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

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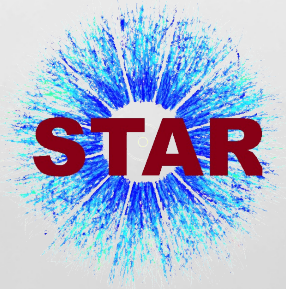



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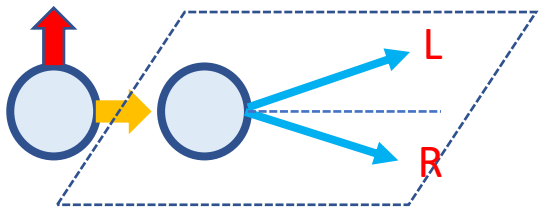
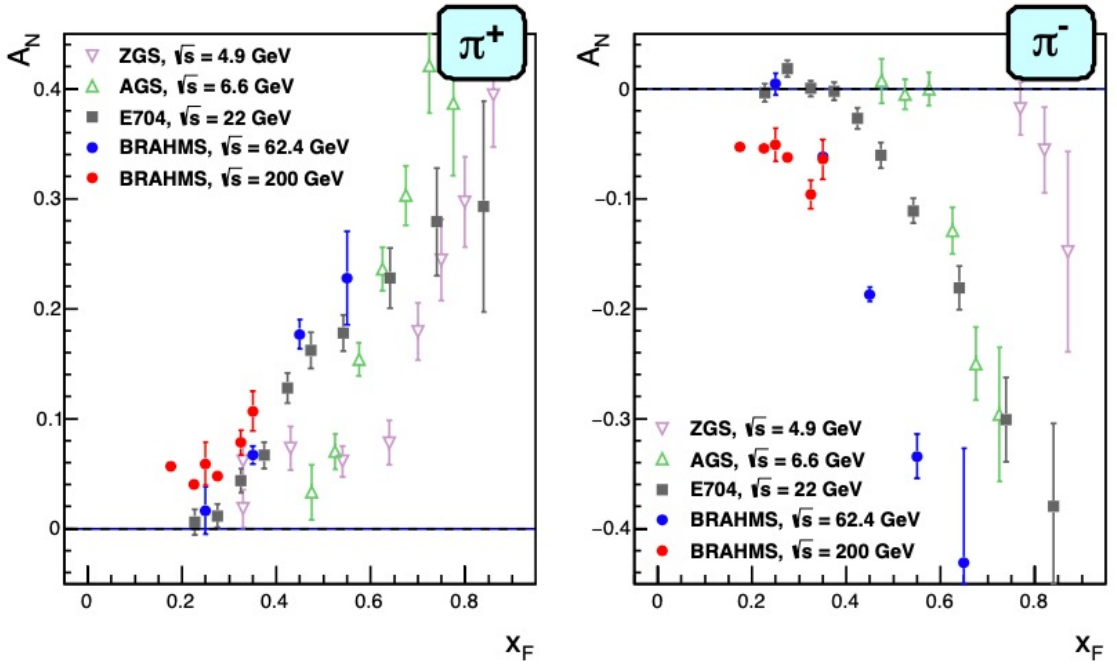
# Challenges in Transverse Single-Spin Asymmetry

- Large transverse single-spin asymmetry ($A_N$) at forward rapidities has been observed 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.

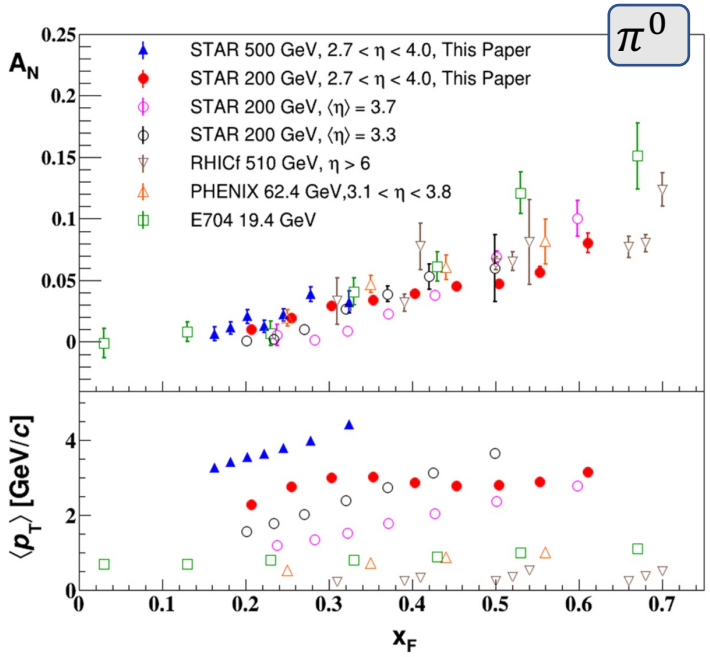



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

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

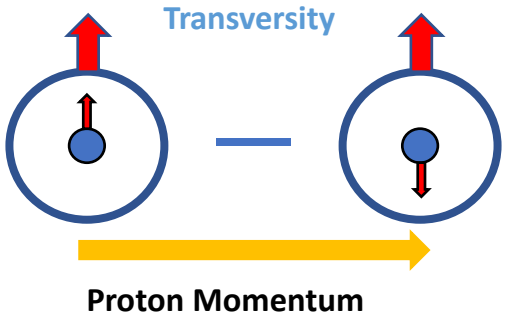


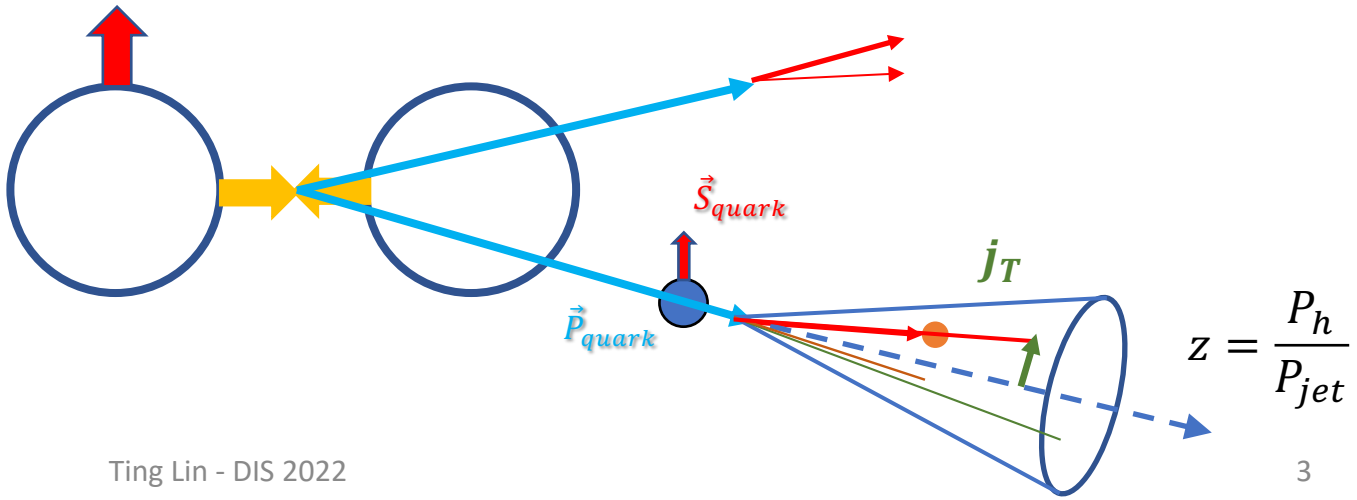

STAR, PRD 103, 092009 (2021)



# 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:

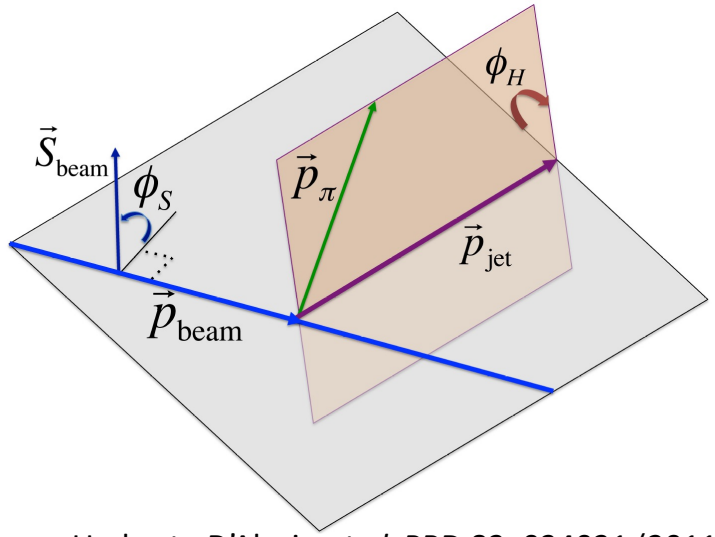
$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$

