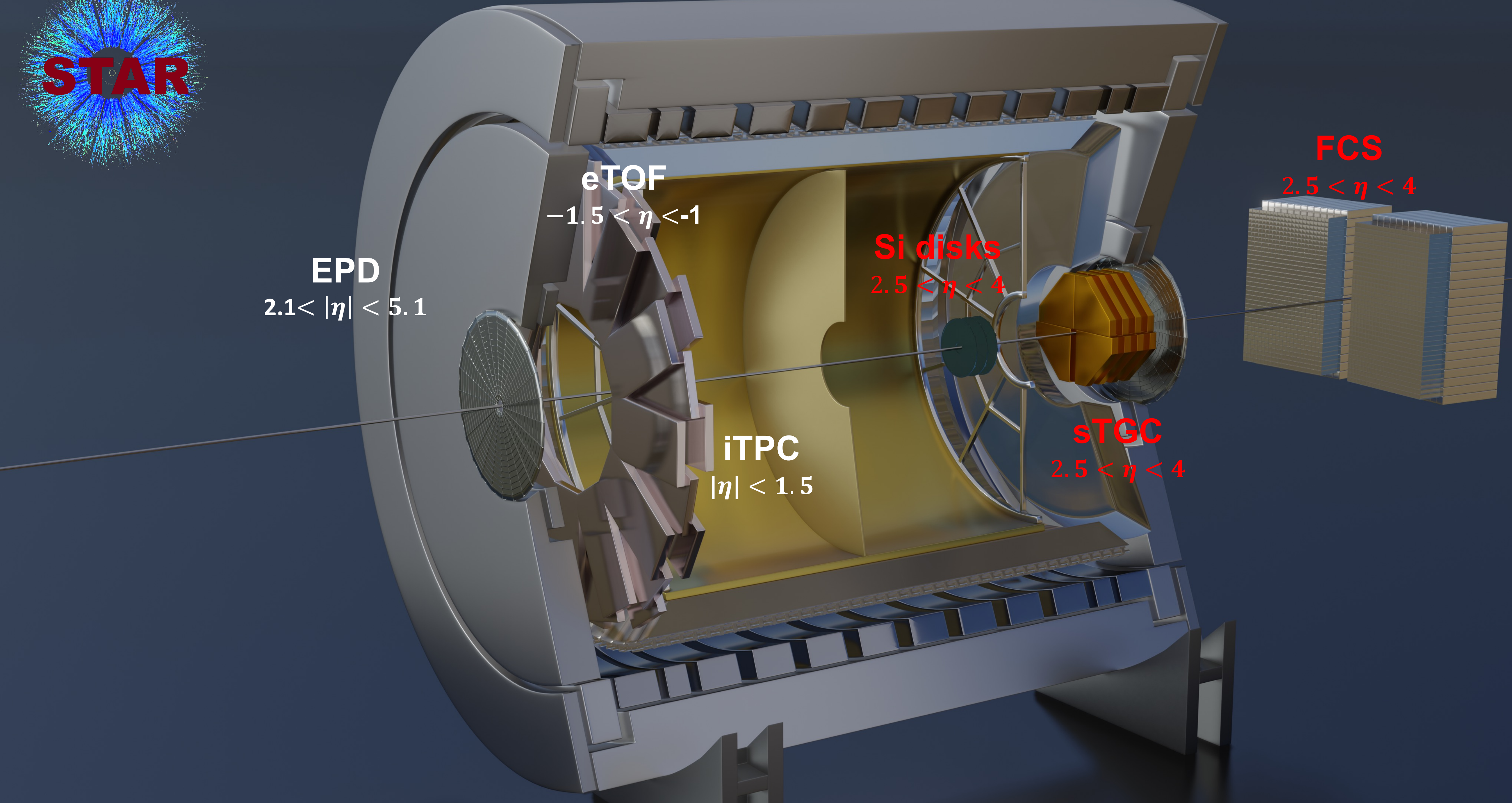
Collins Asymmetry for π^0 in Jets

STAR, PRD 103 (2021) 092009





- Very small Collins asymmetries at both energies;
- Cancellation of the Collins effect of the u/d quark.



