Transverse Single-spin Asymmetries from $p^{\uparrow} + p \longrightarrow jet + X$ and $p^{\uparrow} + p \longrightarrow jet + \pi^{\pm} + X$ at $\sqrt{s} = 500$ GeV at RHIC

James L. Drachenberg

For the STAR Collaboration

October 1, 2013

OUTLINE

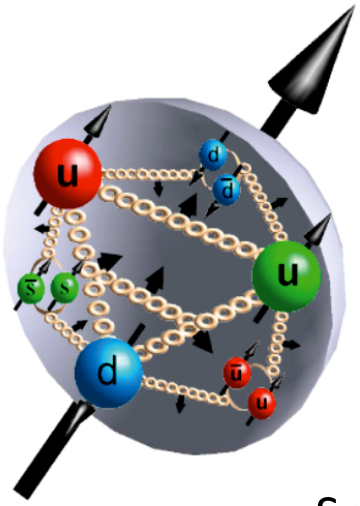
- Introduction
- Event Selection
- Analysis Description
- Systematic Uncertainties
- Preliminary Results
- Conclusions

STAR

Valparaiso University

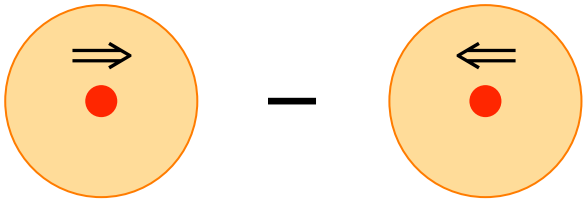
Contributions to Proton Spin Structure

Consider proton moving right



Proton spin ⇒

Δq(x)
Δg(x)



coming into focus:

$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

arXiv:nucl-ex/1304.0079

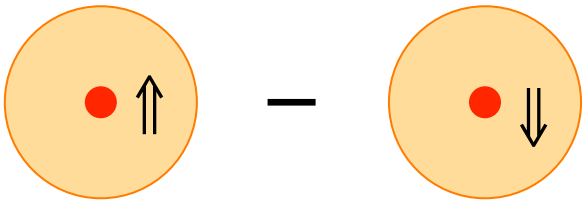
Polarized DIS: ~ 0.3

Spin sum rule: $\left\langle S_z^p \right\rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left\langle L_z \right\rangle$

poorly constrained

Proton spin ⇑

$h_1(x)$

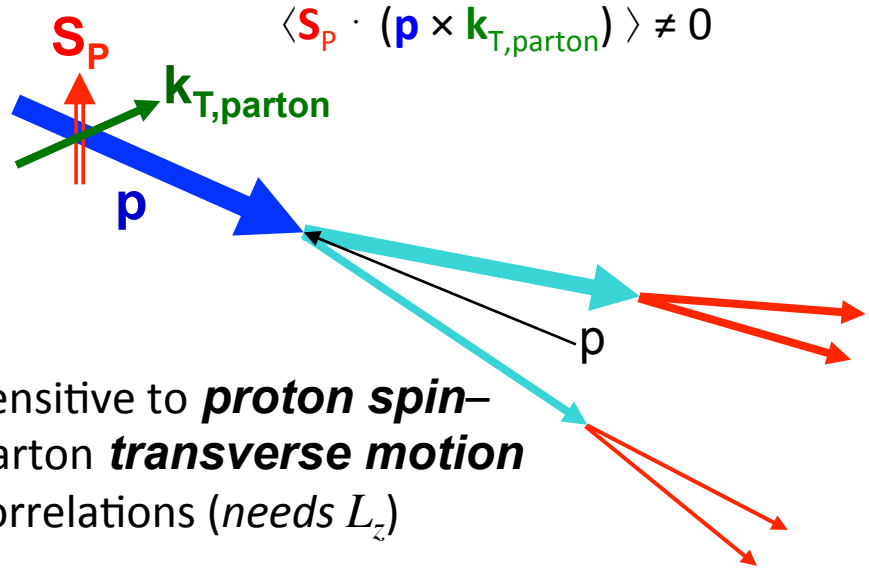


Transversity – data over limited kinematic range: $x_{Bj} \leq 0.3$

Sensitivity to Orbital Motion and Transversity?

Sivers mechanism: asymmetry in the forward jet or γ *production*

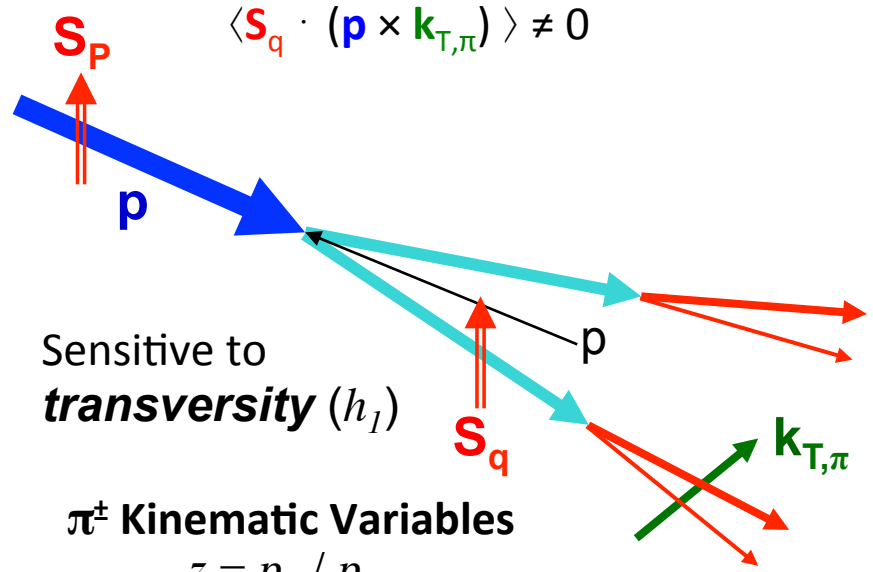
$\langle S_P \cdot (p \times k_{T,parton}) \rangle \neq 0$



Sensitive to ***proton spin***–parton ***transverse motion*** correlations (*needs* L_z)

Collins mechanism: asymmetry in the forward jet *fragmentation*

$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$



Sensitive to ***transversity*** (h_1)

$\pi^{\pm}$ Kinematic Variables

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

$j_T\,(k_{T,\pi}) = \pi\, p_T$ relative to jet axis

Separate Sivers and Collins:

Go beyond inclusive production - *e.g. Jets, correlations, direct photons*

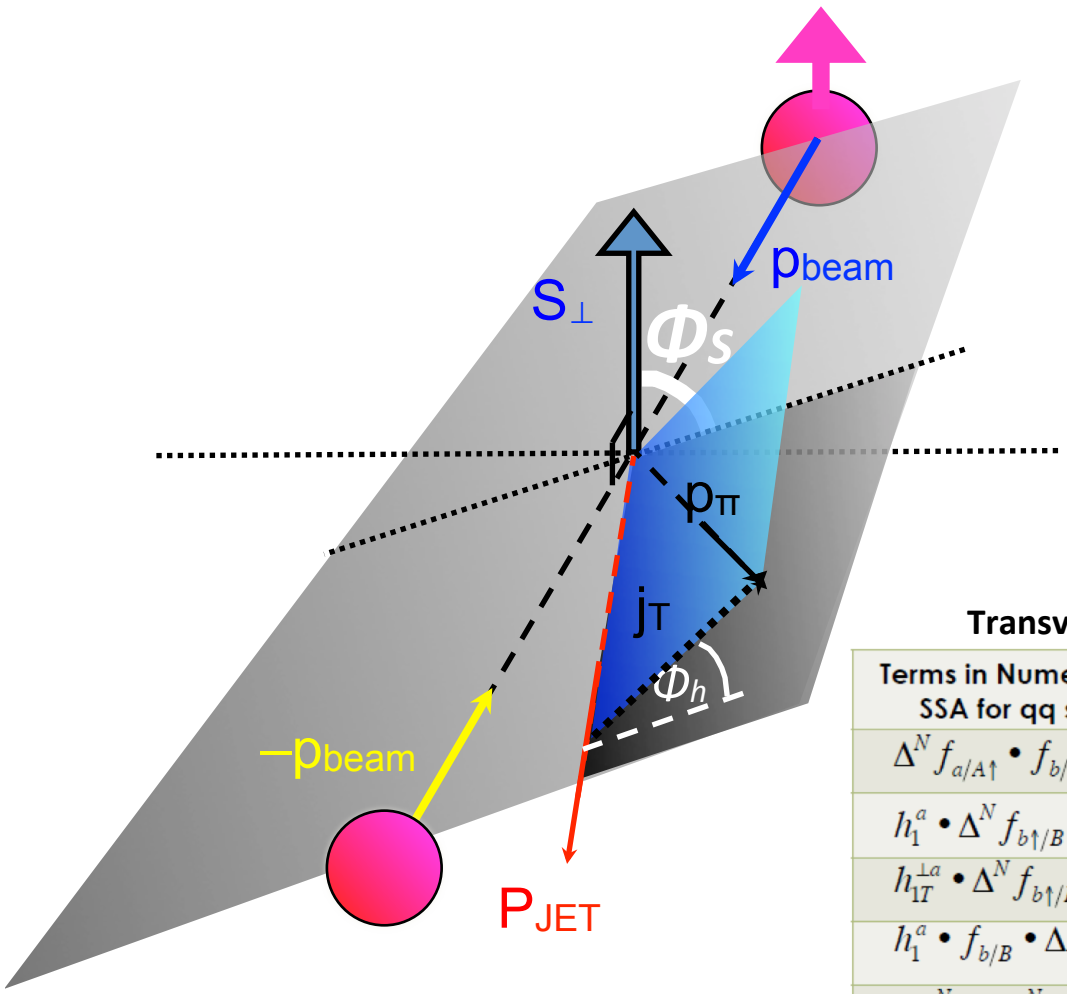
Sivers ~ $\sin(\phi_S)$

ϕ_S—*angle between spin and event plane*

Collins ~ $\sin(\phi_S - \phi_h)$

ϕ_h—*angle of hadron around jet axis*

Transverse Jet Asymmetries



Asymmetry moments sensitive to various contributions (analogous moments sensitive to gluon scattering)

