Constraining Transversity and Nucleon Transverse-polarization Structure Through Polarized-proton Collisions at STAR

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Valparaiso University
for the STAR Collaboration

DIS 2015
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Deep-Inelastic Scattering and
Related Subjects

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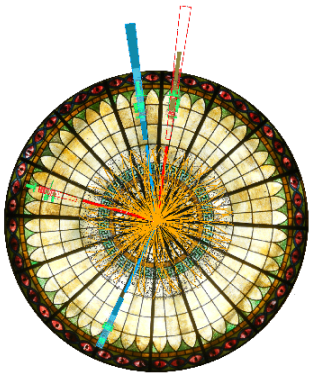


OUTLINE

- Introduction
- RHIC and the STAR detector
- STAR results at $\sqrt{s} = 200$ GeV
- STAR results at $\sqrt{s} = 500$ GeV
- Summary

STAR

Valparaiso University

A Challenge from Transverse Single-spin Asymmetries

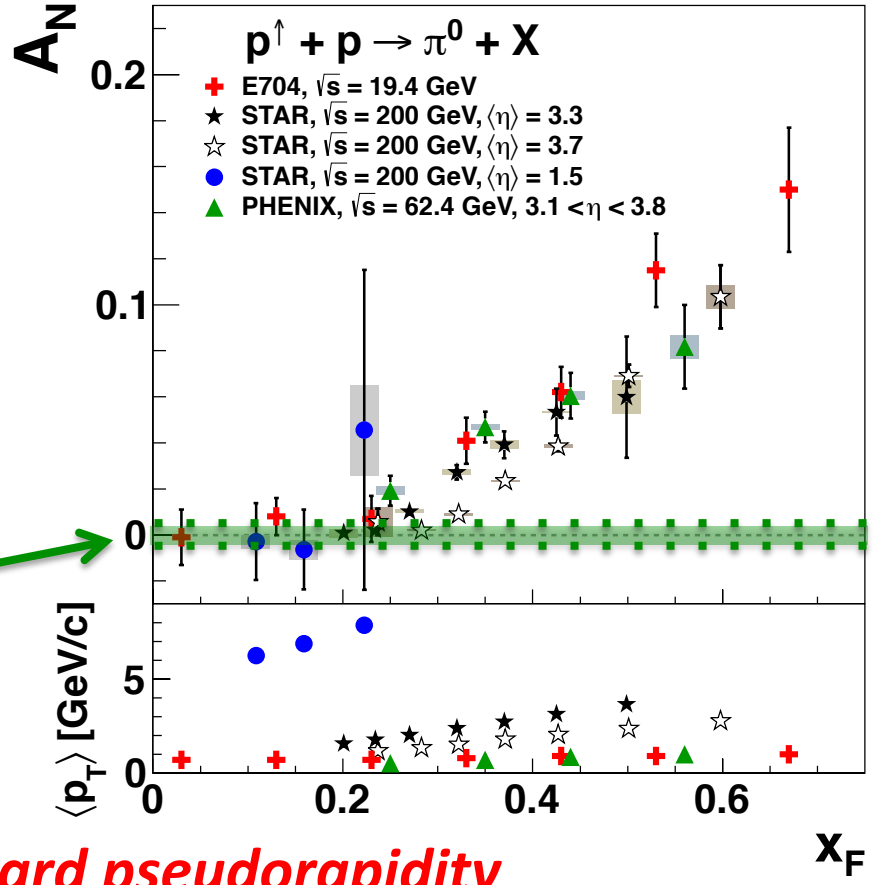
$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$d\sigma^{\uparrow(\downarrow)}$ – cross section for ***leftward*** scattering when beam polarization is spin-**up**(down)

(*Also commonly expressed as* A_N)

Collinear pQCD at leading twist predicts very small A_{UT}

Kane, Pumplin, Repko, PRL 41, 1689 (1978)



PLB 261, 201 (1991)
PRL 101, 222001 (2008)
PRD 89, 012001 (2014)
PRD 90, 012006 (2014)

Sizeable A_{UT} at forward pseudorapidity across a large range of $\sqrt{s}$

Measurements at RHIC in region where NLO pQCD cross-section provides a reasonable description of the data

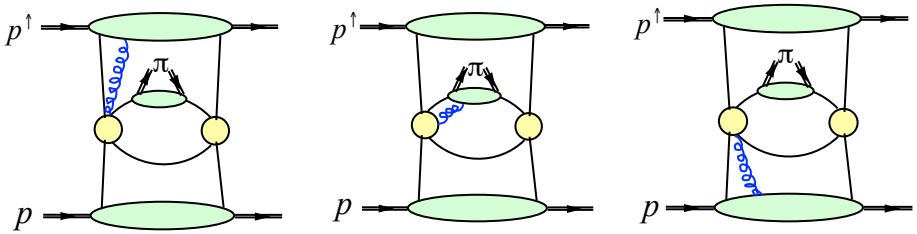
→ Go beyond collinear pQCD at leading twist

→ Insight into transverse polarization structure?

