59th Rencontres de Moriond 2025

Recent TMD Measurements in pp Collisions at RHIC-STAR

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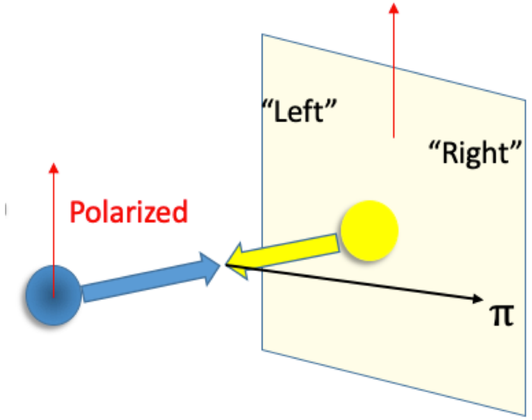
Outline

- Motivation
- Sivers effect
- Collins effect & Transversity
- Outlook & Summary

Challenges in Transverse Single-Spin Asymmetry (TSSA)

➢ Anomalously large A_N in pp collisions observed for nearly 40 years

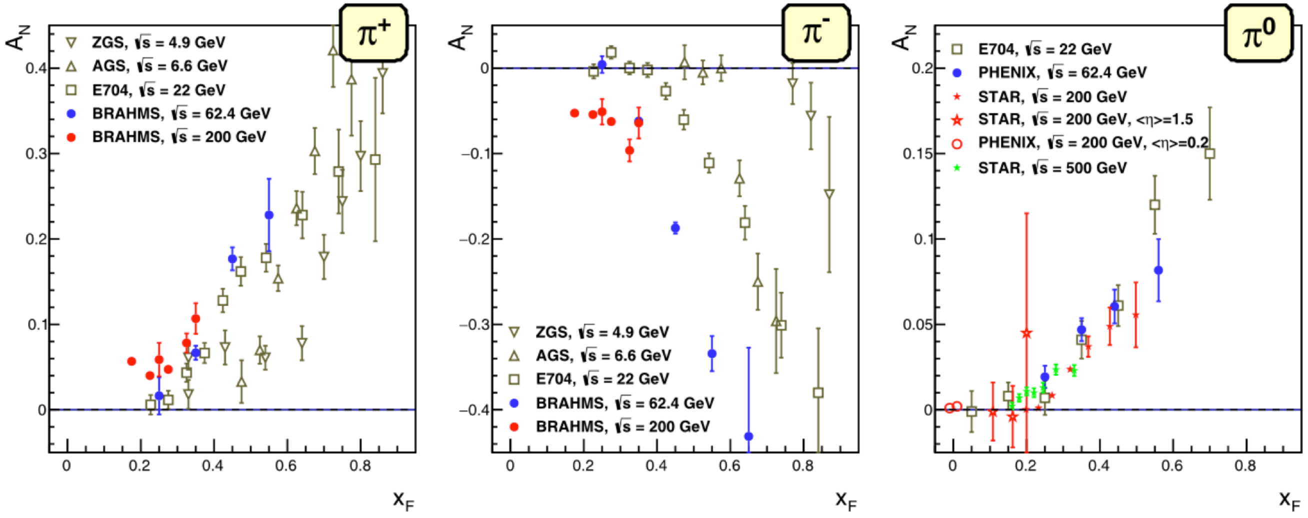


$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- LO QCD predicts $A_N \sim 0$

G. Kane, J. Pumplin, W. Repko, Phys. Rev. Lett 41,1689 (1978)

➢ TSSA of different hadrons at different beam energies



E. C. Aschenauer *et al*. arXiv:1602.03922

- Stable in different C.M. energies
- Interpreted by the twist-3 and transverse-momentum-dependent (TMD) formalisms

$$x_F = \frac{2p_z}{\sqrt{s}}$$

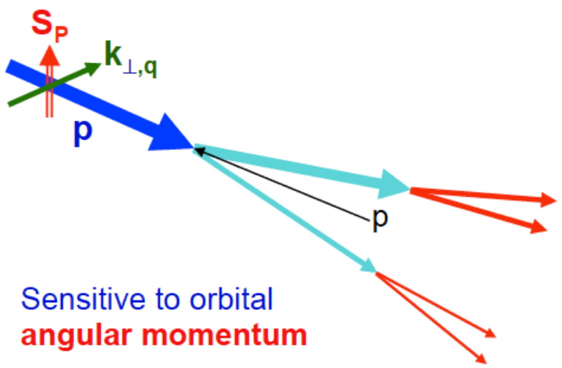
Mechanisms for Transverse Single-Spin Asymmetry

STAR

- Transverse Momentum Dependent (TMD) parton distributions and fragmentation functions.
  - Need two scales (Q and p_T), $Q >> p_T$

✓ **Sivers effect (*Sivers'90*):**

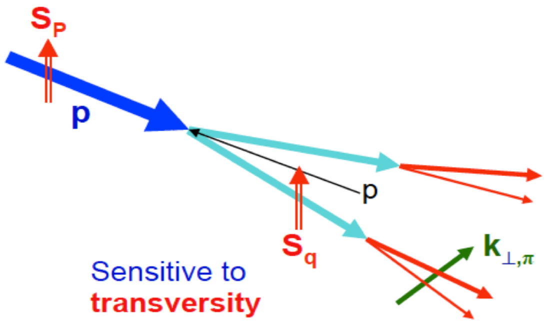
Parton spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)



$$\vec{S} \cdot (\vec{p} \times \vec{k}_\perp)$$

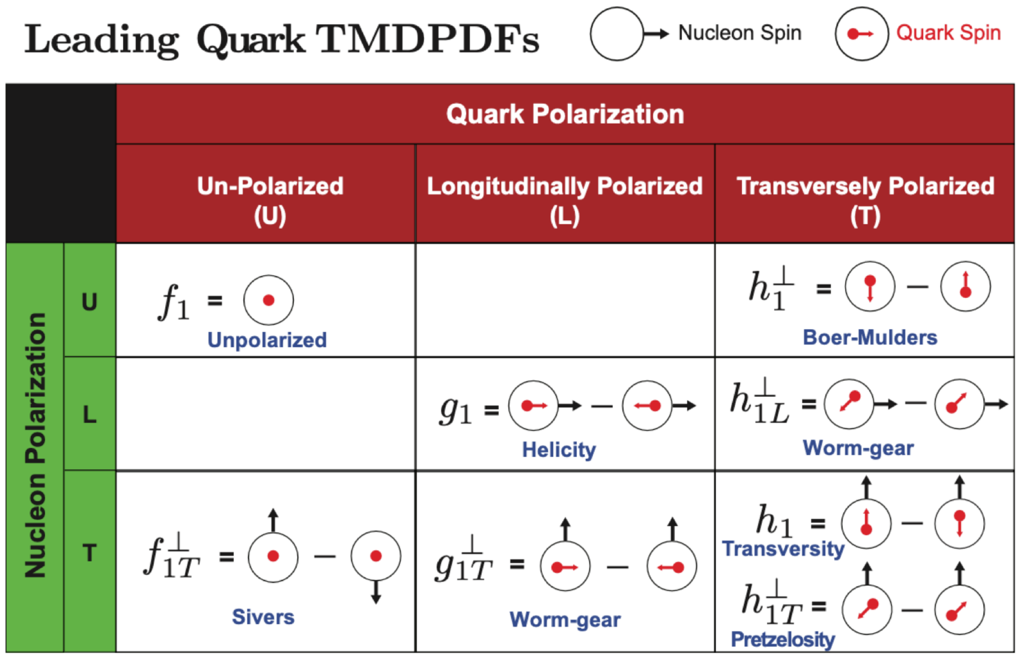
✓ **Collins effect (*Collins'93*):**

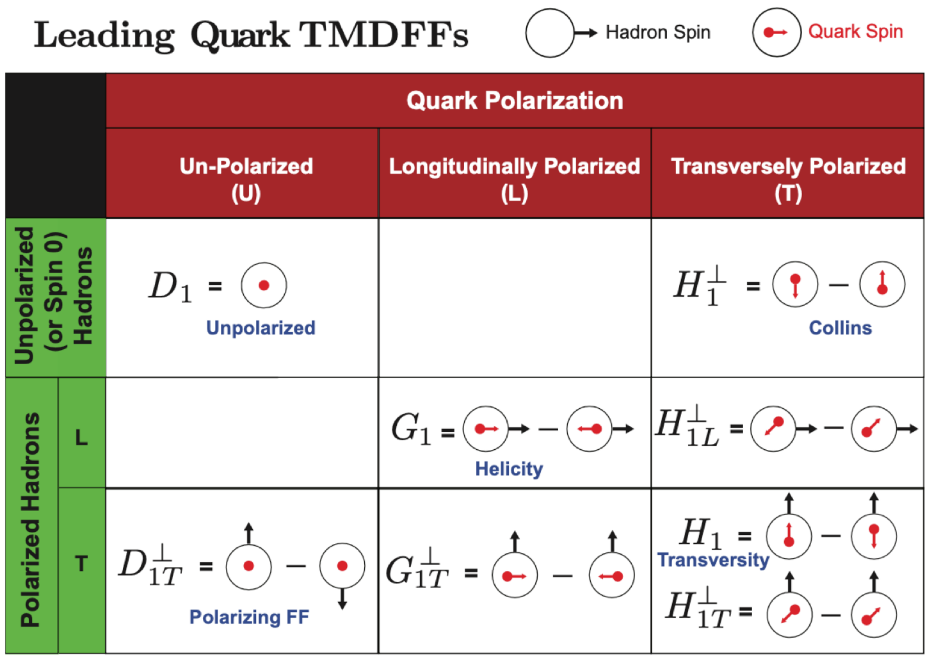
Quark spin and $k_\perp$ correlation in fragmentation process (coupled with transversity)



