Energy Independence of the Collins Asymmetry in pp Collisions

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STAR

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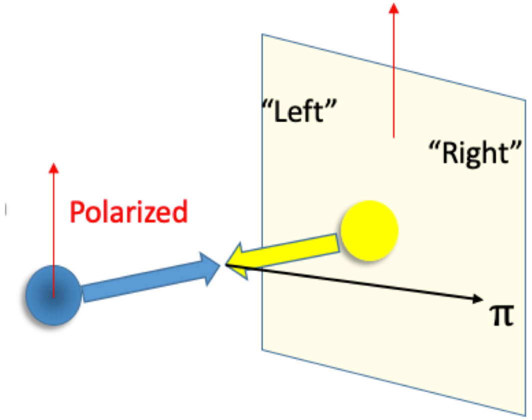
Challenges in Transverse Single-Spin Asymmetry (TSSA)

- Anomalously large A_N in pp collisions observed for many years

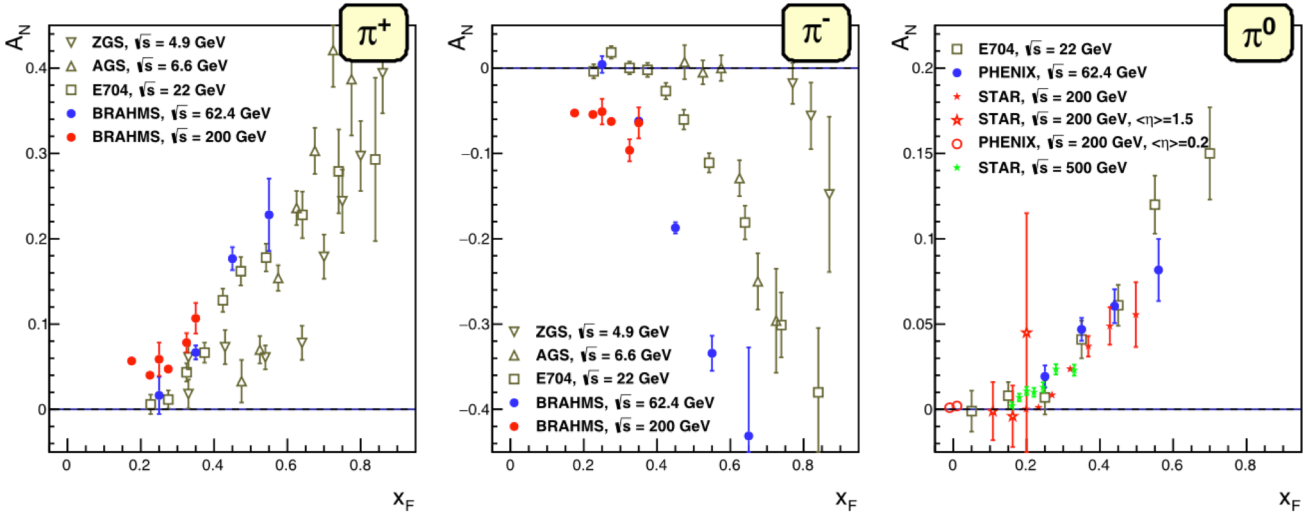


$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- LO QCD predicts $A_N \sim 0$

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

- Left-right asymmetries of different collaborations 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

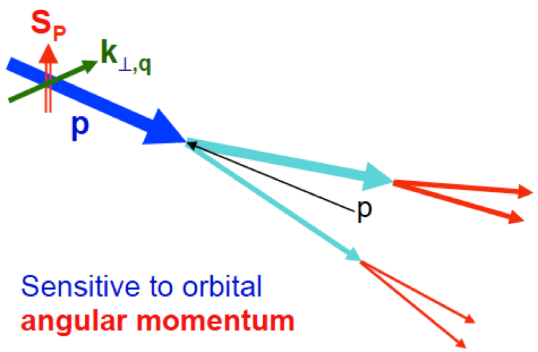
$$x_F = \frac{2p_z}{\sqrt{s}}$$

Mechanisms for Transverse Single–Spin Asymmetry

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

✓ Sivers effect (*Sivers'90*):

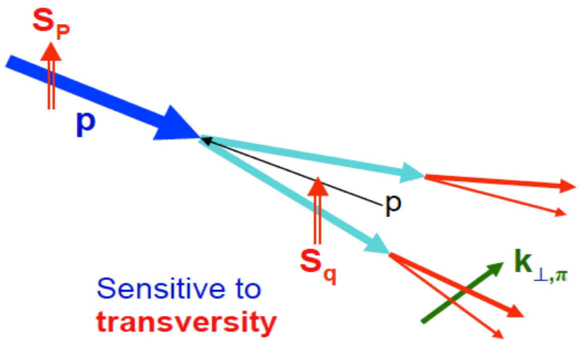
Parton spin and $k_\perp$ correlation in initial state



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

✓ Collins effect (*Collins'93*):

Quark spin and $k_\perp$ correlation in fragmentation process



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

- *In this talk, we focus on Collins effect in pp collisions by measuring TSSA for $\pi^\pm$ inside jet*
- *Investigating TMDs properties such as factorization, universality, and* ***evolution***

TMD evolution

- Collins function with TMD evolution

$$\frac{j_\perp}{z_h M_h} H^{\perp}_{1\,h/q}(z_h, j_\perp^2; Q) = \frac{1}{z_h^2}\int_0^\infty \frac{db\, b^2}{(2\pi)} J_1(j_\perp b/z_h)\, \delta\hat{C}^{\text{collins}}_{i\leftarrow q} \otimes \hat{H}^{\perp(1)}_{1\,h/i}(z_h,\mu_b)\, e^{-\frac{1}{2} S_{\text{pert}}(Q,b_*) - S_{\text{NP}}^{\text{collins}}(Q,b)}$$

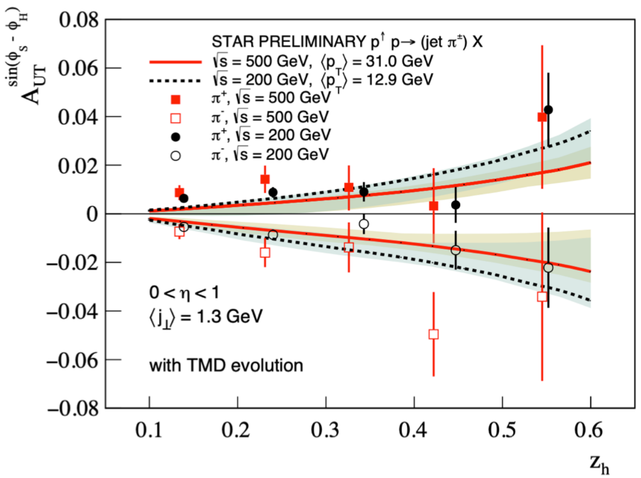
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017), 635–642

