Investigating Transversity with Hadrons in Jets at STAR

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for the STAR Collaboration

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OUTLINE

- Transversity and TSSAs
- STAR
- First results at 500 GeV
- High statistics at 200 GeV
- First look at kaons/protons
- Summary

ABILENE CHRISTIAN UNIVERSITY

STAR
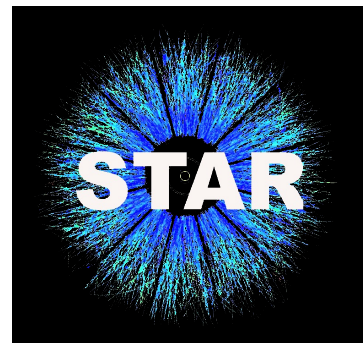
Transversity

Complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF, $f(x)$
- Helicity PDF ($\Delta f(x)$) [*see talk by A. Quintero*]
- 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, $\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$

JAM: PRD 106, 034014 (2022)
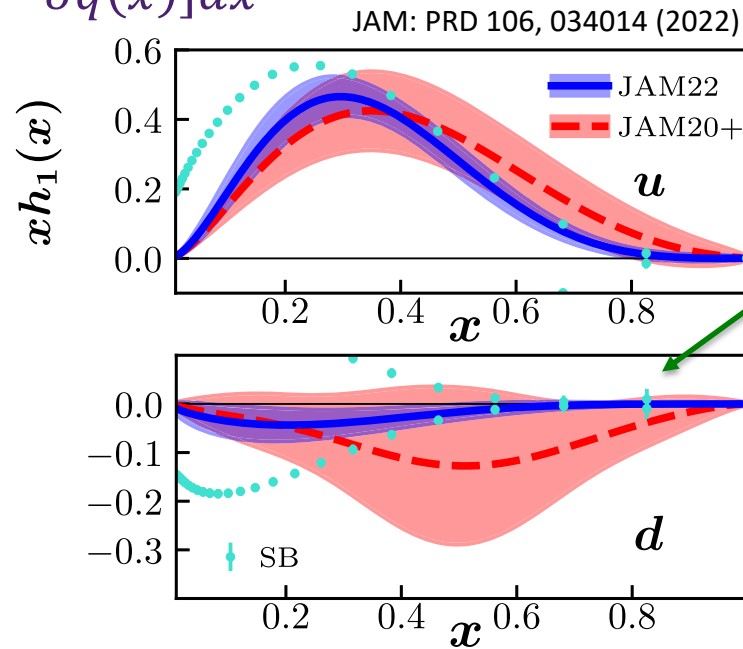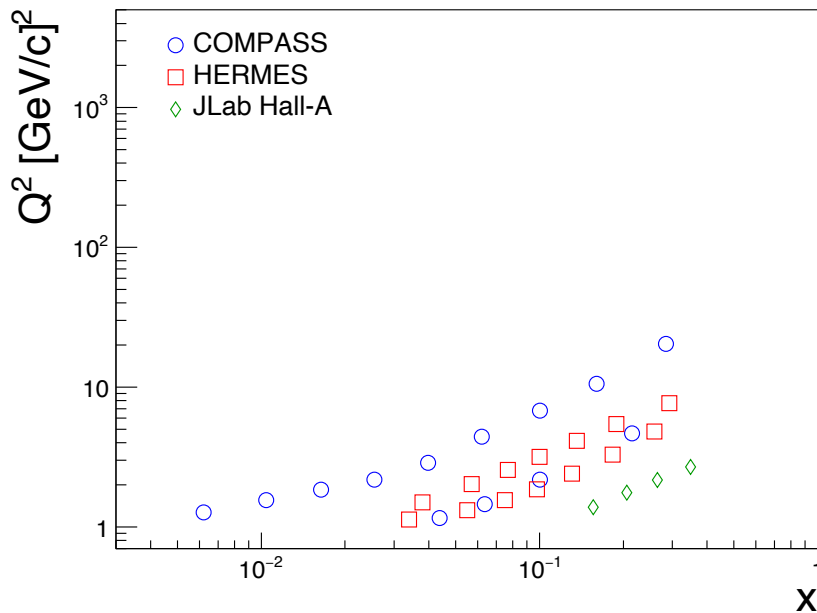
Lots of on-going work and questions

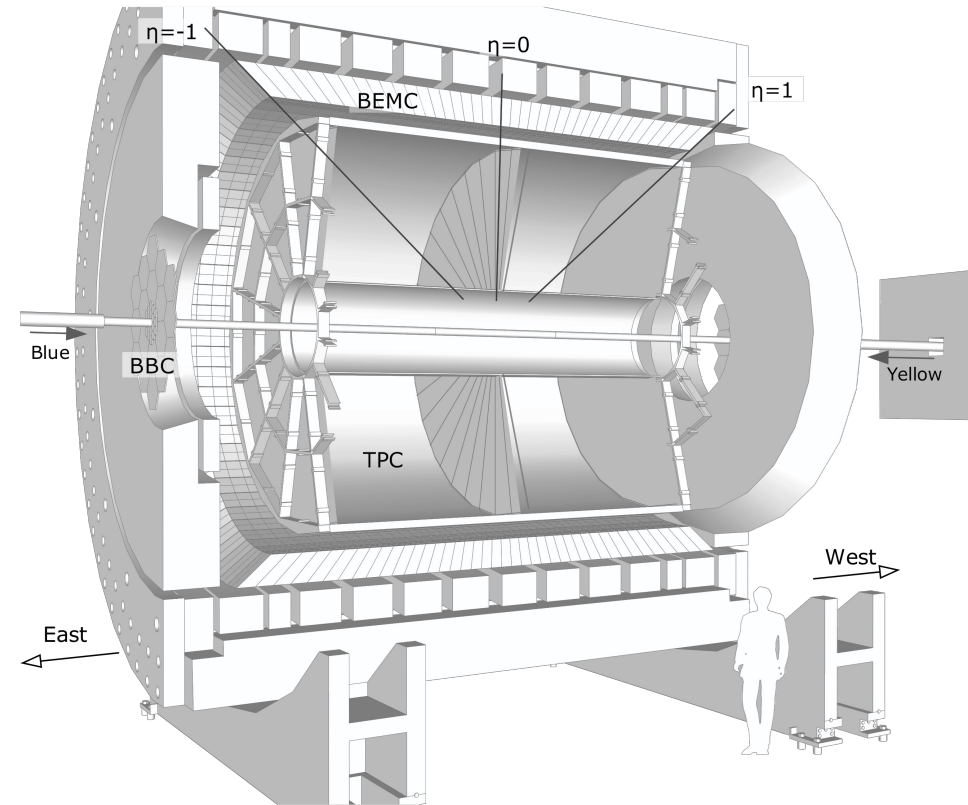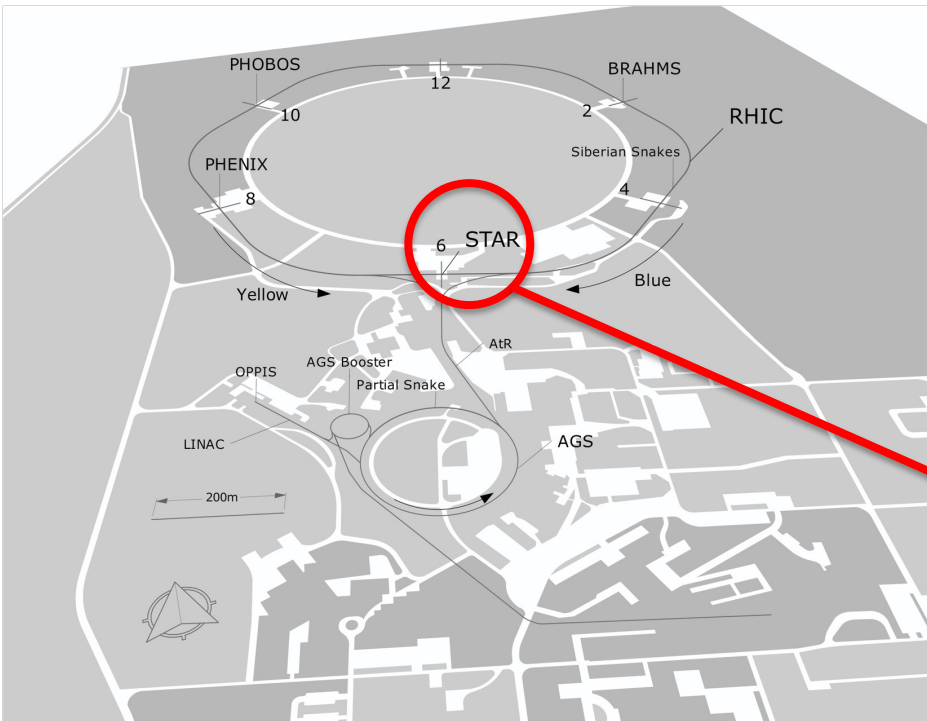d-quark, Soffer bound, consistency with Lattice QCD, etc.