STAR Forward Upgrade Ongoing

Cold QCD Physics for 2022+

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:

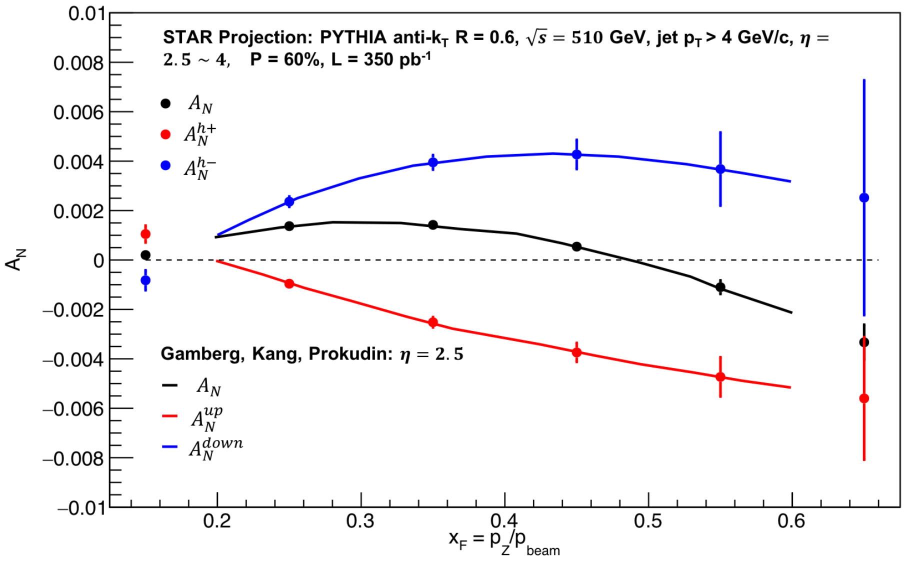
- TMD measurements at high x
  - Transversity, Collins;
  - Sivers through DY and jets
- UPC J/Ψ GPD at forward rapidity;
- Nuclear PDFs and FF:
- R_{pA} for direct photons & DY, and hadrons
- Gluon Saturation through di-hadrons, γ-Jets, di-jets.

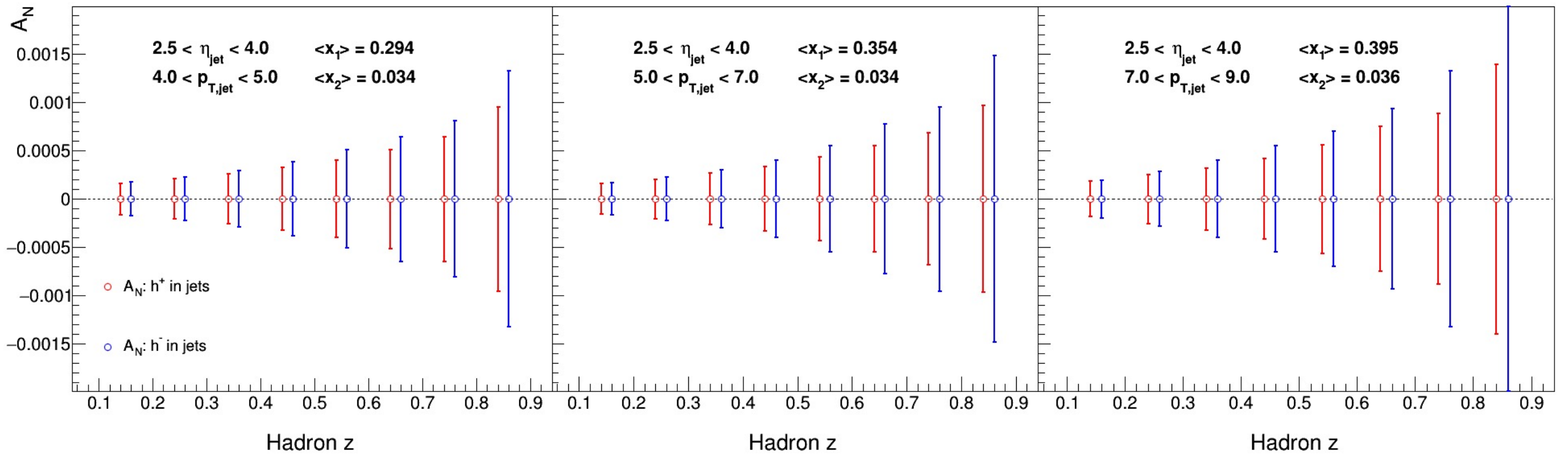
All of these measurements are critical to the scientific success of EIC to test universality and factorization

