SPIN2021

Matsue, Japan

24th International Spin Symposium

October 18 -22, 2021

The 24th International Spin Symposium

Exploring the Quark Transversity and the Collins Fragmentation Functions using Polarized p+p Collisions at STAR

Ting Lin (林挺), for the STAR Collaboration

Shandong University (山东大学)

STAR

SHANDONG UNIVERSITY

山东大学

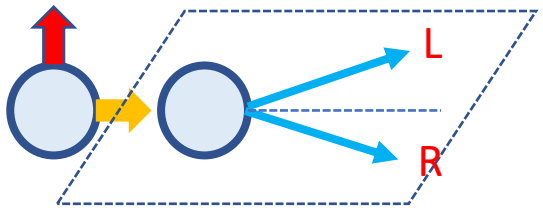
Supported in part by

U.S. DEPARTMENT OF ENERGY

Office of Science

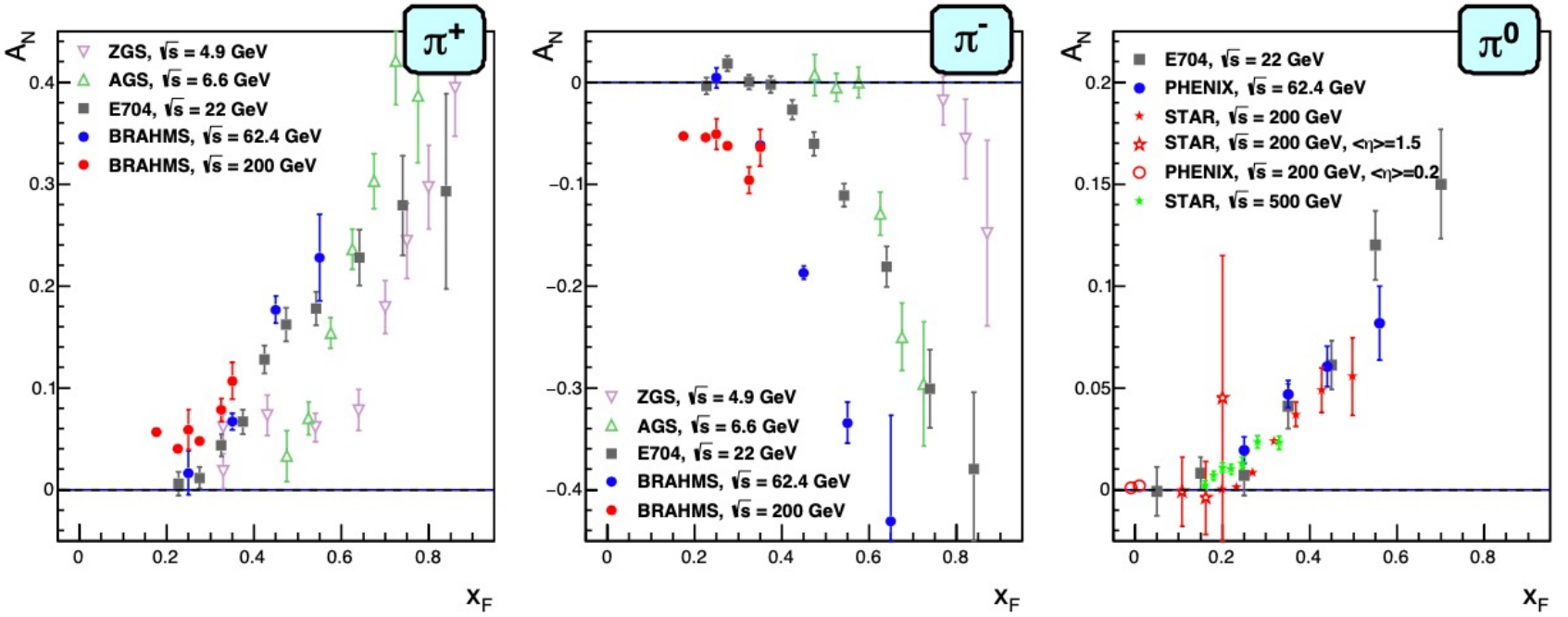
Challenges in Transverse Single-Spin Asymmetry

- Large transverse single-spin asymmetry (A_N) at forward rapidities has been measured in transversely polarized proton-proton collisions;
- pQCD predicts very small asymmetries in the hard scattering process;
- Twist-3 and transverse momentum dependent (TMD) frameworks are developed to describe this transverse spin effect;



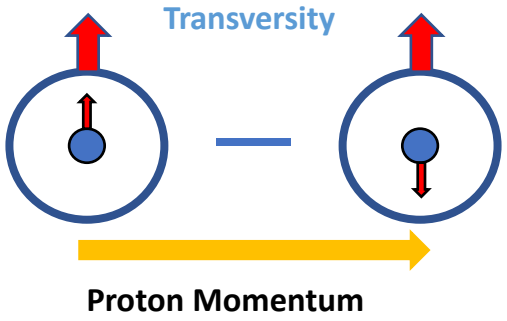
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

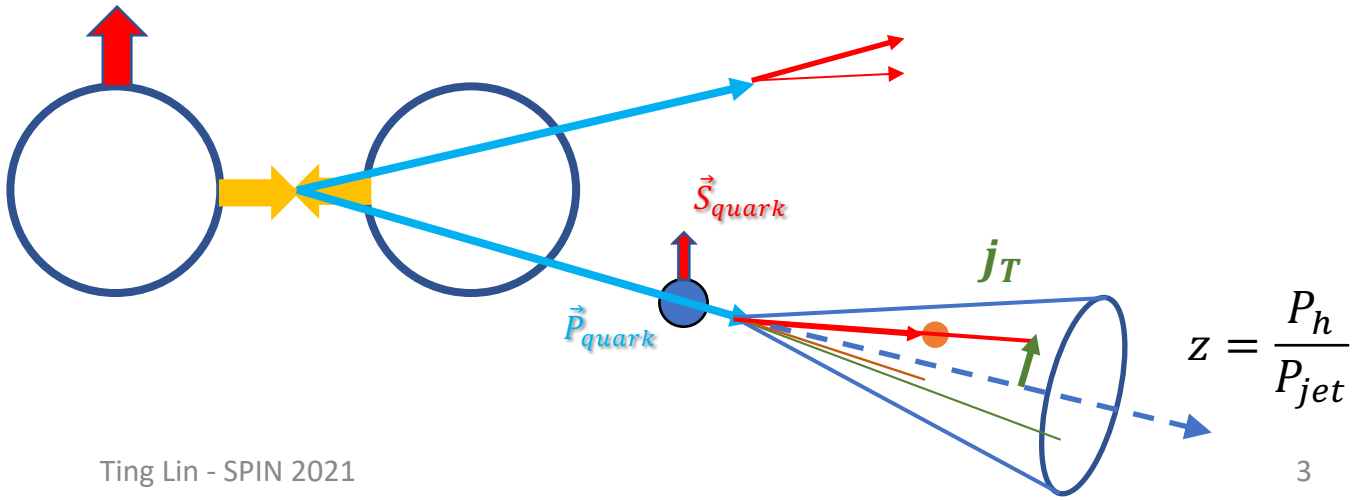
Elke Aschenauer *et al.* arXiv:1602.03922 [nucl-ex]