D'Alesio et al: PLB 803, 135347 (2020)
Radici, Bacchetta: PRL 120, 192001 (2018)
Kang et al: PRD 93, 014009 (2016)

One way to access: SIDIS + e^+e^- via "Collins" or IFF asymmetries

Currently limited reach in (x, Q^2)

Polarized Hadrons Within Jets

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

$S_\perp$

φ_S

p_{beam}

p_π

j_T

φ_H

$-p_{\text{beam}}$

P_{JET}

Collins mechanism

J. Collins, NP B396, 161 (1993)

- Transversely polarized quarks inside transversely polarized proton
- Polarization transfer during hard scattering
- 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 FF

(analogous effect for gluon linear polarization)

$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta^N D_{\pi/q^\uparrow}$

$\Delta^N f_{a/A^\uparrow} \bullet \Delta^N f_{b^\uparrow/B} \bullet \Delta^N D_{\pi/q^\uparrow}$

$\sin(\phi_{S_A})$

$\sin(\phi_{S_A})$

$\sin(\phi_{S_A})$

$\sin(\phi_{S_A} - \phi_H)$

$\sin(\phi_{S_A} - \phi_H)$

$\sin(\phi_{S_A} + \phi_H)$

$\sin(\phi_{S_A} + \phi_H)$

RHIC as Polarized-proton Collider
- "Siberian Snakes" $\rightarrow$ mitigate depolarization resonances
- Choice of spin orientation $\rightarrow$ *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

STAR in 2015

Central Detectors: $|\eta| < 1$

Tracking + PID + E/M Cal.

Jets, $\pi^\pm, K, p, e^\pm, \pi^0, \gamma$
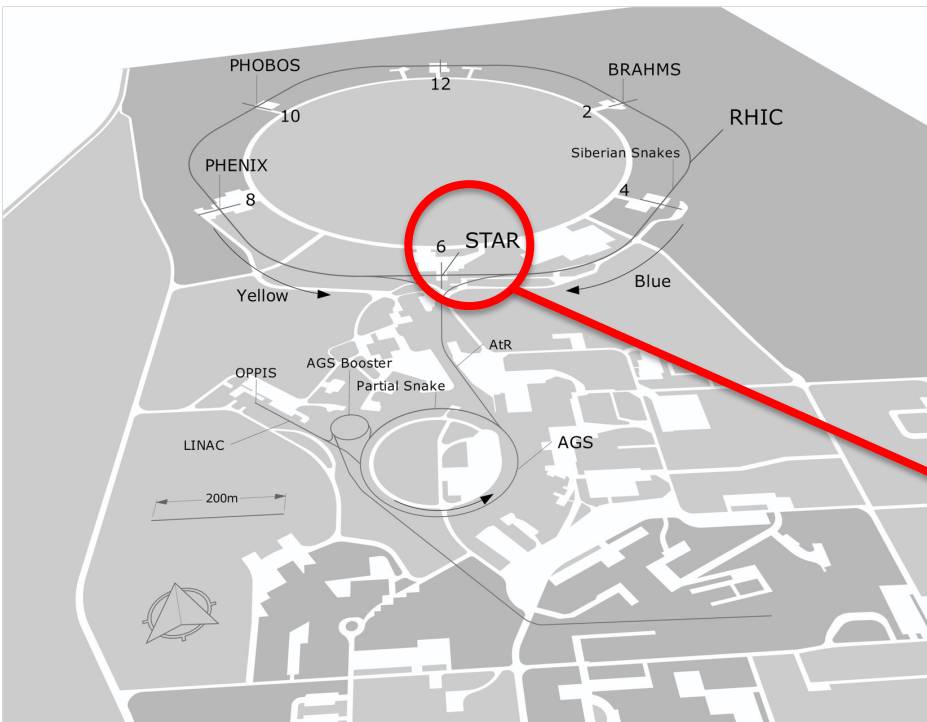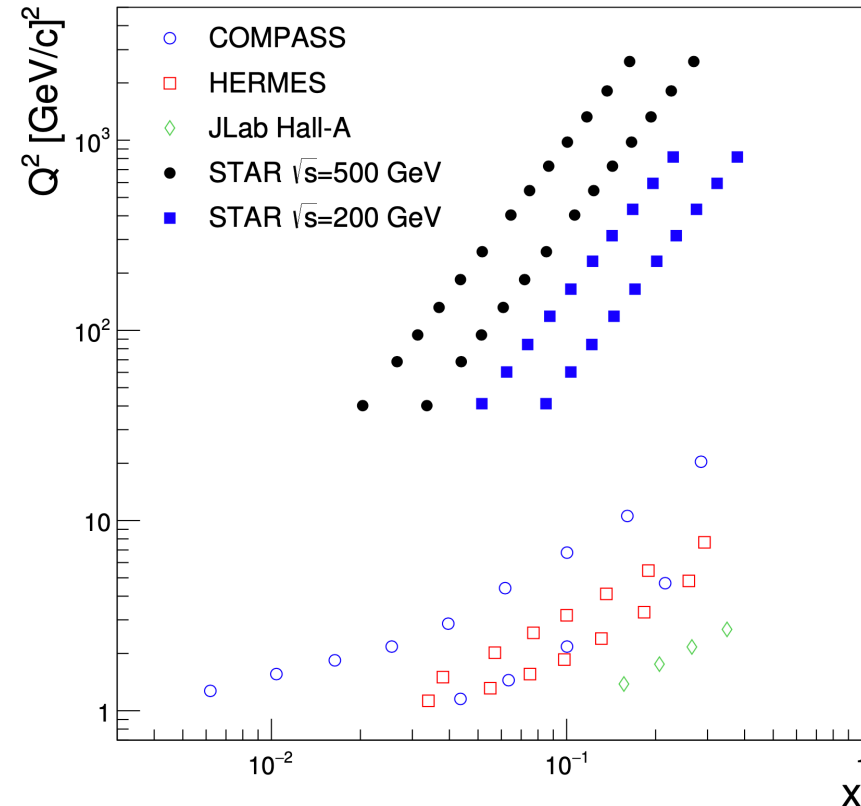
Forward Detectors: $1 < \eta < 2$ and $2.5 < \eta < 4$