$\sqrt{s}$ (GeV)	Species	Luminosity	Year
510	$p^{\uparrow}+p^{\uparrow}$	400 pb^{-1}	2022
200	$p^{\uparrow}+p^{\uparrow}$	235 pb^{-1}	2024
200	$p^{\uparrow}+Au$	1.3 pb^{-1}	2024

- STAR forward upgrade will be fully ready for data taking for Run-22;
- STAR has concluded the collection of longitudinally polarized data, Run-22 and Run-24 will be transverse spin experiments;
- Kinematic coverage for 200 and 500 GeV p+p at STAR is 0.005<x<0.5 with forward upgrades;
- Provides best overlap with the x-Q^2 coverage of EIC.

Sivers and Collins Asymmetries at Forward Rapidity





- STAR Forward Upgrade provides full jet reconstruction;
- FST+sTGC provide very good charge identification capability at forward rapidity;
  - For Sivers: Enhancement of the u/d quarks for positively/negatively charged leading hadrons at forward rapidity;
  - For Collins: Expect dilution of ~26% from p+K in h^+, while h^- will have a purity of 78%.

Conclusion

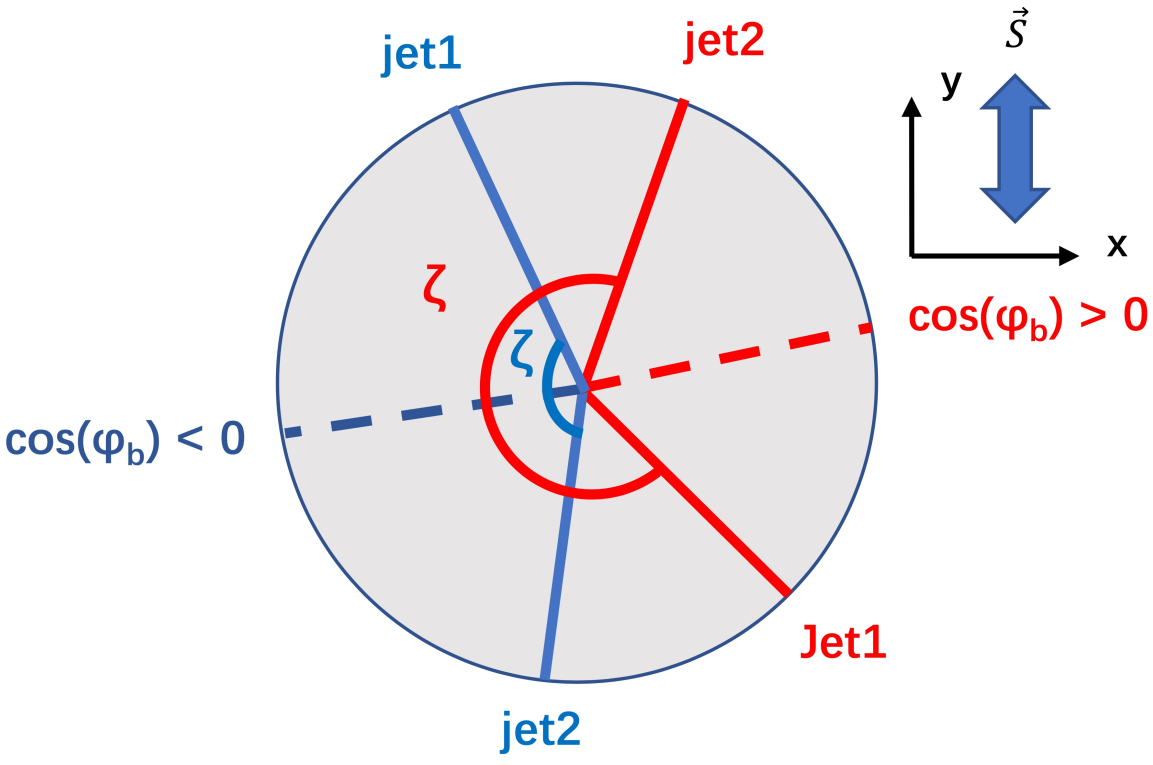
- STAR has concluded the longitudinal polarized data taking;
  - Some remaining papers to finish;
- Many new impactful results from transverse spin measurements;
  - Impact on TMD extraction has become available;
- The Forward Upgrades will be fully ready before 2022;
  - Unique forward and midrapidity physics with the existing and ongoing detector upgrades.

