STAR Results on Transversity and TMD-Related Observables

Bassam Aboona, on behalf of the STAR Collaboration
(he/him/his)
bem4r@physics.tamu.edu

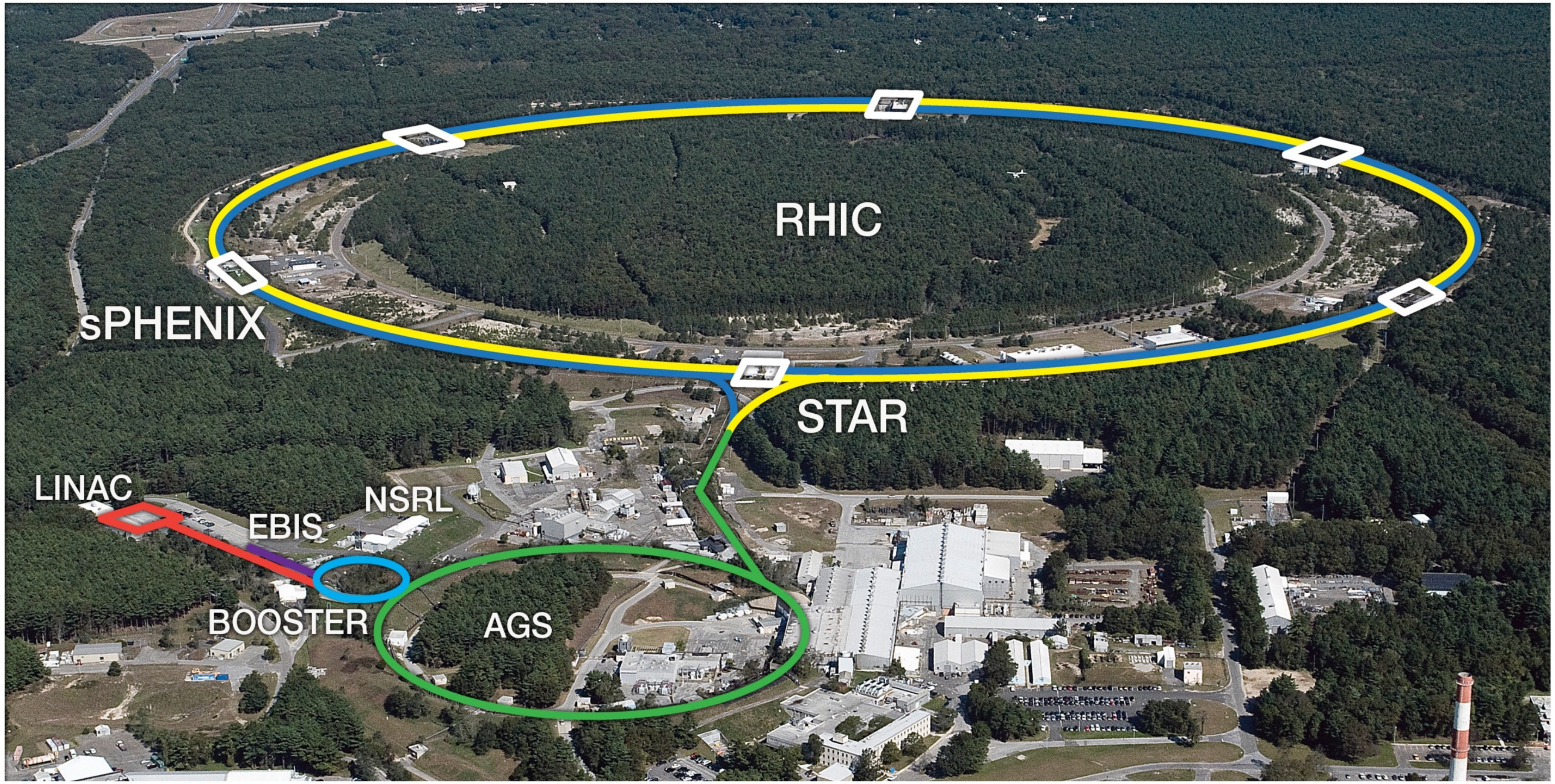
June 3rd -7th, 2024

Supported in part by:

Outline

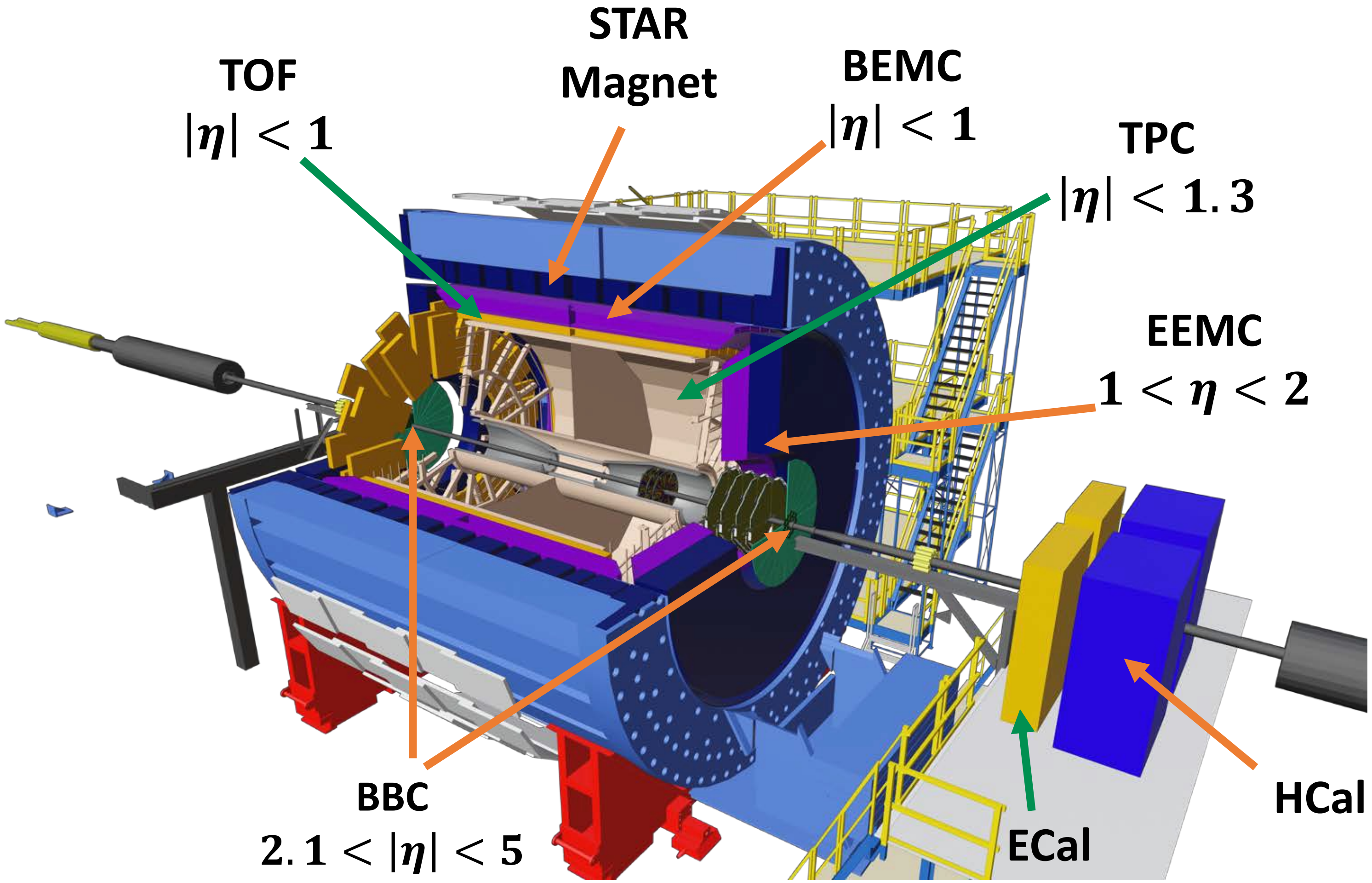
- Introduction
- Sivers Effect
- Transversity and the Collins Effect
- Selected Future Work
- Summary

RHIC: Relativistic Heavy Ion Collider

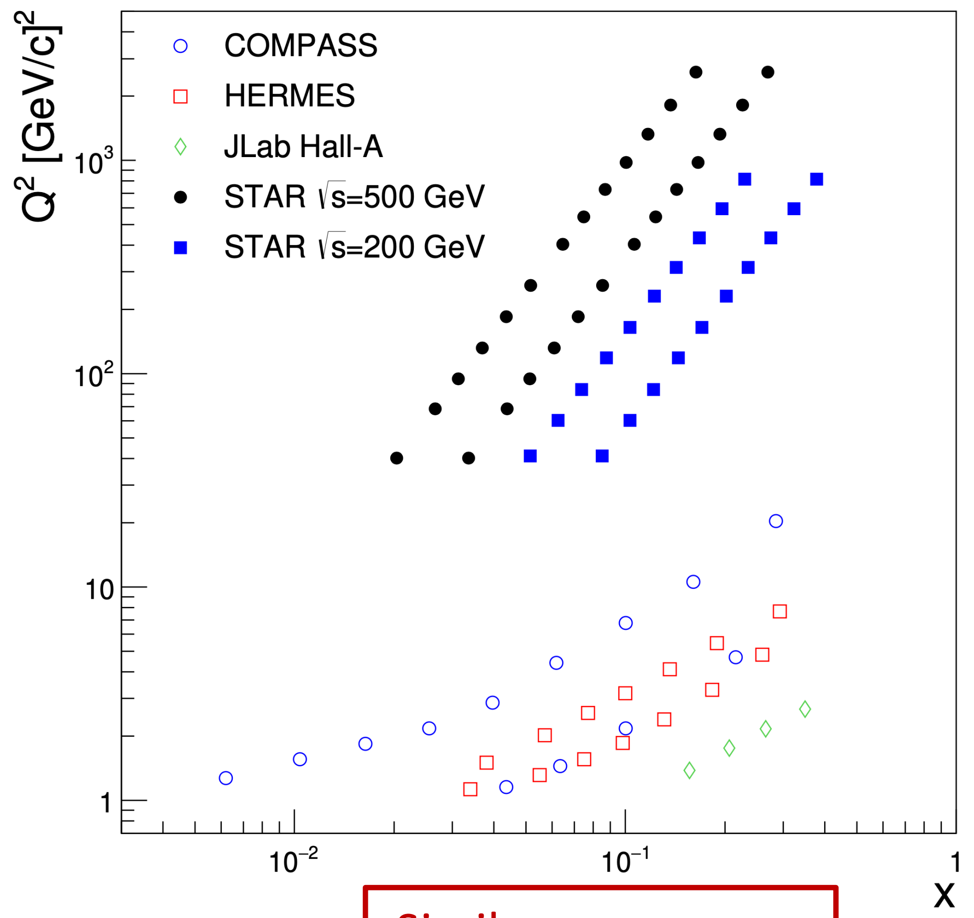


- The only machine in the world capable of colliding high-energy beams of polarized protons
- The beams travel in opposite directions around RHIC's 3.86 km two-lane racetrack
- Offers a wide range of center-of-mass energies (up to 510 GeV)

STAR: Solenoidal Tracker At RHIC



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



- Roman Pots (RP) at 15 meters from the interaction point
- FMS used to be where the current ECal and HCal are and covered $2.6 < \eta < 4.2$

Similar x coverage, but at higher Q^2 when compared to SIDIS

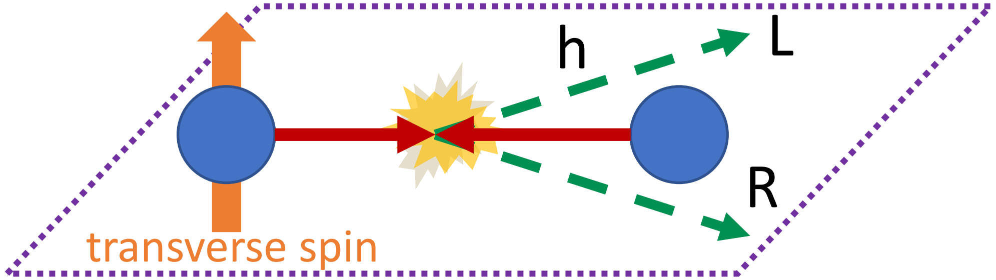
Transverse Single-Spin Asymmetries (TSSA's) - A_N

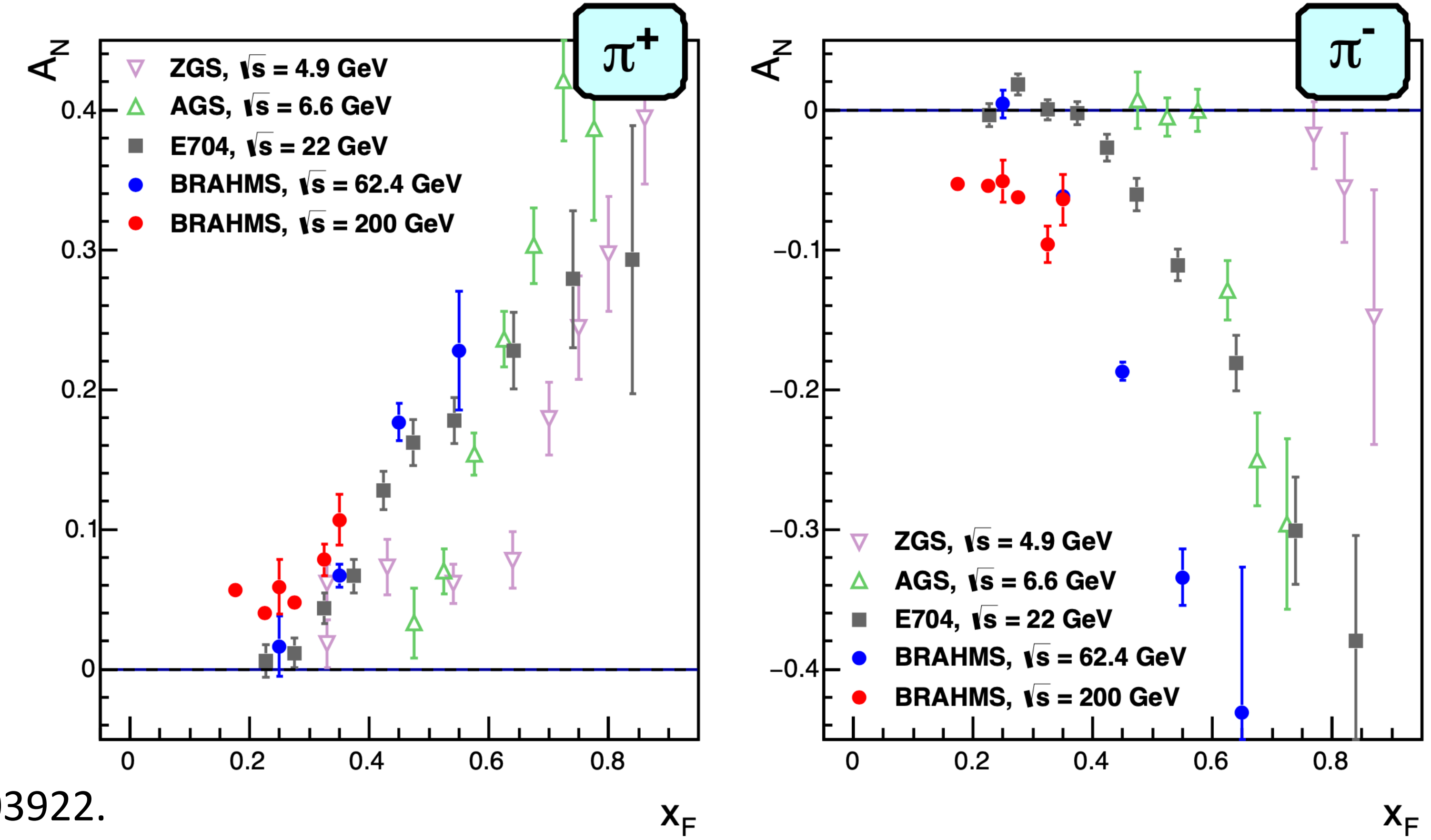
- Since the 1970's, surprisingly, large TSSA's have been observed at forward rapidities in $p^{\uparrow} + p$ collisions

- Perturbative Quantum Chromodynamics (pQCD) predicts very small values for A_N

- Twist-3 and transverse momentum dependent (TMD) theoretical frameworks have been developed to describe this observed large TSSA

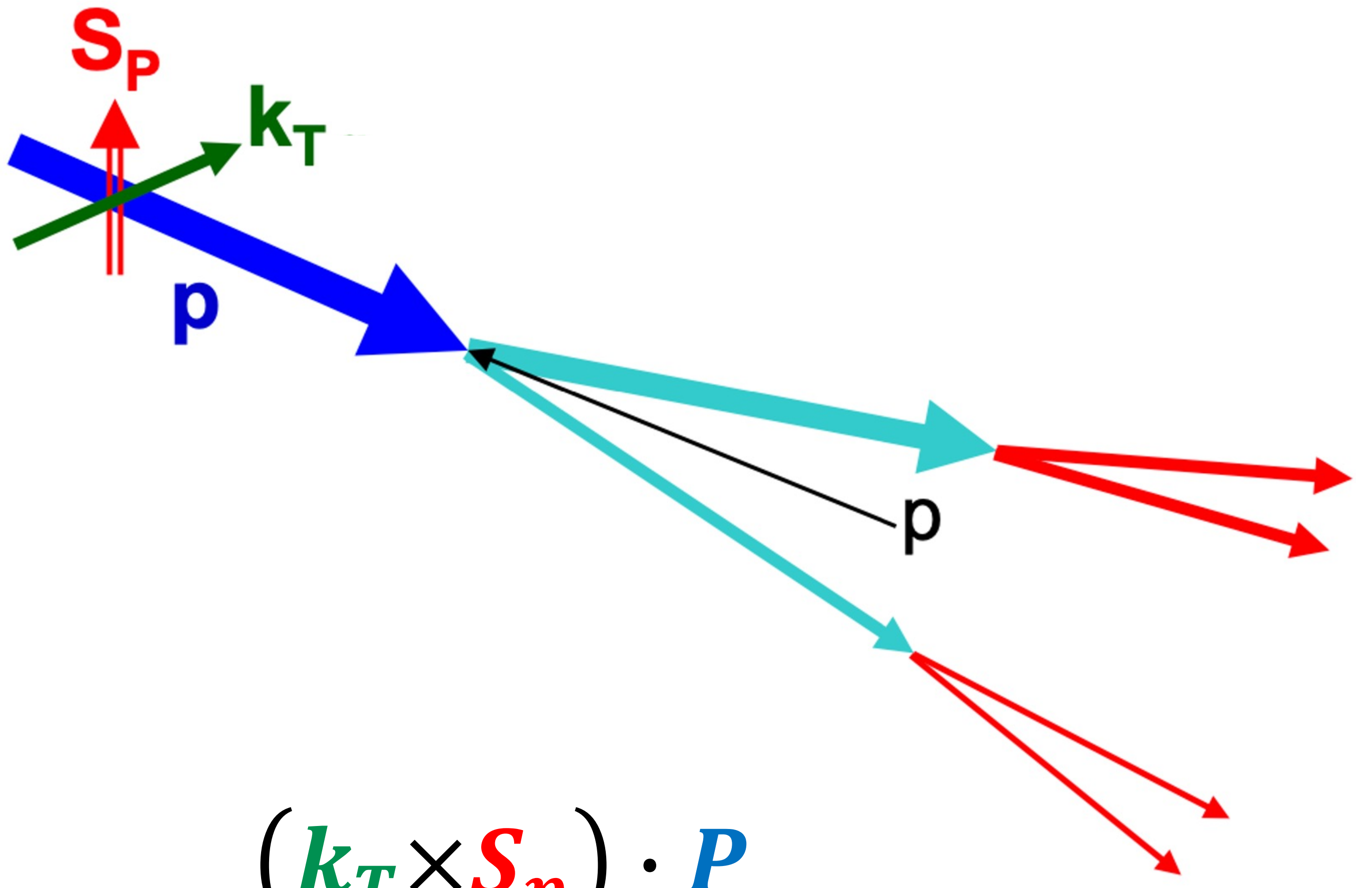
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$





Plot reference: Elke Aschenauer et al., arXiv:1602.03922.

