Exploring Nucleon Structure and Hadronization with Dihadrons and Hadrons in Jets at STAR

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for the STAR Collaboration

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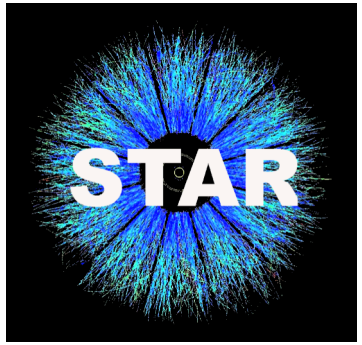
U.S. Department of Energy | Office of Science

OUTLINE

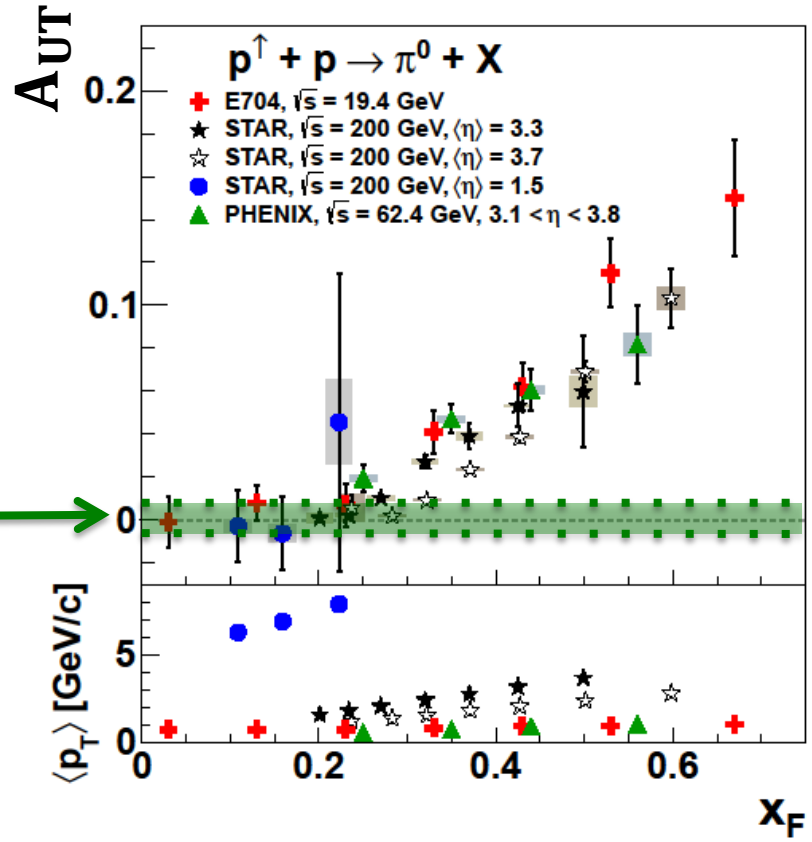
- TSSAs and transversity
- STAR
- Dihadrons at STAR
- Hadrons-in-jets at STAR
- Looking forward
- Summary



A Surprise from Transverse Single-spin Asymmetries

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\sigma^{\uparrow(\downarrow)}$ -- cross section for ***leftward*** scattering when beam polarization is spin-***up***(down)



Collinear pQCD at leading twist: very small A_{UT}

Sizeable A_{UT} at forward pseudorapidity across a large range of $\sqrt{s}$

Measurements at RHIC in region where NLO pQCD cross-section provides a reasonable description of the data

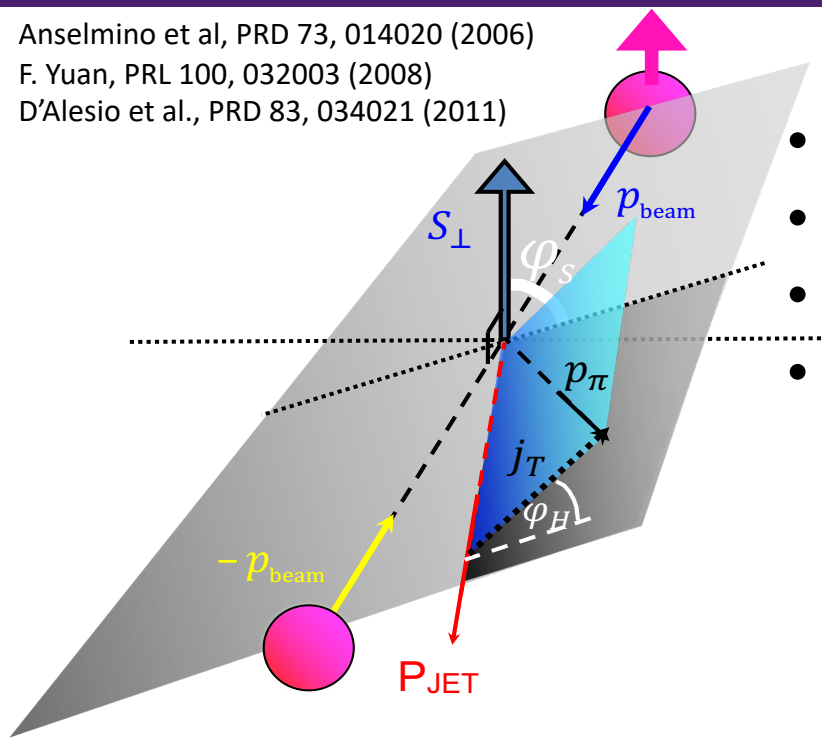
→ Go beyond collinear pQCD at leading twist

→ Insight into transverse polarization structure?