Back Up

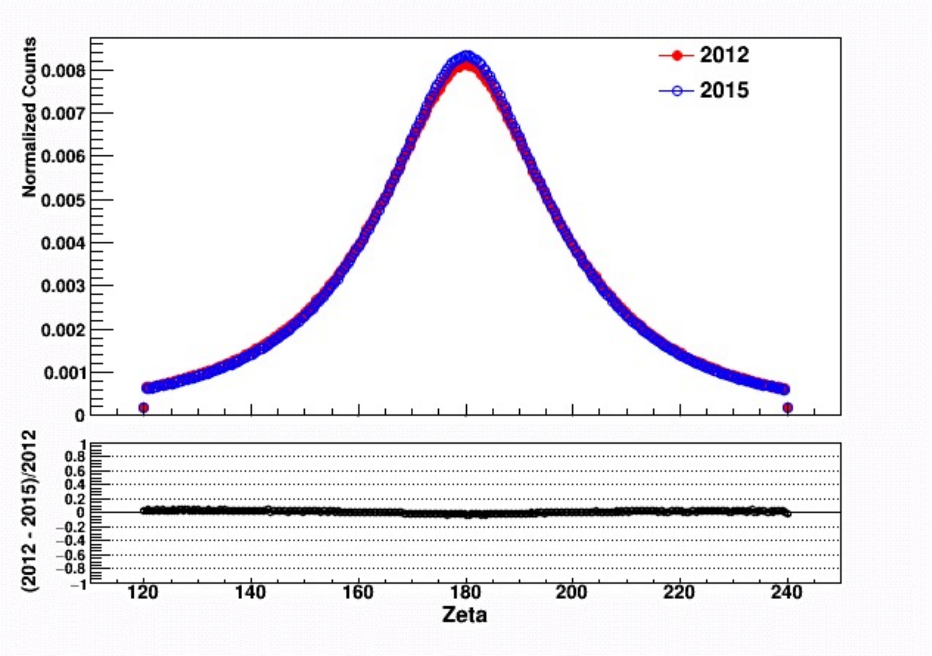
Sivers Effect from Dijet Measurement

The Sivers asymmetry can be probed via the opening angle of dijet in the transverse plane ζ (φ_b is dijet bisector angle):

- ζ > π when $\cos(\varphi_b) > 0$
- ζ < π when $\cos(\varphi_b) < 0$



$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

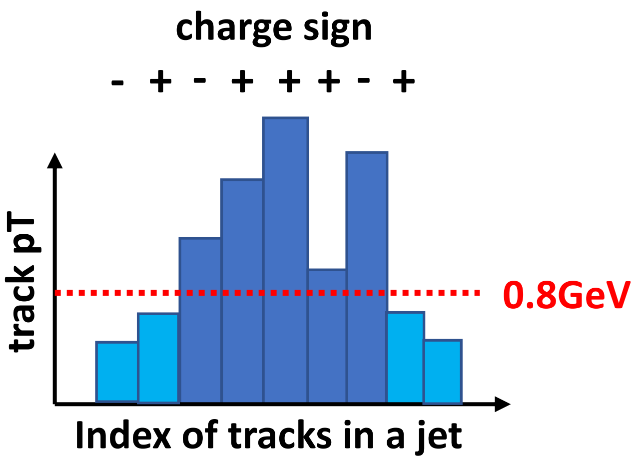


- Sivers effect leads to a spin-dependent centroid shift of ζ;
- $\langle\zeta\rangle^{+}$ is the centroid of ζ for spin-up;
- $\langle\zeta\rangle^{-}$ is the centroid of ζ for spin-down;