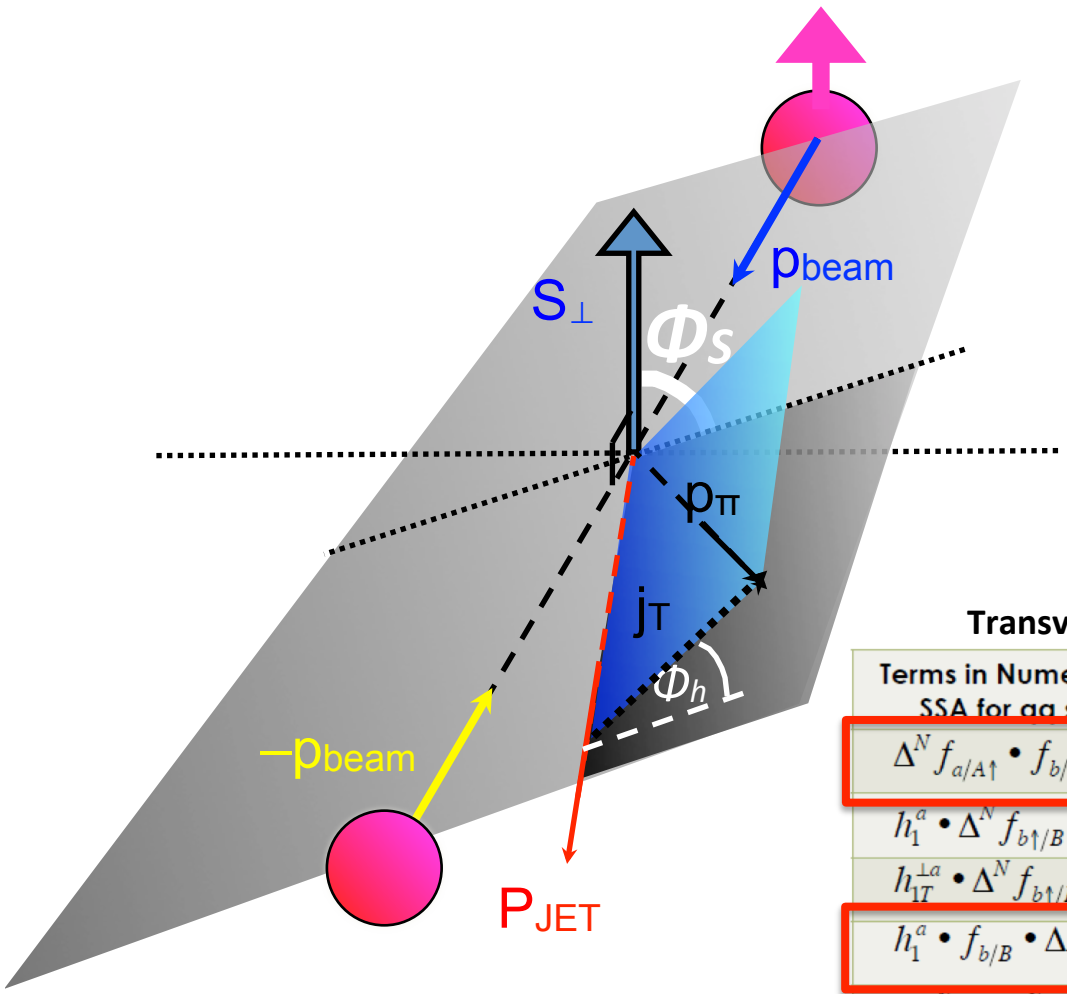
A_{UT} – Transverse single-spin asymmetry (also written A_N)

Transverse Momentum Dependent (TMD) Approach

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	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity • Boer-Mulders • FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity • Boer-Mulders • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers • Boer-Mulders • Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

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

Transverse Jet Asymmetries



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F. Yuan, PRL 100, 032003 (2008)
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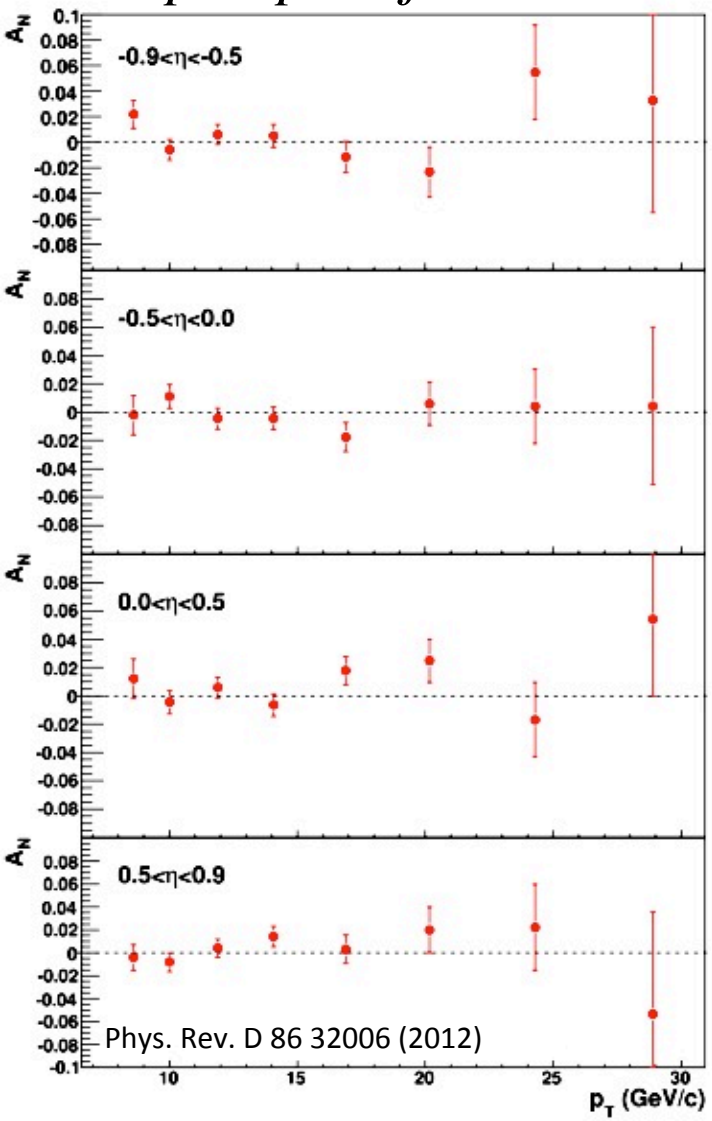
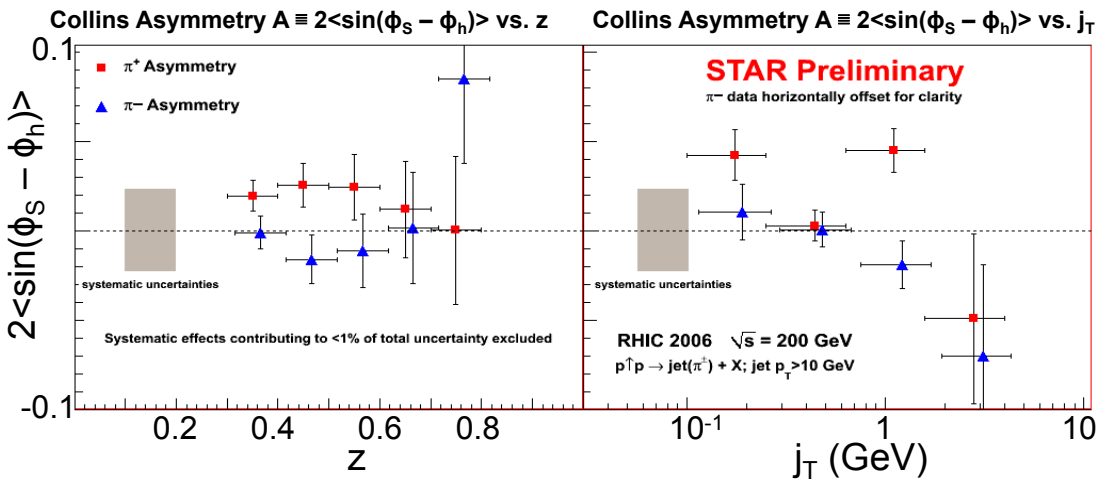
STAR Transverse Jet Asymmetries at Central Pseudorapidity

$$p^{\uparrow} + p \rightarrow jet + X$$



Phys. Rev. D 86 32006 (2012)



STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and √s = 200 GeV (2006)

$A_{UT}^{\sin(\phi_S)}$: consistent with zero

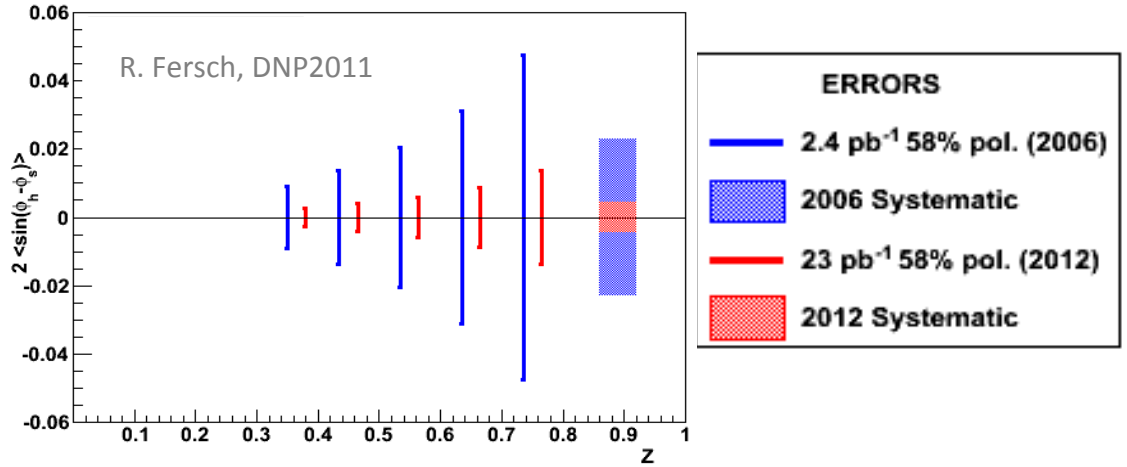
$A_{UT}^{\sin(\phi_S-\phi_h)}$: hints of non-zero asymmetry with charge-sign dependence

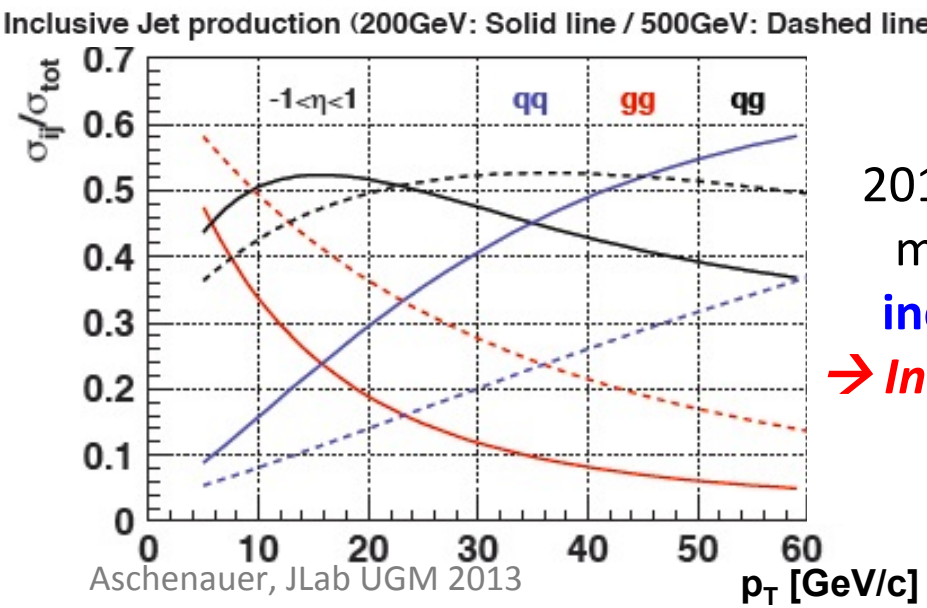
Similarly, di-jet and π^0 A_N at central psuedorapidity and 200 GeV consistent with zero

PRL 99, 142003, PRL. 95, 202001, arXiv:hep-ex/1108.0911

STAR Transverse Jet Asymmetries at Central Pseudorapidity

2012 STAR data provide opportunity for ***higher precision*** *and* ***greatly reduced systematic uncertainties at*** $\sqrt{s} = 200$ ***GeV***





2011 STAR data provide opportunity for first measurements of **central pseudorapidity inclusive jet asymmetries at** $\sqrt{s} = 500$ **GeV**

→ ***Increased sensitivity to gluonic subprocesses***

Moments of Jet Asymmetries at 500 GeV

Various contributions to polarized jet+π cross section (TMD approach)

$$d\sigma\left(\phi_S,\phi_h\right)-d\sigma\left(\phi_S+\pi,\phi_h\right)\sim d\Delta\sigma_0\sin\phi_S$$
$$+d\Delta\sigma_1^-\sin\left(\phi_S-\phi_h\right)+d\Delta\sigma_1^+\sin\left(\phi_S+\phi_h\right)$$
$$+d\Delta\sigma_2^-\sin\left(\phi_S-2\phi_h\right)+d\Delta\sigma_2^+\sin\left(\phi_S+2\phi_h\right)$$

Phys. Rev. D 83, 034021 (2011)

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Phys. Rev. D 83, 034021 (2011)

Negligible under ***maximized*** scenario!

