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

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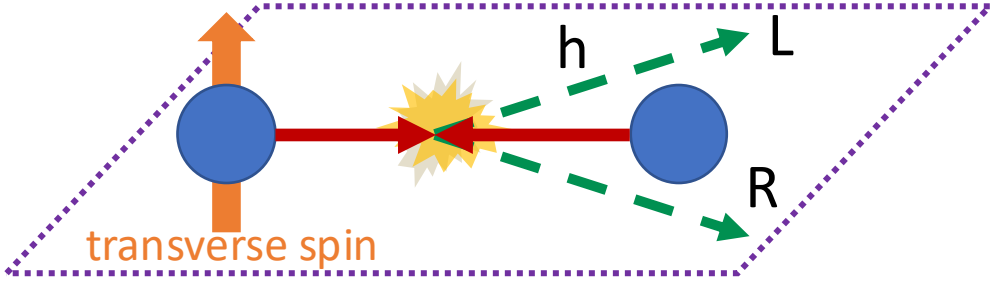
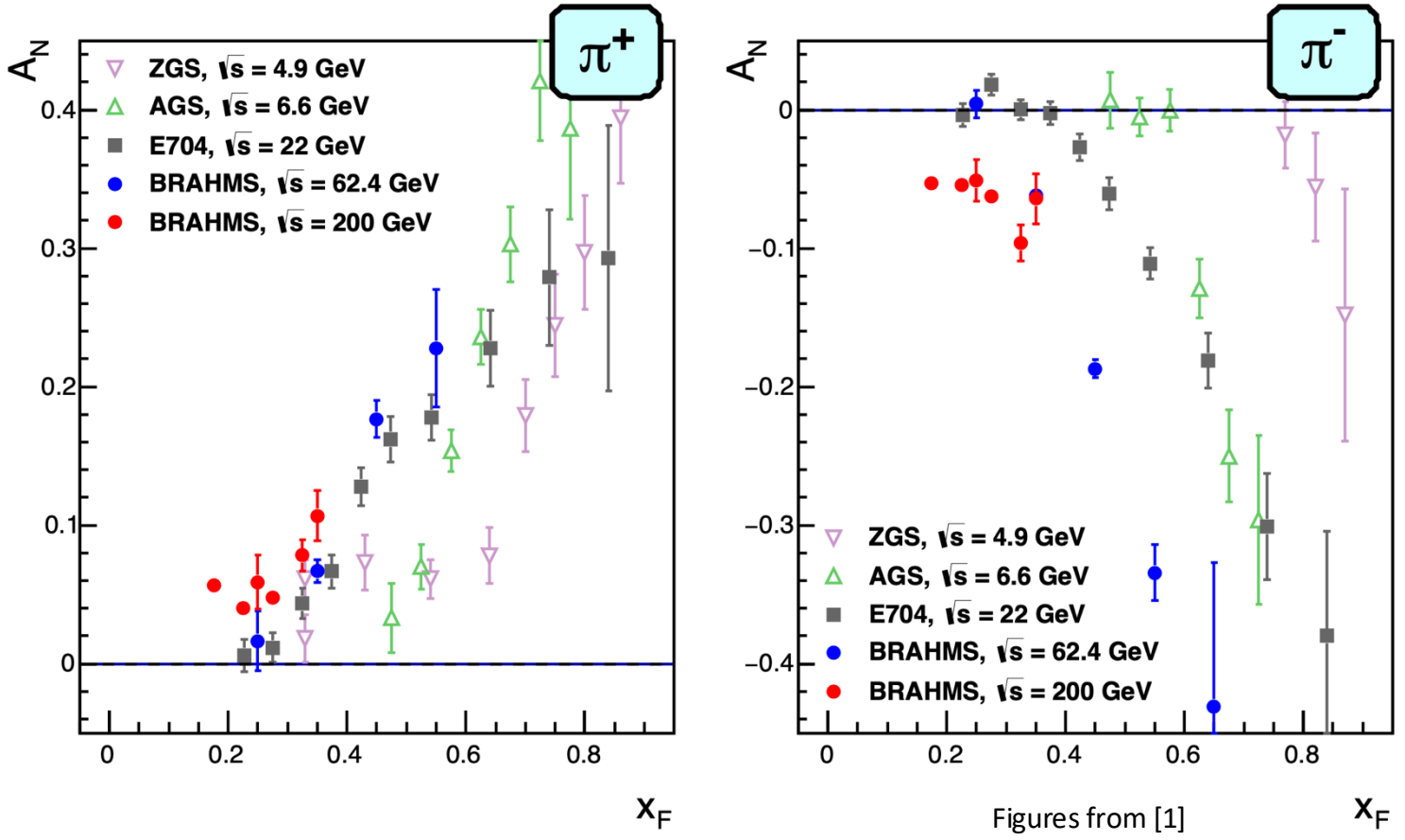
U.S. DEPARTMENT OF ENERGY

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

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

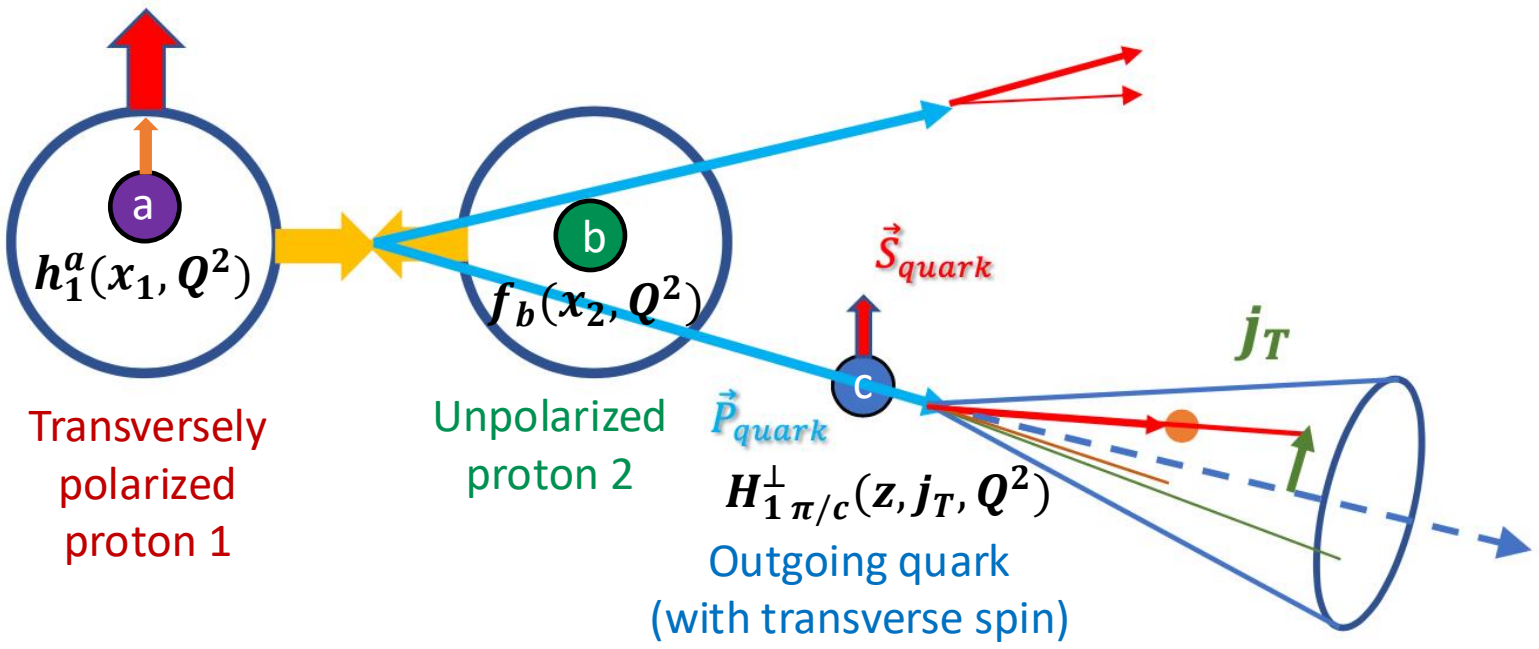




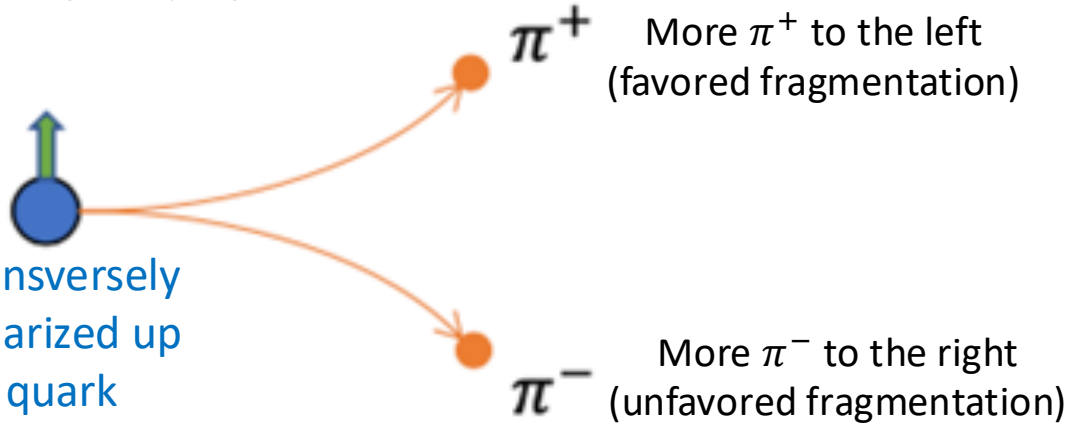
Figures from [1]

