Investigating Nucleon Structure and Hadronization with Hadrons in Jets at STAR

Jim Drachenberg
for the STAR Collaboration

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OUTLINE

- Transversity and TSSAs
- STAR
- Dihadrons at STAR
- Hadrons-in-jets at STAR
- Looking forward

Abilene Christian University

U.S. Department of Energy | Office of Science

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
  - $\Delta q(x) - \delta q(x)$: direct connection to *non-zero OAM components* of proton wave function
  - Tensor charge, $\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$

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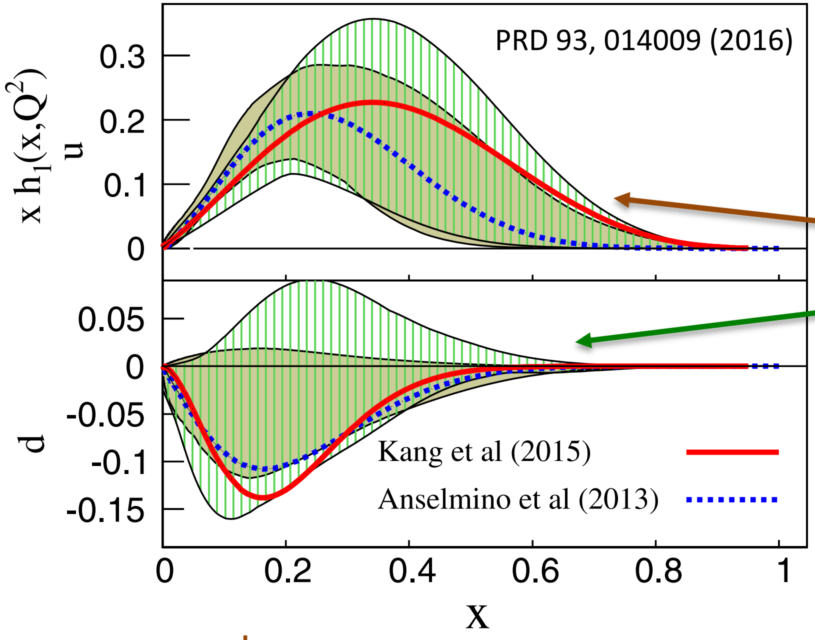

Large uncertainties:
u-quark for $x > 0.1$
d-quark pos or neg?

Kang et al: PRD 93, 014009 (2016)
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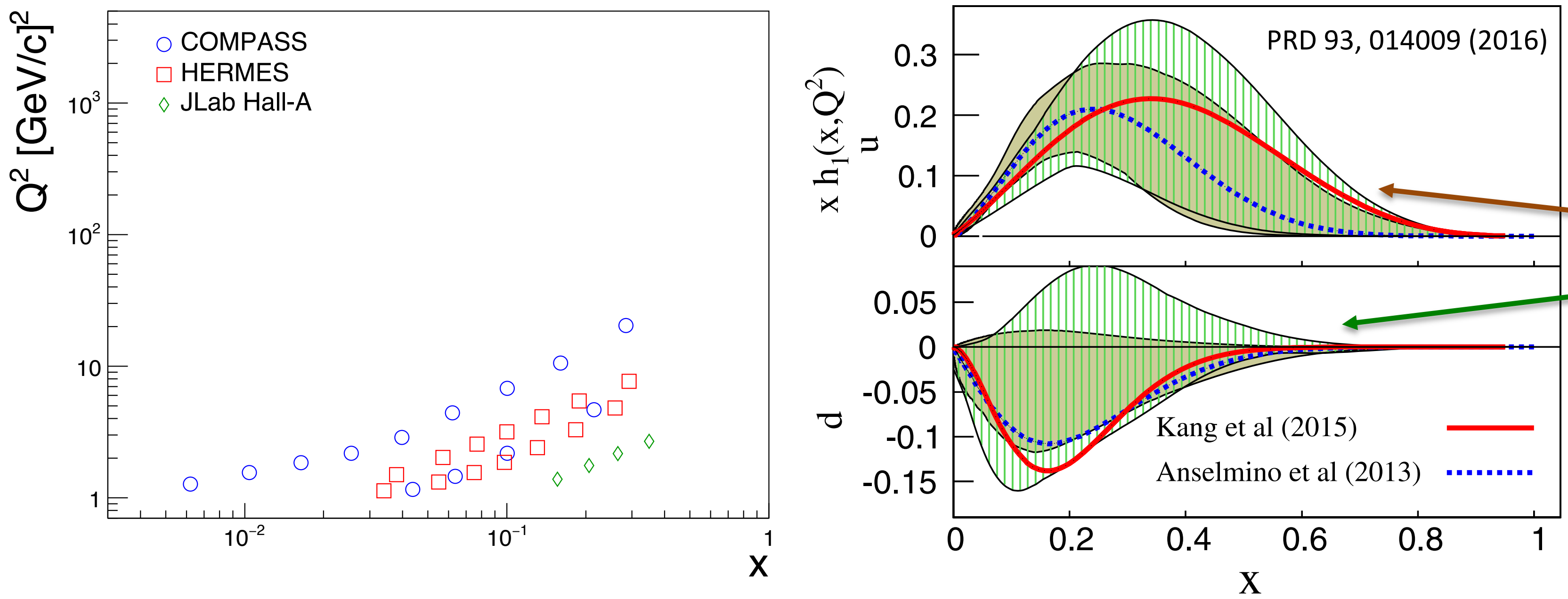

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Currently limited reach in (x, Q^2)

Transverse Single-spin Asymmetries and Transversity

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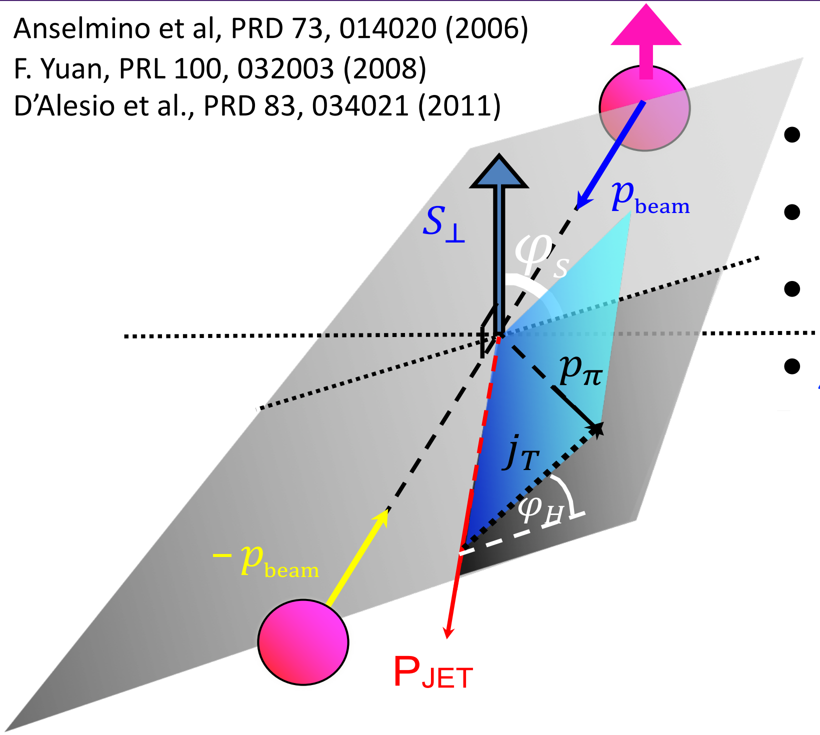
F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)



