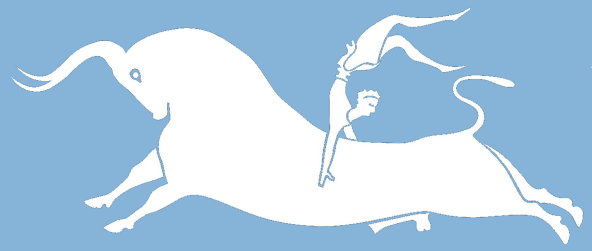

XIII International Conference
on New Frontiers in Physics

26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

STAR

STAR Spin Physics Highlight

Ting Lin (林挺) , for the STAR Collaboration

Shandong University (山东大学)

Supported in part by

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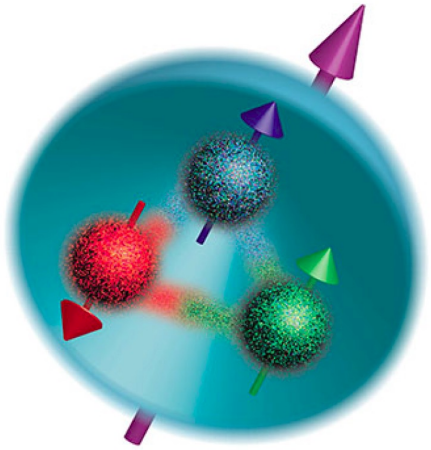
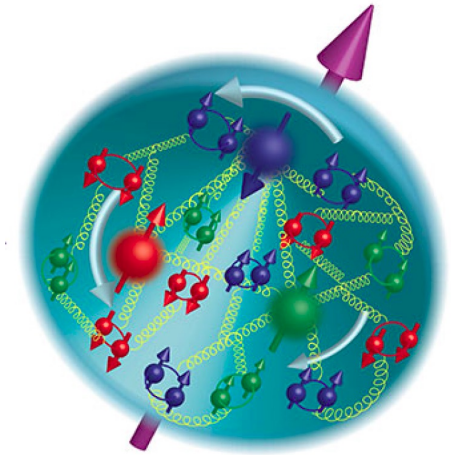
SHANDONG UNIVERSITY 山东大学

Outline

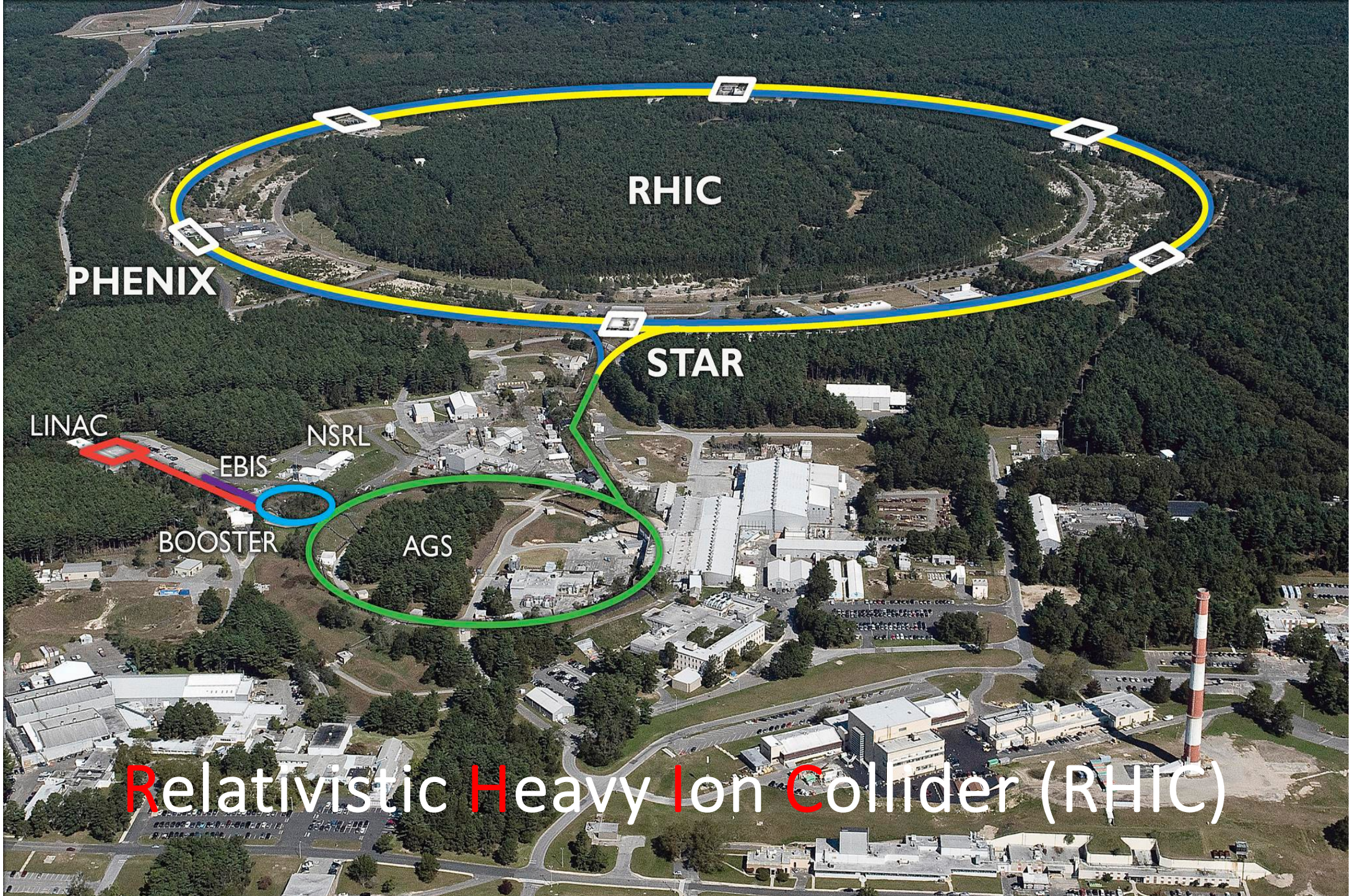
- Motivation
- RHIC Facility and STAR Detector
- Longitudinal Spin Structure
- Transverse Spin Structure
- Summary

Fundamental Questions Regarding Proton Spin



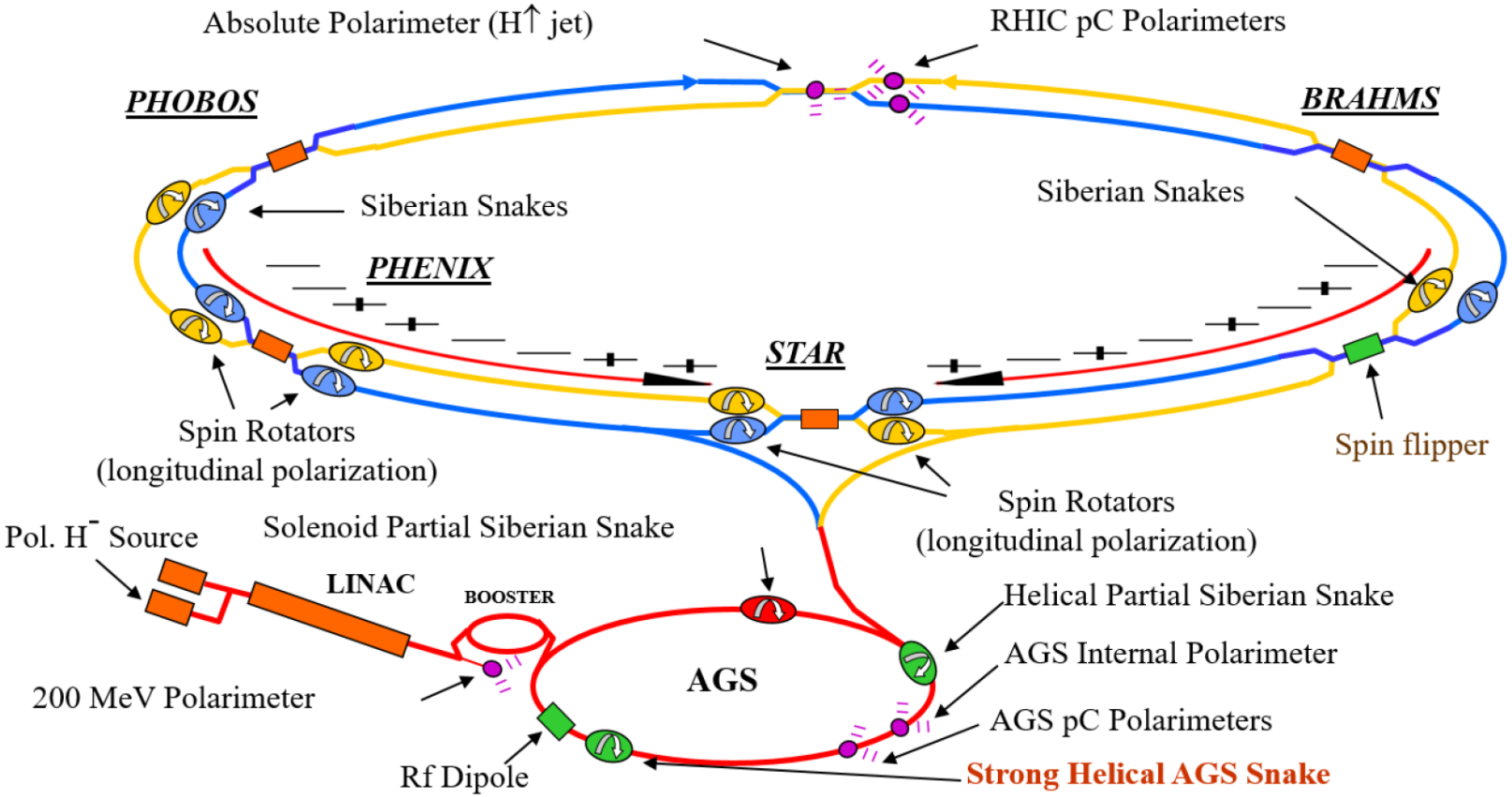


- How do quarks and gluons conspire to provide the proton's spin ½ ?
  - What is the role of gluons and sea quarks?
  - What is the size of the orbital angular momentum?
- What is the dynamic structure of the proton?
  - How do we go beyond longitudinal parton distribution functions to map out the 3D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



