First Observation of Collins Asymmetries for Charged Pions in Jets in $p^{\uparrow}p$ Collisions at STAR

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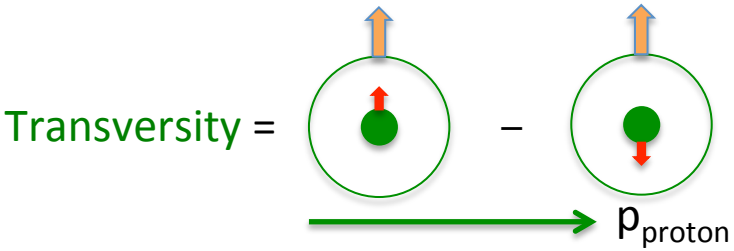
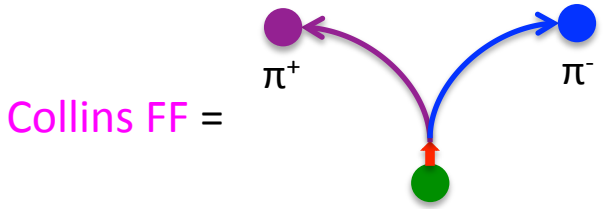
APS Division of Nuclear Physics – Fall Meeting 2015
Santa Fe, NM
October 29, 2015

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



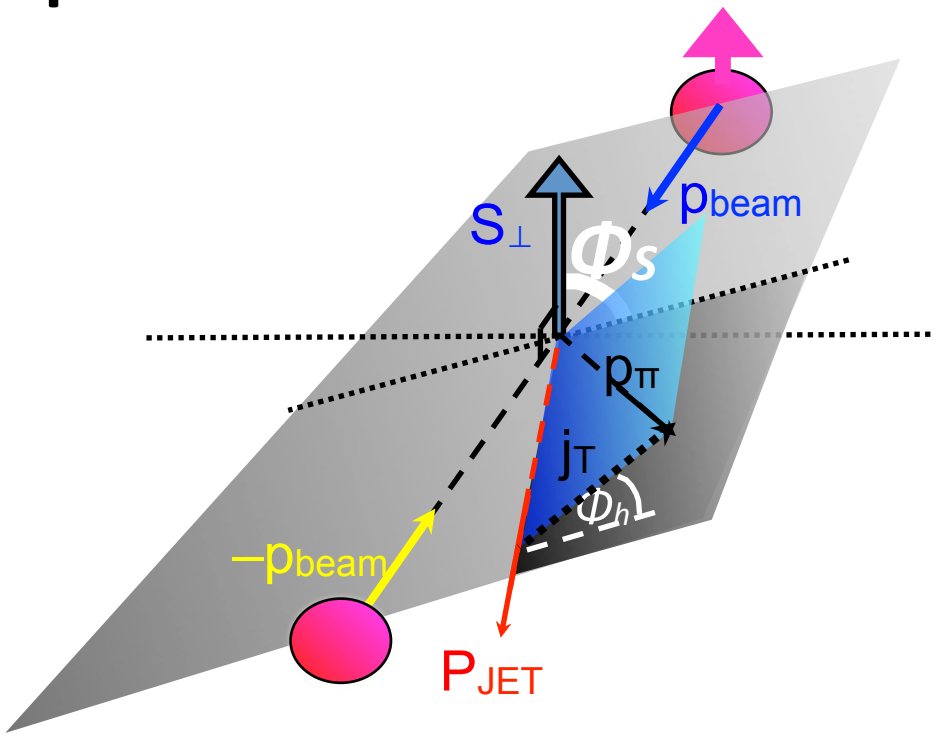


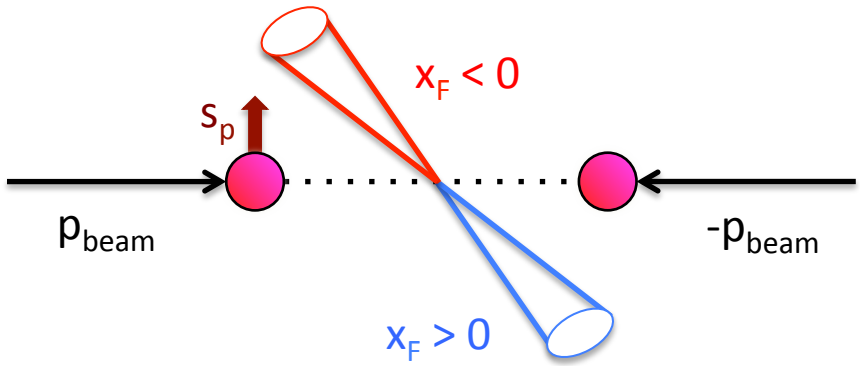
$$A_{UT}^{\pi^{\pm}} \approx \frac{h_1^{q_1}\left(x_1,Q^2\right) f_{q_2}\left(x_2,Q^2\right)\hat{\sigma}_{UT}(\hat{s},\hat{t},\hat{u})\,\Delta D_{q_1}^{\pi^{\pm}}\left(z,j_T\right)}{f_{q_1}\left(x_1,Q^2\right) f_{q_2}\left(x_2,Q^2\right)\hat{\sigma}_{UU} D_{q_1}^{\pi^{\pm}}\left(z,j_T\right)}$$

- 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 Q^2?

Single Spin $p^{\uparrow}p$ Collisions

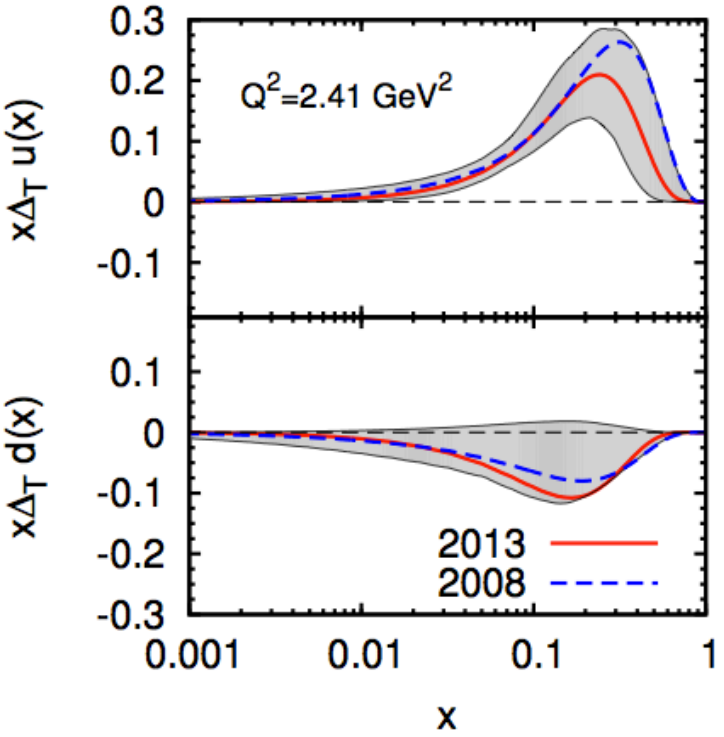
- ϕ_S is defined as the angle between proton spin and reaction plane
- j_T defines particle transverse momentum relative to the jet
- ϕ_H defines angle between jet particle transverse momentum and reaction plane
- $\phi_C = \phi_S - \phi_H$ (Collins Angle)
- Collins modulation
  - $\sin(\phi_S - \phi_H)$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

