Azimuthal transverse single-spin asymmetries of inclusive jets and hadrons within jets from polarized pp collisions at RHIC-STAR

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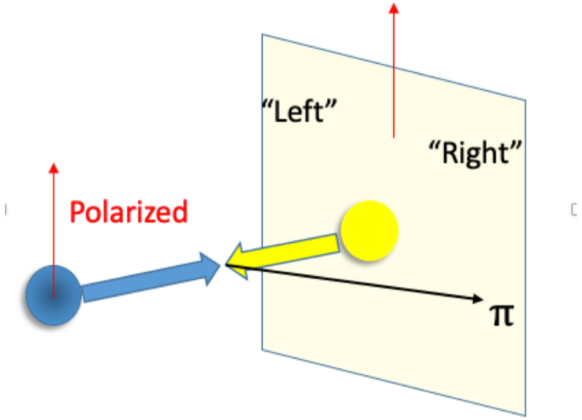
Challenges in Transverse Single-Spin Asymmetry (TSSA)

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

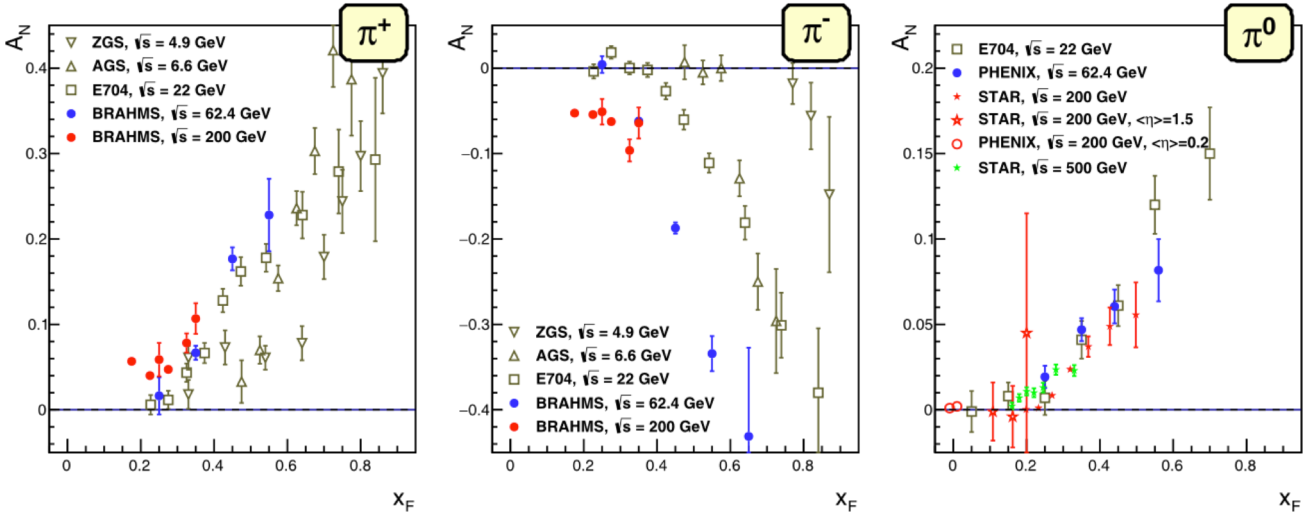


$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- LO QCD predicts $A_N \sim 0$

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

➢ 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

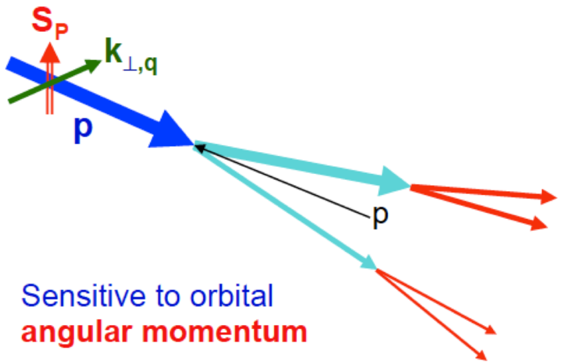
$$x_F = \frac{2p_z}{\sqrt{s}}$$

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*):**

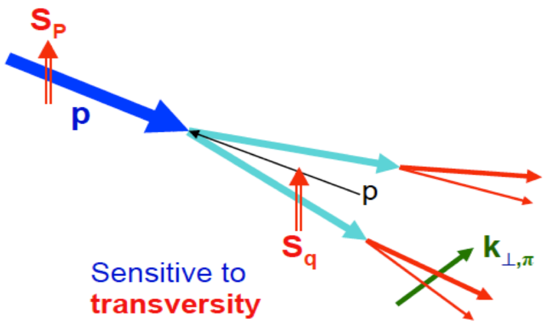
Parton spin and $k_\perp$ correlation in initial state (related to orbital angular momentum)



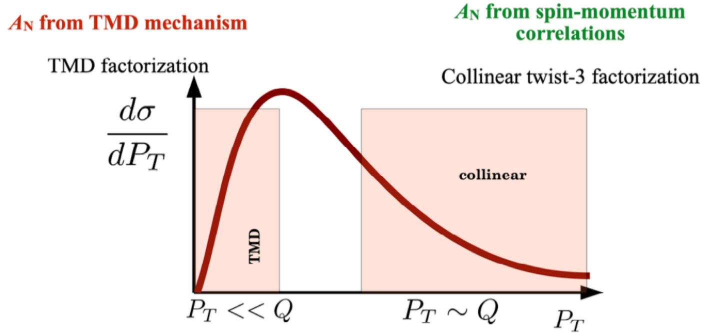
$$\vec{S} \cdot (\vec{p} \times \vec{k}_\perp)$$

✓ **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



X. Ji, J.-W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. Lett. 97, 082002 (2006)

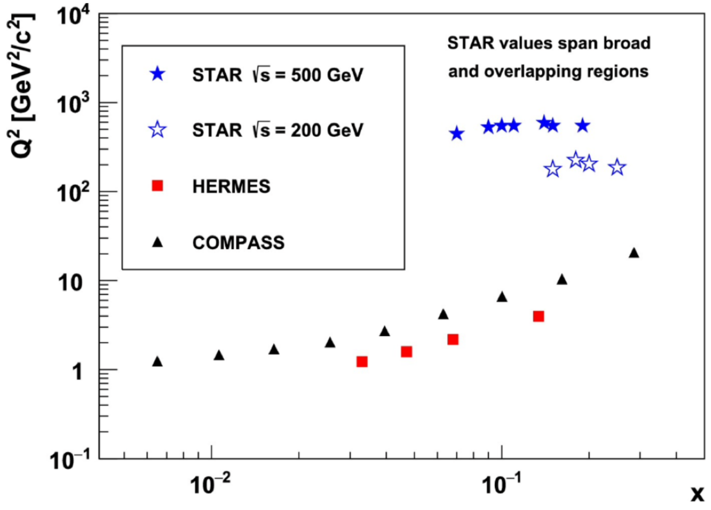
TSSA of pp Collisions

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

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%

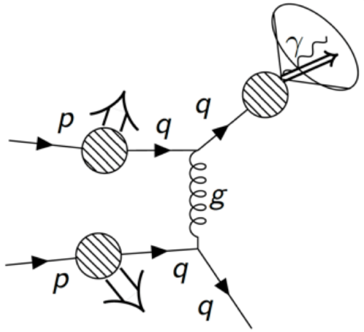
- Measurements at RHIC can reach values of Q^2 that are more than two orders of magnitude higher than current SIDIS experiments

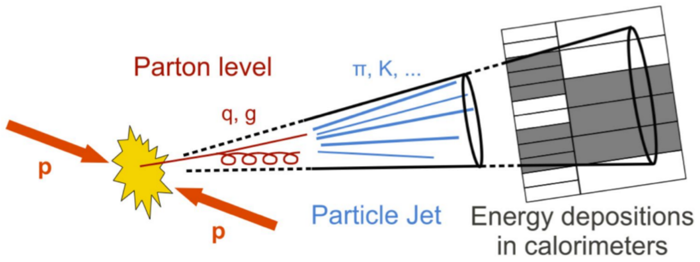
STAR, Phys. Lett. B 780 (2018), 332-339



➢ Collins effect for hadron within jet at STAR

- Separate initial and final state effects
- Jet-p_T ~ hard scale; hadron p_T ~ soft scale
- Validate factorization and universality with SIDIS and e^+e^- annihilation