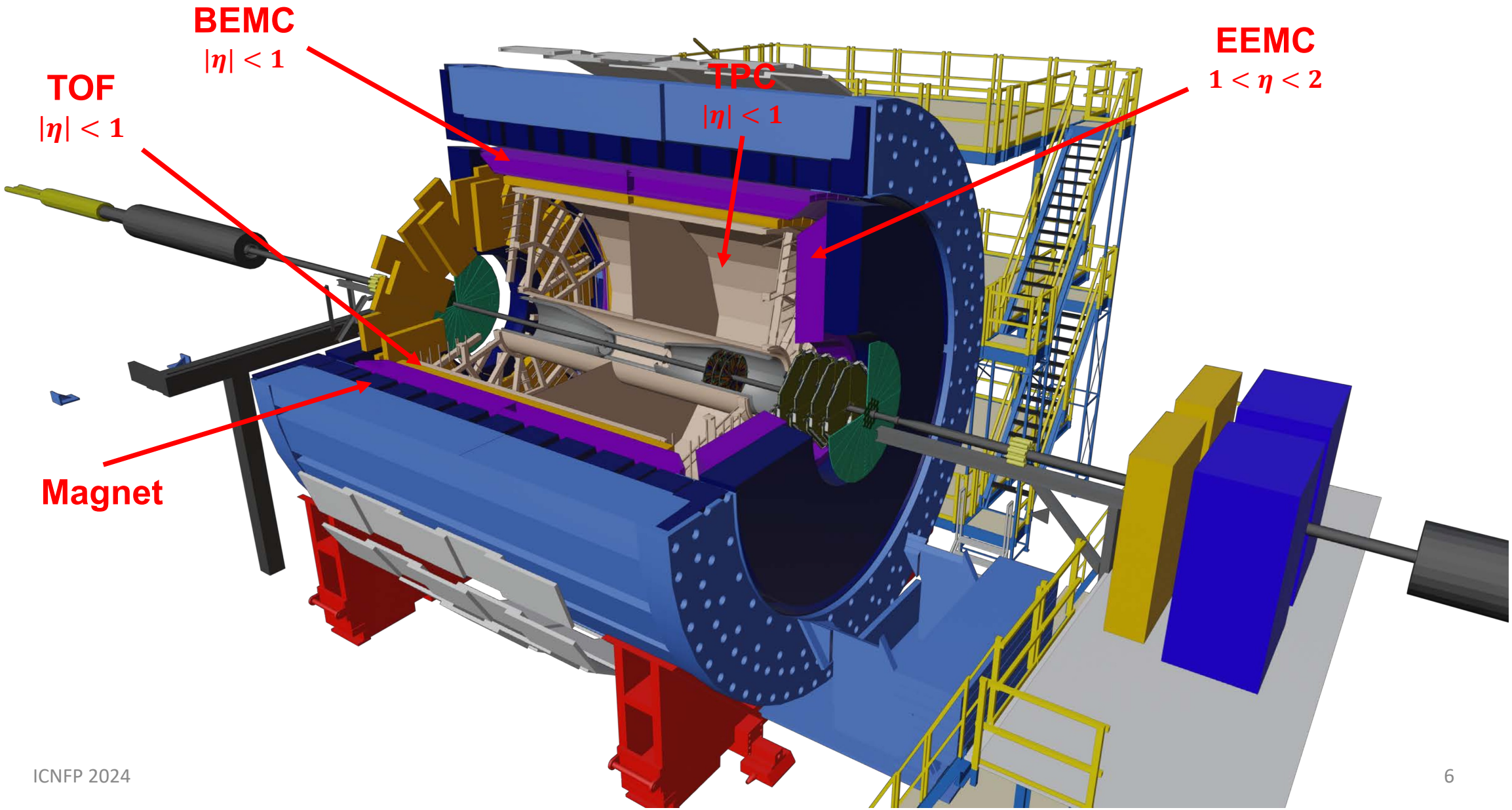
Relativistic Heavy Ion Collider (RHIC)

Relativistic Heavy Ion Collider (RHIC)



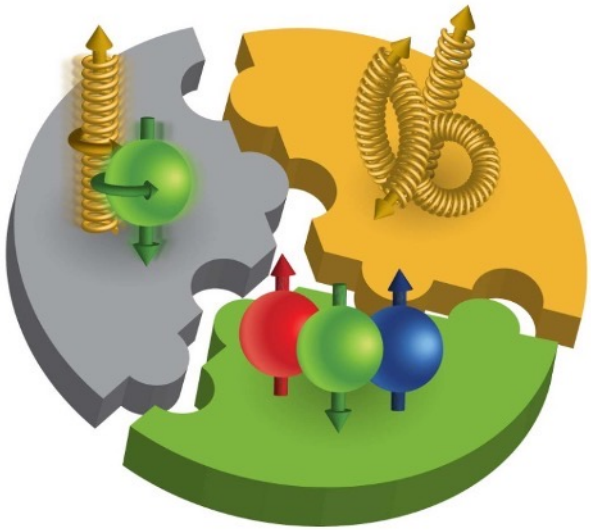
- Spin pattern changes from fill to fill with little depolarization;
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

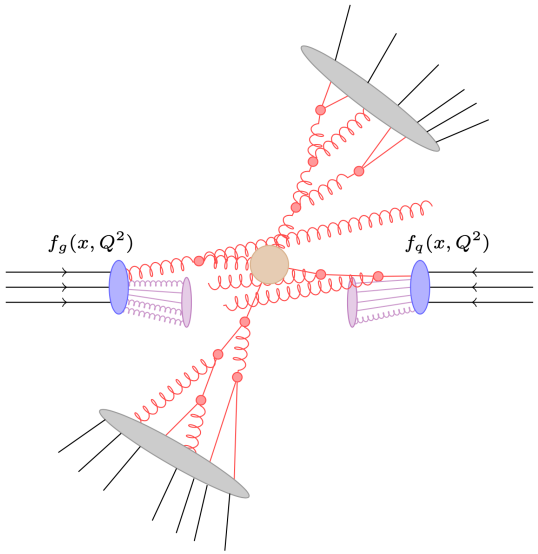
Solenoidal Tracker At RHIC (STAR)



Longitudinal Spin Structure

Spin of the Proton





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

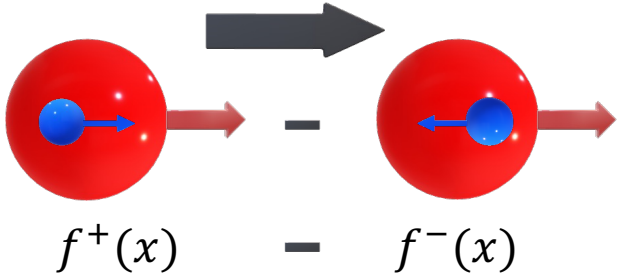
$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

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

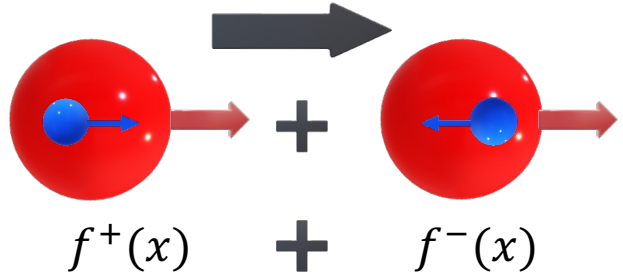
  - $\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$
  - $\Delta G = \int \Delta g(x)dx$

$$d\sigma_{pp\to jet+X} = \sum_{ab} \int f_a(x_1,Q^2) f_b(x_2,Q^2) d\hat{\sigma}_{a+b\to jet+X}(x_1,x_2,Q^2) dx_1 dx_2$$