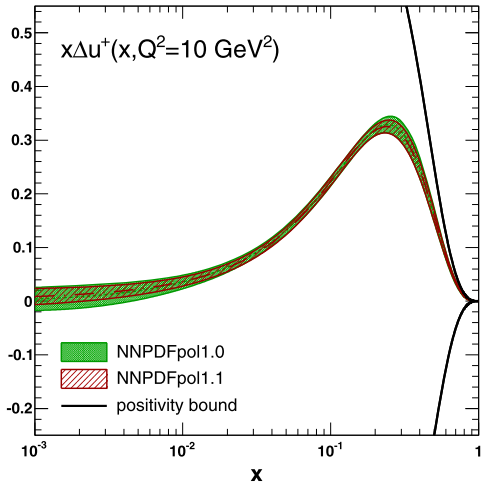


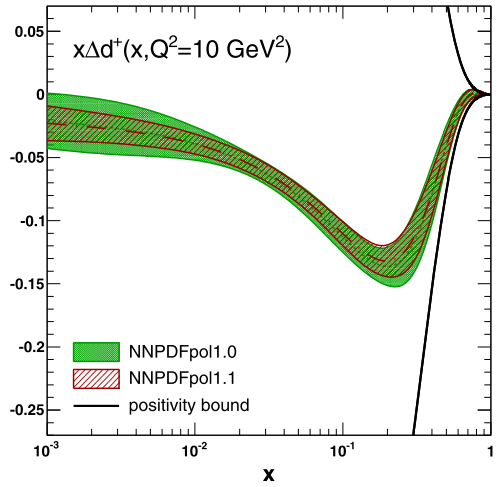


Knowledge of Transversity

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





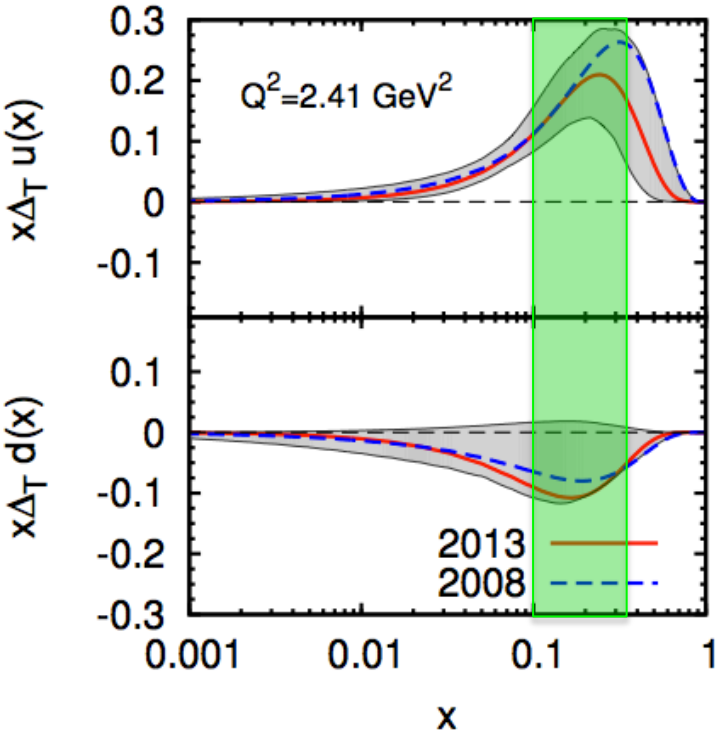


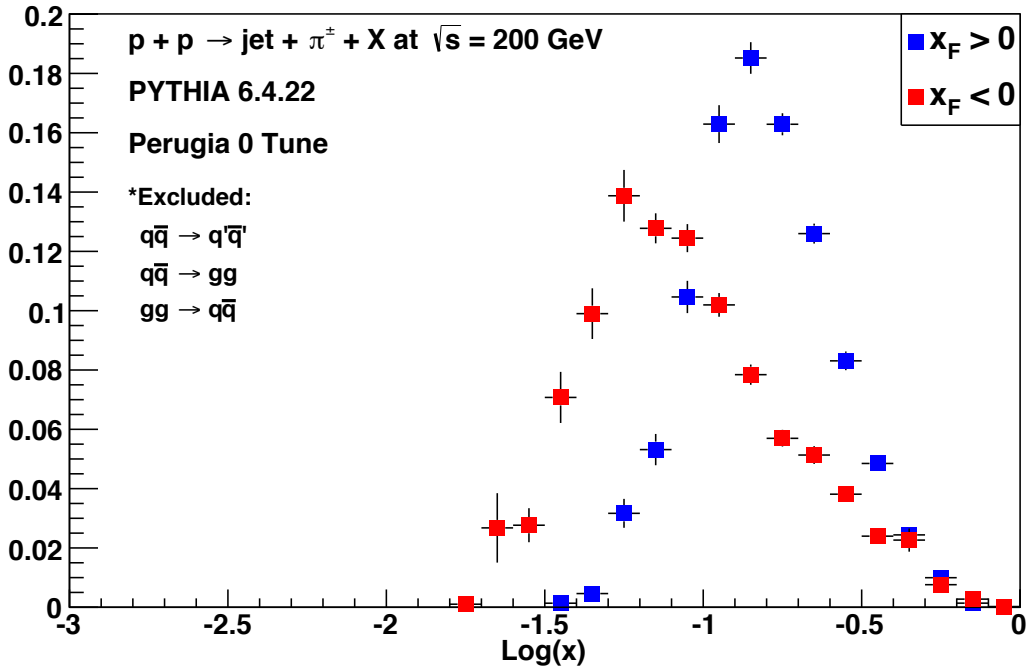
Nuclear Physics B, Vol 887 (2014)

Phys. Rev. D **87** 094019 (2013); See also: arXiv:1505.05589

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 √s = 200 GeV and 500 GeV analyses
- This x range samples the unconstrained portion of $h_1(x)$





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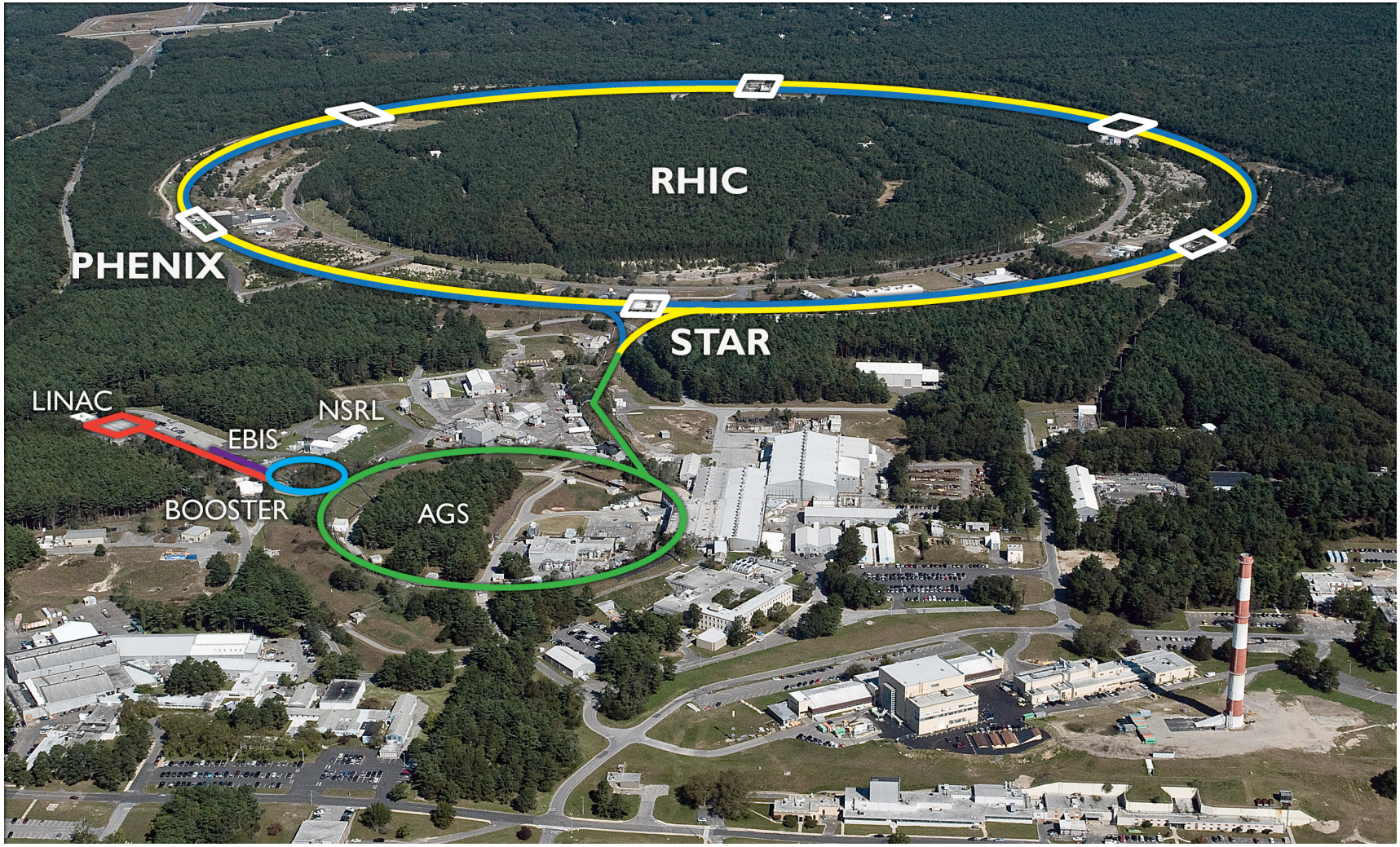
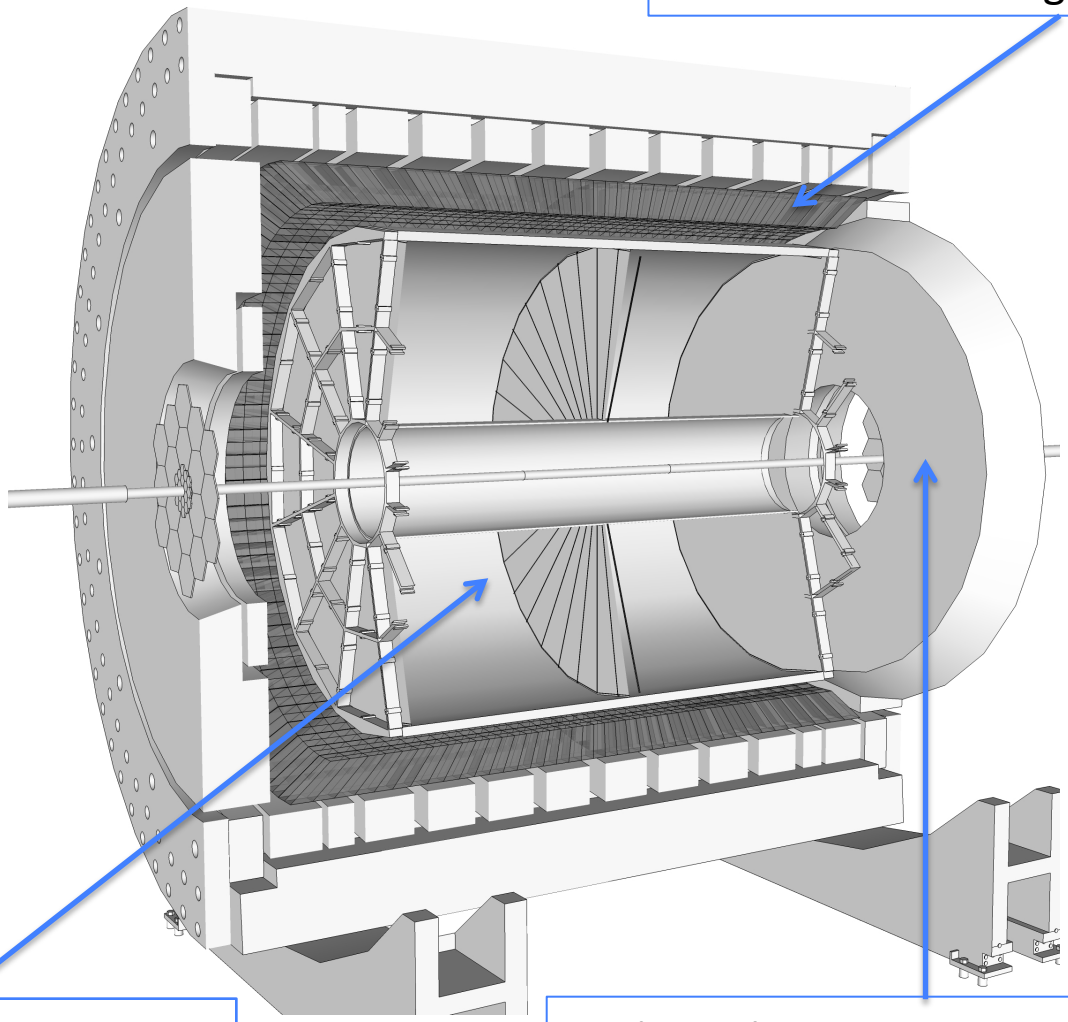
Relativistic Heavy Ion Collider