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

A Mechanism for A_N: The Collins Effect



Diagrams by Ting Lin



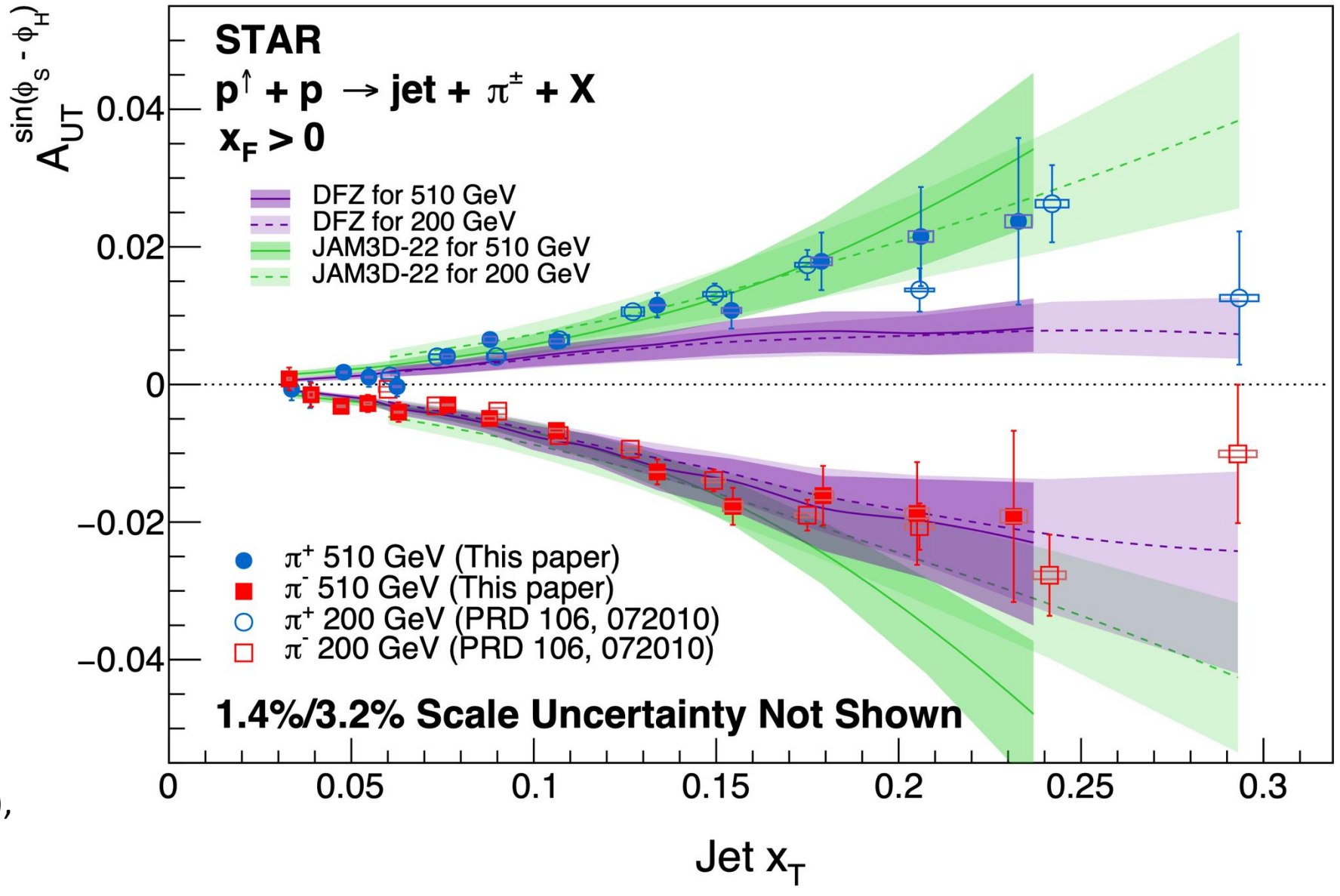
- Probes transversity ⊗ Collins FF
- Measured as an azimuthal modulation of hadrons around the jet axis

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

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



***pp*200:** STAR, *Phys. Rev. D* **106**(7), 072010 (2022).

***pp*510:** 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

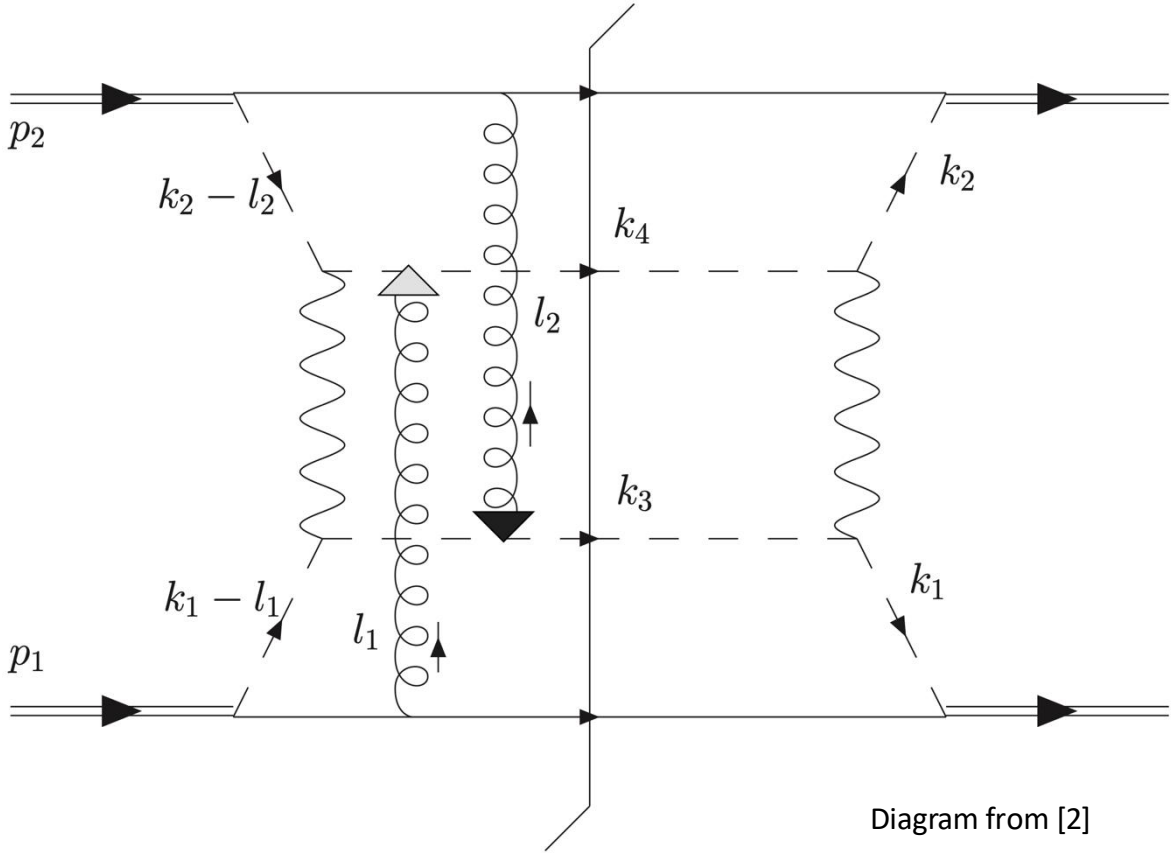


Diagram from [2]

- 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 *p*Au?

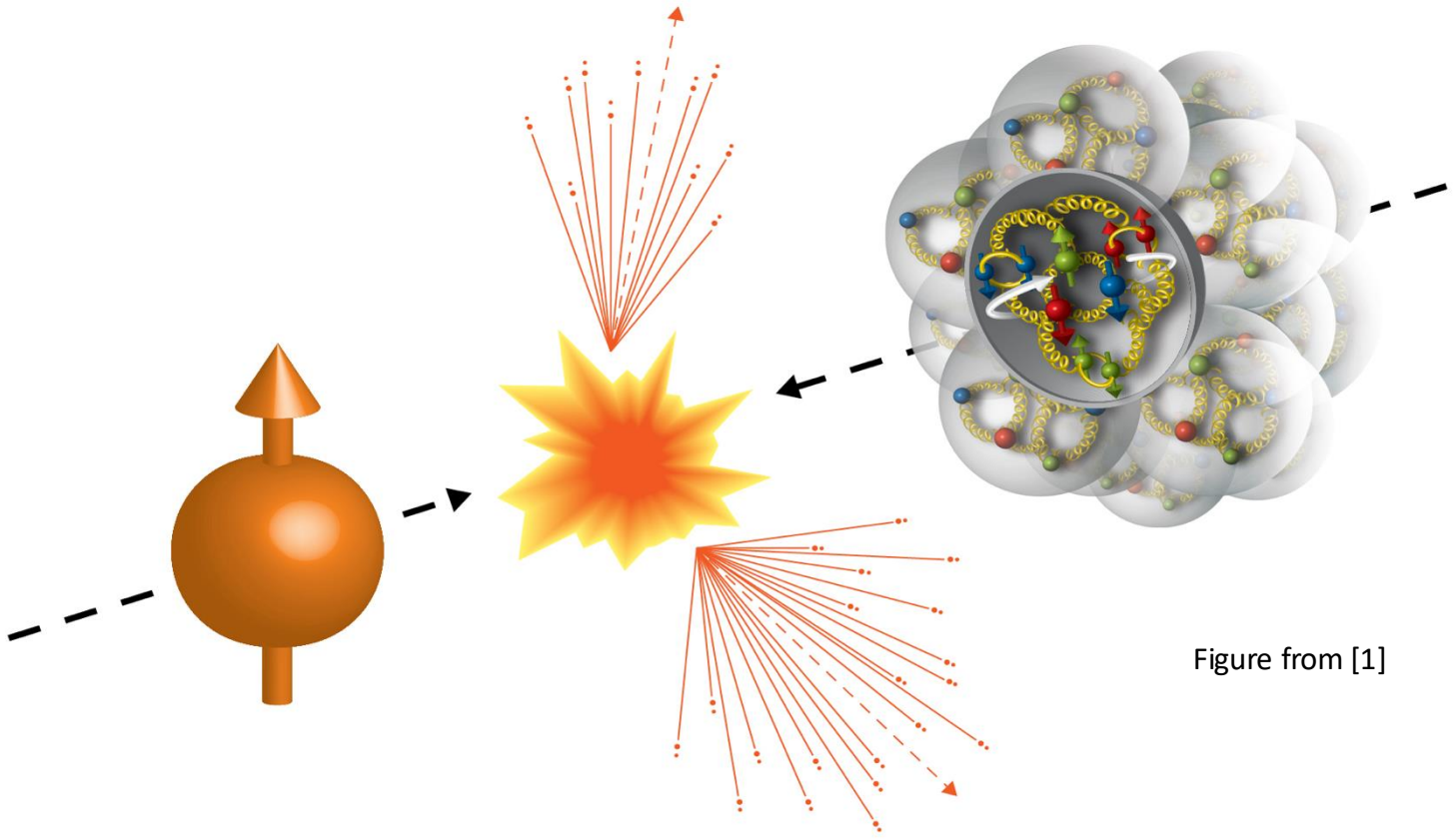
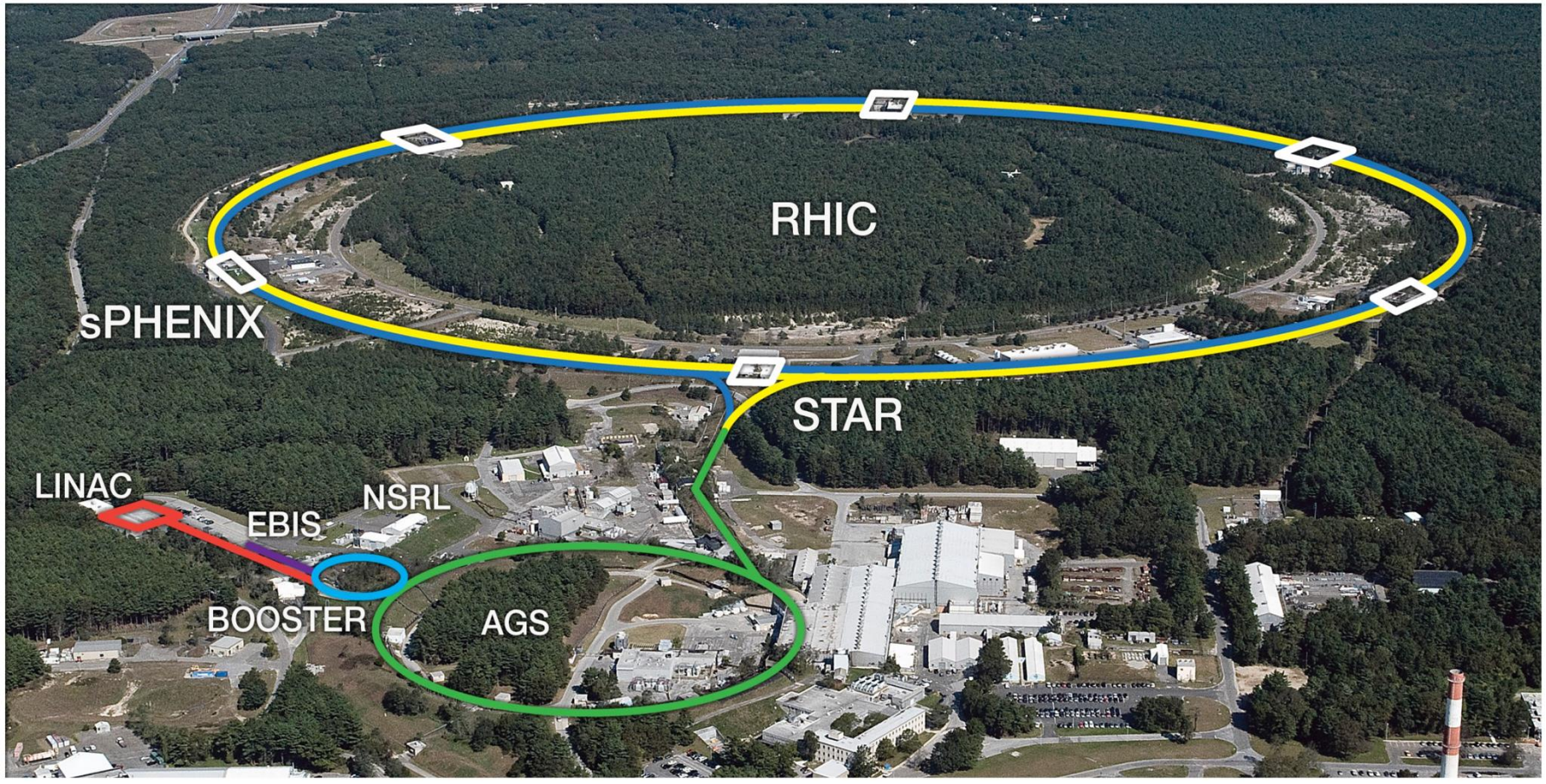


