QPT 2021
Guiyang, China
The 14th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT 2021)

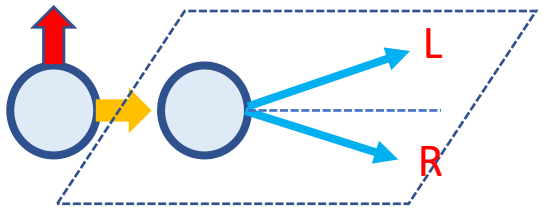
Azimuthal Transverse Single-Spin Asymmetries of Identified Hadrons Within Jets from Polarized pp Collisions at $\sqrt{s}$ = 200 GeV

Ting Lin (林挺), for the STAR Collaboration
Shandong University (山东大学)

Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

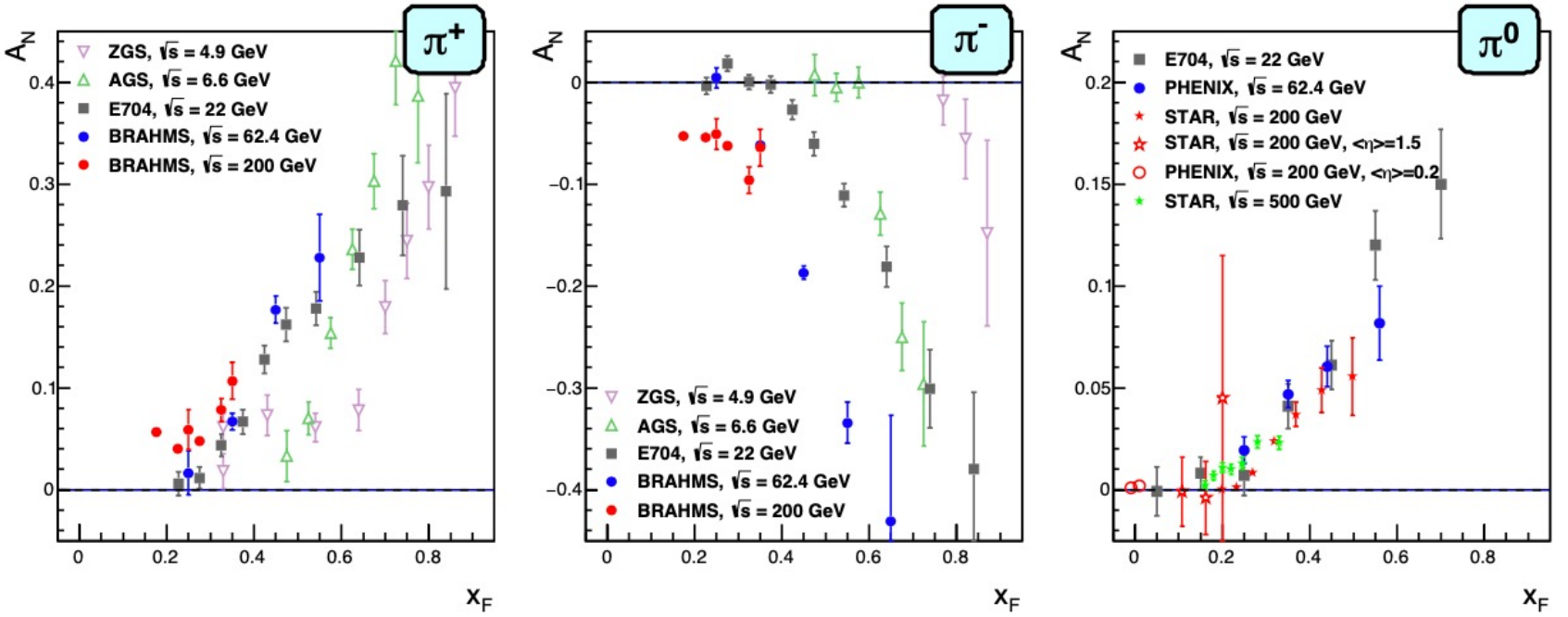
Challenges in Transverse Single-Spin Asymmetry

- 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;



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

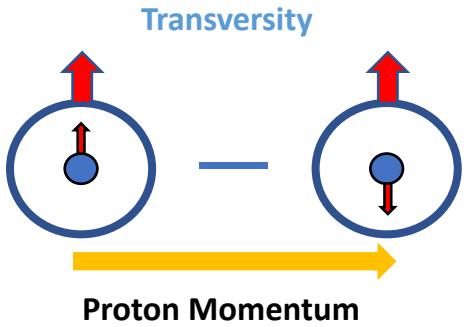
Elke Aschenauer *et al.* arXiv:1602.03922 [nucl-ex]

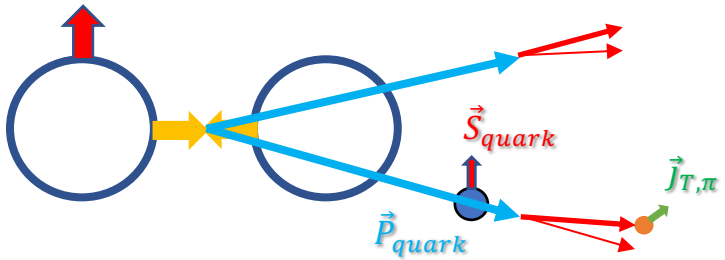


Collins Effect

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, leading to azimuthal modulations of identified charged hadron yields about the jet axis;
  - Integral of transversity gives the nucleon tensor charge ($\delta q = \int_0^1 \left(h_1^q(x) - h_1^{\bar{q}}(x)\right) dx$);
  - Difference of helicity and transversity has direct x-dependent connection to quark orbital angular momentum;
  - Collins fragmentation function in pp probes fundamental questions regarding factorization, universality, and evolution of TMDs.





$$\left\langle \vec{S}_{quark} \cdot (\vec{P}_{quark} \times \vec{J}_{T,\pi}) \right\rangle \neq 0$$