Formalisms for Transverse Single-spin Asymmetries

Transverse Momentum Dependent (TMD) PDFs and FFs

Collinear Twist-3 PDFs and FFs



Y. Koike, RSC Discussion (2004)

Non-zero asymmetry from multi-parton correlation functions

e.g. Qiu and Sterman, PRL 67, 2264 (1991); PRD 59, 014004 (1998)

Correlators closely related to k_T moments of TMDs

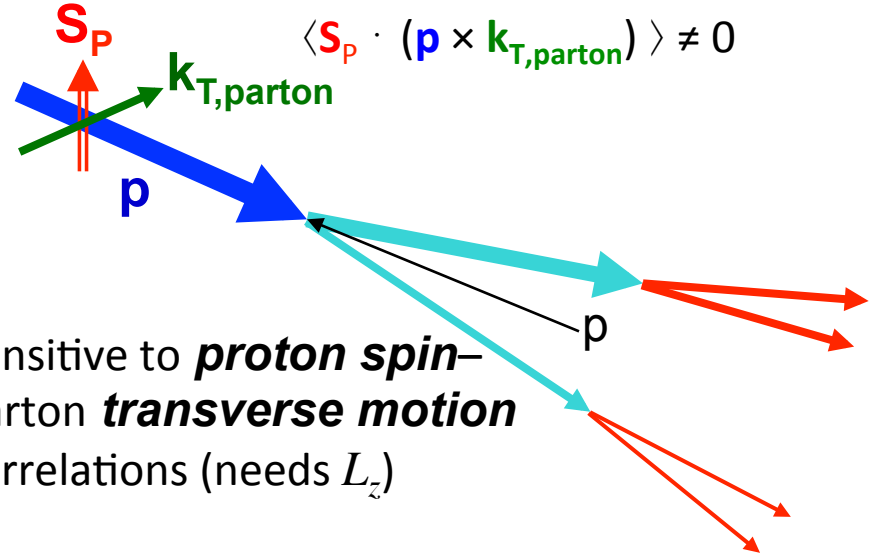
Boer, Mulders, Pijlman, NPB 667, 201 (2003)

Formalisms for Transverse Single-spin Asymmetries

Transverse Momentum Dependent (TMD) PDFs and FFs

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

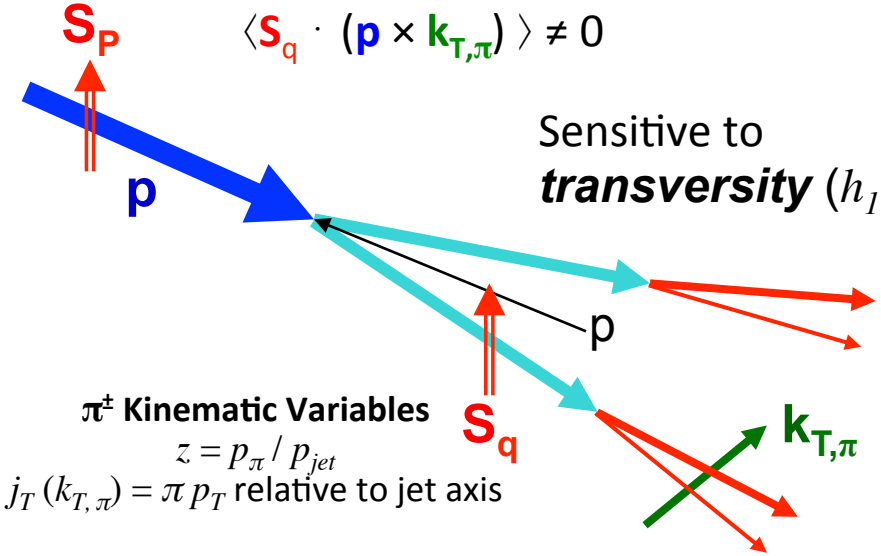
D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