Solenoidal Tracker At RHIC



Data and Cuts

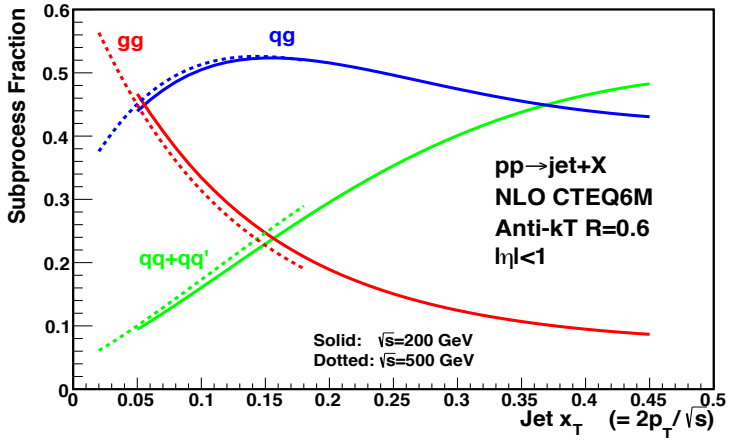
2011

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

2012

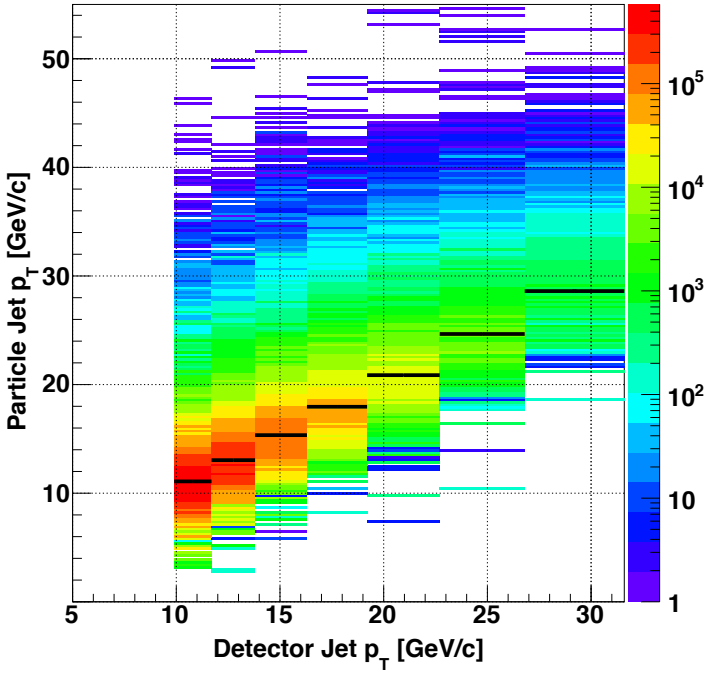
- 20 pb^{-1} transversely polarized p+p collisions at √s = 200 GeV
- Average event weighted polarization: 63%
- Anti-k_T (R = 0.6) jet reconstruction
- $|\eta_{jet}| < 1$
- Jet $p_T > 10$ GeV/c ($x_T > 0.1$) reduces gluon contamination
- $\Delta R_{min} > 0.1$

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



Systematic Uncertainties

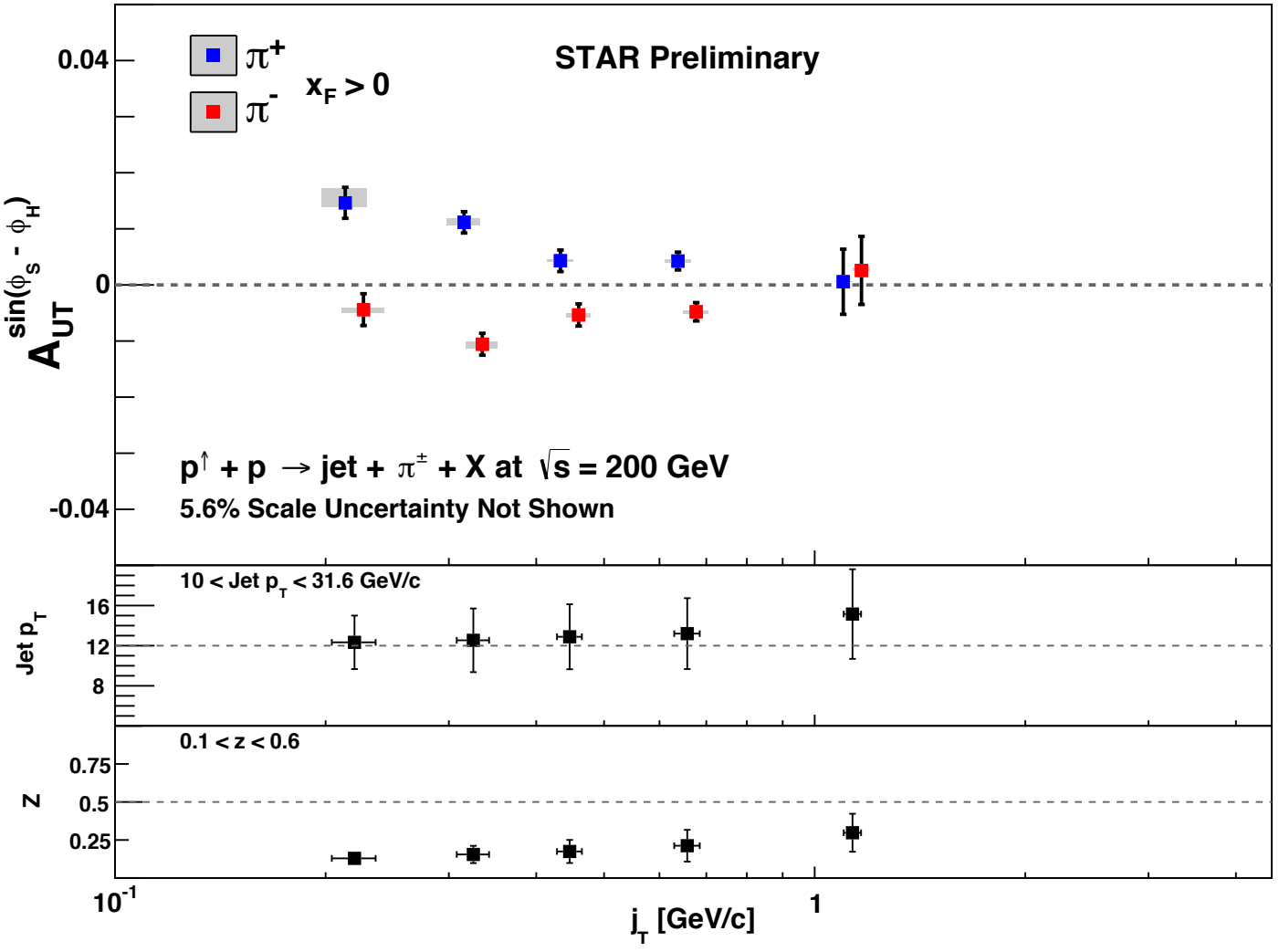
- Use PYTHIA+GEANT to simulate STAR response to QCD processes
  - Embed detector response into zero-bias data
- Correct z, p_T, and j_T to particle level
- Simulation used to estimate systematic errors



