Transverse single-spin asymmetries in polarized pp collisions at RHIC-STAR

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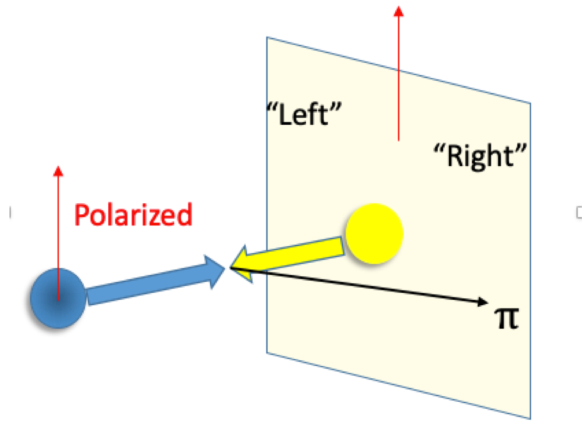
NSFC National Natural Science Foundation of China

Challenges in Transverse Single-Spin Asymmetry (TSSA)

➢ Anomalously large A_N in pp collisions observed for decades

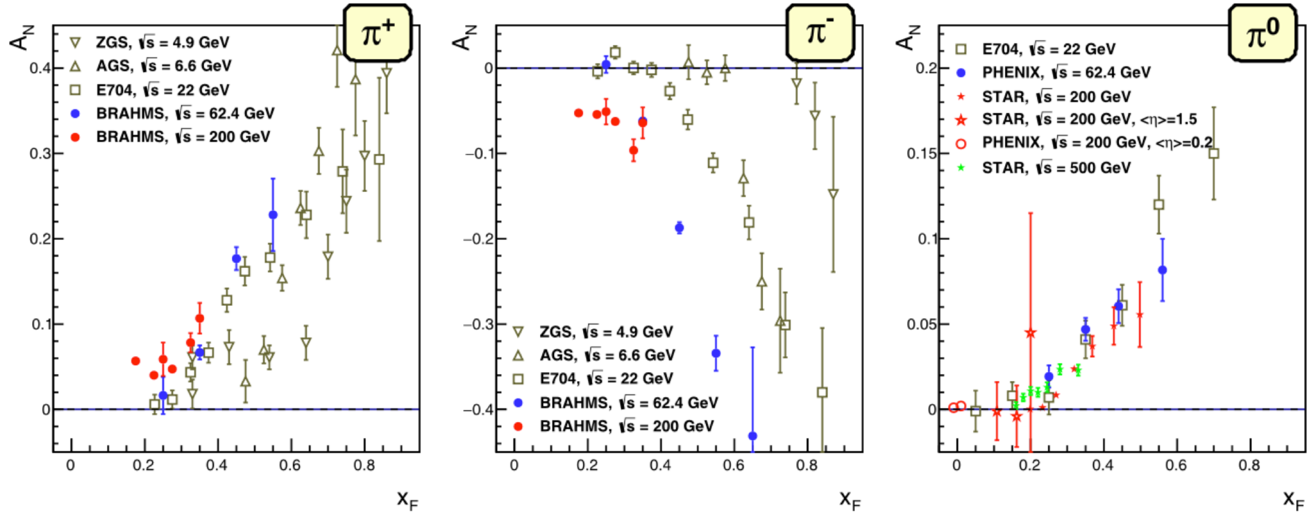


$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

- LO QCD predicts $A_N \sim 0$

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

➢ Left-right asymmetries of different experiments 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

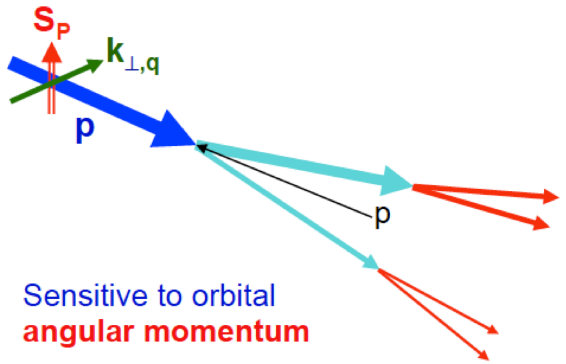
$$x_F = \frac{2p_z}{\sqrt{s}}$$

Mechanisms for Transverse Single–Spin Asymmetry

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

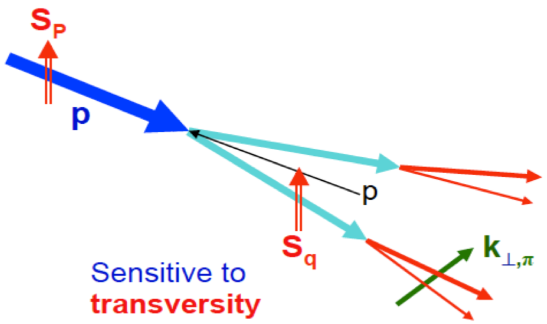
✓ **Sivers effect (*Sivers'90*):**

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



✓ **Collins effect (*Collins'93*):**

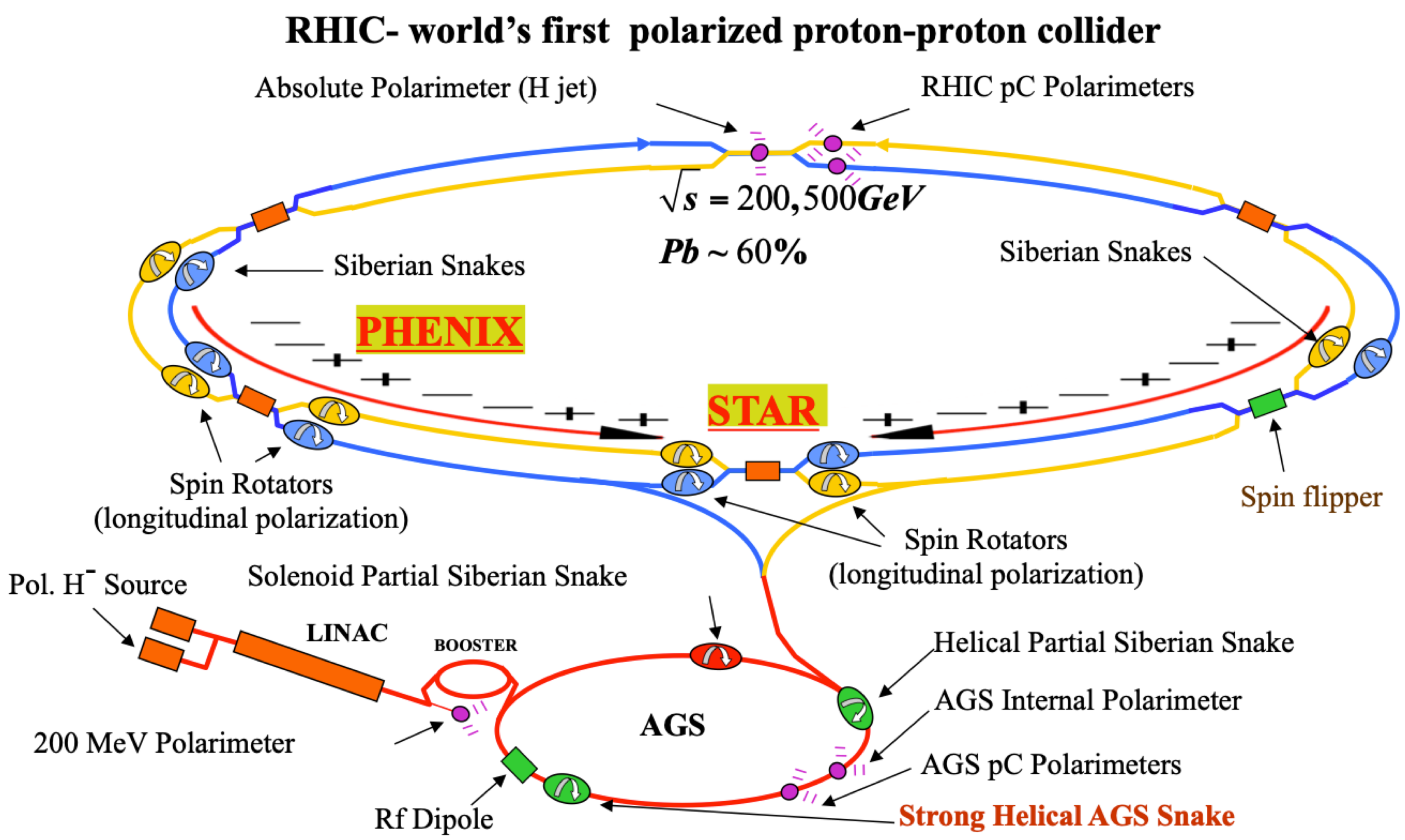
Quark spin and hadron $k_\perp$ correlation in fragmentation process (coupled with transversity)



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

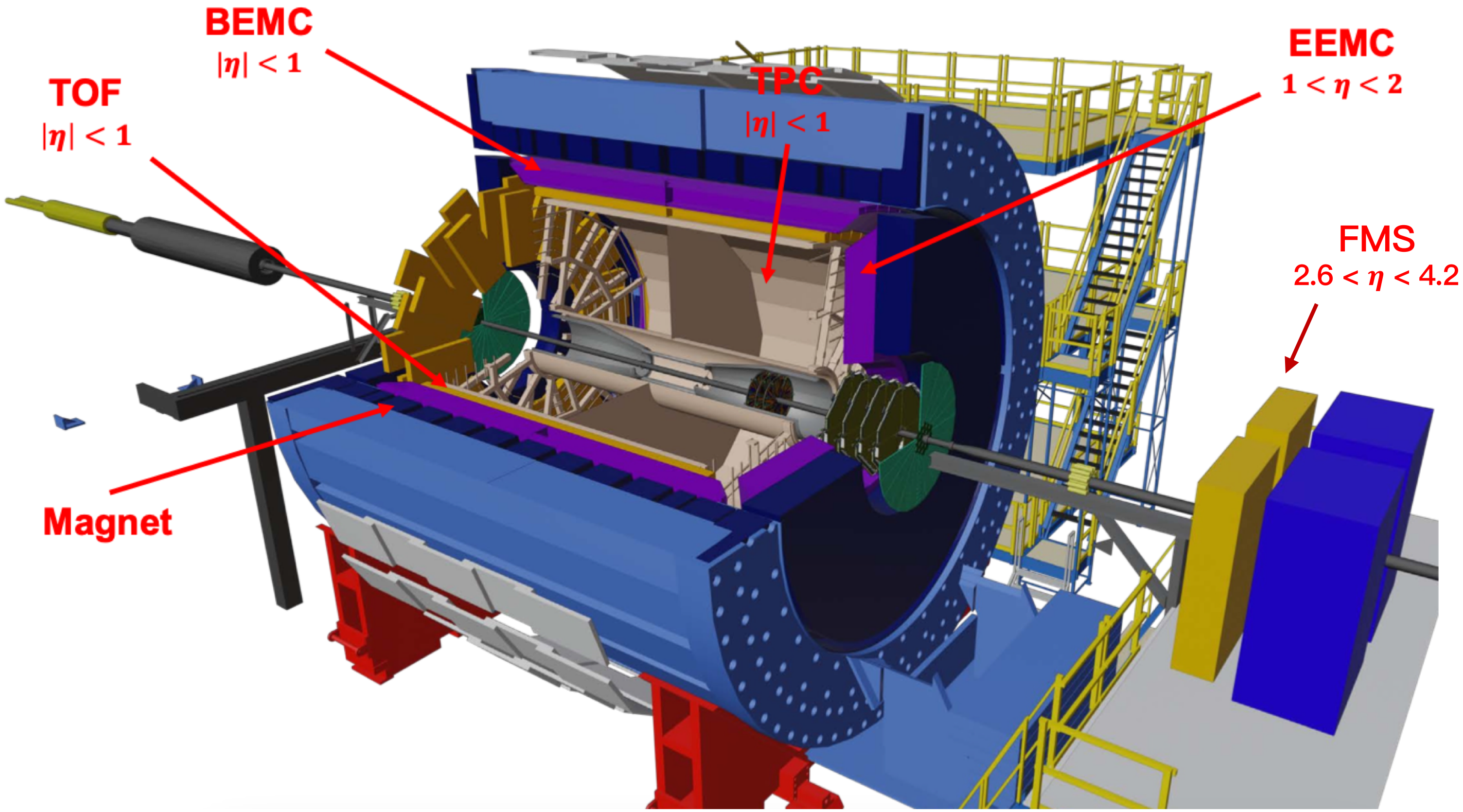
- Twist–3 mechanism (Efremov–Teryaev'82, Qiu–Sterman'91):
  - Collinear/twist–3 multi–parton correlation + fragmentation functions
  - Need one scale (Q or p_T), $Q, p_T >> \Lambda_{QCD}$
  - Consistent with TMD mechanism in the overlapping kinematics region