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

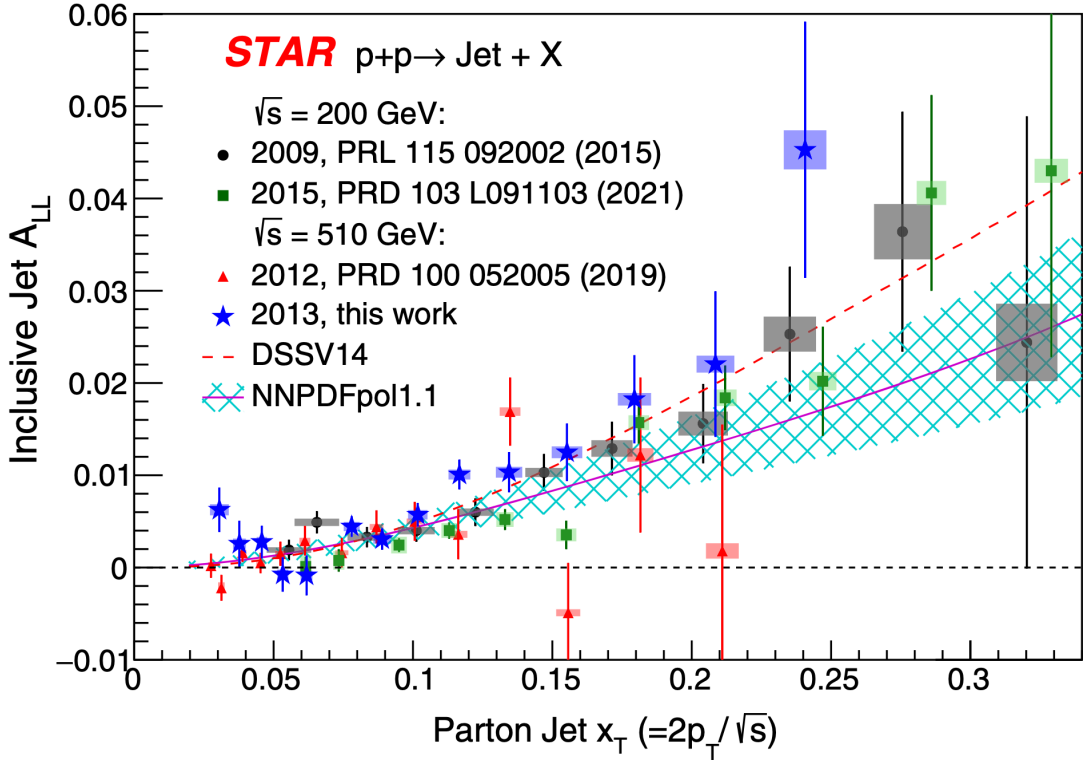


- Unpolarized PDF, $f(x) =$



Probing the Gluon Helicity at RHIC

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



What we measured

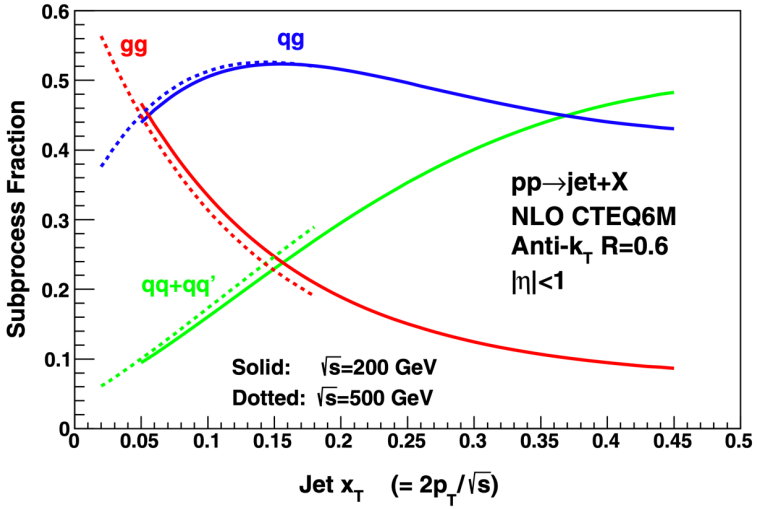
What we hope to learn

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

Measured by others

Calculable

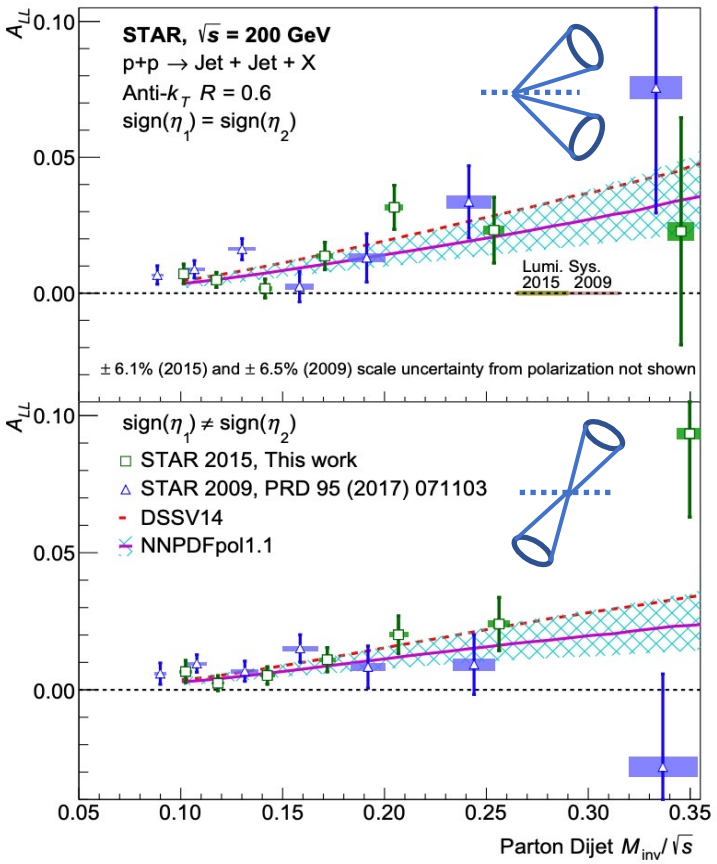
- For most RHIC kinematics, gg and qg dominate, making A_{LL} for jets sensitive to gluon polarization.



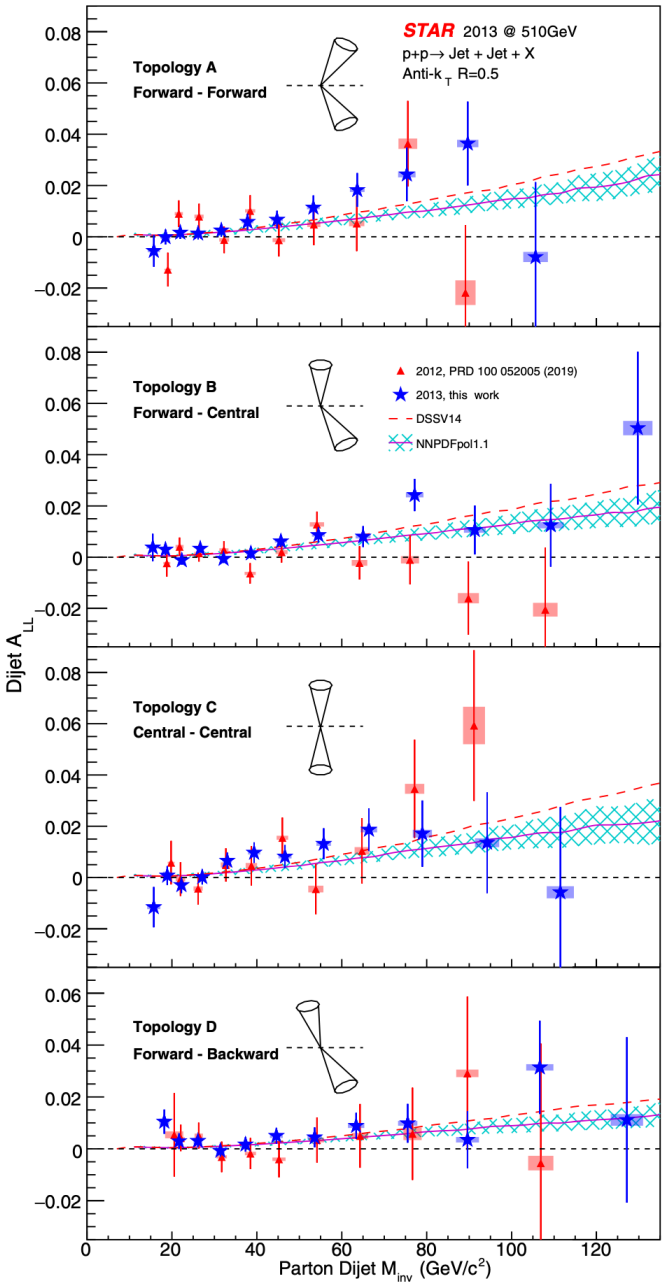
- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05;
- Improved statistical and systematics uncertainties;
- Will significantly reduce uncertainty on gluon polarization once included in global fits.

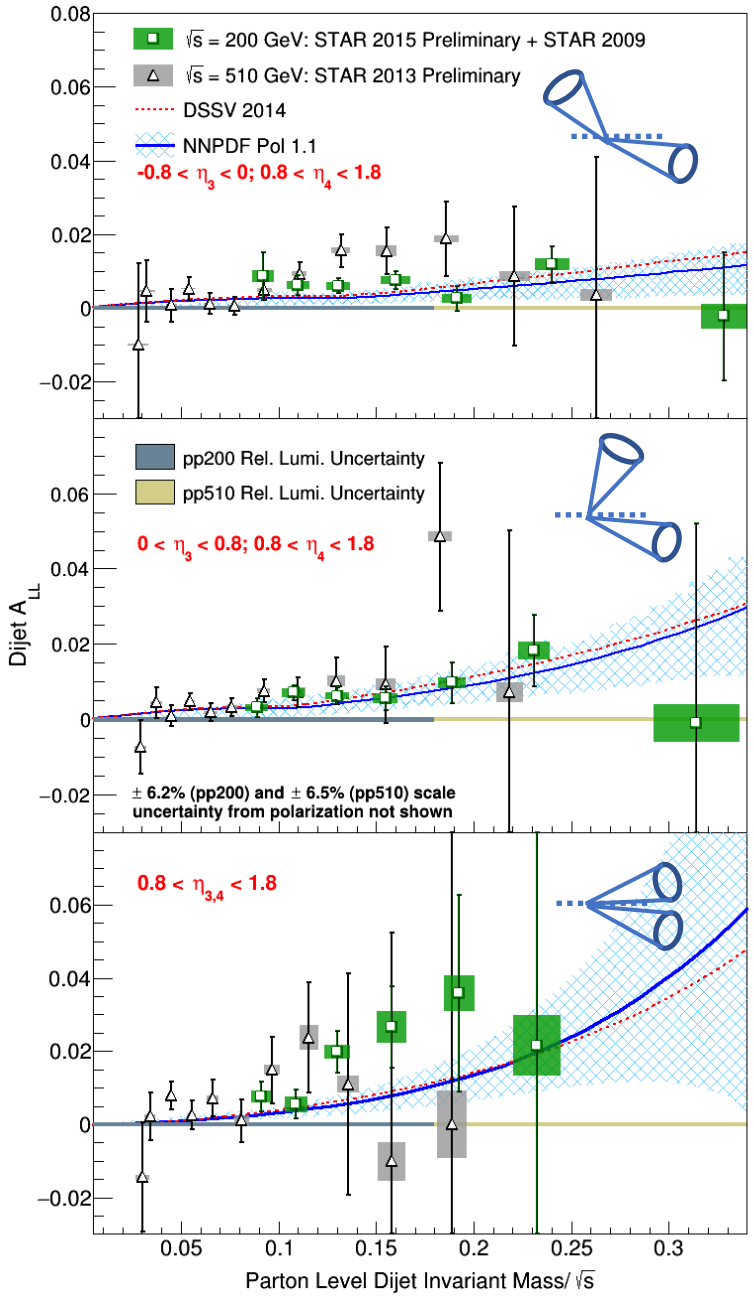
Dijet A_{LL}

STAR, PRD 103 L091103 (2021)