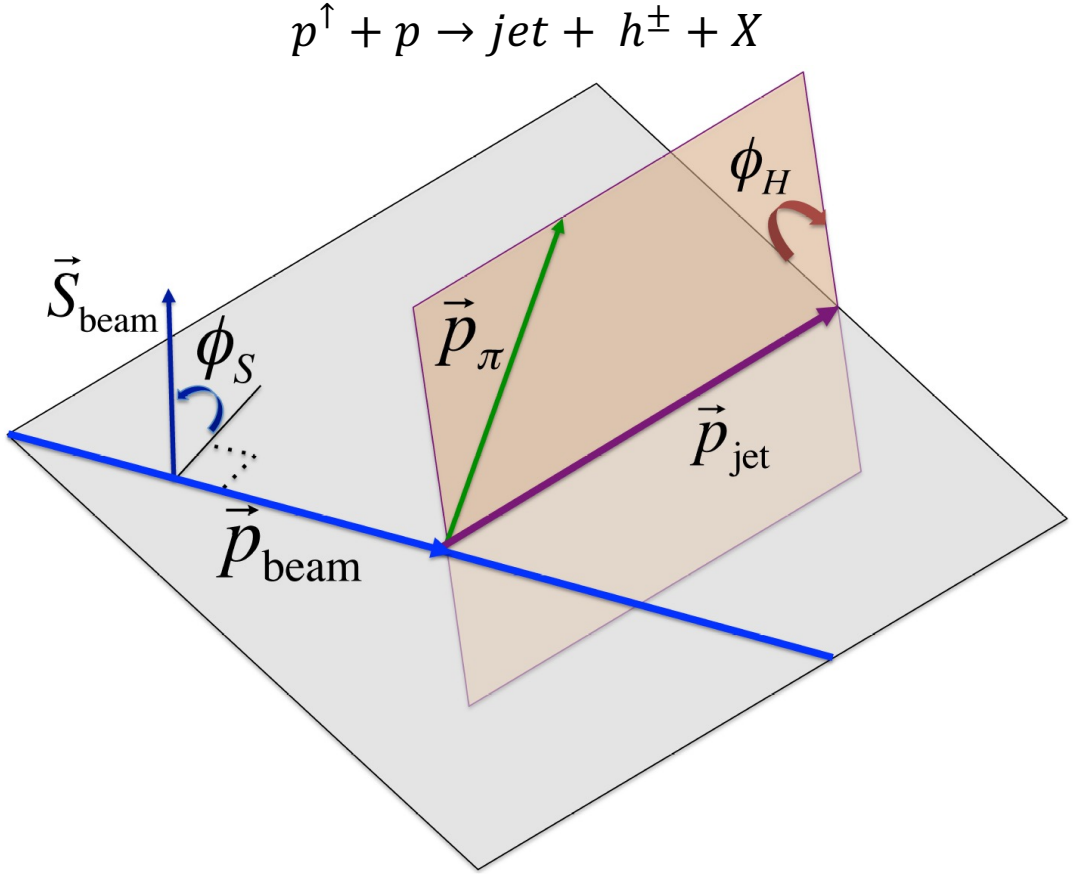
Transverse Single-Spin Asymmetry

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

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

- Different modulations of the transverse single-spin asymmetry can be isolated and studied:

$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$



STAR, Phys. Rev. D 97, 032004 (2018)
Umberto D'Alesio *et al*. Phys. Rev. D 83, 034021 (2011)

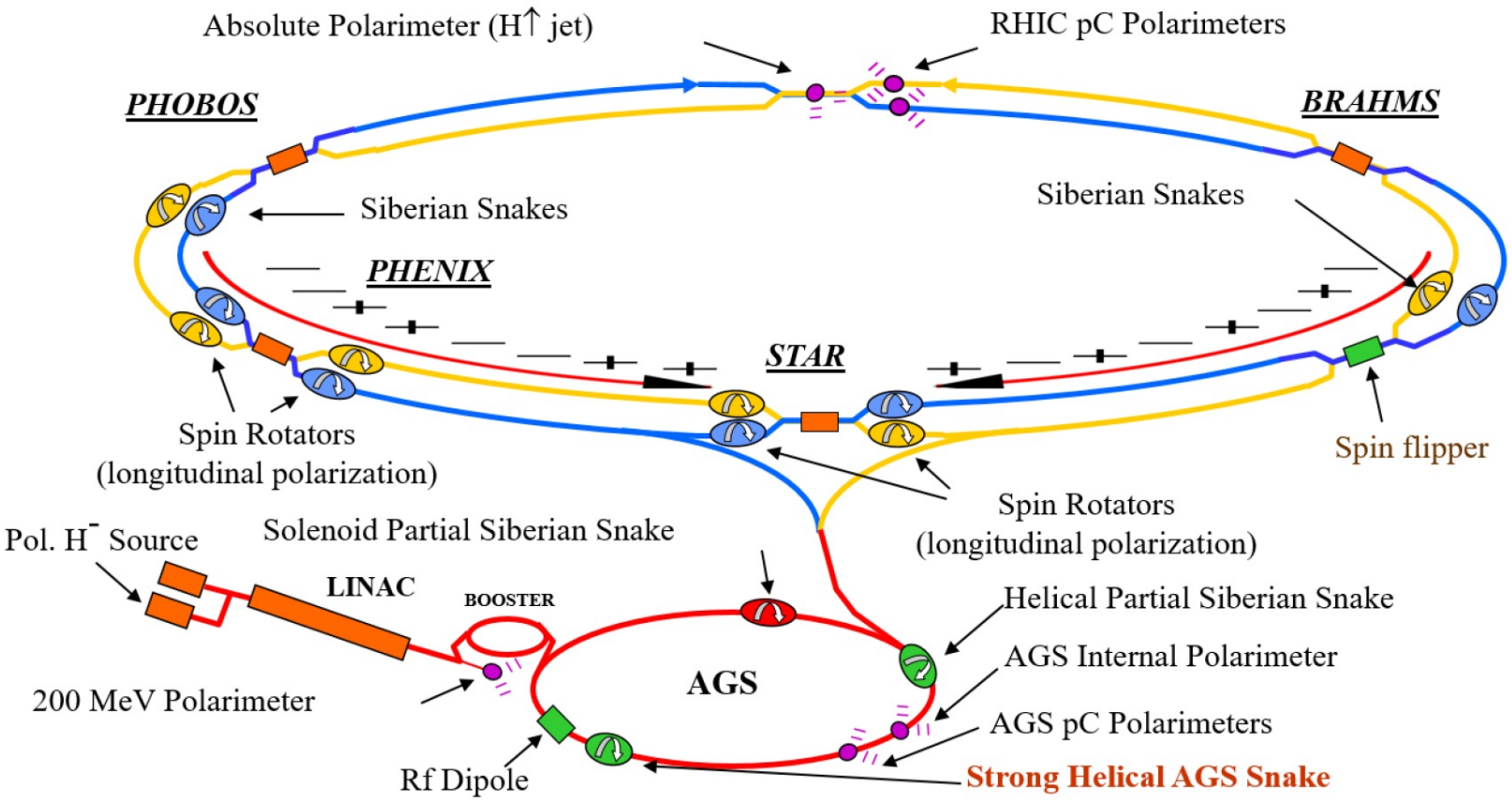
Collins Effect in pp

$$A_{UT}^{\sin(\varphi_S-\varphi_H)} \propto \frac{\sum_{a,b,c} \boldsymbol{h_1^a(x_1,\mu)}\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{Collins}}\ \boldsymbol{H_{1,h/c}^{\perp}(z_h, j_T; Q)}}{\sum_{a,b,c} f_a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{unpol}}\ D_{h/c}(z_h, j_T; Q)}$$