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

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

RHIC as Polarized-proton Collider

- "Siberian Snakes" → mitigate depolarization resonances
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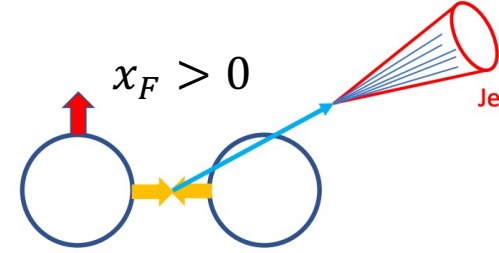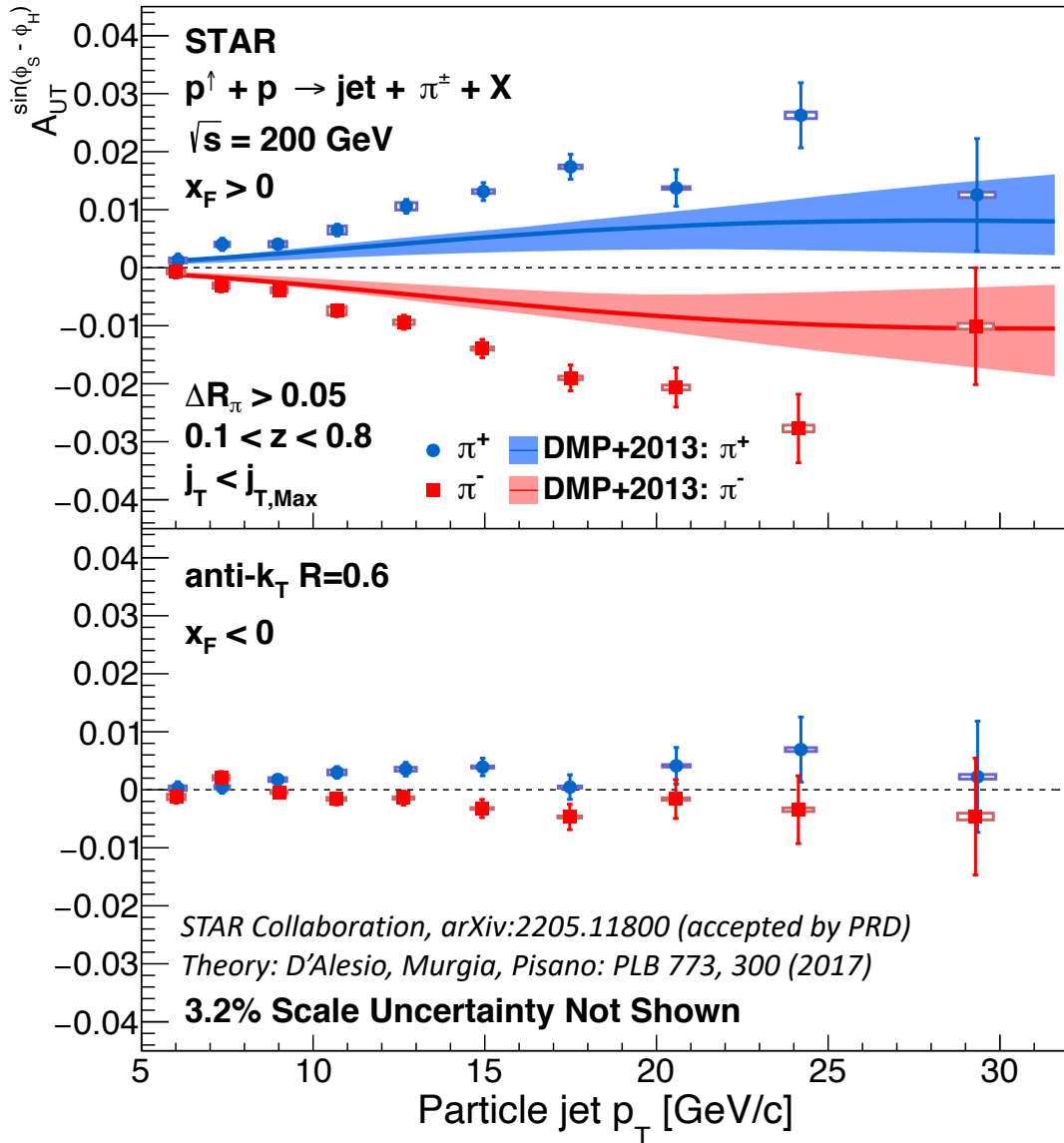Jets $(1 < \eta < 1.8), \pi^0, \gamma, e^{\pm}$

STAR Collaboration, PRD 97, 032004 (2018)

D'Alesio, Murgia, Pisano: PLB 773, 300 (2017)