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 $\phi \in [0,2\pi]$
  - Reconstruction of photon, e, $\pi^0$and triggering

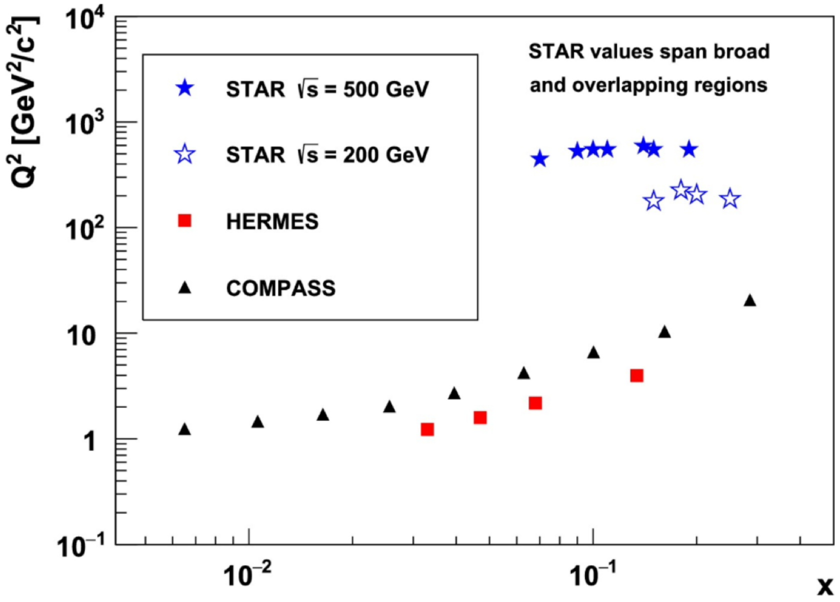
➢ Forward Meson Spectrometer (FMS)
  - $2.6 < \eta < 4.2$,$\phi \in [0,2\pi]$
  - Detect γ, π^0, η

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%

- 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

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

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

Angle Modulations of TSSA in pp Collisions

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

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

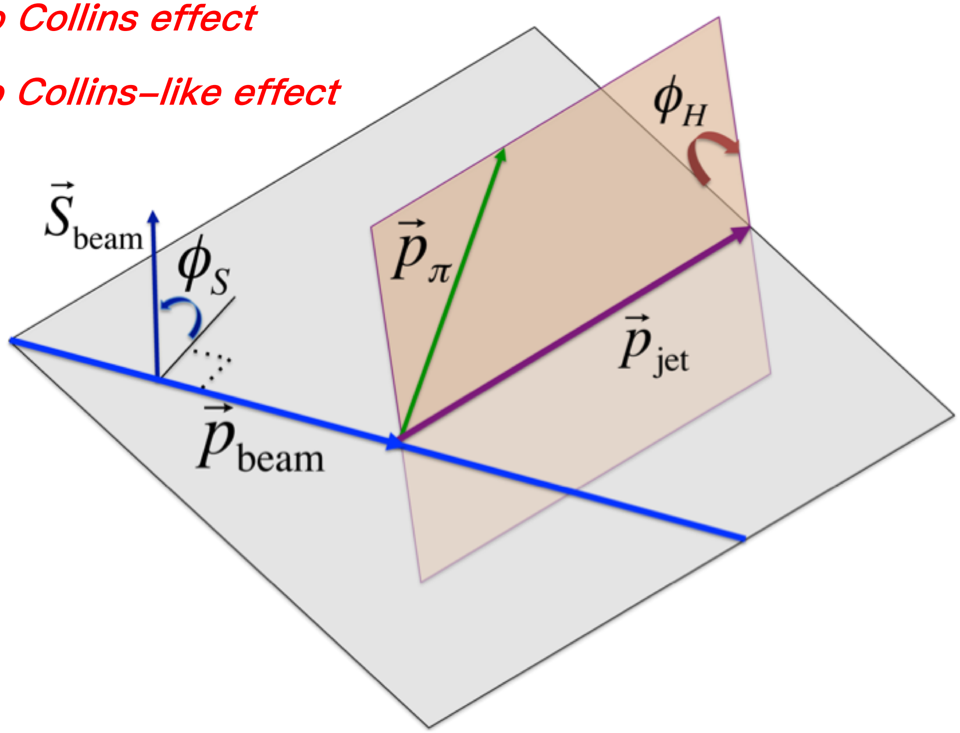
related to Sivers effect

related to Collins effect

related to Collins–like effect

U. D'Alesio, F. Murgia, and C. Pisano, Phys. Rev. D 83,034021 (2011)

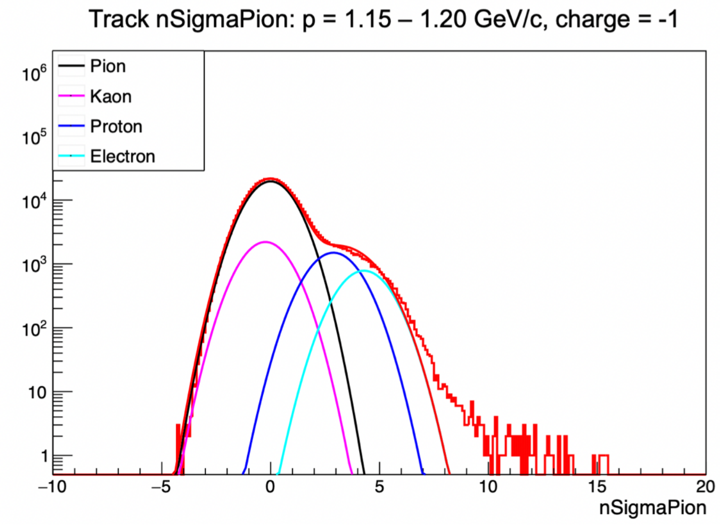
- ϕ_S: azimuthal angle between the proton transverse spin polarization vector and jet scattering plane.
- ϕ_H: azimuthal angle of pion relative to the jet scattering plane.

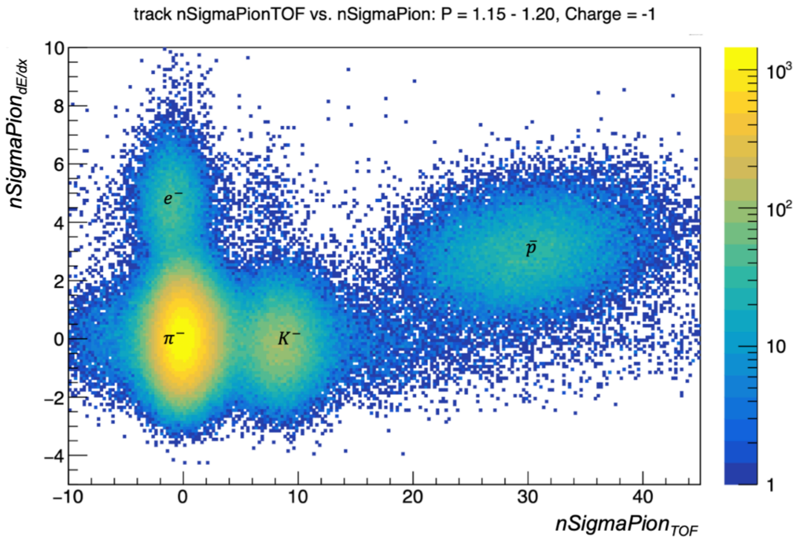


STAR, Phys. Rev. D 97, 032004 (2018)

Particle Identification

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





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

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

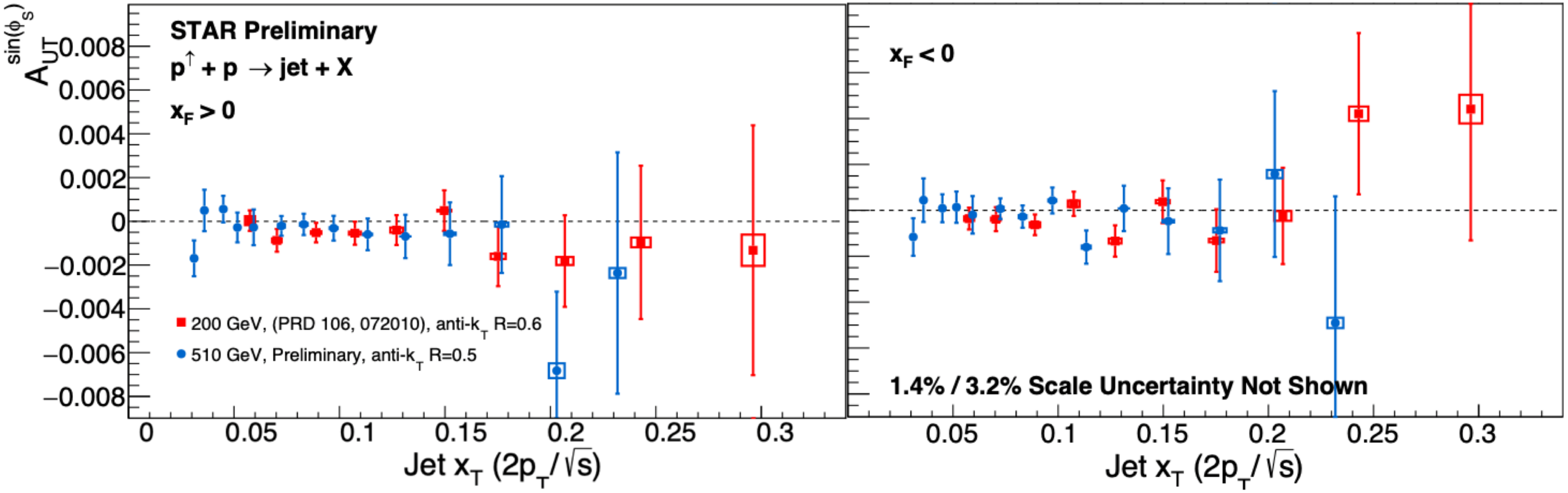
- Determine particle rich region

- 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.
- Extract the pure asymmetry for each particle rich region