Figure from [1]

- *p*Au 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

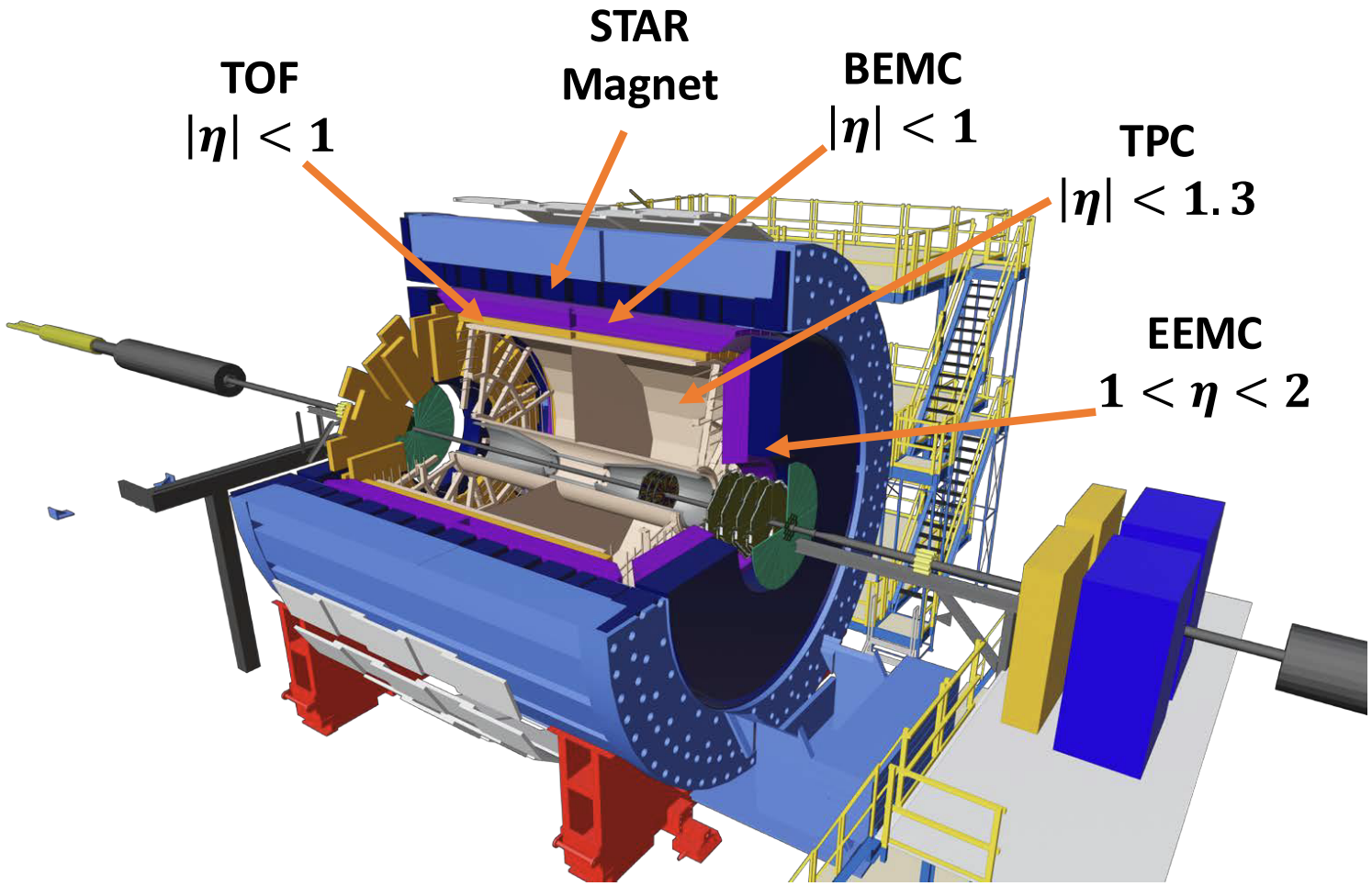
[1] Elke Aschenauer et al., arXiv:1602.03922 [nucl-ex].

RHIC: Relativistic Heavy Ion Collider

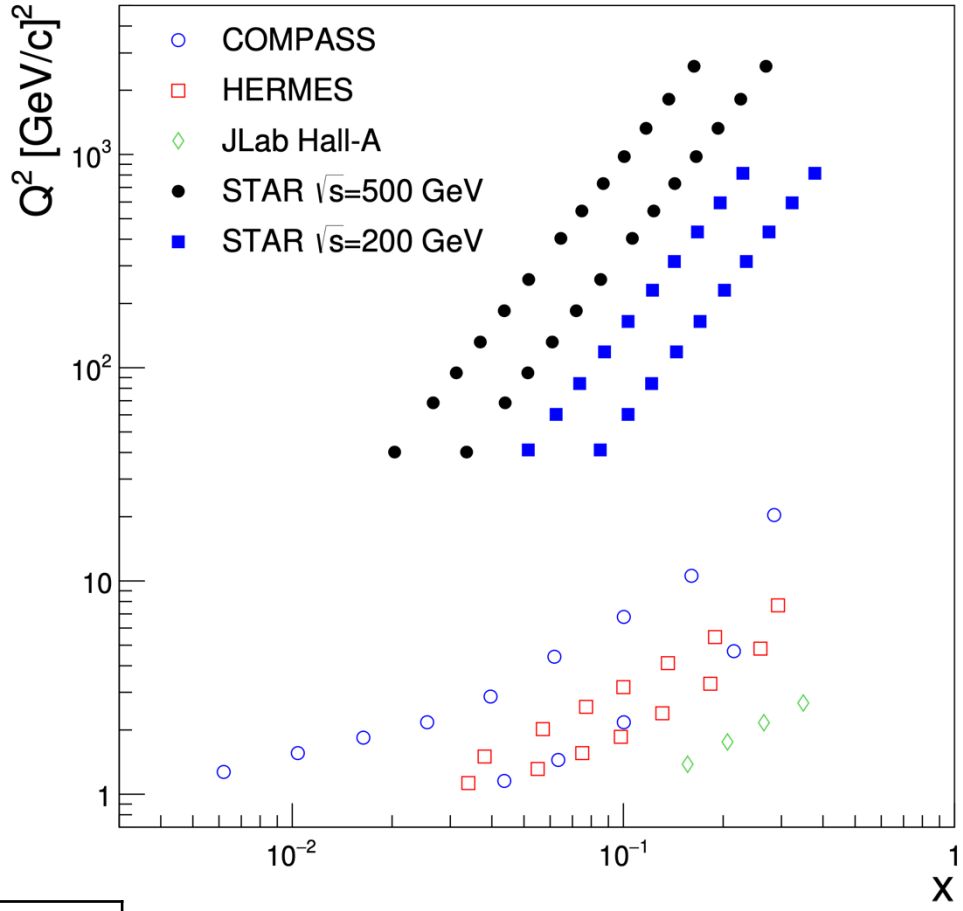


- The only machine in the world capable of colliding high-energy beams of polarized protons
- The beams travel in opposite directions around RHIC's 3.86 km two-lane racetrack
- Provides a wide range of center-of-mass energies (up to 510 GeV)