Jet Charge Tagging

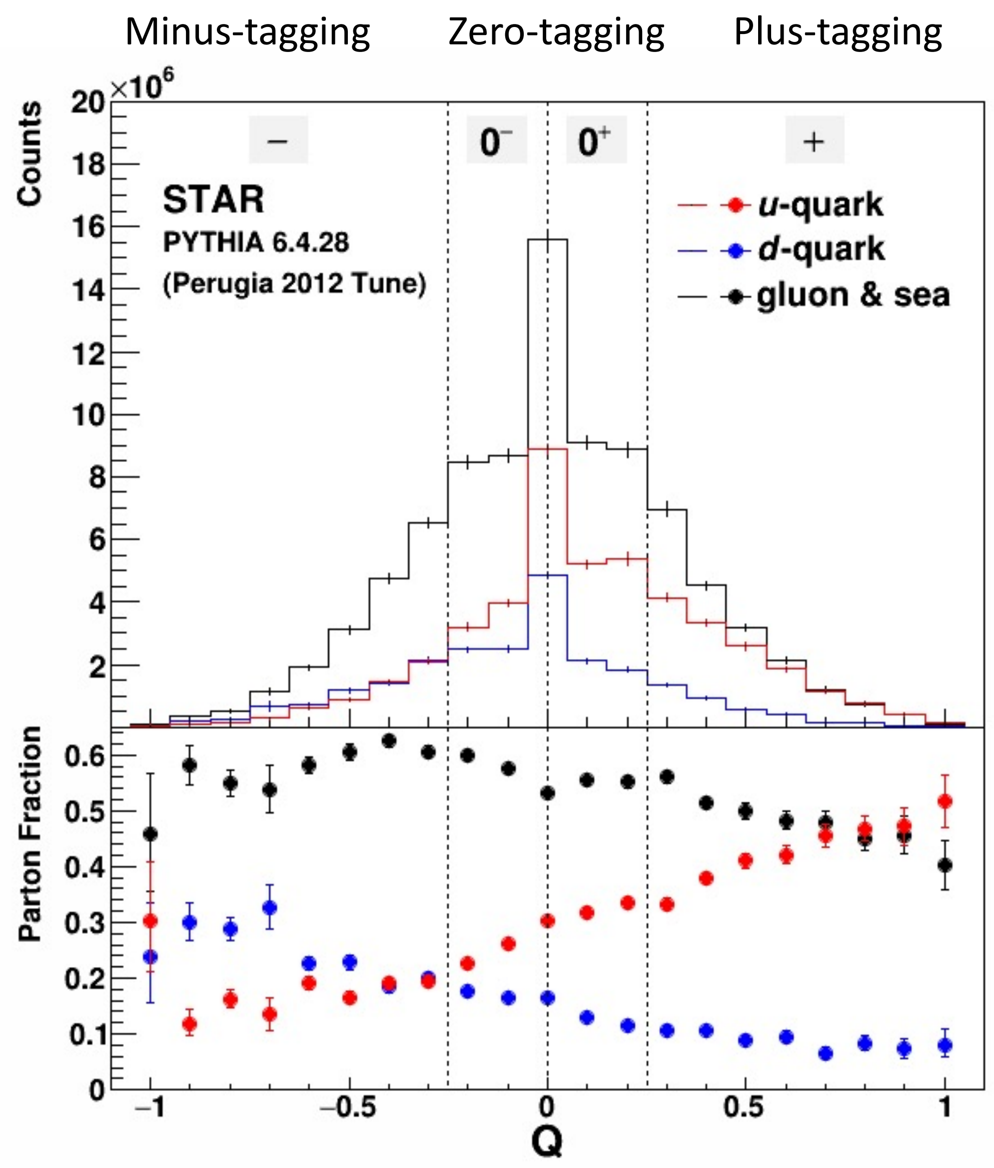
$$Q = \sum_{\substack{tracks \\ p_T > 0.8}} \frac{track\ p}{jet\ p} \times track\ charge$$

Use the **Jet Charge (Q) of the associated jets** to enhance the fraction of **u-quarks and d-quarks** separately.

