Azimuthal transverse single-spin asymmetries of inclusive jets and hadrons within jets from polarized pp collisions at $\sqrt{s}$ = 510 GeV

Yixin Zhang (张宜新),
for the STAR Collaboration
Shandong University (山东大学)

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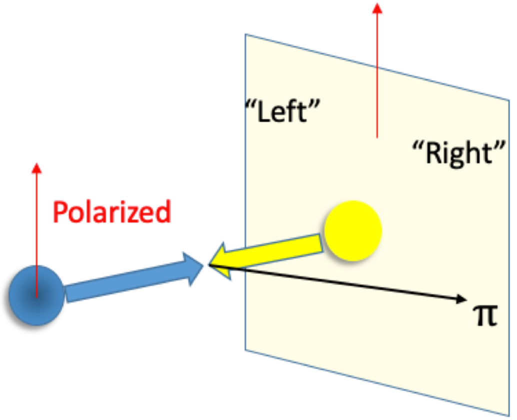
Challenges in Transverse Single-Spin Asymmetry

- 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).

- Left-right asymmetries for different hadrons at different beam energies

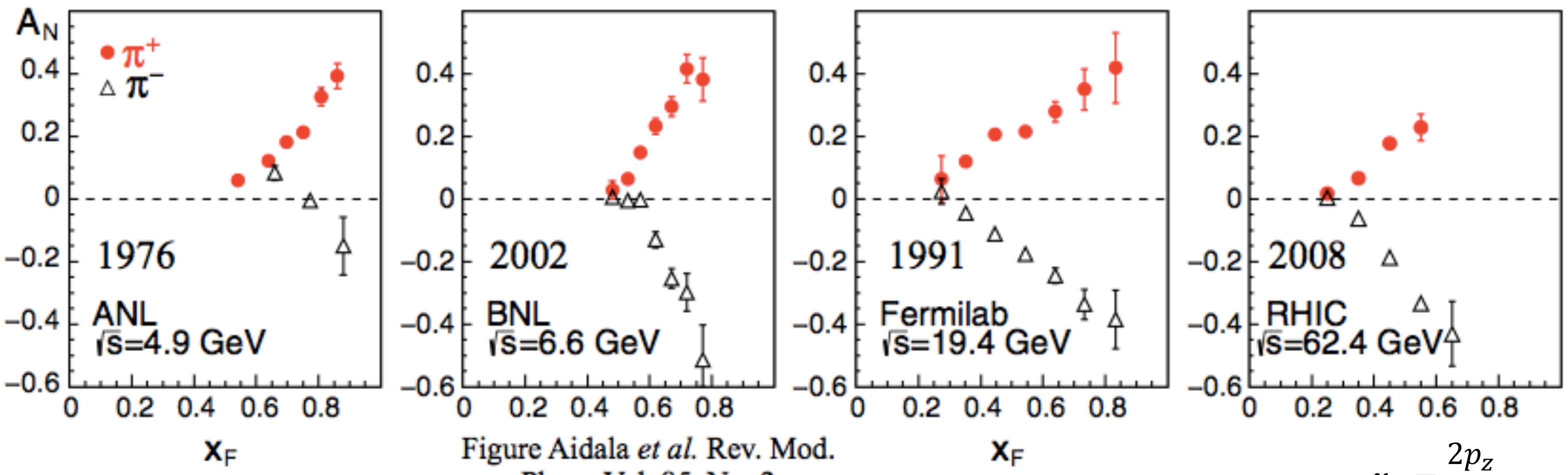


Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

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

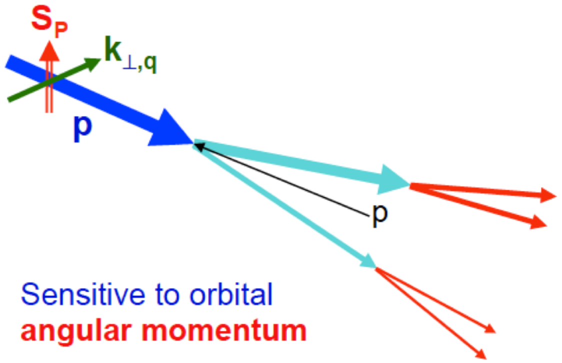
- Explained by the twist-3 and transverse-momentum-dependent (TMD) formalisms

Mechanisms for Transverse Single-Spin Asymmetry

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

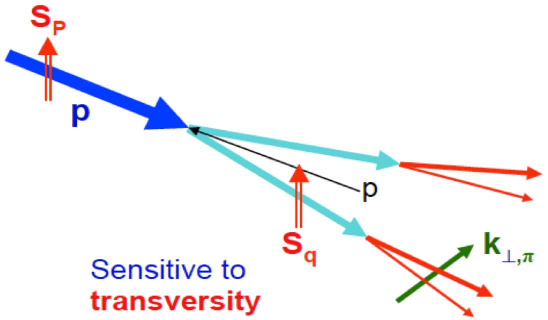
✓ **Sivers effect (*Sivers'90*):**

Parton spin and k_T correlation in initial state (related to orbital angular momentum)



✓ **Collins effect (*Collins'93*):**

Quark spin and k_T correlation in fragmentation process (related to transversity)