Sivers Effect: A Mechanism for A_N



$$\left(\boldsymbol{k_T} \times \boldsymbol{S_p}\right) \cdot \boldsymbol{P}$$

- $\boldsymbol{k_T}$: parton transverse momentum
- $\boldsymbol{S_p}$: proton spin
- $\boldsymbol{P}$: proton momentum

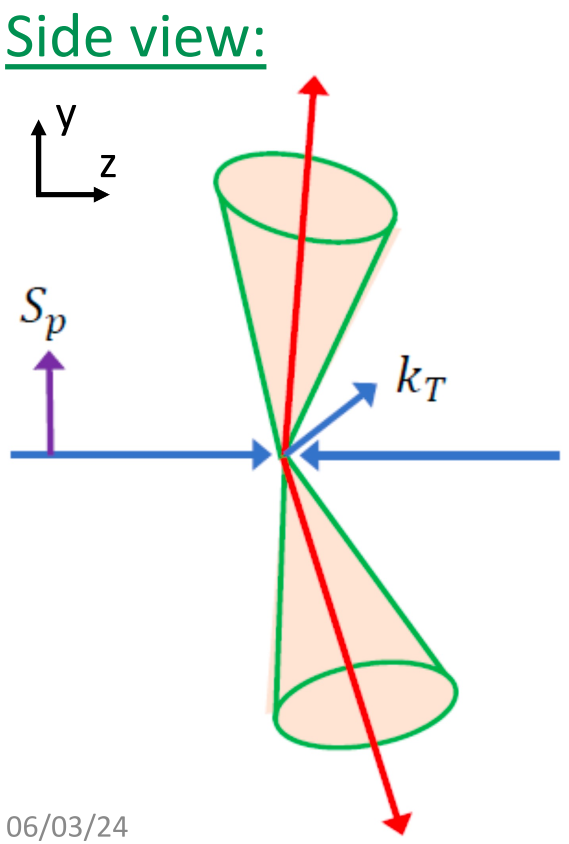
- $f_{1T}^{\perp}(x, k_T, Q^2)$: Describes the relationship between the transverse momentum distribution of unpolarized partons and the transverse spin polarization of the proton [1].
- Characterizes a scalar triple-vector correlation for an unpolarized parton and its polarized parent proton.
- Correlation between partonic orbital motion and proton's spin

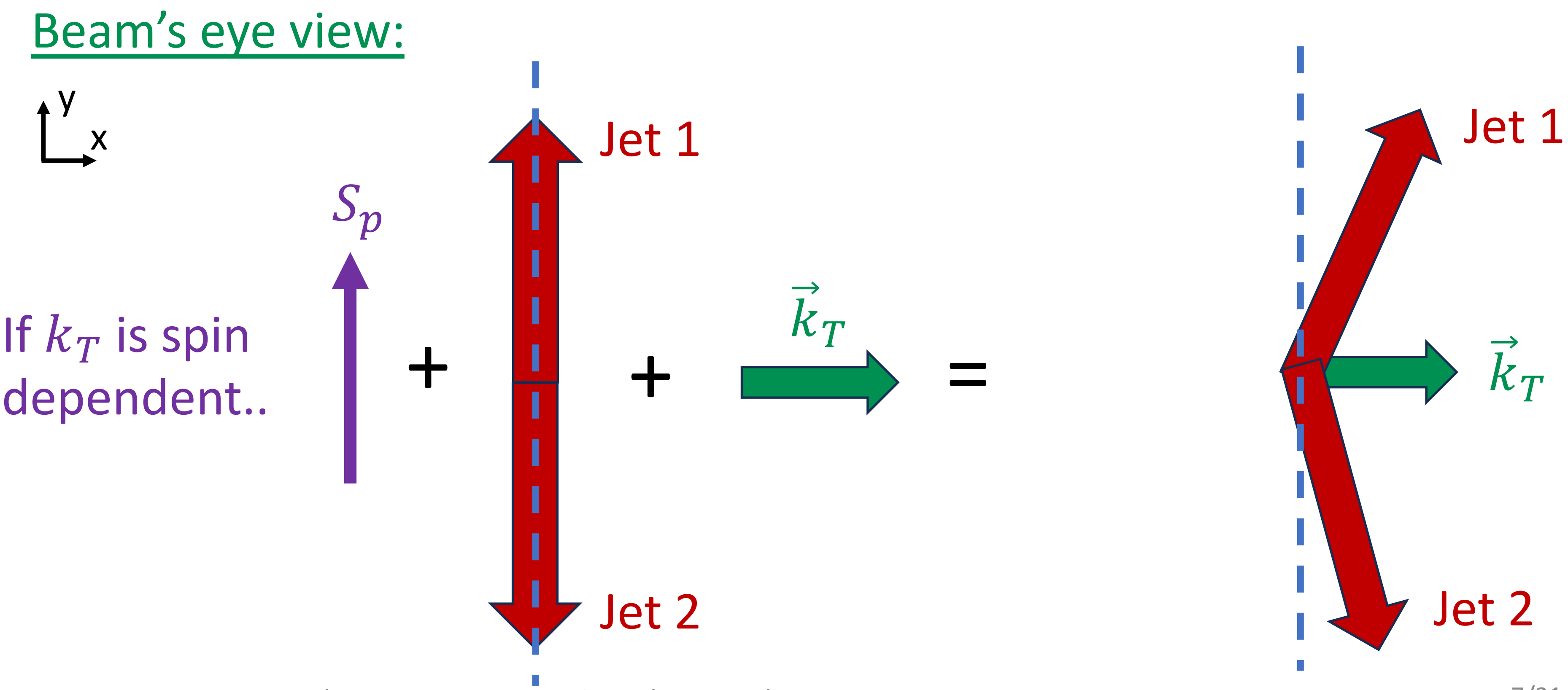
[1] D. Sivers, Phys. Rev. D **41**, 83 (1990).

Probing The Sivers Effect Using Dijet Production

- A transversely polarized proton going in the longitudinal direction can have partons with a spin-dependent transverse momentum k_T

- The k_T provides a kick to the dijet and makes it fold in the direction of the transverse momentum

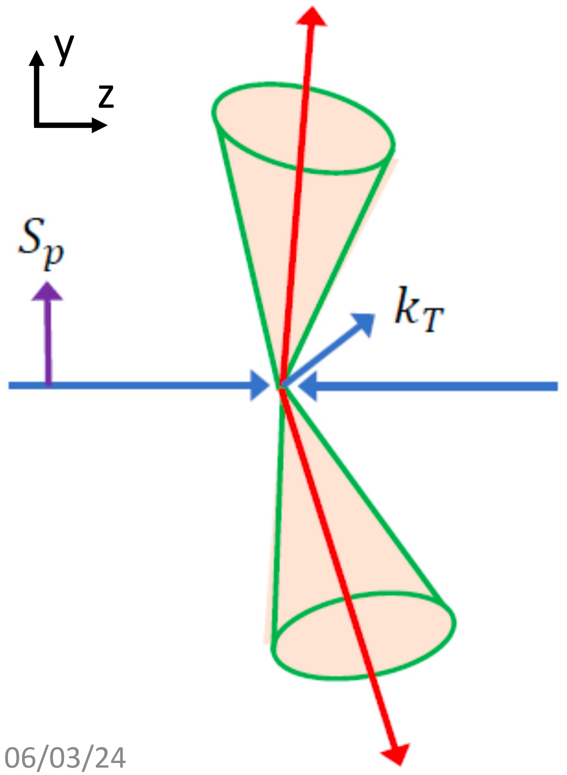




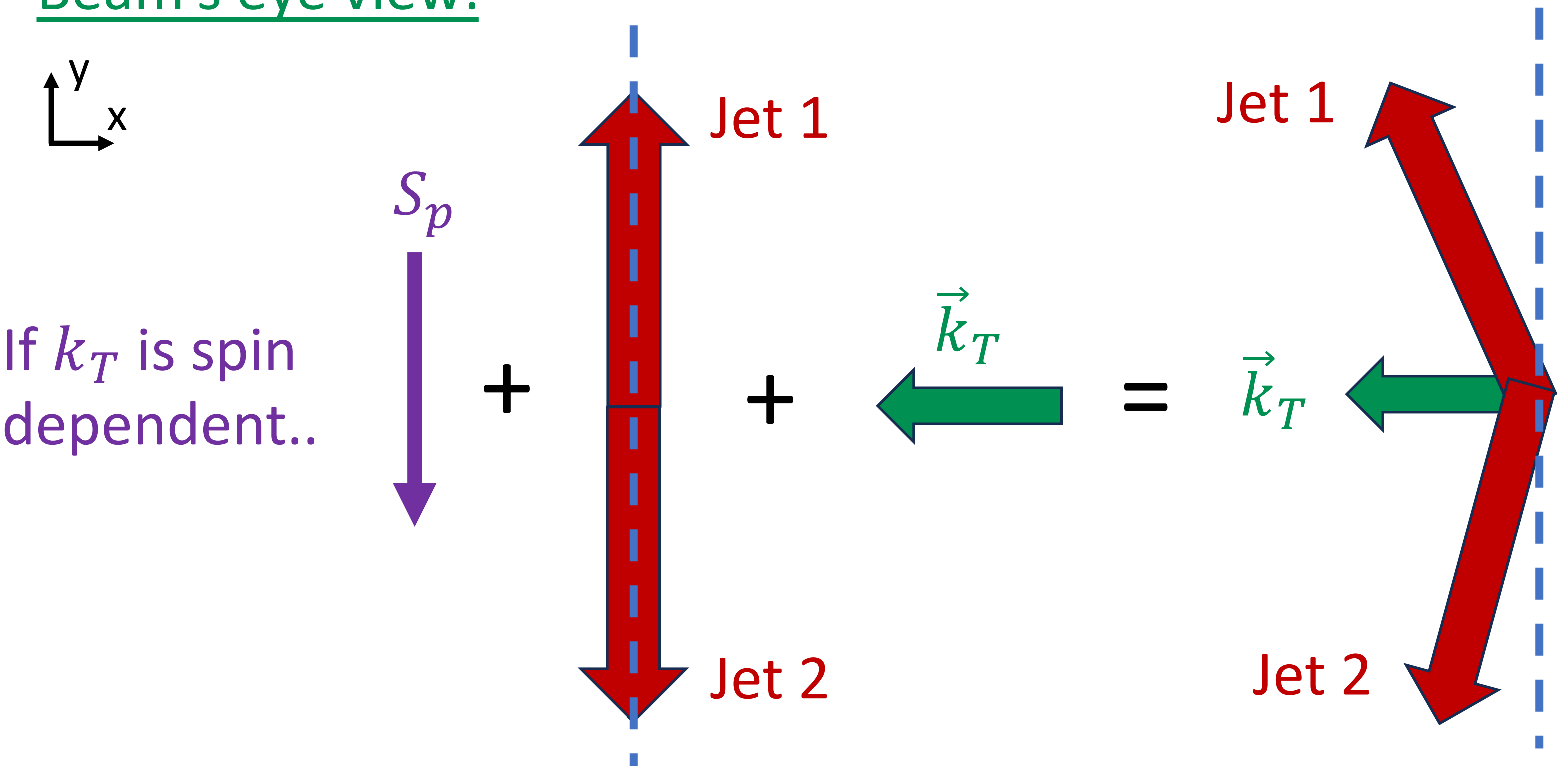
Probing The Sivers Effect Using Dijet Production

- A transversely polarized proton going in the longitudinal direction can have partons with a spin-dependent transverse momentum k_T
- The k_T provides a kick to the dijet and makes it fold in the direction of the transverse momentum

Side view:

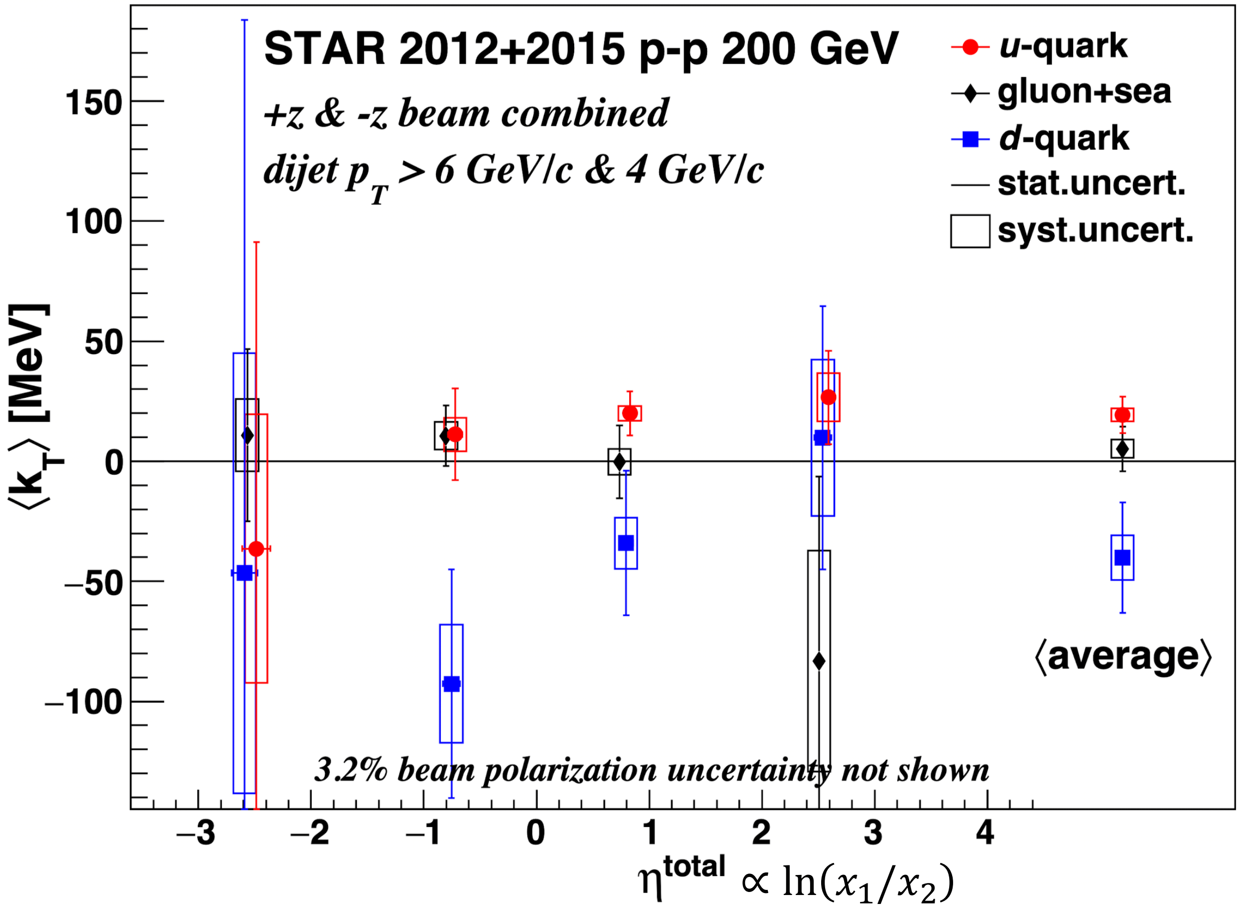


Beam's eye view:



Mean k_T Flavor Dependence

STAR, arXiv:2305.10359



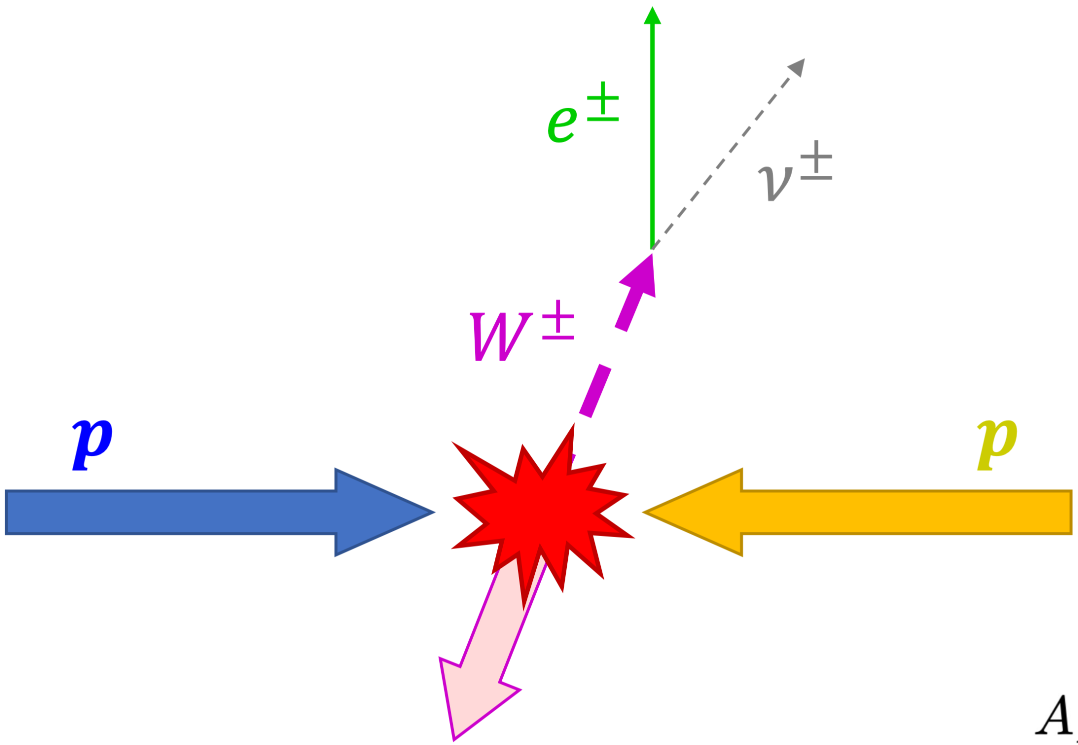
For the first time, there is evidence of non-zero Sivers effect using dijets.