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%

√s = 200 GeV

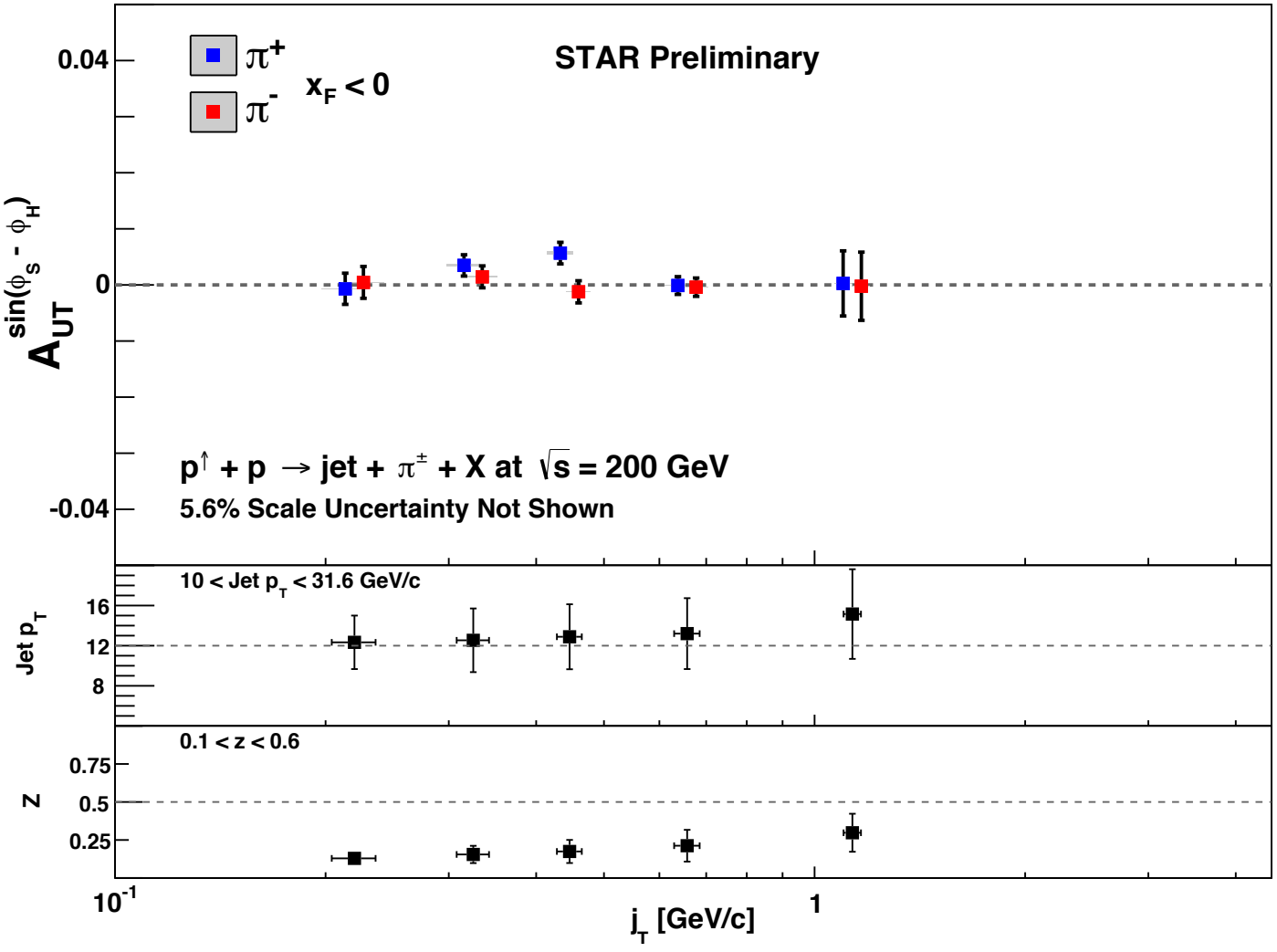
A_{UT} vs. j_T for $x_F > 0$



$$z = \frac{p_\pi}{p_{jet}}$$

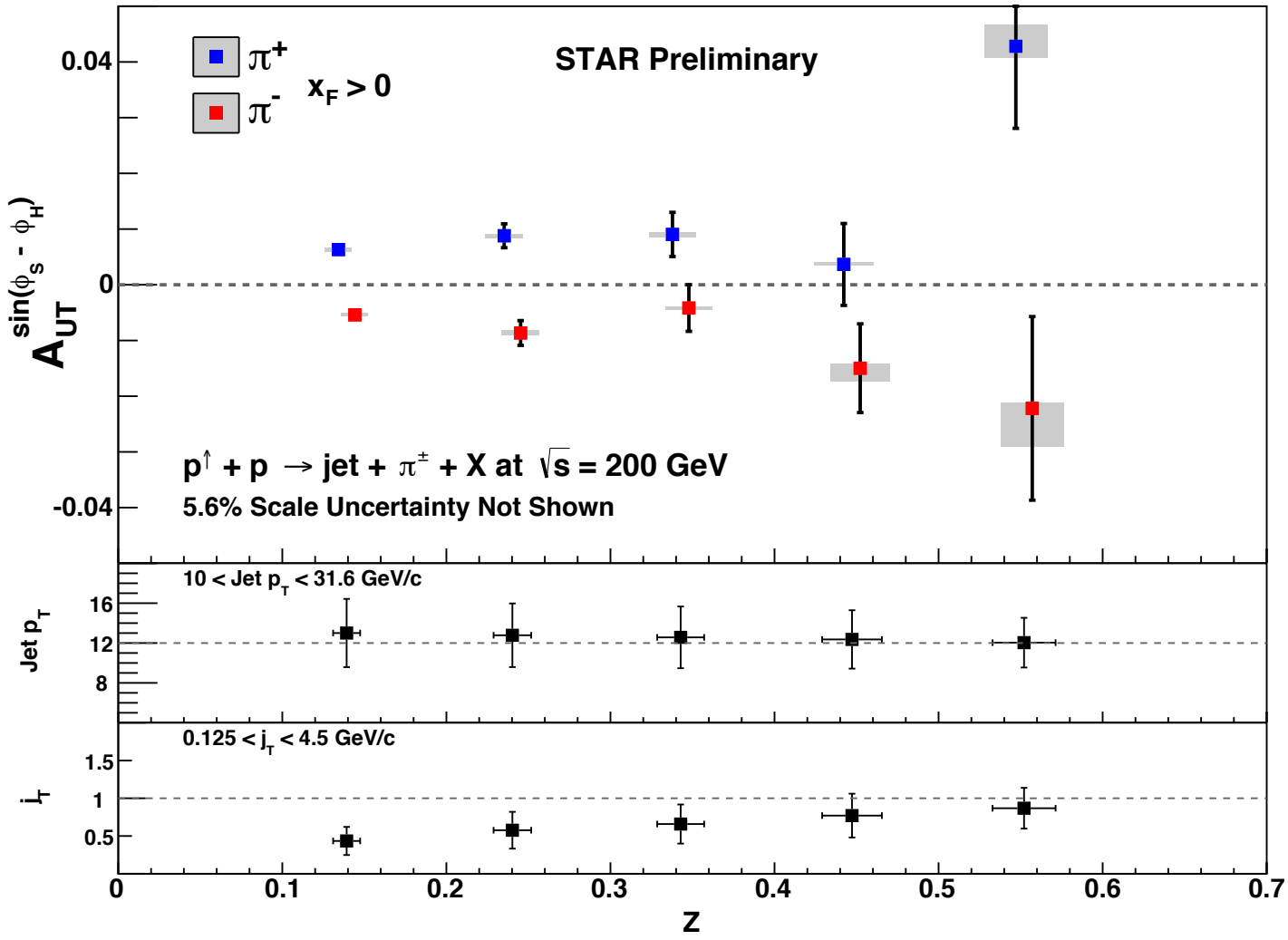
√s = 200 GeV

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



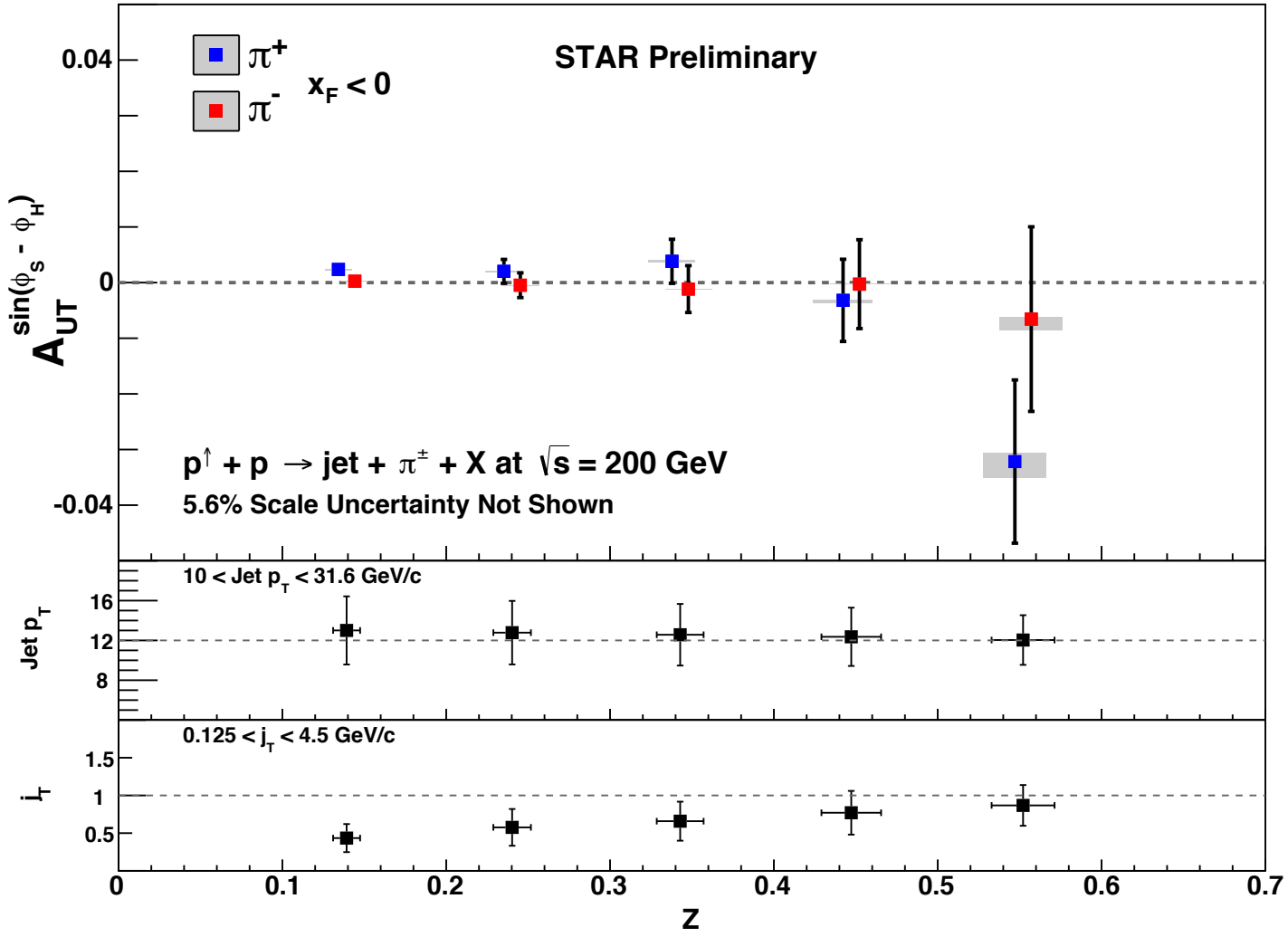
√s = 200 GeV

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



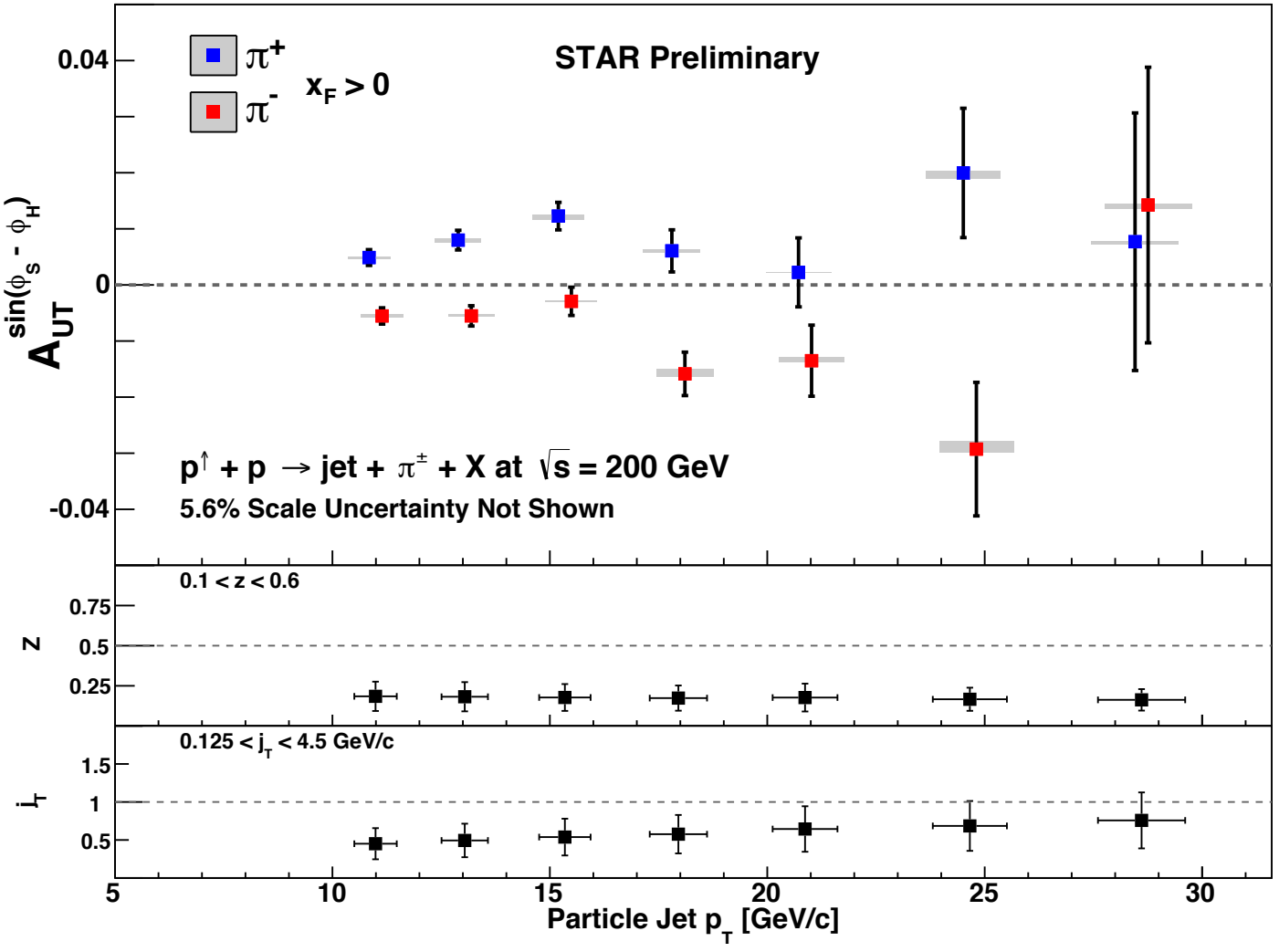
