31st International Workshop on Deep Inelastic Scattering (DIS2024)

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

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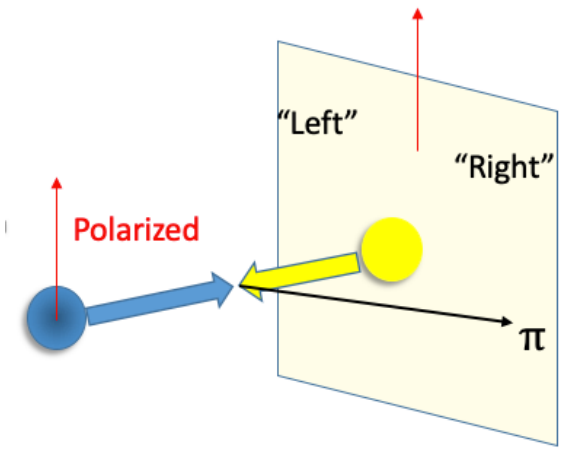
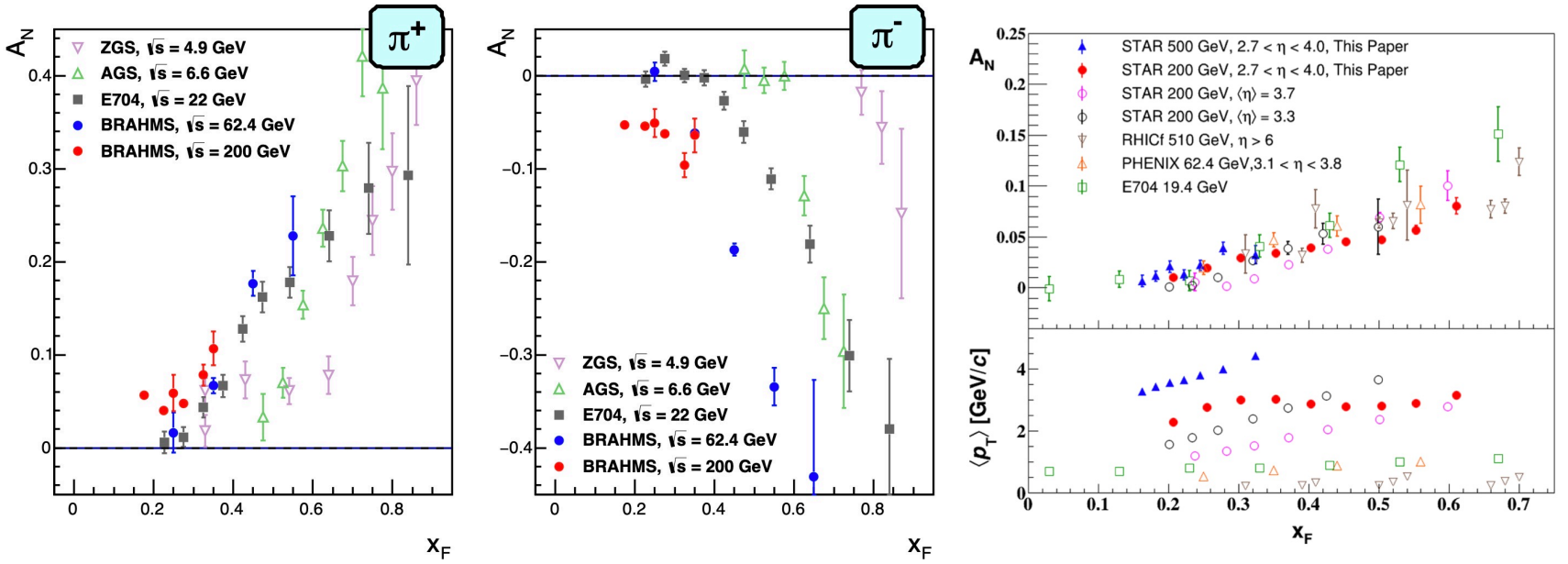
Challenges in Transverse Single-Spin Asymmetries

- Anomalously large A_N in pp collisions observed for over 40 years.



$$A_N = \frac{d\sigma^L - d\sigma^R}{d\sigma^L + d\sigma^R}$$

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



Elke Aschenauer et al. arXiv: 1602.03922 [nucl-ex]

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

$$x_F \equiv 2p_L/\sqrt{s}$$

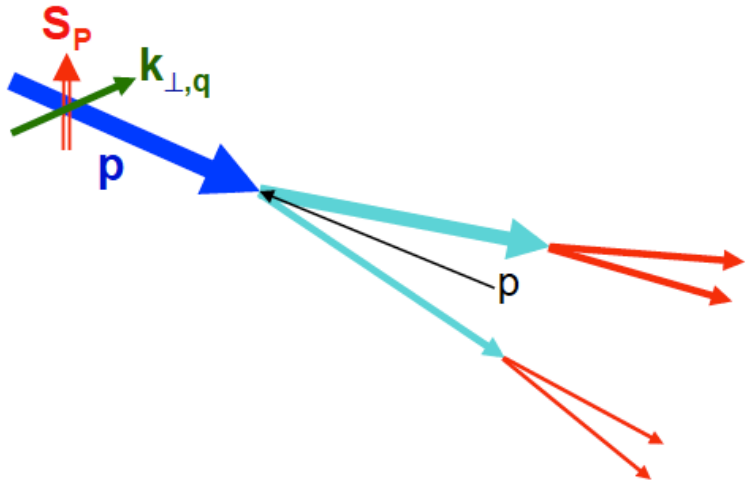
- Leading twist, collinear perturbative QCD fails to describe large A_N.
- Explained by the twist-3 and transverse-momentum-dependent (TMD) formalisms.

Mechanisms for Transverse Single-Spin Asymmetries

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

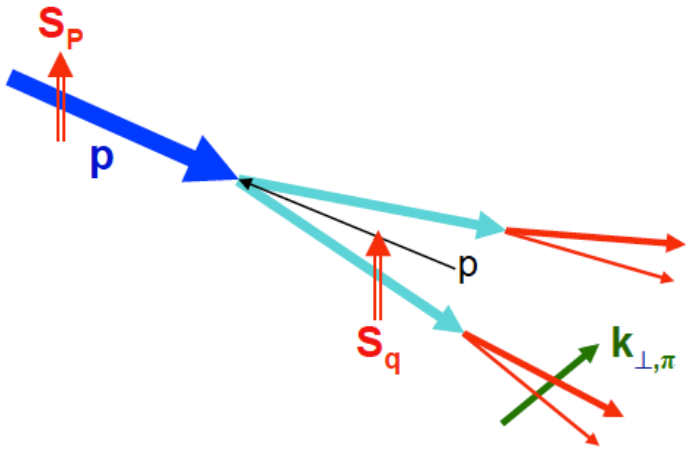
- Transverse Momentum Dependent (TMD) parton distribution and fragmentation functions.
  - ✓ Need two scales (Q and p_T), $Q \gg p_T$
  - ✓ Both mechanisms apply when $Q \gg p_T \gg \Lambda_{QCD}$