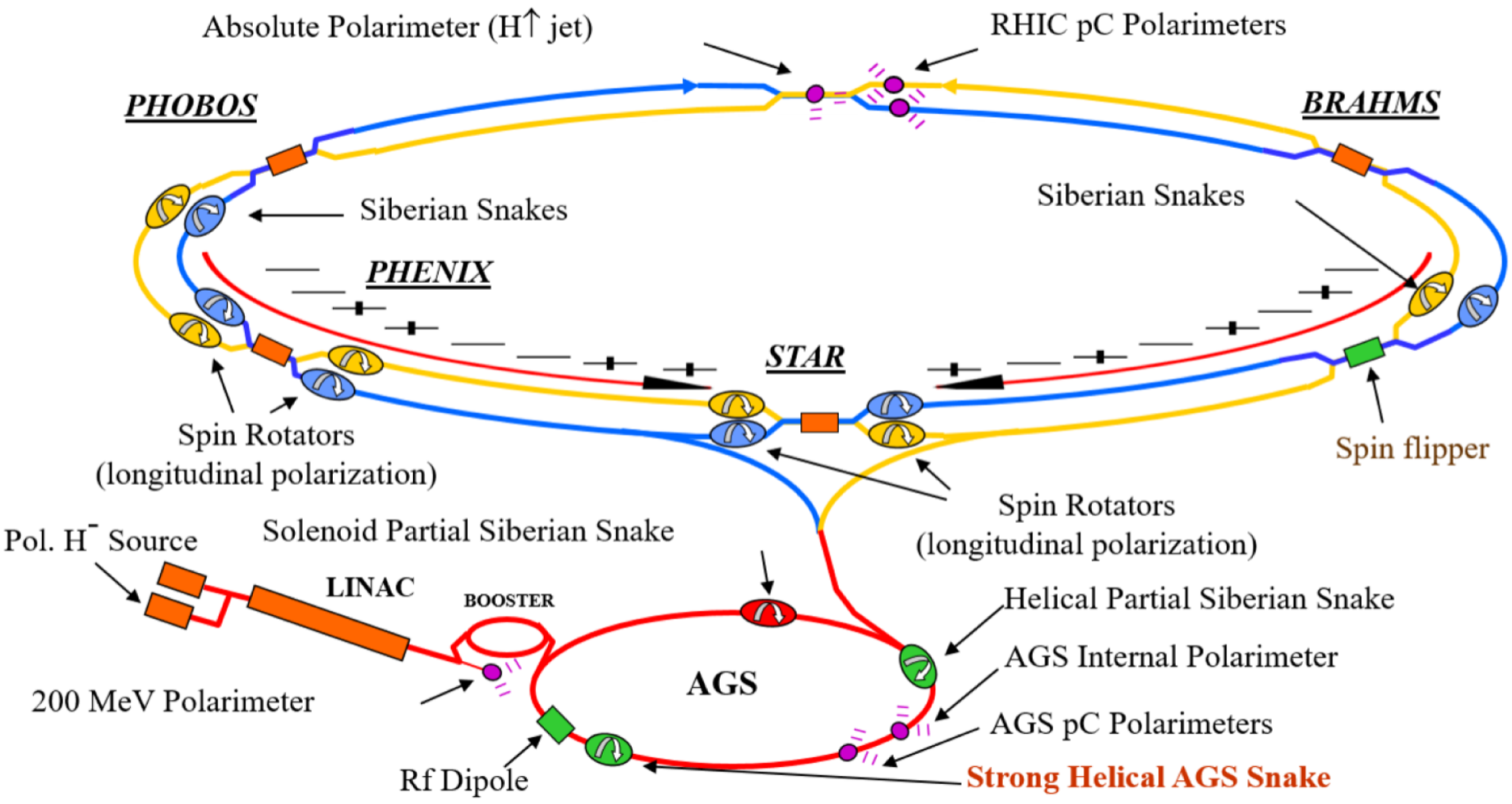




Z. B. Kang, X. Liu, F. Ringer and H. Xing, JHEP 11 (2017), 068

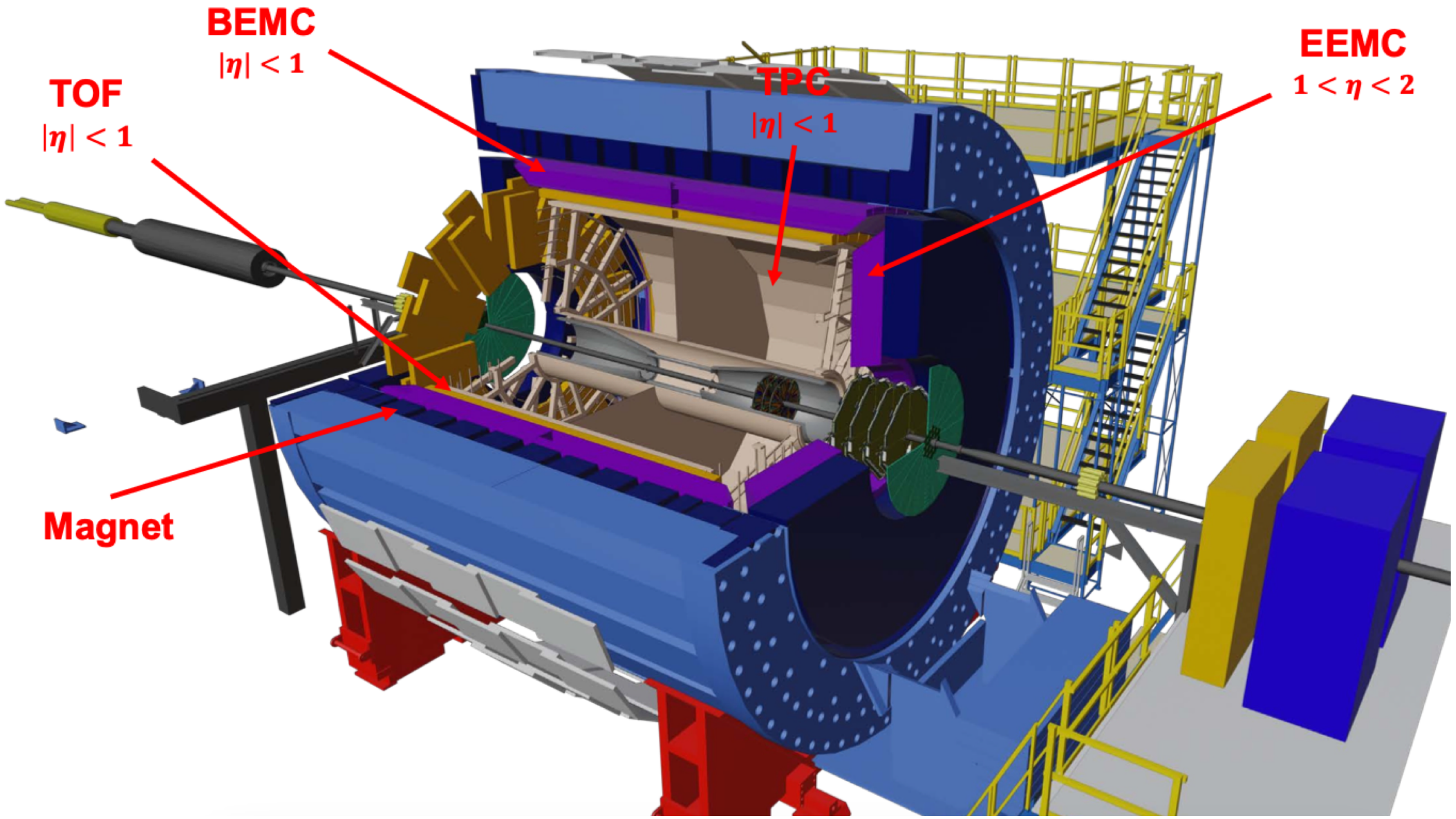
U. D'Alesio, F. Murgia and C. Pisano, Phys. Lett. B 773 (2017), 300-306

Relativistic Heavy Ion Collider (RHIC)