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

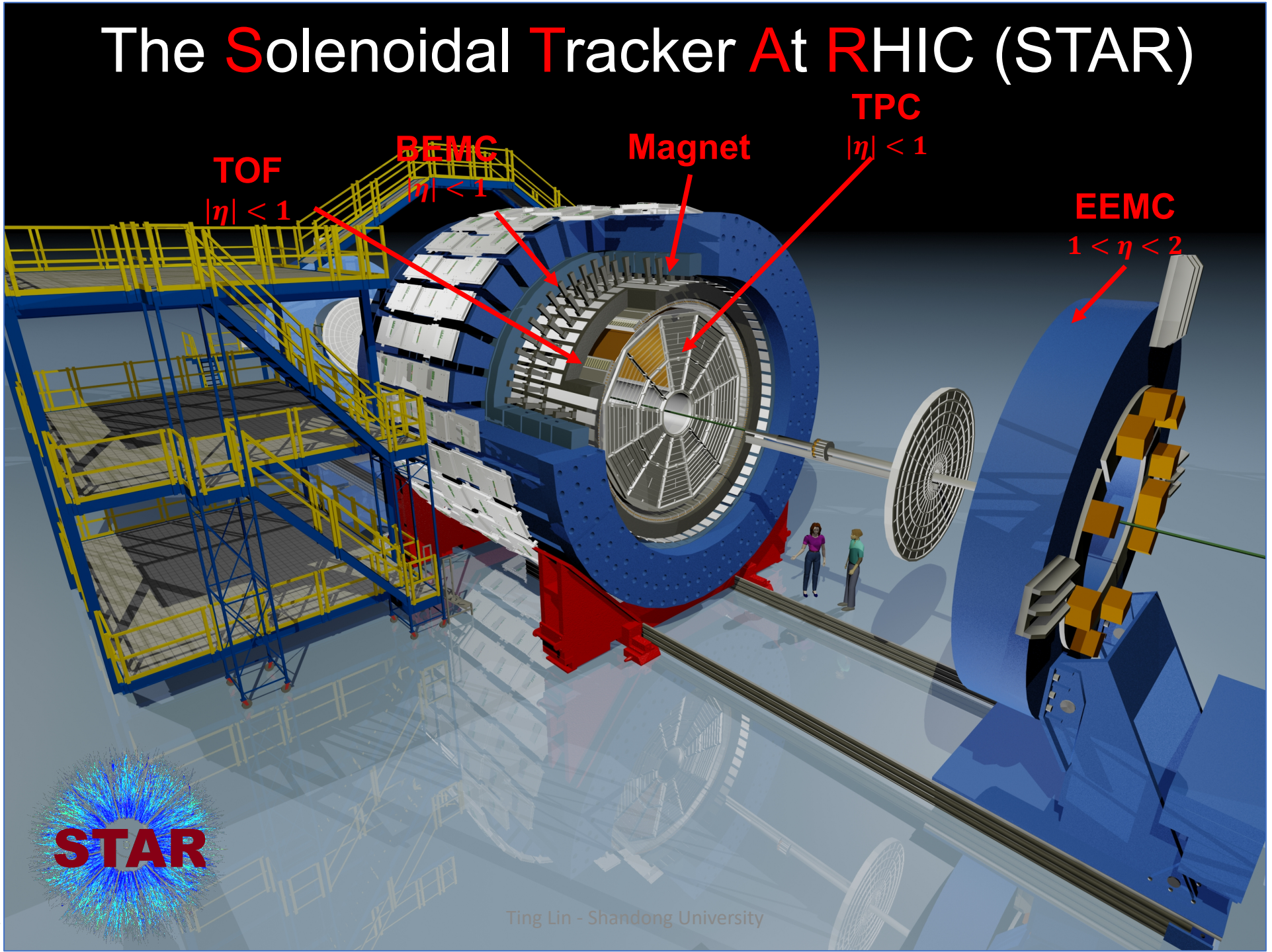
- Collins effect in pp involves a mixture of collinear and TMD factorization:
  - Initial jet production involves the collinear transversity $\boldsymbol{h_1^a}$;
  - Polarized quark then fragments according to the TMD Collins fragmentation function $\boldsymbol{H_{1,h/c}^{\perp}}$;
- Cleaner kinematic separation of transversity and TMD physics than SIDIS, which convolutes the TMD transversity with the Collins FF.

Relativistic Heavy Ion Collider (RHIC)



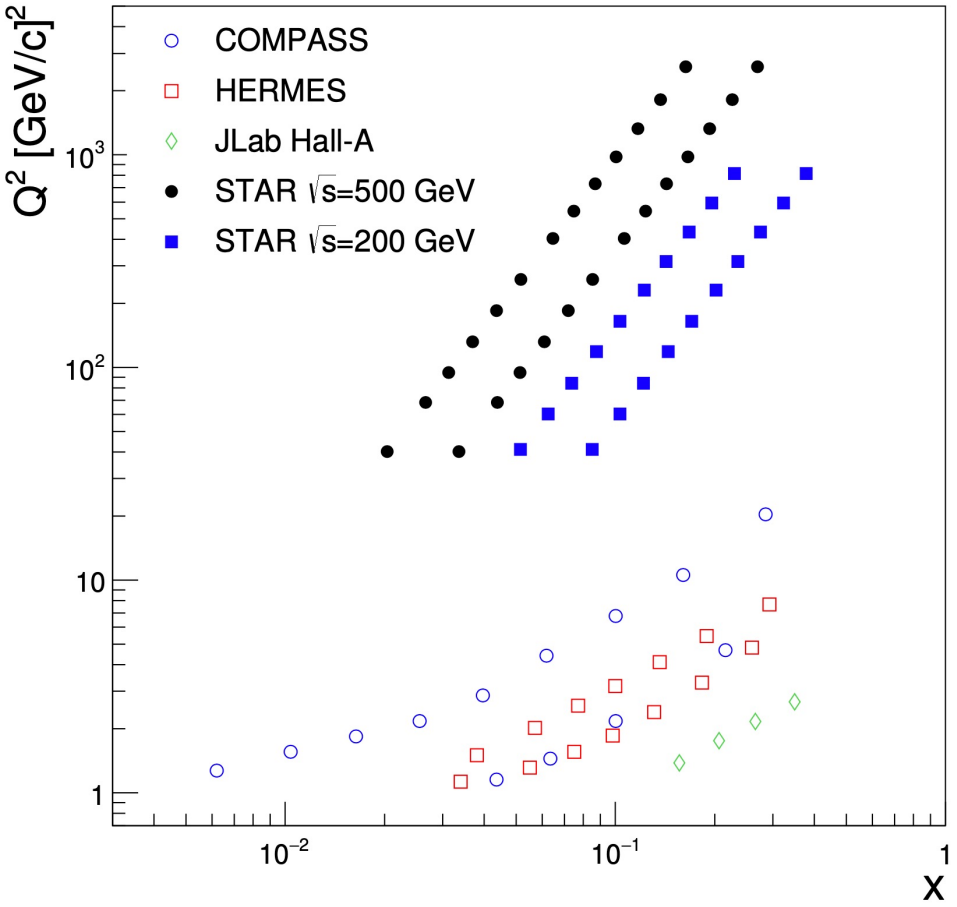
- World's first and only polarized proton+proton collider;
  - Provide polarized proton+proton collisions up to 510 GeV;
- Spin pattern changes from fill to fill with little depolarization;
  - Siberian snakes preserve the polarization;
  - Spin rotators select spin orientation;
  - proton-Carbon (pC)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

