Investigating Transversity and Fragmentation Functions with Hadrons in Jets at STAR

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for the STAR Collaboration

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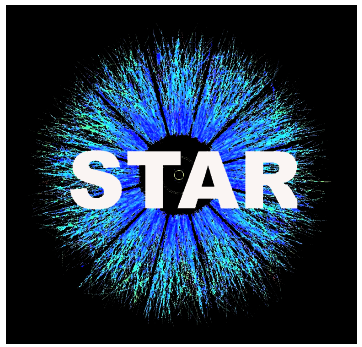
OUTLINE

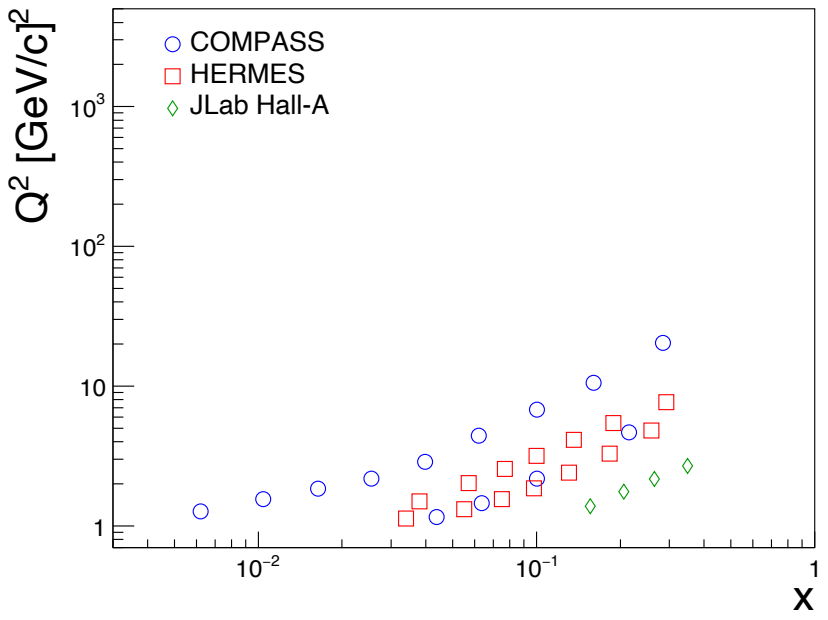
- Transversity and TSSAs
- STAR
- Hadrons-in-jets at STAR
- Looking forward

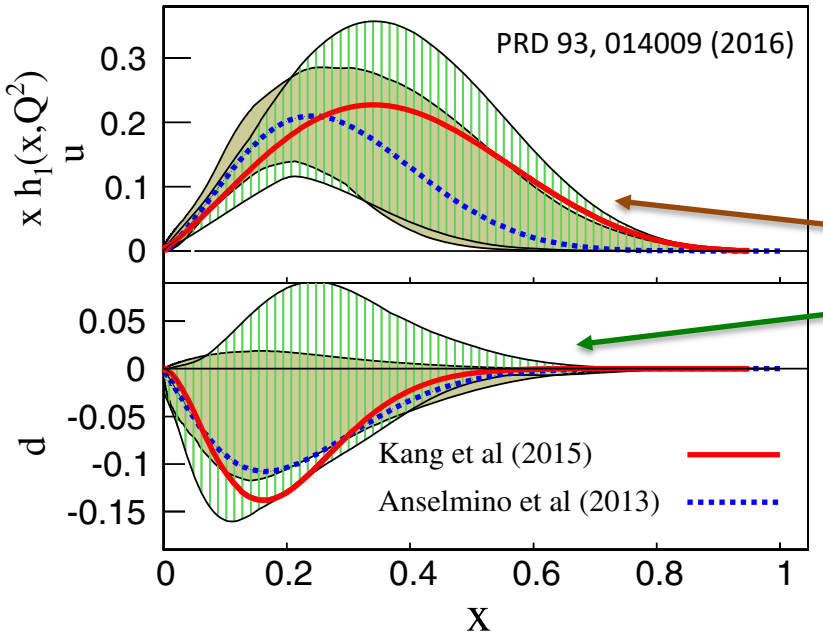


Transversity

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, $\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$





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

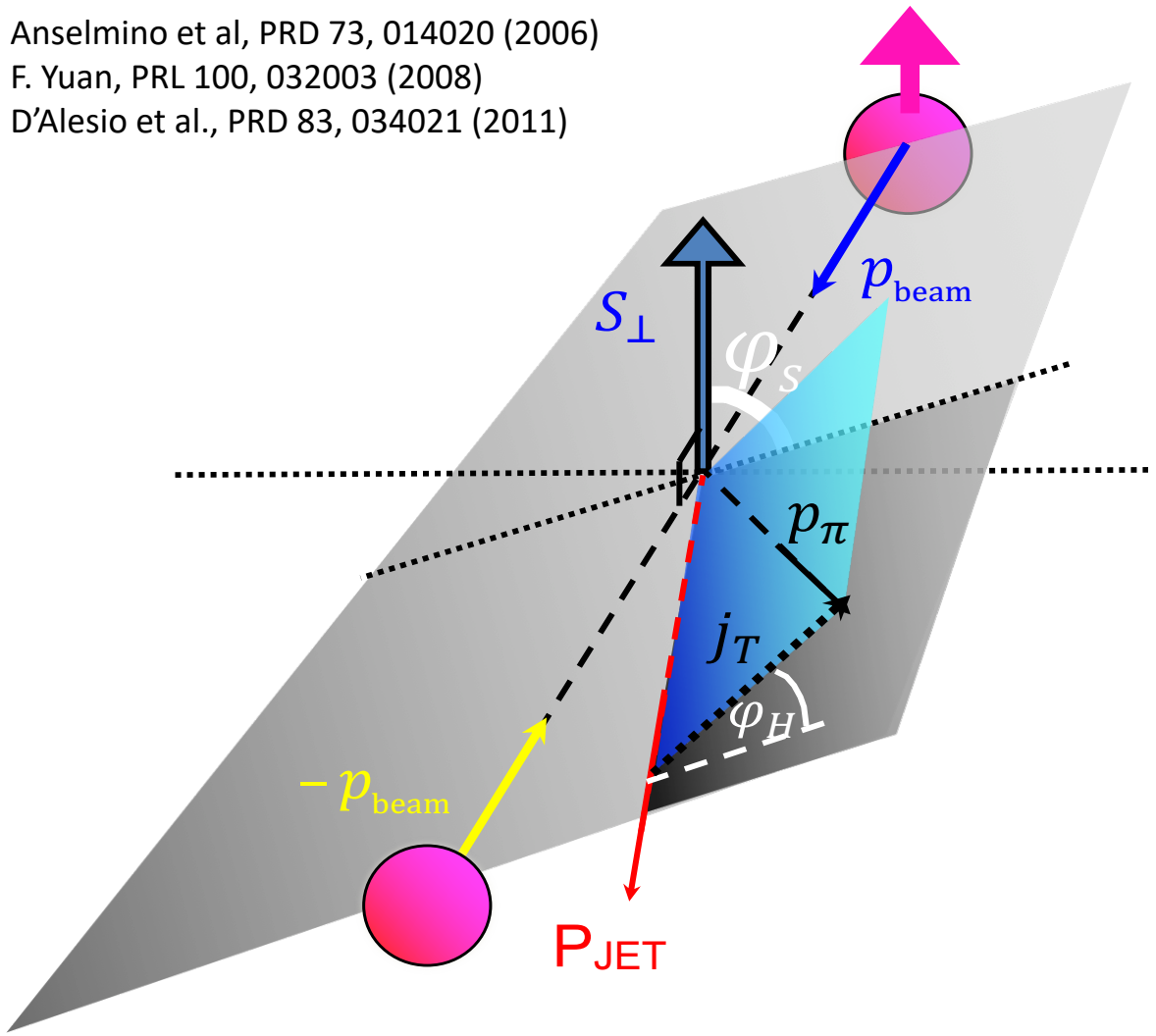
Kang et al: PRD 93, 014009 (2016)
Anselmino et al: PRD 87, 094019 (2013)
Radici et al: JHEP 05, 123 (2015)