- Twist-3 mechanism (Efremov-Teryaev'82, Qiu-Sterman'91):
  - Collinear/twist-3 quark-gluon correlation + fragmentation functions
  - Need one scale $(Q\ or\ p_T), Q, p_T >> \Lambda_{QCD}$
  - Consistent with TMD mechanism in the overlapping kinematics region

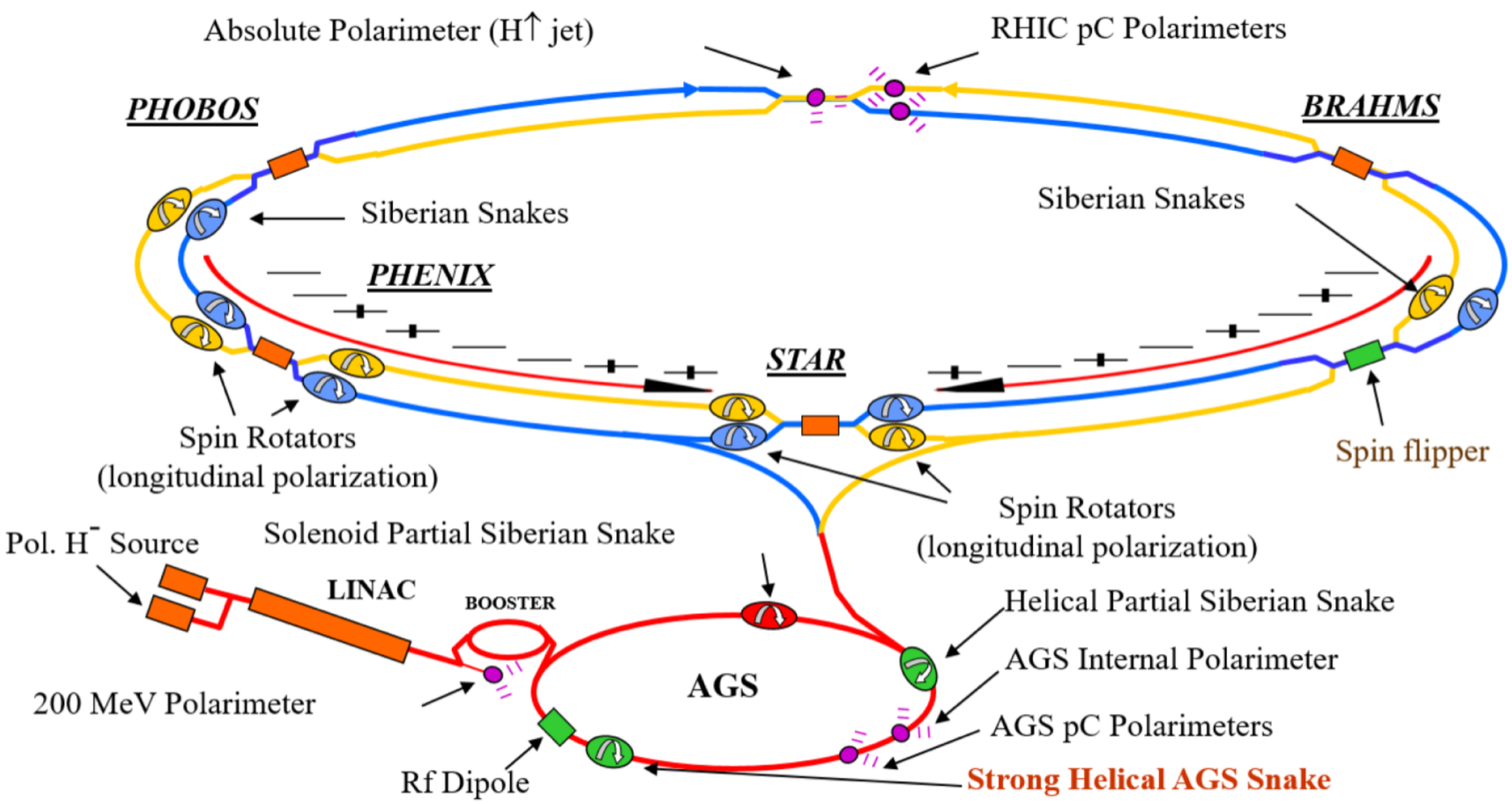
TMDs





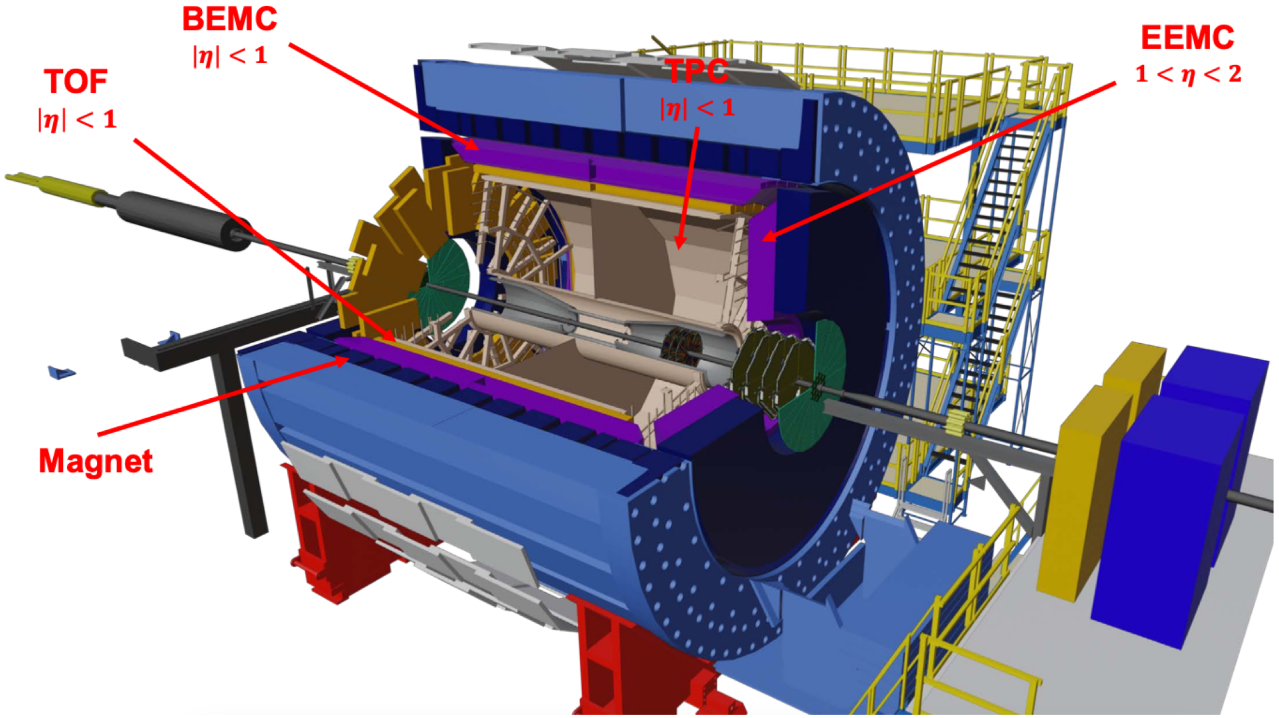
STAR Measurements	Mechanisms
Jet asymmetry, $\langle k_T \rangle$ via dijet, W/Z asymmetry	Sivers function $f_{1T}^\perp$
Hadron in jet asymmetry	Transversity h_1 + Collins function $H_1^\perp$
Di-hadron asymmetry	Transversity h_1 + IFF $H_1^\sphericalangle$
Hyperon spin transfer	Transversity h_1 + Polarized FF H_1
$\Lambda(\overline{\Lambda})$ in jet polarization	Polarizing FF $D_{1T}^\perp$

Relativistic Heavy Ion Collider (RHIC)



- The world's only machine capable of colliding high-energy polarized protons
- Beam can be either transversely or longitudinally polarized at $\sqrt{s}$ = 200 GeV or 500/510 GeV

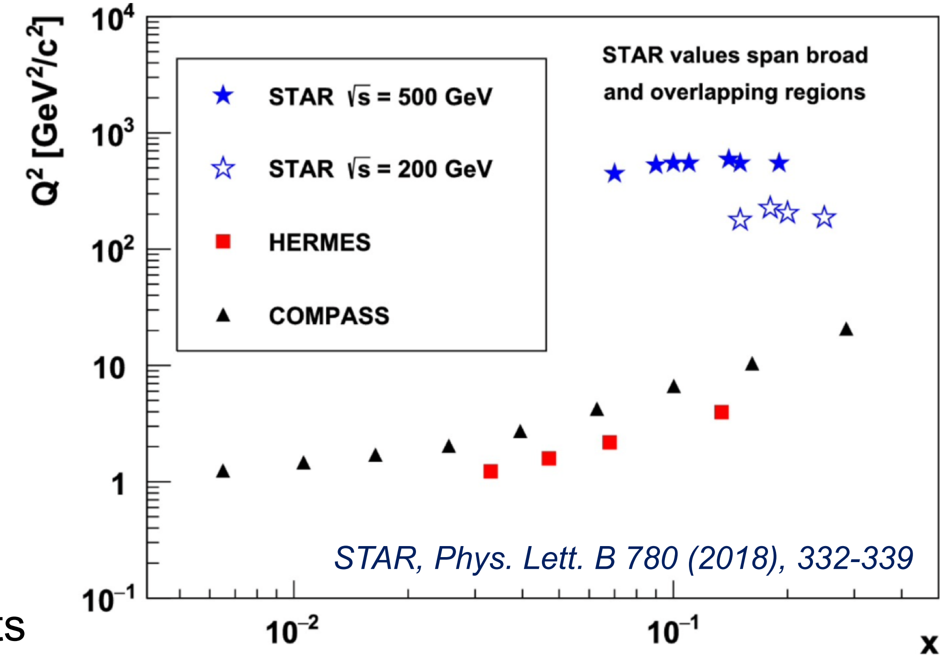
The Solenoidal Tracker At RHIC (STAR)