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

Collins mechanism: asymmetry in the forward jet *fragmentation*

J. Collins, NP B396, 161 (1993)



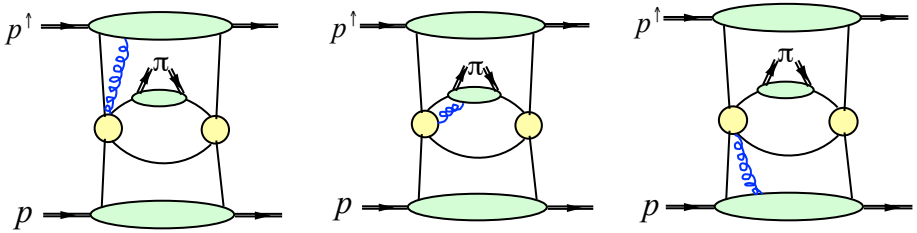
Sensitive to ***transversity*** (h_1)

$\pi^{\pm}$ Kinematic Variables

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

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

Collinear Twist-3 PDFs and FFs



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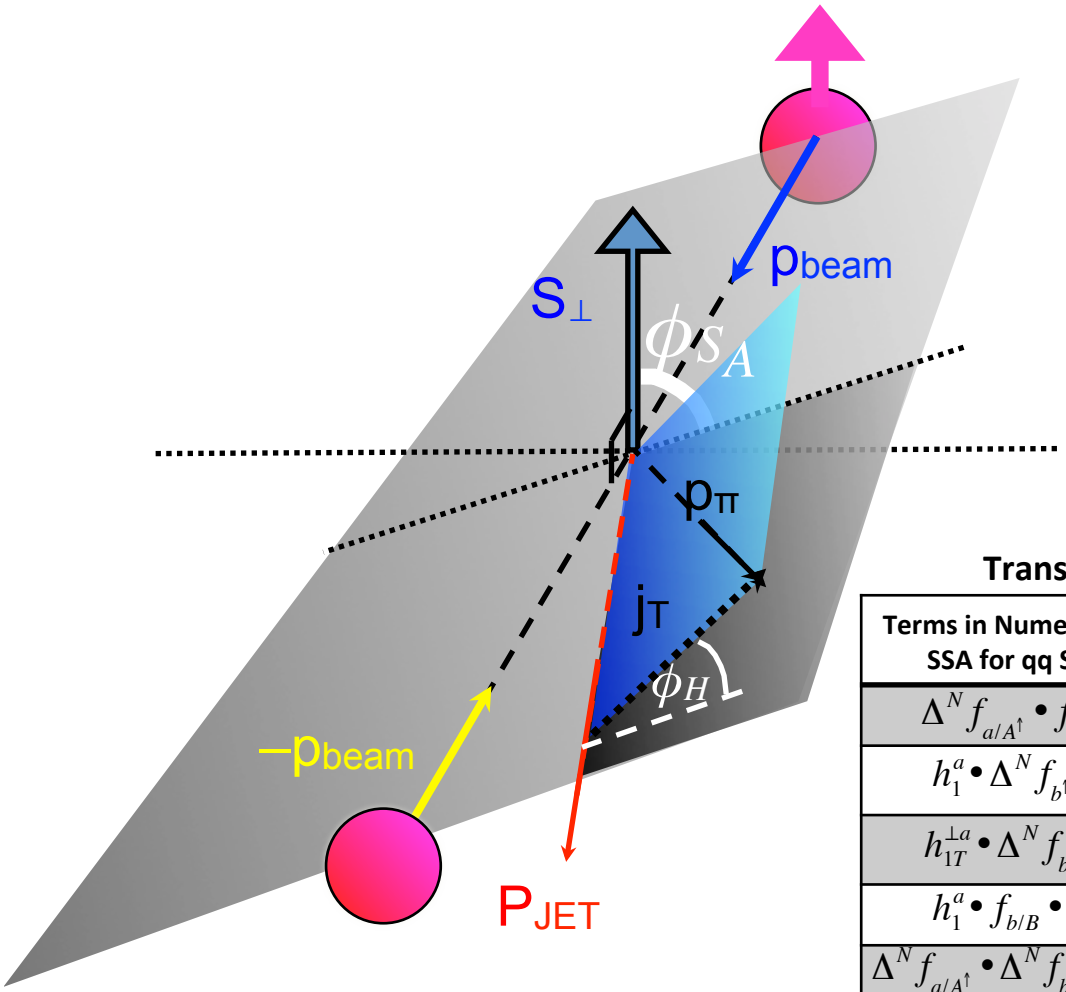
Transverse Asymmetries for Quark Jets