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

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

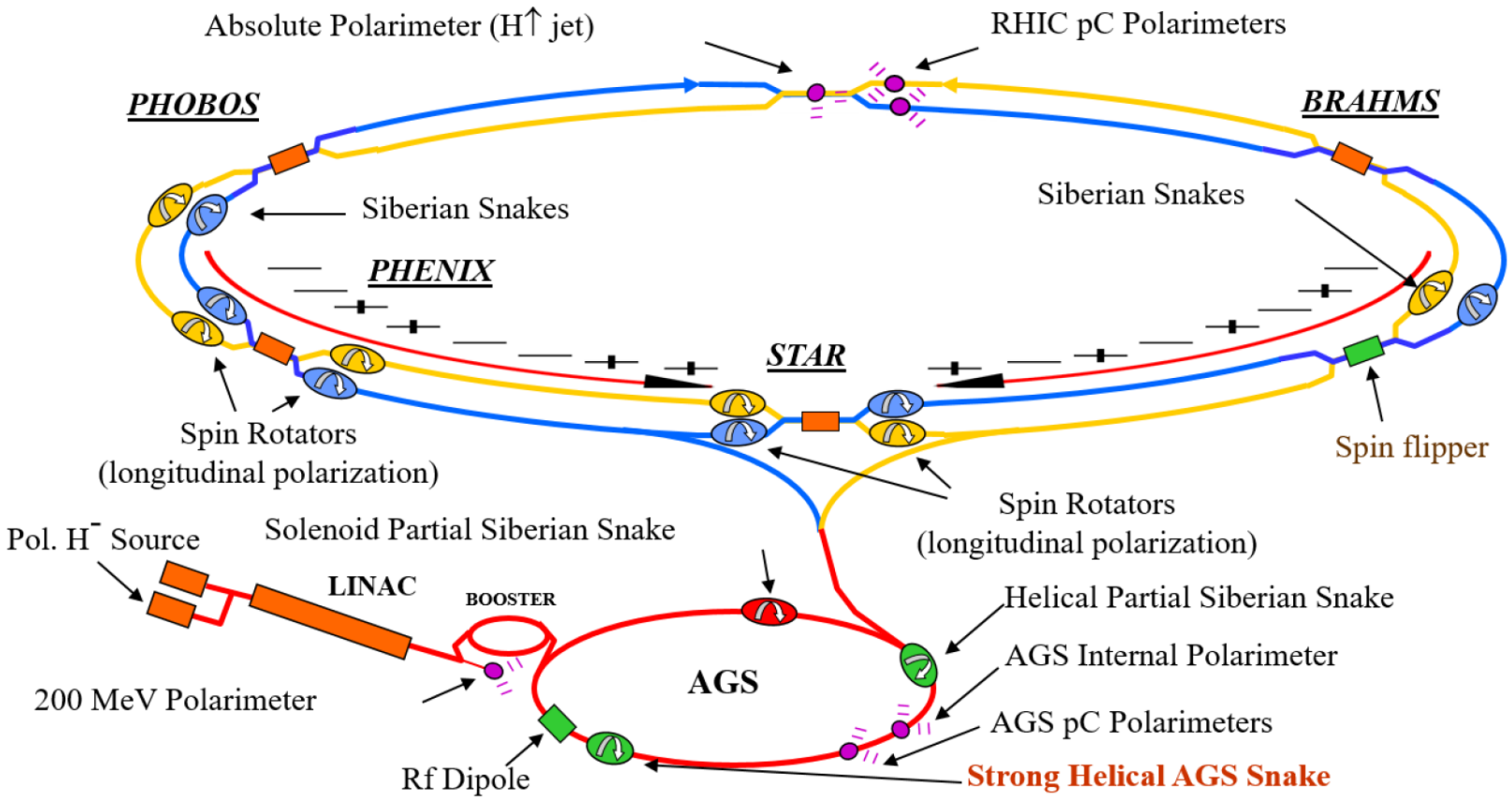
Zhong-Bo Kang *et al.*, JHEP 11, 068 (2017) and PLB 774, 635 (2017)

- 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 than previous SIDIS measurements;
- At EIC, full jet reconstruction will enable similar kinematic separation.



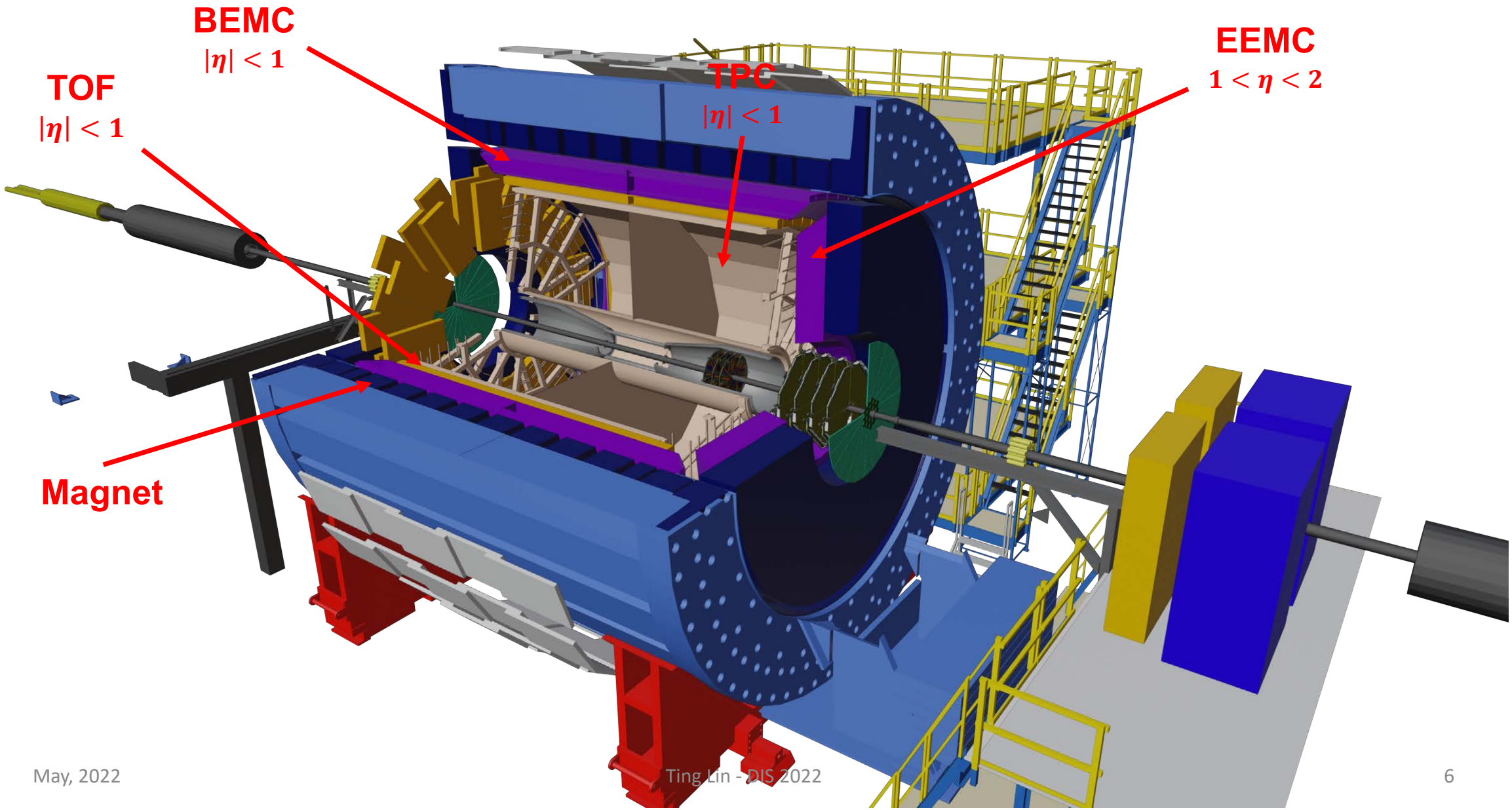

Umberto D'Alesio *et al*. PRD 83, 034021 (2011)