STAR: Solenoidal Tracker At RHIC



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

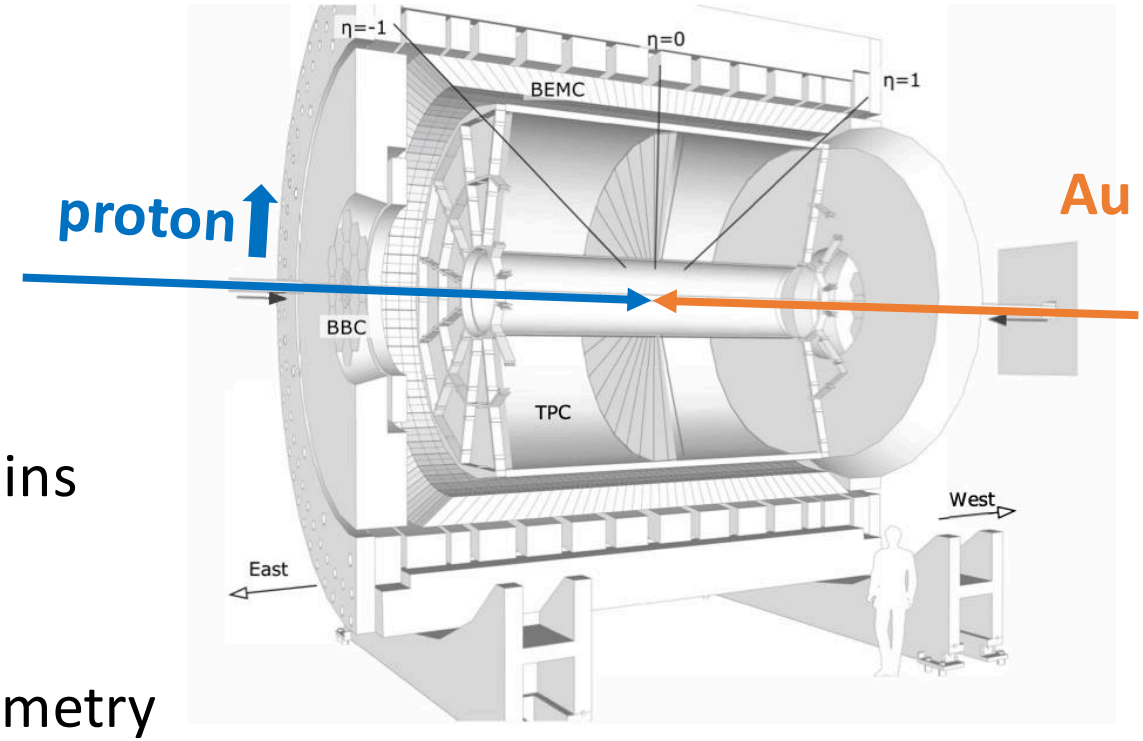


PID and tracking	TOF and TPC cover $\|\eta\| < 1$ and full azimuth
Calorimetry and triggering	BEMC covers $\|\eta\| < 1$ and full azimuth EEMC covers $1.08 < \eta < 2.0$ and full azimuth

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

Analysis and Data Information

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

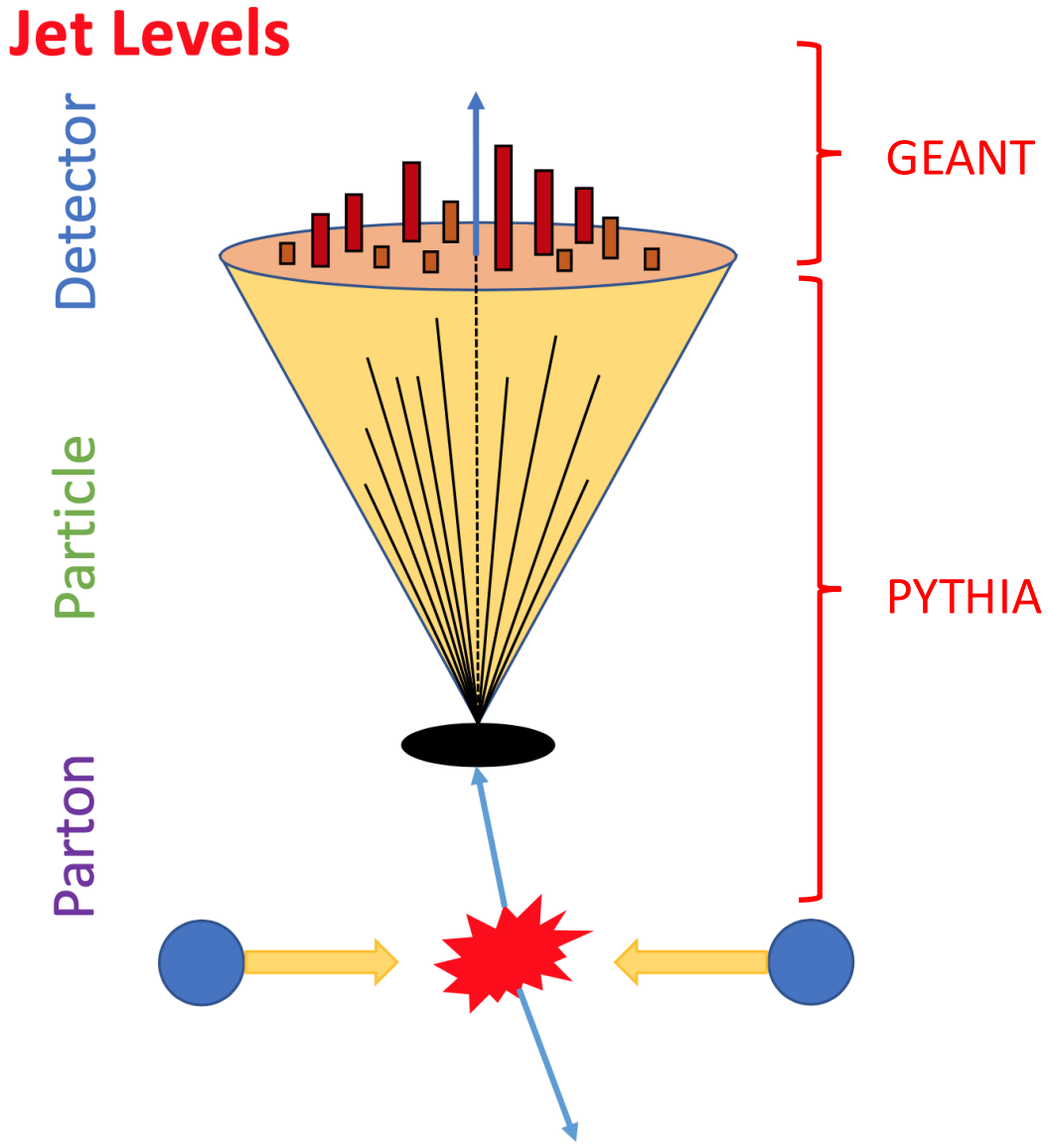


The jet axis is required to be in $0 \leq \eta \leq 0.9$

- 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*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



Observable

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

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

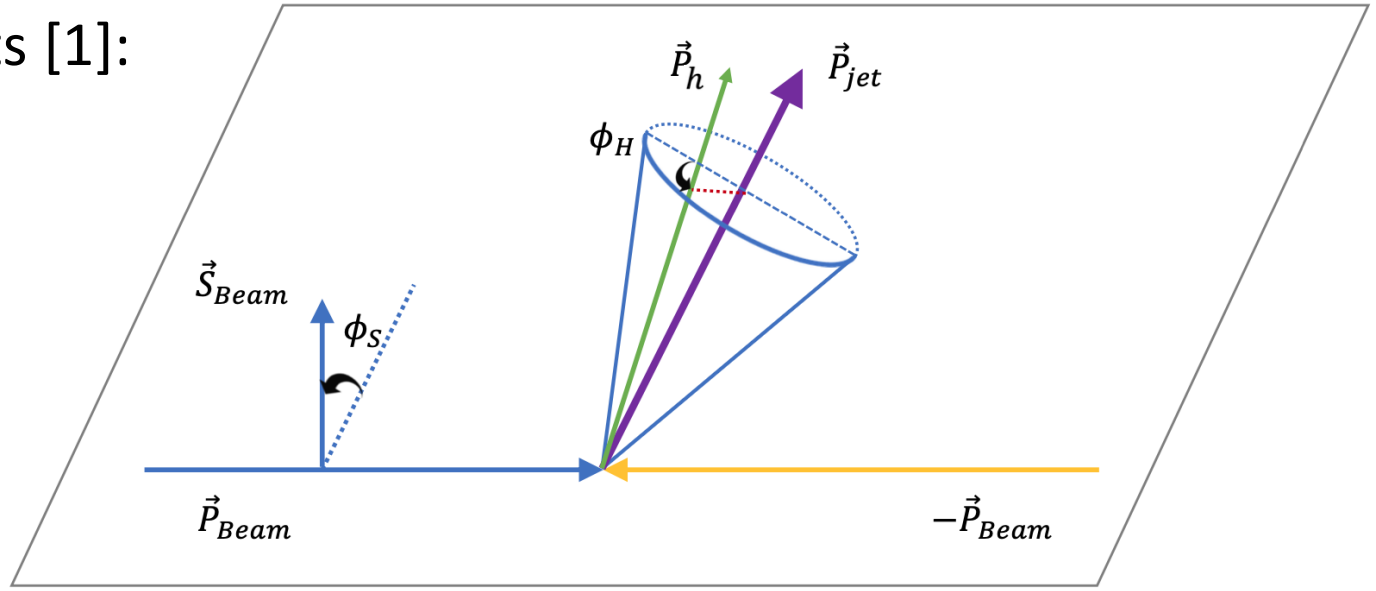


Diagram from Ting Lin and [2]

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

- 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

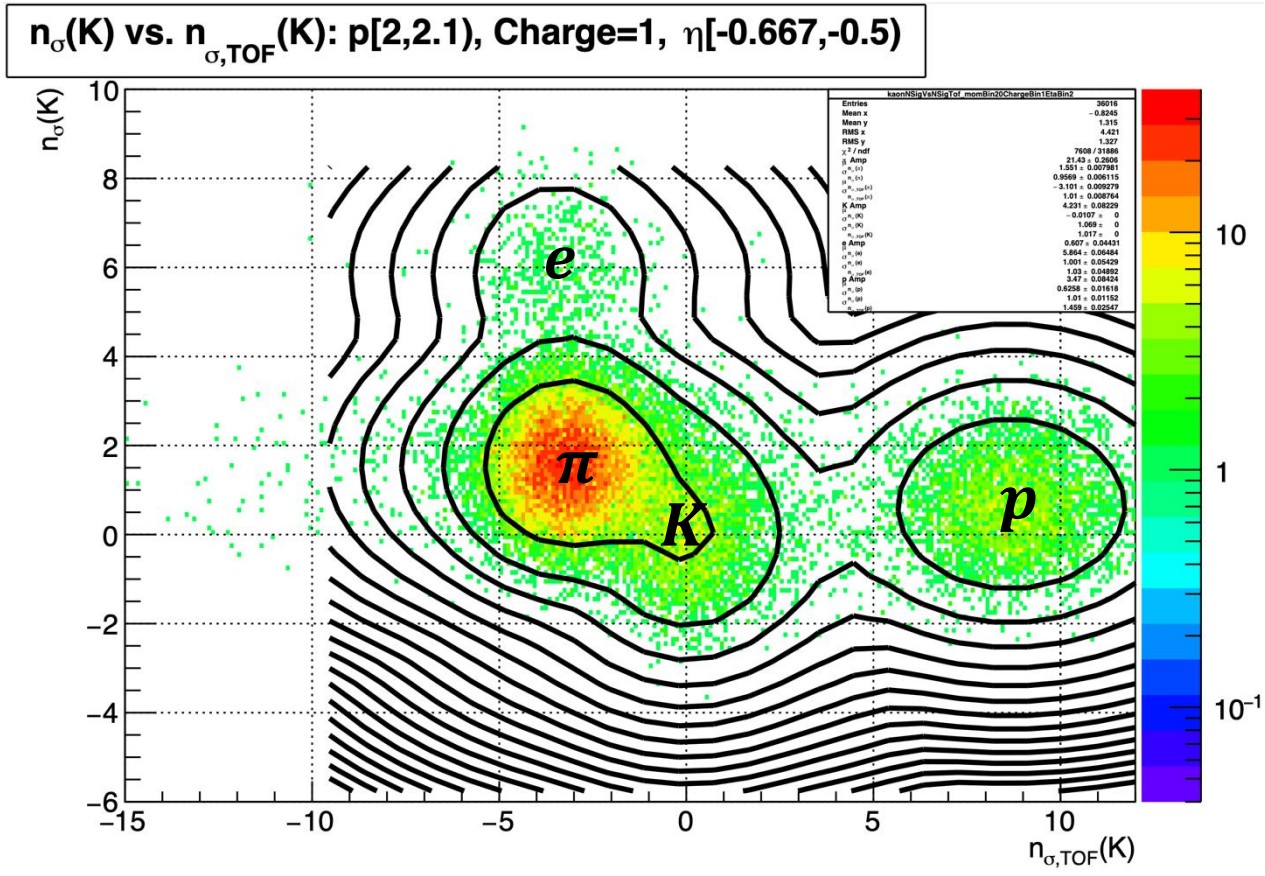
[1] U. D'Aesio, F. Murgia, and C. Pisano, Phys. Rev. D **83**, 034021 (2011).
[2] Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, Phys. Lett. B **774**, 635 (2017).