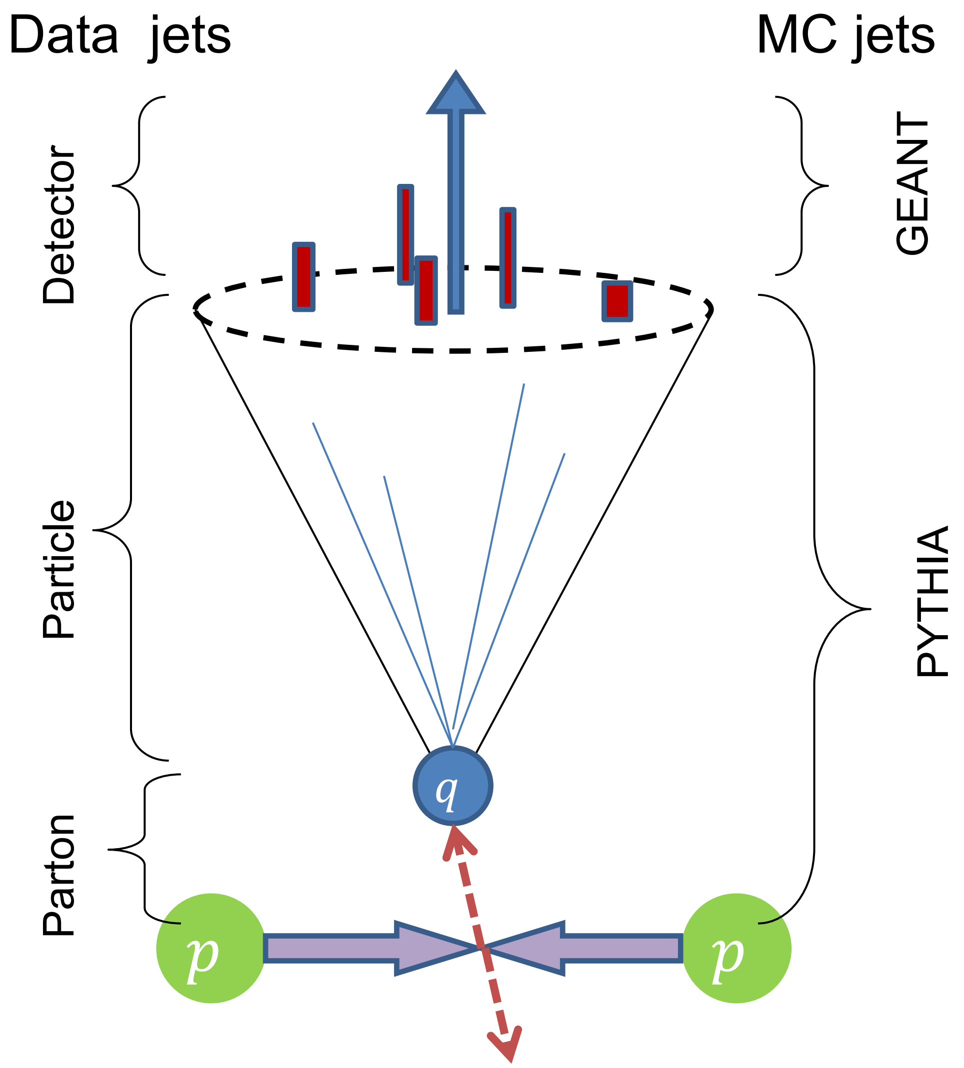
- RHIC is the world's only machine capable of colliding high-energy polarized protons

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

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

Angle Modulations of TSSA in pp Collisions

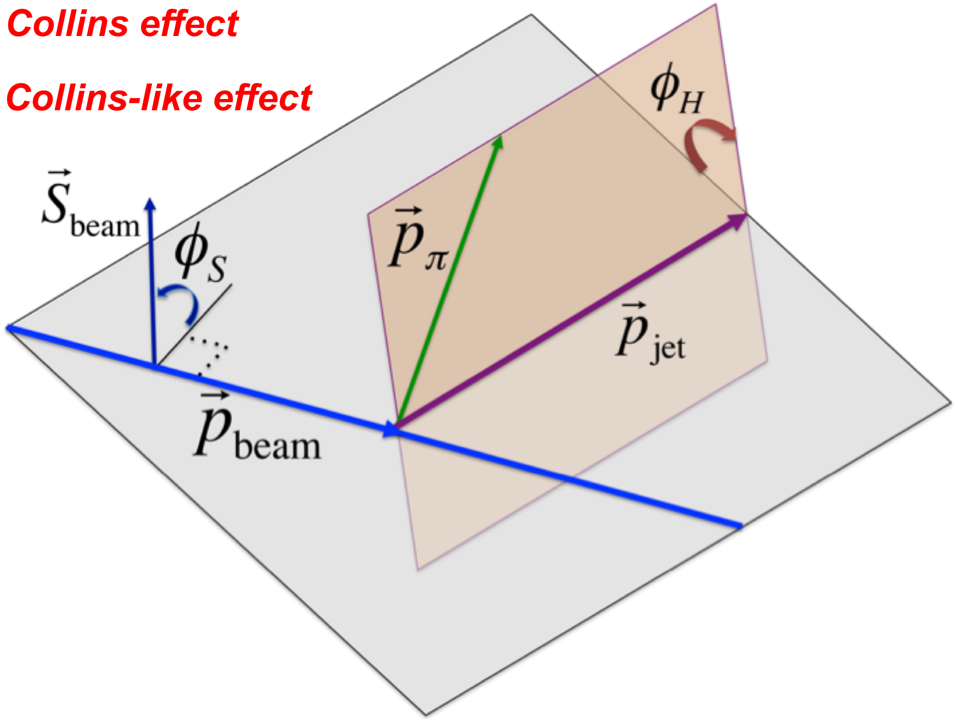
- For $\pi^{\pm}$ within jets in pp collisions, the spin dependent cross section can be expressed:

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

related to Sivers effect

related to Collins effect

related to Collins-like 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 Transverse Single-Spin Asymmetries

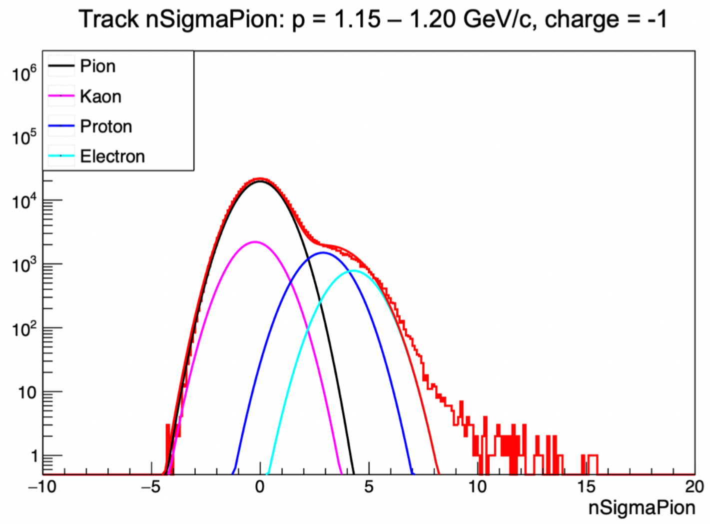
- Cross-ratio method to extract the asymmetries of different modulations.

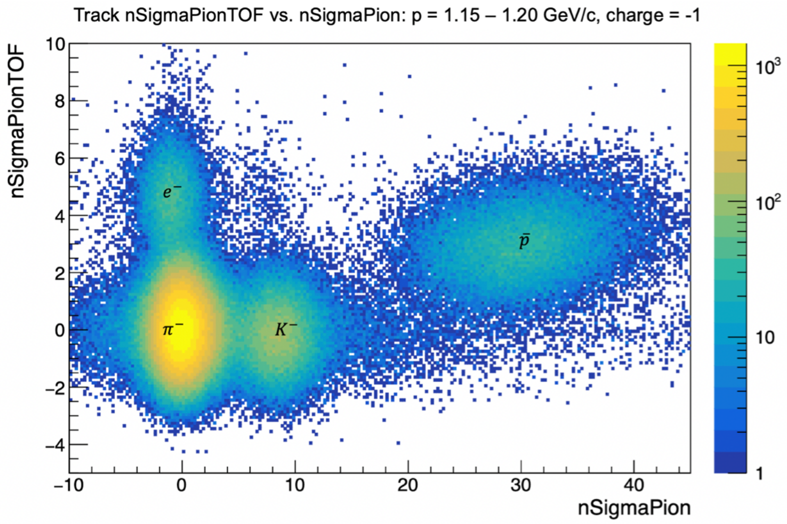
$$A_N sin(\phi) = \frac{1}{P} \cdot \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

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

Particle Identification

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





$$n\sigma_{dE/dx} = \frac{1}{\sigma_{\text{exp}}} \ln\left(\frac{dE/dx_{\text{meas}}}{dE/dx_{\text{theo}}}\right)$$