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

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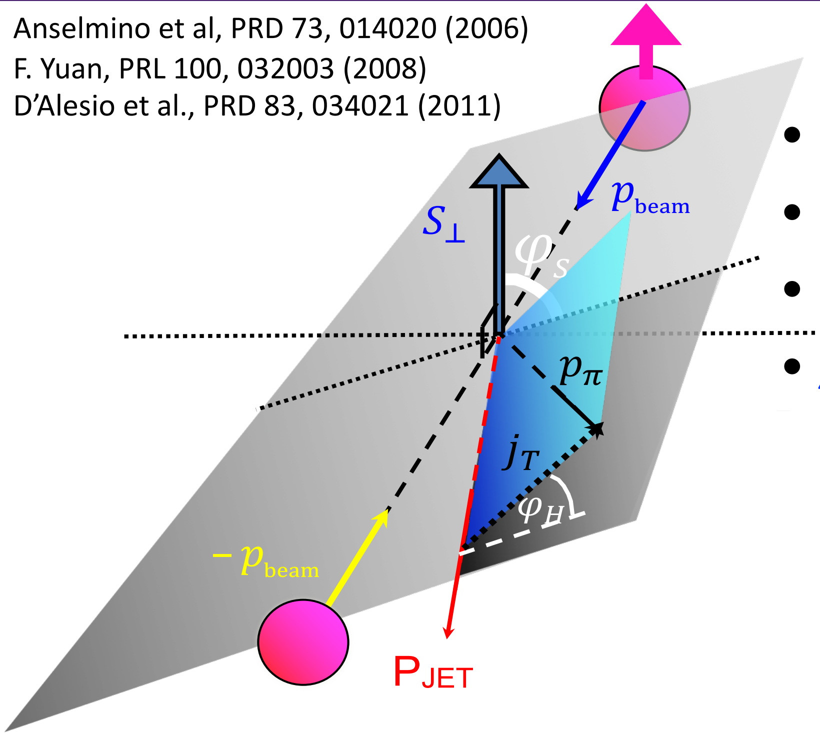

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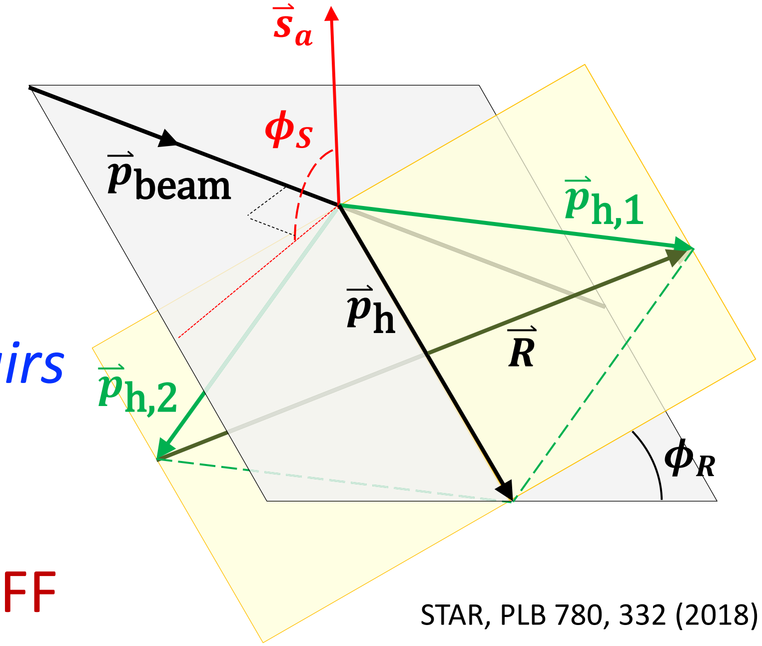


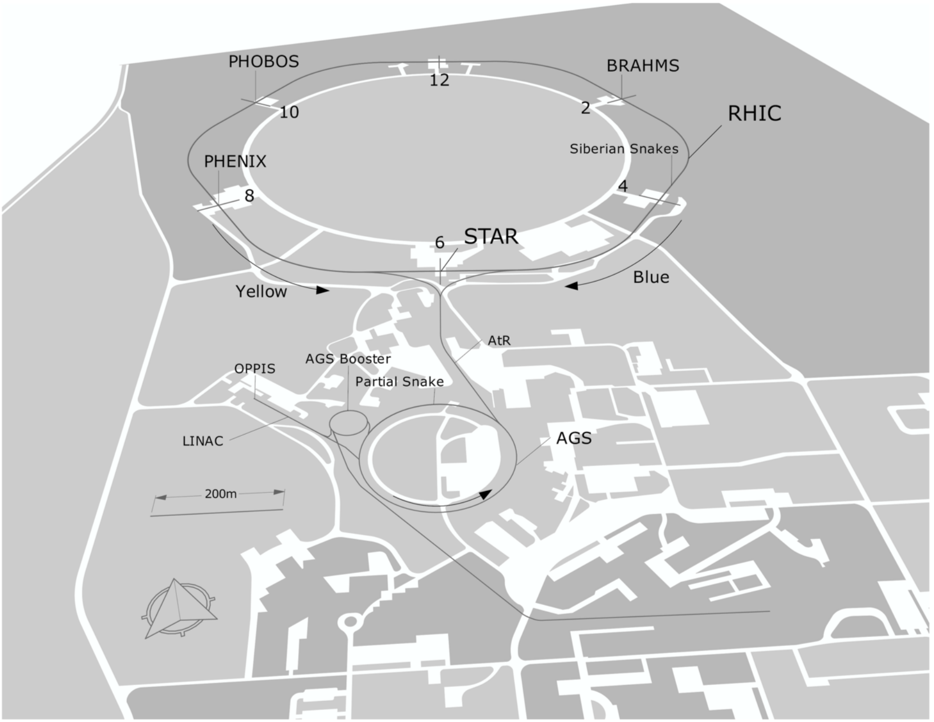
STAR, PLB 780, 332 (2018)

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

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

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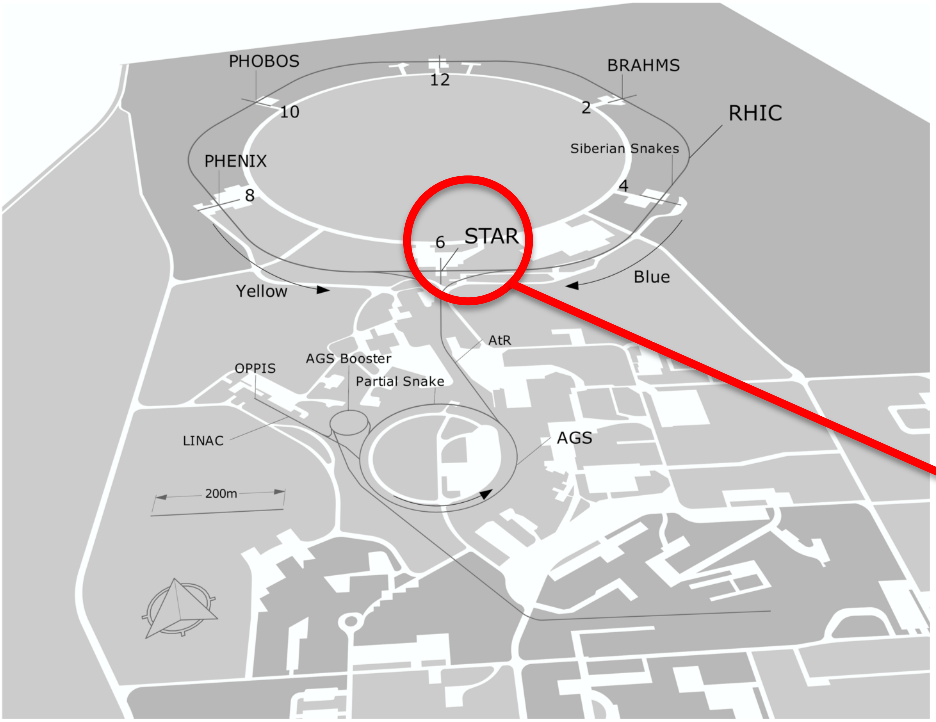