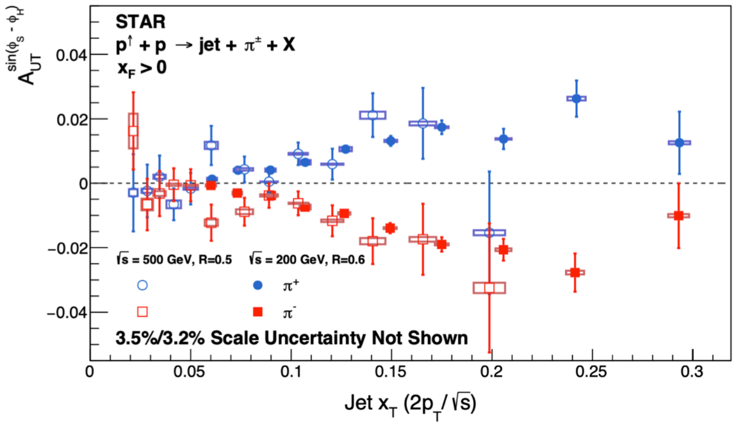
- Energy scale part
- perturbative

- TMD part
- **non-perturbative**

✓ *The non-perturbative part of TMD evolution requires experimental data input*

- TMD evolution in Collins asymmetry



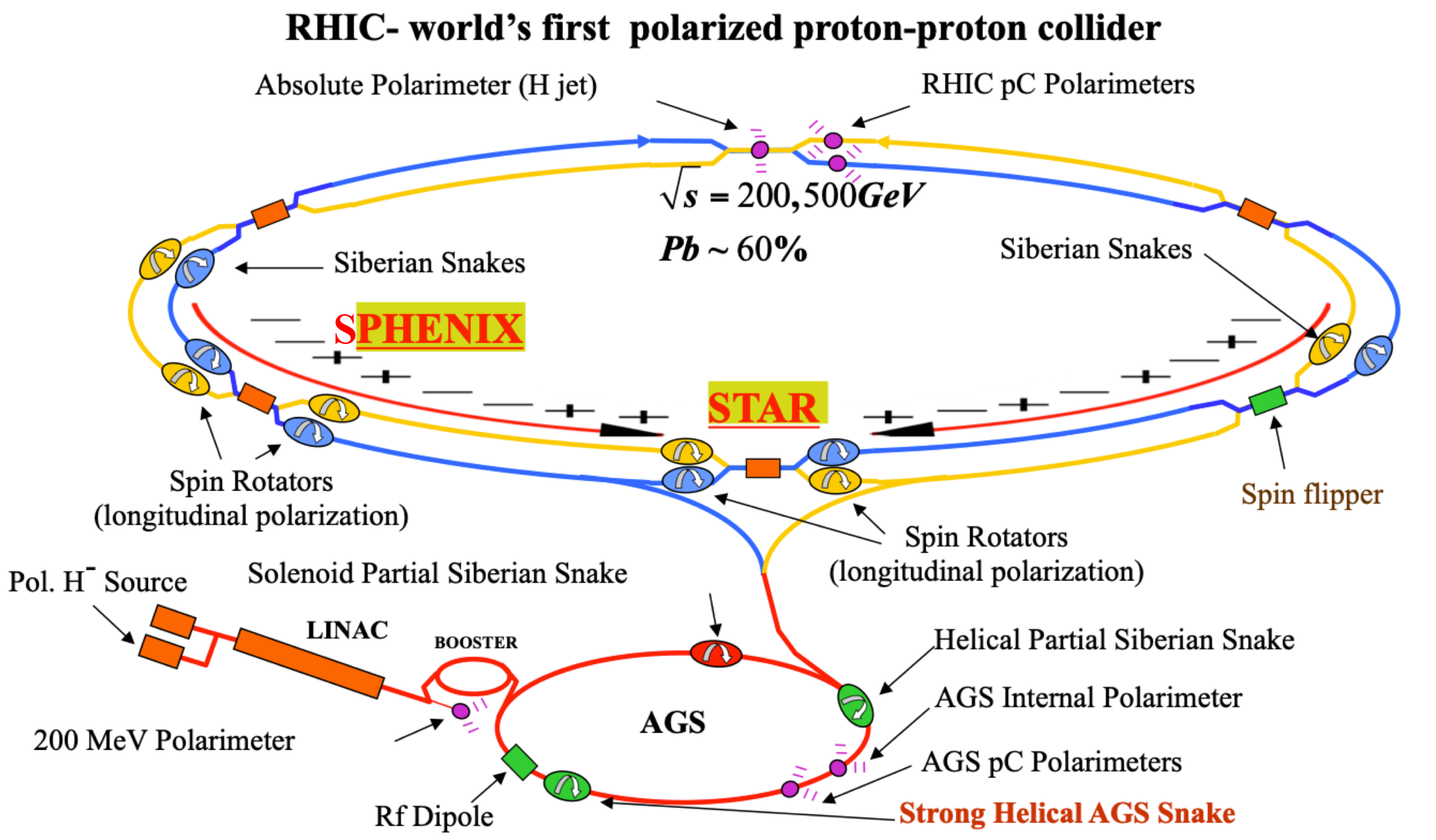


200GeV (run12+15): *STAR, Phys. Rev. D 106, 072010 (2022)*
500GeV (run11): *STAR, Phys. Rev. D 97, 032004 (2018)*

- Theoretically, a moderate but visible suppression of the Collins asymmetry has been predicted with the growth of Q^2
- Experimentally, STAR measured Collins results at 200 GeV and 500 GeV, but the 500 GeV data lack enough statistics to study TMD evolution quantitatively

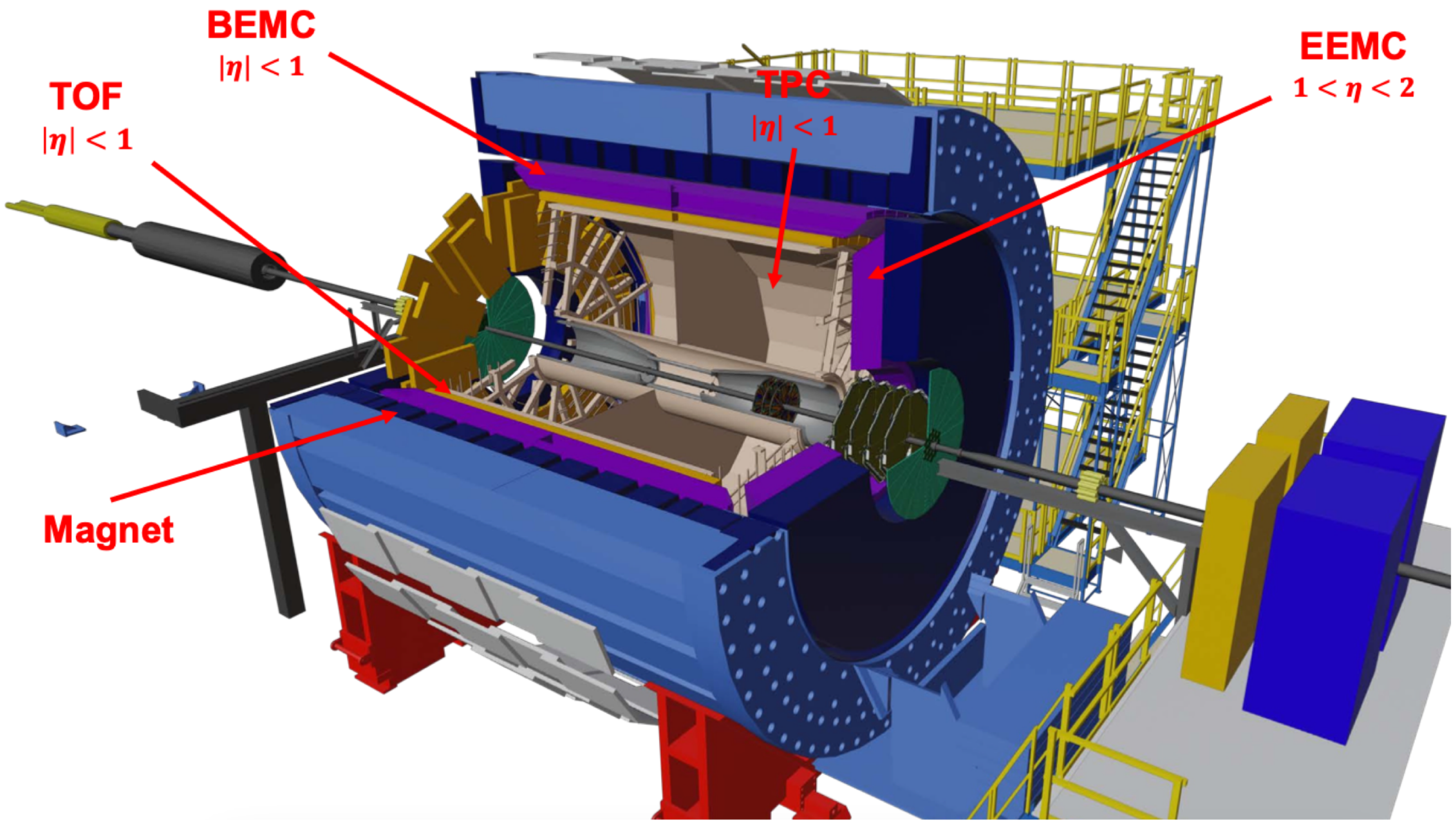
✓ *More data is needed to constrain TMD theory*

Relativistic Heavy Ion Collider (RHIC)



The Solenoidal Tracker At RHIC (STAR)

- Subsystems used in this talk



- 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 $\phi \in [0,2\pi]$
  - Energy deposition of photon, e, π^0
  - Triggering

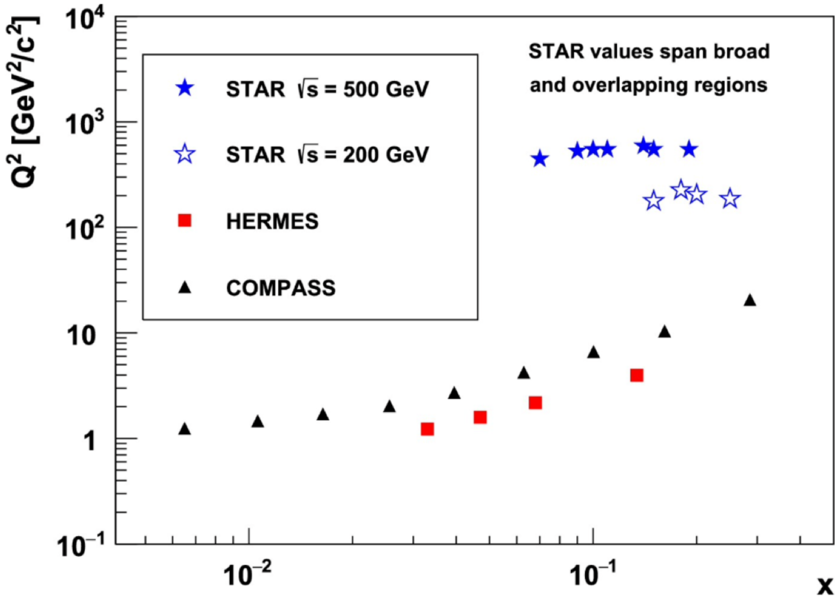
TSSA of pp Collisions

➢ Transversely polarized proton–proton collision data in recent years at STAR

Year	2011	2012	2015	2017	2022	2024
$\sqrt{s}$ (GeV)	500	200	200	510	508	200
$L_{int}\ (pb^{-1})$	25	14	52	350	400	~170
Polarization	53%	57%	57%	55%	52%	53% / 57%

Run11 500 GeV   Run12+15 200 GeV   Run17 510 GeV (this talk)

- Measurements at RHIC can reach values of Q^2 that are more than two orders of magnitude higher than other experiments