Sivers effect (*Sivers'90*):
Parton spin and k_T correlation in initial state



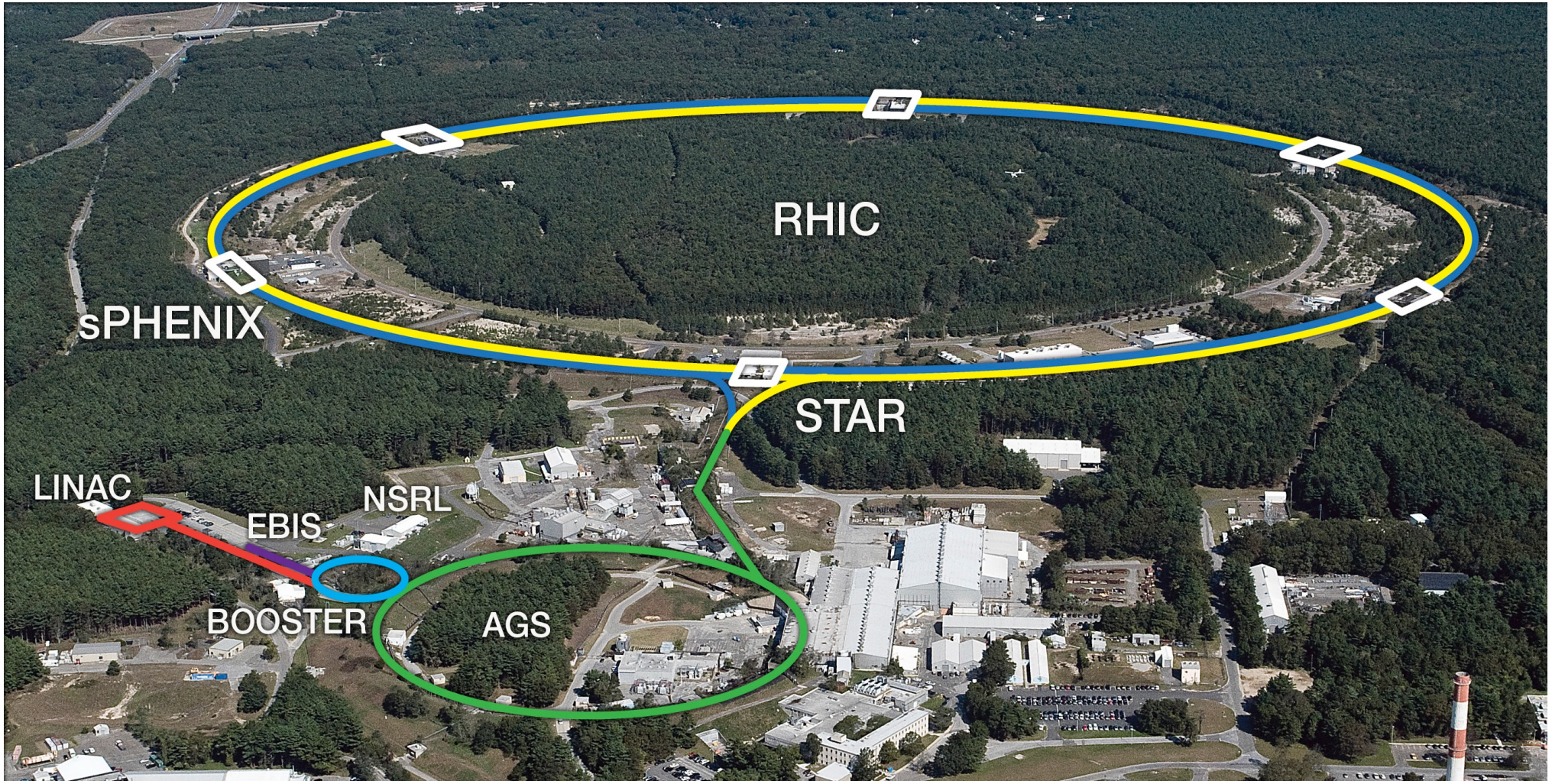
$$\vec{S} \cdot (\vec{p} \times \vec{k}_T)$$

Collins effect (*Collins'93*):
Quark spin and k_T correlation in fragmentation process (related to transversity)



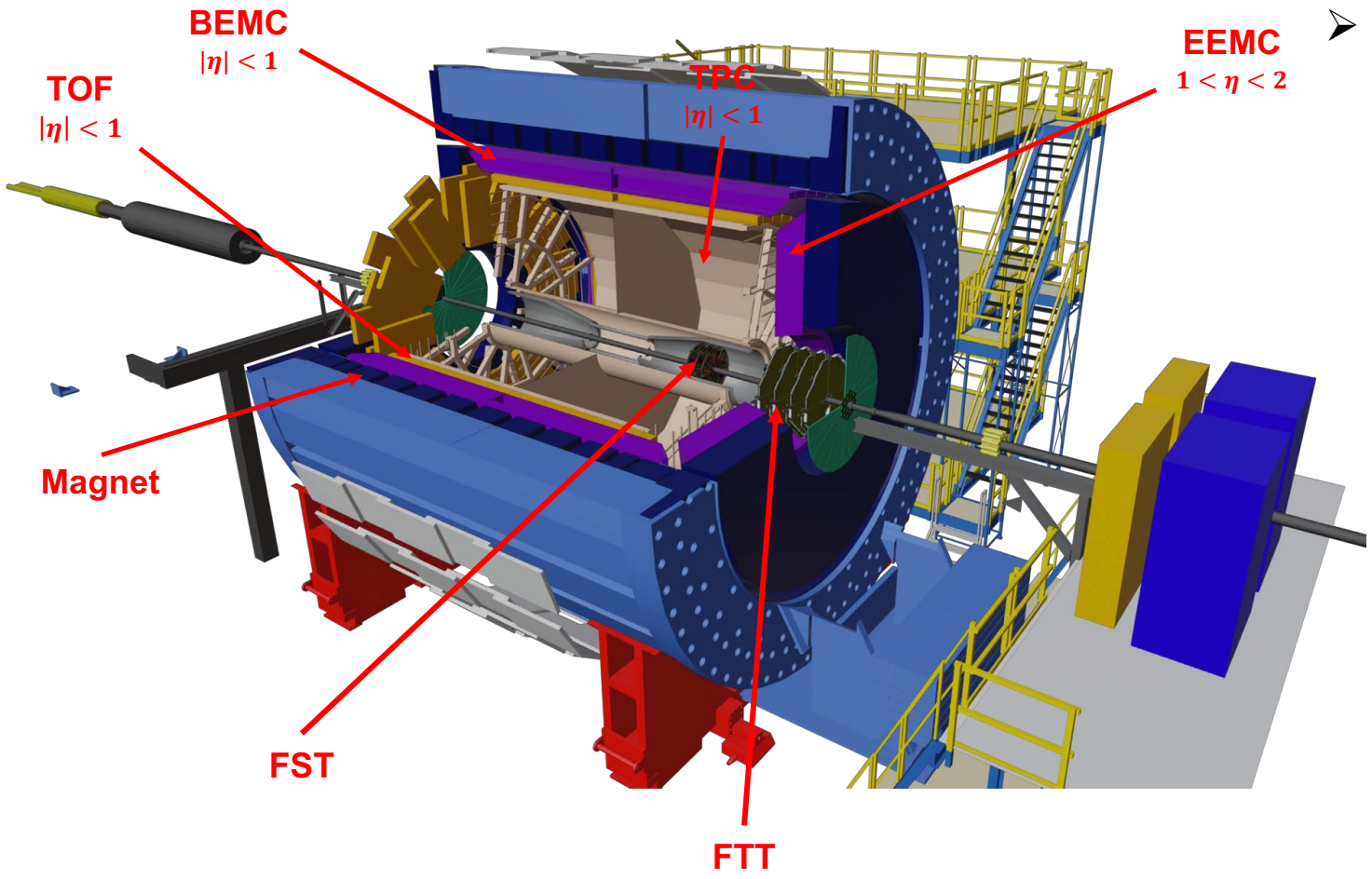
We will study Sivers effect with inclusive jet, and Collins effect with hadron in jets in pp collisions at STAR.

