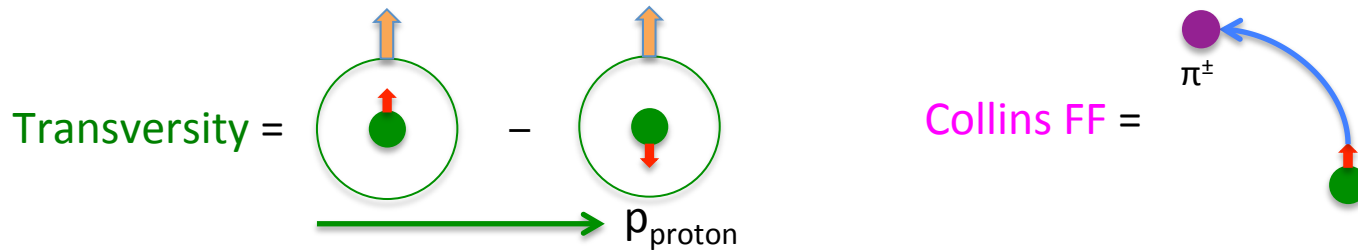




Azimuthal Single-Spin Asymmetries of Charged Pions in Jets in $p^\uparrow p$ Collisions at STAR

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For the STAR Collaboration
APS April Meeting 2015 – Baltimore, MD
April 12, 2015

Using Jets as a Tool to Access Transversity in $p^\uparrow + p$ Collisions

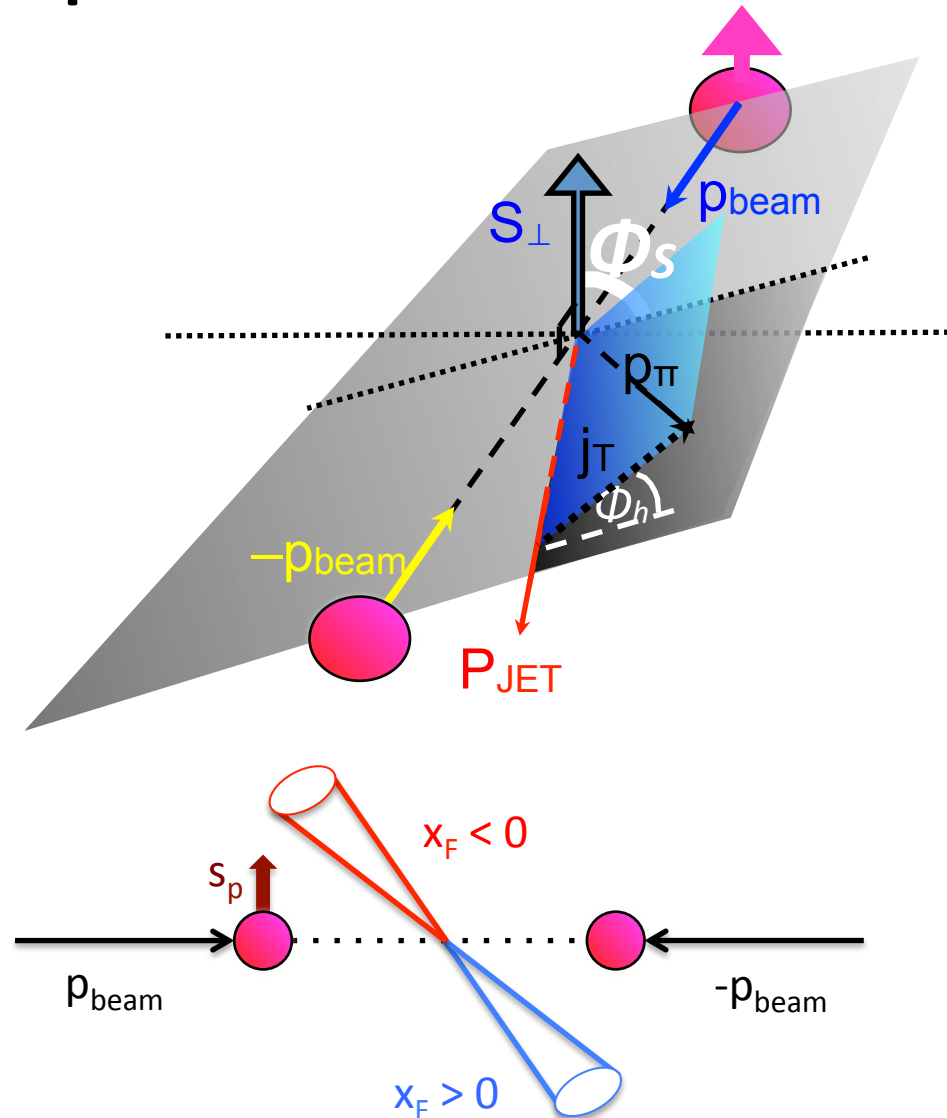


$$A_{UT}^{\pi^\pm} \approx \frac{h_1^{q_1}(x_1, k_T) f_{q_2}(x_2, k_T) \hat{\sigma}_{UT}(\hat{s}, \hat{t}, \hat{u}) \Delta D_{q_1}^{\pi^\pm}(z, j_T)}{f_{q_1}(x_1, k_T) f_{q_2}(x_2, k_T) \hat{\sigma}_{UU} D_{q_1}^{\pi^\pm}(z, j_T)}$$

- Single-spin asymmetries in hadronic collisions may help answer these questions
 - How does transversity behave at high x ($0.1 < x < 0.35$)?
 - What is the dependence of the Collins FF on pion transverse momentum (j_T)?
 - Is the Collins asymmetry universal?
 - How do these asymmetries evolve with \sqrt{s} ?

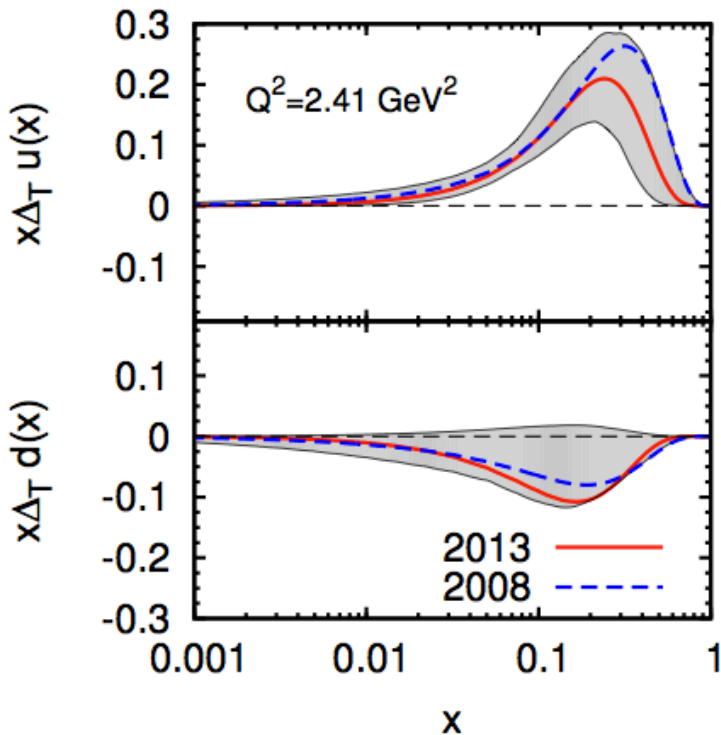
Single Spin $p^\uparrow p$ Collisions

- ϕ_S is defined as the angle between proton spin and reaction plane
- j_T defines particle transverse momentum in jet
- ϕ_H defines angle between jet particle transverse momentum and reaction plane
- $\phi_C = \phi_S - \phi_H$ (Collins Angle)
- Collins modulation
 - $\sin(\phi_S - \phi_H)$
 - PRD 83 034021 (2011)

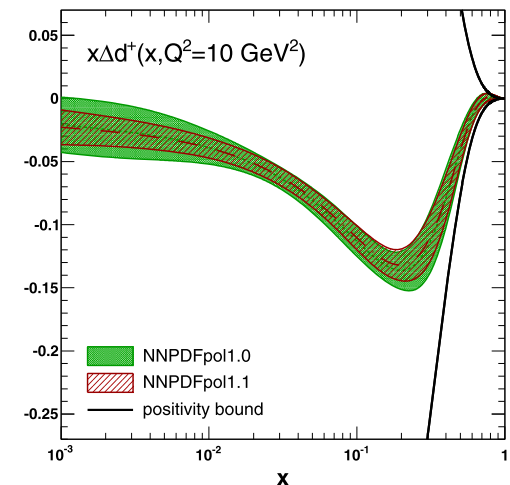
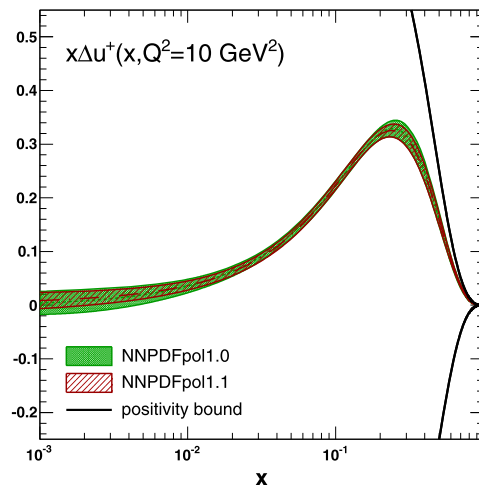