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

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

Sample PID plot



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

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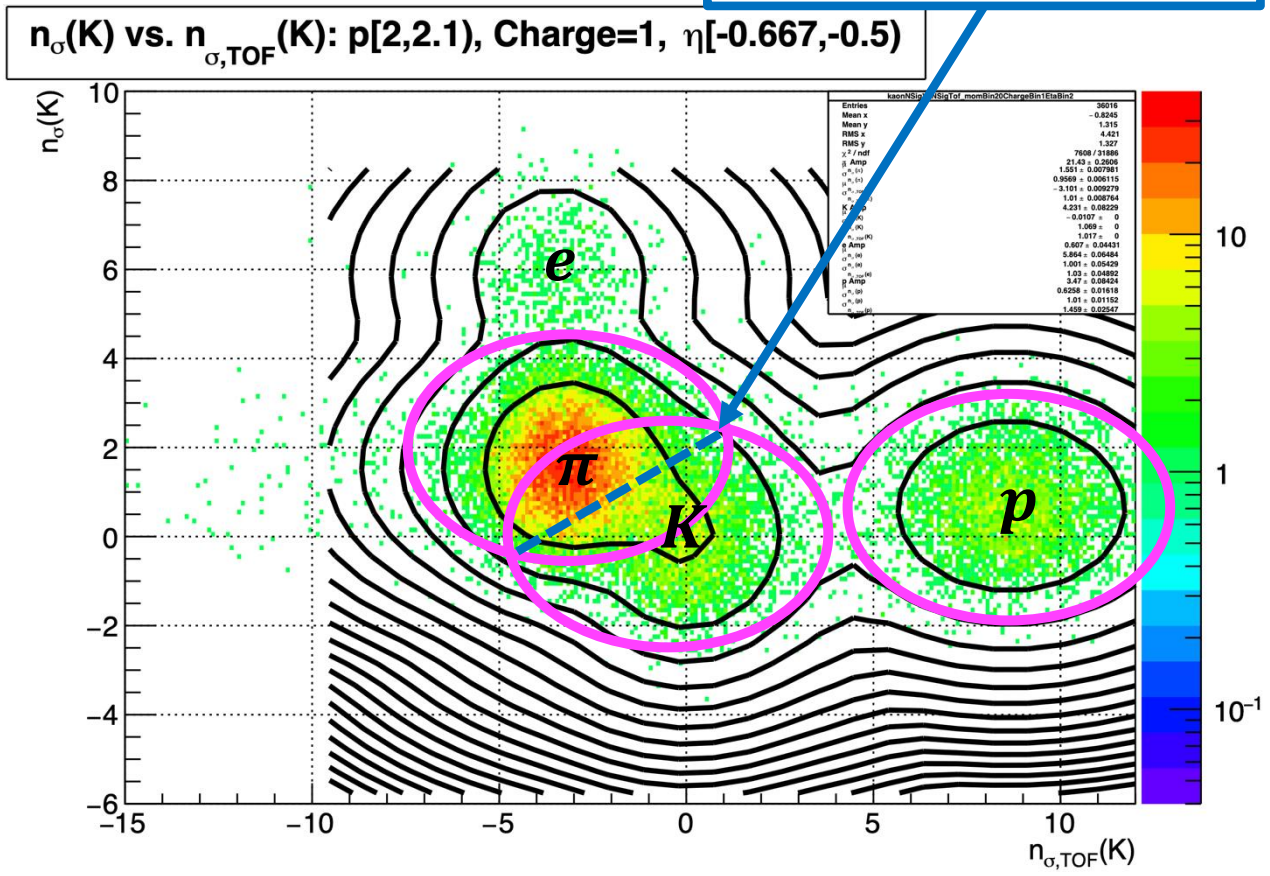
Sample PID plot

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

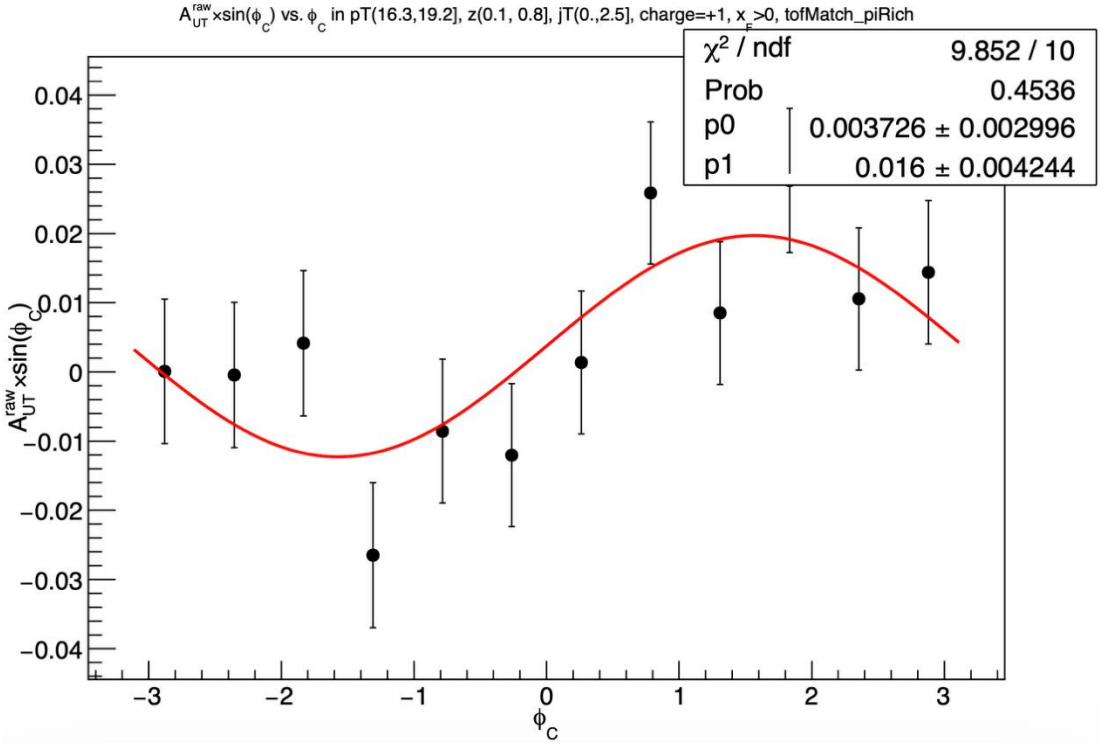


Charge separated and binned in p^{track} and η^{track} bins

Raw and Pure Collins Asymmetry Extraction

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

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



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

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

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

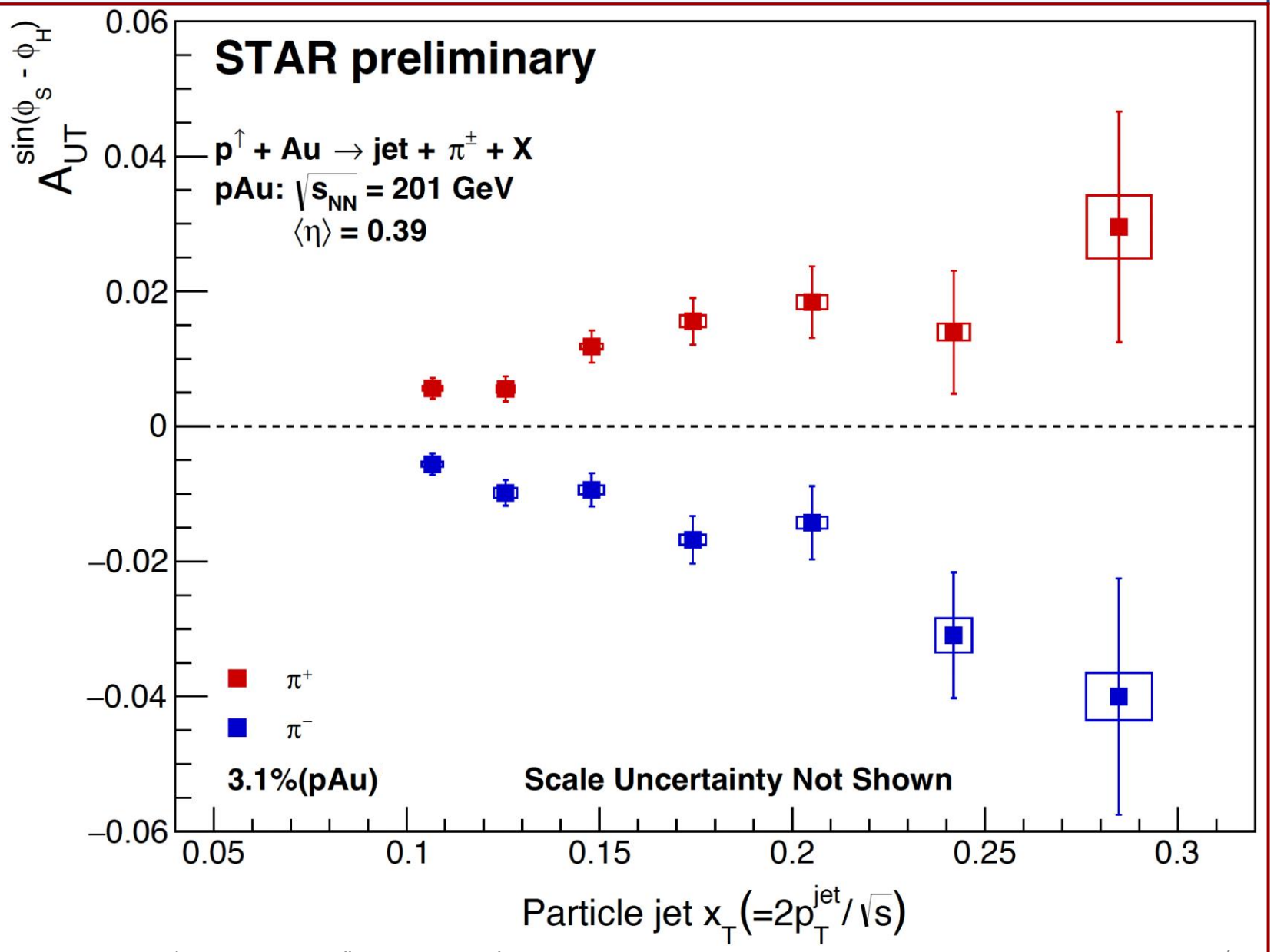
$$\begin{bmatrix} A_{\pi\,raw}^{UT\ TOF+TPC} \\ A_{K\,raw}^{UT\ TOF+TPC} \\ A_{p\,raw}^{UT\ TOF+TPC} \\ A_{\pi\,raw}^{UT\ TPC} \\ A_{K\,raw}^{UT\ TPC} \\ A_{p\,raw}^{UT\ TPC} \end{bmatrix} = \begin{bmatrix} f_{\pi_{rich}}^{\pi\ TOF+TPC} & f_{\pi_{rich}}^{K\ TOF+TPC} & f_{\pi_{rich}}^{p\ TOF+TPC} \\ f_{K_{rich}}^{\pi\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

