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STAR

Transverse Spin Physics at STAR

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山东大学
SHANDONG UNIVERSITY

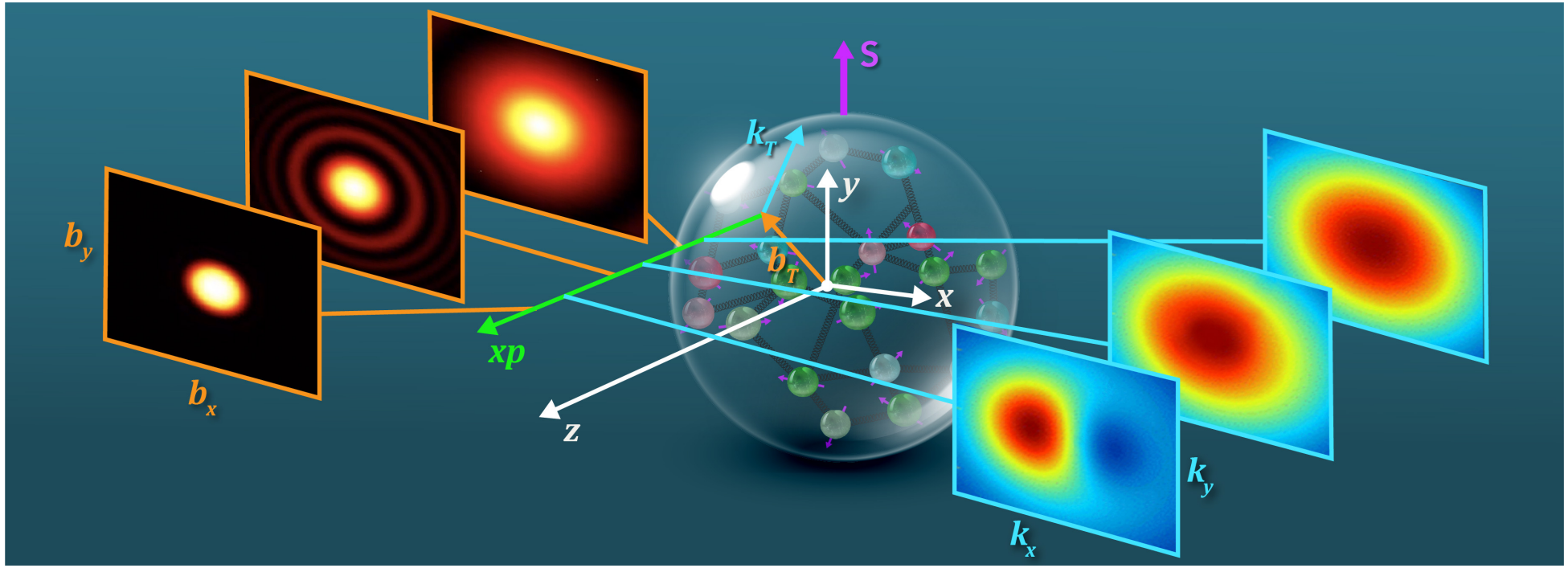
2nd workshop on advancing the understanding of non-perturbative QCD using energy flow @ Stony Brook University
Nov 6 – 9, 2023

Outline

- Motivation
- RHIC Facility and STAR Detector
- Transverse Spin Physics Results from STAR
- Outlook and Summary

Three-Dimensional Imaging of The Proton

2023 NSAC Long Range Plan, arXiv 2303.02579



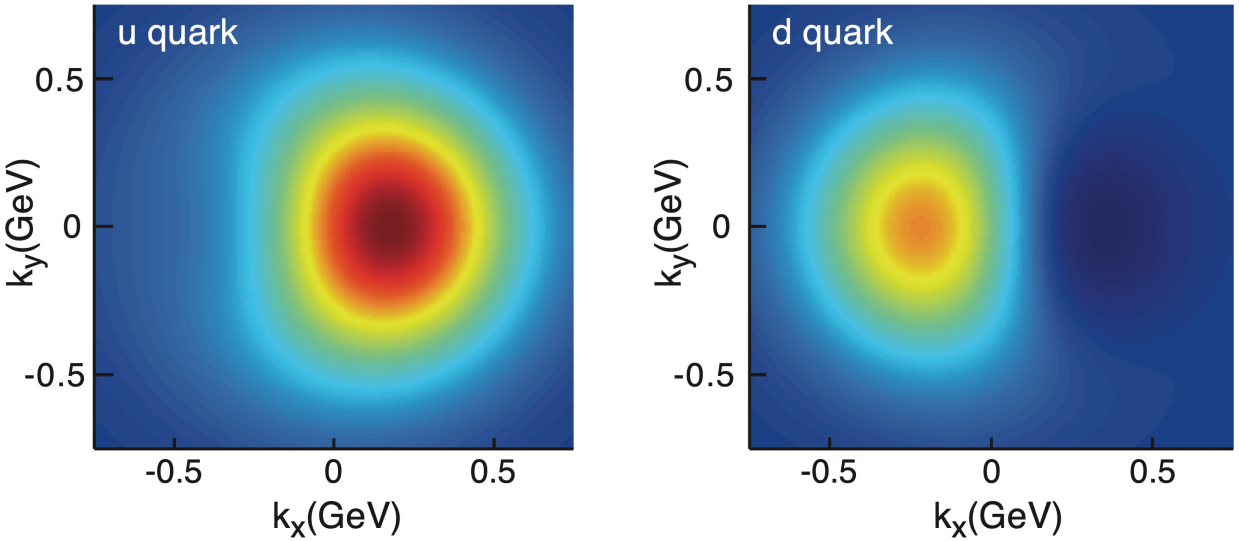
- Generalized Parton Distribution functions (GPDs) reveal the correlation of the partons' transverse spatial distribution and longitudinal momentum density;
- Transverse-Momentum-Dependent parton distribution functions (TMDs) encode information on how the momentum of quarks and gluons are correlated with the parent hadron properties;
- GPDs and TMDs are intimately connected to each other and are unified under the concept of Wigner distributions.

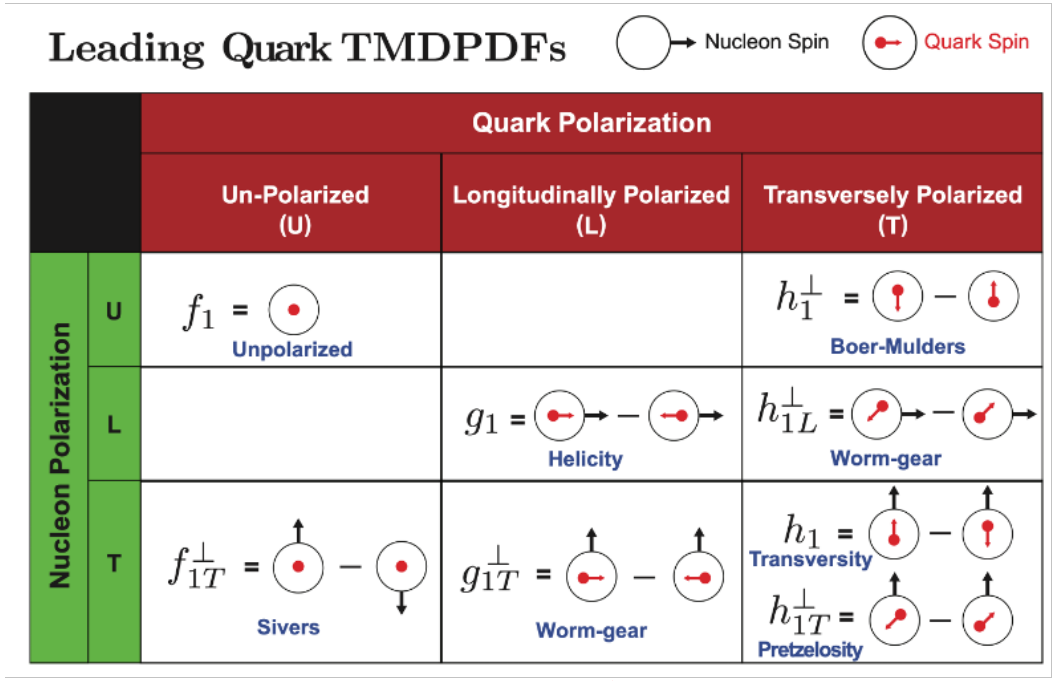
TMD Parton Distribution Functions

TMD Handbook, arXiv:2304.03302 [hep-ph]

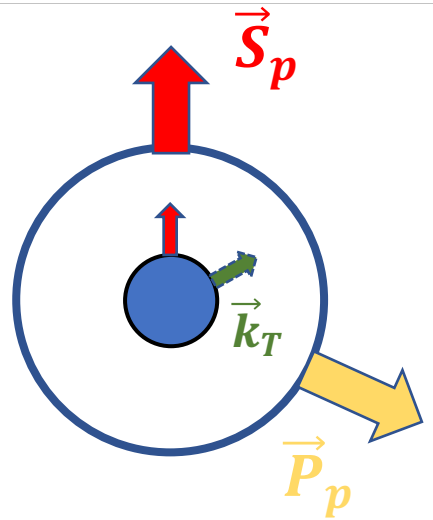
EIC White Paper arXiv:1212.1701

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



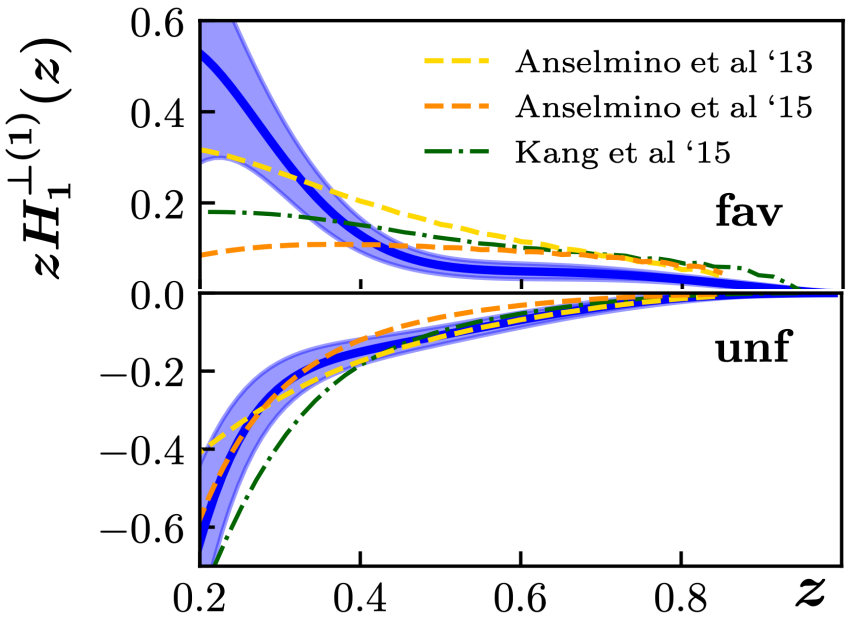


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

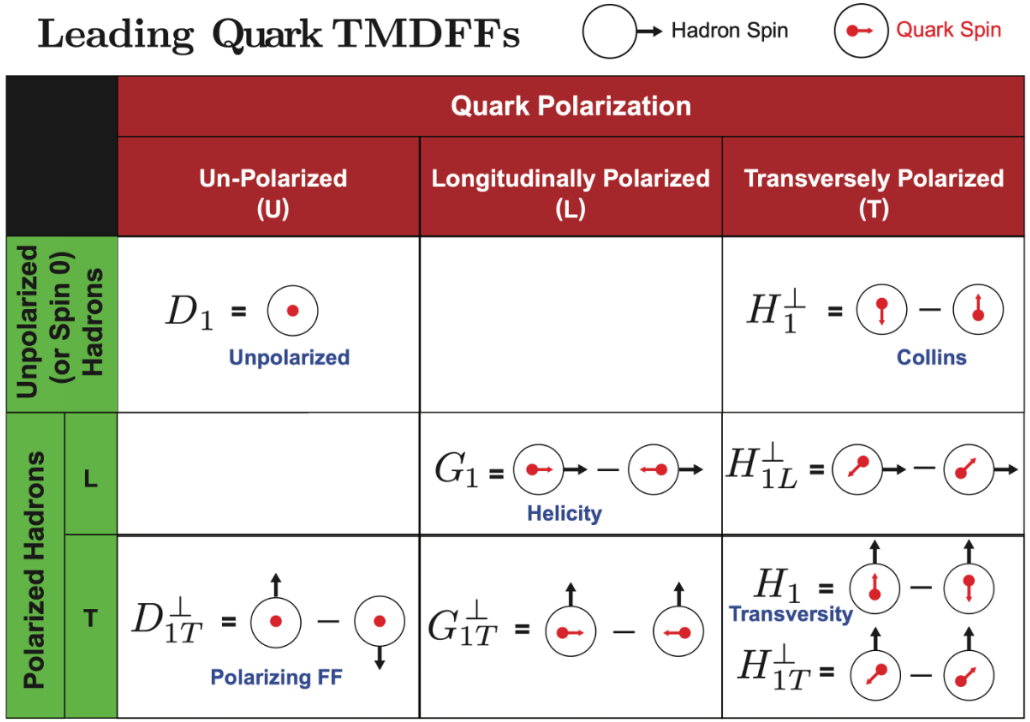


TMD Fragmentation Functions

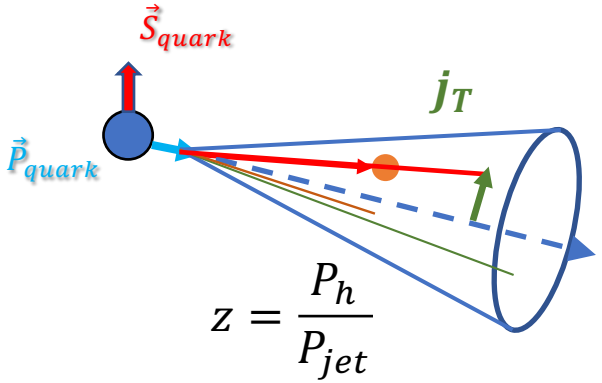
JAM Collaboration Phys. Rev. D, 106 034014 (2022)



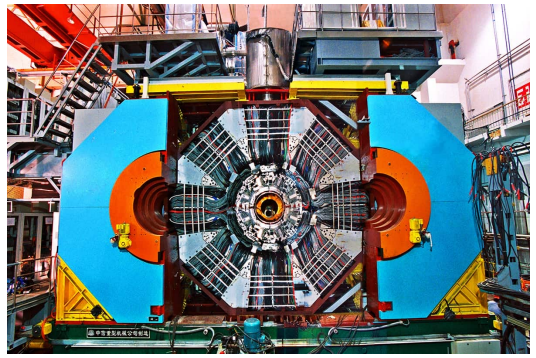
TMD Handbook, arXiv:2304.03302 [hep-ph]

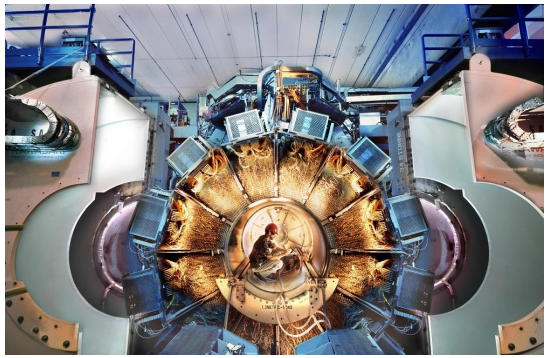


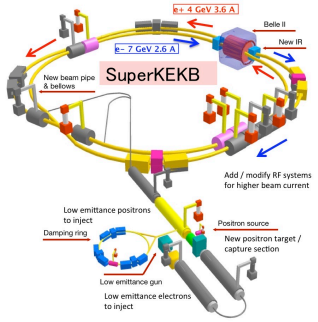
- The nonperturbative fragmentation process is encapsulated in a TMD fragmentation function (TMD FF), the final-state analog of the TMD PDF;
- Describe the correlation between the polarization and transverse momentum of the fragmenting quark and the properties of the final-state hadron.