- Time Projection Chamber (TPC)
  - $|\eta| < 1$ and $\phi \in [0, 2\pi]$
  - Main detector for tracking and PID
- Time Of Flight (TOF)
  - $|\eta| < 1.0$ and $\phi \in [0, 2\pi]$
  - Improve PID of tracks
- ElectroMagnetic Calorimeter
  - BEMC: $|\eta| < 1.0$ and $\phi \in [0, 2\pi]$.
  - EEMC: $1.08 < \eta < 2.0$ and $\phi \in [0, 2\pi]$
  - Reconstruction of photon, e, π^0 and triggering

- Transversely polarized pp collision data relevant to this talk

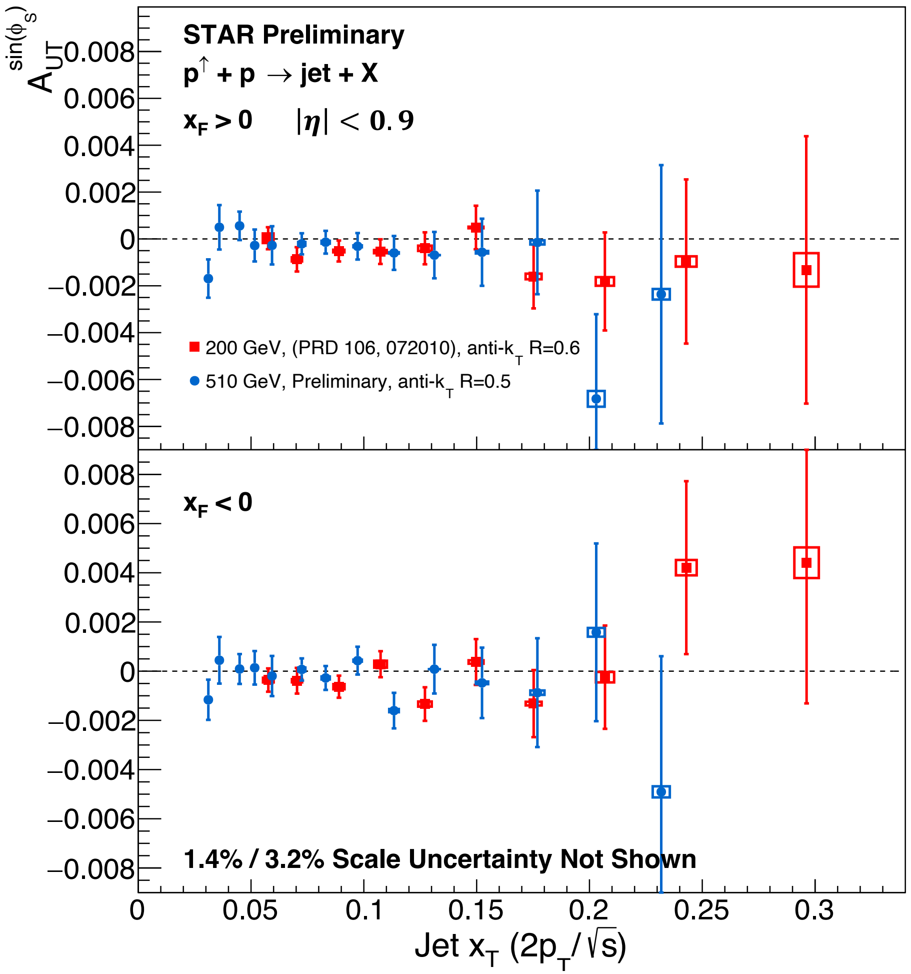
Year	2011	2012	2015	2017
$\sqrt{s}$ (GeV)	500	200	200	510
L_{int} (pb^{-1})	25	22	52	350
Polarization	53%	57%	57%	55%



- Similar x region but high Q^2, which is not probed by prior experiments

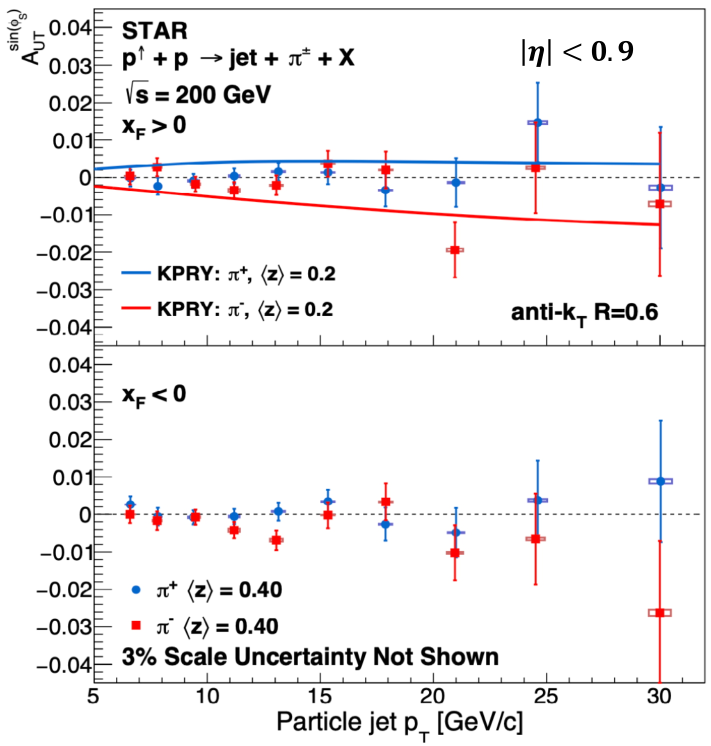
Transverse Single Spin Asymmetry of Jet

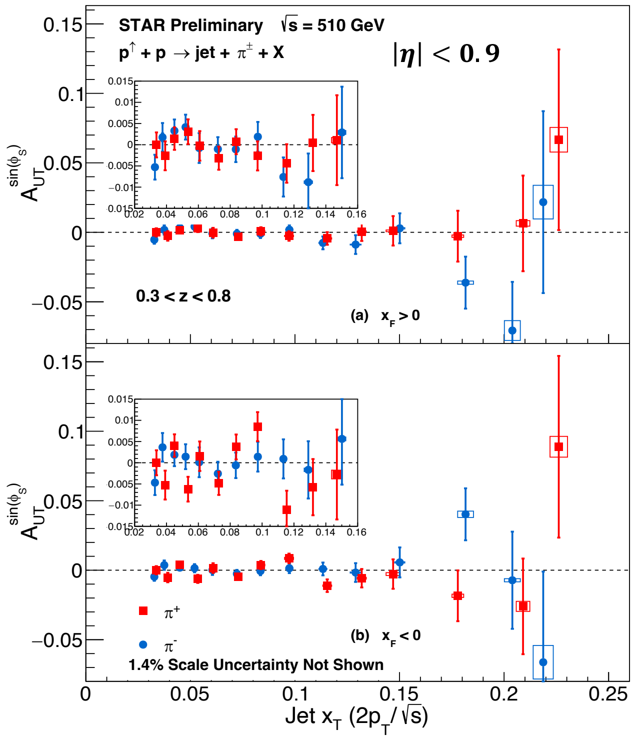
➢ A_N for inclusive jet



➢ A_N for $\pi^{\pm}$ tagged inclusive jet

- $\pi^{\pm}$ tagged to enhance quark jet fraction

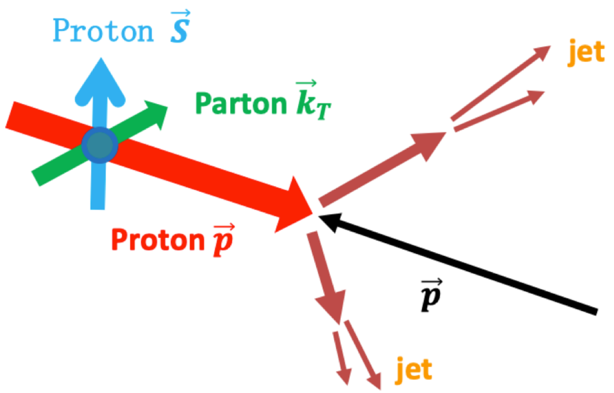


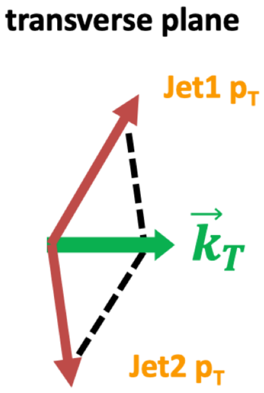


STAR, Phys. Rev. D 106, 072010 (2022)

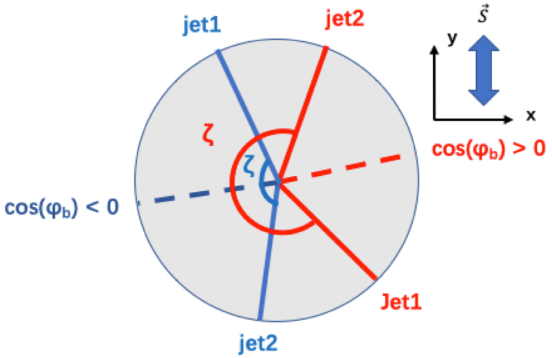
- Sensitive to twist-3 correlators associated with the gluon Sivers function
- Consistent with zero within uncertainty