Accessed through global analyses in SIDIS + e^+e^-, e.g. via "Collins" or IFF asymmetries

Currently limited reach in (x, Q^2) [*see talks by B. Pokhrel, N. Ghimire*]

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)



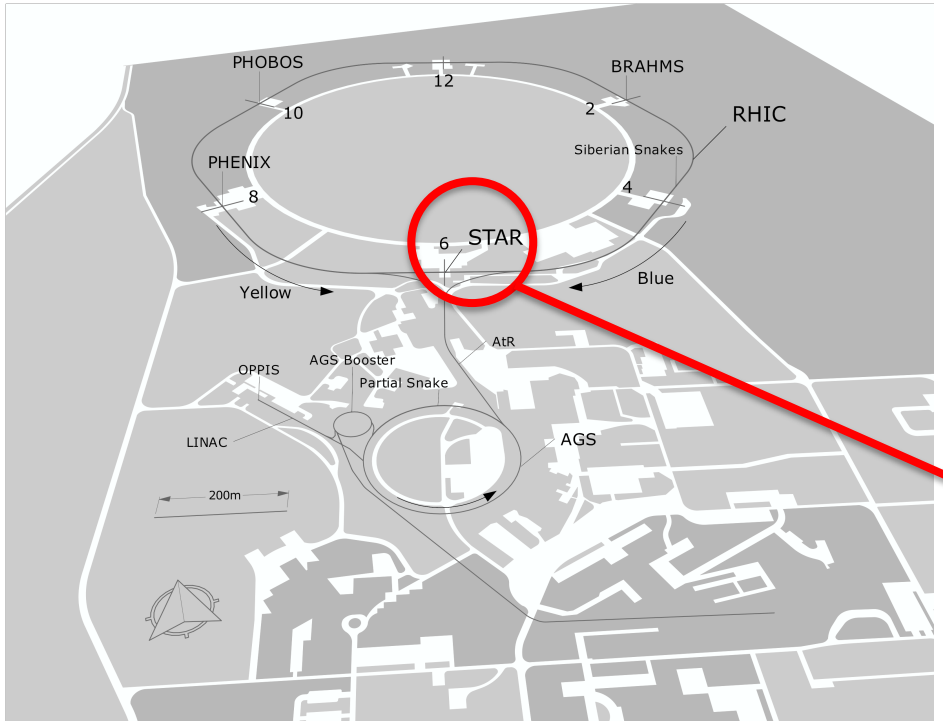
Collins mechanism

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

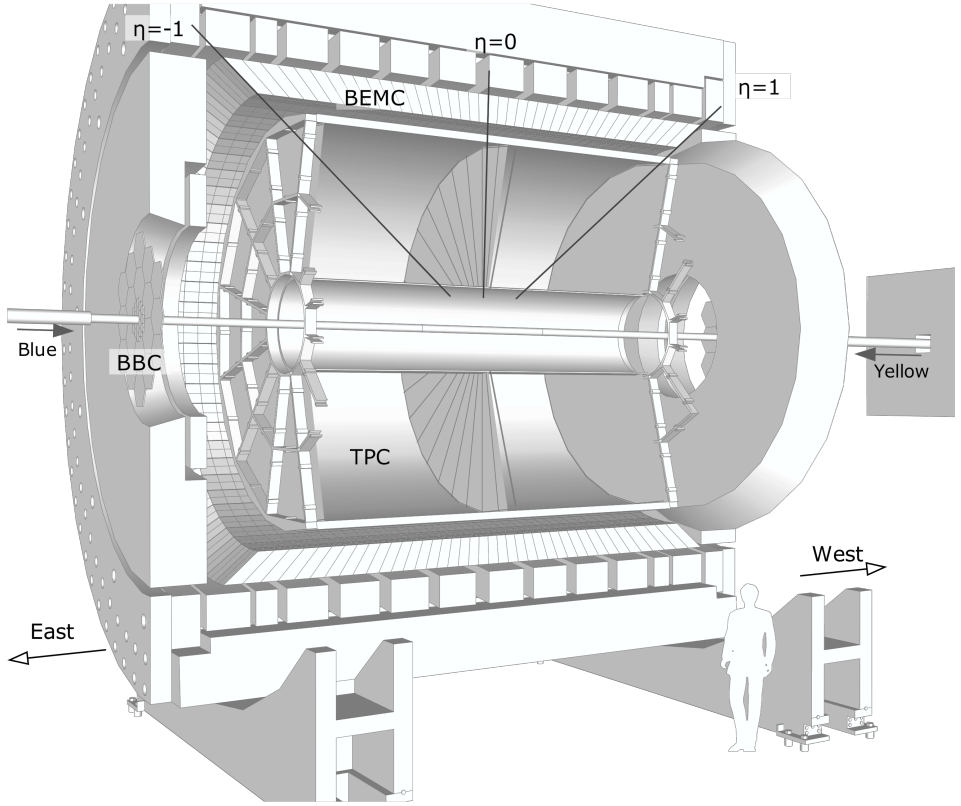
(*analogous effect for gluon linear polarization*)

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.