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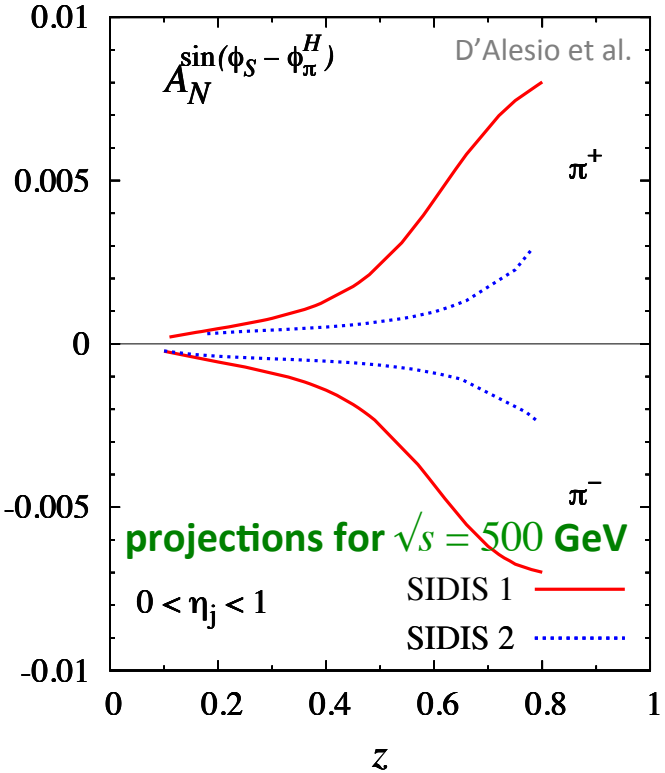
Phys. Rev. D 83, 034021 (2011)



Possible non-zero contributions,

expected to be quite small

e.g. Phys. Rev. Lett. 95, 202001 (2005);
Phys. Rev. Lett 99, 142003 (2007);
Phys. Rev. D 86, 032006 (2012);
arXiv:hep-ex/1108.0911

Moments of Jet Asymmetries at 500 GeV

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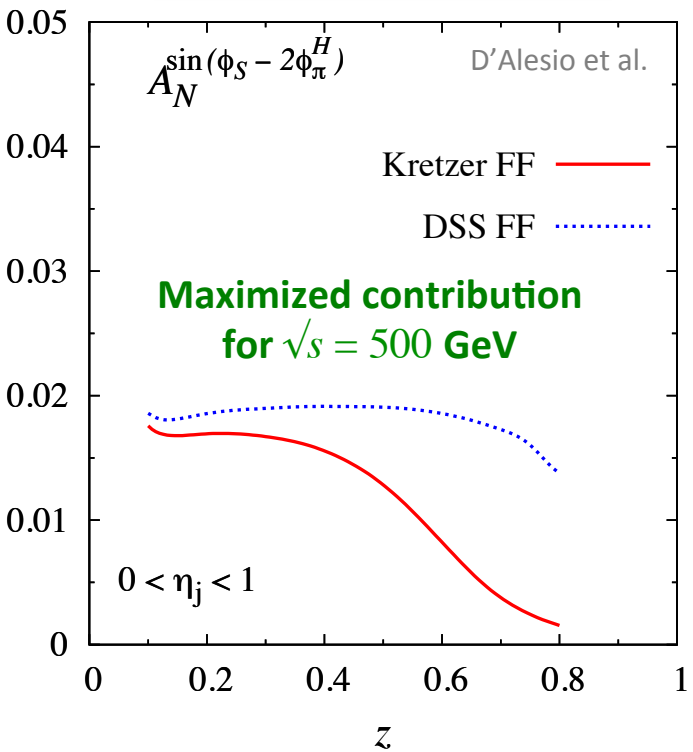
Phys. Rev. D 83, 034021 (2011)



"Collins-like" asymmetry:

Sensitive to linearly polarized gluons

Completely unconstrained!

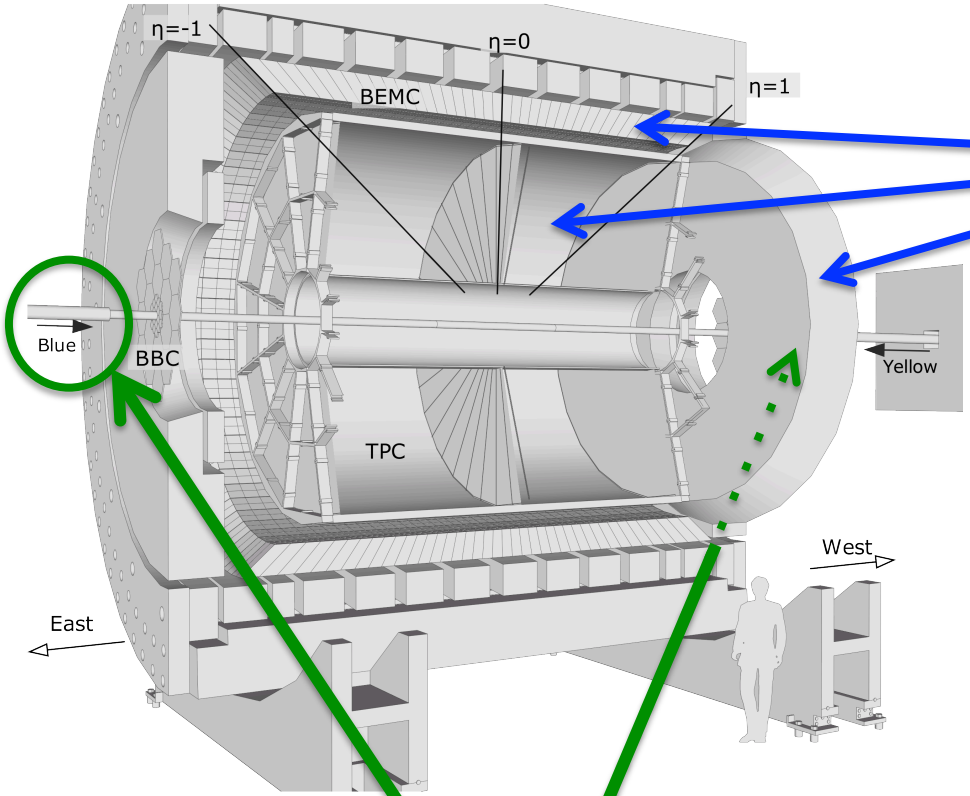
Gluon helicity density matrix

$$\rho = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & -P_{lin}e^{-2i\phi} \\ -P_{lin}e^{2i\phi} & 1-P_{circ} \end{pmatrix}$$

Off-diagonal terms related to linear polarization in (xy) plane at angle ϕ to x-axis

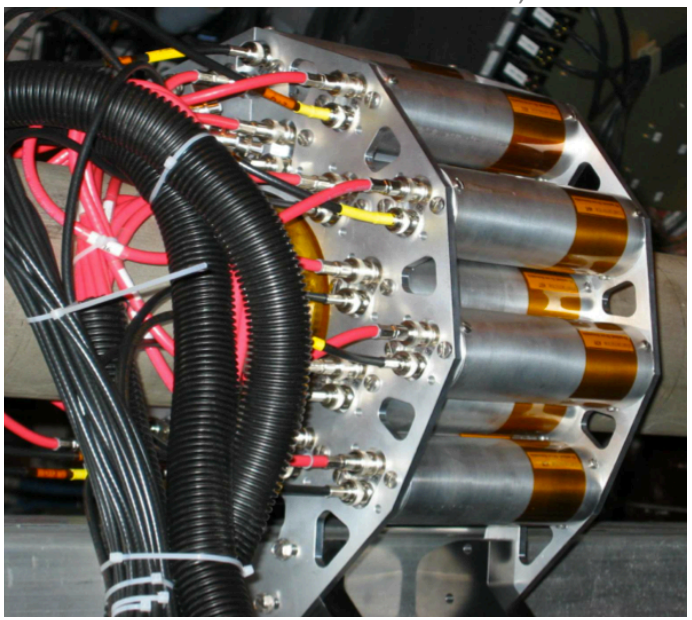
Phys Rev. D 73, 014020 (2006)

Solenoidal Tracker at RHIC



Jet reconstruction utilizes
TPC + Barrel + Endcap EMC

J. Zhou, M.S. Thesis

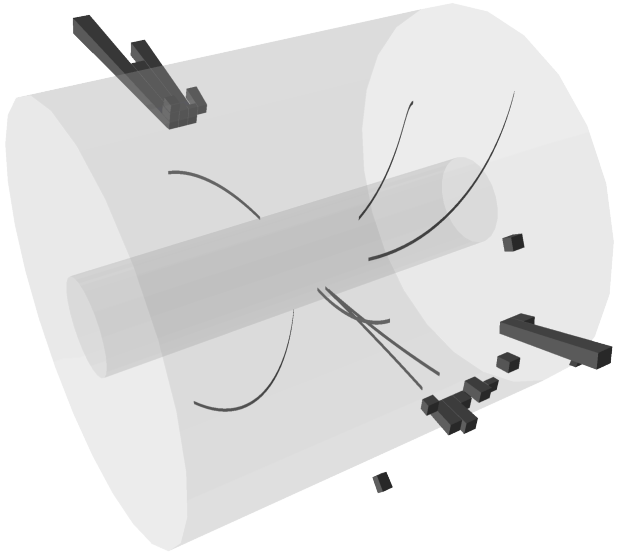


Minbias Trigger: coincidence in vertex position detector (VPD)

- Pb+plastic scintillator with PMT readout
- 570 cm from interaction point
- $4.24 < |\eta| < 5.1, \ \eta = -\ln\left[\tan(\theta/2)\right]$

Jet Reconstruction in STAR

STAR Di-jet event at detector-level



Anti-k_T algorithm
JHEP 0804, 063 (2008)