Shown results from
E704, PLB 261, 201 (1991)
STAR, PRL 101, 222001 (2008)
STAR, PRD 89, 012001 (2014)
PHENIX, PRD 90, 012006 (2014)

Transverse Single-spin Asymmetries and Transversity

Anselmino et al, PRD 73, 014020 (2006)
F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)



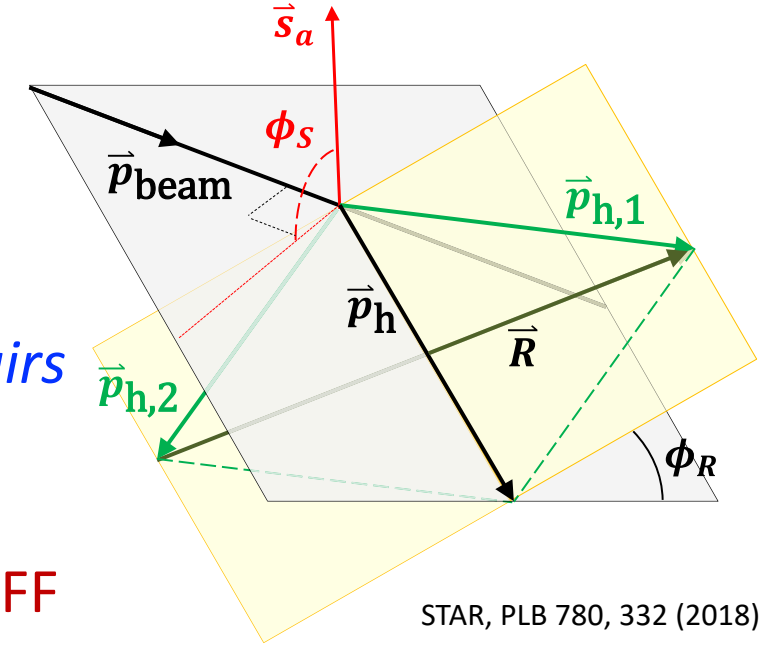
Collins mechanism [J. Collins, NP B396, 161 (1993)]

- Transversely polarized quarks inside transversely polarized proton
- Quark polarization transfer during hard scatter
- Distribution of hadrons correlated to quark polarization
- *Azimuthal asymmetry in distribution of hadrons within the jet*
  - Requires non-zero quark transversity
  - Requires spin-dependent ***TMD*** fragmentation function

Dihadron fragmentation functions, aka "IFF"

e.g. Bacchetta and Radici, PRD 70, 094032 (2004)

- *Azimuthal asymmetry in orientation of hadron pairs fragmenting from same parent quark*
  - Requires non-zero quark transversity
  - Requires spin-dependent ***collinear*** di-hadron FF

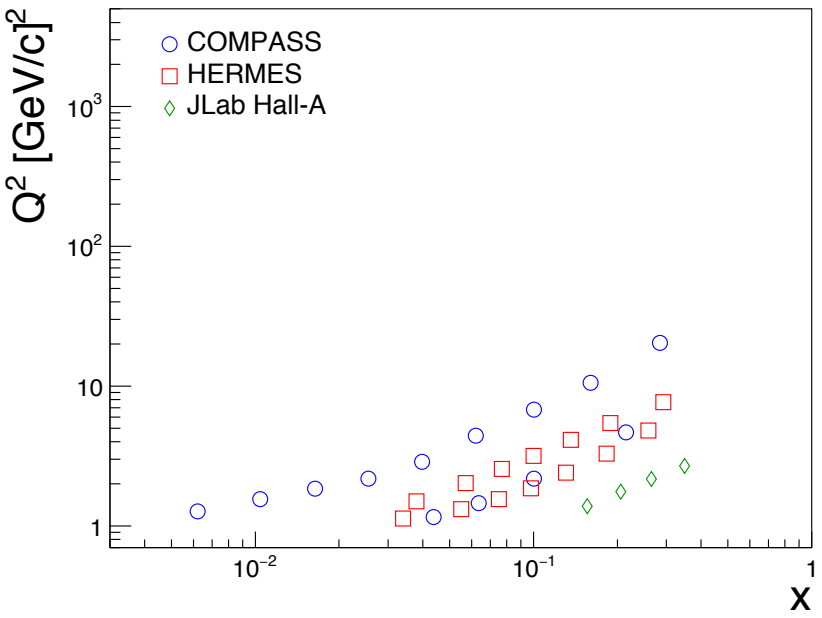


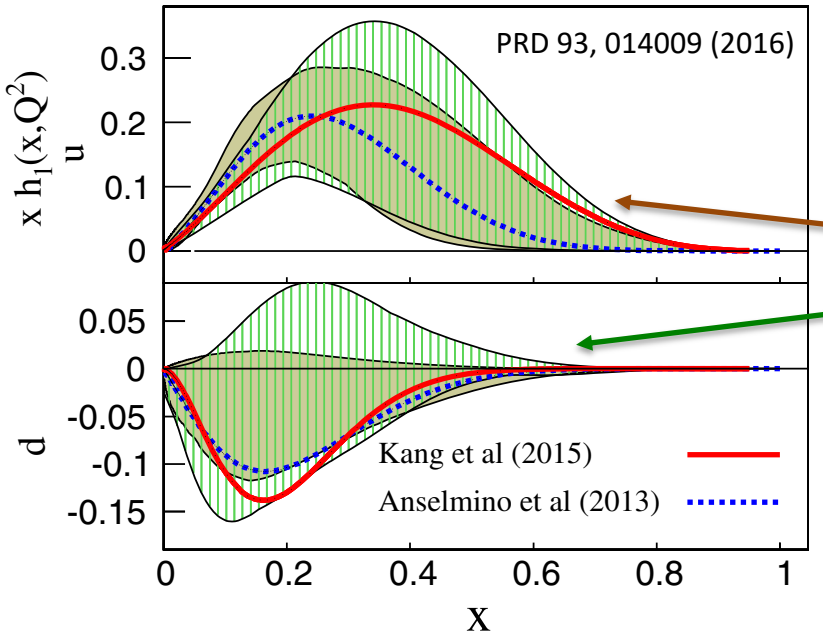
STAR, PLB 780, 332 (2018)