- Jet charge tagging combined with unfolding used to determine the quark flavor.
- Tagged $\langle k_T \rangle$ represents a mixture of partons
- Obtaining parton fractions from simulation allows for measuring the individual parton $\langle k_T \rangle$

Results:

- d-quark $\langle k_T \rangle \approx -2\ u$-quark $\langle k_T \rangle$
- The $\langle k_T \rangle$ for gluon and sea quarks combined is consistent with zero

$W^{\pm}$ Boson Reconstruction and A_N



- Left and right asymmetry of the $W^{\pm}$ production with respect to the spin of the polarized proton

- Sensitive to the Sivers TMD function – $Q^2 = M_W^2 \sim 6500 \text{ GeV}^2$

- A_N is measured via azimuthal angle

$$A_N \cdot cos(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{\sqrt{N_{\uparrow}(\phi) N_{\downarrow}(\phi+\pi)} - \sqrt{N_{\uparrow}(\phi+\pi) N_{\downarrow}(\phi)}}{\sqrt{N_{\uparrow}(\phi) N_{\downarrow}(\phi+\pi)} + \sqrt{N_{\uparrow}(\phi+\pi) N_{\downarrow}(\phi)}}$$

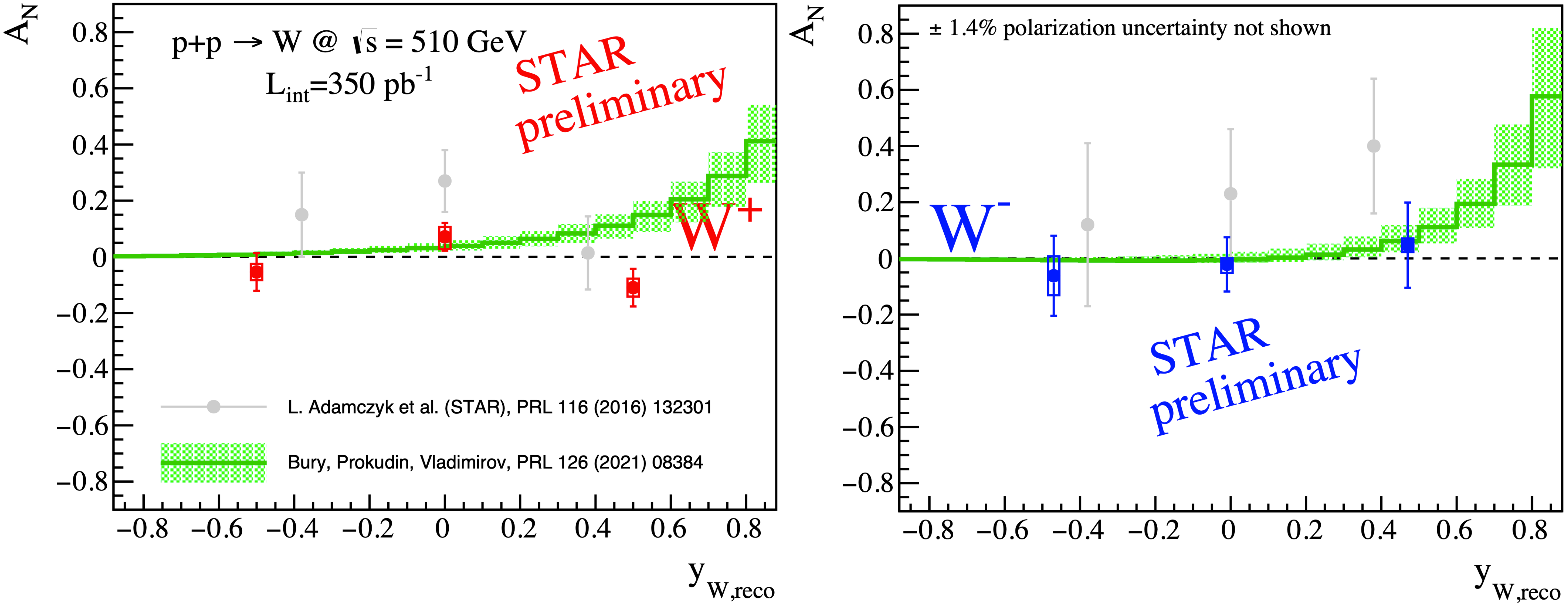
Use TPC tracks and EMC hits to measure $W^{\pm}$ recoil from collision:

$$\vec{p}_{T,W} = \vec{p}_{T,e} + \vec{p}_{T,\nu} = -\vec{p}_{T,recoil}$$

$$\vec{p}_{T,recoil} = \sum (\vec{p}_{T,TPC} + \vec{E}_{T,EMC})$$

$\langle P \rangle$: Mean beam polarization
$N_{\uparrow}(N_{\downarrow})$: Yield in spin up (down) state
ϕ: Azimuthal angle

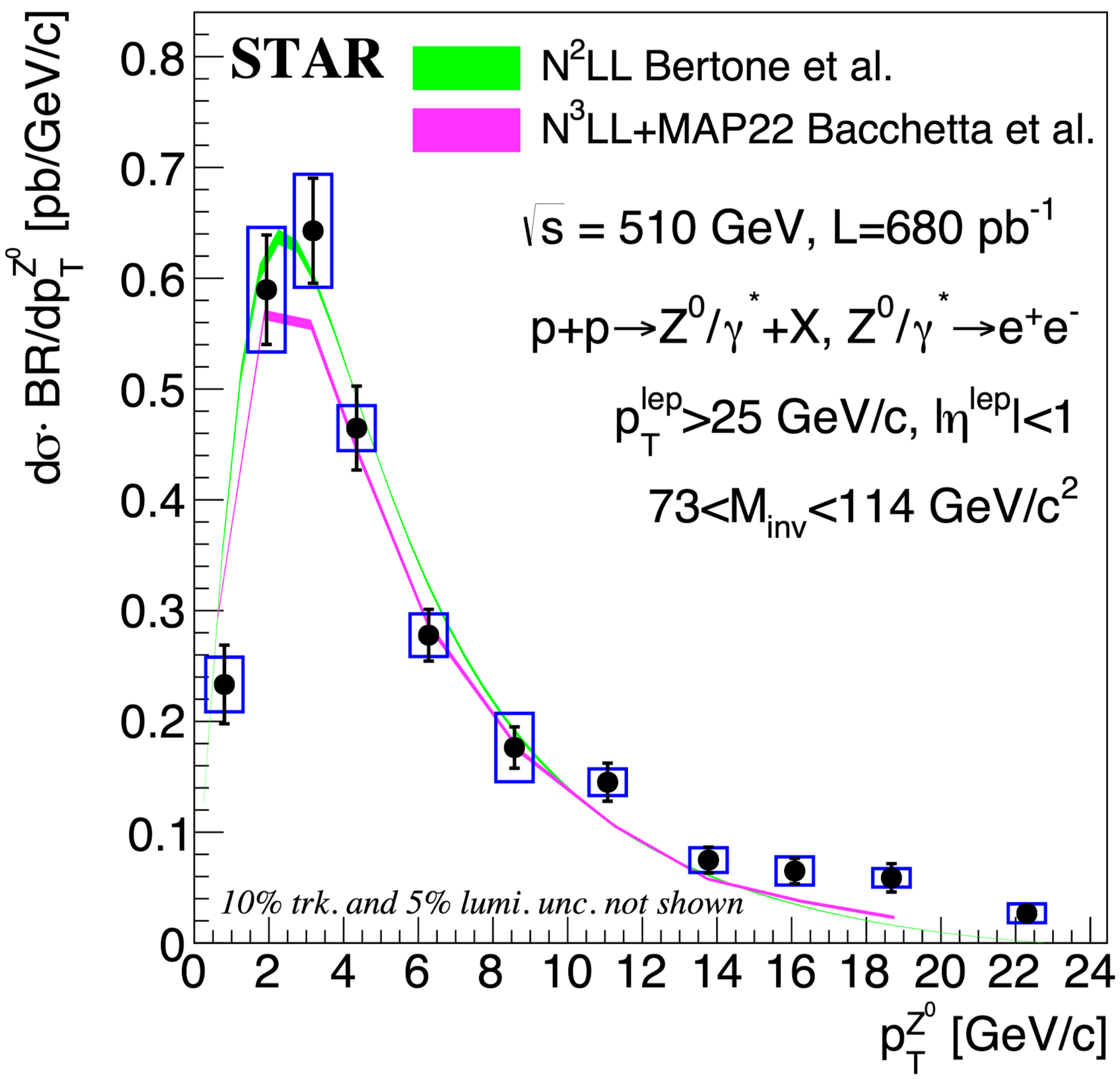
A_N Preliminary Results of $W^{\pm}$



- Results are generally consistent with the model predictions
- STAR results will have biggest impact on high-x region of the quark Sivers function

Z^0/γ^* Cross Section

STAR, *Phys. Lett.* B **854** (2024) 138715



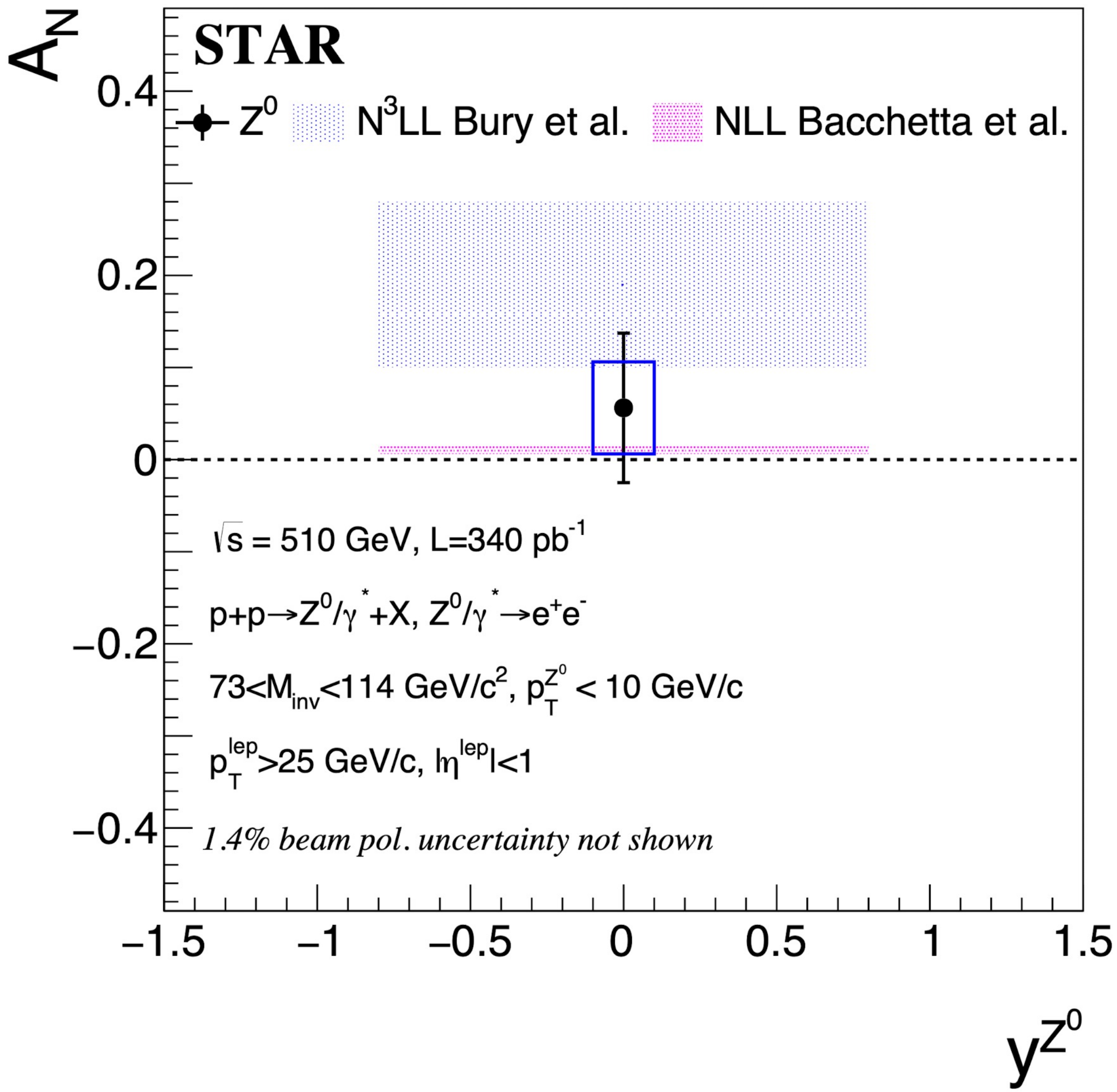
- Z^0 events are reconstructed via:

$$p + p \to Z^0 \to e^+ + e^-$$

- Serves as a test of the universality of unpolarized TMDs
- Provides insights into the x and Q^2 evolution of unpolarized TMDs
  - RHIC energies provide access to higher x compared to the Tevatron and LHC

$Z^0/\gamma^* A_N$

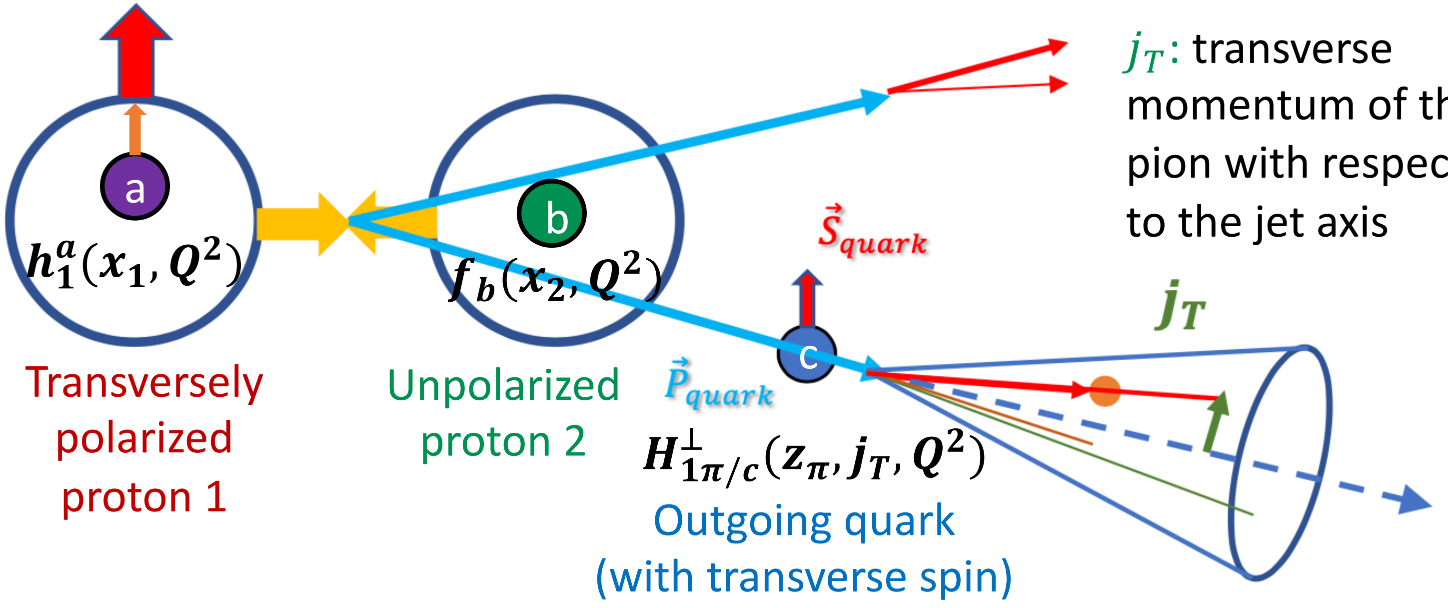
STAR, *Phys. Lett.* B **854** (2024) 138715



- $p_T^{Z^0}$ is limited to < 10 GeV/c to stay within the kinematic region where the polarized TMD approach is applicable
- This result will allow for the extraction of the Sivers TMD PDF, and especially for valence quarks in the region $x \geq 0.1$
- Unable to provide a conclusive statement regarding the sign-change hypothesis of the Sivers function

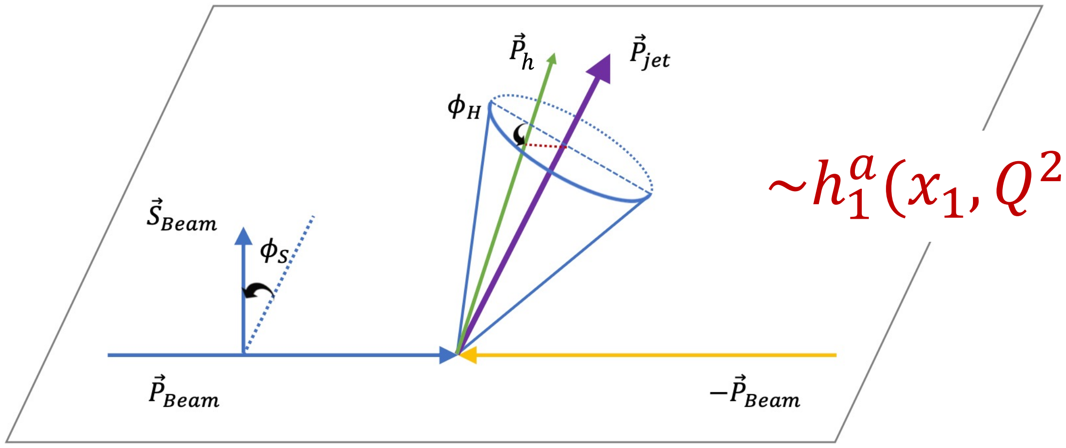
$$\text{Sivers}_{\text{DIS}} = -\text{Sivers}_{\text{DY}} \text{ or } \text{Sivers}_{W^{\pm},Z^0}$$

Collins Effect: A Mechanism for A_N



j_T: transverse momentum of the pion with respect to the jet axis

z_π: longitudinal momentum fraction of the pion



- The relationship between the leading-twist (twist-2) collinear transversity, $h_1^a(x_1, Q^2)$, and the TMD Collins fragmentation function, $H_{1\pi/c}^{\perp}(z_\pi, j_T, Q^2)$