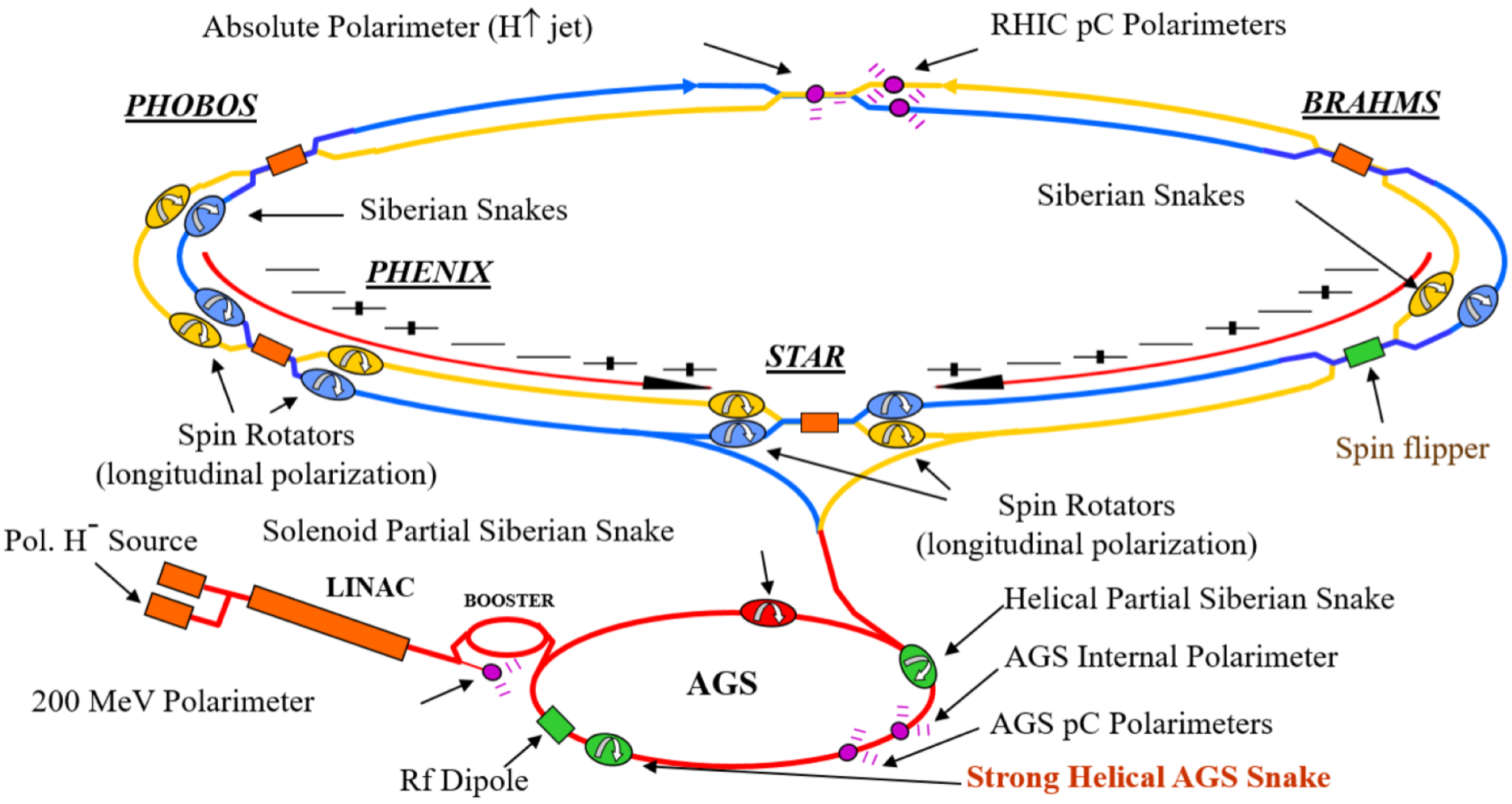


$$\vec{S} \cdot (\vec{p} \times \vec{k}_T)$$

- Twist-3 mechanism (Efremov-Teryaev'82, Qiu-Sterman'91):
  - Collinear/twist-3 quark-gluon correlation + fragmentation functions
  - Need one scale $(Q \ or \ p_T), Q, p_T >> \Lambda_{QCD}$
  - Both mechanisms apply when $Q >> p_T >> \Lambda_{QCD}$

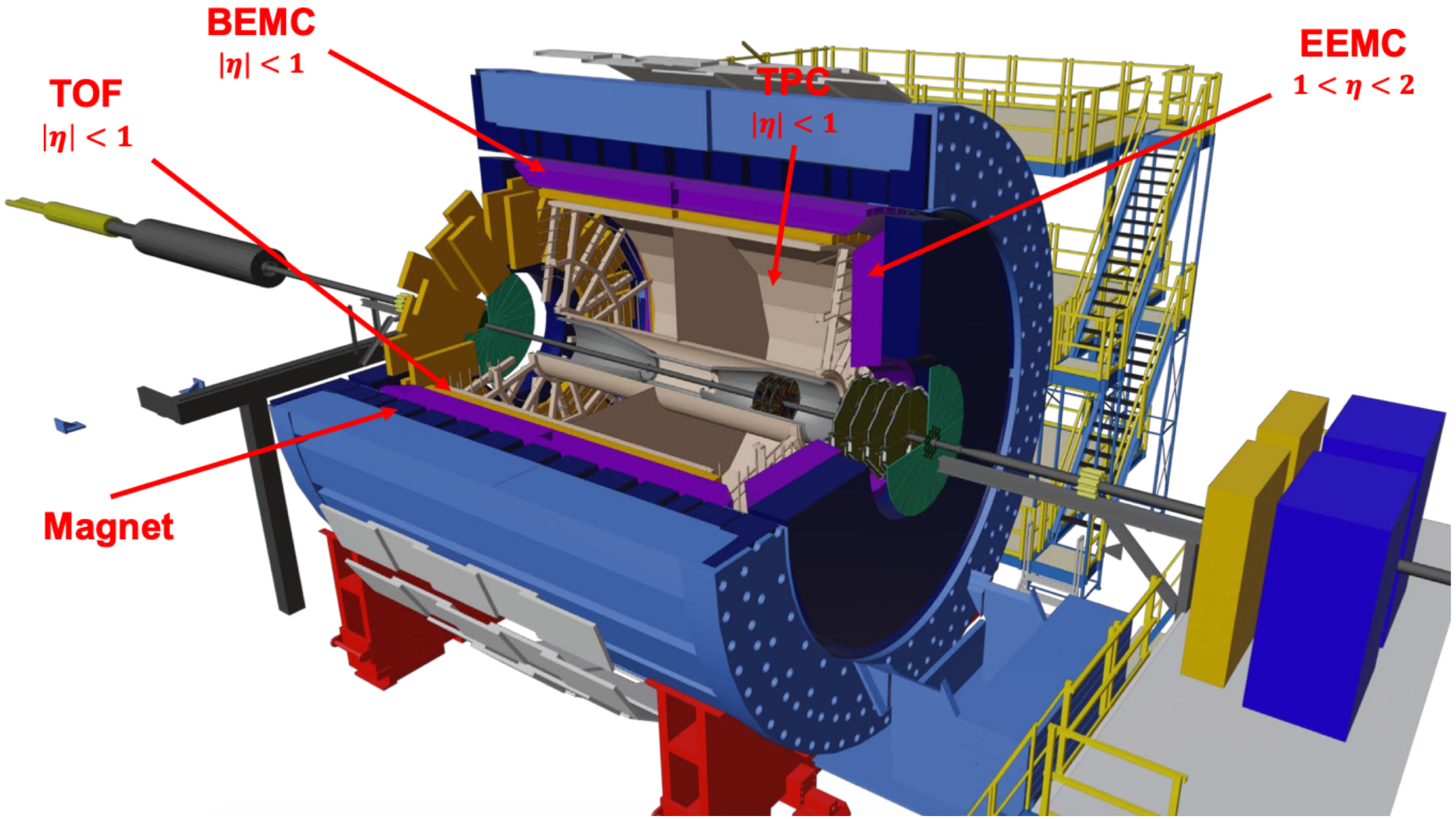
◆ **We will study Sivers effect with inclusive jet, and Collins effect with hadron in jets in pp collisions at STAR**

Relativistic Heavy Ion Collider (RHIC)



- RHIC is the world's only machine capable of colliding high-energy beams of polarized protons

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

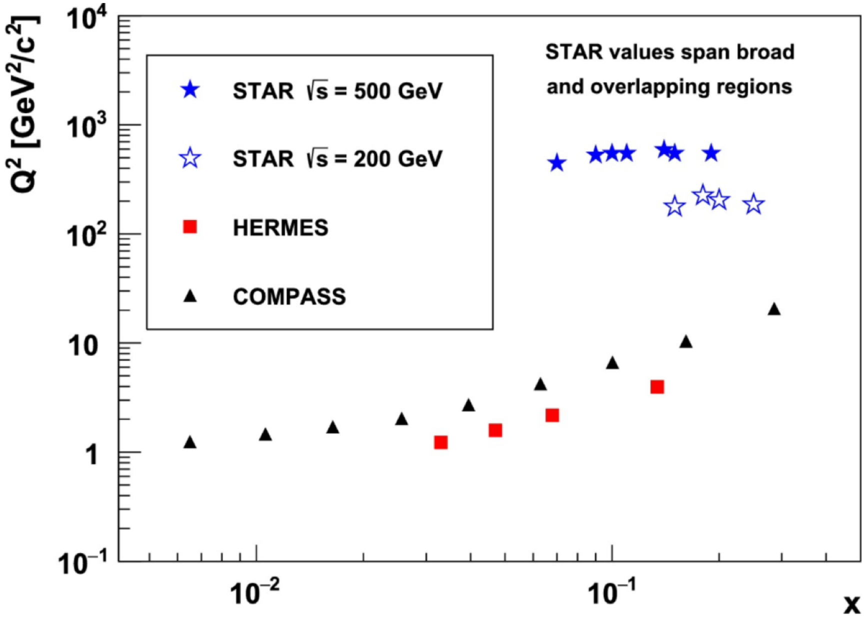
STAR Data of pp Collision and Kinematic Coverage

STAR

- Transversely polarized proton-proton collision data in recent years

Year	2011	2012	2015	2017	2022
$\sqrt{s}$ (GeV)	500	200	200	510	508
L_{int} (pb^{-1})	25	14	52	350	400
Polarization	53%	57%	57%	55%	52%

- STAR measurements overlap much of the x range of SIDIS but at a dramatically higher range of Q^2