STAR, PRD 105, 092011 (2022)

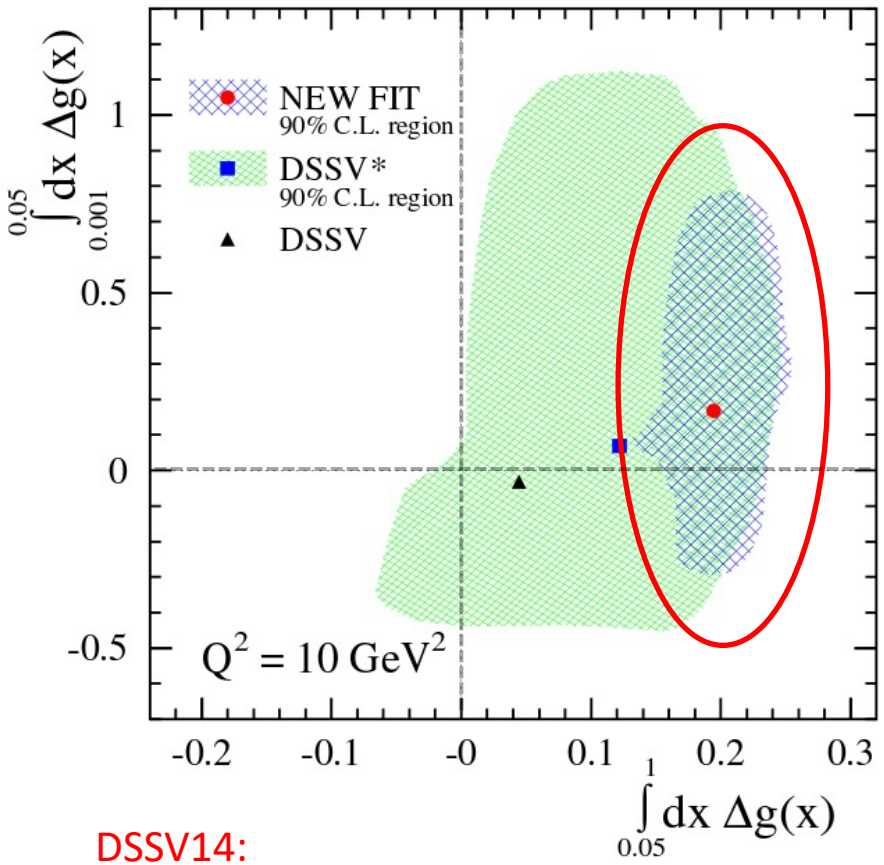




- Dijet captures more information from the hard scattering and provide a more direct link to the initial kinematics than inclusive probes.

Impact of the New STAR Results

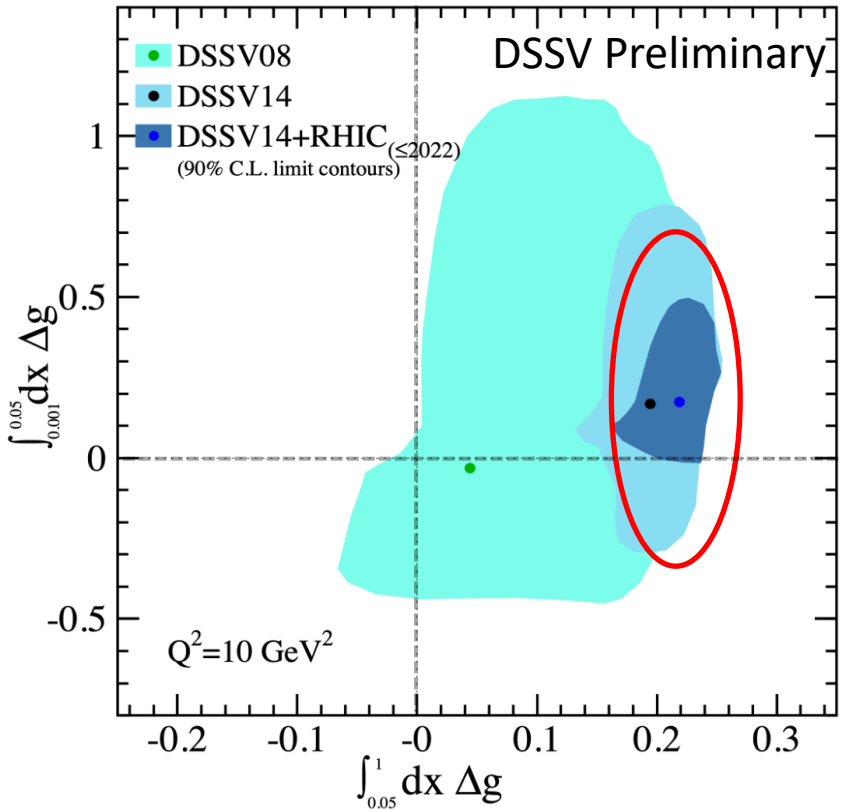
DSSV, PRL 113, 012001(2014)



DSSV14:

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20^{+0.06}_{-0.07}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15^{+0.65}_{-0.45}$

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



DSSV14 + RHIC (≤2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.17^{+0.33}_{-0.17}$

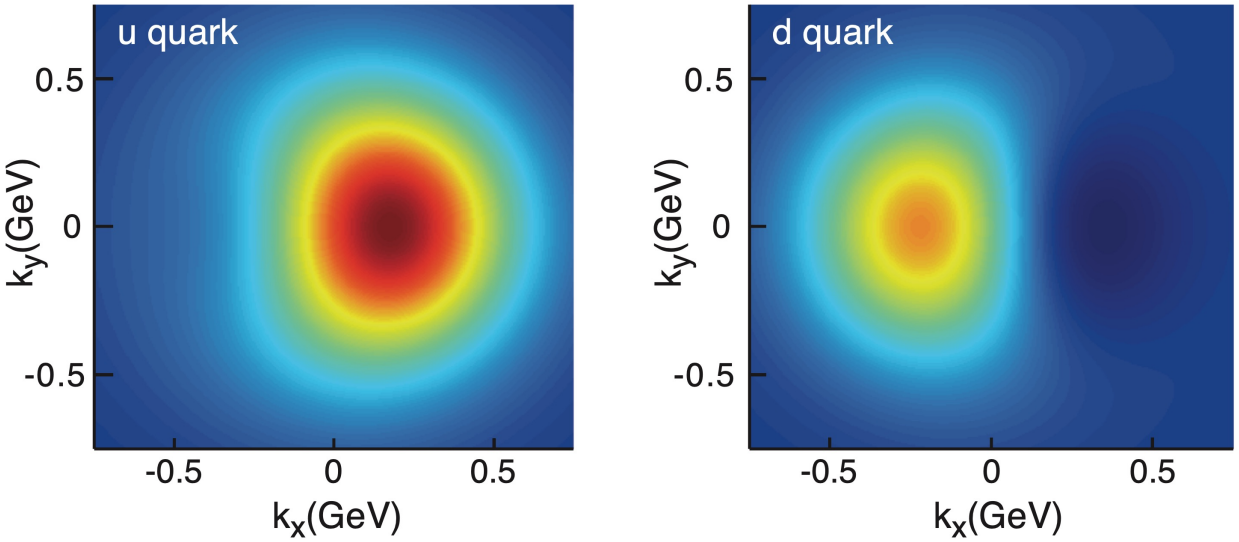
3D Tomography of the Nucleon:

TMD

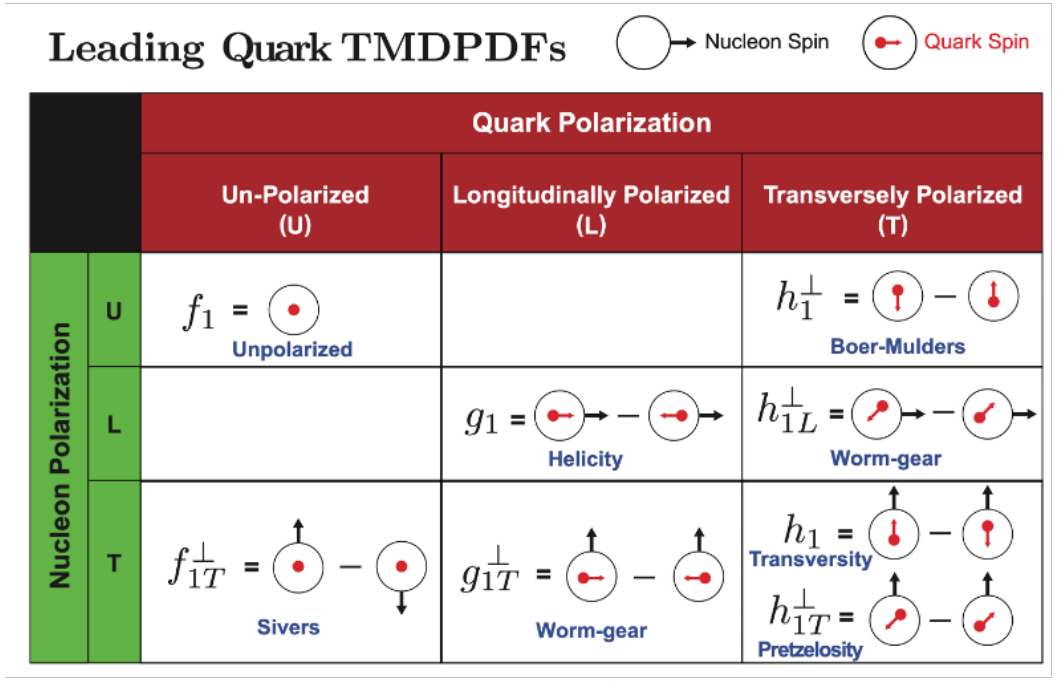
TMD Parton Distribution Functions

EIC White Paper arXiv:1212.1701

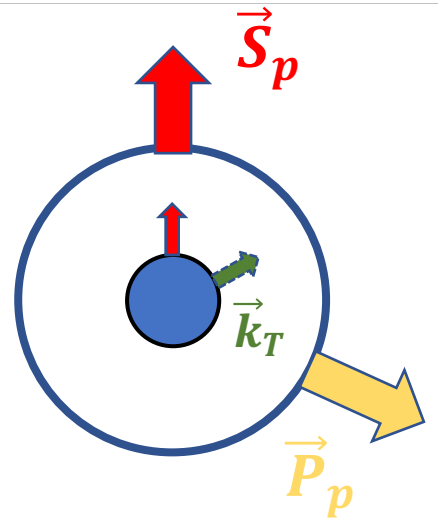
$x\, f_1(x, k_T, S_T)$



TMD Handbook, arXiv:2304.03302 [hep-ph]

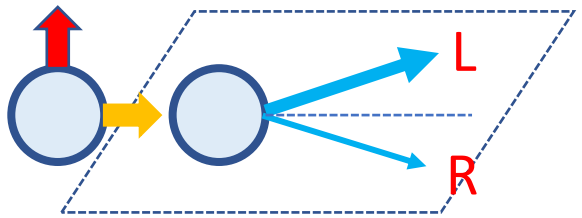


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

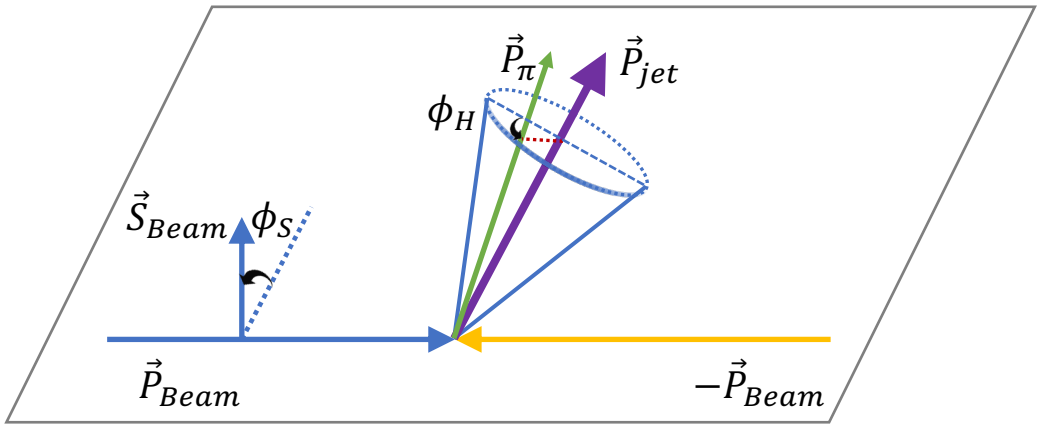


Transverse Single-Spin Asymmetry

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



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



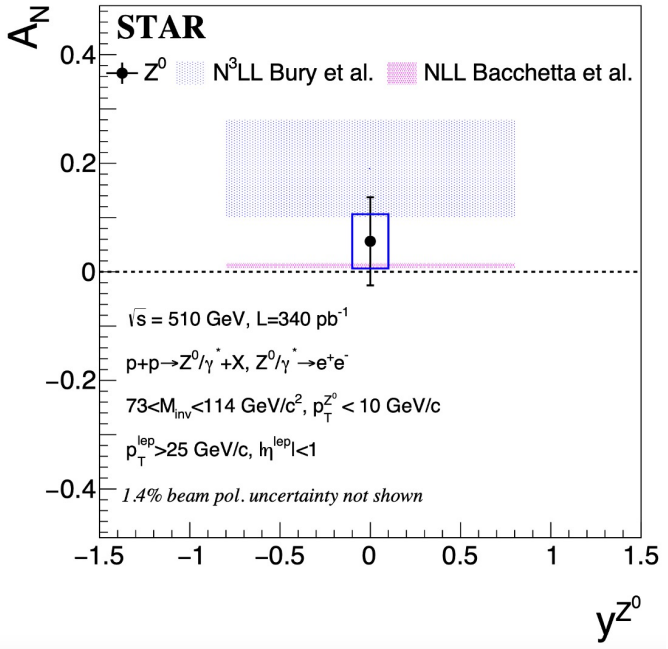
$$A_N = \frac{d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)}{d\sigma^{\uparrow}(\phi_S, \phi_H) + d\sigma^{\downarrow}(\phi_S, \phi_H)} \sim A_{UT}^{Sivers} \sin(\phi_S) + A_{UT}^{Collins} \sin(\phi_S - \phi_H)$$

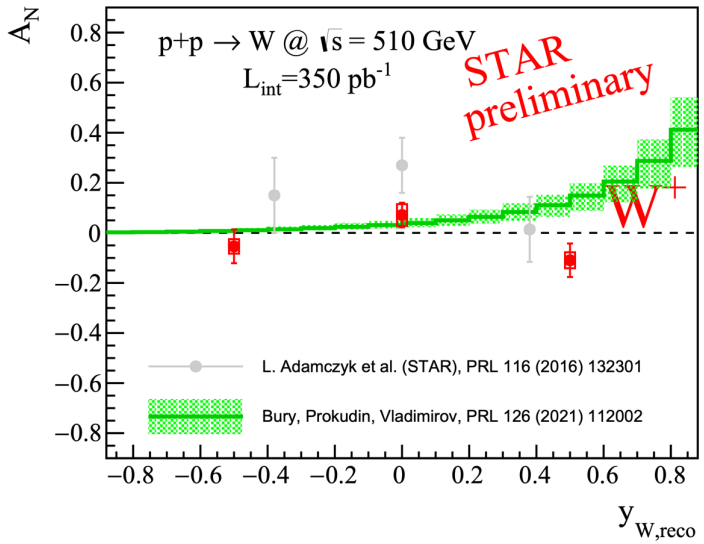
$\sim f_{1T}^{\perp} \otimes D_1$ $\sim h_1 \otimes H_1^{\perp}$

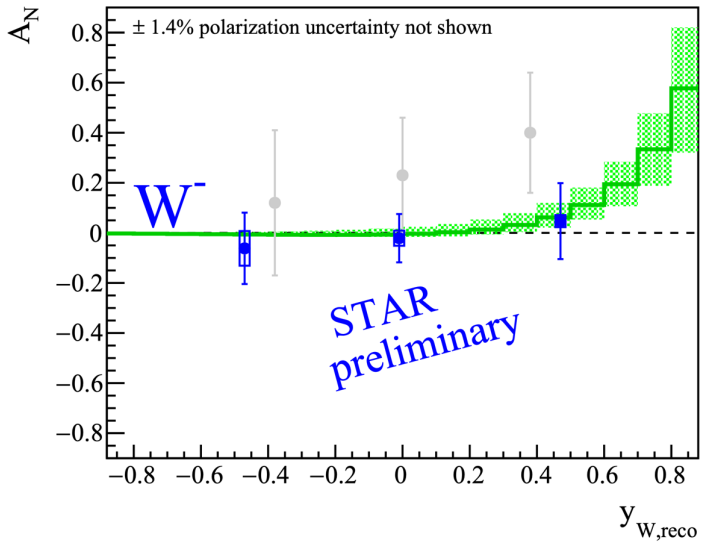
- Each TMD PDF is convoluted with a fragmentation function and appears with a independent harmonic modulations (azimuthal asymmetry amplitudes).