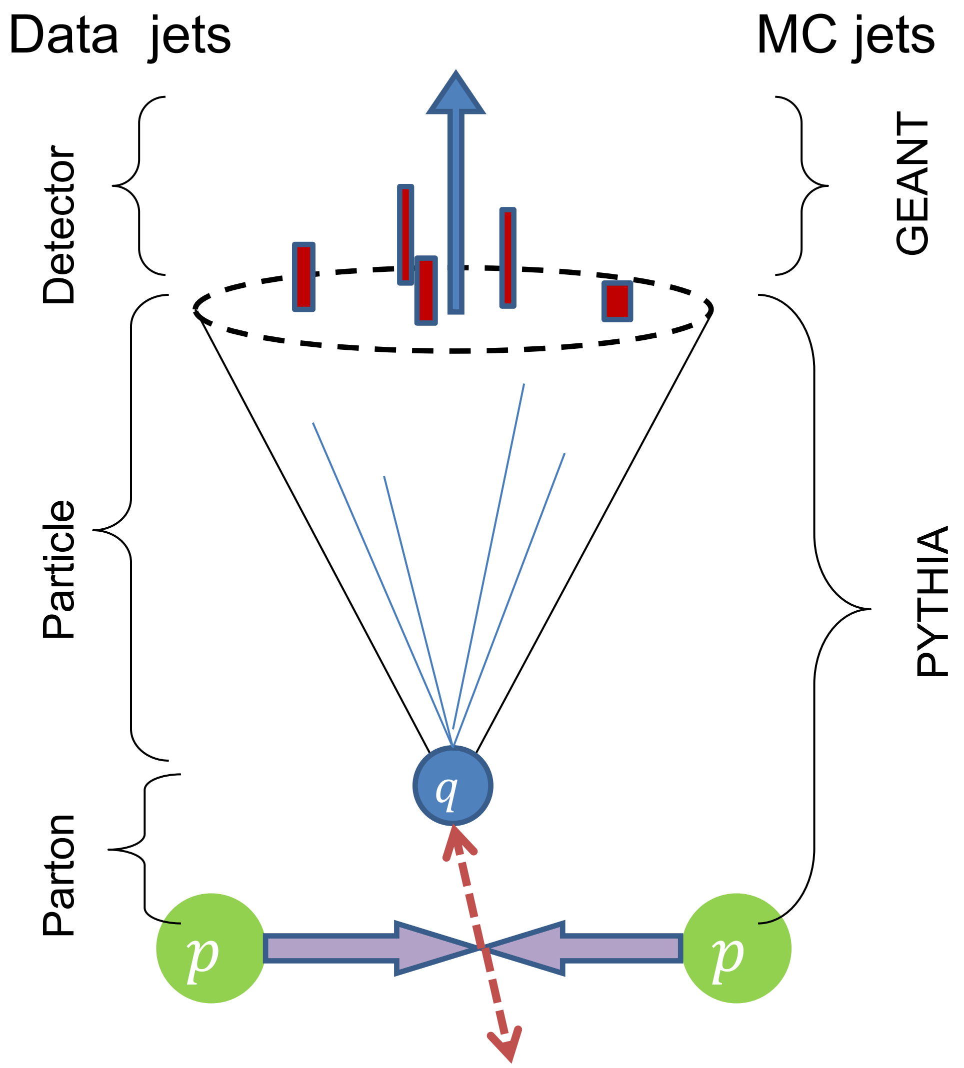
STAR, Phys. Lett. B 780 (2018), 332–339

➢ Collins effect for hadron within jets

- Separate initial and final state effects
- **jet–p_T** ~ hard scale (Q); hadron j_T ~ soft scale
- Validate universality with SIDIS and e^+e^- annihilation

F. Yuan, Phys. Rev. Lett.100,032003(2008)

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

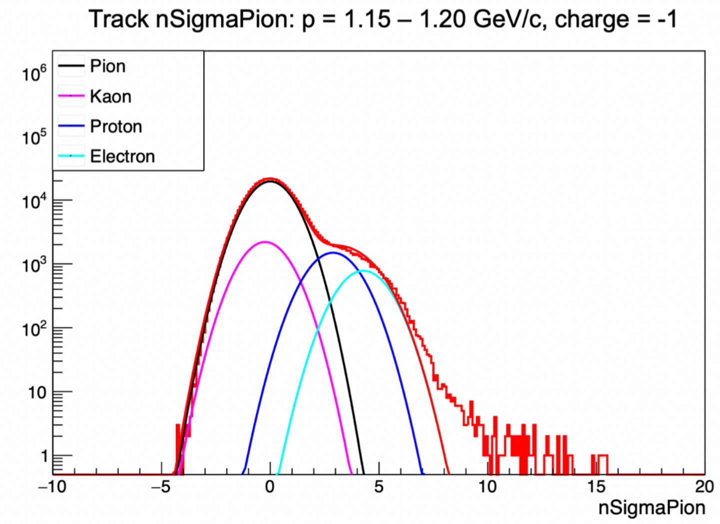
STAR, Phys. Rev. D 100, 052005 (2019)

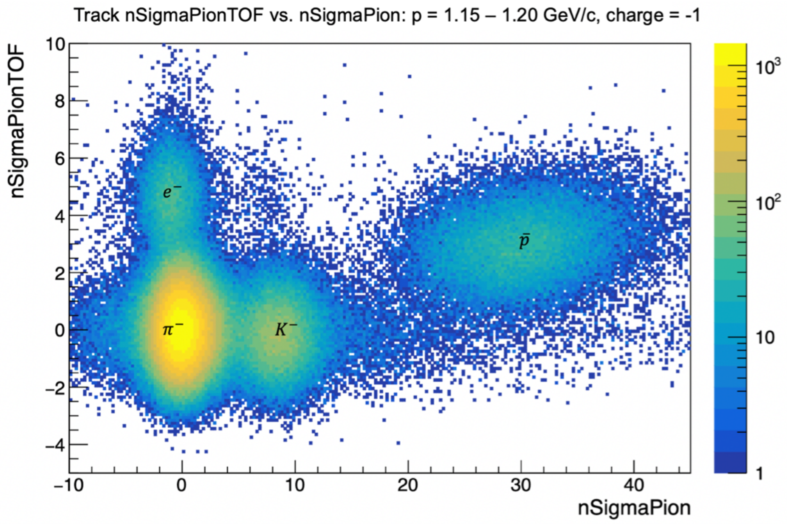
➢ **Simulation**

- PYTHIA 6.4 with STAR adjustment of Perugia 2012
- Kinematic correction & Systematic uncertainty estimation

Particle Identification

- Particle identification with TOF unmatched (left) and matched (right)





$$n_\sigma(\pi) = \frac{1}{\sigma_{dE/dx}} \ln\left(\frac{dE/dx_{\mathrm{meas}}}{dE/dx_{\pi,\mathrm{calc}}}\right)$$

$$n_{\sigma,\mathrm{TOF}}(\pi) = \frac{\mathrm{TOF}_{\mathrm{meas}} - \frac{L}{c\beta_\pi(p)}}{\sigma_{\mathrm{TOF}}}$$

- 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
- Cancel other particles contamination

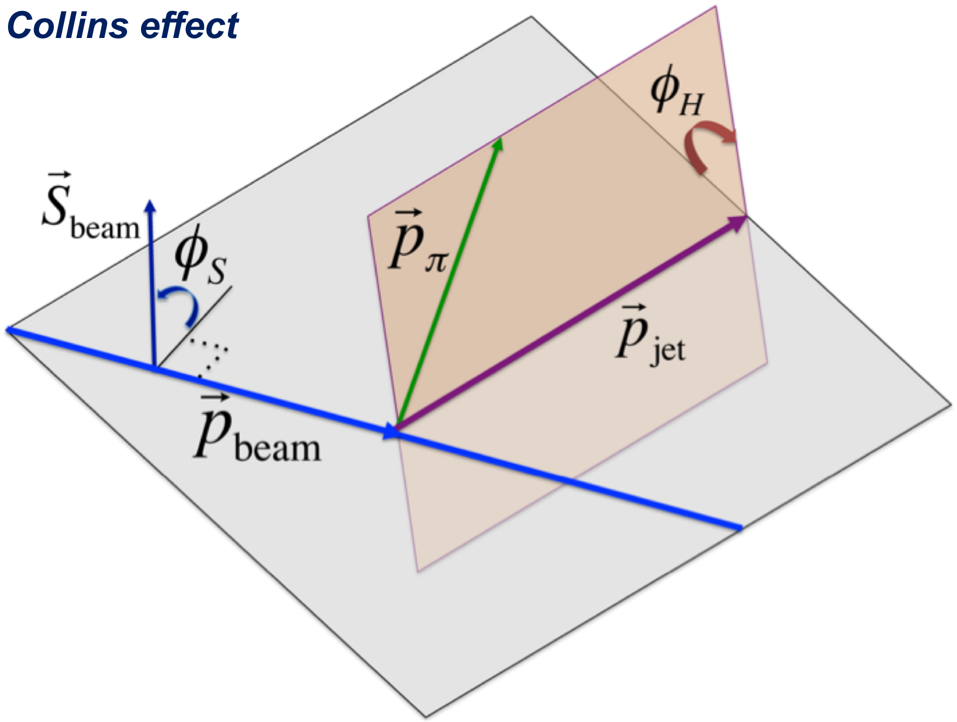
Angular Modulations of TSSA

➢ 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

related to Collins effect



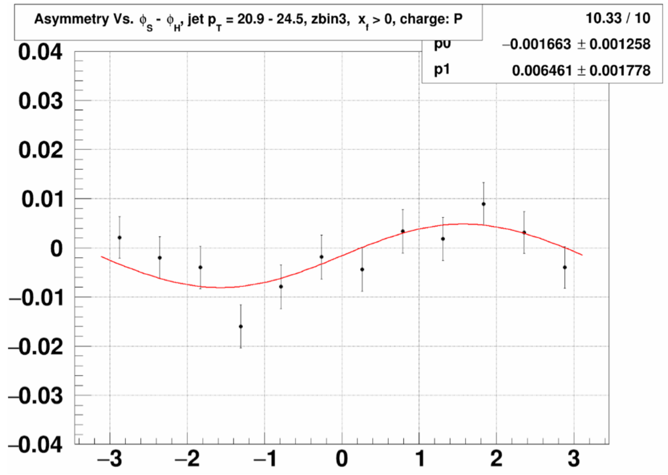
STAR, Phys. Rev. D 97, 032004 (2018)

- ϕ_S: azimuthal angle between the proton transverse spin polarization vector and jet scattering plane
- ϕ_H: azimuthal angle of pion relative to the jet scattering plane