Collins Effect

- Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction;
  - Collins effect combines the quark transversity in the proton with the spin-dependent Collins fragmentation function;
  - $D_{h/q,S_q}(z, \boldsymbol{j_T}) = D_{h/q}(z, \boldsymbol{j_T}) + \frac{1}{zM_h} H_1^{\perp q}(z, \boldsymbol{j_T}) \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T)$;





Transverse Single-Spin Asymmetry

- For pions within jets, the spin dependent cross section is:

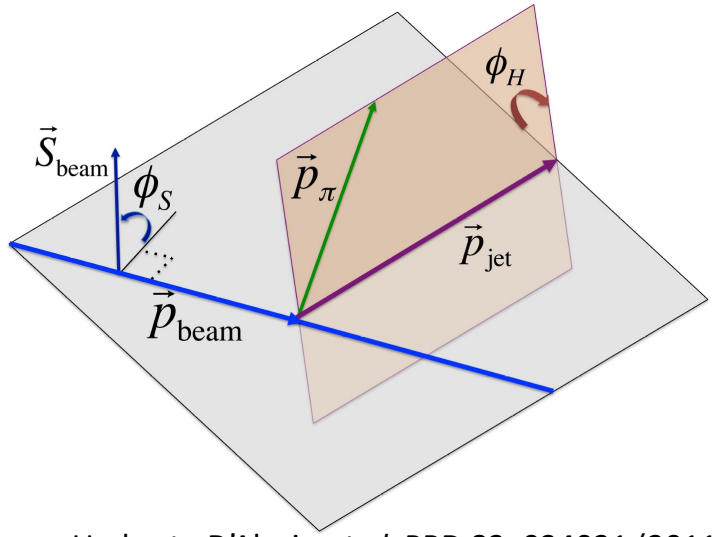
$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$

$$\sim \mathrm{d}\Delta\sigma_0 \sin(\phi_S) + \mathrm{d}\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + \mathrm{d}\Delta\sigma_1^{+} \sin(\phi_S + \phi_H) + \mathrm{d}\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H) + \mathrm{d}\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)} \xrightarrow[\phi=\phi_S-\phi_H]{} \frac{\sum_{a,b,c} \boldsymbol{h_1^a(x_1,\mu)}\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{Collins}}\ \boldsymbol{H_{1,h/c}^{\perp}(z_h, j_T; Q)}}{\sum_{a,b,c} f_a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{unpol}}\ D_{h/c}(z_h, j_T; Q)}$$

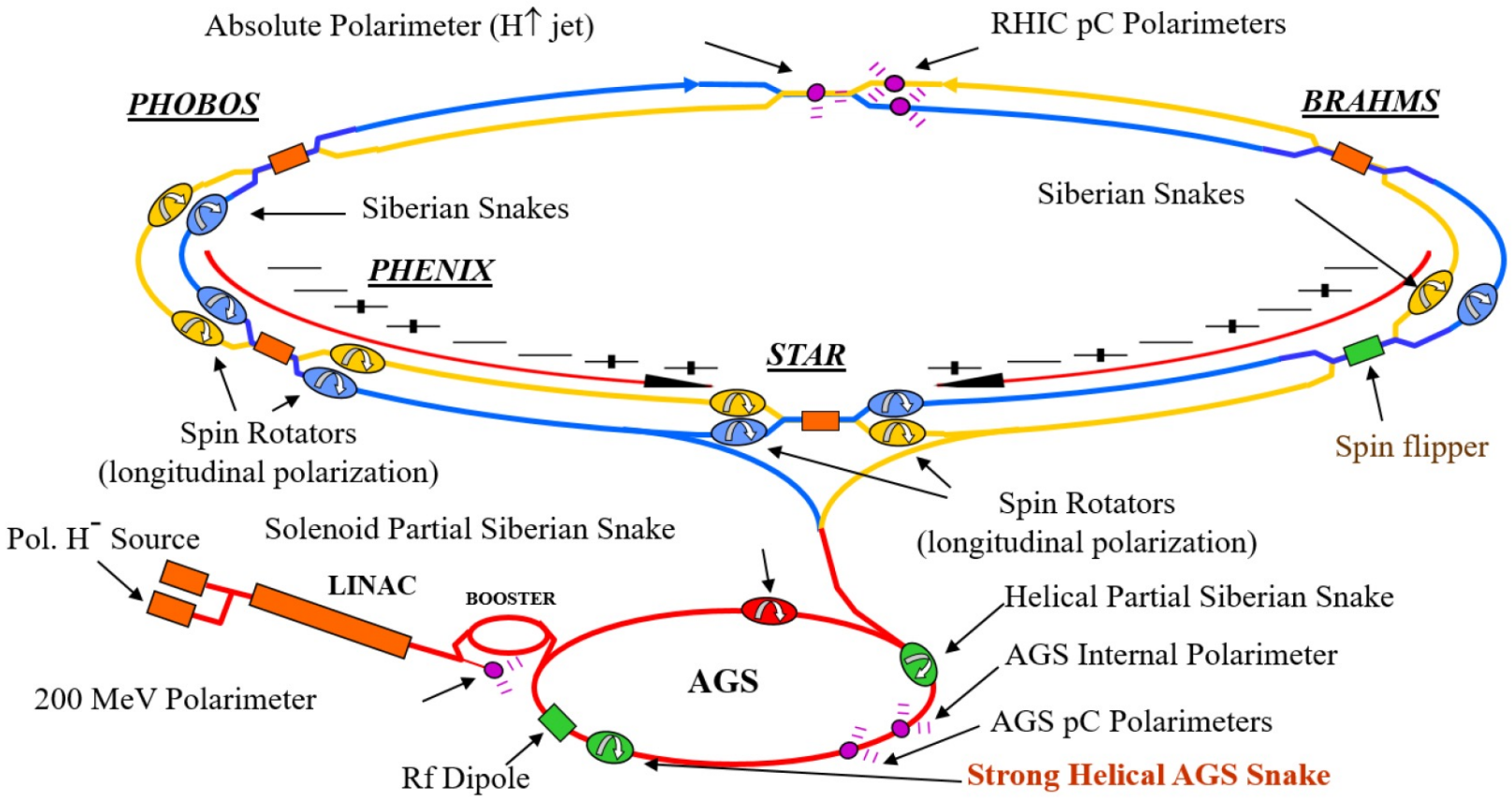
Zhong-Bo Kang *et al.*, JHEP 11, 068 (2017) and PLB 774, 635 (2017)

- Collins effect in pp involves a mixture of collinear and TMD factorization:
  - Initial hard scattering involves the collinear transversity $\boldsymbol{h_1^a}$;
  - Polarized quark then fragments according to the TMD Collins fragmentation function $\boldsymbol{H_{1,h/c}^{\perp}}$;
- Cleaner kinematic separation of transversity and TMD physics;
- At EIC, full jet reconstruction will enable similar kinematic separation.