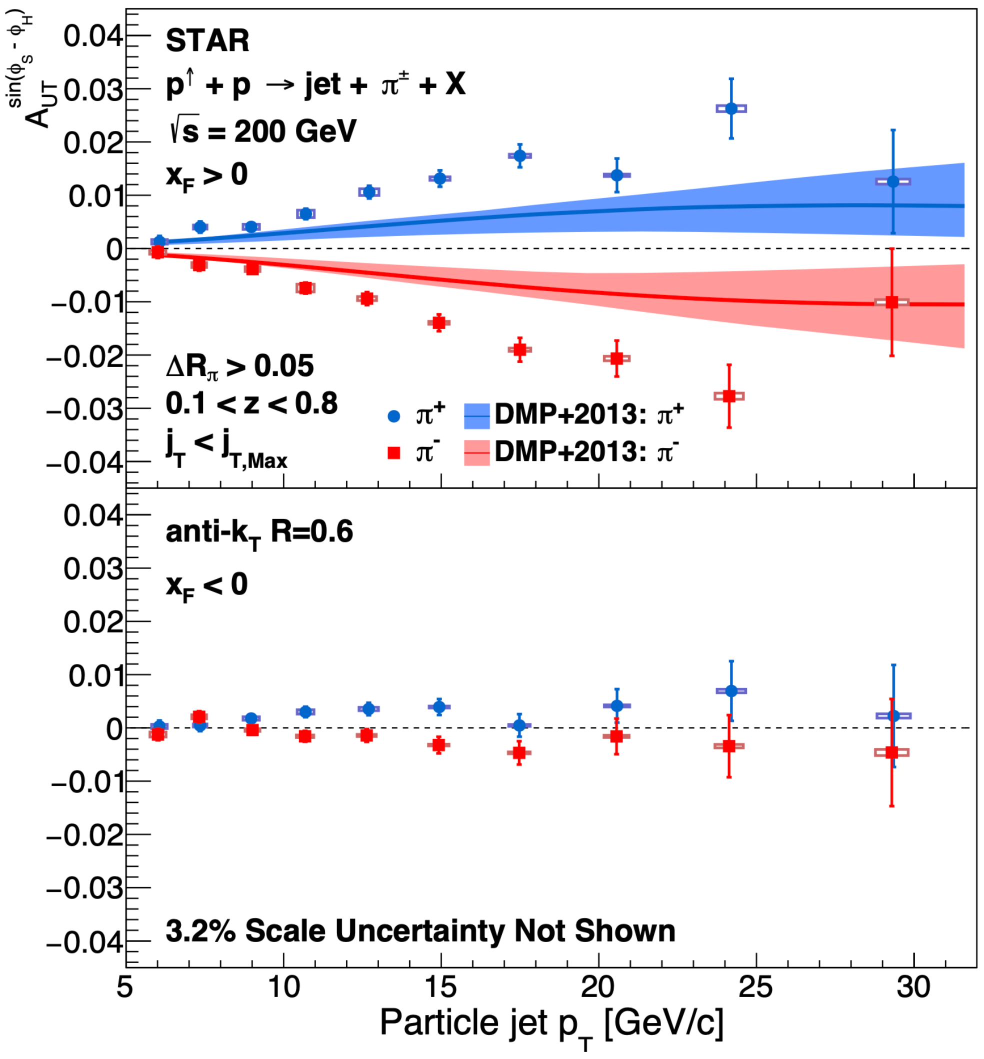
$$\frac{d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)}{d\sigma^{\uparrow}(\phi_S, \phi_H) + d\sigma^{\downarrow}(\phi_S, \phi_H)} \propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + \boxed{A_{UT}^{\sin(\phi_S - \phi_H)}} \sin(\phi_S - \phi_H) + \ldots$$

$$\sim h_1^a(x_1, Q^2) \otimes H_{1\pi/c}^{\perp}(z, j_T, Q^2)$$

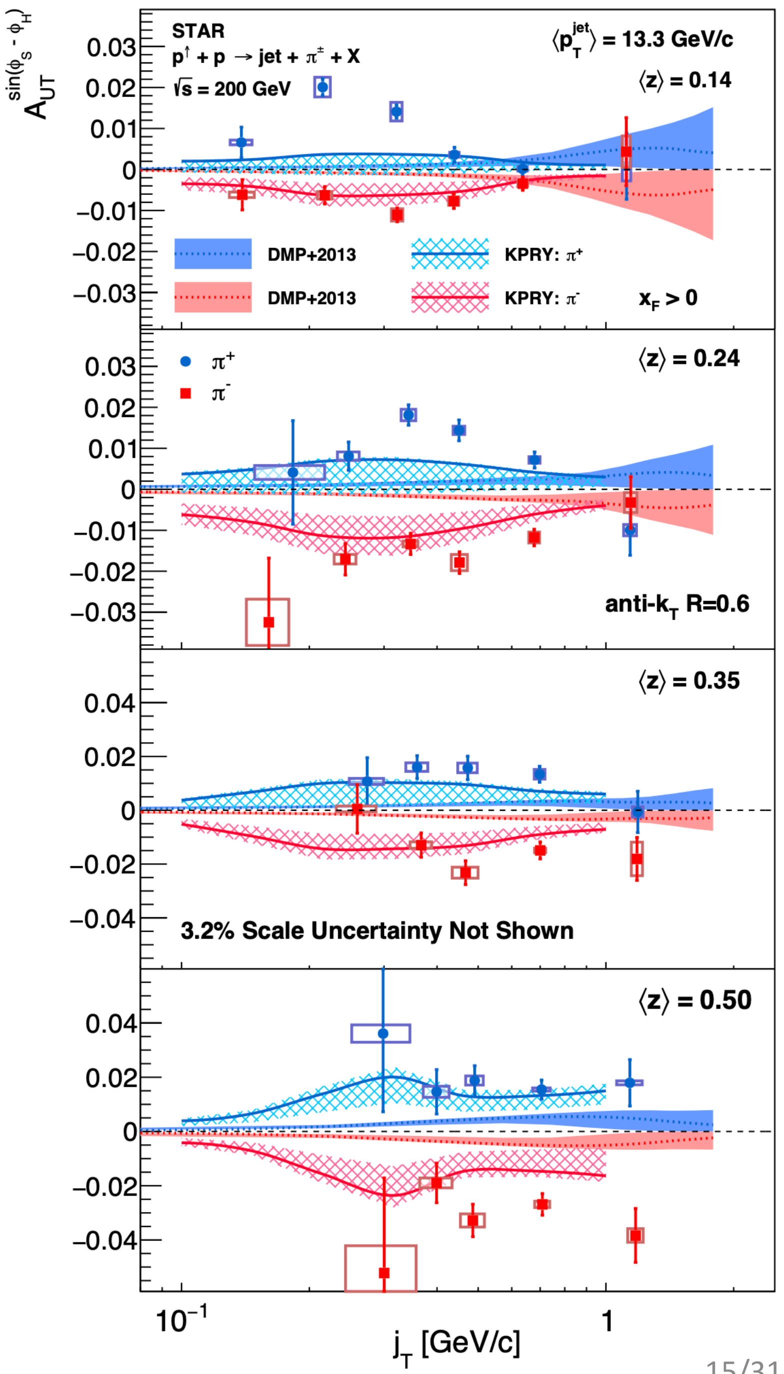
J. C. Collins, Nucl. Phys. B **396**, 161 (1993).
Z.-B. Kang *et al.*, JHEP **11**, 068 (2017).
Z.-B. Kang *et al.*, Phys. Lett. B **774**, 635 (2017).
U. D'Aesio *et al.*, Phys. Rev. D **83**, 034021 (2011).

$\pi^{\pm}$ Collins Asymmetry at $\sqrt{s} = 200$ GeV

- Integrated over a wide range of z and j_T to provide sensitivity to the collinear transversity, $h_1^a(x, Q^2)$
- The hadron j_T and z binning allows sensitivity to the Collins FF, $H_{1\,\pi/c}^{\perp}(z_\pi, j_T, Q^2)$
- In general, model calculations underestimate experimental data

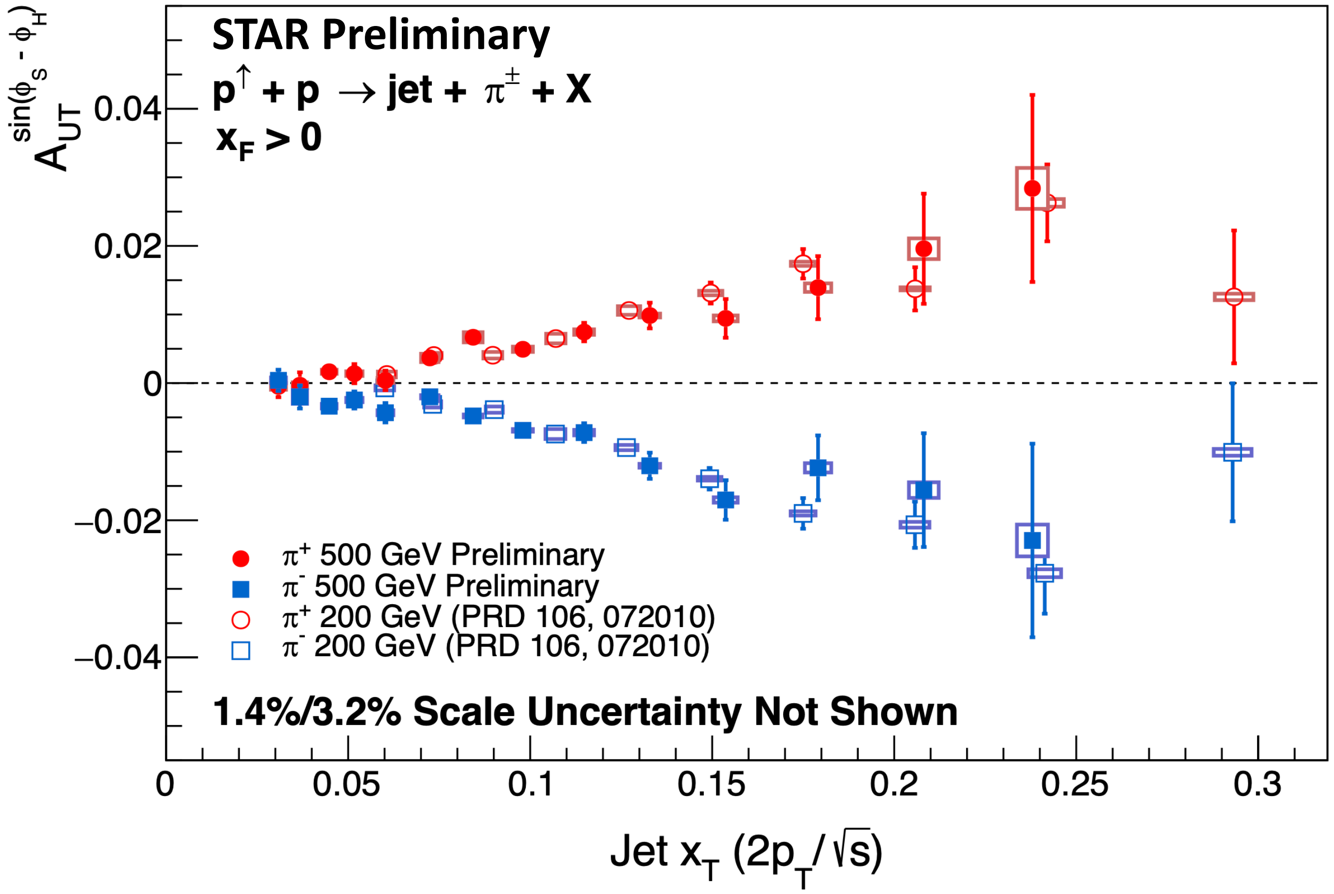


STAR, Phys. Rev. D **106**, 072010 (2022).

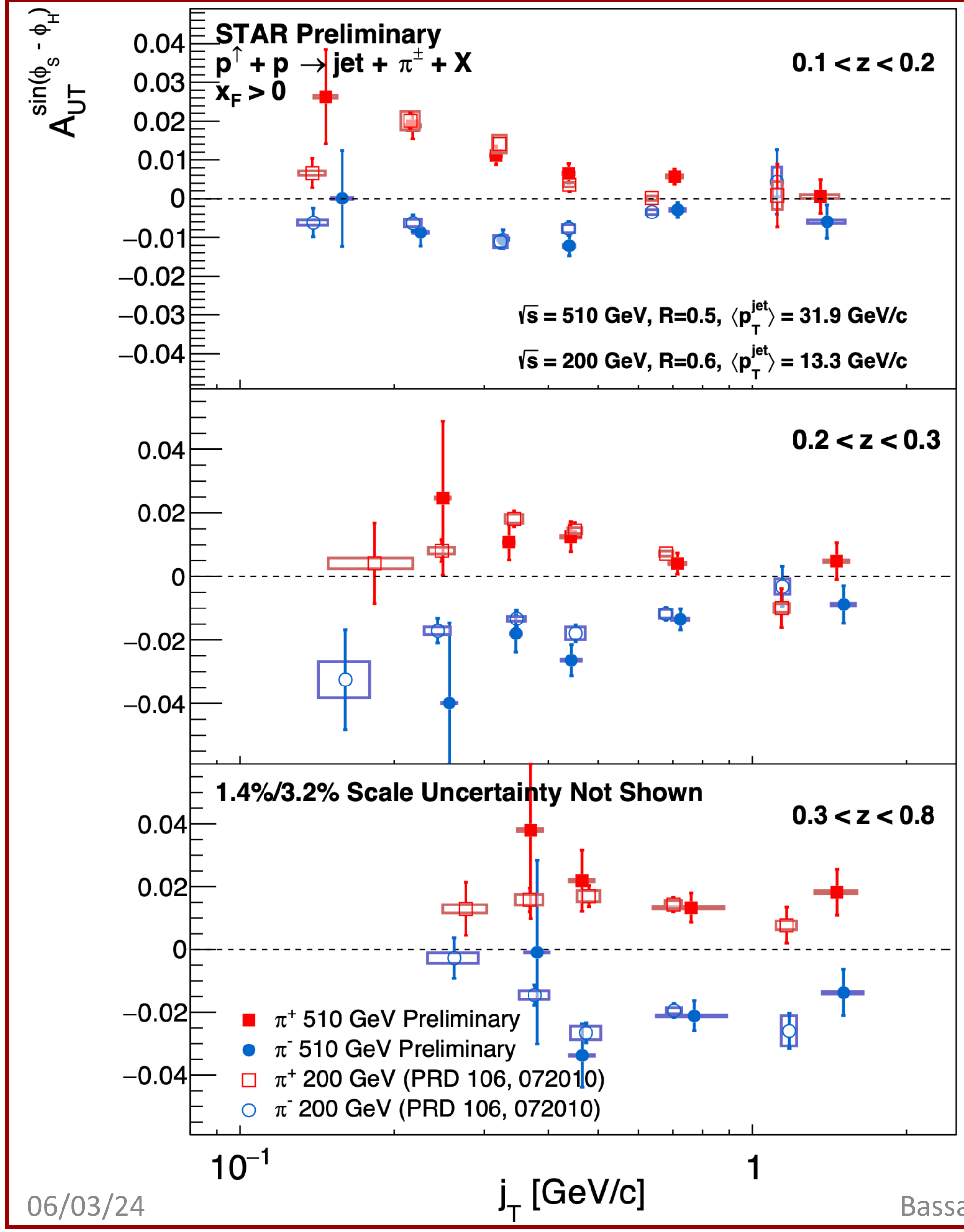


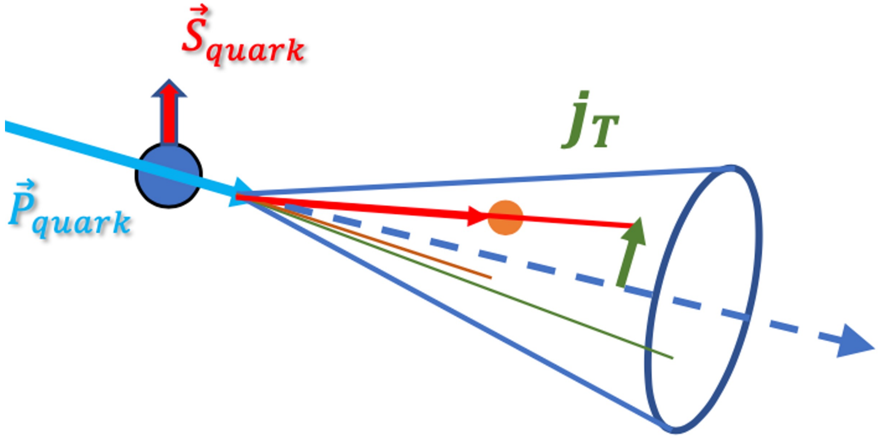
$\pi^{\pm}$ Collins Asymmetry at $\sqrt{s} = 200$ and 510 GeV

- Results from the two beam energies match each other very well
- Little, if any, energy dependence when comparing the 200 GeV results to the 510 GeV results
    - Q^2 values differ by a factor of 6 between 200 GeV and 510 GeV results
- Sets constrains on evolution effects



$\pi^{\pm}$ Collins Asymmetry at $\sqrt{s} = 200$ and 510 GeV



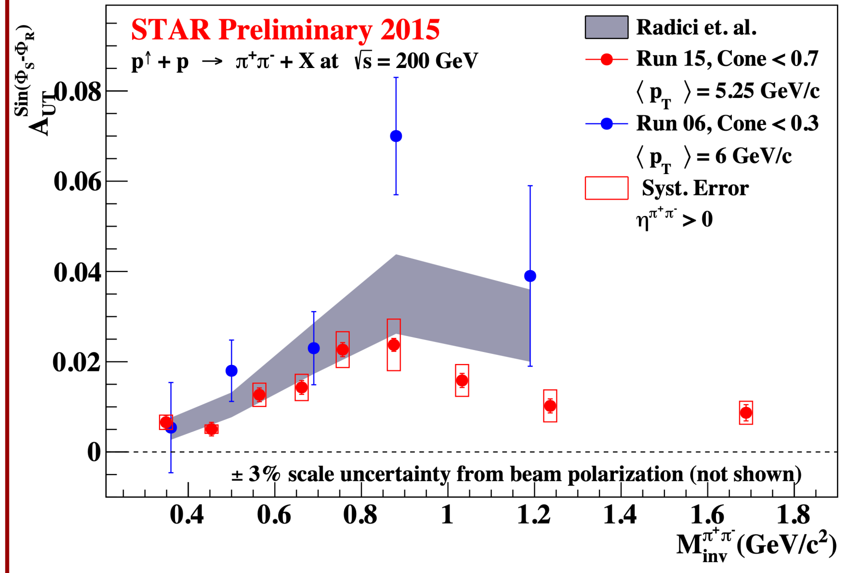


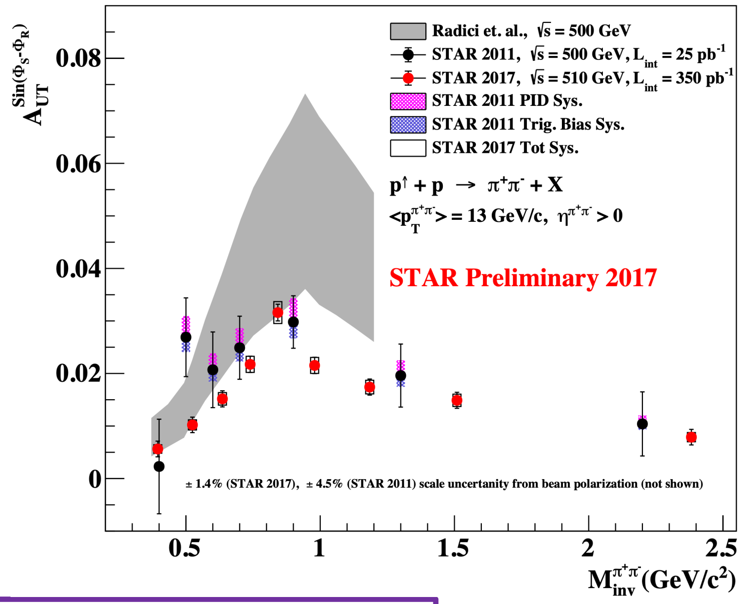
z: longitudinal momentum fraction of the pion

