



Testing Factorization and Universality of the Collins Asymmetry with p Au Collisions

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May 4th - 8th, 2026

Supported in part by:



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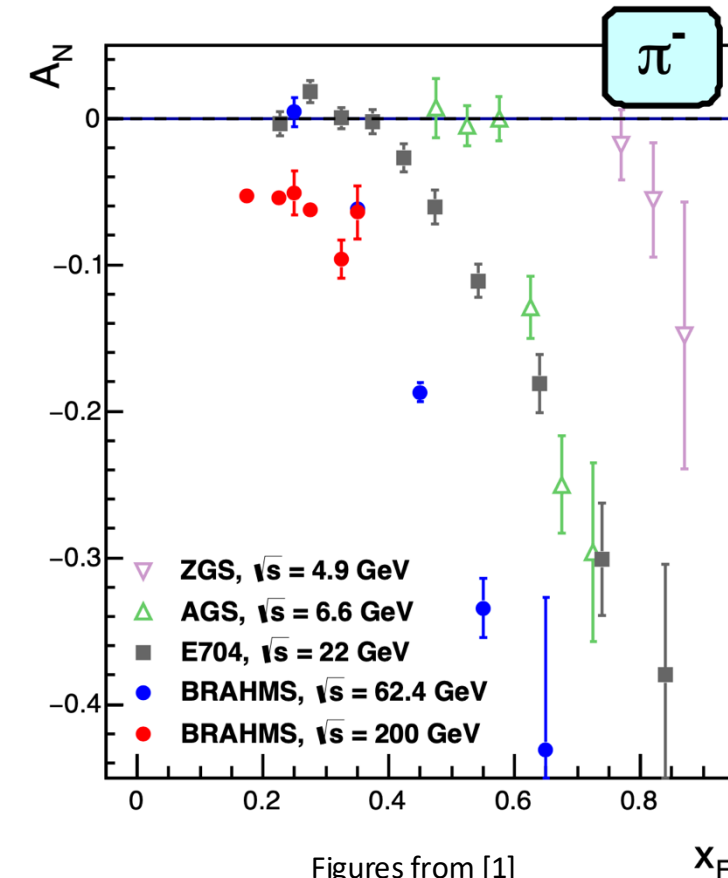
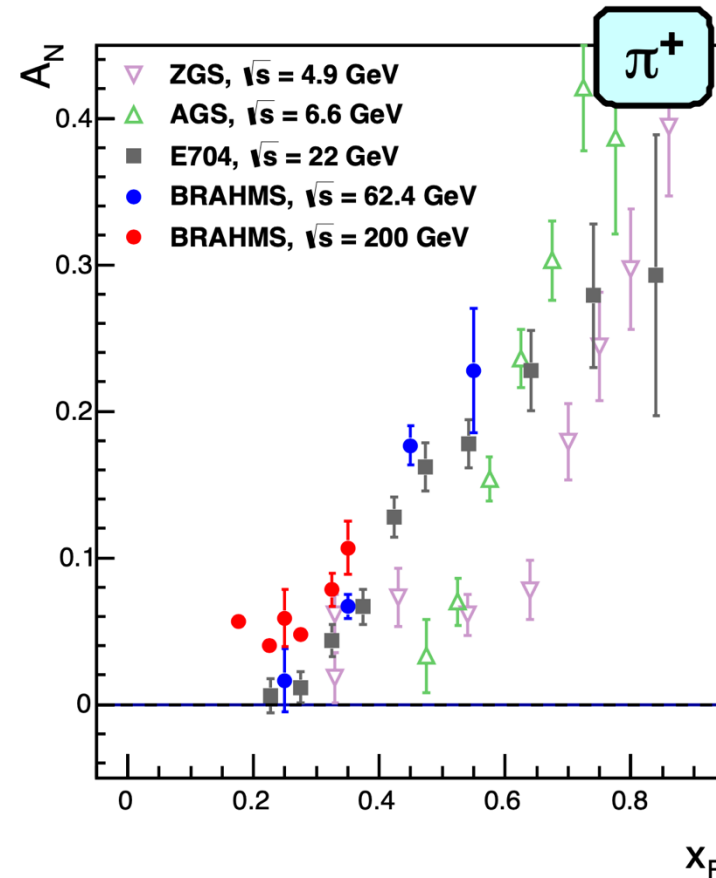
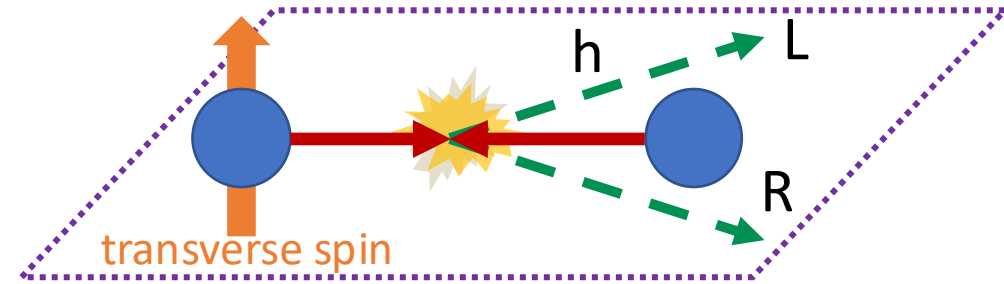


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Transverse Single-Spin Asymmetries (TSSA's) - A_N

- Large TSSAs have been observed in forward hadron production in polarized pp collisions since the 1970s
- Perturbative QCD predicts A_N to be small
- Twist-3 and TMD frameworks were developed to explain these large asymmetries

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



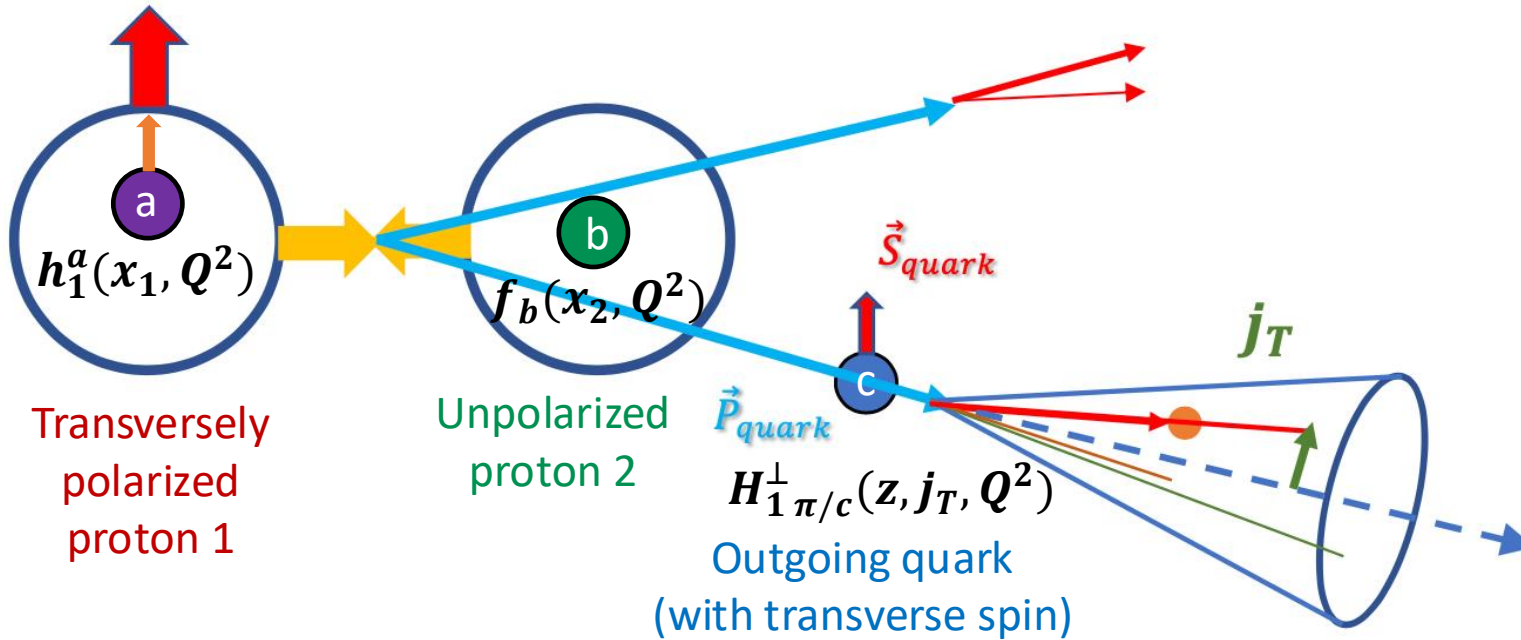
Figures from [1]

x_F

2/23

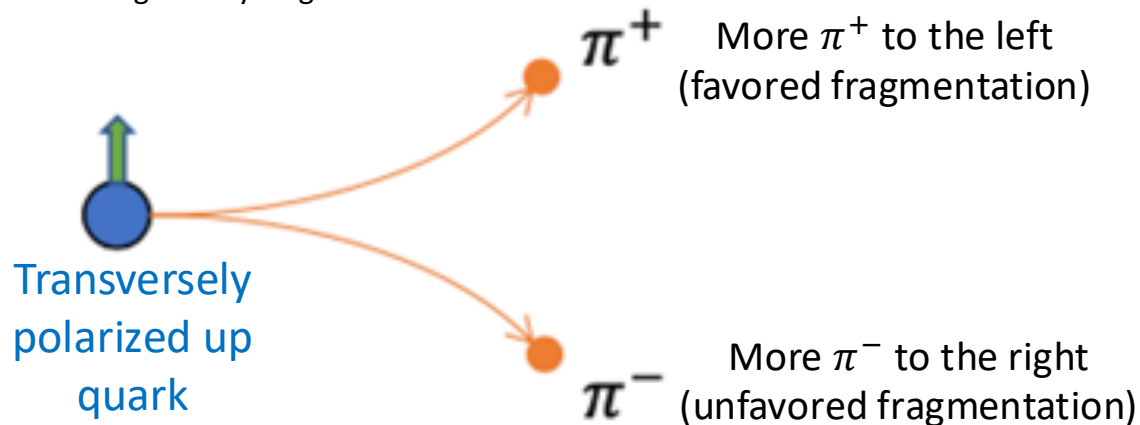
[1] Elke Aschenauer et al., arXiv:1602.03922 [nucl-ex].

A Mechanism for A_N : The Collins Effect



- Probes transversity \otimes Collins FF
- Measured as an azimuthal modulation of hadrons around the jet axis

Diagrams by Ting Lin



J. C. Collins, Nucl. Phys. B **396**, 161 (1993).
 Z.-B. Kang, X. Liu, F. Ringer, and H. Xing, JHEP **11**, 068 (2017).
 Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017).