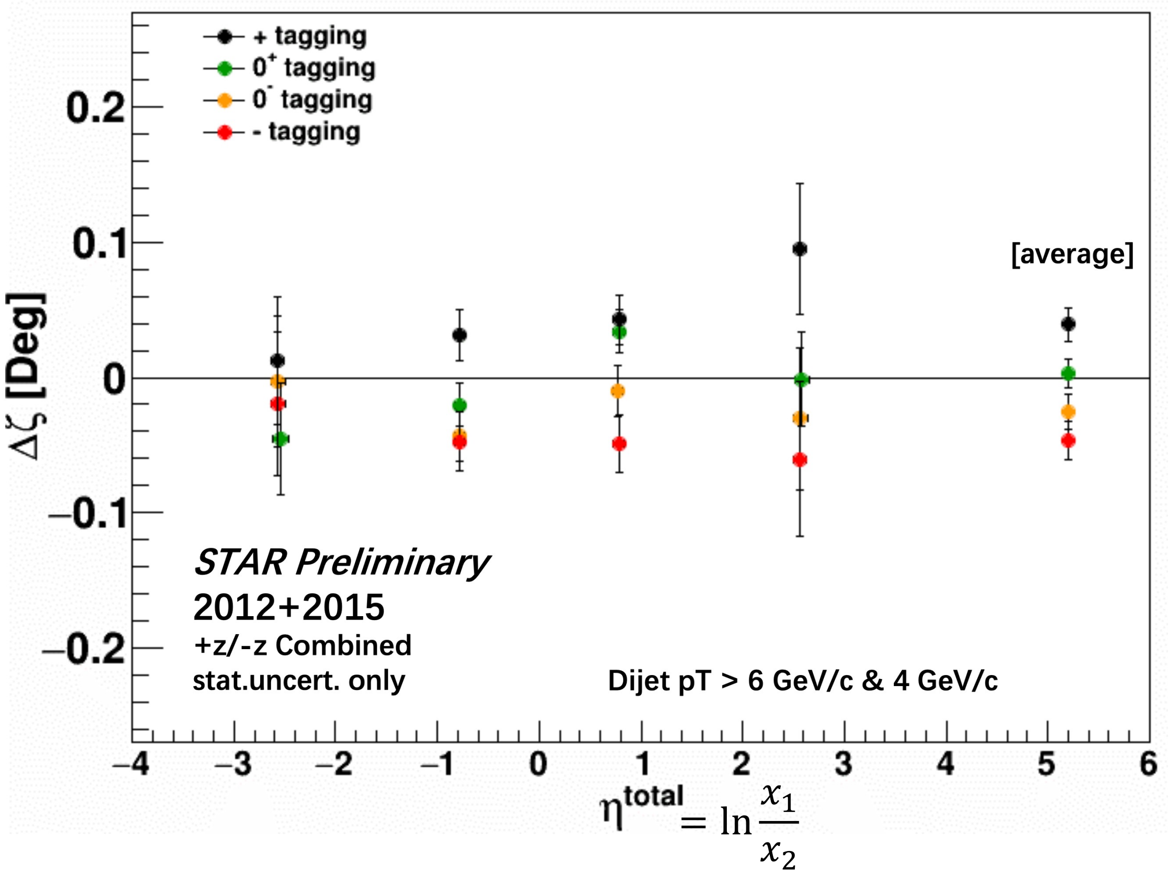


Data is divided into four bins:

1. Plus tagging ($Q \geq 0.25$) : enhances u
2. Zero+ tagging ($0 \leq Q < 0.25$) : less enhancement to u
3. Zero- tagging ($-0.25 < Q < 0$) : less enhancement to d
4. Minus tagging ($Q \leq -0.25$) : enhances d



Sivers Effect from Dijet Measurement



- Large separation (~5σ) between plus-tagging and minus-tagging;
- First observation of non-zero Sivers asymmetries in dijet production of polarized proton collisions.