Extraction of TSSA

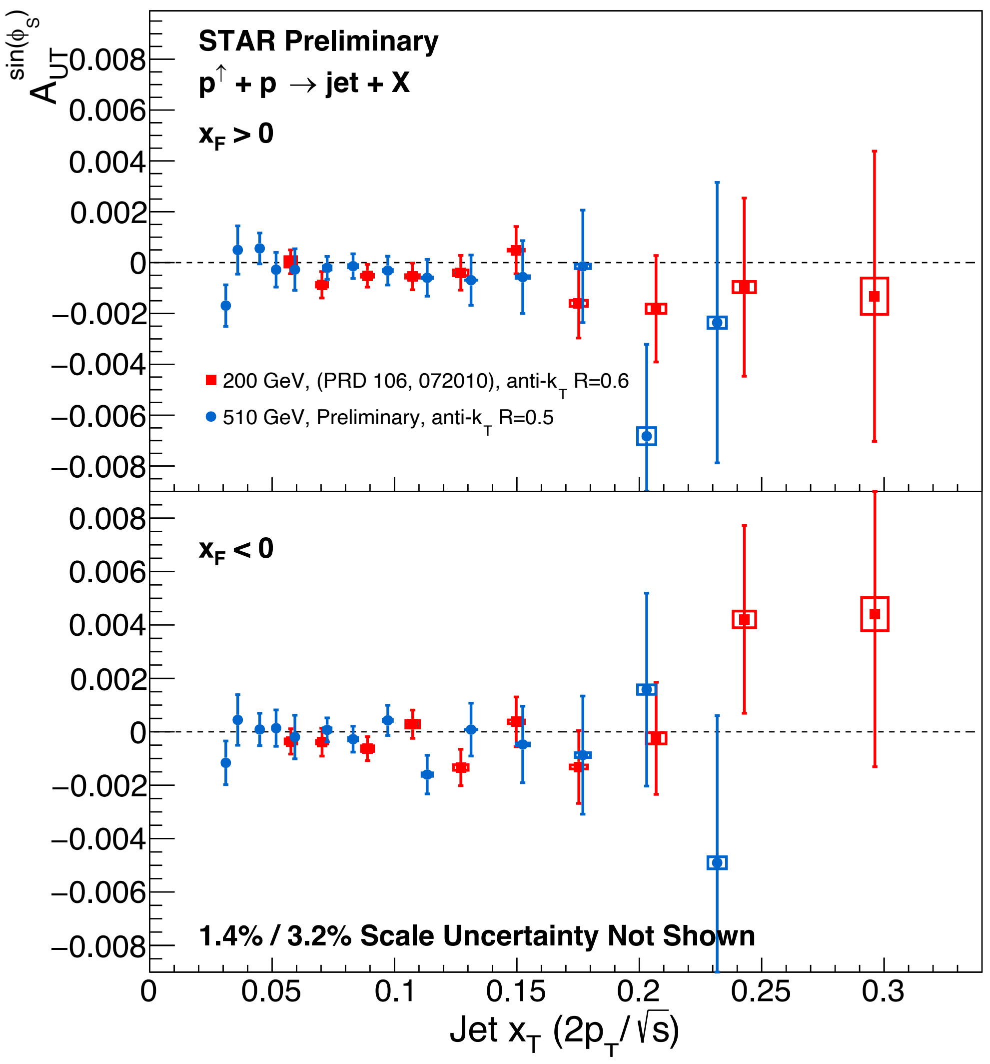
- Cross-ratio method to extract the asymmetries of different modulations

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



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

Inclusive Jet Asymmetry

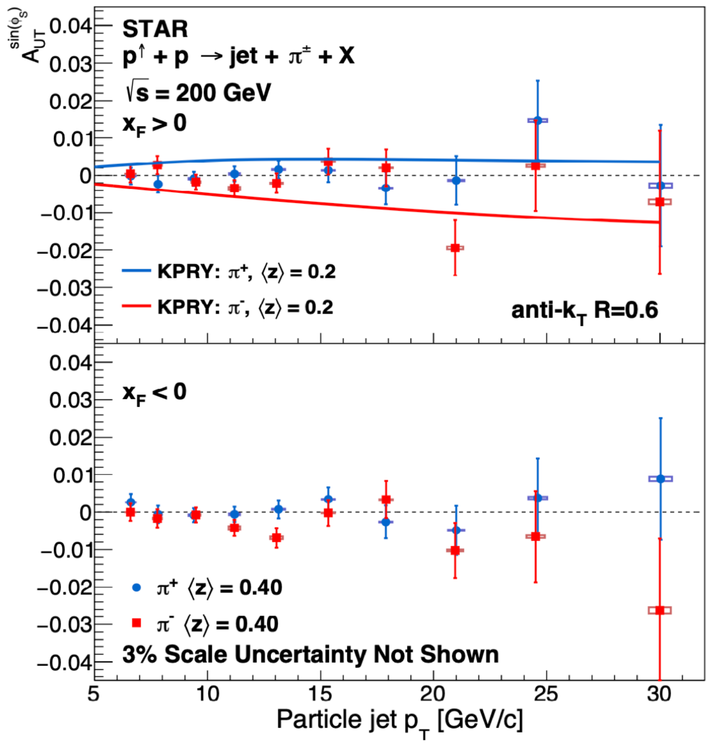


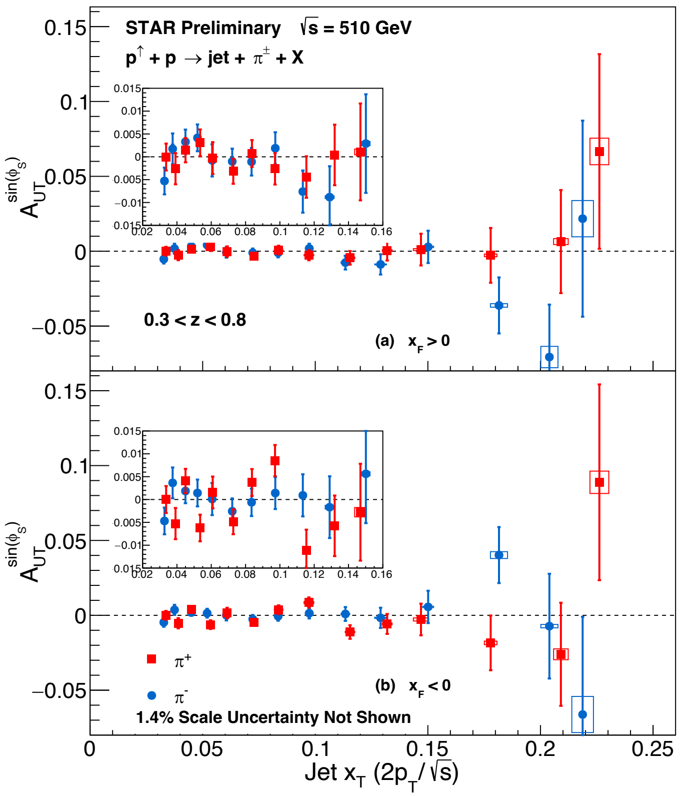
- Sensitive to twist-3 correlator associated with the gluon Sivers function

- High-precision measurements show that the inclusive jet asymmetry is very small

Asymmetry of $\pi^{\pm}$–tagged Jet

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

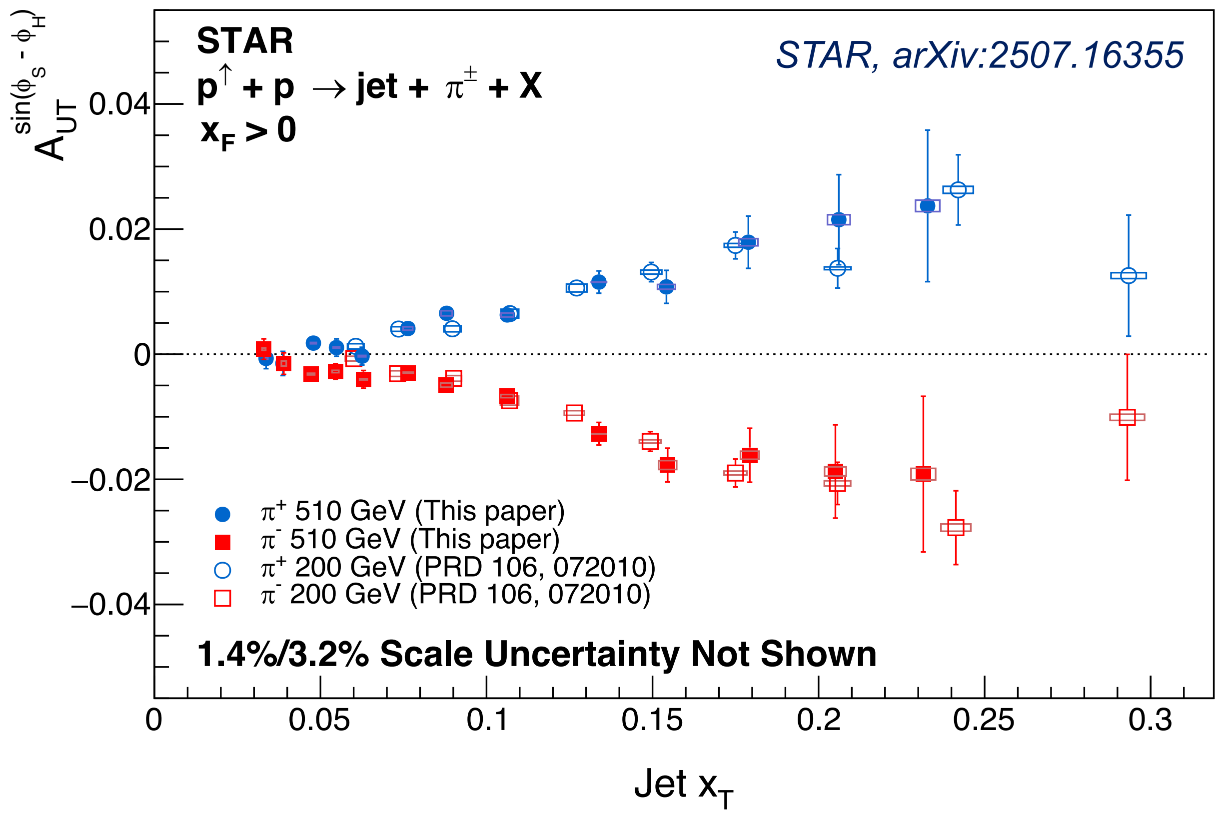




- Quark flavor separations are enhanced by tagging $\pi^{\pm}$
- The experimental measurements are comparable to the theoretical predictions

Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017), 635–642

Collins Asymmetry at 510/200 GeV: Test TMD Evolution



Why jet x_T ?