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

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

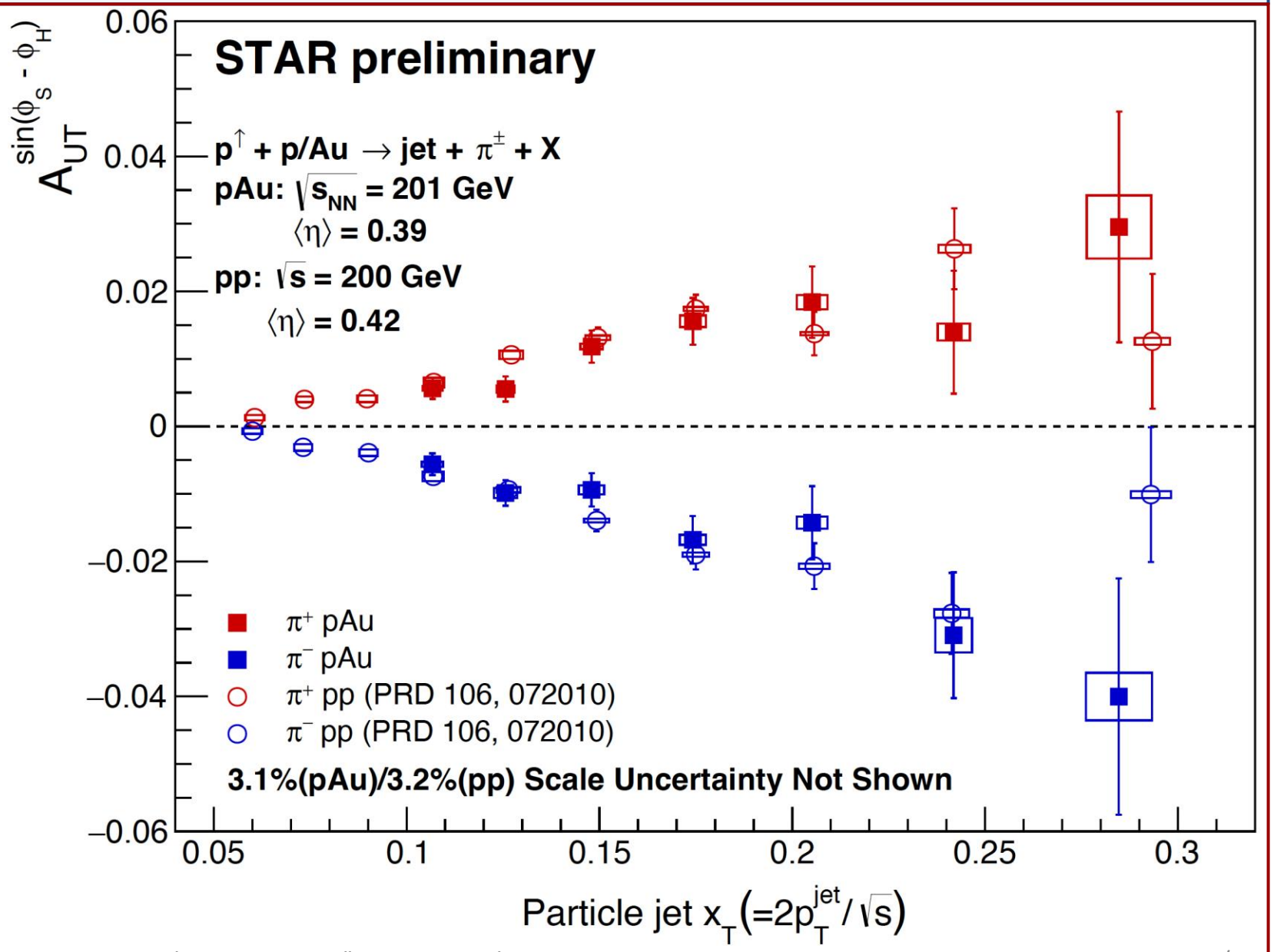
*p*Au Collins Asymmetry from STAR 2015 Data

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



*p*Au Collins Asymmetry from STAR 2015 Data

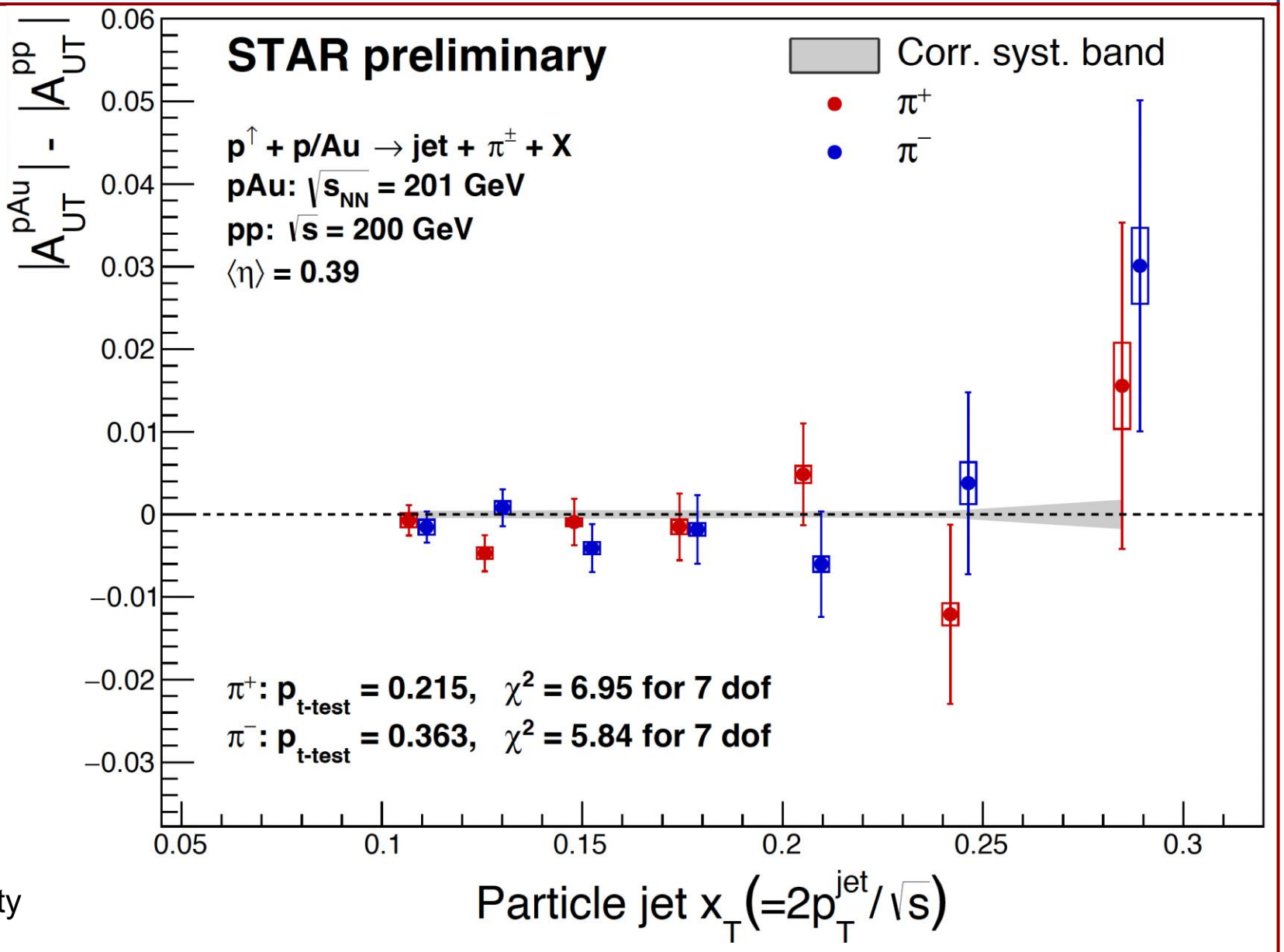
- Positive asymmetry for π^+
- Negative asymmetry for π^-
- The *p*Au asymmetries exhibit the same charge-sign pattern and overall x_T dependence as the published *pp* results