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

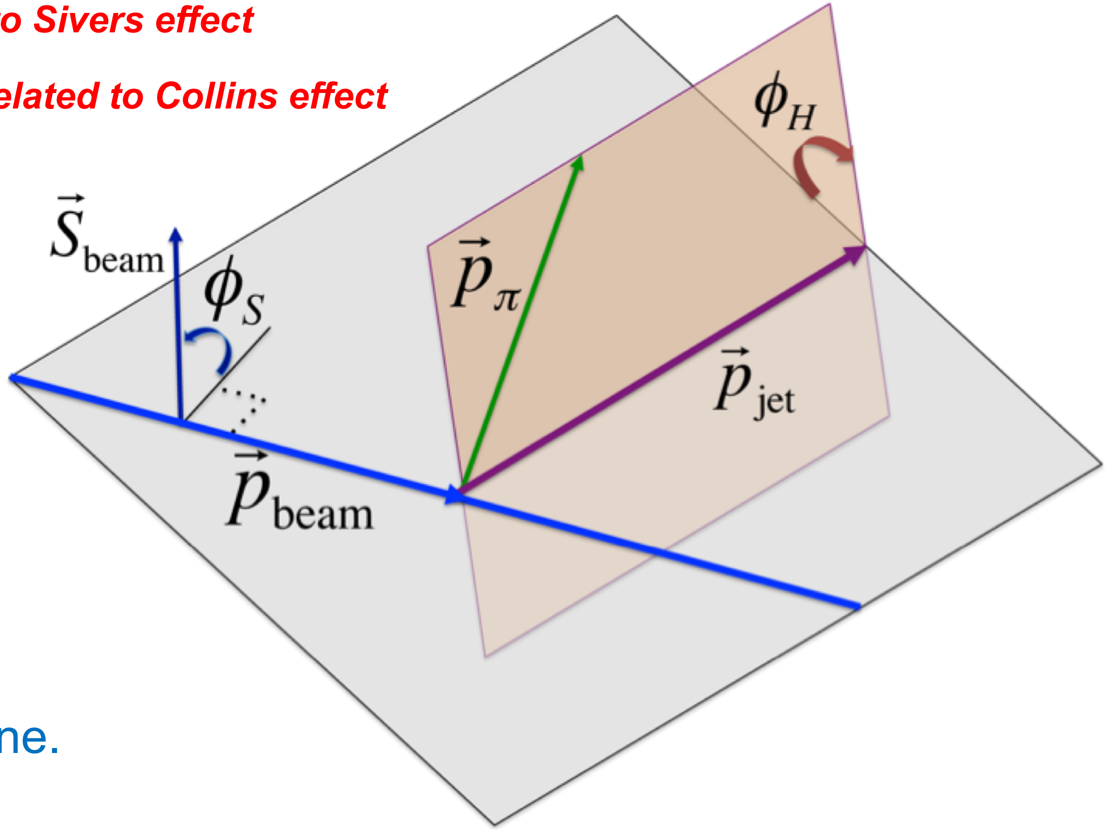
Extraction of Transverse Single-Spin Asymmetry

- For $\pi^{\pm}$ within jets in pp collisions, the spin dependent cross section can be expressed:

$$\frac{d^{\sigma^{\uparrow}}(\phi_S,\phi_H) - d^{\sigma^{\downarrow}}(\phi_S,\phi_H)}{d^{\sigma^{\uparrow}}(\phi_S,\phi_H) + d^{\sigma^{\downarrow}}(\phi_S,\phi_H)} \propto \begin{aligned} & A_{UT}^{sin(\phi_S)}\, sin(\phi_S) \\ & + A_{UT}^{sin(\phi_S-\phi_H)}\, sin(\phi_S-\phi_H) \\ & + A_{UT}^{sin(\phi_S-2\phi_H)}\, sin(\phi_S-2\phi_H) \\ & + A_{UT}^{sin(\phi_S+\phi_H)}\, sin(\phi_S+\phi_H) \\ & + A_{UT}^{sin(\phi_S+2\phi_H)}\, sin(\phi_S+2\phi_H) \end{aligned}$$

related to Sivers effect (first term)

related to Collins effect (second term)



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

- ϕ_S: azimuthal angle between the proton transverse spin polarization vector and jet scattering plane.

- ϕ_H: azimuthal angle of pion relative to the jets scattering plane.

Extraction of Transverse Single-Spin Asymmetries

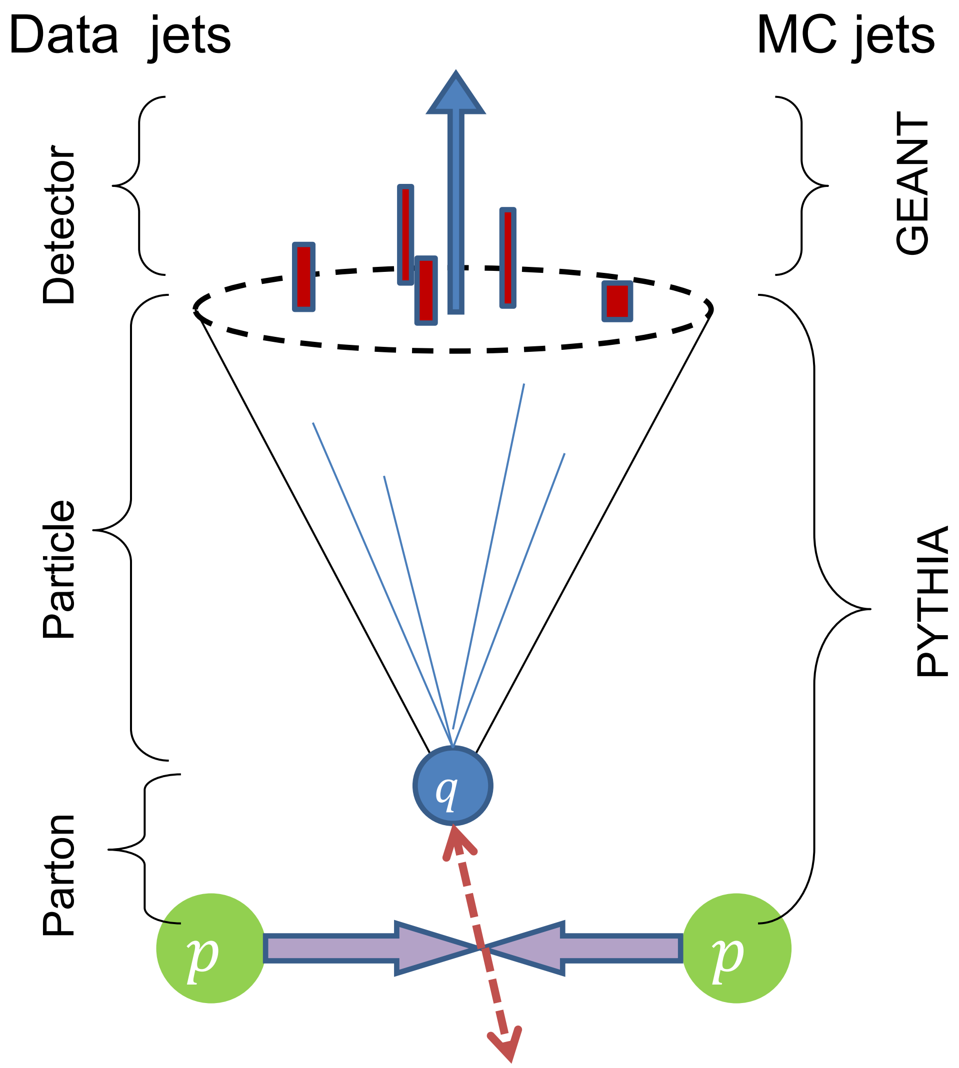
STAR

- Cross-ratio method to extract the asymmetries of different modulations.

$$A_N sin(\phi) = \frac{1}{P} \cdot \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

- Cross ratio formalism can cancel detector efficiencies and spin dependent luminosity.
- $N^{\uparrow}$(or $N^{\downarrow}$) is the yield for a given spin state.