Sivers Effect in Dijet production



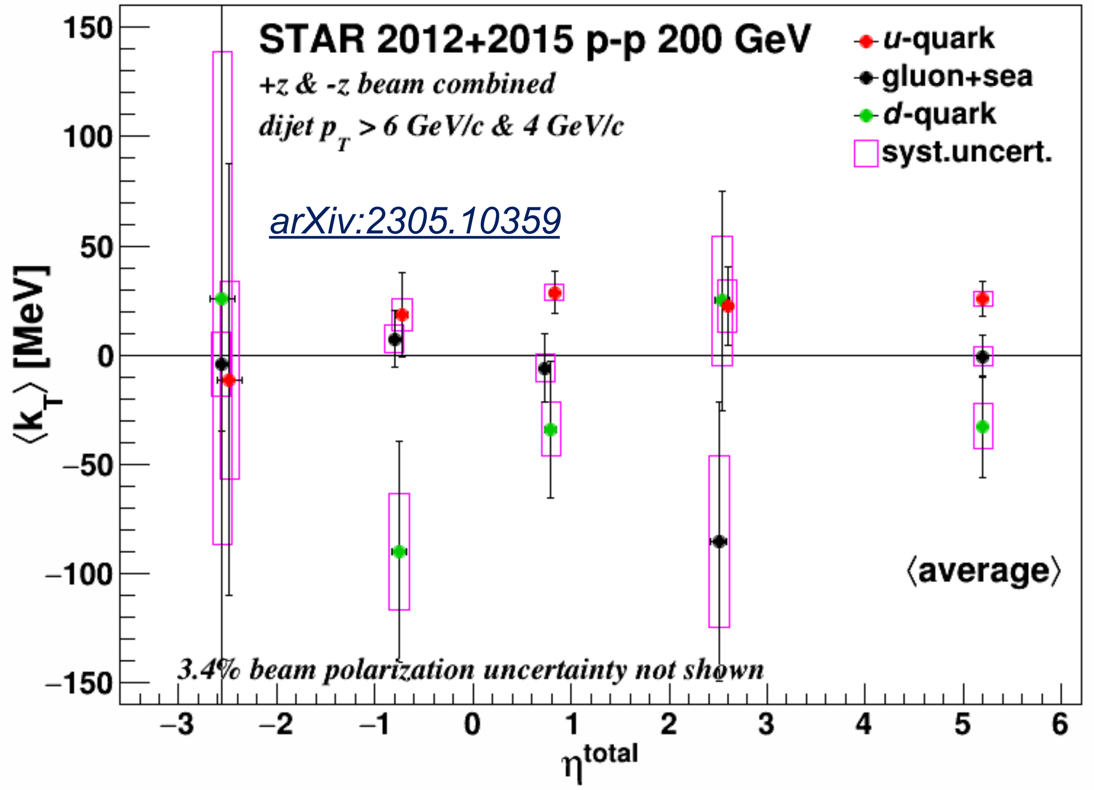


Intrinsic k_T produce a "tilt" of the dijet opening angle



- Asymmetry can be probed via the signed opening angle ζ
- Jet Charge (Q) of the associated jets to enhance the fraction of u-quarks and d-quarks
- Converting the $\Delta\zeta$ asymmetry to $\langle \boldsymbol{k_T} \rangle$ using model
- Inverting the Q-tagged $\langle \boldsymbol{k_T} \rangle$ to individual parton $\langle \boldsymbol{k_T} \rangle$

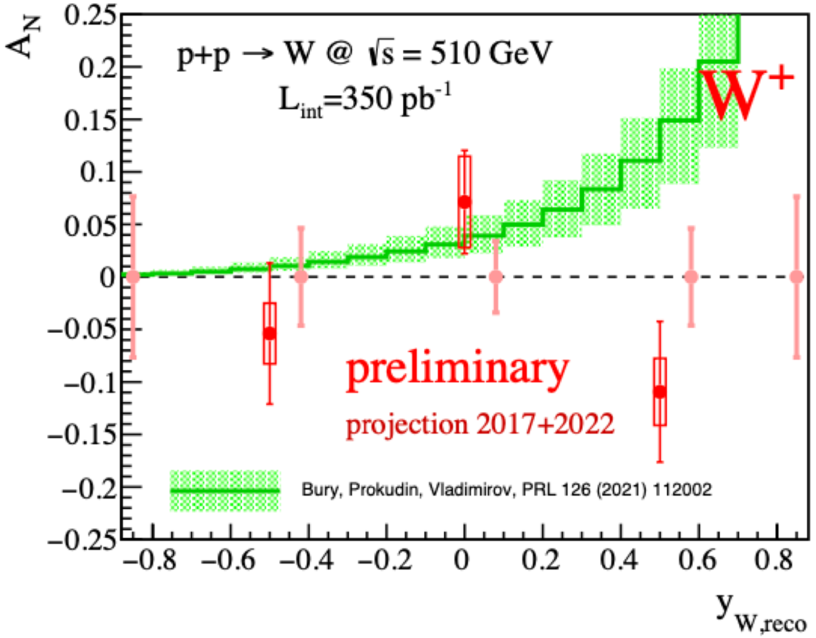
➢ Average transverse momentum $\langle k_T \rangle$ for individual partons

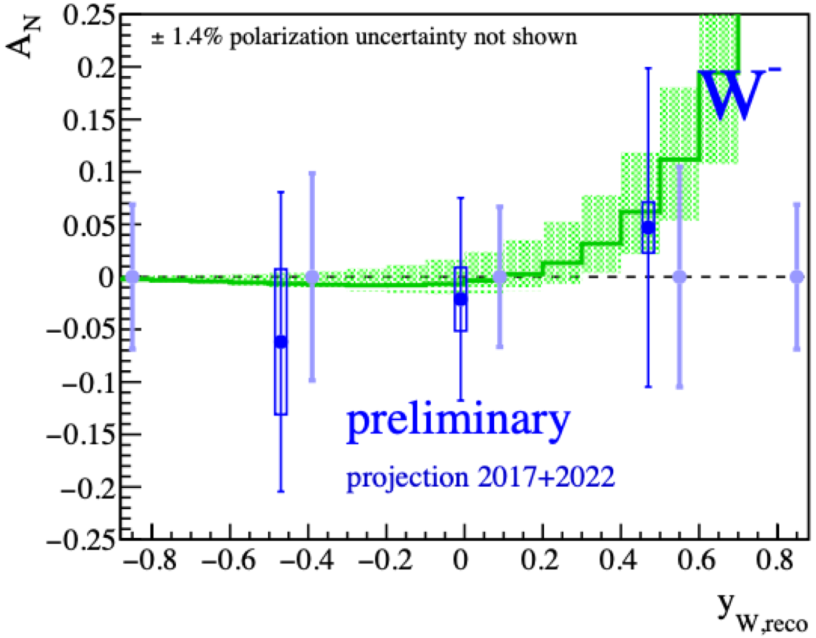


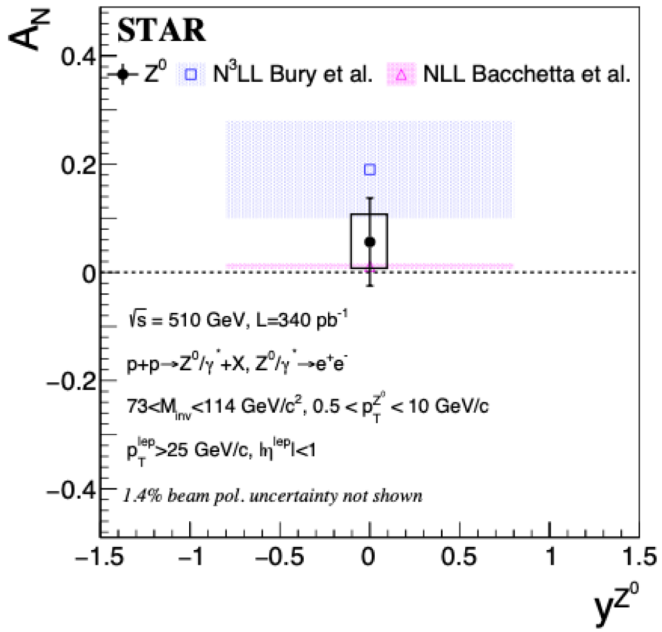
- First time that nonzero Sivers signals in pp dijet production are observed
- $2\langle k_T^u \rangle \approx \langle k_T^d \rangle \qquad \langle k_T^{g+sea} \rangle \sim 0$

Asymmetry of weak bosons

➢ Preliminary results of W/Z A_N from run17 data at $\sqrt{s}$ = 510 GeV







STAR, Phys. Lett. B 854 (2024) 138715

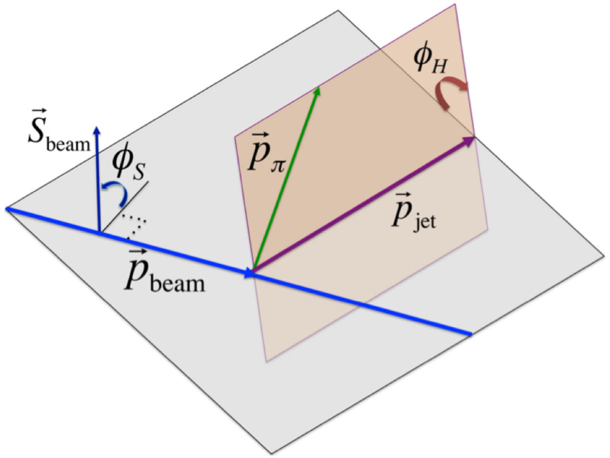
- Test sign change of Sivers function from SIDIS and Drell-Yan:

$$f_{h/q^{\uparrow}}^{SIDIS}(x, k_T, Q^2) = -f_{h/q^{\uparrow}}^{p+p\to DY}(x, k_T, Q^2)$$