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

STAR, PLB 854 (2024) 138715



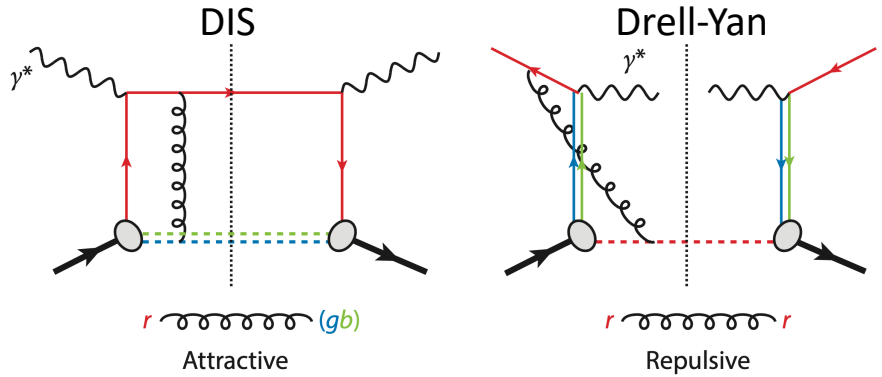




- Test the nonuniversality nature of Sivers function:

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

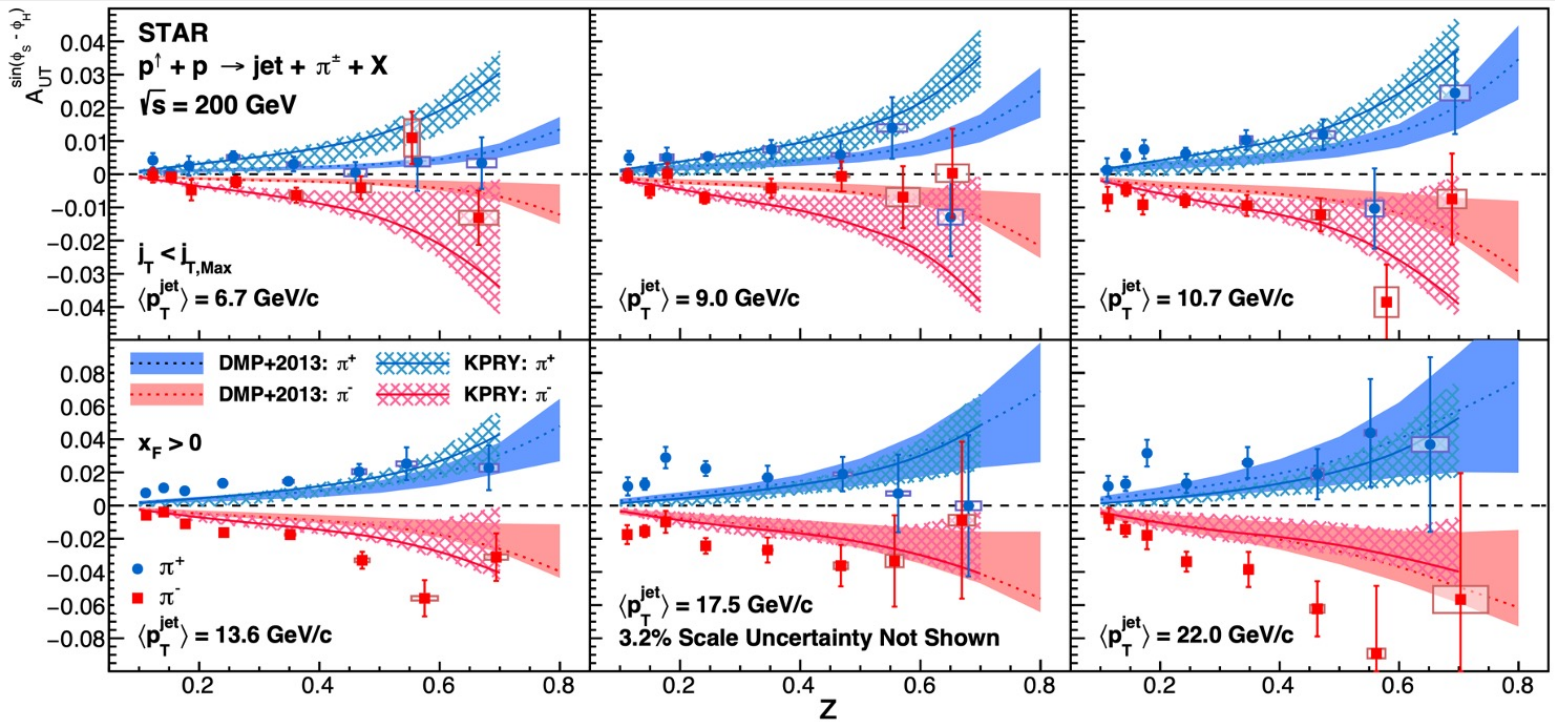
- A fundamental prediction from the gauge invariance of QCD.

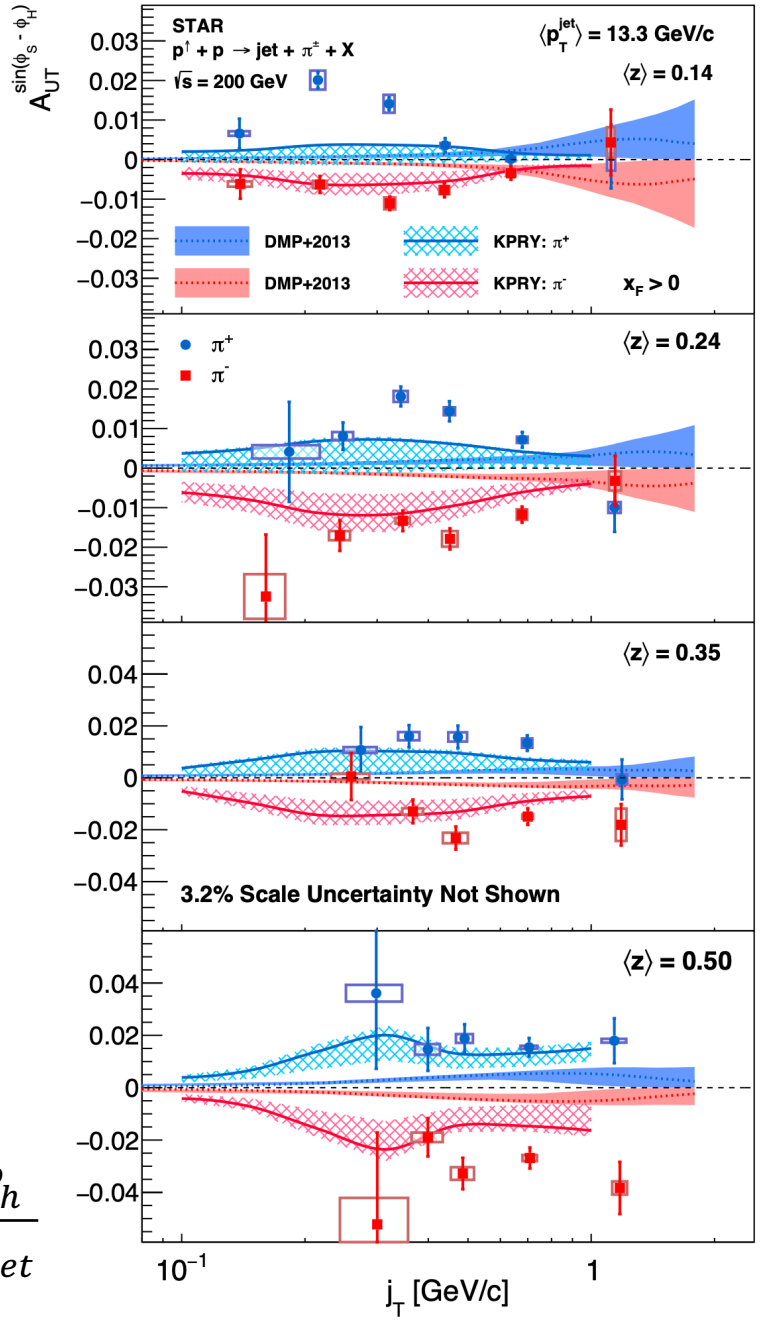


A_N for $\pi^{\pm}$ in Jets

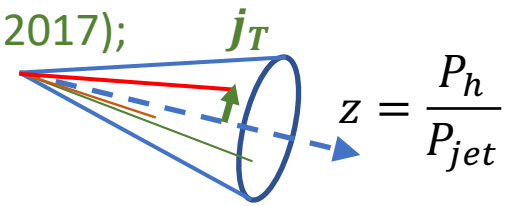
STAR, PRD 106, 072010 (2022)

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





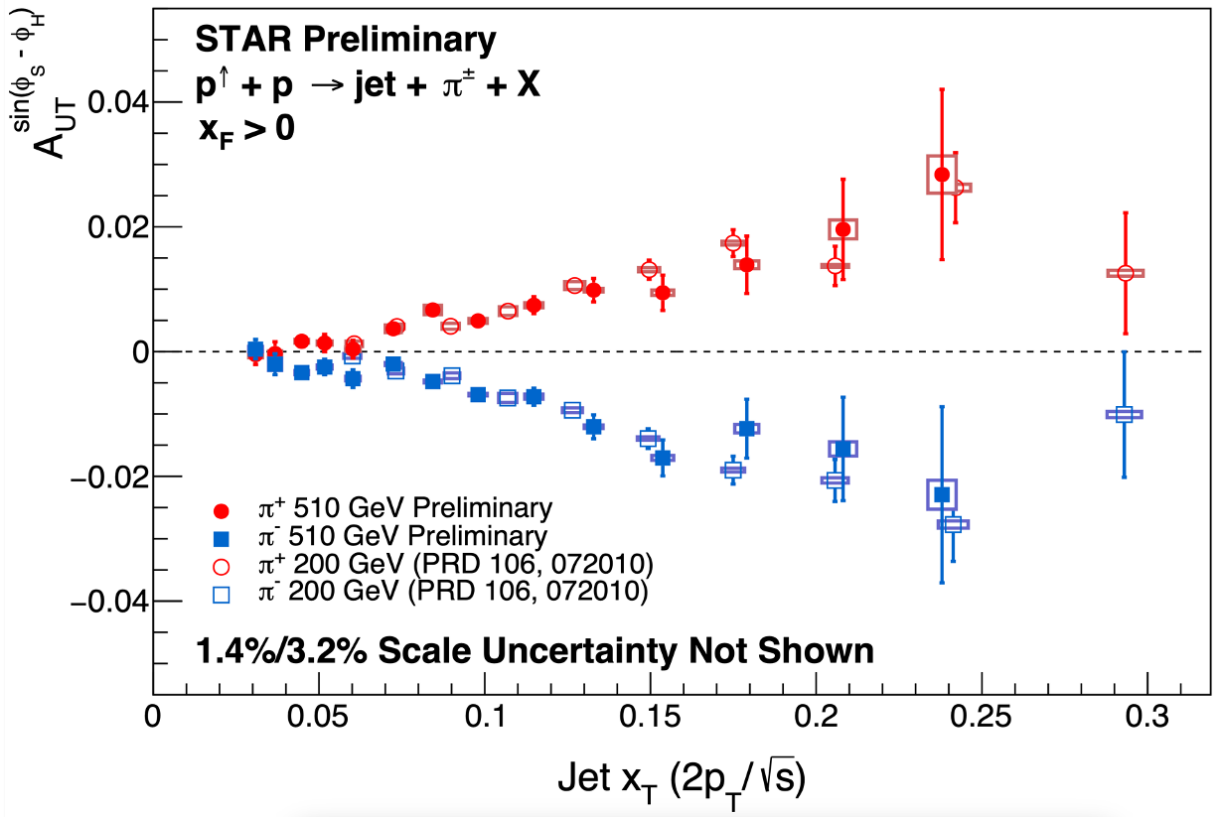
- DMP+2013 model from Umberto D'Alesio *et.al.*, PLB 773, 300 (2017);
- KPRY model from Zhong-Bo Kang *et. al.*,PLB 774, 635 (2017);
- Both assume universality and factorization.