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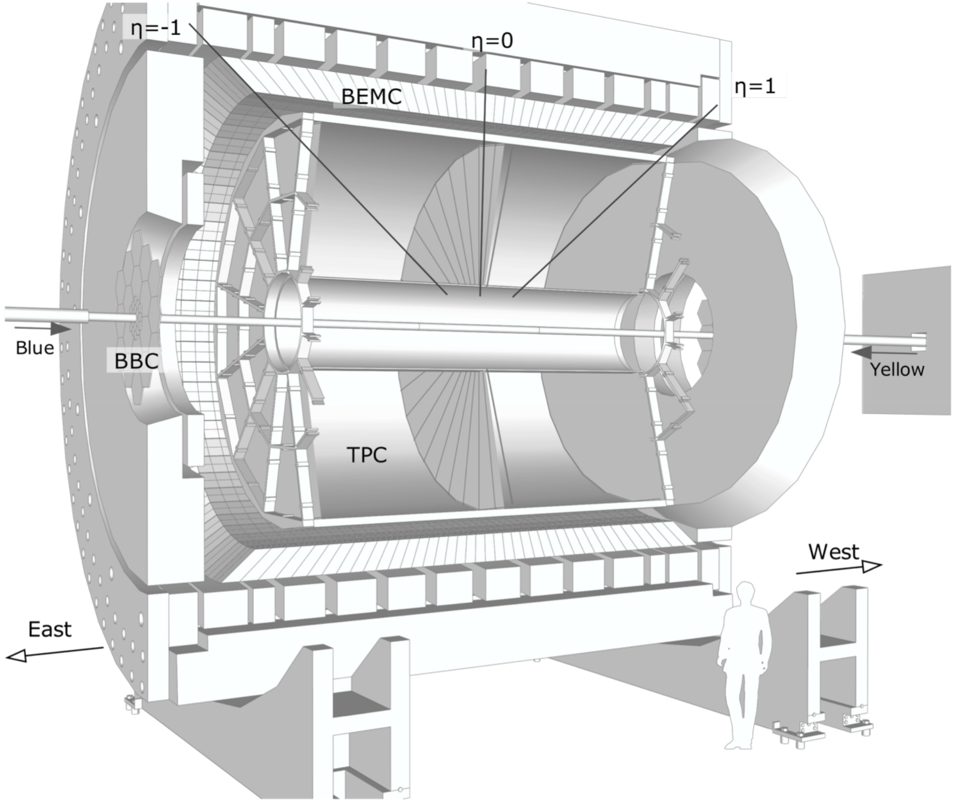

Central Detectors: $|\eta| < 1$

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

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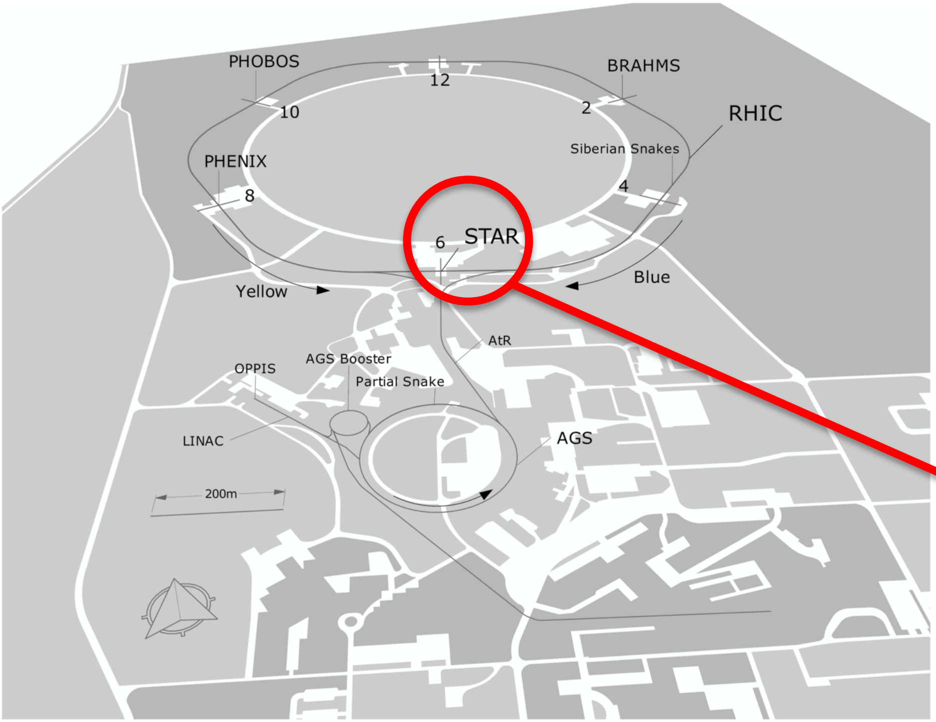

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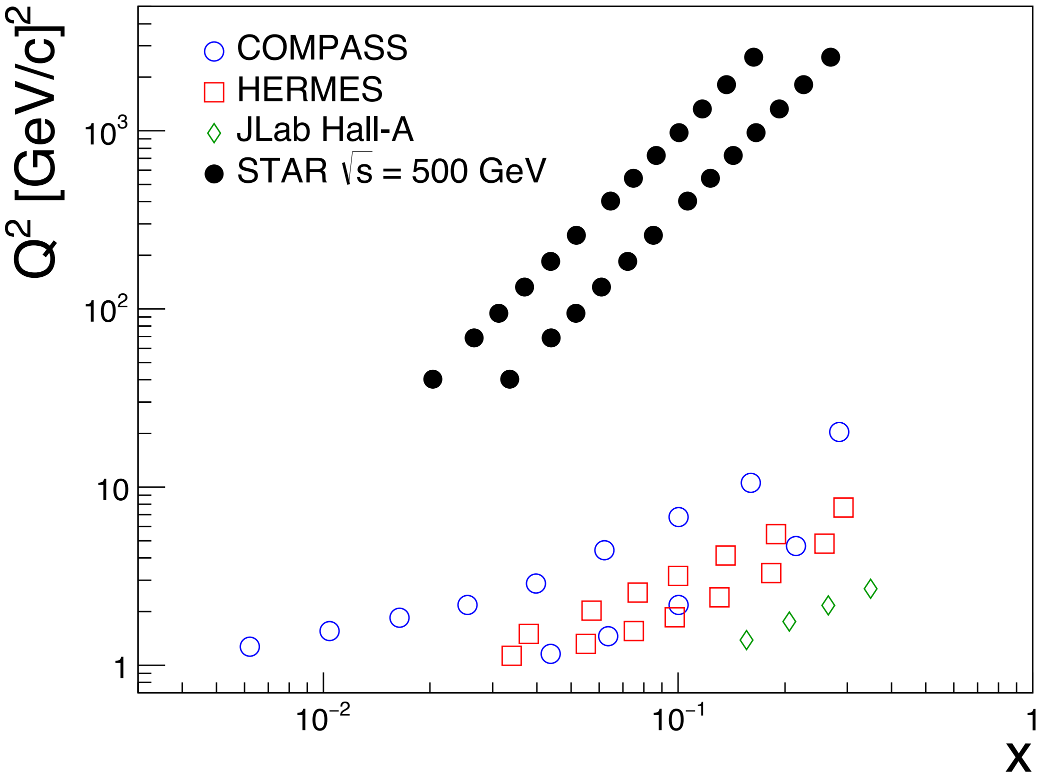

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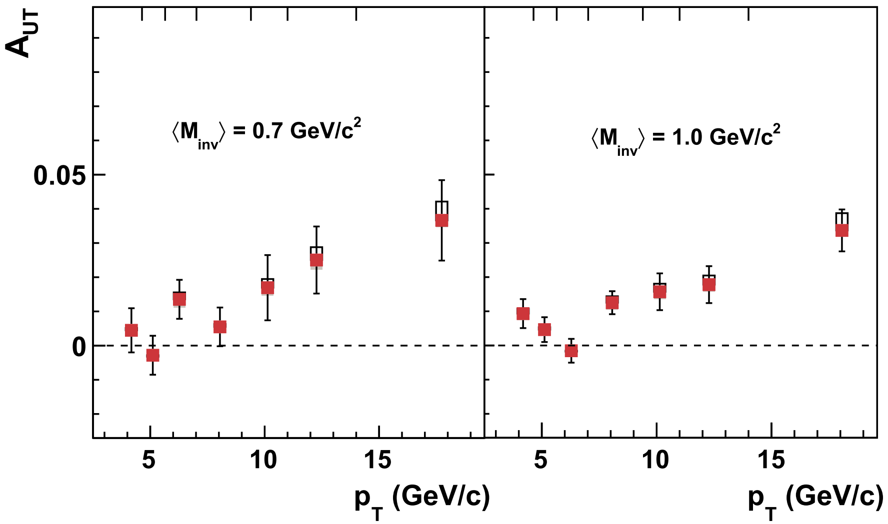
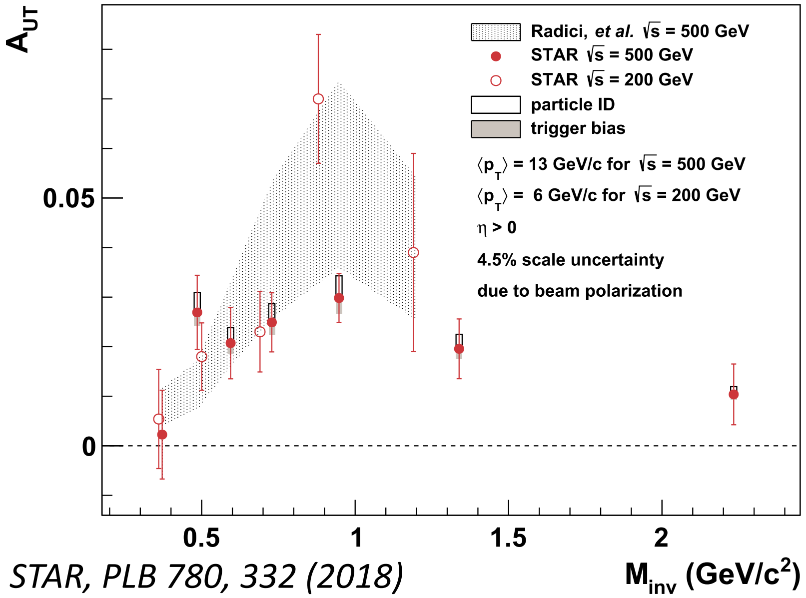
Dihadron Asymmetries at STAR