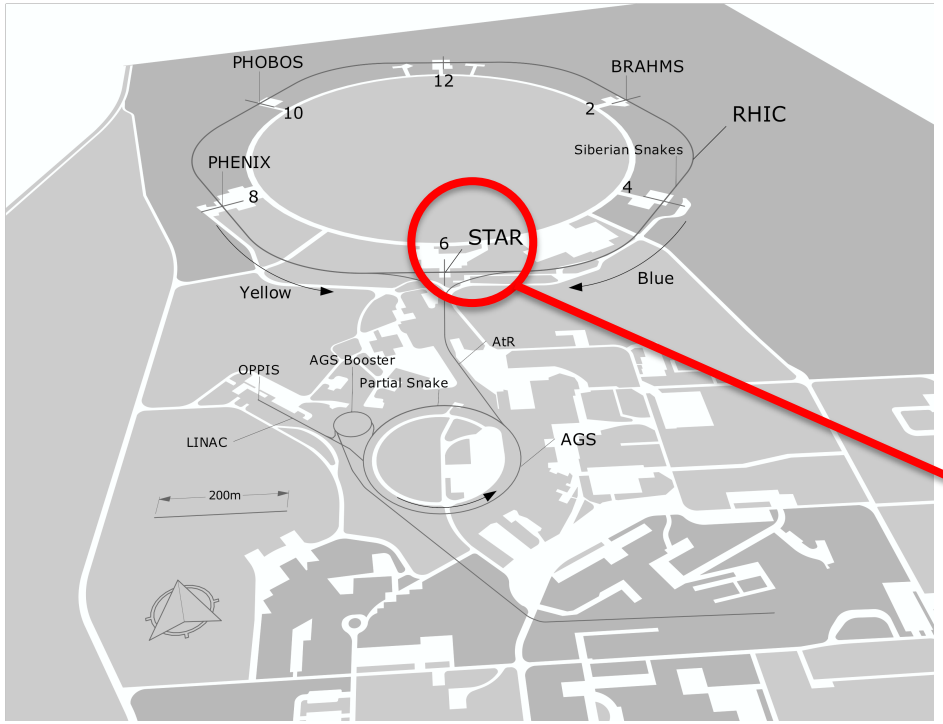
Jets, $\pi^{\pm}, K, p, e^{\pm}, \pi^{0}, \gamma$

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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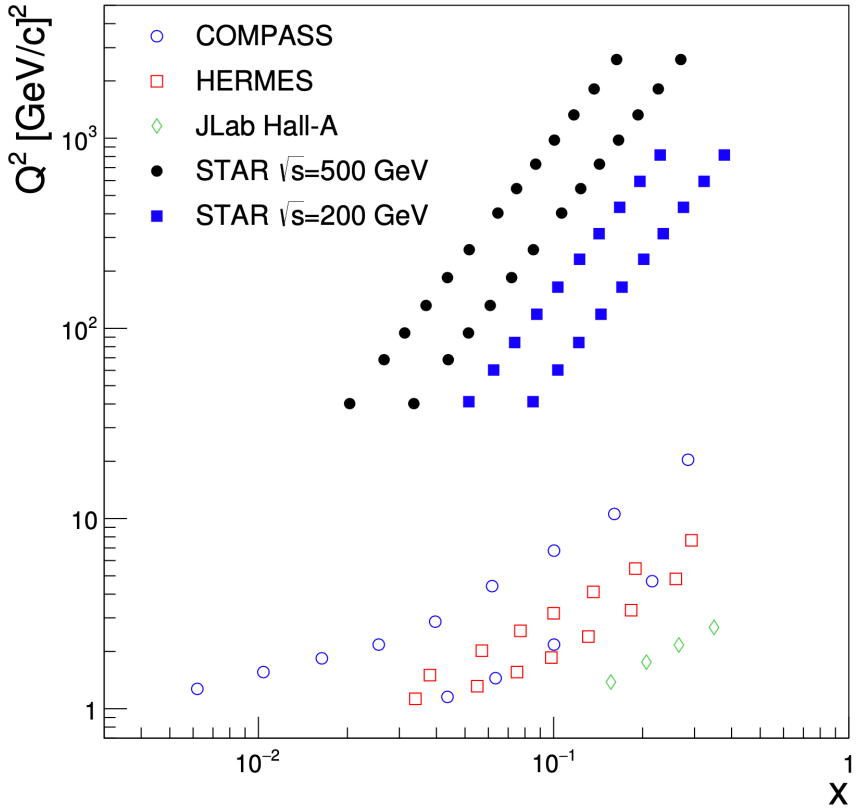