*Kang, Prokudin, Ringer, Yuan: PLB 774, 635 (2017)*
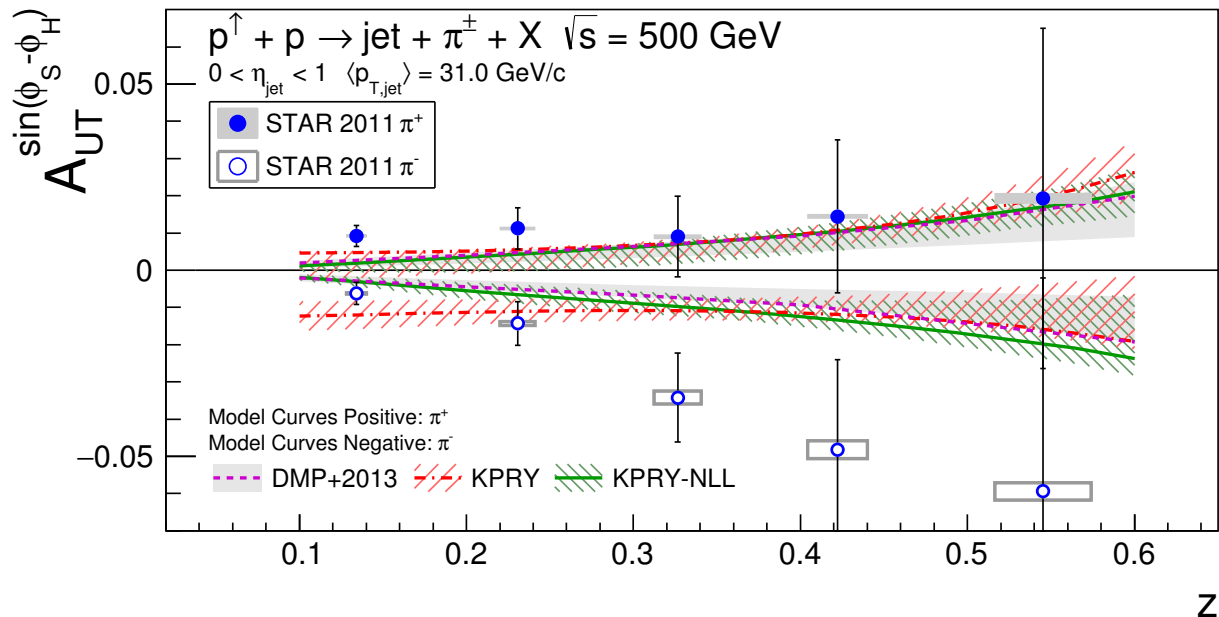
- **Consistent with models based on SIDIS/e^+e^-**
- **Suggest robust factorization and universality**
  - *Not yet sensitive to evolution assumptions*
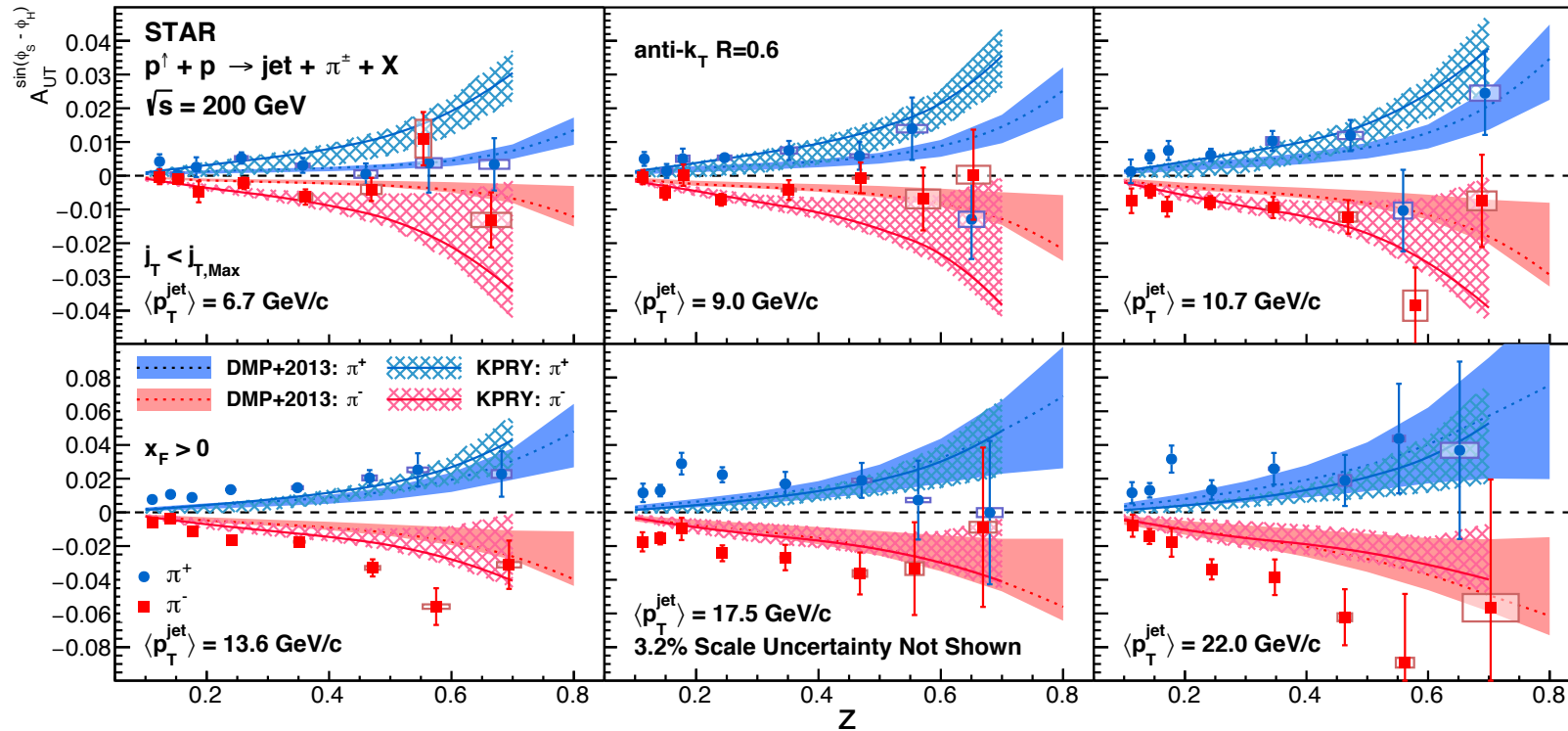- First look at dependence on momentum transverse to jet axis, j_T
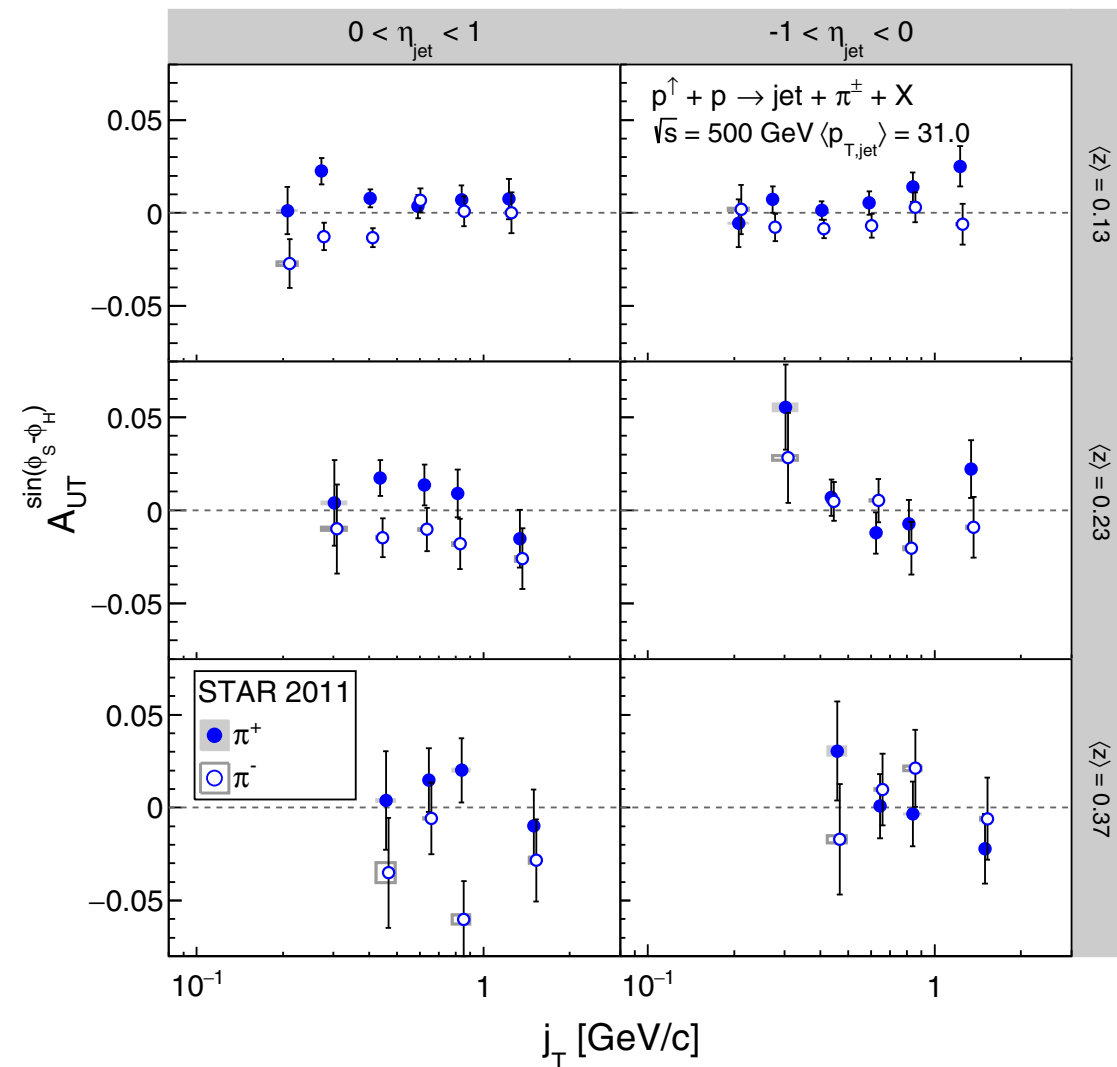
- $22\ pb^{-1}$ at $\sqrt{s} = 200$ GeV in 2012
- $52\ pb^{-1}$ at $\sqrt{s} = 200$ GeV in 2015
- Excellent consistency between data sets
  - Large asymmetries for forward scattering
  - Small asymmetries for backward scattering
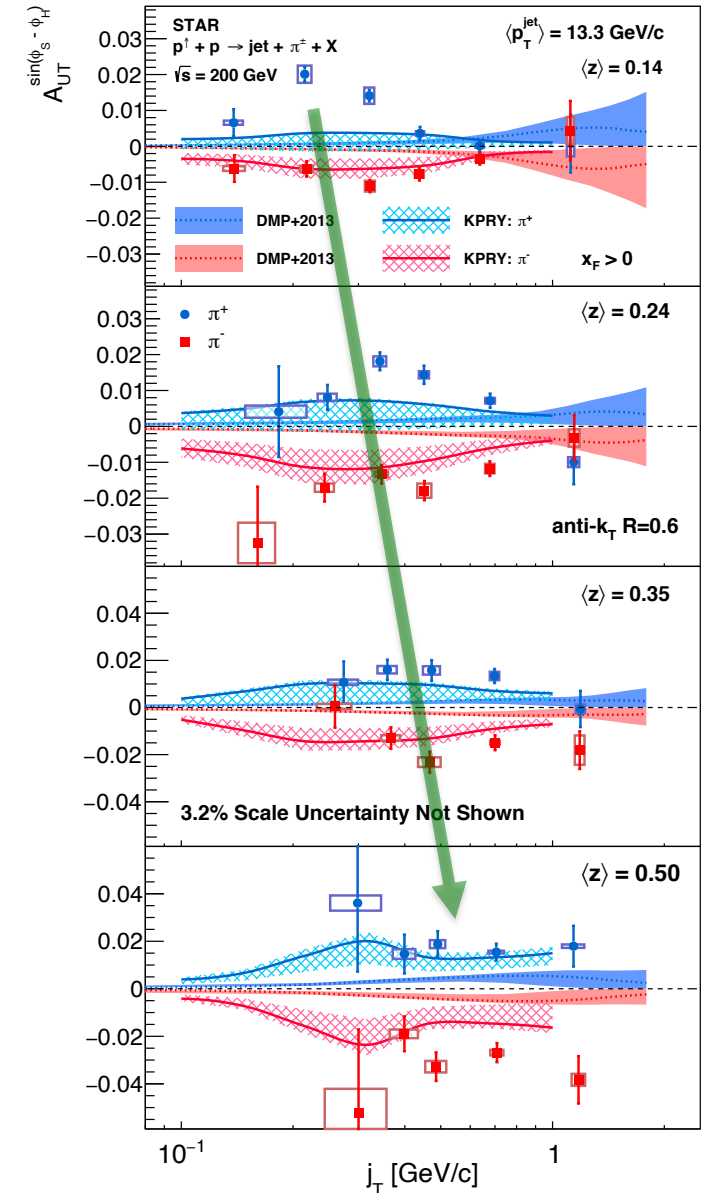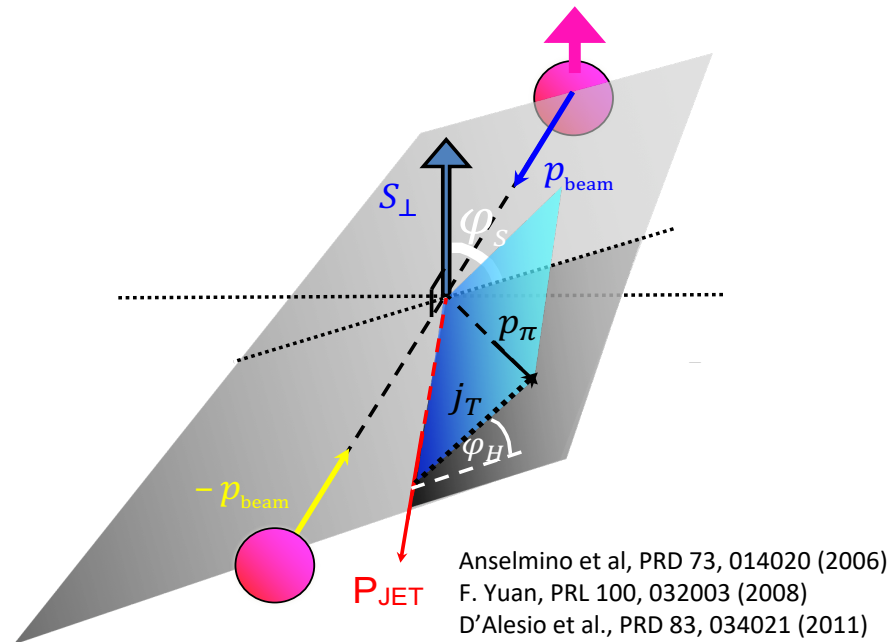- Provide valuable constraints for models
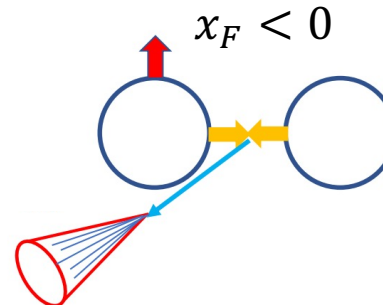
- z dependence in bins of jet p_T
- DMP+2013 – no TMD evolution
- KPRY – TMD evolution to NLL