The Solenoidal Tracker At RHIC (STAR)



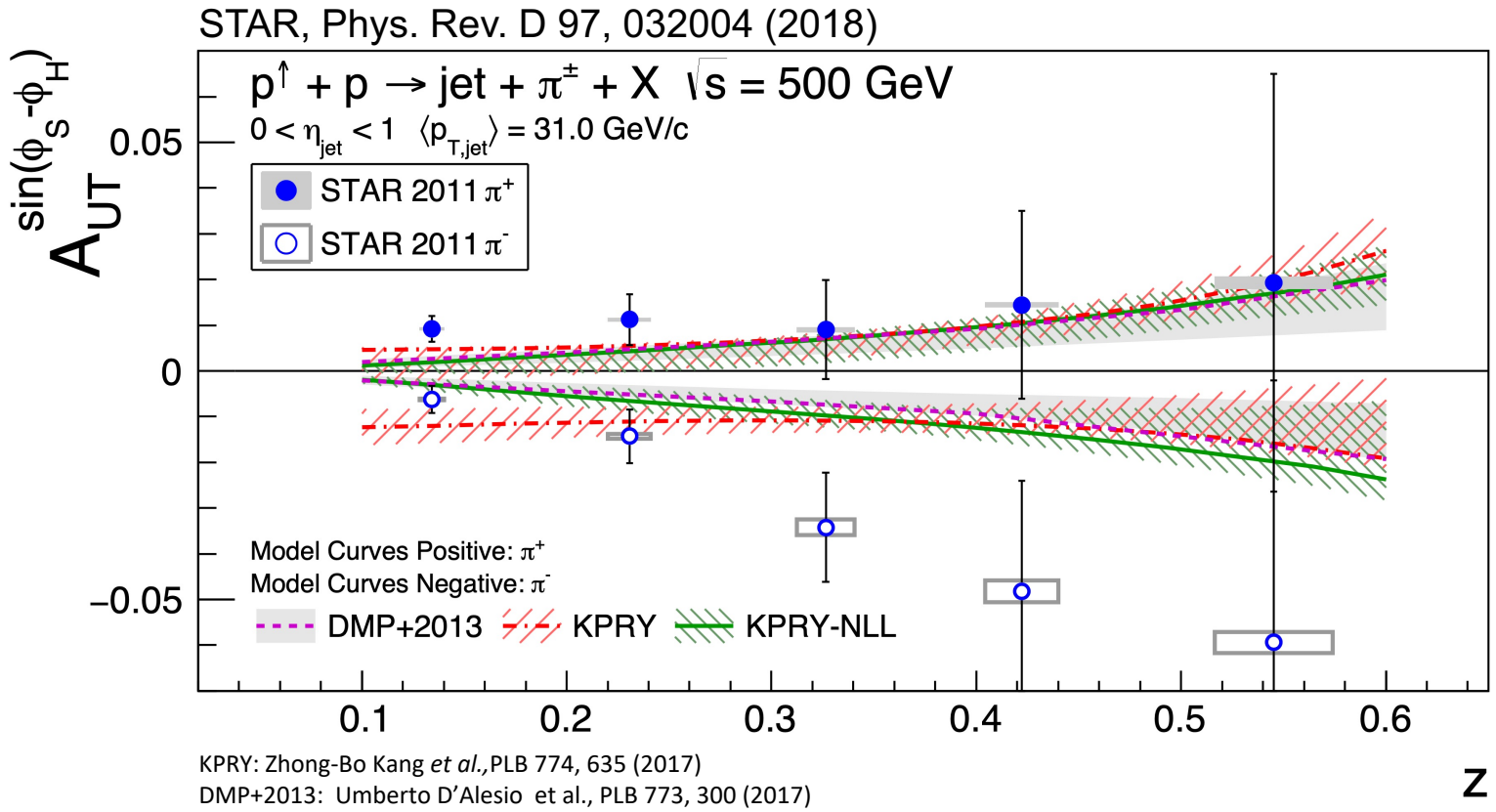
STAR Data and Kinematic Coverage

Year	2011	2012	2015	2017
$\sqrt{s}$ (GeV)	500	200	200	510
L_{int} (pb^{-1})	25	14	52	320
Polarization	53%	57%	57%	55%



- 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 will provide additional experimental constraints on evolution effects and insights into the size and nature of TMD observables at the future Electron-Ion Collider.