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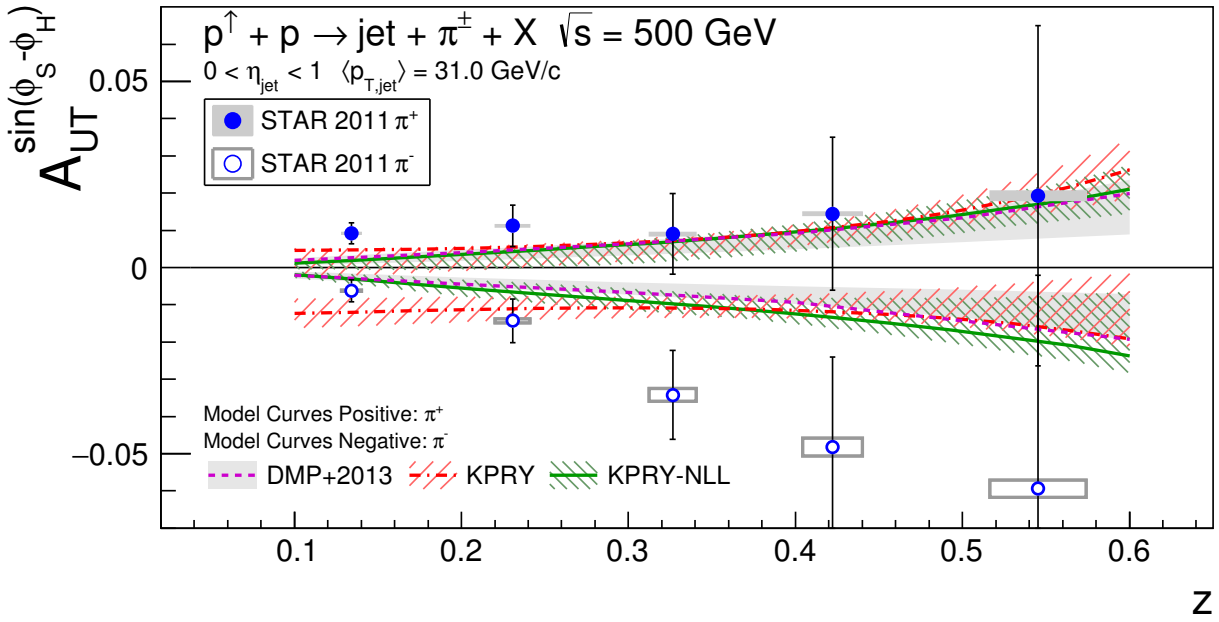
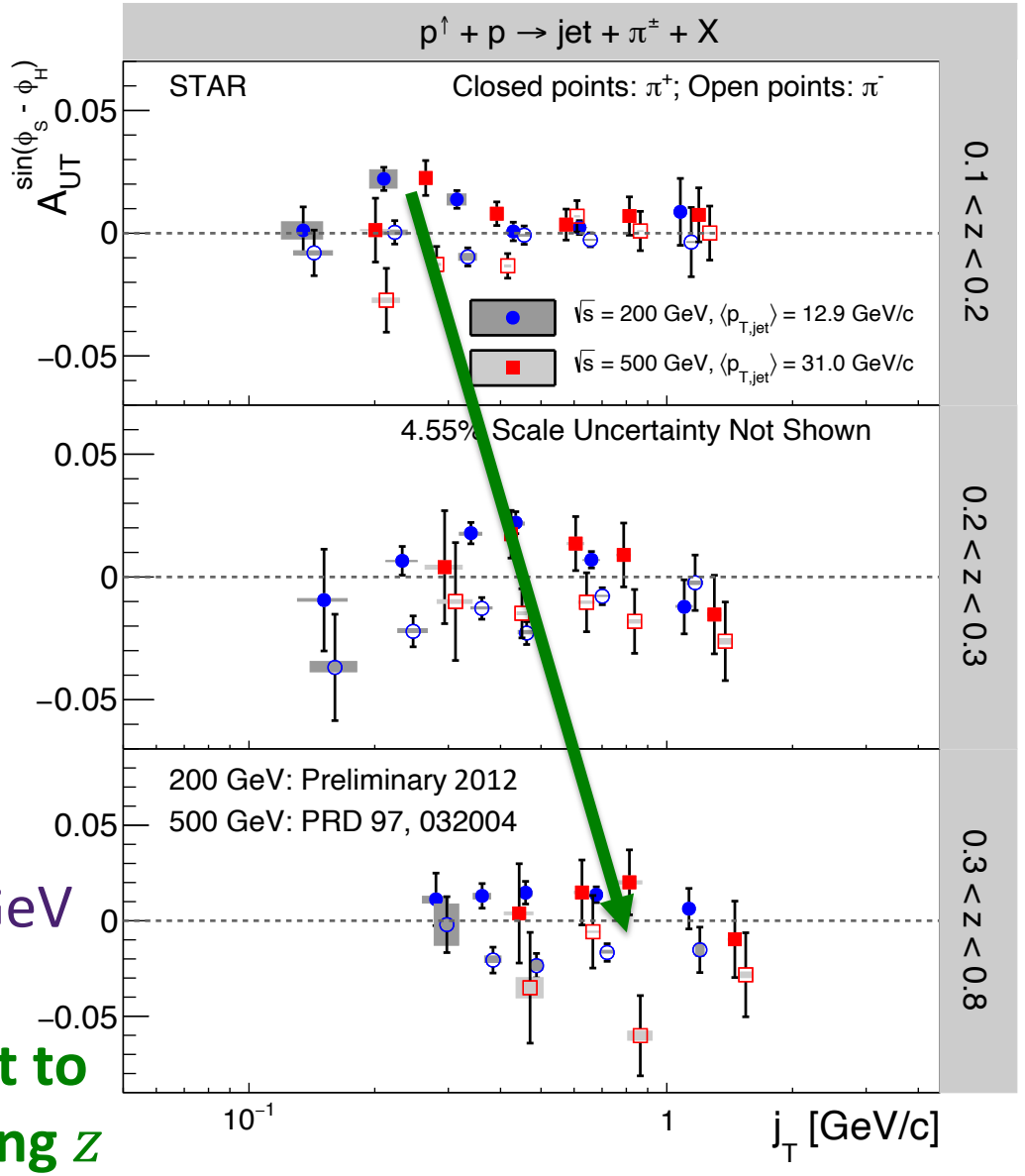
Collins Effect at STAR