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)



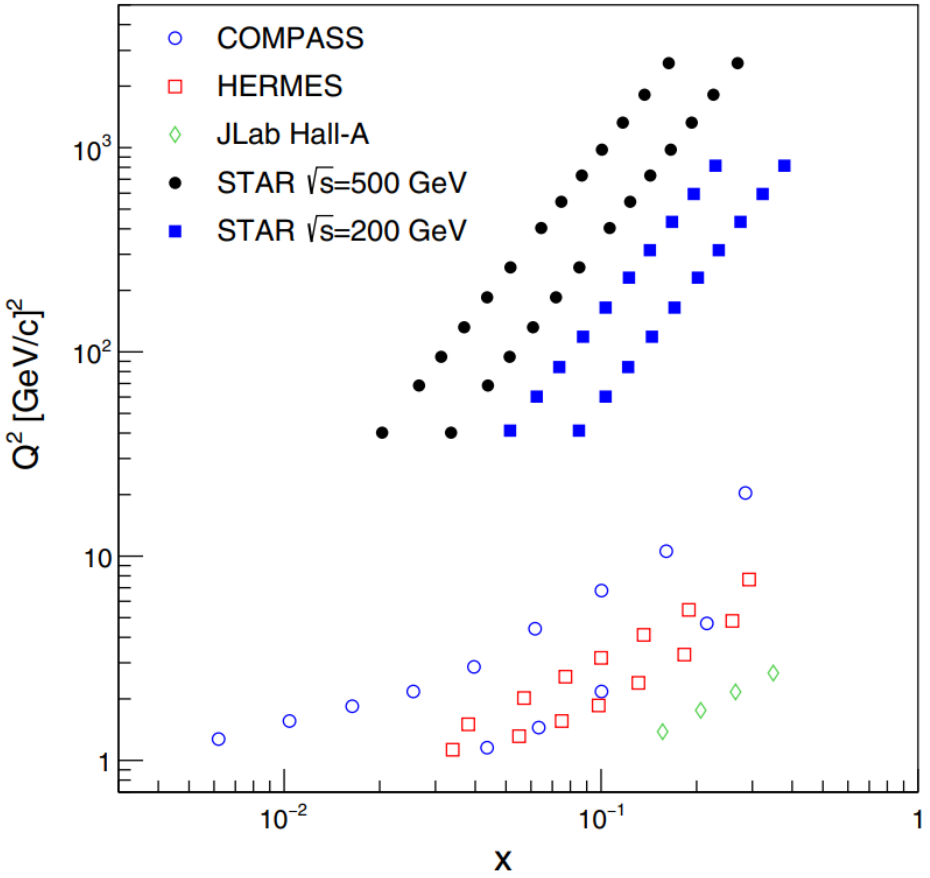
➢ STAR sub-system related to this anlysis：

- Time Projection Chamber (TPC)
  - ✓ $|\eta| < 1.0$ 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 data of transverse polarized pp collisions					
Year	2011	2012	2015	**2017**	2022
$\sqrt{s}$ (GeV)	500	200	200	**510**	508
L_{int} (pb^{-1})	25	14	52	**320**	400
Polarization	53%	57%	57%	**55%**	52%

- STAR measurements overlap much of the x range with SIDIS but at a dramatically higher range of Q^2.
- Results of Collins effect at higher values of Q^2 will provide necessary input on the evolution of TMD functions.



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

Extraction of Transverse Single-Spin Asymmetries

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

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

related to Sivers effect

relative to Collins effect

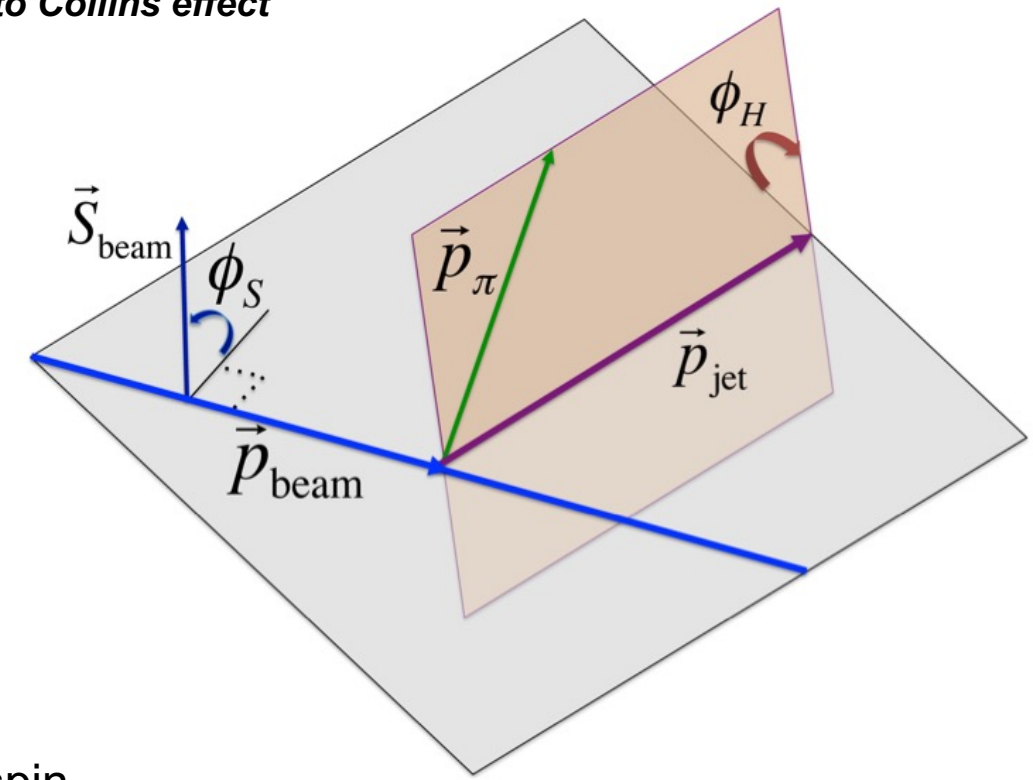
U. D'Alesio et al. Phys. Rev. D 83 034021 (2011)

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

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

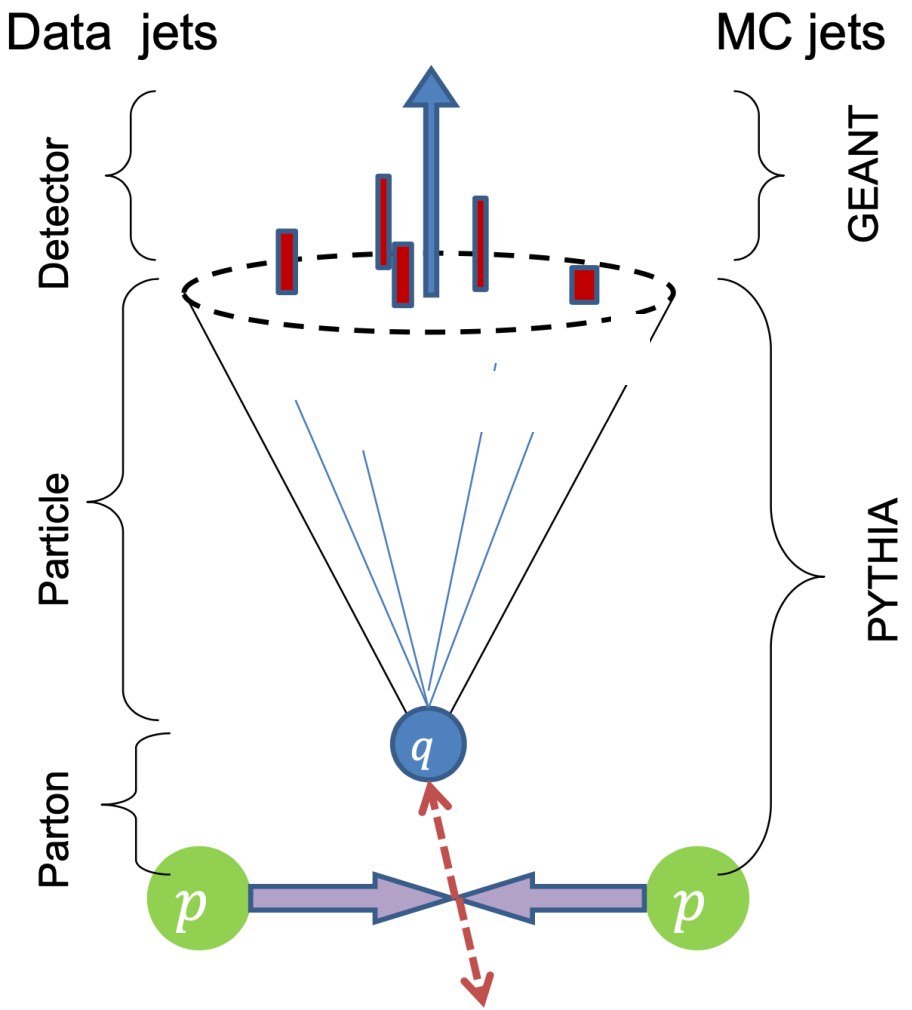
$N^{\uparrow}$(or $N^{\downarrow}$) is the yield for a given spin state.