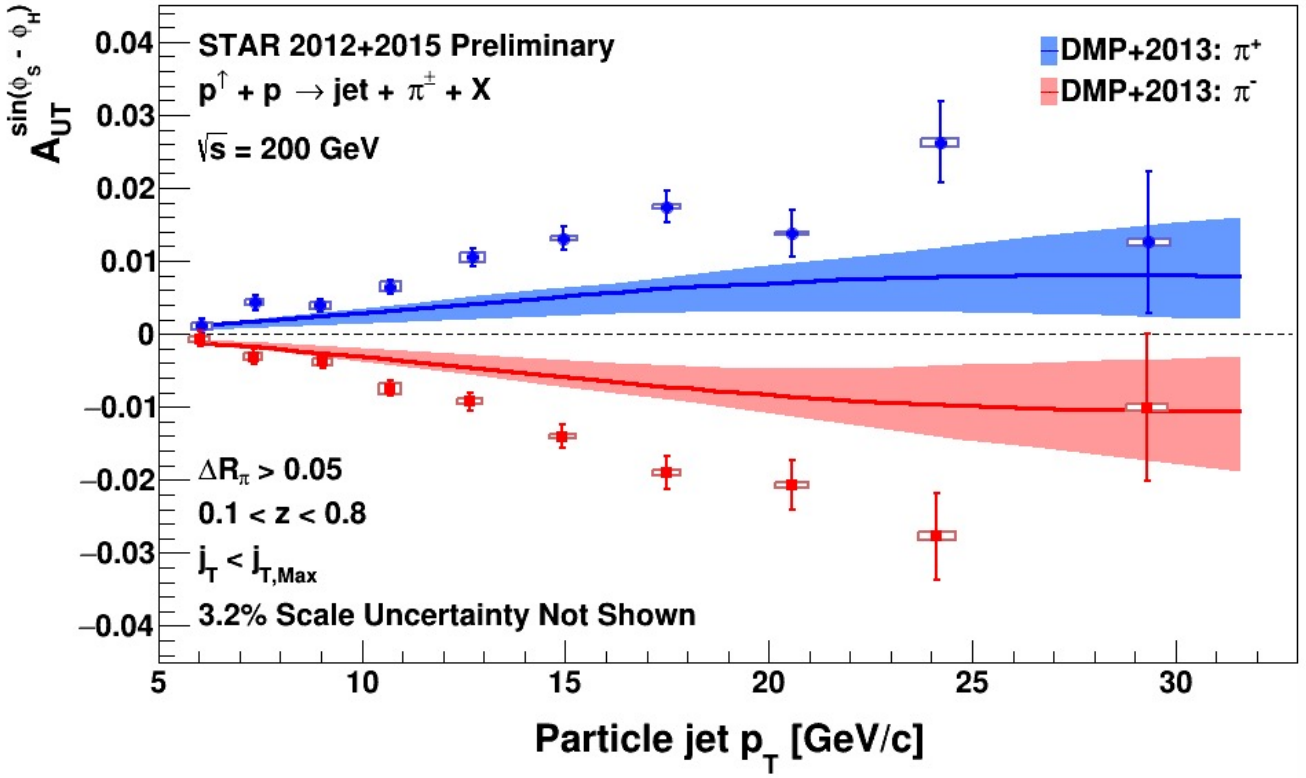
Collins Asymmetry from STAR

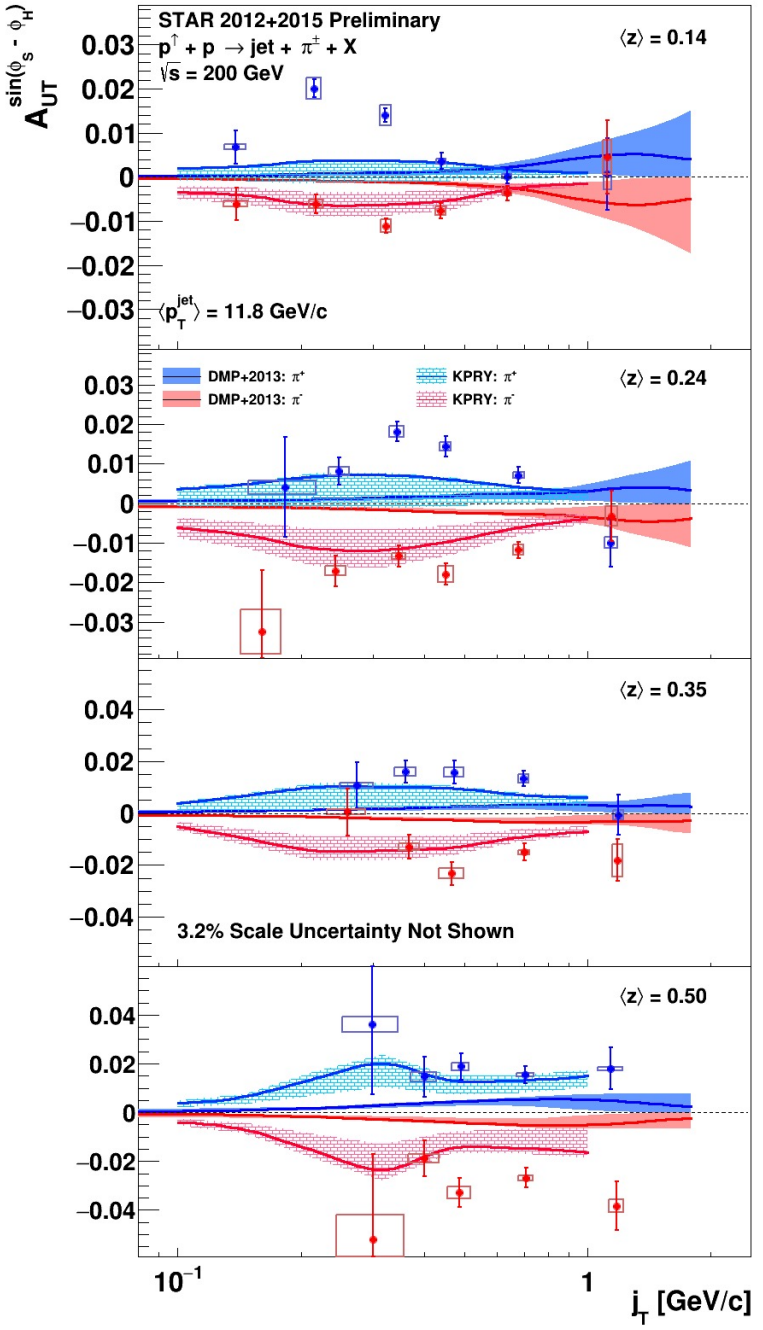


KPRY: Zhong-Bo Kang *et al.,*PLB 774, 635 (2017)
DMP+2013: Umberto D'Alesio et al., PLB 773, 300 (2017)

- First Collins effect measurements in pp collisions are qualitatively described by two recent 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.