Transversity

Complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF, $f(x)$
- Helicity PDF ($\Delta f(x)$)
- Transversity ($h_1(x)$ or $\delta q(x)$) – chiral odd → requires another chiral-odd distribution
  - $\Delta q(x) - \delta q(x)$: direct connection to *non-zero OAM components* of proton wave function
  - Tensor charge, $\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$





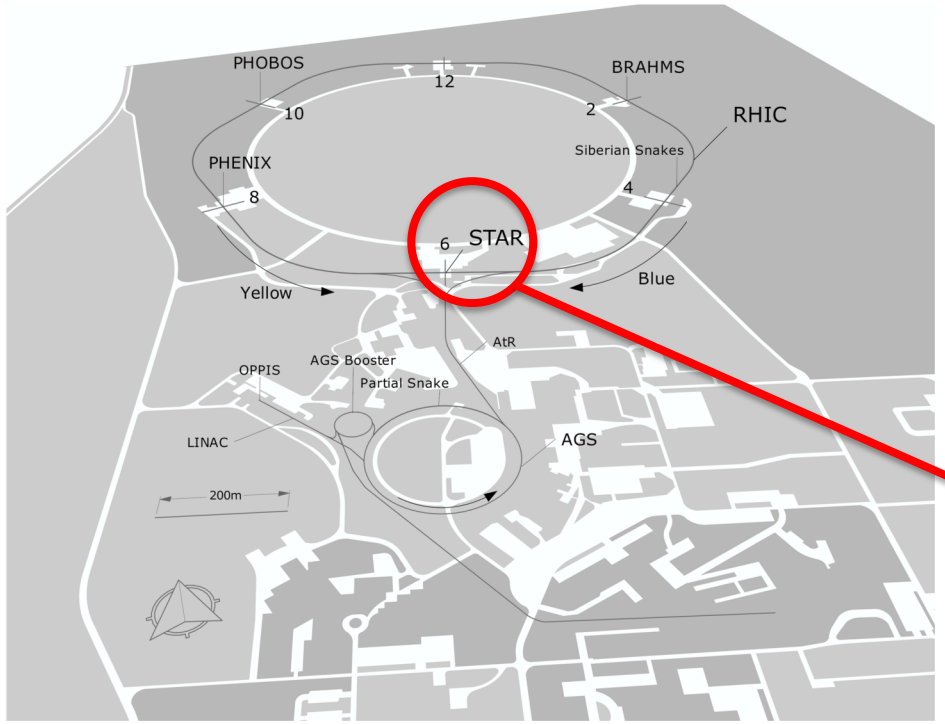
Large uncertainties:
u-quark for $x > 0.1$
d-quark pos or neg?

Kang et al: PRD 93, 014009 (2016)
Anselmino et al: PRD 87, 094019 (2013)
Radici et al: JHEP 05, 123 (2015)

Global analyses access in SIDIS + e^+e^-, e.g. via "Collins" or IFF asymmetries

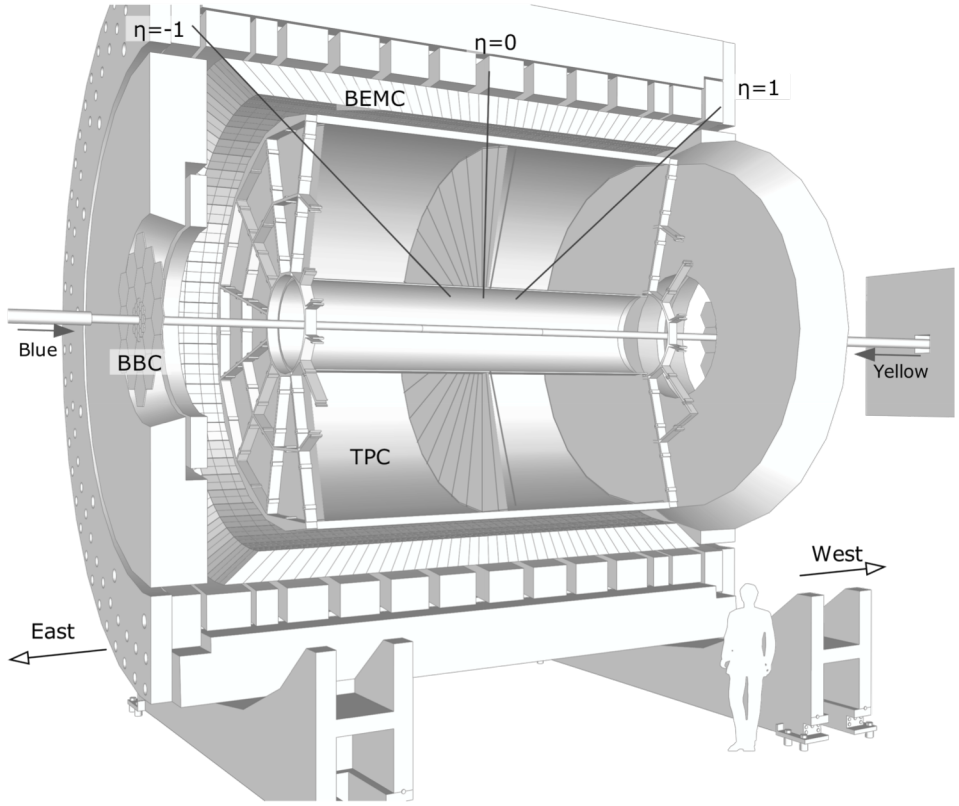
Currently limited reach in (x, Q^2)