# Relativistic Heavy Ion Collider (RHIC)



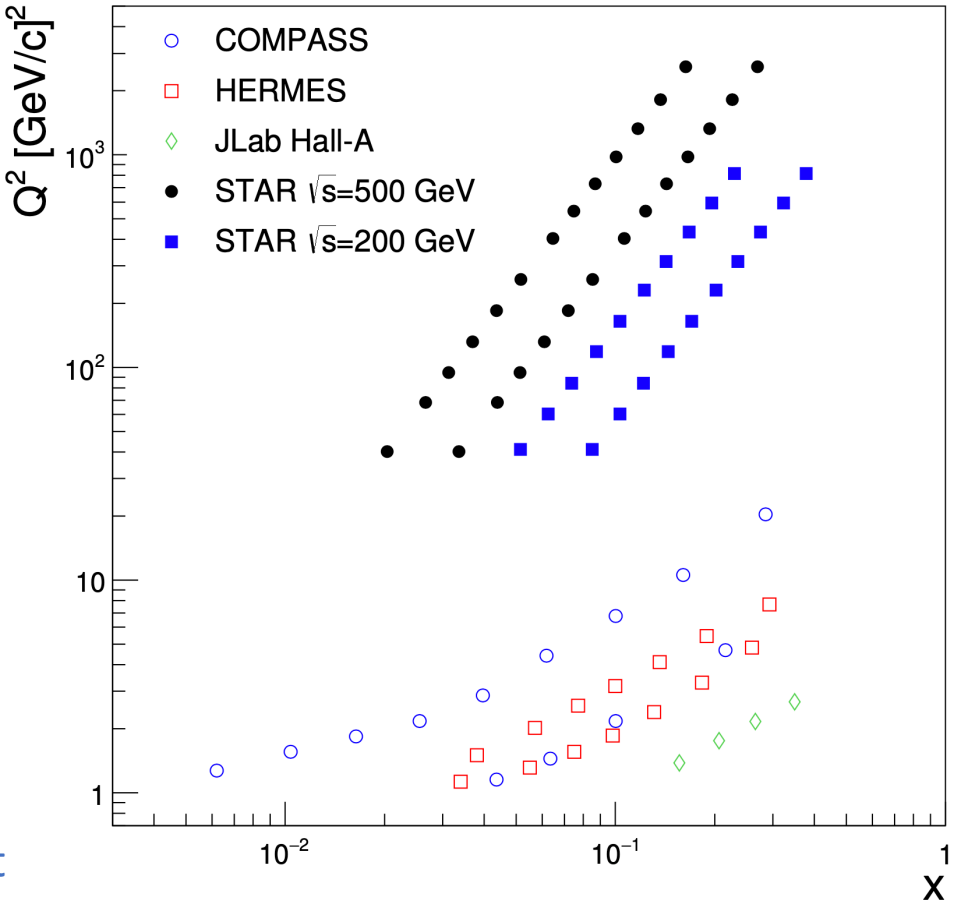

- World's first and only polarized proton+proton collider;
  - Provide polarized proton+proton collisions up to 510 GeV;
- Spin pattern changes from fill to fill with little depolarization;
  - Siberian snakes preserve the polarization;
  - Spin rotators select spin orientation;
  - proton-Carbon (pC)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

# Solenoidal Tracker At RHIC (STAR)



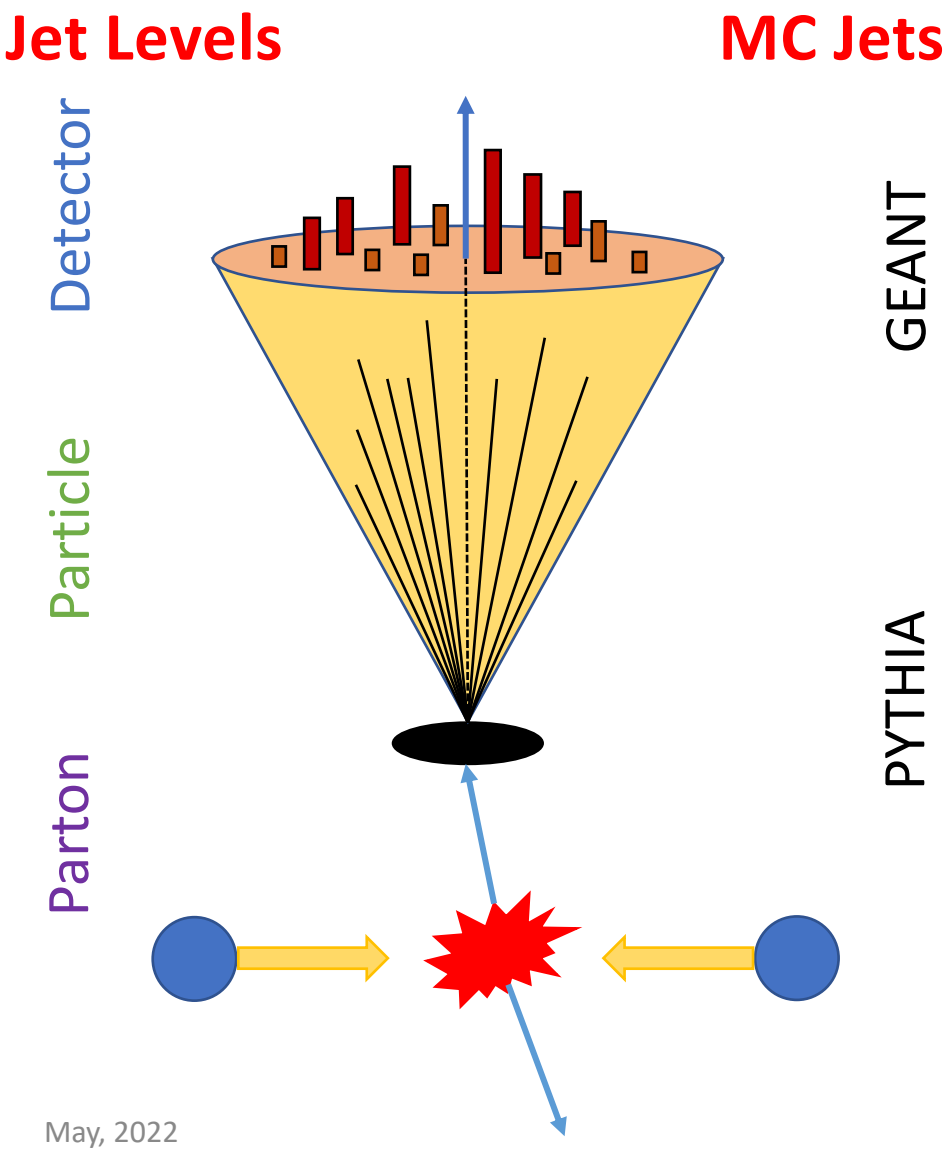
# STAR Data and Kinematic Coverage

| Year | 2011 | 2012 | 2015 | 2017 | 2022 |
|---|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 500 | 200 | 200 | 510 | 510 |
| $L_{int}$ $(pb^{-1})$ | 25 | 22 | 52 | 350 | ~400 |
| Polarization | 53% | 57% | 57% | 58% | ~52% |




- 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.

# Jet Reconstruction




**Anti-$k_T$ Algorithm:**

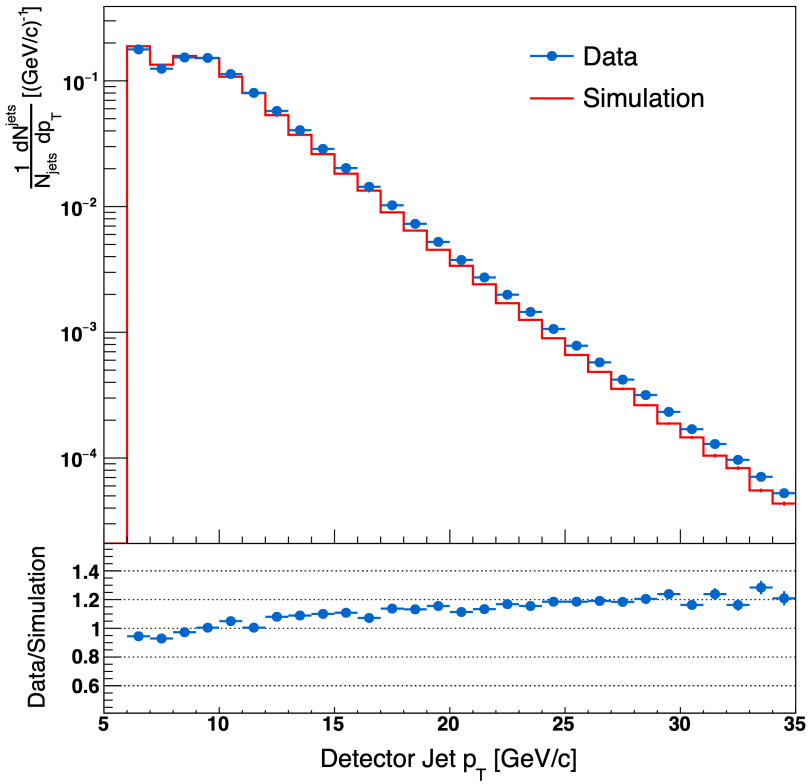
- Radius = 0.6;
- Less sensitive to underlying event and pile-up effects;
- Used in both data and simulation;