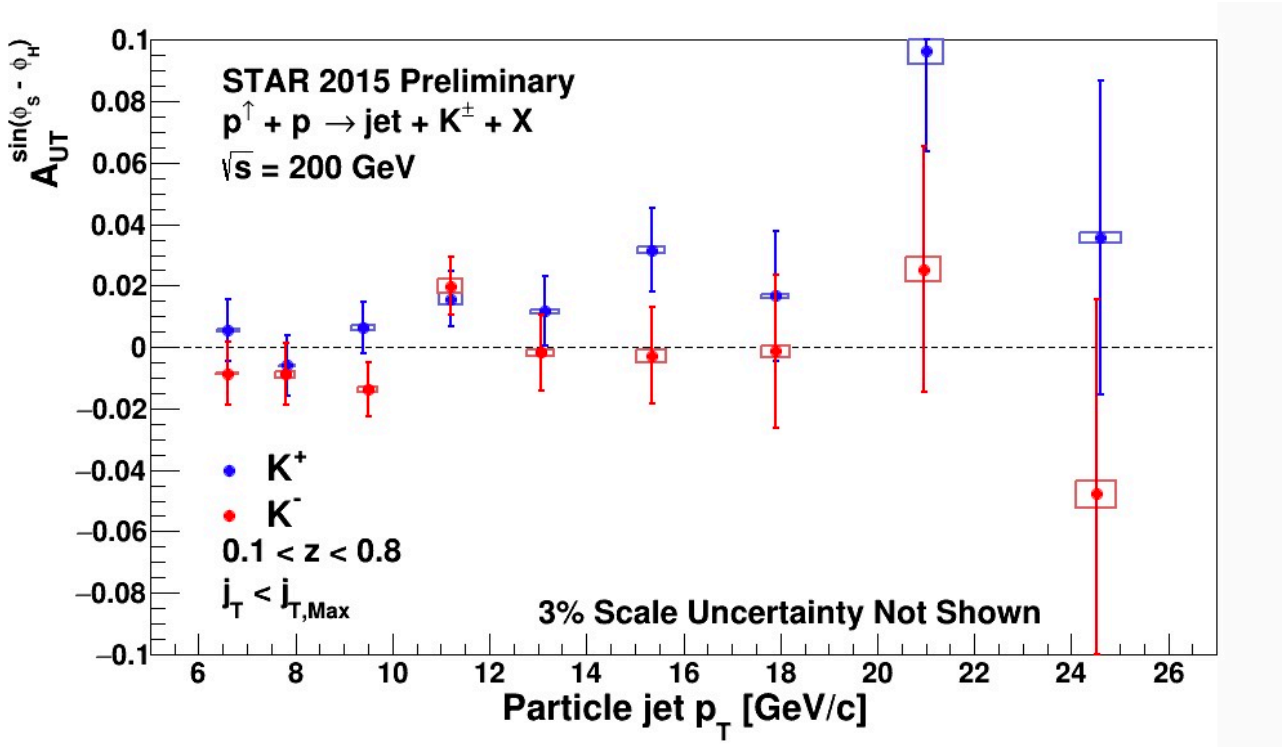
$\pi^{\pm}$ Azimuthal Distribution in Jets





- Significant Collins asymmetries have been observed from 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.

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

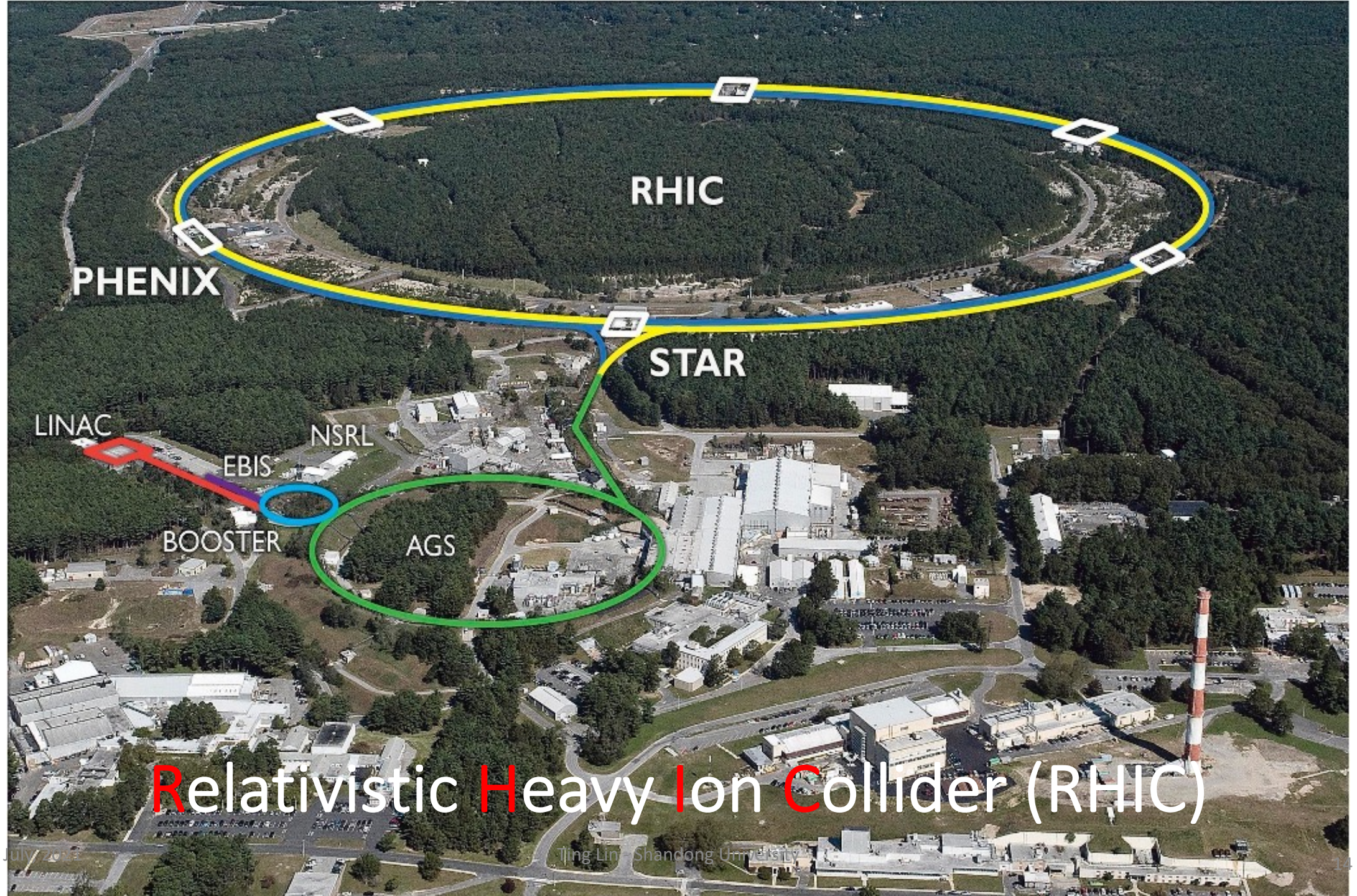


- K^{+}, which can be produced through favored fragmentation of a valence u quark, has asymmetries that are consistent within the currently large statistical uncertainties with the π^{+} asymmetries;
- K^{-}, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero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

Summary

- We present the most precise measurement of Collins asymmetry for charged hadrons inside jets at 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 measurement to confirm the difference due to the fragmentations;
- There is also an ongoing analysis using 510 GeV p+p dataset from 2017 (~320 pb^{-1}), which will provide precise measurements at lower momentum fraction region.