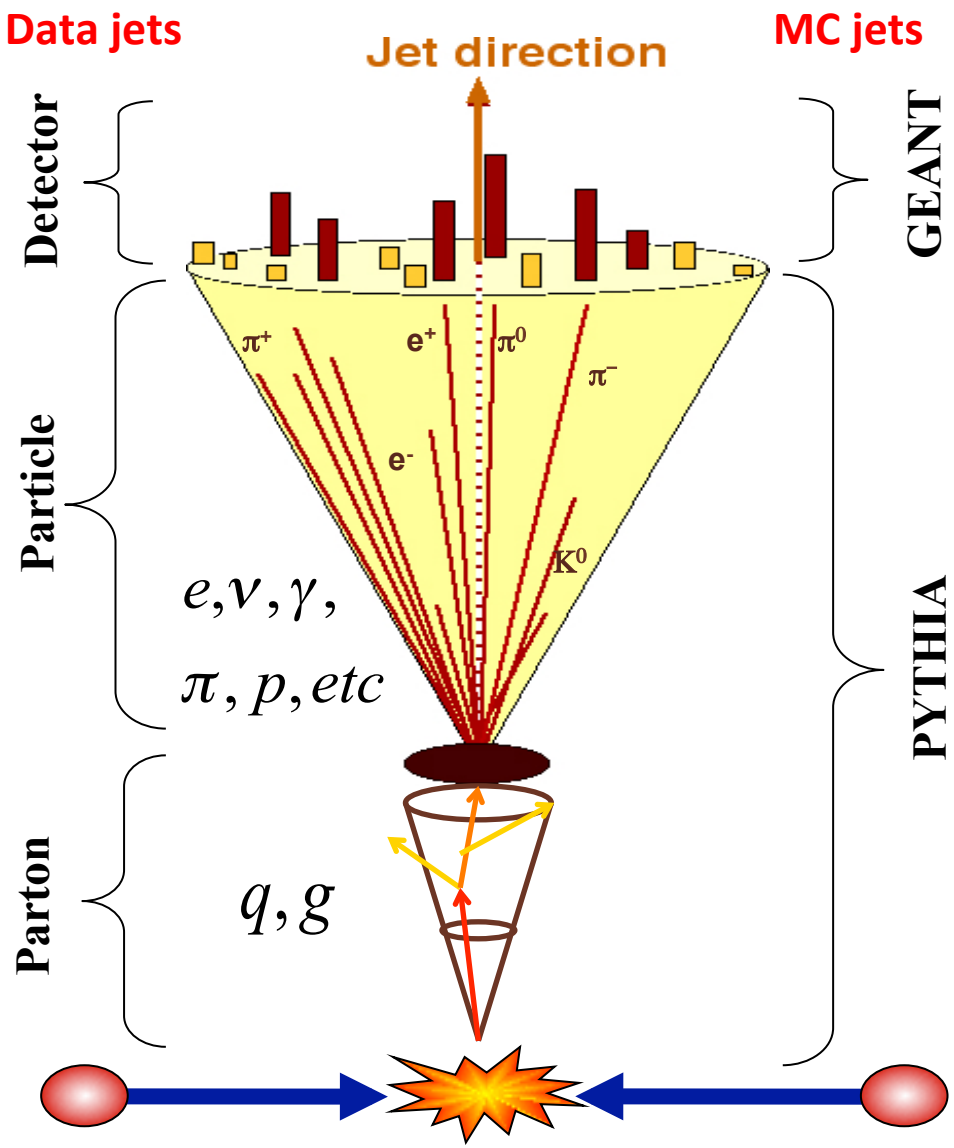
Radius parameter R = 0.6

Use **PYTHIA** + **GEANT** to quantify detector response

$\pi^{\pm}$ Kinematic Variables

z – π momentum / jet momentum

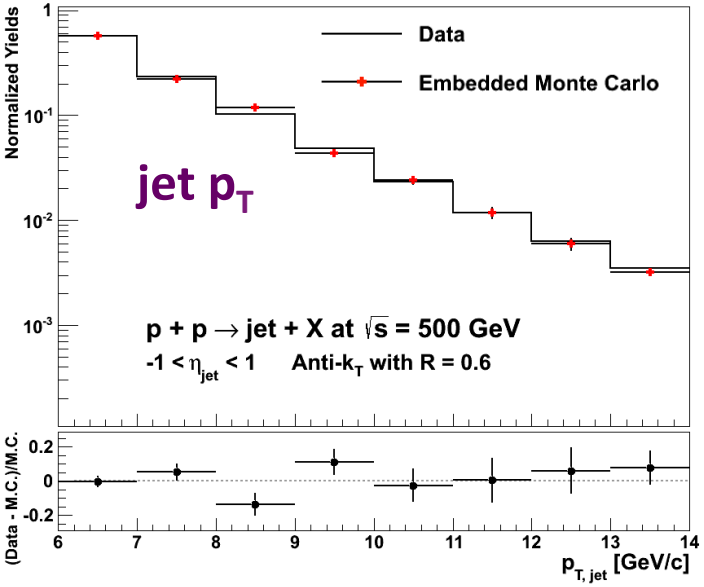
j_T – π p_T relative to jet axis



2011 STAR Event Selection

- **Center of mass energy, $\sqrt{s}$ = 500 GeV**
- **Total integrated luminosity of 25 pb^{-1} for all transverse runs**
- **Polarization for present analysis: 54±3%**
- Good event vertex with $|z_{vertex}| < 30$ cm
- **Jet Reconstruction:**
  - $N_{hits,\ track} > 12$
  - Track association with event vertex
  - Minimum track $p_T > 0.2$ GeV/c
  - Minimum tower energy > 0.2 GeV
- **Jet requirements:**
  - No charged particles with $p_T > 30$ GeV/c
  - Total charged-particle $p_T > 0.5$
  - Neutral-energy fraction < 0.98
  - $|\eta_{jet}| < 1.0$ (and within detector acceptance of BEMC+TPC)
  - $6 < p_{T,jet} < 55$ GeV/c
- **Pion Requirements:**
  - Restriction on dE/dx: $-1 < n_\sigma(\pi) < 2.5$ (contamination < 3%)
  - $(\eta_{jet}-\eta_{ch})^2 + (\phi_{jet}-\phi_{ch})^2 > (0.1)^2$
  - $N_{hits,\ dE/dx} > 5$

Studies with Embedded Monte Carlo



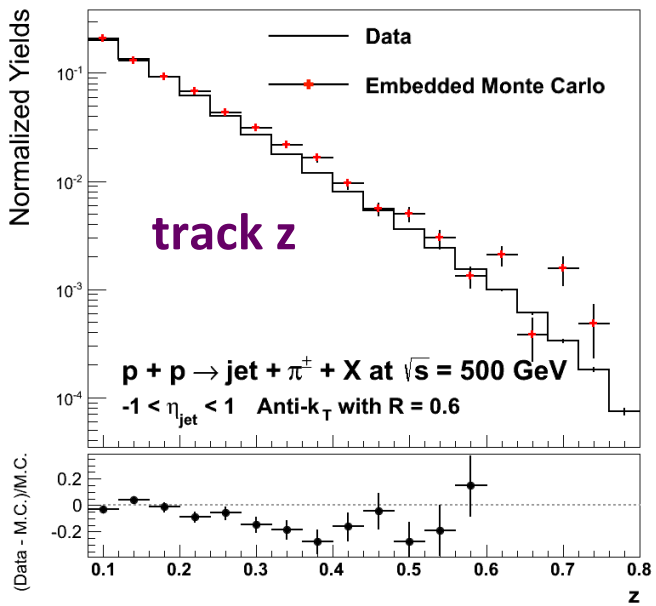
Systematic shifts in reconstructed kinematic variables and azimuthal resolutions evaluated by comparing to Monte Carlo embedded in real zero-bias data

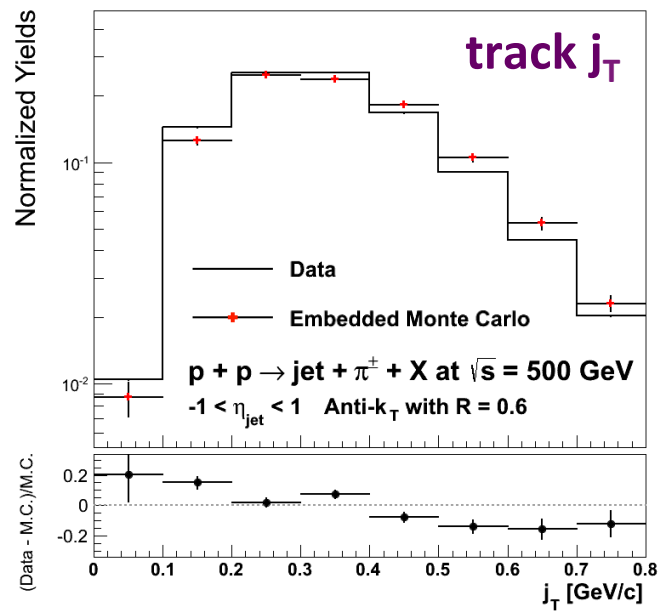
simulate effects of real, out-of-time pile-up

Detector-level jets matched both to ***parton and particle jets*** with matched event vertex

Kinematic shifts evaluated at particle level

Corresponding parton-jet p_T ~0.6-1.4 GeV/c lower





Sources of Systematic Uncertainty

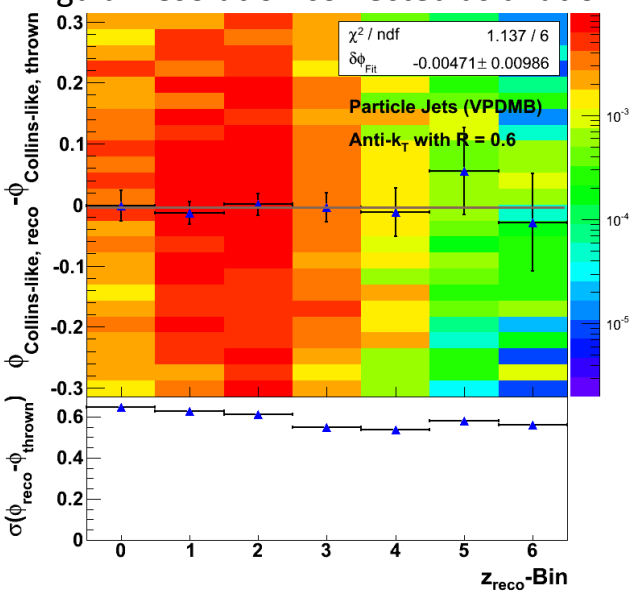
Dominant systematic uncertainty from reconstructed jets unassociated with parton jets

→ *Take difference between measured A_{UT} and A_{UT} assuming dilution*

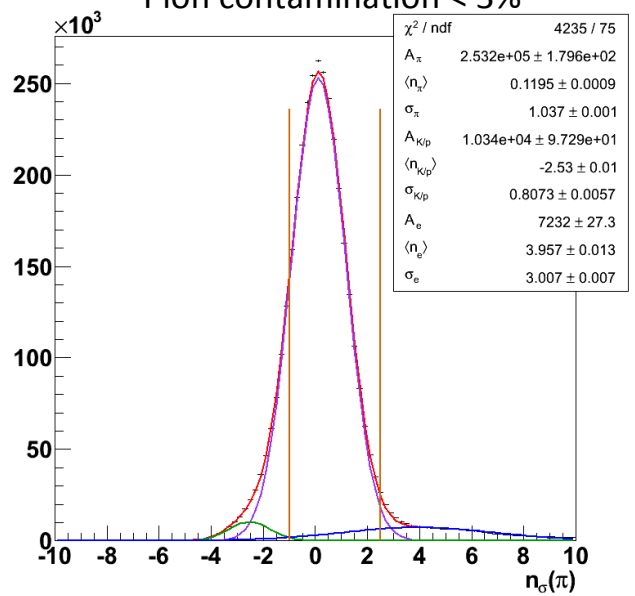
Further systematic uncertainties:

- Resolution of relevant azimuthal angles
  → ***corrected as dilution to measured asymmetry***
- "leak-through" of other moments of A_{UT}
- Pion contamination from K/p and $e^{\pm}$ (< 3%)
- Polarization uncertainty (correlated vertical scale uncertainty, σ(P)/P = 5.6%)

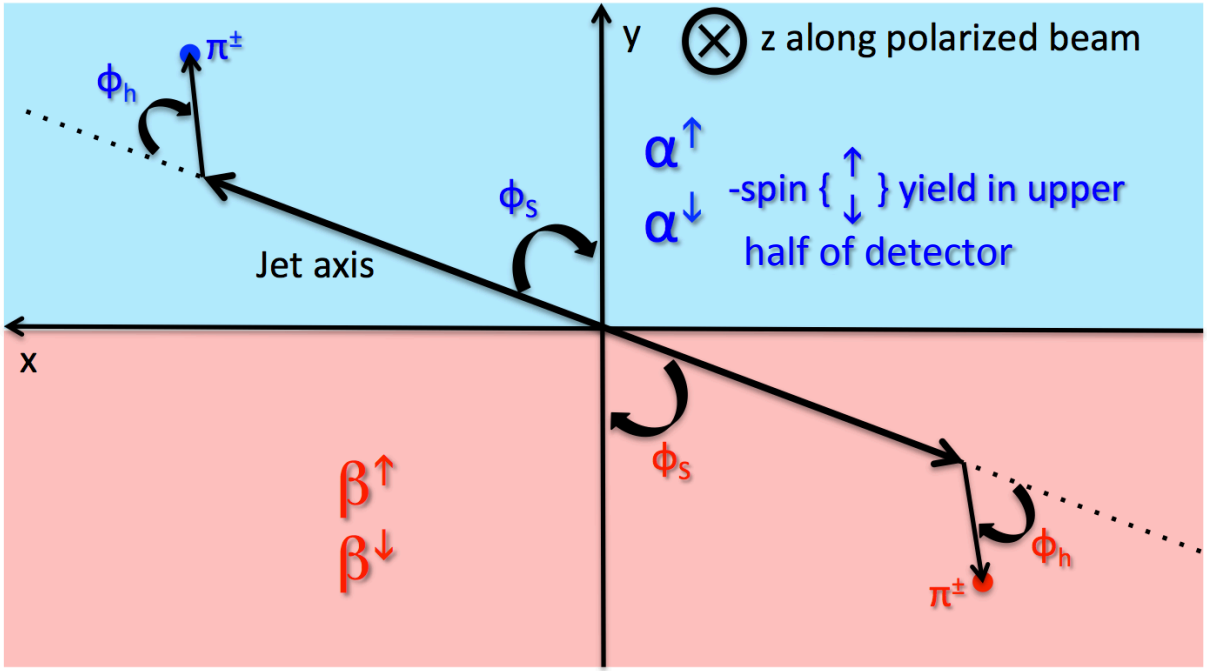
Angular resolution corrected as dilution



Pion contamination < 3%



Asymmetry Measurements

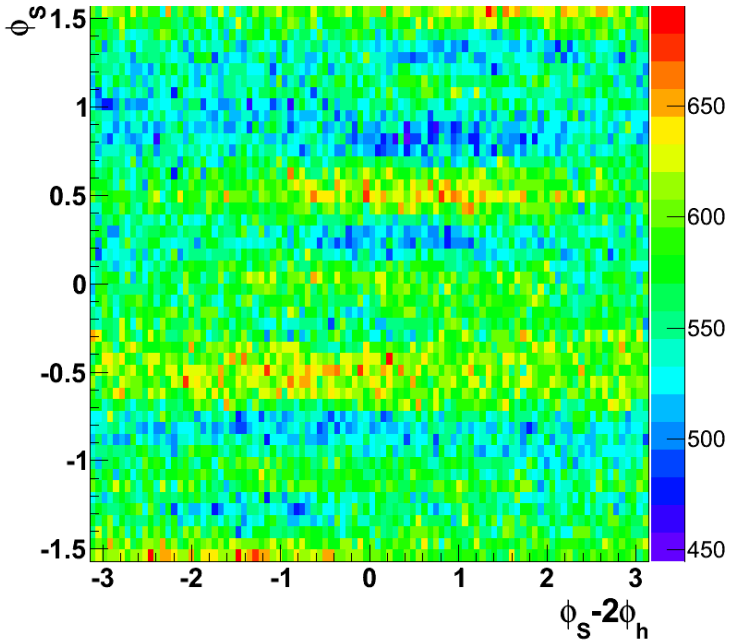


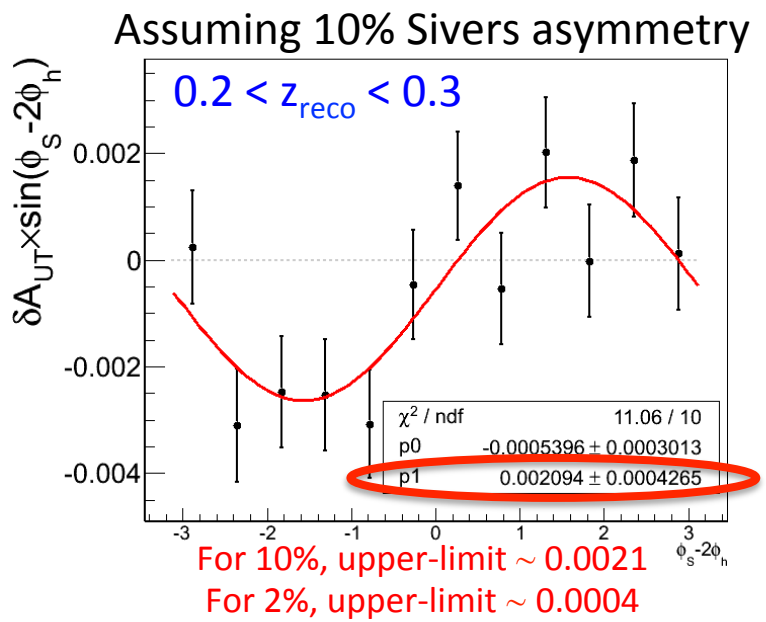
α and β yields are functions of $\left\{ \begin{array}{c} \Delta\phi = \phi_S - \phi_h \\ \phi_S \end{array} \right\}$ integrated over $\left\{ \begin{array}{c} \phi_S \\ \Delta\phi \end{array} \right\}$

$$\varepsilon = \frac{1}{P} \frac{\sqrt{\alpha^{\uparrow}\beta^{\downarrow}} - \sqrt{\alpha^{\downarrow}\beta^{\downarrow}}}{\sqrt{\alpha^{\uparrow}\beta^{\downarrow}} + \sqrt{\alpha^{\downarrow}\beta^{\downarrow}}}$$

For uniform acceptance: $\varepsilon \left\{ \begin{array}{c} \Delta\phi \\ \phi_S \end{array} \right\} = \left\{ \begin{array}{c} A_{Collins} \sin(\Delta\phi) \\ A_{Sivers} \sin(\phi_S) \end{array} \right\}$

Estimating Leak-through Systematic





Acceptance inefficiencies can allow non-zero effects to "leak through" and distort desired observable

Quantify distortion by event-weighting unpolarized data yields and calculating resulting asymmetries

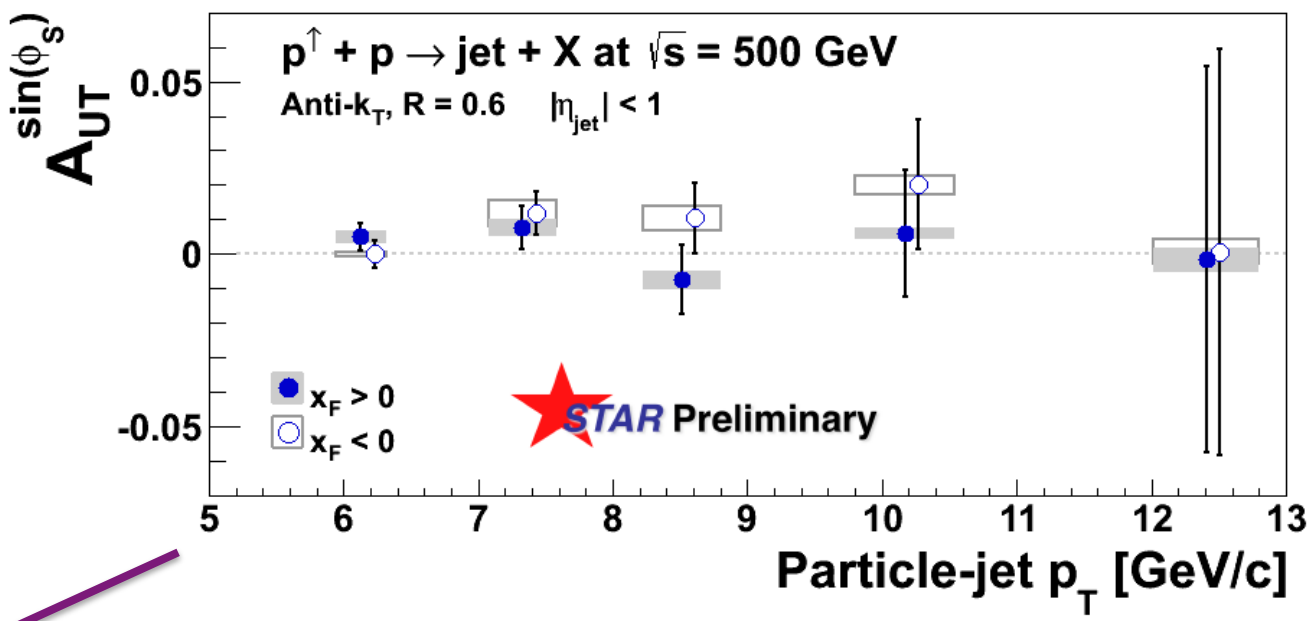
Reasonable acceptance + small observed asymmetries
→ **Small upper-limits on "leak-through" systematic**