STAR Collaboration, arXiv:2205.11800 (accepted by PRD)
Theory: D'Alesio, Murgia, Pisano: PLB 773, 300 (2017)
Theory: Kang, Prokudin, Ringer, Yuan: PLB 774, 635 (2017)

- Asymmetries show dependence on both z and jet p_T
- General consistency with models at lower jet p_T
- Discrepancies at higher jet p_T
- Authors emphasize that *transverse momentum dependence* of fragmentation functions in models is not well understood
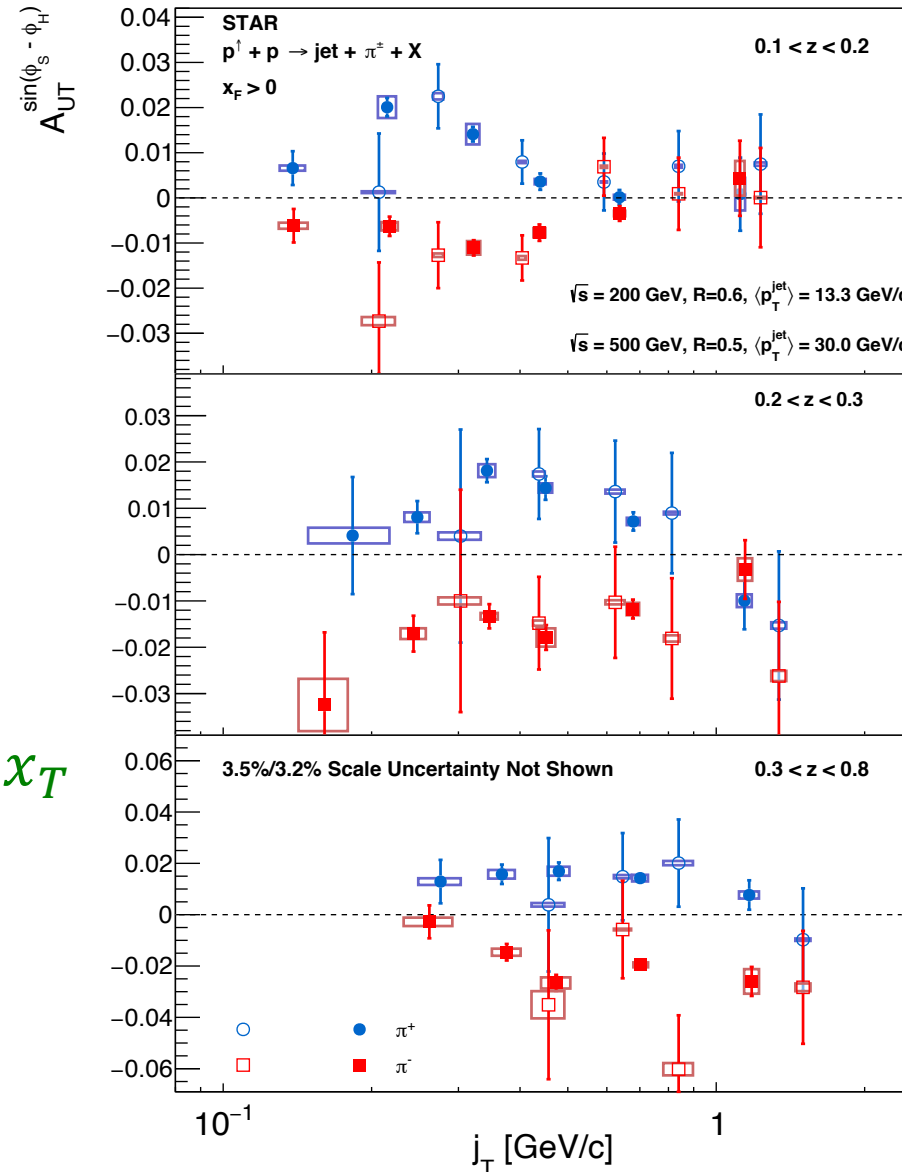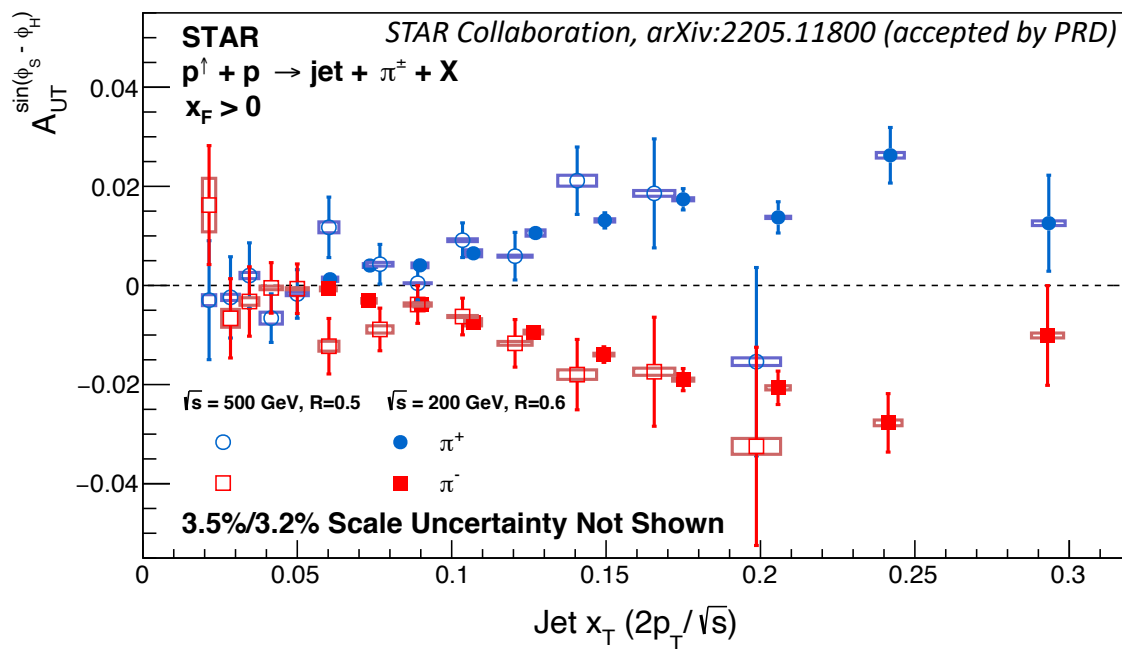
- **Significantly improved precision for j_T analysis**
- **Tension with models at low z**
- **Peak appears to shift to higher j_T for increasing z**
  - Suggests asymmetry does not factorize as most models assume, e.g. $A_{UT} \sim f(j_T) \times g(z)$

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

$$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta^N D_{\pi/q^\uparrow}$$

$$\Delta^N f_{a/A^\uparrow} \bullet \Delta^N f_{b/B} \bullet \Delta^N D_{\pi/q}$$