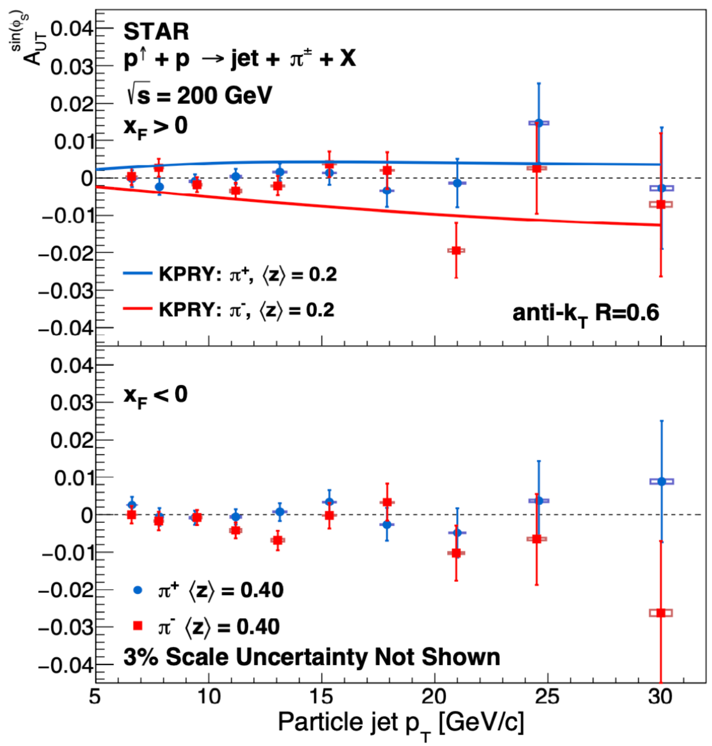
Sivers Asymmetry of Inclusive Jets at 200 GeV & 510 GeV

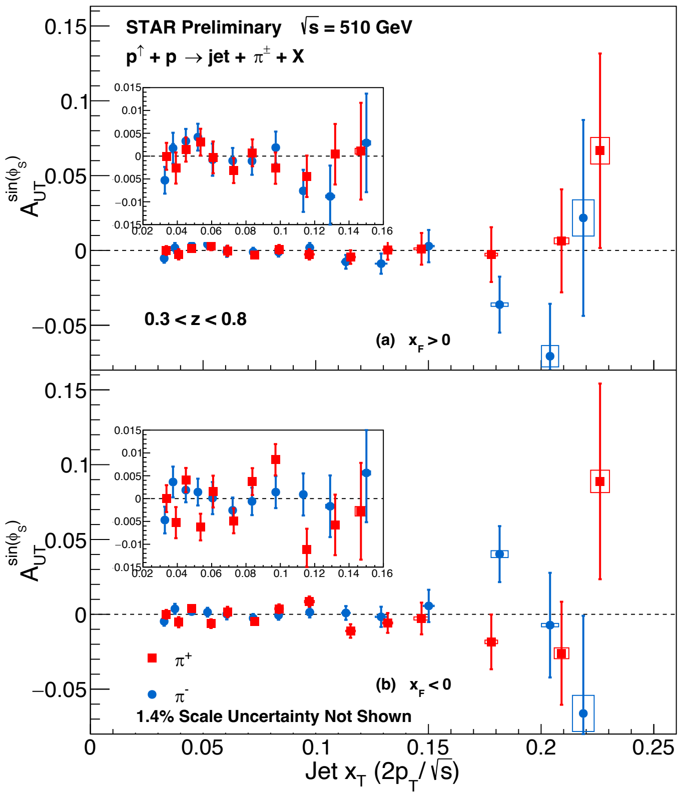


- Sensitive to twist–3 correlator associated with the gluon Sivers function
- High–precision measurements show that the inclusive jet asymmetry is very small.

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

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



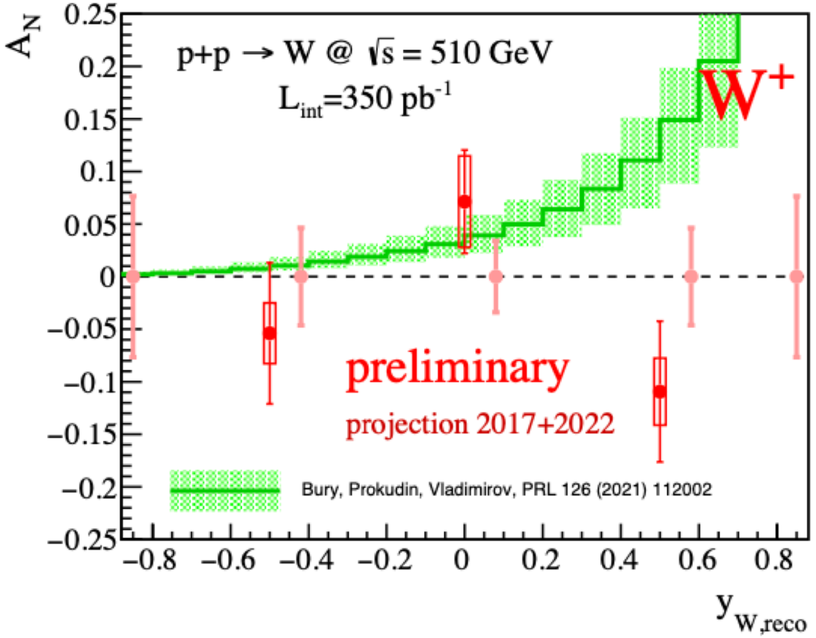


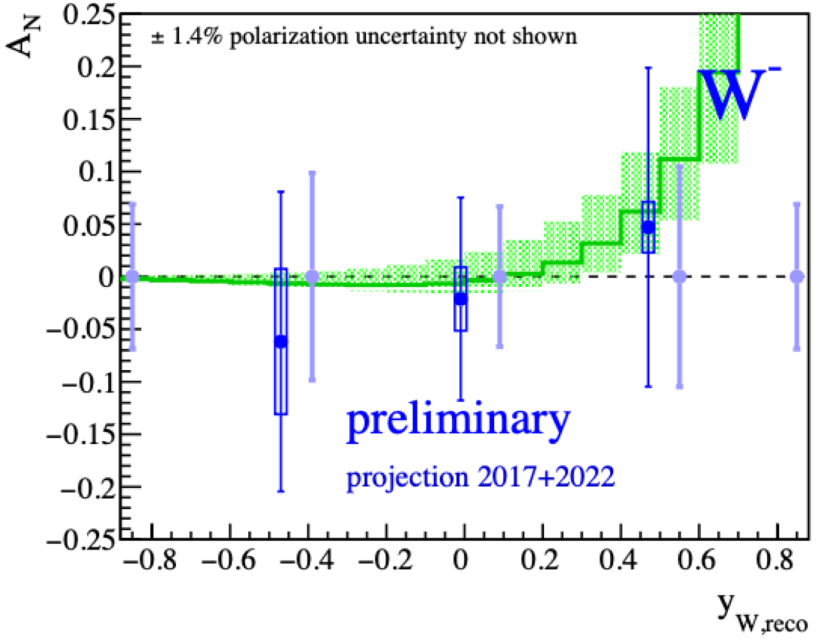
- Quark jet fractions are enhanced by tagging $\pi^{\pm}$
- The experimental measurements are comparable to the theoretical predictions.

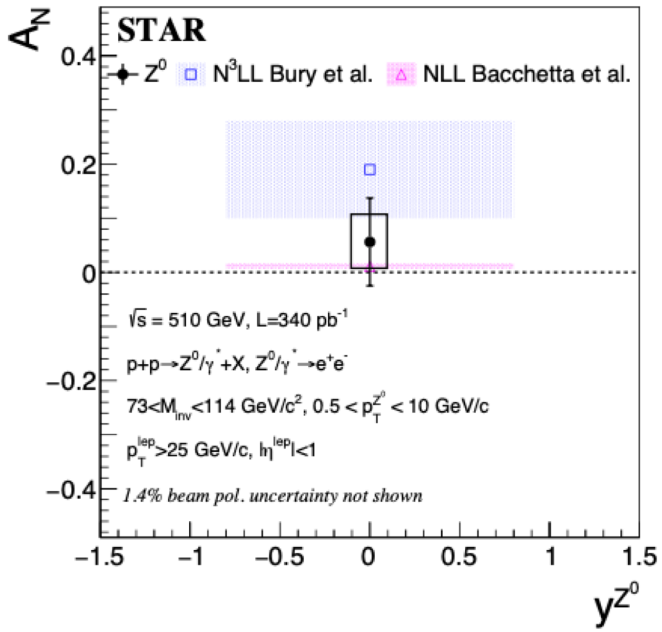
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017), 635–642

Sivers 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

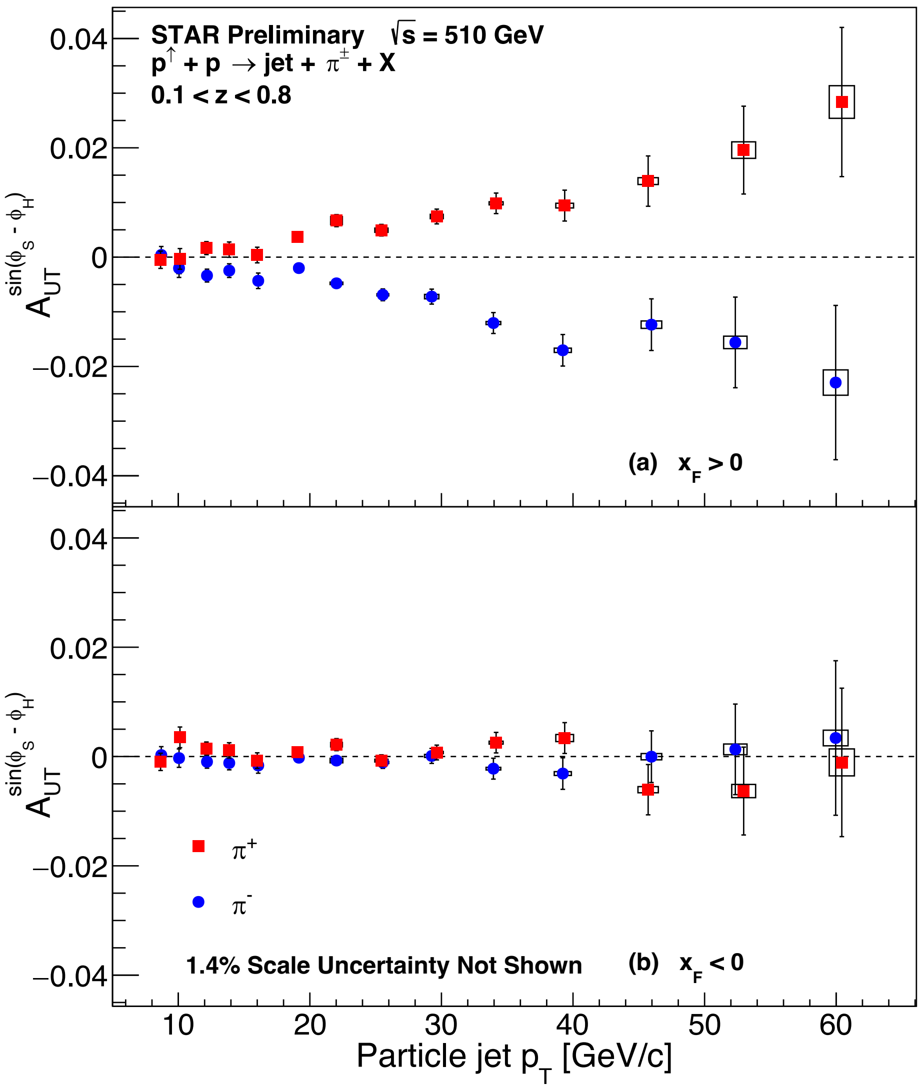
- Test sign change of Sivers function from SIDIS and Drell–Yan:

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

- 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 at 510/500 GeV

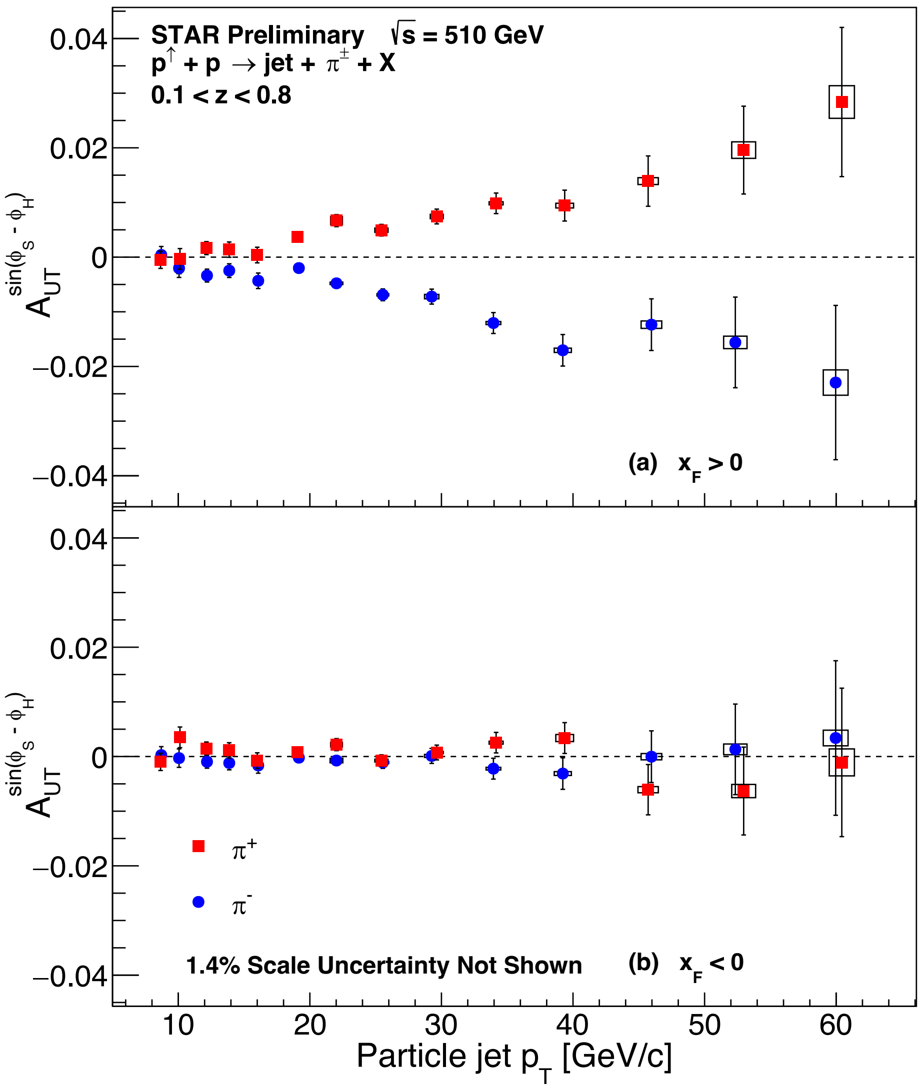
➢ Collins results as a function of jet p_T



- 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.

Collins Asymmetry at 510/500 GeV

➢ Collins results as a function of jet p_T



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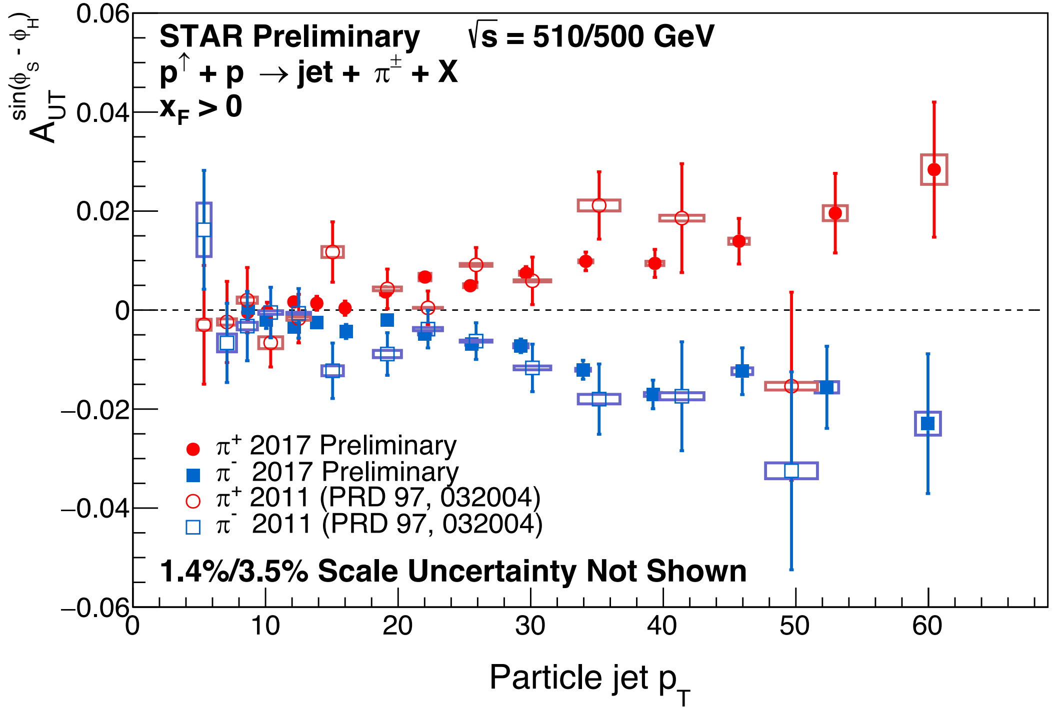
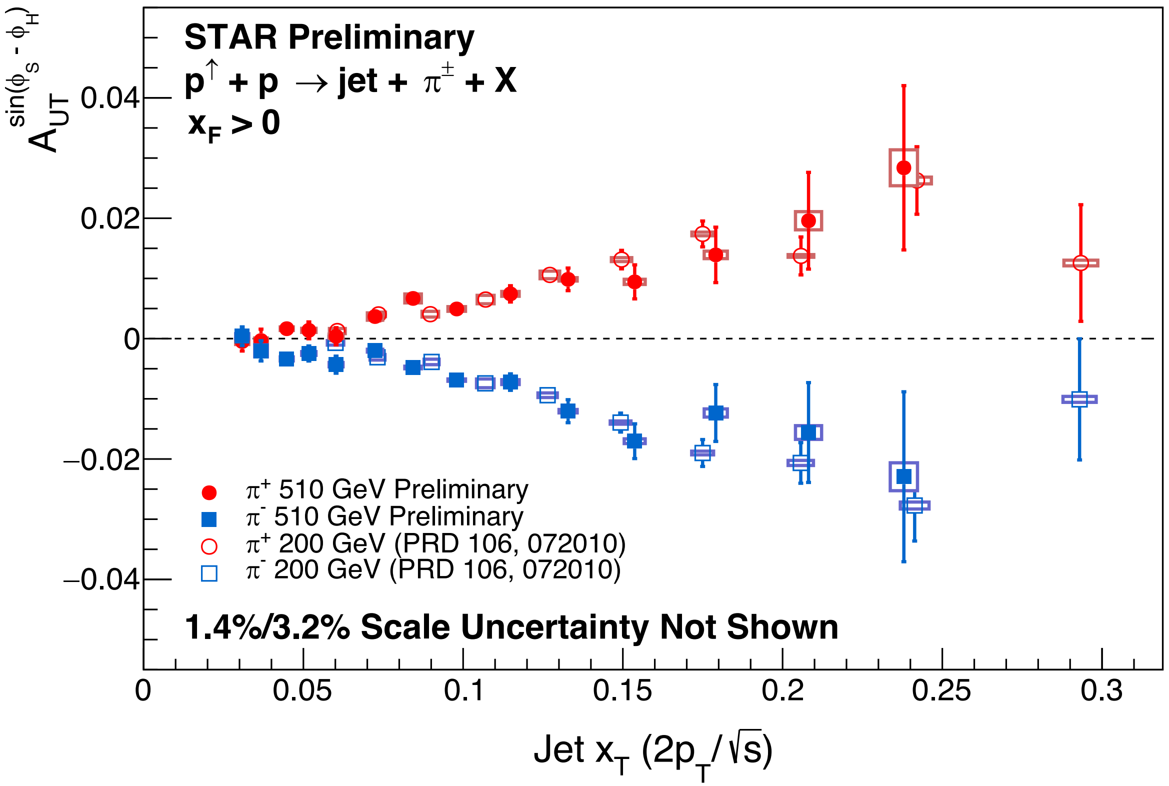


- New results are consistent with previous run11 data, but with 13 times more statistics

Collins Asymmetry at 510/200 GeV: Test TMD Evolution

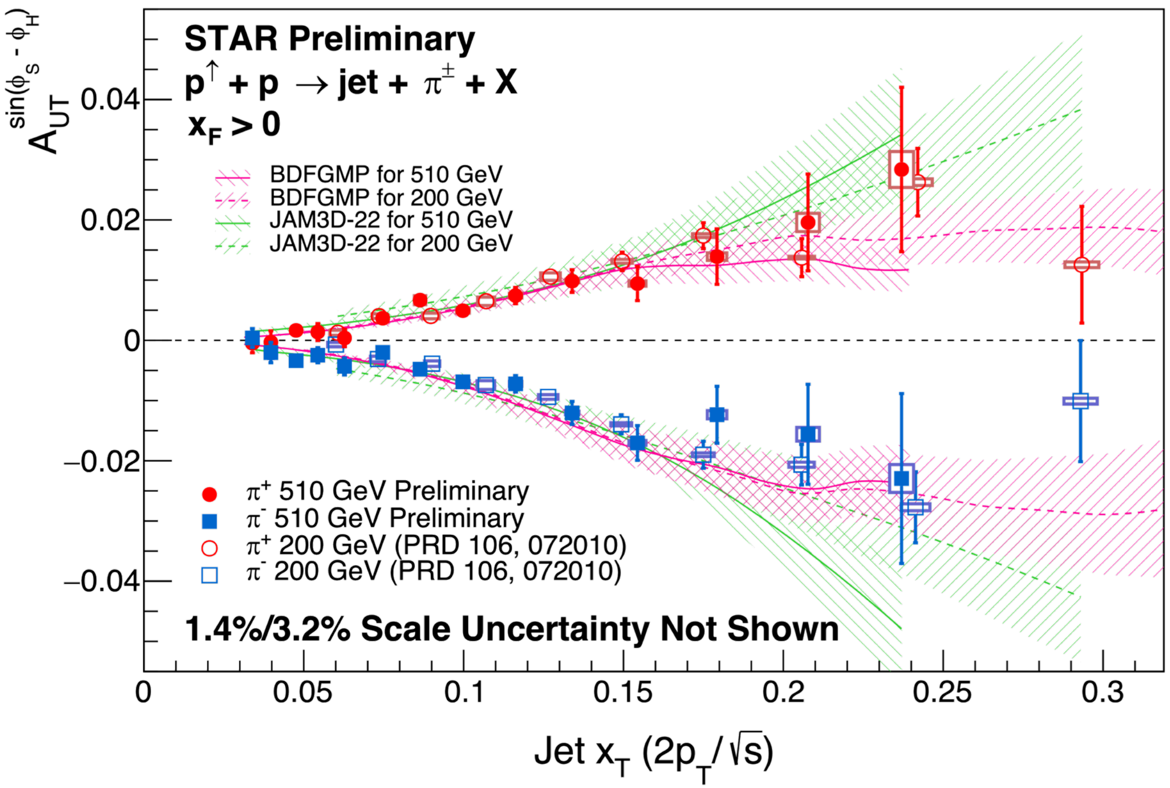
- Comparison of Collins asymmetry $vs.$ jet$-x_T$