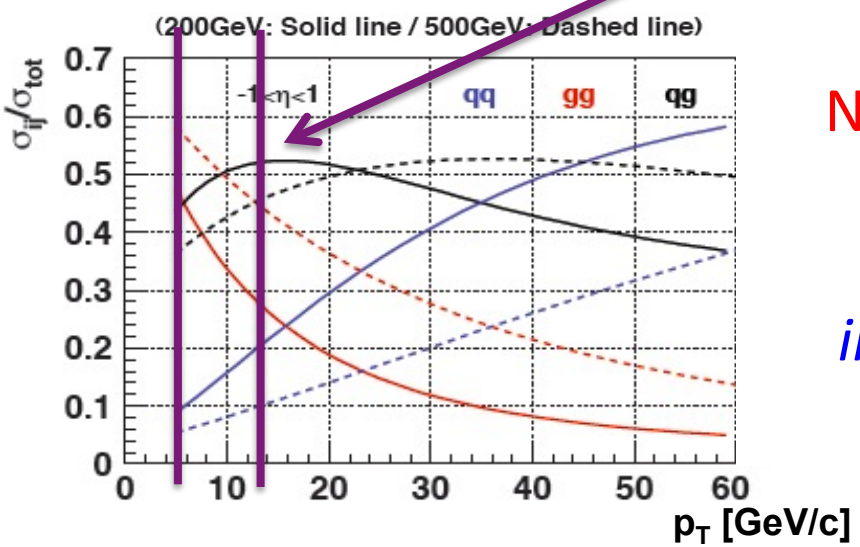
Sivers Asymmetries

Asymmetries shown as function of particle-jet p_T

Corresponding parton-jet p_T lower by 0.6-1.4 GeV/c

Horizontal errors include uncertainties from statistics, calorimeter gains, efficiencies, track momentum, and tracking efficiency





No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s} = 500$ GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s} = 200$ GeV

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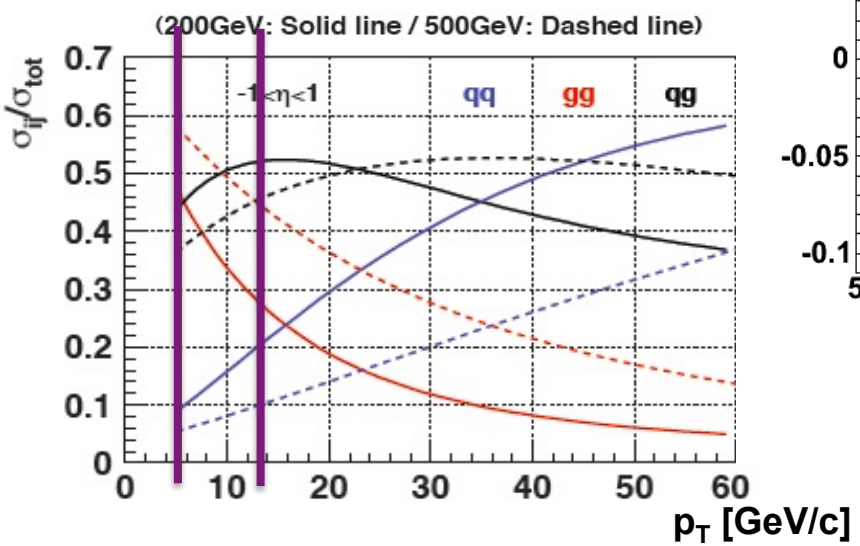
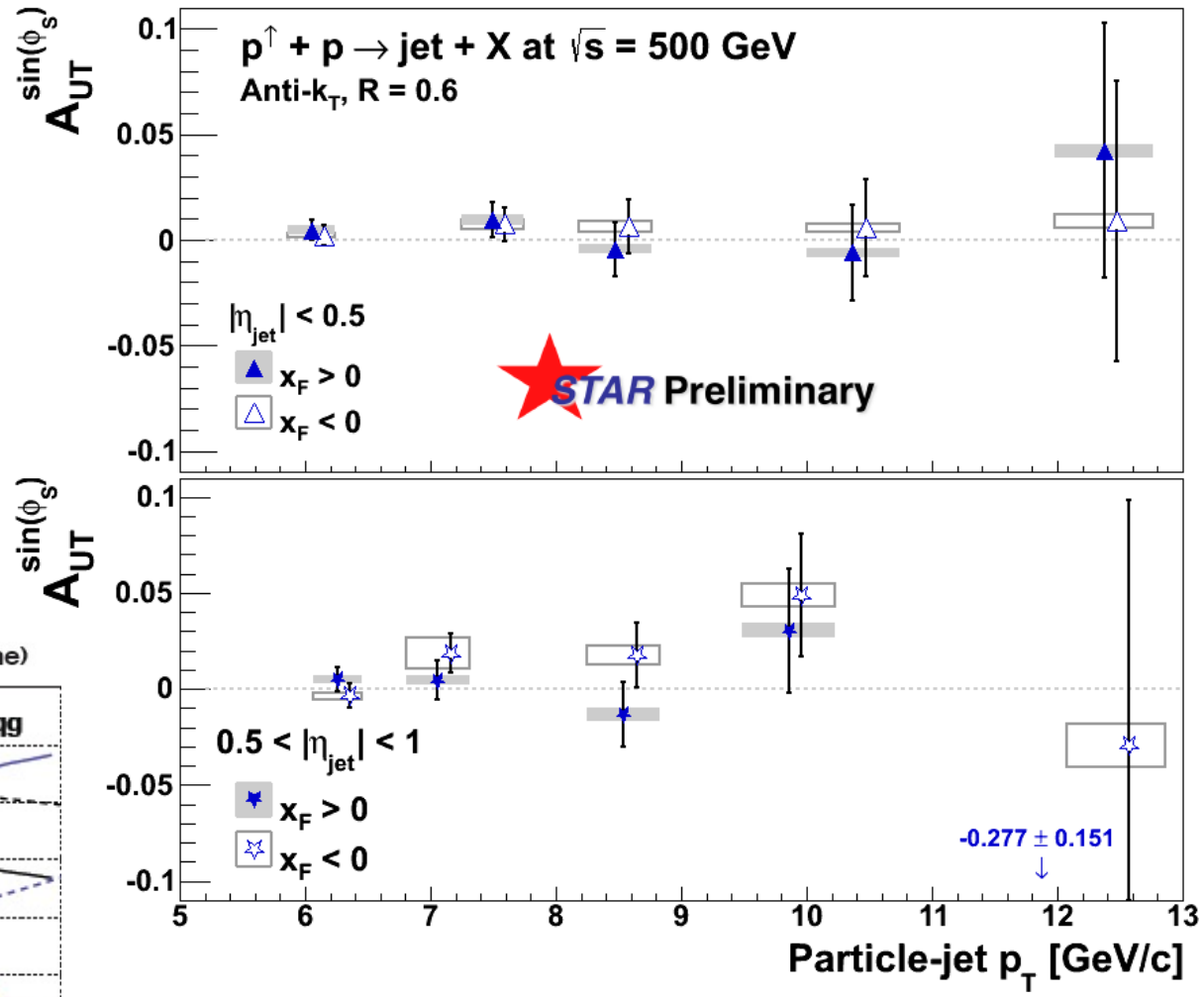
Horizontal errors include uncertainties from statistics, calorimeter gains, efficiencies, track momentum, and tracking efficiency