√s = 200 GeV

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



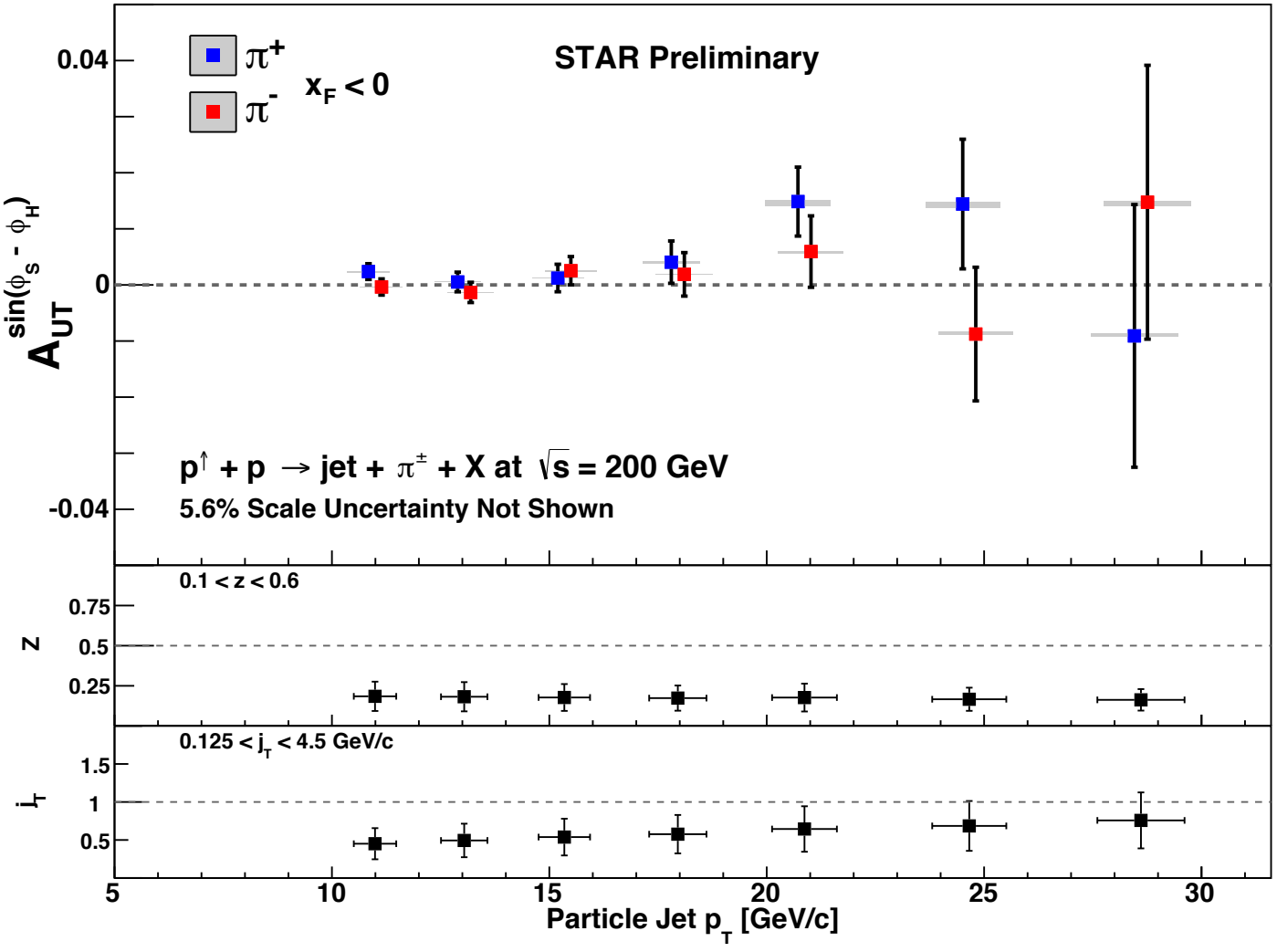
√s = 200 GeV

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



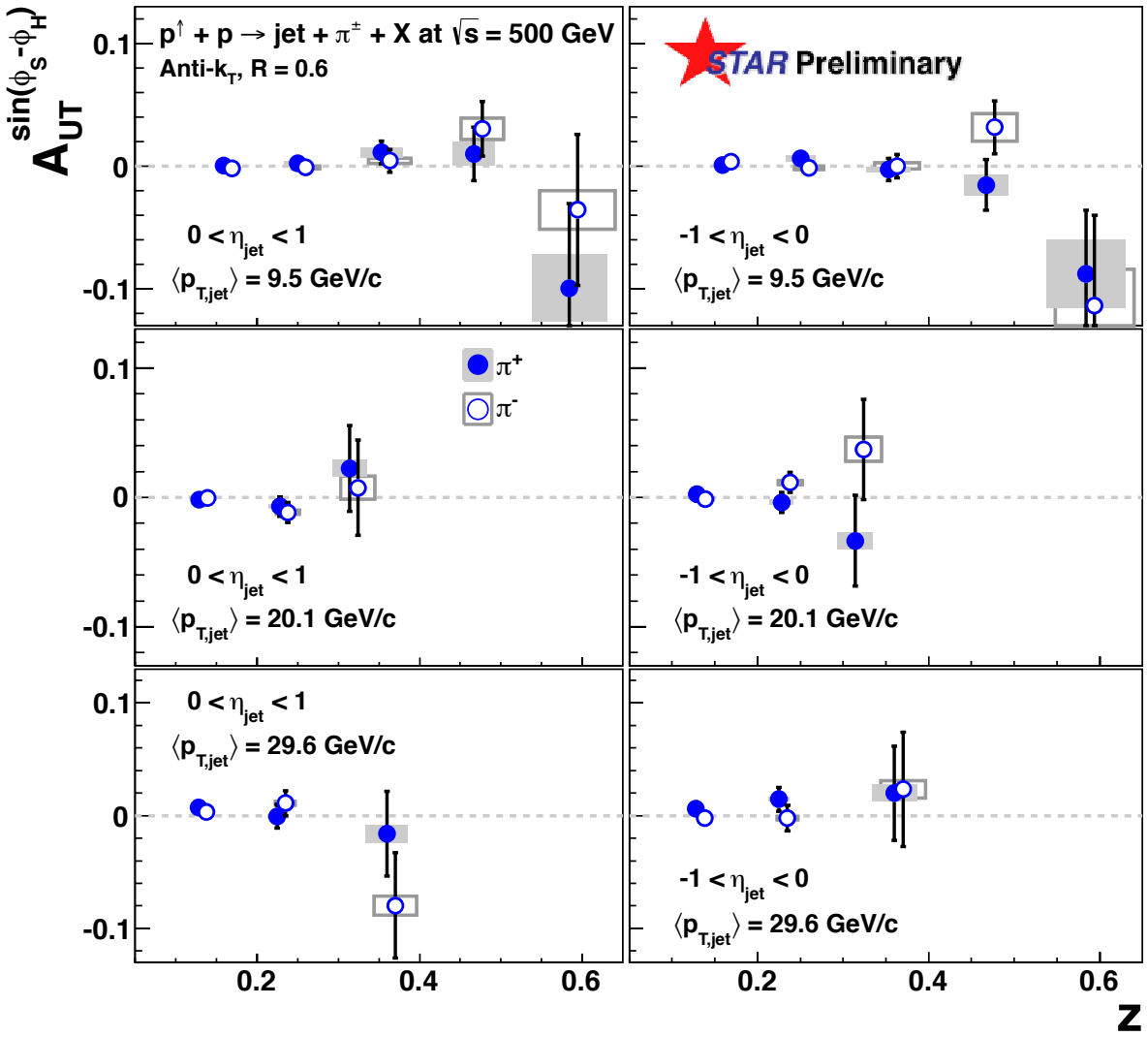
√s = 200 GeV

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



√s = 500 GeV

A_{UT} vs. z



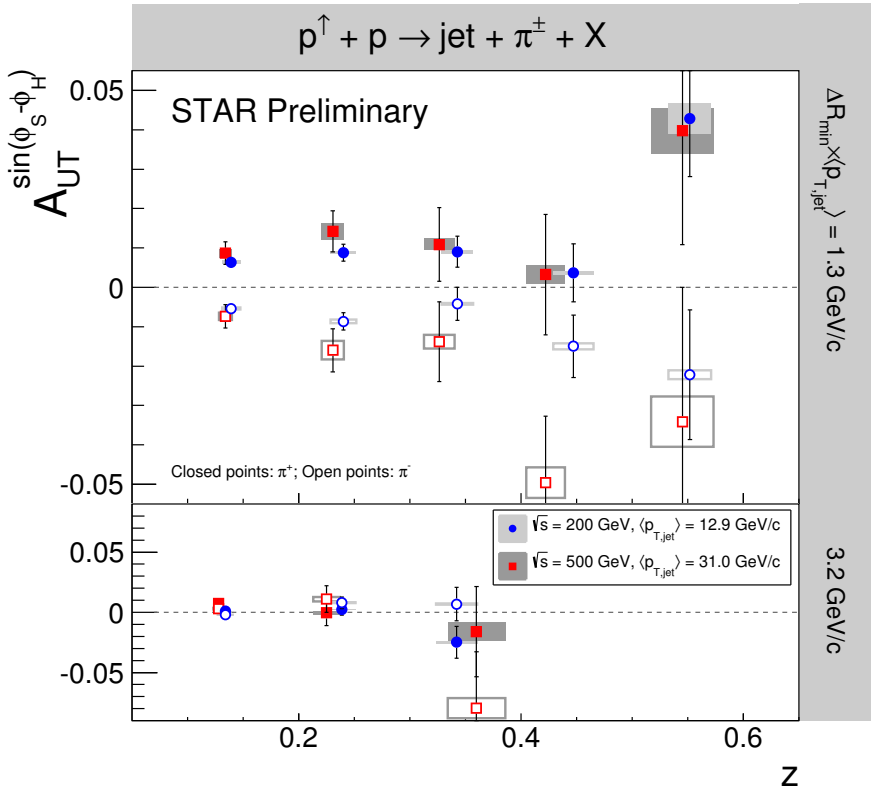
Is 200 GeV Consistent with 500 GeV?