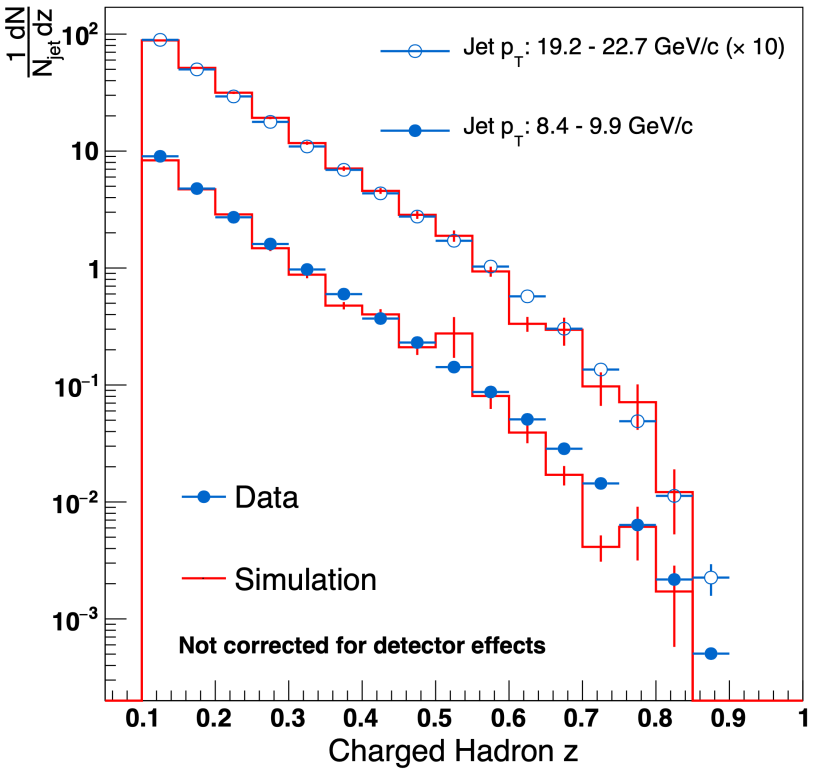
**Simulation:** PYTHIA 6.4 Perugia 2012 with additional tuning to STAR data;

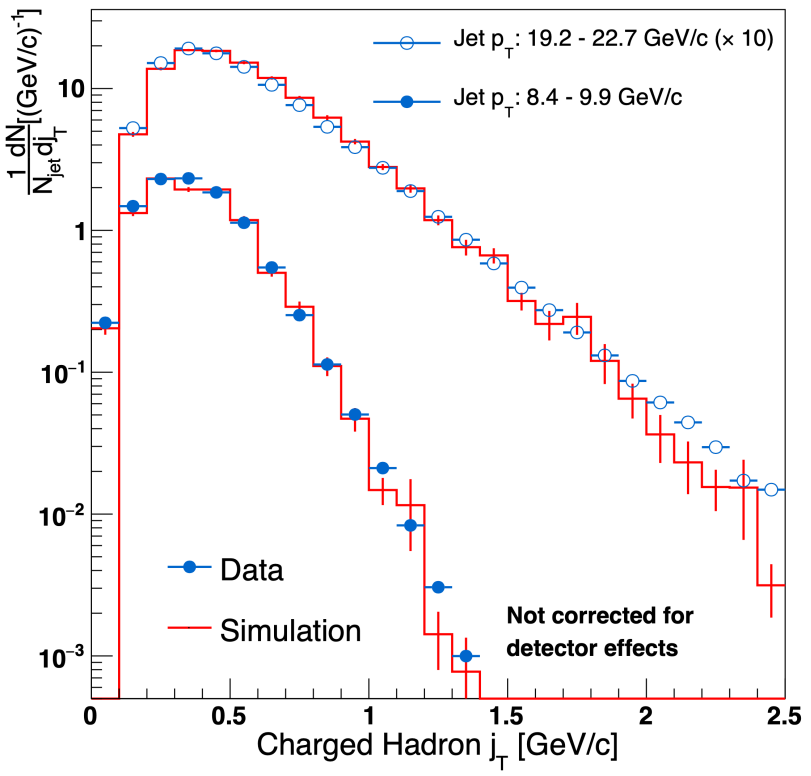
**Three Simulation Levels :**

- 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.

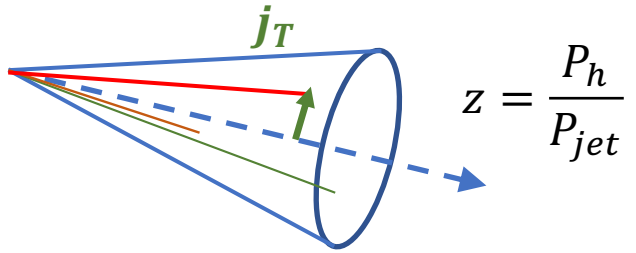
# Data and Simulation Comparison



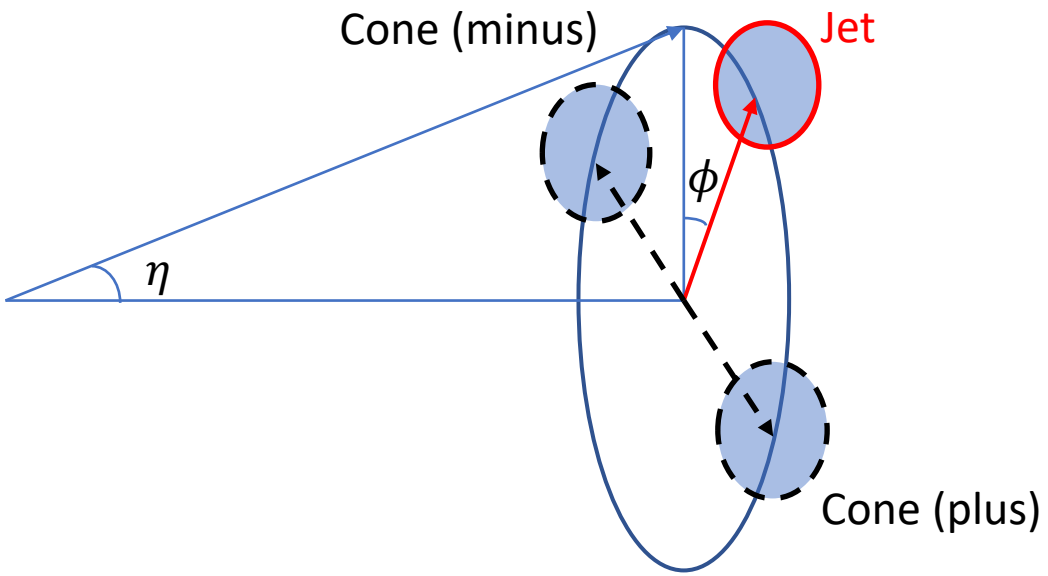



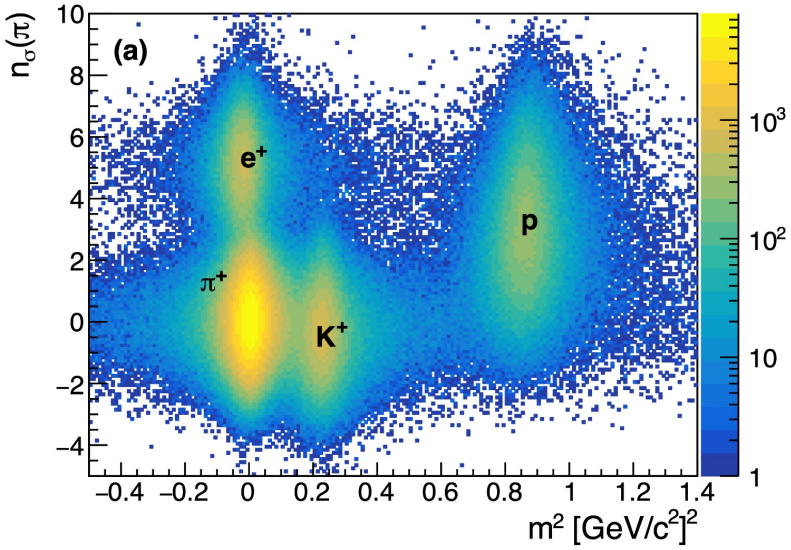

- Data and simulation are in agreement;
- The measured jet kinematics are corrected back to particle level in the final results.