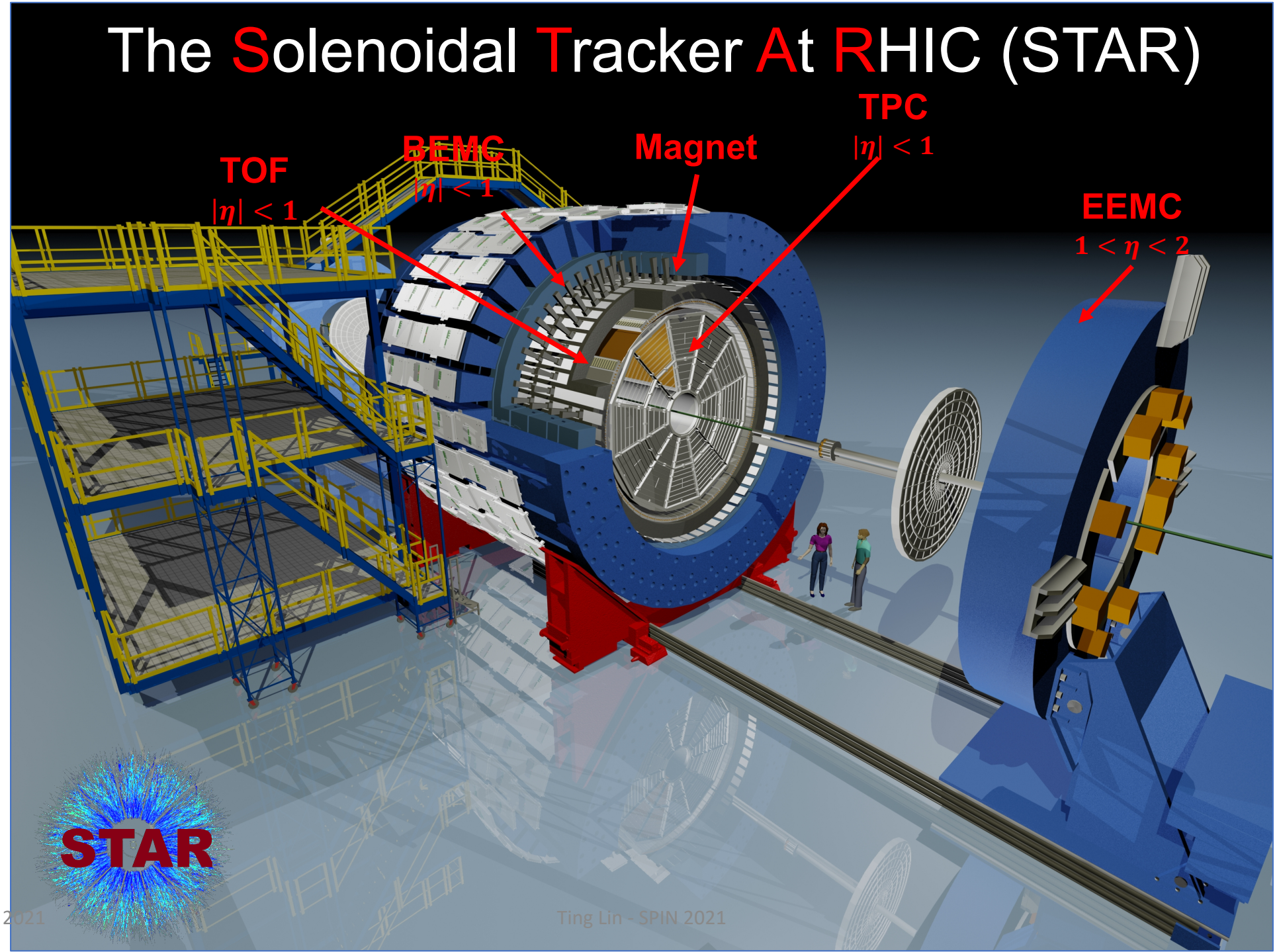
Umberto D'Alesio *et al*. PRD 83, 034021 (2011)

Relativistic Heavy Ion Collider (RHIC)



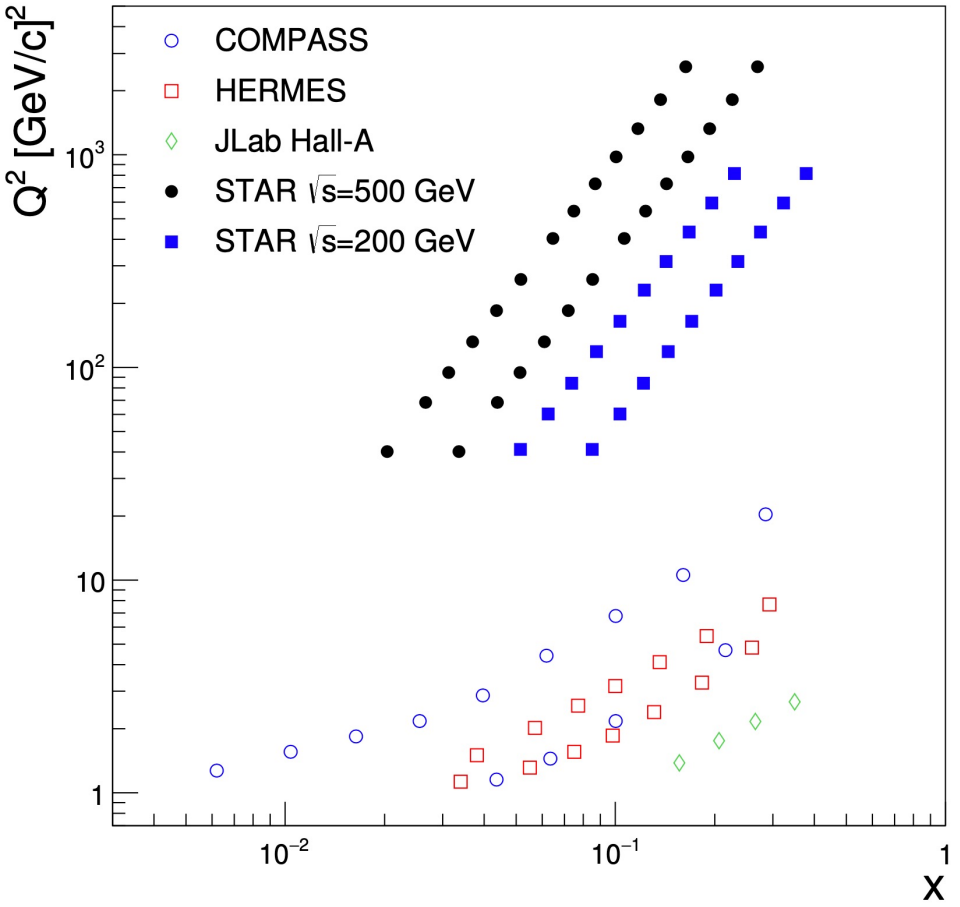
- World's first and only polarized proton+proton collider;
  - Provide polarized proton+proton collisions up to 510 GeV;
- Spin pattern changes from fill to fill with little depolarization;
  - Siberian snakes preserve the polarization;
  - Spin rotators select spin orientation;
  - proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

The Solenoidal Tracker At RHIC (STAR)