- $\pi^{\pm}$ 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
- At higher $\langle j_T \rangle$, the asymmetries (bottom) both go away
- Resulting asymmetries are quite sensitive to the sampled $\pi^{\pm}$ 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 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**

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- During the 2015 RHIC run, STAR recorded more than twice the 2012 data set, which will allow for a more detailed multi-dimensional study of the Collins effect
- Extraction of Collins asymmetry in p+A collisions will provide insights to spin dependent hadronization in cold nuclear matter

Backup

Single-Spin Asymmetries (SSA)

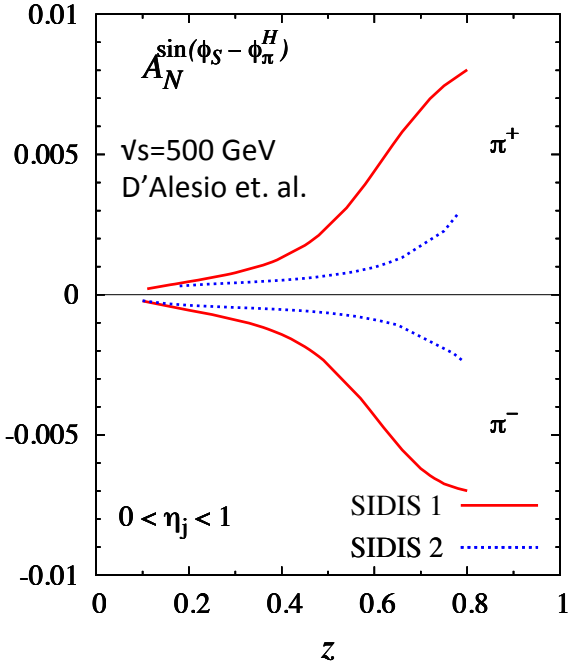
- There are multiple contributions to transverse single-spin asymmetries in the TMD framework
- STAR is sensitive to several modulations

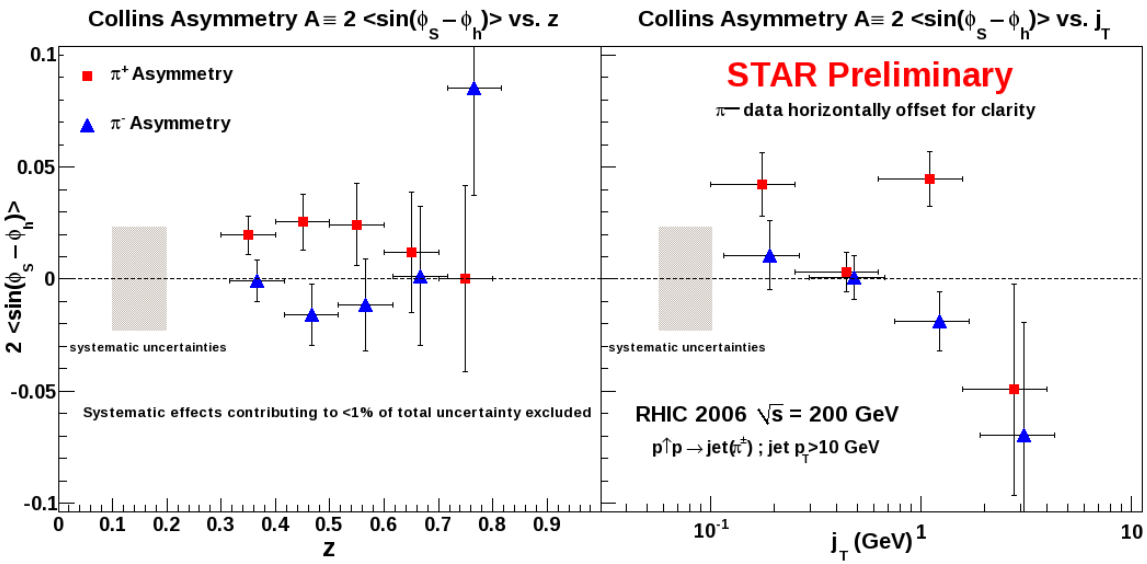
Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers•PDF•FF	$\sin\left(\varphi_{S_A}\right)$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulders•FF	$\sin\left(\varphi_{S_A}\right)$
$h_{1T}^{\perp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

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

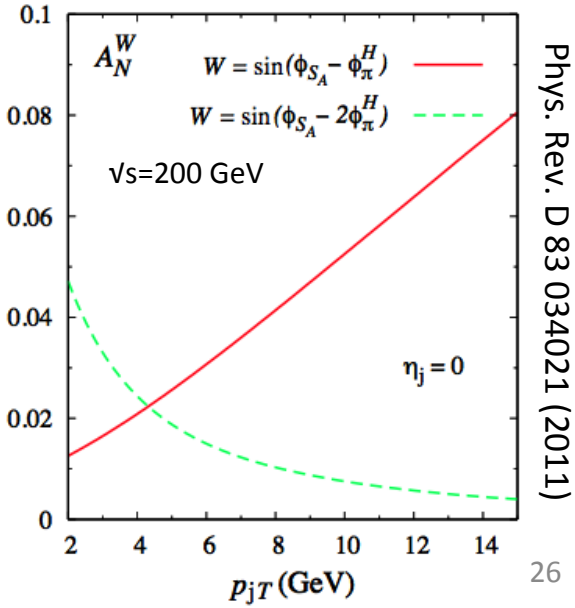
Previous STAR Results and Theory

- 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)



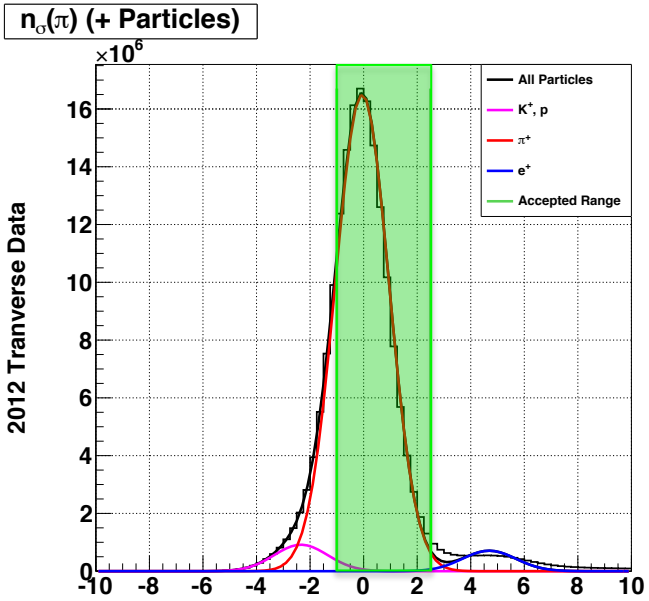
Phys. Rev. D 83 034021 (2011)