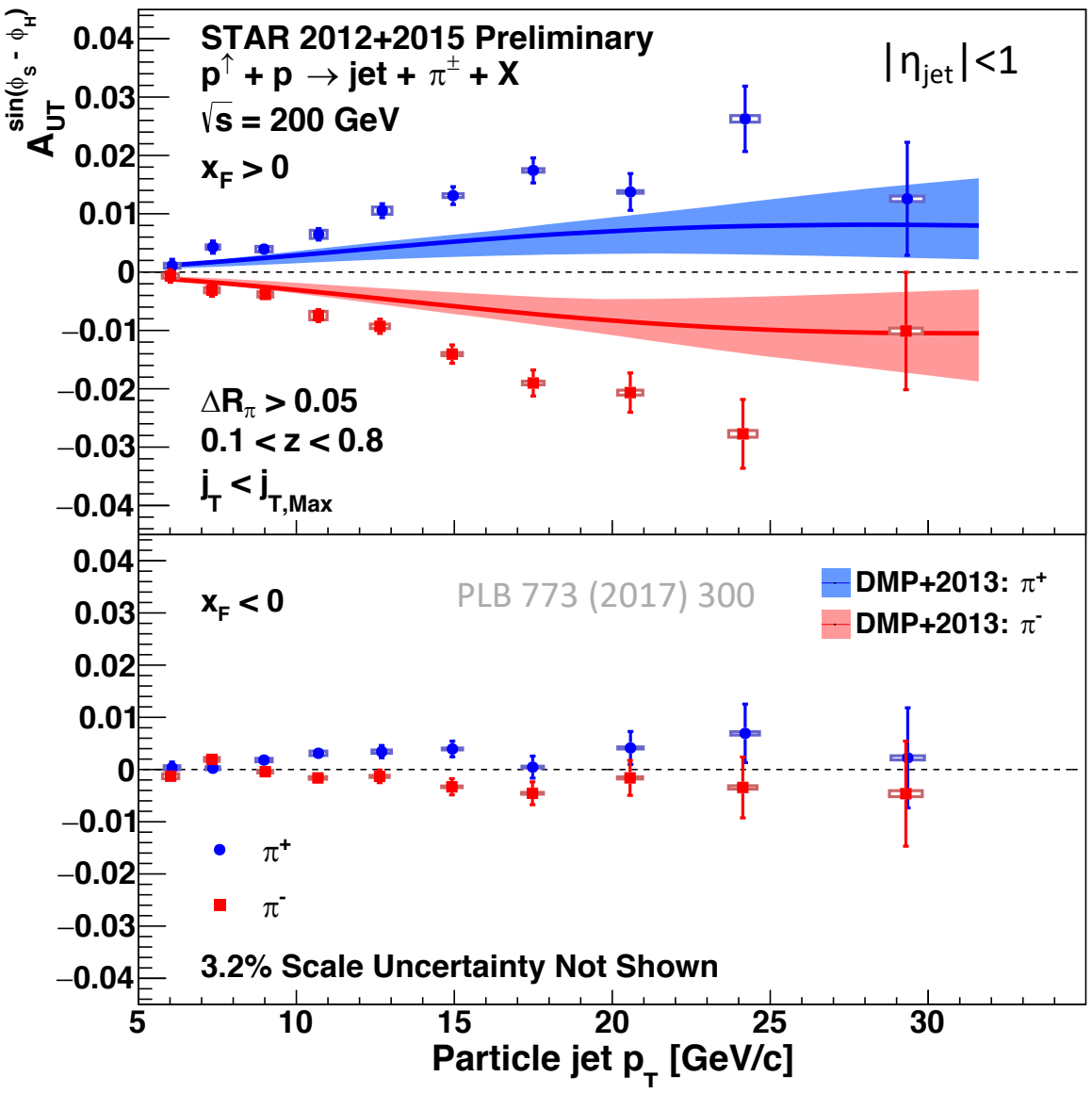


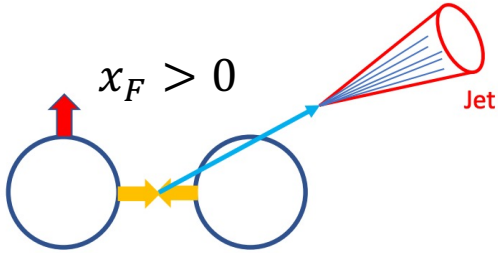
- Consistent with models based on SIDIS/e^+e^-
- Suggest robust factorization and universality
  - *Not yet sensitive to evolution assumptions*
- Consistency between 500 GeV and preliminary 200 GeV data (2012 RHIC run) for common $x_T = 2p_{T,\mathrm{jet}}/\sqrt{s}$

Peak appears to shift to higher j_T for increasing z

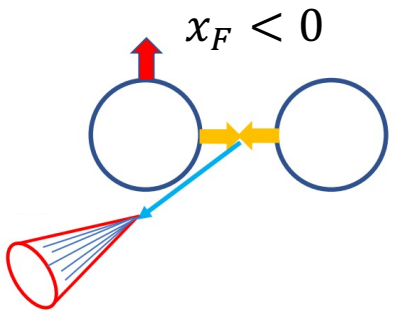
STAR Collaboration, PRD 97, 032004 (2018)
D'Alesio, Murgia, Pisano: PLB 773, 300 (2017)
Kang, Prokudin, Ringer, Yuan: PLB 774, 635 (2017)

STAR 2015 Data: Higher Statistics at 200 GeV



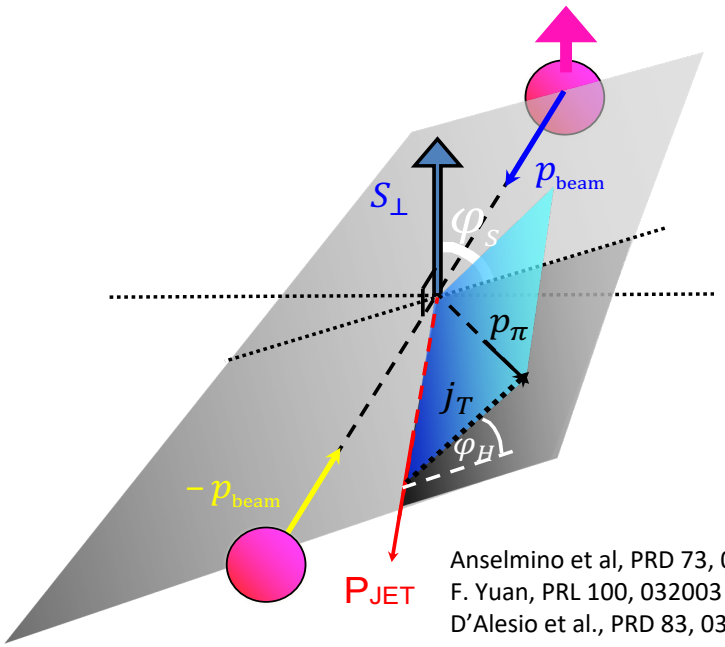


- $52\ \mathrm{pb}^{-1}$ of $p^{\uparrow} + p$ at $\sqrt{s} = 200$ GeV
  - *Roughly twice the amount collected in 2012*
- Excellent consistency with 2012 preliminary data
  - Large asymmetries for forward scattering
  - Small asymmetries for backward scattering
- Should provide valuable constraints for models



STAR 2015 Data: Higher Statistics at 200 GeV

- Significantly improved precision for j_T study
- As with previous data peak appears to shift to higher j_T for increasing z
  - Suggests asymmetry does not factorize as most models assume, e.g. $A_{UT} \sim f(j_T) \times g(z)$



