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Recent Cold QCD Results from STAR

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SHANDONG UNIVERSITY

QCD & High Energy Interactions
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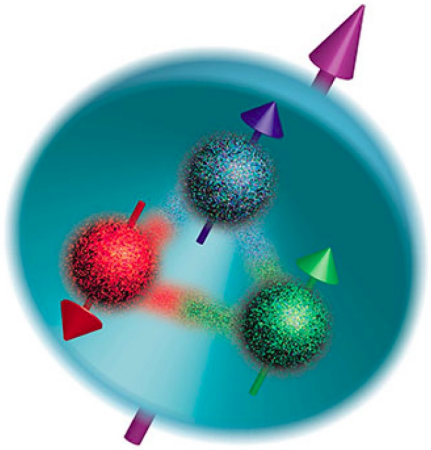
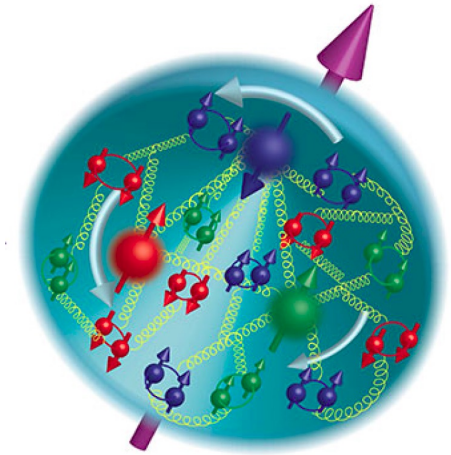
Fundamental Questions Regarding Proton Spin





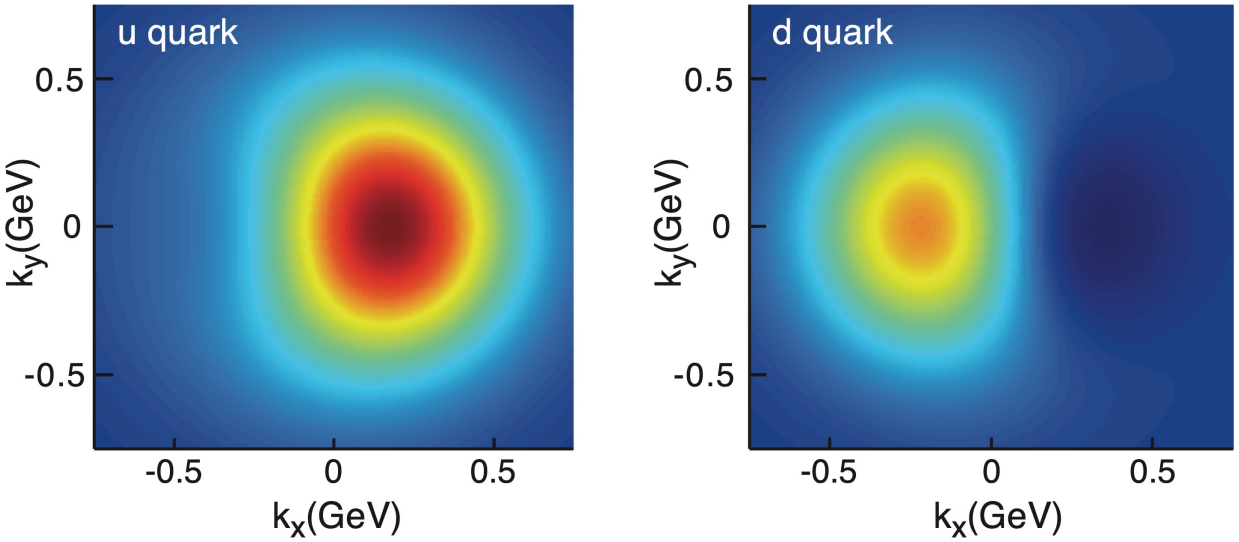
- How do quarks and gluons conspire to provide the proton's spin ½ ?
  - What is the role of gluons and sea quarks?
  - What is the size of the orbital angular momentum?
- What is the dynamic structure of the proton?
  - How do we go beyond longitudinal parton distribution functions to map out the 3D structure?
  - Can we visualize color interactions in QCD?

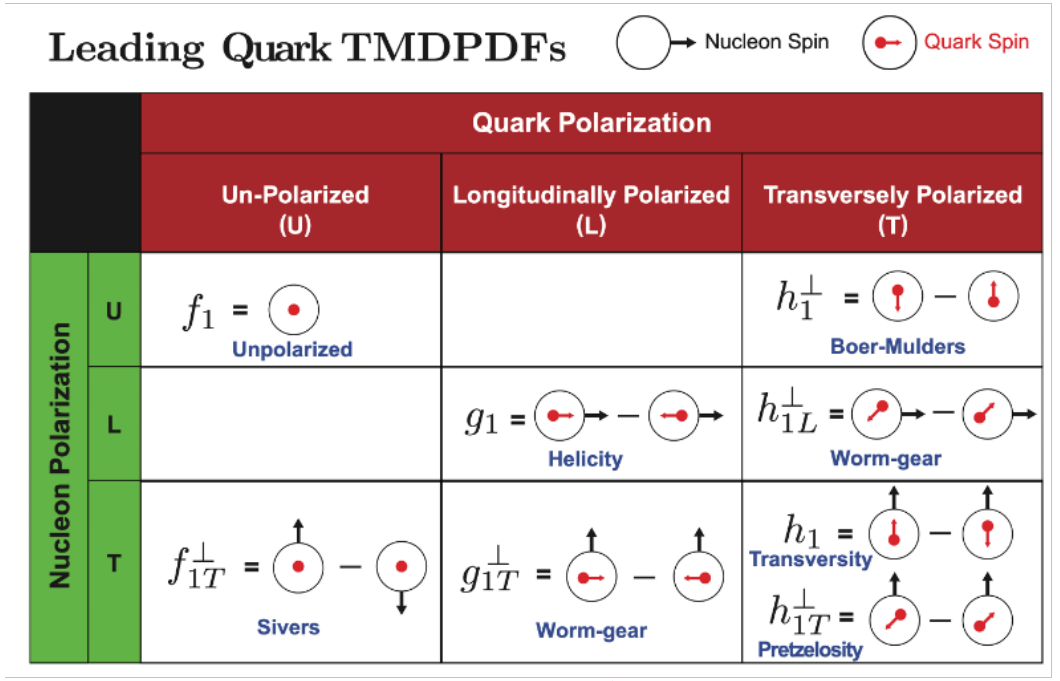
TMD Parton Distribution Functions

TMD Handbook, arXiv:2304.03302 [hep-ph]