The Solenoidal Tracker at RHIC



RHIC as Polarized-proton Collider

- "Siberian Snakes" → mitigate depolarization resonances
- Choice of spin orientation → ***independent of experiment***
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill



Central Detectors: $|\eta| < 1$

Tracking + PID + E/M Cal.

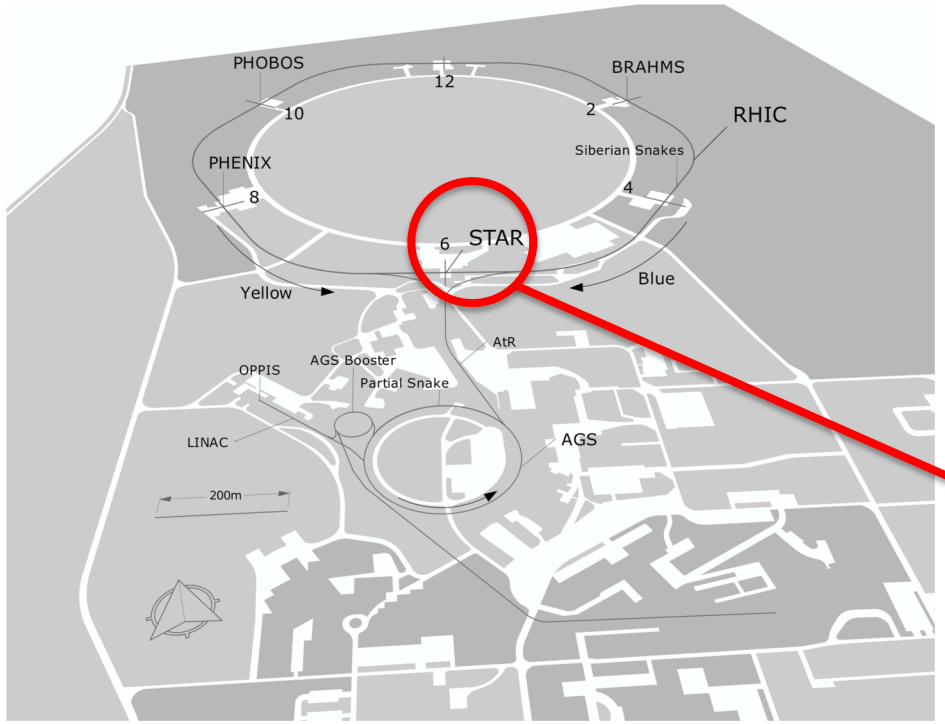
Jets, $\pi^{\pm}, K, p, e^{\pm}, \pi^{0}, \gamma$

Forward Detectors: $1 < \eta < 2$ and $2.5 < \eta < 4$

Tracking ($1 < \eta < 1.3$) + E/M Cal.

Jets ($1 < \eta < 1.8$), $\pi^{0}, \gamma, e^{\pm}$

The Solenoidal Tracker at RHIC



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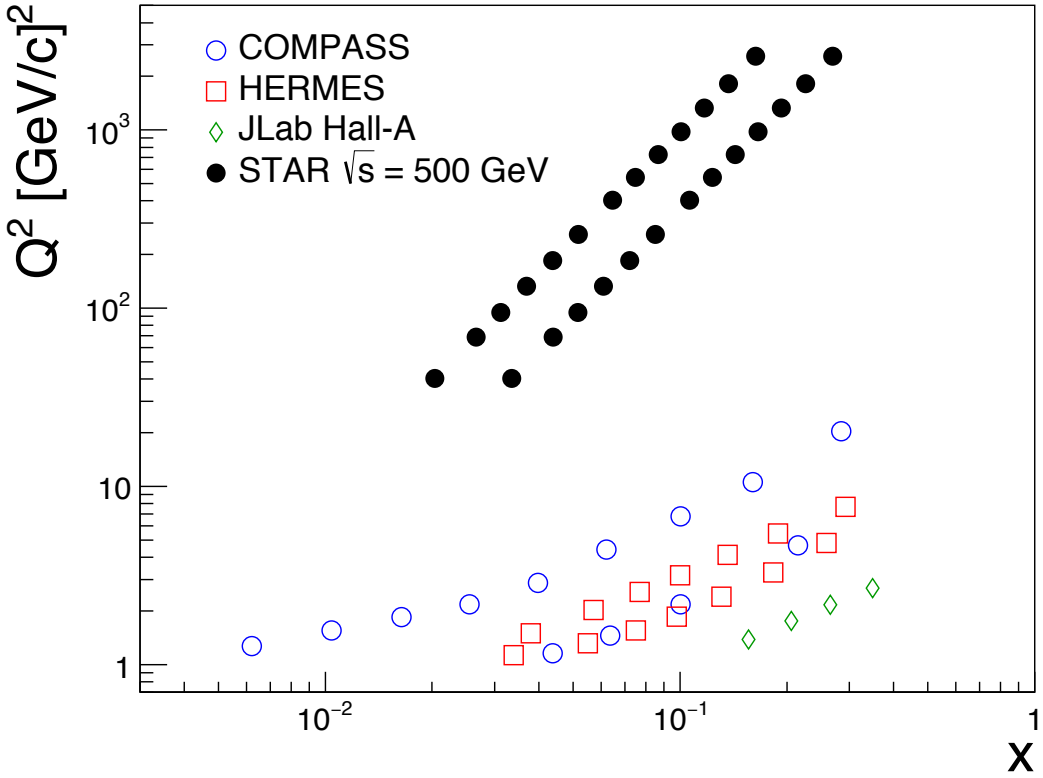