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





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!

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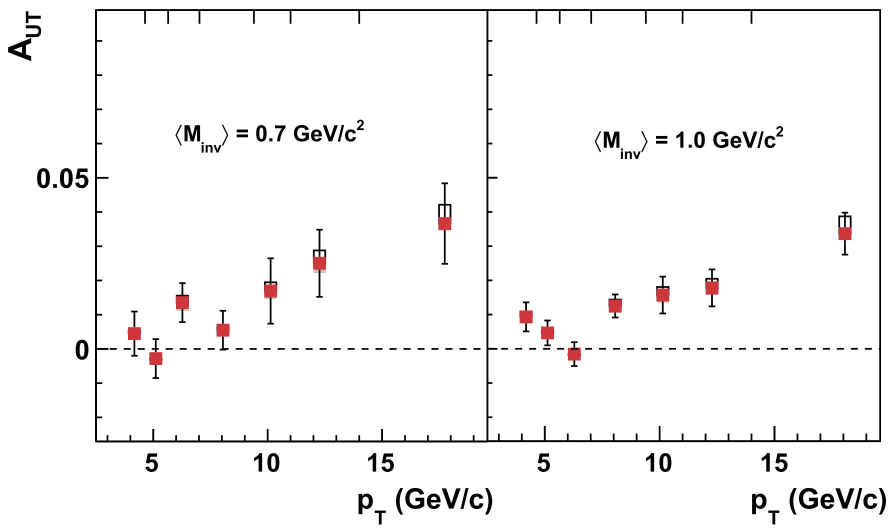
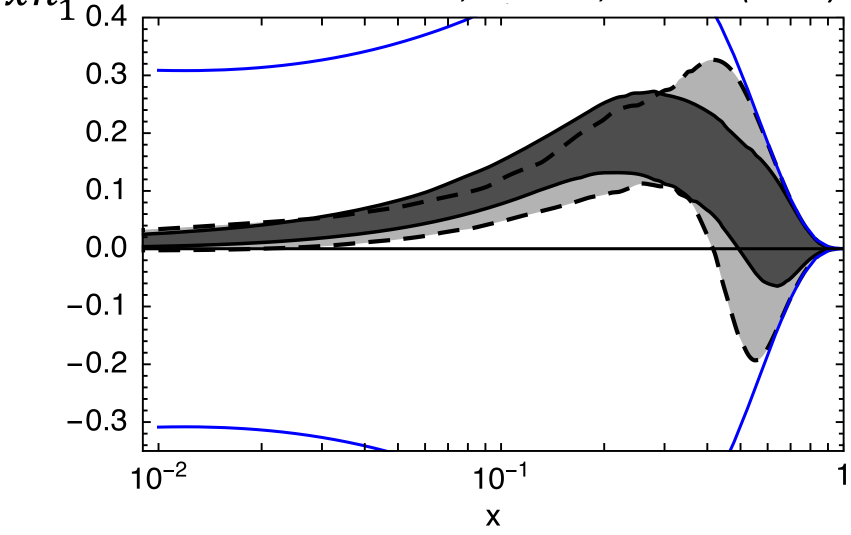
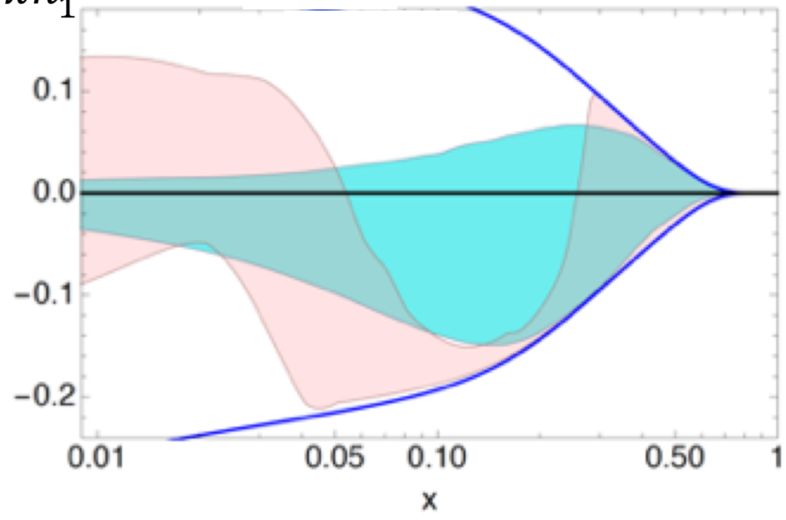
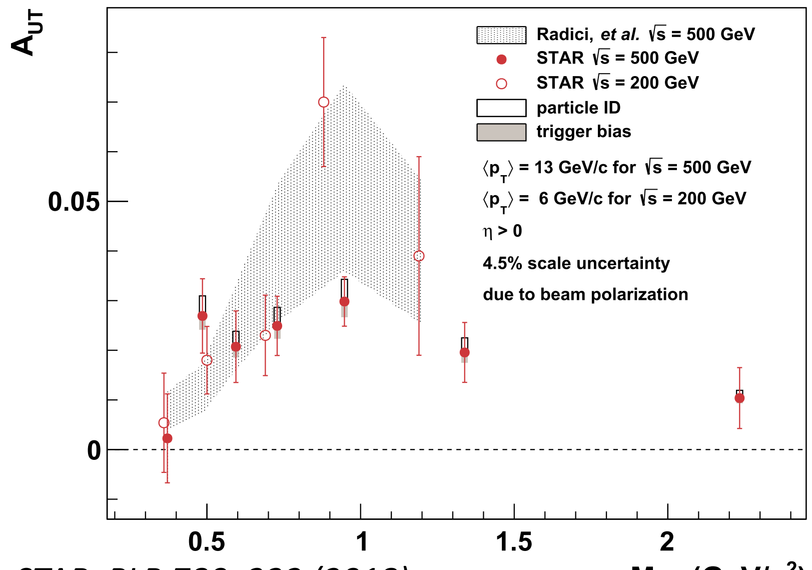


Radici and Bacchetta, PRL 120, 192001 (2018)



Red band: JHEP 1505, 123 (2015)





STAR, PLB 780, 332 (2018)

M_{inv} (GeV/c²)