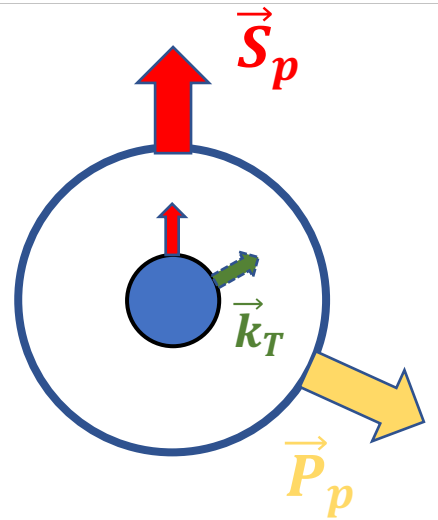
EIC White Paper arXiv:1212.1701

$x\, f_1(x, k_T, S_T)$

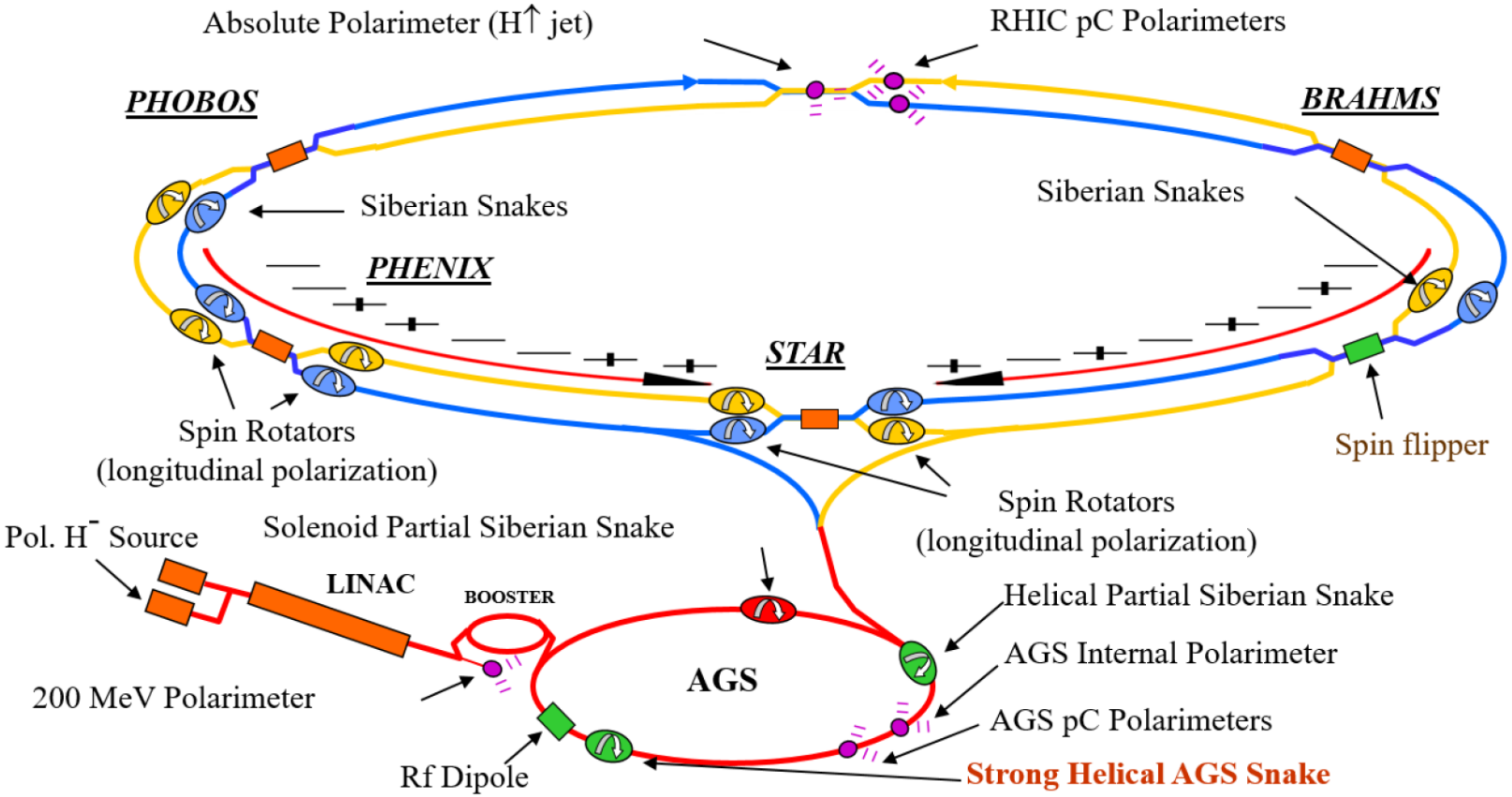




- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

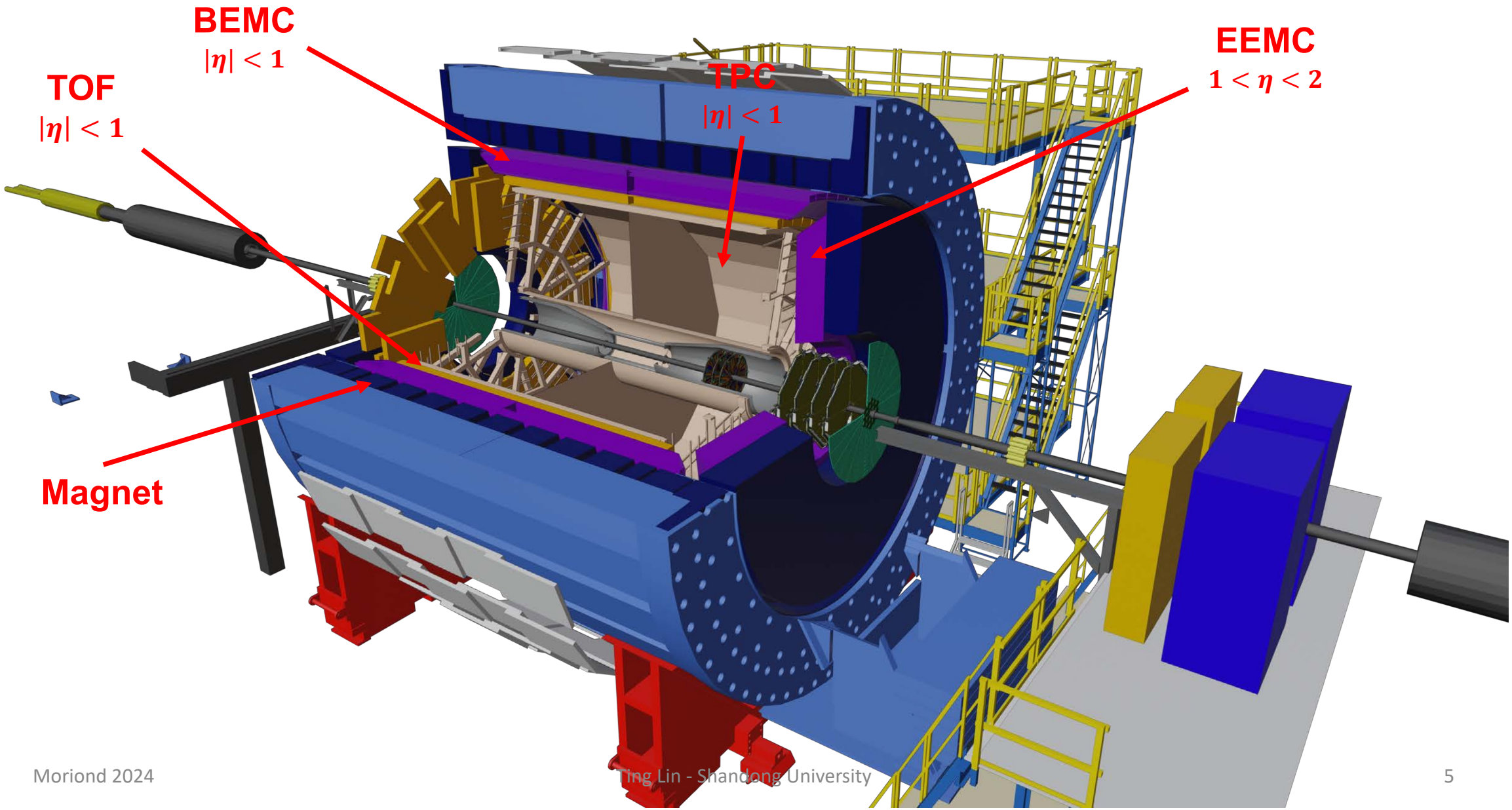


Relativistic Heavy Ion Collider (RHIC)



- Spin pattern changes from fill to fill with little depolarization;
- Siberian snakes preserve the polarization;
- Spin rotators select spin orientation;
- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

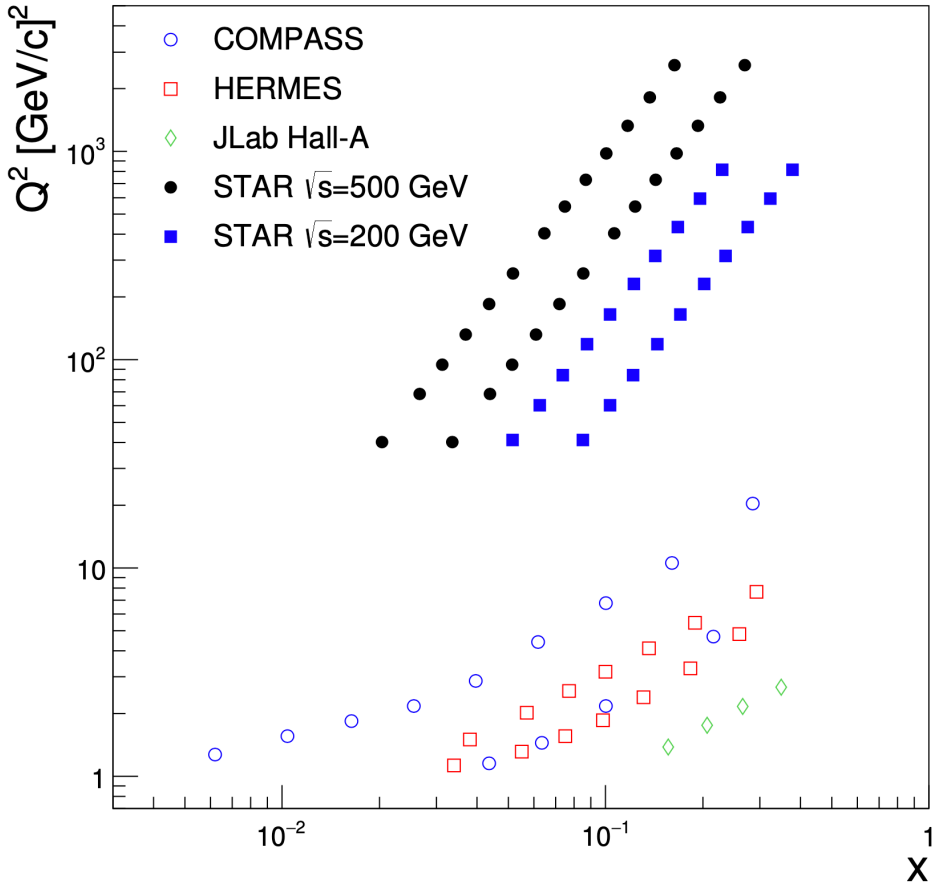
Solenoidal Tracker At RHIC (STAR)



STAR Data and Kinematic Coverage

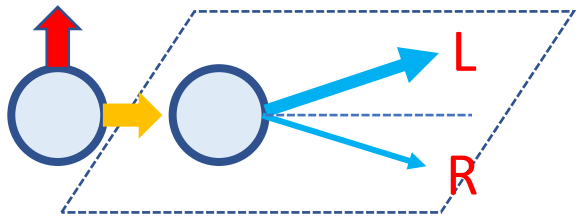
Year	2011	2012	2015			2017	2022	2024
$\sqrt{s}$ (GeV)	500	200	200			510	508	200
L_{int} (pb^{-1})	23	22	pp 52	pAu 0.45	pAl 1	320	400	TBD
Polarization	53%	57%	57%	60%	54%	55%	53%	TBD

- STAR covers a similar range in momentum fraction to that of SIDIS experiments but at much higher Q^2;
- 200 GeV results provide better statistical precision at larger momentum fraction regions while 500 GeV results probe lower values.
- These two different energies provide experimental constraints on evolution effects and insights into the magnitude and nature of TMD observables that will be measured at EIC.