- In general, the results and theoretical calculations are consistent
- Provide input to extraction of the Sivers function, especially for valance quarks at high x ($x \geq 0.1$)
- Run 22 data will further reduce the statistical uncertainty and push to larger rapidity $y^{W/z}$

Collins Asymmetry of Hadron in Jet

➢ Extraction of Collins asymmetry of hadron in jet



$$\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto h_1(x) \otimes H_1^{\perp} \sim \begin{array}{l} A_{UT}^{sin(\phi_S)}\, sin(\phi_S) \\ +A_{UT}^{sin(\phi_S-\phi_H)}\, sin(\phi_S-\phi_H) \\ +A_{UT}^{sin(\phi_S-2\phi_H)}\, sin(\phi_S-2\phi_H) \end{array}$$

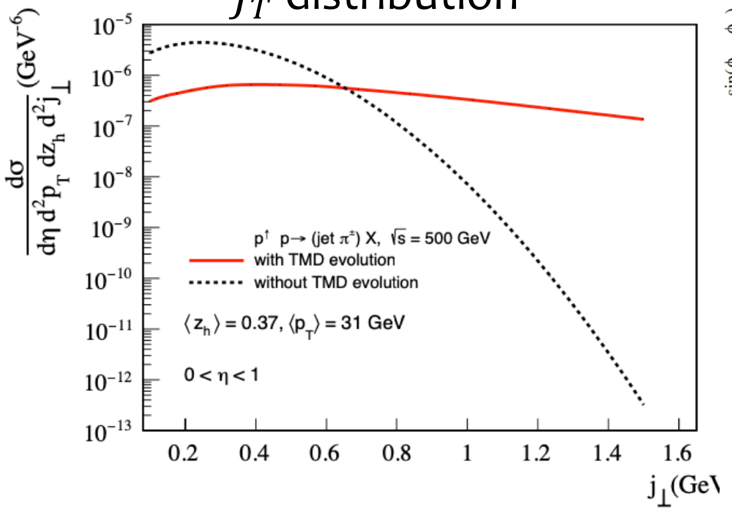
- Sensitive to transversity and Collins function

STAR, Phys. Rev. D 97, 032004 (2018)

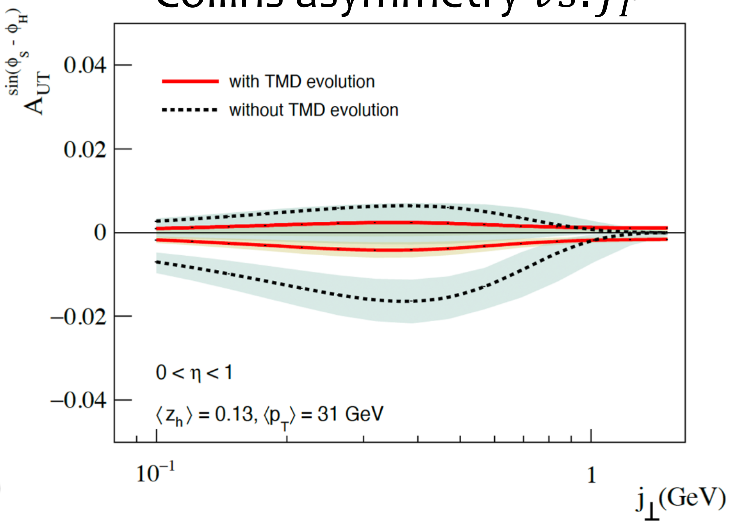
U. D'Alesio *et al*, Phys. Rev. D 83, 034021 (2011)

➢ Model calculations

j_T distribution



Collins asymmetry $vs.\, j_T$

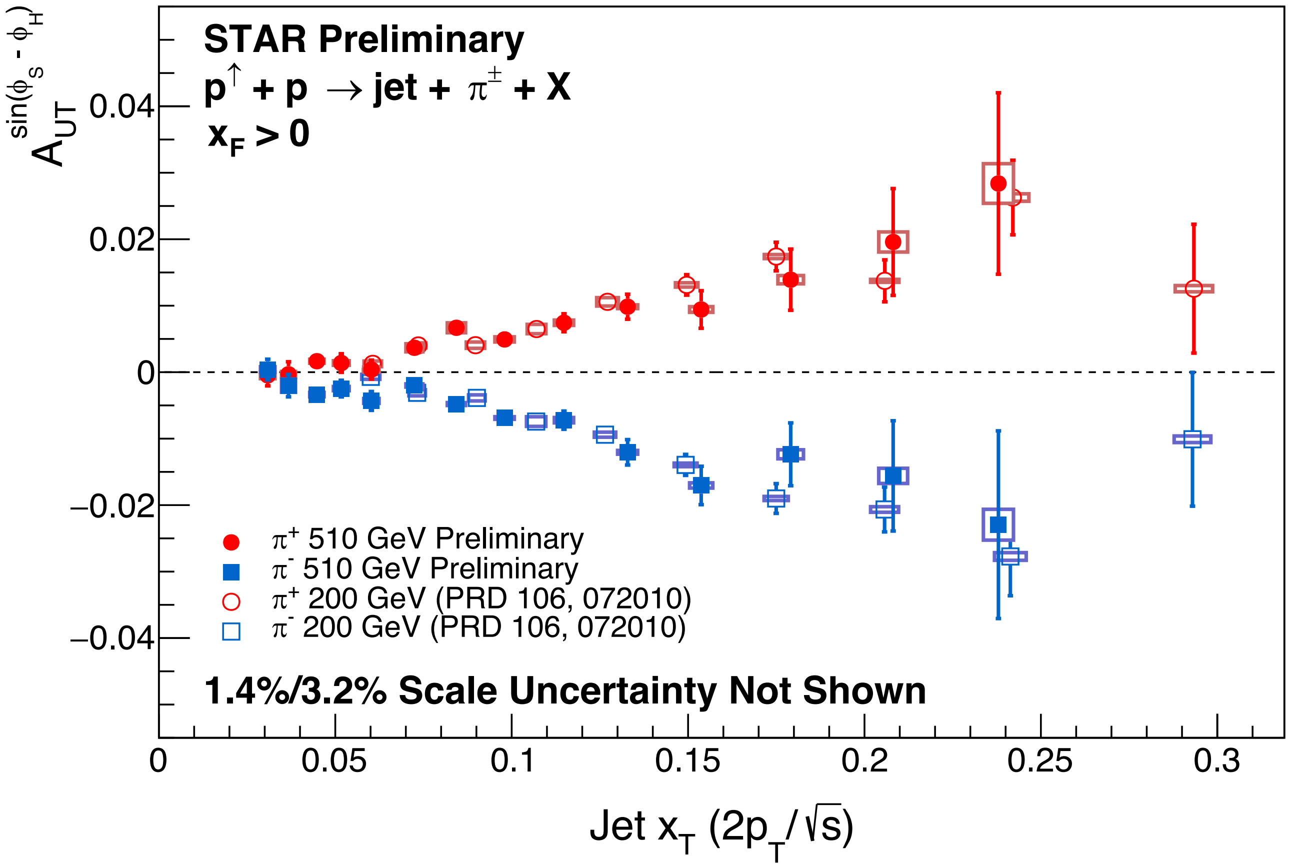


- Apply a mixture factorization
- Global analyses from SIDIS and e^+e^- annihilation
- Test universality of Collins fragmentation functions for different processes

Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017)