Knowledge of Transversity

- Distribution is chiral odd, accessibility limited in inclusive lepton scattering
- Transversity much less constrained than it's helicity counterpart



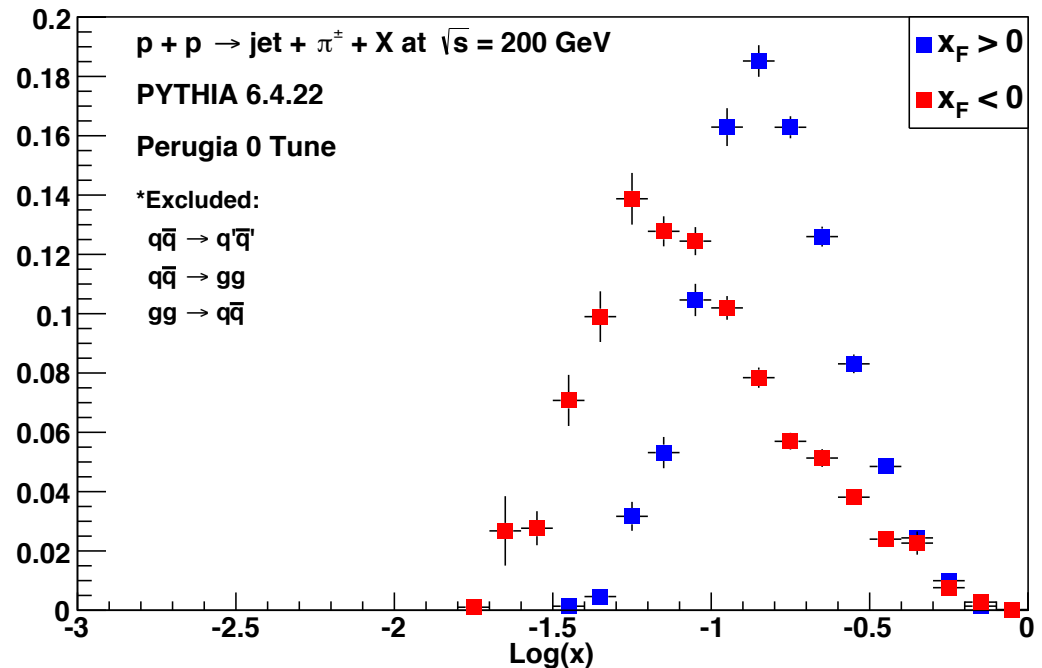
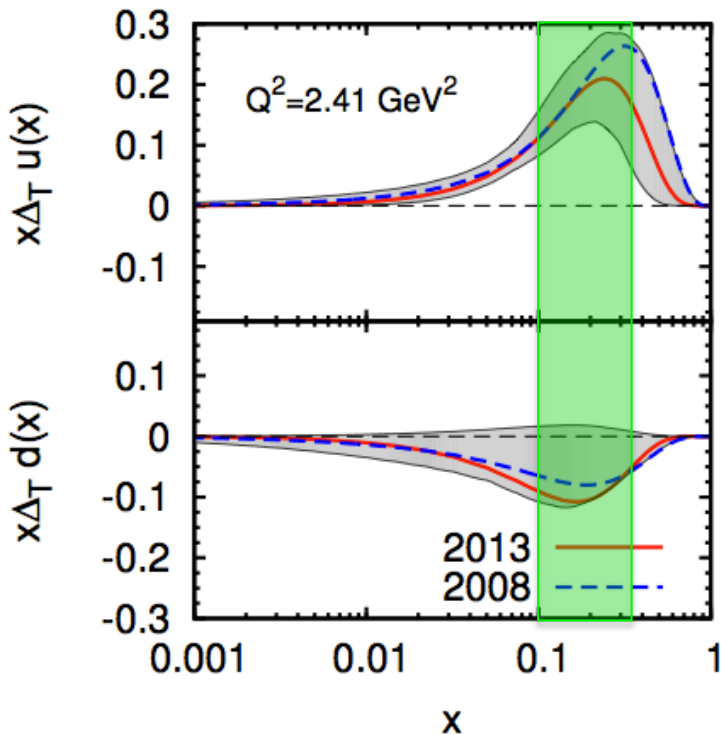
Phys. Rev. D **87** 094019 (2013)



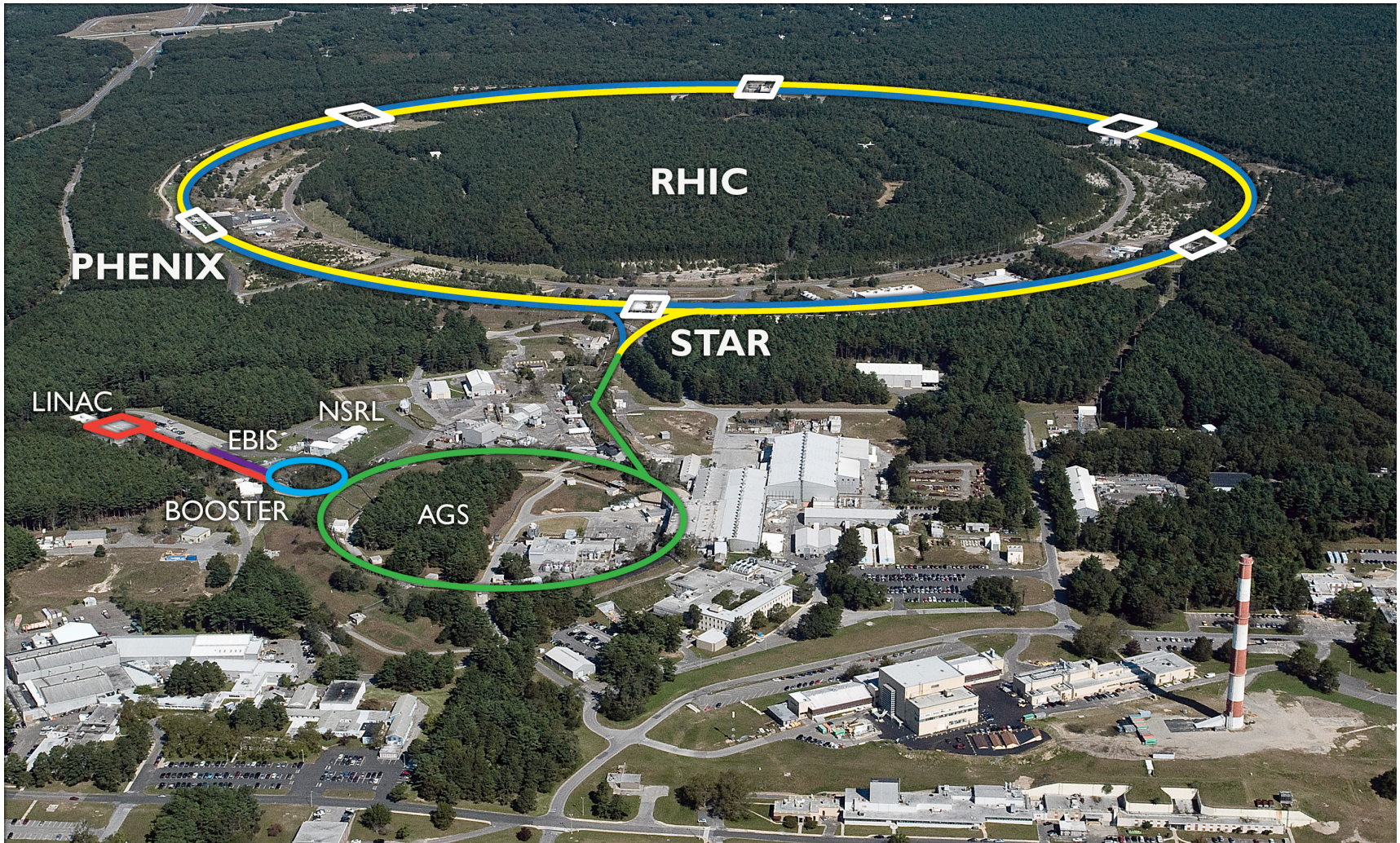
Nuclear Physics B, Vol 887 (2014)