STAR Data and Kinematic Coverage

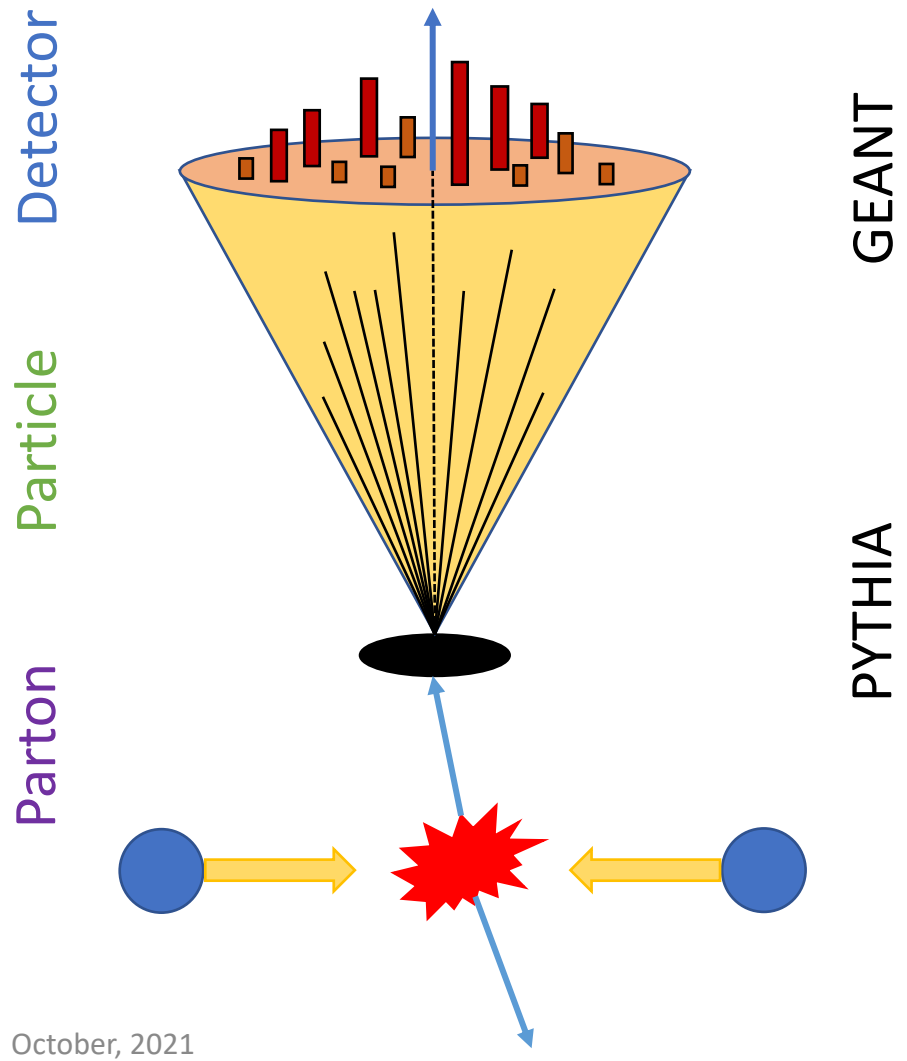
Year	2011	2012	2015	2017
$\sqrt{s}$ (GeV)	500	200	200	510
L_{int} (pb^{-1})	25	14	52	350
Polarization	53%	57%	57%	58%



- STAR covers a similar range in momentum fraction (x) to that of SIDIS experiments with much higher Q^2;
- 200 GeV results provide better statistical precision at higher momentum fraction region than 500 GeV results;
- 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 the future Electron-Ion Collider.

Jet Reconstruction

Jet Levels **MC Jets**



Anti-k_T Algorithm:

- Radius = 0.6;
- Less sensitive to underlying event and pile-up effects;
- Used in both data and simulation;

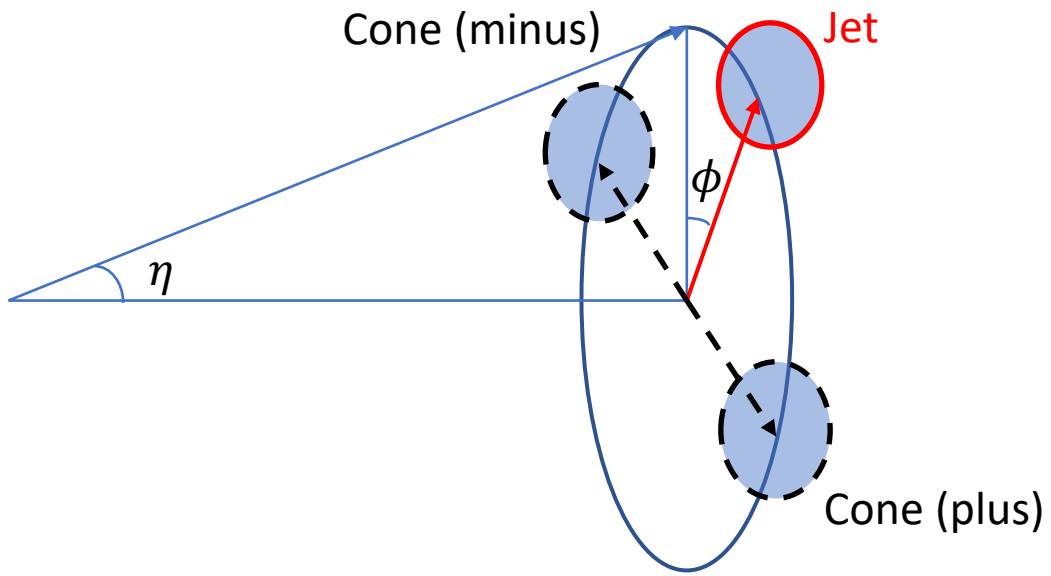
Simulation: PYTHIA 6.4 Perugia 2012 with additional tuning to STAR data;

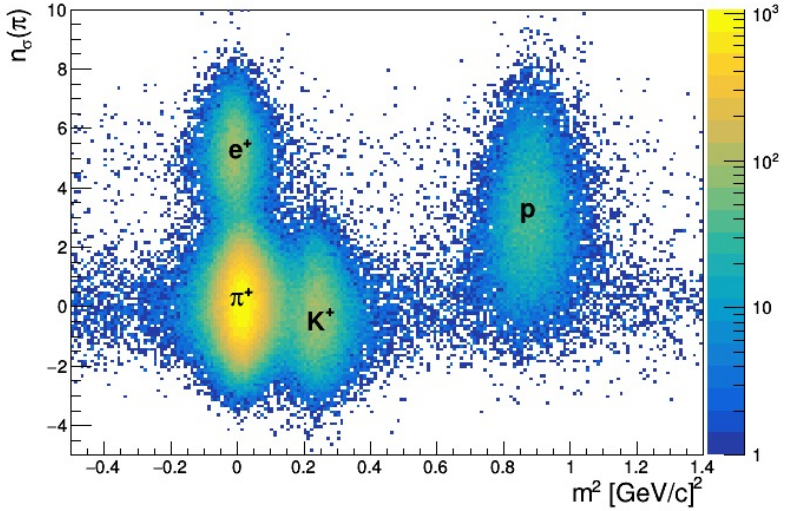
Three Simulation Levels :