- Cross ratio formalism can cancel detector efficiencies and spin dependent luminosity.



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

Jet Reconstruction

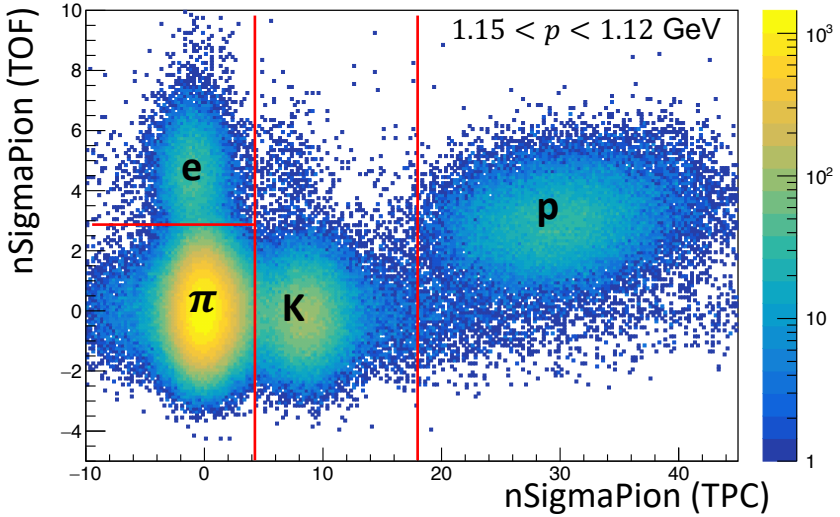


- **Jet**:
  - Anti-k_T algorithm with $R = 0.5$
  - TPC tracks and EMC energy deposition as input
  - Underlying event estimated by off-axis cone method

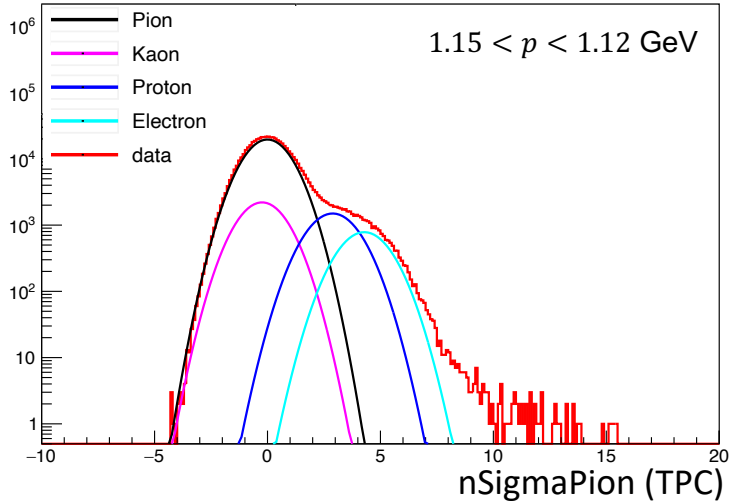
- **Simulation:**
  - PYTHIA 6.4.28 + GEANT 3
  - Kinematic correction & Systematic uncertainty estimation

Particle Identification and Asymmetries Purification

- Particle rich region for TOF matched :



- Particle rich region for TOF unmatched:



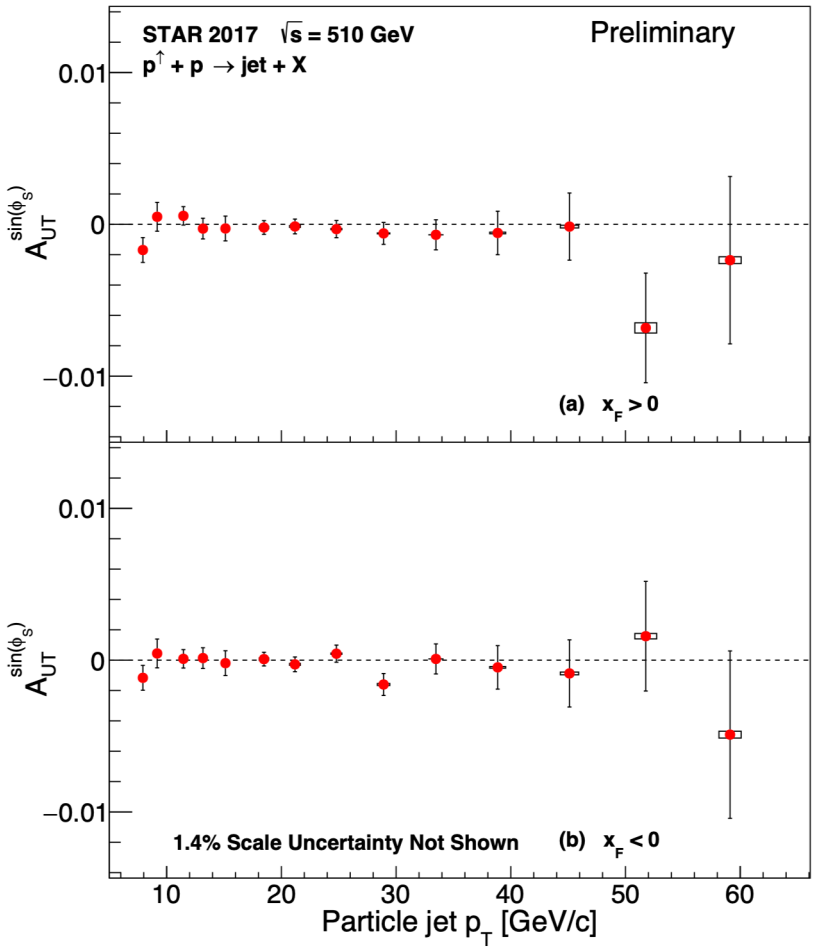
- Good particle identification through TPC and TOF.
- Raw asymmetries can be extracted in each particle rich region.
- Calculate the fraction of particle type in each particle rich region as matrix element for asymmetries purification.
- Asymmetries purification through Moore-Penrose inverse.

$$\begin{pmatrix} f_{\pi_{rich}}^{\pi\ TOF} & f_{\pi_{rich}}^{K\ TOF} & f_{\pi_{rich}}^{p\ TOF} \\ f_{K_{rich}}^{\pi\ TOF} & f_{K_{rich}}^{K\ TOF} & f_{K_{rich}}^{p\ TOF} \\ f_{p_{rich}}^{\pi\ TOF} & f_{p_{rich}}^{K\ TOF} & f_{p_{rich}}^{pTOF} \\ f_{\pi_{rich}}^{\pi\ TPC} & f_{\pi_{rich}}^{K\ TPC} & f_{\pi_{rich}}^{p\ TPC} \\ f_{K_{rich}}^{\pi\ TPC} & f_{K_{rich}}^{K\ TPC} & f_{K_{rich}}^{p\ TPC} \\ f_{p_{rich}}^{\pi\ TPC} & f_{p_{rich}}^{K\ TPC} & f_{p_{rich}}^{p\ TPC} \end{pmatrix} \begin{pmatrix} A_{\pi\ pure}^{UT} \\ A_{K\ pure}^{UT} \\ A_{p\ pure}^{UT} \end{pmatrix} = \begin{pmatrix} A_{\pi,TOF\ raw}^{UT} \\ A_{K,TOF\ raw}^{UT} \\ A_{p,TOF\ raw}^{TOF} \\ A_{\pi,TPC\ raw}^{UT} \\ A_{K,TPC\ raw}^{UT} \\ A_{p,TPC\ raw}^{UT} \end{pmatrix}$$