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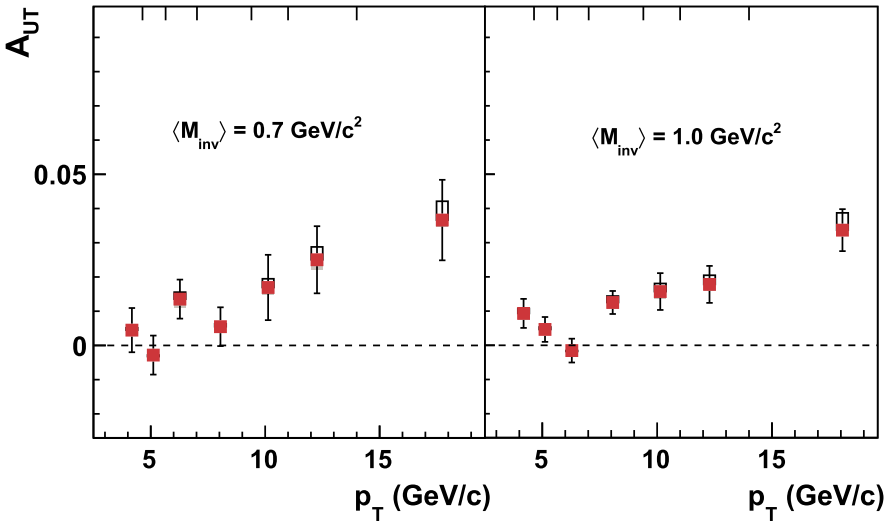
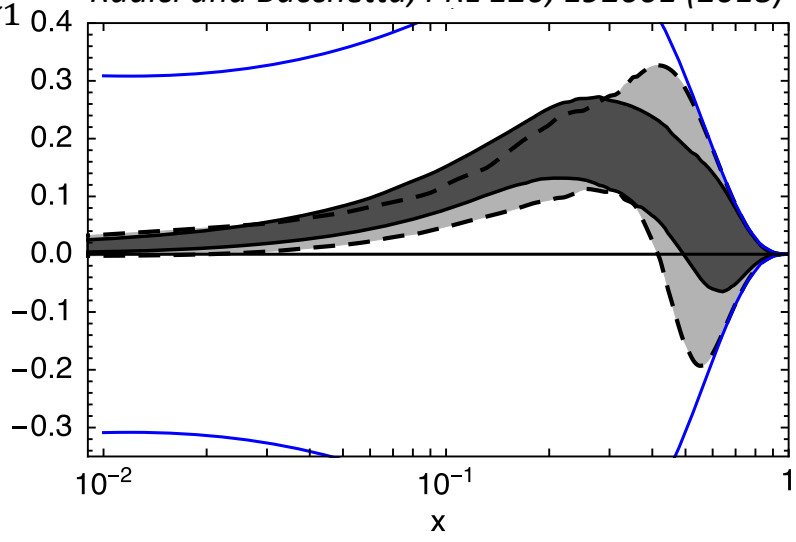
Dihadron Asymmetries at STAR

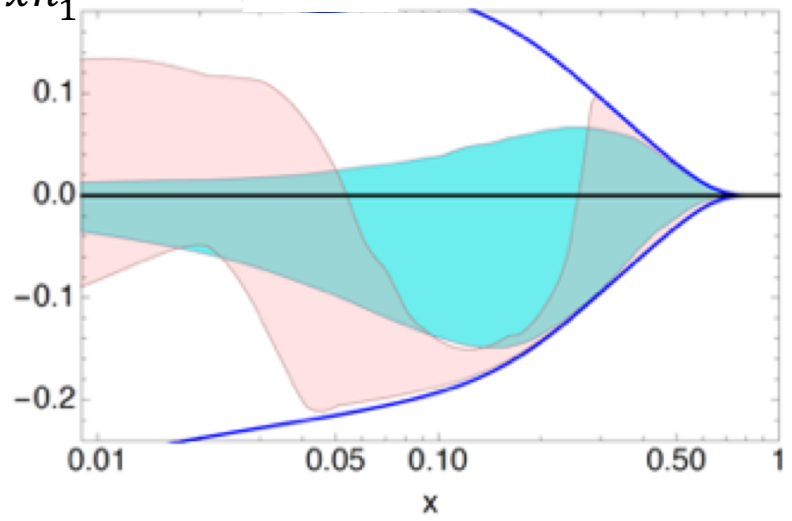
$p^{\uparrow} + p \to \pi^+\pi^- + X$ at $\sqrt{s} = 500$ GeV