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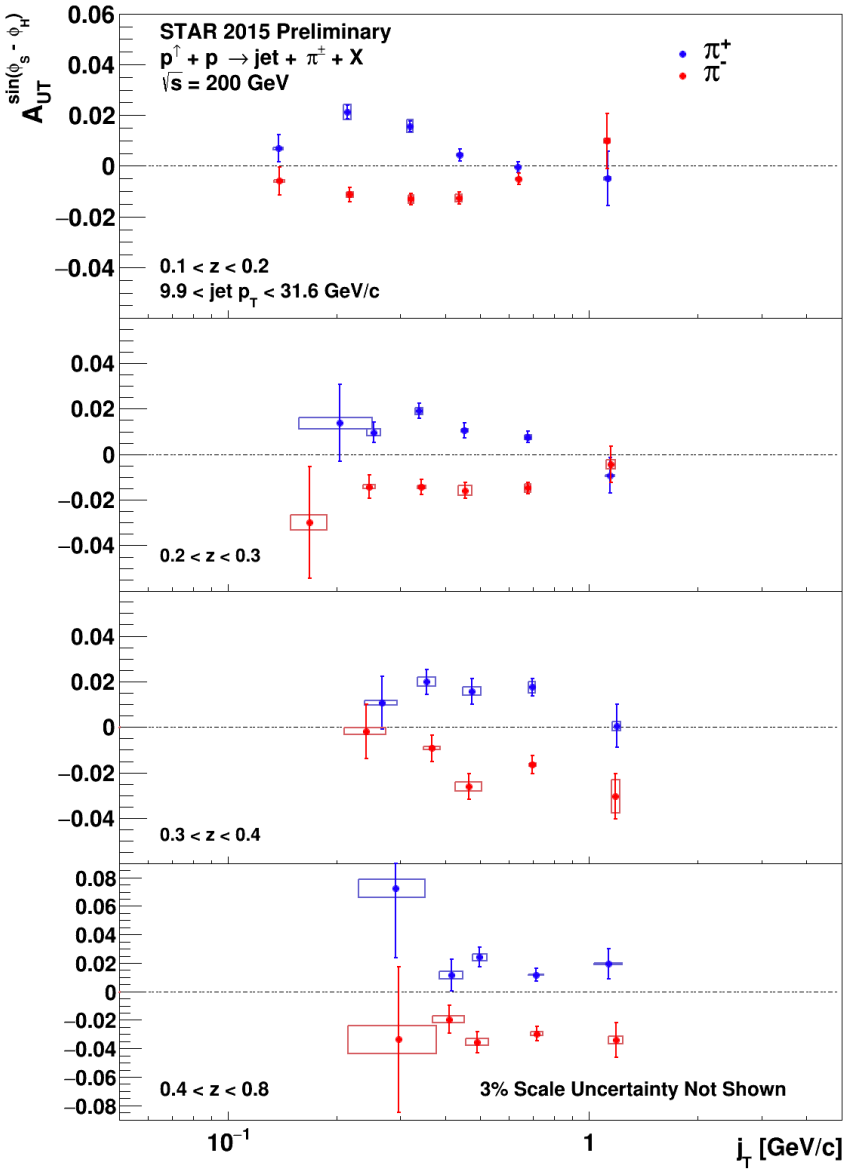
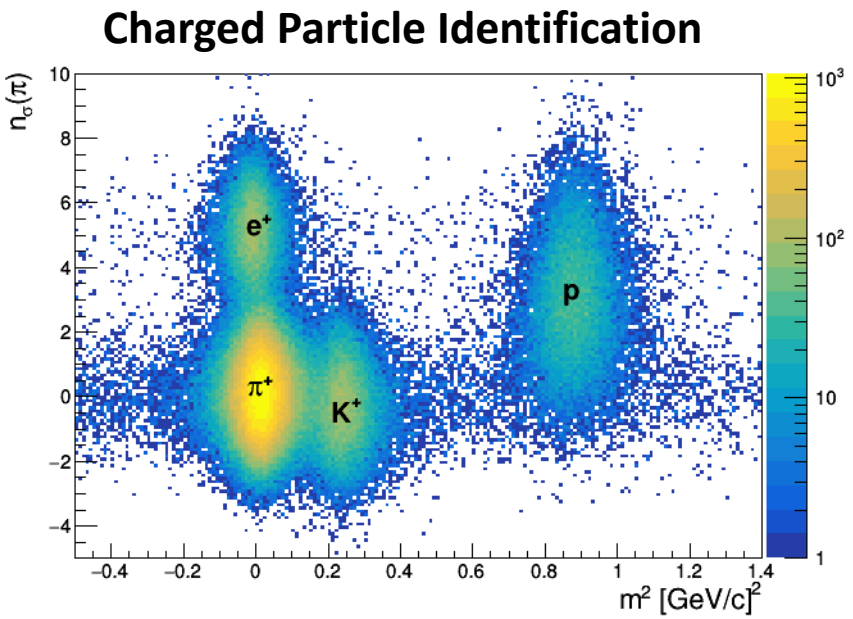
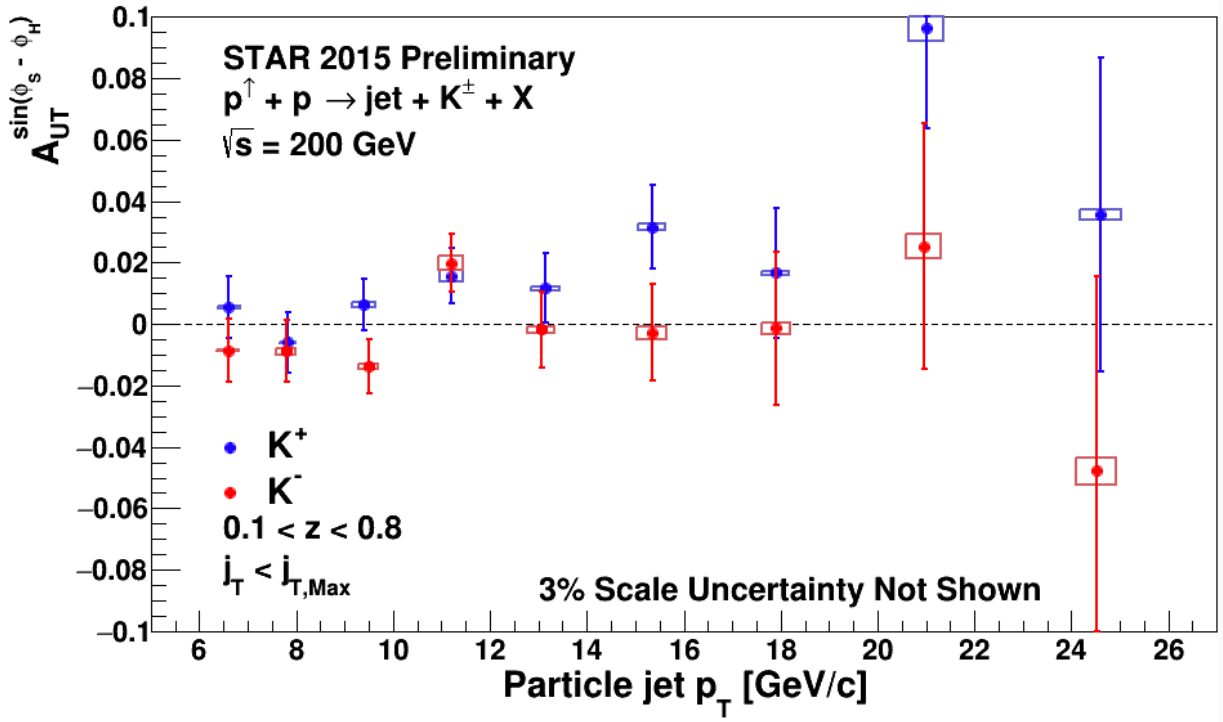