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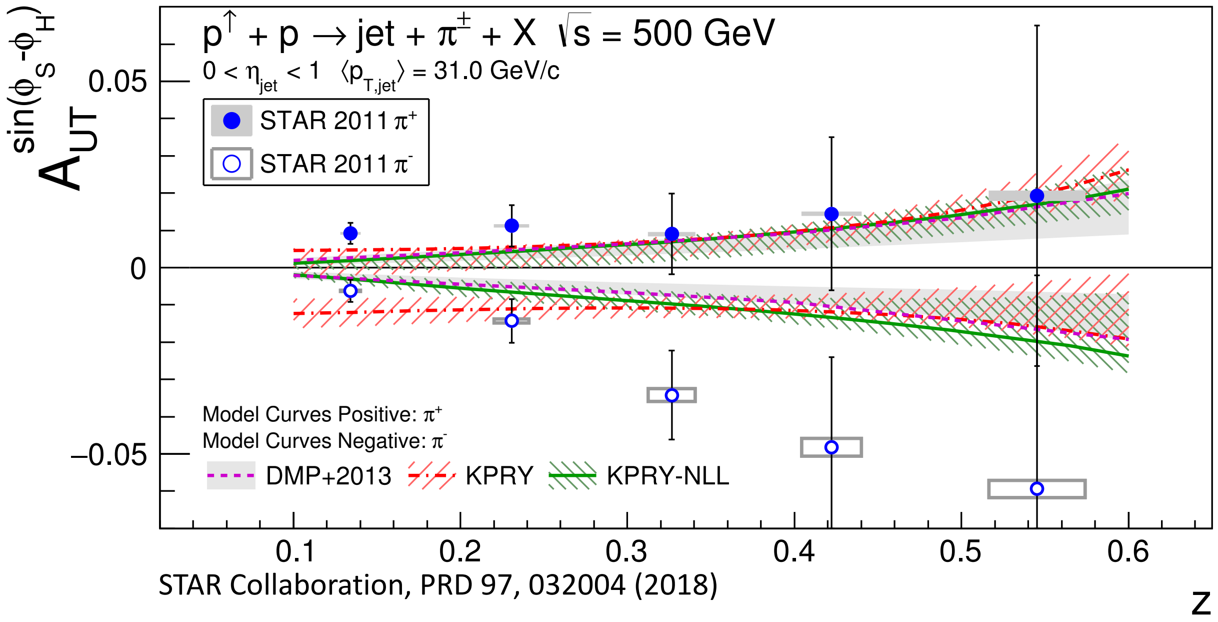
- Invariant mass dependence: data are consistent with 68% of replicas based on SIDIS & e^+e^- data

  → 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**
- *Bands = uncertainty on model calculations*

Consistency between models and STAR data at 95% confidence level

→ Suggests robust factorization and universality

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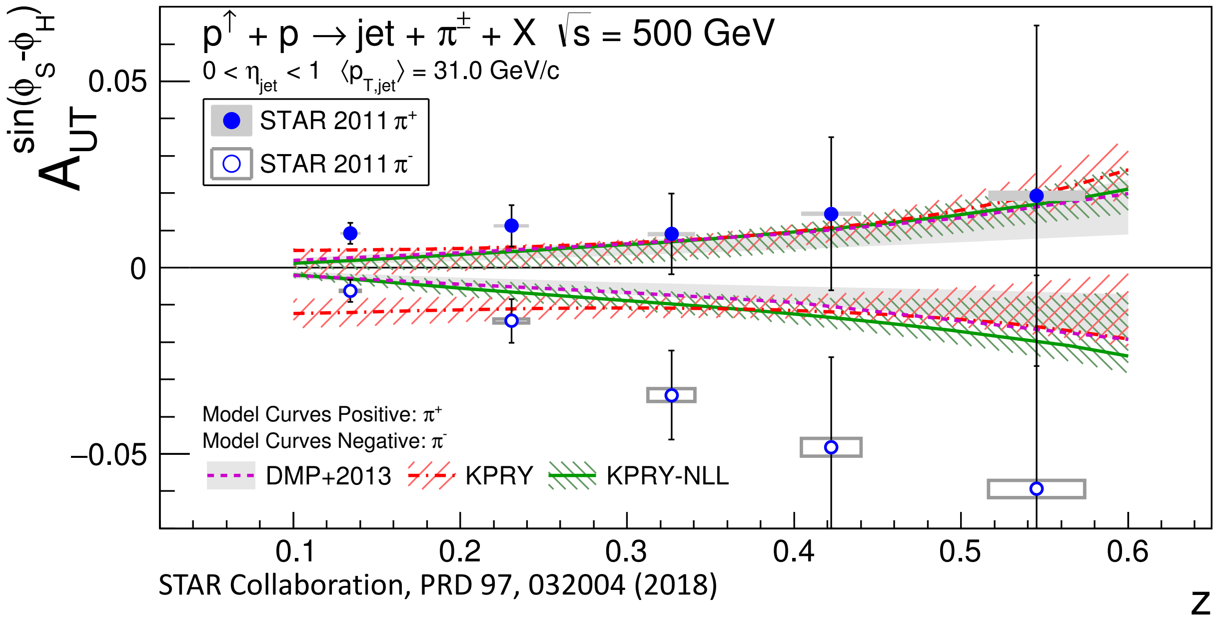

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To evolve or not to evolve?

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

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

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

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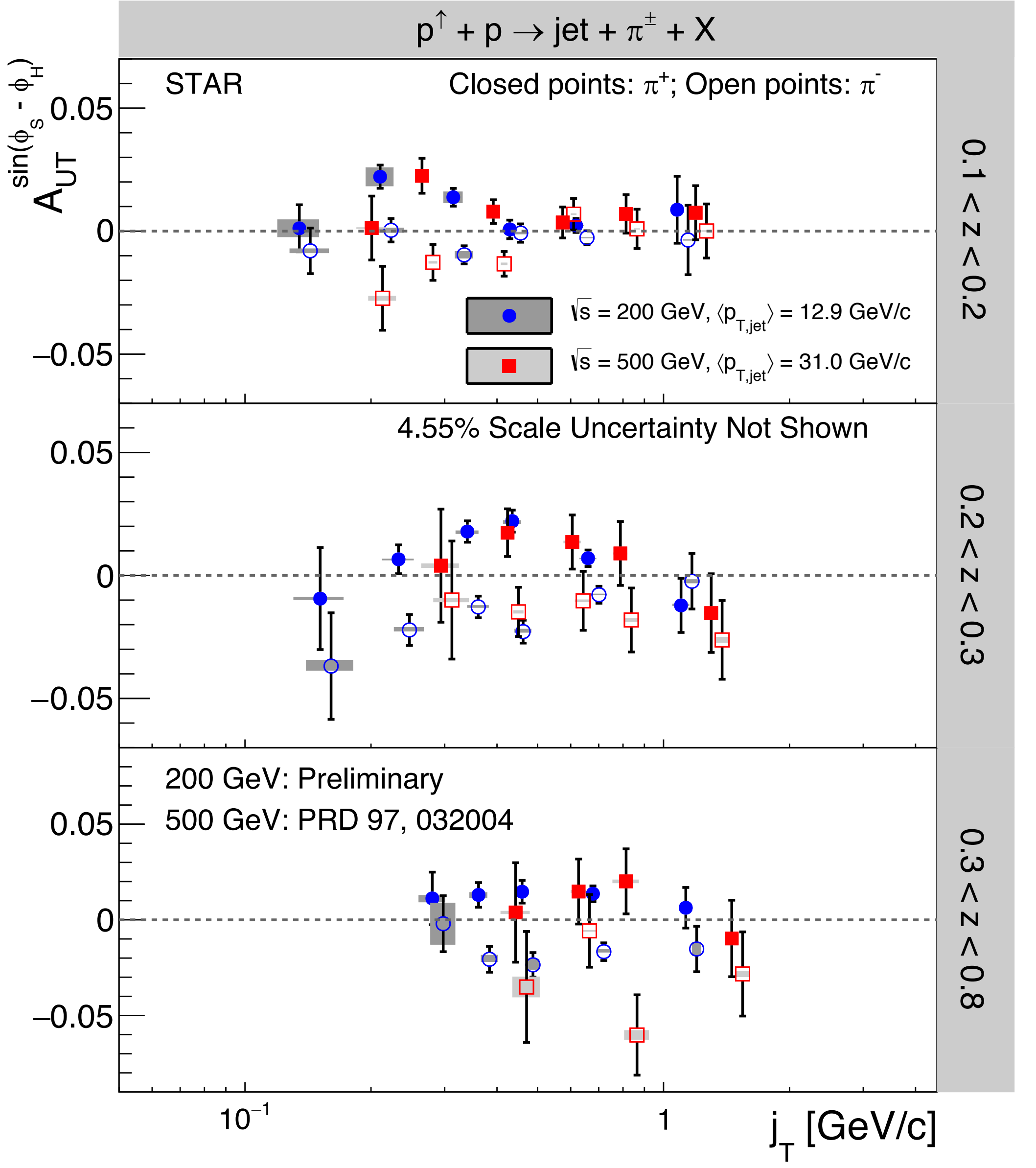
$$A_{UT} \sim f(j_T) \times f(z)$$



See T. Lin's talk, later in this session!