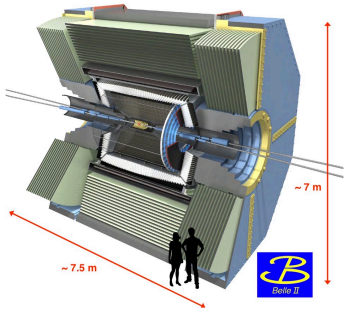


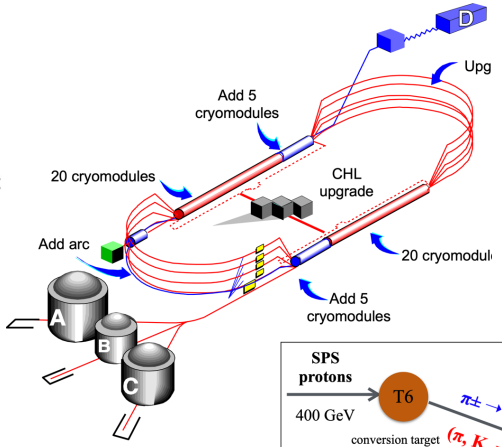
Experimental TMD Probes

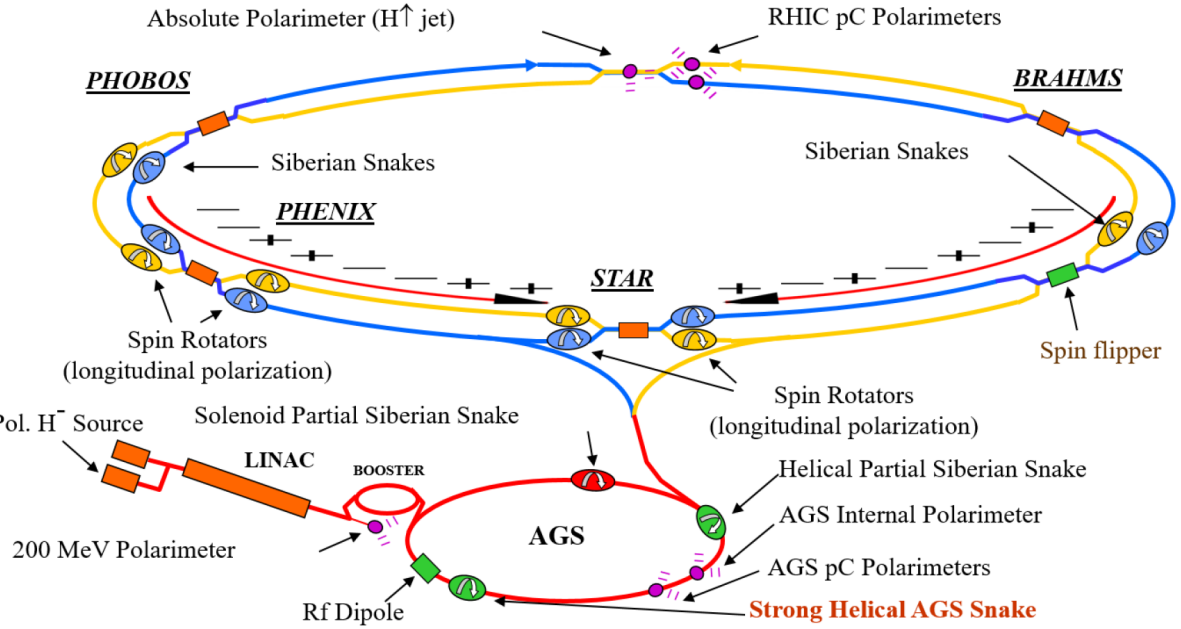


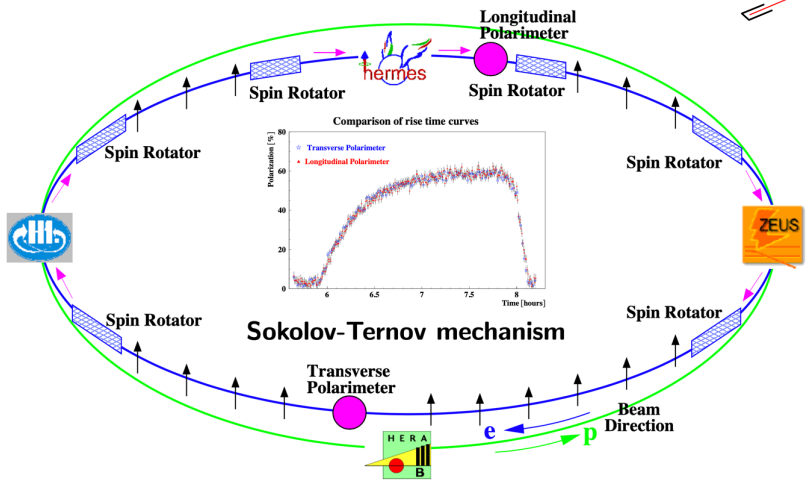


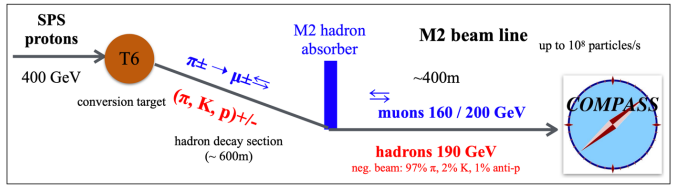


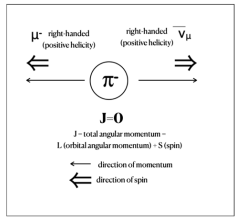


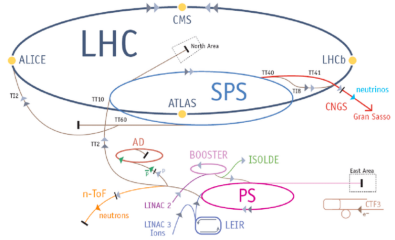


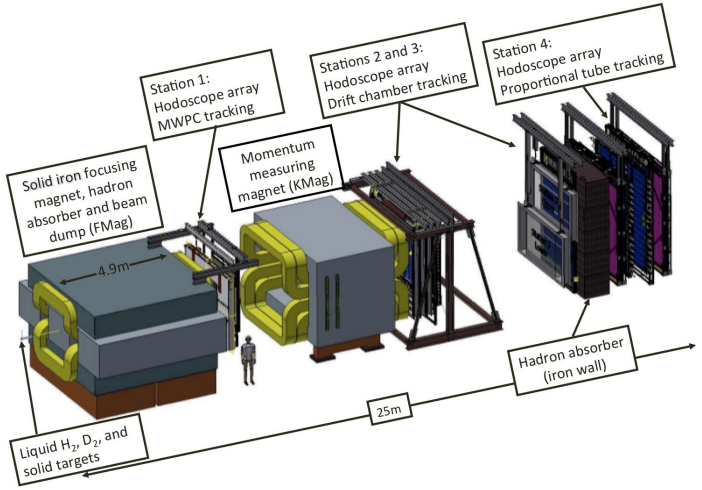




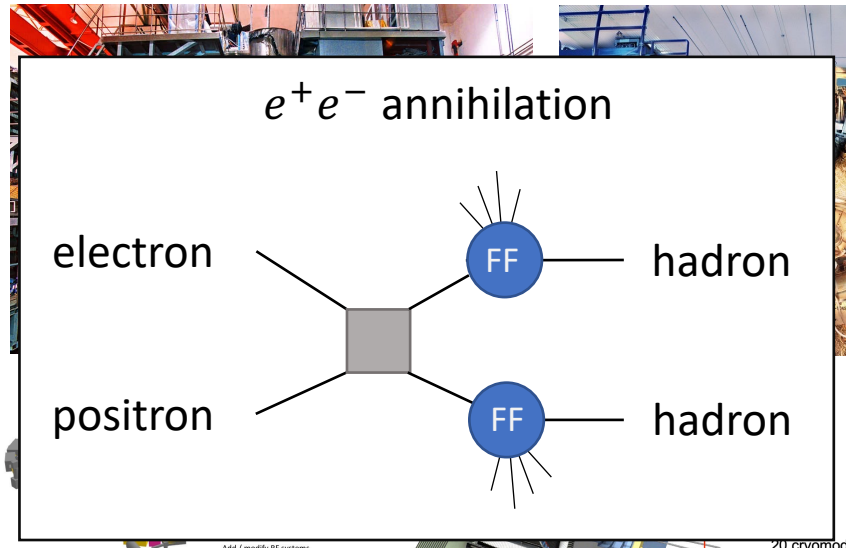


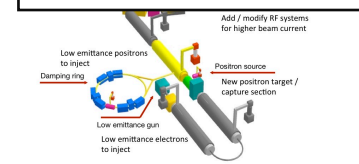


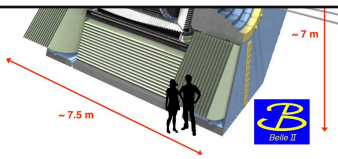


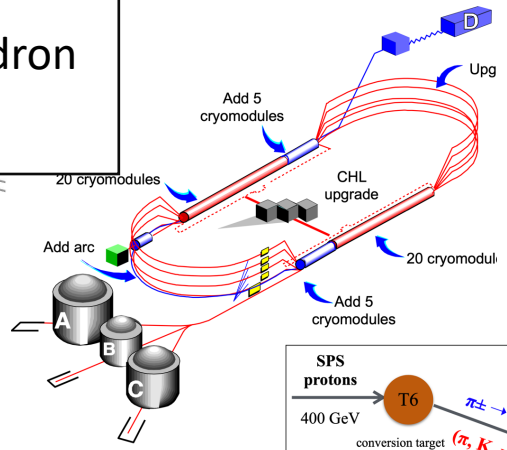


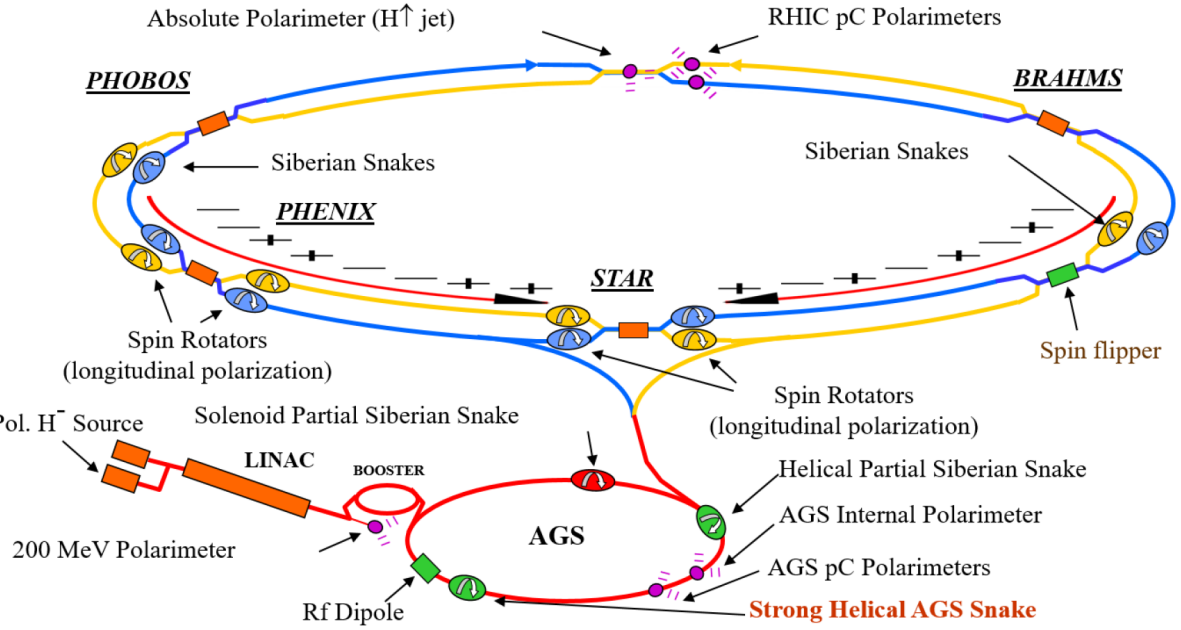
Experimental TMD Probes

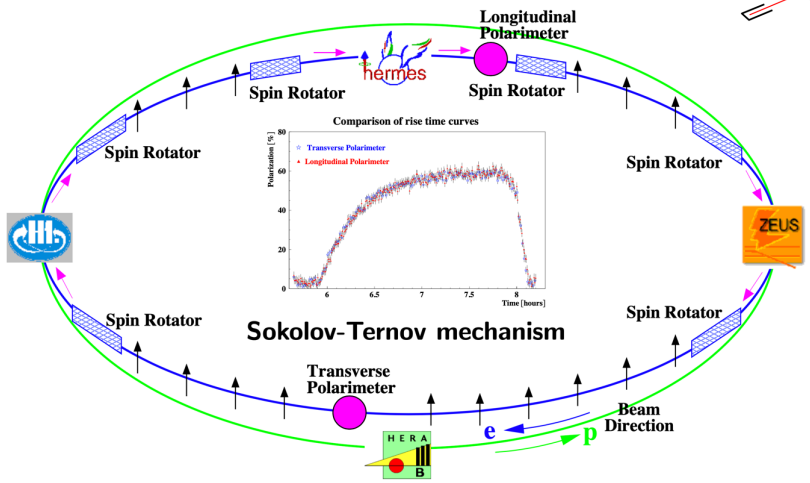


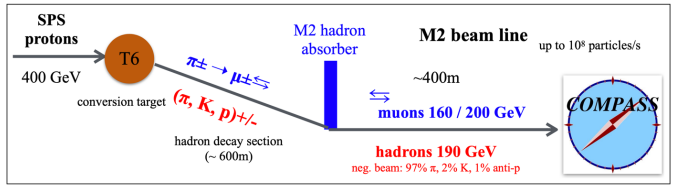


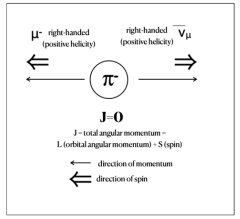


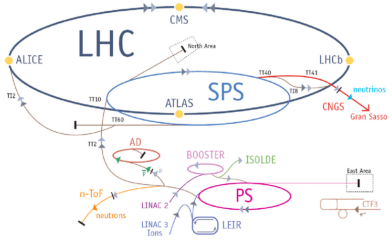


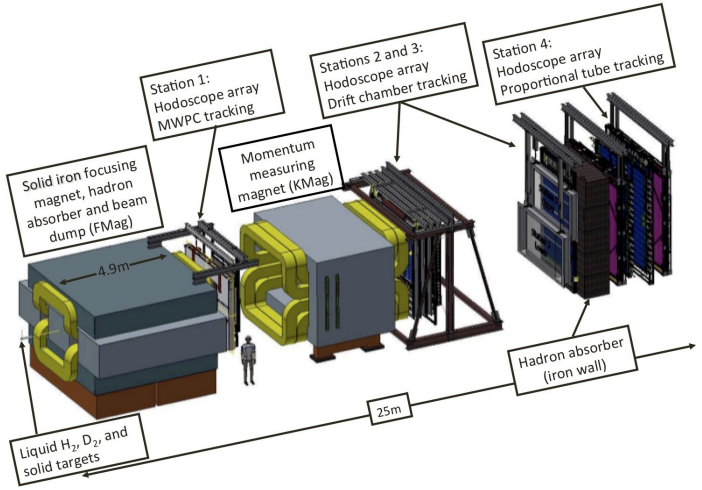












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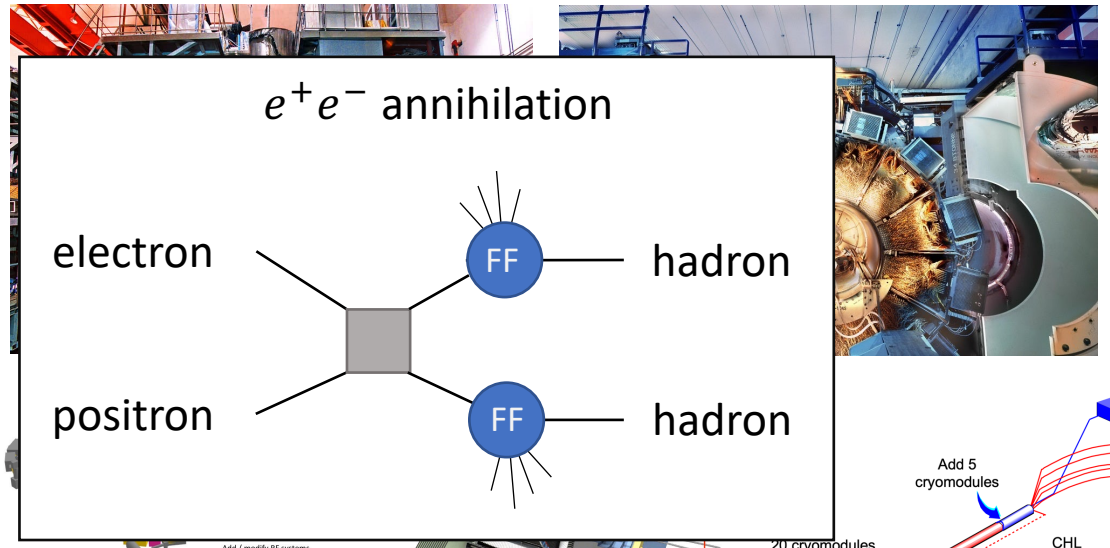