- The high precision Collins results of 510 GeV and 200 GeV nicely align with jet x_T scale, giving almost no energy dependence
- At the same jet x_T , 200 GeV and 500 GeV results correspond to the same x in transversity distribution

Collins Asymmetry at 510/200 GeV: Test TMD Evolution

- Comparison of Collins asymmetry $vs.$ jet$-x_T$



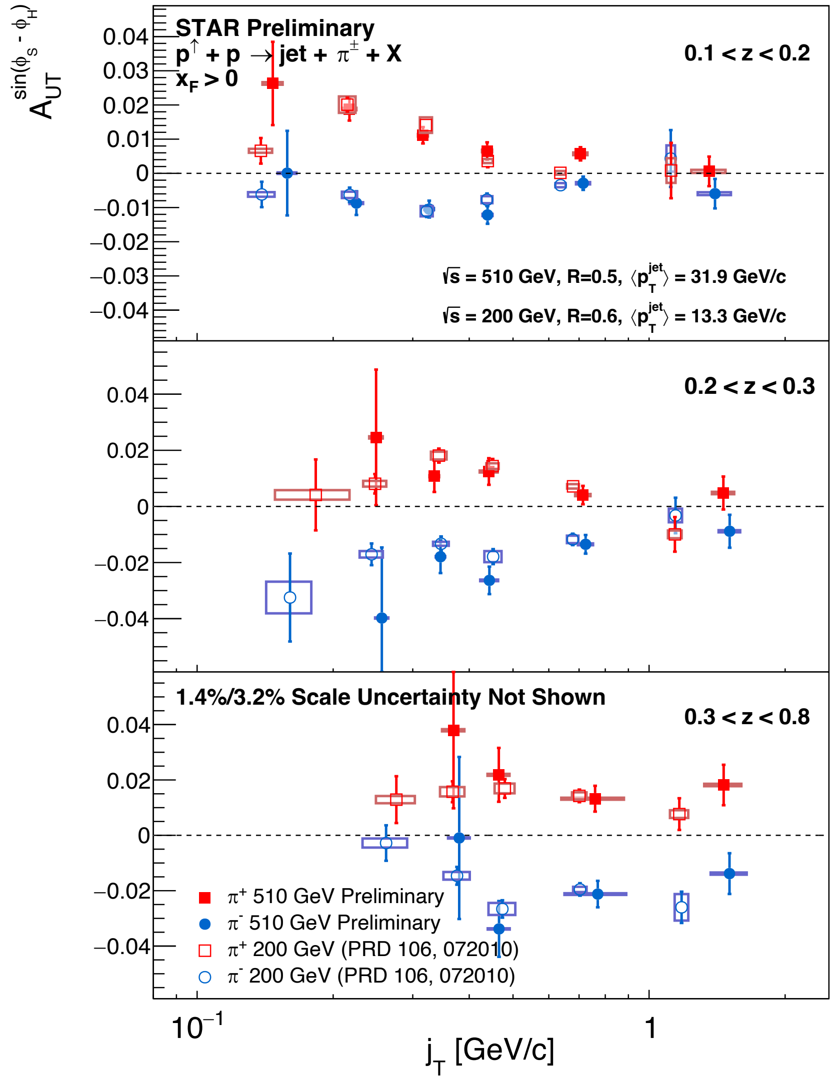
L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato, [JAM], Phys. Rev. D 106 (2022), 034014

M. Boglione, U. D'Alesio, C. Flore, J. O. Gonzalez–Hernandez, F. Murgia and A. Prokudin, Phys. Lett. B 854 (2024), 138712

- Model calculations without TMD evolution are generally consistent with measurements

Collins Asymmetry at 510/200 GeV: Test TMD Evolution

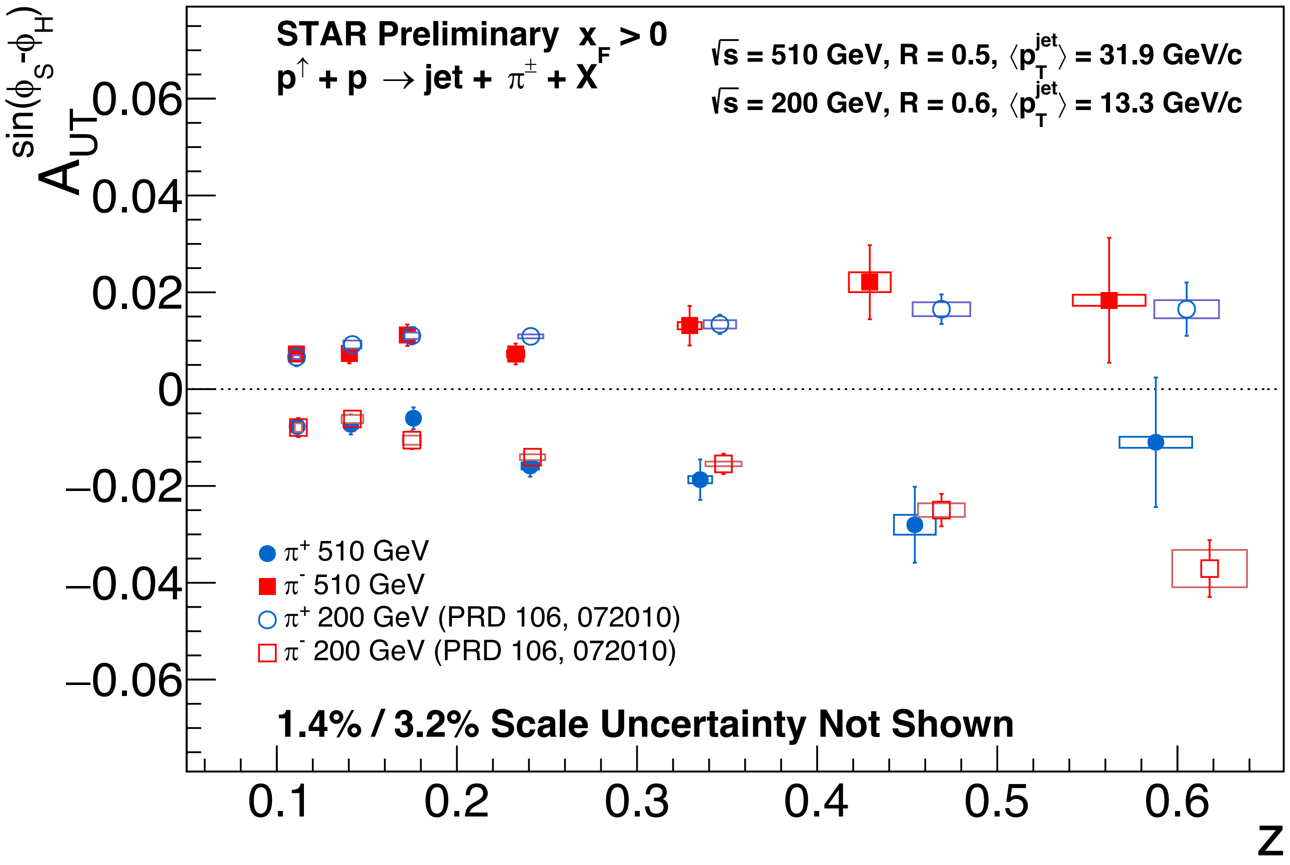
➢ Comparison of Collins asymmetry $vs.$ hadron j_T



- Similar jet x_T for 200 GeV and 510 GeV, allowing for comparisons of measurements at similar parton momentum fraction regions
- Again, Collins results of two energies align with pion j_T scale, no significant energy dependence observed

j_T : pion's transverse momentum relative to jet axis

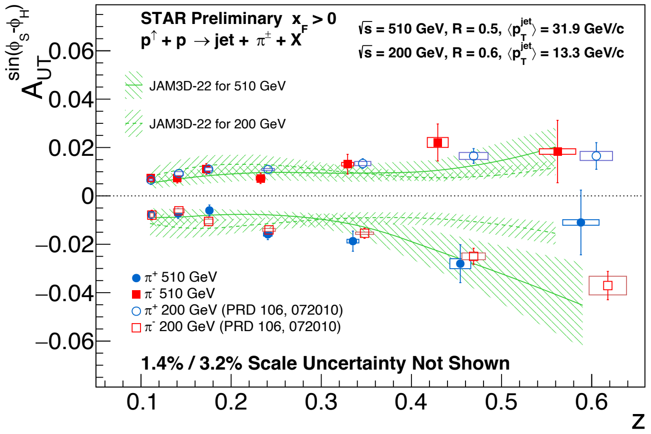
Collins Asymmetry at 510/200 GeV: Test TMD Evolution

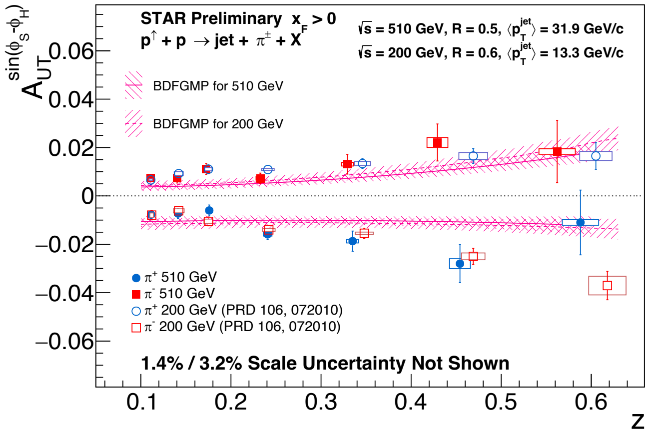


- The Collins asymmetries as a function of z also show good consistency

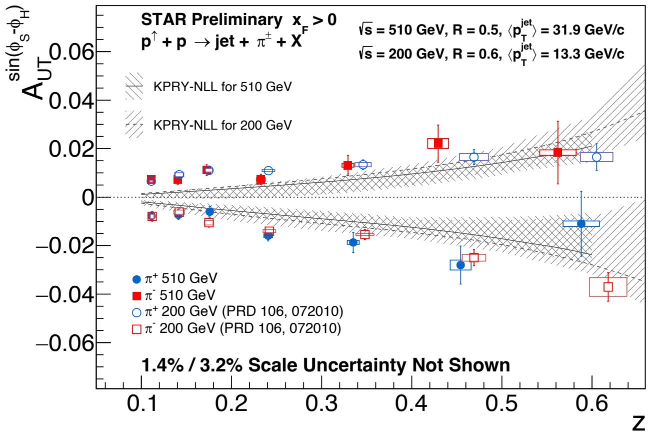
Theoretical Calculations with/without TMD Evolution

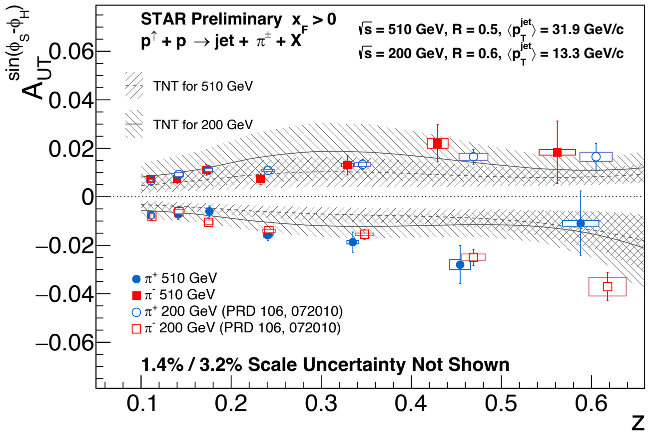
Without TMD evolution:





With TMD evolution:



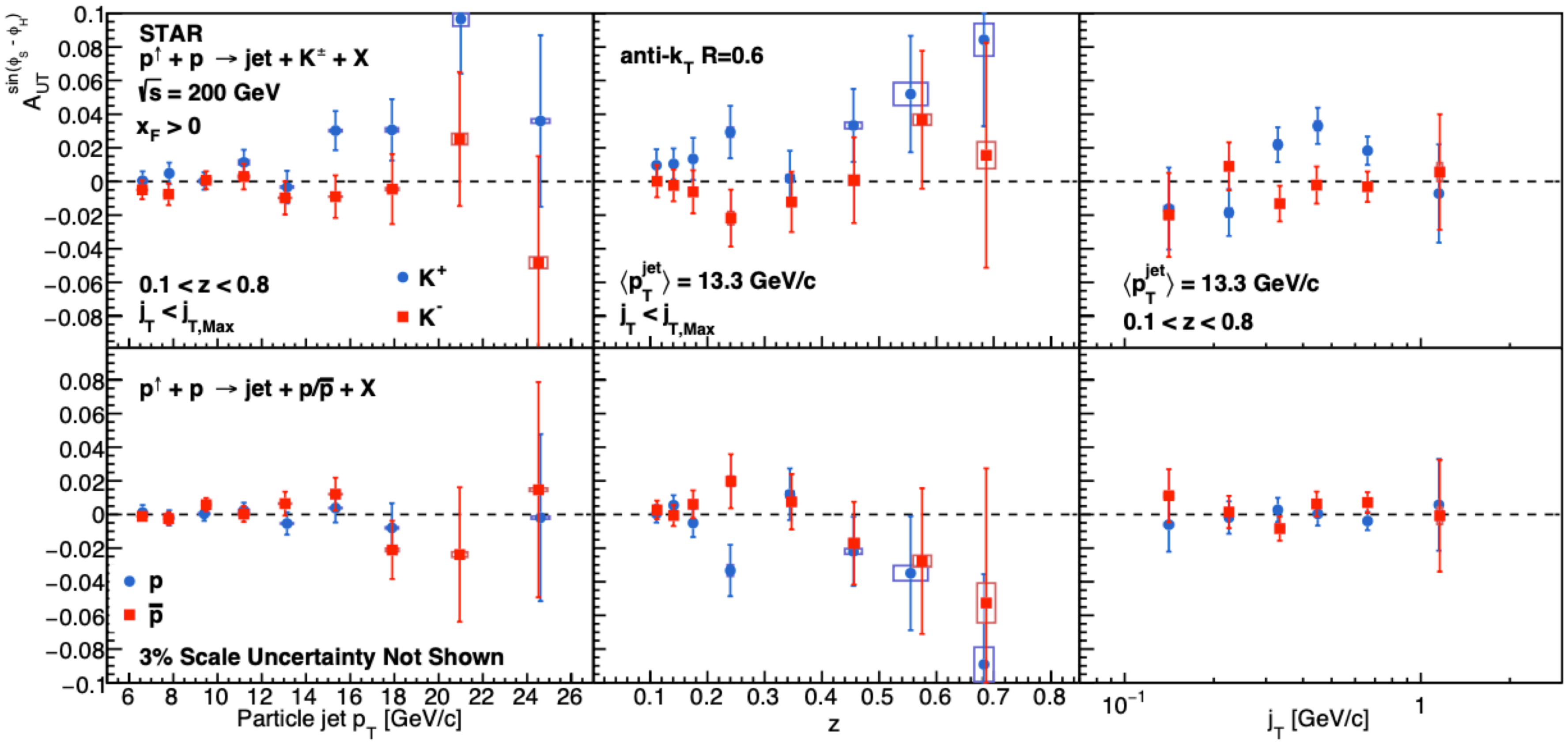


L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato, [JAM], Phys. Rev. D 106 (2022), 034014
M. Boglione, U. D'Alesio, C. Flore, J. O. Gonzalez-Hernandez, F. Murgia and A. Prokudin, Phys. Lett. B 854 (2024), 138712
Z. B. Kang, A. Prokudin, F. Ringer and F. Yuan, Phys. Lett. B 774 (2017), 635–642
C. Zeng, H. Dong, T. Liue, P. Sun and Y. Zhao, arXiv:2412.18324

- All models are consistent with our data in general, with weak energy dependence

Collins Asymmetry of K & p

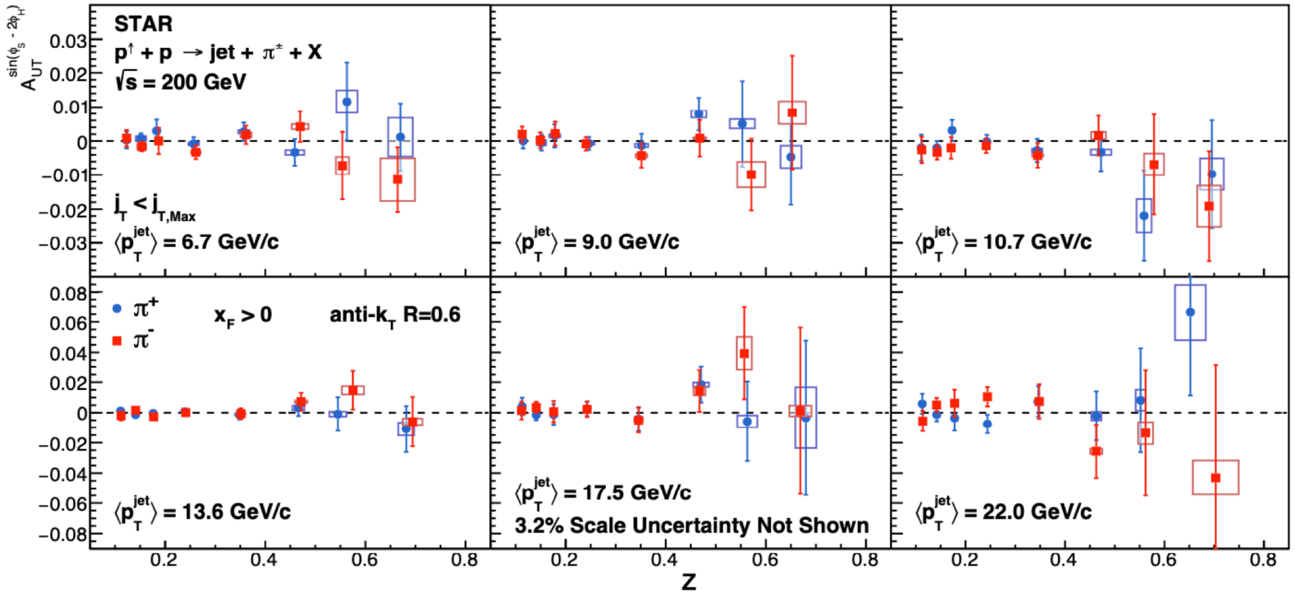
STAR, Phys. Rev. D 106, 072010 (2022)



- K^+ has a contribution from favored fragmentation of u quarks, similar in magnitude to those for π^+
- K^- can only come from unfavored fragmentation, are consistent with zero within uncertainties
- Collins asymmetry of proton is consistent zero

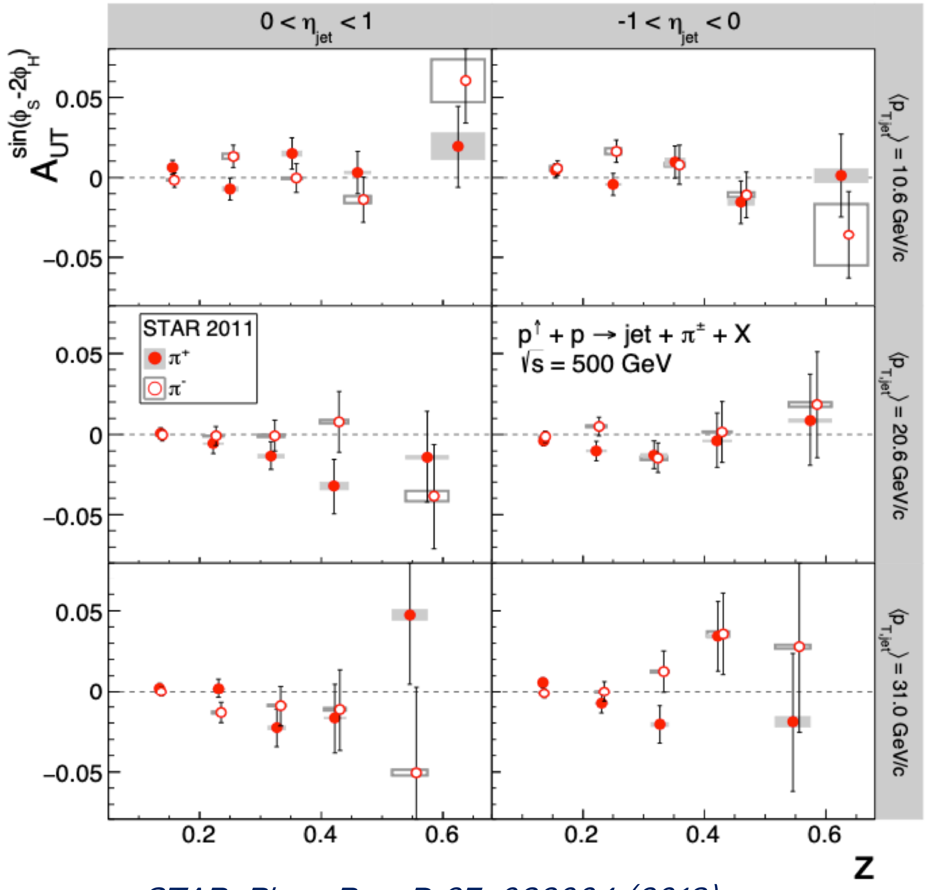
Collins–like Asymmetry of $\pi^{\pm}$

- Results at 200GeV, as a function of z



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

- Results at 500GeV, as a function of z

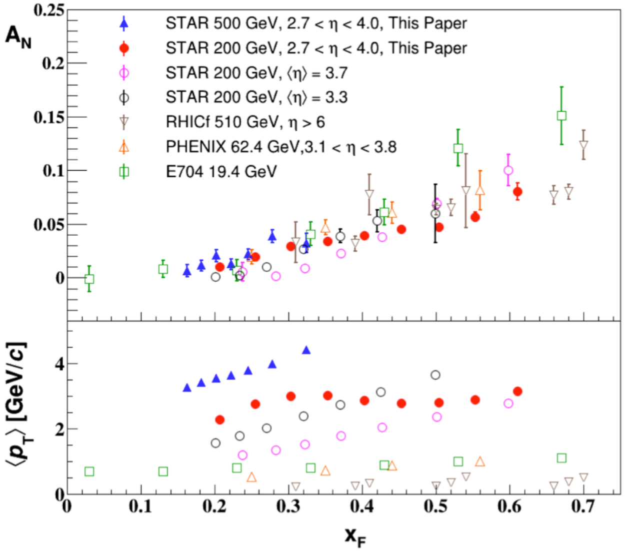


STAR, Phys. Rev. D 97, 032004 (2018),

- Sensitive to linearly polarized gluons inside a transversely polarized proton
- No significant asymmetry for either collision energy