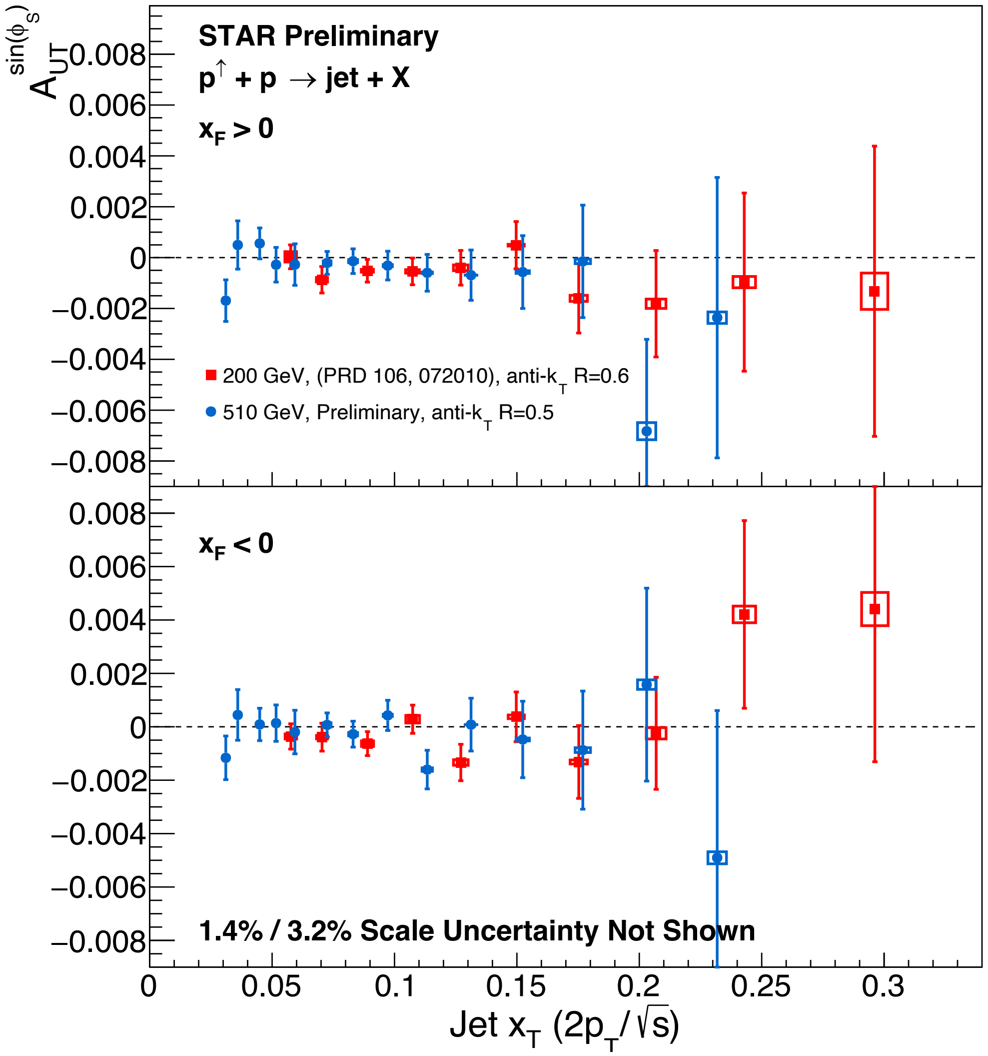
$$n\sigma_{TOF} = \frac{TOF_{\text{meas}} - \frac{L}{c\beta(p)}}{\sigma_{\text{eff}}}$$

➢ Asymmetries purification through Moore-Penrose inverse.

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

- $f^{j}_{i\ rich}$: the fraction of particle type j in the i-rich sample.
- Subtract other particles contamination

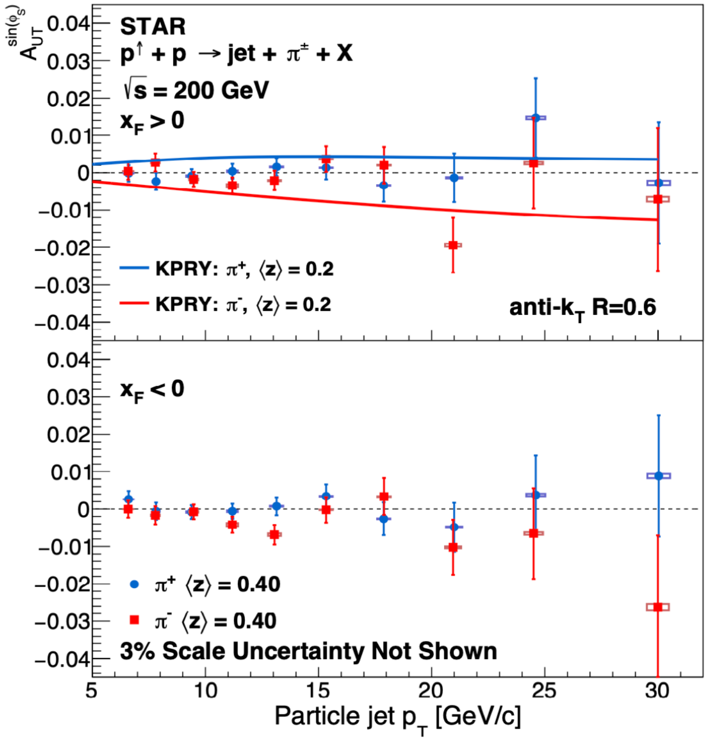
Sivers Asymmetry of Inclusive Jet at 200 GeV & 510 GeV

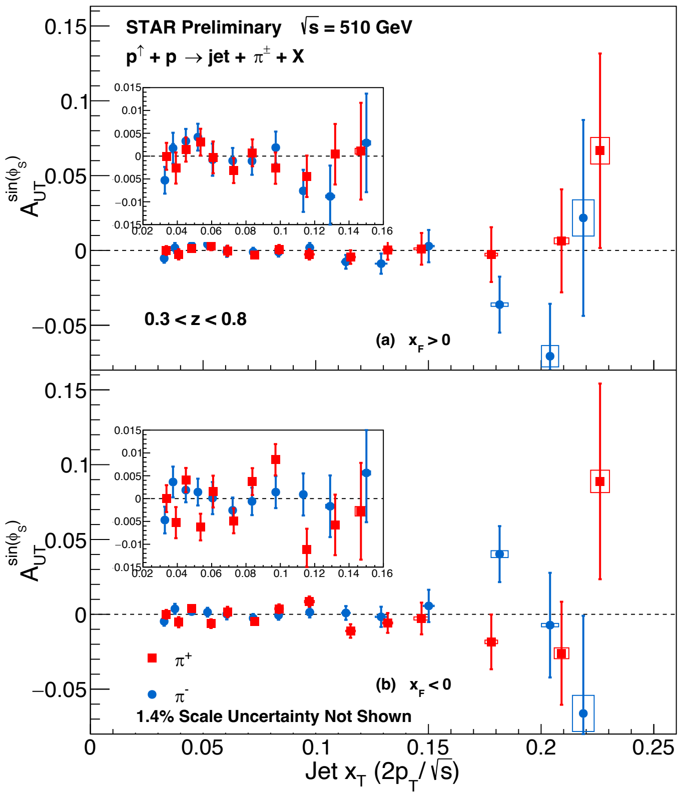


- Sivers asymmetries for inclusive jets are consistent with 0.
- Sensitive to twist-3 correlators associated with the gluon Sivers function

Sivers Asymmetry of Hadron-Tagged Jet at 200 GeV & 510 GeV

M. Abdallah et al. [STAR], Phys. Rev. D 106, 072010 (2022)



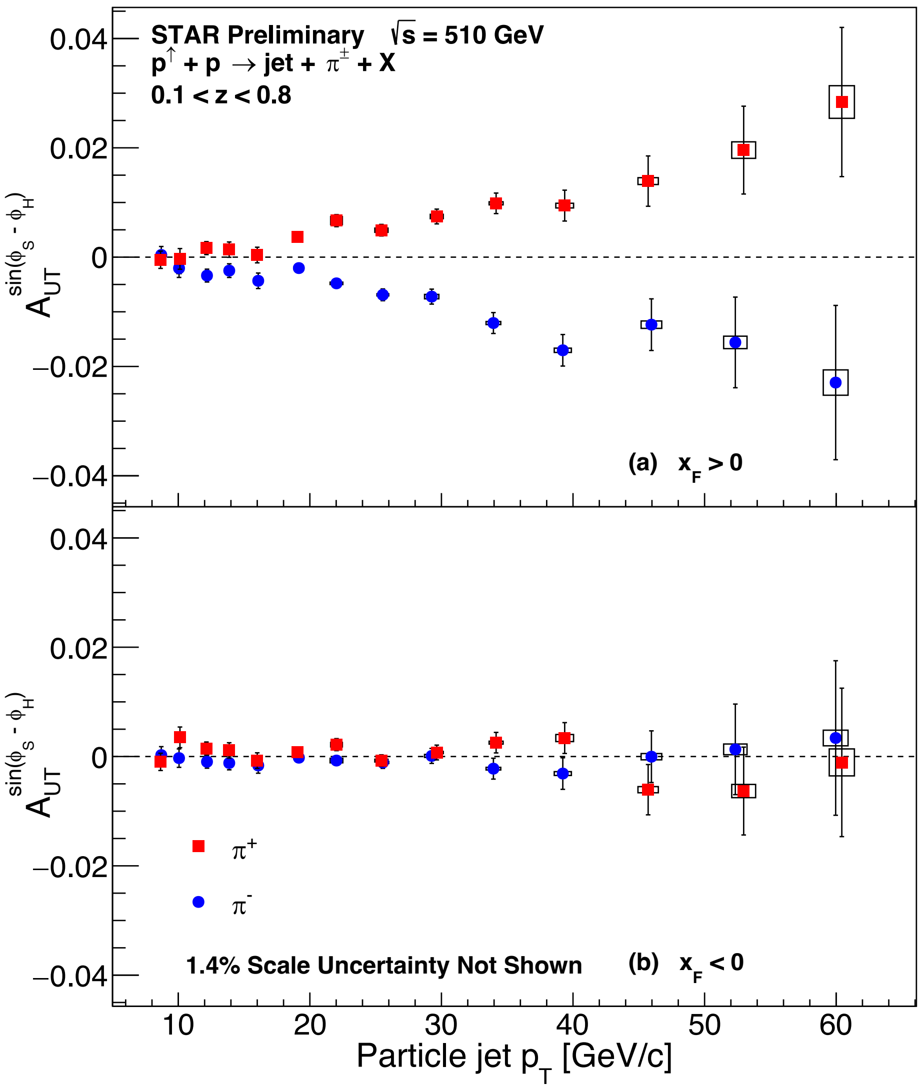


- Quark jet fractions are enhanced by tagging $\pi^{\pm}$
- Asymmetries are consistent with zero at mid-rapidity
- Theoretical expectations from the KPRY model