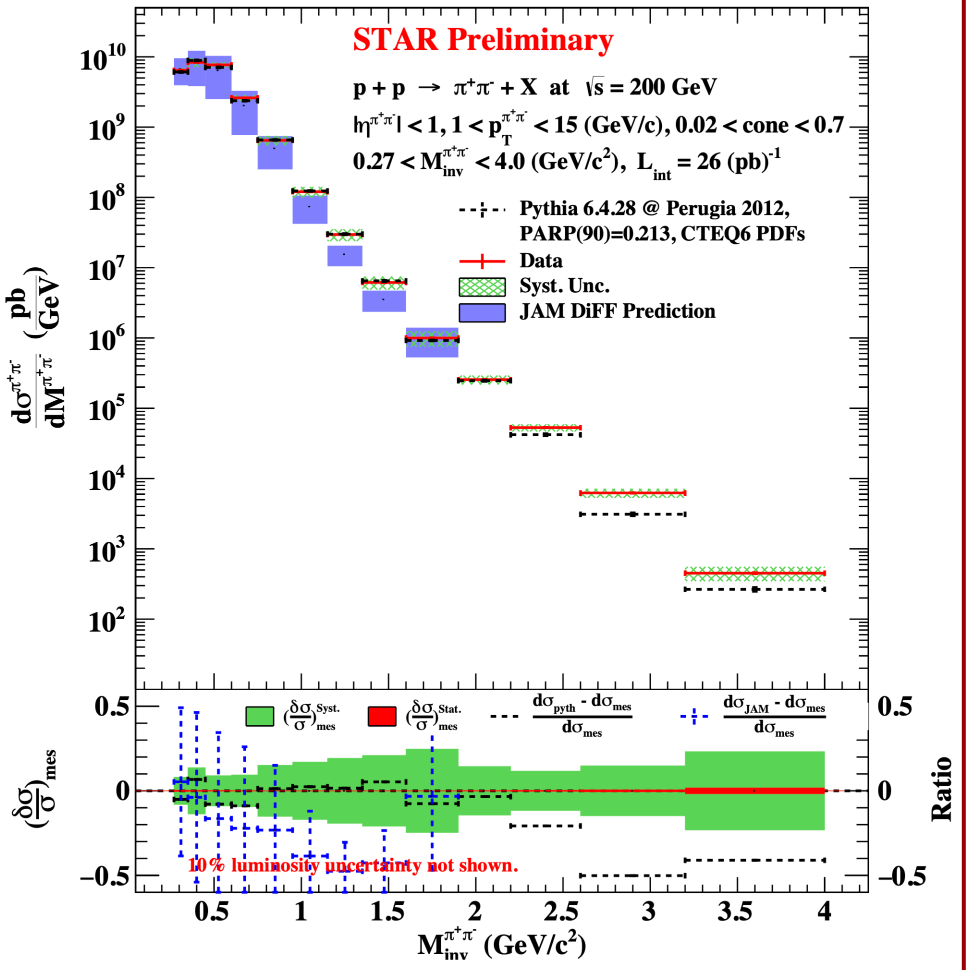
j_T: transverse momentum of the pion with respect to the jet axis

- z and j_T binning allows sensitivity to the Collins FF, $H_{1\pi/c}^{\perp}(z_\pi, j_T, Q^2)$
- Good agreement between the 200 and 510 GeV results
- Little to no energy dependence

Di-pion Asymmetries and Cross-Section Measurements







$$A_{UT} \propto \frac{h_1^a(x) \otimes H_1^{\sphericalangle \pi^+\pi^-}(z, M_h^2)}{f_1^a \otimes D_1^{\pi^+\pi^-}}$$

a) New measurements of A_{UT} at 200 and 510 GeV

b) First measurement of unpolarized $\pi^+\pi^-$ cross section at 200 GeV

(a) + (b) → model independent extraction of $h_1^q(x)$

Learn more from Bernd Surrow's talk, "STAR IFF Measurements," during the Thursday morning session.

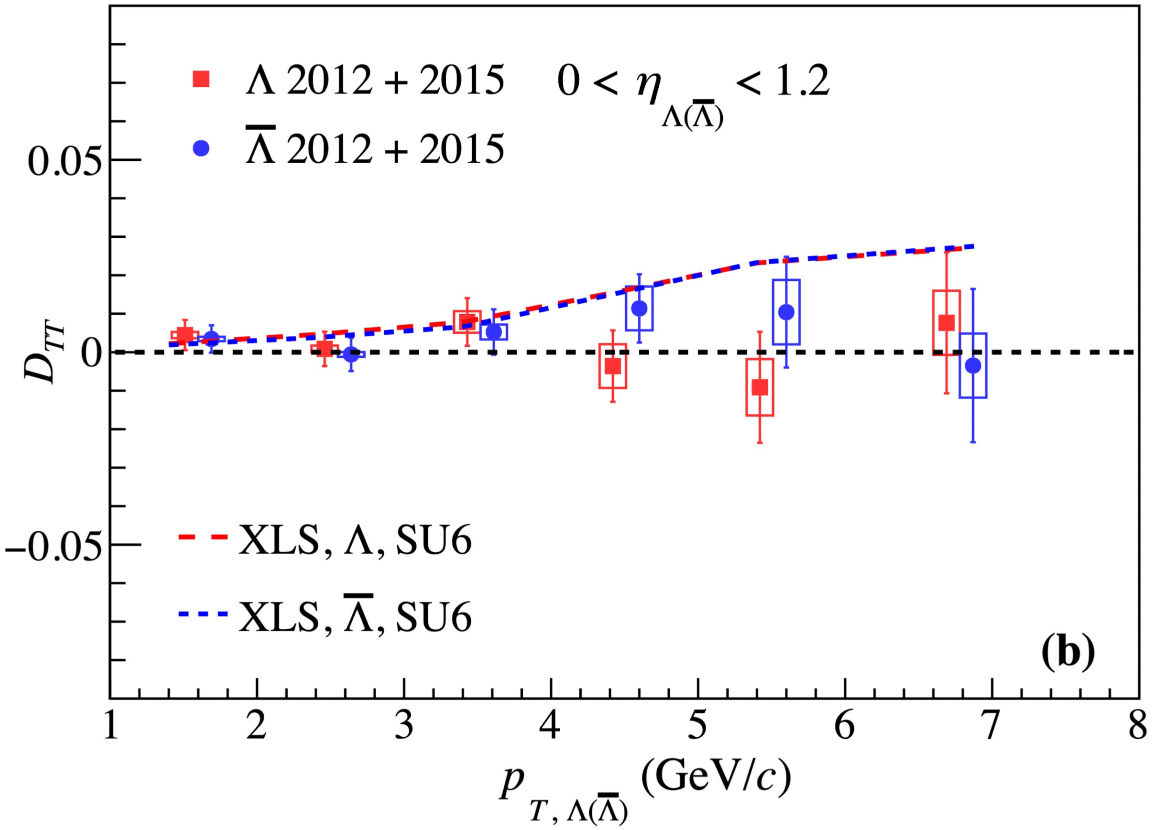
Λ and $\bar{\Lambda}$ Hyperon Transverse Spin Transfer - D_{TT}

$$D_{TT}^{\Lambda} = \frac{d\sigma(p^{\uparrow}p \to \Lambda^{\uparrow}X) - d\sigma(p^{\uparrow}p \to \Lambda^{\downarrow}X)}{d\sigma(p^{\uparrow}p \to \Lambda^{\uparrow}X) + d\sigma(p^{\uparrow}p \to \Lambda^{\downarrow}X)} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \underbrace{\delta f_a(x_a)}_{\text{transversity}} f_b(x_b) \underbrace{\delta\sigma(ab \to cd)}_{\text{pQCD calculable}} \underbrace{\delta D^{\Lambda}(z)}_{\text{polarized FF}}$$

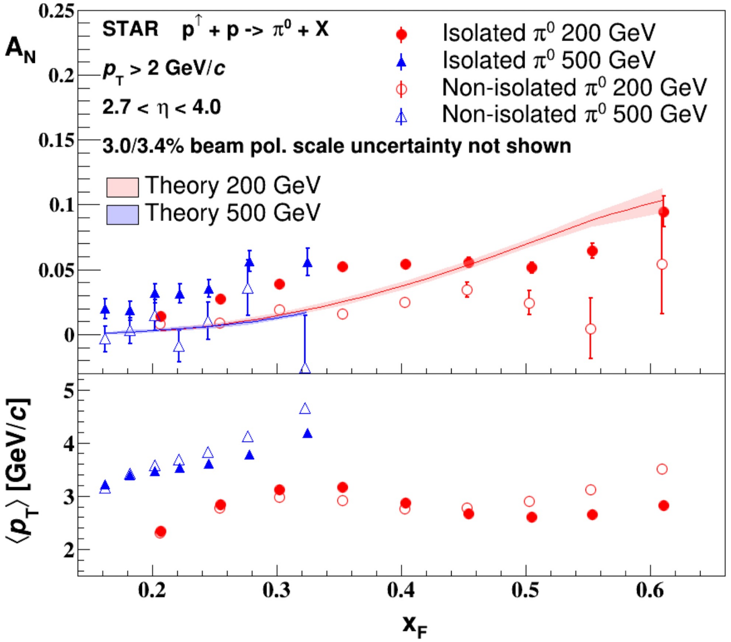
- $\Lambda(\bar{\Lambda})$ D_{TT} is sensitive to the (anti-)strange quark transversity in the proton
- Λ and $\bar{\Lambda}$ results are consistent with each other within uncertainties
- D_{TT} is consistent with zero

STAR, Phys. Rev. D **109**, 012004 (2024).

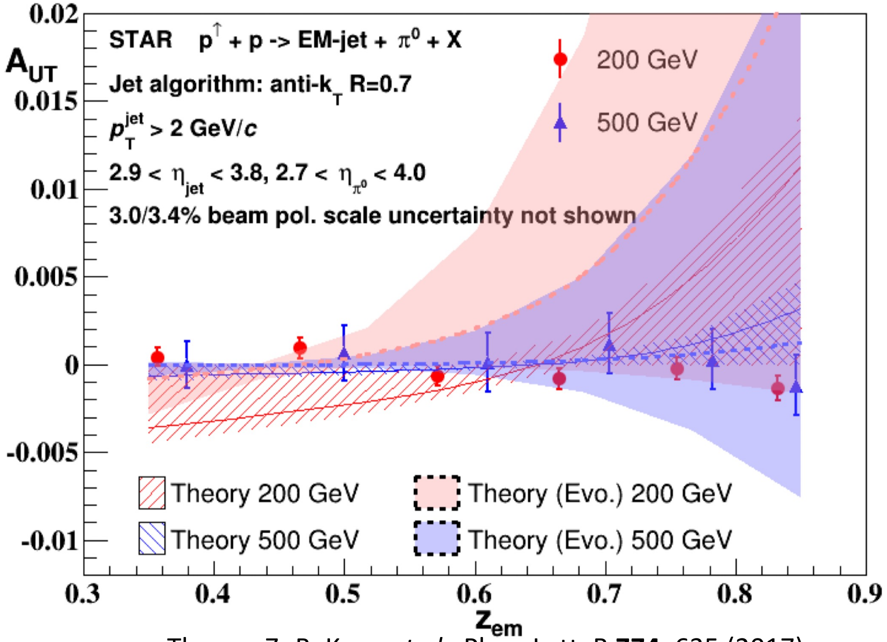


Theory: Q. H. Xu *et al.*, Phys. Rev. D, **73**(7), 077503 (2006).

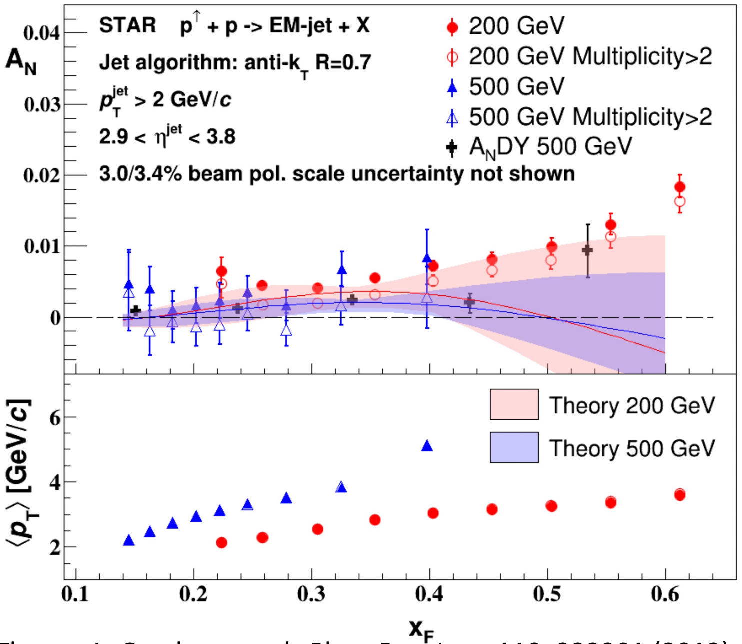
Previous STAR Results



Theory: J. Cammarota *et al.*,Phys. Rev. D **102**, 054002 (2020).



Theory: Z.-B. Kang *et al.*, Phys. Lett. B **774**, 635 (2017).

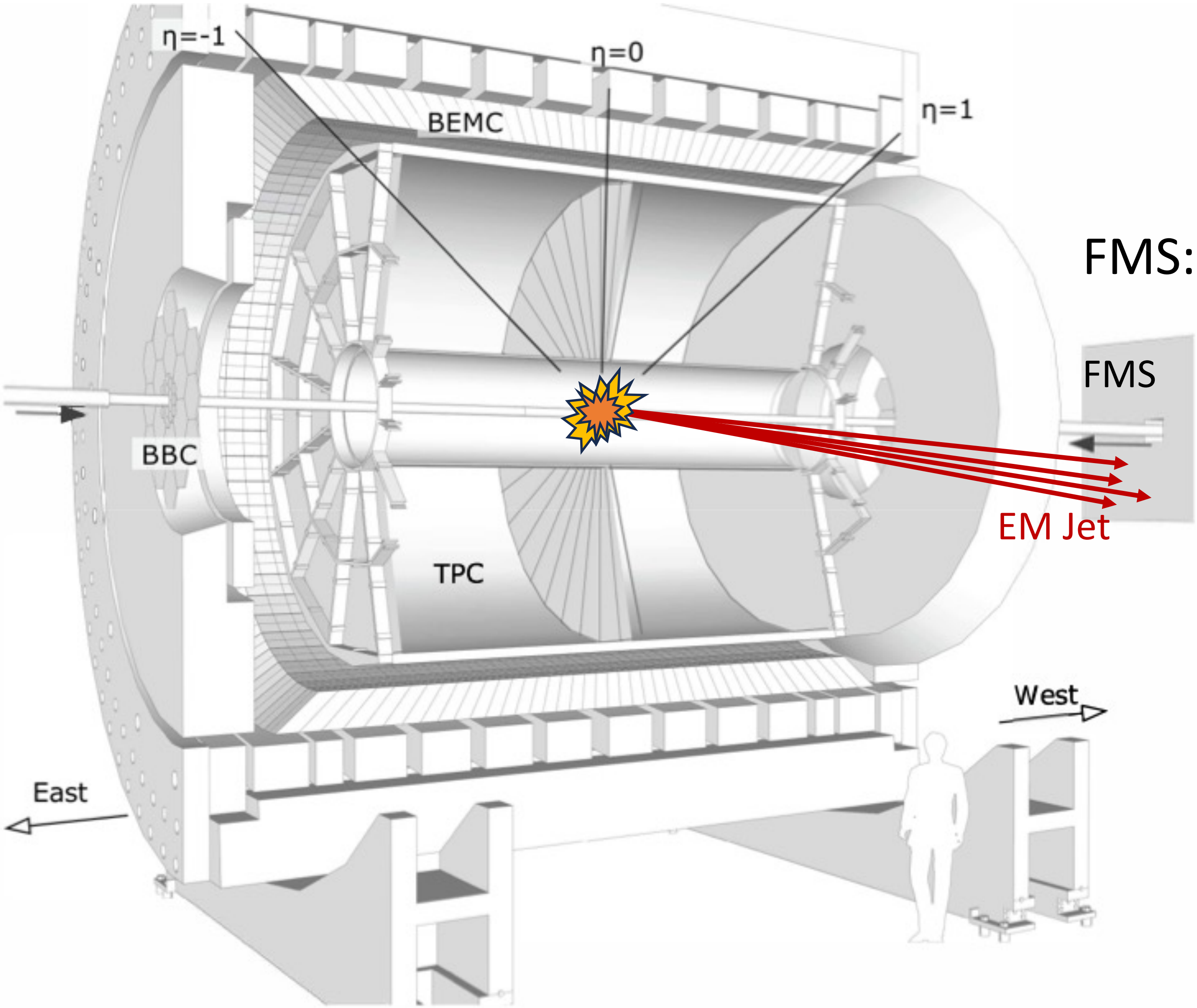


Theory: L. Gamberg *et al.*, Phys. Rev. Lett. 110, 232301 (2013).

Observations and Measurements: (STAR) J. Adam *et al.*, Phys. Rev. D **103**, 092009 (2021).	**Conclusion**
• Small A_N is observed for non-isolated π^0 in EM-jets (non-isolated = other photons are allowed in the jet) • Small Collins asymmetry for π^0 in EM-jet	Collins effect can't account for the large TSSA
• Small jet A_N for inclusive EM-jets • For $x_F \lesssim 0.3$: DIS-based model for the Sivers effect describes the non-isolated π^0 results well, but not the isolated results	Sivers effect can't account for large TSSA
• Large A_N is observed for isolated π^0 in EM-jets (isolated = no other photons in the jet)	Diffractive process?