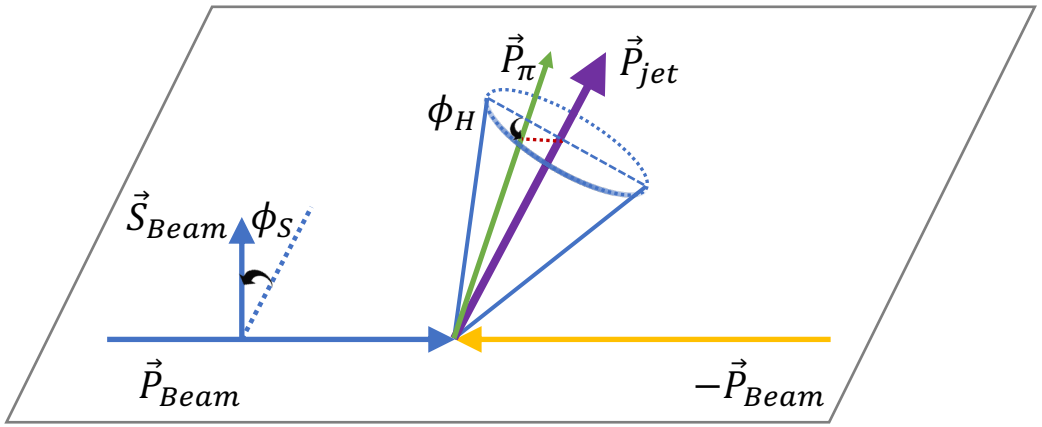


Transverse Single-Spin Asymmetry

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



$$p^{\uparrow} + p \rightarrow \text{Jet} + \pi^{\pm} + \text{X}$$

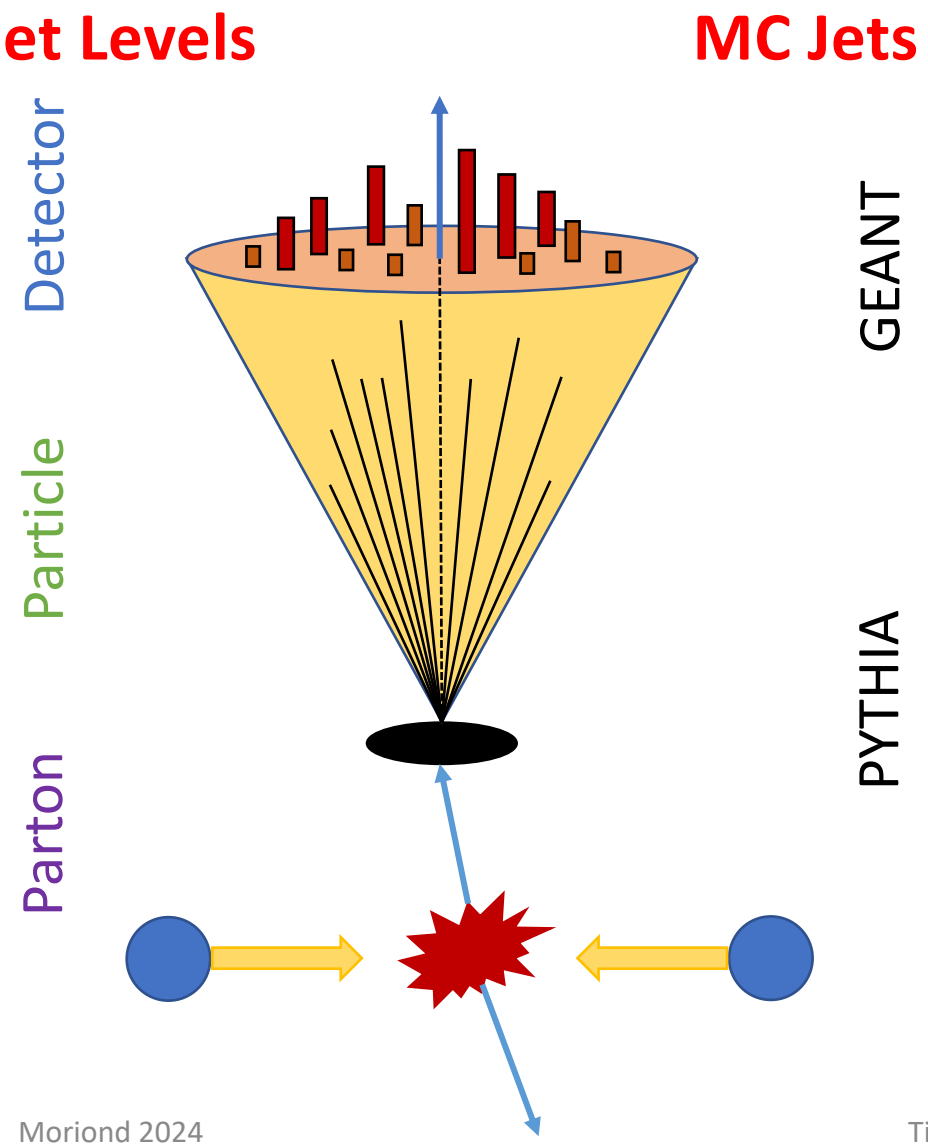


$$A_N = \frac{d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)}{d\sigma^{\uparrow}(\phi_S, \phi_H) + d\sigma^{\downarrow}(\phi_S, \phi_H)} \sim A_{UT}^{Sivers} \sin(\phi_S) + A_{UT}^{Collins} \sin(\phi_S - \phi_H)$$

$\sim f_{1T}^{\perp} \otimes D_1$ $\sim h_1 \otimes H_1^{\perp}$

- Each TMD PDF is convoluted with a fragmentation function and appears with a independent harmonic modulations (azimuthal asymmetry amplitudes).

Jet Reconstruction



Anti-K_T Algorithm:

- Radius = 0.6 for pp200, and 0.5 for pp500;
- Less sensitive to underlying event and pile-up effects;
- Used in both data and simulation;

Simulation:

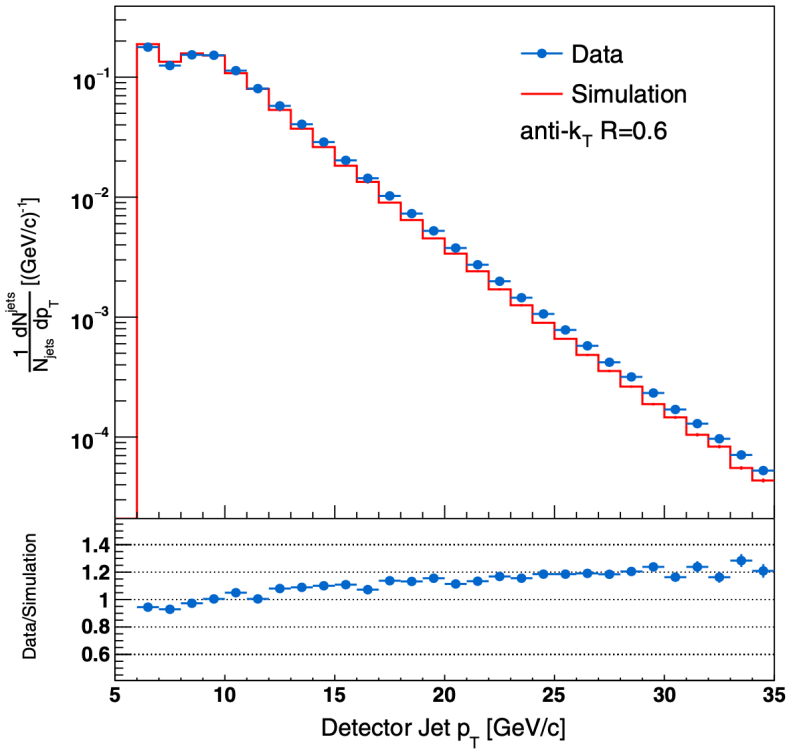
- PYTHIA 6.4 with STAR adjustment of Perugia 2012;

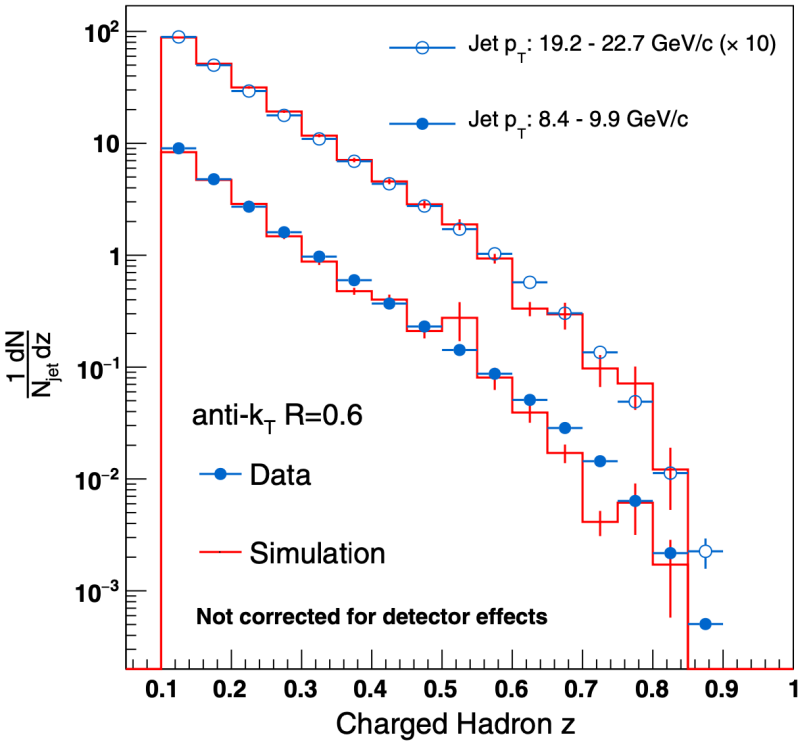
Three Simulation Levels :