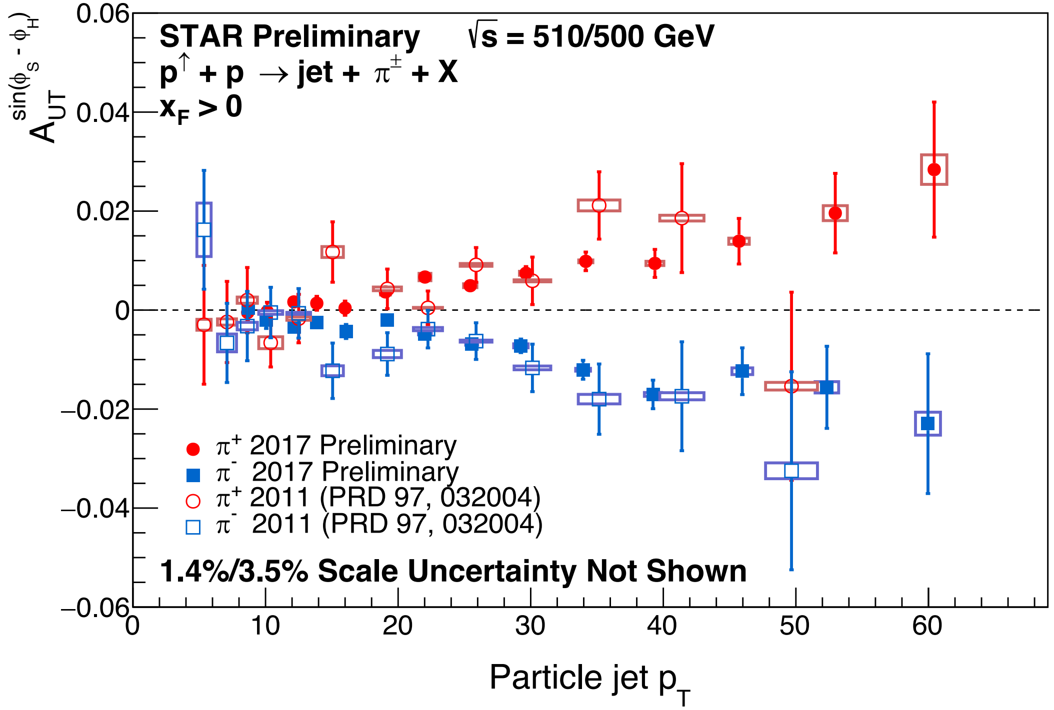
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017)

Collins Asymmetry of pion at 510/500 GeV

- Collins results as a function of jet p_T



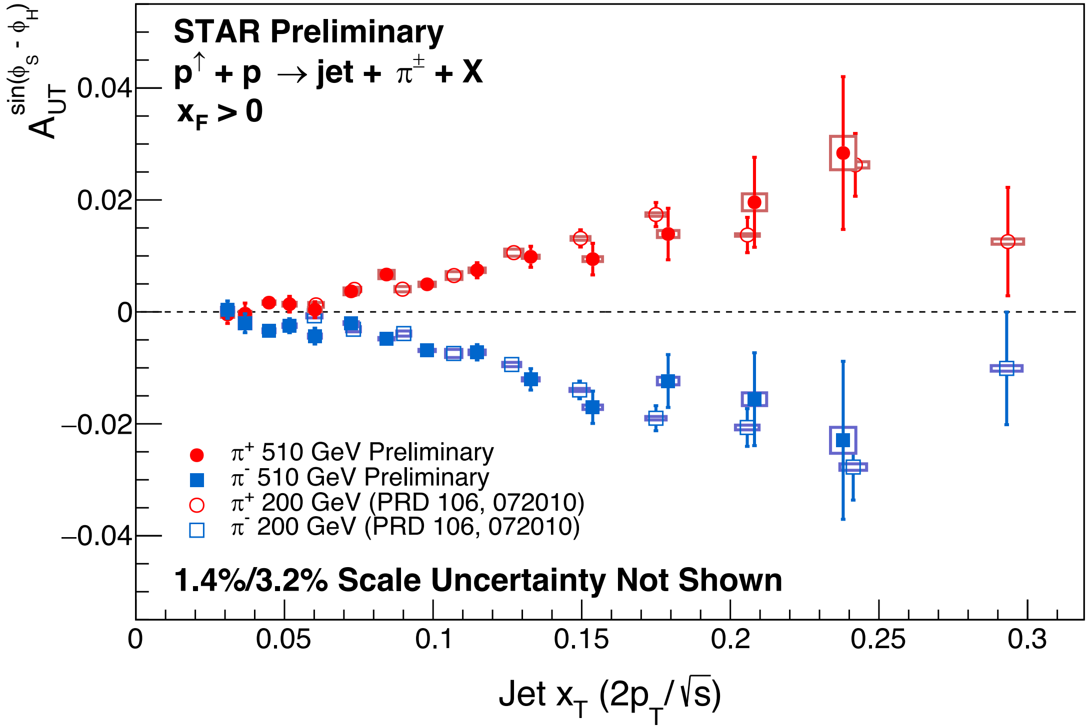
- Positive for π^+ and negative for π^-, and increase with increasing jet p_T for $x_F > 0$
- The asymmetries for $x_F < 0$ are consistent with 0.



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

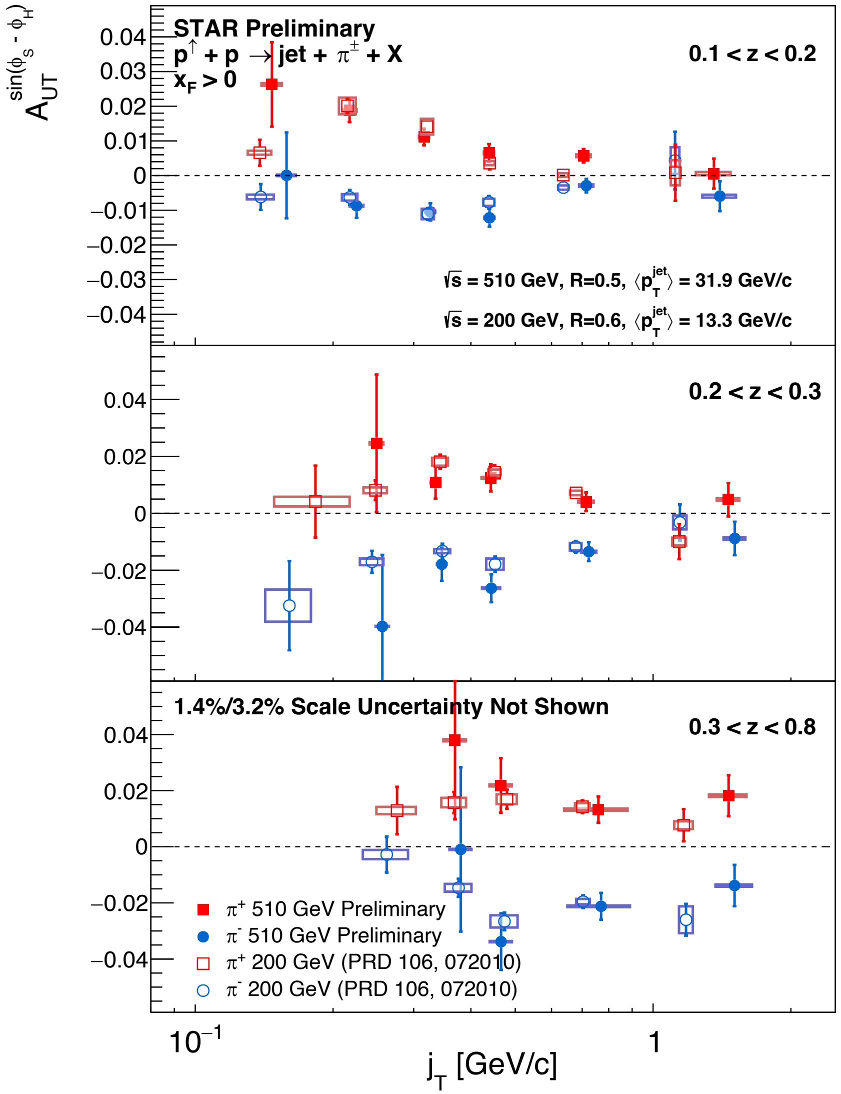
Collins Asymmetry of pion at 510/200 GeV: Test the TMD Evolution