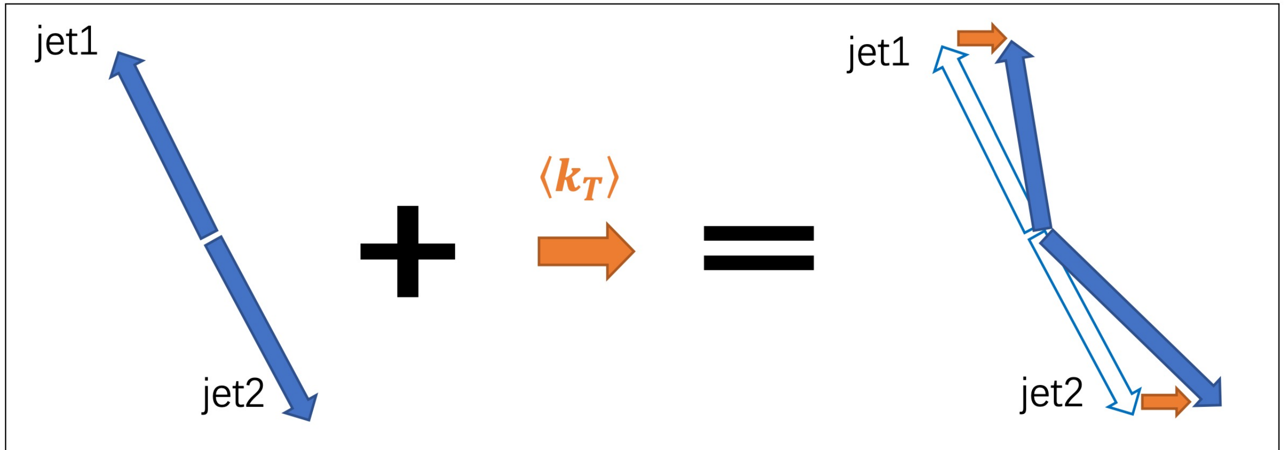
Converting the $\Delta\zeta$ asymmetry to $\langle k_T \rangle$

Three steps are taken to convert the $\Delta\zeta$ asymmetry to $\langle k_T \rangle$:

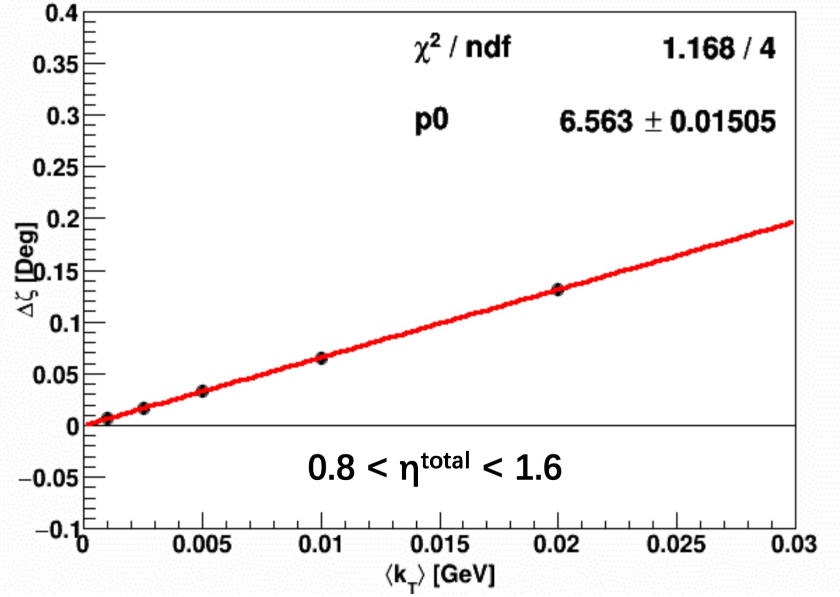
I. Correct detector jet pT to parton pT with machine learning.