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

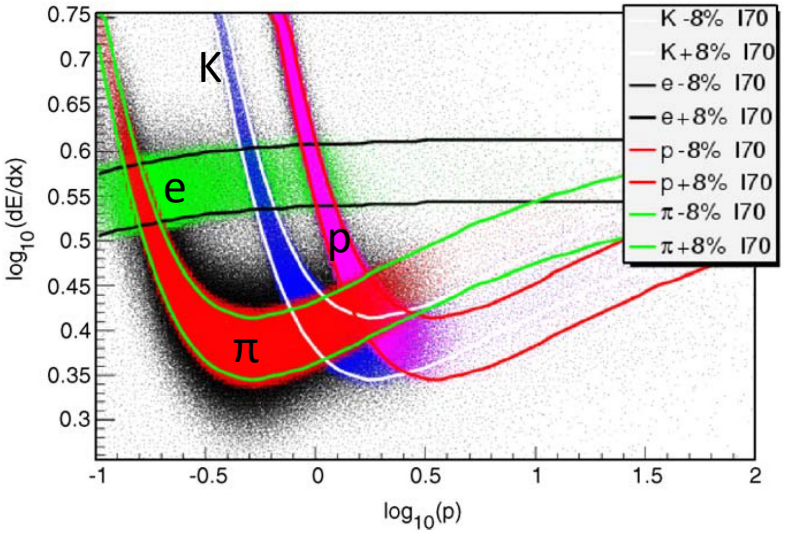
Underlying Event and Particle Identification

STAR, Phys. Rev. D **100**, 052005 (2019)



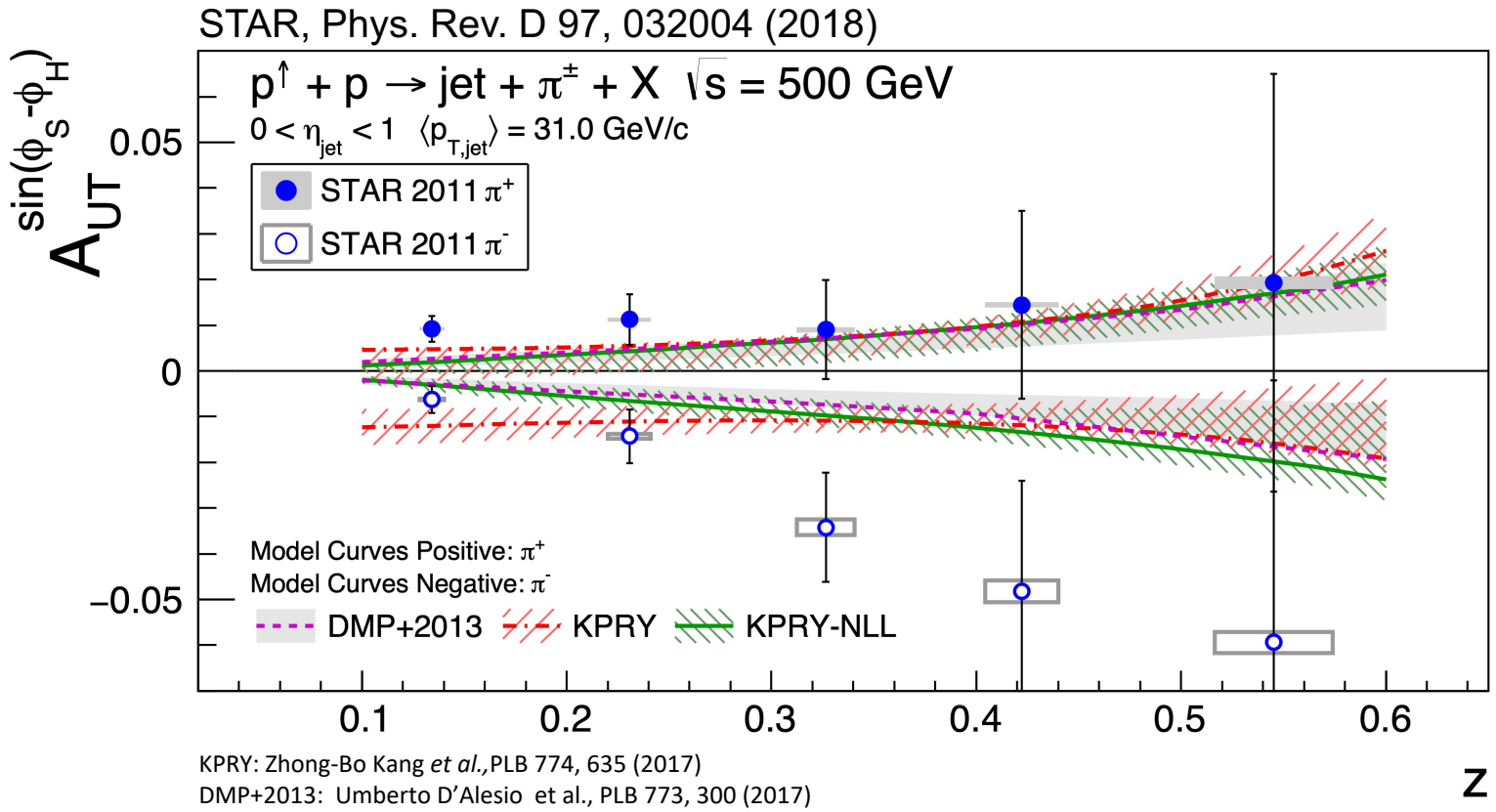


Ming Shao *et al.* NIM A558 (2006)



- Particle jet p_T values are corrected for underlying event activity measured using the off-axis cone method;
- Spin asymmetries are corrected for the dilution from the underlying event contribution;
- Good particle identification from TPC and TOF.