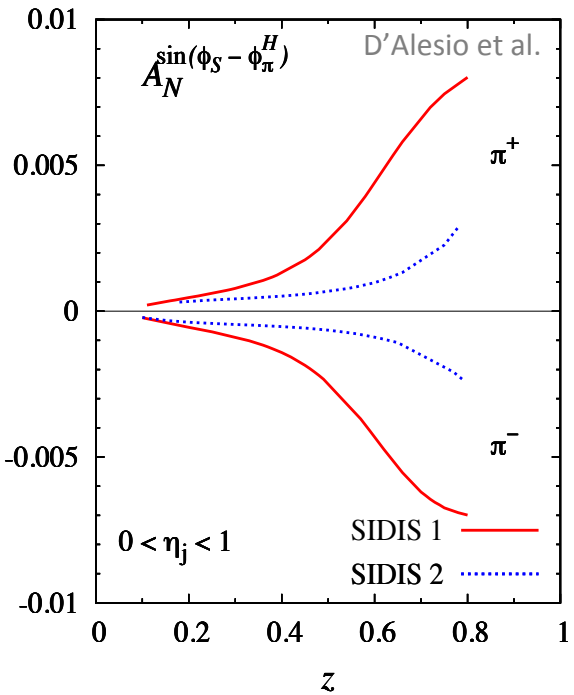


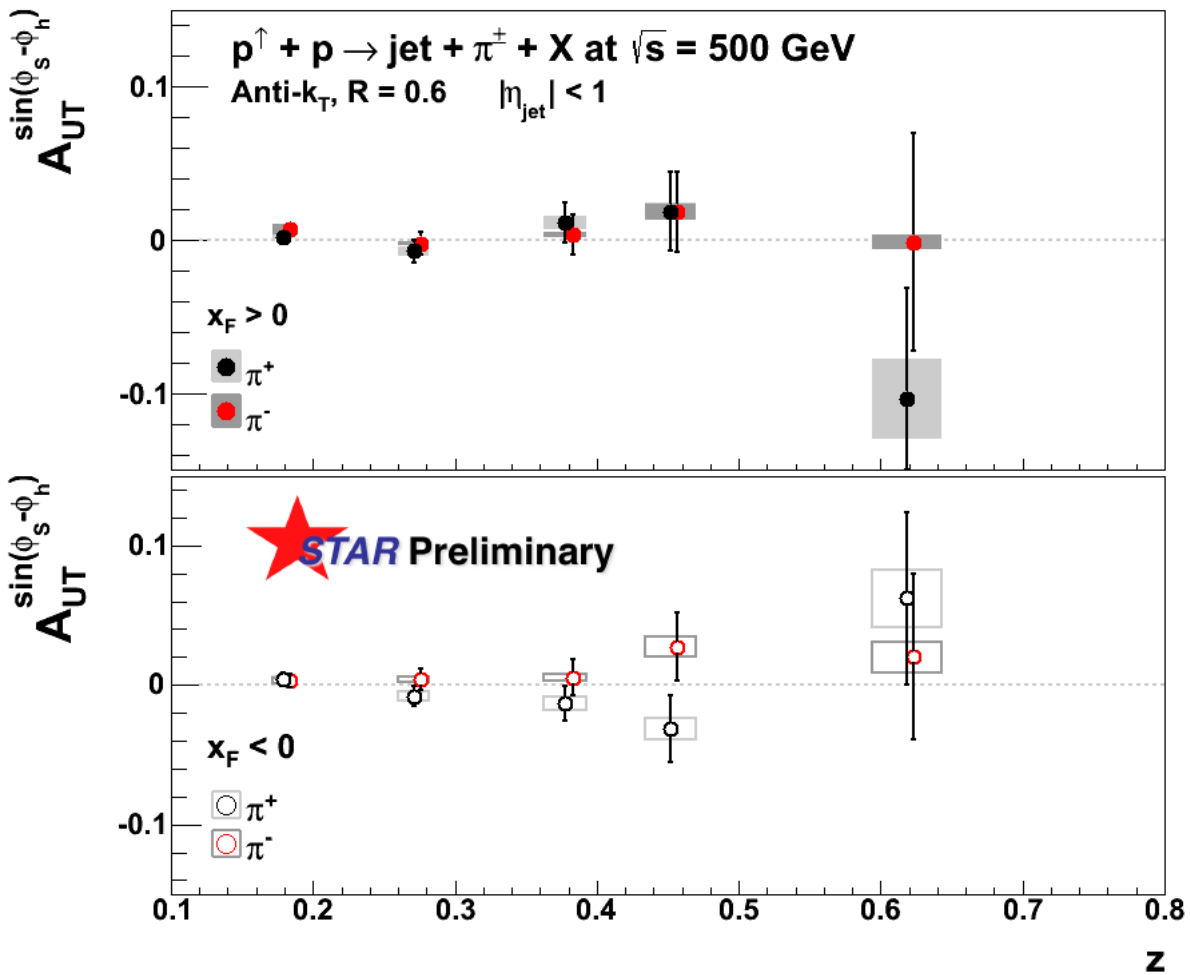
Measured asymmetries shown in η-bins

No sign of sizable asymmetry

Collins Asymmetries

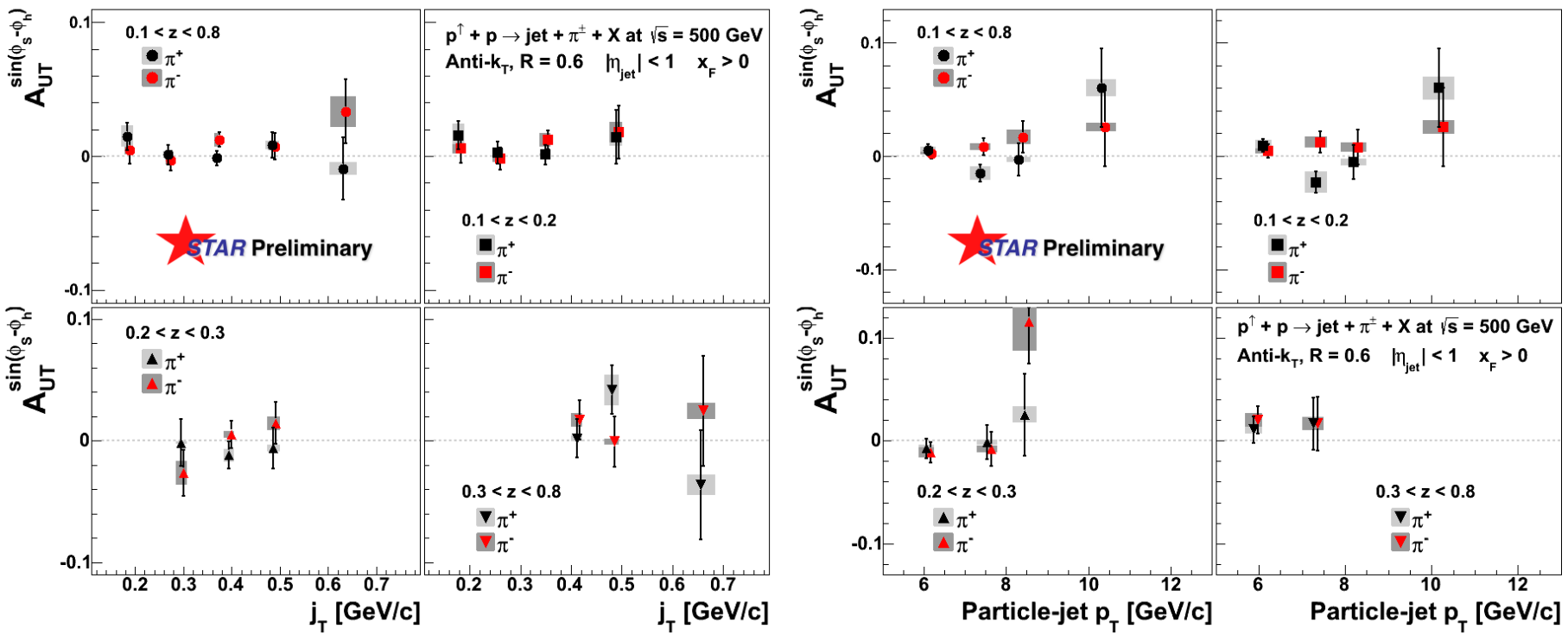
Increased gluonic subprocesses at √s = 500 GeV lead to expectation of ***small Collins asymmetry*** until larger z





Present data do not have sufficient statistics at high-z to observe Collins asymmetry of order 1%

Collins Asymmetries



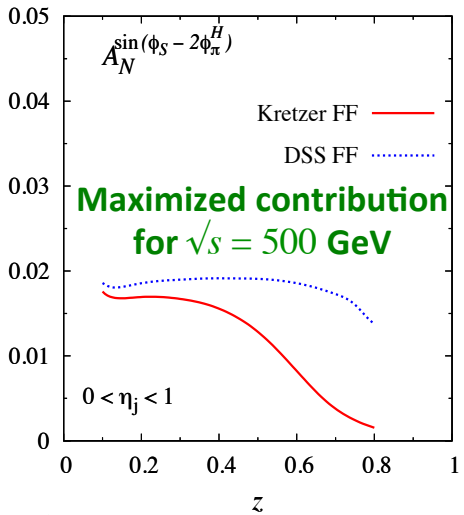
Present model predictions expect negligible effects for A_{UT} vs. j_T integrated over z > 0.1

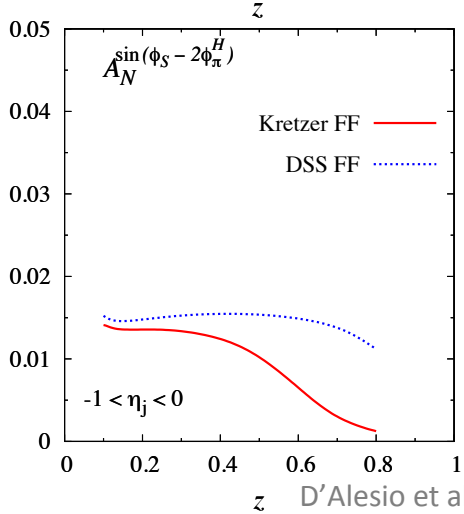
Measured asymmetries shown for $x_F > 0$ (i.e. $0 < \eta_{jet} < 1$) in z-bins

No sign of non-zero asymmetry as a function of j_T or jet p_T

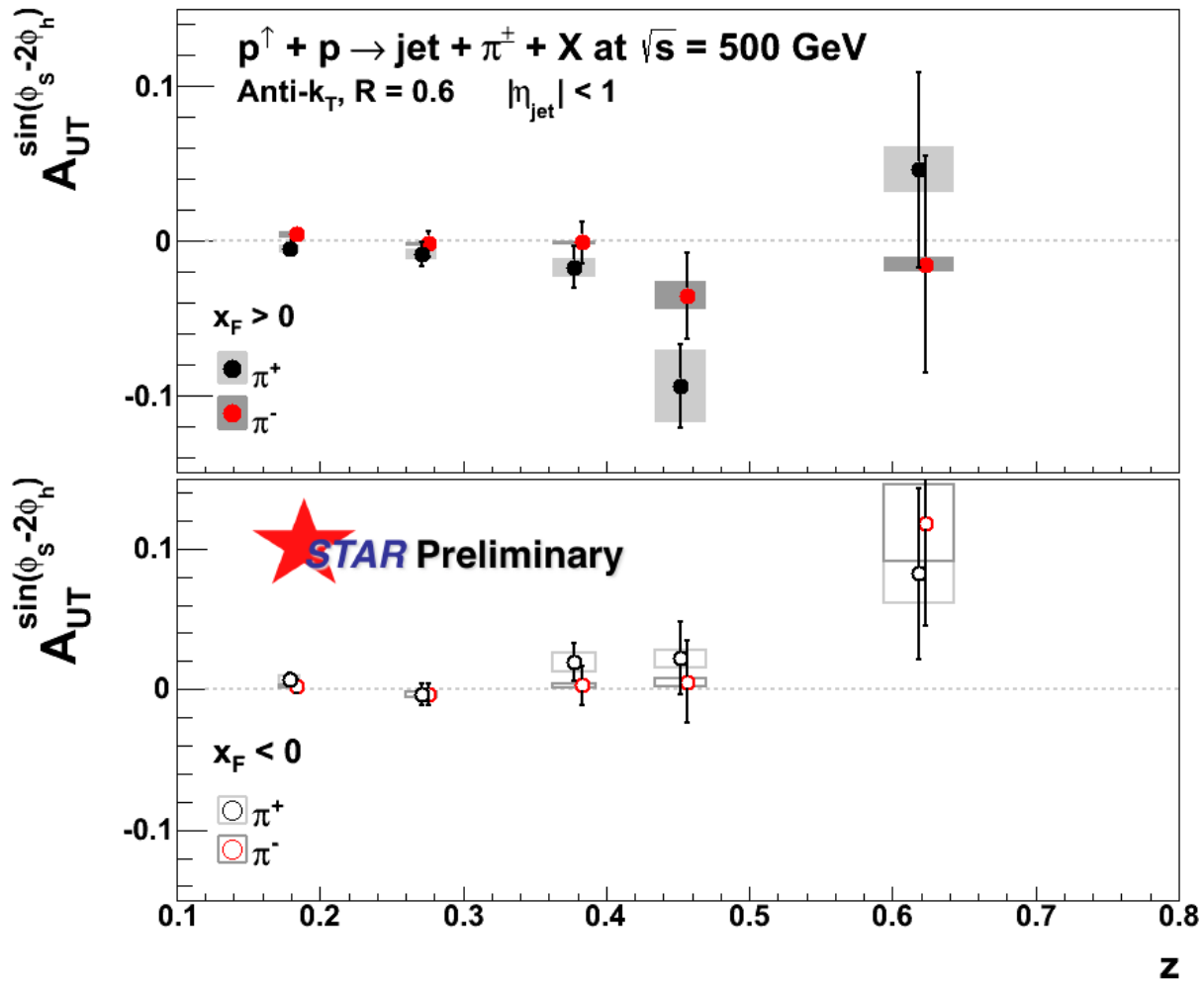
Similarly, no sign of positive effect for backward region ($x_F < 0$), as expected

Collins-like Asymmetries





D'Alesio et al.