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- Models agree relatively well but more work needed
  - ***More unpolarized data! (see R. Salinas's talk)***
  - More detailed modeling

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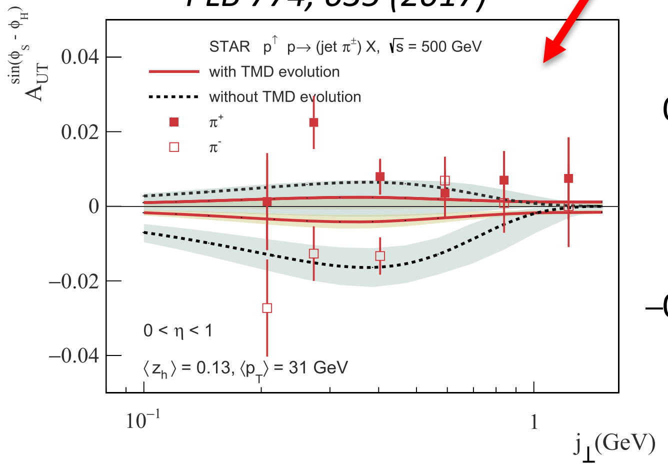
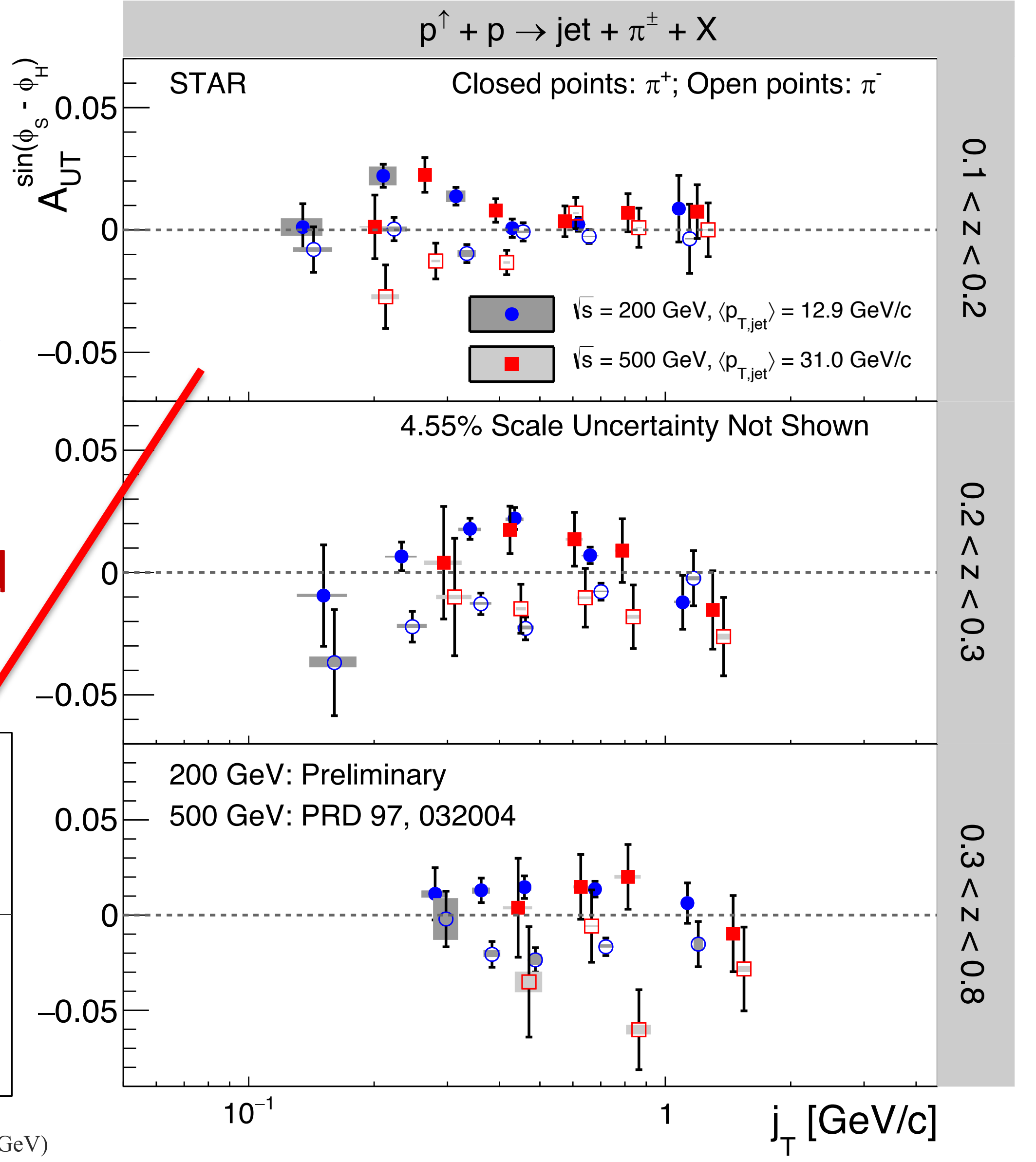
PLB 774, 635 (2017)





500 GeV: STAR Collaboration, PRD 97, 032004 (2018)
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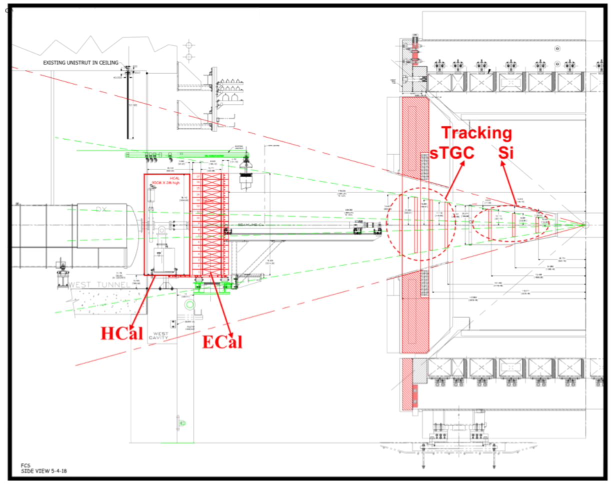
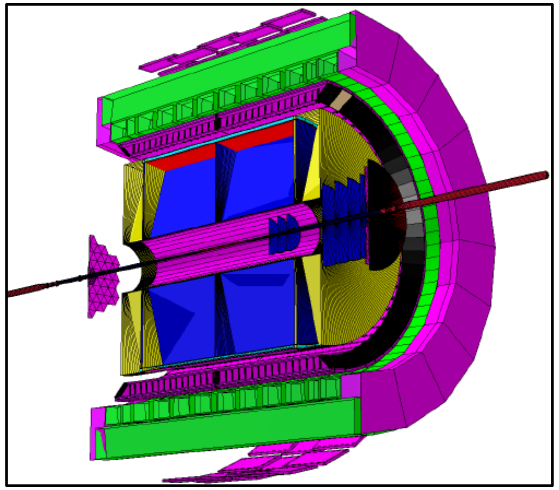
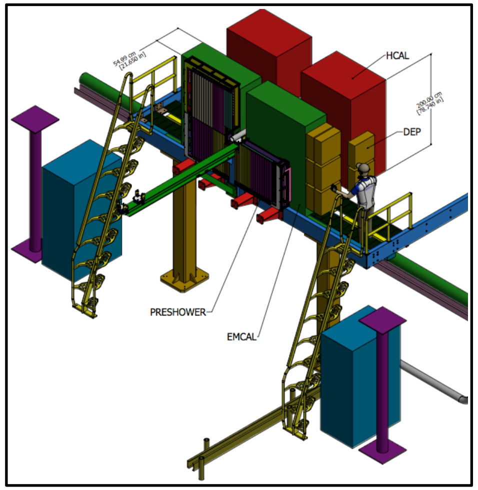
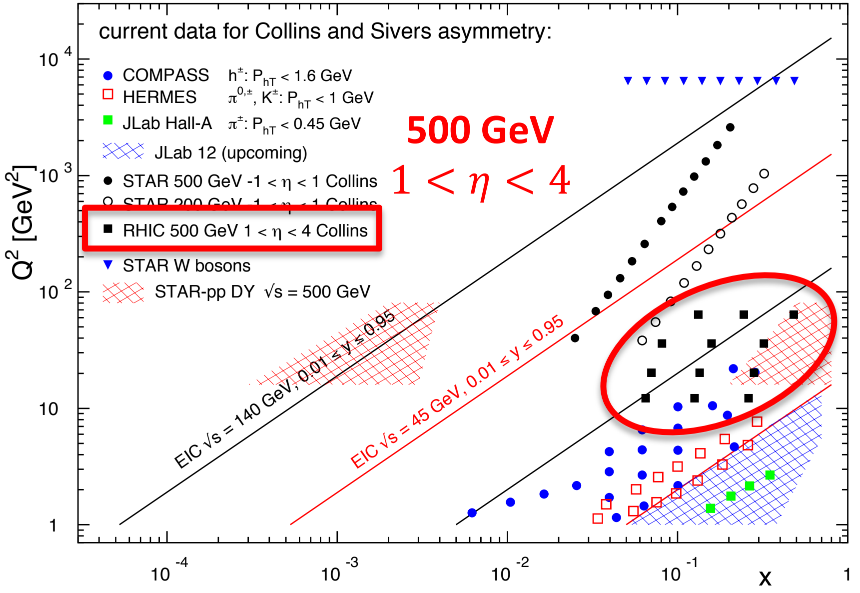
STAR Looking Forward