STAR Kinematic Coverage

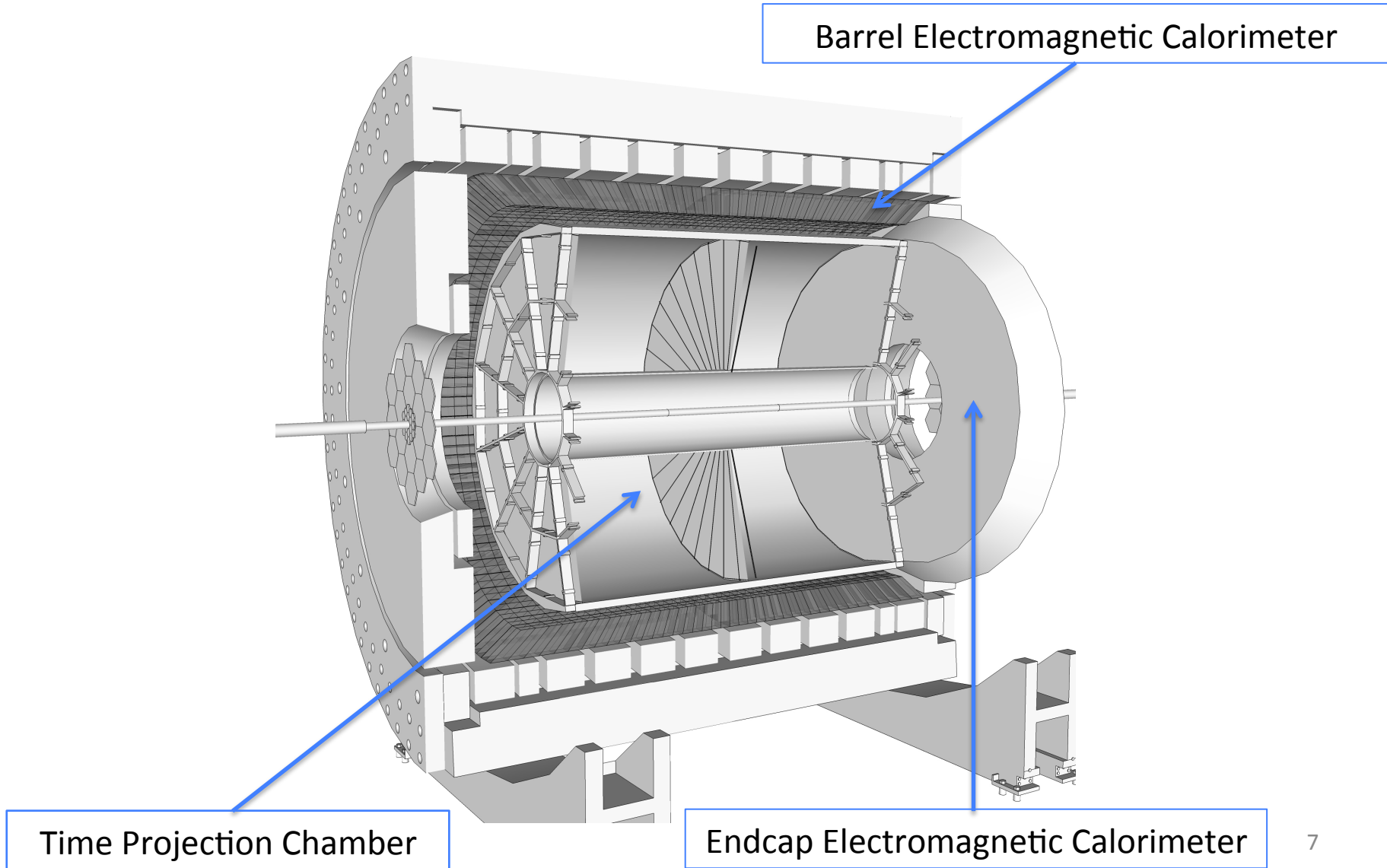
- Analysis of forward and backward scattered jets yields access to a broad range of momentum fractions
- Distribution of sampled x values is consistent between $\sqrt{s} = 200$ GeV and 500 GeV analyses
- This x range samples the unconstrained portion of $h_1(x)$



Relativistic Heavy Ion Collider



Solenoidal Tracker At RHIC



Data and Cuts

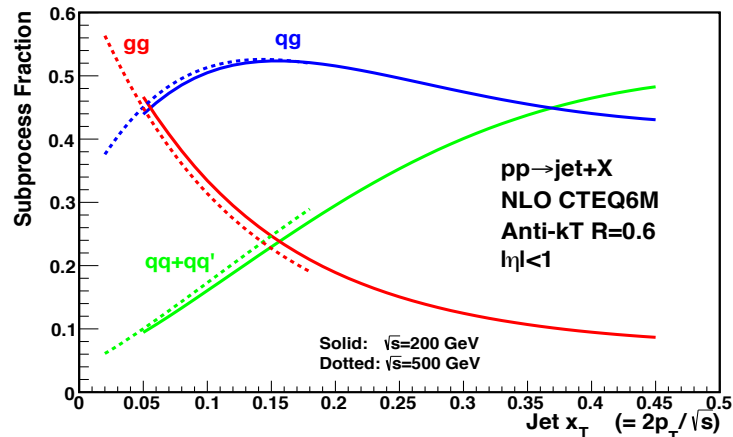
2011

- 25 pb⁻¹ transversely polarized p+p collisions at $\sqrt{s} = 500$ GeV
- Average event weighted polarization: 53%
- Anti-k_T (R = 0.6) jet reconstruction
- $|\eta_{\text{jet}}| < 1$
- Binning with increasing average jet p_T values will sample different fractions of quark subprocesses
- $\Delta R_{\text{min}} > 0.1$

$$\Delta R = \sqrt{(\varphi_{\text{jet}} - \varphi_{\pi})^2 + (\eta_{\text{jet}} - \eta_{\pi})^2}$$

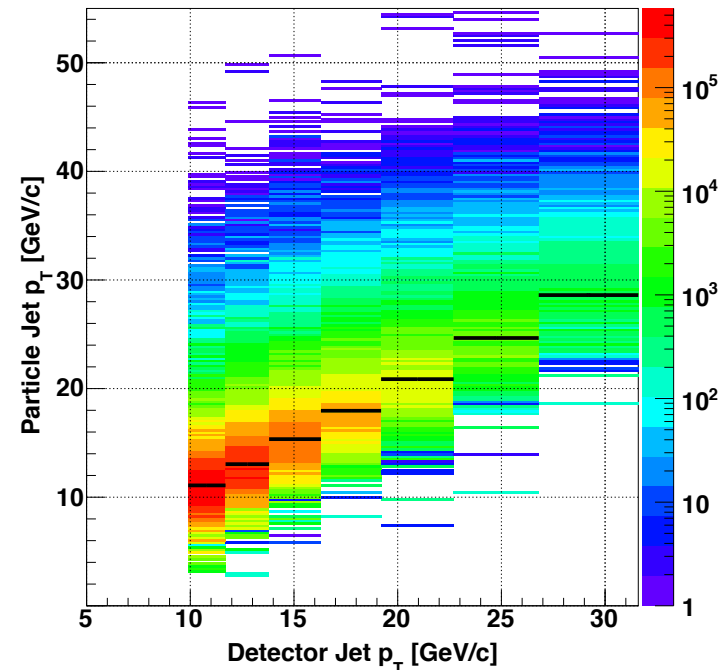
2012

- 20 pb⁻¹ transversely polarized p+p collisions at $\sqrt{s} = 200$ GeV
- Average event weighted polarization: 63%
- Anti-k_T (R = 0.6) jet reconstruction
- $|\eta_{\text{jet}}| < 1$
- Jet p_T > 10 GeV/c ($x_T > 0.1$) reduces gluon contamination
- $\Delta R_{\text{min}} > 0.1$