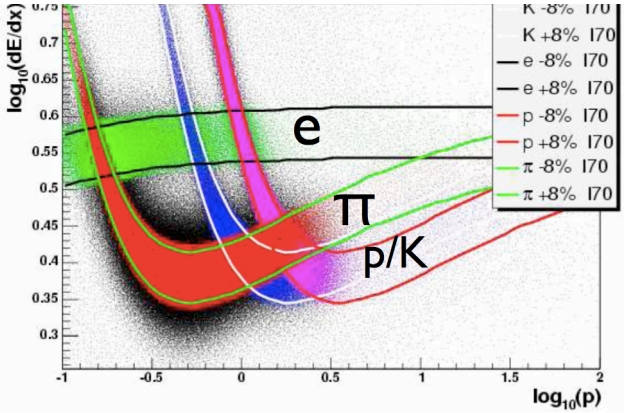
Identifying Charged Pions

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

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

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

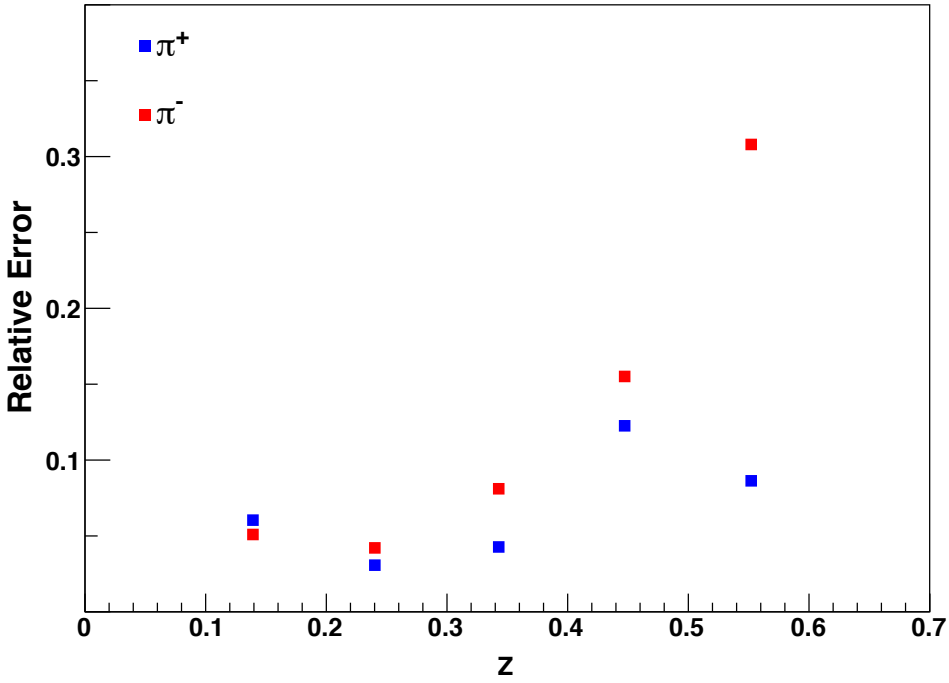




Nucl.Instrum.Meth. A558:419-429,2006

φ_c Reconstruction Bias

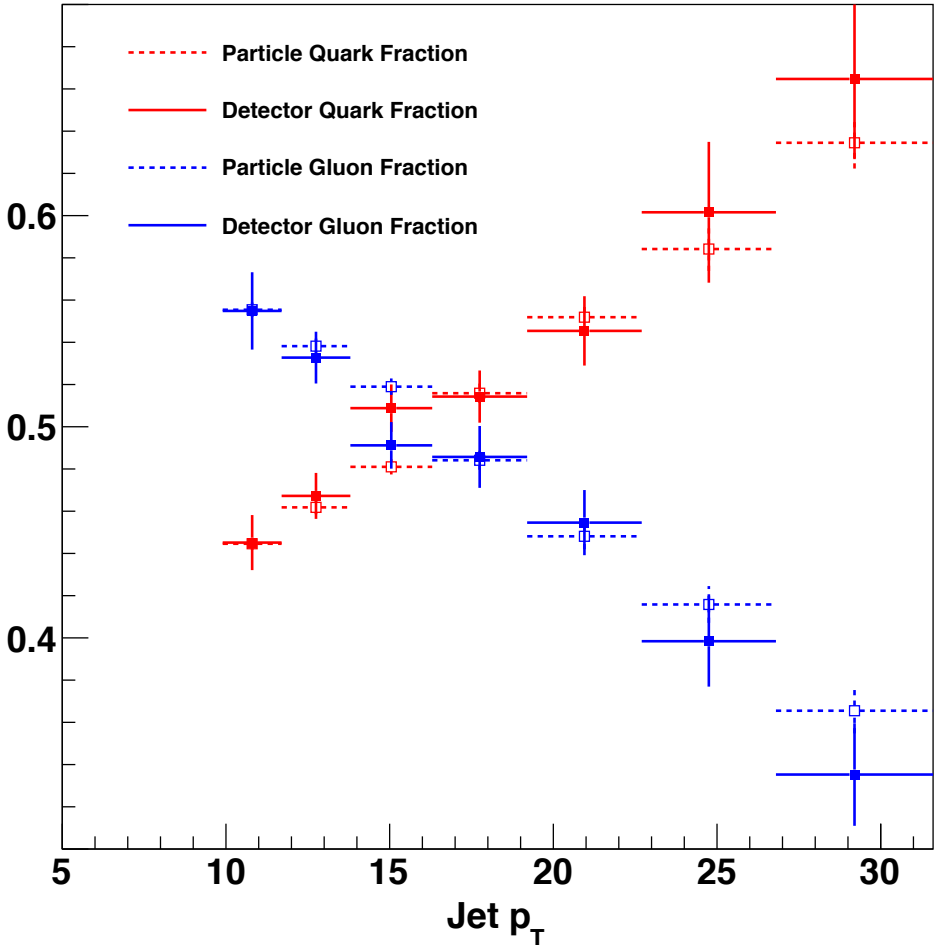
- Detector resolution and incorrect reconstruction of φ_c will decrease measured asymmetry
- Seed simulation with an asymmetry weight extracted from data
- Repeat analysis at detector and particle levels of simulation, and extract asymmetry
- Relative error gives estimate of φ_c resolution and reconstruction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



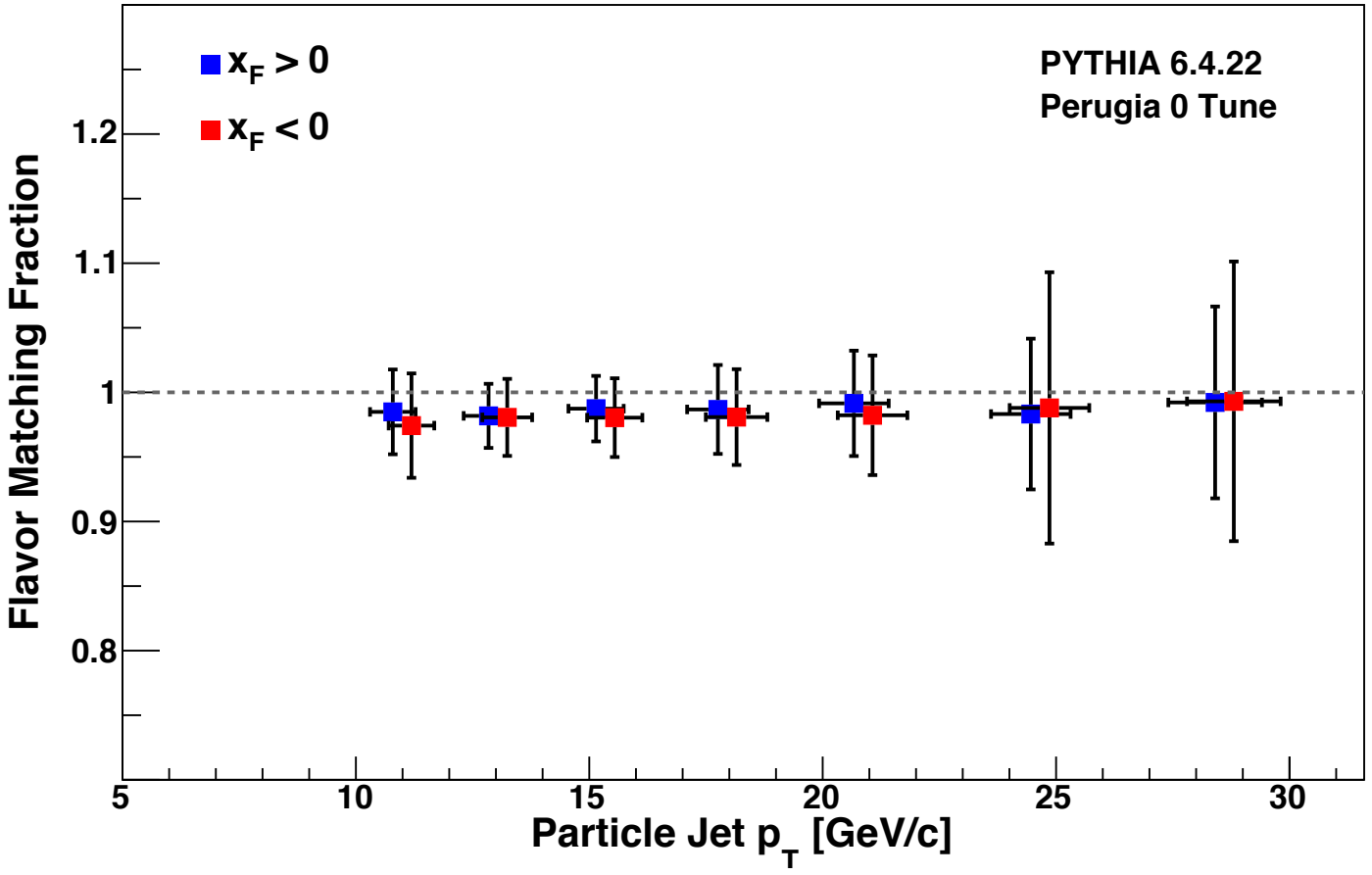
$$Error = \frac{A_{UT}^{Particle} - A_{UT}^{Detector}}{A_{UT}^{Detector}}$$