- x_T corresponds to parton x at both energies
- $A_{UT}^{Collins} \sim h_1^q \otimes \Delta\hat{\sigma} \otimes H_1^{\perp}$
- In pp collisions, jet p_T serves as the hard scale Q

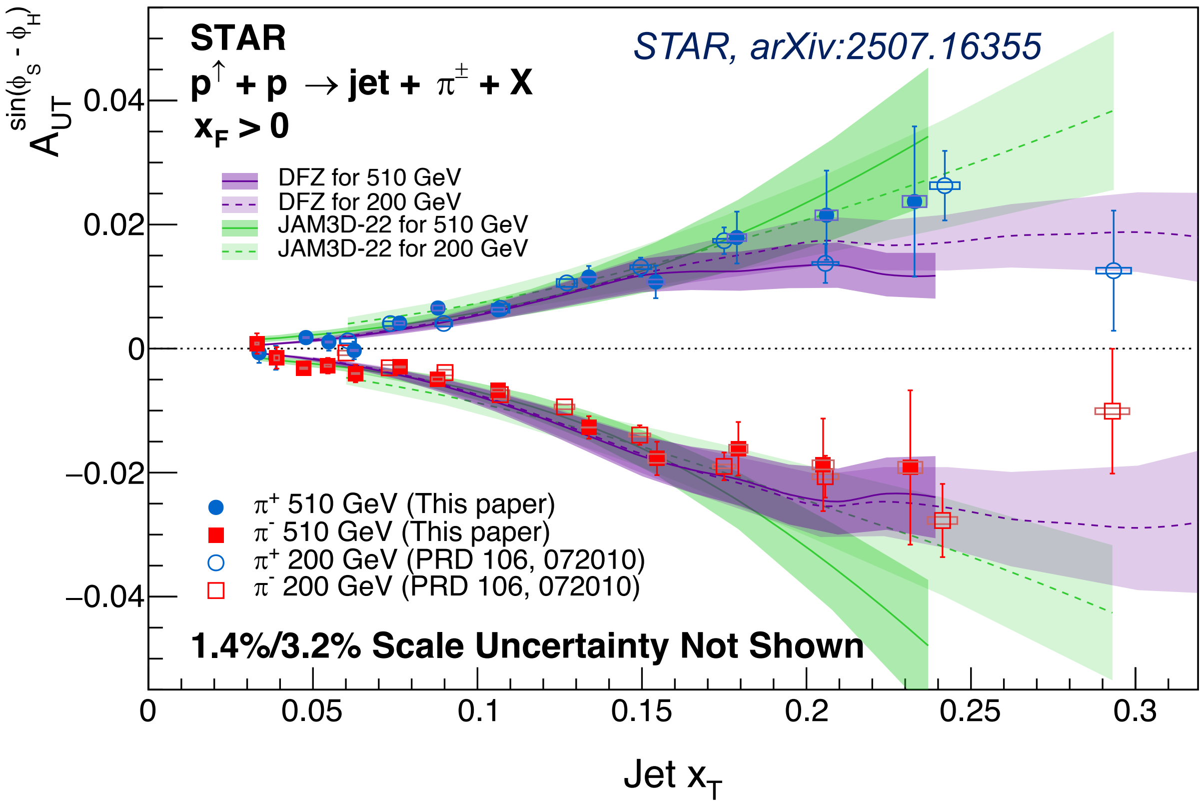
✓ This comparison fully reflects the properties of the TMD evolution

✓ At a give x_T bin, there is a factor of more than 6 difference in Q^2 between 200 GeV and 510 GeV

$x_T \equiv \frac{2 \cdot p_{T,jet}}{\sqrt{s}}$, jet transverse momentum scaled by the center-of-mass energy

- Collins results of two energies nicely align with jet x_T scale, indicating there is no scale dependence

Comparison to theoretical predictions



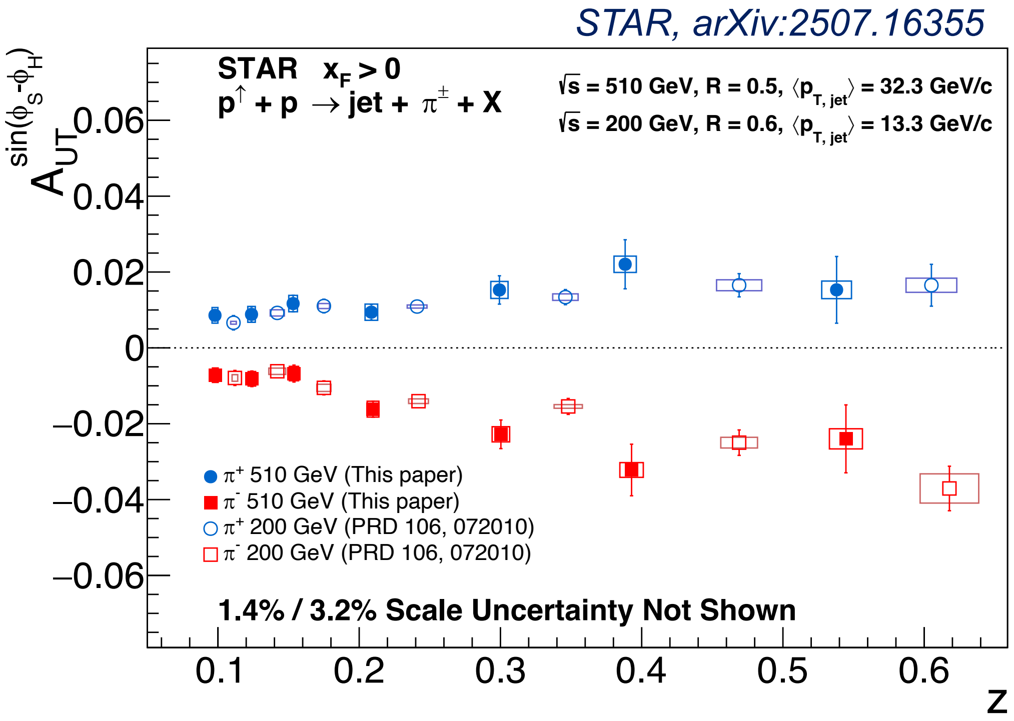
L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato, [JAM], Phys. Rev. D 106 (2022), 034014

U. D'Alesio, C. Flore and M. Zaccheddu, arXiv:2506.21959

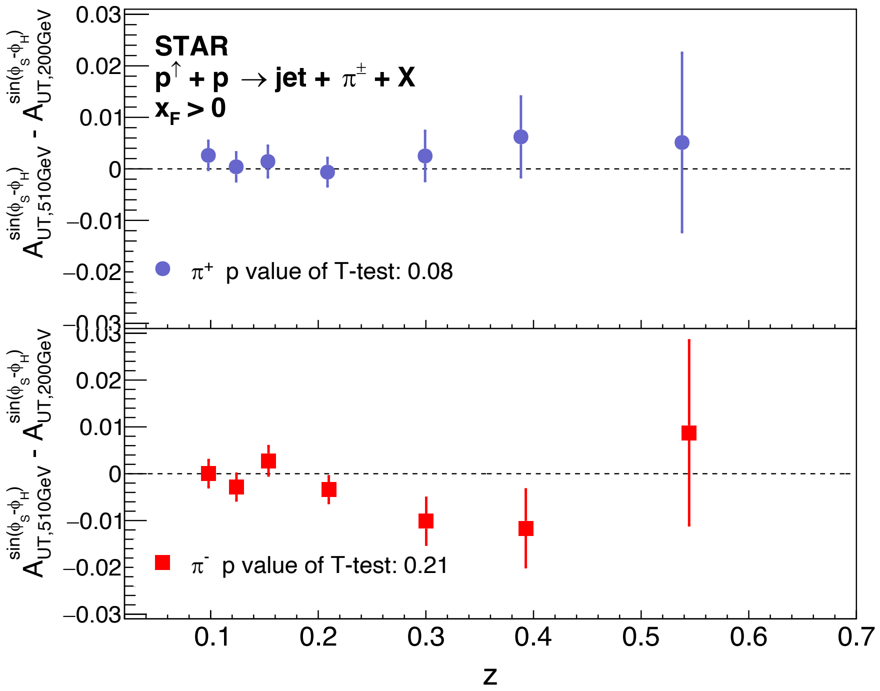
- The available theoretical calculations currently do not include TMD evolution
- JAM3D-22 includes e^+e^-, SIDIS and pp data; DFZ includes e^+e^-, SIDIS data
- The data agree with both theoretical models with x up to $\sim$0.2
- The agreement with DFZ calculations supports the universality of Collins function and TMD factorization

Collins Asymmetry $vs.$ z

➢ Collins results $vs.$ z



➢ t–test



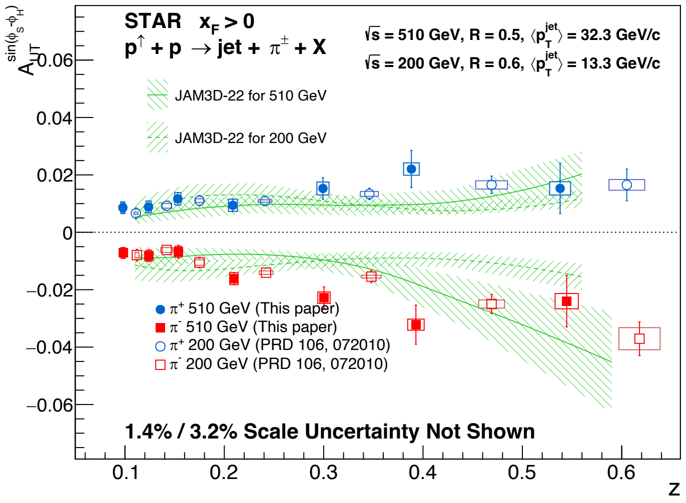
- $z = \frac{\vec{p}_{jet} \cdot \vec{p}_{\pi}}{|\vec{p}_{jet}|^2}$, longitudinal momentum fraction carried by $\pi^{\pm}$
- $< p_T^{200\ GeV} >= 13.3\ GeV/c$; $< p_T^{510\ GeV} >= 32.3\ GeV/c$, ensuring the same x_T

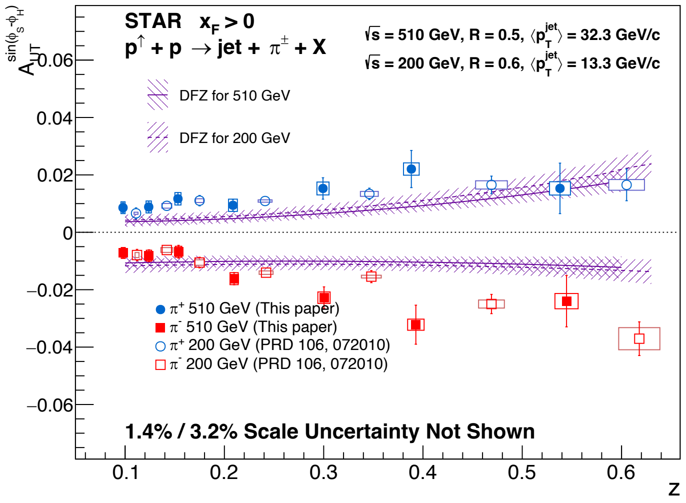
- To accommodate the z difference between two energies, we fit the 200 GeV results and include the difference caused by z difference from fitting function