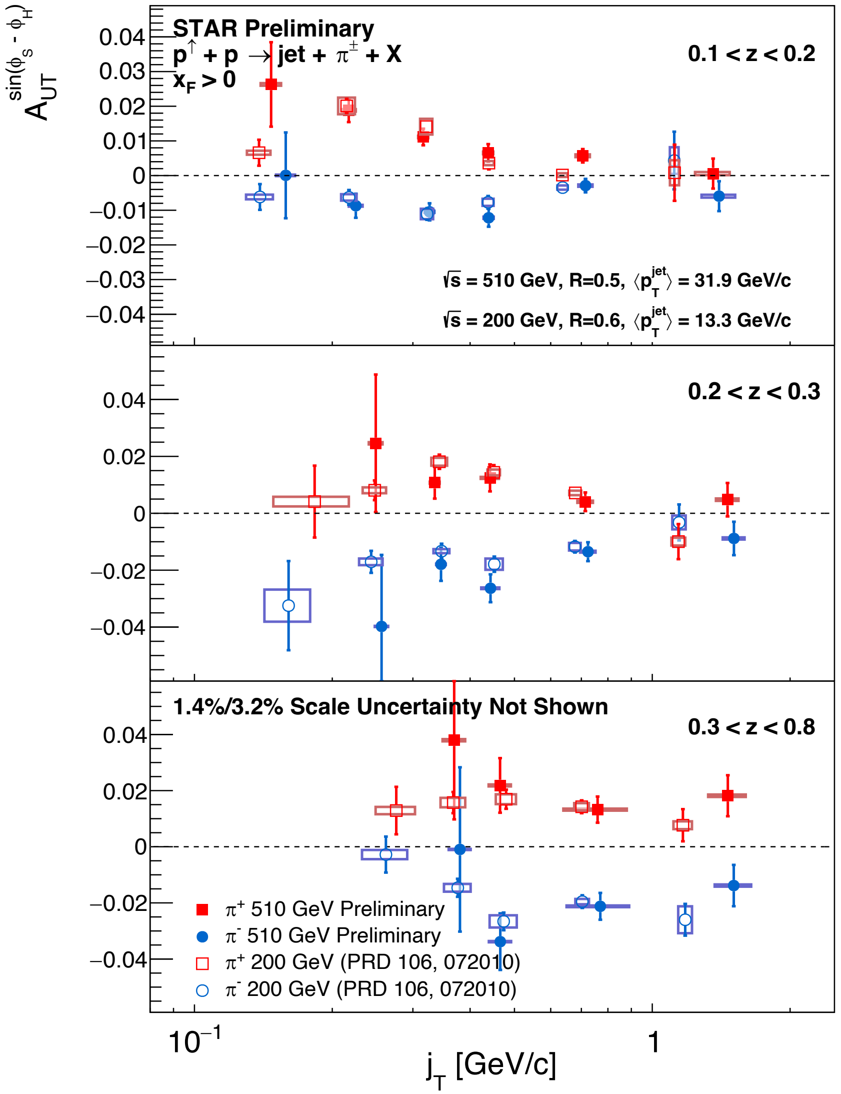
Collins Asymmetry of Hadron in Jet

- Collins asymmetry vs. jet-x_T of 200GeV & 510GeV



- Collins asymmetry vs. pion j_T of 200GeV & 510GeV

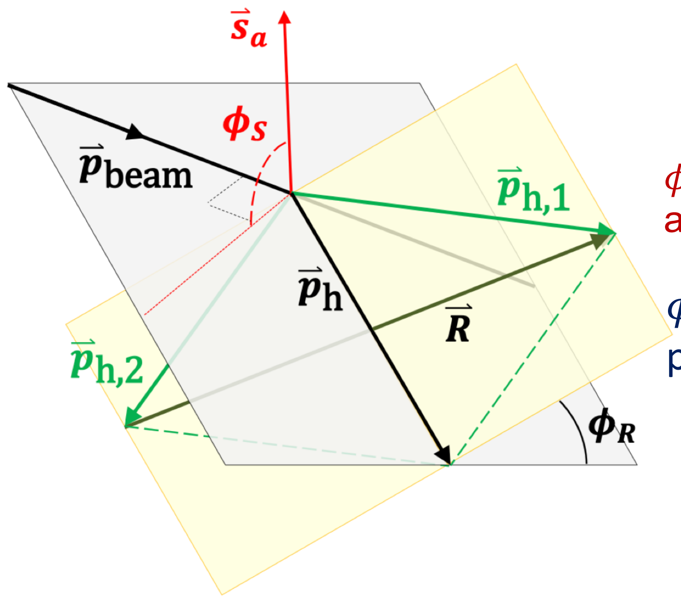
j_T : pion's transverse momentum relative to jet axis



- Nicely align with jet x_T & hadron j_T scale, giving almost no energy dependence.
- Provide important constraints on the TMD evolution

Probing Transversity in Dihadron Production

- Di-hadron correlation asymmetry is sensitive to transversity (h_1) and interference fragmentation function ($H_1^{\sphericalangle}$)



ϕ_S = Angle between scattering plane and polarization of incident beam

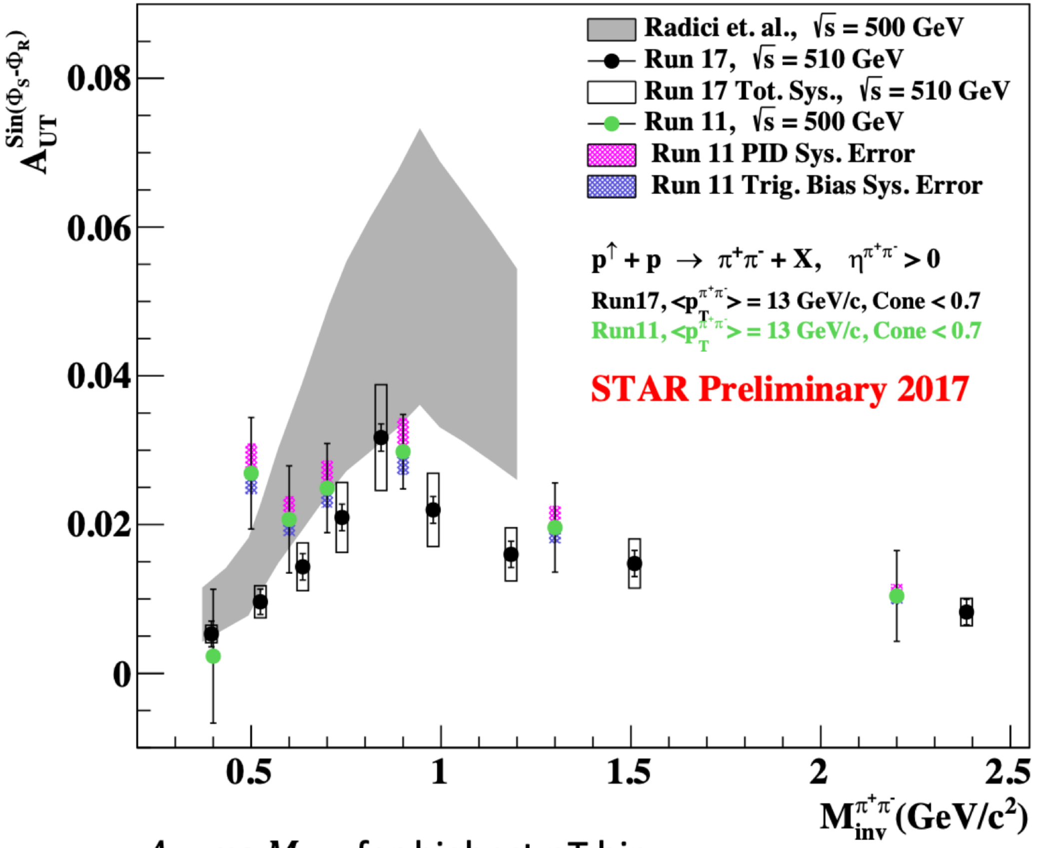
ϕ_R = Angle between scattering plane and dihadron plane

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto h_1(x) H_1^{\sphericalangle}(z, M^2)$$

$$z = \frac{E^{h^+h^-}}{E^{parton}}$$

M^2 = Invariant mass of hadron pair

- Results of di-hadron asymmetry in pp collisions



A_{UT} vs M_{inv} for highest pT bin.

STAR, Phys. Lett. B 780 (2018), 332-339

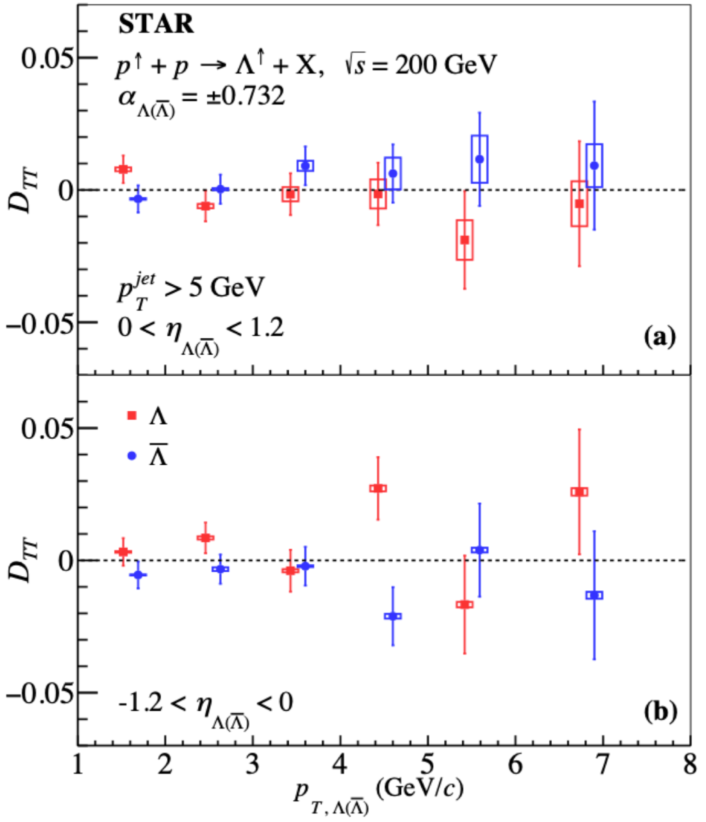
- Run17 results are consistent with Run11 results with much high precision
- Enhancement around the ρ mass

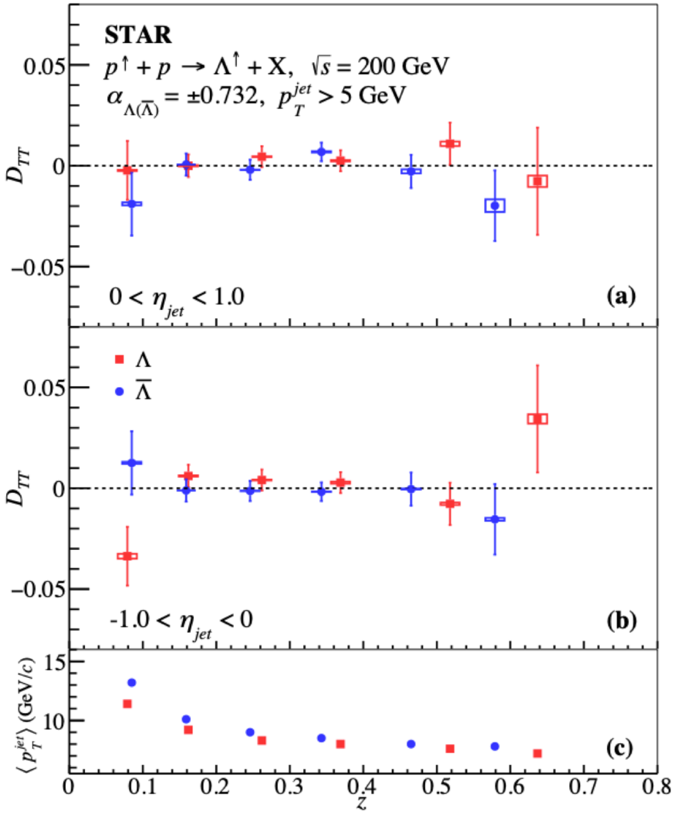
$\Lambda(\bar{\Lambda})$ Hyperon Spin Transfer D_{TT}