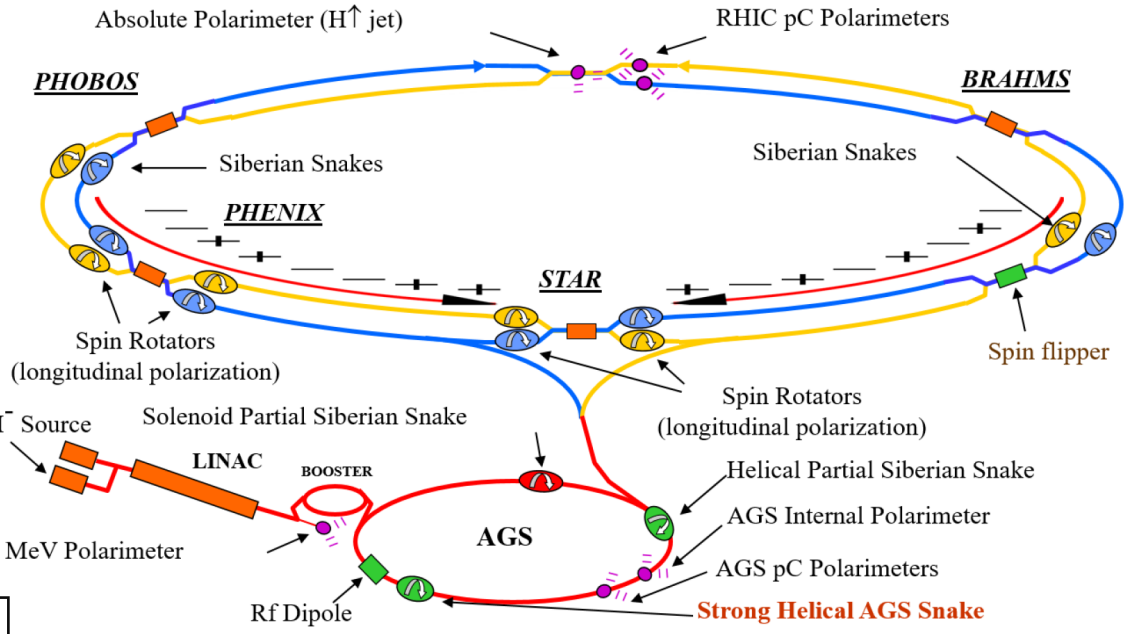

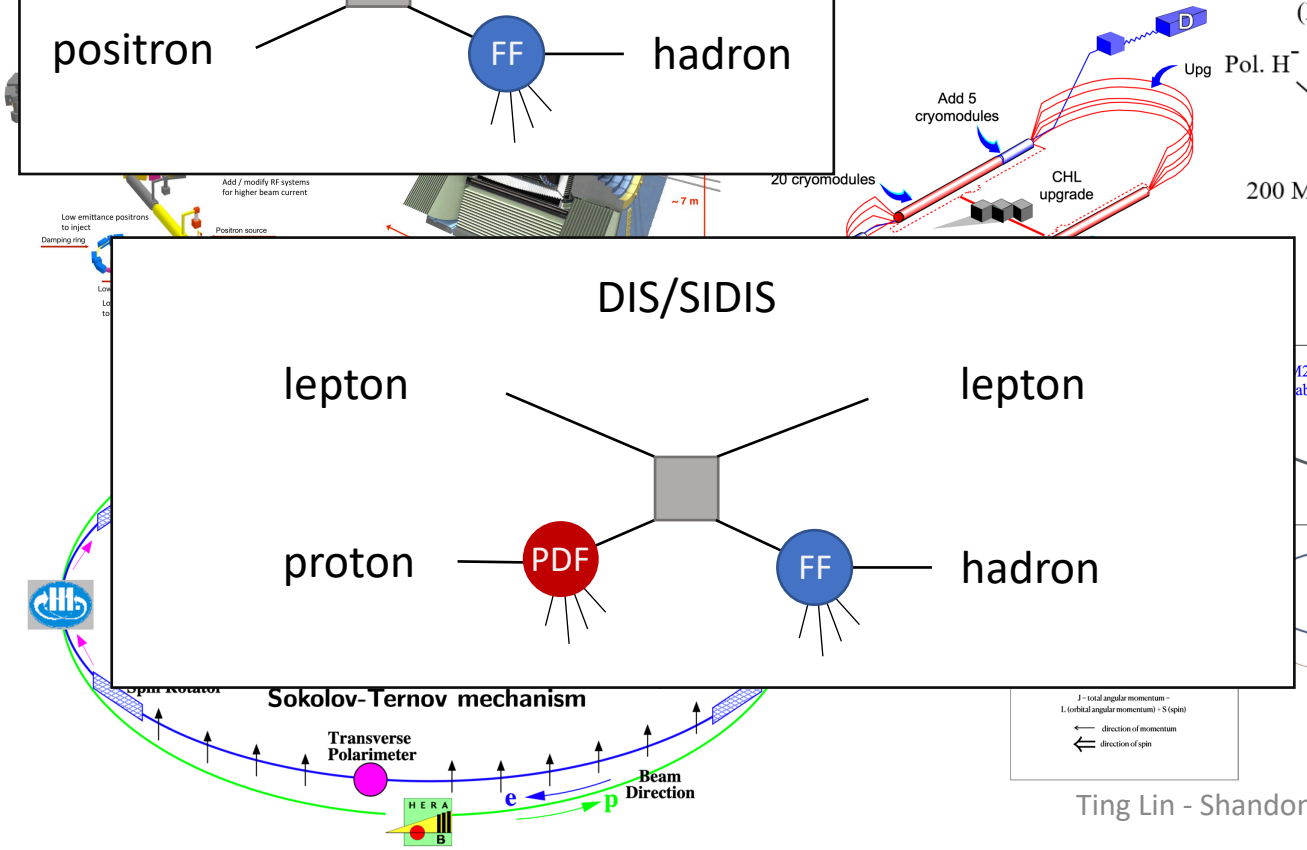

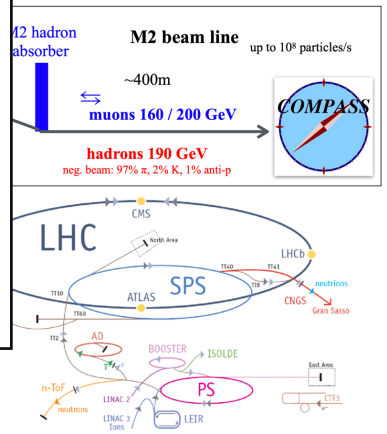

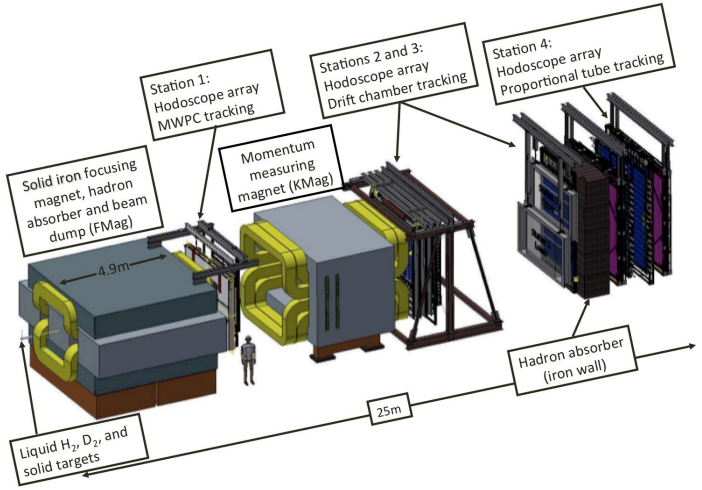

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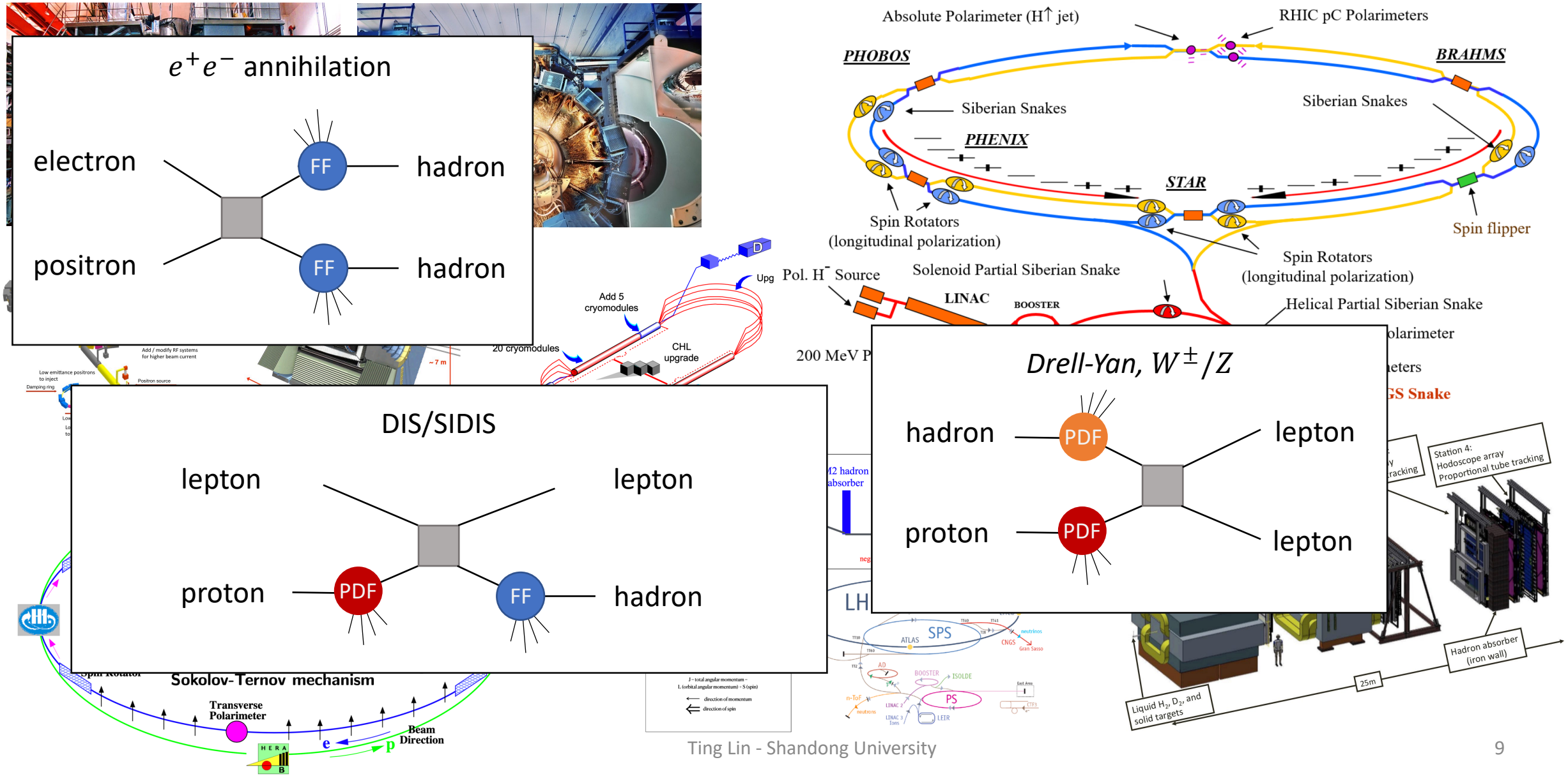

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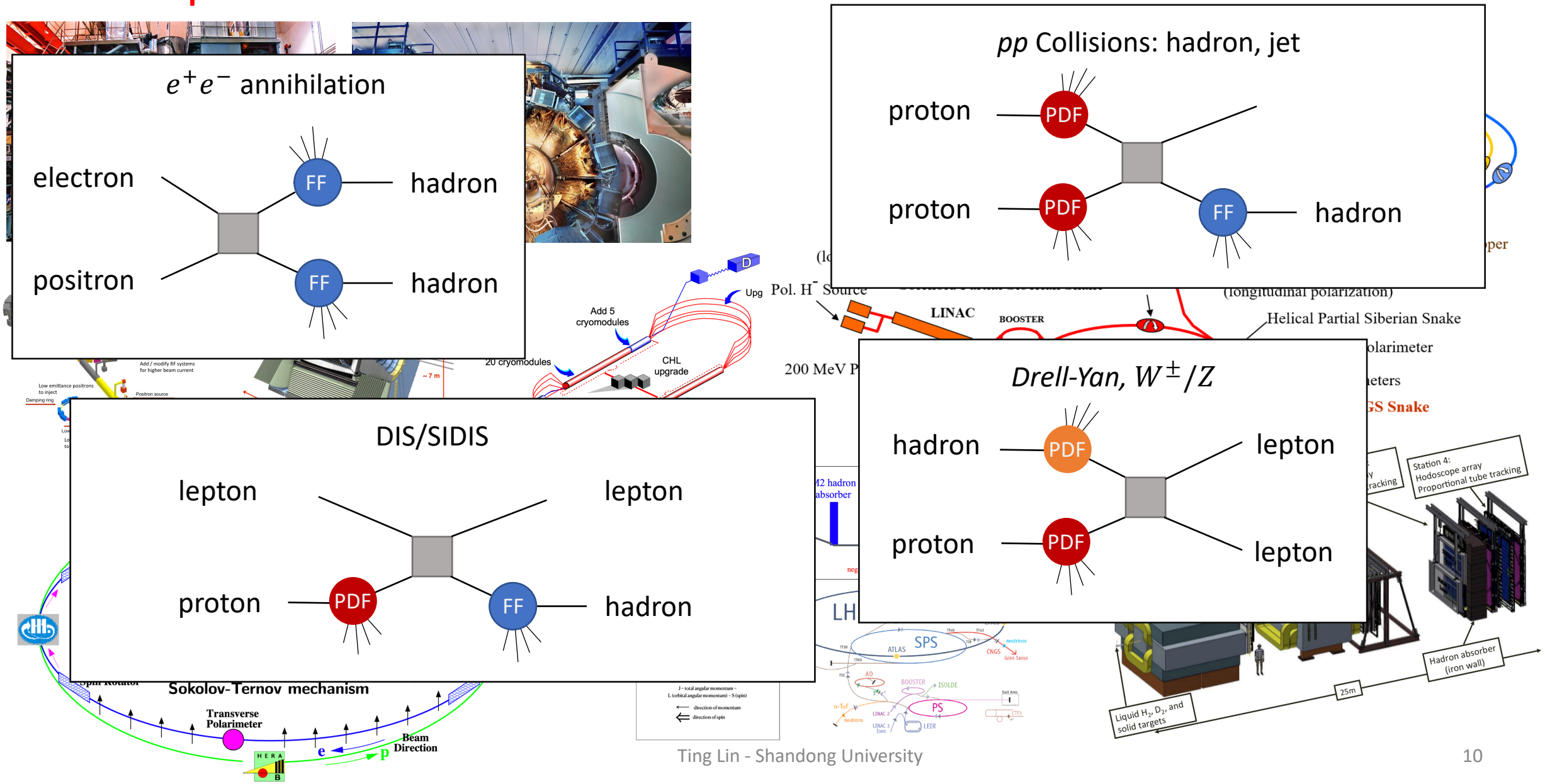
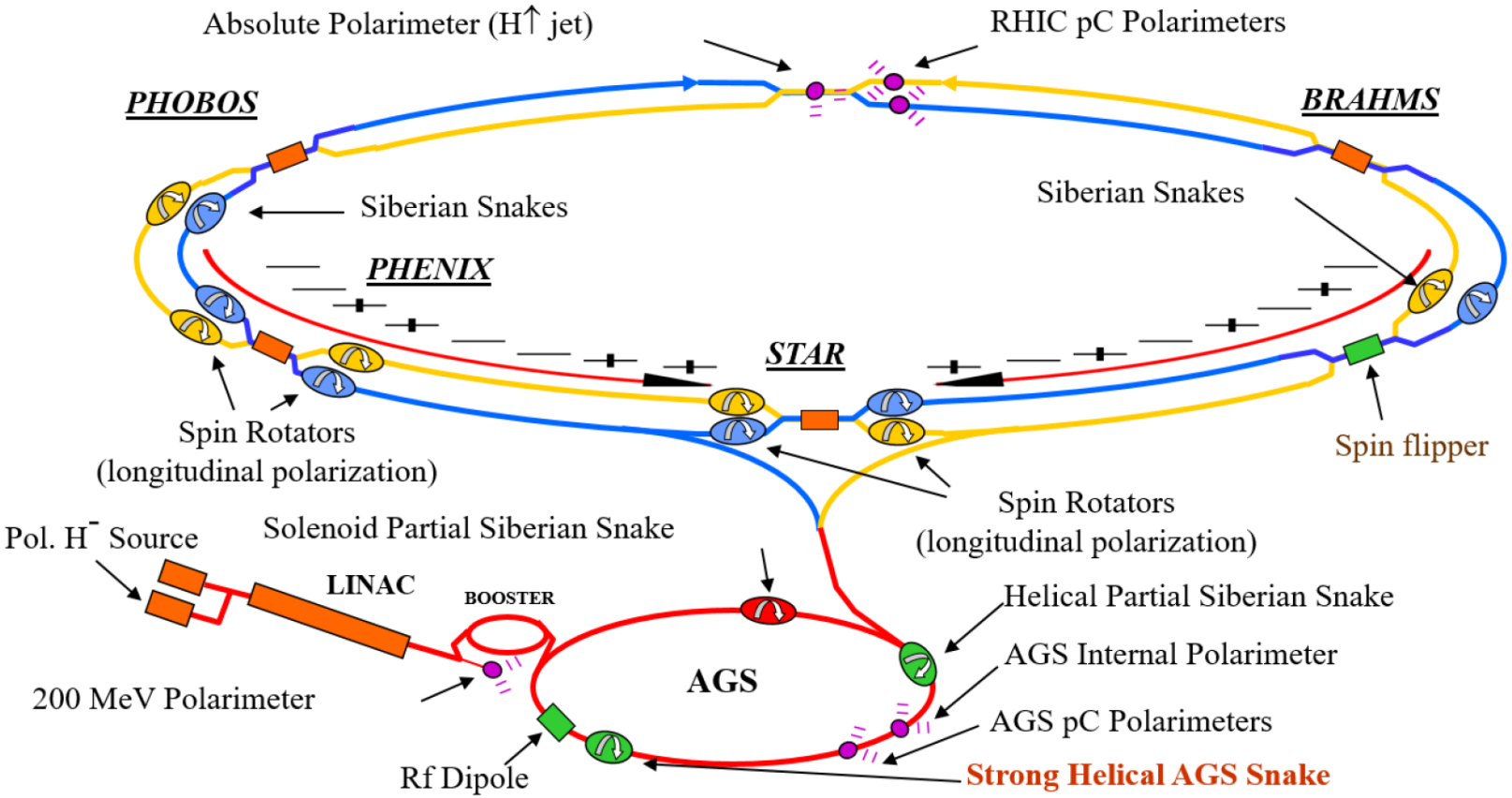
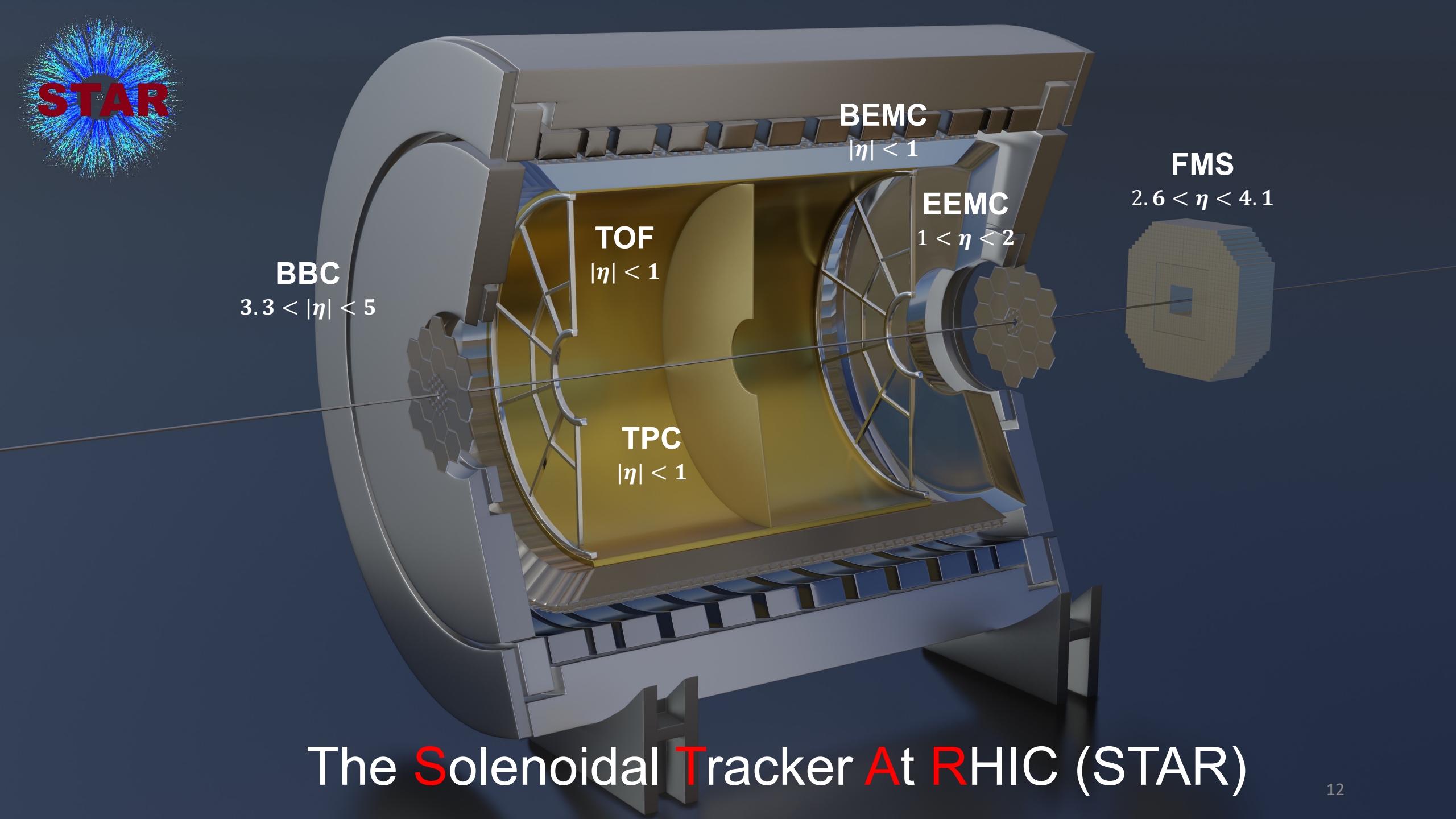