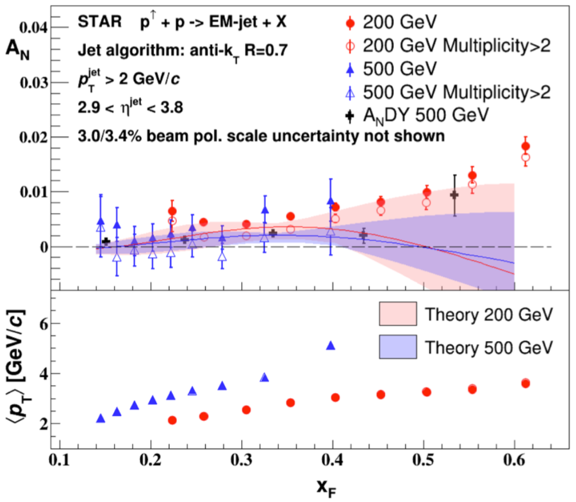
π^0 Asymmetry in Forward Region

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



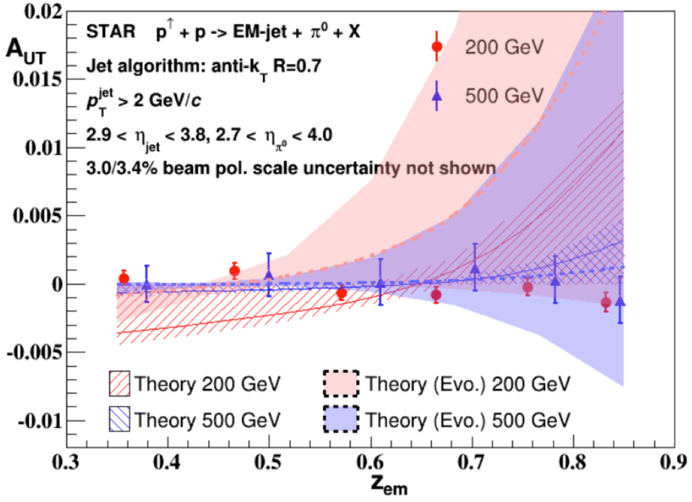
- Sizeable A_N for forward π^0

➢ Sivers effect contribution

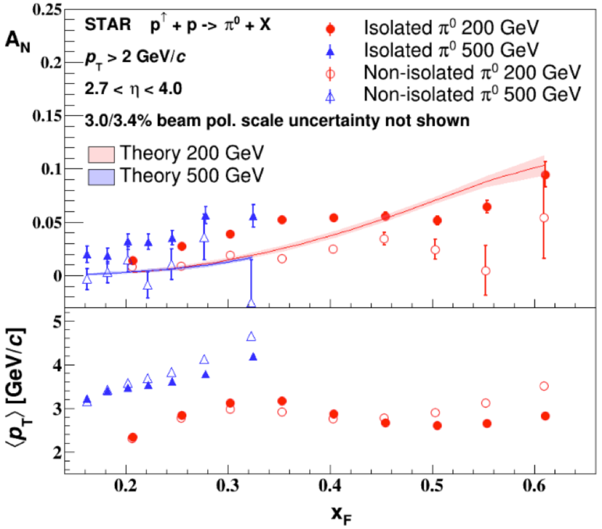


- Magnitude of inclusive EM jet asymmetry is limited

➢ Collins effect contribution



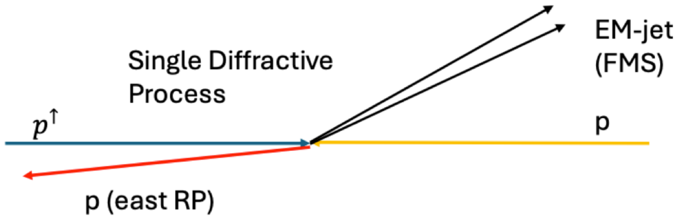
- Collins asymmetry of π^0 inside EM jet is consistent with zero



- 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**

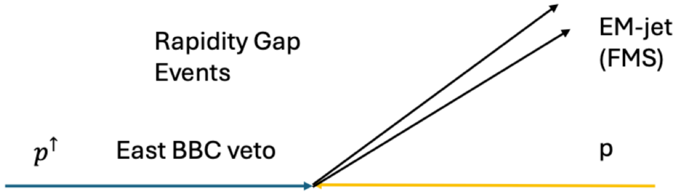
Diffractive Electromagnetic Jets Asymmetry

➢ Single diffractive process

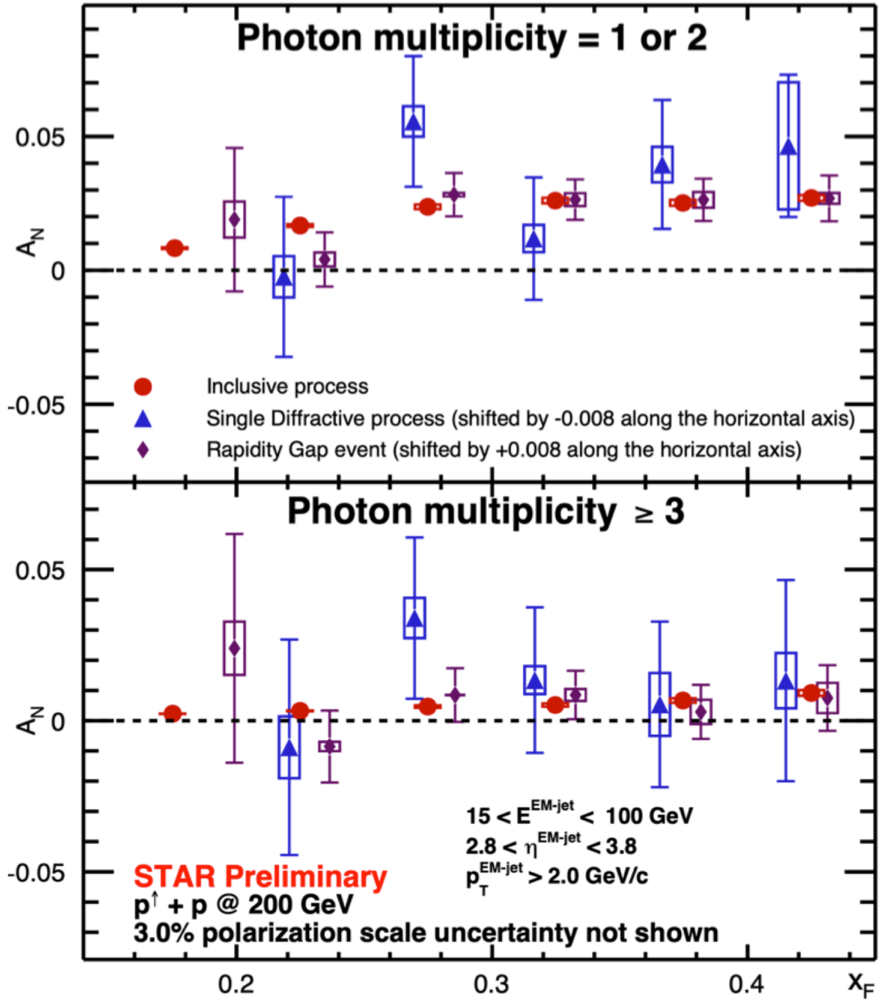


- $p^{\uparrow} + p \rightarrow p +$ EM–jet $+ X$
- 1 east roman pots (RP) track , no requirement on west RP
- 1 EM–jet per event is allowed

➢ Rapidity gap event



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

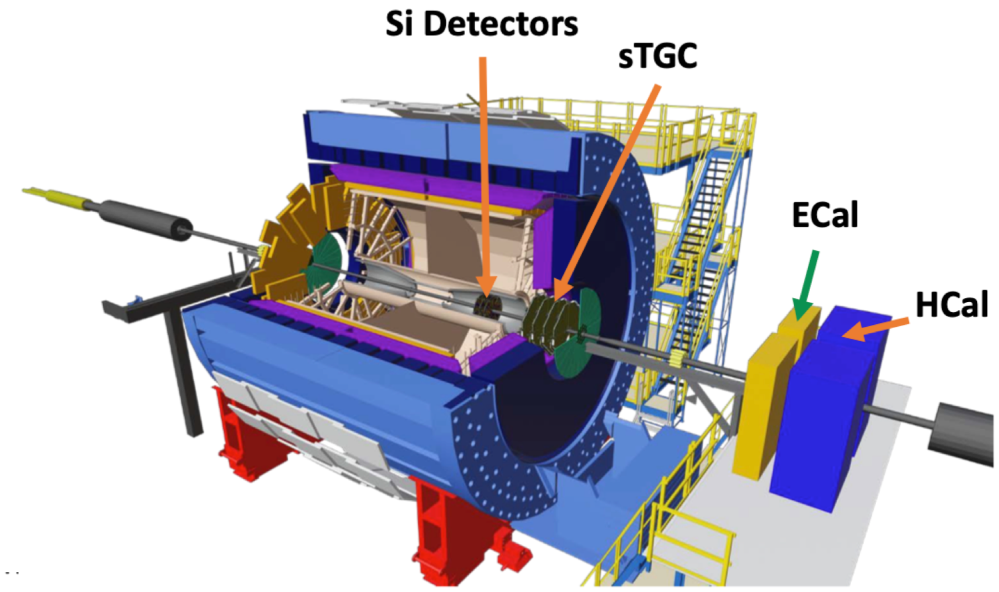


- The single diffractive and rapidity gap EM–jet A_N are consistent within uncertainty
- The observed inclusive π^0 asymmetry is unlikely to originate from diffractive processes