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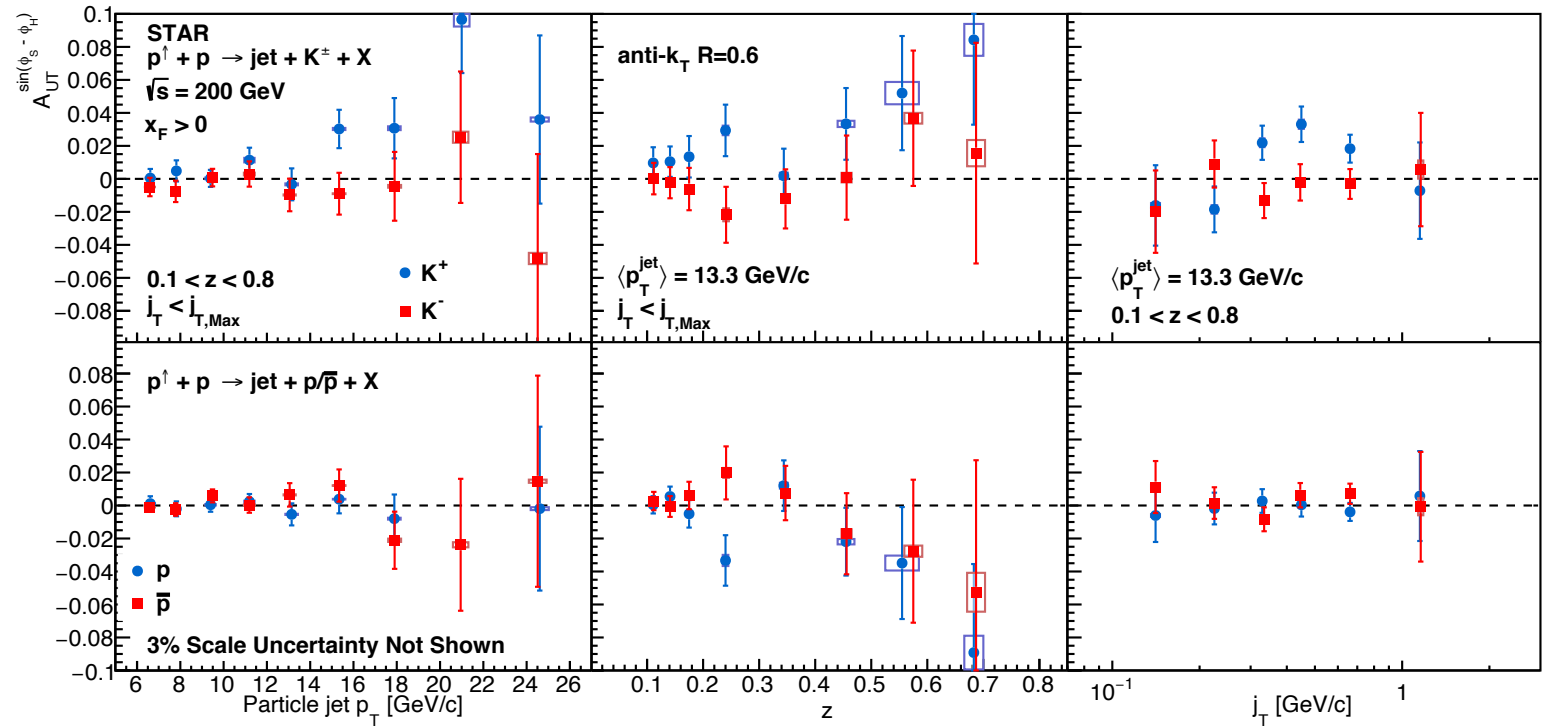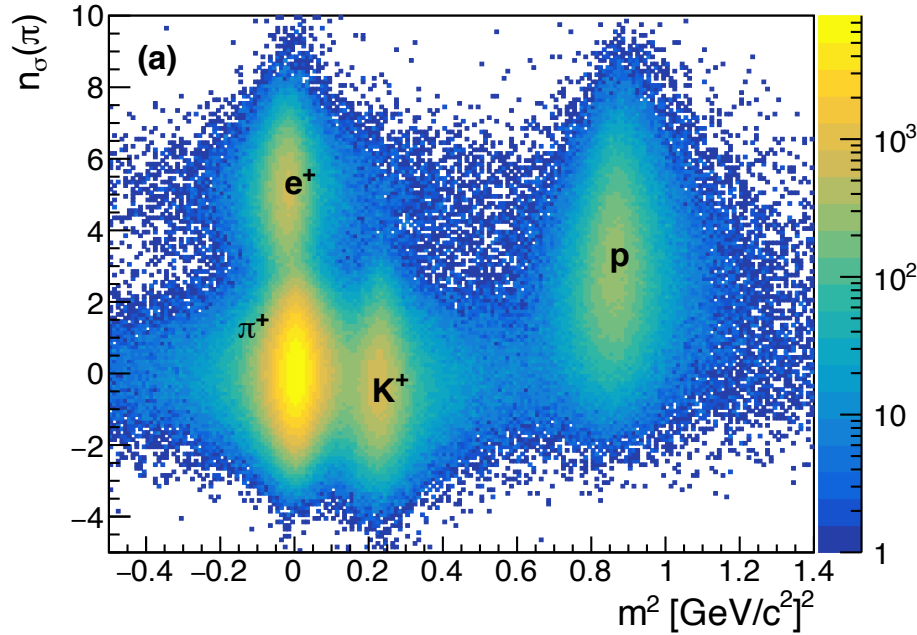Theory: Kang, Prokudin, Ringer, Yuan; PLB 774, 635 (2017)

STAR
$p^{\uparrow} + p \rightarrow jet + \pi^{\pm} + X$
$x_F > 0$

STAR Collaboration, arXiv:2205.11800 (accepted by PRD)

$A_{UT}^{\sin(\phi_S - \phi_H)}$

$\sqrt{s} = 500$ GeV, R=0.5 $\sqrt{s} = 200$ GeV, R=0.6

	π^+
○ π^+	● π^+
□ π^-	■ π^-

3.5%/3.2% Scale Uncertainty Not Shown

Jet x_T ($2p_T/\sqrt{s}$)

STAR
$p^{\uparrow} + p \rightarrow jet + \pi^{\pm} + X$
$x_F > 0$

$0.1 < z < 0.2$

$\sqrt{s} = 200$ GeV, R=0.6, $\langle p_T^{jet} \rangle = 13.3$ GeV/c
$\sqrt{s} = 500$ GeV, R=0.5, $\langle p_T^{jet} \rangle = 30.0$ GeV/c

$0.2 < z < 0.3$

3.5%/3.2% Scale Uncertainty Not Shown $0.3 < z < 0.8$

	π^+
○	● π^+
□	■ π^-

j_T [GeV/c]

- Consistency between 200 and 500 GeV for overlapping x_T
  – Asymmetries begin to increase around $x_T \approx 0.07$
  – Consistency extends to j_T dependence, as well
- Q^2 differs by a factor of 6

STAR
$p^{\uparrow} + p \rightarrow jet + \pi^{\pm} + X$ $0.1 < z < 0.2$

Charged Particle Identification

- Charged particle ID from TPC and time-of-flight
- Asymmetries for K^+ similar in size to π^+ (favored u-quark fragmentation)
- Asymmetries for K^- (unfavored fragmentation) consistent with zero
  - Similar observations to
- Asymmetries for protons