Relativistic Heavy Ion Collider (RHIC)



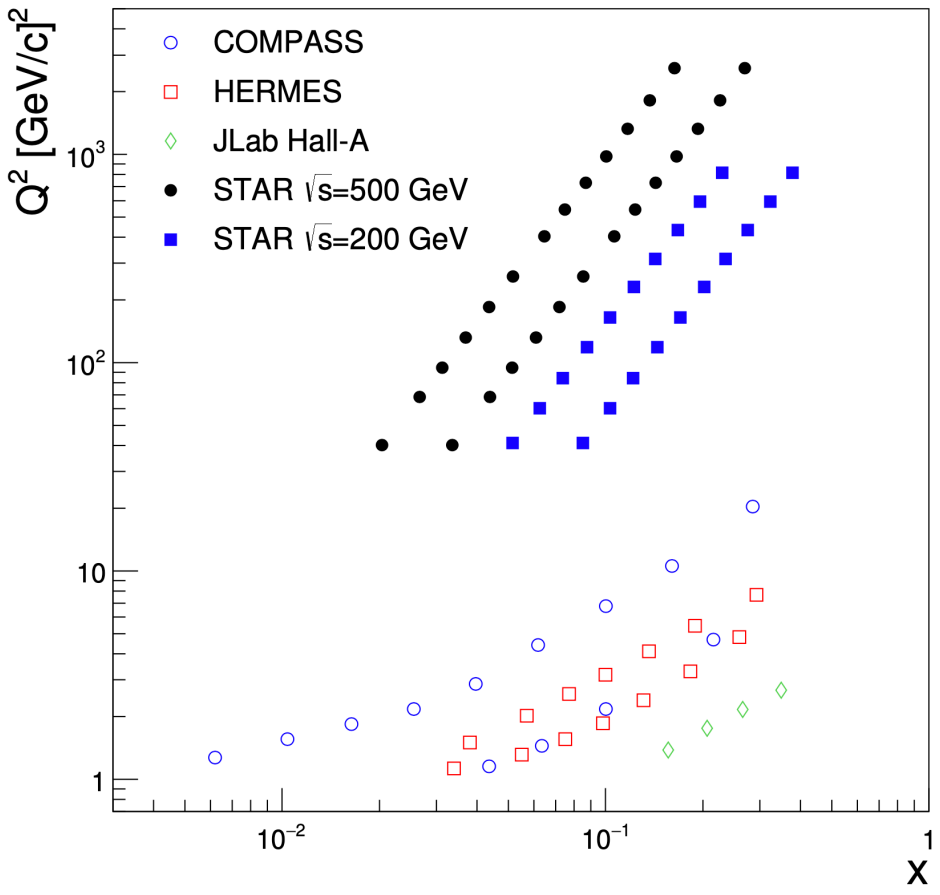
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.



The Solenoidal Tracker At RHIC (STAR)

STAR Data and Kinematic Coverage

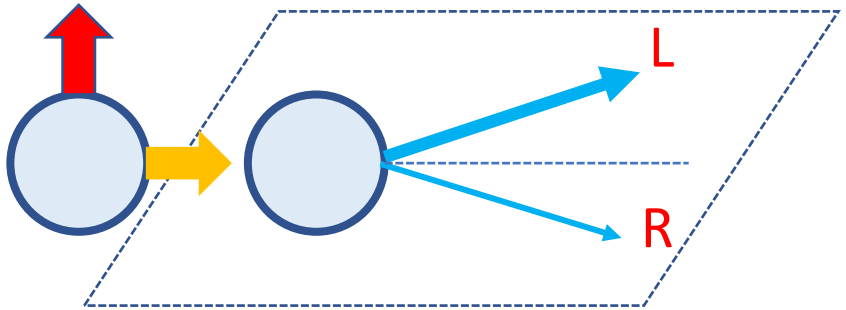
Year	2011	2012	2015	2017	2022	2024
$\sqrt{s}$ (GeV)	500	200	200	510	508	200
L_{int} (pb^{-1})	23	22	52	320	400	TBD
Polarization	53%	57%	57%	55%	53%	TBD



- 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 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.

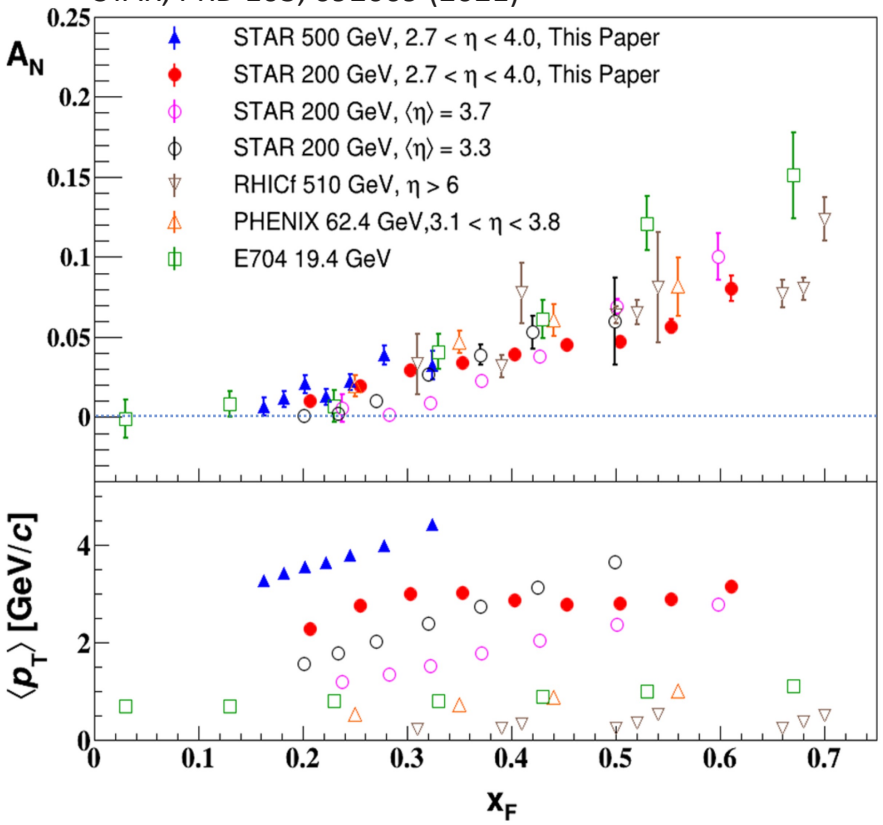
Transverse Single-Spin Asymmetry

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



$p^{\uparrow} + p \rightarrow \pi^0 + X$

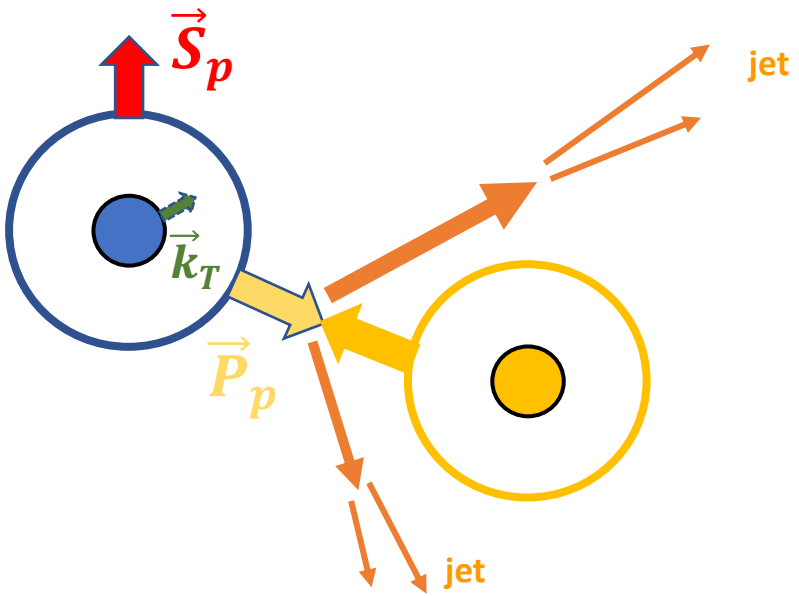
STAR, PRD 103, 092009 (2021)



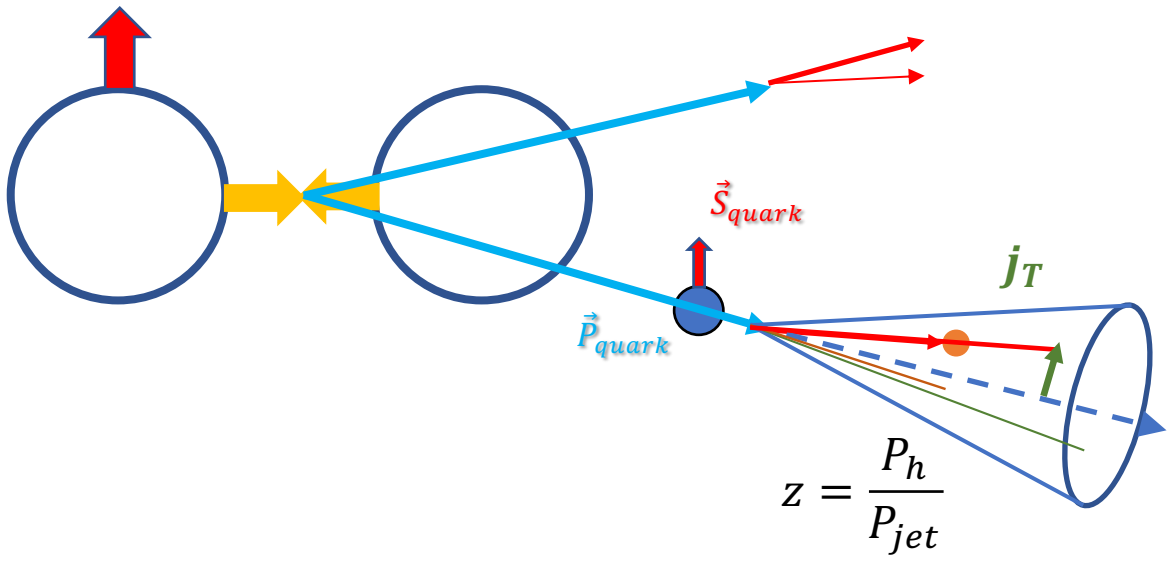
- Large transverse single-spin asymmetry (A_N) has been observed in transversely polarized pp collisions;
- Possible contributions: twist-3 correlators associated with the Sivers functions, Collins FF, diffractive Processes.

Initial and Final State Effect

Sivers Effect



Collins Effect

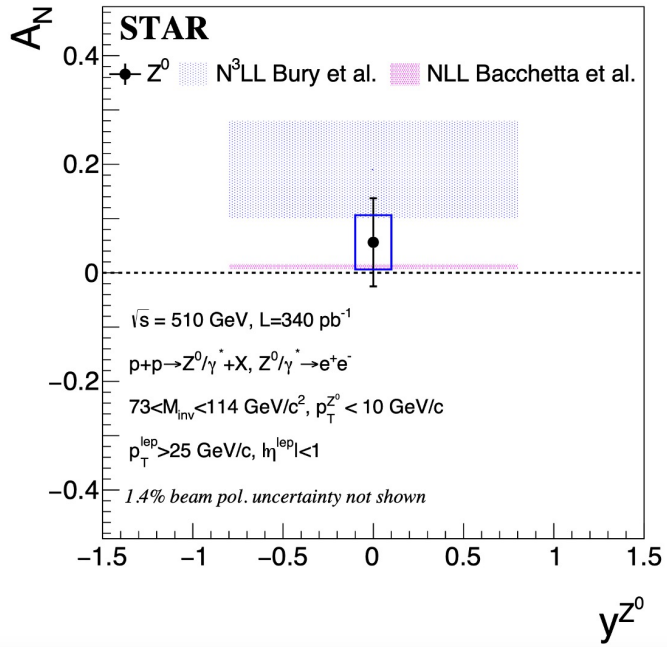


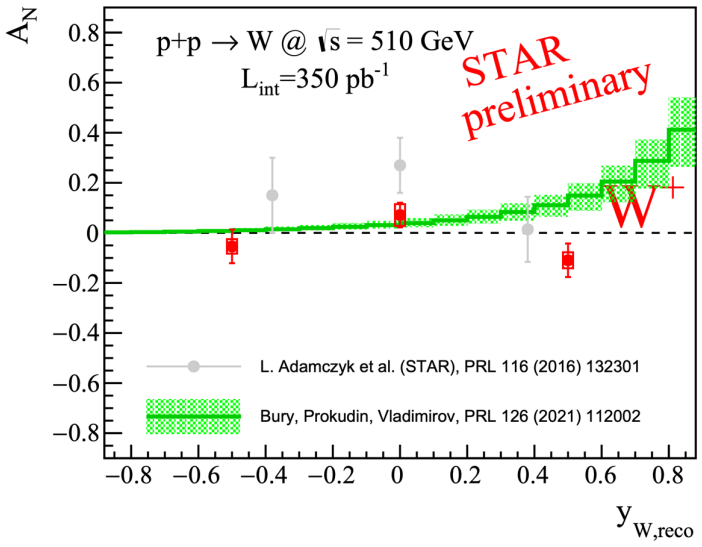
- Correlations of initial-state parton transverse momentum with proton's spin and momentum: $\sim \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T)$
- Non-universality exhibits the process dependence.