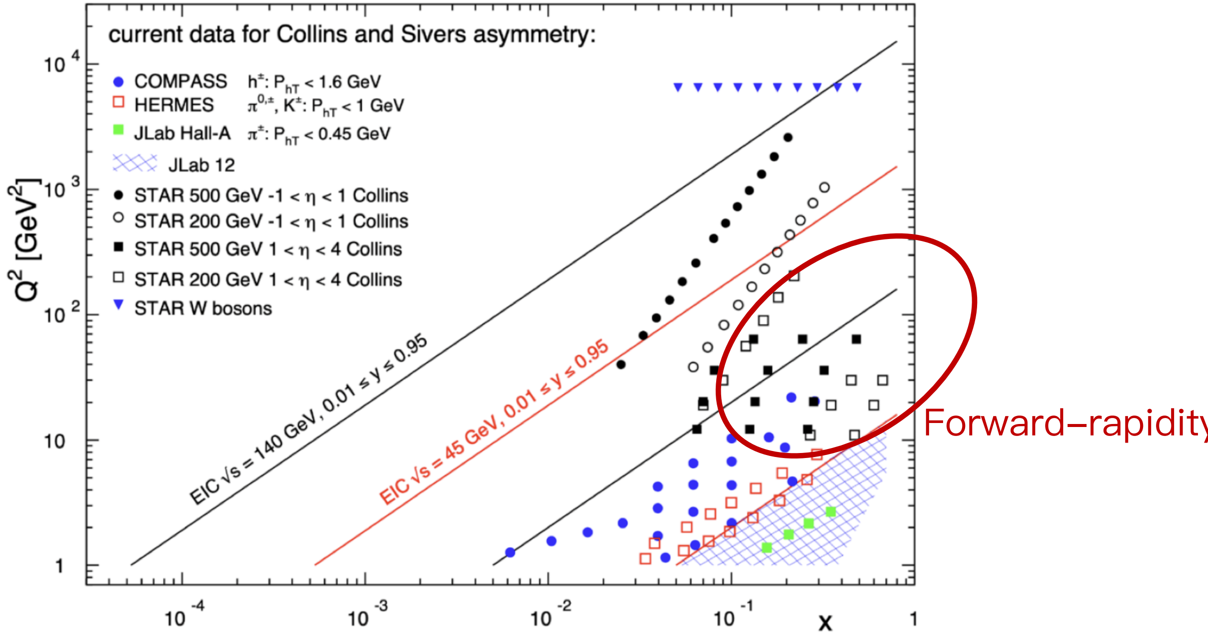
Outlook

- 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%

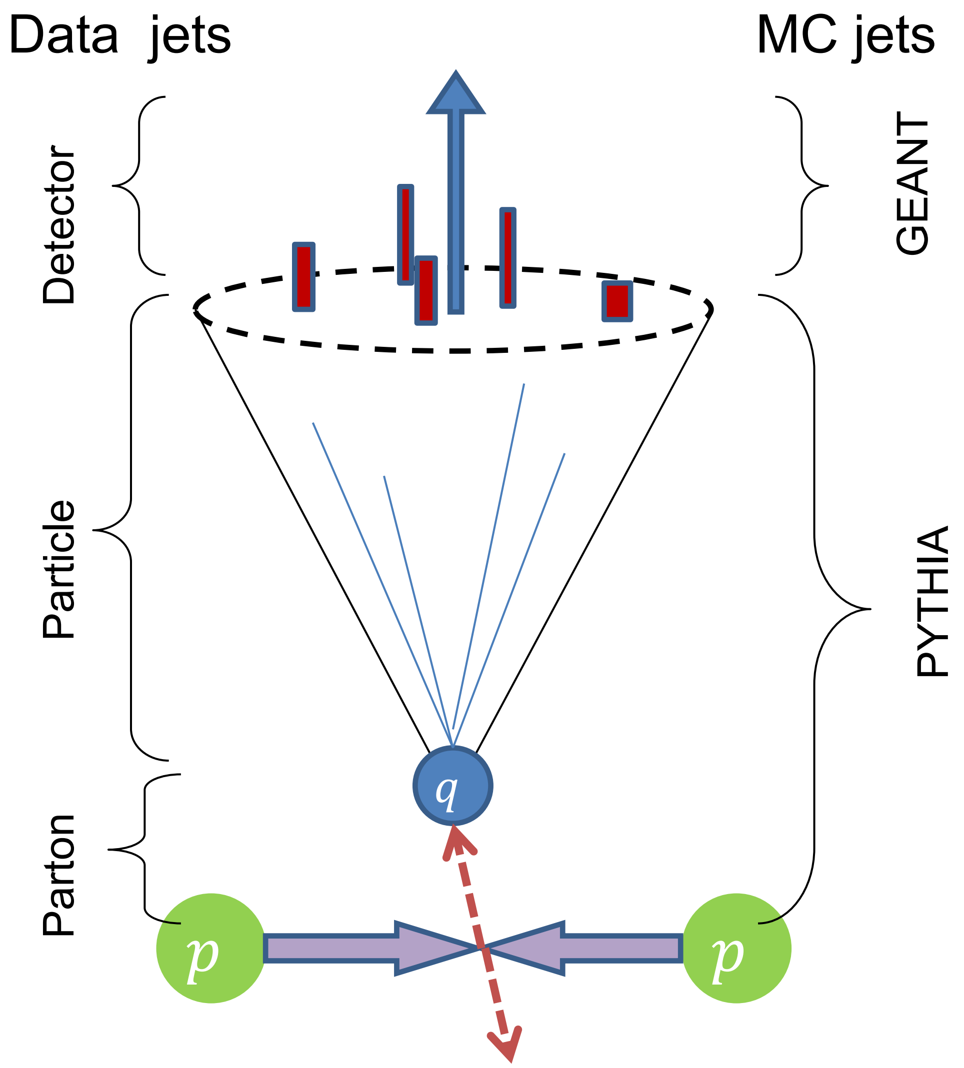
Summary

- The high-precision Collins asymmetries for π^+ and π^- results at 510 GeV, in good agreement with 200 GeV data, indicating a very weak energy dependence of the Collins effect
- No significant Sivers asymmetry or Collins-like asymmetry observed in pp collision at mid-rapidity
- W/Z boson asymmetries can provide important input to extraction of the Sivers function
- These measurements, together with pp data after STAR forward upgrade, will provide valuable insights into the three-dimensional structure of the proton

Thank you for the attention!

Back up

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

Extraction of Transverse Single-Spin Asymmetries

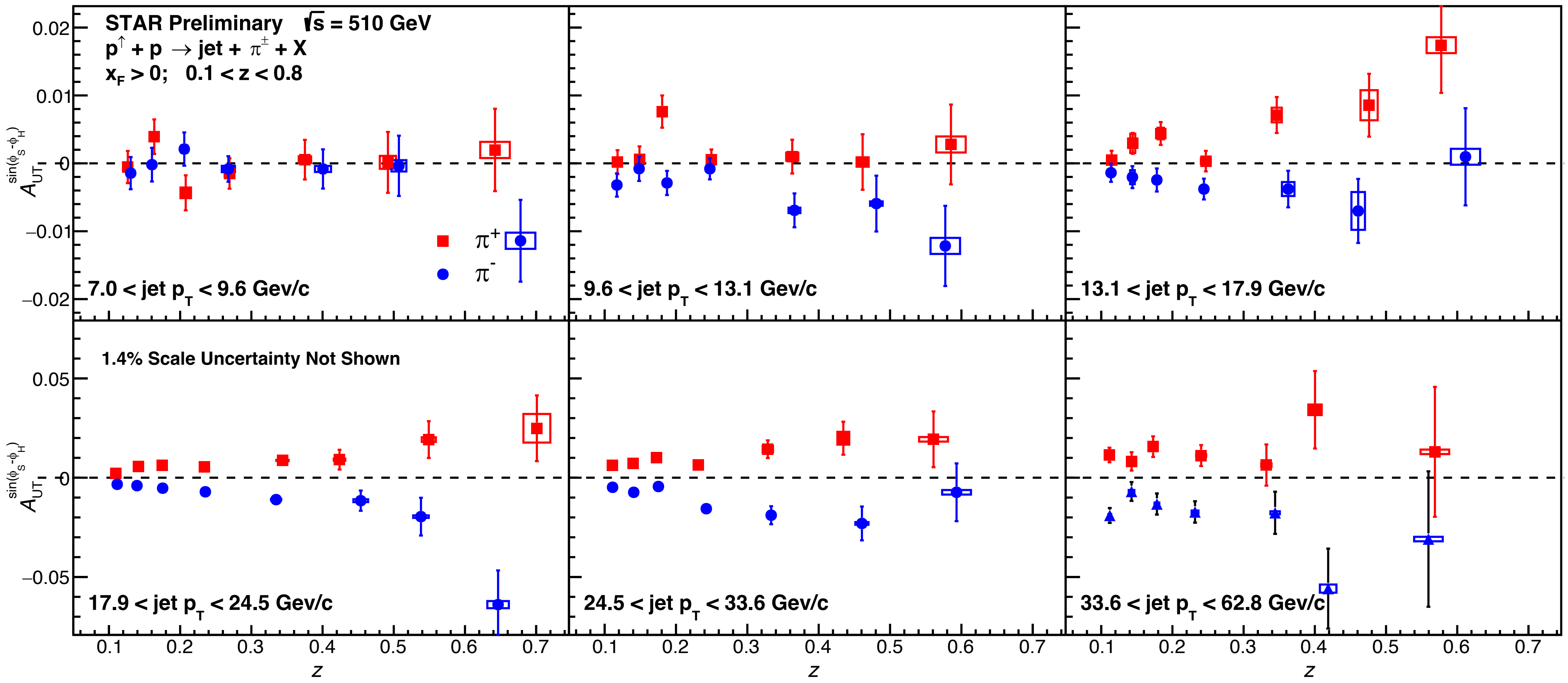
- Cross-ratio method to extract the asymmetries of different modulations.

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

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

Collins Asymmetry from STAR 2017 Data

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

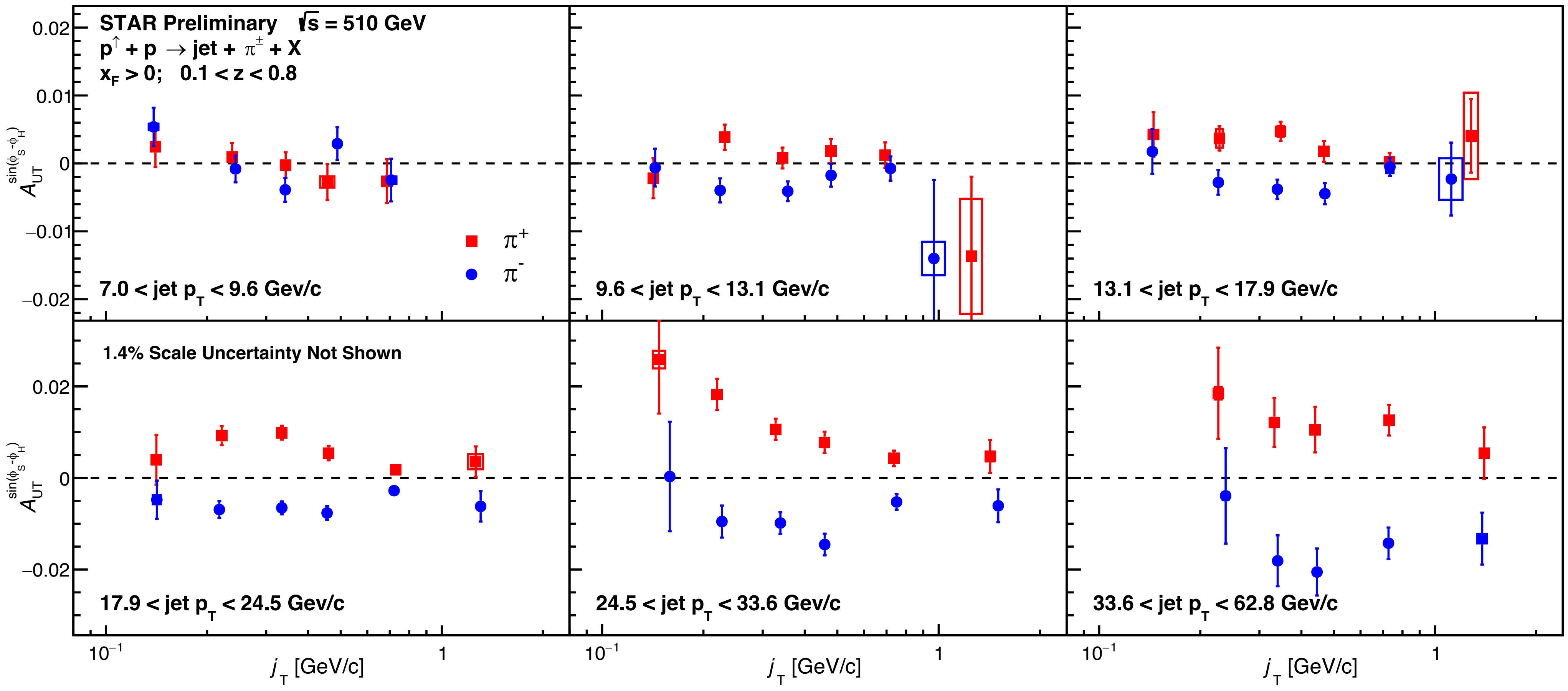


z : the pion's longitudinal momentum fraction in the jet

- 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