Relevant Event Classes

Inclusive EM-Jet Event:



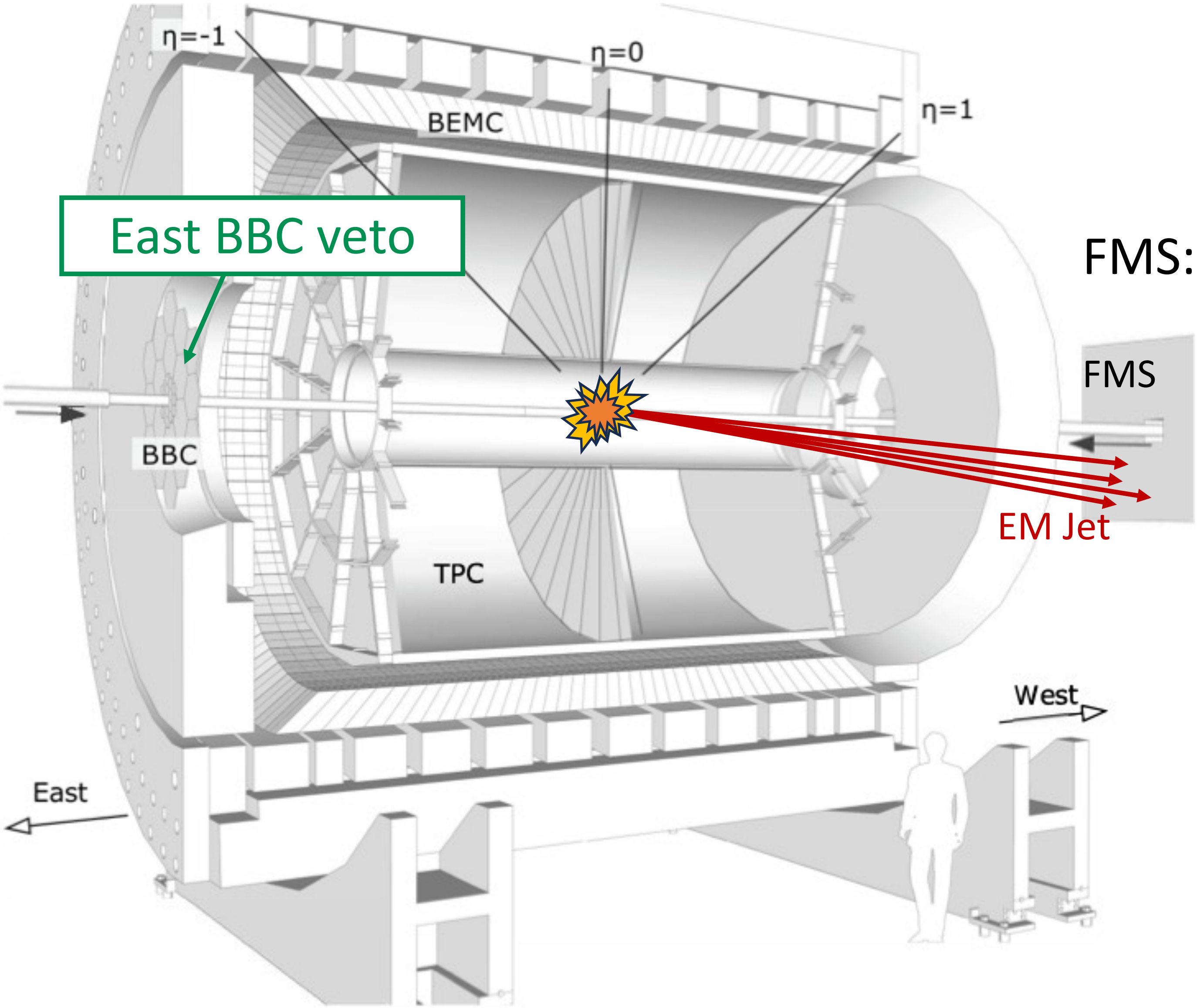
FMS: $2.5 < \eta < 4$

Relevant Event Classes

<u>Rapidity Gap (RG) Event:</u>

Vetoing hadrons in the BBC η range suppresses a large fraction of the non-diffractive events – RG events are highly enriched in diffractive processes

East BBC: $-5 < \eta < -2$



Relevant Event Classes

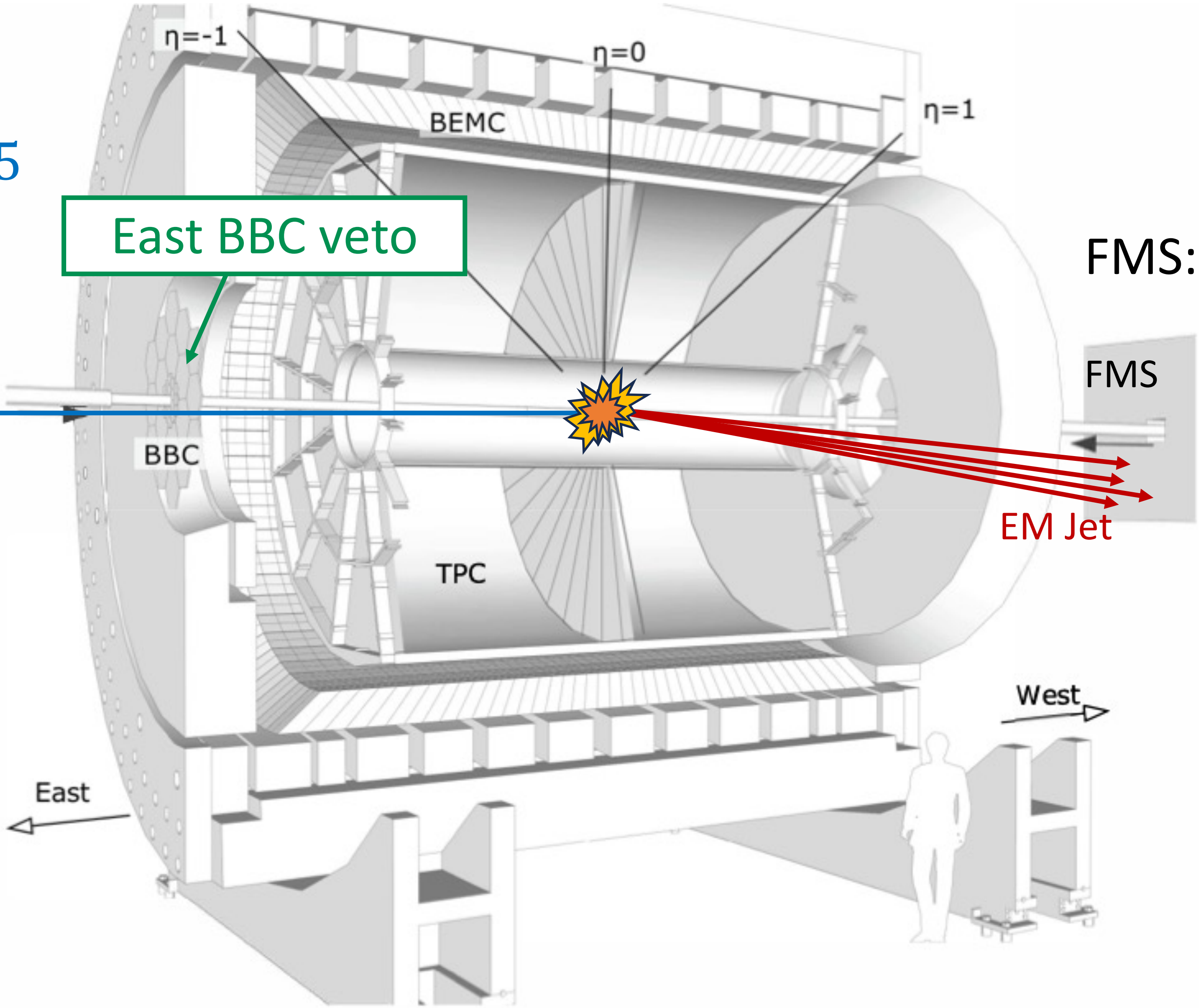
Single Diffractive Event:

Intact proton has an $\xi < 0.15$

East roman pots: $\eta < -6$

Roman pot

Intact proton

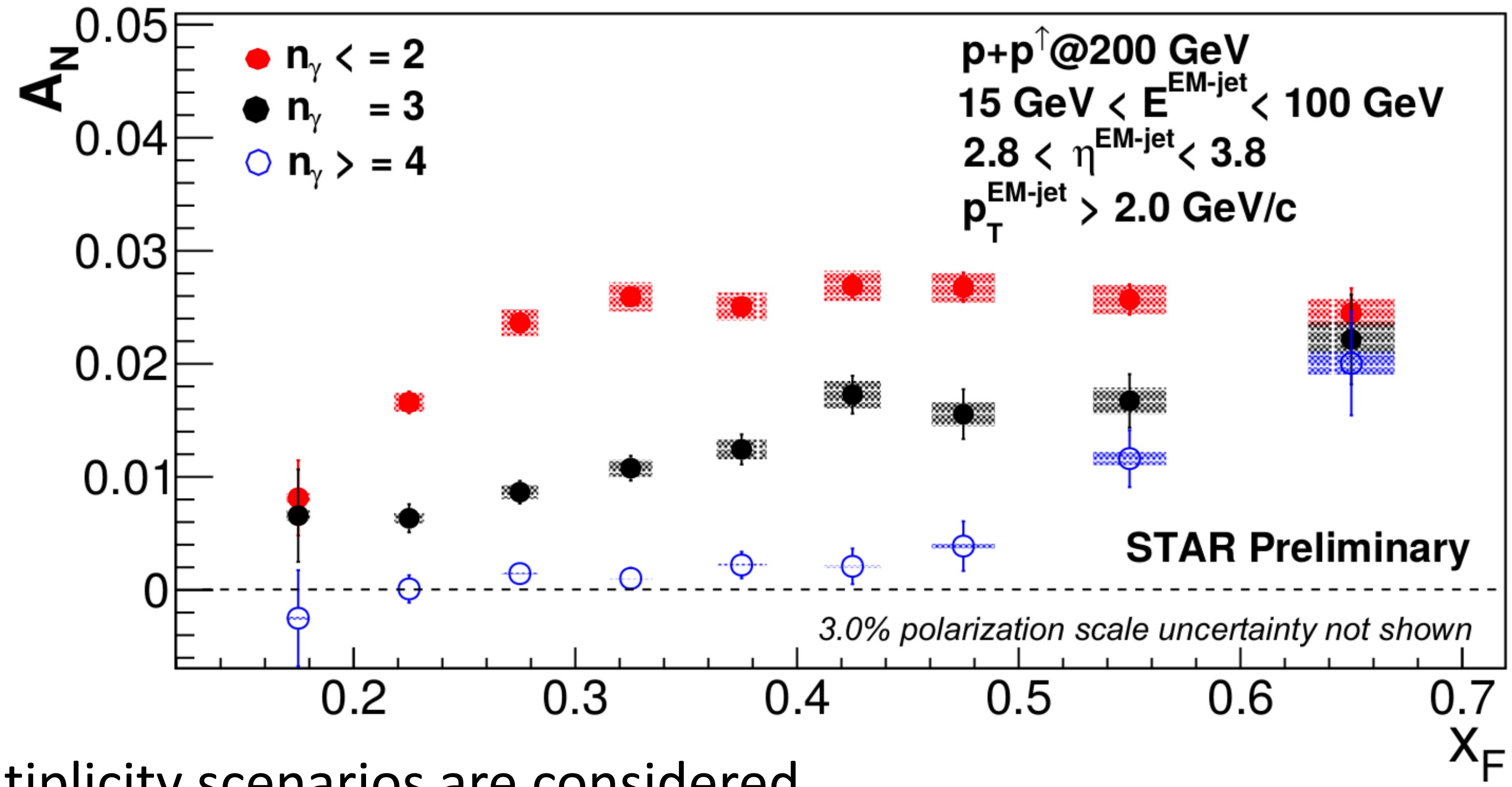


FMS: $2.5 < \eta < 4$

East BBC: $-5 < \eta < -2$

Forward Rapidity: A_N for Inclusive EM-Jets

- EM-jets are reconstructed using only photons
- Photon candidates are obtained from the Forward Meson Spectrometer (FMS) on the west side of STAR



- Three different photon multiplicity scenarios are considered
  - Multiplicity dependence is observed
- EM-jets with only 1 or 2 photons have the largest A_N
  - Could this point to a contribution to the observed A_N from diffractive processes?

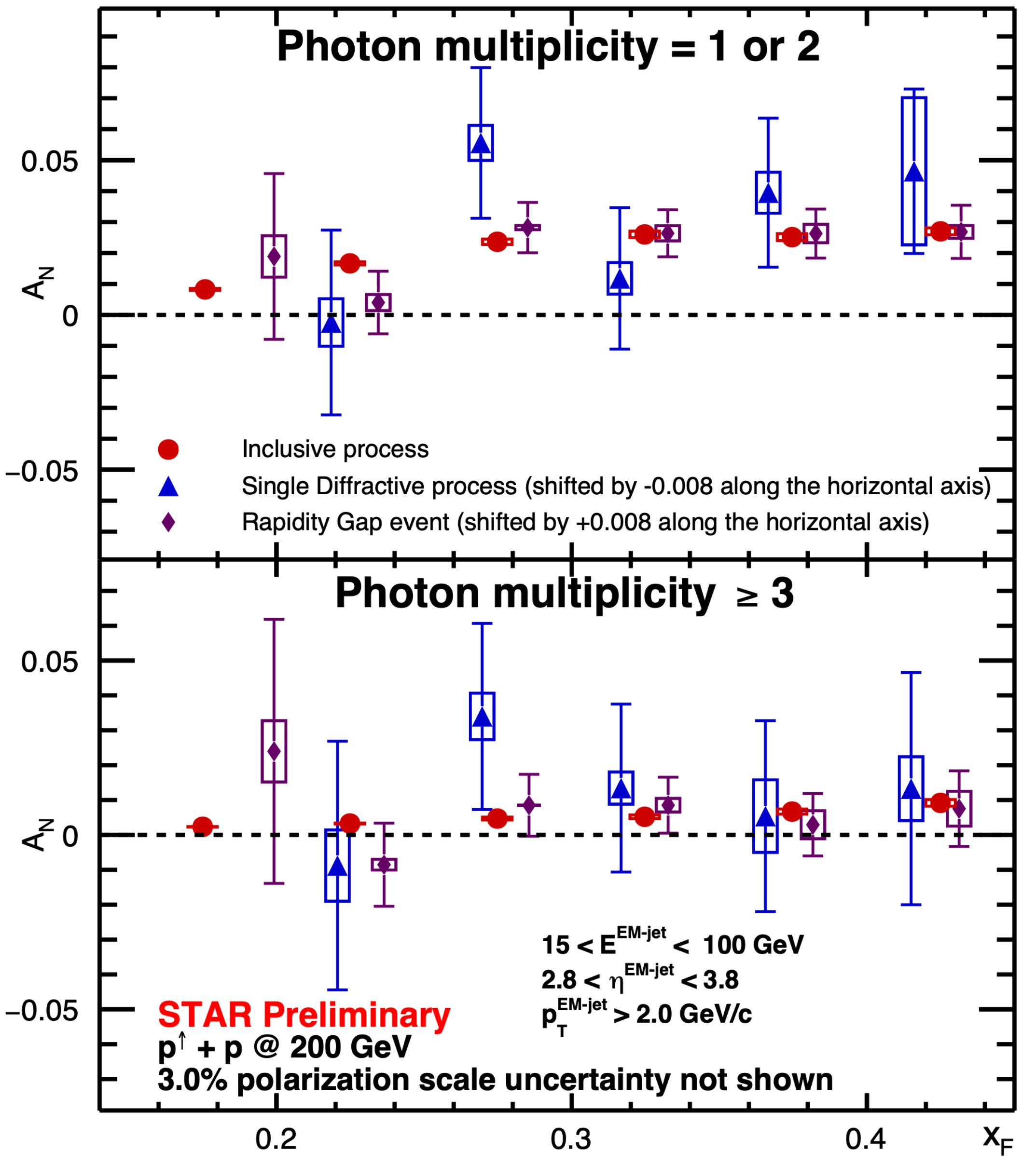
Diffractive Process and A_N

$p + p \rightarrow$ EM-jet $+ X$ Inclusive EM-jet

$p + p \rightarrow$ EM-jet $+ X$ RG events (at least 50% of RG events are single diffractive)

$p + p \rightarrow p +$ EM-jet $+ X$ Single diffractive process

- A_N consistent within uncertainties for all three processes
- If A_N has significant contributions from diffractive processes, then A_N from diffractive events is expected to have a large magnitude
- Current results do not provide evidence in favor of a diffractive process having a large contribution to A_N

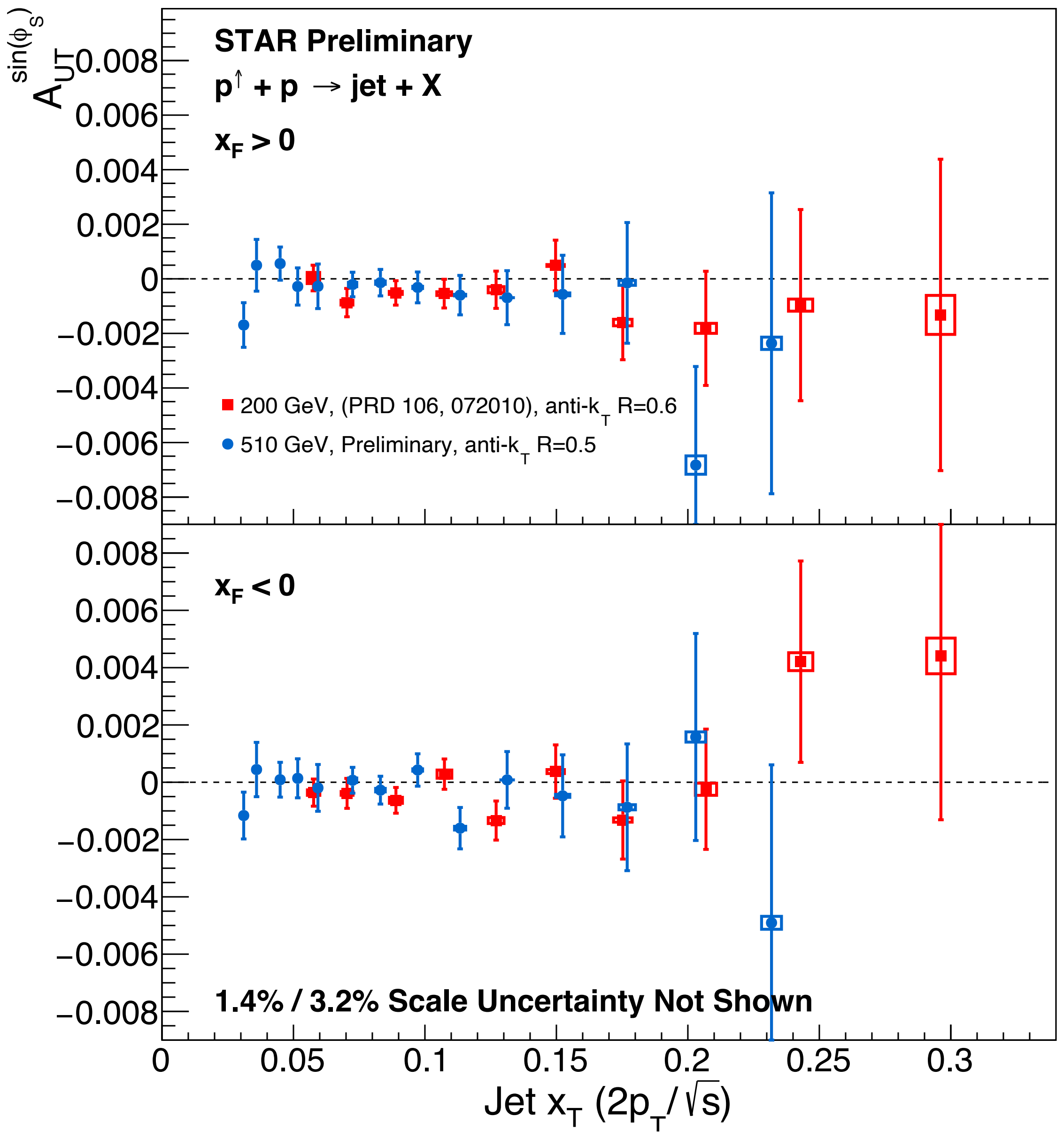


Mid-Rapidity: Inclusive Jet Asymmetry at 200 and 510 GeV

- At low p_T, the inclusive jet asymmetry is sensitive to the twist-3 correlators associated with the gluon Sivers function