***pp*200:** STAR, *Phys. Rev. D* **106**(7), 072010 (2022).

Comparing STAR *p*Au to *pp* Results

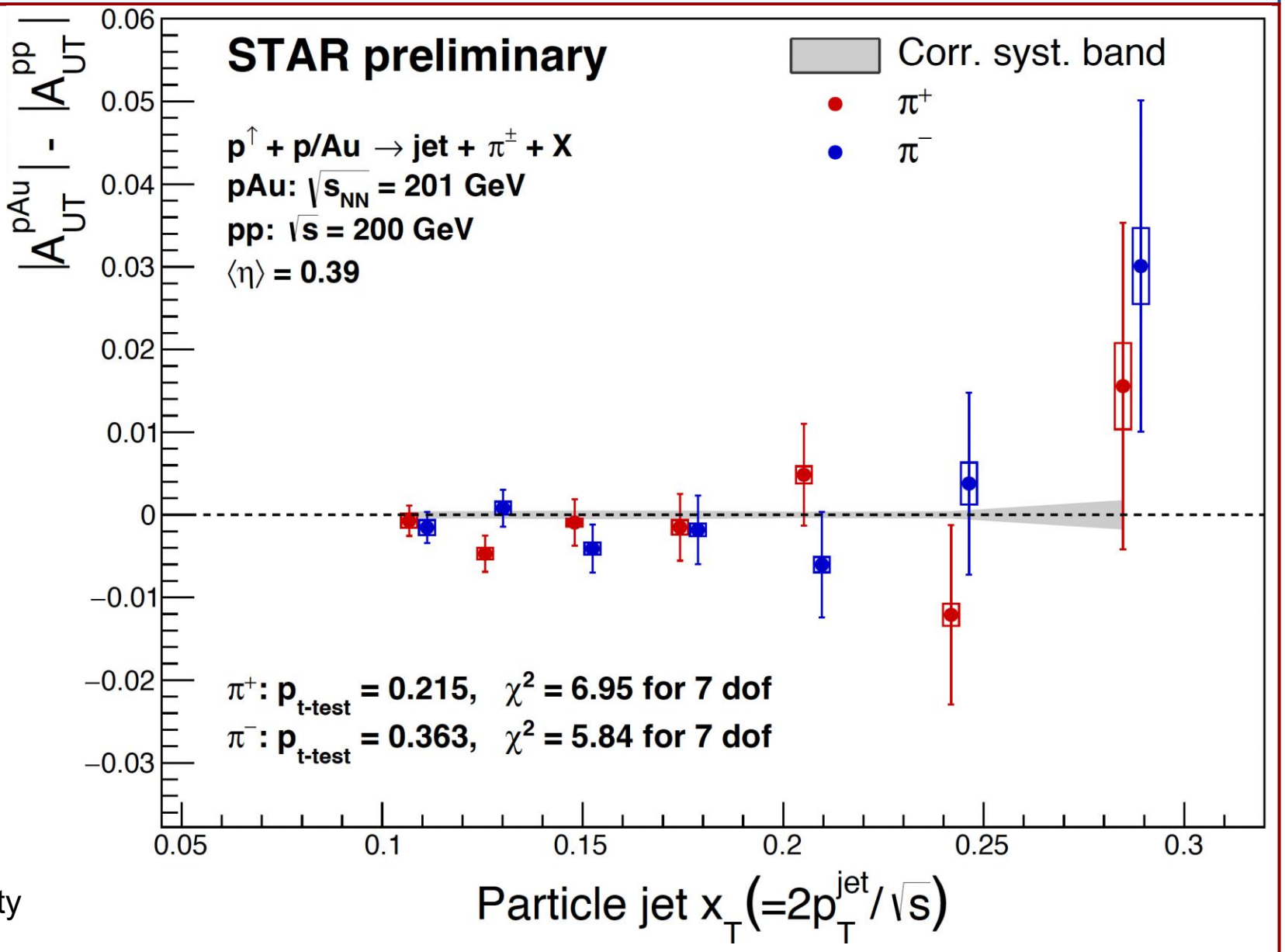
- No significant *p*Au–*pp* difference
- Statistical tests are consistent with zero difference



π^- results slightly offset horizontally for clarity

Comparing STAR *p*Au to *pp* Results

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



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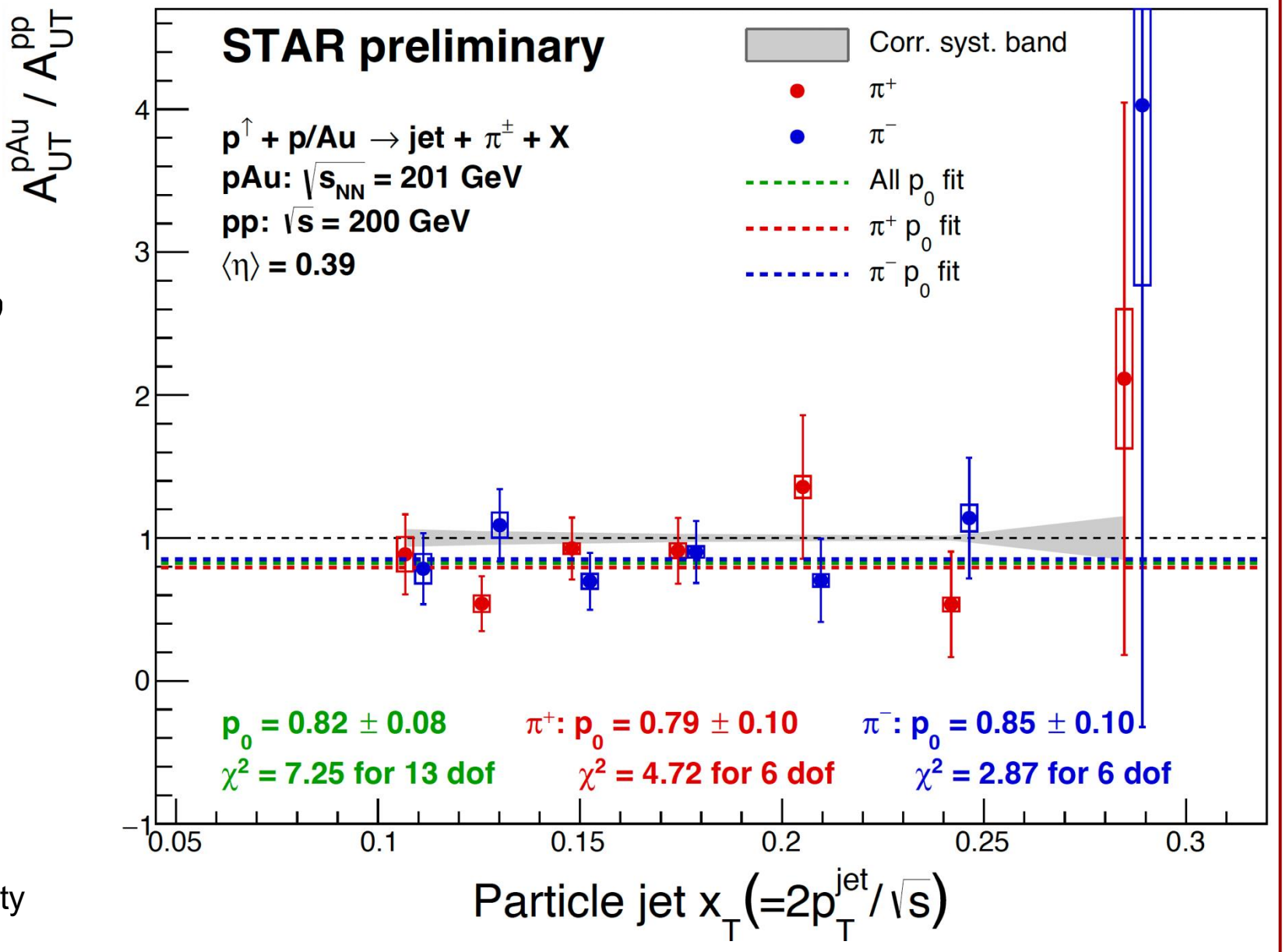
Comparing STAR *p*Au to *pp* Results