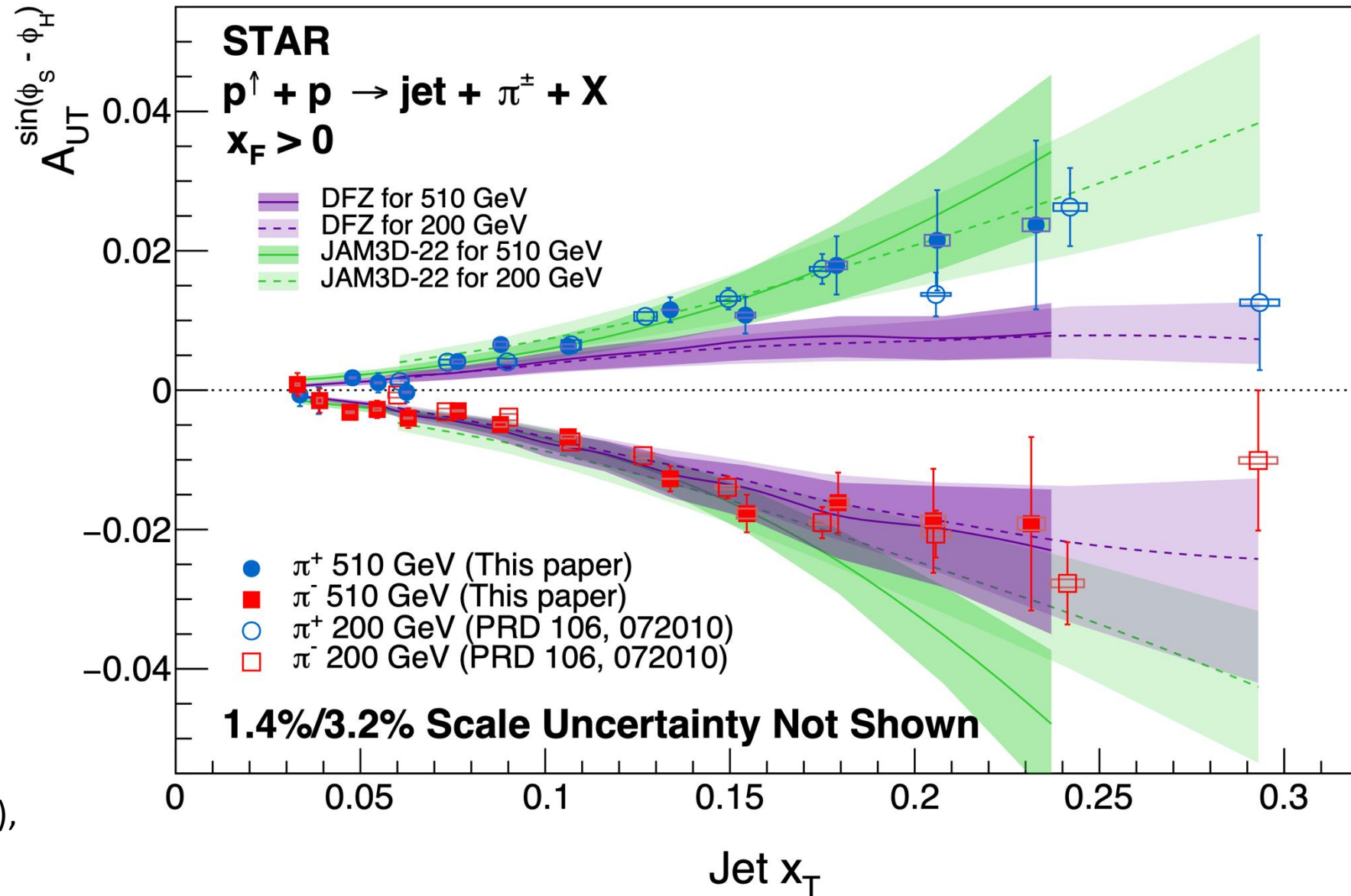
Previous STAR pp Collins Results

STAR has observed large Collins asymmetries for pions in jets at midrapidity in polarized pp collisions at $\sqrt{s} = 200$ and 510 GeV

$$x_T = \frac{2p_T^{jet}}{\sqrt{s}}$$

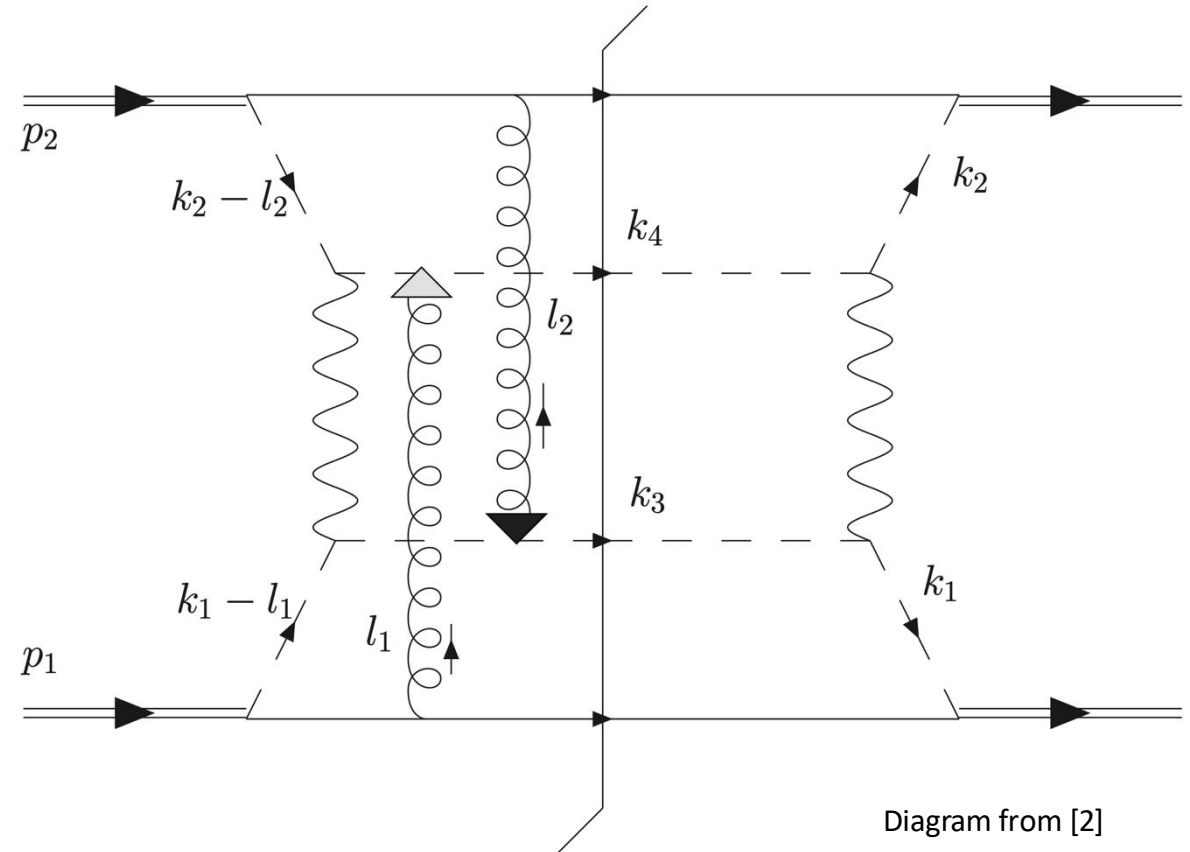
pp200: STAR, *Phys. Rev. D* **106**(7), 072010 (2022).

pp510: STAR, *Phys. Rev. Lett.* **135**(26), 261902 (2025).



TMD Factorization and Universality

- TMD factorization and universality are essential for measurements of one process to enable predictions for other processes
- In hadro-production, TMD factorization is predicted to fail for TMD PDFs [1, 2]
- The argument involves extra soft-gluon color interactions not present in SIDIS
- The size of the effect is not predicted, and the implications for TMD FFs are not established



- For the specific case of the Collins asymmetry, explicit calculations have shown that factorization is preserved at the one- and two-gluon exchange level [3, 4]

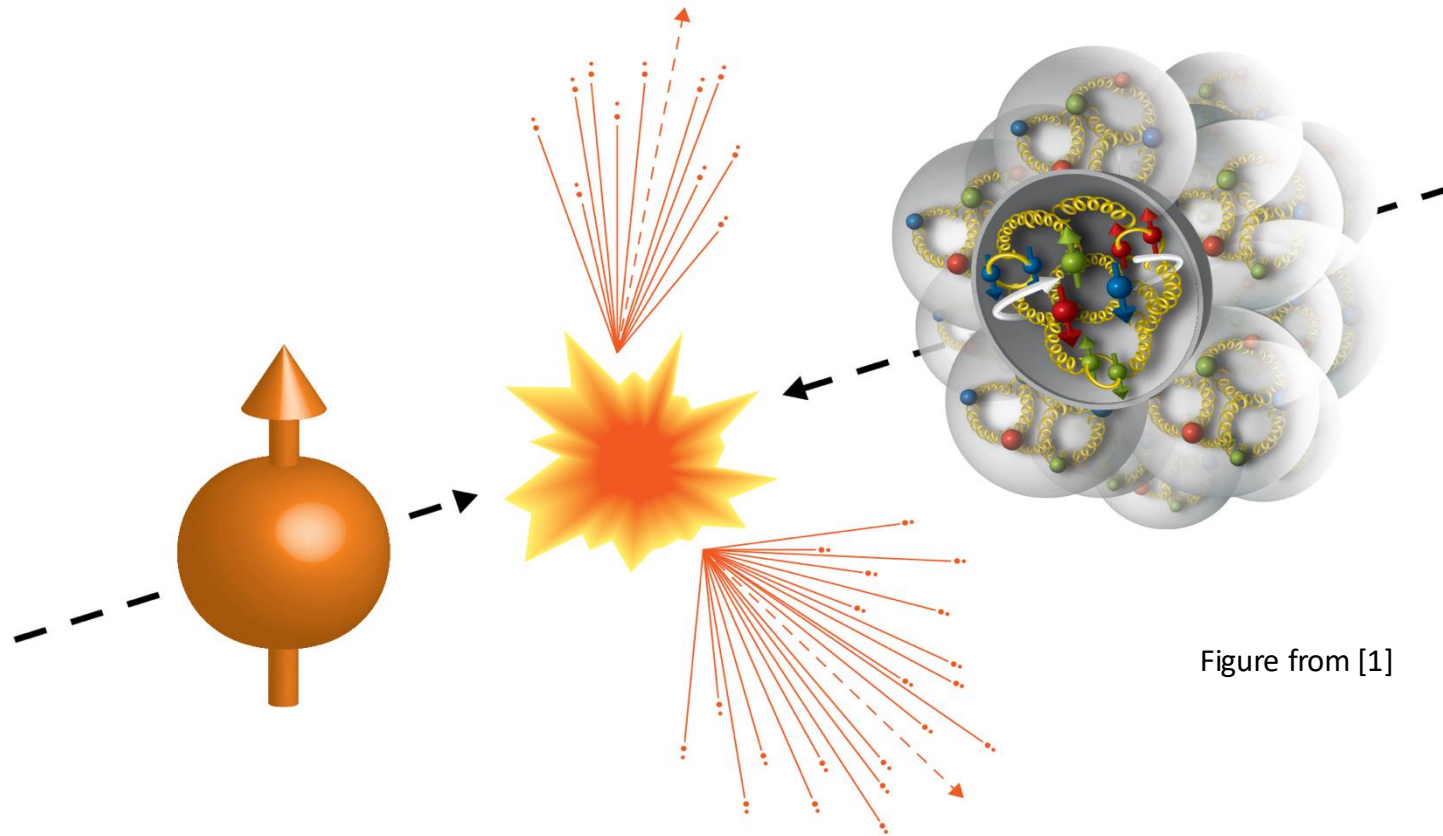
[1] Collins and J.-W. Qiu, Phys. Rev. D **75**, 114014 (2007).

[2] T. C. Rogers and P. J. Mulders, Phys. Rev. D **81**, 094006 (2010).

[3] F. Yuan, Phys. Rev. Lett. **100**, 032003 (2008).