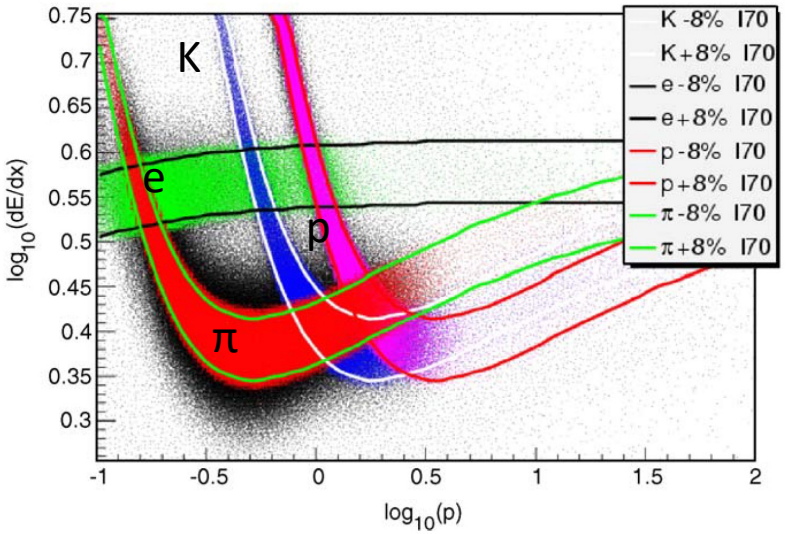
# Underlying Event and Particle Identification

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



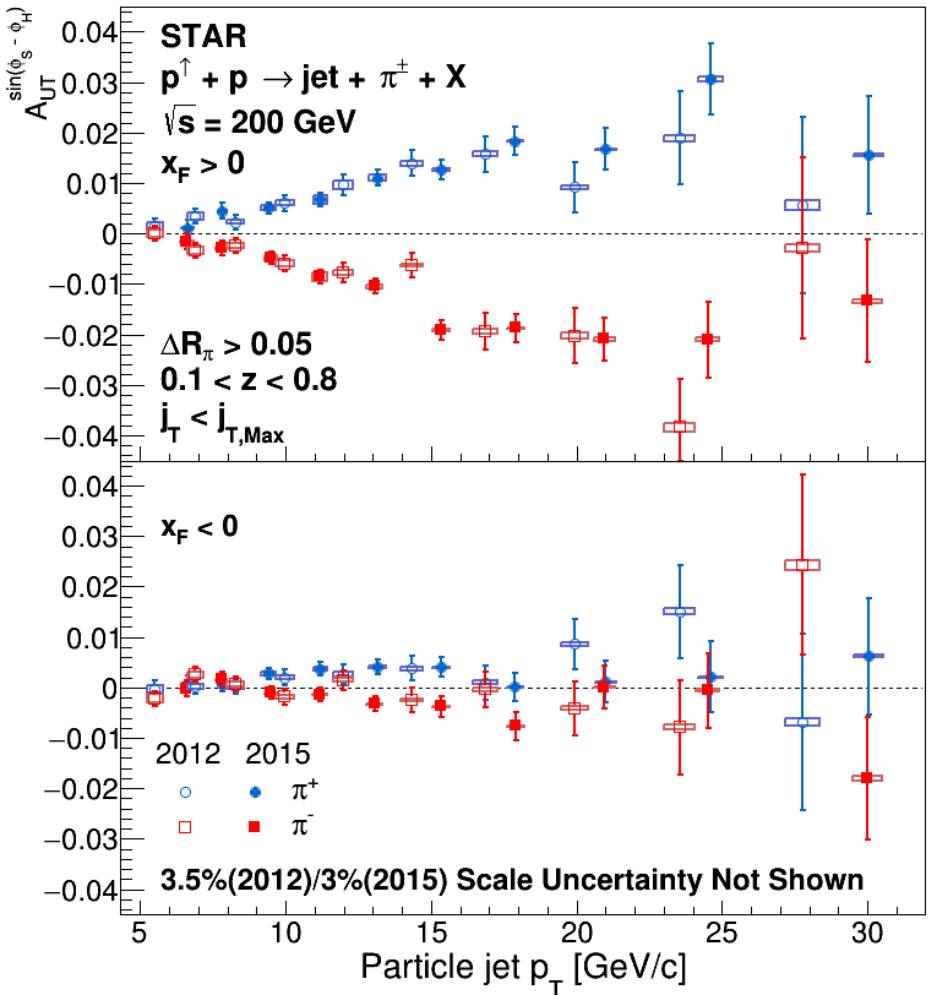




Ming Shao *et al.* NIM A558 (2006)

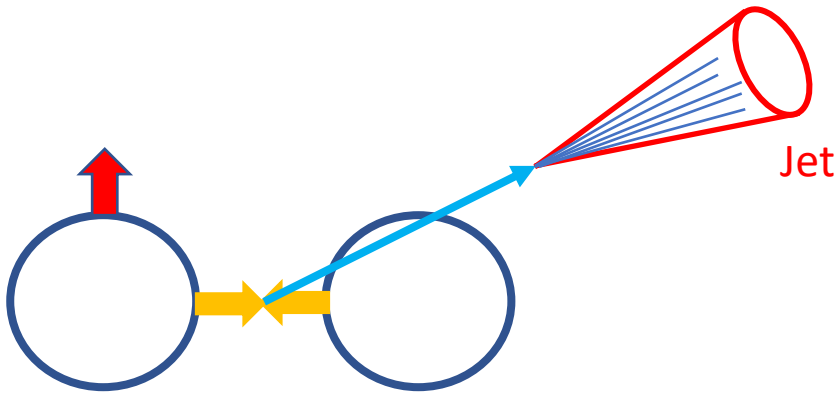



- Particle jet $p_T$ values are corrected for underlying event activity measured using the off-axis cone method;
- Spin asymmetries are corrected for the dilution from the underlying event contribution;
- Good particle identification from TPC and TOF.

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




Top panel:

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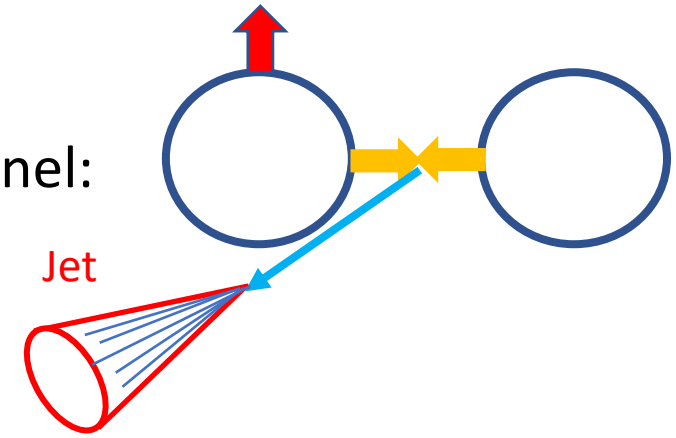
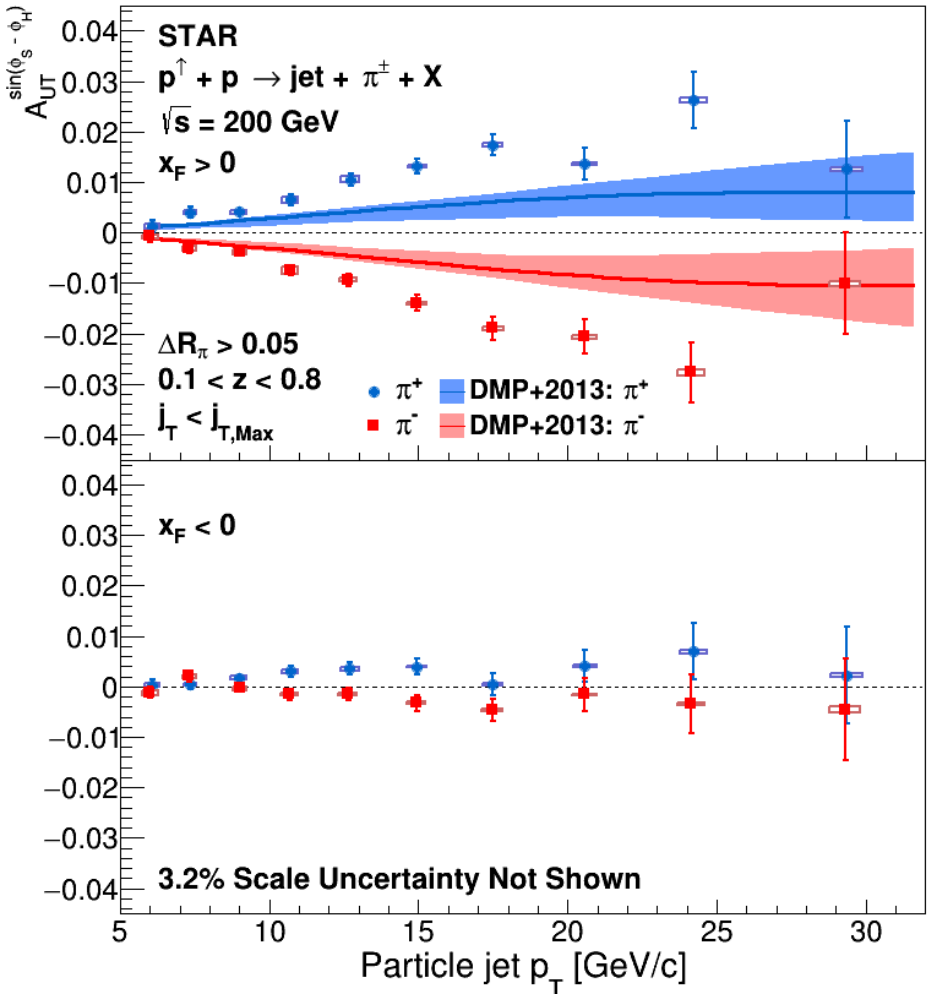



- Results from the independent analyses of two different RHIC running periods are in good agreement.