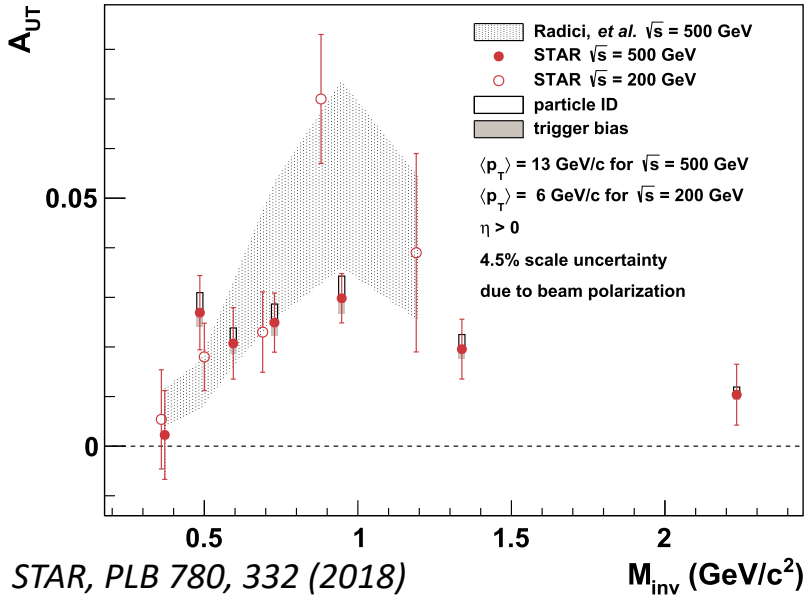


$xh_1^{u_v}$ *Radici and Bacchetta, PRL 120, 192001 (2018)*



$xh_1^{d_v}$ *Red band: JHEP 1505, 123 (2015)*





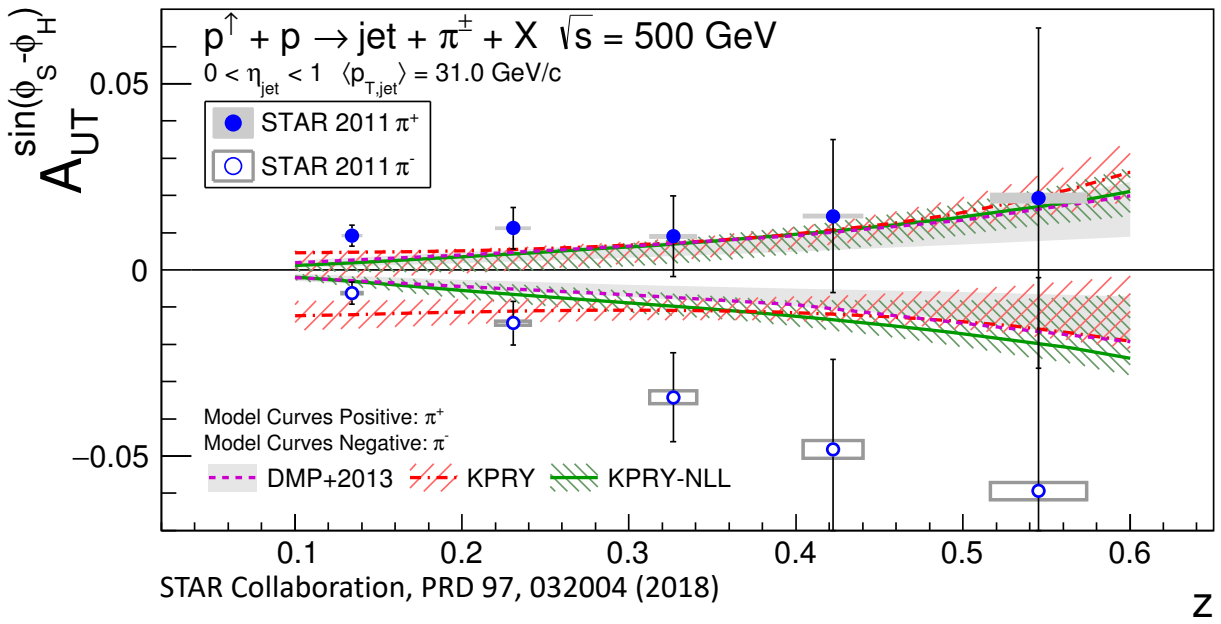
STAR, PLB 780, 332 (2018)

Significant dihadron asymmetries at RHIC (200 & 500 GeV)

- *Strong dependence on pair p_T*
- Invariant mass dependence: data are consistent with 68% of replicas based on SIDIS & e^+e^- data

  → Same as in SIDIS!
- 200 GeV: ***Significant impact*** on IFF global transversity analysis!
  - Improved precision of valence u-quark
  - Valence d qualitatively more similar to Collins extractions

Collins Effect at STAR



STAR Collaboration, PRD 97, 032004 (2018)

First-ever Collins Asymmetries in $p^{\uparrow} + p$

Models based on SIDIS/e^+e^-

- *Assume universality and robust factorization*
- **DMP&KPRY: no TMD evolution**
- **KPRY-NLL: TMD evolution up to NLL**

Consistency between models and STAR data at 95% confidence level

→ Suggests robust factorization and universality

To evolve or not to evolve?

$\chi^2/\nu = 14/10$ (w/o) vs. $17.6/10$ (with)

For now, "Beauty is in the eye of the beholder!"

(a.k.a. need more data!)