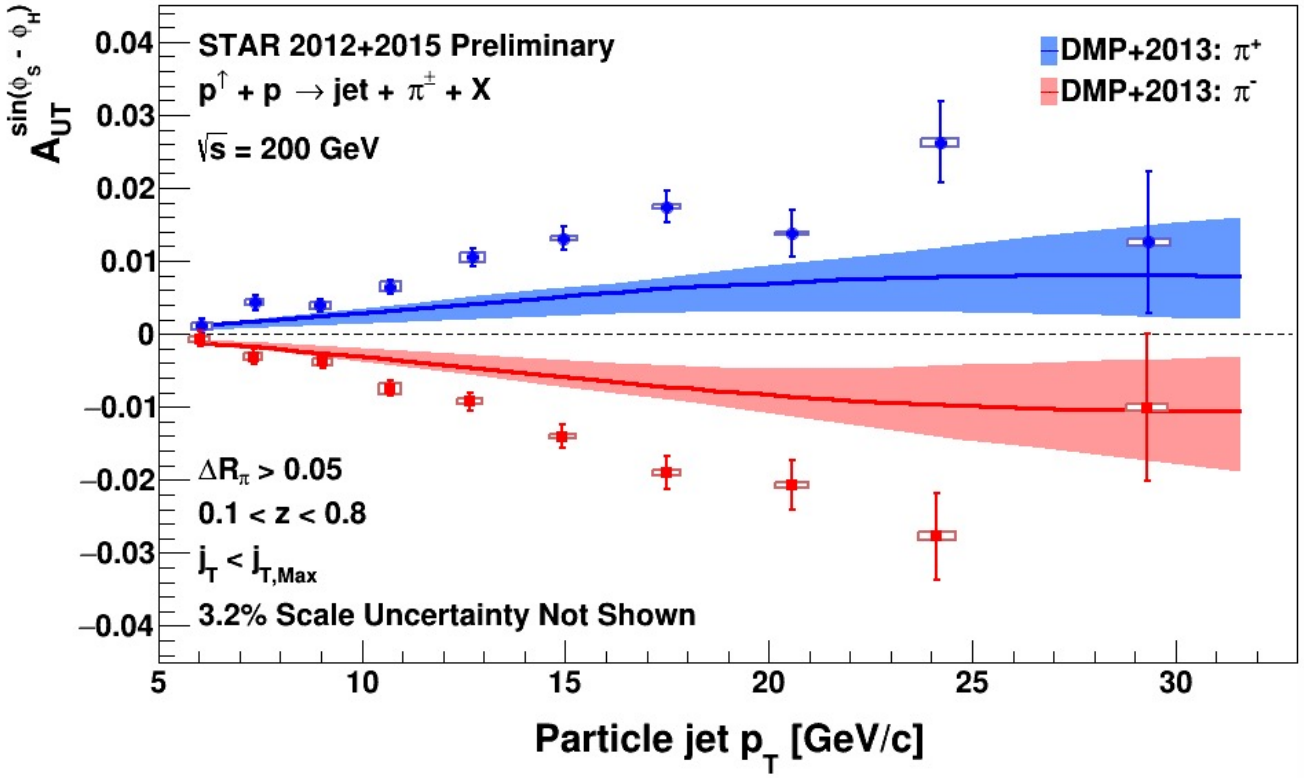
Collins Asymmetry from STAR

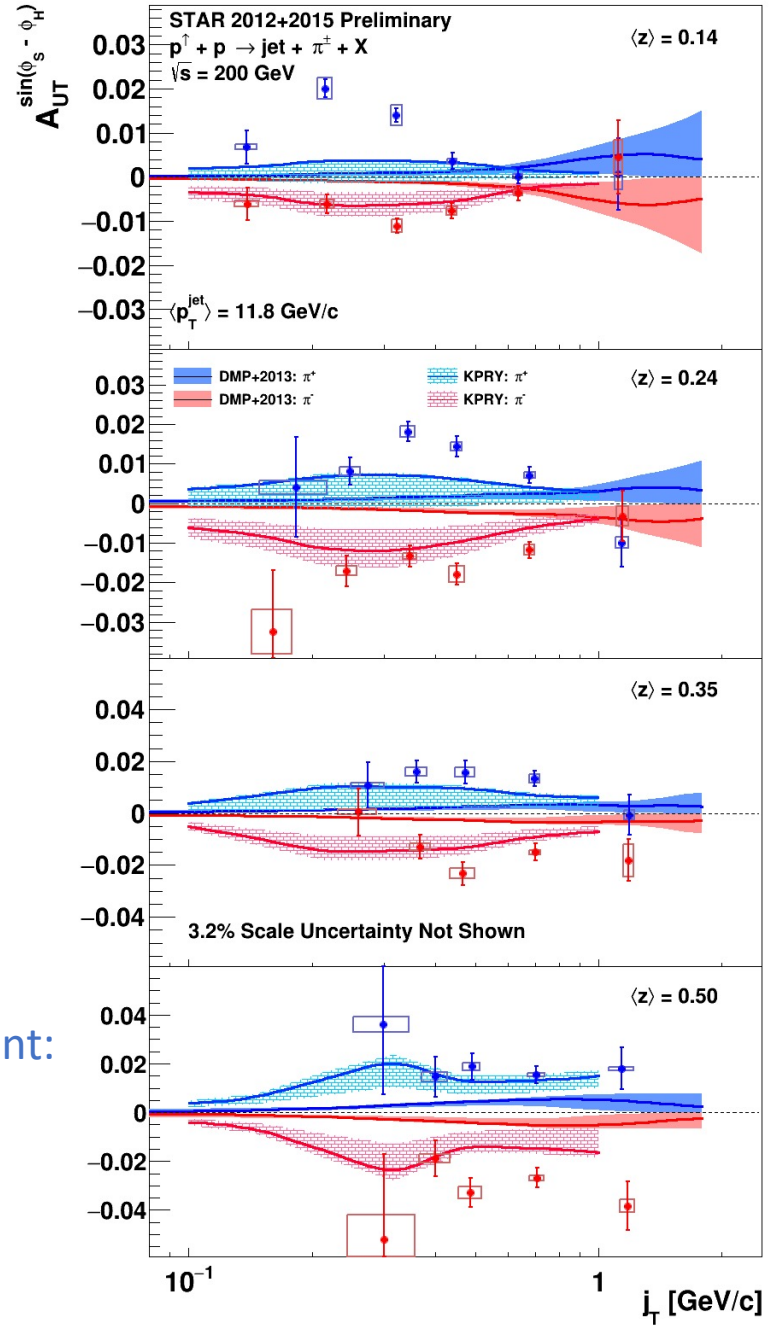


KPRY: Zhong-Bo Kang *et al.,*PLB 774, 635 (2017)
DMP+2013: Umberto D'Alesio et al., PLB 773, 300 (2017)

- First Collins effect measurements in pp collisions are qualitatively described by two theoretical calculations that combine the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions:
  - Assume universality and factorization;
  - DMP&KPRY: no TMD evolution;
  - KPRY-NLL: TMD evolution up to NLL.

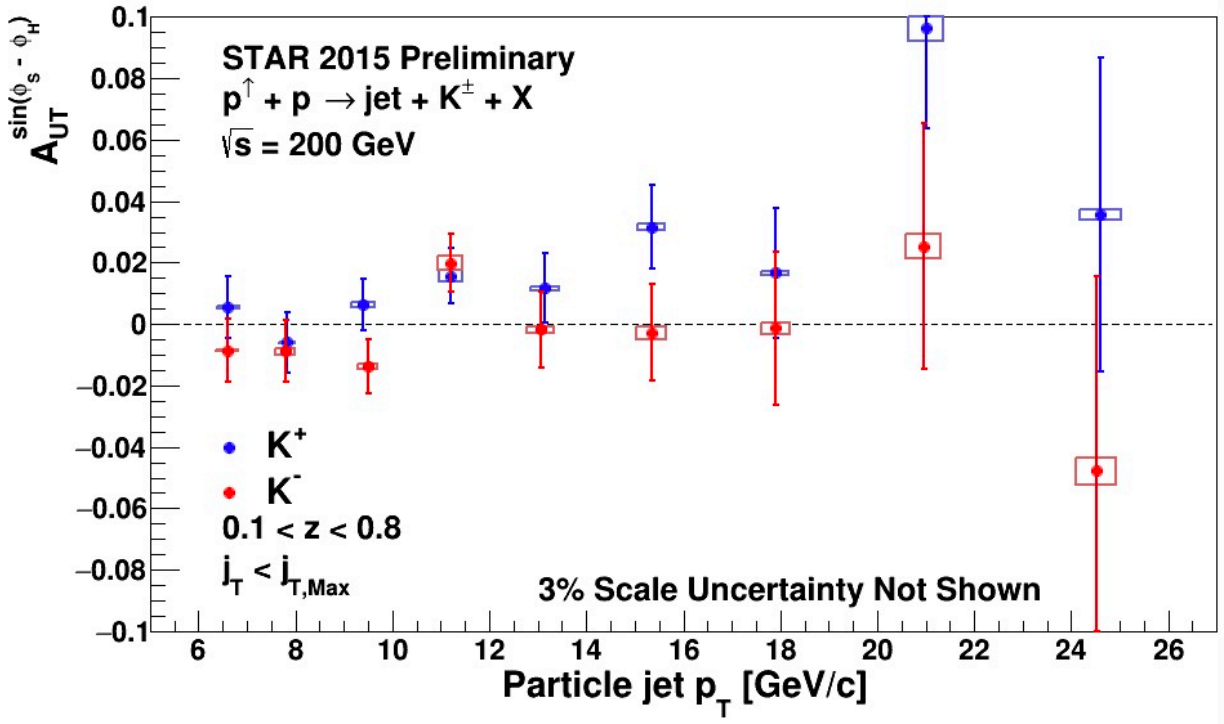
$\pi^{\pm}$ Azimuthal Distribution in Jets





- Significant Collins asymmetries have been observed in 200 GeV measurement:
  - Collinear transversity is probed most directly in the jet p_T dependence;
  - Collins TMD FF is sensitive to the (j_T, z) dependence;
  - Sizable differences between data and theoretical calculations.