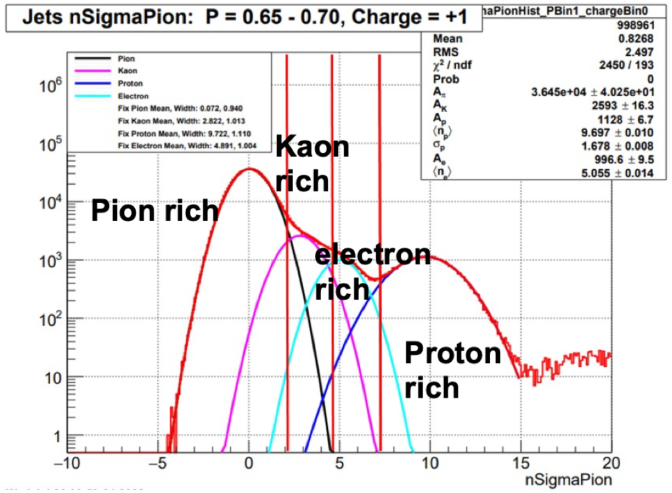
Jet Reconstruction

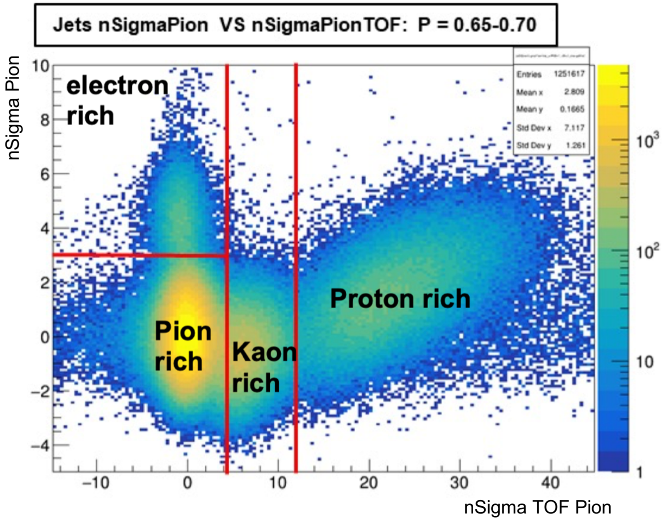


- **Jet reconstruction :**
  - Anti-K_T algorithm with $R = 0.5$
  - TPC tracks and EMC energy deposition as input
  - Off-axis cone method to estimate underlying event contribution
- **Simulation**
  - PYTHIA 6.4.28 + GEANT3
  - Partonic $p_T > 5\mathrm{GeV}/c$
  - Kinematic correction & Systematic uncertainty estimation

Particle identification and Asymmetries purification

- Particle rich region for TOF unmatched / matched





- Good particle identification through TPC and TOF.
- Raw asymmetries can be extracted in different particle rich region.
- Calculate the fraction of particle type in each particle rich region as matrix element for asymmetries purification.

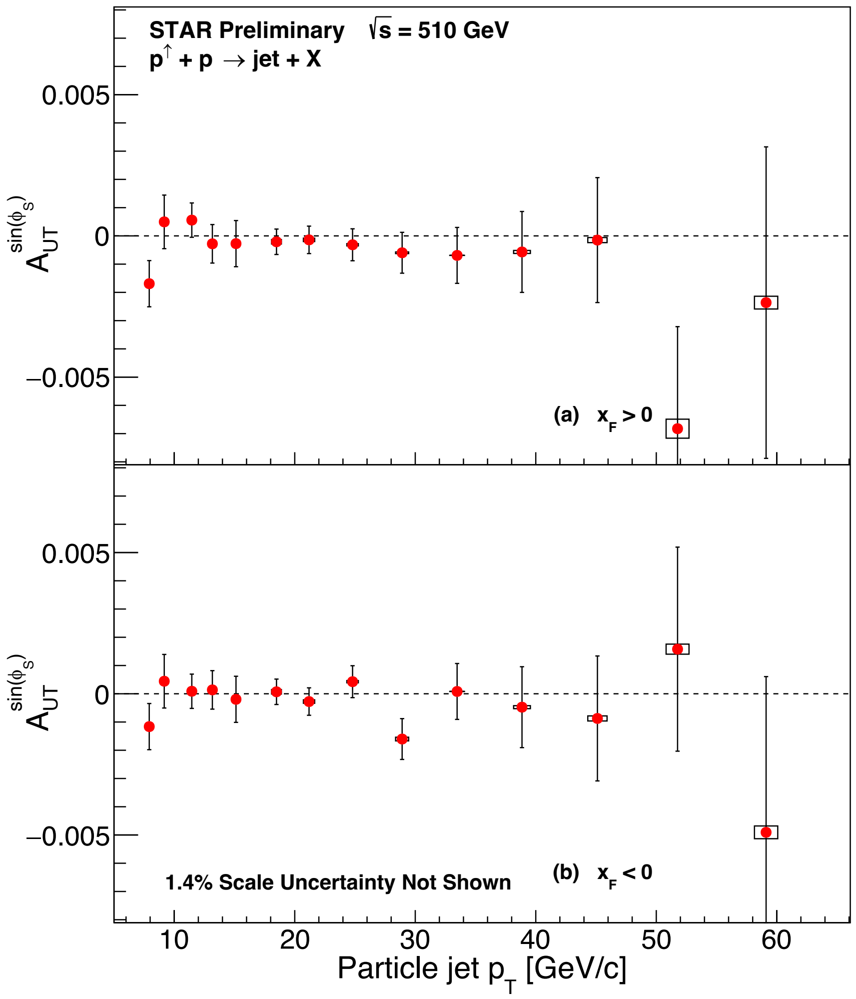
- Asymmetries purification through Moore-Penrose inverse.

$$\begin{pmatrix} f_{\pi\,rich}^{\pi\,TOF} & f_{\pi\,rich}^{K\,TOF} & f_{\pi\,rich}^{p\,TOF} \\ f_{K\,rich}^{\pi\,TOF} & f_{K\,rich}^{K\,TOF} & f_{K\,rich}^{p\,TOF} \\ f_{p\,rich}^{\pi\,TOF} & f_{p\,rich}^{k\,TOF} & f_{p\,rich}^{p\,TOF} \\ f_{\pi\,rich}^{\pi\,dE/dx} & f_{\pi\,rich}^{K\,dE/dx} & f_{\pi\,rich}^{p\,dE/dx} \\ f_{K\,rich}^{\pi\,dE/dx} & f_{K\,rich}^{K\,dE/dx} & f_{K\,rich}^{p\,dE/dx} \\ f_{p\,rich}^{\pi\,dE/dx} & f_{p\,rich}^{K\,dE/dx} & f_{p\,rich}^{p\,dE/dx} \end{pmatrix} \begin{pmatrix} A_{,\pi\,pure} \\ A_{K\,pure} \\ A_{p\,pure} \end{pmatrix} = \begin{pmatrix} A_{\pi\,raw}^{TOF} \\ A_{K\,raw}^{TOF} \\ A_{p\,raw}^{TOF} \\ A_{\pi\,raw}^{dE/dx} \\ A_{K\,raw}^{dE/dx} \\ A_{p\,raw}^{dE/dx} \end{pmatrix}$$