- 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:** ***Funded by NSF MRI***
    - ***Significant progress***, e.g. beam tests, prototype runs, detector construction









See D. Kapukchyan's talk in Gluon Spin in proton-proton Collisions

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  - Access transversity via dihadrons (collinear) and Collins (TMD)
  - Test TMD factorization/universality and evolution
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Stay tuned!

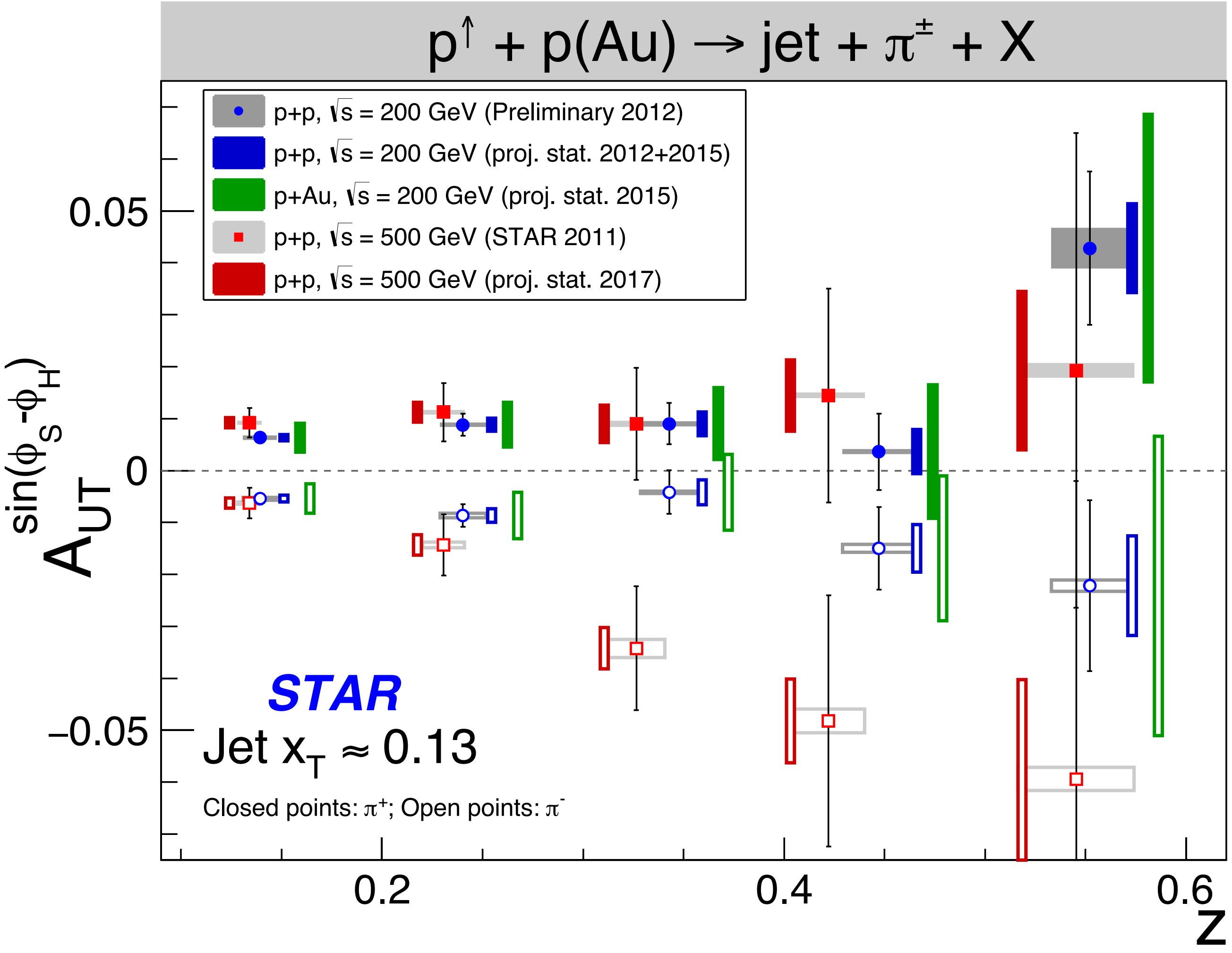
Back-up Slides

In Progress

Successful runs in 2015 and 2017

- Far more precise comparison of 200 and 500 GeV
- Possible extraction of kaon Collins
- First look at Collins in $p + A$

  → *Unique window into hadronization*



500 GeV: STAR Collaboration, PRD 97, 032004 (2018)
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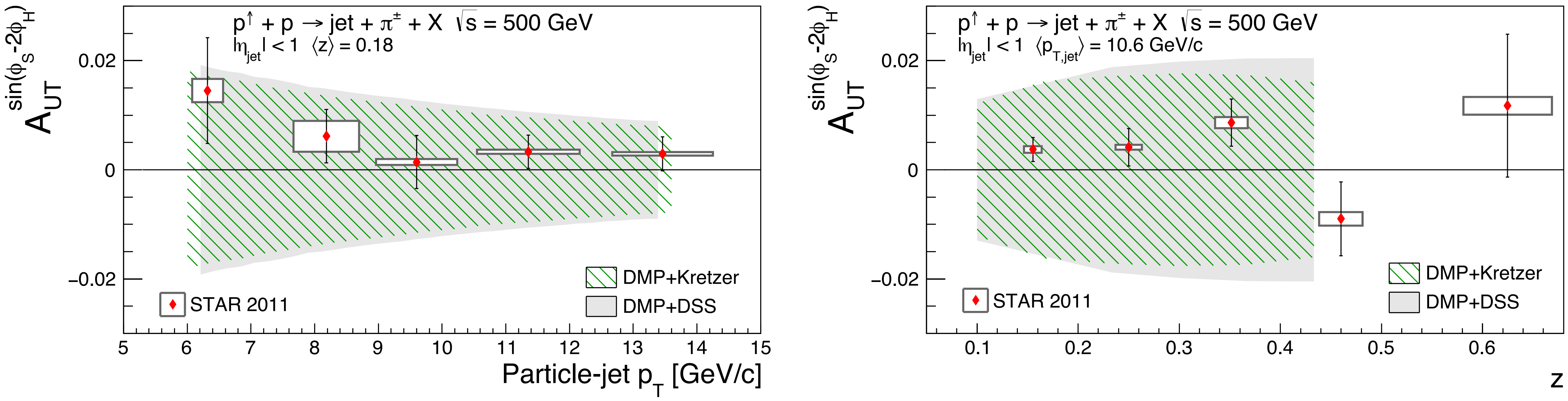
Collins-like Effect at RHIC

Collins-like effect

- Sensitive to linearly polarized gluons in a transversely polarized proton
- Asymmetries consistent at zero in 500 GeV (shown) and also preliminary 200 GeV
- STAR data provide first-ever constraints