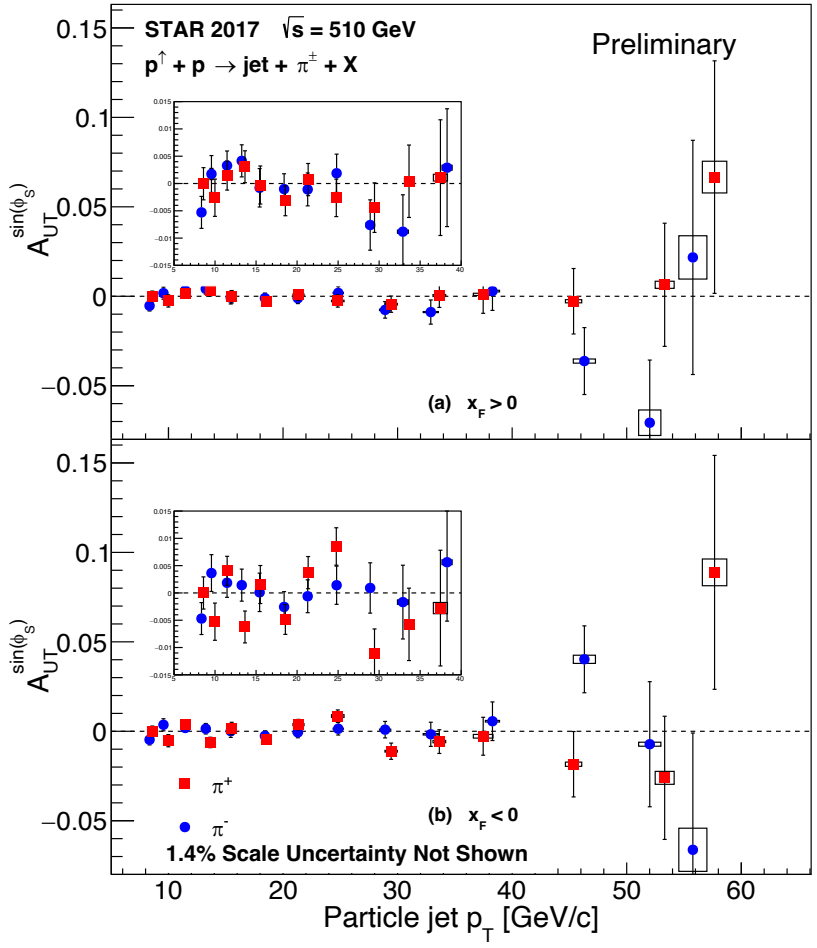
$f_{i_{rich}}^{j}$ the fraction of particle type j in the i-rich sample.

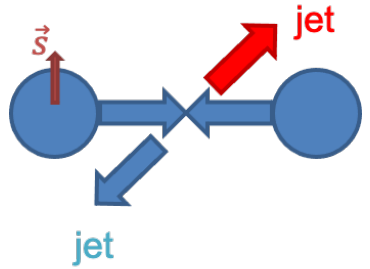
Sivers Asymmetries from STAR 2017 Data

- Sivers results for inclusive jet:

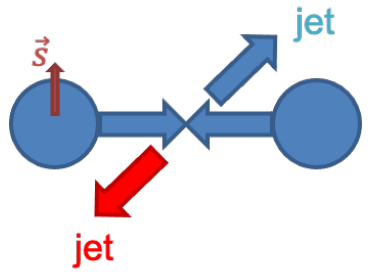


- Sivers results for pion tagged jet:





$x_F > 0$

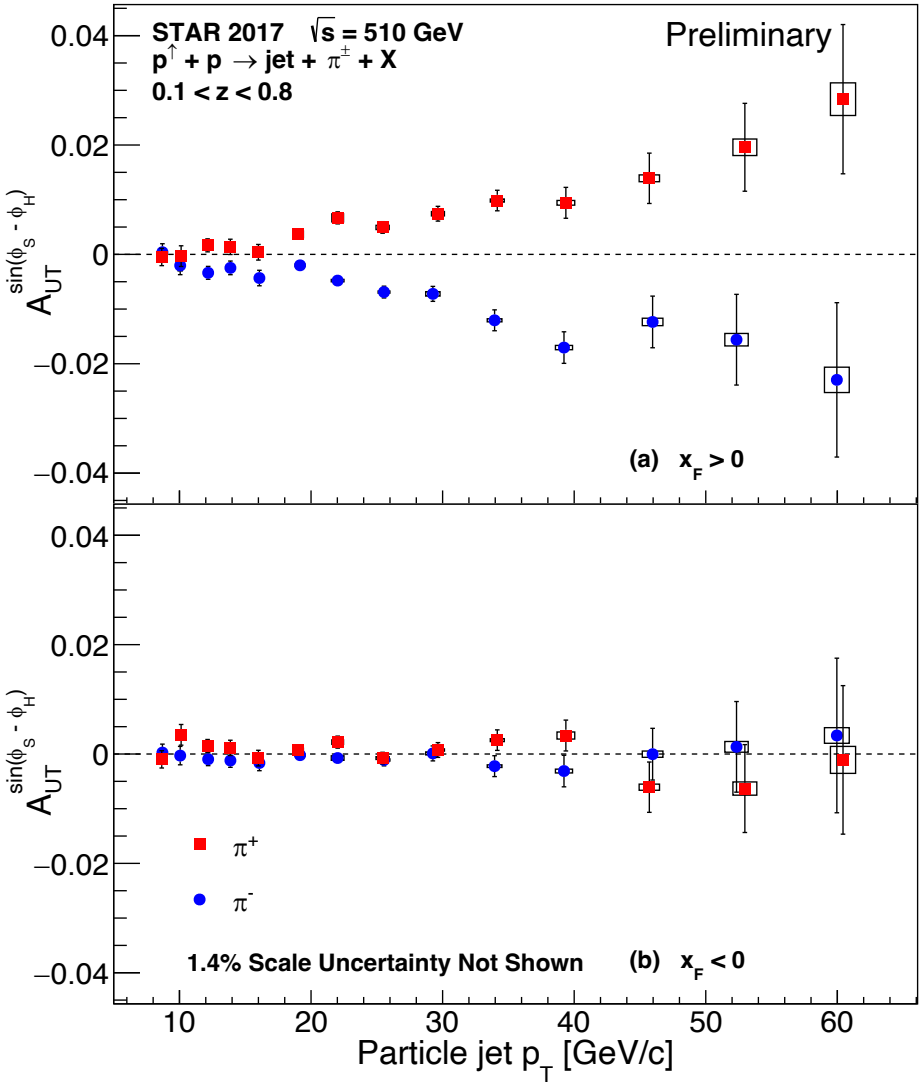


$x_F < 0$

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

Collins Asymmetries from STAR 2017 Data

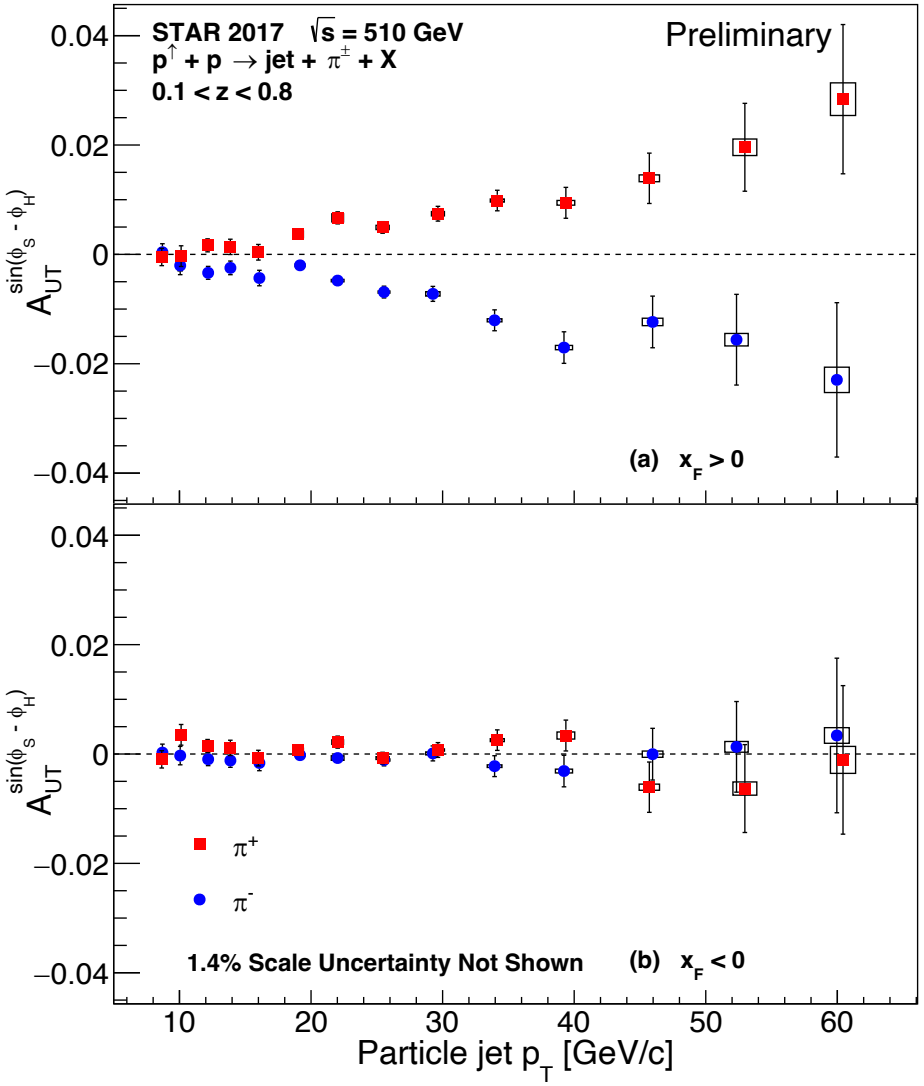
- Collins results as a function of jet p_T:



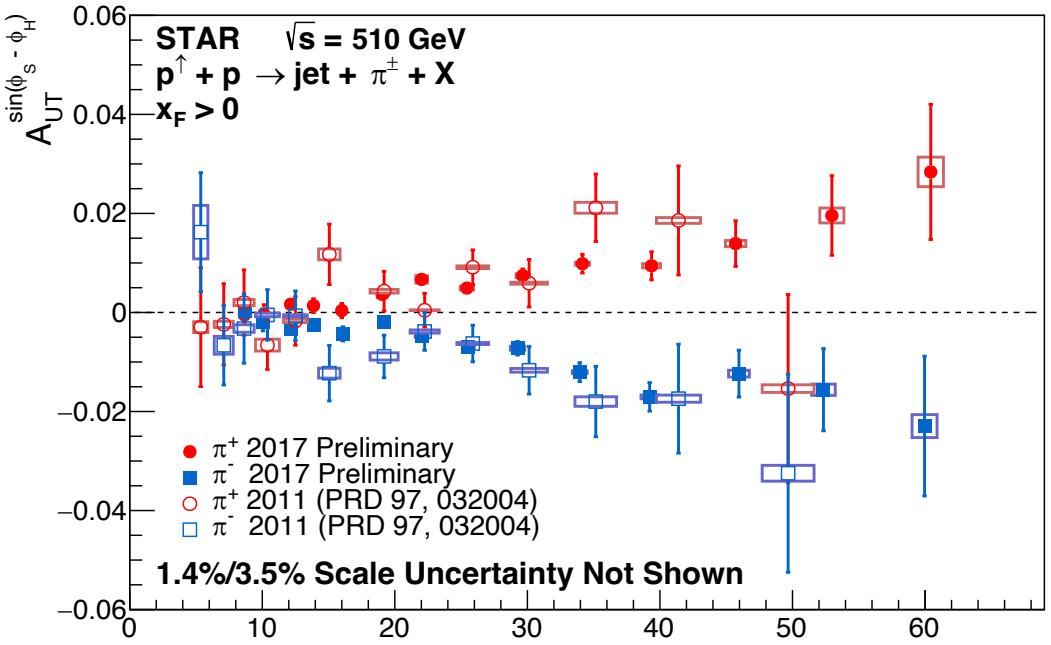
- Positive for π^+ and negative for π^-, and increase with increasing jet p_T for $x_F > 0$.
- The asymmetries for $x_F < 0$ are consistent with 0.

Collins Asymmetries 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.

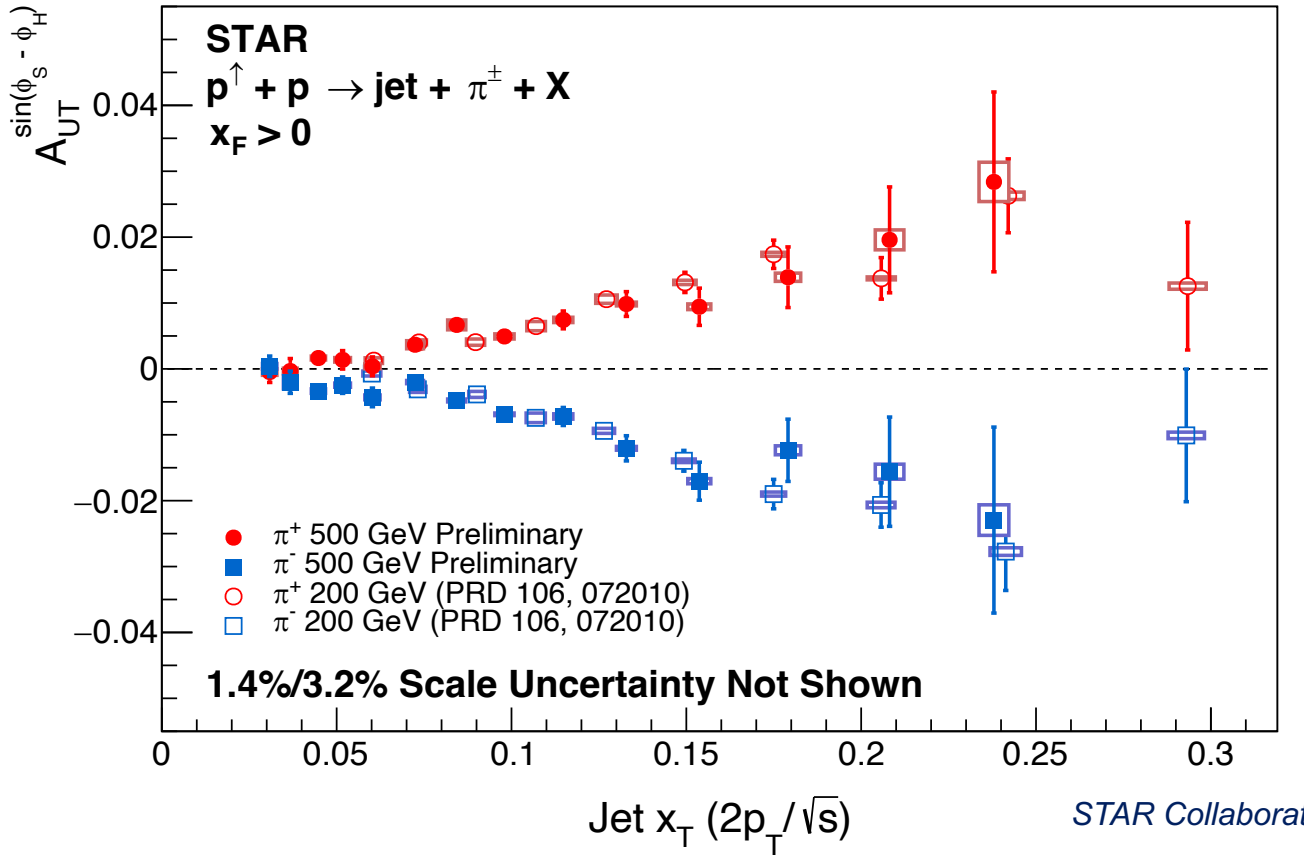


STAR Collaboration, Phys. Rev. D 97, 032004

- New results are consistent with previous 2011 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 510 GeV:

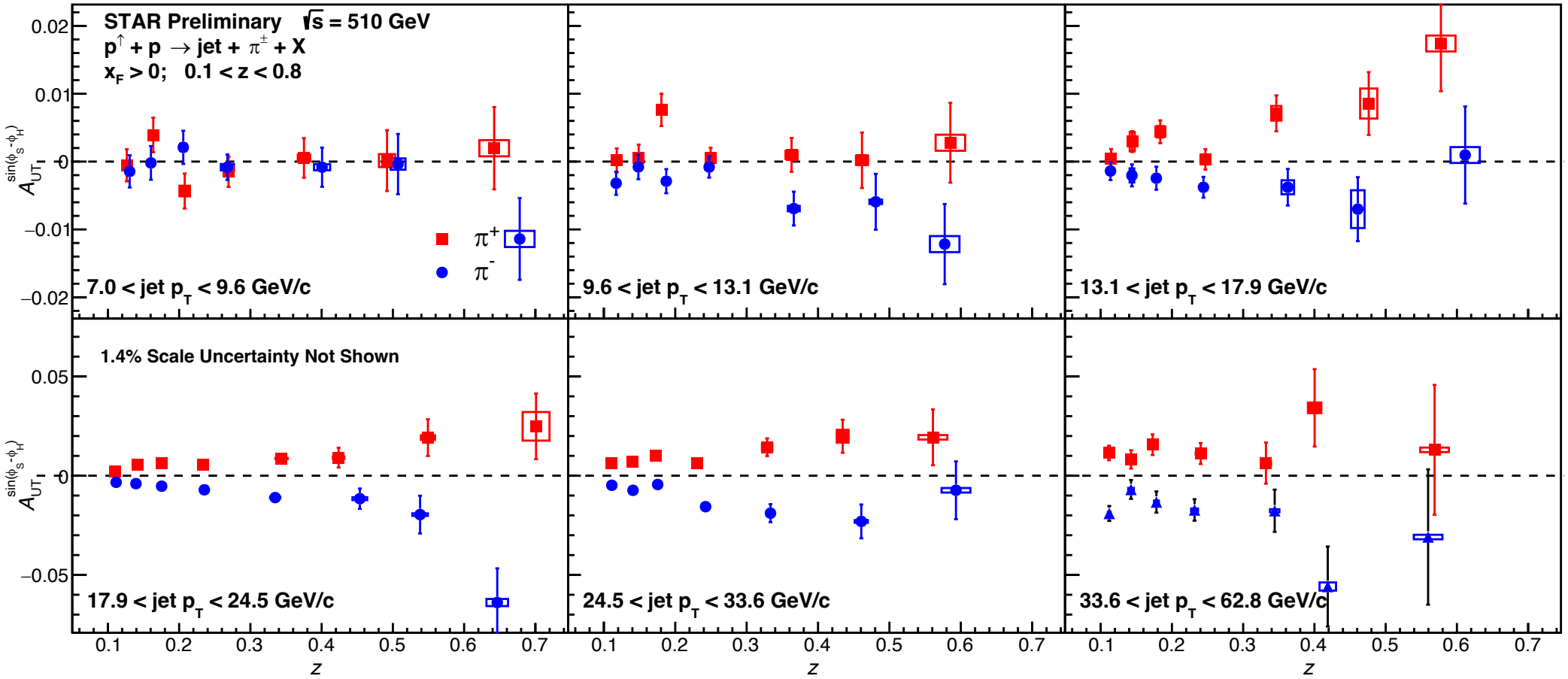


STAR Collaboration, Phys. Rev. D 106, 072010

- The high precision Collins results of 510 GeV and 200 GeV nicely align with jet $x_T \equiv 2p_T/\sqrt{s}$ scale, almost **no energy dependence.**
- These data provide important constraints on the scale evolution for Collins asymmetries.

Collins asymmetries from STAR 2017 data

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

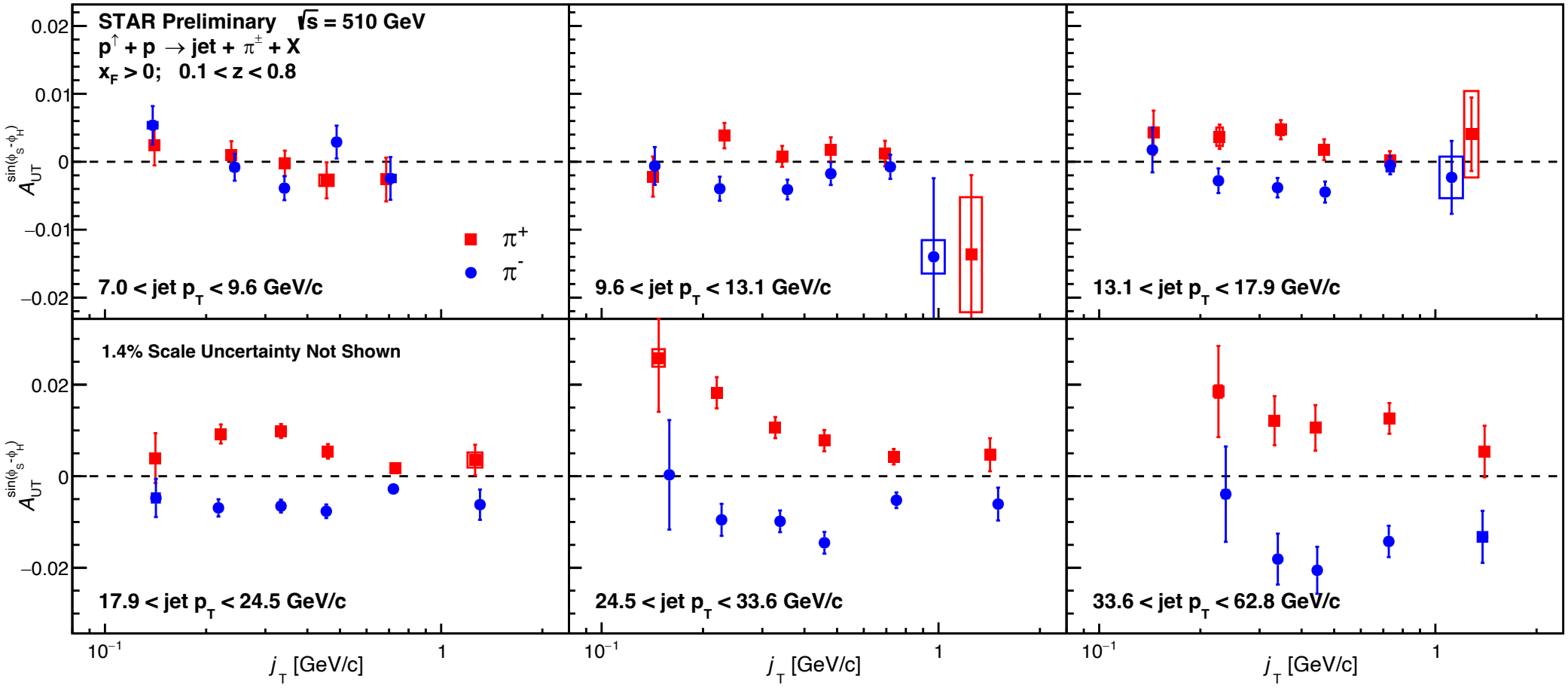


z : the pion's longitudinal momentum fraction in the jet

- Providing the experiment data to constrain the Collins FF, $H_1^{\perp}(z, j_T)$.