$K^{\pm}$ Azimuthal Distribution in Jets



- K^{+}, which can be produced through favored fragmentation of a valence u quark, has asymmetries that are consistent with the π^{+} asymmetries within statistical uncertainties;
- K^{-}, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero at the current precision.

Additional Modulations: "Collins-like" Effect

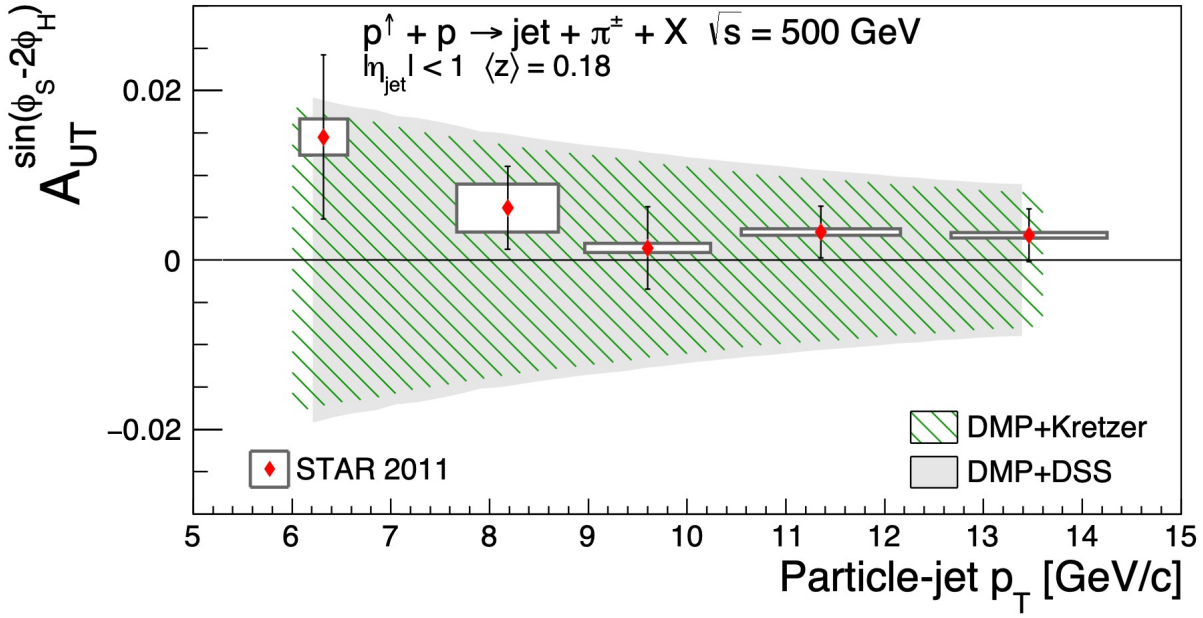
$$d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)$$

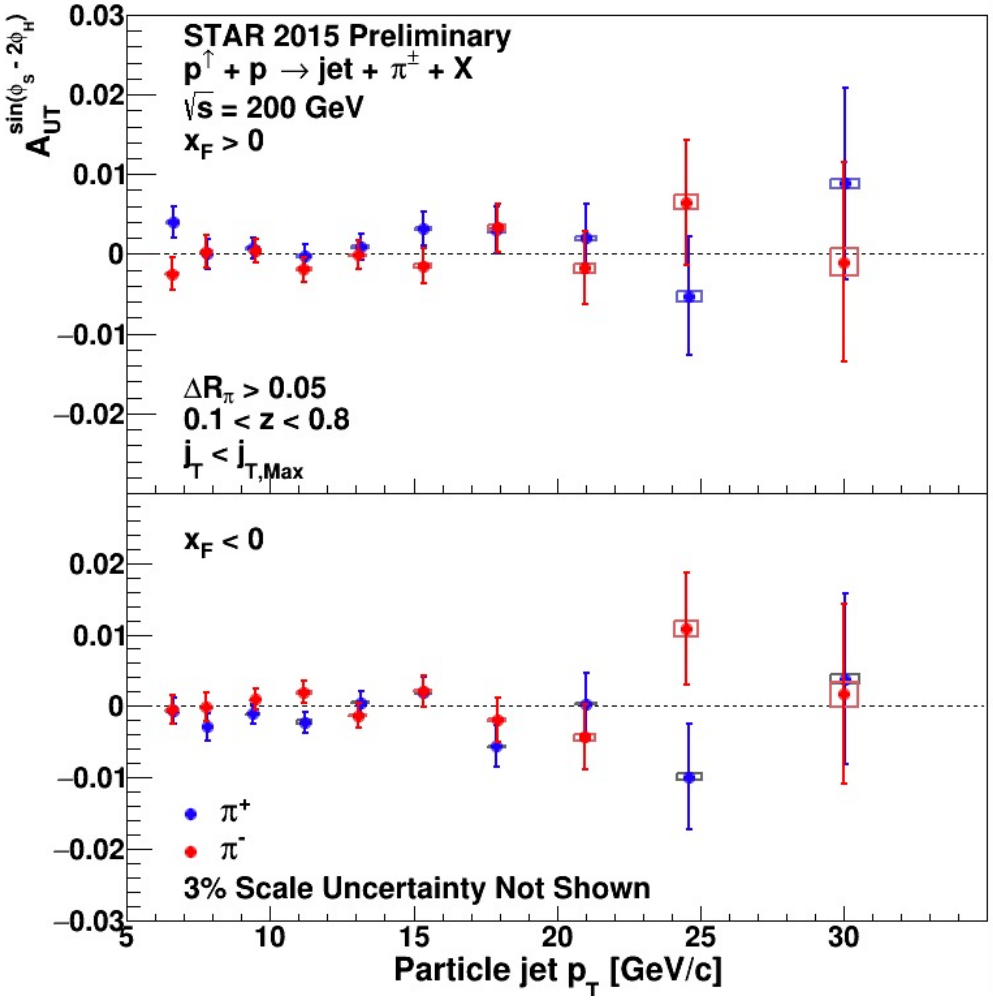
$$\sim \mathrm{d}\Delta\sigma_0 \sin(\phi_S)$$

$$+\mathrm{d}\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + \mathrm{d}\Delta\sigma_1^{+} \sin(\phi_S + \phi_H)$$

$$+\mathrm{d}\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H) + \mathrm{d}\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$

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





- Collins-like effect is sensitive to the linearly polarized gluons in a polarized proton;
- Asymmetries are consistent with zero.