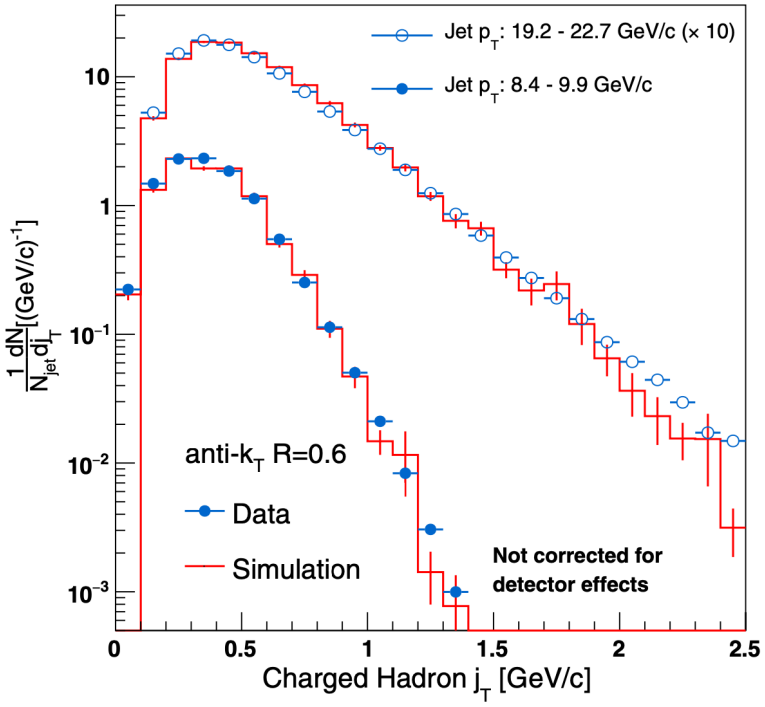
- Parton – hard scattered partons involved in 2->2 hard scattering event from Pythia;
- Particle – partons propagate and hadronize into stable and color-neutral particles;
- Detector – detector response to the stable particles.

Data and Simulation Comparison

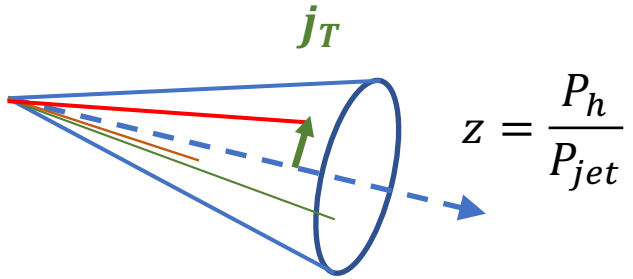
STAR, PRD 106, 072010 (2022)



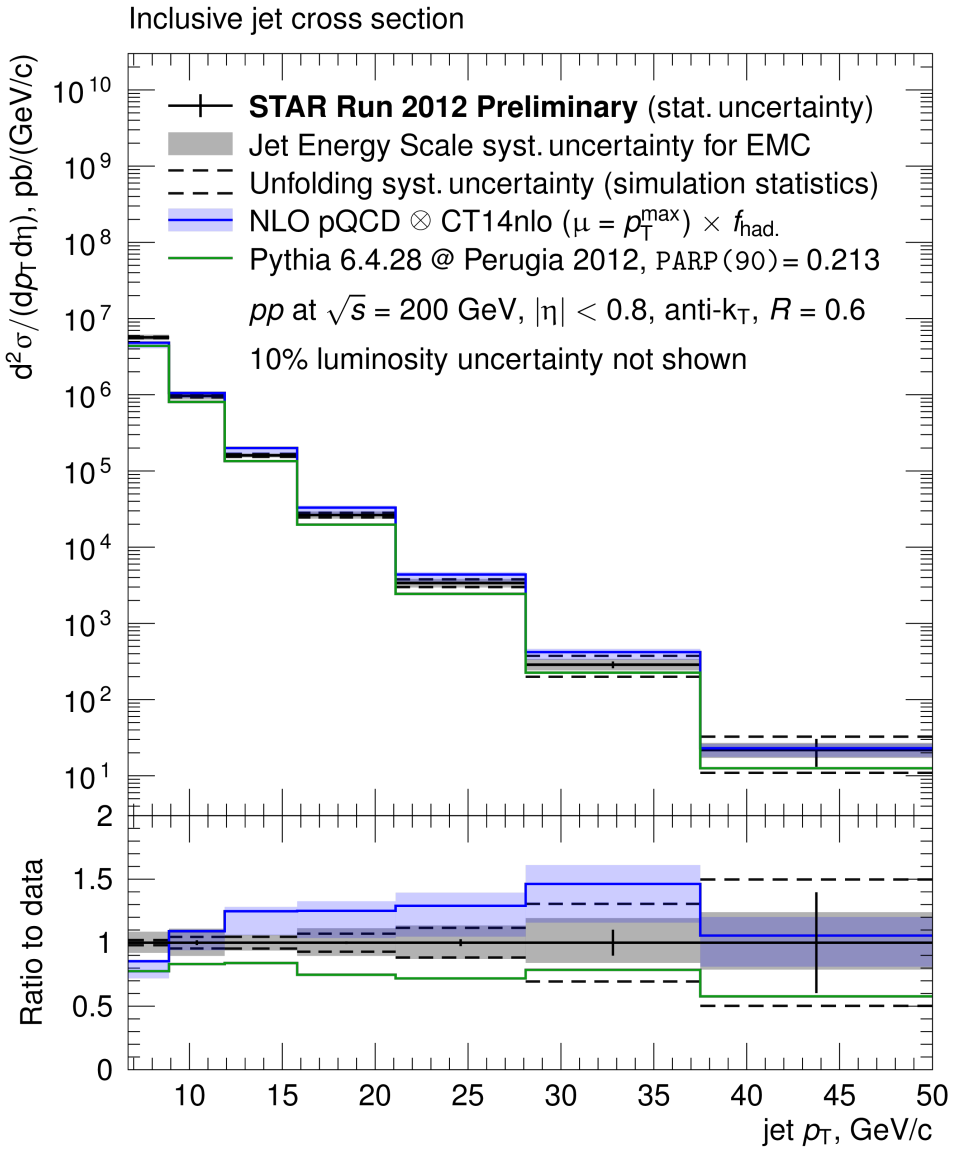


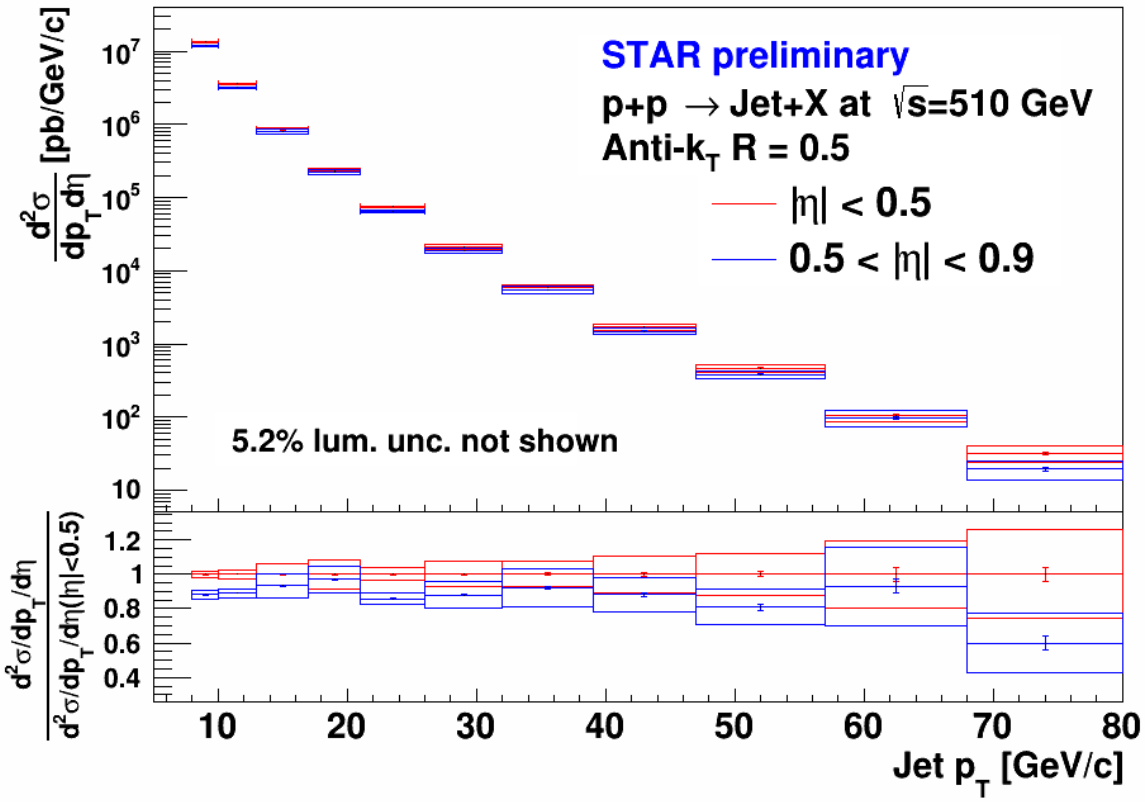


- Jets are reconstructed from both data and simulation;
- Very good agreement between data and simulation for various jet comparisons;
- Detector conditions are well understood and reproducible.