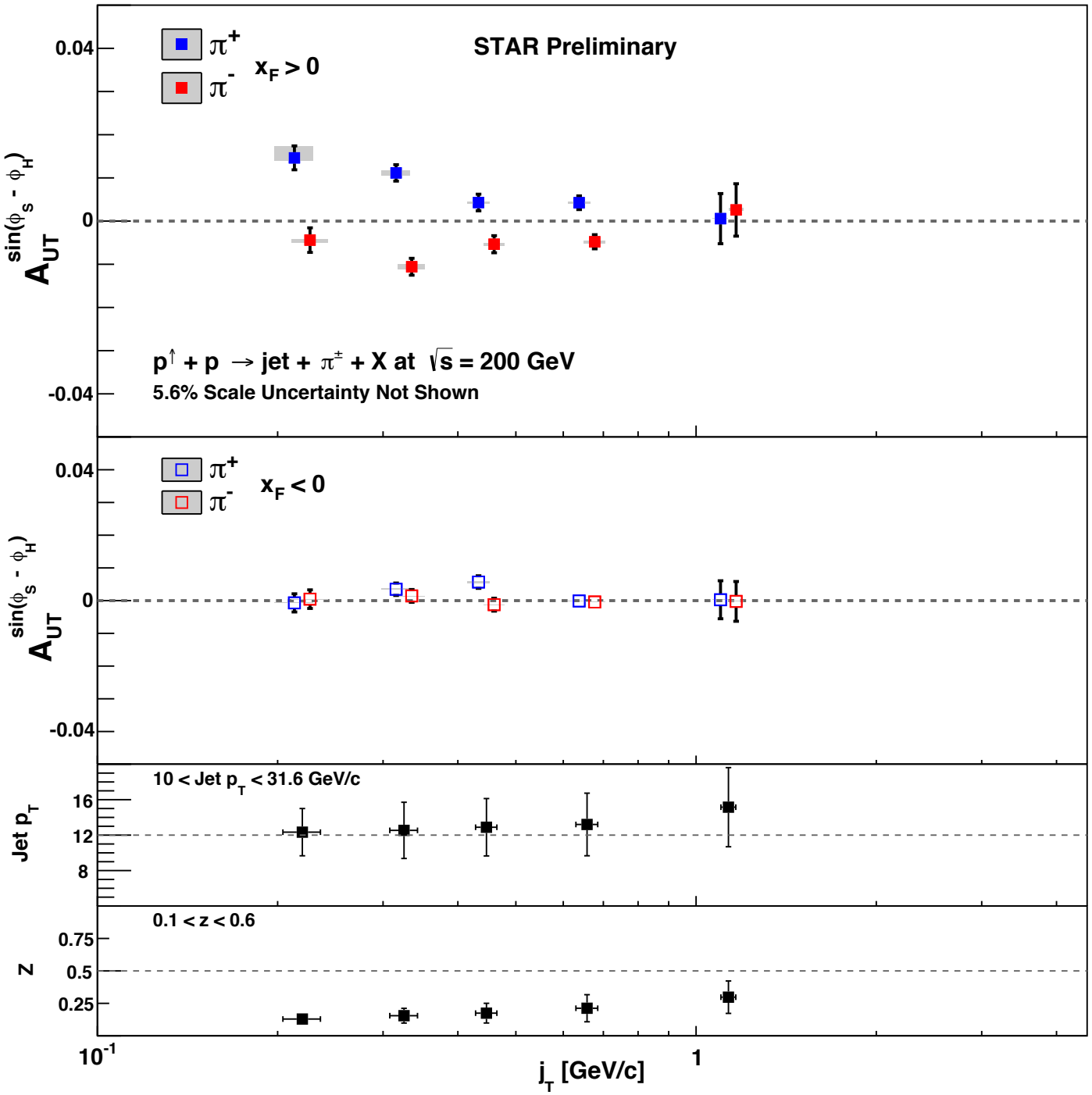
Trigger Bias

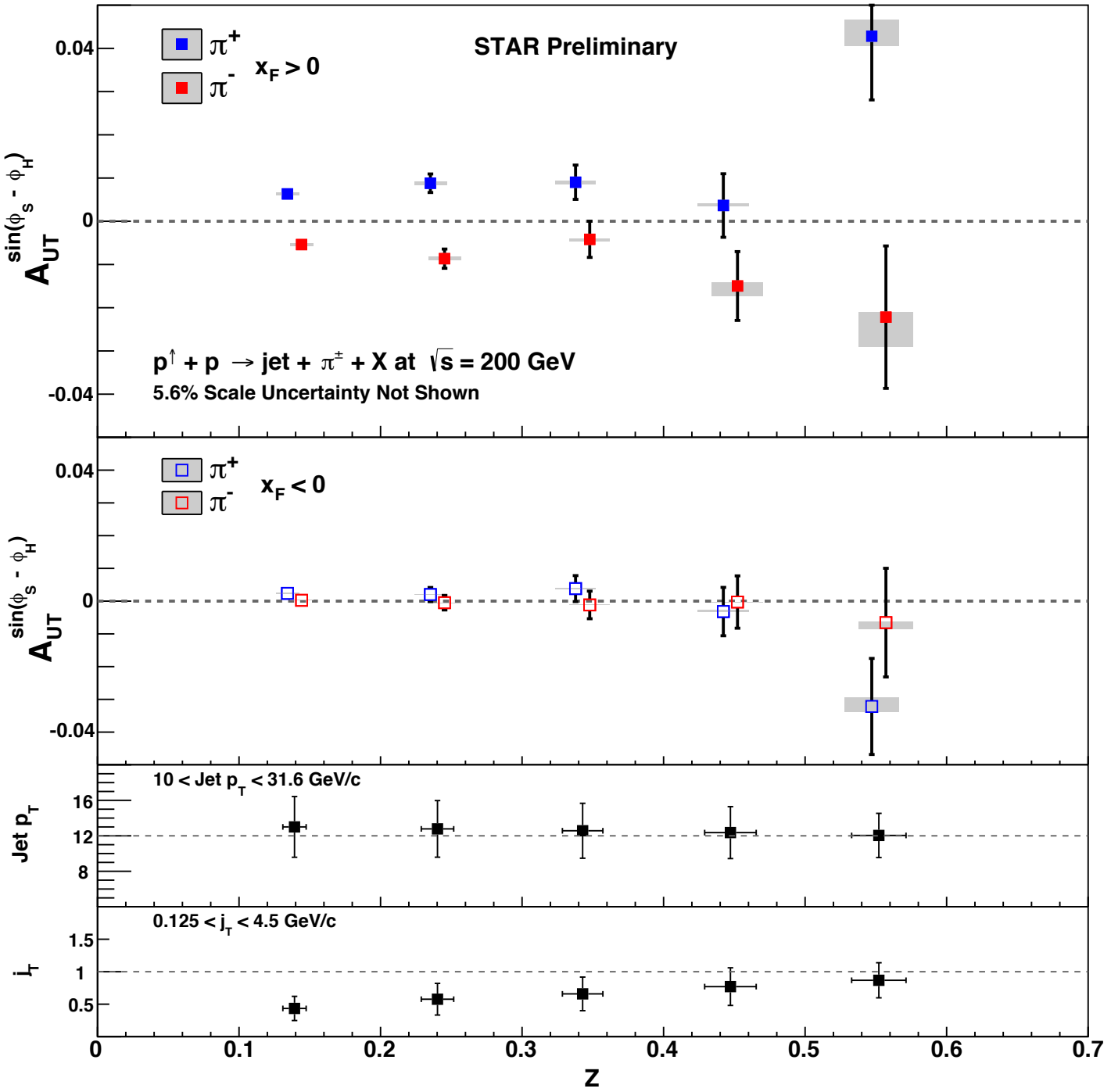
- Trigger used to collect this data is biased towards quark jets
- Increased quark contributions will enhance measured asymmetry
- Contributes 5% to overall systematic uncertainty



Flavor Matching Fractions




STAR Preliminary
π^+
π^-
$x_F > 0$
$\sin(\phi_S - \phi_H)$ A_{UT}
0.04
0
-0.04
$p^\uparrow + p \rightarrow$ jet + $\pi^\pm$ + X at $\sqrt{s}$ = 200 GeV
5.6% Scale Uncertainty Not Shown
π^+
π^-
$x_F < 0$
$\sin(\phi_S - \phi_H)$ A_{UT}
0.04
0
-0.04
10 < Jet p_T < 31.6 GeV/c
Jet p_T
16
12
8
0.1 < z < 0.6
z
0.75
0.5
0.25
10^{-1}
1
j_T [GeV/c]


STAR Preliminary
π^+
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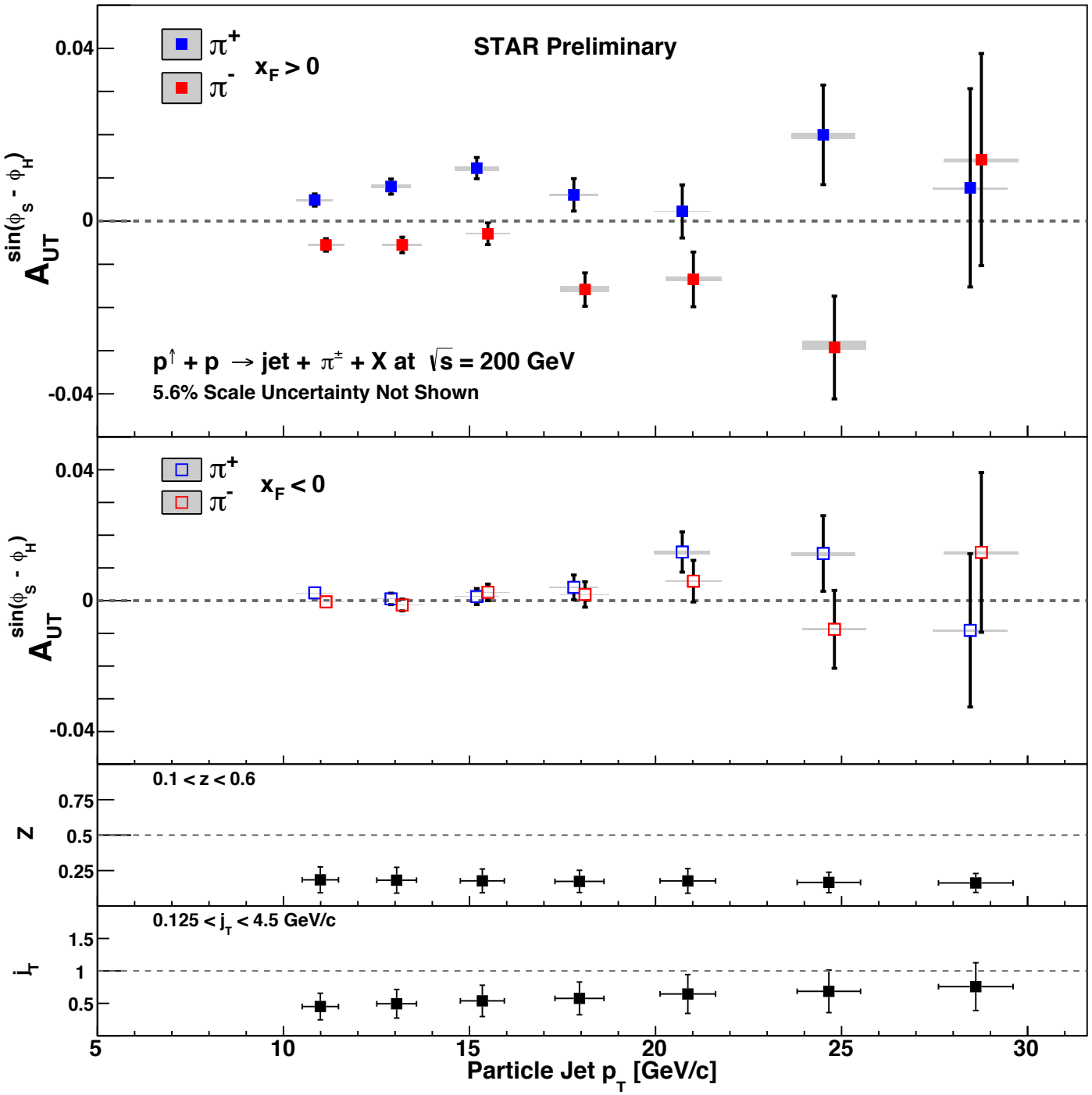
$x_F > 0$
$p^\uparrow + p \rightarrow jet + \pi^\pm + X$ at $\sqrt{s} = 200$ GeV
5.6% Scale Uncertainty Not Shown
$A_{UT}^{\sin(\phi_s - \phi_H)}$
$x_F < 0$
10 < Jet p_T < 31.6 GeV/c
Jet p_T
0.125 < j_T < 4.5 GeV/c
j_T
z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π+
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sin(φs - φH) AUT
0.04
0
-0.04
π+
π-
xF < 0
0.1 < z < 0.6
z
0.75
0.5
0.25
0.125 < jT < 4.5 GeV/c
jT
1.5
1
0.5
5
10
15
20
25
30
Particle Jet pT [GeV/c]