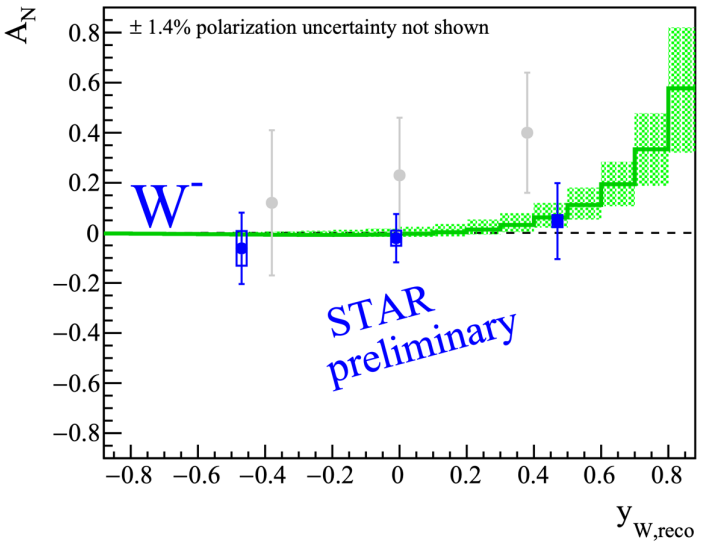
- Correlation between the polarization of a scattered quark and the momentum of hadron fragment transverse to the scattered quark direction: $\sim \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T)$;
- Chiral-odd, should couple with another chiral-odd distributions.

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

STAR, arXiv: 2308.15496



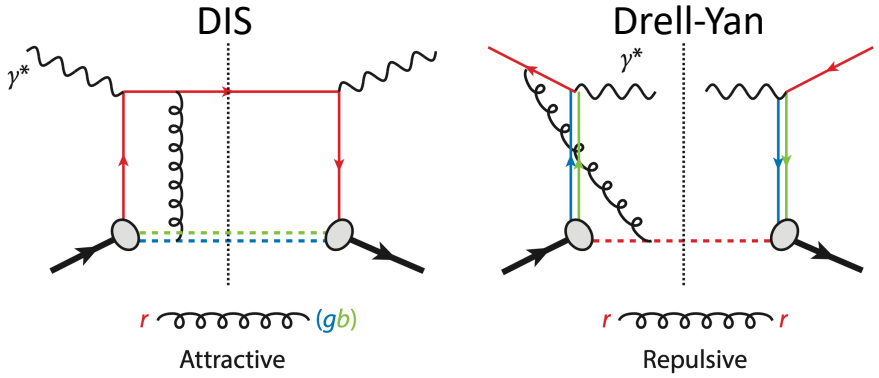




- Test the nonuniversality nature of Sivers function:

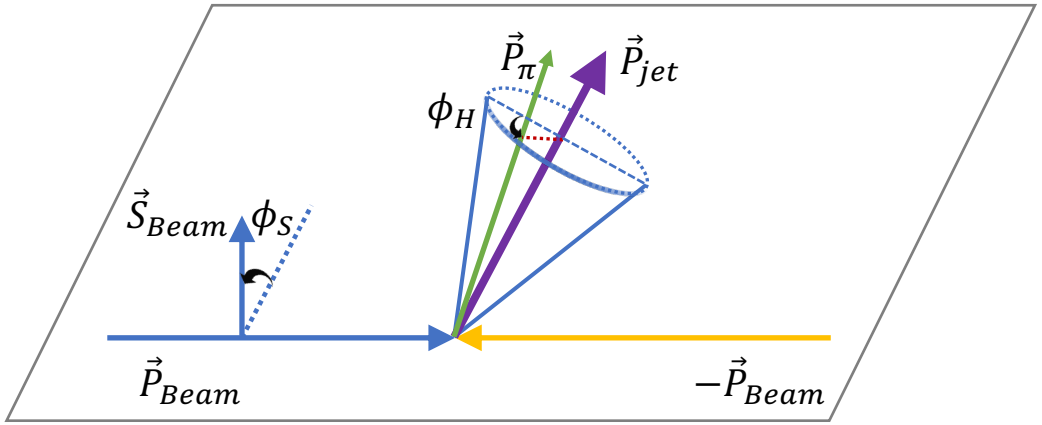
$$\text{Sivers}_{SIDIS} = -\text{Sivers}(\text{Drell} - \text{Yan or } W/Z)$$

- A fundamental prediction from the gauge invariance of QCD.



Separating the Initial and Final State Effect

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



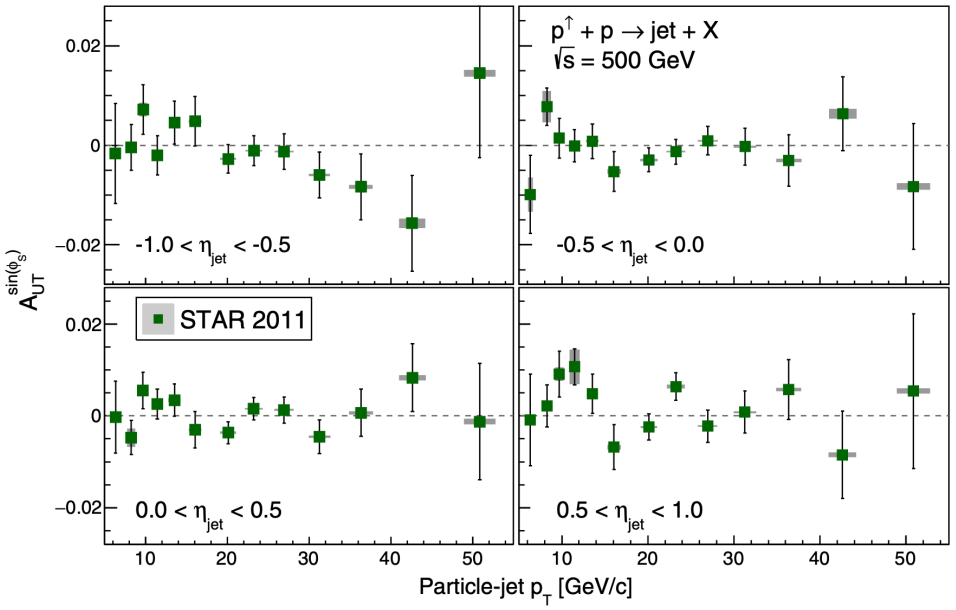
$$d\sigma^{\uparrow}(\phi_S, \phi_H) \sim A_{UT}^{Sivers} \sin(\phi_S) + A_{UT}^{Collins} \sin(\phi_S - \phi_H)$$

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

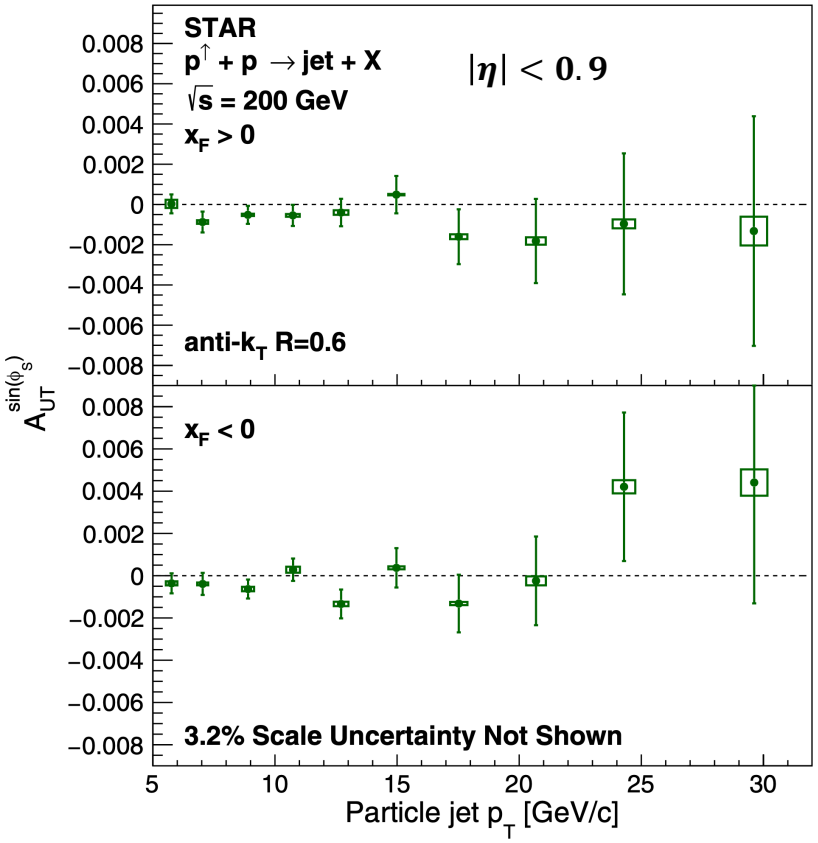
- Each TMD PDF is convoluted with a fragmentation function and appears with a independent harmonic modulations (azimuthal asymmetry amplitudes).

A_N for Inclusive Jet

STAR, PRD 97, 032004 (2018)



STAR, PRD 106, 072010 (2022)



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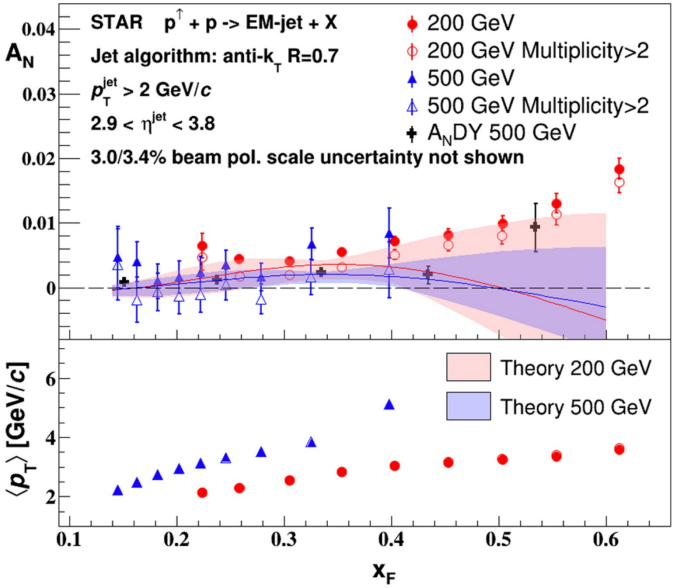
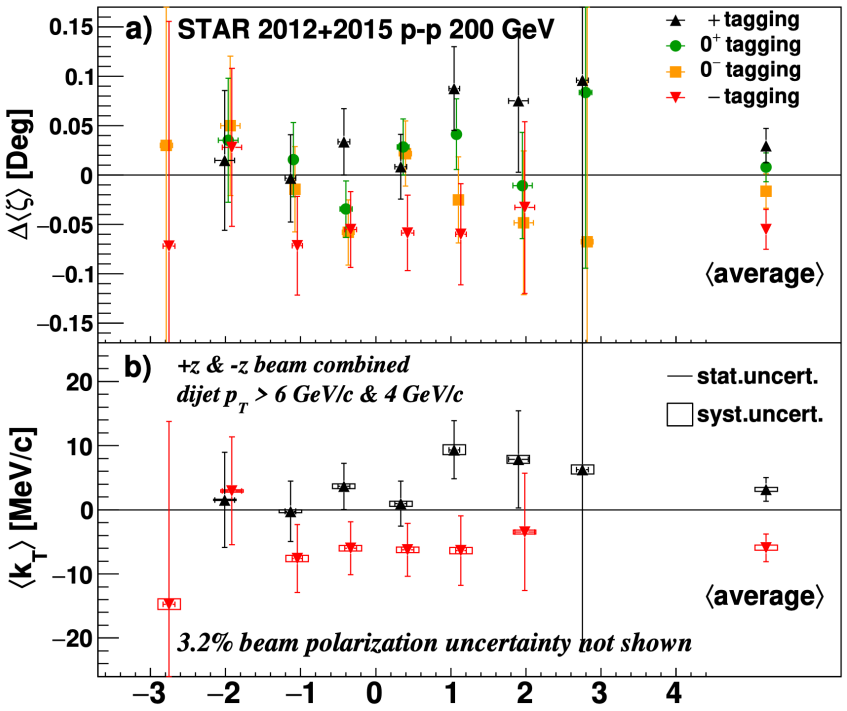


- Inclusive jet A_N are sensitive to the Sivers function via the twist-3 correlators;
- Free of final-state contributions.

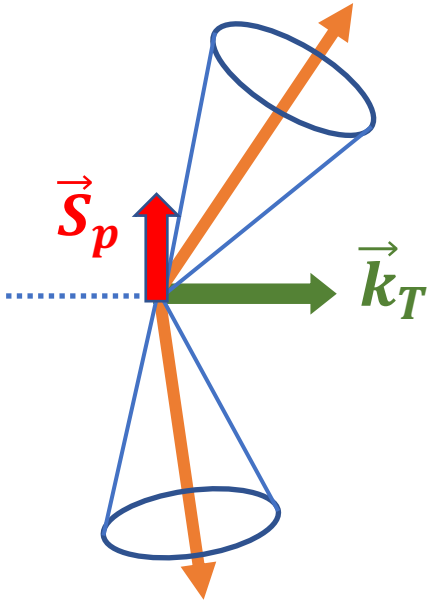
Transverse Single-Spin Asymmetries for Dijet