Inclusive Jet Cross Section

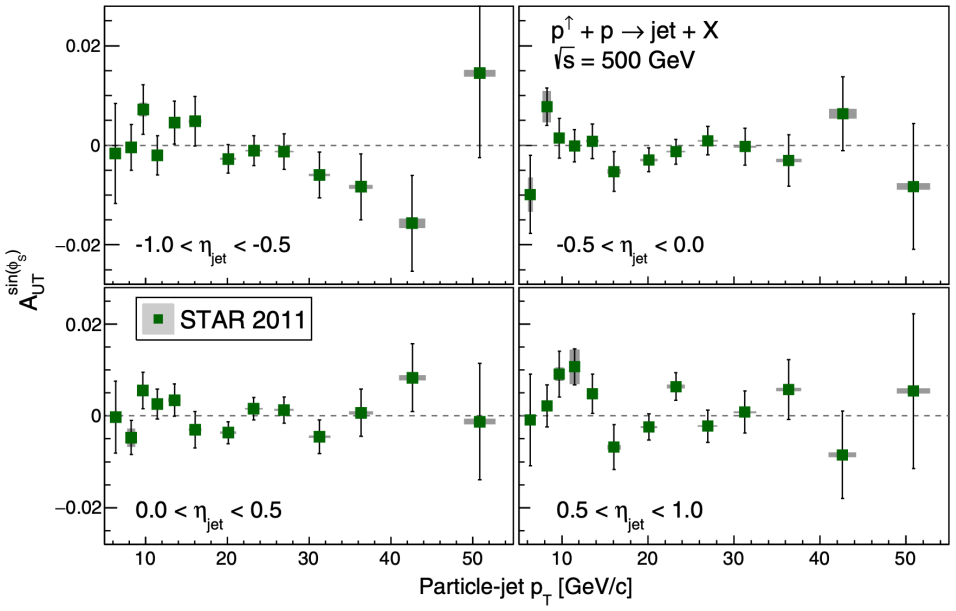




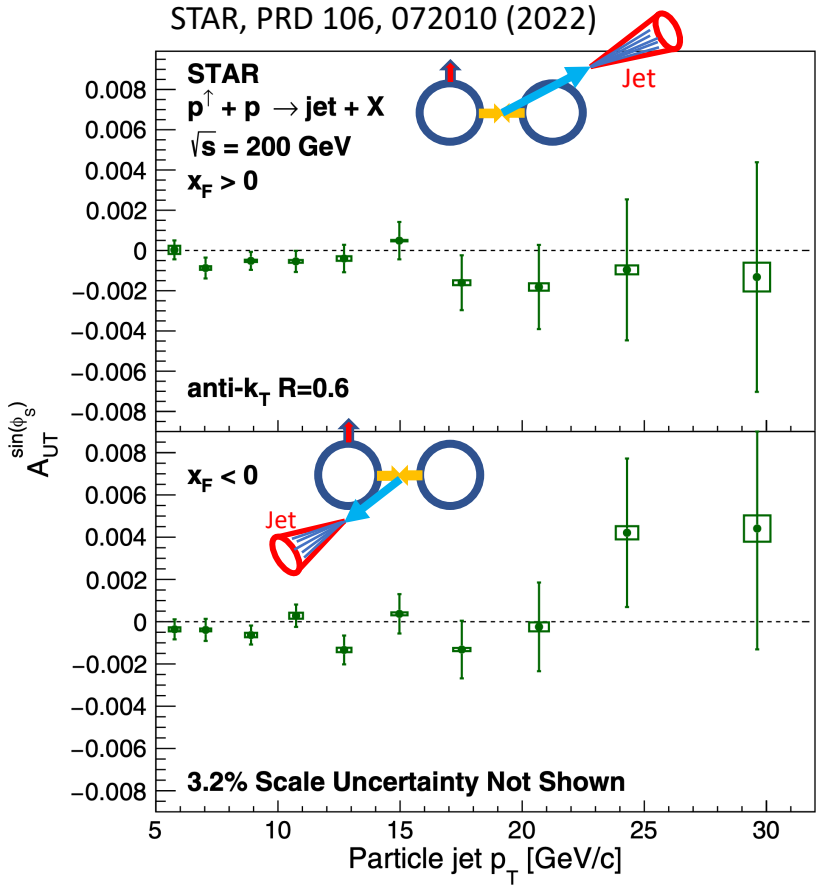
- The largest uncertainty is from the EM calorimeter response;
- The measured jet cross sections are in good agreement with NLO pQCD prediction.

A_N for Inclusive Jet

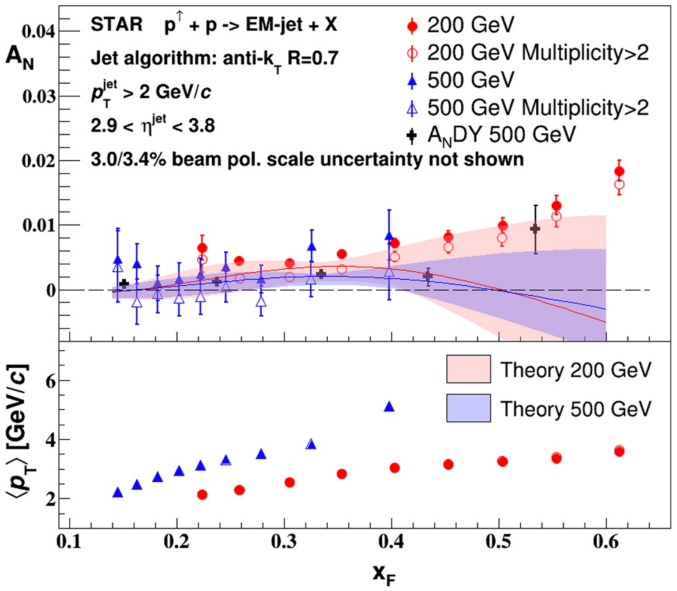
STAR, PRD 97, 032004 (2018)



STAR, PRD 106, 072010 (2022)



STAR, PRD 103, 092009 (2021)