Systematic Uncertainties

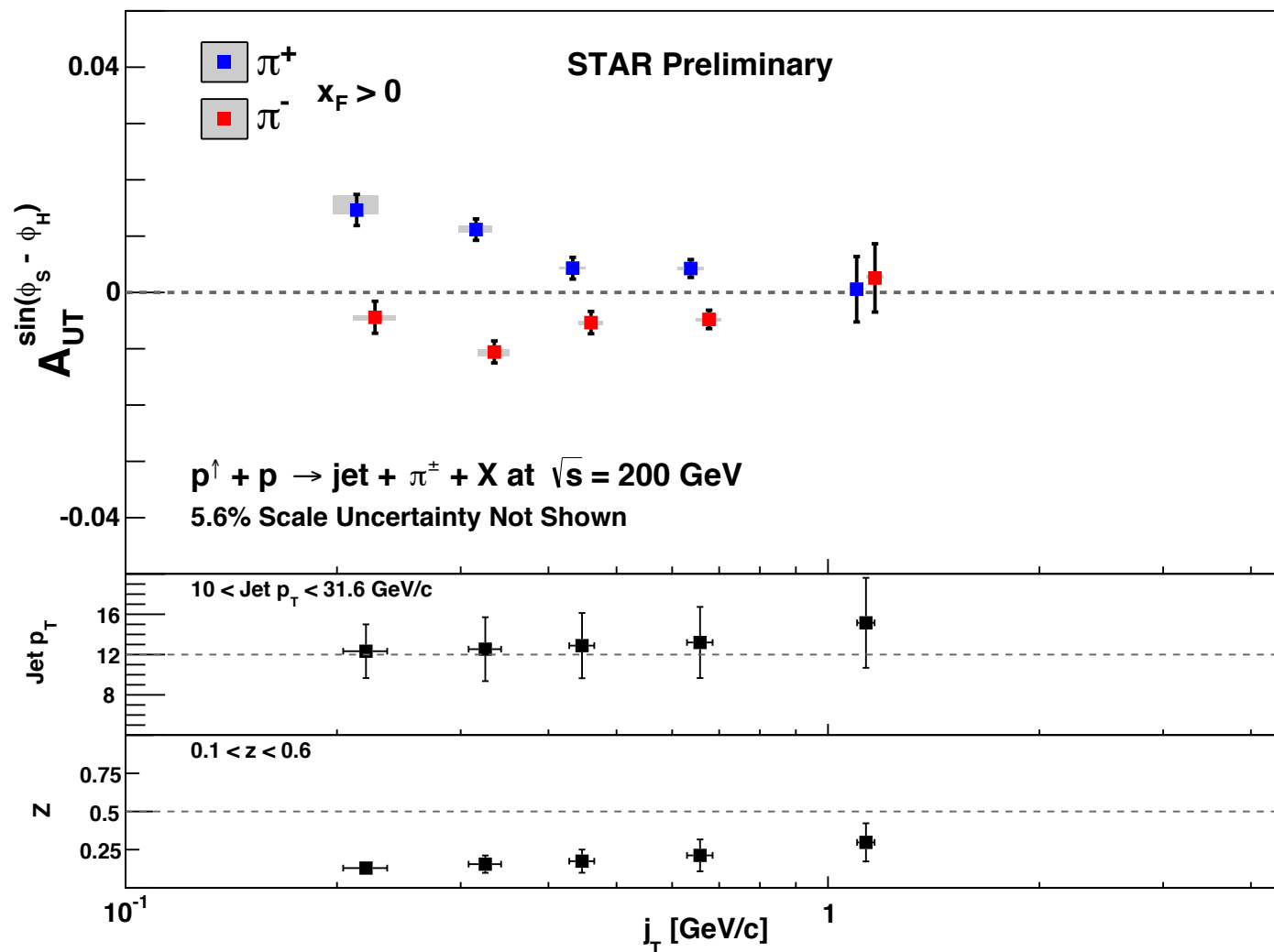
- Use PYTHIA+GEANT to simulate STAR response to QCD processes
 - Embed detector response into zero-bias data
- Correct z , p_T , and j_T to particle level
- Simulation used to estimate systematic errors



Uncertainty	200 GeV	500 GeV
Pion Mis-Identification	< 3%	< 20%
φ_c Reconstruction Bias	< 30%	< 7% on correction
Trigger Bias	5%	< 17% (low $\langle p_T \rangle$)
“Leak Through”	Negligible	< 5%

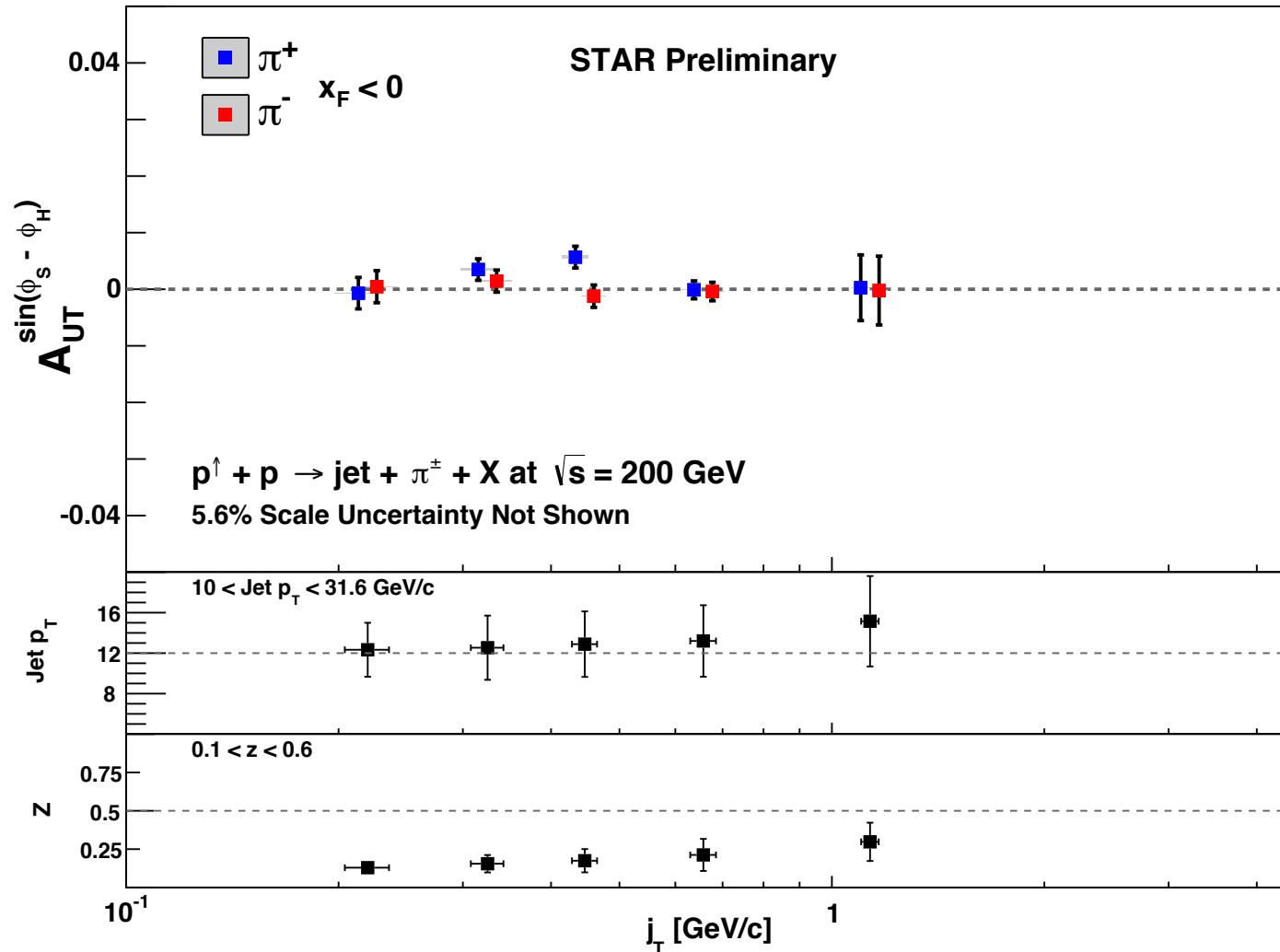
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. j_T for $x_F > 0$



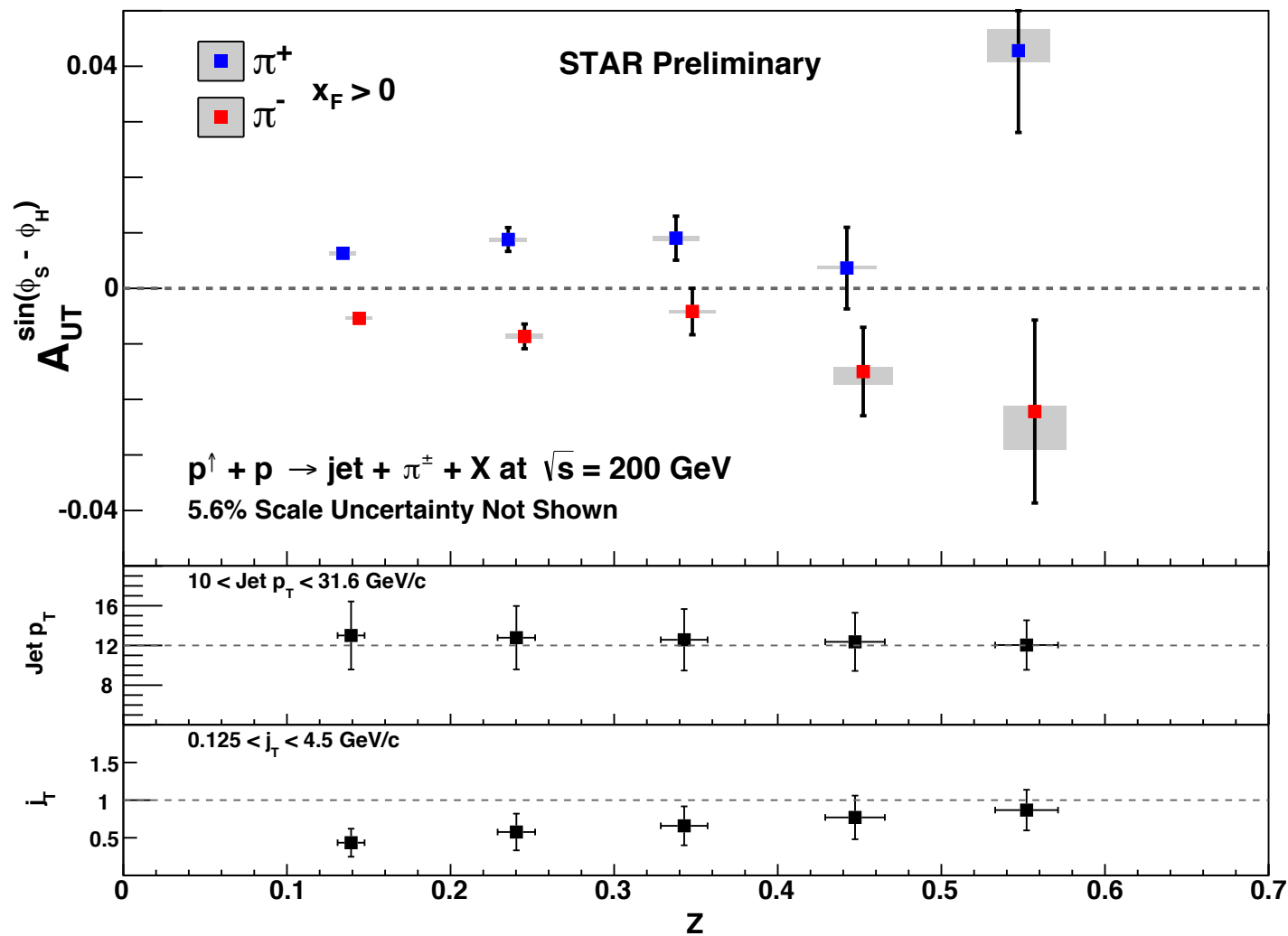
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. j_T for $x_F < 0$