STAR, arXiv:2305.10359

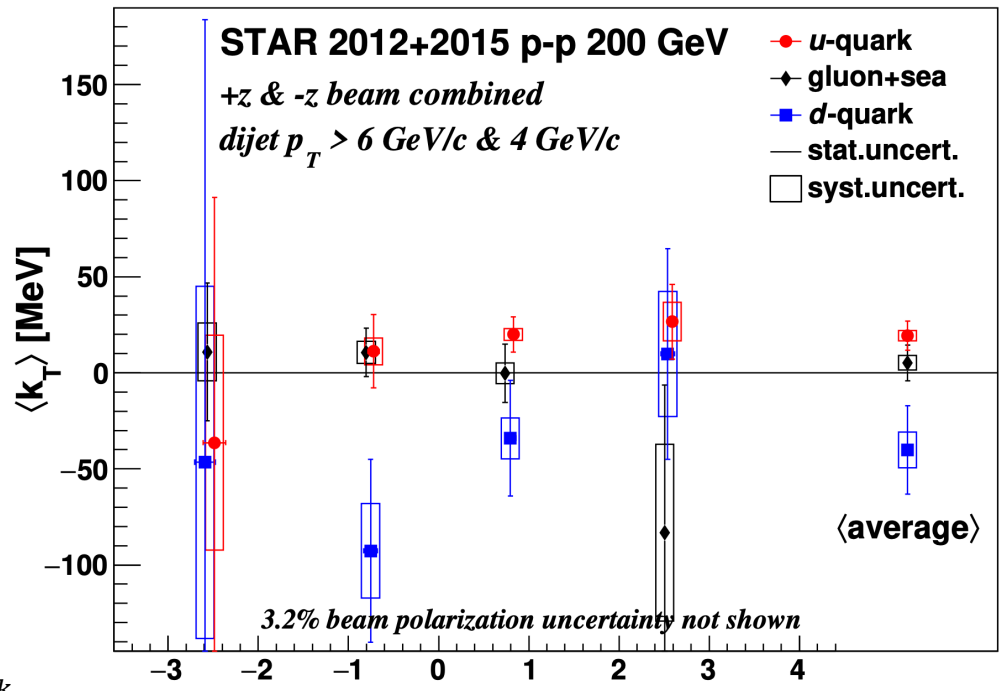


$$\eta^{total} = \ln\frac{x_1}{x_2}$$

transverse plane



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



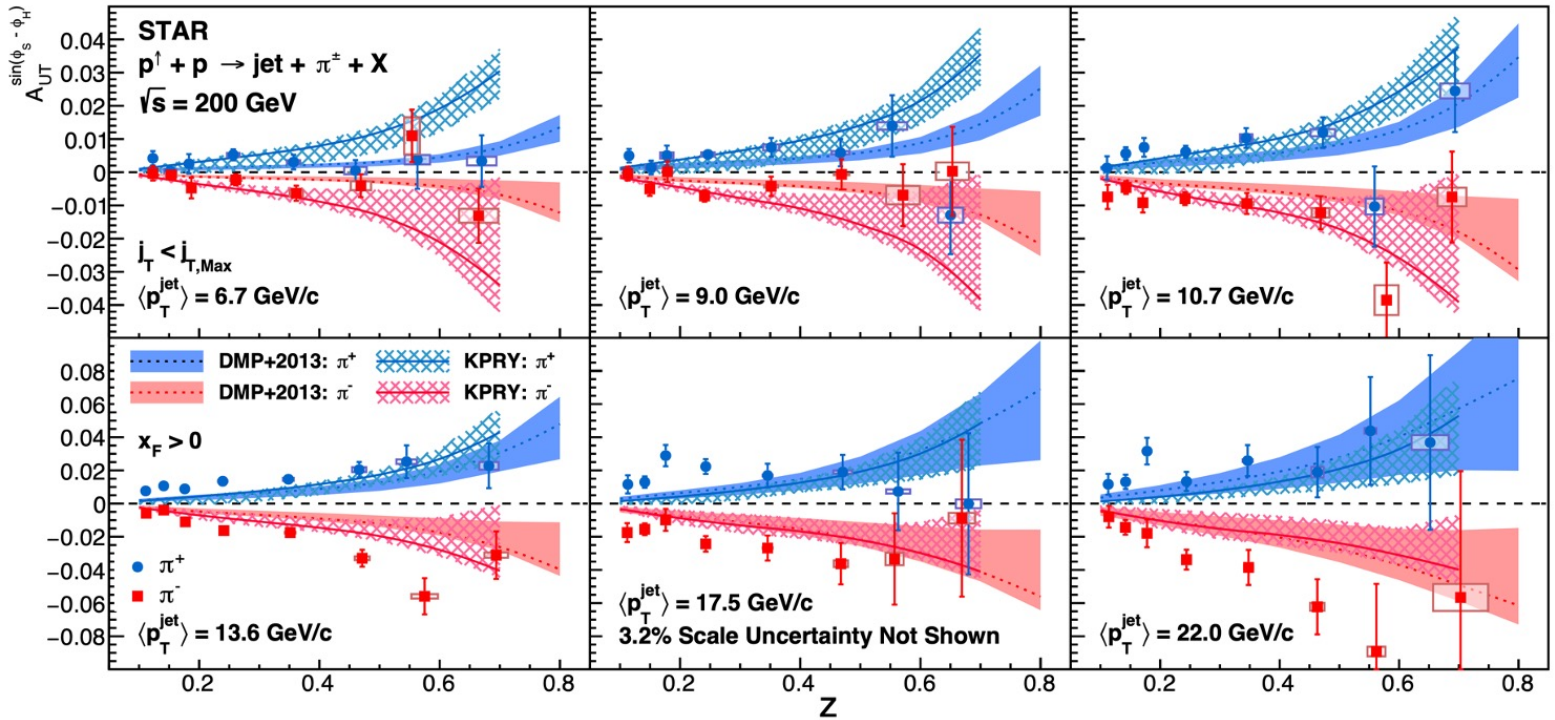
$$\eta^{total} = \ln\frac{x_1}{x_2}$$

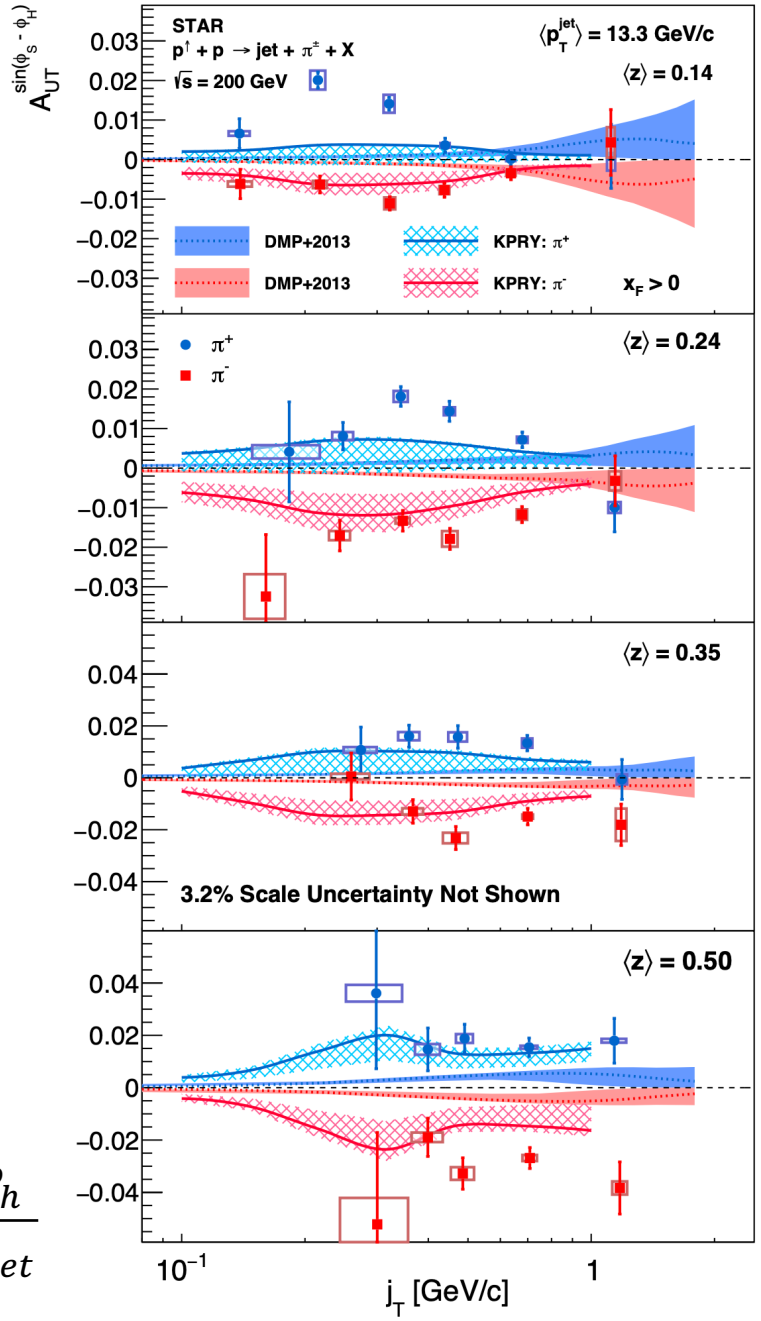
- First observation of non-zero Sivers asymmetries in dijet production in polarized p+p collisions;
- $\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6$ MeV/c, $\langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3$ MeV/c, $\langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8$ MeV/c.

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

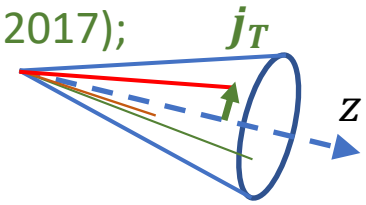
STAR, PRD 106, 072010 (2022)

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





- 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.



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

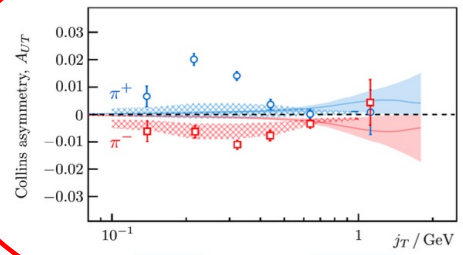


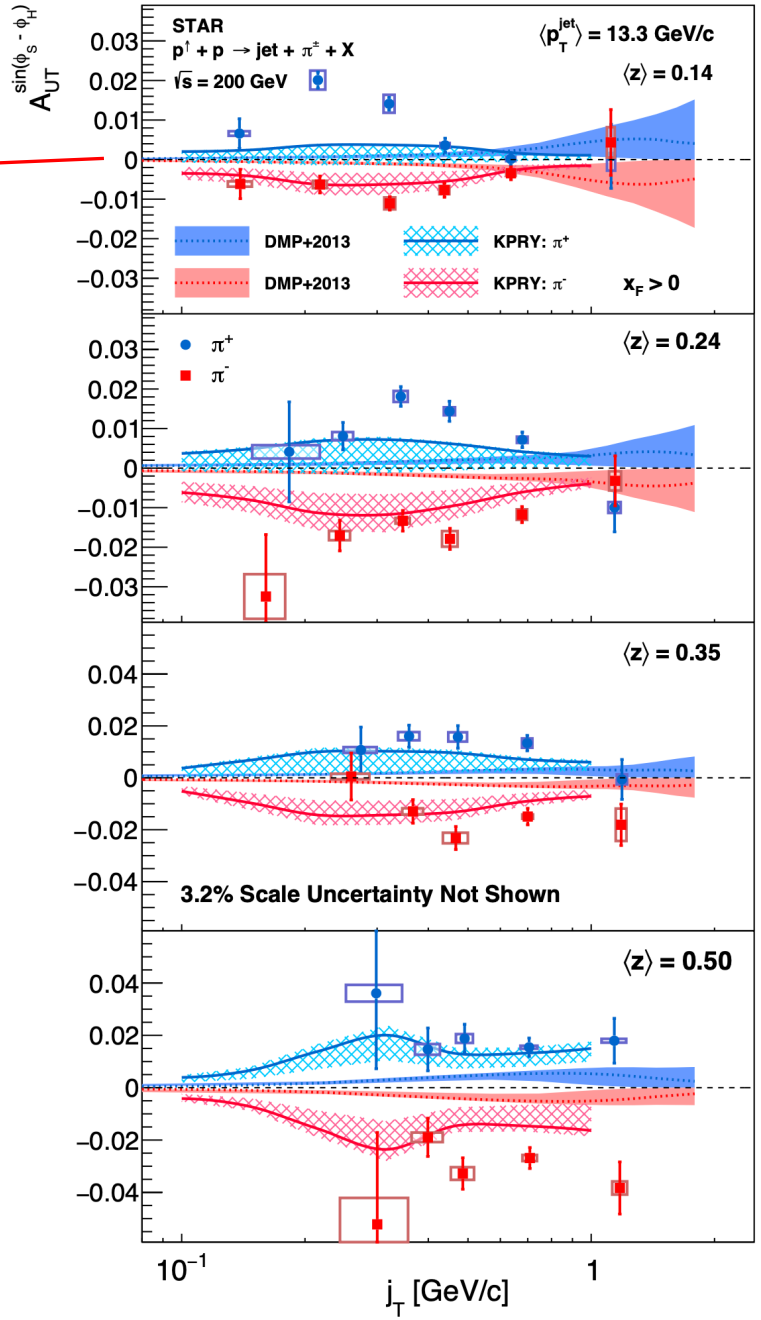
Figure 3.5. Measurements by the STAR experiment at RHIC of the Collins asymmetries for positive and negative pion production in transversely polarized proton-proton collisions. The Collins TMD distribution describes a spin–momentum correlation in the process of hadronization and is shown here as a function j_T, the momentum of the pion transverse to the jet axis. Theoretical evaluations are shown as bands that do not describe the π^+ data well, indicating the need for improved theoretical understanding [5].

To understand how quarks and gluons in QCD relate to detectable bound states requires studying additional hadrons (i.e., beyond protons and neutrons).

Mesons built from the lightest up, down, and strange quarks, such as the pions, kaons, and etas, are the lightest hadrons and are the most abundantly produced. Studying these mesons can provide insight into the mechanism responsible for the emergence of hadron mass and can be used to determine the ratio of the up and down quark masses in a model-independent manner. Measurements of pion structure and the pion decay rate were recently completed at Jefferson Lab, and a wider program of meson structure studies is planned at Jefferson Lab and at the EIC.

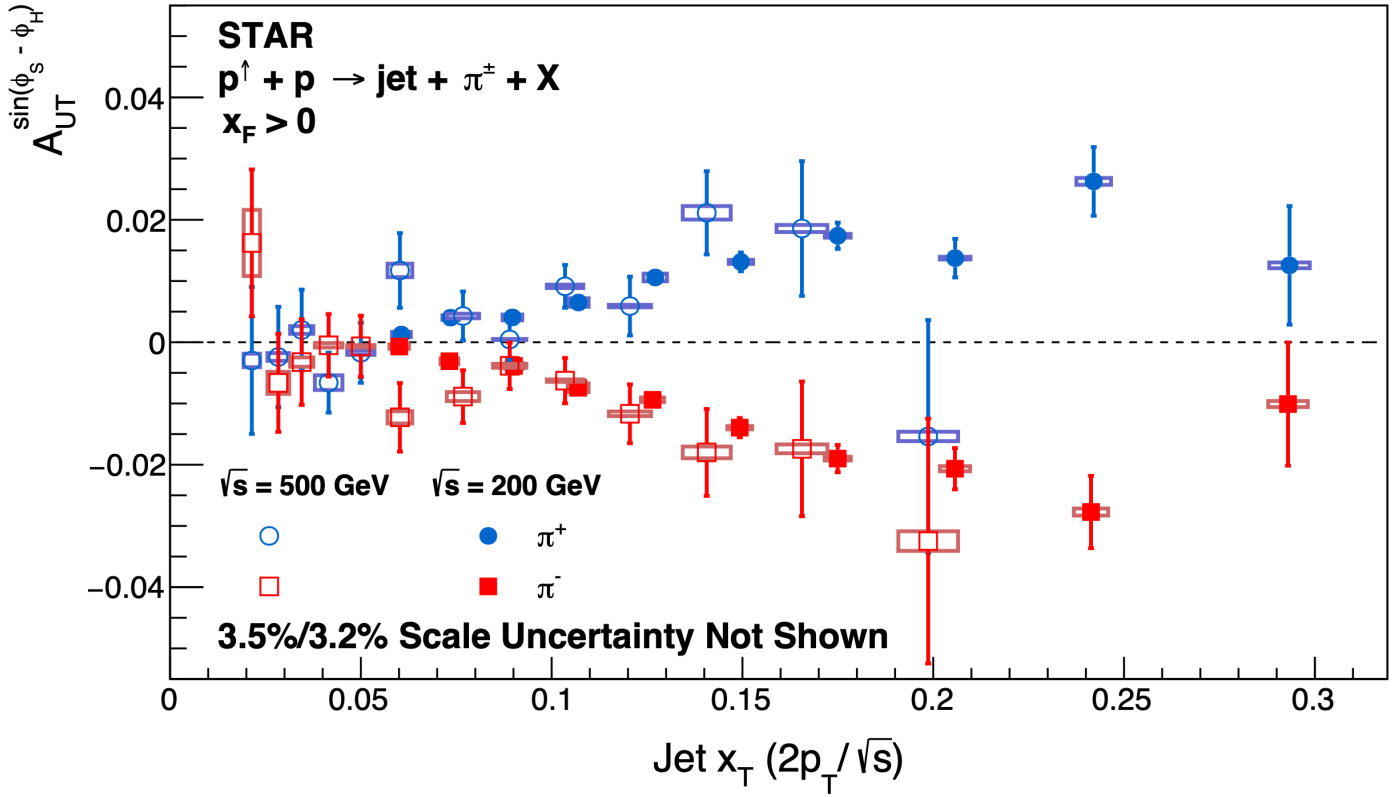
3.2.5. SPECTRUM OF EXCITED HADRONS

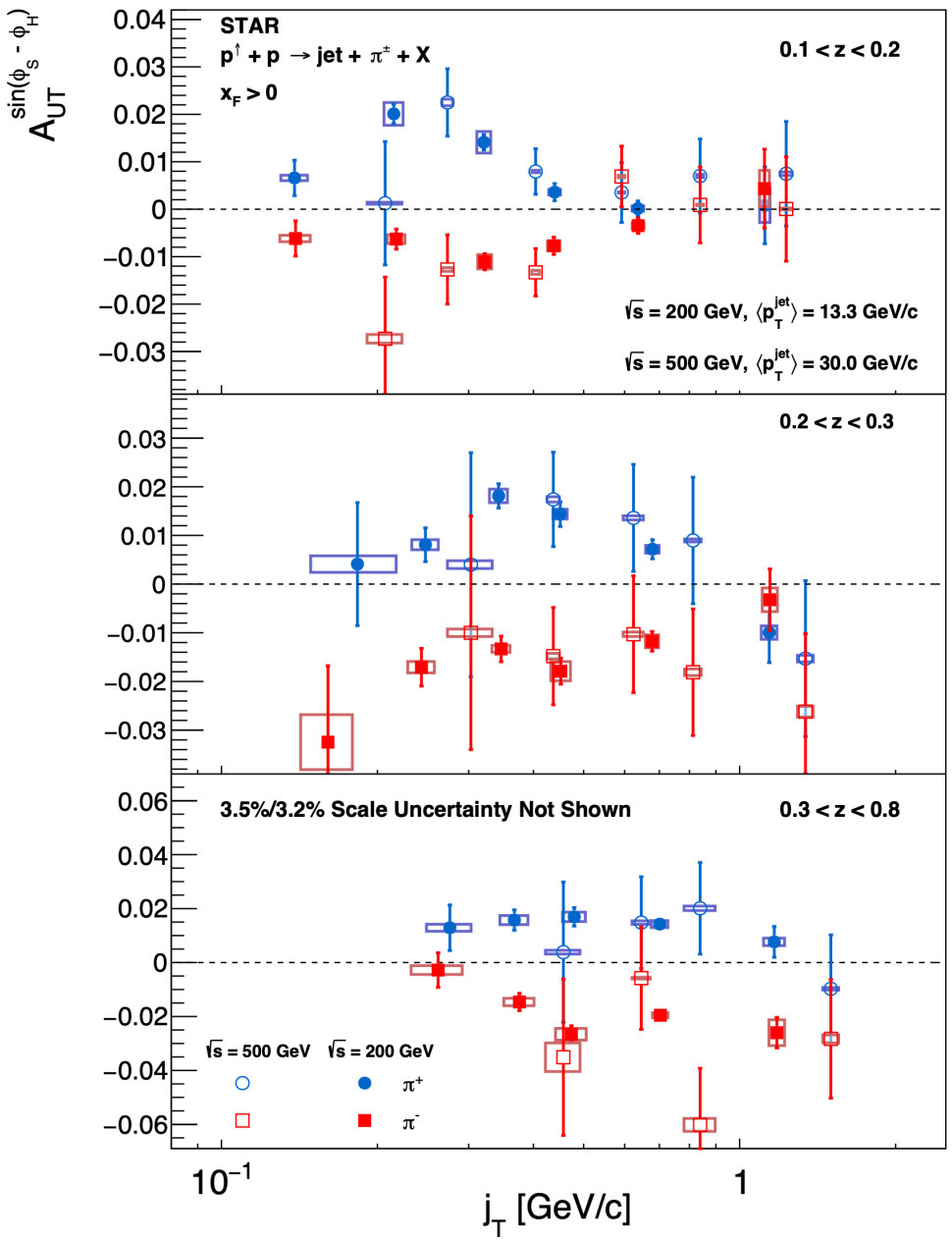
Just as atomic spectroscopy explores excited states of atoms by studying decays to their ground states by photon emission, hadron spectroscopy explores the possible bound combinations of quarks and gluons allowed by the interactions of QCD. Most hadrons, beyond the lightest few, appear as short-lived resonances that promptly decay into detectable lighter hadrons. Characteristic quantum properties of the hadron resonances are inferred from the measured