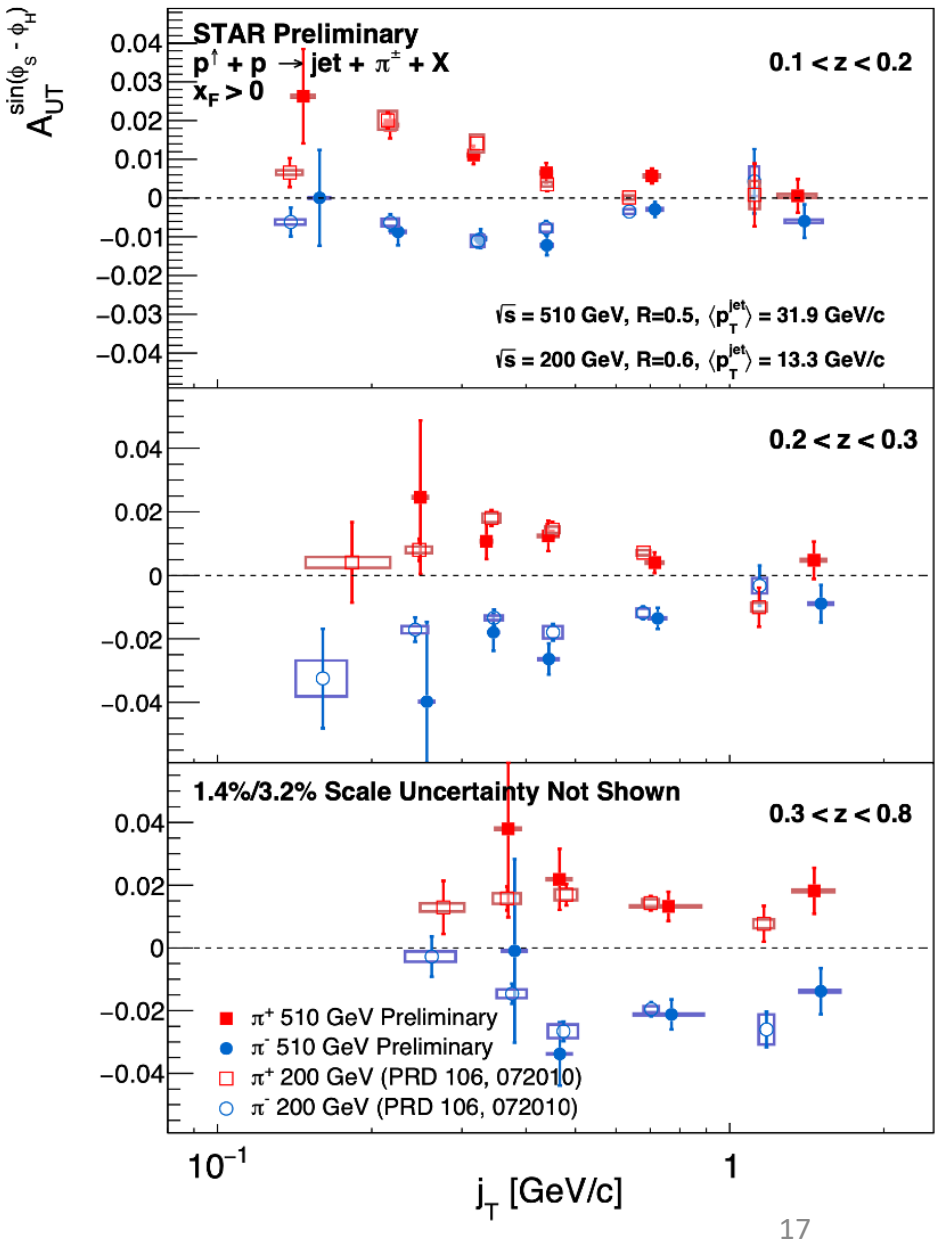


$$z = \frac{P_h}{P_{jet}}$$

See Yixin Zhang's talk
27th August, 12:00am, Room 2

Comparison with pp 510 GeV

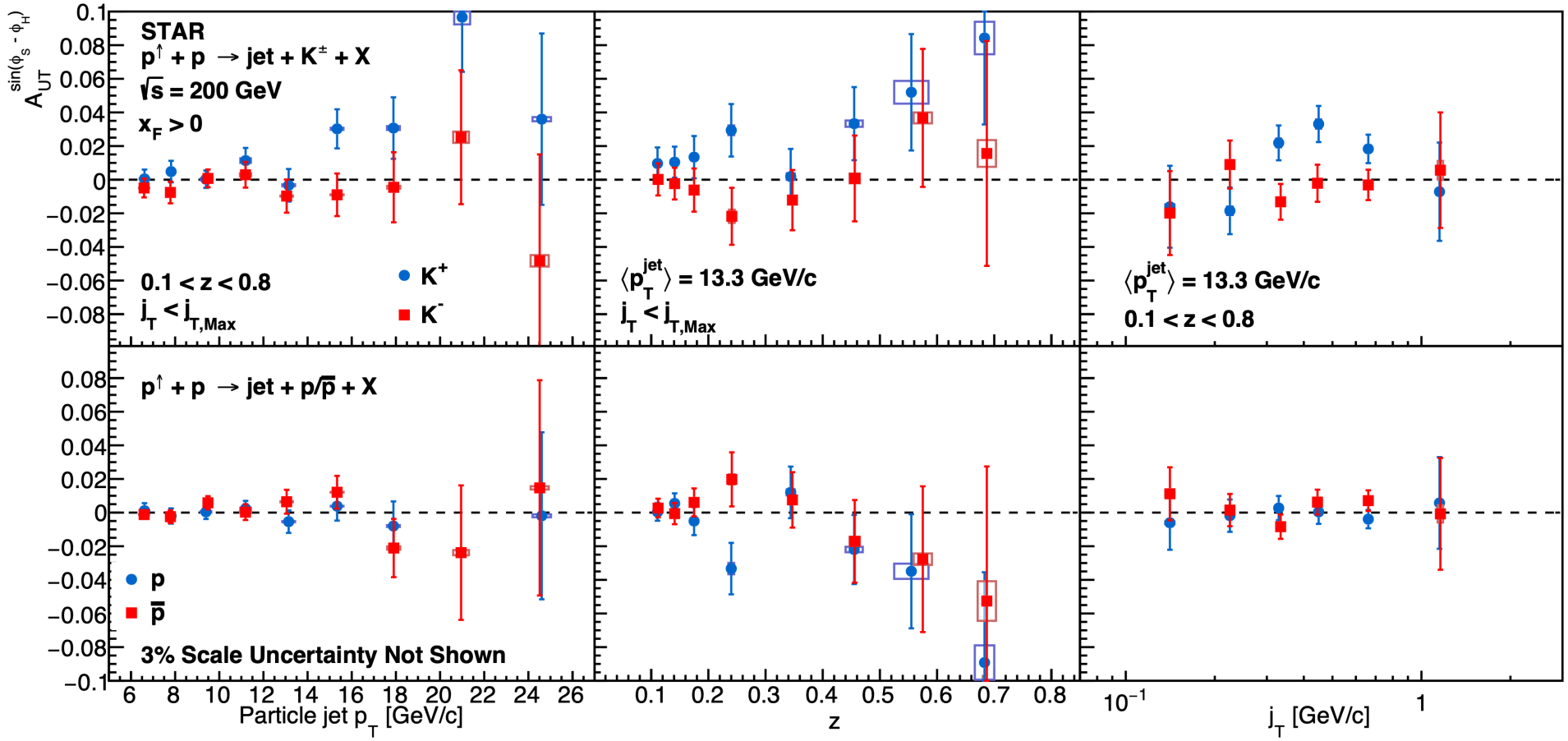




- The asymmetries agree at $0.06 < x_T < 0.2$, Q^2 differ by a factor of 6;
- Collins asymmetry has a weak energy dependence in hadronic collisions;
- z and j_T dependences of the Collins FF are closely related.