- The results at the two energies are in good agreement under t–test

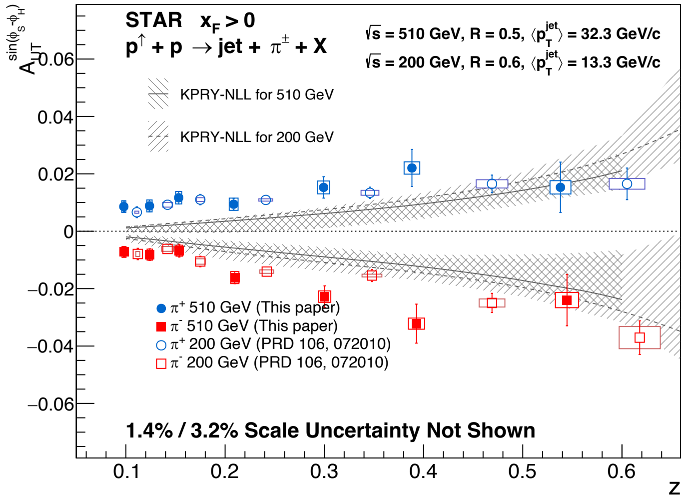
Theoretical Calculations with/without TMD Evolution

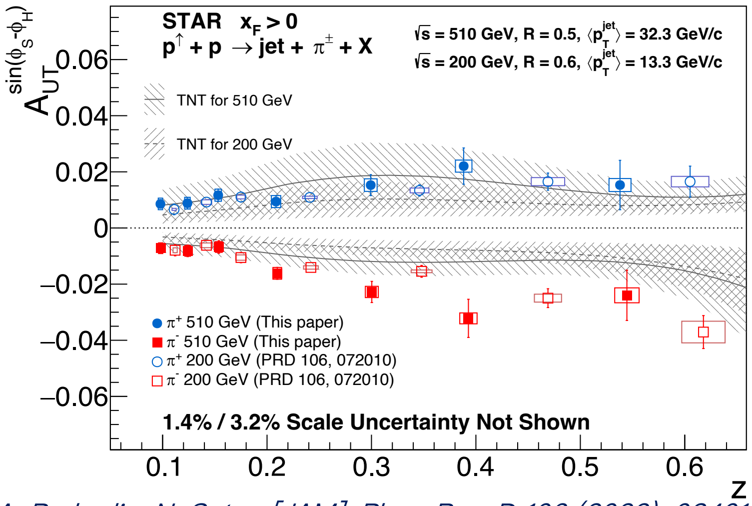
Without TMD evolution:





With TMD evolution:

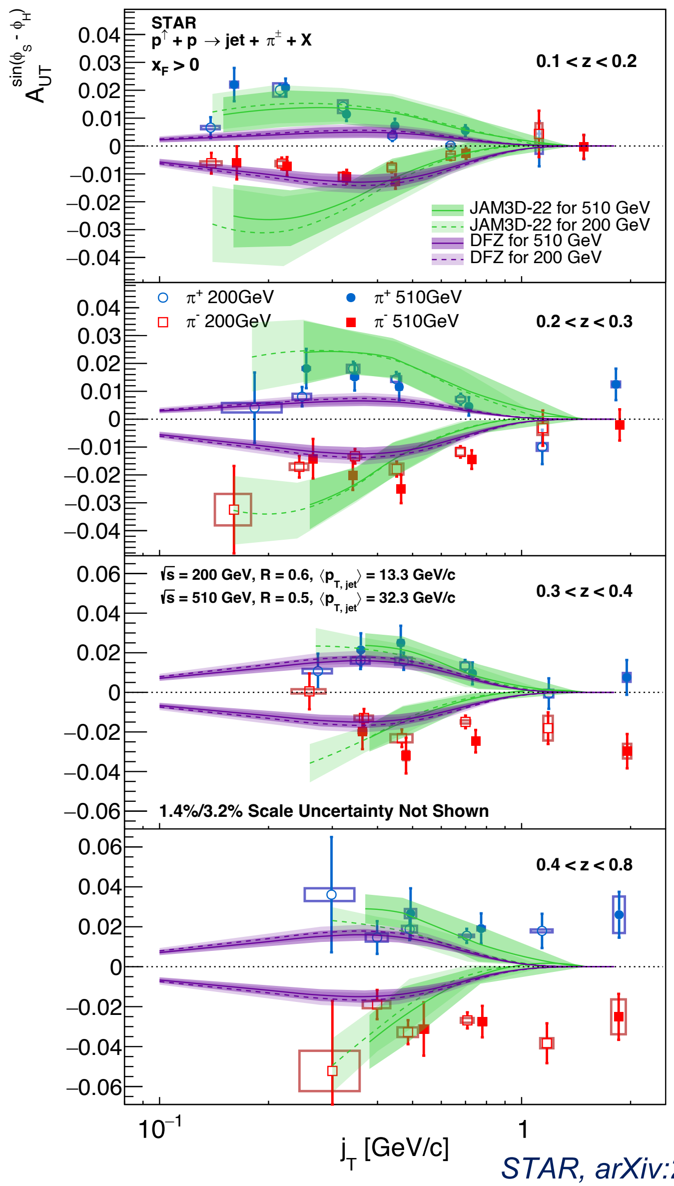




- Data input of theoretical calculations
  - JAM3D-22: e^+e^-, SIDIS and pp
  - DFZ, KPRY, TNT: e^+e^-, SIDIS
- The data can constrain the non-perturbative parameters in the Collins function
- Again, the comparison of data with the DFZ, KPRY and TNT models provide a test of universality of Collins function and TMD factorization

L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato, [JAM], Phys. Rev. D 106 (2022), 034014
U. D'Alesio, C. Flore and M. Zaccheddu, arXiv:2506.21959
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017), 635–642
C. Zeng, H. Dong, T. Liue, P. Sun and Y. Zhao, arXiv:2412.18324
STAR, arXiv:2507.16355

Collins Asymmetry $vs.$ j_T



STAR, arXiv:2507.16355

- The results are consistent at both energies, indicating very weak TMD evolution of the Collins effect in hadronic collisions
- Effectively constrain the Collins function $H_1^{\perp}(z, j_T^2, Q)$
- Both models generally follow the data trend, yet significant discrepancies remain, in particular when j_T and z are both large

- $j_T = \frac{|\vec{p}_{jet} \times \vec{p}_{\pi}|}{|\vec{p}_{jet}|}$, pion's transverse momentum relative to jet axis

Summary & outlook

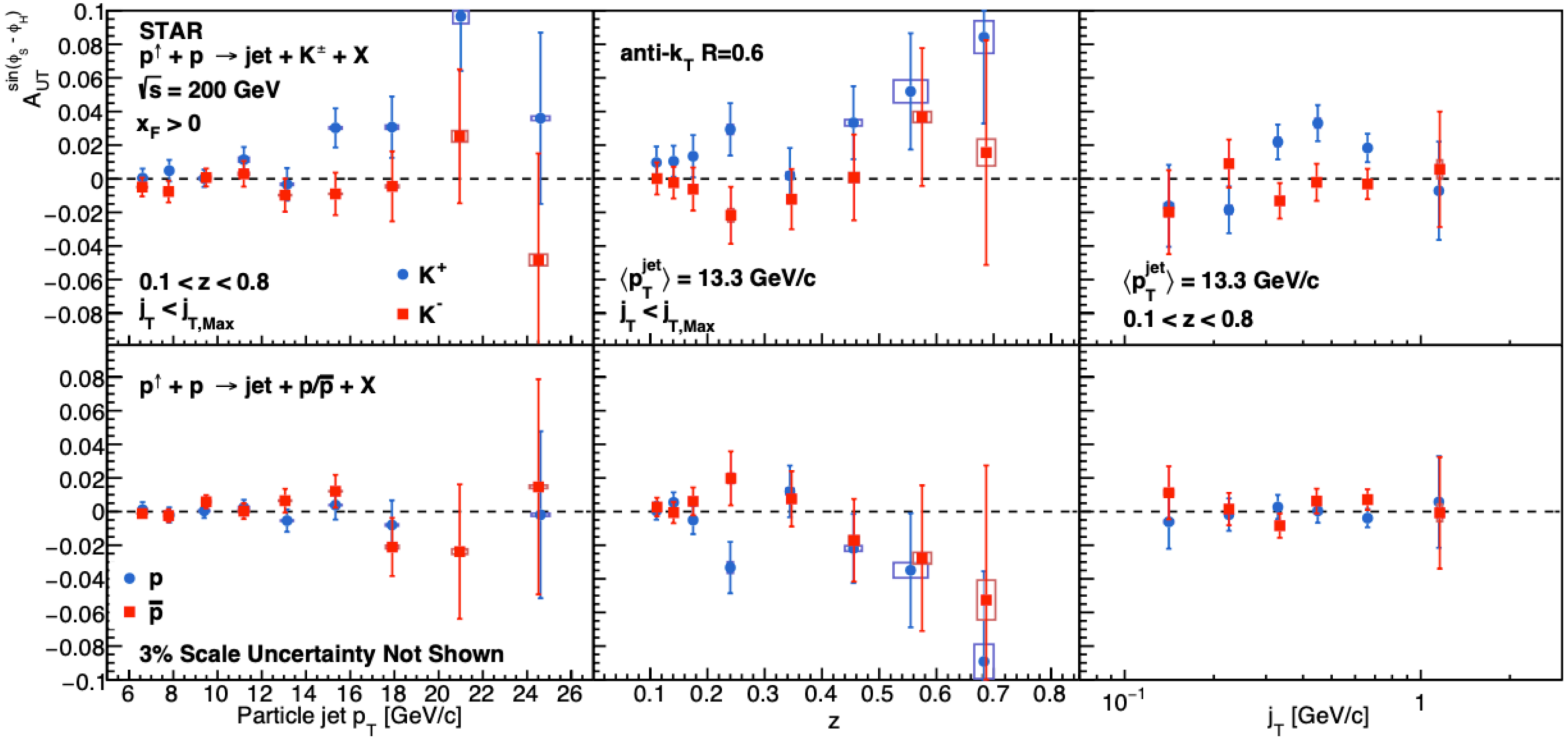
- Measurement of transverse single-spin asymmetries of $\pi^{\pm}$ within jets in pp at $\sqrt{s} = 510$ GeV with STAR 2017 data
- The high precision Collins asymmetry for $\pi^{\pm}$ results at $\sqrt{s} = 510$ GeV, in good consistency with 200 GeV data, indicating there is a very weak TMD evolution
- No significant Sivers asymmetry observed in pp collision at mid-rapidity
- Transverse polarized pp data taken at STAR, provides a unique opportunity to study Collins and Sivers effect in the forward $(2.5 < \eta < 4)$ region
- These pp data will provide the baseline for the ultimate universality test when compared to similar measurements in ep collisions at the future EIC