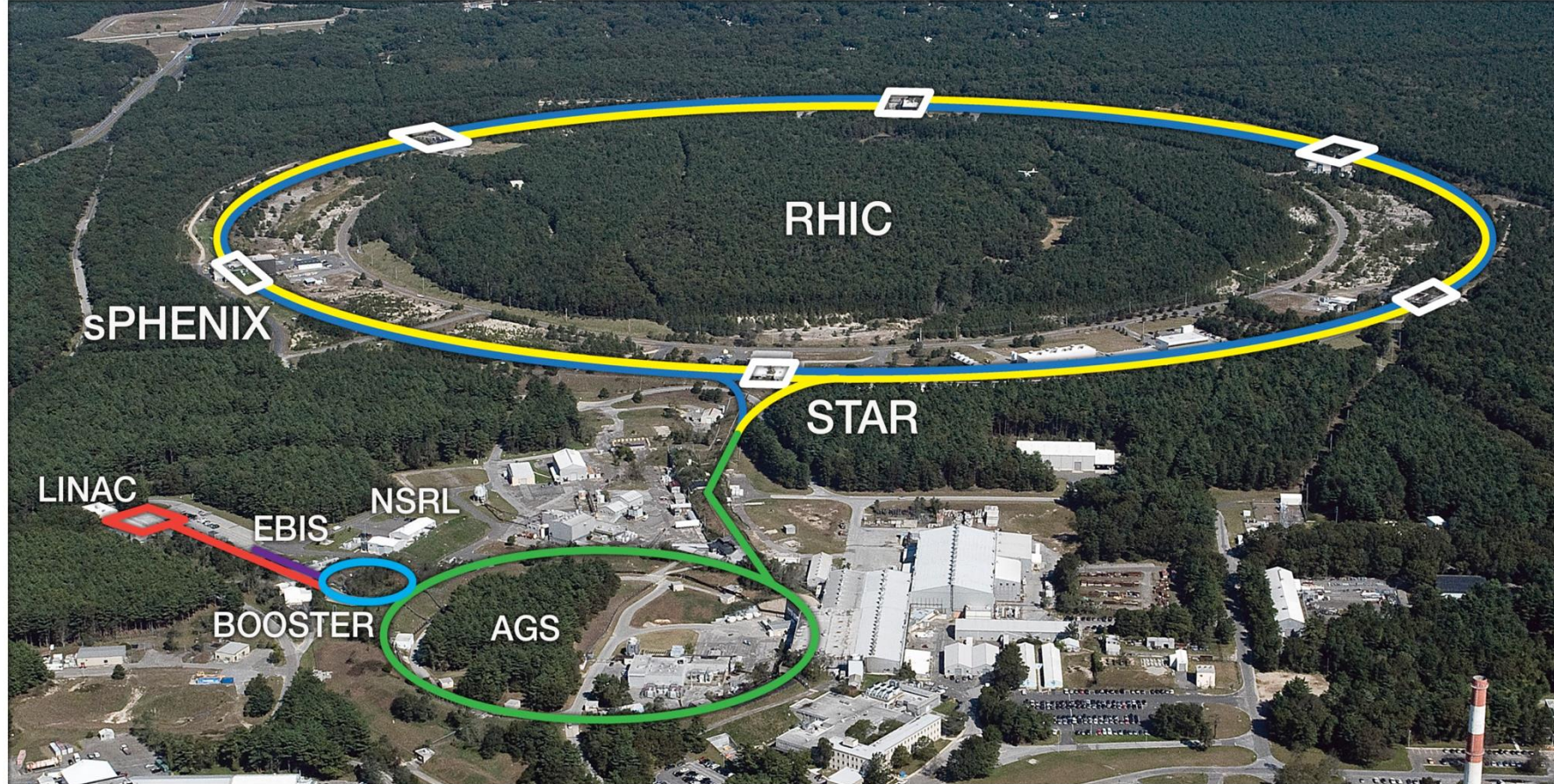
[4] F. Yuan, Phys. Rev. D **77**, 074019 (2008).

Why Polarized pAu ?



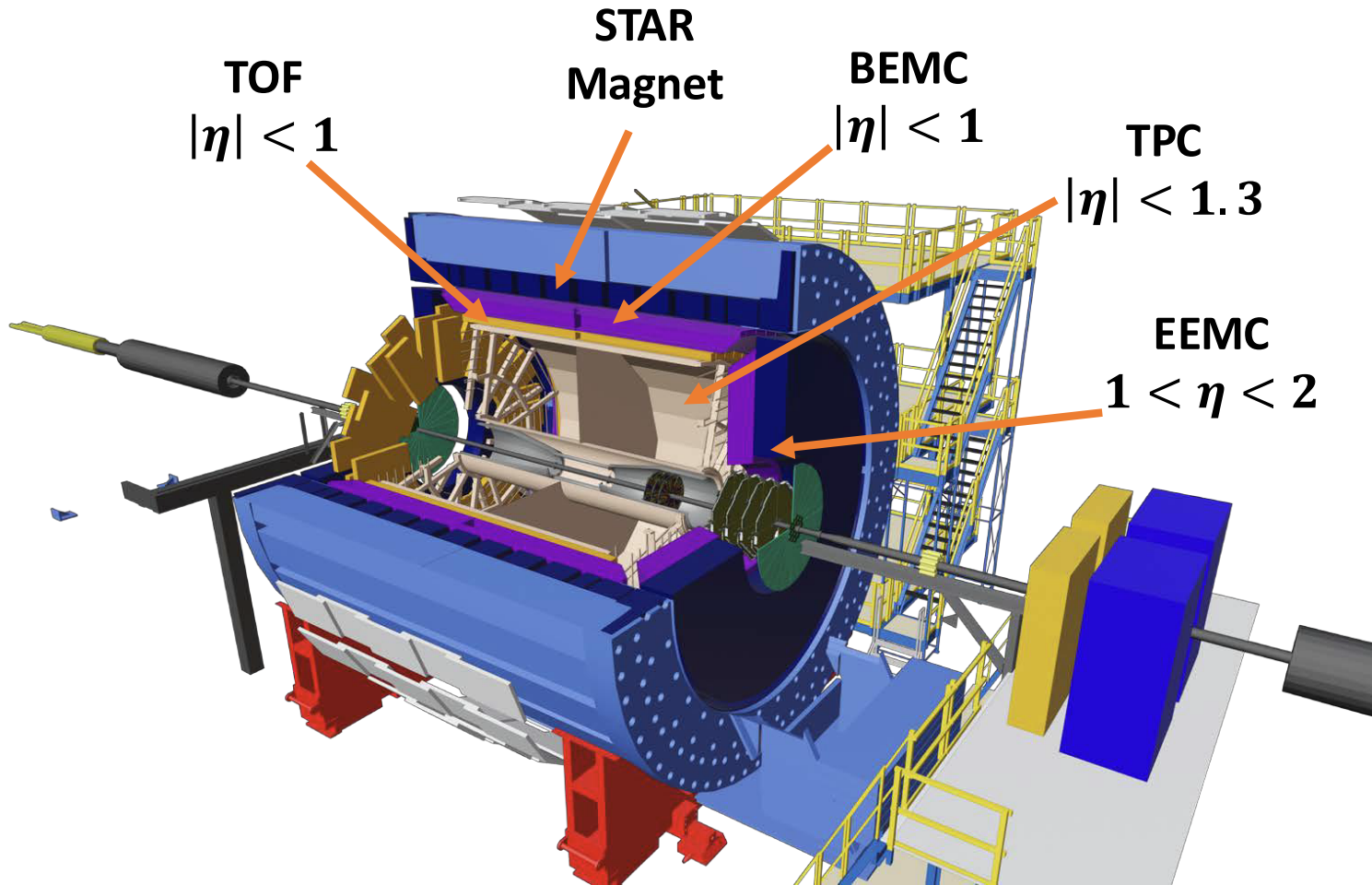
- pAu provides a nuclear environment to test possible departures from pp
- Probes the spin dependence of cold nuclear matter effects
- Provides insight into the factorization and universality of TMD functions

RHIC: Relativistic Heavy Ion Collider

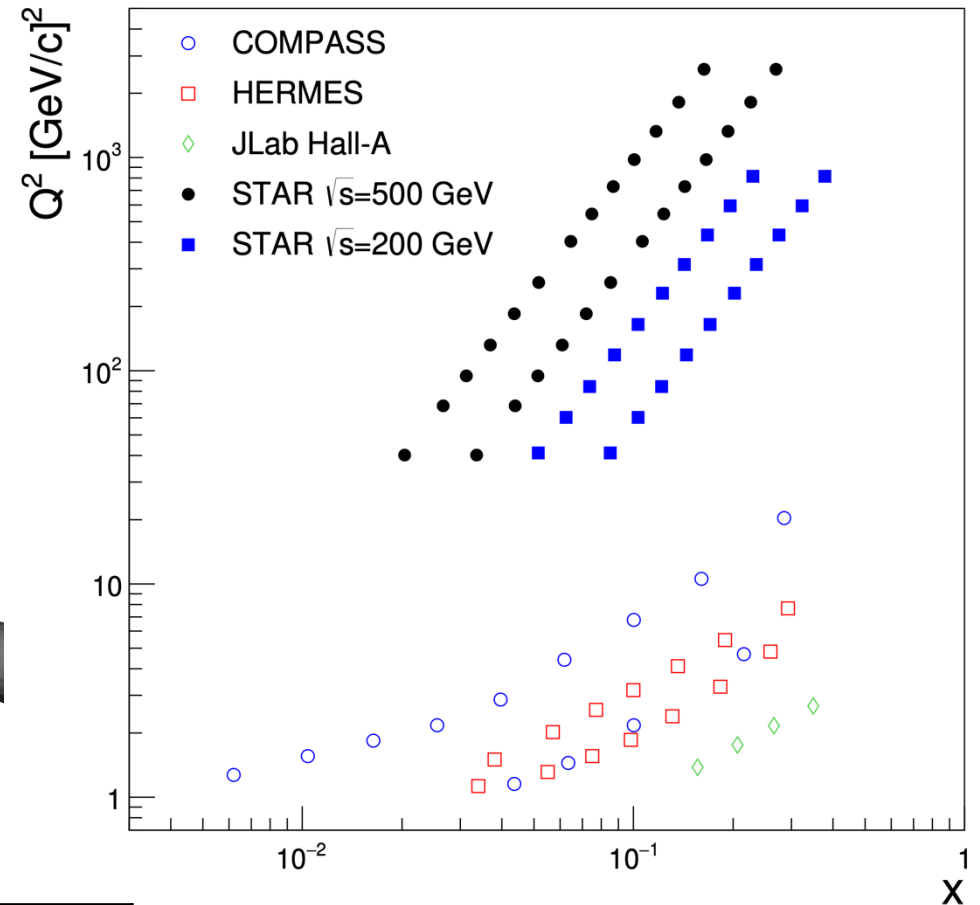


- The only machine in the world capable of colliding high-energy beams of polarized protons
- The beams travel in opposite directions around RHIC's 3.86 km two-lane racetrack
- Provides a wide range of center-of-mass energies (up to 510 GeV)

STAR: Solenoidal Tracker At RHIC



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



PID and tracking	TOF and TPC cover $ \eta < 1$ and full azimuth
Calorimetry and triggering	BEMC covers $ \eta < 1$ and full azimuth EEMC covers $1.08 < \eta < 2.0$ and full azimuth

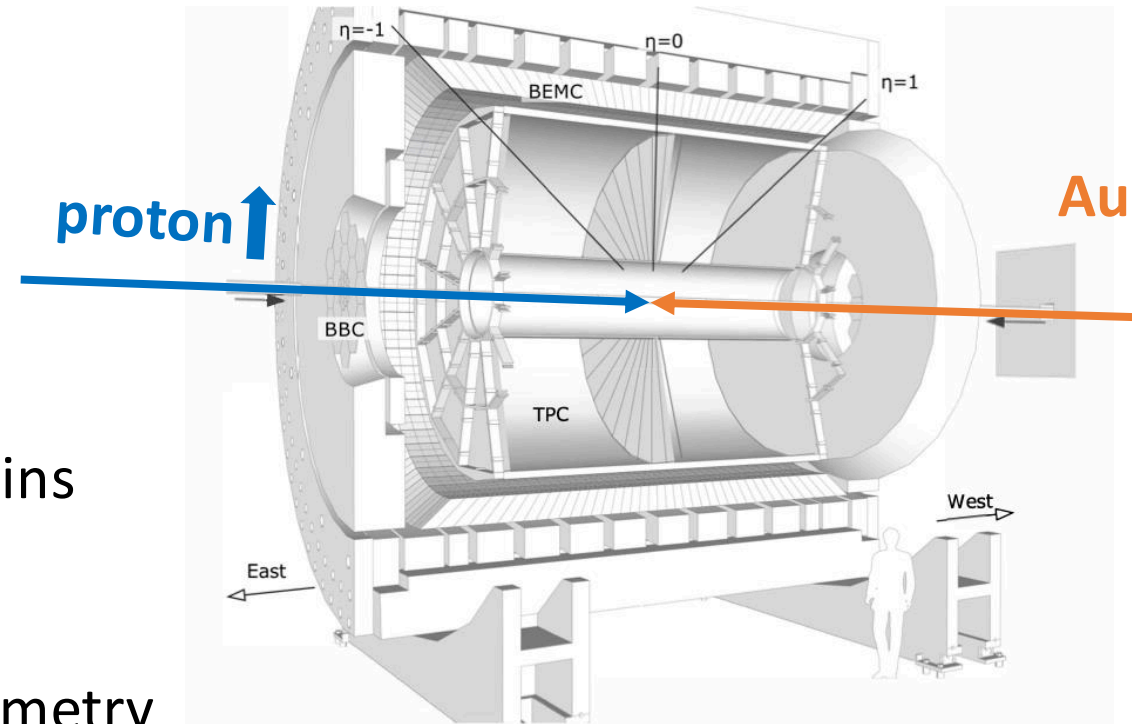
Similar x coverage, but at higher Q^2 than SIDIS