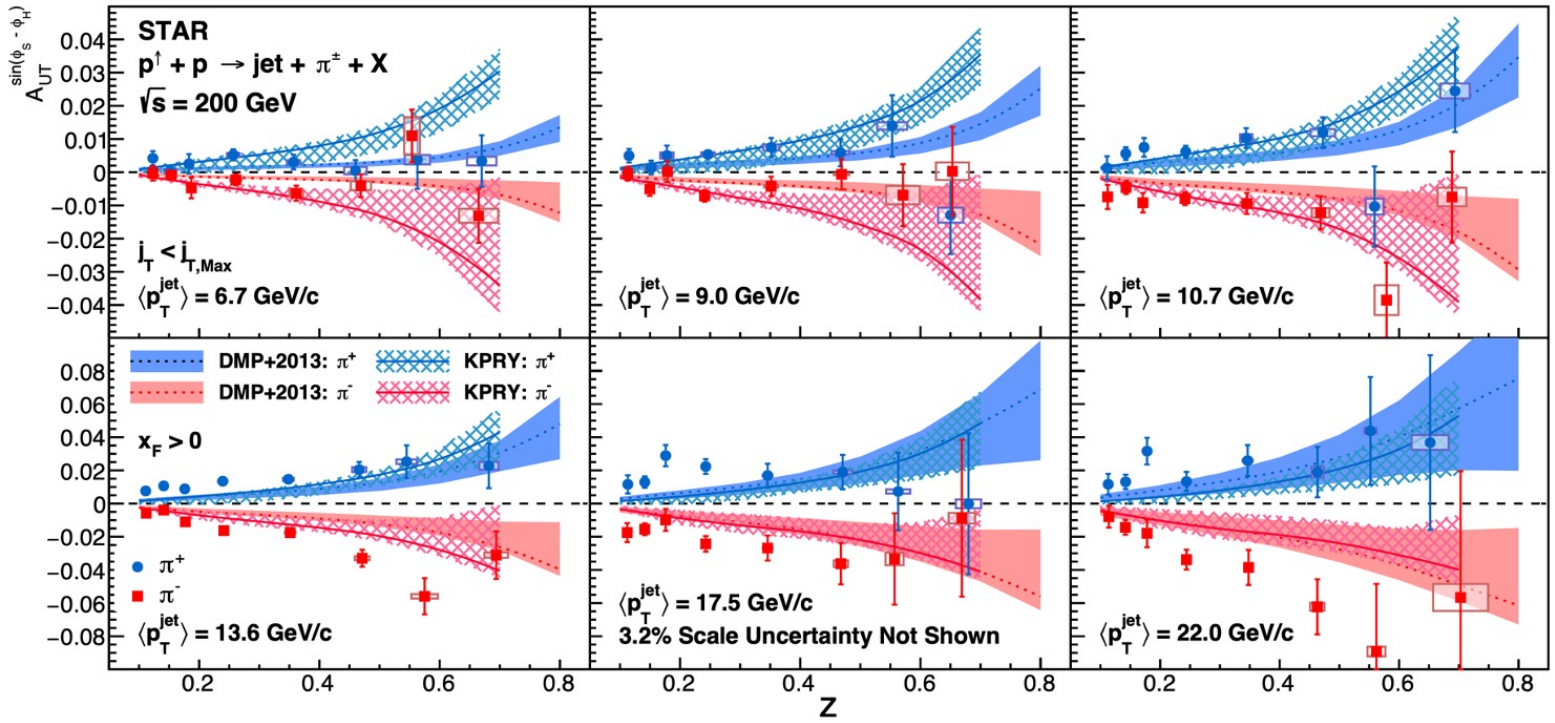


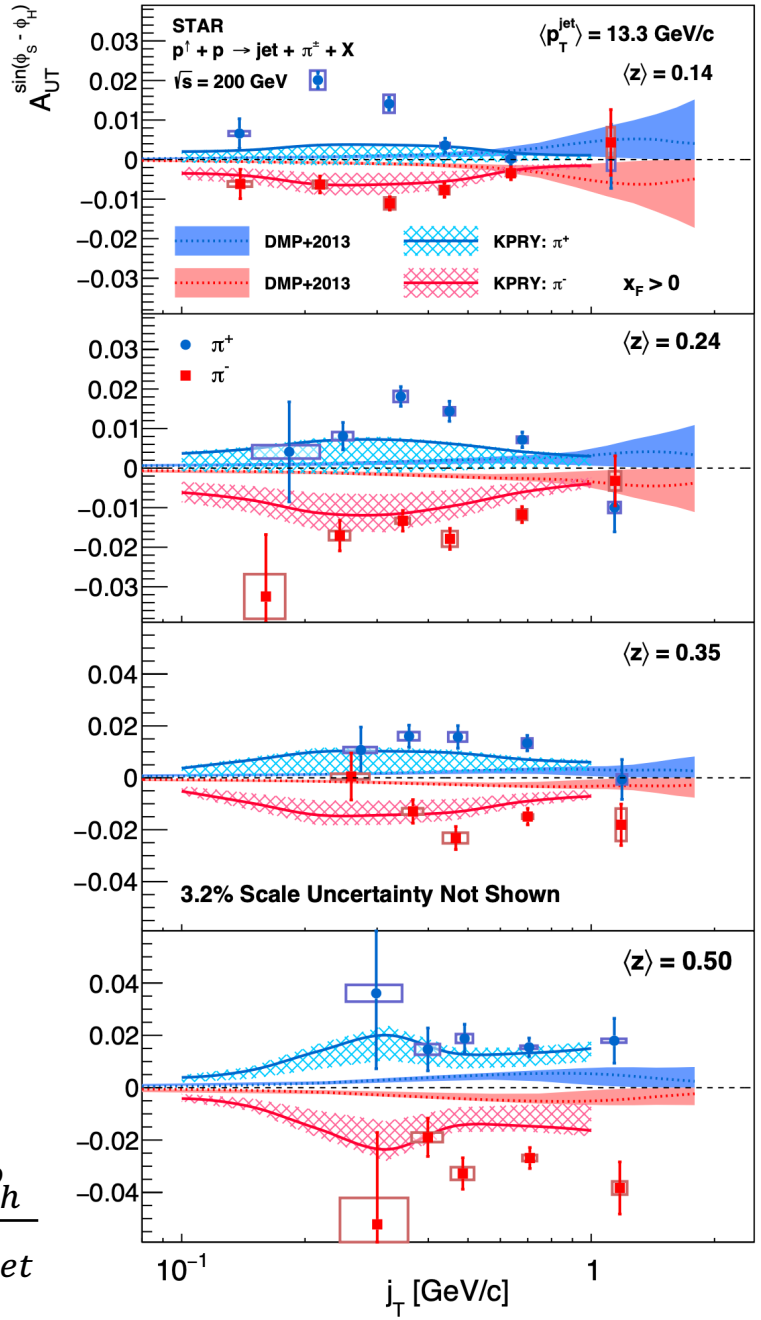
- Inclusive jet A_N are sensitive to the Sivers function via the twist-3 correlators;
- Free of final-state contributions.

A_N for $\pi^{\pm}$ in Jets

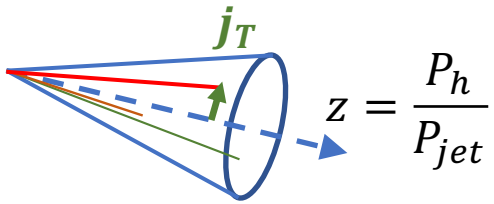
STAR, PRD 106, 072010 (2022)