- As a function of jet-x_T



- As a function of hadron j_T

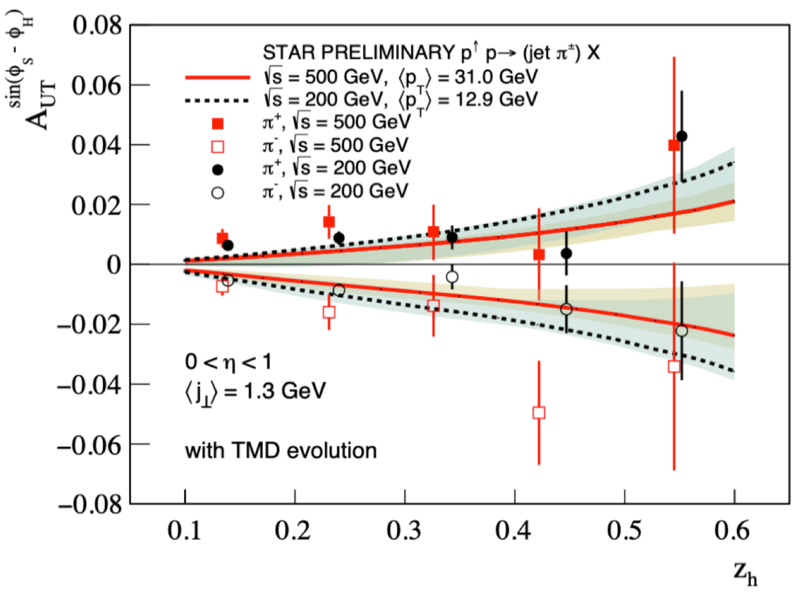
j_T : pion's transverse momentum relative to jet axis



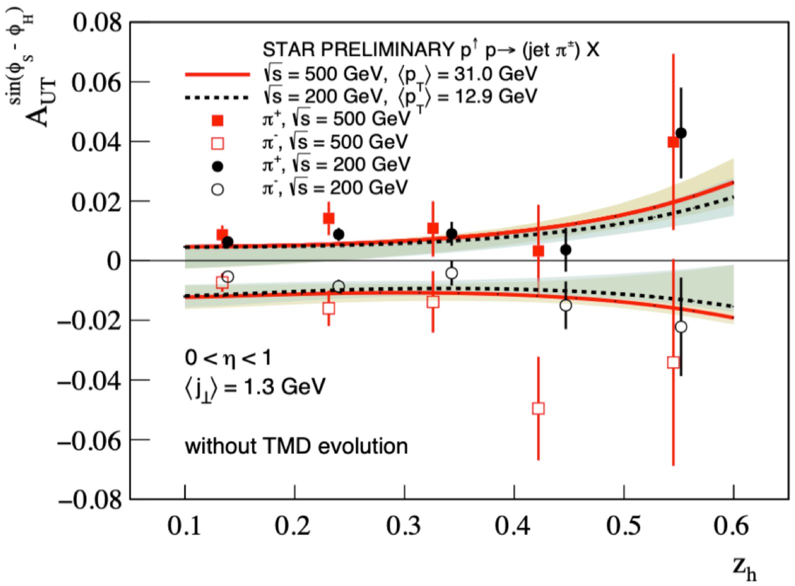
- The high precision Collins results of 510 GeV and 200 GeV nicely align with jet x_T & hadron j_T scale, giving almost no energy dependence.
- These data provide important constraints on the scale evolution for Collins asymmetry.

Theoretical Model

- With TMD evolution



- Without TMD evolution



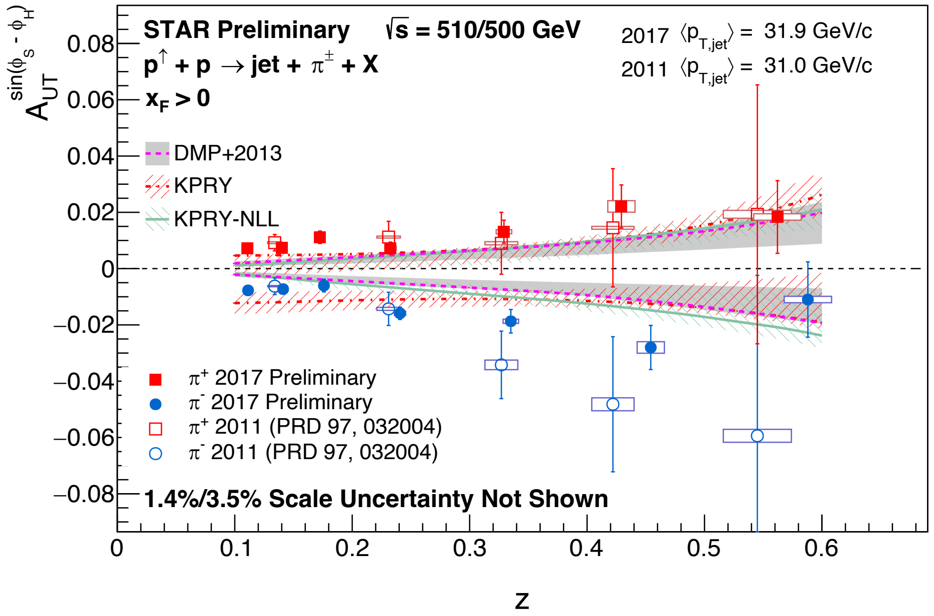
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017)

- A collinear factorization for the production of the jet, a TMD factorization for the hadron $j_\perp$ distribution inside the jet
- Global fit based on SIDIS and e^+e^- annihilation
- The Collins asymmetry will be suppressed by TMD evolution

Comparison to Theoretical Calculations

- 500/510GeV, as a function of z

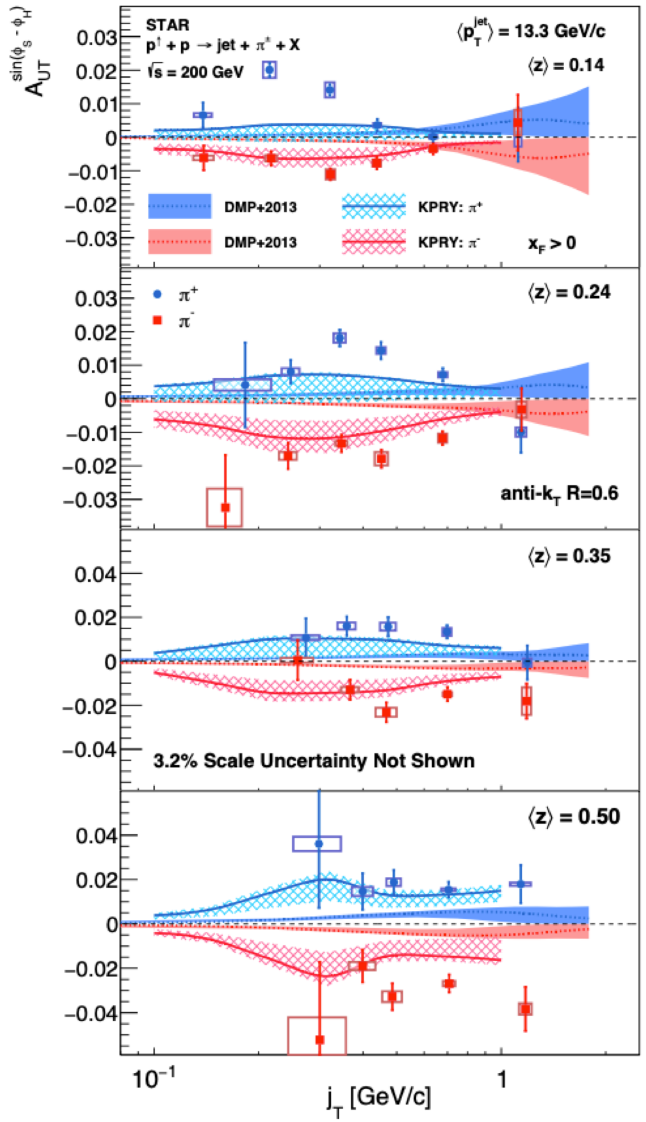
  z : pion's longitudinal momentum fraction in jet



U. D'Alesio, F. Murgia and C. Pisano, Phys. Lett. B 773 (2017), 300-306
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017)