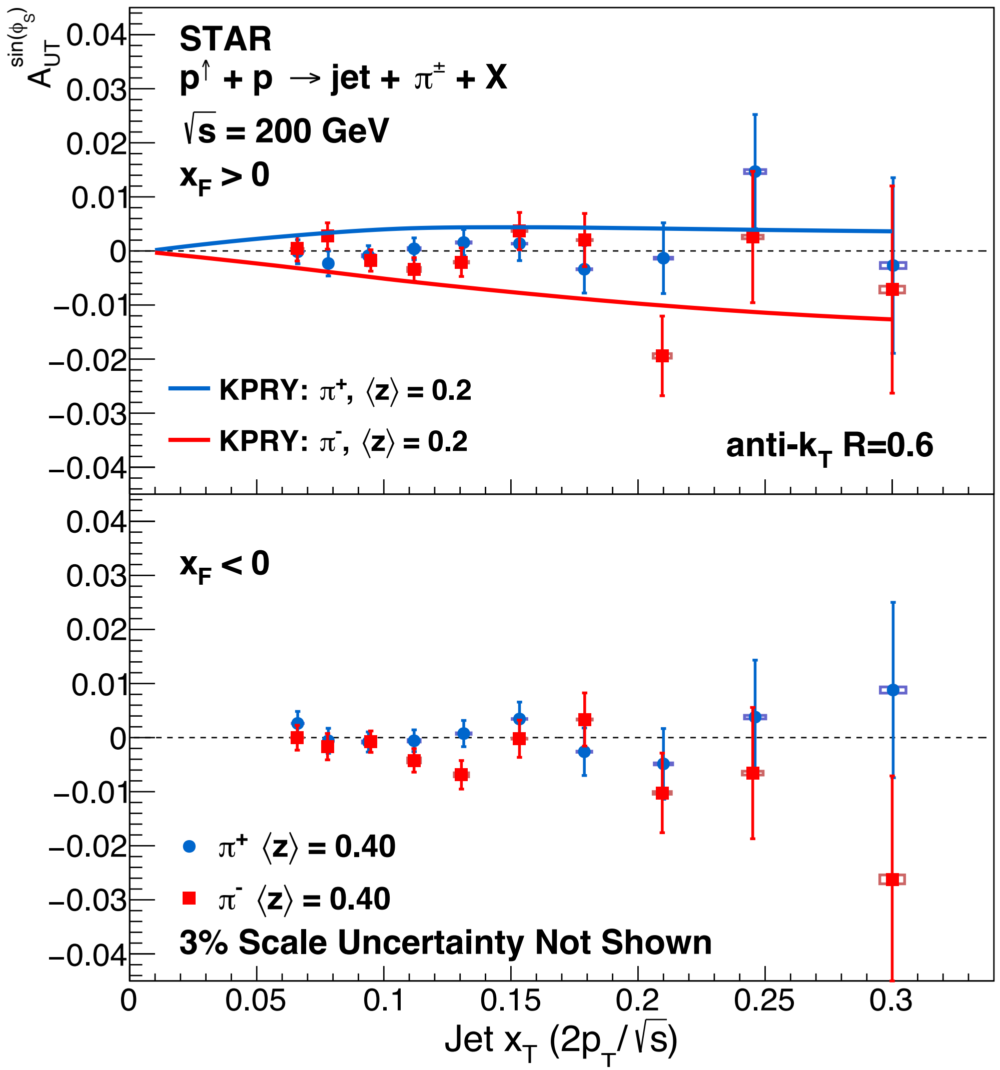
- 510 GeV results extend the measurement to lower values of x

- Results are consistent with zero within uncertainties

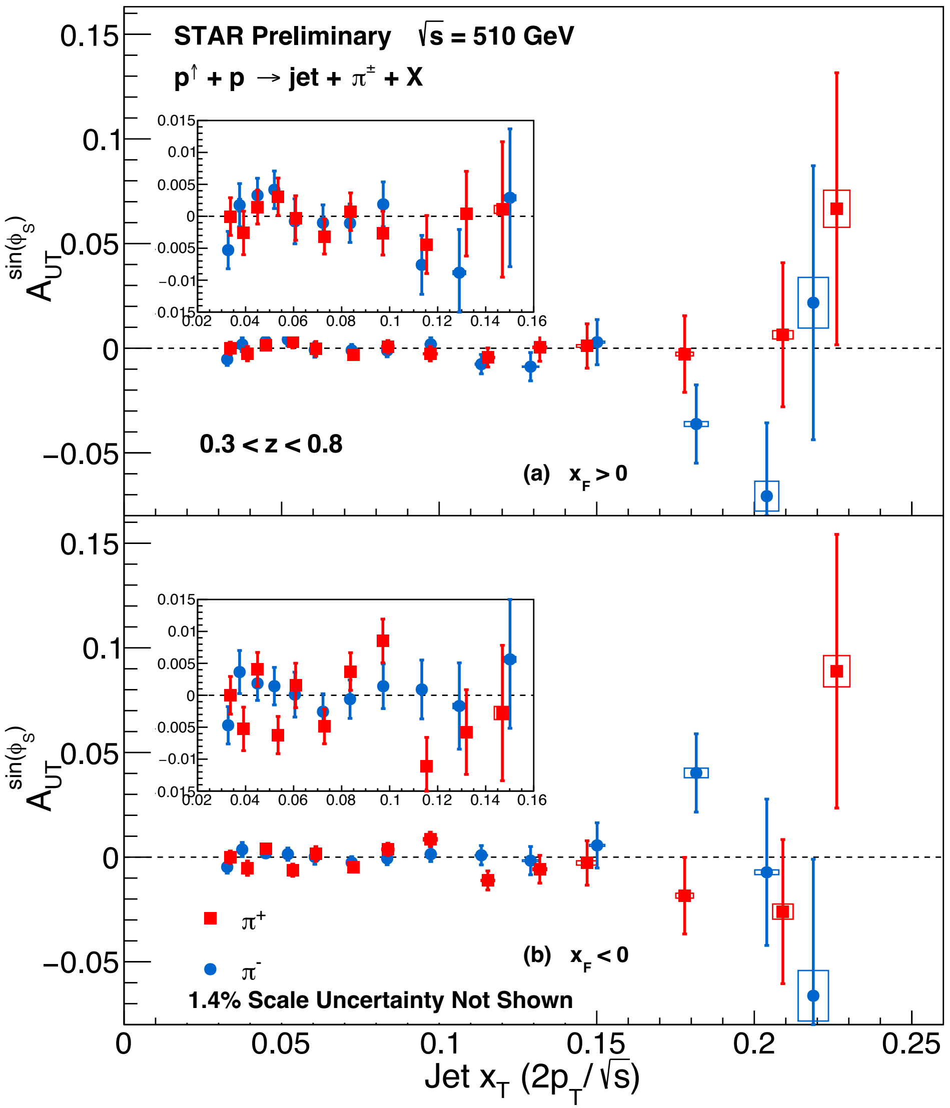


Mid-Rapidity: Pion Tagged Jet Asymmetry at 200 and 510 GeV

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



u (for π^+) and d (for π^-) quark functions are enhanced by performing the pion tagging, providing sensitivity to the twist-3 correlators associated with the quark Sivers function



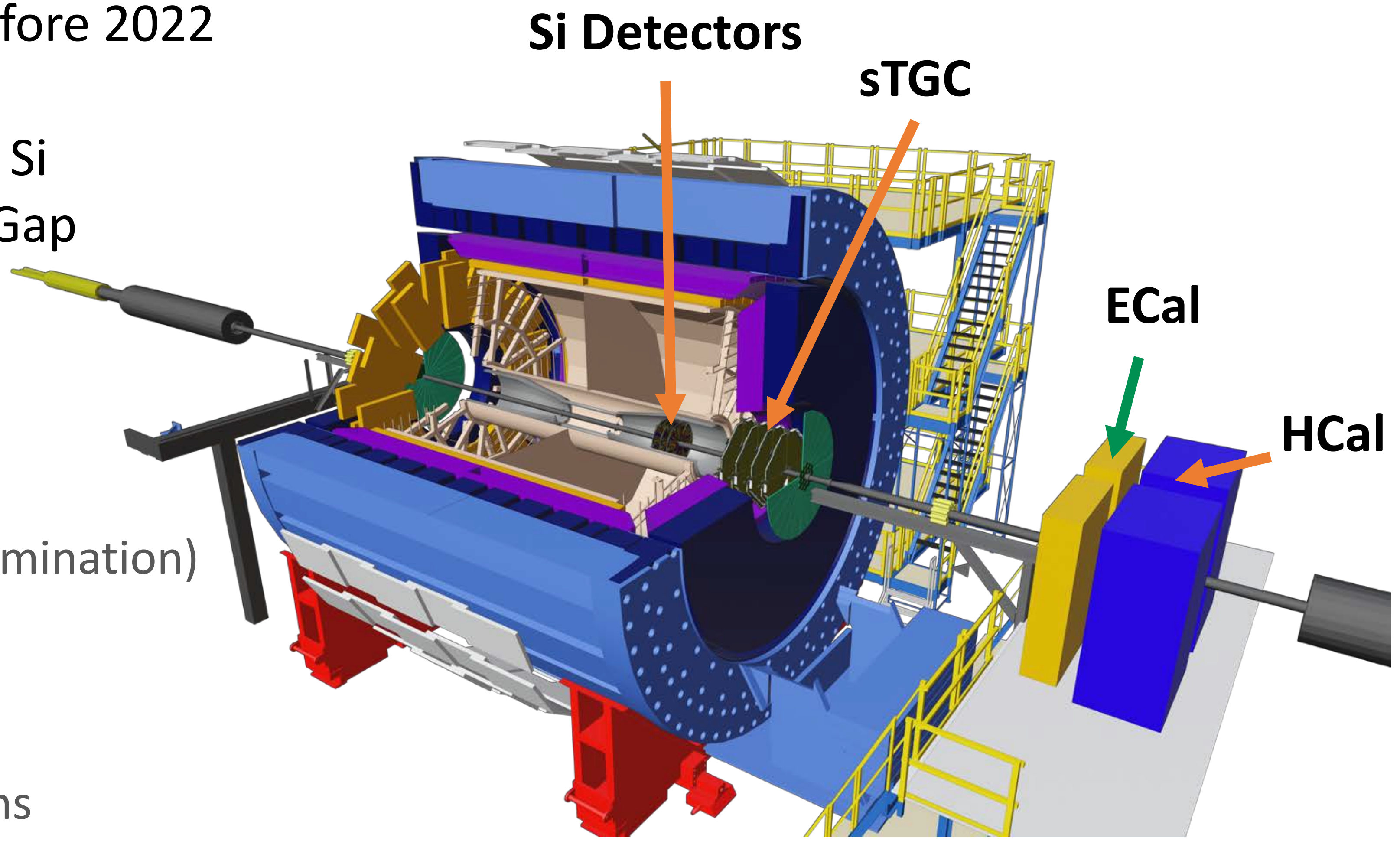
KPRY: Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017), arXiv:1707.00913

Results are consistent with zero within uncertainties

Outlook

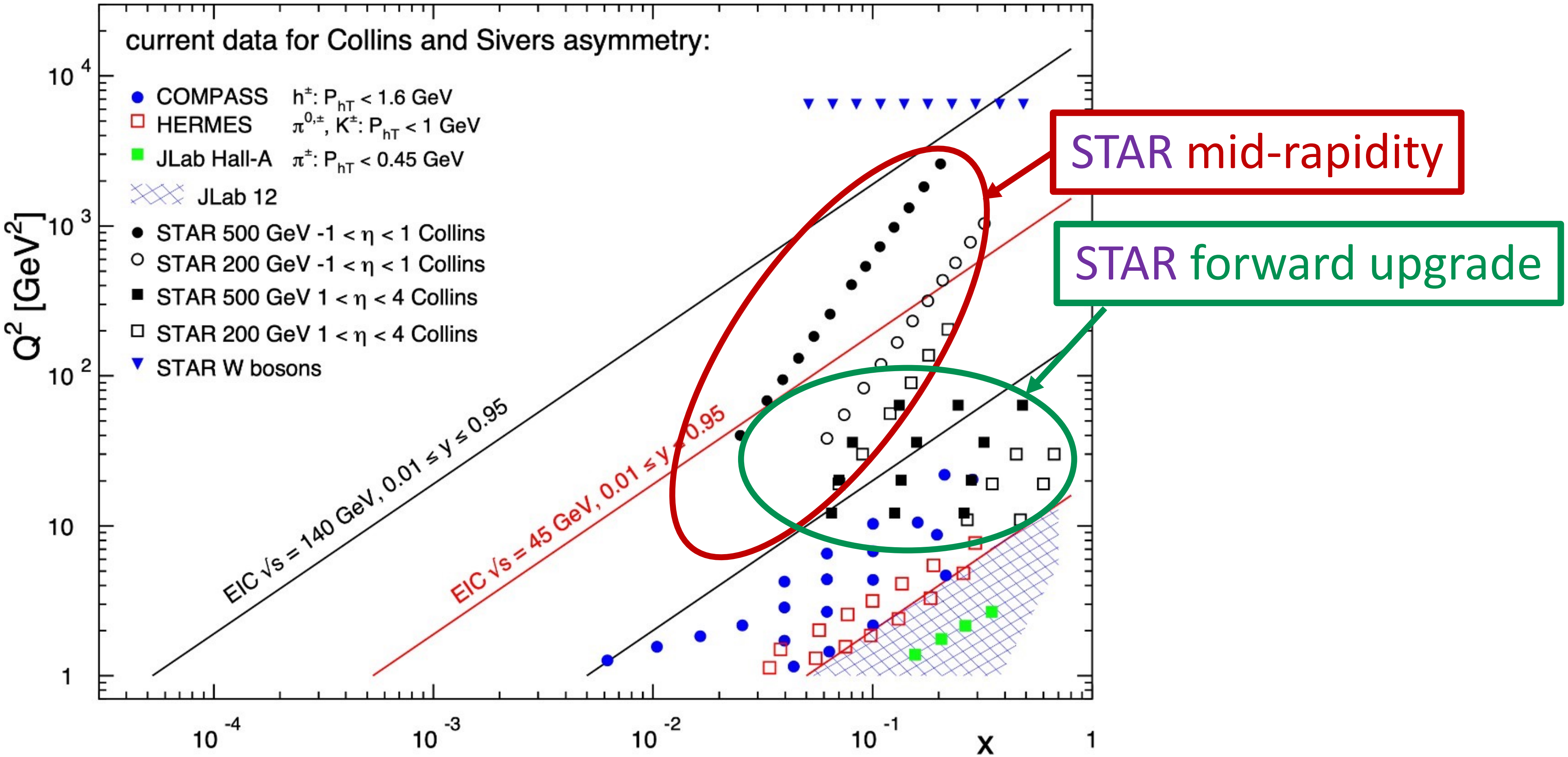
STAR Forward Upgrade:

- Installed and commissioned before 2022
- $2.5 < \eta < 4$
- Charged particle tracking using Si detectors and small-strip Thin Gap Chambers (sTGC)
- Electromagnetic and hadronic calorimetry
- Capable of measuring:
    - $h^{\pm}$, $e^{\pm}$ (with good e/h discrimination) Photons, π^0
    - Jets, hadrons in jets
    - Lambda's
    - Drell-Yan and J/ψ di-electrons
    - Mid-forward and forward-forward correlations



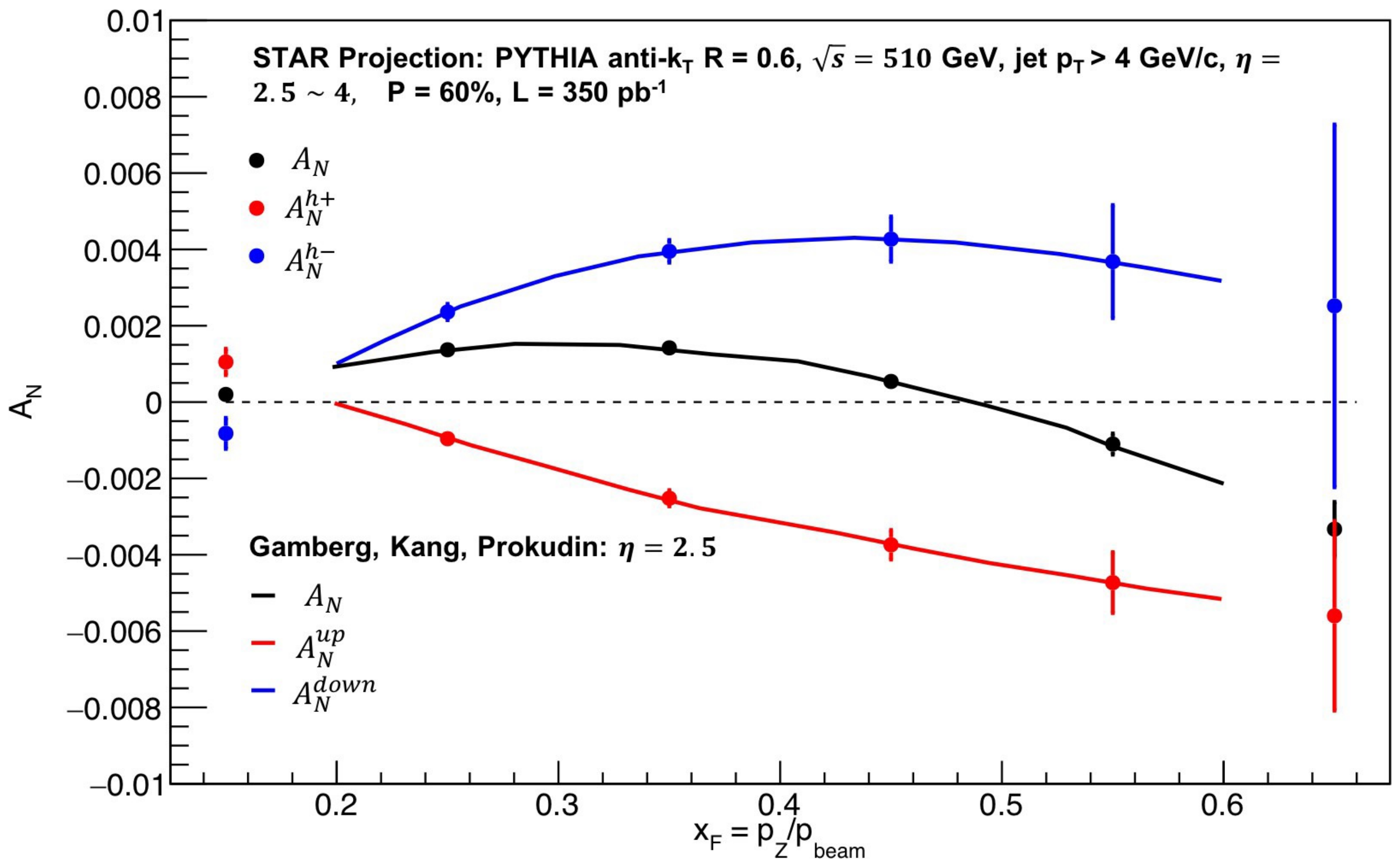
- Quarks up to $x{\sim}0.5$ and gluons down to $x{\sim}0.001$