➢ Transverse spin transfer D_{TT}

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

- Related to transversity $\boldsymbol{h_1}$ and polarized FF $\boldsymbol{H_1}$

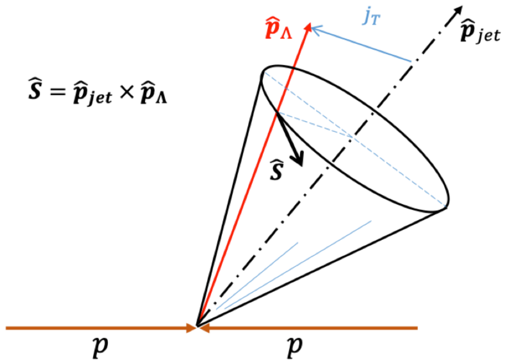




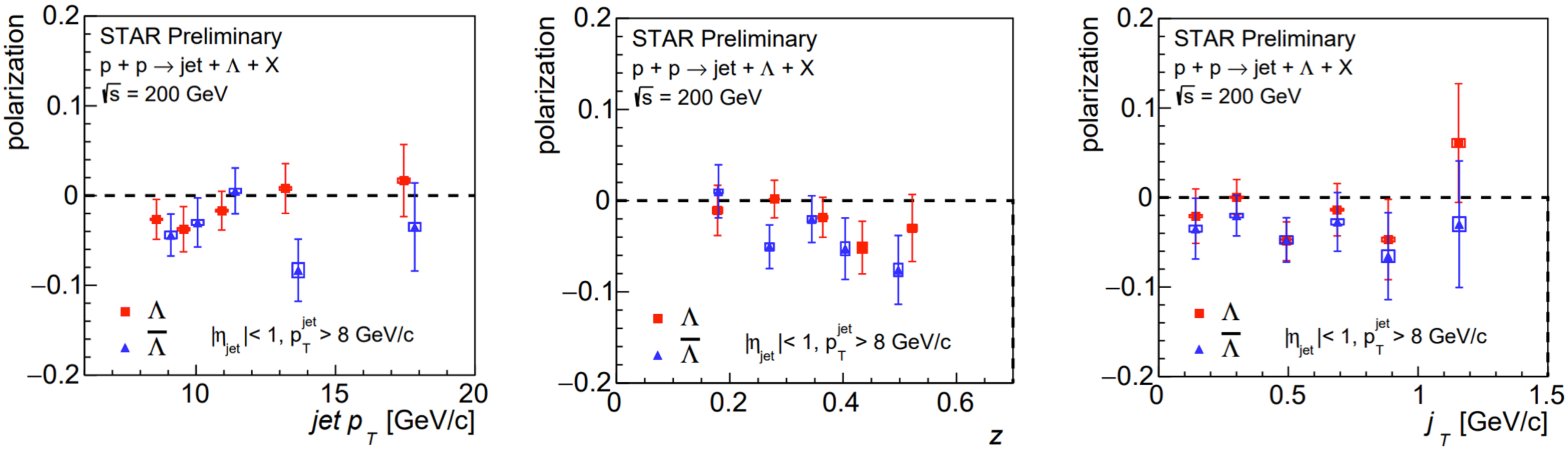
STAR, Phys. Rev. D 109 (2024) 1, 012004

- Direct probe of the transversely polarized fragmentation function $\boldsymbol{H_1}$
- First measurement of D_{TT} vs. z of $\Lambda(\bar{\Lambda})$
- Λ and $\bar{\Lambda}$ are consistent with each other within uncertainties
- Indicate small polarized FF and/or small transversity of the strange quark and anti-quark inside the proton

$\boldsymbol{\Lambda(\bar{\Lambda})}$ Polarization inside Jet



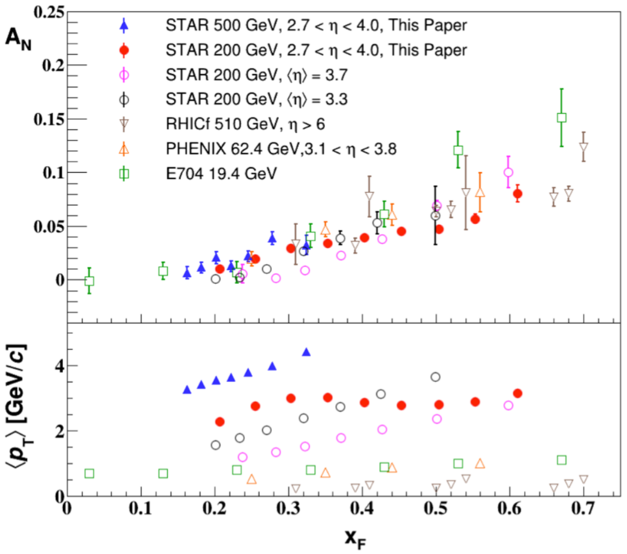
- Related to polarizing fragmentation functions $\boldsymbol{D_{1T}^{\perp}}$, which can be measured in pp collision via $\boldsymbol{\Lambda(\bar{\Lambda})}$ in jet



- First measurements of polarization of $\boldsymbol{\Lambda(\bar{\Lambda})}$ within jet in unpolarized pp collisions at $\sqrt{s}$ = 200 GeV
- Significant nonzero polarization signals were observed
- Test of universality of polarizing FF with e^+e^- data

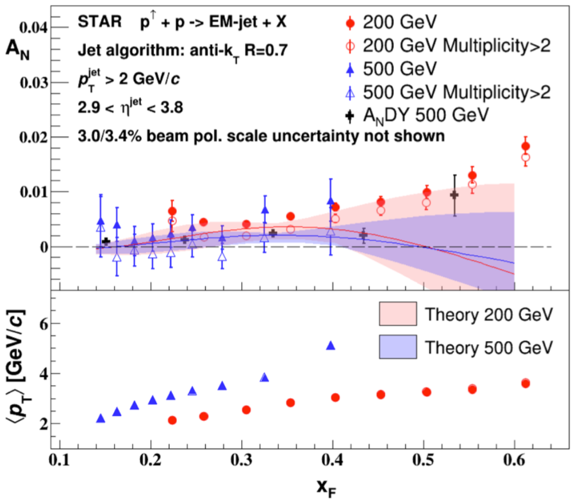
π^0 Asymmetry in Forward Region

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



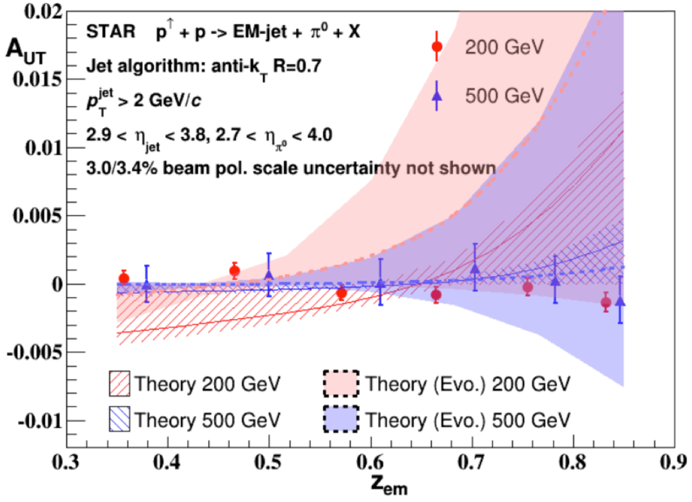
- Sizeable A_N for forward π^0

➢ Sivers effect contribution

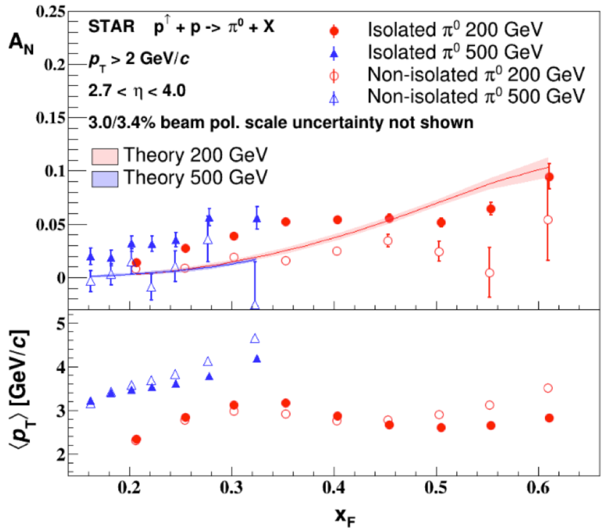


- Magnitude of inclusive EM jet asymmetry is limited

➢ Collins effect contribution



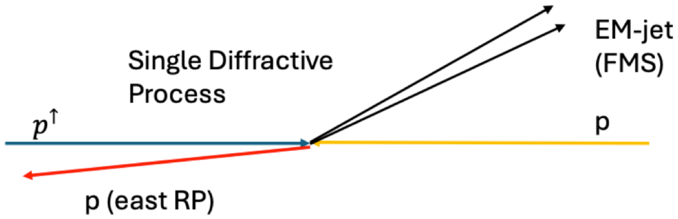
- Collins asymmetry of π^0 inside EM jet is consistent with zero



- The A_N of the isolated π^0 was found to be significantly larger than that for non-isolated ones
- Indicating the possible contribution from the **diffractive process**