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

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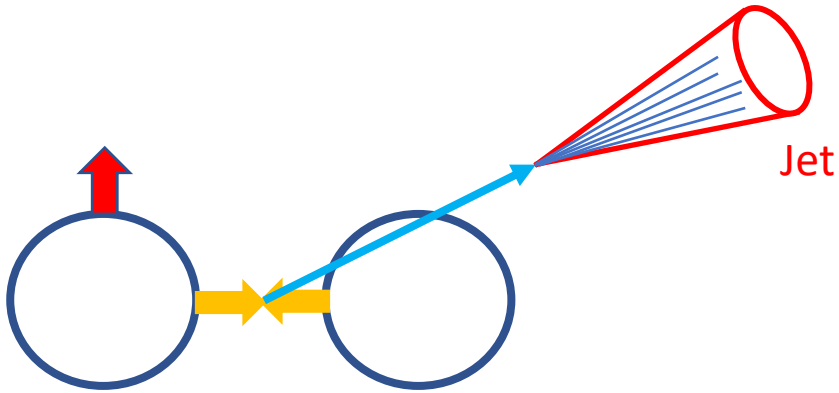


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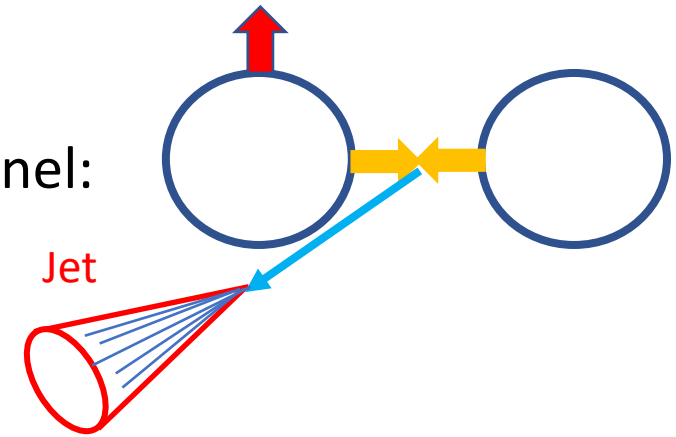
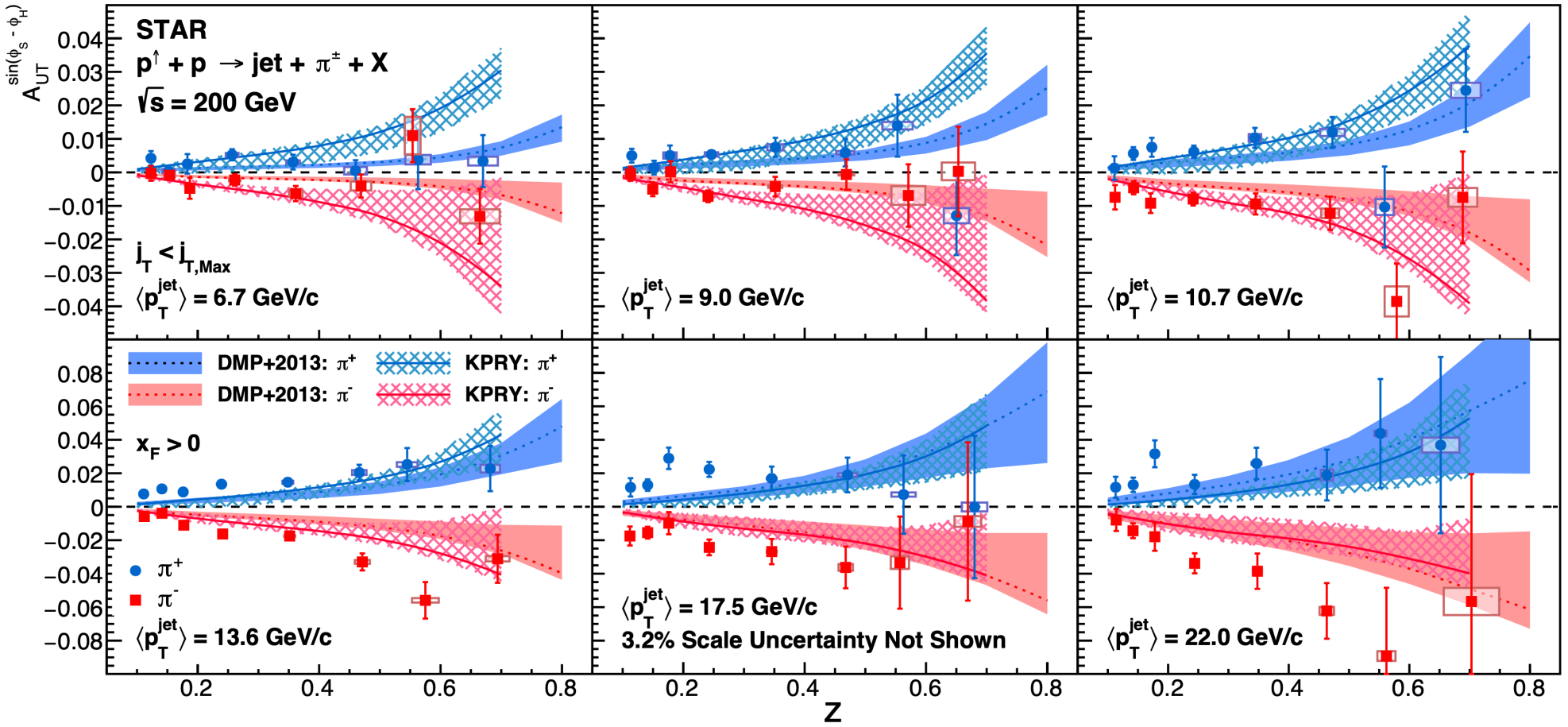
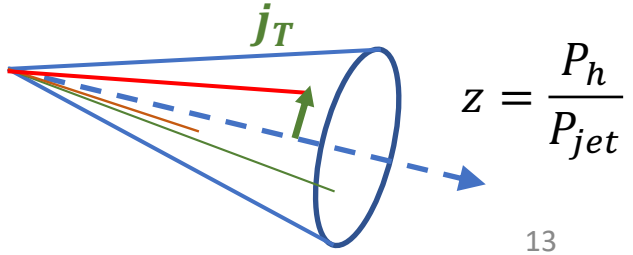



- Theoretical expectations are based on the DMP+2013 model (Umberto D'Alesio *et.al.*, PLB 773, 300 (2017)) that combines quark transversity from SIDIS with the Collins FF from $e^+e^-$ collisions.

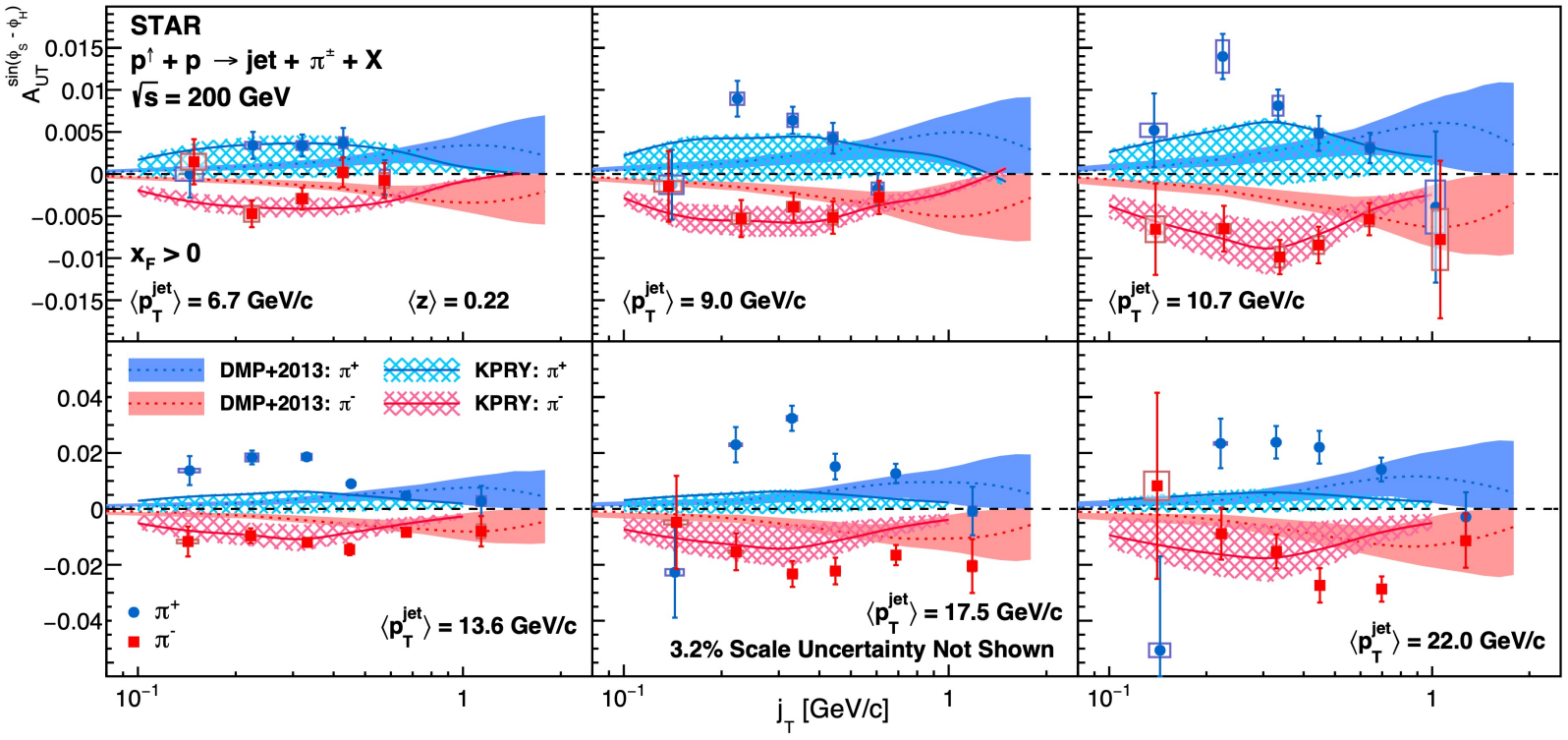
# $\pi^{\pm}$ Azimuthal Distribution in Jets