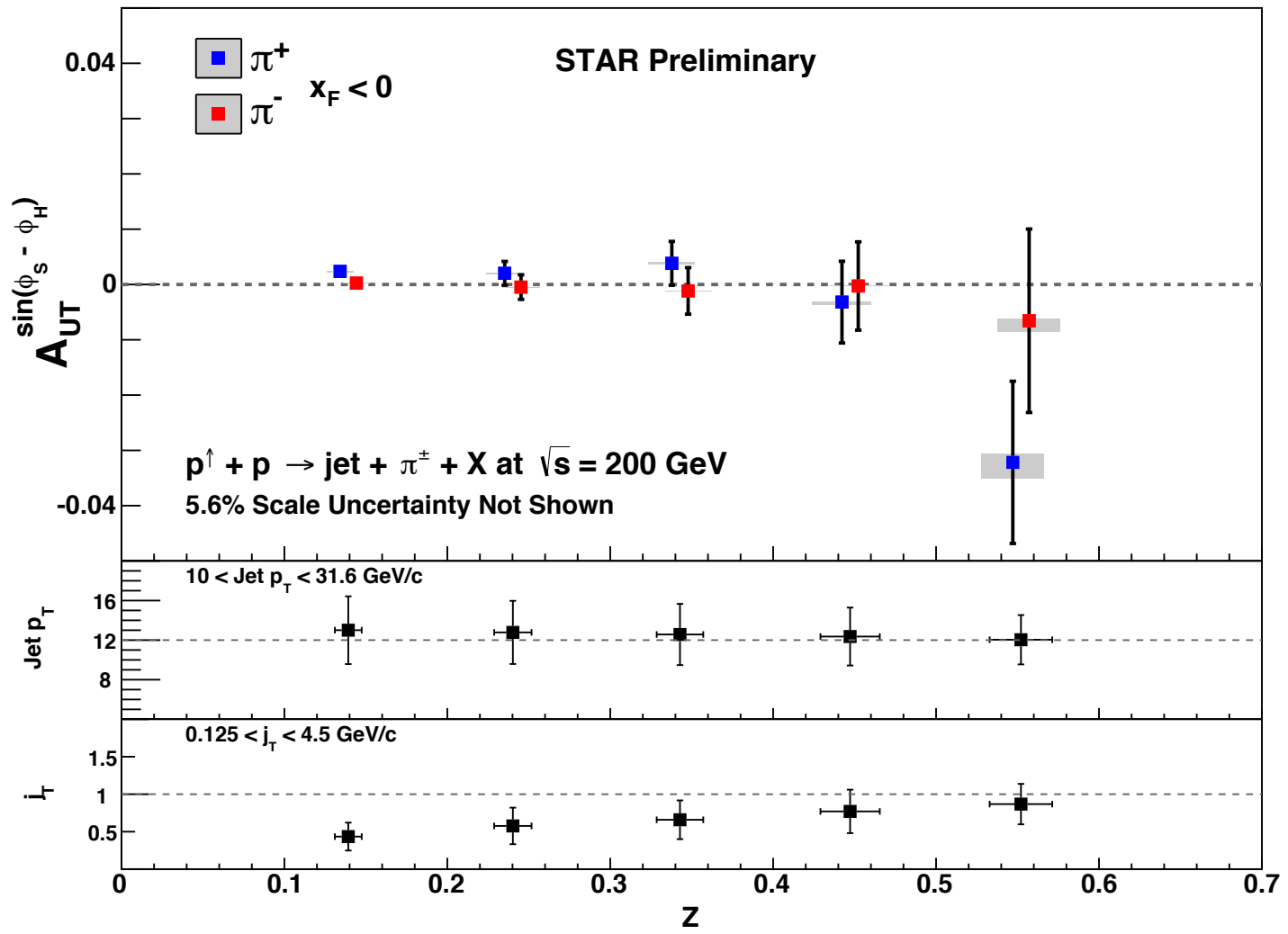
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. z for $x_F > 0$



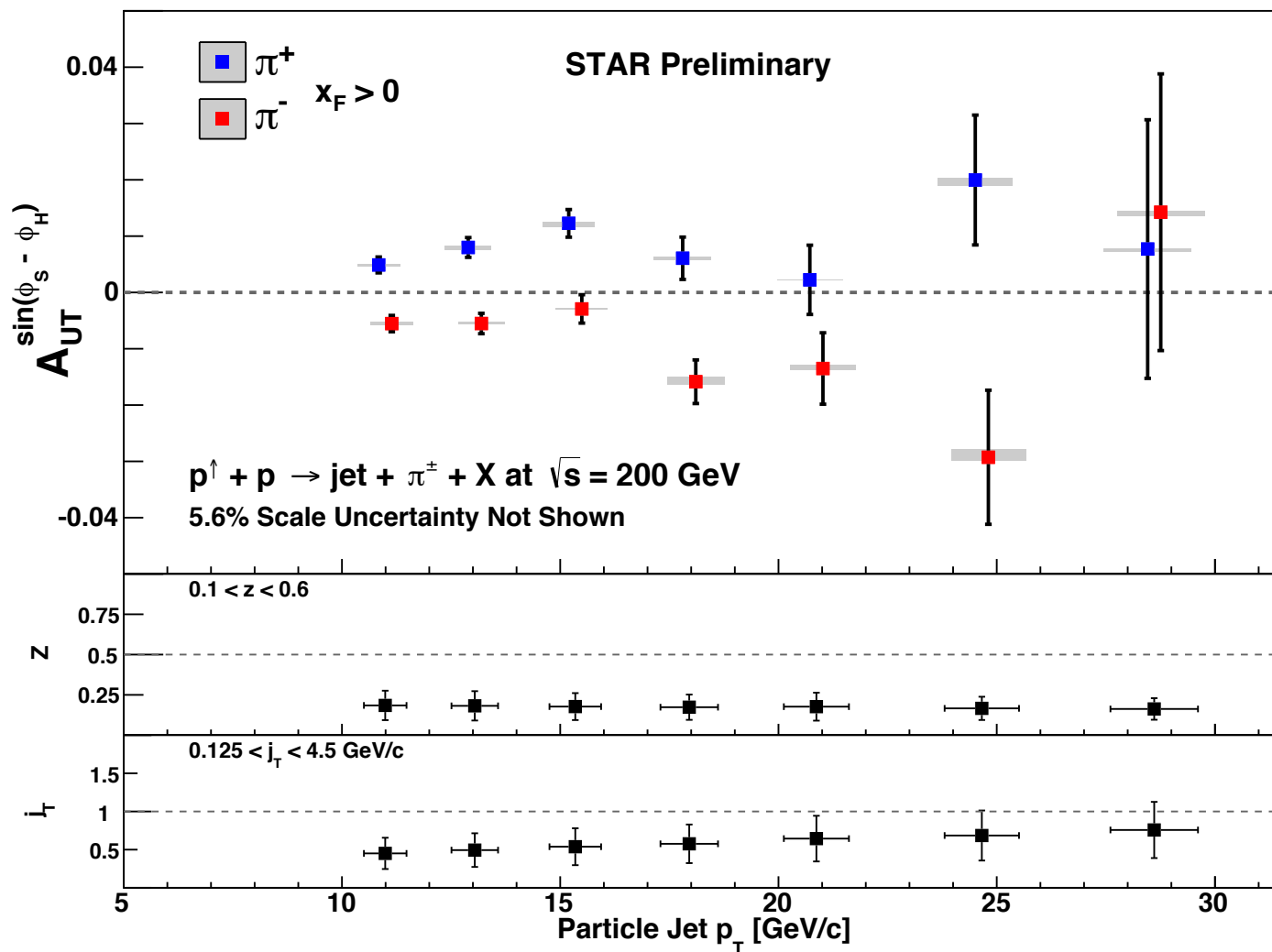
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. z for $x_F < 0$