Back up

Collins Asymmetry of K & p

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

$$\sim A_{UT}^{sin(\phi_S-\phi_H)}\, sin(\phi_S-\phi_H)$$

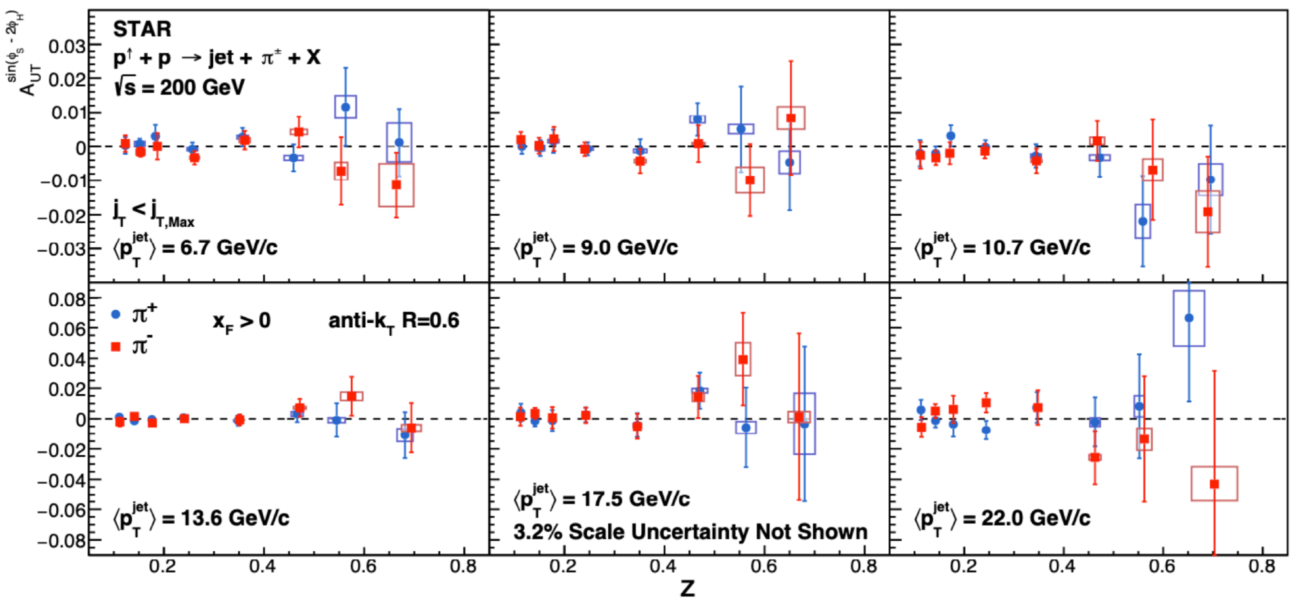


- The results for K^+ have a contribution from favored fragmentation of u quarks, are similar in magnitude to those for π^+
- The results for K^-, which can constrain s-quark contribution, are consistent with zero so far
- Fragmentation into $p(\bar{p})$ is much more complicated than into mesons, and is not expected to produce Collins asymmetry

Collins-like Asymmetry of pion

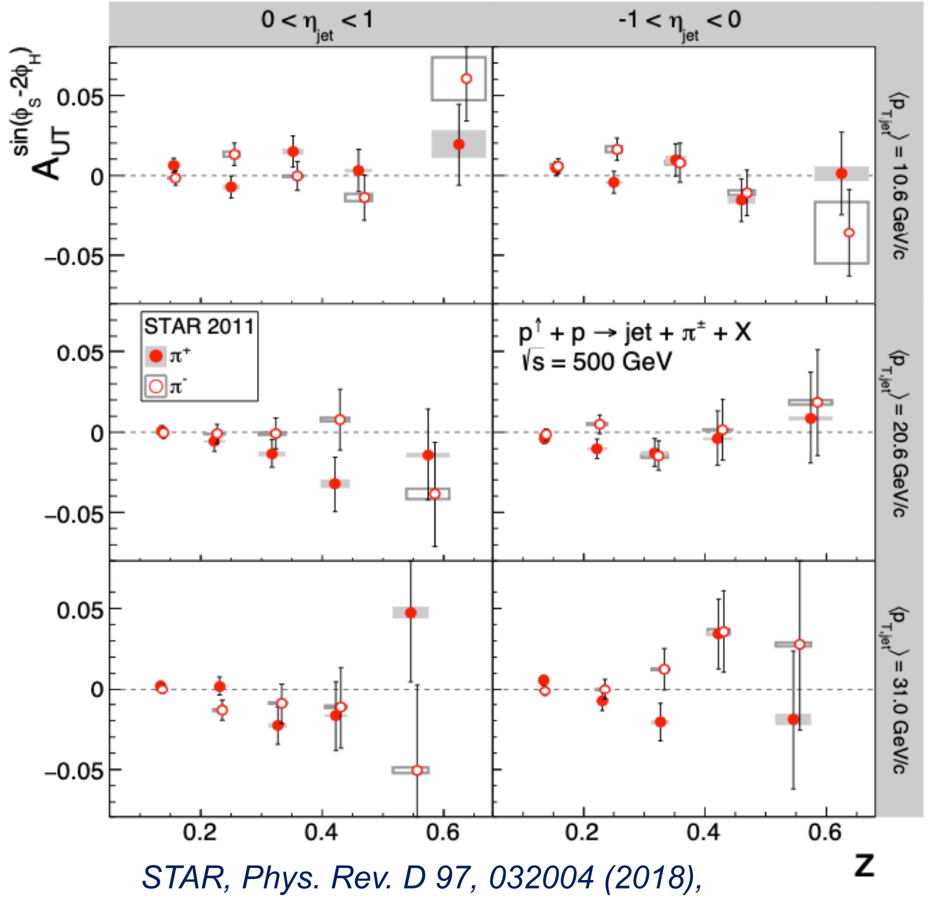
$\sim A_{UT}^{sin(\phi_S - 2\phi_H)} sin(\phi_S - 2\phi_H)$

- Results at 200GeV, as a function of z



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

- Results at 500GeV, as a function of z

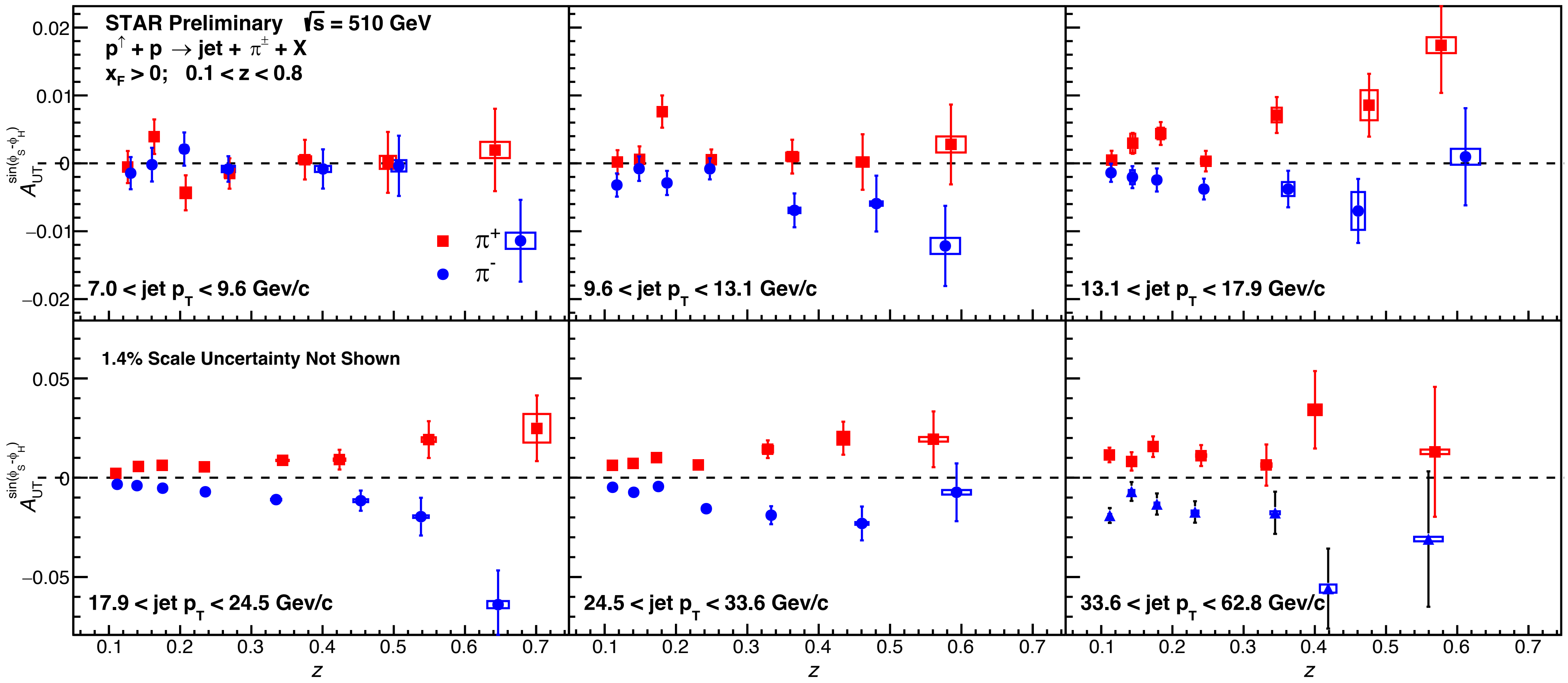


STAR, Phys. Rev. D 97, 032004 (2018),

- Sensitive to gluon linear polarization coupled to the "Collins-like" fragmentation function
- No significant asymmetry has been observed