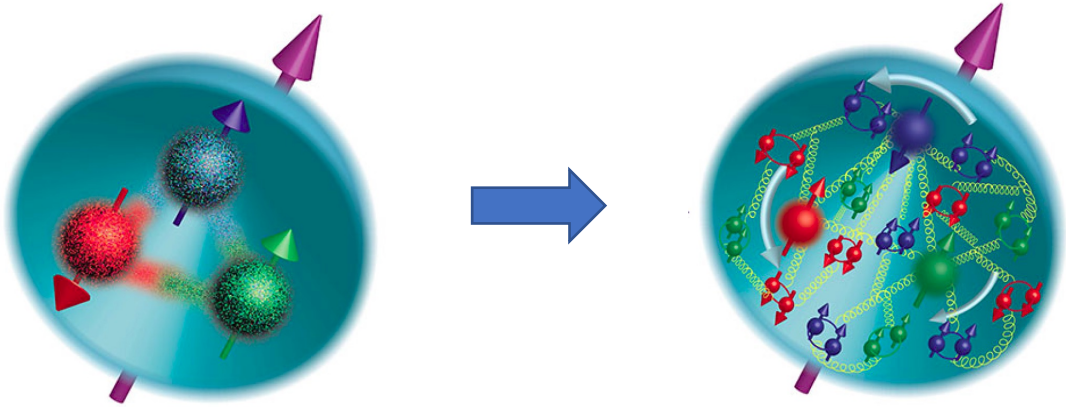
BackUp

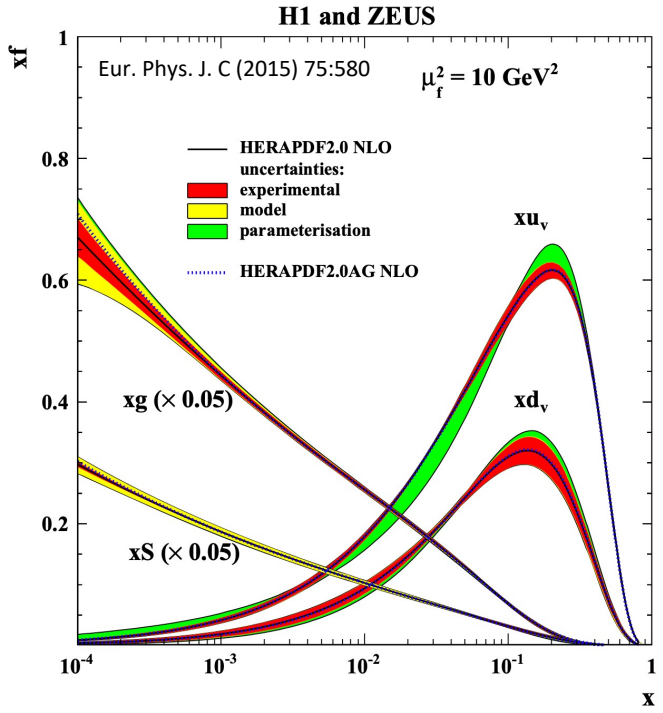


Relativistic Heavy Ion Collider (RHIC)

Transversity

Nucleon Structure:

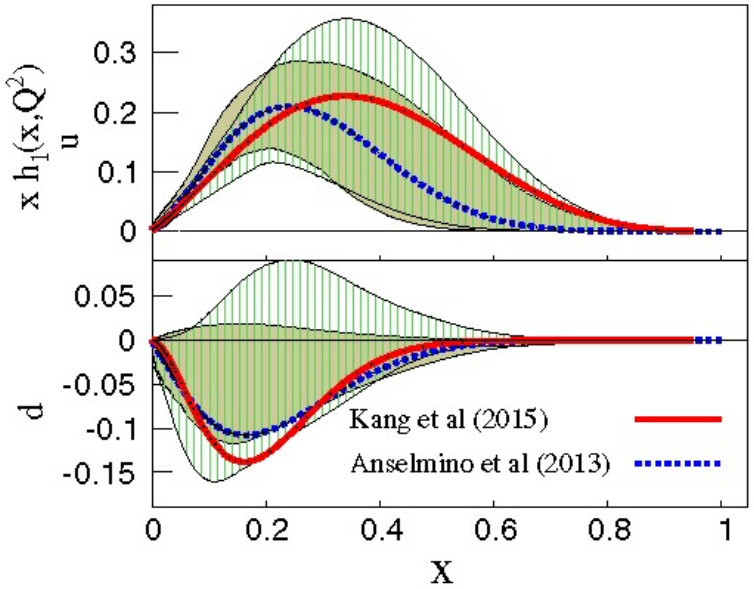




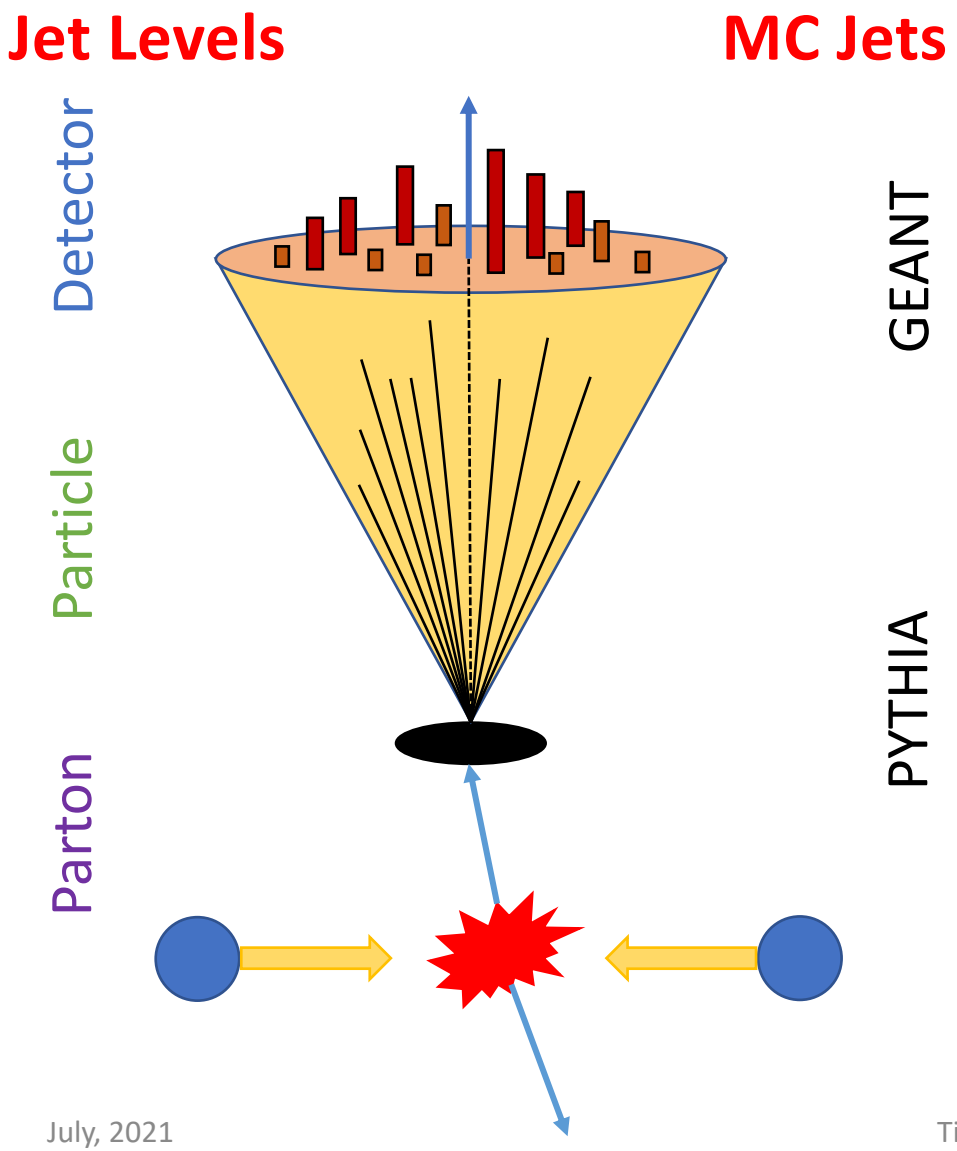
A complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF, $f(x)$;
- Helicity PDF, $\Delta f(x)$;
- Transversity, $h_1(x)$;
  - Quark polarization along spin of a transversely polarized proton;
  - Chiral odd, so it requires another chiral odd distribution:
    - Collins fragmentation function;
    - Transverse spin transfer to lambda (Λ);
    - Interference fragmentation function (IFF).