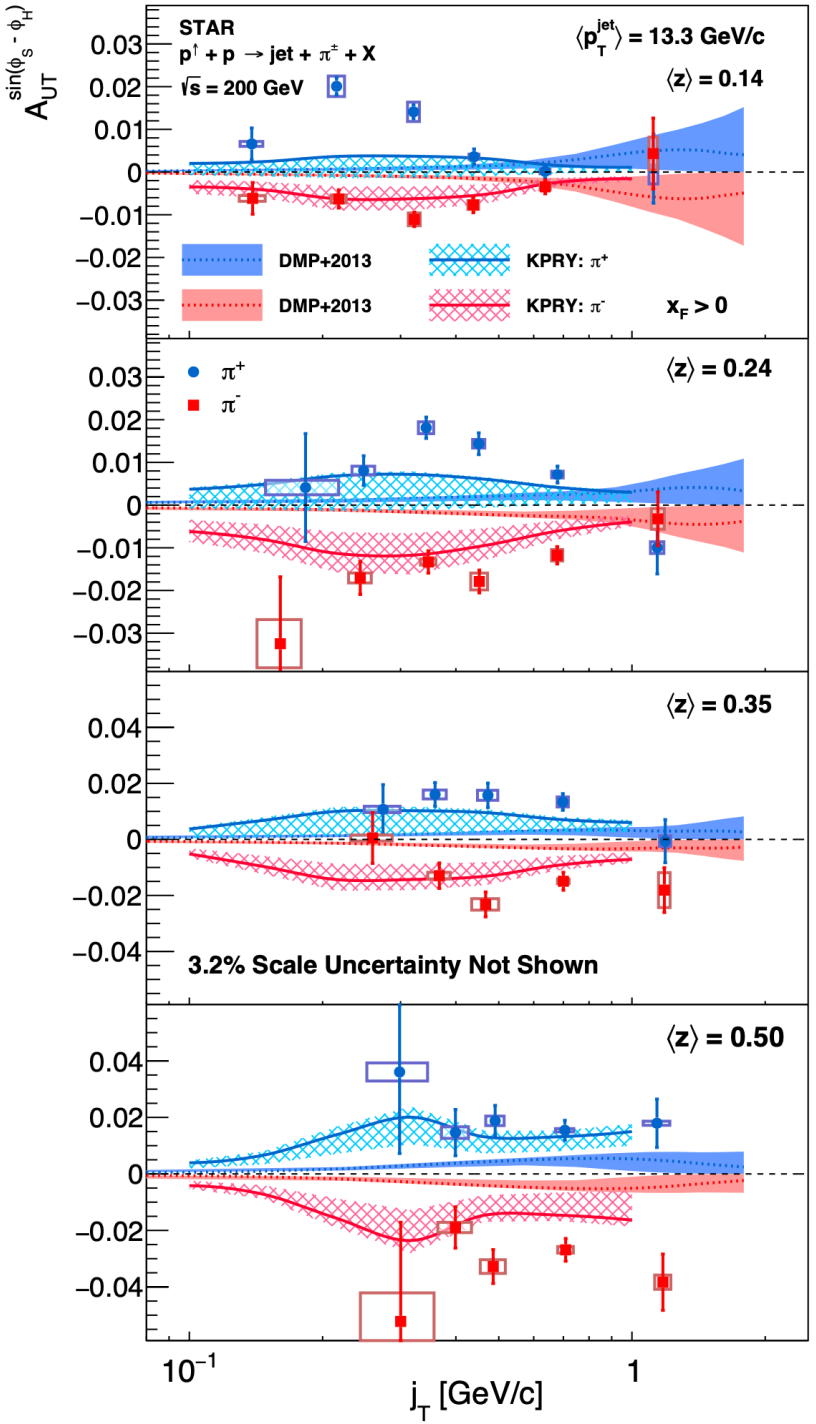



- DMP+2013 model from Umberto D'Alesio *et.al.*, PLB 773, 300 (2017);
- KPRY model from Zhong-Bo Kang *et. al.*,PLB 774, 635 (2017);
- Both assume universality and factorization.