Comparison with 500 GeV Results

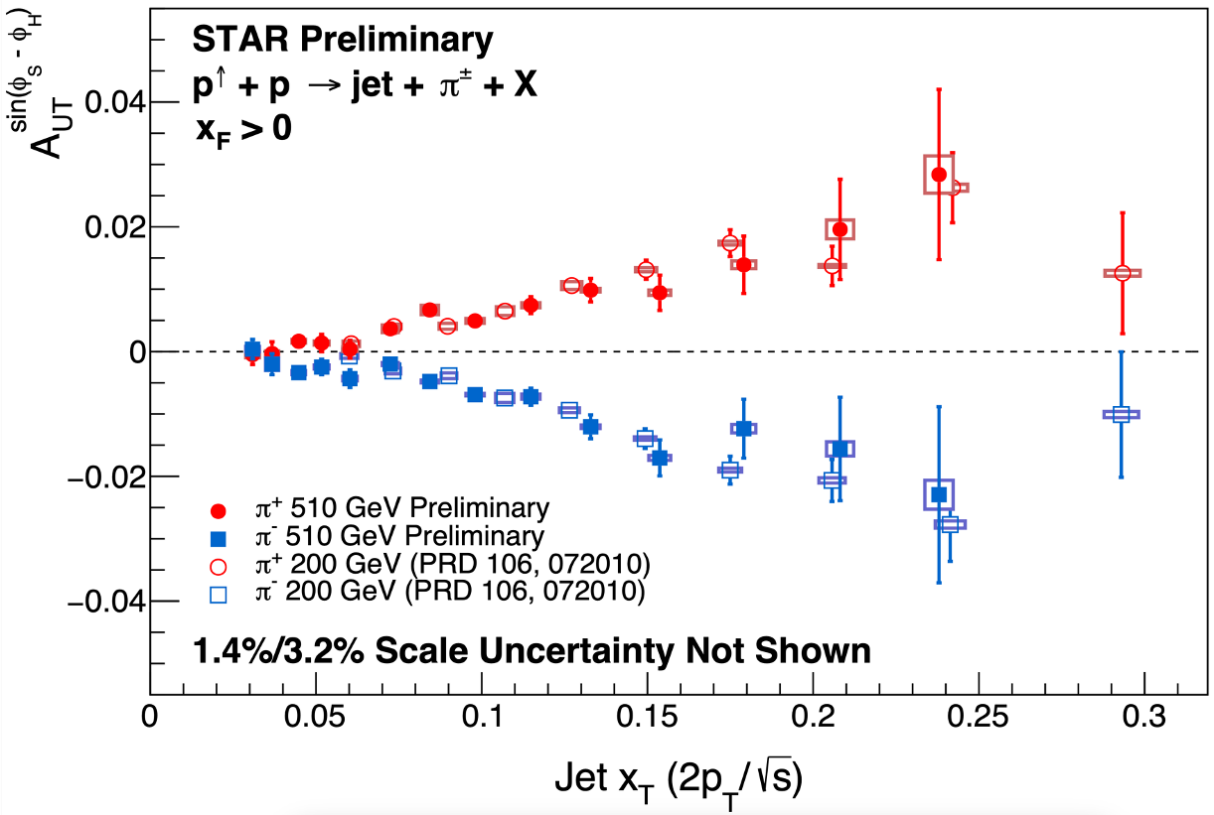
pp500 from: STAR, Phys. Rev. D 97, 032004 (2018)

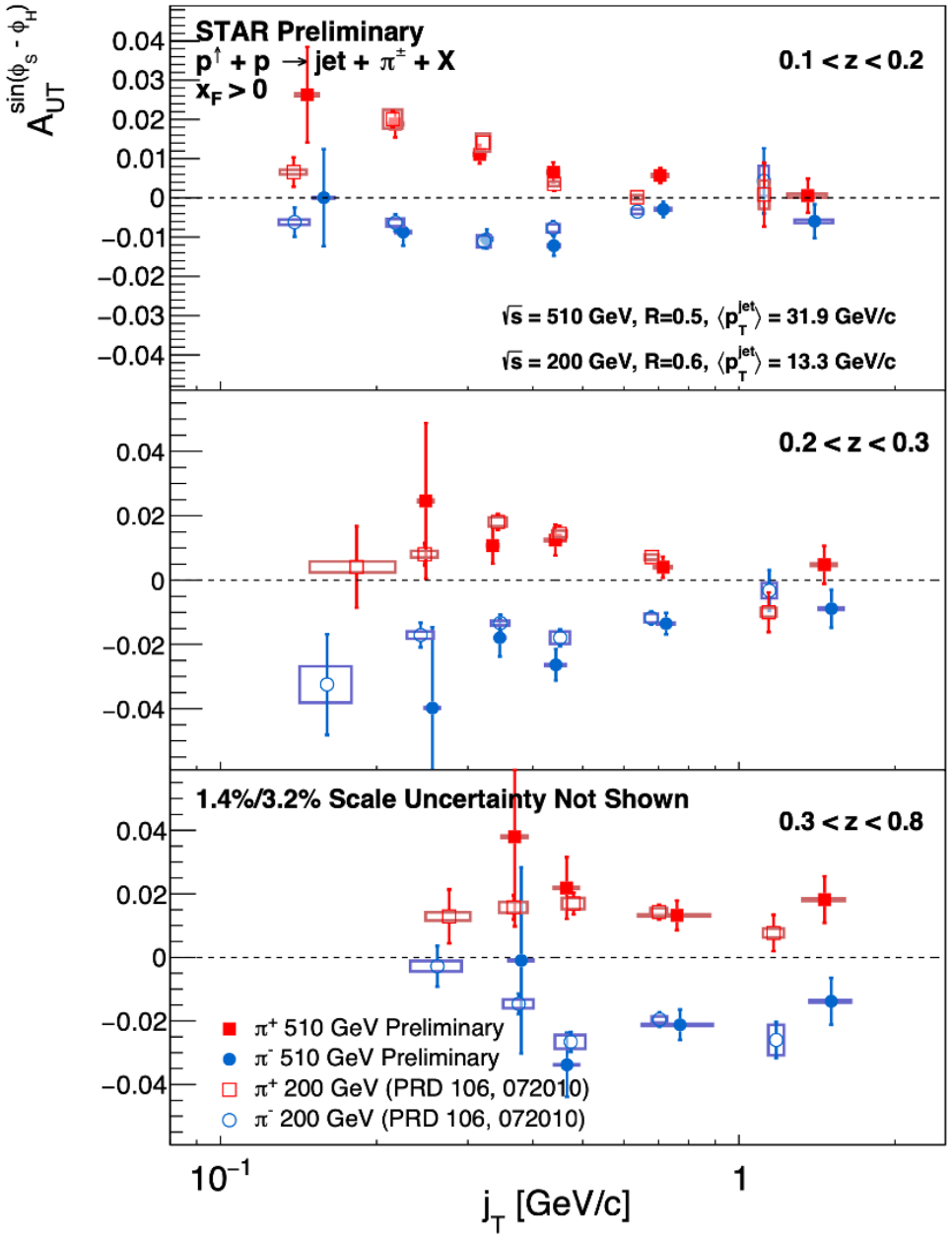




- The asymmetries agree at $0.06 < x_T < 0.2$, Q^2 differ by a factor of 6;
- Collins asymmetry has a weak energy dependence in hadronic collisions;
- z and j_T dependences of the Collins FF are closely related.

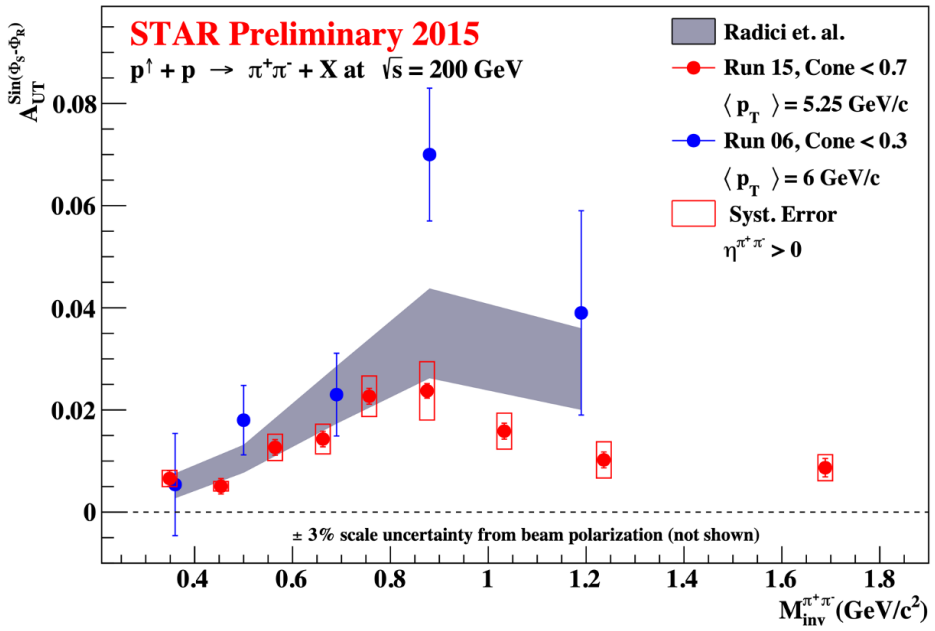
Comparison with 510 GeV Results

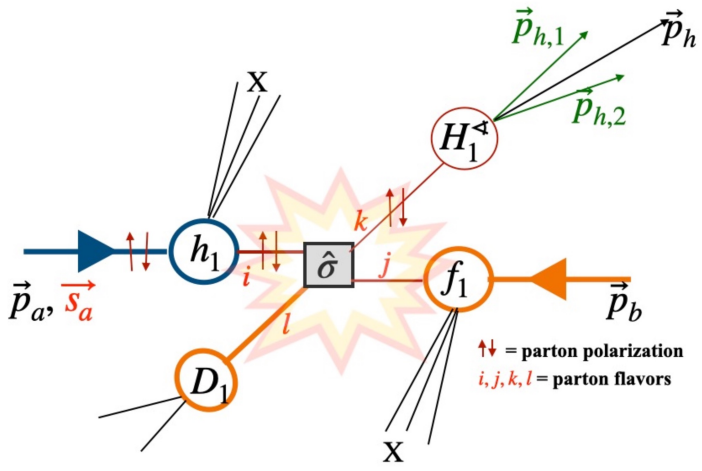


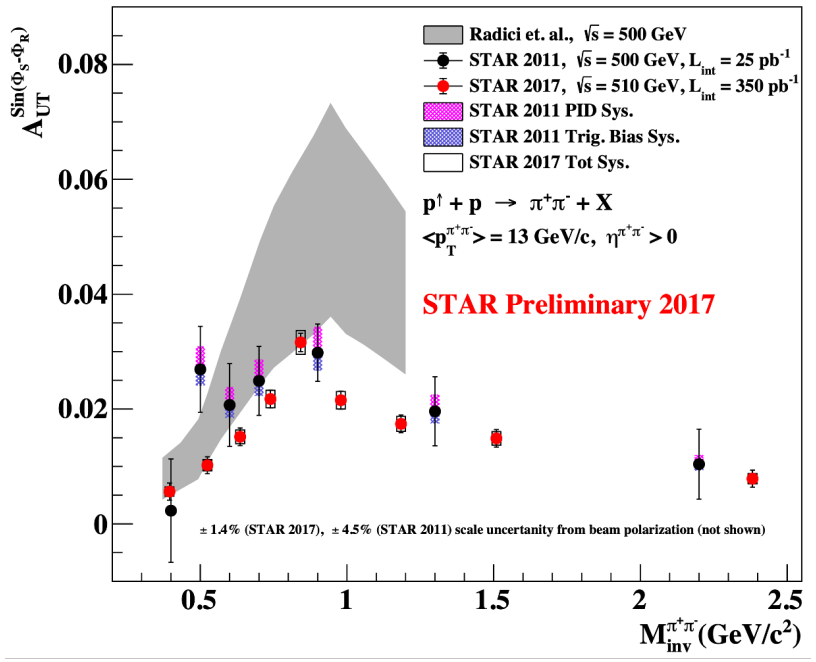


- More precise measurement using 2017 pp510 dataset confirm the previous findings.

A_N for Di-hadron Measurement





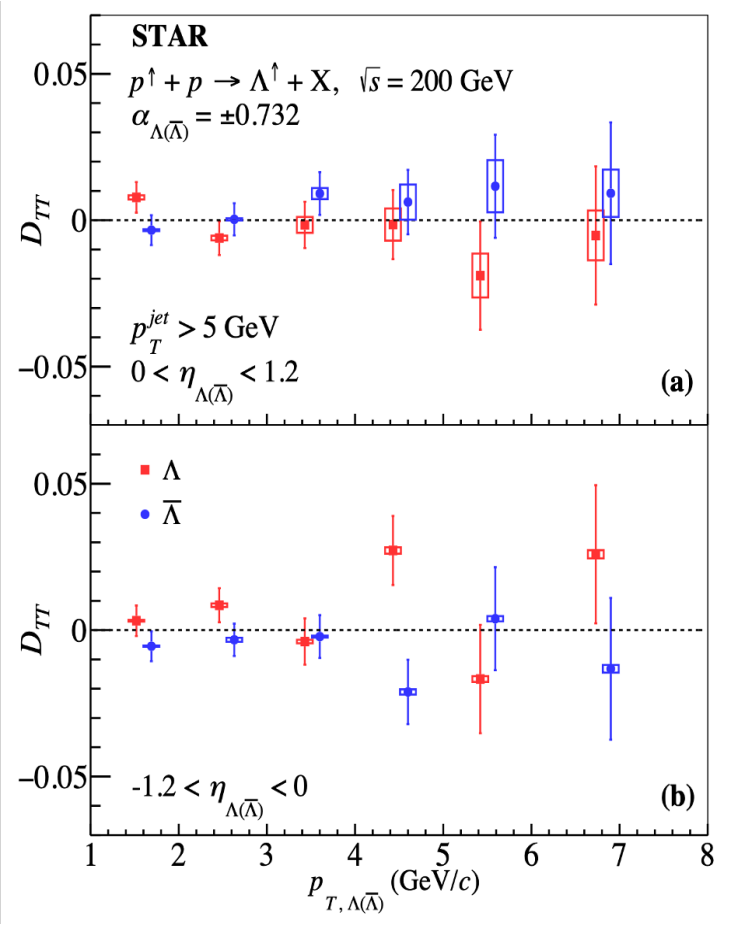


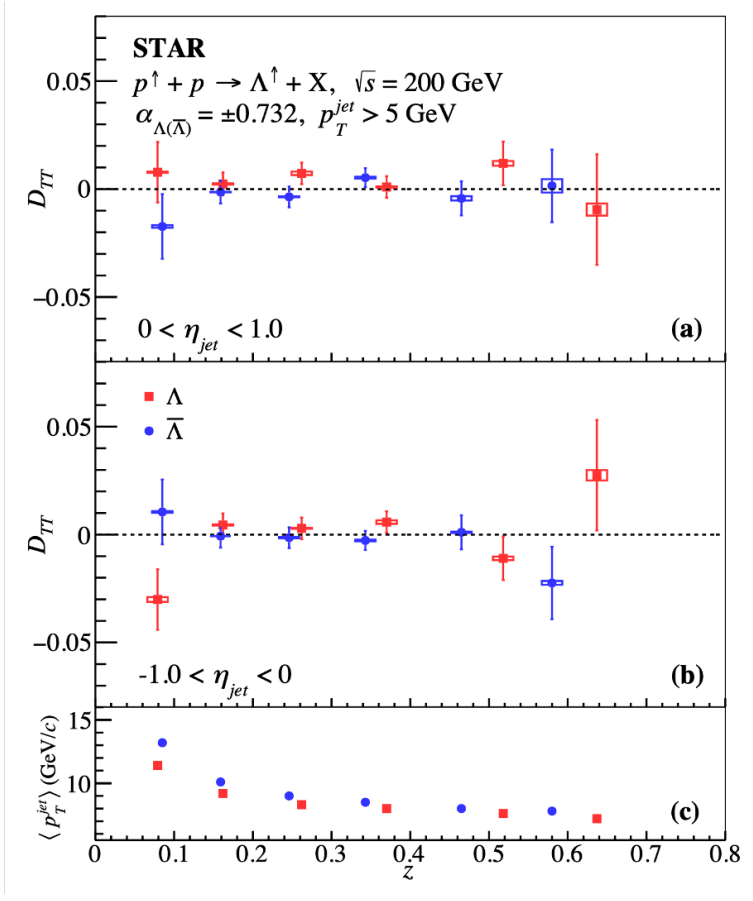
$$d\sigma_{UT} \propto \int dx_a dx_b h_1(x_a) f_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

- 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.