- 200GeV, as a function of j_T

  j_T : pion's transverse momentum relative to jet axis

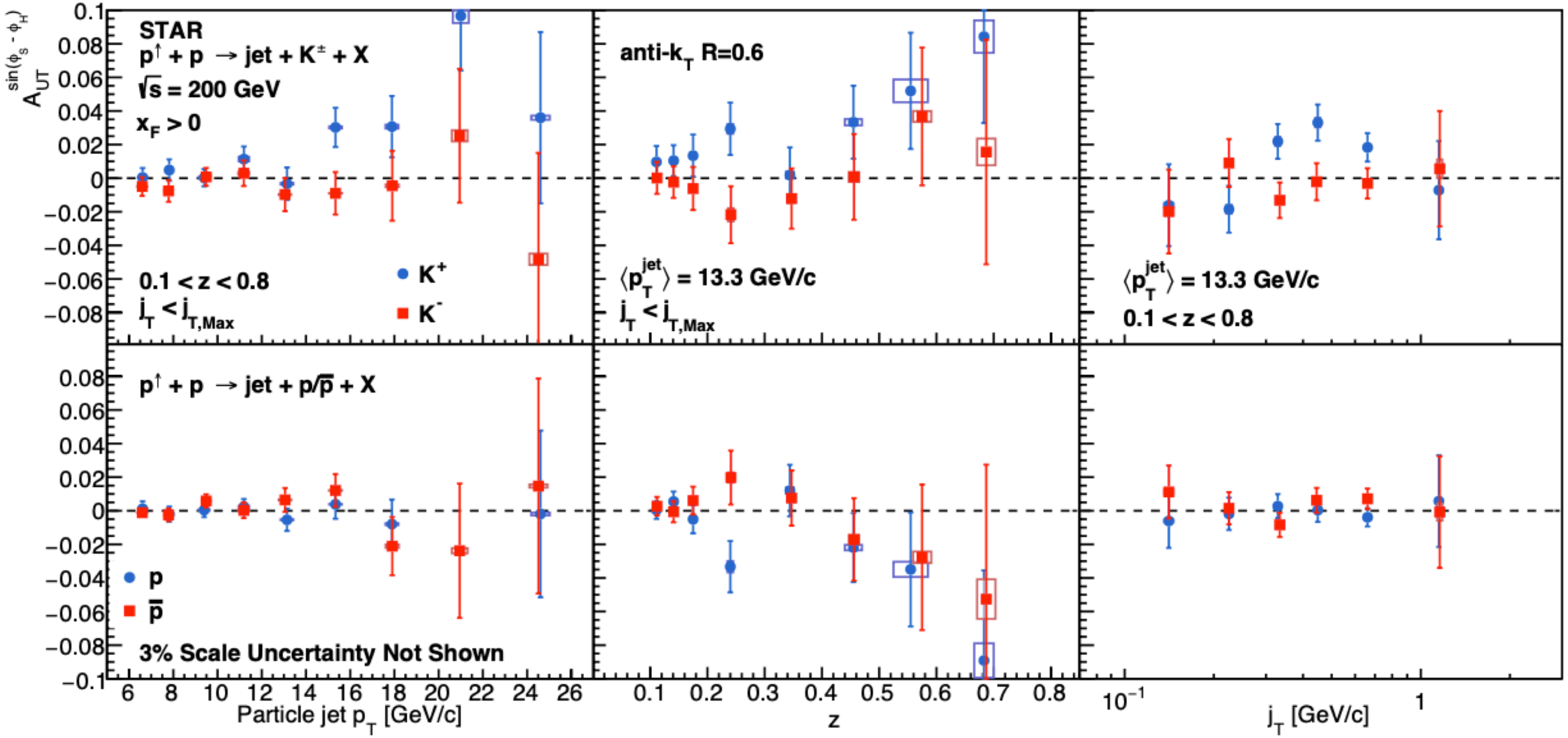


STAR, Phys. Rev. D 106, 072010 (2022)

- Experimental results and theories are in agreement, but model calculations undershoot the observed asymmetries.
- DMP+2013 and KPRY apply the collinear QCD evolution, assume universality and factorization
- KPRY model also apply TMD evolution beyond collinear assumption

Collins Asymmetry of K & p

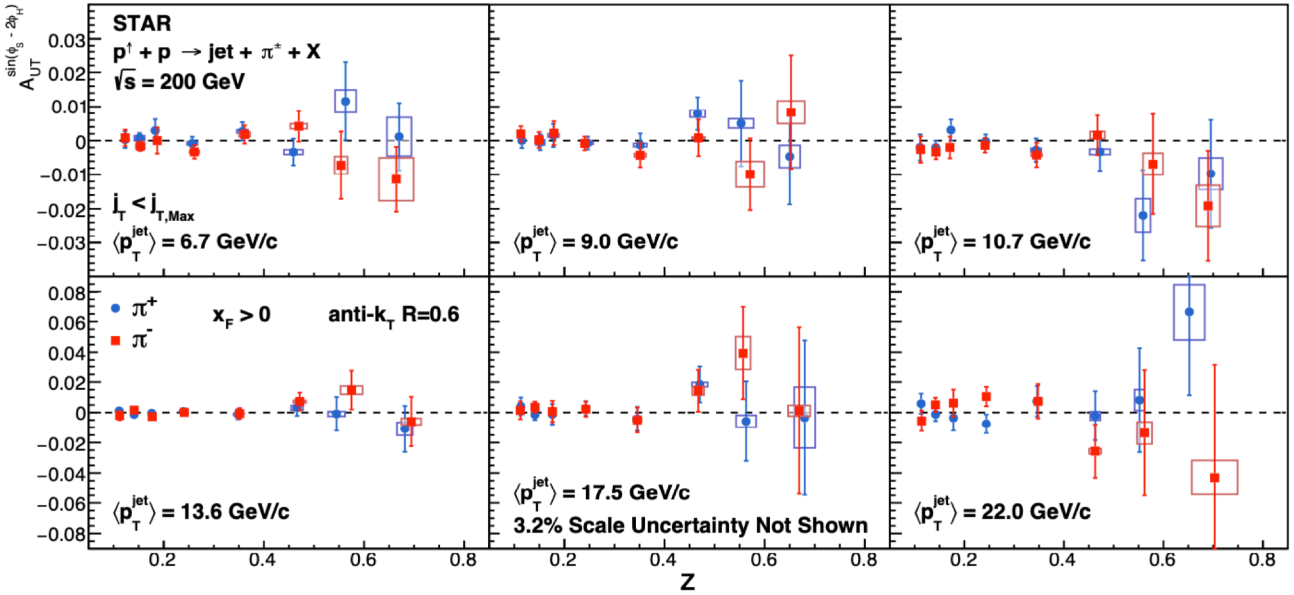
STAR, Phys. Rev. D 106, 072010 (2022)



- The results for K^+ have a contribution from favored fragmentation of u quarks, are similar in magnitude to those for π^+
- While the results for K^- can only come from unfavored fragmentation, are consistent with zero within uncertainties
- Fragmentation into protons is not expected to produce Collins asymmetries.

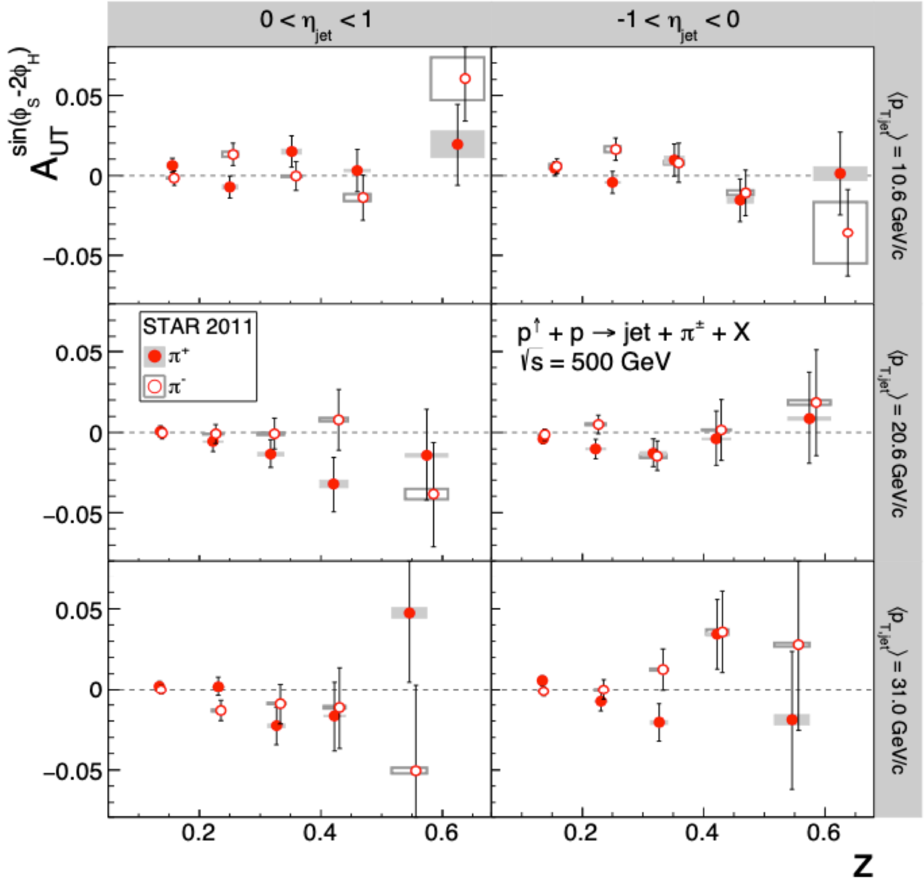
Collins-like Asymmetry of pion

- 200GeV, as a function of z



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

- 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 for either collision energy