II. Use simple kinematic modeling of $\langle k_T \rangle$, calculate $\Delta\zeta$ with corrected pT, and get $\Delta\zeta$-$\langle k_T \rangle$ correlation.

Kinematic model (transverse plane)



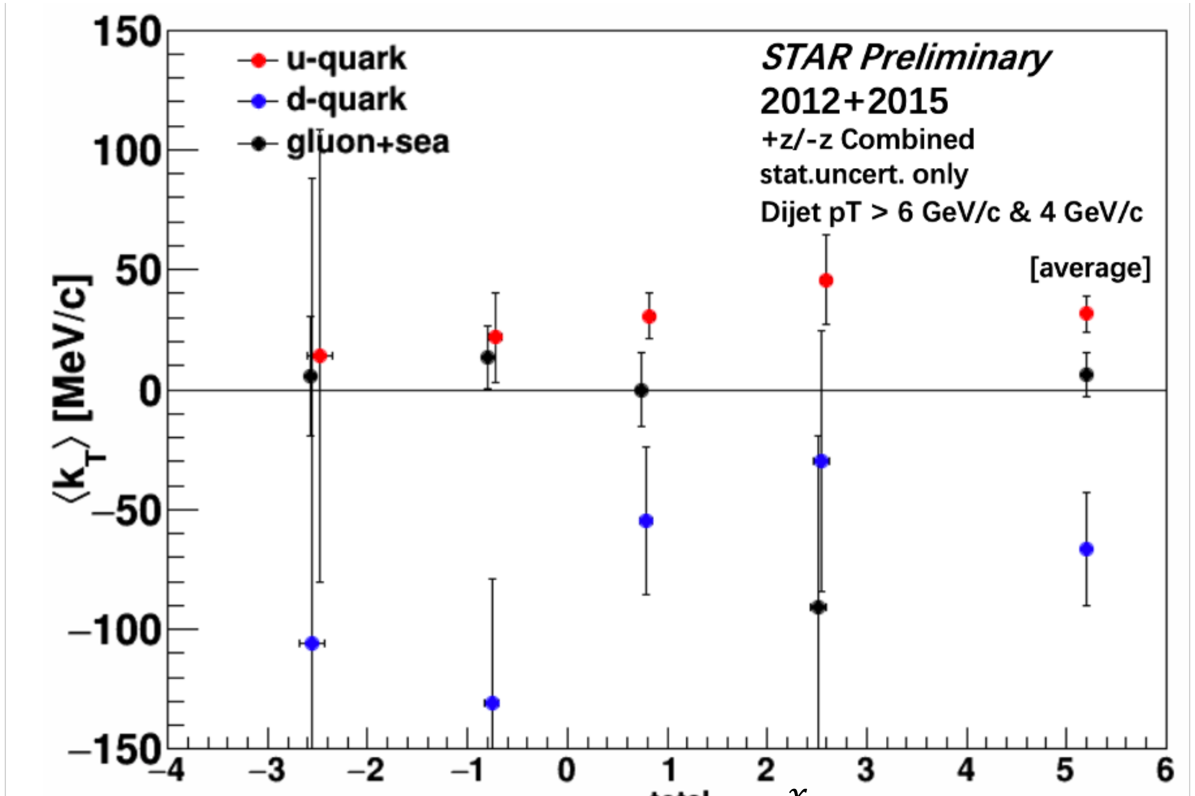
$\Delta\zeta$ - $\langle k_T \rangle$ correlation



III. Convert the $\Delta\zeta$_vs_ η^{total} results to $\langle k_T \rangle$ _vs_ η^{total} results :

$$\langle k_T \rangle = \Delta\zeta \ / \ slope$$

Sivers Effect from Dijet Measurement



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

- Further unfolded the asymmetry to k_T of individual partons;
- $\langle k_T^u \rangle$ ≈ 31 MeV/c, $\langle k_T^d \rangle$ ≈ -55 MeV/c, $\langle k_T^{g+sea} \rangle$ ≈ 0 MeV/c.