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

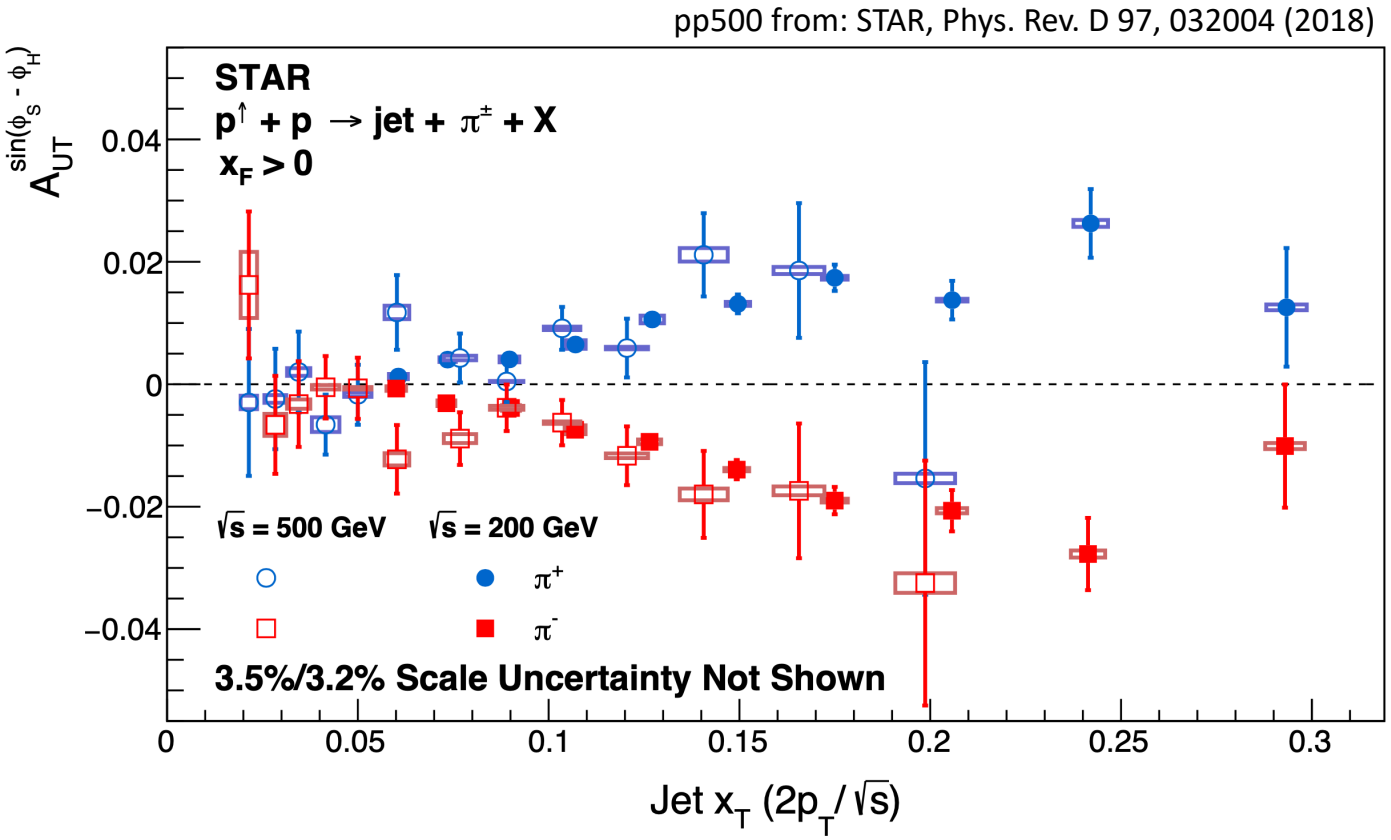


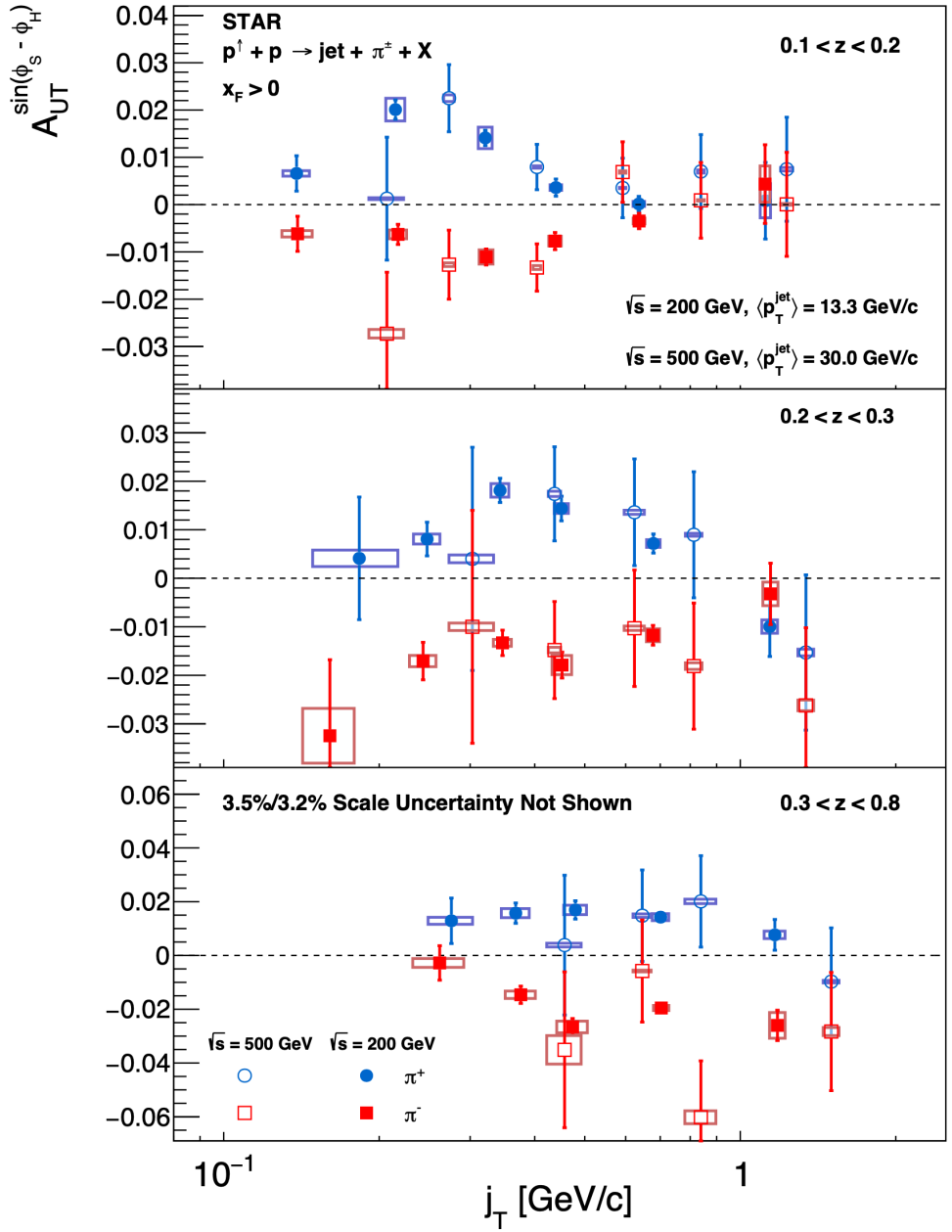




- Collins TMD FF is sensitive to the ($j_T$, z) dependence;
- Our results slightly favor the KPRY model than DMP+2013;
- Sizable differences between data and both theoretical calculations.

# Comparison with 500 GeV Results

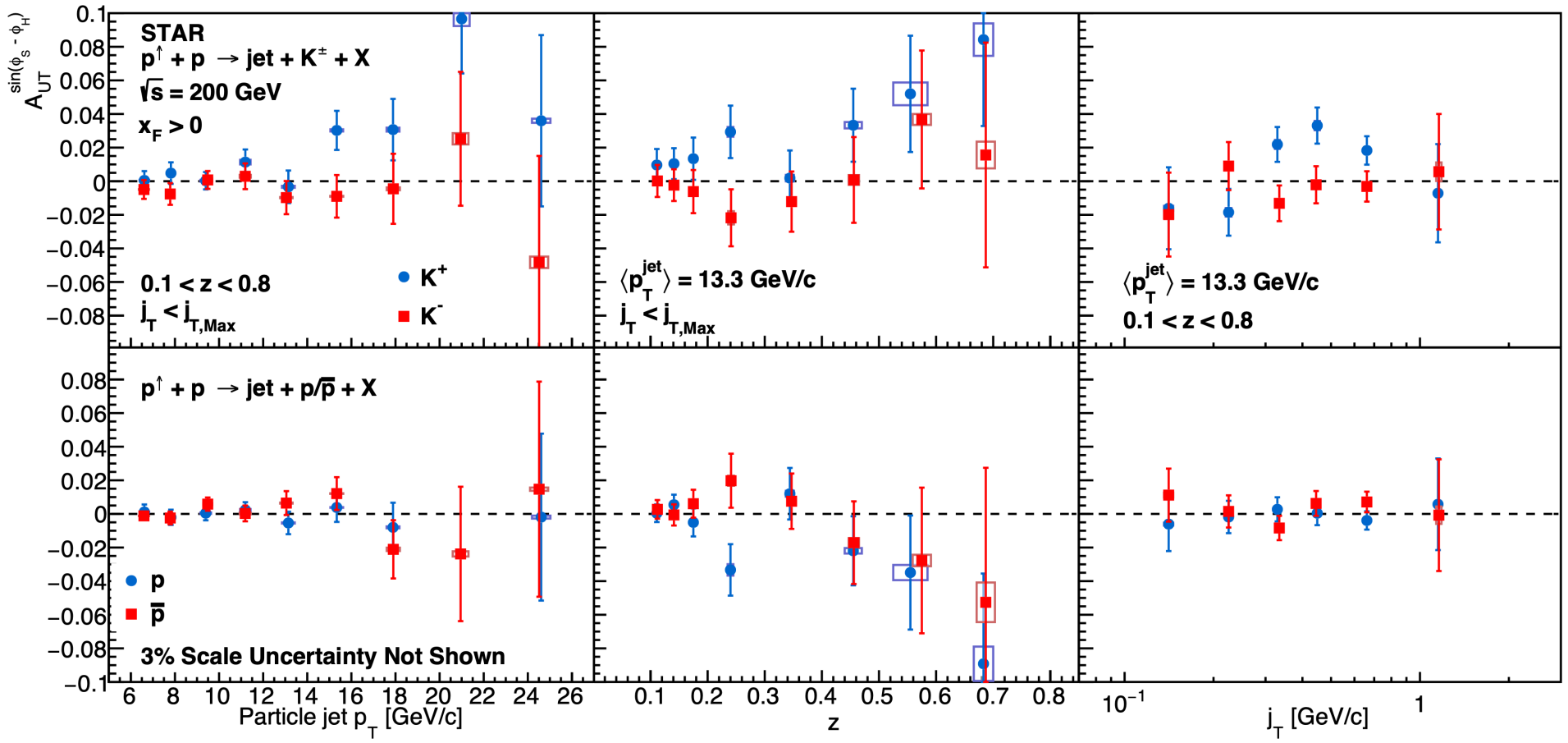
pp500 from: STAR, Phys. Rev. D 97, 032004 (2018)




- The asymmetries agree at $0.06 < x_T < 0.2$, $Q^2$ differ 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.

# $K^{\pm}$ and Proton Azimuthal Distribution in Jets




- $K^{+}$, with contribution from favored fragmentation of u quarks, has similar magnitude of asymmetries to $\pi^{+}$;
- $K^{-}$, 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.

# Summary

- The most precise measurements to date of the TSSA for charged hadrons inside jets in hadronic interactions are presented;
- The asymmetries agree with previous measurement at $\sqrt{s} = 500$ GeV, indicating a weak energy dependence of Collins effect in hadronic collisions;
- The asymmetries for charged pions are larger than the theoretical calculations which may indicate larger quark transversity;
- The Collins asymmetries for charged kaons and protons are statistically limited, need further measurements to confirm the difference due to fragmentation.