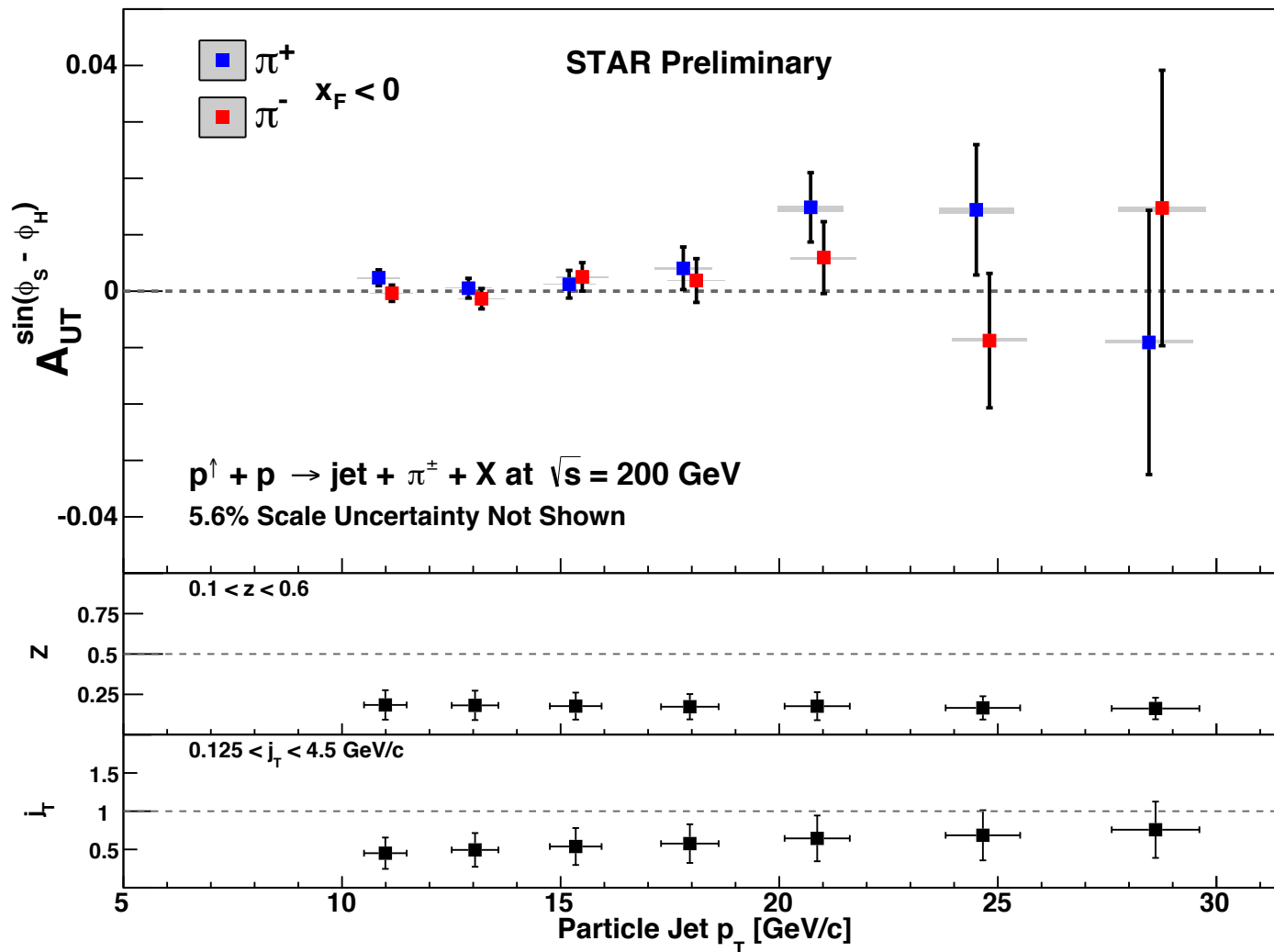
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. p_T for $x_F > 0$