Analysis and Data Information

Run Year	2015
Run Period	$p\text{Au}$ at $\sqrt{s_{NN}} = 201$ GeV
Number of events	~ 323 million
Luminosity from good runs	361 nb^{-1}

The jet axis is required to be in $0 \leq \eta \leq 0.9$

- Polarized proton-going direction, where the Collins asymmetry is the largest in pp
- The Au-going direction has smaller Collins asymmetry in pp and larger background in $p\text{Au}$



Jet Reconstruction

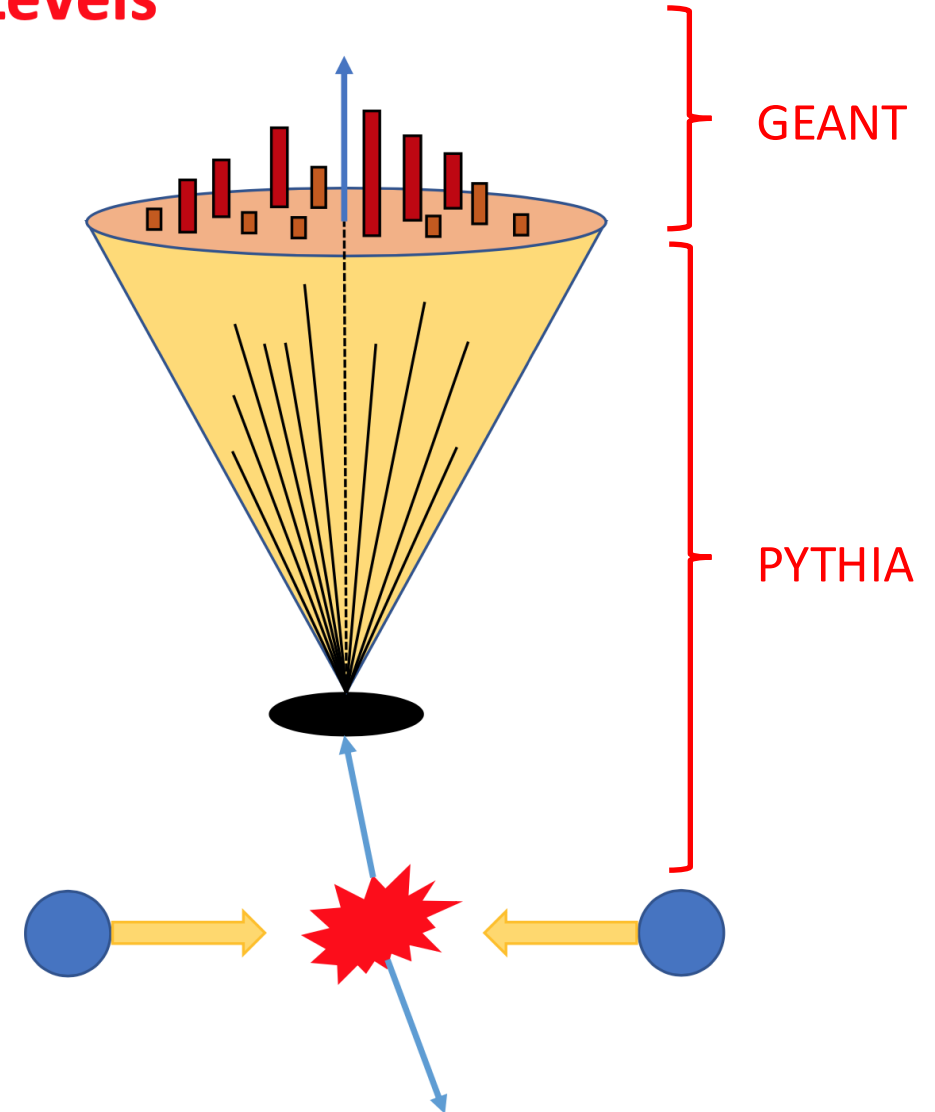
- TPC and EMC data are used to reconstruct anti- k_T jets with $R = 0.6$
- Corrections and detector effects are estimated with PYTHIA 6 + GEANT3 embedding

Jet Levels

Detector

Particle

Parton



Observable

Equation for the relative difference of the spin-dependent cross sections of hadrons in jets [1]:

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

- Measure $A_{UT}^{\sin(\phi_S - \phi_H)}$ for identified pions in jets
- ϕ_S : proton spin angle relative to reaction plane
- ϕ_H : hadron angle around the jet axis

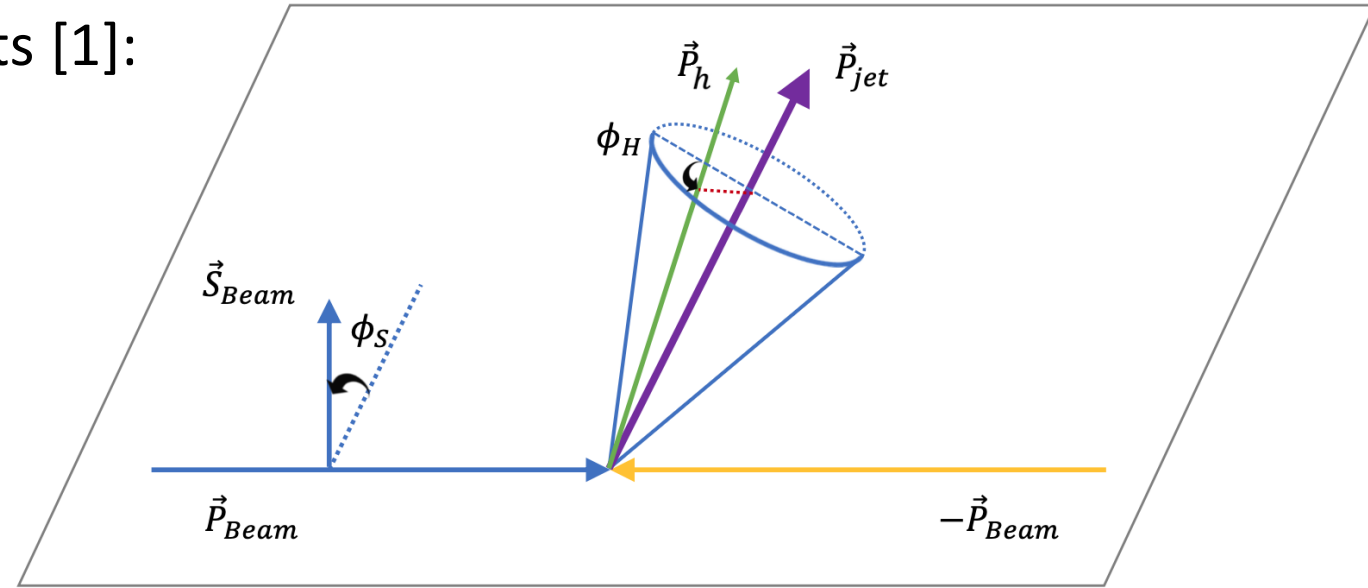


Diagram from Ting Lin and [2]

Reaction plane is defined by polarized beam momentum, \vec{p}_{Beam} , and the momentum of the scattered jet, \vec{p}_{jet}

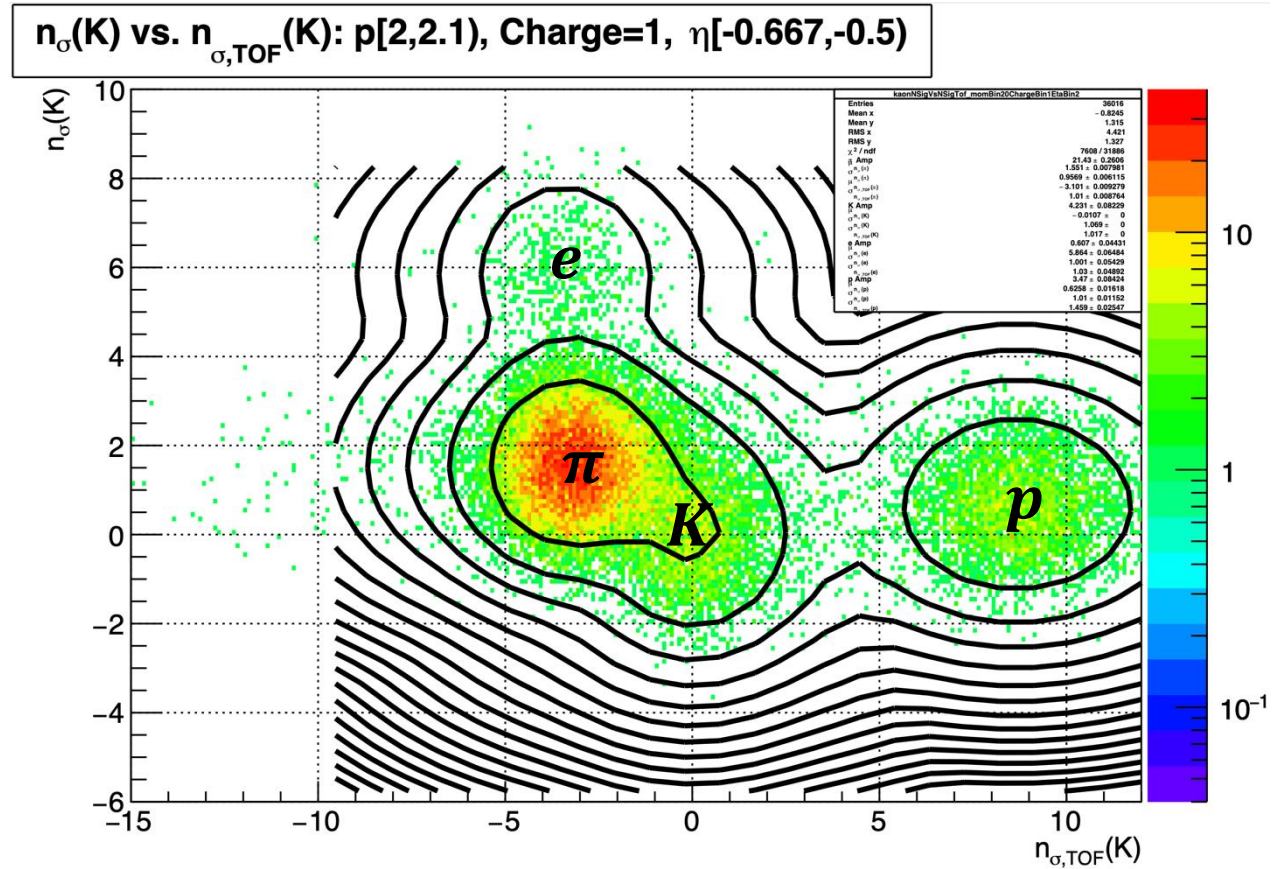
[1] U. D'Aesio, F. Murgia, and C. Pisano, Phys. Rev. D **83**, 034021 (2011).