Summary & Outlook

- New preliminary results on transverse single-spin asymmetries of jets and $\pi^{\pm}$ within-jets in pp at $\sqrt{s} = 510$ GeV with STAR 2017 data

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

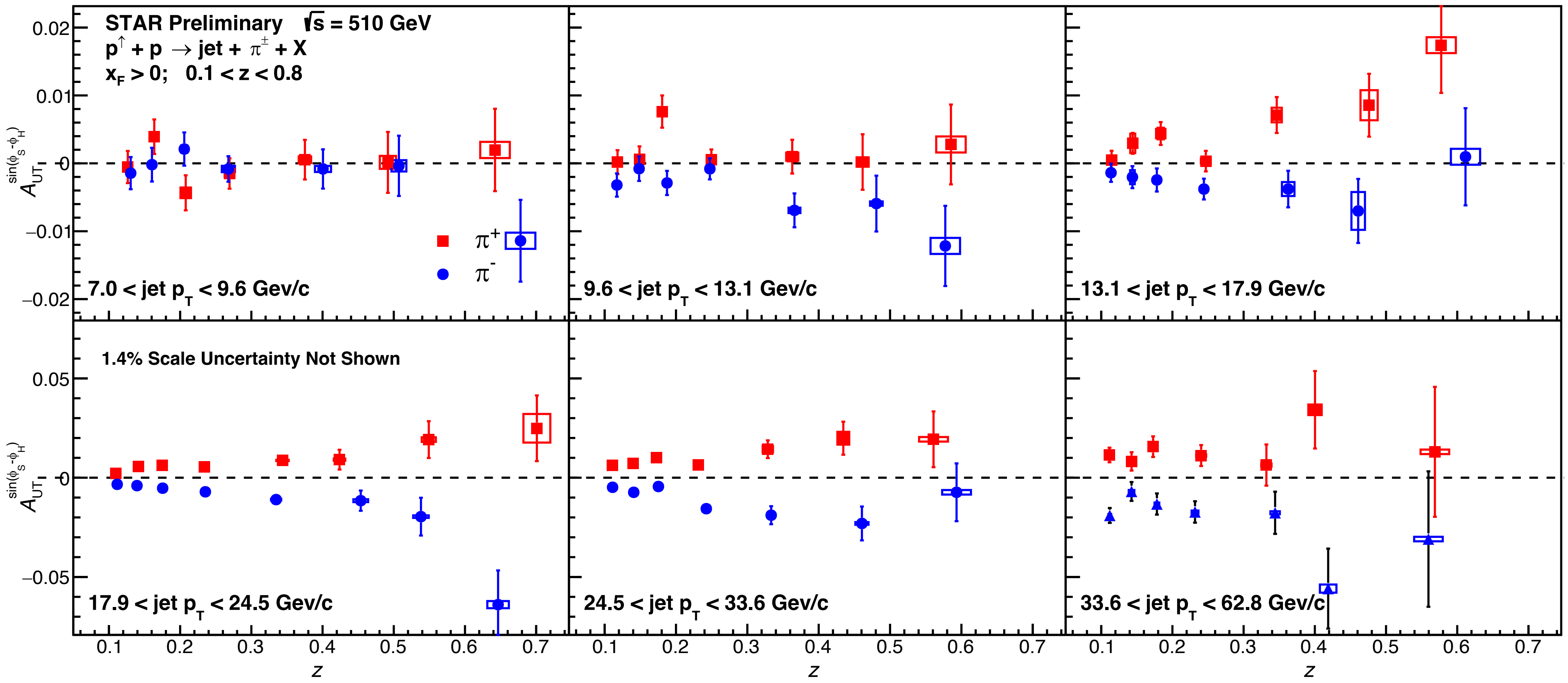
- No significant Sivers asymmetry or Collins-like asymmetry observed in pp collision.

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

Back up

Collins Asymmetry from STAR 2017 Data

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

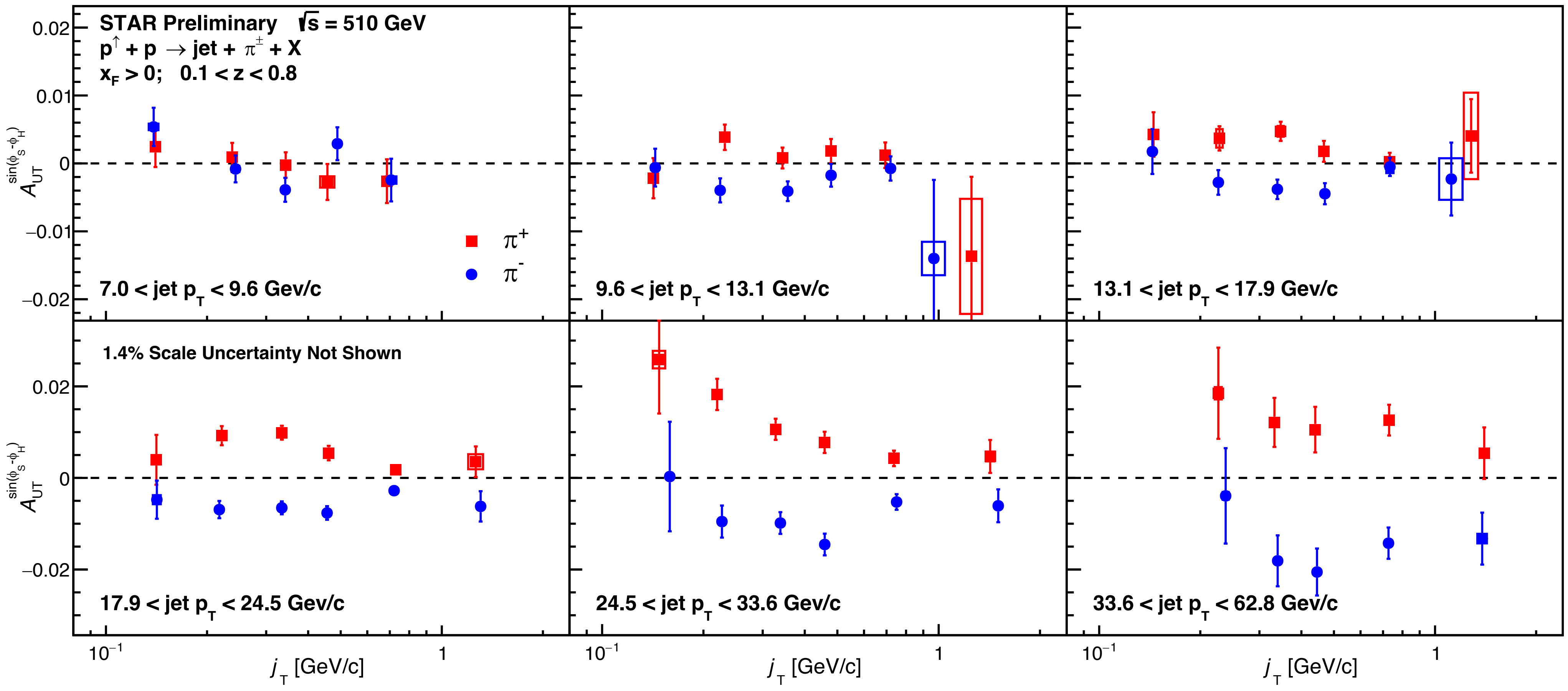


z： the pion's longitudinal momentum fraction in the jet

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

Collins Asymmetry from STAR 2017 Data

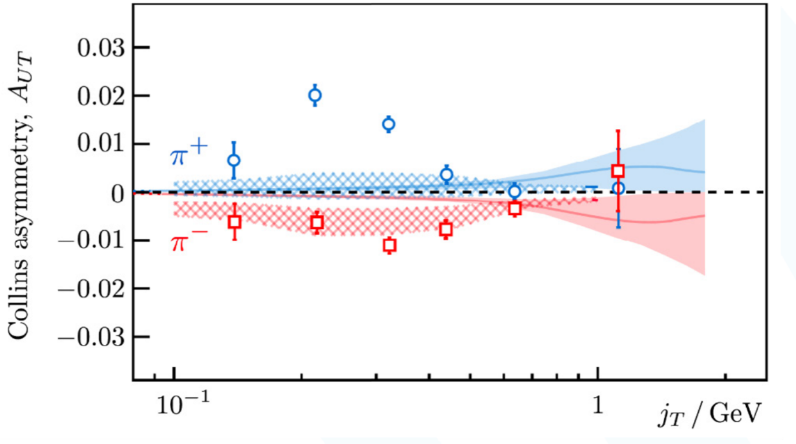
➢ Collins results as a function of j_T in different jet p_T regions at 510 GeV:



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

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

- Recent Collins results Highlighted in the "2023 Long Range Plan for Nuclear Science"



M. Abdallah et al. [STAR], Phys. Rev. D 106, no.7, 072010 (2022)

- Significantly larger than the theoretical predictions
- Providing new insight on spin–momentum correlations, challenging some contemporary theoretical models