$A_N \sim h_1 \otimes H_1^{\perp}$



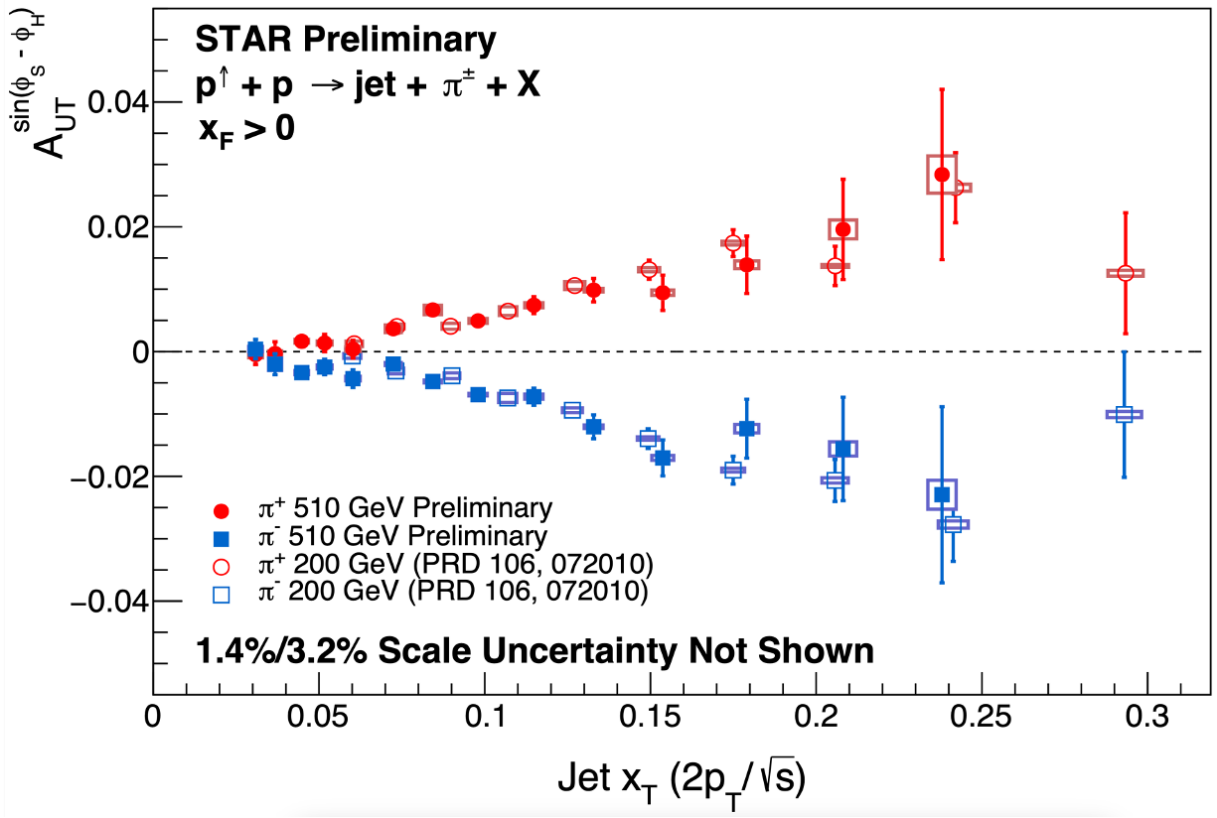


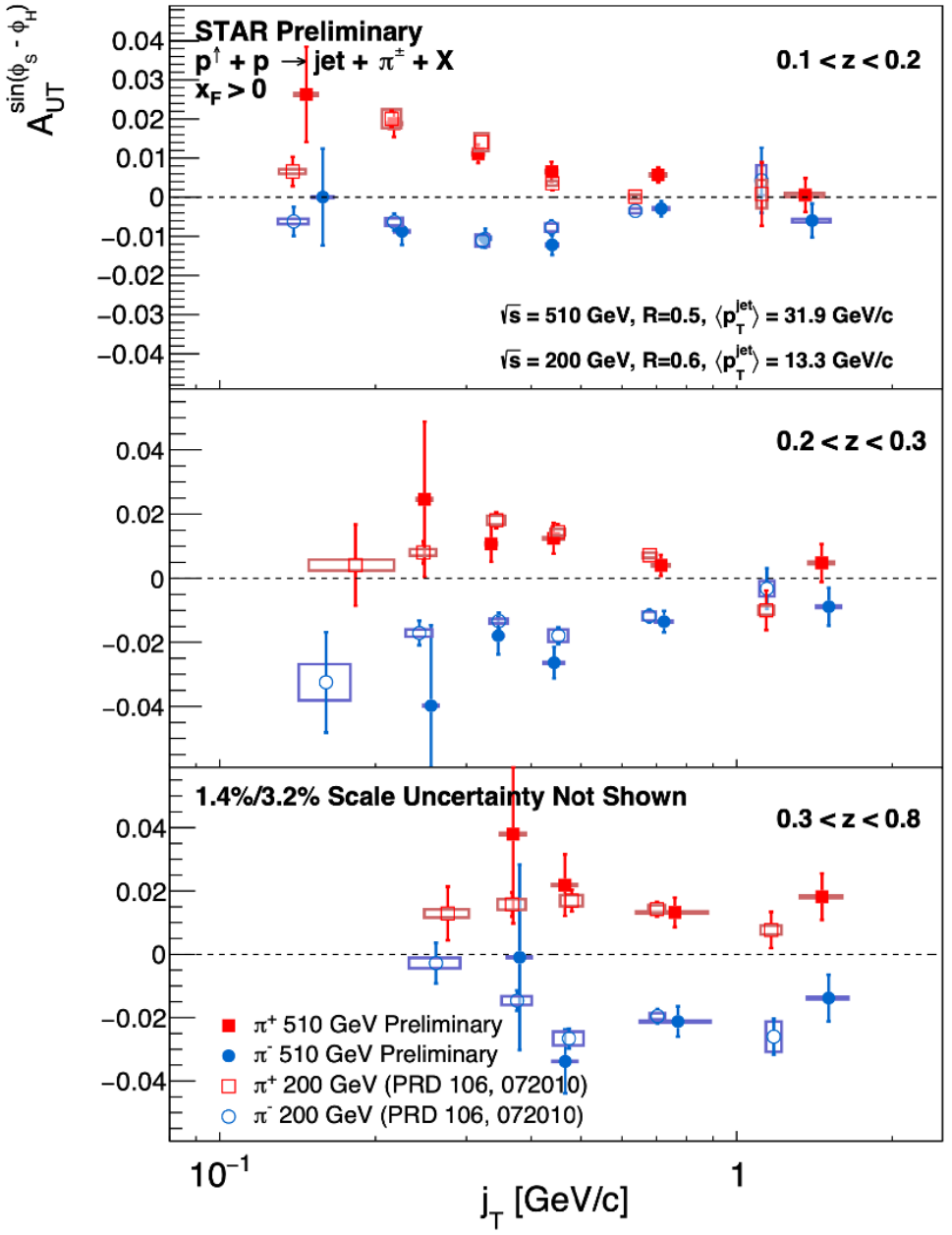
- DMP+2013 model from Umberto D'Alesio *et.al.*, PLB 773, 300 (2017);
- KPRY model from Zhong-Bo Kang *et. al.*,PLB 774, 635 (2017);
- Both assume universality and factorization.



$$z = \frac{P_h}{P_{jet}}$$

New 510 GeV Results

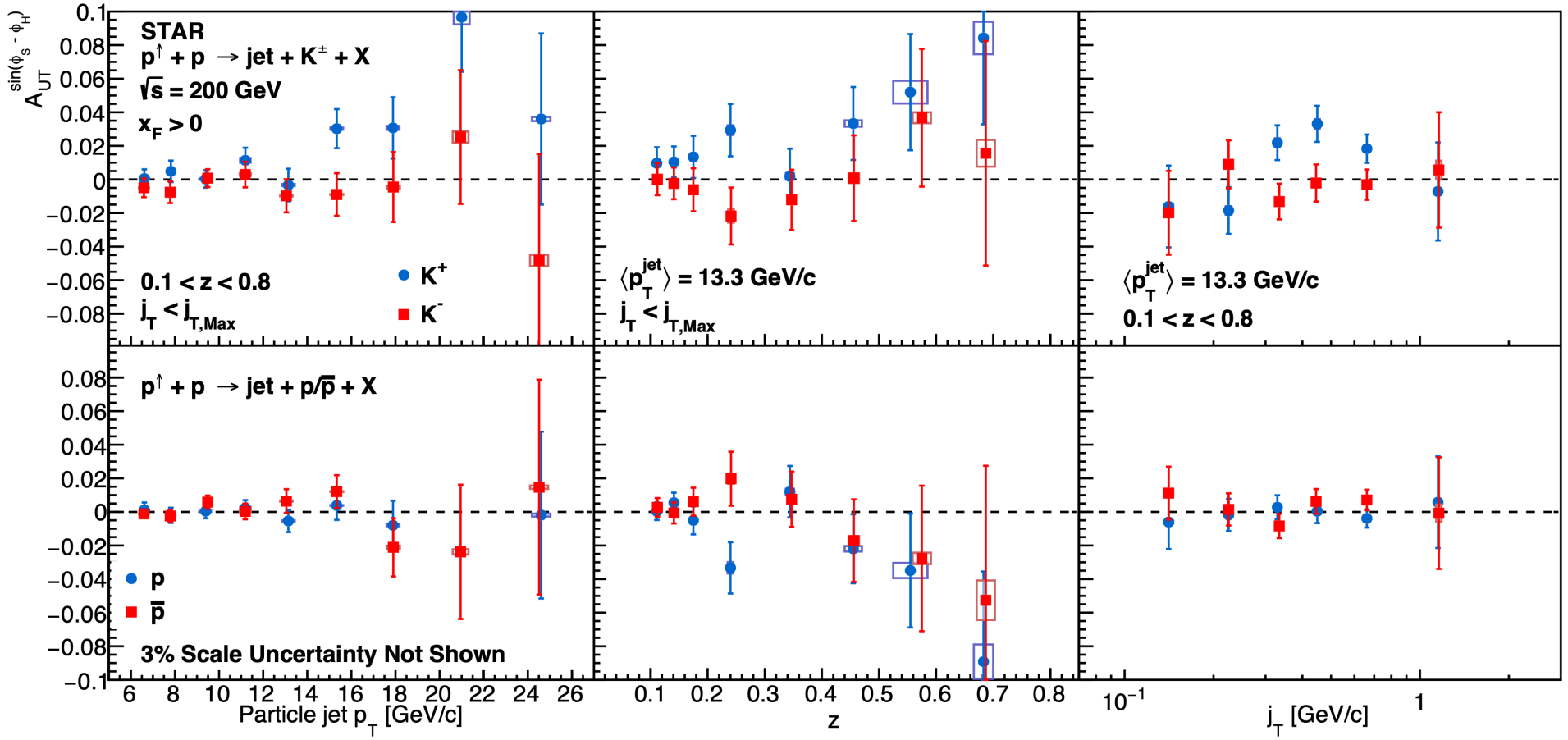




- The asymmetries agree at $0.06 < x_T < 0.2$, Q^2 differs by a factor of 6;
- Collins asymmetry has a weak energy dependence in hadronic collisions;
- z and j_T dependences of the Collins FF are closely related.

A_N for $K^{\pm}$and Proton in Jets

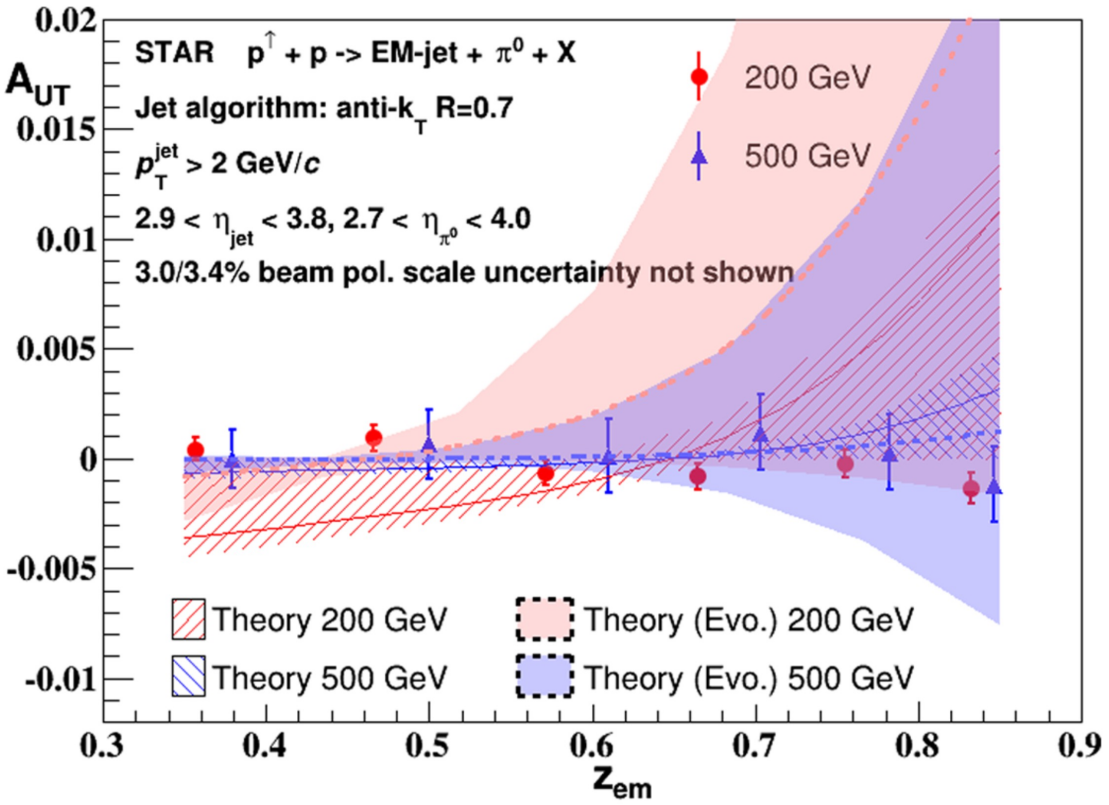
STAR, PRD 106, 072010 (2022)