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

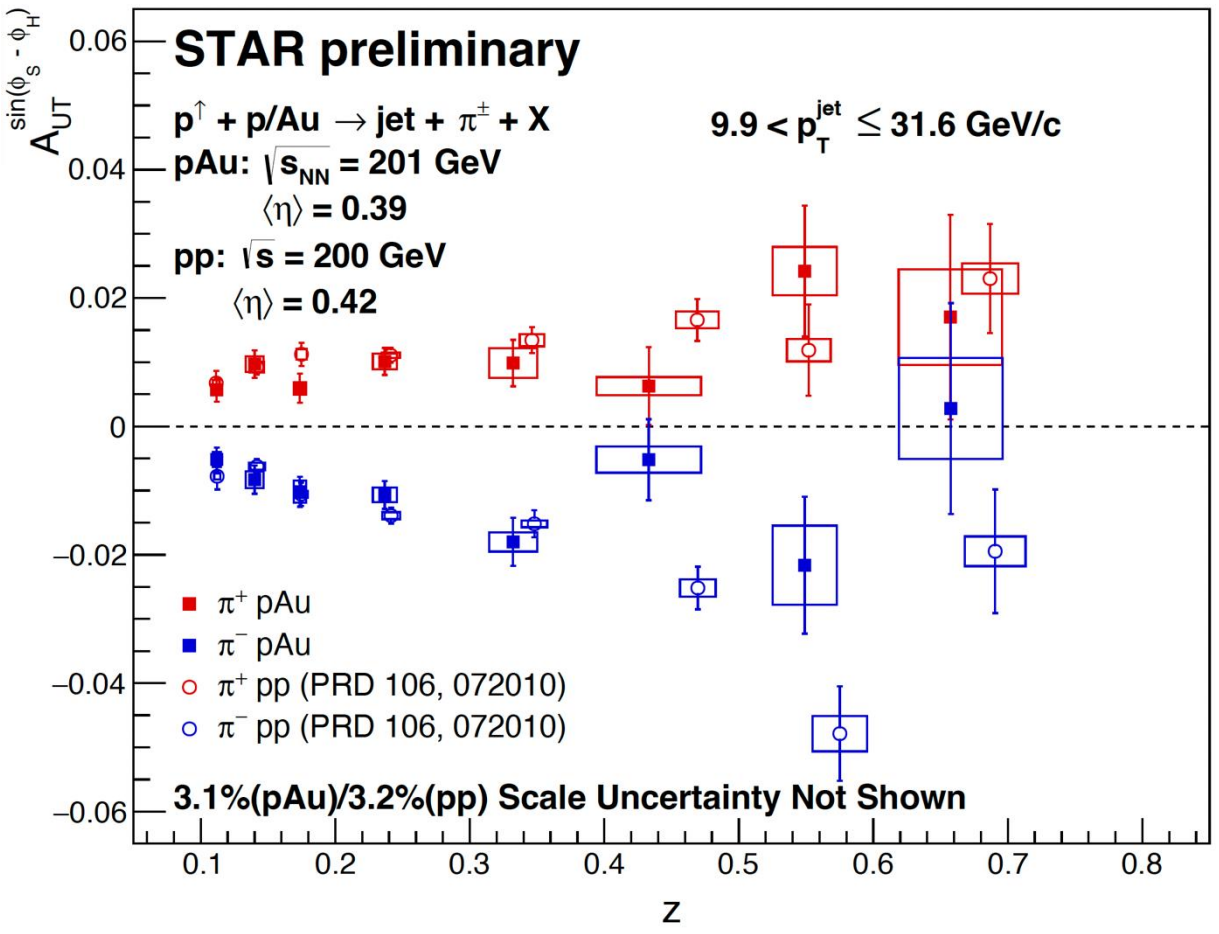
Comparing STAR *p*Au to *pp* Results

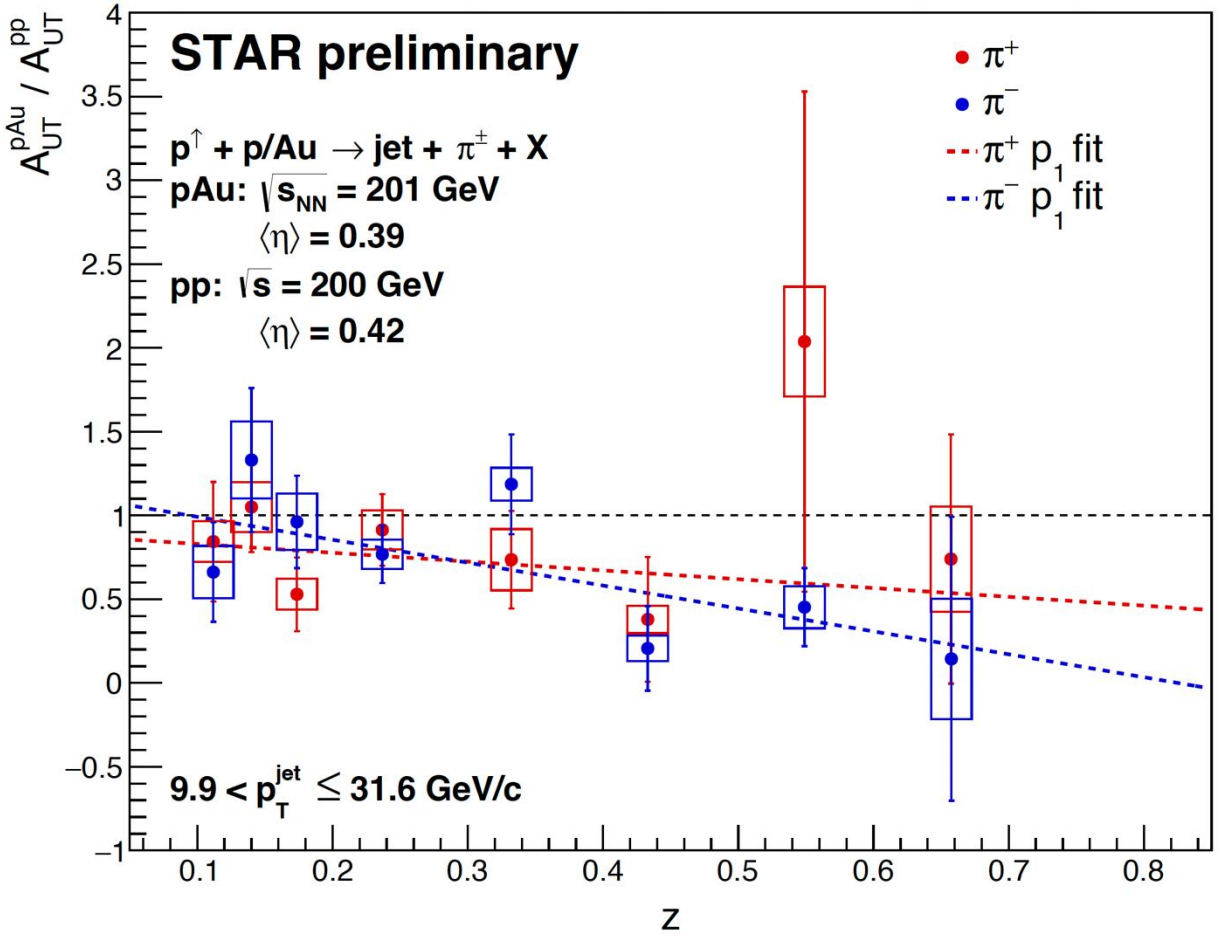
- If we make the likely naive assumption that any *p*Au vs. *pp* difference is independent of x_T, we find …
- A possible $\sim 18\%$ average suppression in *p*Au relative to *pp* at the $\sim 2\sigma$ level



π^- results slightly offset horizontally for clarity

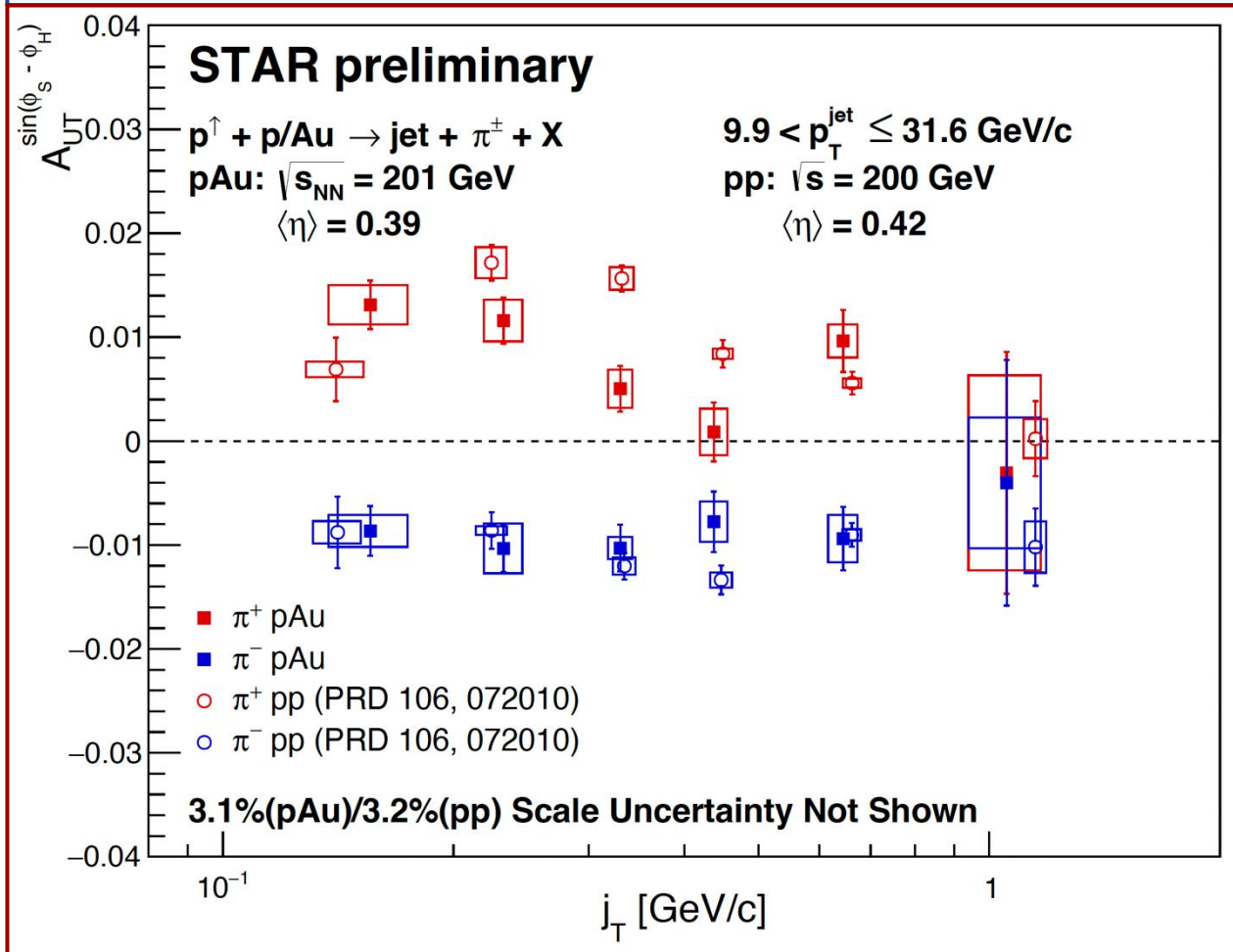
$A_{UT}^{\sin(\phi_S-\phi_H)}$ vs. Hadron Longitudinal Momentum Fraction z

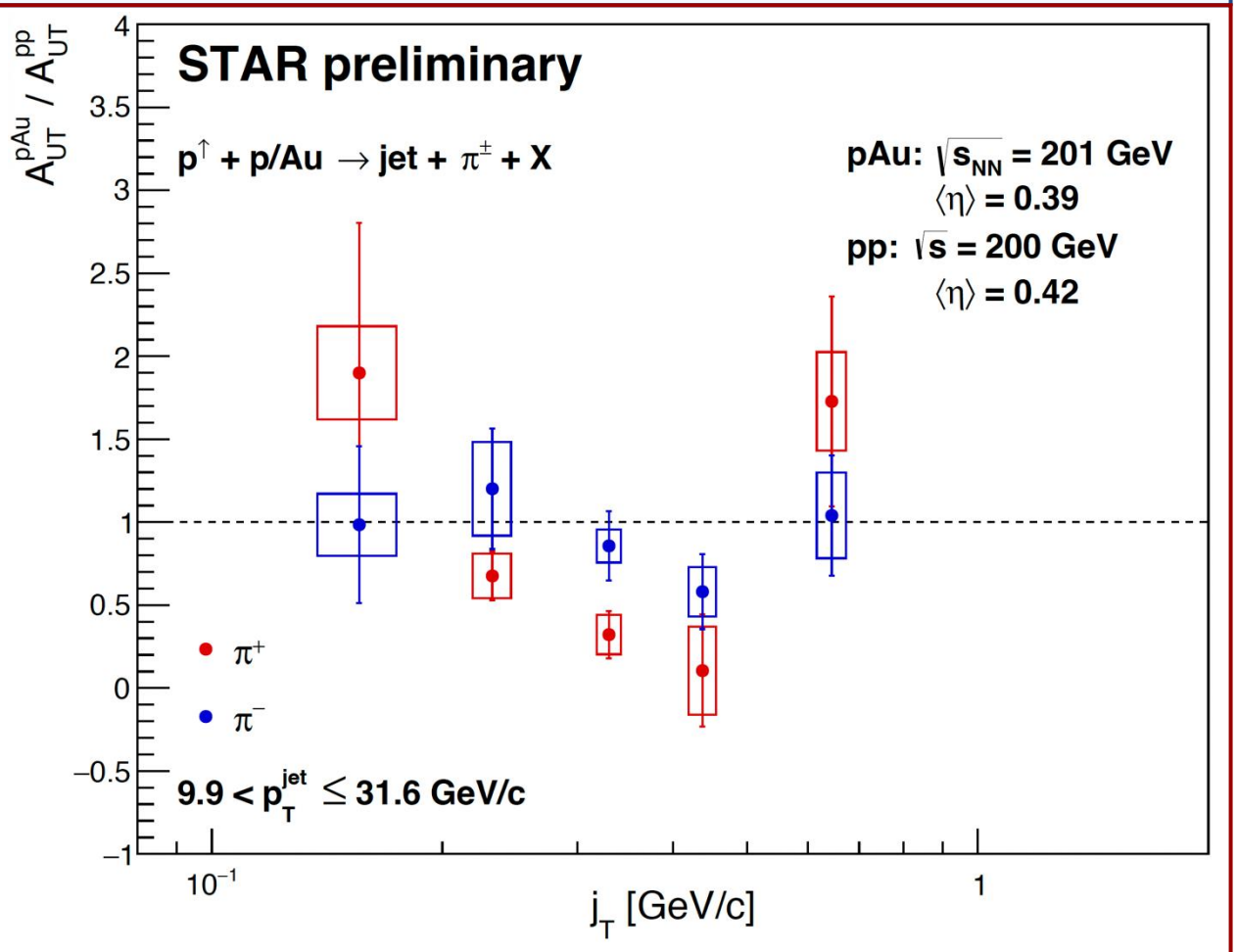




- For π^-, at the 2σ level, the data suggest less suppression at low z and more suppression at high z (slope $= -1.4 \pm 0.7$)
- For π^+, the best fit slope is also negative, but it only differs from zero by $\sim 0.5\sigma$ (slope $= -0.5 \pm 1.0$)

$A_{UT}^{sin(\phi_S-\phi_H)}$ 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 *p*Au collisions at $\sqrt{s_{NN}} = 201$ GeV

- Within the current uncertainties, the polarized *p*Au Collins asymmetries are consistent with the published STAR polarized *pp* results at $\sqrt{s} = 200$ GeV

- The *p*Au/*pp* comparison may indicate a modest suppression in *p*Au 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