Lambda Polarization in Transversely Polarized Proton

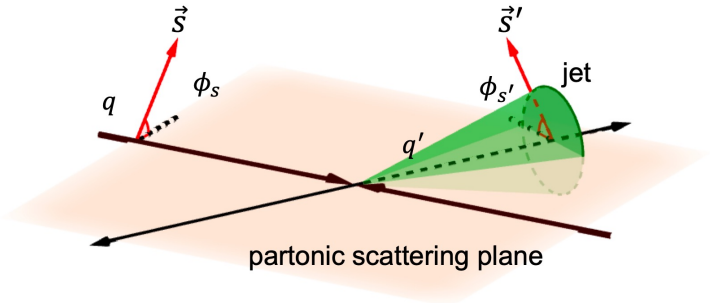
STAR, arXiv: 2309.14220





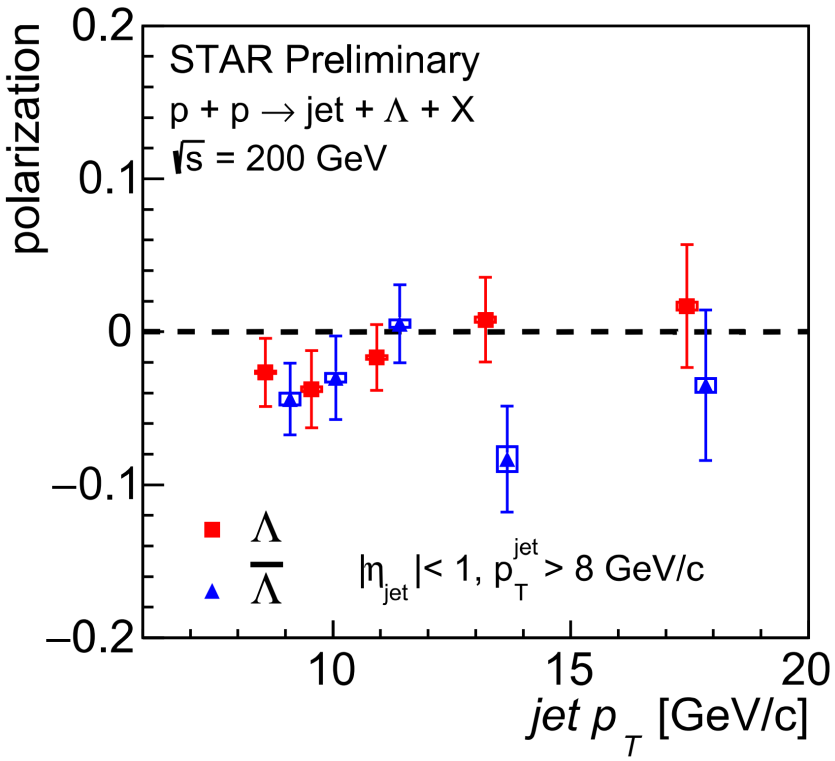
$$D_{TT} = \frac{d\sigma^{(p^{\uparrow}p \rightarrow \Lambda^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p \rightarrow \Lambda^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p \rightarrow \Lambda^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p \rightarrow \Lambda^{\downarrow}X)}}$$

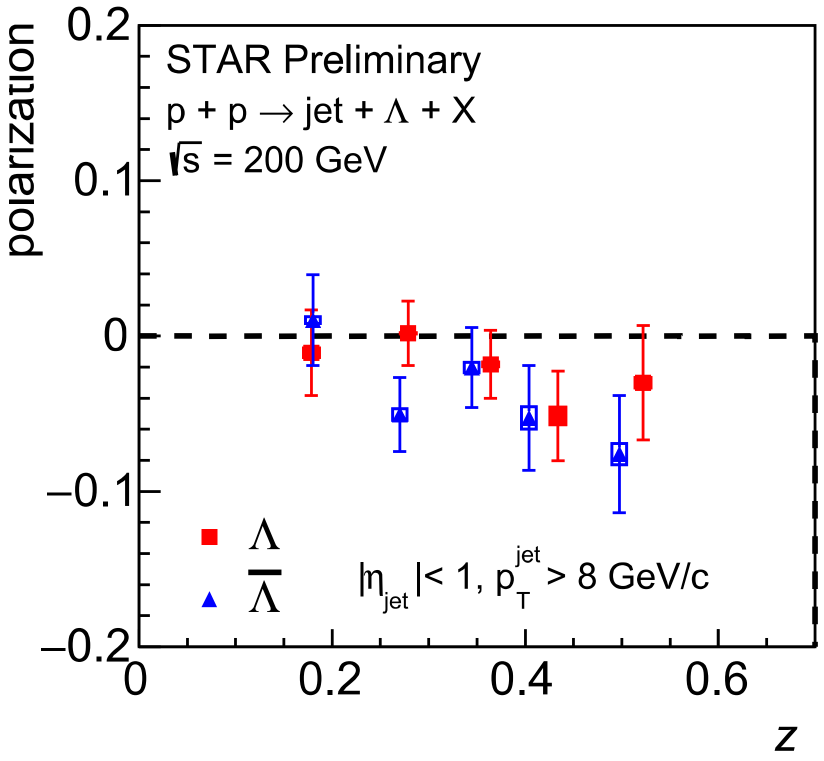
$$\frac{dN}{d\cos\theta^*} \propto A(1 + \alpha_{\Lambda} P_{\Lambda} \cos\theta^*)$$

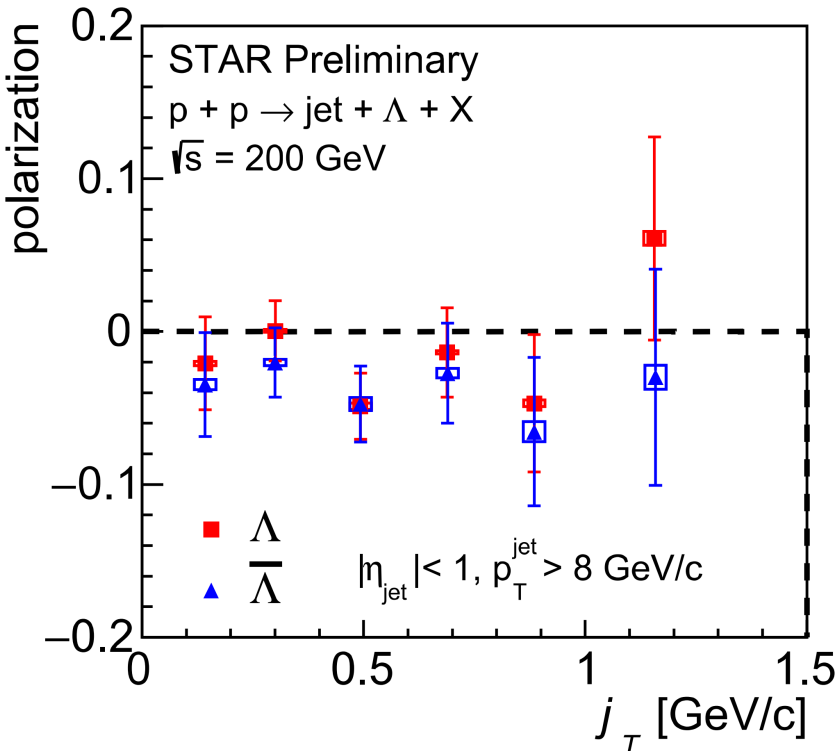


- These results provide insights into the strange quark and anti-quark transversity in the proton;
- The first measurement of the D_{TT} $vs.z$ directly probes the polarized fragmentation functions.

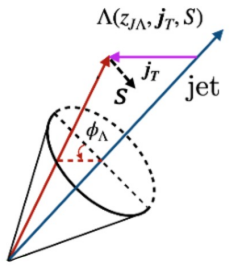
Lambda Polarization in Un-Polarized Proton







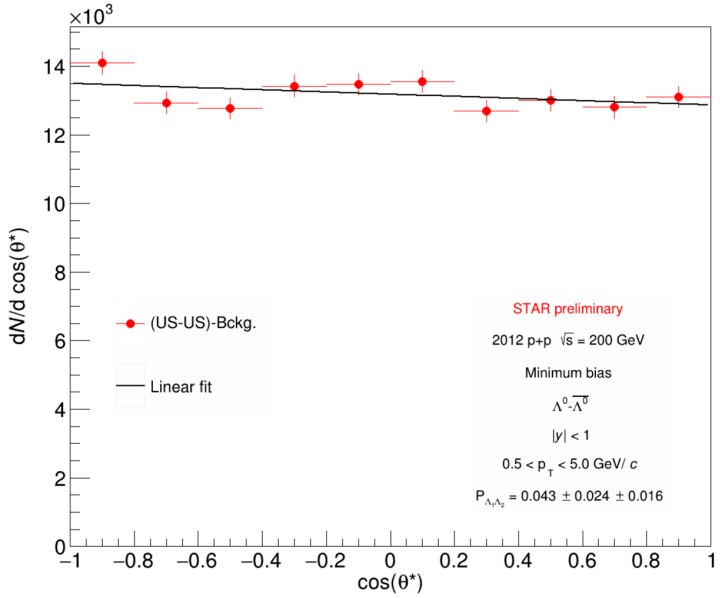
- First measurement of transverse polarization of Λ-in-jet at pp 200 GeV;
- These results probe polarizing fragmentation function which might contribute to Λ spontaneous polarization.



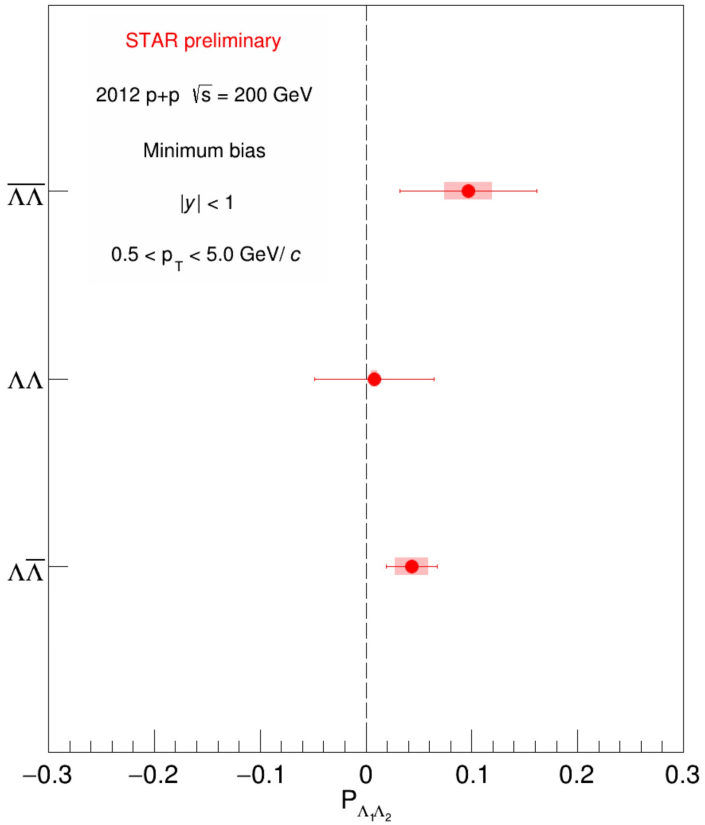
$\hat{S} = \hat{p}_{jet} \times \hat{p}_{\Lambda}$

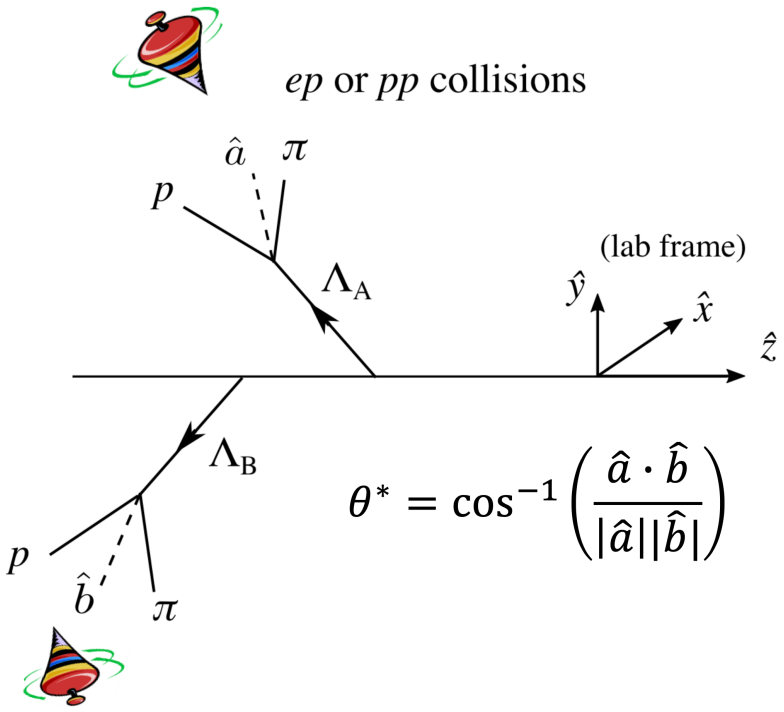
$\hat{S}$: polarization direction we defined

Lambda Spin-Spin Correlation



$$\frac{dN}{d\cos(\theta^*)} = 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$



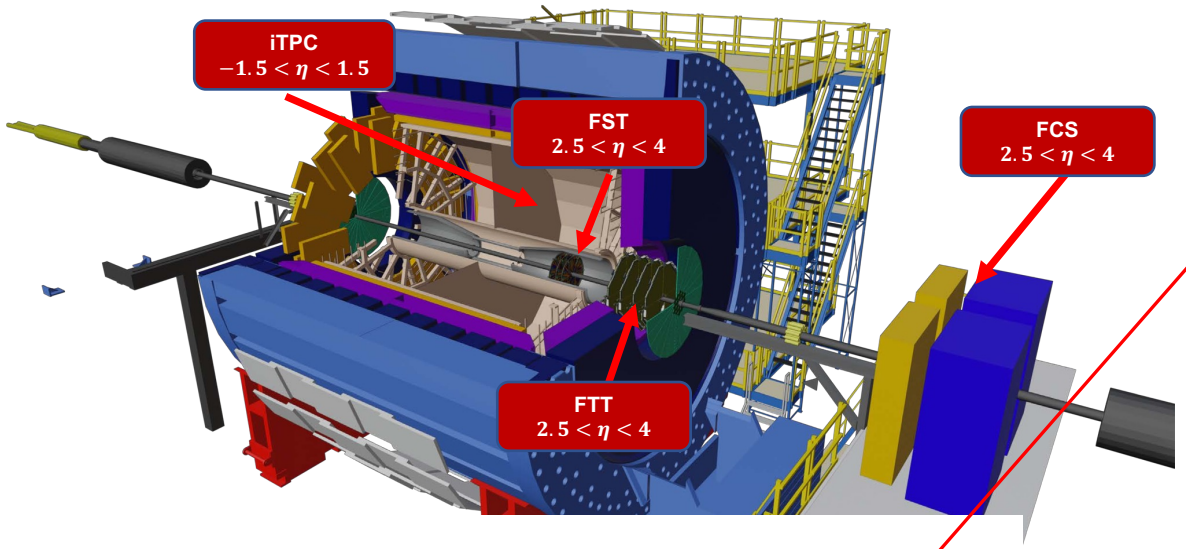


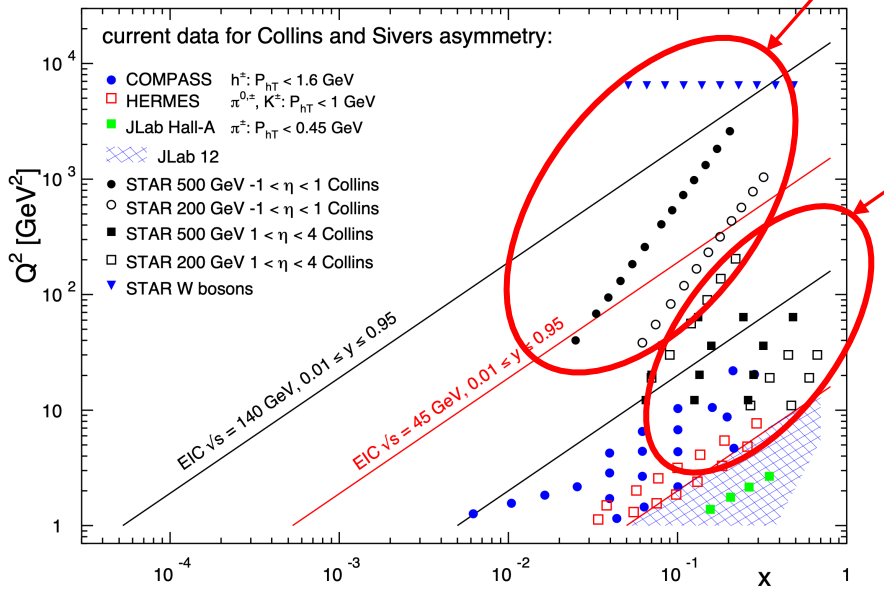
$$\theta^* = \cos^{-1}\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

W. Gong, et al., Phys. Rev. D 106 3, L031501(2022)

- First ever measurement of Λ hyperon spin-spin correlations;
- Data suggest no spin-spin correlation of initial state s (anti-) quark pair.

Outlook





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.

$2.5 < \eta < 4$

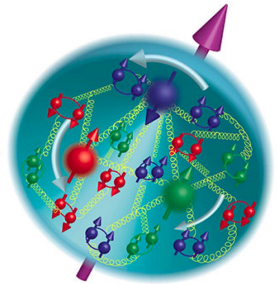
Physics Topics:

- 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.

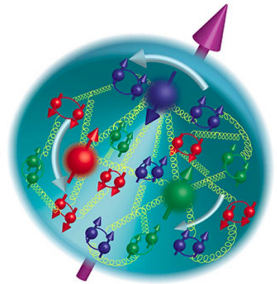
- Large p+p 508 GeV sample from 2022 currently under analyses (w/ forward upgrades);
- Upcoming p+p and possibly p+Au 200 GeV runs in 2024 and 2025.

Summary



- Significant progress towards the understanding of the internal spin structure of nucleon at STAR;
  - Complementarity of 3D structure of nucleon measurements from lepton scattering and hadron-hadron collisions;
- 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!