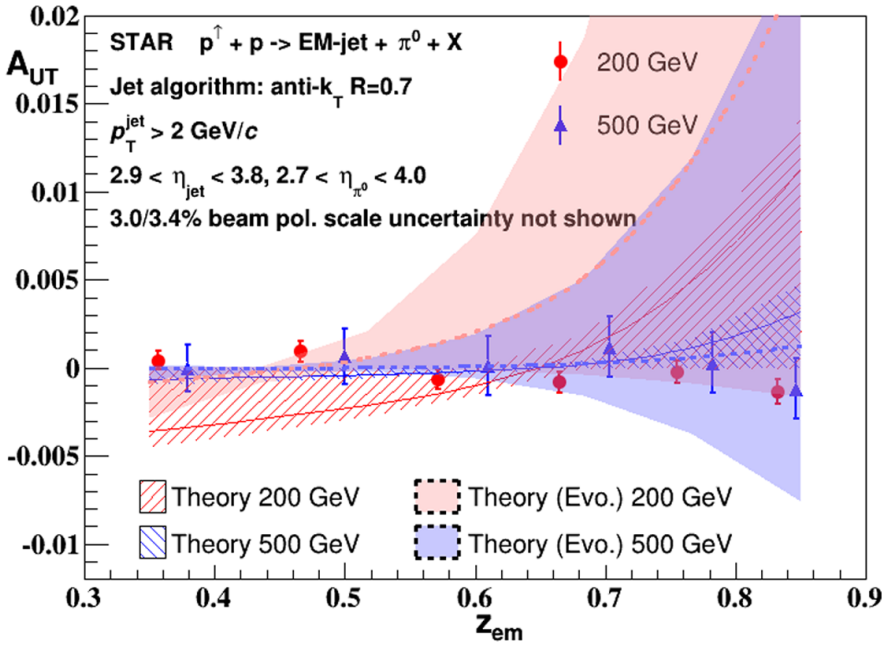
Kaon Asymmetries at 200 GeV

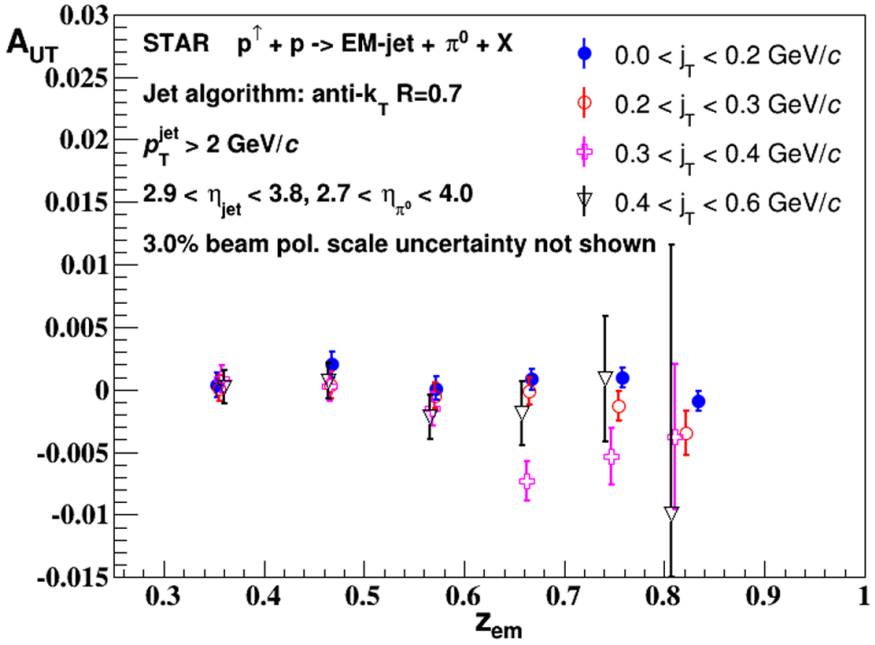




- Charged particle ID from TPC and time-of-flight
- Asymmetries for K^+ about 1.5σ larger than π^+
  - K^+ can be produced through favored u-quark fragmentation
- Asymmetries for K^- consistent with zero
- Similar observations to SIDIS data

Neutral Pion in Electromagnetic Jet Asymmetries





STAR Collaboration, PRD 103, 092009 (2021)

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

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

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
  - Collins asymmetries consistent with expectations based on SIDIS
- **STAR Collins asymmetries at 200 and 500 GeV informing model calculations**
  - Asymmetries exhibit x_T scaling
  - Shape of asymmetries appears to depend on j_T
- **Preliminary results from 2015 dataset**
  - Improved precision at 200 GeV
  - First look at kaon asymmetries
- **Published results for forward π^0 in EM-jet**
  - Asymmetries small with possible dependence on j_T
- **Analysis of (un)polarized data from recent runs underway**

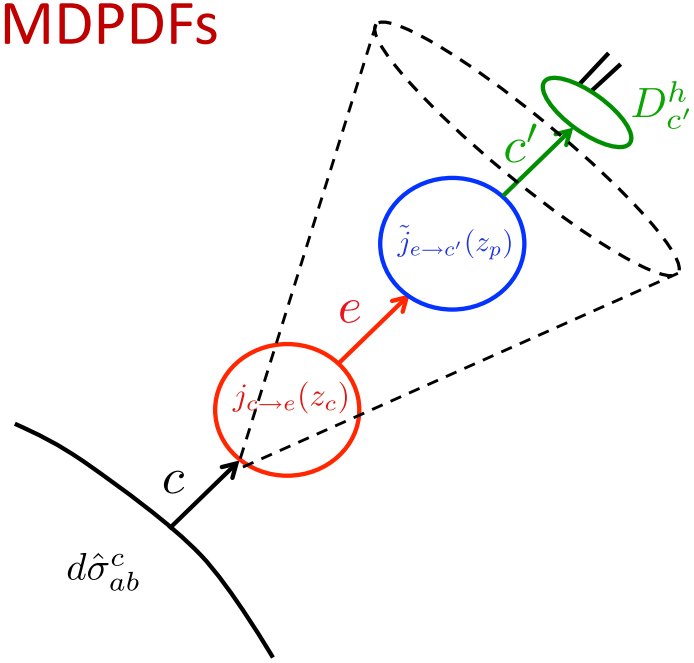
Stay tuned!

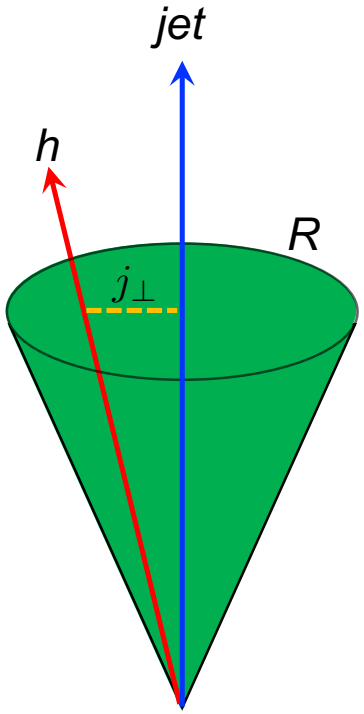
Back-up Slides

Unpolarized Hadrons Within Jets

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





Status of In-jet FF Analysis

$$\frac{1}{\sigma_{jet}}\frac{d^3\sigma_{jet(\pi)}}{dp_T dz dj_T} = \frac{1}{N_{jet}}\frac{d^3N_{jet(\pi)}}{dp_T dz dj_T} \times \frac{\epsilon_{\text{vtx reco}} \otimes \epsilon_{\text{jet reco}}}{\epsilon_{\text{vtx reco}} \otimes \epsilon_{\text{jet reco}} \otimes \epsilon_{\text{track reco}}}$$