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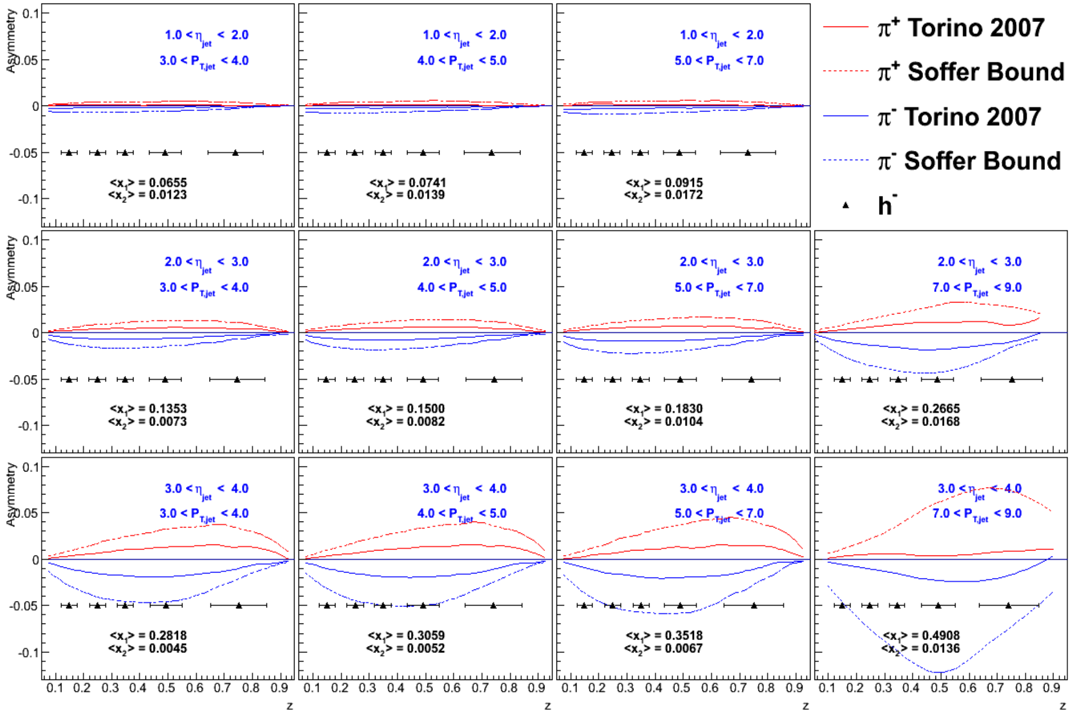
Transversity

Utilize $p + p \rightarrow \text{jet}(h^{\pm})$, as at midrapidity

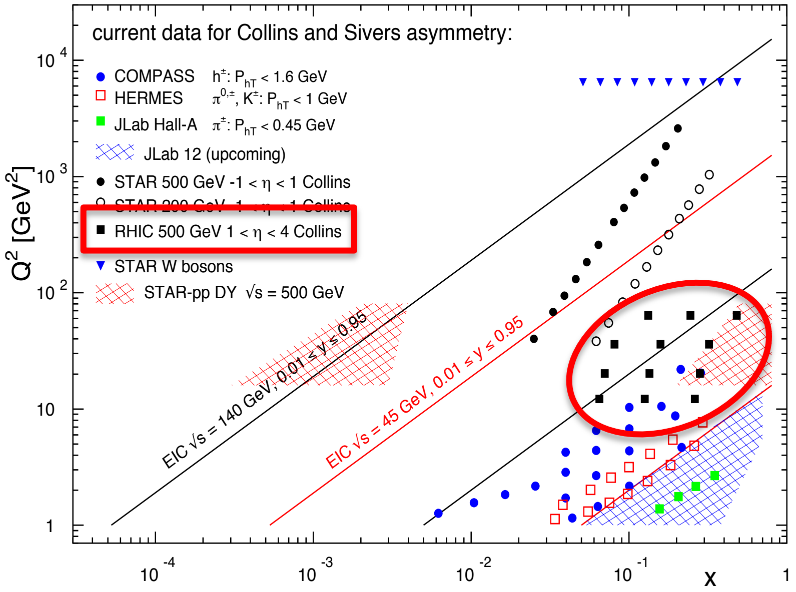
Pushing forward = higher x:

Simulation Studies

- Precision for 385 pb^{-1} delivered lumi (16 weeks = 1.2 fb^{-1})
- Momentum smearing of hadrons & jets
- Dilution due to beam remnant, underlying event, and kaon+proton contamination



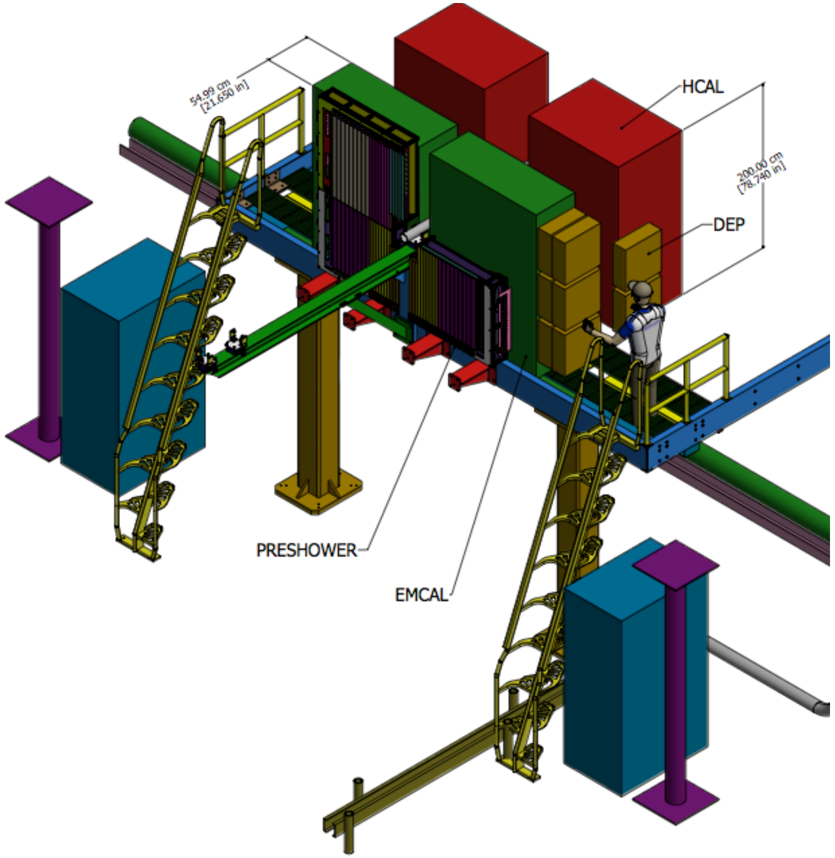
500 GeV: $1 < \eta < 4$



New with STAR forward upgrade:

- Probe transversity at high x (0.05 to 0.5) and Q^2 (10 to 100 GeV^2)
- Quantitative test of Collins function universality and evolution
- ***Critical information for the lead-up to EIC!***

The STAR Forward Upgrade: Calorimetry



Performance Needs

ECal: $\sim 10\%/\sqrt{E}$ (pp/pA) and $\sim 20\%/\sqrt{E}$ (AA)

reuse PHENIX PbSC calorimeter with new readout

- **Benefit:** significant cost reduction!
- **Tradeoff:** uncompensated calorimeter system

Secured 1 sector (2592 towers) PbSc towers: $5.52 \times 5.52 \times 33\ \mathrm{cm}^3$ $(18\ X_0)$

- 66 sampling cells with 1.5 mm Pb, 4 mm Sc
- Ganged together by penetrating wavelength-shifting fibers for light collection

HCal: $\sim 60\%/\sqrt{E}$ (pp/pA)

- Sandwich iron-scintillator plate sampling cal.
- Same readout for both calorimeters

Cost:

ECal: \$0.41M
HCal: \$1.56M
Preshower: \$0.06M
Total: ~\$2.0M*
**includes contingency (15-35%) and manpower*

Intensive R&D on both calorimeters as part of STAR and EIC Detector R&D, including FNAL test beam and STAR in situ tests