[2] Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017).

Identifying Particle-Rich Regions

- TPC and TOF data are used to perform particle identification
- A particle fraction matrix is constructed for each particle type in each particle-rich region

Sample PID plot



$$\mathbf{M} = \begin{bmatrix}
 f_{\pi_{rich}}^{\pi \text{ TOF+TPC}} & f_{\pi_{rich}}^{K \text{ TOF+TPC}} & f_{\pi_{rich}}^{p \text{ TOF+TPC}} \\
 f_{K_{rich}}^{\pi \text{ TOF+TPC}} & f_{K_{rich}}^{K \text{ TOF+TPC}} & f_{K_{rich}}^{p \text{ TOF+TPC}} \\
 f_{p_{rich}}^{\pi \text{ TOF+TPC}} & f_{p_{rich}}^{K \text{ TOF+TPC}} & f_{p_{rich}}^{p \text{ TOF+TPC}} \\
 f_{\pi_{rich}}^{\pi \text{ TPC}} & f_{\pi_{rich}}^{K \text{ TPC}} & f_{\pi_{rich}}^{p \text{ TPC}} \\
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 f_{p_{rich}}^{\pi \text{ TPC}} & f_{p_{rich}}^{K \text{ TPC}} & f_{p_{rich}}^{p \text{ TPC}}
 \end{bmatrix}$$

Charge separated and binned in p^{track} and η^{track} bins

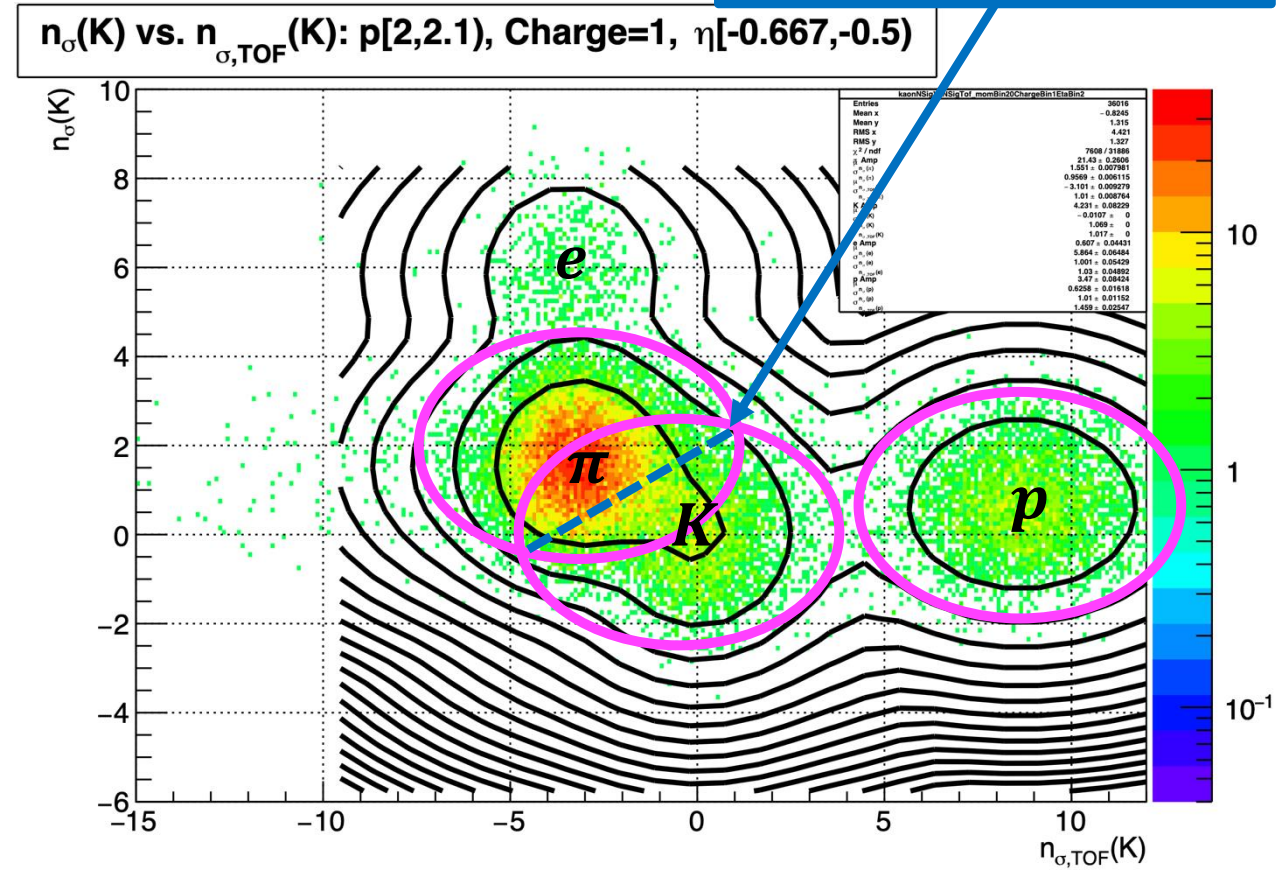
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 f_{p_{rich}}^{\pi \text{ TPC}} & f_{p_{rich}}^{K \text{ TPC}} & f_{p_{rich}}^{p \text{ TPC}}
 \end{bmatrix}$$

Sample PID plot

Example: The dividing line between pion-rich and kaon-rich regions



Charge separated and binned in p^{track} and η^{track} bins

Raw and Pure Collins Asymmetry Extraction

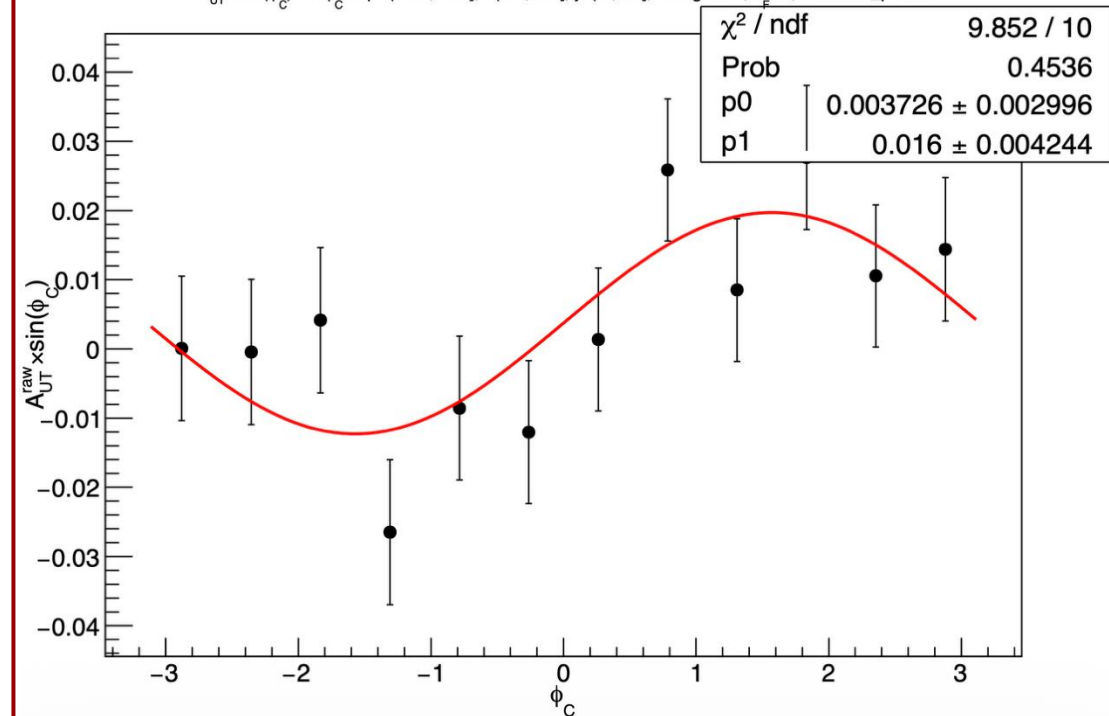
Extracting the Collins asymmetry using the cross-ratio method [1]:

$$A_N \sin(\phi_C) = \frac{\sqrt{N_{1,\alpha}^{\uparrow} N_{1,\beta}^{\downarrow}} - \sqrt{N_{1,\alpha}^{\downarrow} N_{1,\beta}^{\uparrow}}}{\sqrt{N_{2,\alpha}^{\uparrow} N_{2,\beta}^{\downarrow}} + \sqrt{N_{2,\alpha}^{\downarrow} N_{2,\beta}^{\uparrow}}}$$

Here, N_i is the P^i -weighted particle yield for a given particle species (π, K, p) when the spin state is up (\uparrow) or down (\downarrow) in the upper (α) or lower (β) detector half.

$$A_{raw} = M A_{pure}$$

$A_{UT}^{raw} \times \sin(\phi_C)$ vs. ϕ_C in pT(16.3,19.2], z(0.1, 0.8], |T|(0.,2.5], charge=+1, $x_F > 0$, tofMatch_piRich



Fit function: $p_0 + p_1 \times \sin(\phi_C)$

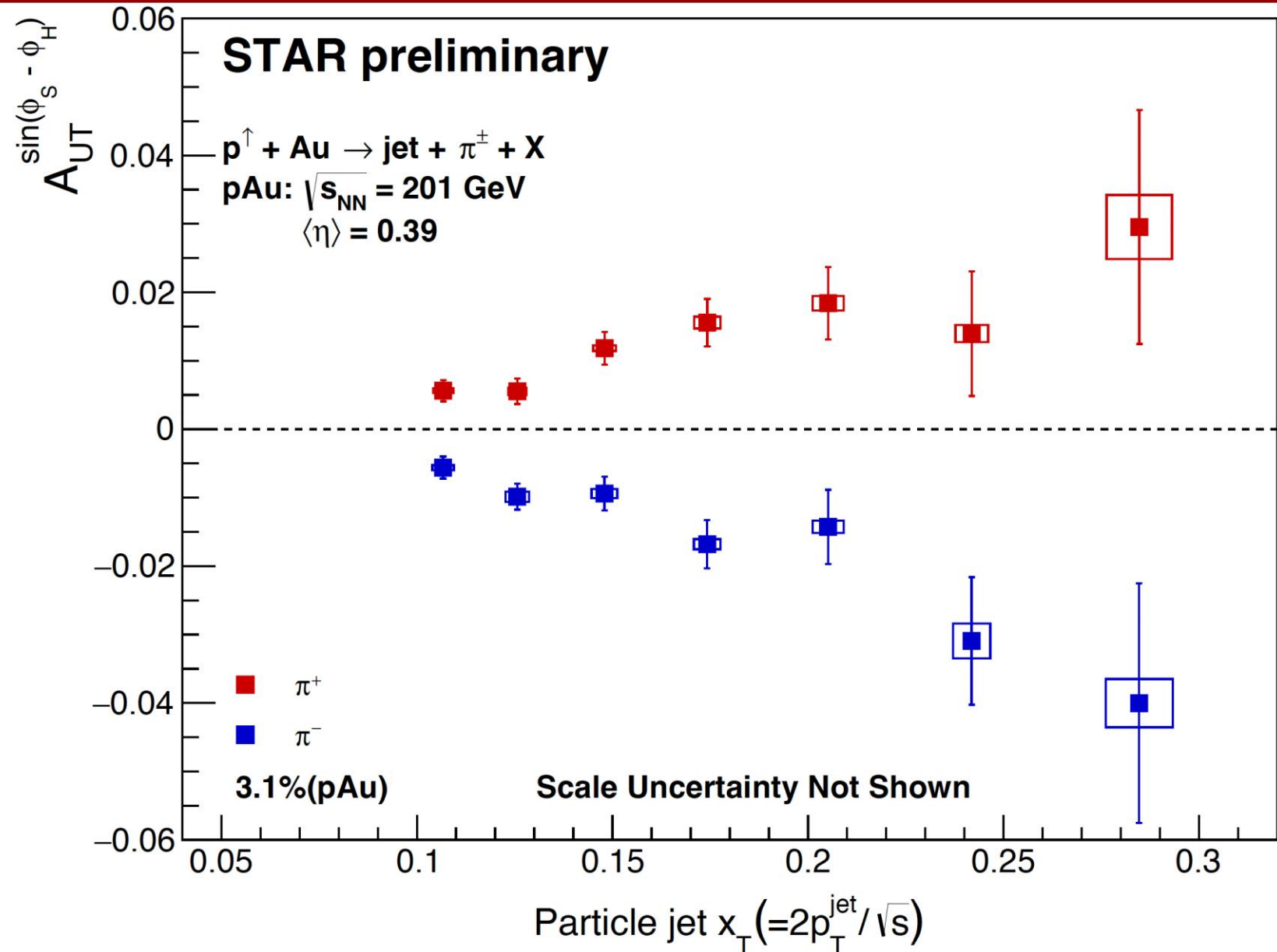
$$\begin{bmatrix} A_{\pi raw}^{UT TOF+TPC} \\ A_{K raw}^{UT TOF+TPC} \\ A_{p raw}^{UT TOF+TPC} \\ A_{\pi raw}^{UT TPC} \\ A_{K raw}^{UT TPC} \\ A_{p raw}^{UT TPC} \end{bmatrix} = \begin{bmatrix} f_{\pi rich}^{\pi TOF+TPC} & f_{\pi rich}^{K TOF+TPC} & f_{\pi rich}^{p TOF+TPC} \\ f_{K rich}^{\pi TOF+TPC} & f_{K rich}^{K TOF+TPC} & f_{K rich}^{p TOF+TPC} \\ f_{p rich}^{\pi TOF+TPC} & f_{p rich}^{K TOF+TPC} & f_{p rich}^{p TOF+TPC} \\ f_{\pi rich}^{\pi TPC} & f_{\pi rich}^{K TPC} & f_{\pi rich}^{p TPC} \\ f_{K rich}^{\pi TPC} & f_{K rich}^{K TPC} & f_{K rich}^{p TPC} \\ f_{p rich}^{\pi TPC} & f_{p rich}^{K TPC} & f_{p rich}^{p TPC} \end{bmatrix} \begin{bmatrix} A_{\pi pure}^{UT} \\ A_{K pure}^{UT} \\ A_{p pure}^{UT} \end{bmatrix}$$