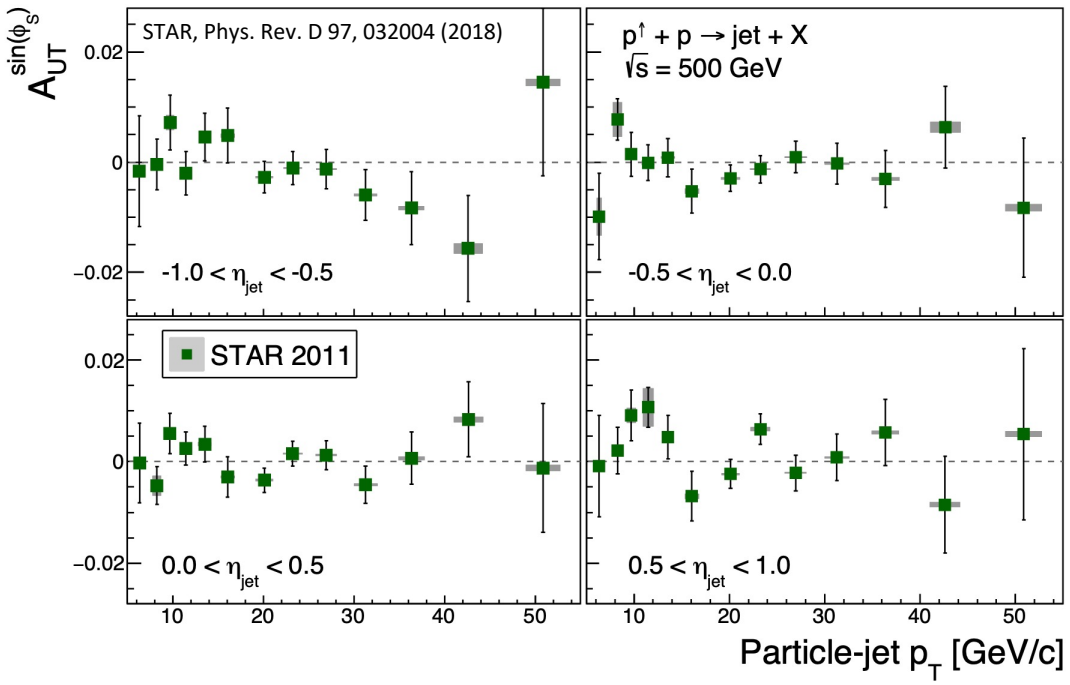
Additional Modulations: Inclusive Jet A_N

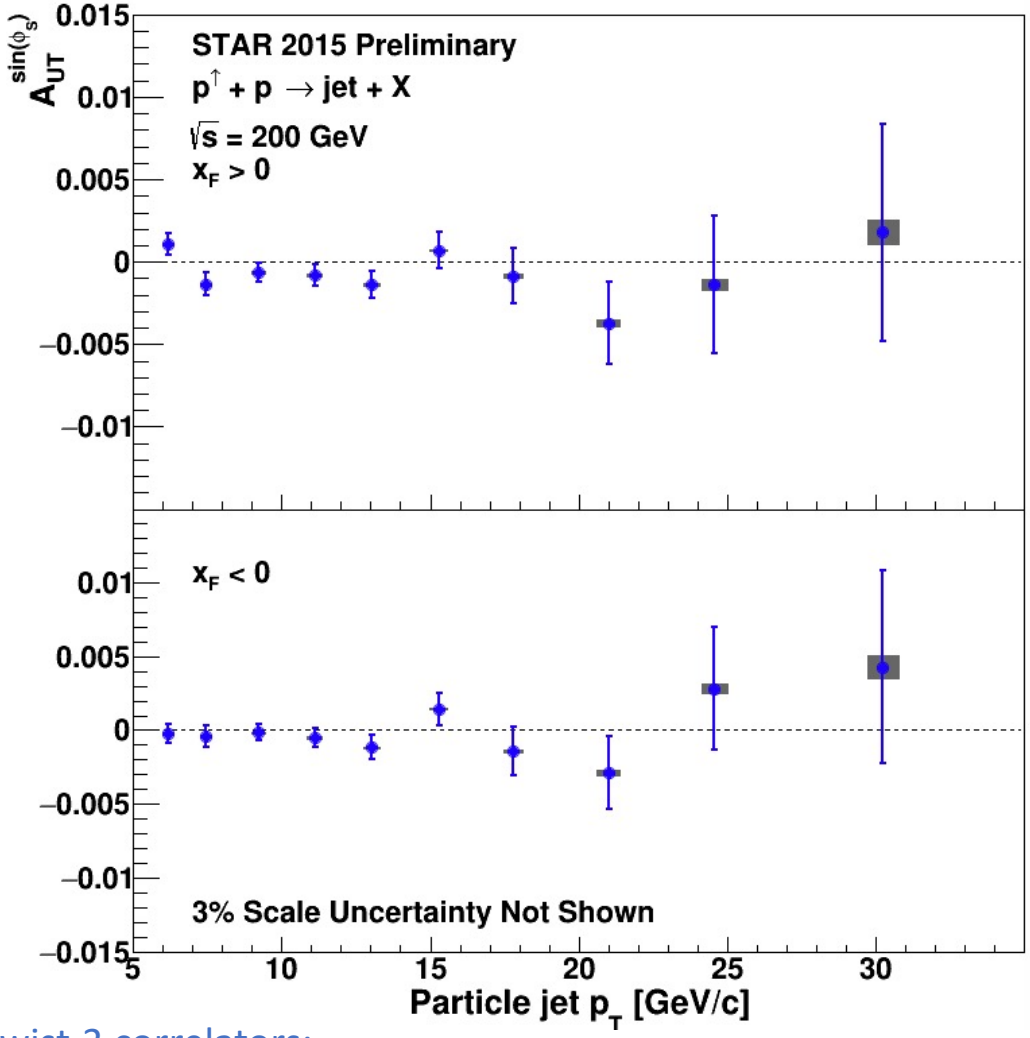
$$d\sigma^{\uparrow}(\phi_S, \phi_H) - d\sigma^{\downarrow}(\phi_S, \phi_H)$$

$$\sim \mathrm{d}\Delta\sigma_0 \sin(\phi_S)$$

$$+\mathrm{d}\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + \mathrm{d}\Delta\sigma_1^{+} \sin(\phi_S + \phi_H)$$

$$+\mathrm{d}\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H) + \mathrm{d}\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$





- Inclusive jet A_N is sensitive to the gluon Sivers function via the twist-3 correlators;
- With high precision 2015 data, asymmetries are consistent with zero.

Summary

- We present the most precise measurements of Collins asymmetries for charged hadrons inside jets in 200 GeV pp collisions to date;
  - The measured asymmetries for charged pions are larger than the theoretical calculations which may indicate larger quark transversity;
  - The measured asymmetries for charged kaons are statistically limited; need further measurements to confirm the difference due to fragmentation;
- Ongoing analyses using 510 GeV p+p dataset from 2017 (~350 pb^{-1}, ~13 times more than 2011), which will provide precise measurements at lower momentum fraction region.