Asymmetries of Neutral Pions in Electromagnetic Jets
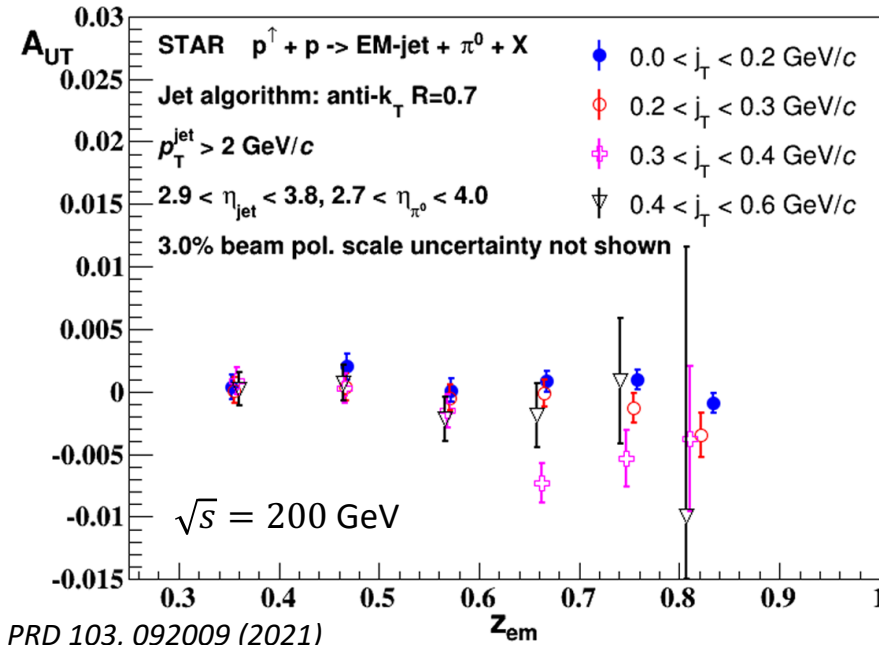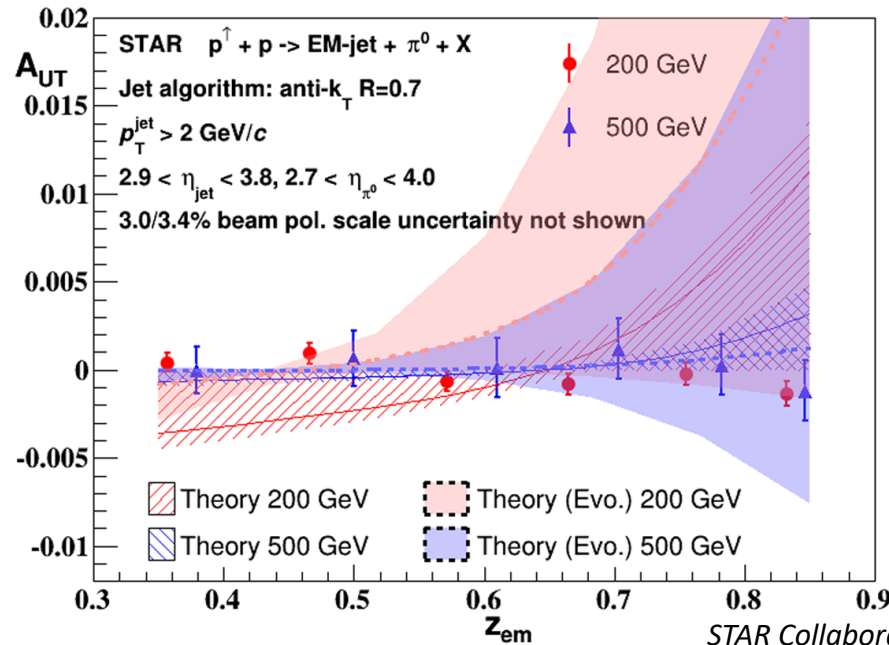
STAR Collaboration, PRD 103, 092009 (2021)
Theory: Kang, Prokudin, Ringer, Yuan, PLB 774, 635 (2017)

- Electromagnetic (EM) jets reconstructed with photon candidates in forward EM calorimeter ($2.7 < \eta < 4.0$)
- Asymmetries plotted vs. $z_{em} = E_{\pi^0}/E_{\rm jet}$
- Asymmetries integrated over j_T are small
  - *Expected from mixing of u and d-quarks for which the Collins effect has opposite sign*
- Possible dependence on j_T

Summary

- **TSSAs at STAR provide a unique window to nucleon structure and fragmentation functions**
  - Access transversity via dihadrons (collinear) and Collins (TMD)
  - Test TMD factorization/universality and evolution
  - Collins asymmetries consistent with expectations based on SIDIS
- **STAR Collins asymmetries informing model calculations**
  - Asymmetries exhibit x_T scaling
  - Shape of asymmetries appears to depend on j_T
- **Results from 2012 and 2015 datasets**
  - Improved precision at 200 GeV
  - First look at kaon and proton asymmetries in $p + p$
- **Published results for forward π^0 in EM-jet**
  - Asymmetries small with possible dependence on j_T
- **Analysis of high-statistics 510 GeV data taken in 2017 underway**
- **Analysis of (un)polarized data from recent runs underway**
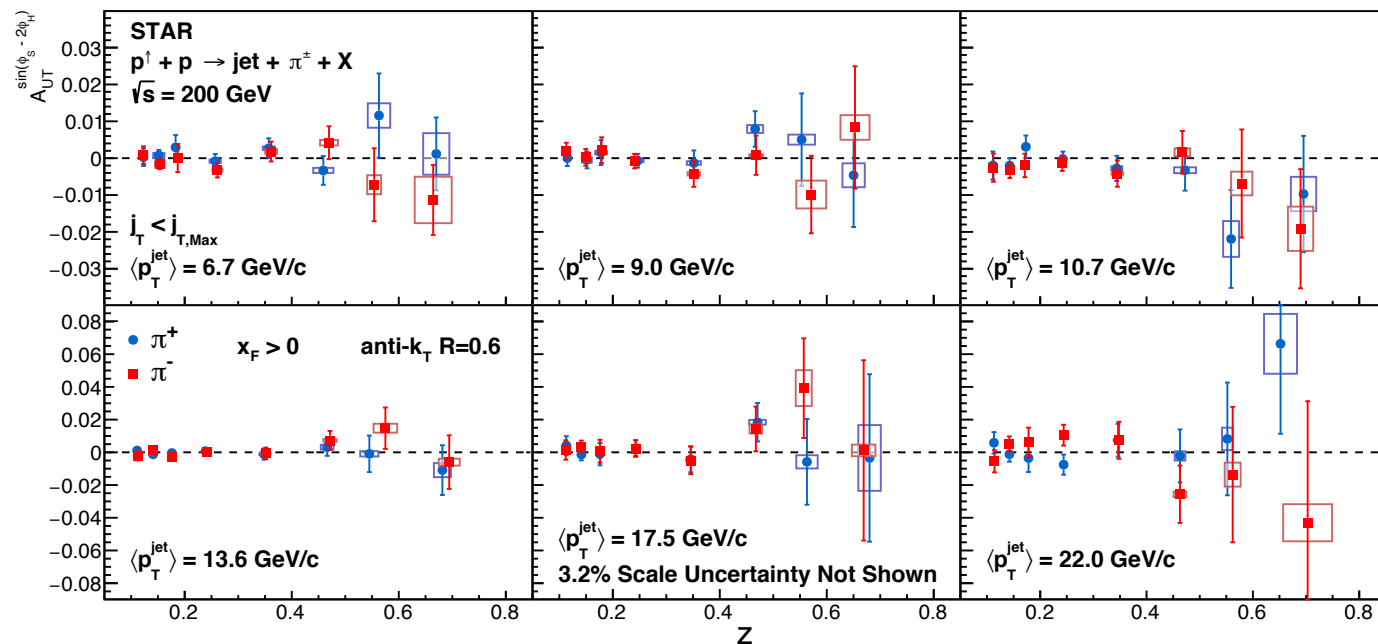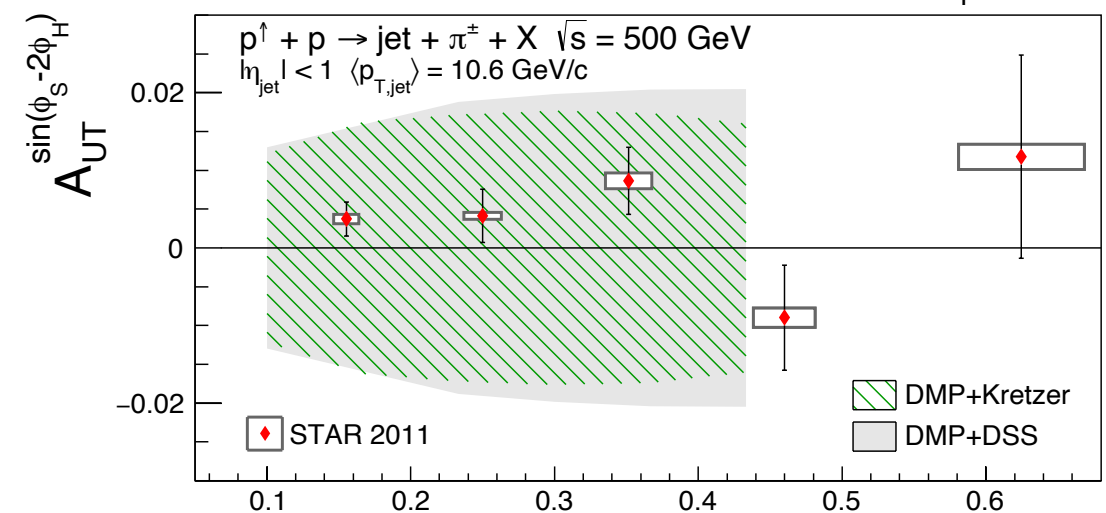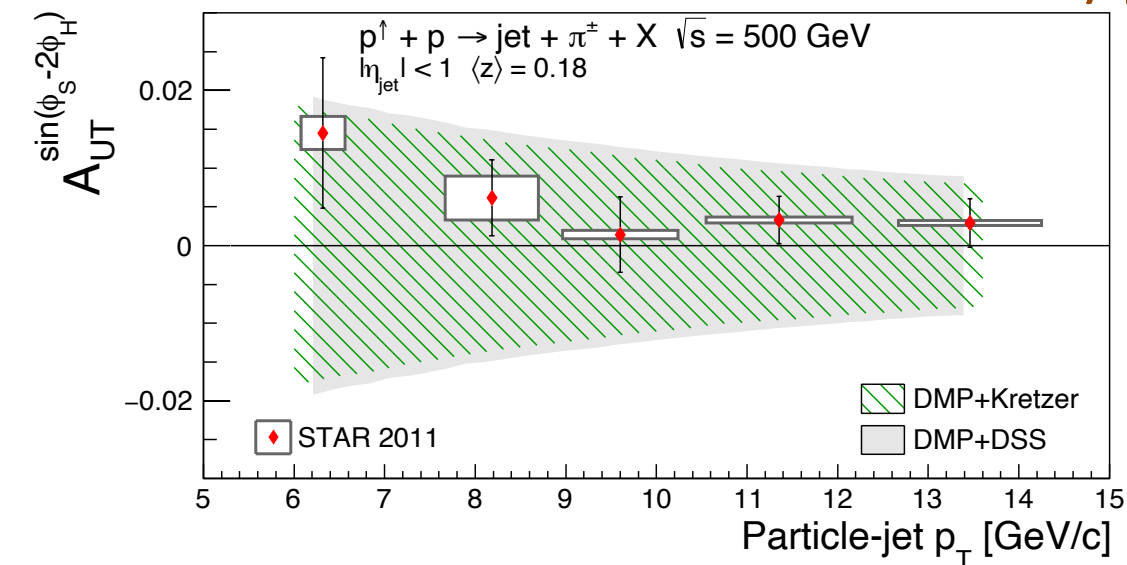
Stay tuned!