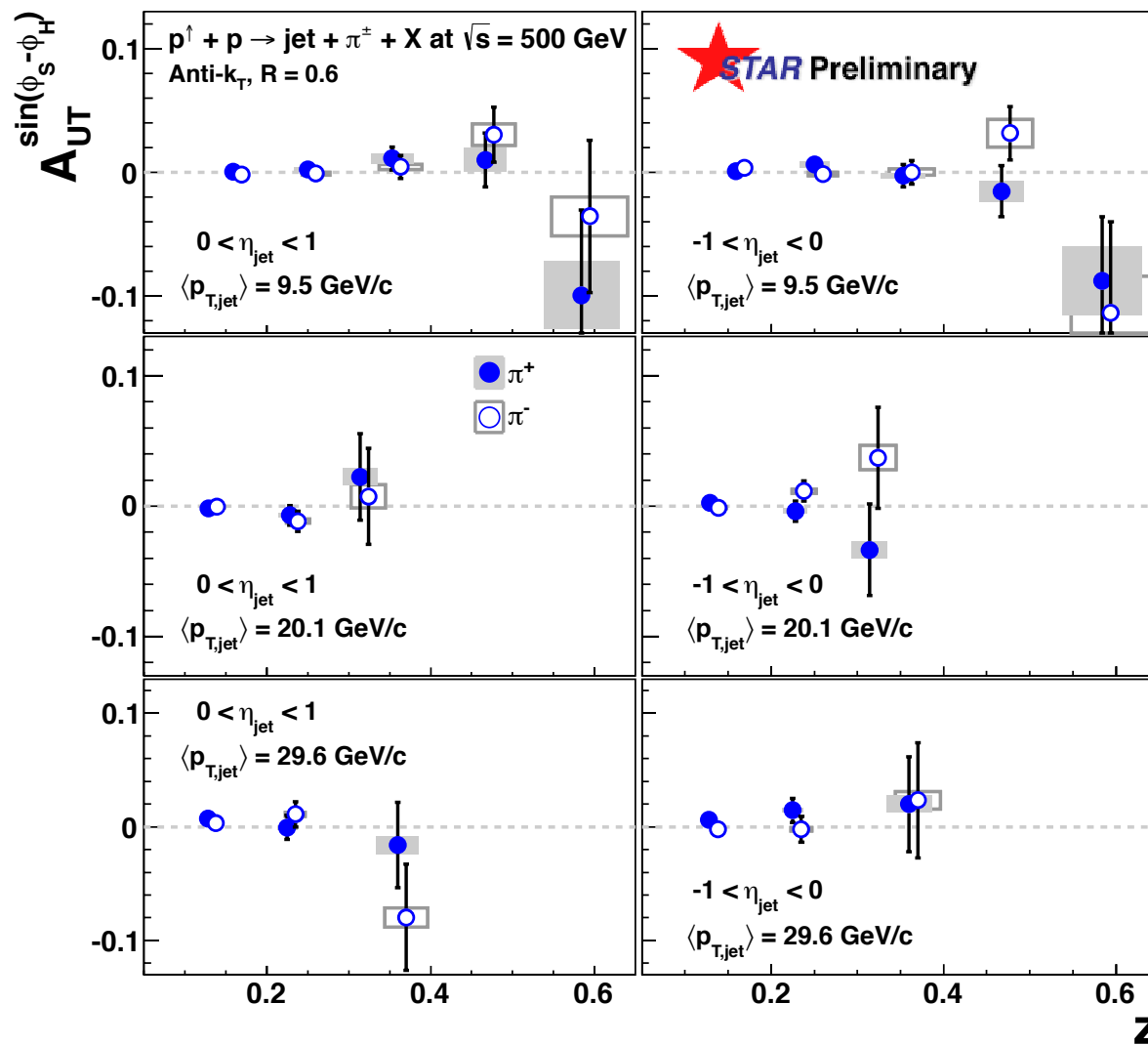
$\sqrt{s} = 200 \text{ GeV}$

A_{UT} vs. p_T for $x_F < 0$



$\sqrt{s} = 500 \text{ GeV}$

A_{UT} vs. z



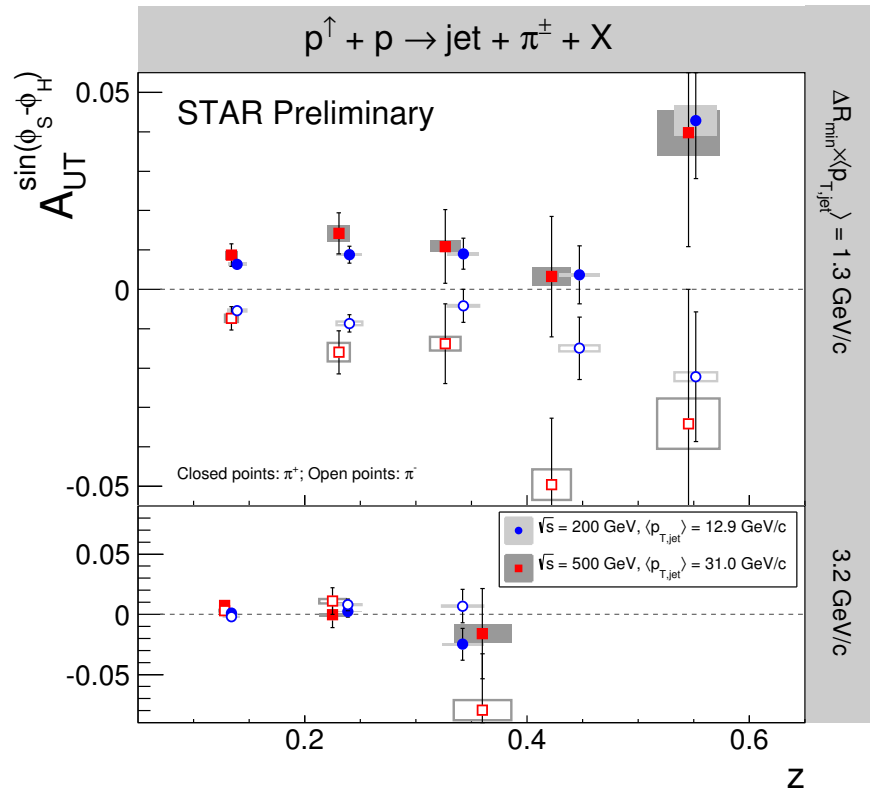
Is 200 GeV Consistent with 500 GeV?

- π^\pm kinematics are dictated by the ΔR_{\min} cut

$$\langle j_T \rangle_{\min} \approx z \times \Delta R_{\min} \times \langle p_T \rangle$$

- Collins z asymmetry is driven by the z and j_T correlation
- If $\langle j_T \rangle$ too large, there will be no observed asymmetry in z
- ΔR_{\min} cut *was* the same for 2011 and 2012 analyses
 - Causes 500 GeV analysis to sample a **higher** $\langle j_T \rangle$
- What happens if the ΔR_{\min} cut is lowered in 500 GeV analysis to match with the 200 GeV $\langle j_T \rangle$?
 - Similarly for the converse: raising ΔR_{\min} cut raised in 200 GeV analysis to match up with 500 GeV $\langle j_T \rangle$

200 vs. 500 GeV Comparison



- Matching kinematics to sample lower $\langle j_T \rangle$ (top) shows that the two energies have asymmetries which are extremely similar in shape and magnitude
- The higher $\langle j_T \rangle$ asymmetries (bottom) both go away
- Resulting asymmetries are quite sensitive to the sampled π^\pm kinematics

Summary

- **The Collins asymmetry is a unique channel to access transversity**
 - Jet asymmetries in p+p collisions offer the unique ability to map out the j_T dependence of the Collins asymmetries, test the universality of the TMD observables and quantify factorization breaking effects in hadronic collisions.

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- **These results are the first statistically significant non-zero Collins asymmetries measured in hadronic collisions**
 - Greater than 6σ in $\sqrt{s} = 200$ GeV
 - Greater than 5σ in $\sqrt{s} = 500$ GeV

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- **These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the Q^2 evolution and universality of TMD functions**
- During current RHIC run, STAR expects to record twice the 2012 data set, allowing for more detailed multi-dimensional study of the Collins effect

Backup

Single-Spin Asymmetries (SSA)

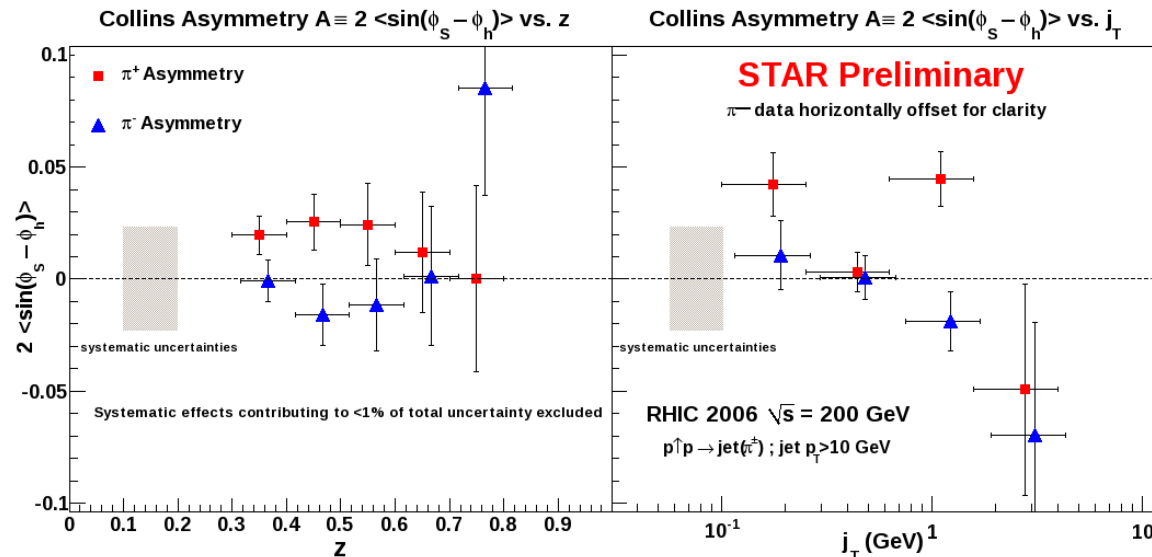
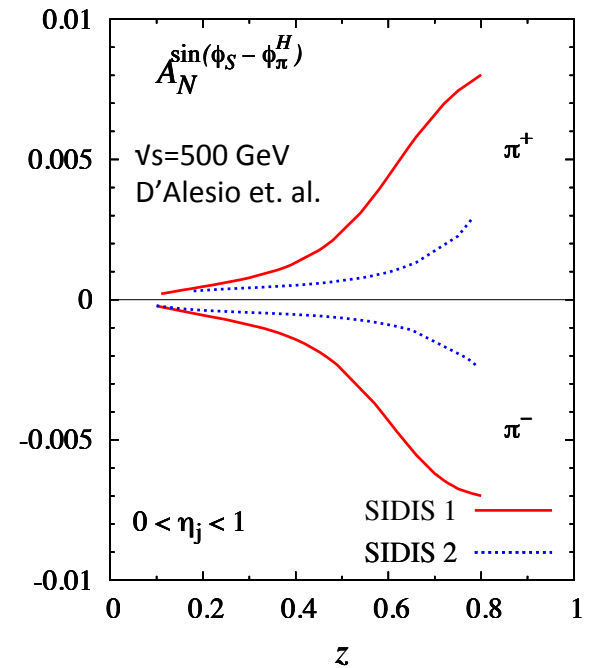
- There are multiple contributions to transverse single-spin asymmetries in the TMD framework
- STAR is sensitive to several modulations

Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \cdot f_{b/B} \cdot D_{\pi/q}$	Sivers•PDF•FF	$\sin(\varphi_{S_A})$
$h_1^a \cdot \Delta^N f_{b\uparrow/B} \cdot D_{\pi/q}$	Transversity•Boer-Mulders•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \cdot \Delta^N f_{b\uparrow/B} \cdot D_{\pi/q}$	Pretzelosity•Boer-Mulders•FF	$\sin(\varphi_{S_A})$
$h_1^a \cdot f_{b/B} \cdot \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \cdot \Delta^N f_{b\uparrow/B} \cdot \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \cdot f_{b/B} \cdot \Delta D_{\pi/q\uparrow}$	Pretzelosity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \cdot \Delta^N f_{b\uparrow/B} \cdot \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

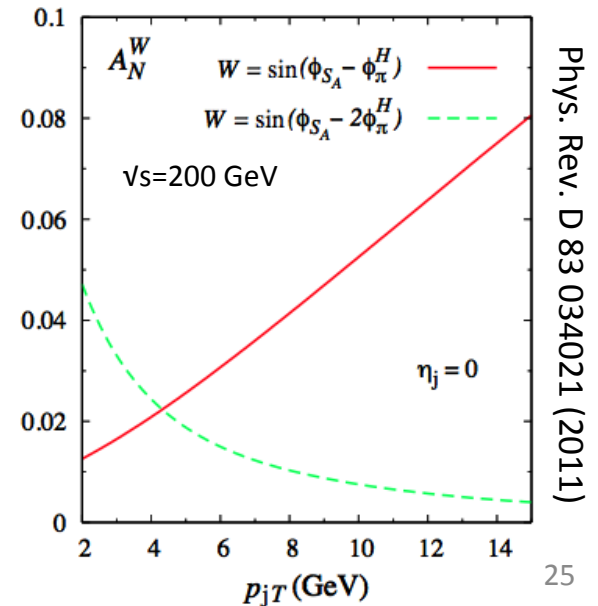
*Analogous modulations for gg scattering also exist Phys. Rev. D 83 034021 (2011)