A_{pure} is obtained via matrix inversion using the Moore-Penrose pseudoinverse

[1] G. G. Ohlsen and P. W. Keaton, Nucl. Instrum. Meth. 109, 41 (1973).

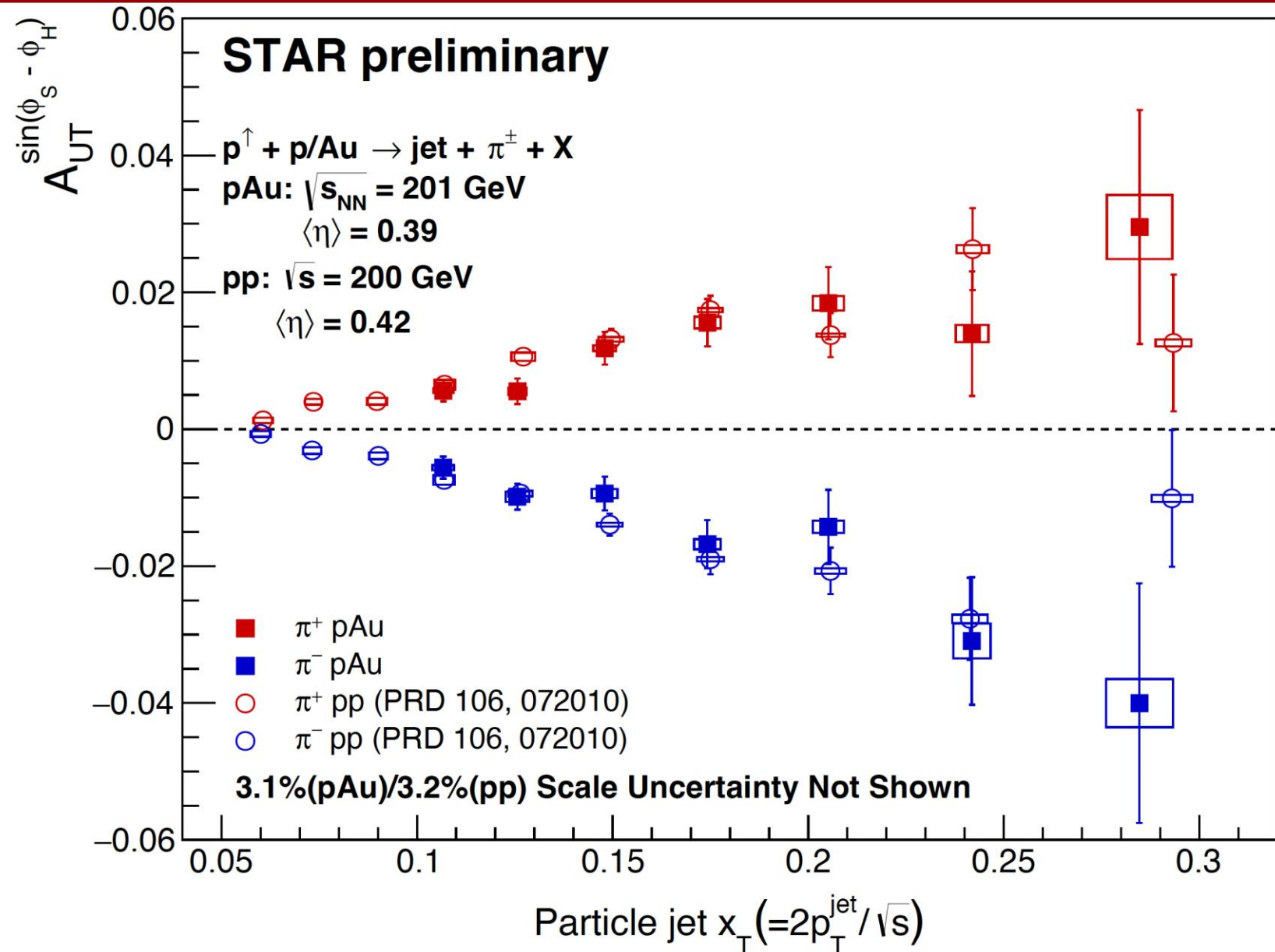
pAu Collins Asymmetry from STAR 2015 Data

- Positive asymmetry for π^+
- Negative asymmetry for π^-



p Au Collins Asymmetry from STAR 2015 Data

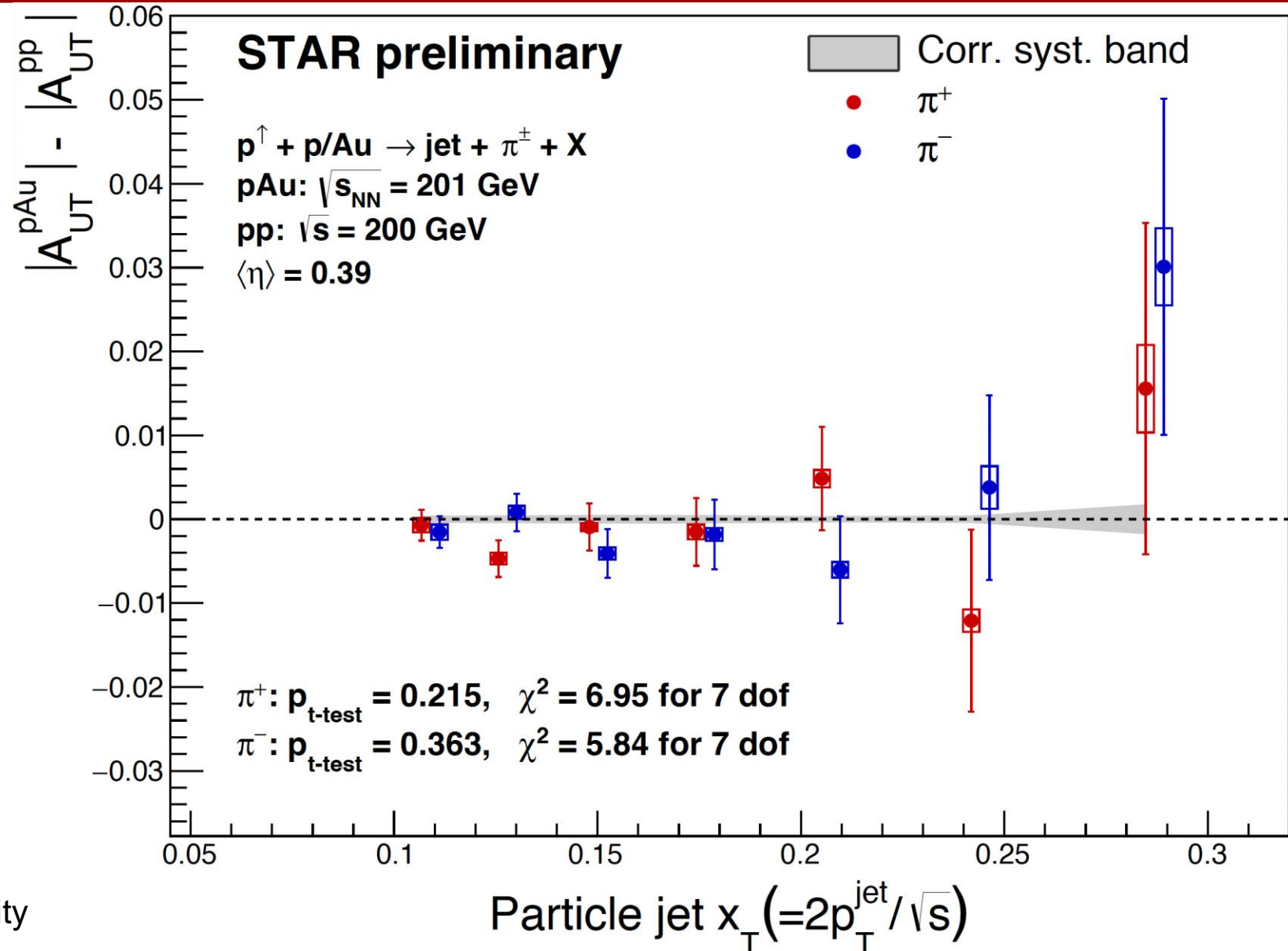
- Positive asymmetry for π^+
- Negative asymmetry for π^-
- The p Au asymmetries exhibit the same charge-sign pattern and overall x_T dependence as the published pp results



pp200: STAR, *Phys. Rev. D* **106**(7), 072010 (2022).