Outlook



- The mid + forward rapidity capabilities of STAR complement the future EIC kinematic coverage
- The forward upgrade will bridge the kinematic region between mid-rapidity STAR and SIDIS
    - great for future Collins measurements

Outlook



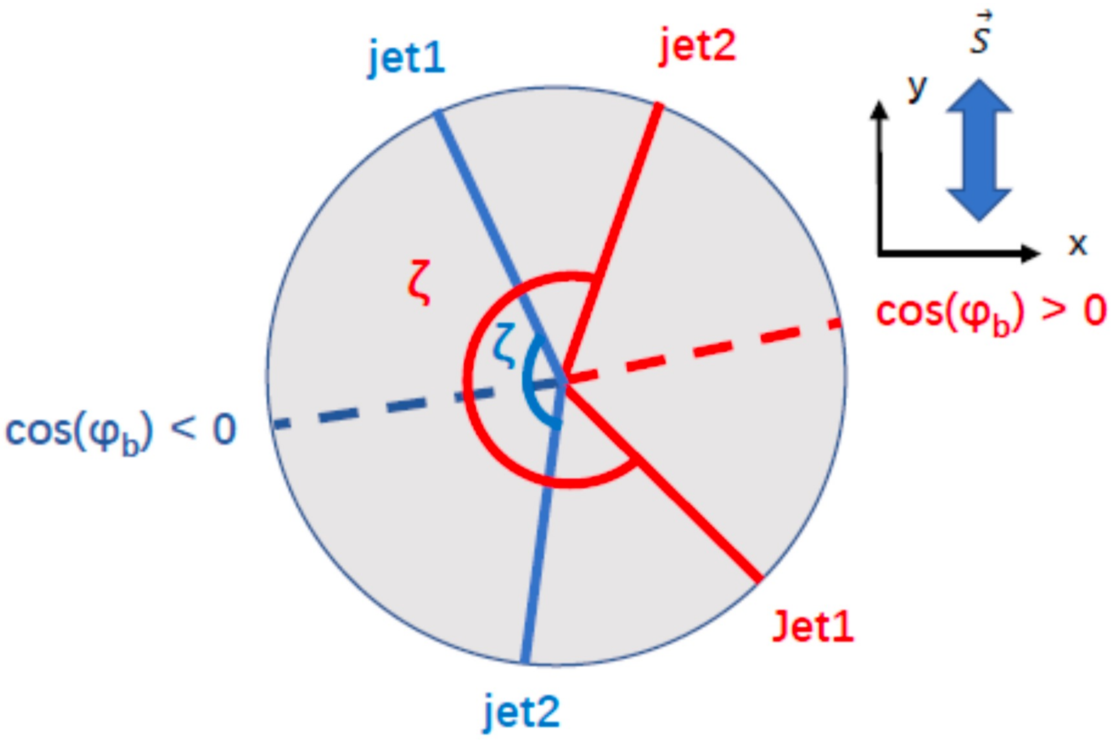
- A_N for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with $z > 0.5$
- Up to 10σ separation between plus-tagged and minus-tagged jet A_N

Summary

- Spin-dependent $\langle k_T \rangle$ from dijet production and A_N from $W^{\pm}/Z^0$ studies at STAR provide probes for the Sivers effect
- The Z^0 cross section gives insights into the evolution of the unpolarized TMDs
- The Collins effect is studied at two energy levels and show little to no energy dependence
- Di-pion asymmetries and cross-section results from STAR can provide the initial steps to model-independent transversity extractions
- $\Lambda(\overline{\Lambda})\ D_{TT}$ is sensitive to the (anti-)strange quark transversity in the proton
- EM-jet A_N results at forward rapidity for single diffractive processes show no large contribution for the observed large TSSA in the forward direction
- The Forward Upgrade extends the kinematic range of the measurements at STAR, which are essential for universality studies at the future EIC

Backup

Probing The Sivers Effect Using Dijet Production



- φ_b: dijet bisector angle
- $\zeta > \pi$ if $\cos(\varphi_b) > 0$
- $\zeta < \pi$ if $\cos(\varphi_b) < 0$

- The signed opening angle, ζ, is sensitive to the spin-dependent partonic k_T involved in characterizing the Sivers effect.
- A Conversion from the spin-dependent ζ asymmetries ($\Delta\zeta$) to Sivers $\langle k_T \rangle$ can be achieved

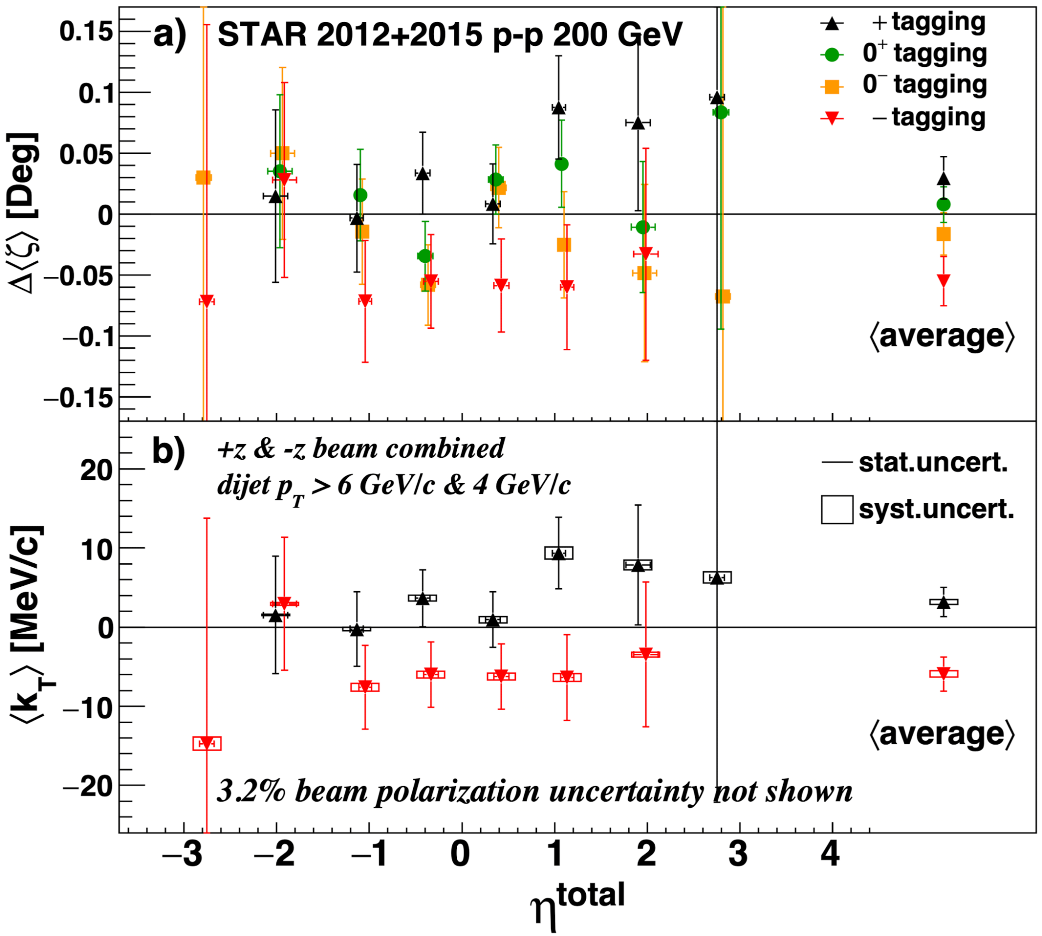
$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

$\langle\zeta\rangle^{\pm}$: the centroid of the distribution for spin-up/spin-down proton beams

P: magnitude of beam polarization

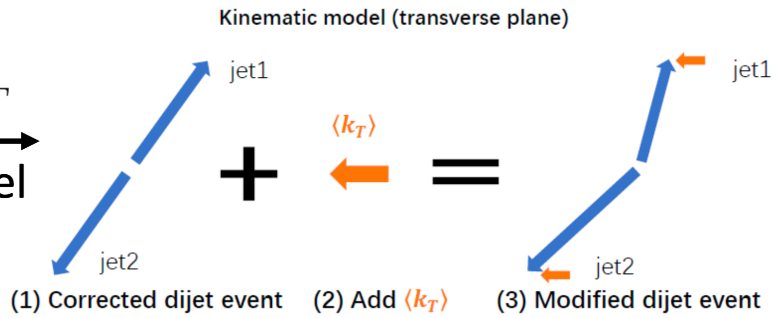
Tagged $\Delta\zeta$ and $\langle k_T \rangle$ From Tagged Dijet Production

STAR, arXiv:2305.10359

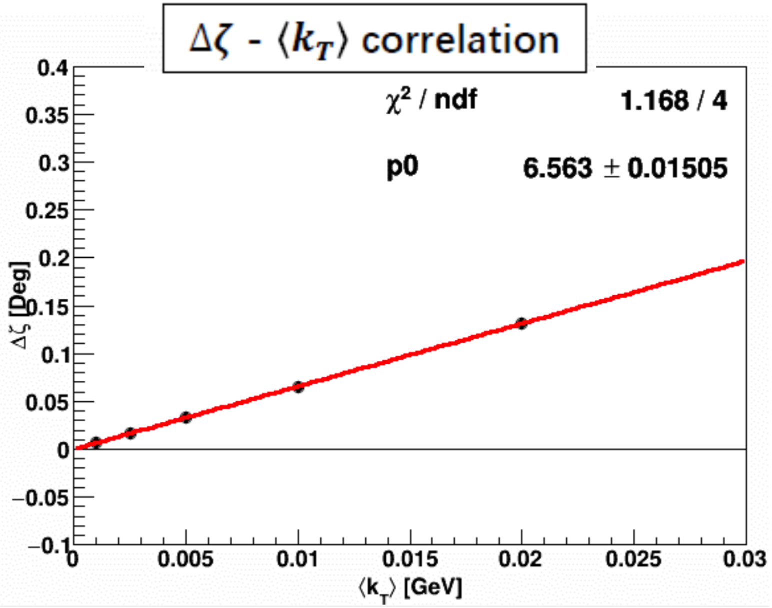


- $\sim 3.1\sigma$ separation between + and − tagging
- Asymmetry shifts from positive to negative when going from + to − tagging → strong evidence that Sivers $\langle k_T \rangle$ in u and d are opposite

$\Delta\zeta$- $\langle k_T \rangle$ Correlation: correct jet p_T → to parton level



map $\Delta\zeta$-$\langle k_T \rangle$ → correlation



+: enhancing the fraction of u

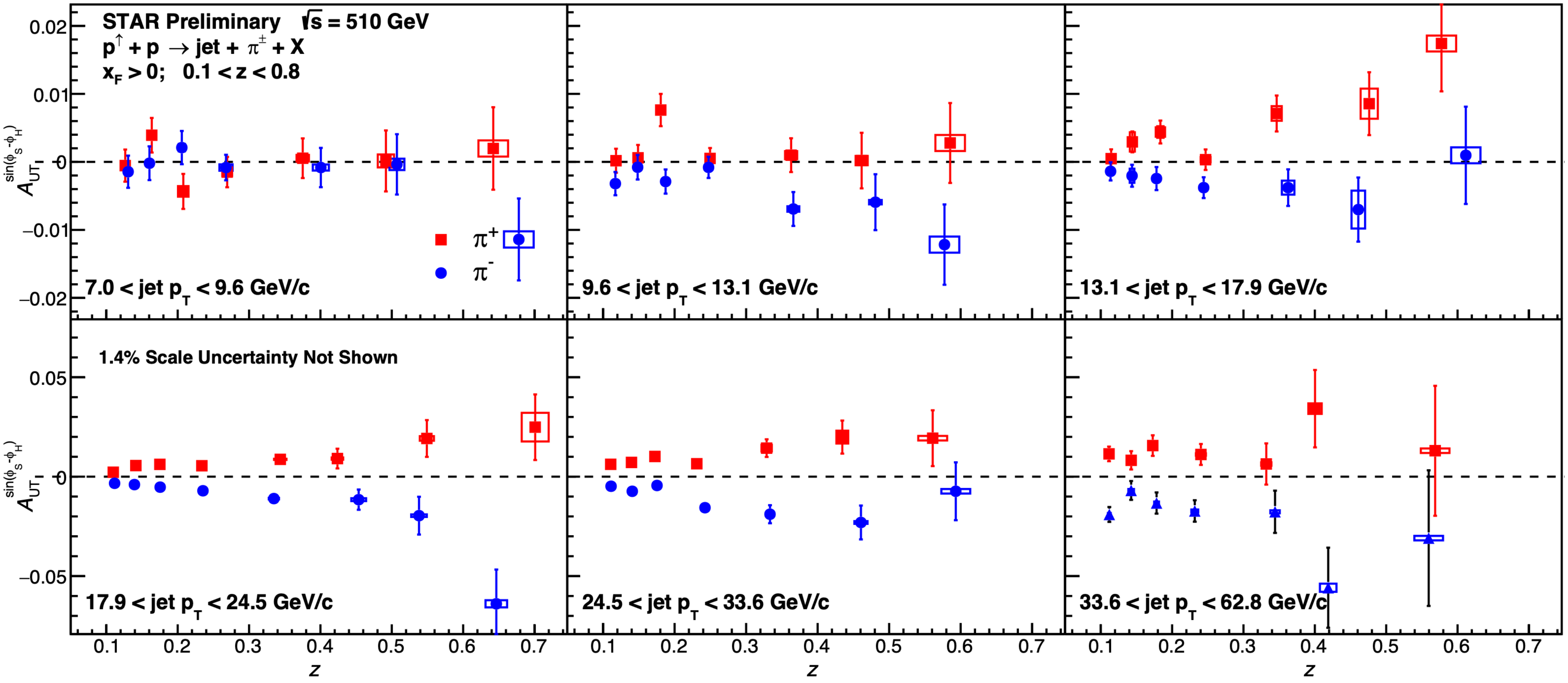
0^+: less enhancement in the u fraction

0^-: less enhancement in the d fraction

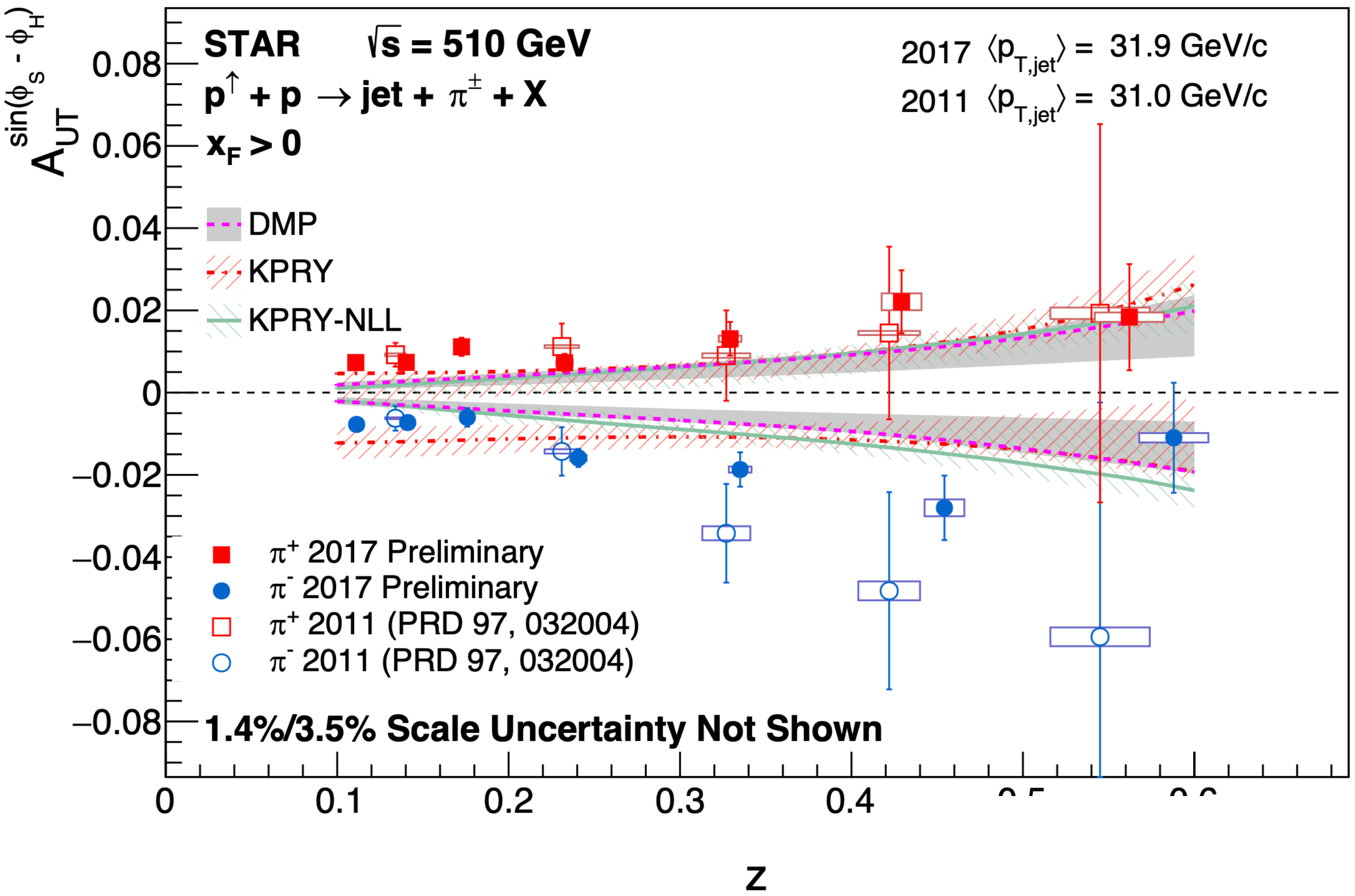
−: enhancing the fraction of d

$$\eta^{total} = \eta_1 + \eta_2 \propto \ln(x_1/x_2)$$

Collins Asymmetry vs. z from 510 GeV



Collins Asymmetry from 510 GeV vs. Theory



Theory curves:

- KPRY: Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017), arXiv:1707.00913
- DMP+2013: U. D'Alesio, F. Murgia, and C. Pisano, Phys. Lett. B **773**, 300 (2017), arXiv:1707.00914

- The 2011 and 2017 experimental results for A_{UT} agree with each other
- Overall, the theoretical models underestimate the experimental results

Detailed Future Work

- EM-Jet A_N:
  - Data from Run 2022 and 2024 using the Forward Upgrade will improve precision of measurement
- Dijet Sivers:
  - Combining existing results with data from 2017 and 2022 at 510 and 508 GeV, respectively, to explore the x-dependence of the measurement
- $W^{\pm}$ and Z^0 A_N:
  - STAR recorded 400 pb^{-1} during Run 2022 utilizing the Forward Upgrade detectors
  - iTPC extends the η coverage
- Collins Asymmetries:
  - Use polarized $p + \mathrm{Au}$ data from 2015 to measure the Collins asymmetry
  - Use 2022 and 2024 data with the Forward Upgrade for Collins measurements in the forward direction
- Di-pion Asymmetries:
  - Use data from Run 2022 and 2024 to perform a precision measurement of IFF asymmetries of pion and kaons