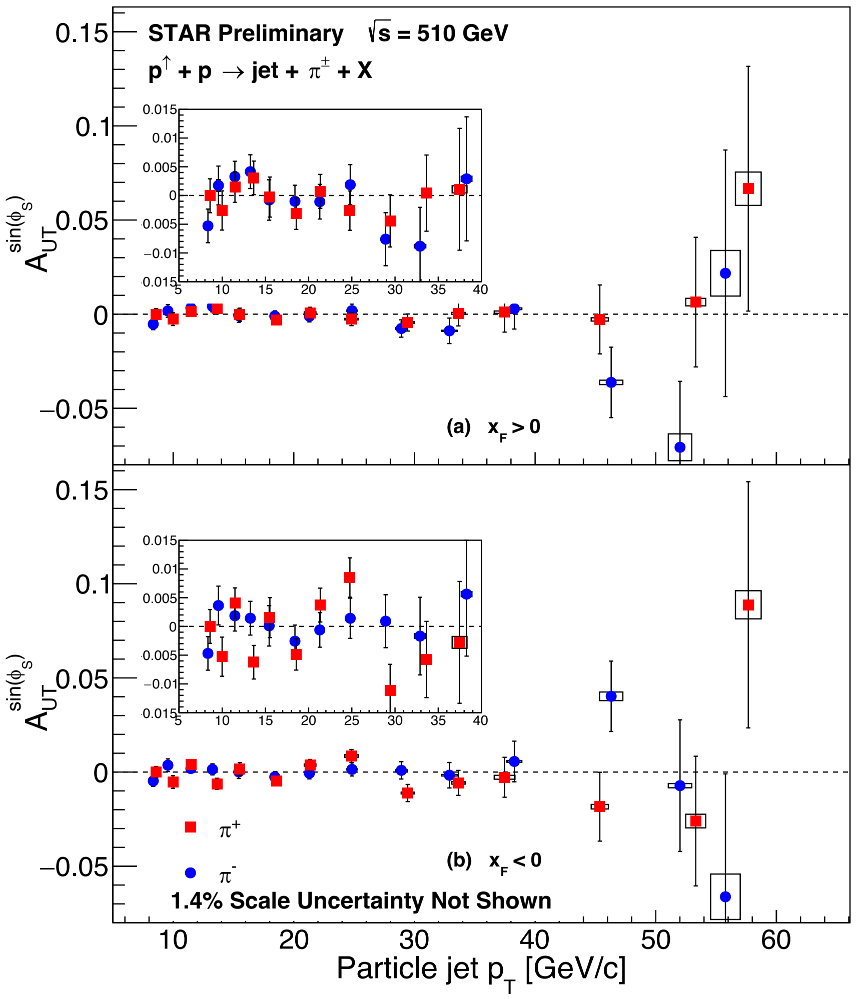
$f_{i\,rich}^{j}$: the fraction of particle type j in the i-rich sample.

Sivers Asymmetry from STAR 2017 Data

➢ Results for inclusive jet



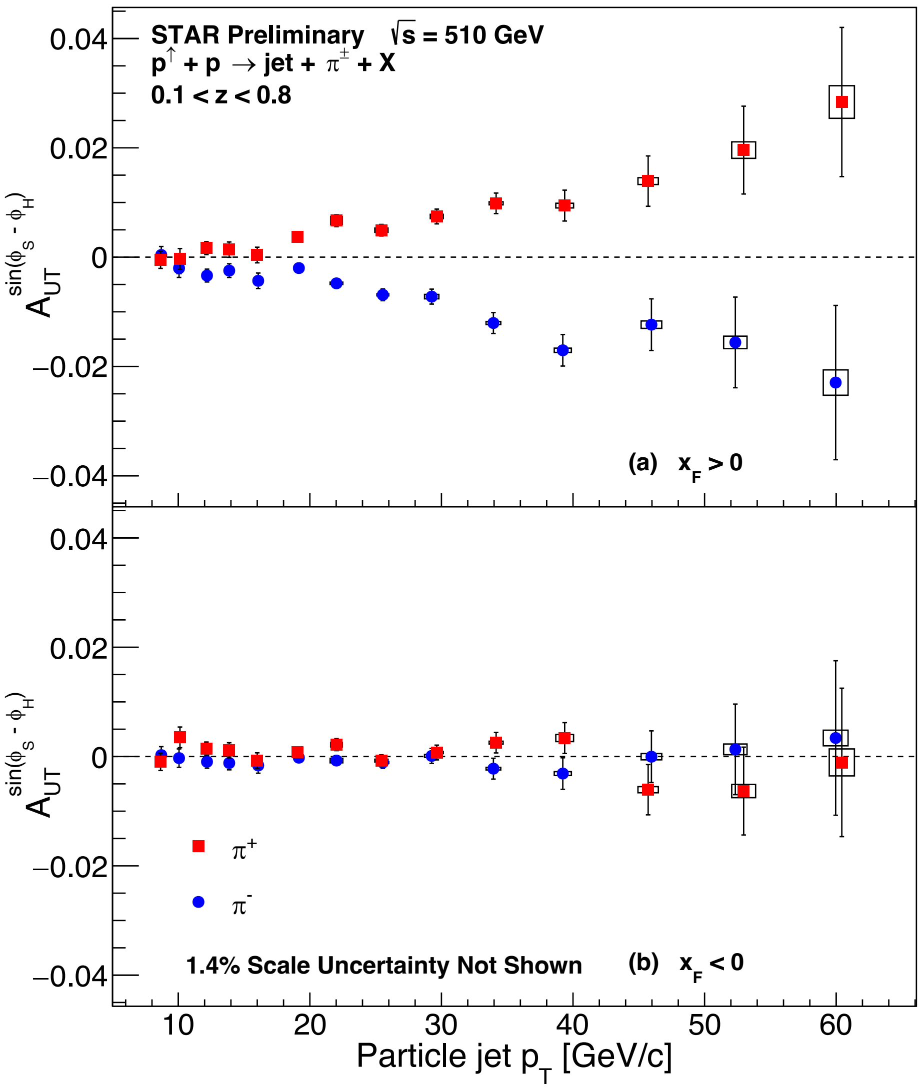
➢ Results for $\pi^{\pm}$ tagged jet



- Sivers asymmetries for inclusive jets and pion tagged jets are consistent with 0.
- Sensitive to Sivers function at twist-3.

Collins Asymmetry from STAR 2017 Data

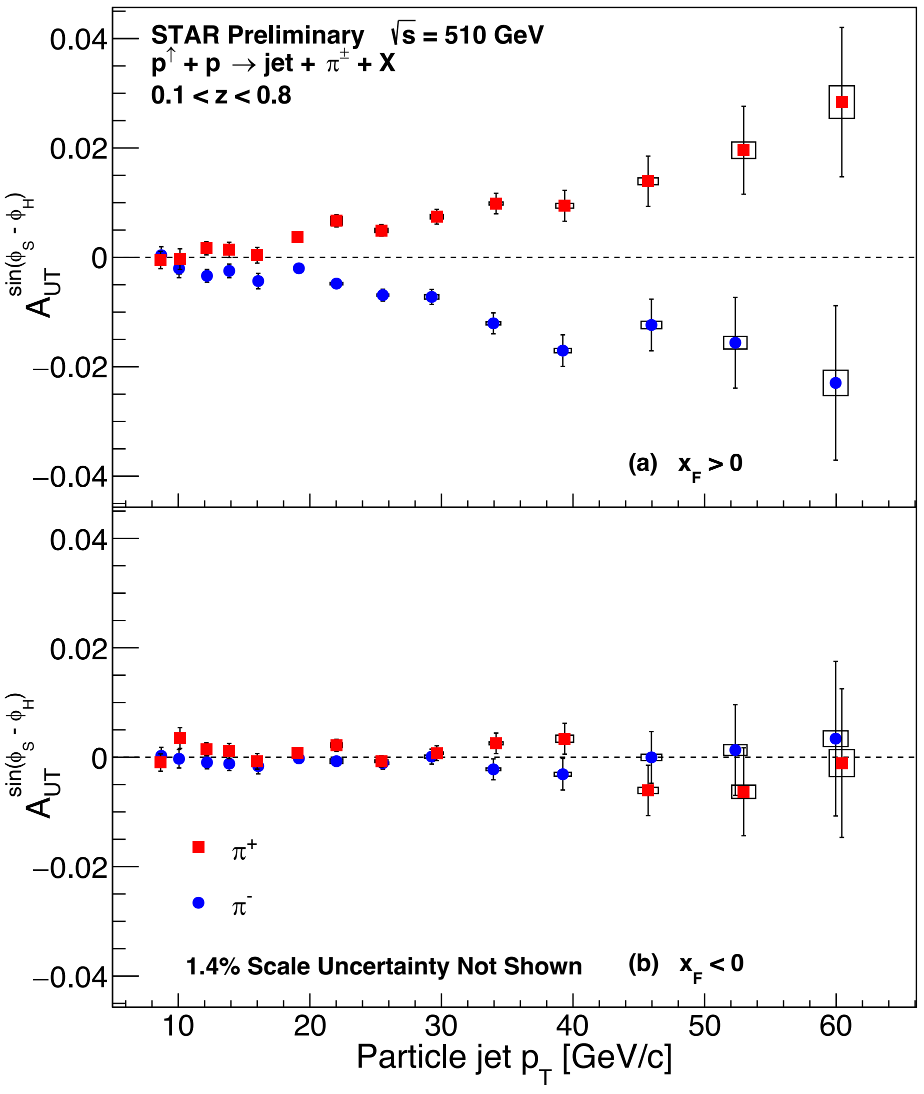
- Collins results as a function of jet p_T