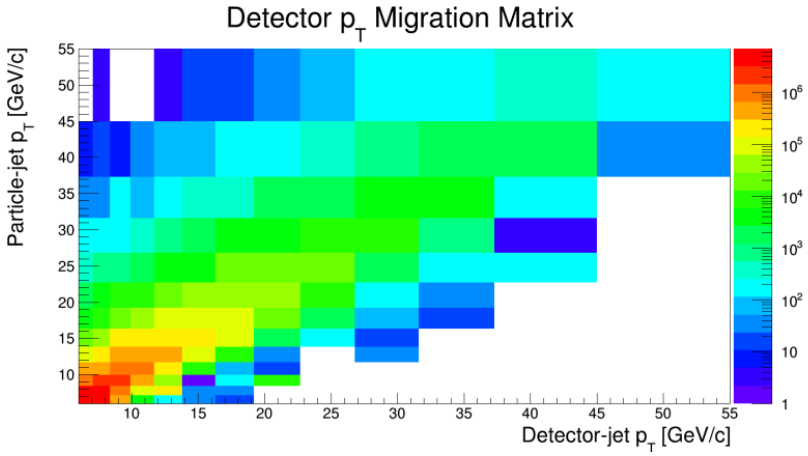
Two key steps in analysis

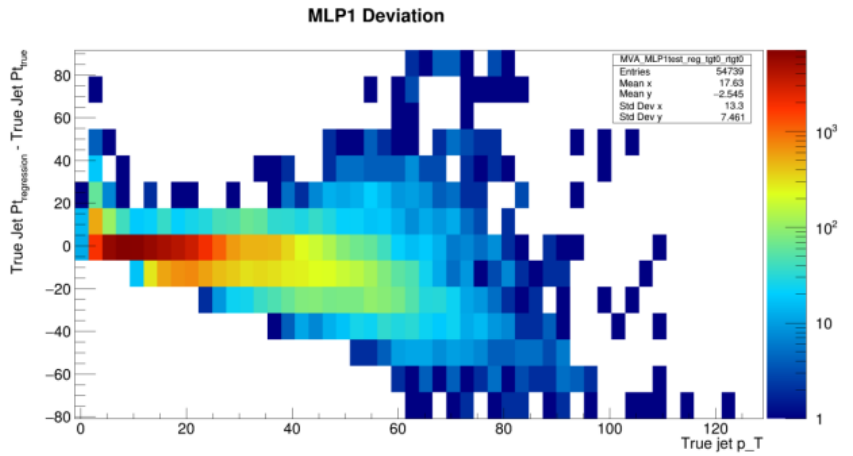
- Efficiency corrections (tracking and jet reconstruction)
- Bin migration correction, aka "unfolding"
  - Unfold in jet p_T, pion z, and pion j_T

Try different methods to minimize systematic uncertainties, e.g.

- 2-D and 3-D Bayesian with RooUnfold
- ROOT's Toolkit for Multivariate Analysis (TMVA)
  - Multilayer perceptron and boosted decision trees

Embedded Monte Carlo Studies

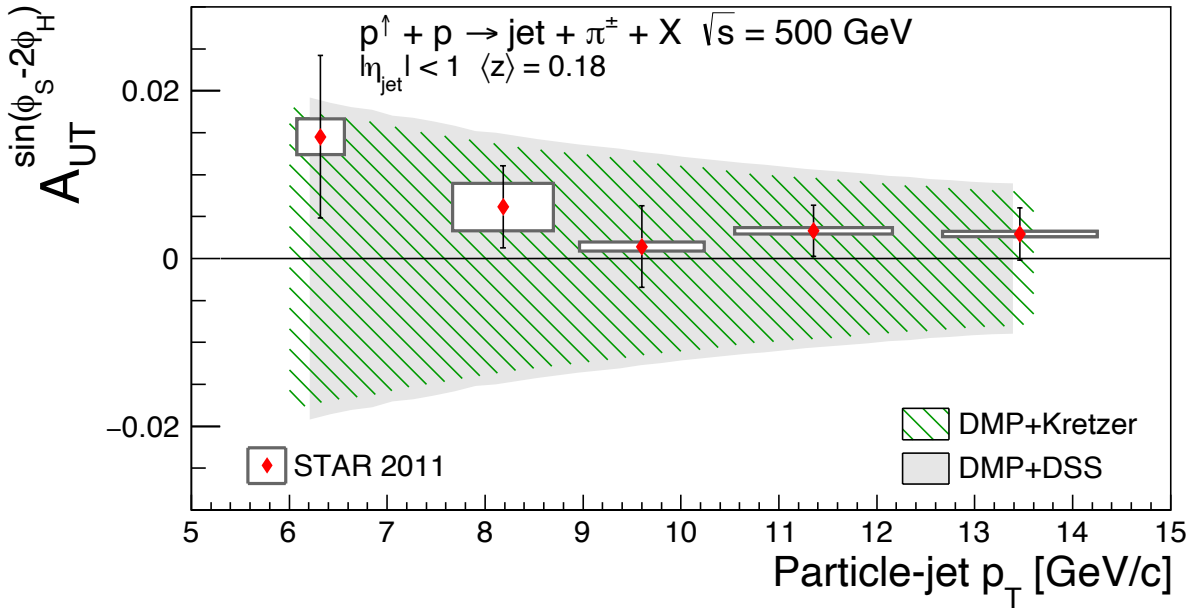


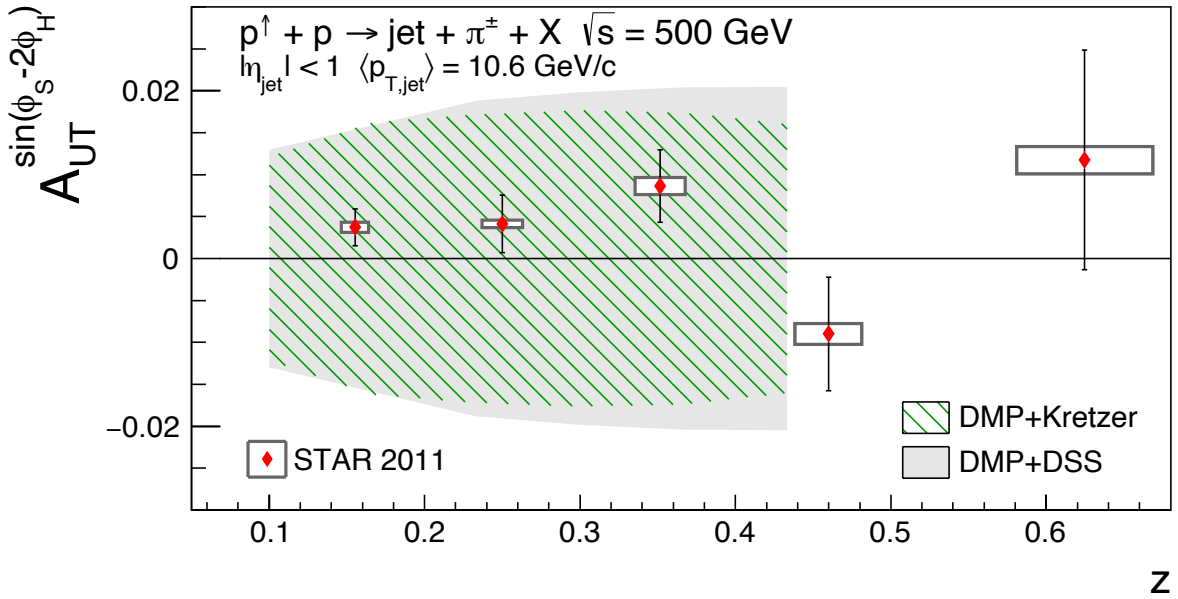


Collins-like Effect at RHIC

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





STAR Collaboration, PRD 97, 032004 (2018)