Collins Asymmetry from STAR 2017 Data

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

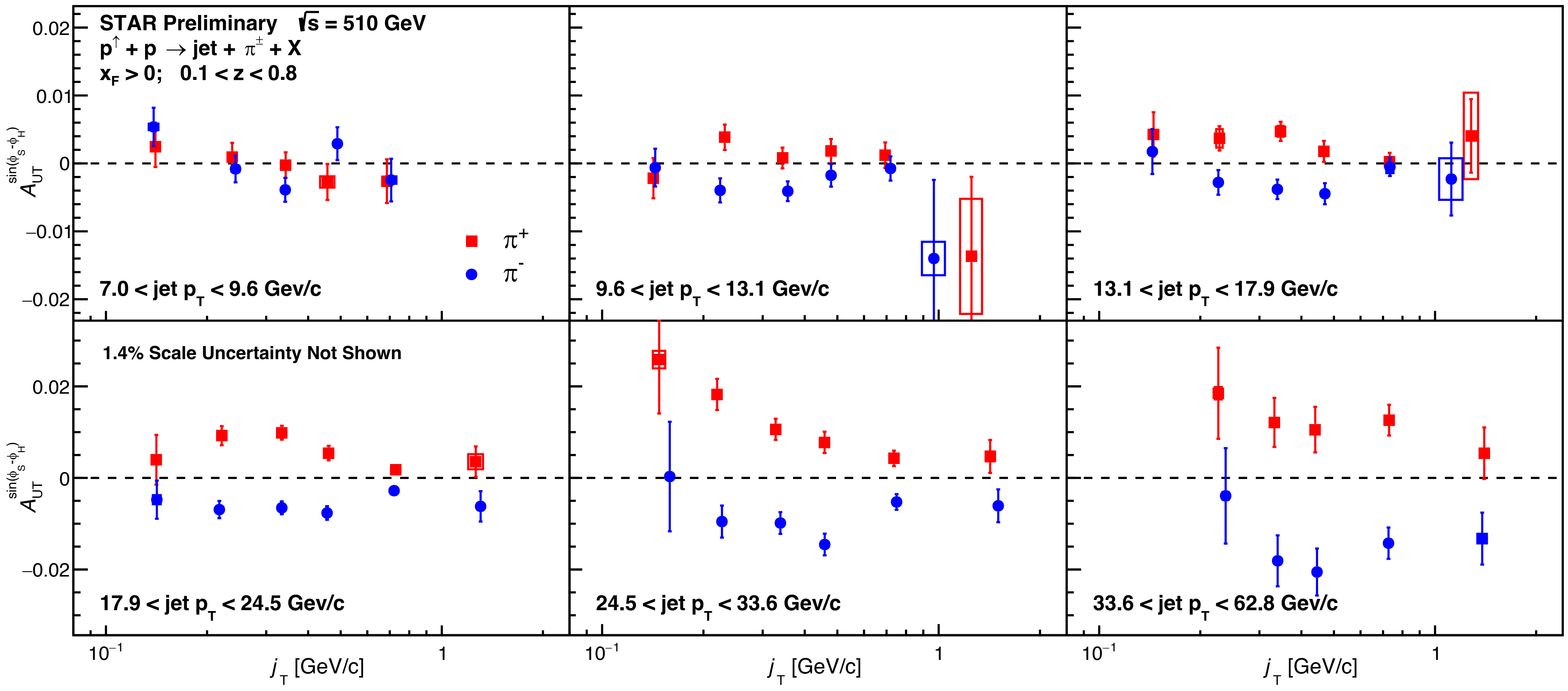


z : the pion's longitudinal momentum fraction in the jet

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

Collins Asymmetry from STAR 2017 Data

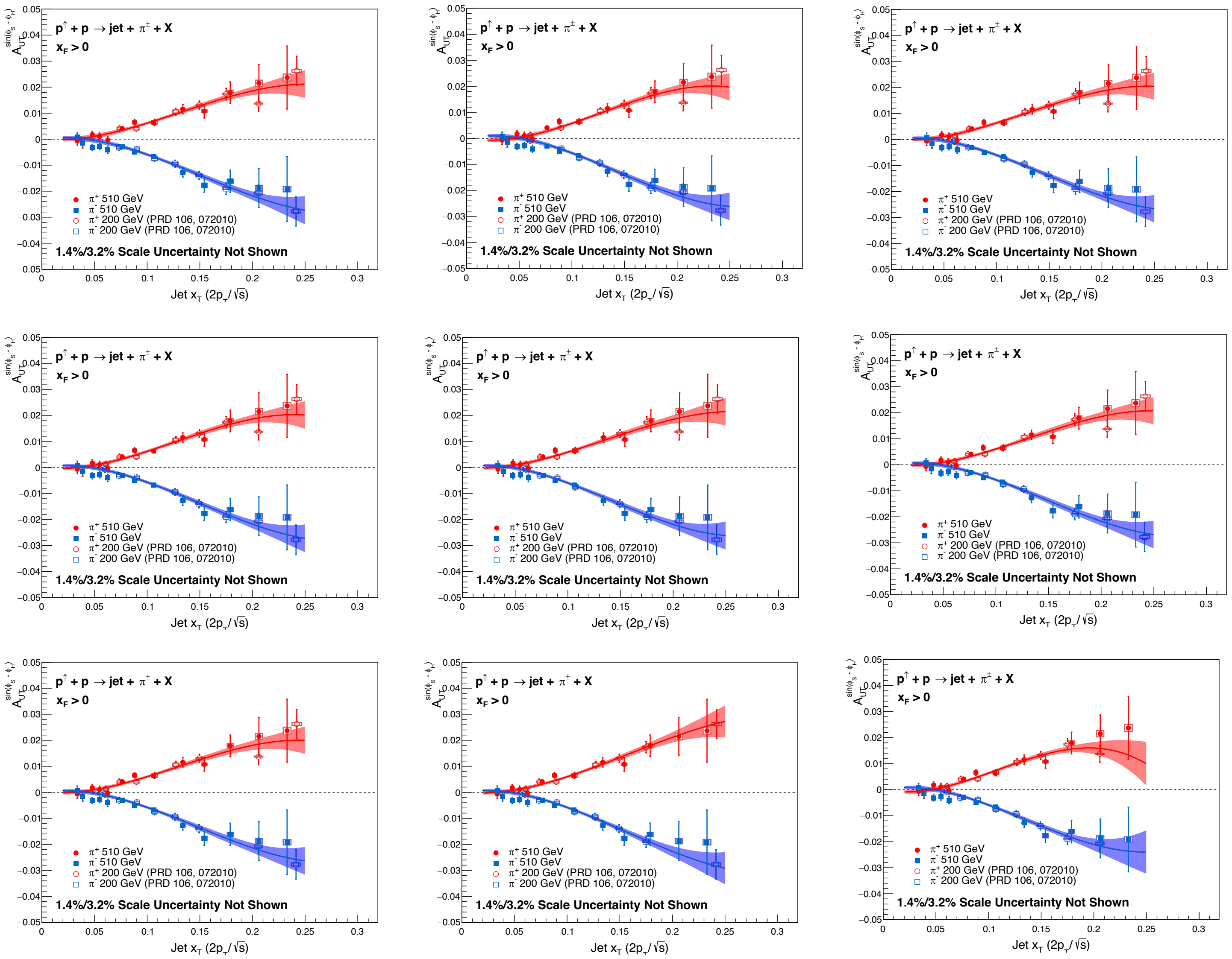
➢ Collins results as a function of j_T in different jet p_T regions at 510 GeV:



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

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

Comparison between 200GeV and 510GeV results



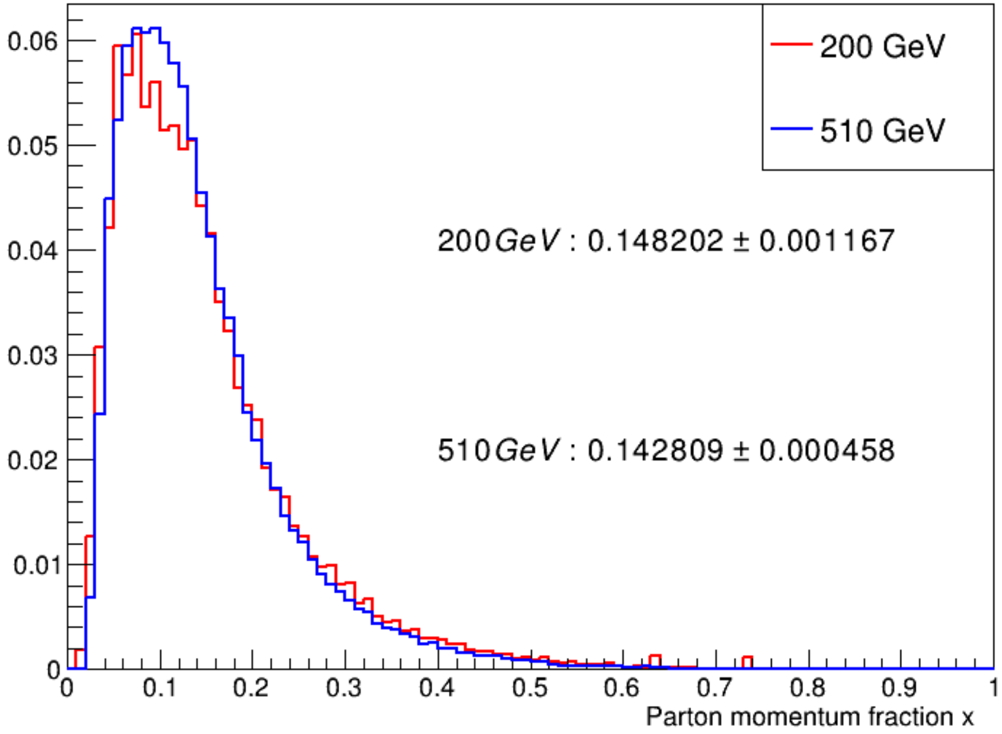
- Discard each point in 200GeV in sequence and perform fitting to cancel the uncertainties correlation
- Fit the 200GeV results with function $f(x) = ax^3 + bx^2 + cx$
- Shifting the A_{UT}^{200GeV} results to the xT_510 points by adding slope*(xT_510-xT_200):

$$A_{UT}^{200GeV,shift} = A_{UT}^{200GeV} + f(x_T^{510\ GeV}) - f(x_T^{200\ GeV})$$

- T-test for the consistency of two results

$$t = \left| \frac{< A_{510\ GeV/c} - A_{200\ GeV/c}^{shift} >}{StdDev/\sqrt{n}} \right|$$

x–distribution



- Simulation of Pythia 8
- $x_T^{200GeV} = x_T^{510GeV}$
- Both the mean value and the shape of the x distributions are consistent