Comparing STAR pAu to pp Results

- No significant pAu – pp difference
- Statistical tests are consistent with zero difference

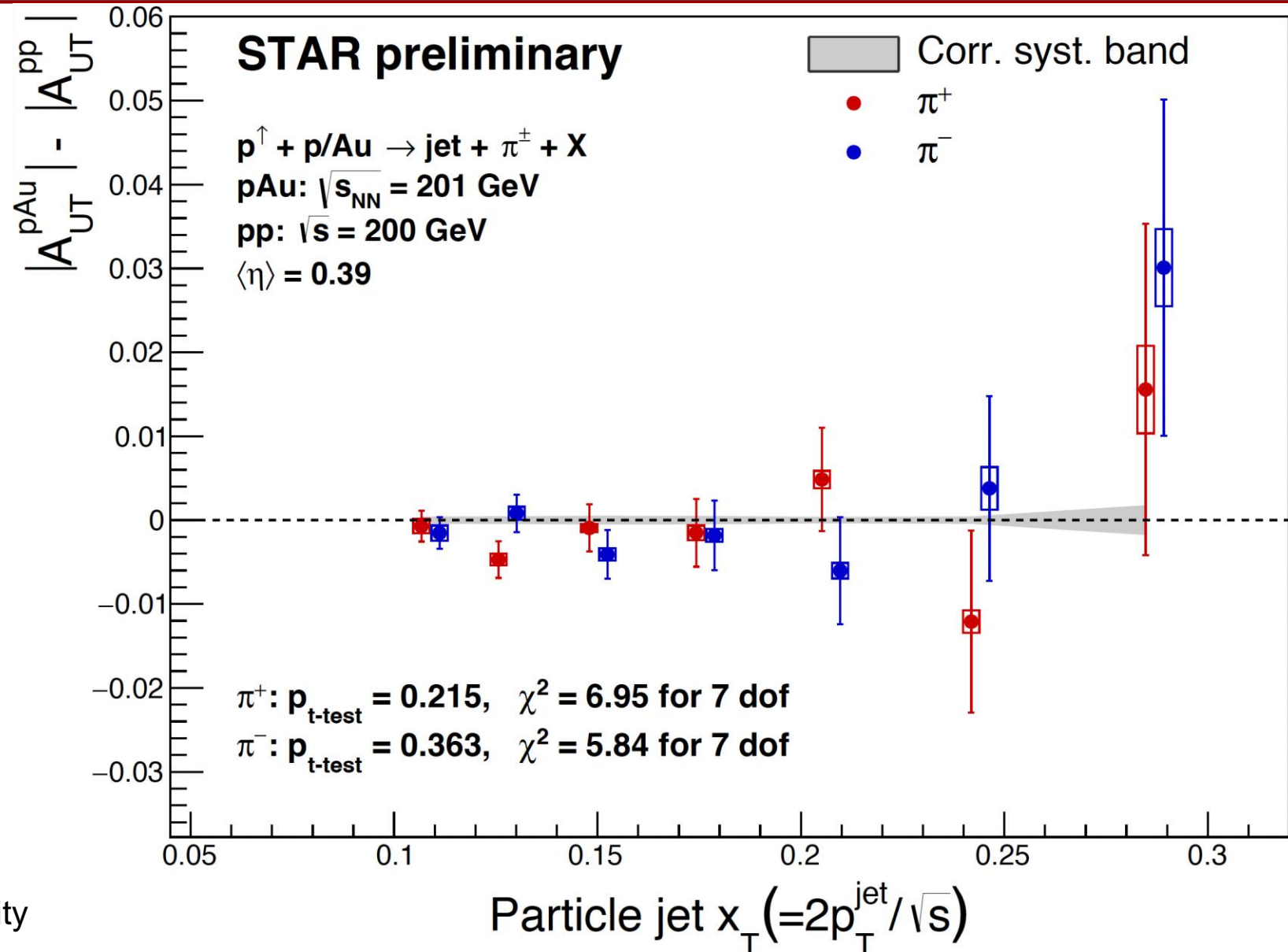


π^- results slightly offset horizontally for clarity

Comparing STAR pAu to pp Results

- No significant pAu – pp difference
- Statistical tests are consistent with zero difference
- $|A_{UT}^{pAu}| < |A_{UT}^{pp}|$ for nine of the data points, while $|A_{UT}^{pAu}| > |A_{UT}^{pp}|$ for five of the data points. Therefore ...

π^- results slightly offset horizontally for clarity



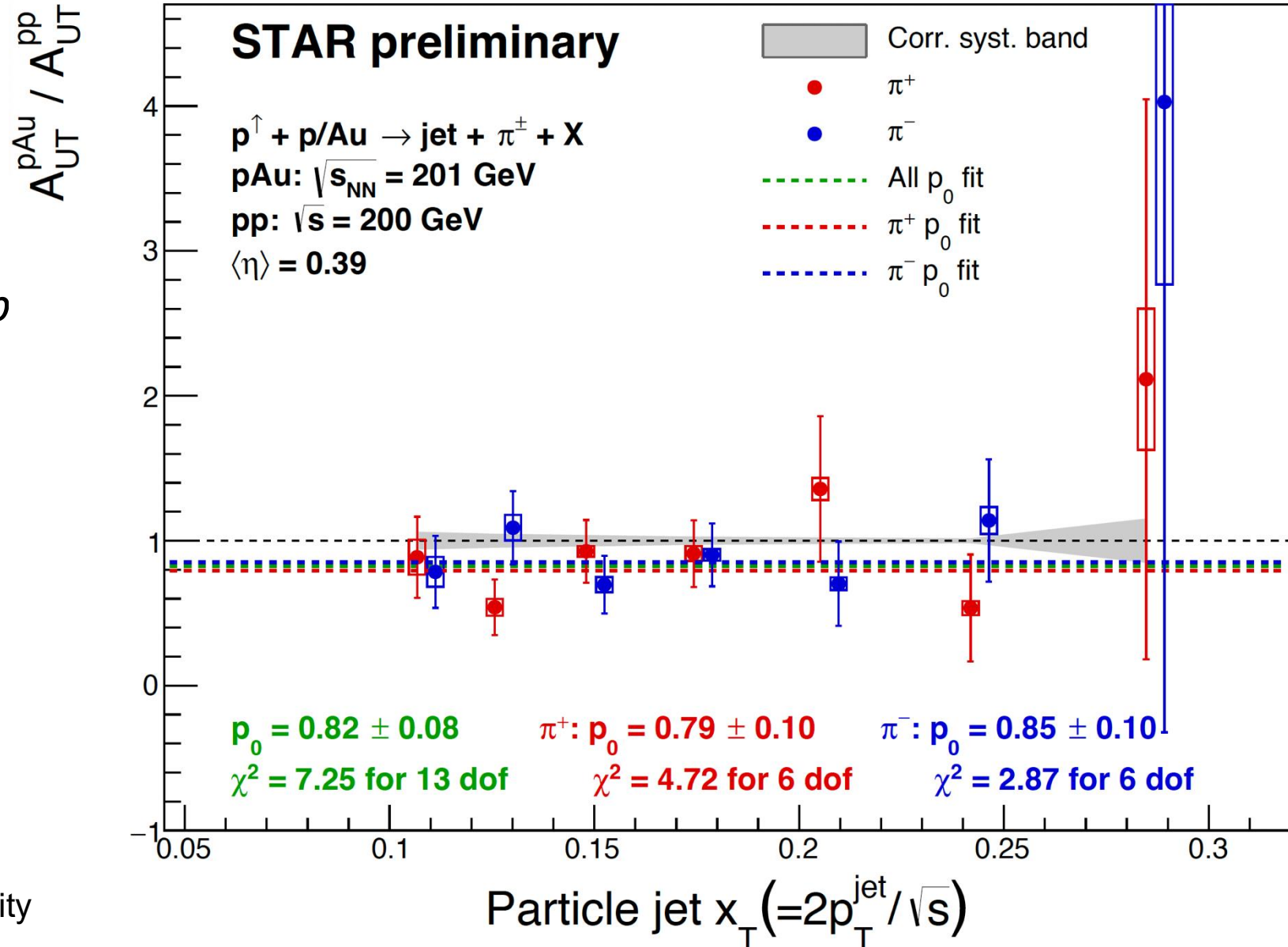
Comparing STAR pAu to pp Results

- If we make the likely naive assumption that any pAu vs. pp difference is independent of x_T , we find ...

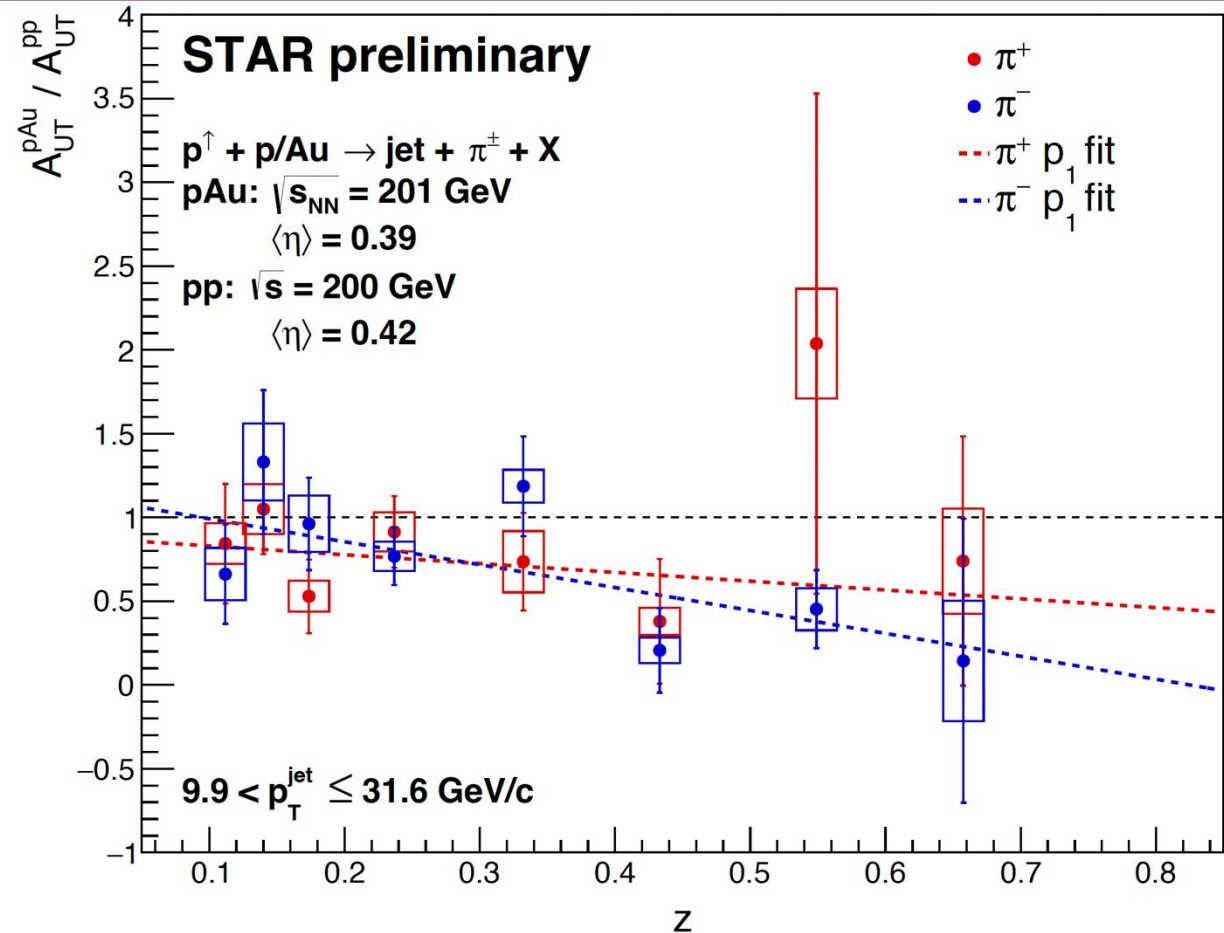
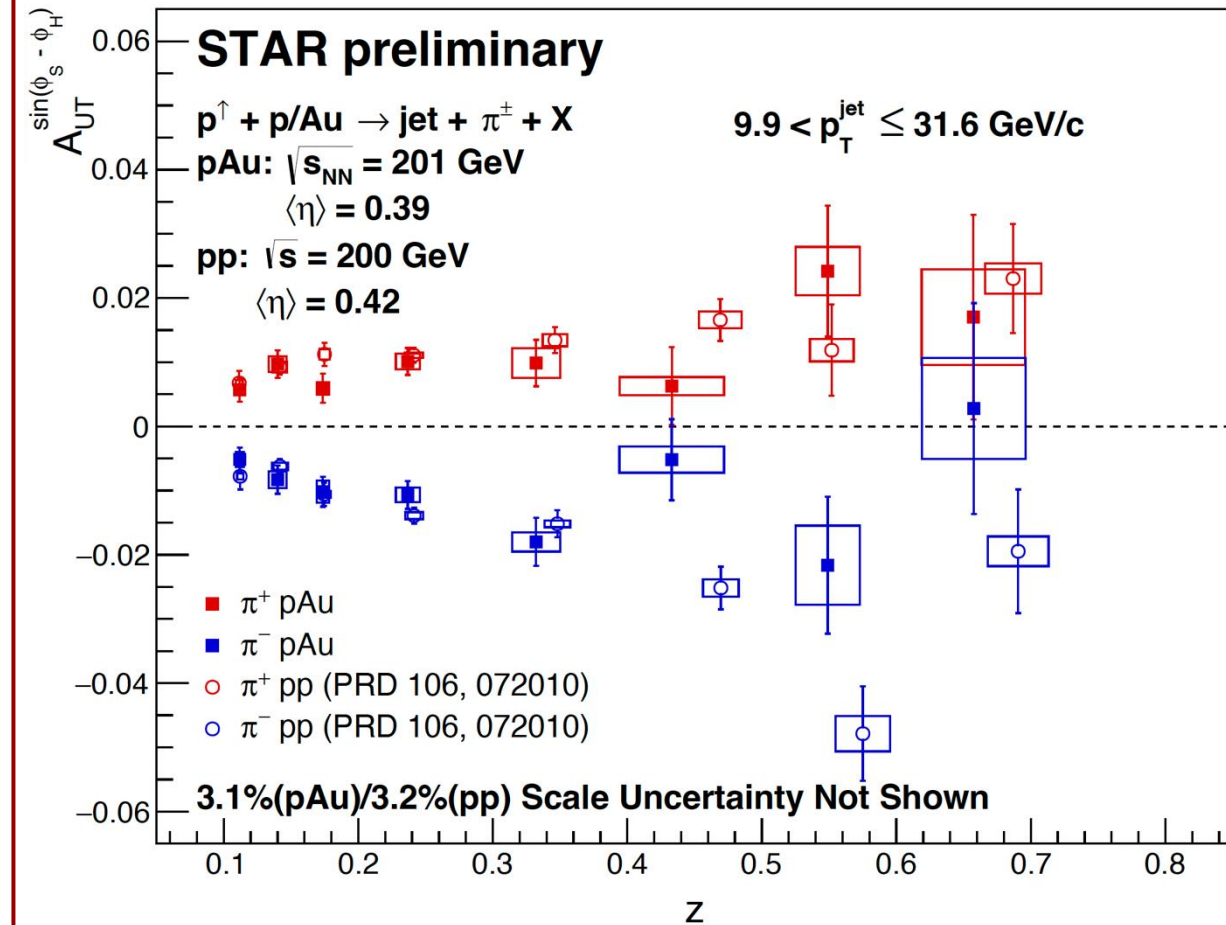
Comparing STAR pAu to pp Results