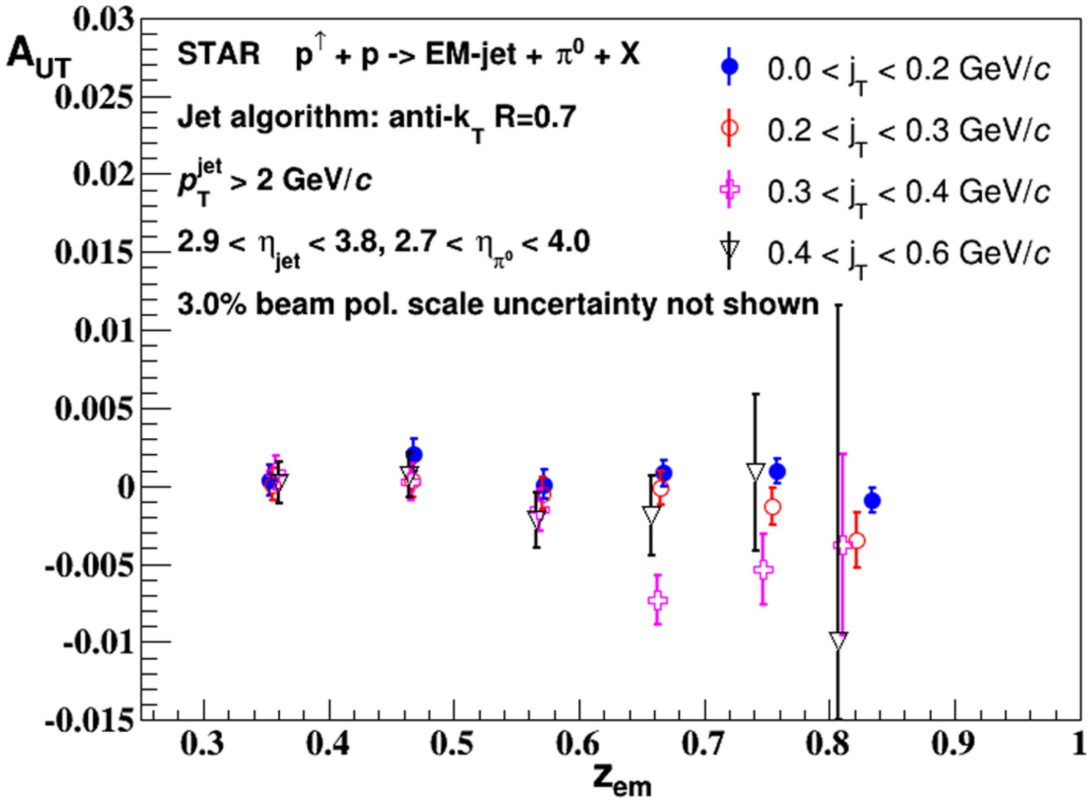


- K^+, with contribution from favored fragmentation of u quarks, has similar magnitude of asymmetries to π^+;
- K^-, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero;
- Proton and anti-proton's asymmetries are all consistent with zero at one sigma level.

A_N for π^0 in Jets

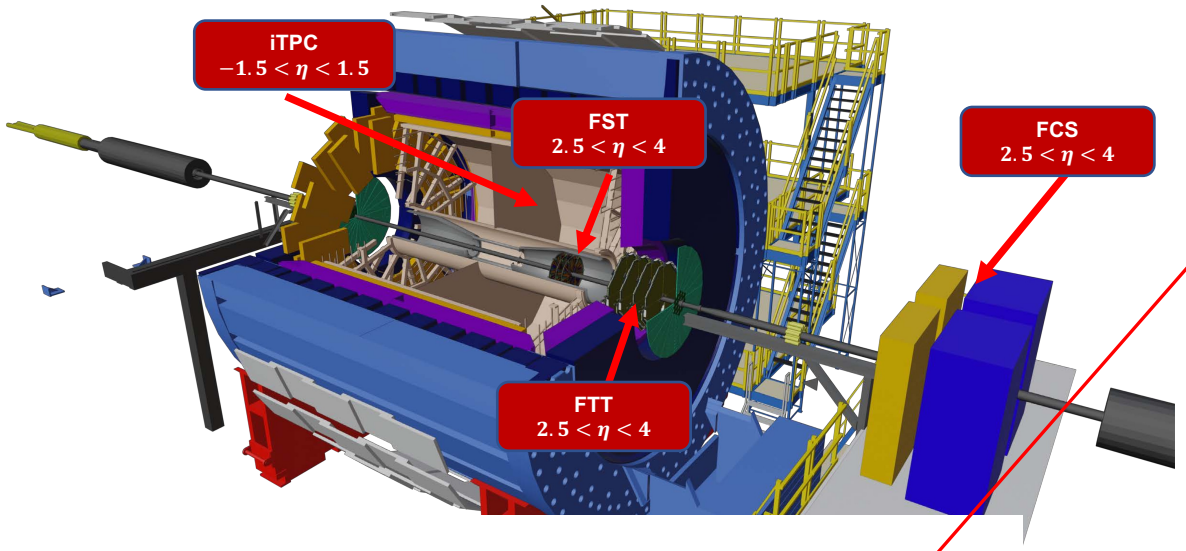
STAR, PRD 103, 092009 (2021)

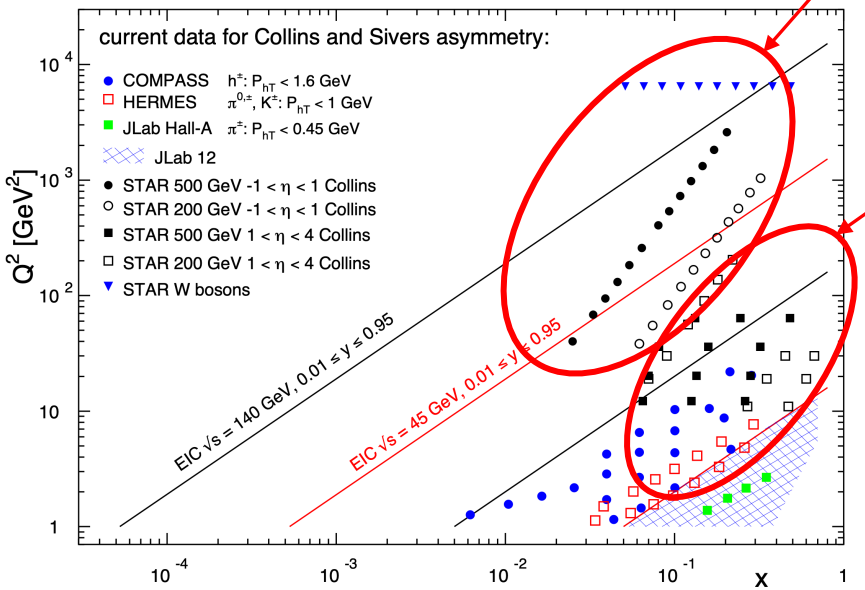




- Small Collins asymmetries at both energies;
- Cancellation of the Collins effect of the u/d quark.

Outlook





Mid Rapidity → **Forward Rapidity**

$-1.5 < \eta < 1.5$

Physics Topics:

Improve statistical precision:

- Sivers effect in dijet and W/Z production;
- Collins effect for hadrons in jets;
- Transversity and IFF;
- Diffractive studies for spatial imaging of nucleon;
- GPD E_g through UPC J/Ψ;
- Nuclear PDF and fragmentation function.

$2.5 < \eta < 4$

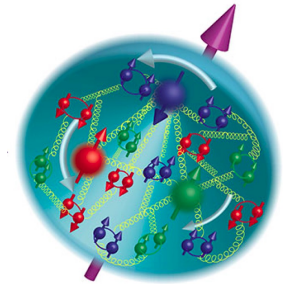
Physics Topics:

- TMD measurements at high x
  - Transversity, Collins;
  - Sivers through DY and jets
- UPC J/Ψ GPD at forward rapidity;
- Nuclear PDFs and FF;
- R_{pA} for direct photons and DY;
- Gluon Saturation through di-hadrons, γ-Jets, di-jets.

All of these measurements are critical to the scientific success of EIC to test universality and factorization.

- Large p+p 508 GeV sample from 2022 currently under analyses (w/ forward upgrades);
- Upcoming p+p in 2024 and possibly p+Au in 2025.

Summary



- Significant progress towards the understanding of the internal spin structure of nucleon at STAR;
  - Complementarity of 3D structure of nucleon measurements from lepton scattering and hadron-hadron collisions;
- Many new impactful results from transverse spin measurements;
  - Made the first observation of transversity, Sivers and Collins effect in pp collisions;
- Unique forward and midrapidity physics with recent upgrades;
  - Overlap kinematic coverage with EIC;
  - Establish the validity and limits of factorization and universality.