Previous STAR Results and Theory

- Non-zero Collins asymmetries predicted at midrapidity for 200 GeV proton collisions
- Hints of significant statistical differences in asymmetries for the two charges found in previous 2006 Collins measurement at STAR
 - Systematic errors are very large



AIP Conf. Proc. 1441, 233 (2012)



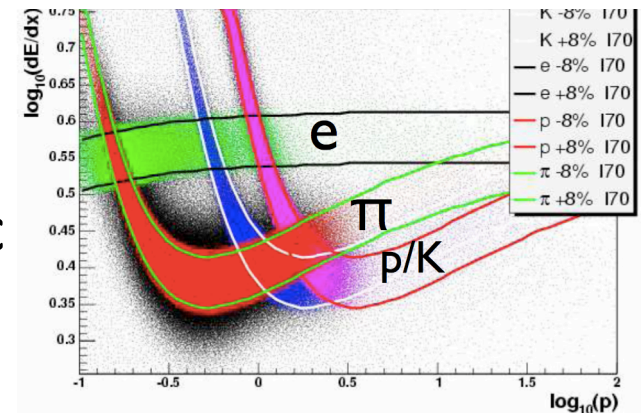
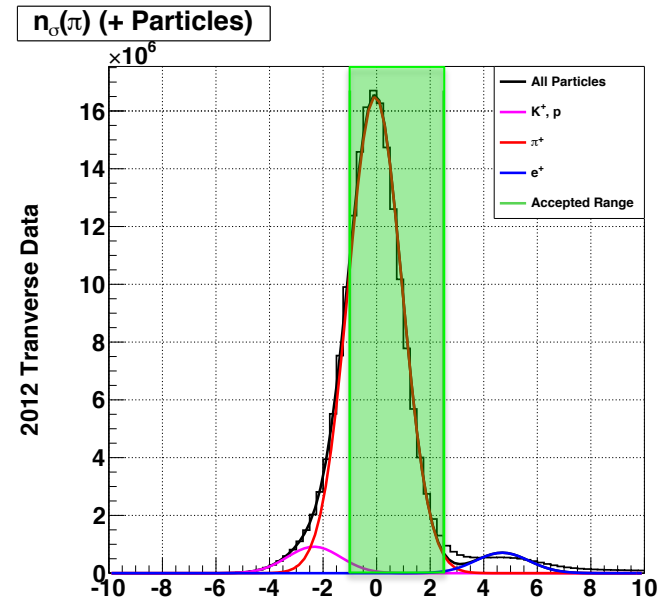
Phys. Rev. D 83 034021 (2011)

Identifying Charged Pions

- Pions identified from TPC track dE/dx
- Use $-1 < n_{\sigma}(\pi) < 2.5$ cut to identify pions in jets

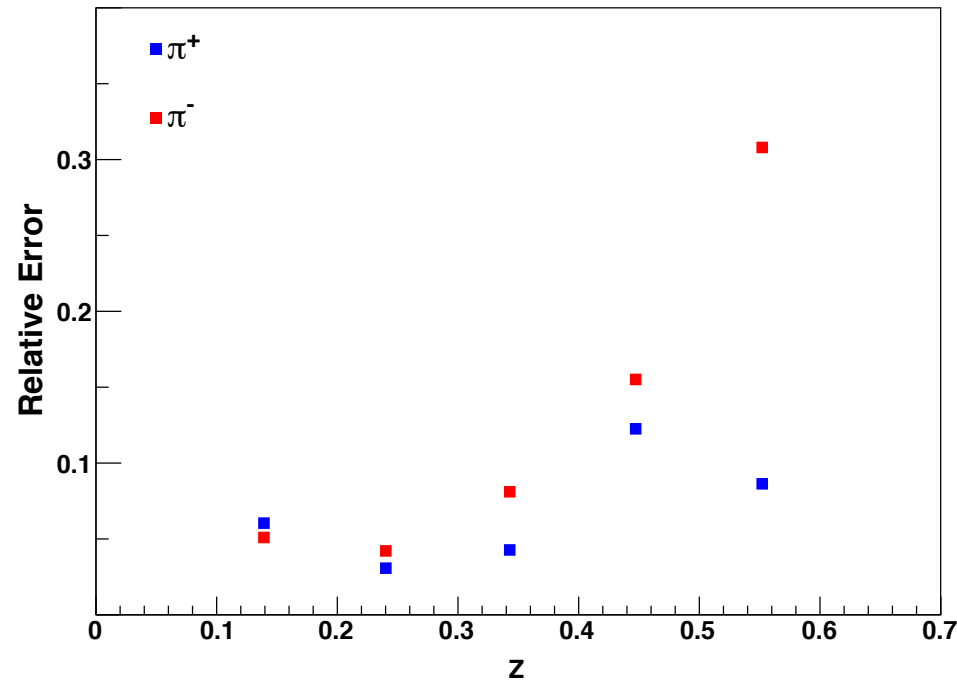
$$n_{\sigma}(\pi) = \frac{1}{\sigma_{\text{exp}}} \ln \left(\frac{dE/dx_{\text{obs}}}{dE/dx_{\pi, \text{calc}}} \right)$$

- Kaons, protons, and electrons contaminate the pion sample
- This contamination is p_T independent contributes less than 3% to the overall systematic uncertainty



φ_c Reconstruction Bias

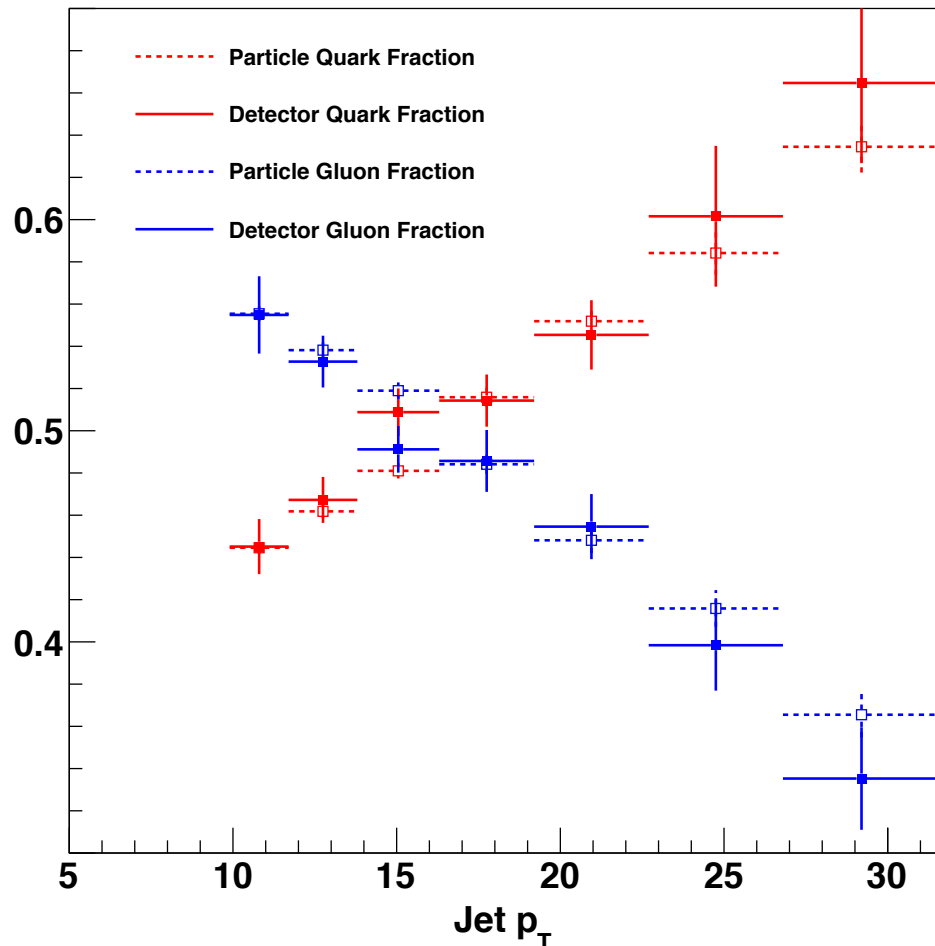
- Detector resolution and incorrect reconstruction of φ_c will decrease measured asymmetry
- Seed simulation with an asymmetry weight extracted from data
- Repeat analysis at detector and particle levels of simulation, and extract asymmetry
- Relative error gives estimate of φ_c resolution and reconstruction errors



$$Error = \frac{A_{UT}^{Particle} - A_{UT}^{Detector}}{A_{UT}^{Detector}}$$

Trigger Bias

- Trigger used to collect this data is biased towards quark jets
- Increased quark contributions will enhance measured asymmetry
- Contributes 5% to overall systematic uncertainty



Flavor Matching Fractions