Collins asymmetries from STAR 2017 data

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

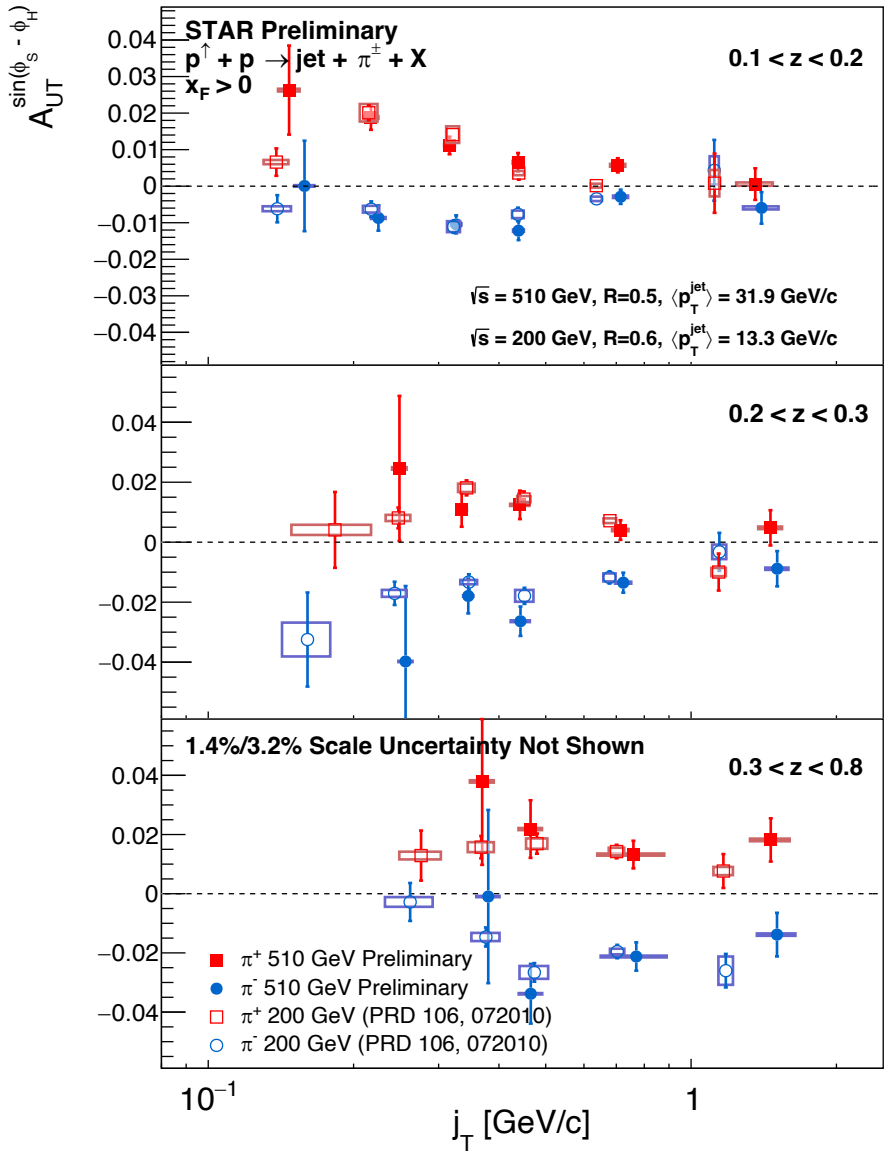


j_T : the pion's transverse momentum relative to the jet axis

- Providing the experiment data to constrain the Collins FF, $H_1^{\perp}(z, j_T)$.

Comparison to STAR 200 GeV Results

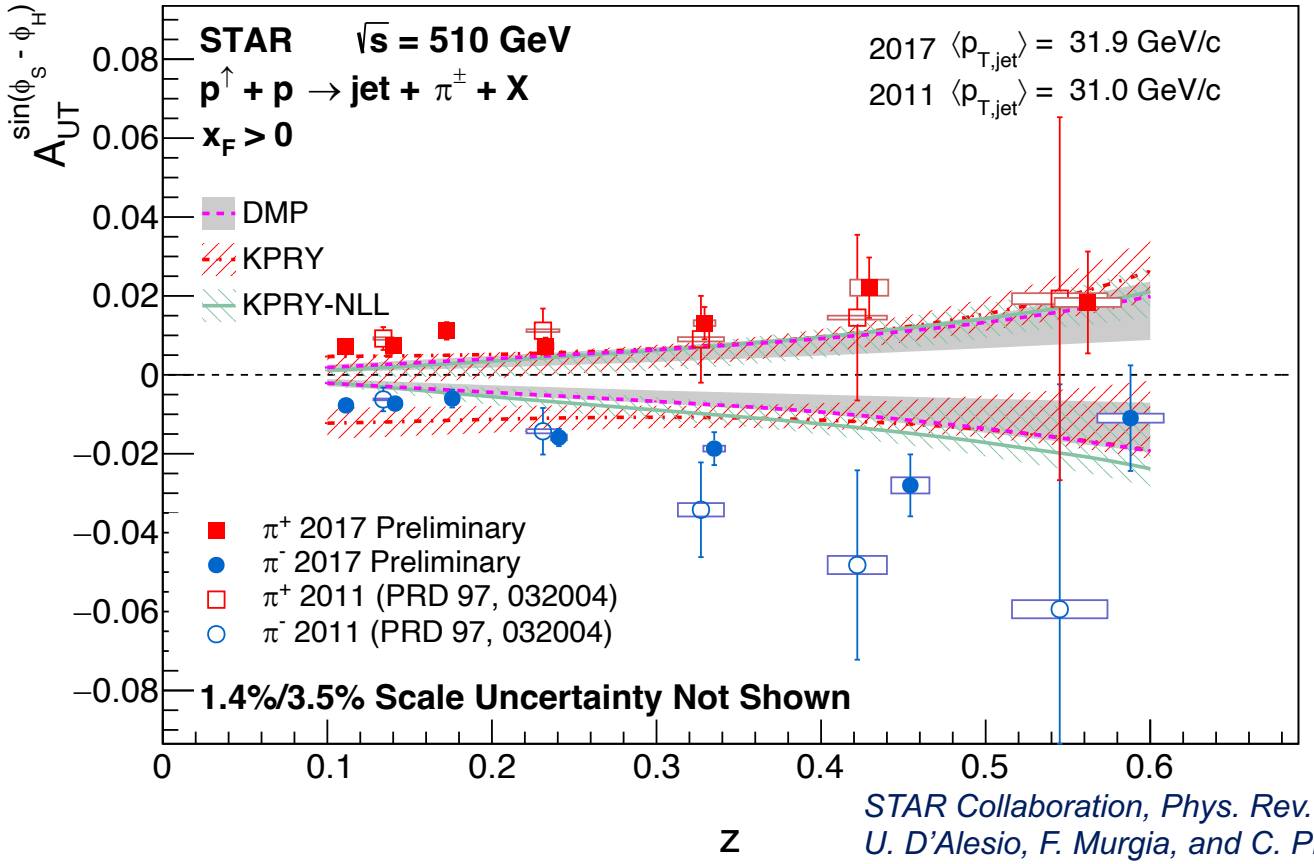
- Collins results as a function of j_T for 200 GeV and 510 GeV:
  - In the same x_T bin, the Collins asymmetries vs. j_T in different z regions are also in good agreement for 510 GeV and 200 GeV results.
  - No energy dependence observed again.



STAR Collaboration, Phys. Rev. D 106, 072010

Comparison to theoretical calculations

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



STAR Collaboration, Phys. Rev. D 97, 032004
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

- Preliminary results of Sivers asymmetries for inclusive jets and Collins asymmetries for $\pi^{\pm}$ within jets in pp collisions at $\sqrt{s} = 510$ GeV with STAR 2017 data, ~14 times more statistics to previous measurement with 2011 data.

- The high precision Collins results, in excellent consistency with 200 GeV data vs. x_T, no energy dependence observed, which provide important constraints on the scale evaluation, and testing of universality for Collins asymmetries.

- A large data sample of transverse polarized pp data taken in 2022 at STAR (~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.