STAR Collaboration, PRD 97, 032004 (2018)
D'Alesio, Murgia, Pisano: PLB 773, 300 (2017)
Kang, Prokudin, Ringer, Yuan: PLB 774, 635 (2017)

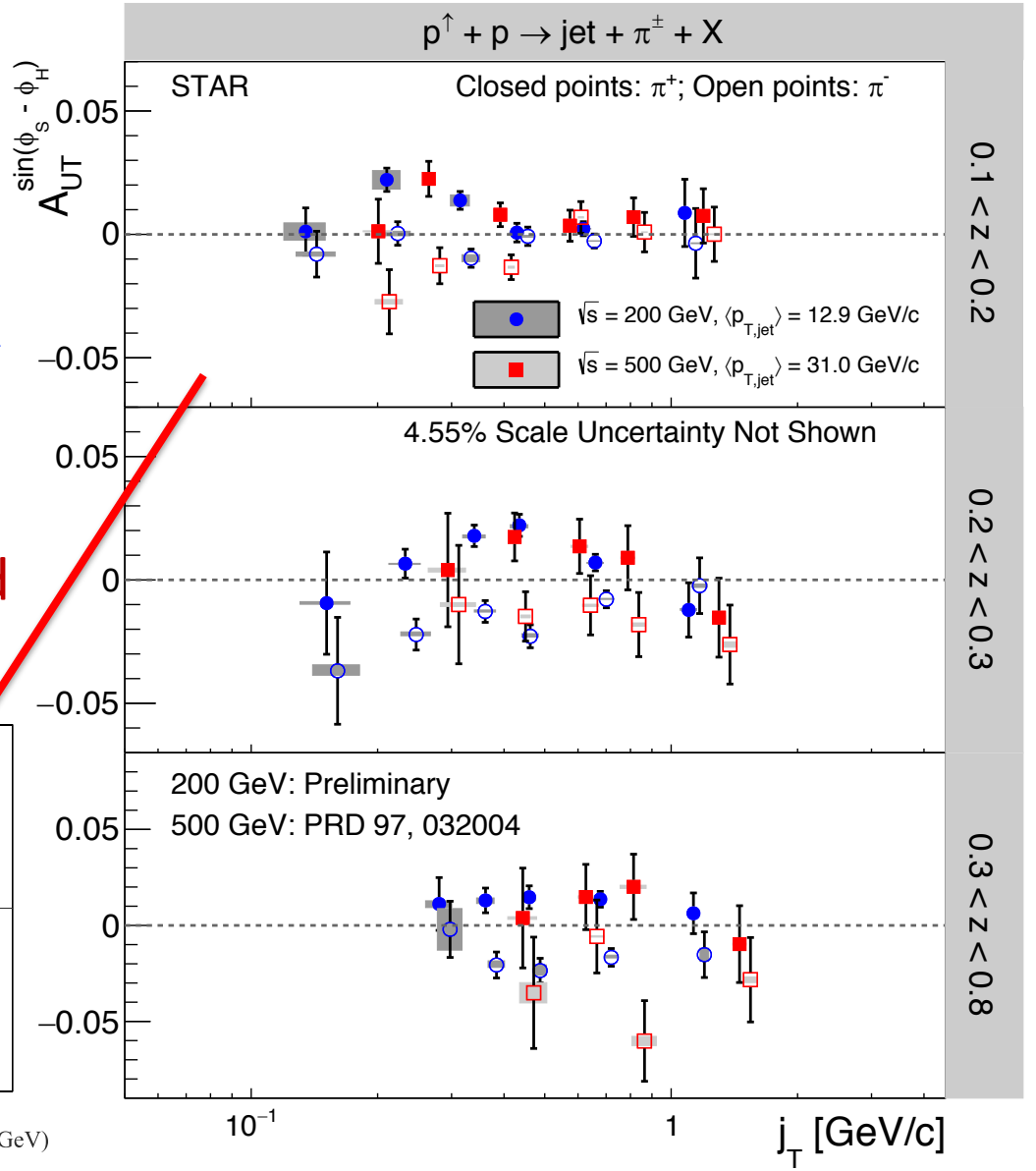
Collins Effect at STAR

Compare published 500 GeV to ***preliminary*** 200 GeV

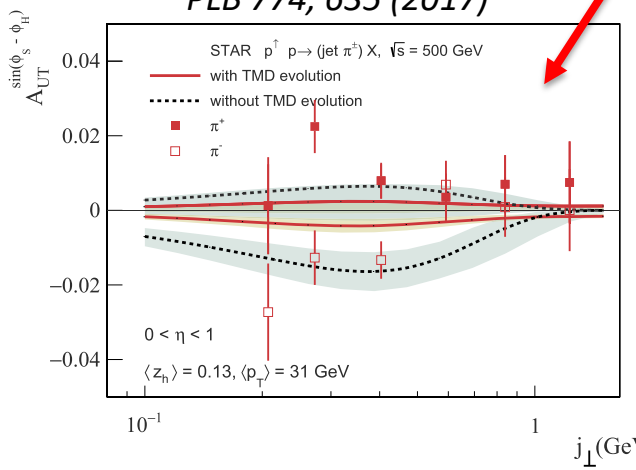
- 200 and 500 GeV in ***complete agreement*** for common x_T
- Shape of asymmetries vs. j_T changes with z
  - Peak appears to shift to higher j_T for increasing z
  - Suggests asymmetry does not factorize as

$$A_{UT} \sim f(j_T) \times f(z)$$

- Models agree relatively well but more work needed
  - ***More unpolarized data!***
  - More detailed modeling



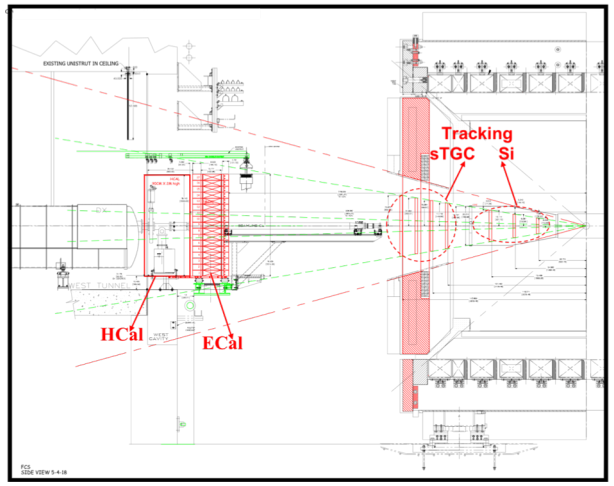
PLB 774, 635 (2017)