- If we make the likely naive assumption that any pAu vs. pp difference is independent of x_T , we find ...
- A possible $\sim 18\%$ average suppression in pAu relative to pp at the $\sim 2\sigma$ level

π^- results slightly offset horizontally for clarity

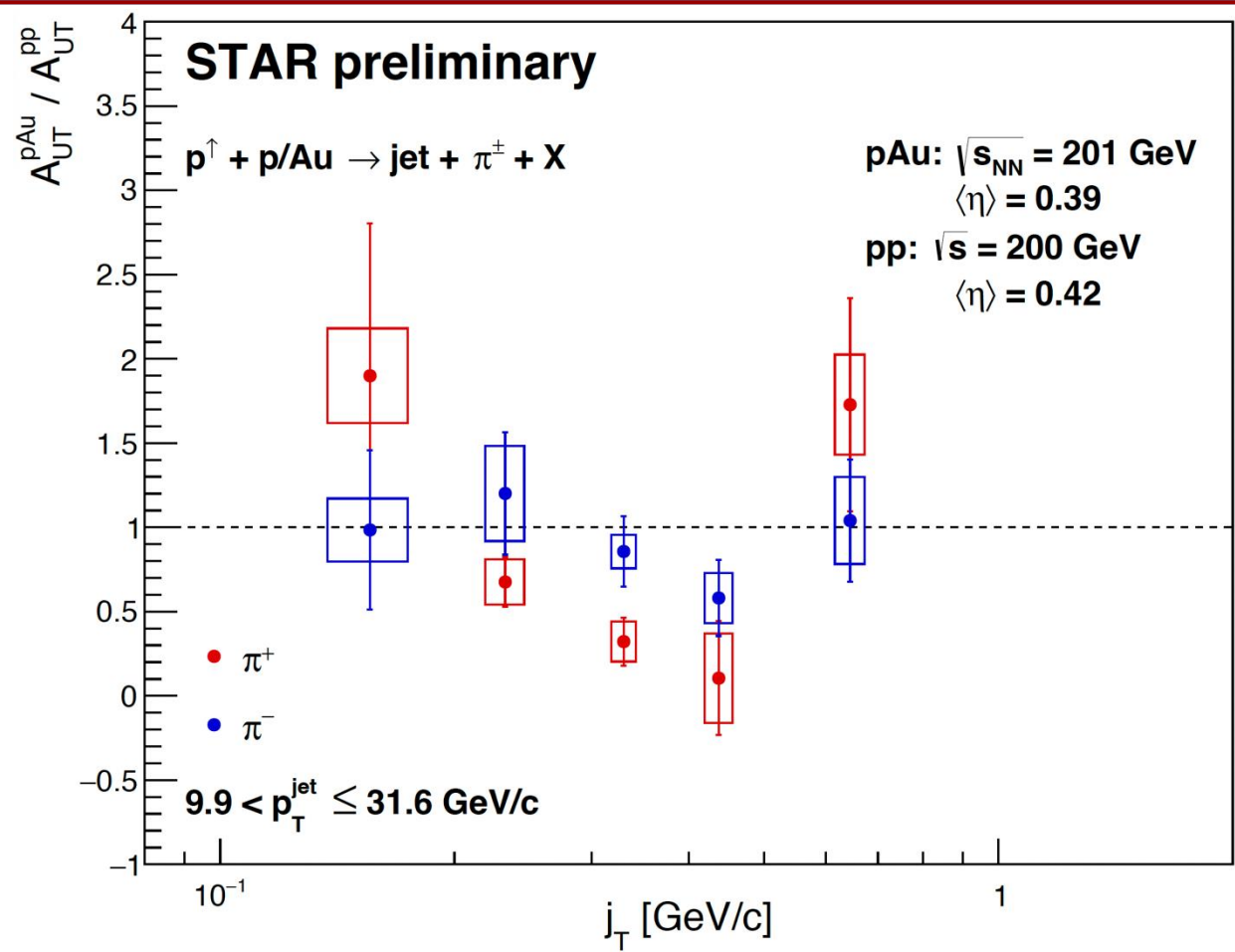
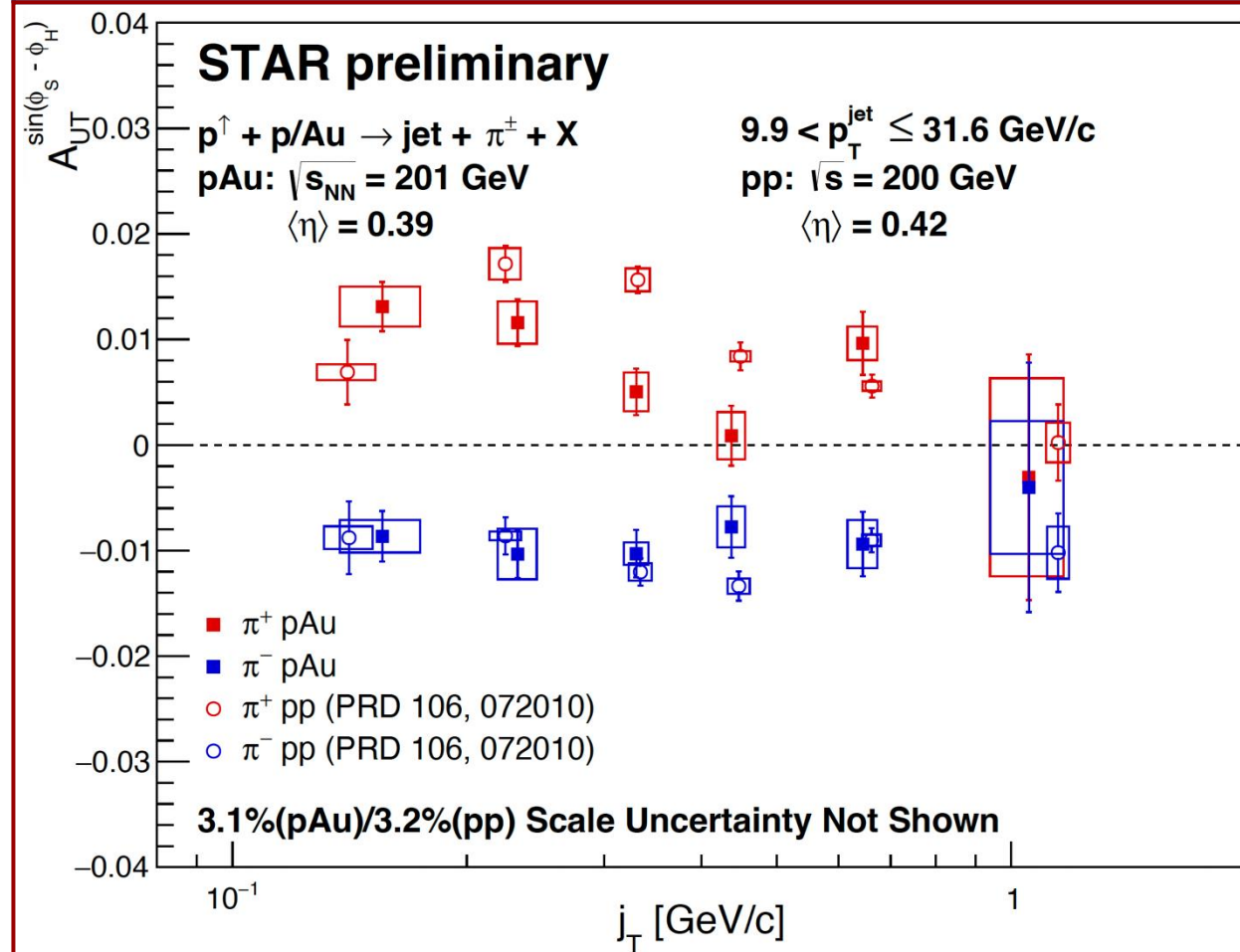


$A_{UT}^{\sin(\phi_S - \phi_H)}$ vs. Hadron Longitudinal Momentum Fraction z



- For π^- , at the 2σ level, the data suggest less suppression at low z and more suppression at high z (slope = -1.4 ± 0.7)
- For π^+ , the best fit slope is also negative, but it only differs from zero by $\sim 0.5\sigma$ (slope = -0.5 ± 1.0)

$A_{UT}^{\sin(\phi_S - \phi_H)}$ vs. Hadron Transverse Momentum j_T



The π^+ data may suggest suppression at intermediate j_T , but the statistical precision is limited

Conclusion and Going Forward

- Preliminary STAR measurement of the Collins asymmetry for π^+ and π^- in polarized pAu collisions at $\sqrt{s_{NN}} = 201$ GeV
- Within the current uncertainties, the polarized pAu Collins asymmetries are consistent with the published STAR polarized pp results at $\sqrt{s} = 200$ GeV
- The pAu/pp comparison may indicate a modest suppression in pAu possibly due to:
 - Nuclear PDF effects?
 - Nuclear fragmentation function effects?
 - Factorization breaking effects?
 - Something else?
- Model calculations are required to further explore the origin of the possible suppression

Thank you!

Backup