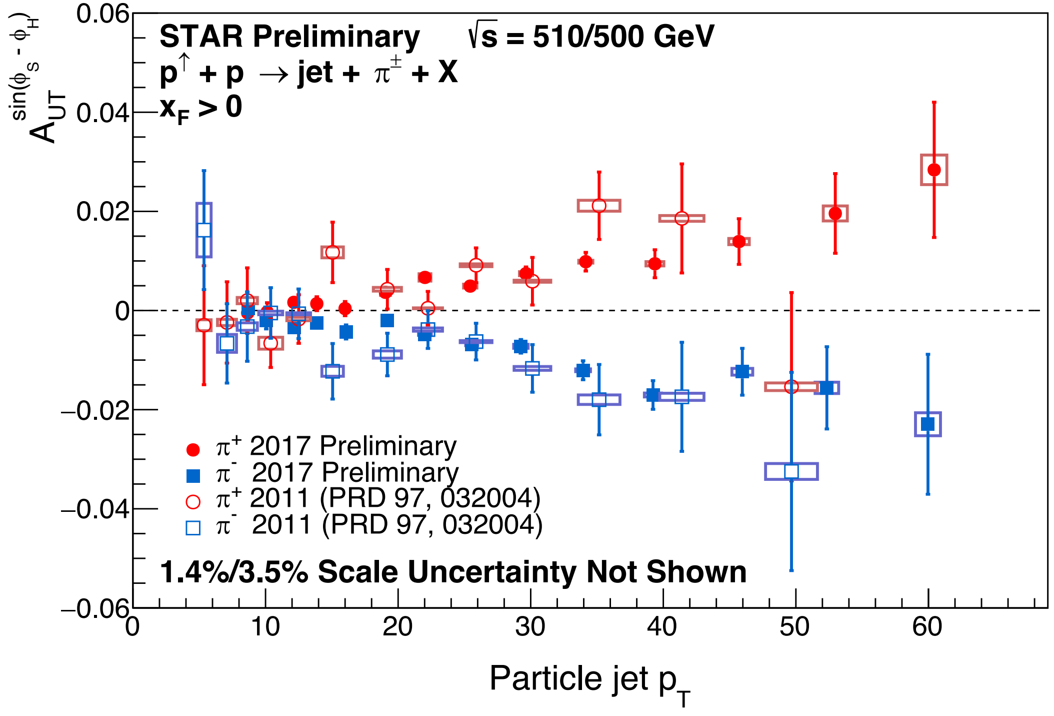
- Positive for π^+ and negative for π^-, and increase with increasing jet p_T for $x_F > 0$
- The asymmetries for $x_F < 0$ are consistent with 0.

Collins Asymmetry from STAR 2017 Data

➢ Collins results as a function of jet p_T



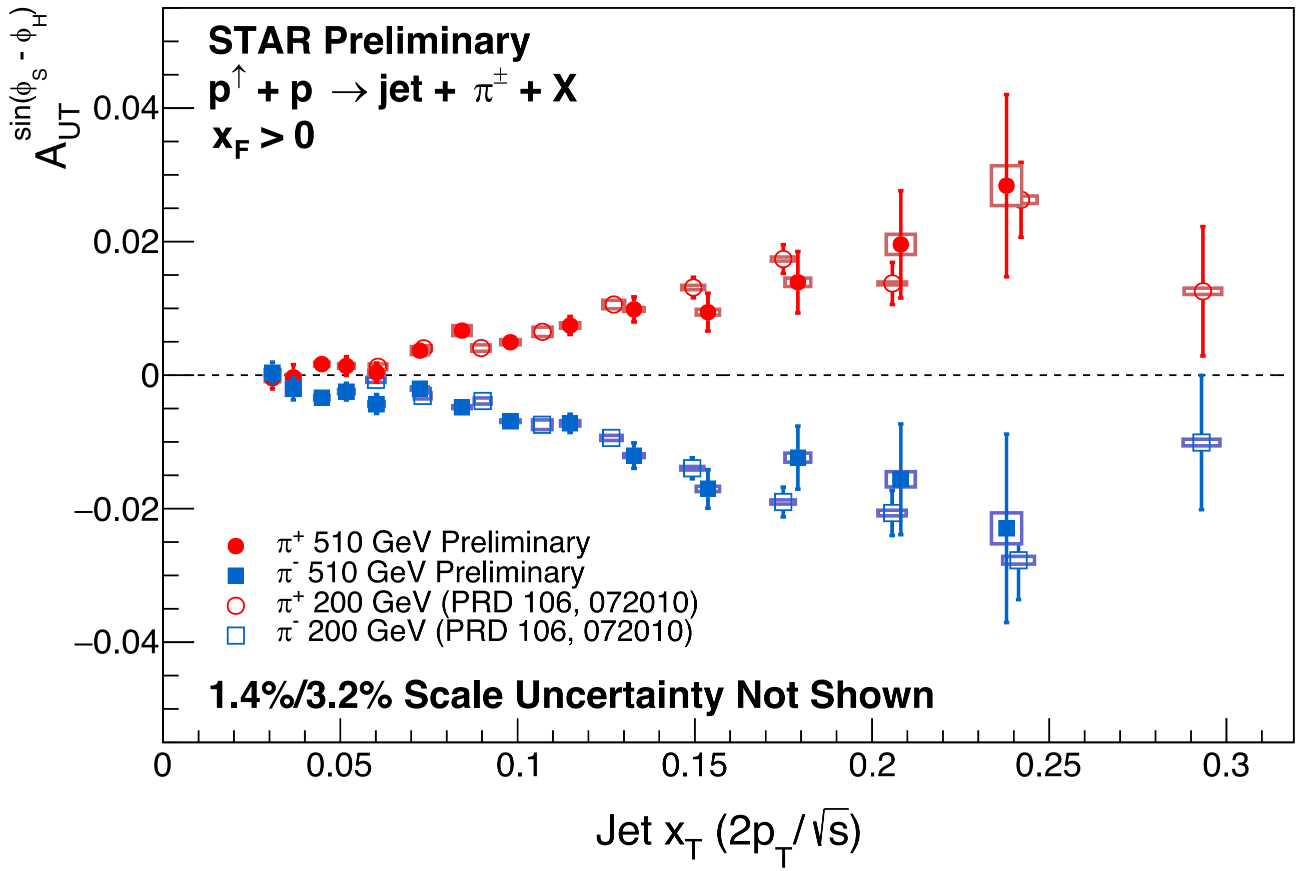
- Positive for π^+ and negative for π^-, and increase with increasing jet p_T for $x_F > 0$
- The asymmetries for $x_F < 0$ are consistent with 0.