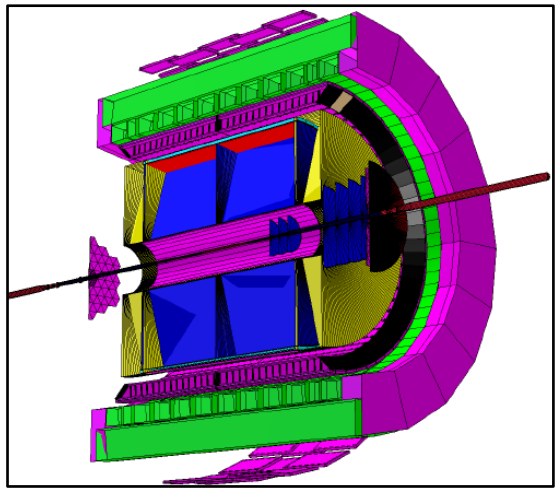


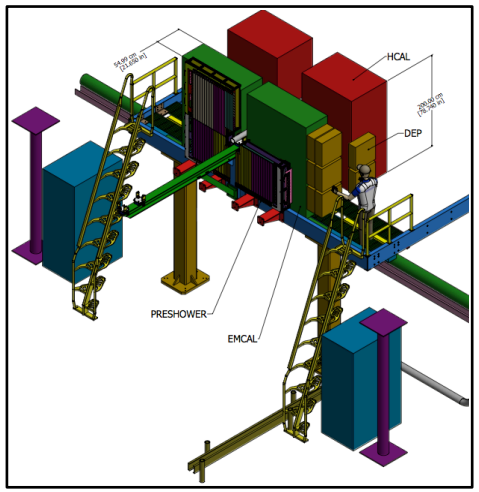
500 GeV: STAR Collaboration, PRD 97, 032004 (2018)
200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040

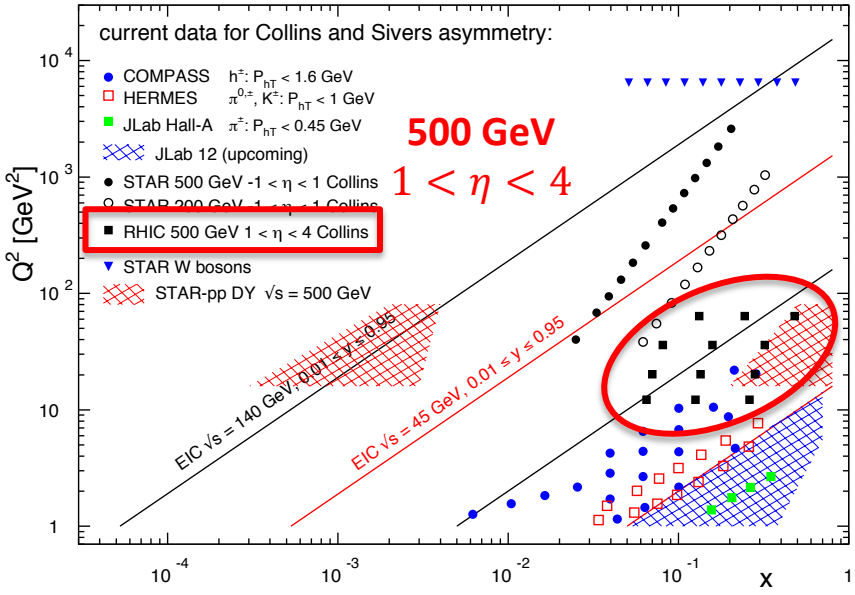
STAR Looking Forward

- High-stats data from 2015 (200 GeV pp & pA) and 2017 (500 GeV pp) under analysis
- STAR after RHIC BES-II, e.g. FY22 and beyond: *enhanced sensitivity to high (and low) x*
  - First $p+p$ runs with STAR iTPC upgrade
  - First runs with STAR forward upgrade
    - Forward ECAL+HCAL+Tracking: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648
    - Transversity at high x via forward "Collins" and IFF
    - **HCAL:** ***Very positive feedback from NSF and fully expect to receive funding!***
    - ***Significant progress***, e.g. beam tests, prototype runs, detector construction









Summary

- **TSSAs at STAR provide a unique window to nucleon structure and hadronization**
  - Access transversity via dihadrons (collinear) and Collins (TMD)
  - Test TMD factorization/universality and evolution
  - STAR dihadron and Collins asymmetries consistent with expectations based on SIDIS
- **First global transversity analysis including $p+p$ dihadron data**
  - Constraints for u-quark improved over previous IFF extraction
  - d-quark extraction including pp data qualitatively more similar to Collins extractions
- **STAR Collins asymmetries at 200 and 500 GeV informing model calculations**
  - Asymmetries appear to exhibit x_T scaling
  - Appears that the asymmetry does not factorize as $A_{UT} \sim f(j_T) \times f(z)$
  - Analysis of (un)polarized data from recent runs underway
- **Preparation for future STAR polarized runs, including forward upgrade, well underway**
  - HCAL: *Very positive feedback from NSF and fully expect to receive funding!*
  - Significant progress on beam tests, prototype runs, detector construction, etc.

Stay tuned!