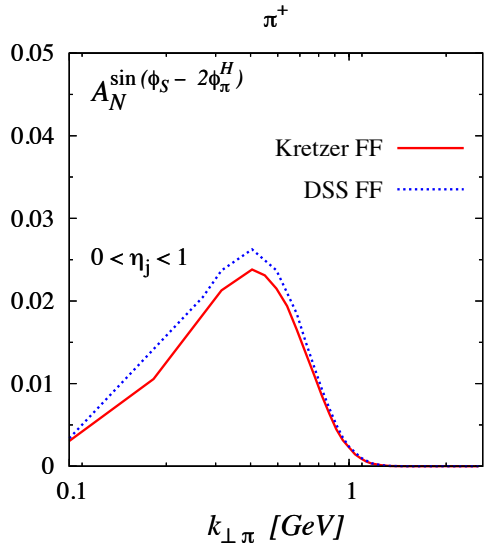


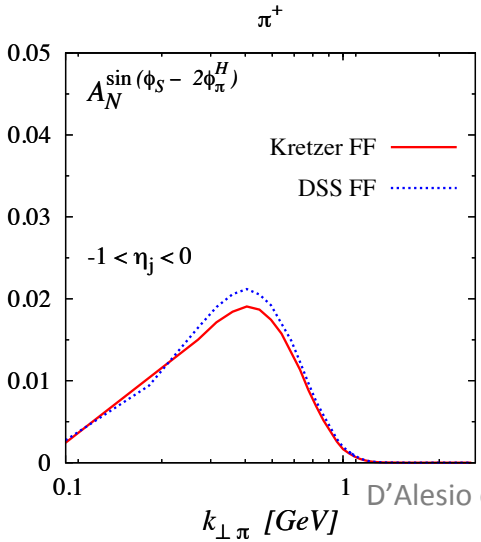
Model predictions shown for "maximized" effect, saturated to positivity bound

Until now, Collins-like asymmetries completely unconstrained

→ ***Sensitive to linearly polarized gluons***

Collins-like Asymmetries





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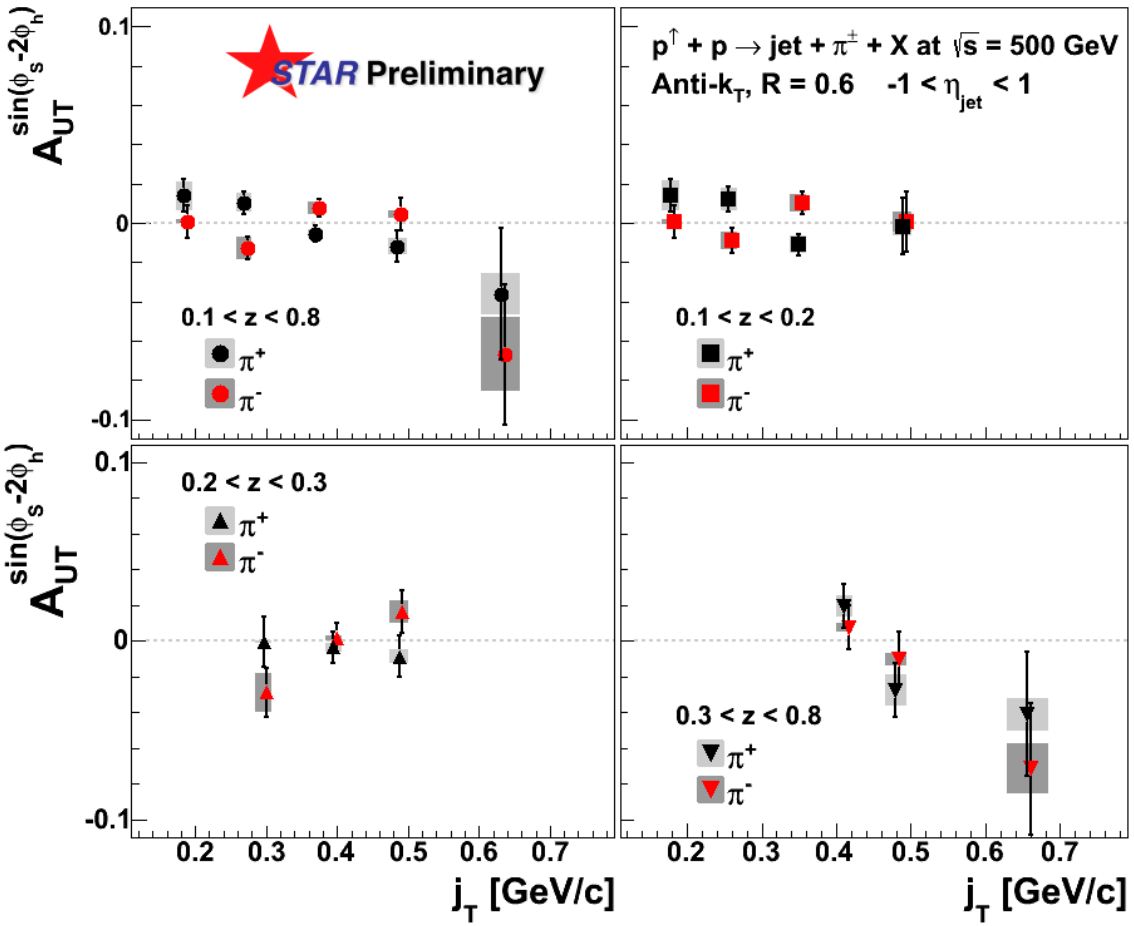
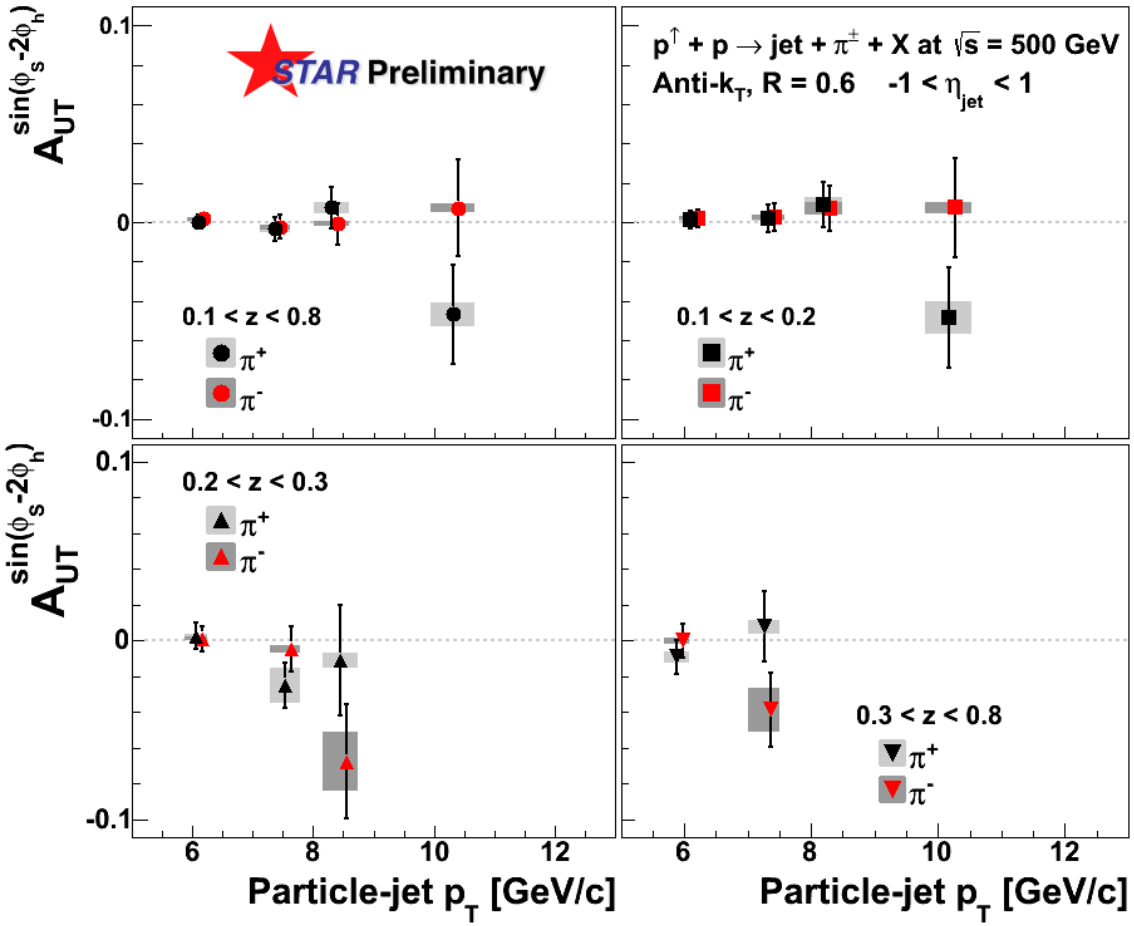


Measured asymmetries shown for -1 < η < 1 in z-bins

Consistently below 2% maximum from model

Collins-like Asymmetries



Similarly, no large effect observed as a function of jet p_T

Measured asymmetries shown for $-1 < \eta < 1$ in z-bins

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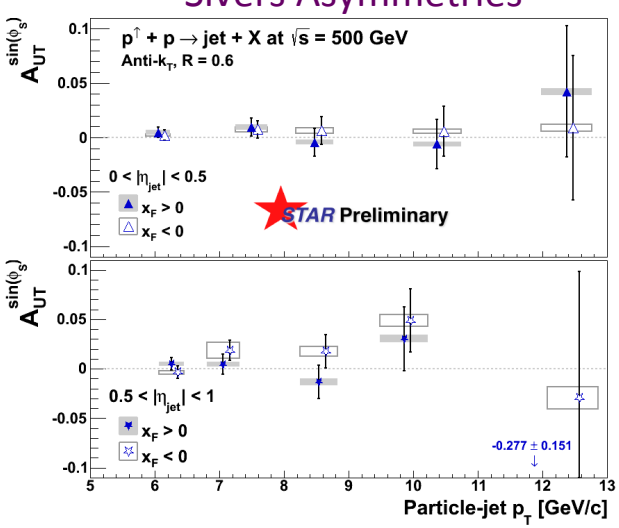
- **First measurements of Collins-like asymmetries *will help place constraints on model predictions* beyond maximal projections from positivity bounds**

Looking Forward

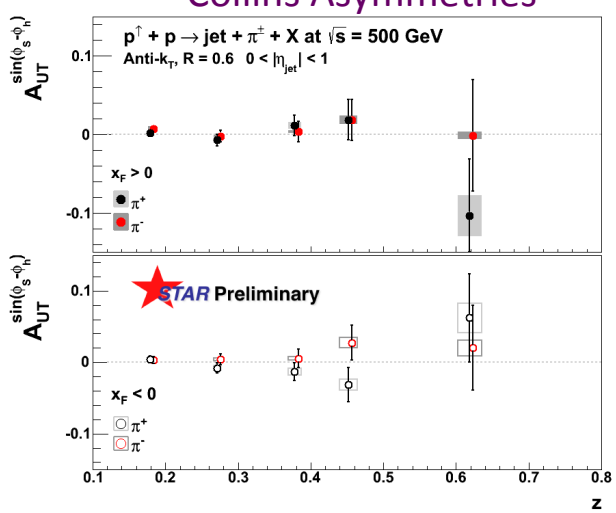
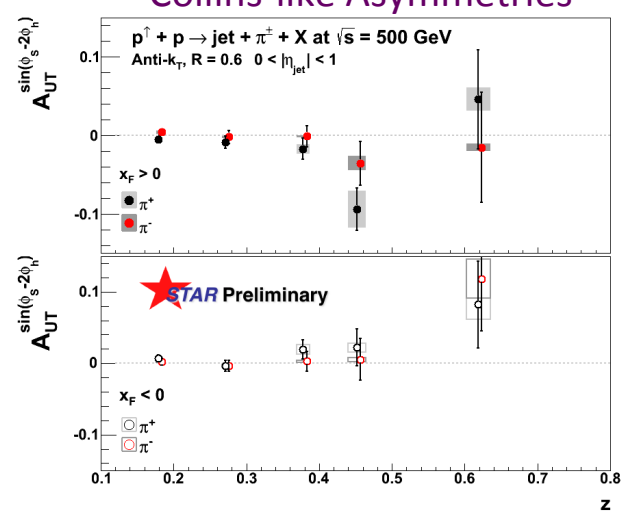
- Additional data from 2011 jet-patch triggers will allow **much greater precision** for higher jet p_T (above 7 GeV/c)
- High precision measurements from 2012 at $\sqrt{s} = 200$ GeV will allow greater sensitivity to effects from quark subprocesses

STAR Preliminary Results at $\sqrt{s}$ = 500 GeV

Sivers Asymmetries



Collins Asymmetries



Collins-like Asymmetries