Zhong-Bo Kang *et al*. Phys. Rev. D 93, 014009 (2016)



Jet Reconstruction



Anti-K_T Algorithm:

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

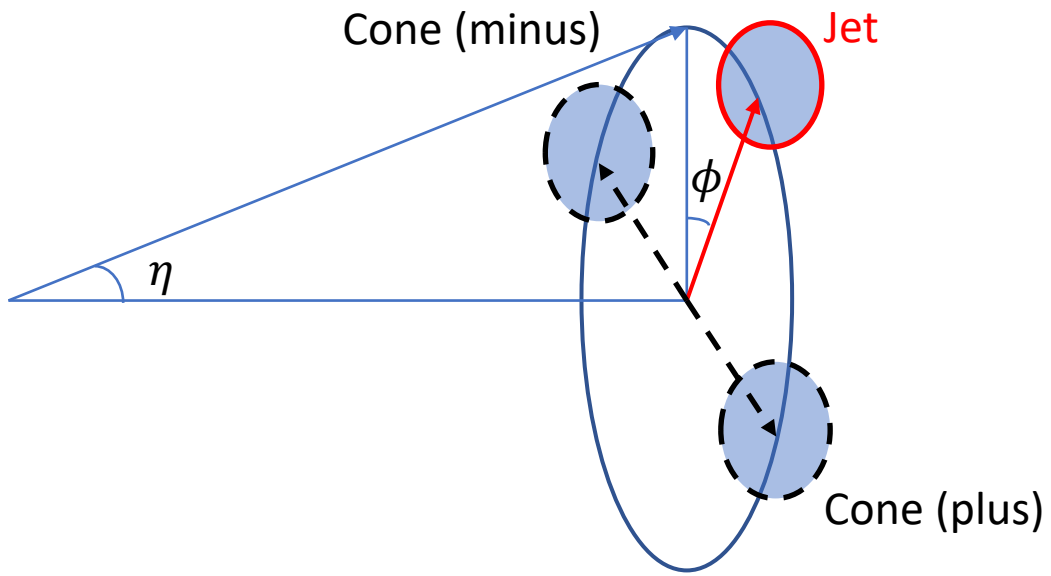
Simulation: PYTHIA 6.4 with STAR adjustment of Perugia 2012;

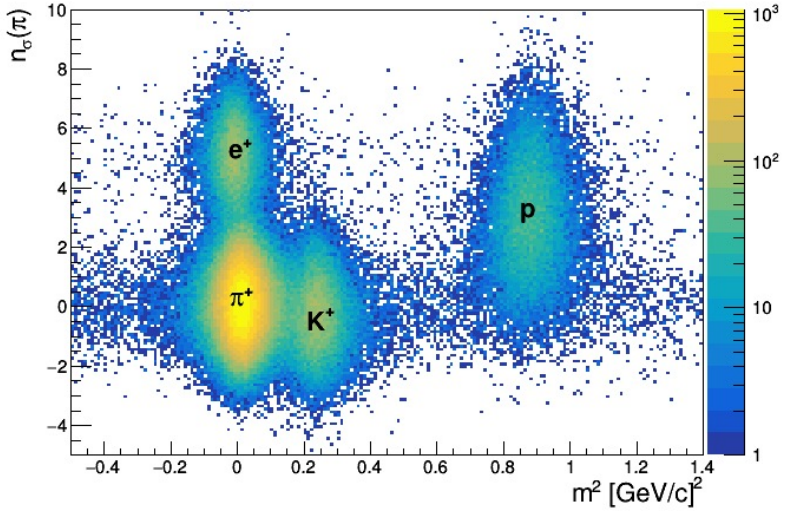
Three Simulation Levels :

- 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.

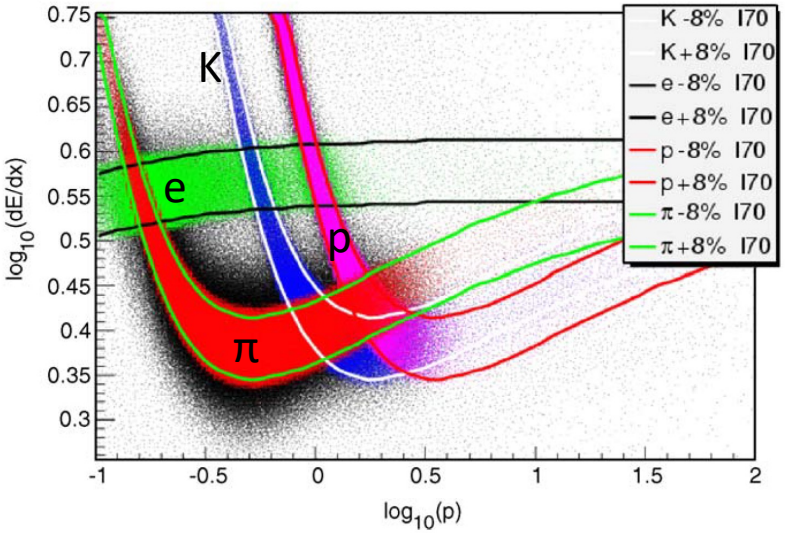
Underlying Event and Particle Identification

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.