- New results are consistent with previous run11 data, but with 14 times more statistics

Comparison to STAR 200 GeV Results

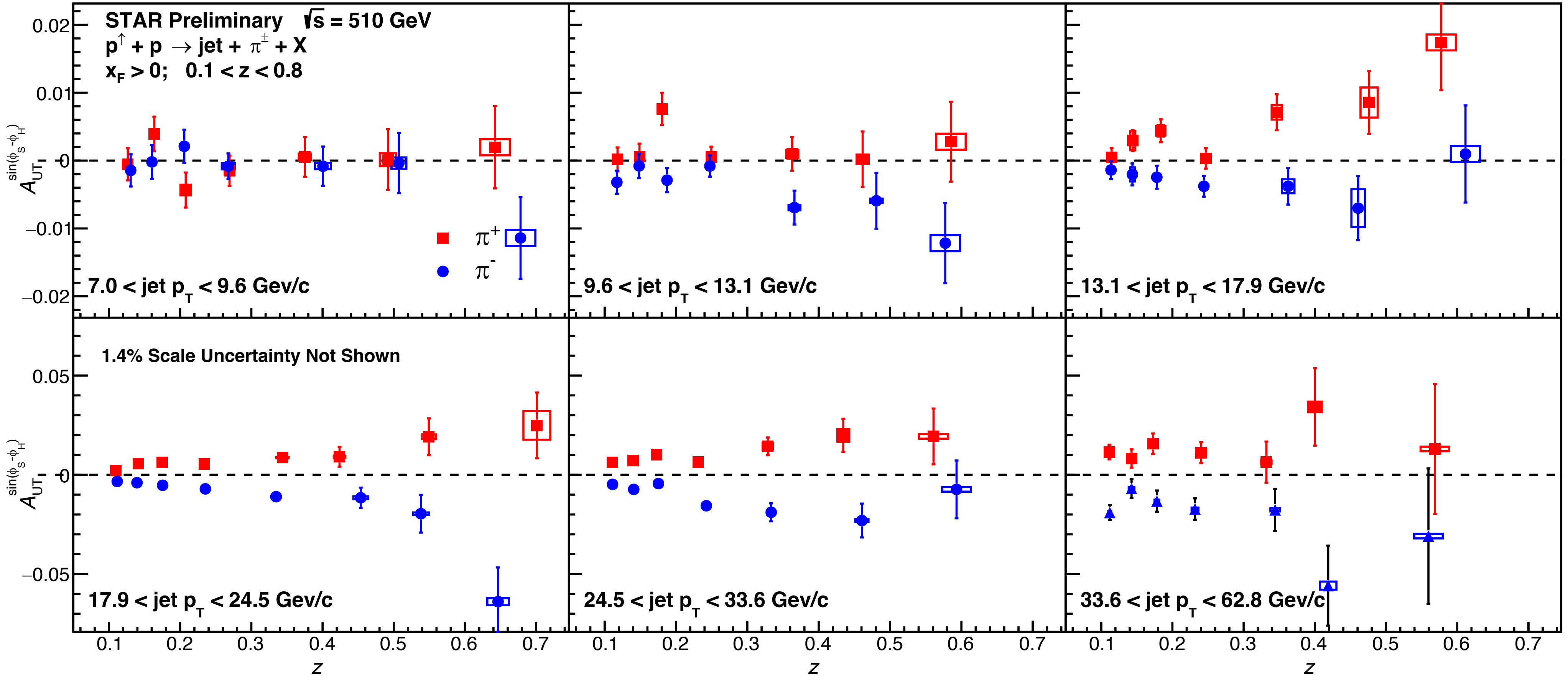
➢ Collins results as a function of x_T for 200 GeV and 510GeV:



- The high precision Collins results of 510 GeV and 200 GeV nicely align with jet x_T scale, giving almost no energy dependence.
- These data provide important constraints on the scale evolution for Collins asymmetry.

Collins Asymmetry from STAR 2017 Data

- Collins results as a function of z in different jet p_T regions at 510 GeV:

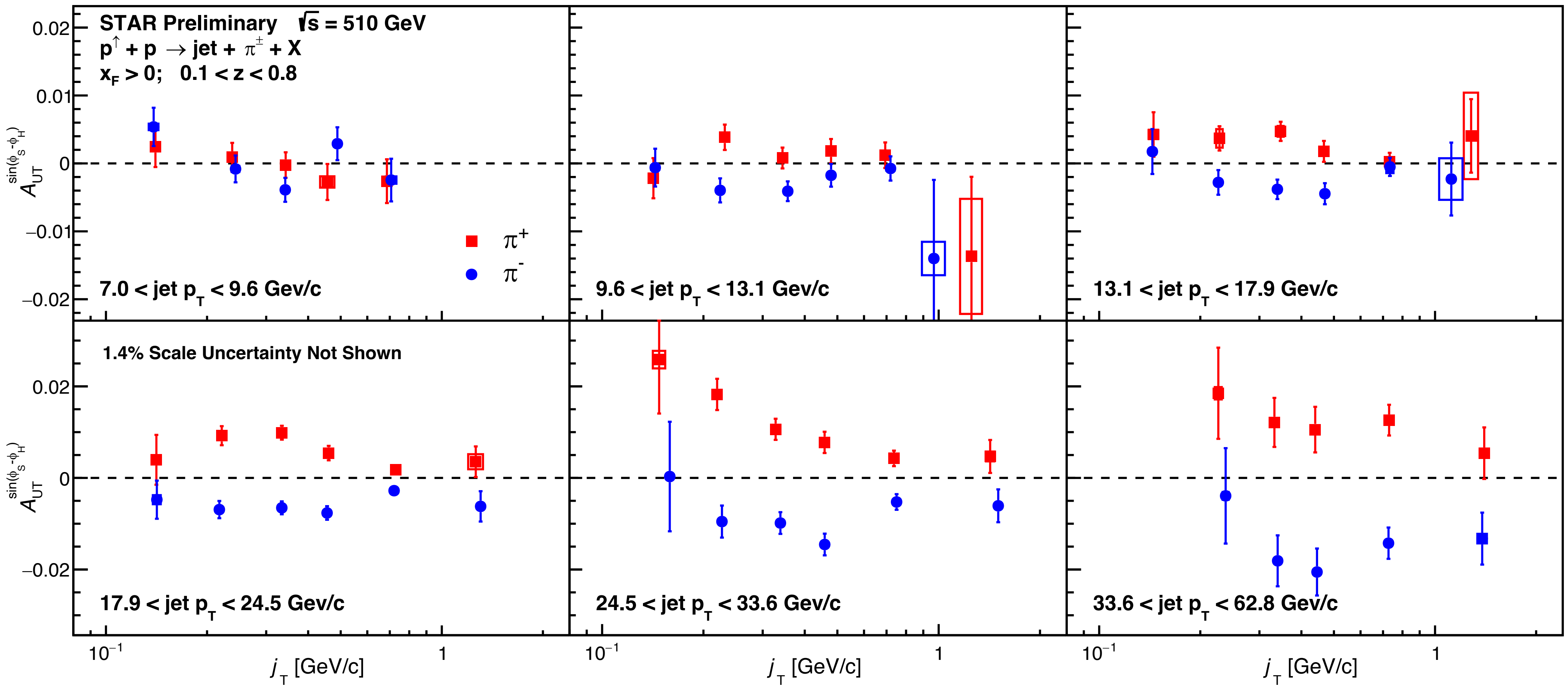


z：the pion's longitudinal momentum fraction in the jet

- These results provide more detailed constraints on the Collins fragmentation function

Collins Asymmetry from STAR 2017 Data

➢ Collins results as a function of j_T in different jet p_T regions at 510 GeV:

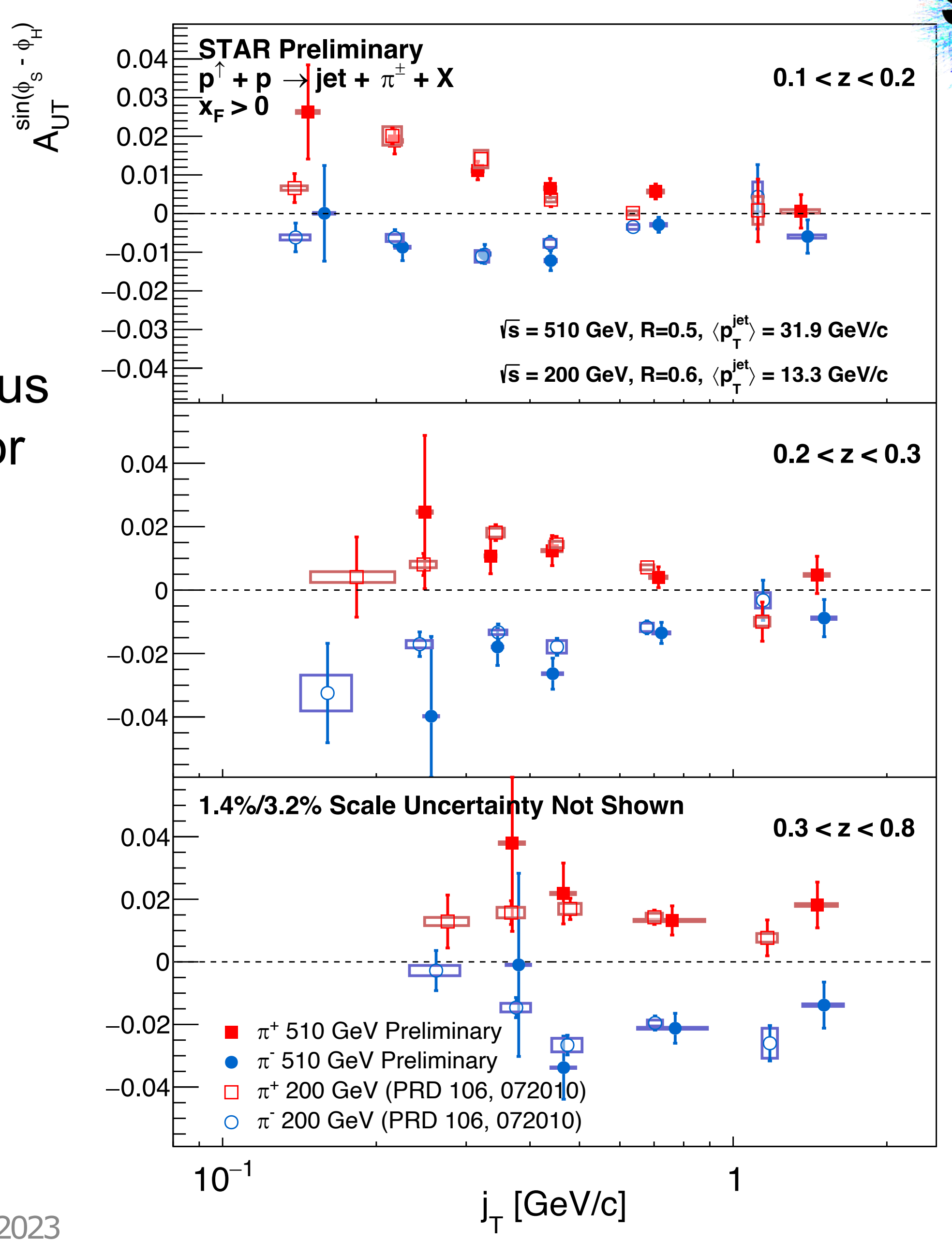


j_T : charged pion's transverse momentum relative to the jet axis

- These results provide more detailed constraints on the Collins fragmentation function

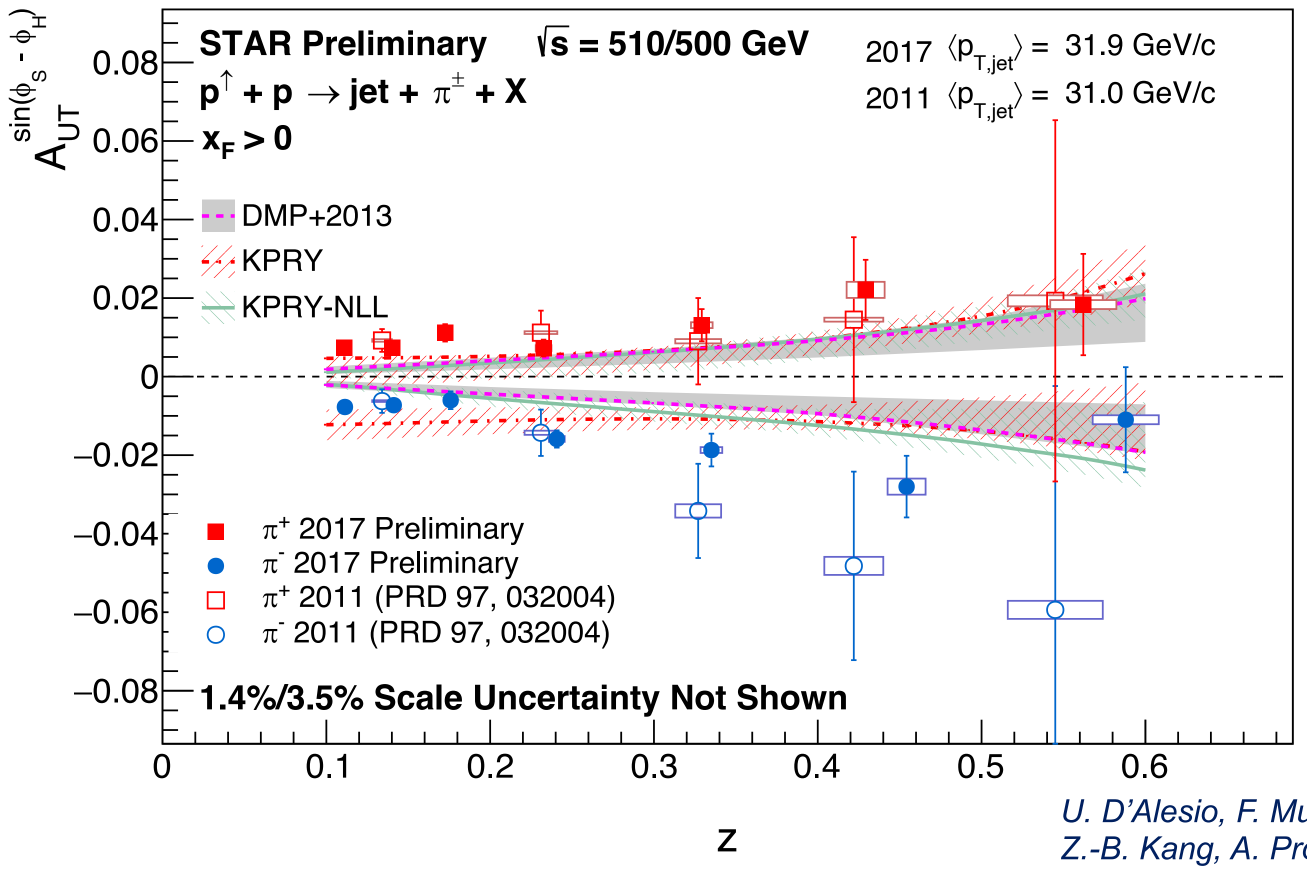
Comparison to STAR 200 GeV Results

- Collins results as a function of j_T for 200 GeV and 510 GeV:
  - In the same x_T bin, the Collins asymmetries versus j_T in different z regions are in good agreement for 510 GeV and 200 GeV
  - No energy dependence observed again



Comparison to theoretical calculations

➢ Collins results as a function of z , compared with theoretical results:



U. D'Alesio, F. Murgia, and C. Pisano, Phys. Lett. B 773, 300
Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B 774, 635

- The results of z dependence from two RHIC running periods are in good agreement.
- Generally, experimental results and theories are in agreement, but model calculations slightly undershoot the observed asymmetries.

Summary & Outlook

- New preliminary results on transverse single-spin asymmetries of jets and $\pi^{\pm}$ in-jets in pp at $\sqrt{s} = 510$ GeV with STAR 2017 data, 14 times more statistics to previous measurement with 2011 data.

- No significant non-zero Sivers asymmetries have been observed at 510 GeV in pp collision.

- The high precision Collins asymmetries for π^+ and π^- results at 510 GeV, in excellent consistency with 200 GeV data versus x_T, no energy dependence observed.

- Collins asymmetries for π^+ and π^- versus z and j_T are also reported.

- These data provide important constraints on the scale evolution, and test of universality for Collins asymmetry.

- A large data sample of transverse polarized p+p data taken in 2022 at STAR ($\sim 400 pb^{-1}$), with the forward detectors ($2.5 < \eta < 4$) installed, provides an unique opportunity to study Collins and Sivers asymmetries in the forward region.