Back-up Slides

Following the approach of PRD 92, 054015 (2015) and JHEP11 (2017) 068

- Formulate NLO partonic cross-section in terms of *universal* jet functions
- Also define semi-inclusive transverse-momentum-dependent (TMD) jet functions
- Facilitate comparison with standard TMDFF from SIDIS and e^+e^- using inclusive jets with $j_\perp \ll p_{T,\mathrm{jet}} \times R$ calculated relative to *standard jet axis*
- Argue FFs universal to NLO, *including TMDFFs*
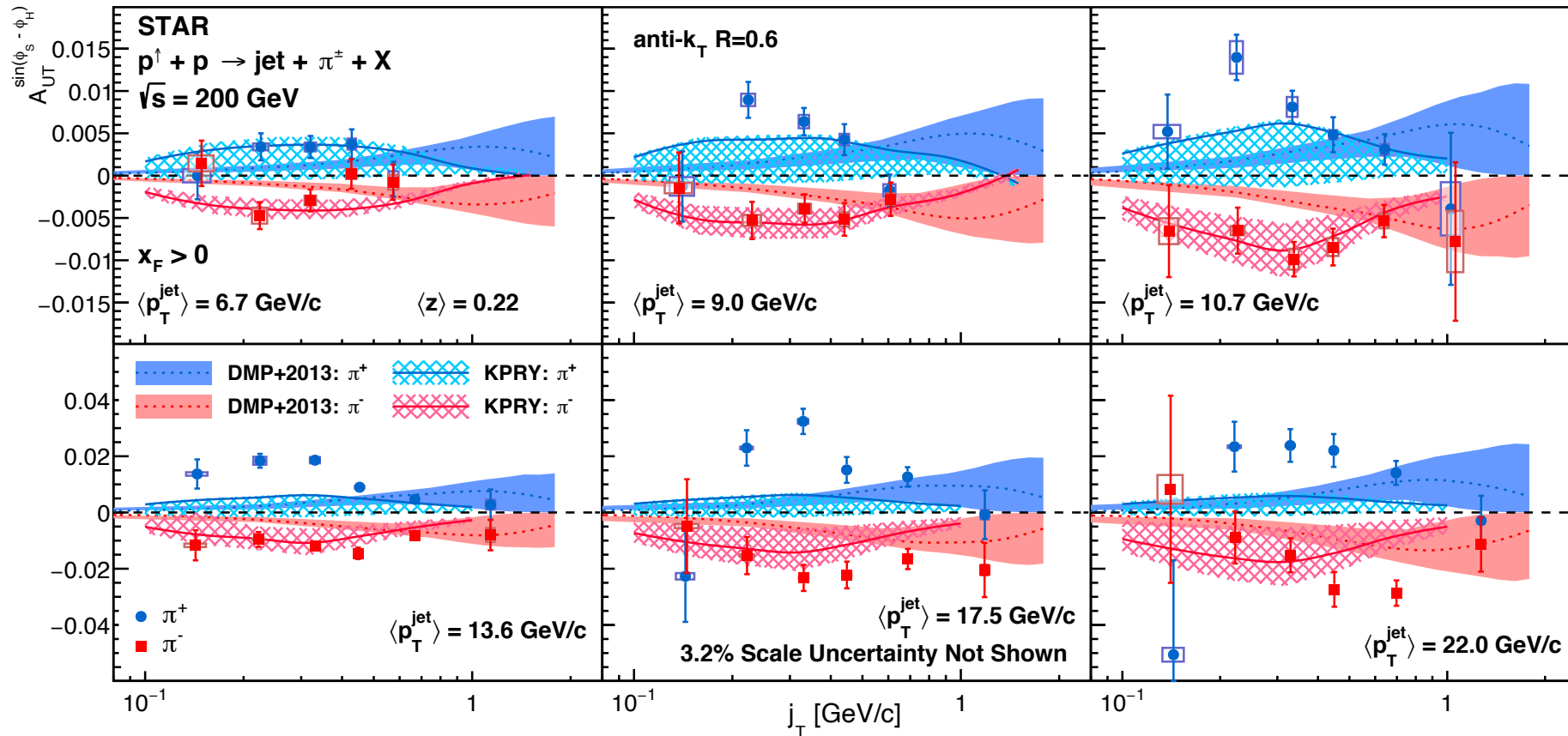- No dependence on TMDPDFs
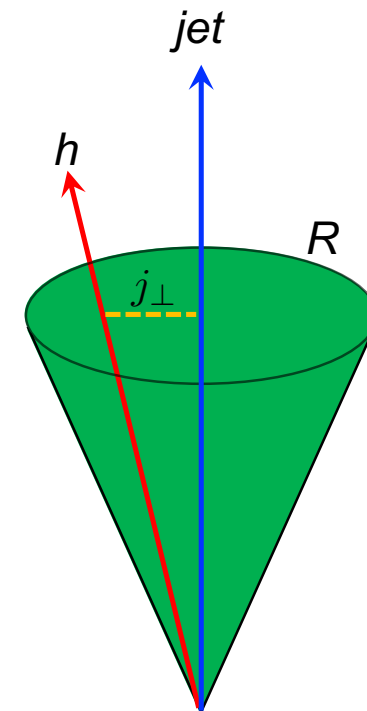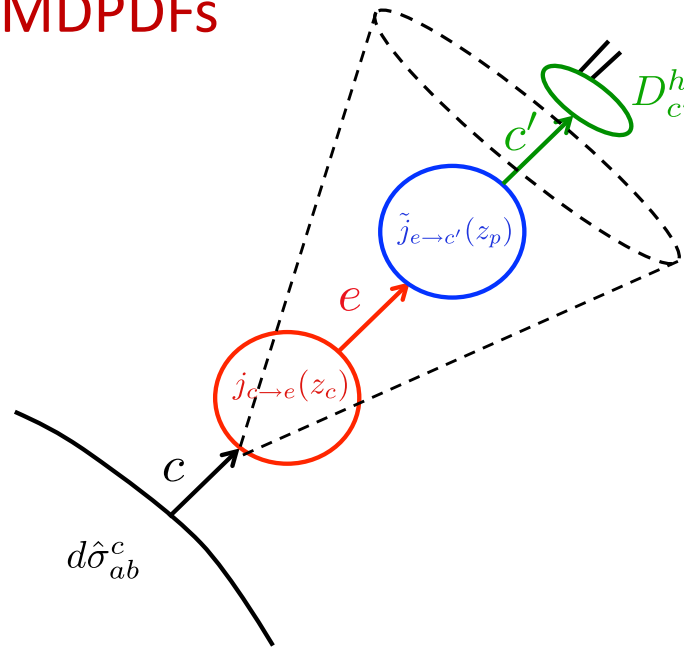
Collins-like effect: Sensitive to linearly polarized gluons in a transversely polarized proton

STAR Collaboration, PRD 97, 032004 (2018)

STAR Collaboration, arXiv:2205.11800

- j_T dependence in bins of jet p_T

STAR Collaboration, arXiv:2205.11800