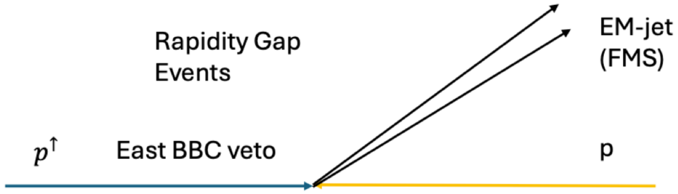
Diffractive Electromagnetic Jets Asymmetry

➢ Single diffractive process

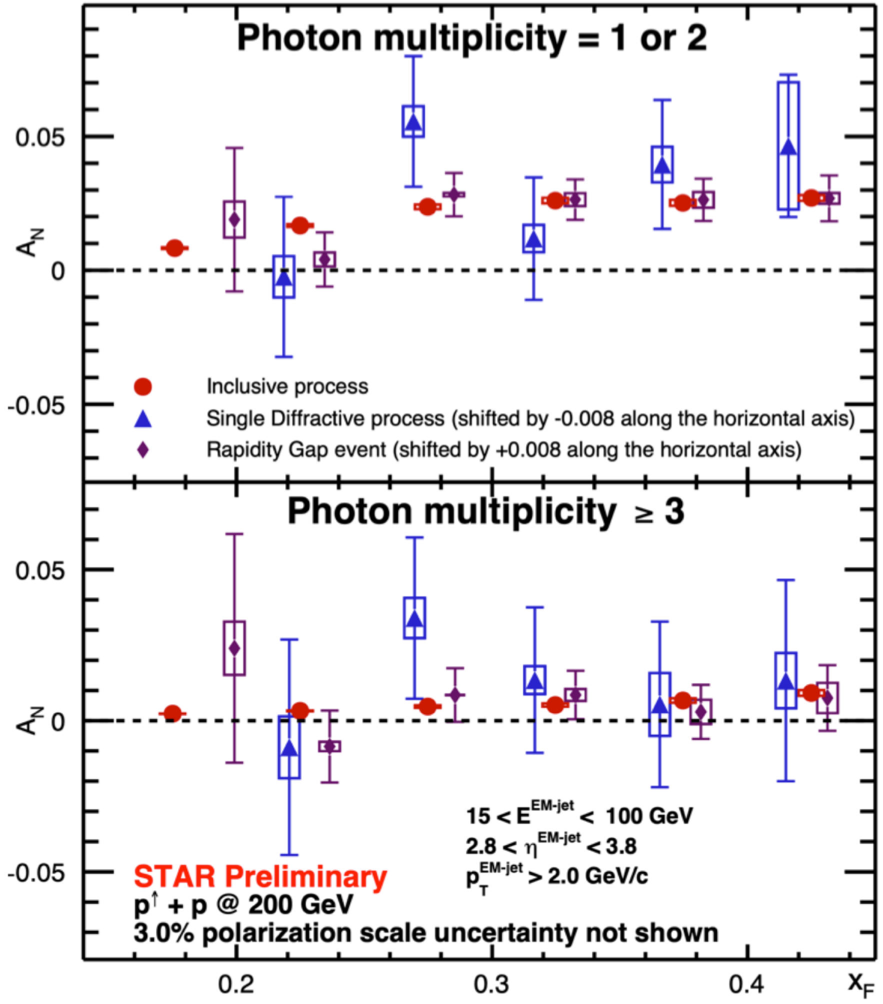


- $p^{\uparrow} + p \rightarrow p + \text{EM-jet} + X$
- 1 east roman pots (RP) track , no requirement on west RP
- 1 EM-jet per event is allowed

➢ Rapidity gap event



- $p^{\uparrow} + p \rightarrow p + p + \text{EM-jet} + X$
- No RP track requirement
- 1 EM-jet per event is allowed

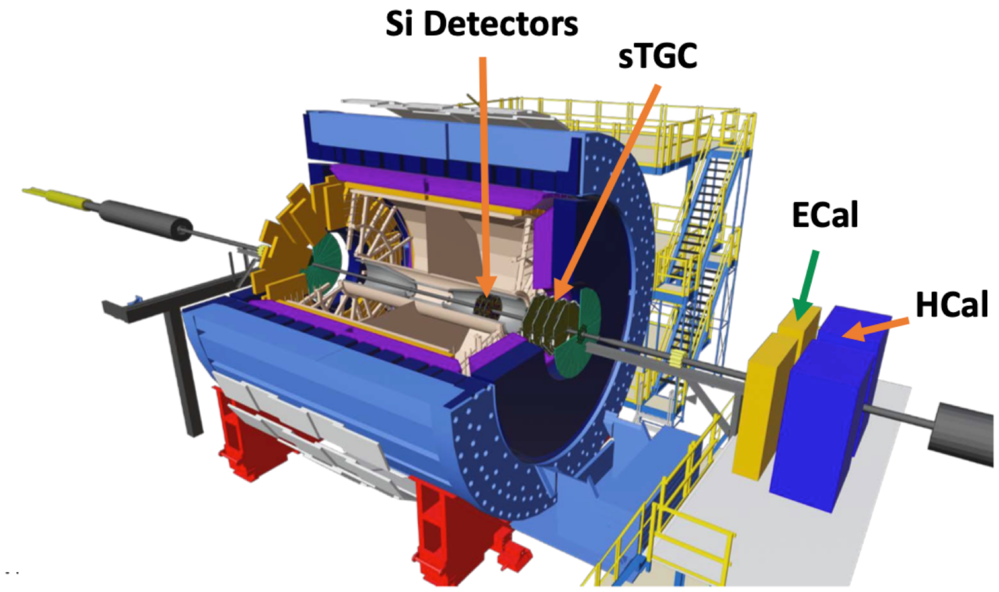


- The single diffractive and rapidity gap EM-jet A_N are consistent within uncertainty
- The observed inclusive π^0 asymmetry is unlikely to originate from diffractive processes

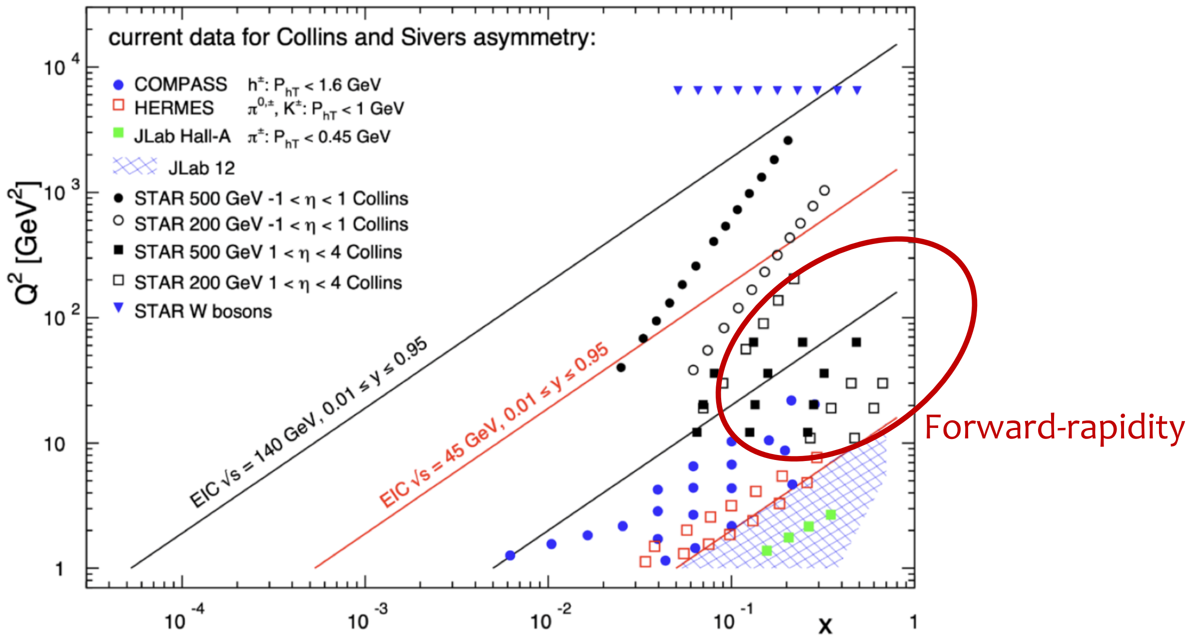
Outlook

- STAR Forward Detector Upgrade ($2.5 < \eta < 4$)

Tracking system & calorimetry system



arXiv:2302.00605



- Successfully collected pp data at 510 and 200GeV during 2022 and 2024
- x extends up to ~0.5, with charged particle tracking and electromagnetic and hadronic calorimetry
- Complement the kinematic coverage of ep data from the EIC

Year	2022	2024
$\sqrt{s}$ (GeV)	510	200
L_{int} (pb^{-1})	400	~170
Polarization	52%	53% / 57%

Summary

- **Sivers Effect Breakthrough**: First observation of non-zero k_T signal in pp via dijet analysis confirms initial-state spin-momentum correlations; W/Z boson asymmetries constrain process-dependent sign reversal

- **Collins Effect & Transversity Probing**: Energy-independent Collins asymmetries (200/510 GeV) indicate a weak TMD evolution; Hadron-in-jet asymmetries and dihadron correlations jointly constrain transversity h_1, testing universality compared with SIDIS and e^+e^- results

- **Polarizing / Polarized FF Constraints**: First pp measurement of $\Lambda(\overline{\Lambda})$ polarization in jets probes polarizing FF $D_{1T}^{\perp}$; Hyperon spin transfers provide a direct probe of the transversely polarized fragmentation function H_1

- **Beyond-TMD Mechanisms**: Isolated π^0 asymmetries exclude diffractive dominance, suggesting other mechanism, such as higher-twist effect

- **Technology Advances**: Established pp collisions as precision tool for 3D nucleon structure; Developing techniques bridge to EIC-era TMD studies