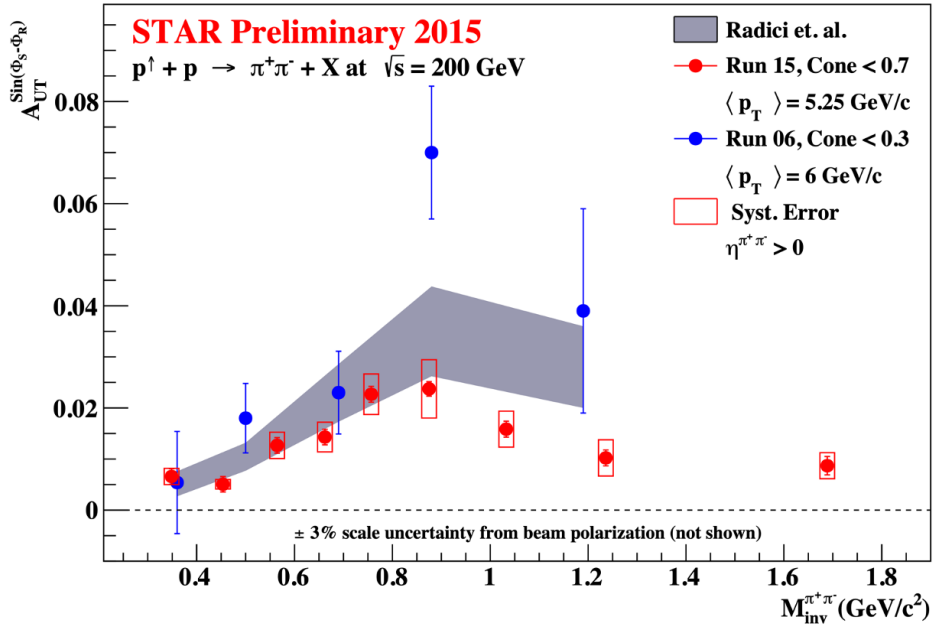
A_N for $K^{\pm}$and Proton in Jets

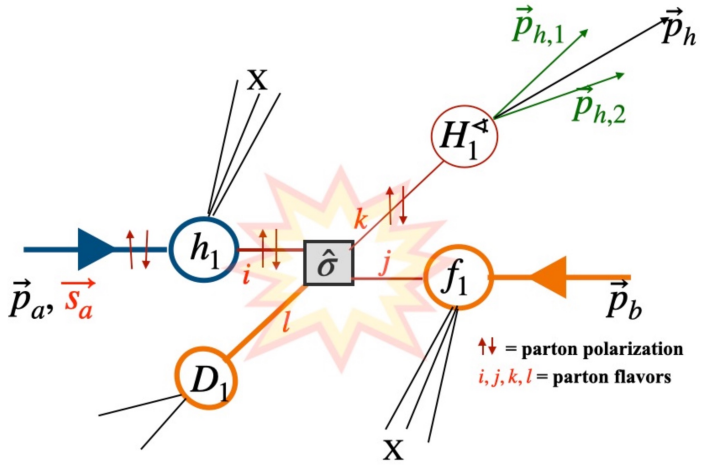
STAR, PRD 106, 072010 (2022)

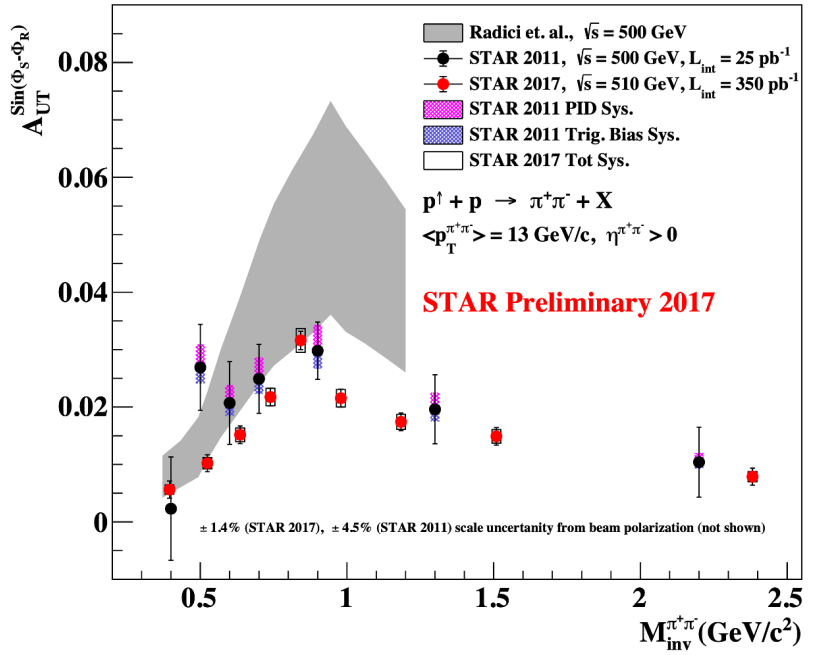


- K^+, with contribution from favored fragmentation of u quarks, has similar magnitude of asymmetries to π^+;
- K^-, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero;
- Proton and anti-proton's asymmetries are all consistent with zero at one sigma level.

A_N for Di-hadron Measurement





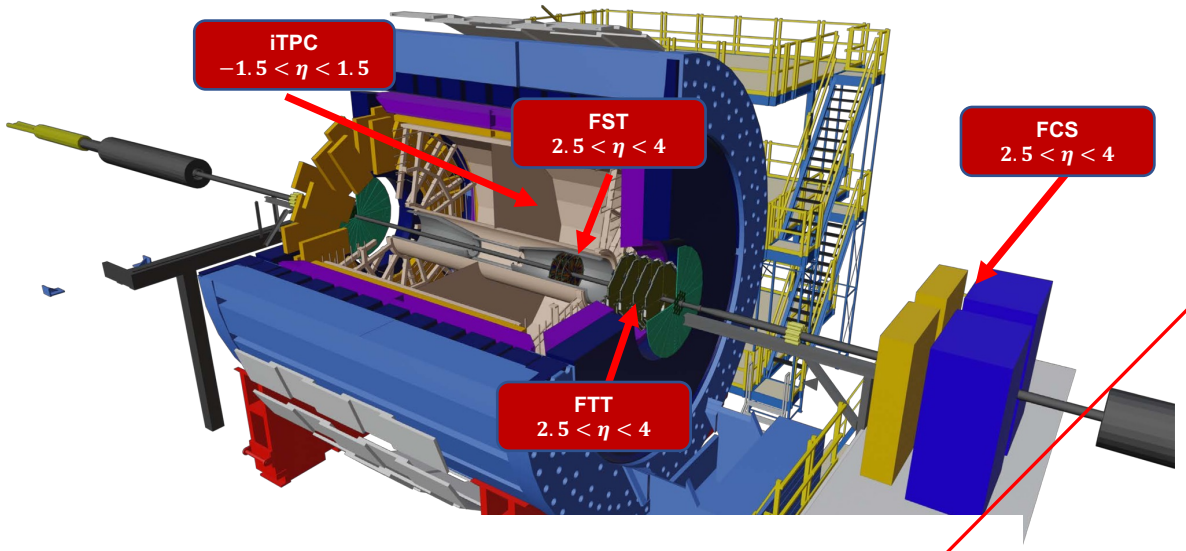


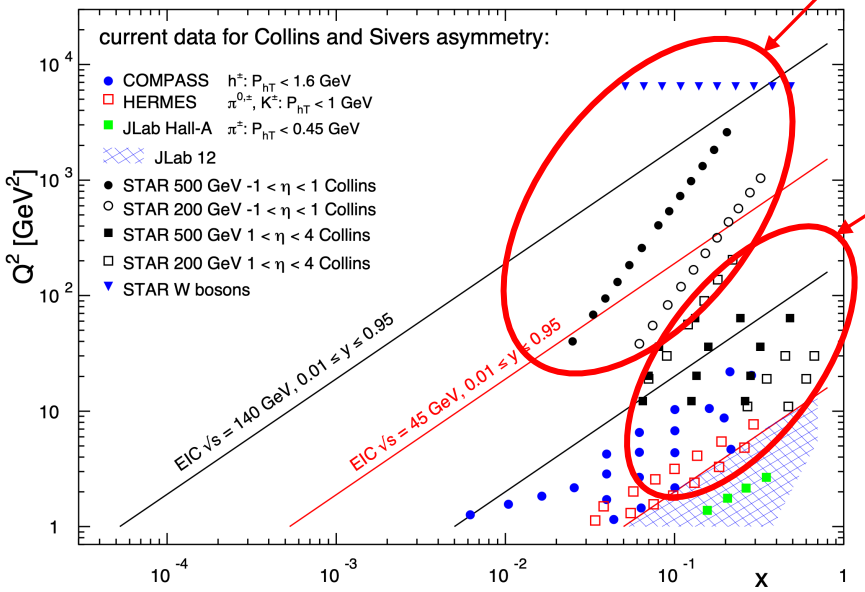
$$d\sigma_{UT} \propto \int dx_a dx_b h_1(x_a) f_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

- Spin dependent di-hadron correlations probe collinear quark transversity coupled to the interference fragmentation function;
- Theoretical expectations from fits to existing SIDIS and e^+e^- data, assuming the universality hold.

Outlook

See Xilin Liang's talk
27th August, 11:00am, Room 2





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.

$2.5 < \eta < 4$

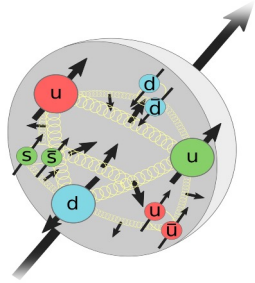
Physics Topics:

- 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.

- Large p+p 508 GeV sample from 2022 under analyses;
- Large p+p 200 GeV data taking ongoing now.

Summary



- Significant progress towards understanding the internal spin structure of nucleon at STAR:
  - Confirm the previous finding of positive gluon polarization inside proton;
  - New insights into the transversity, Sivers and Collins effect in pp collisions;
- RHIC will conclude the polarized pp collisions this year:
  - Longitudinal spin program has few remaining results to be published soon;
  - Unique transverse spin physics program with recent upgrades is ongoing.