Asymmetry modulations sensitive to various contributions (often involving *transversely polarized quarks* or *linearly polarized gluons*)

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	Modulation
$\Delta^N f_{a/A^\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin\left(\phi_{S_A}\right)$
$h_1^a \bullet \Delta^N f_{b^\uparrow/B} \bullet D_{\pi/q}$	Transversity • Boer-Mulders • FF	$\sin\left(\phi_{S_A}\right)$
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Anselmino et al., PRD 73, 014020 (2006)
F. Yuan, PRL 100, 032003 (2008)
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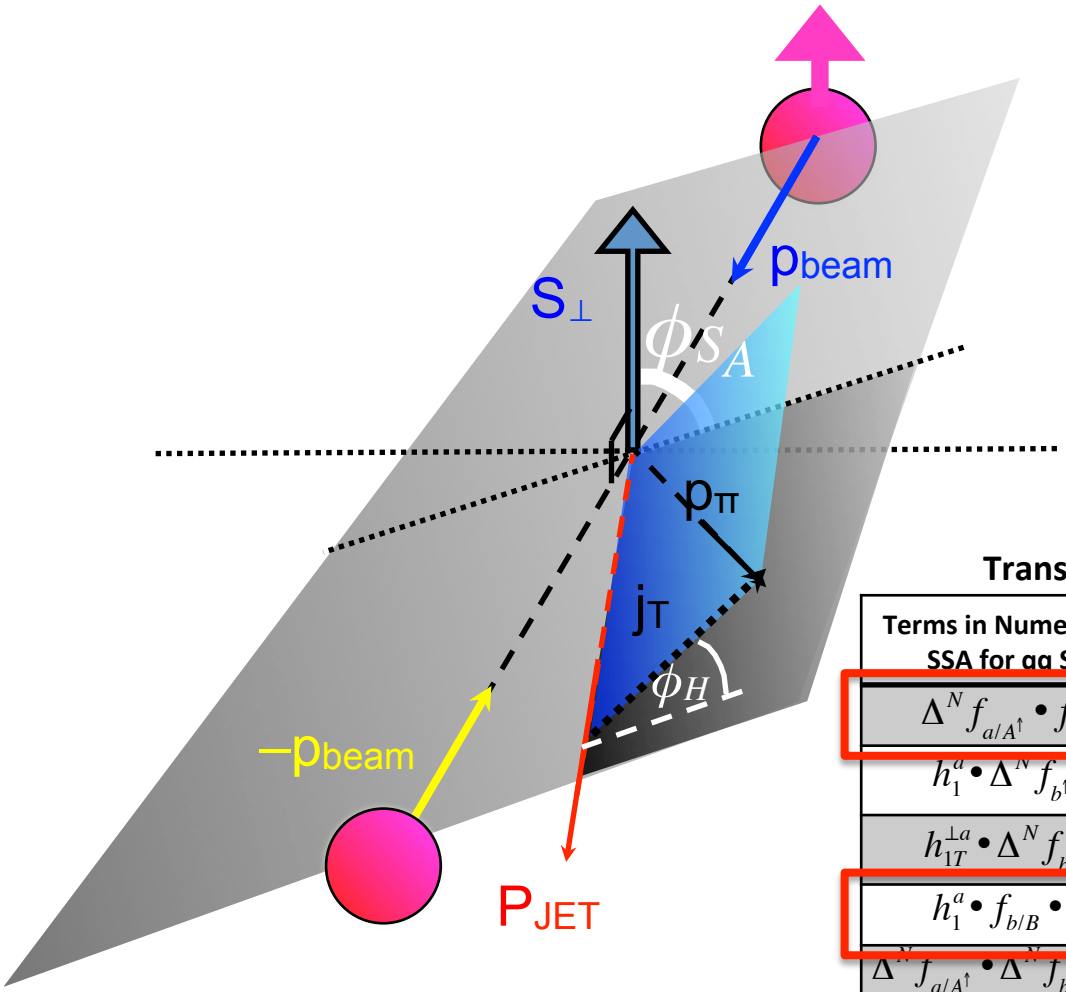

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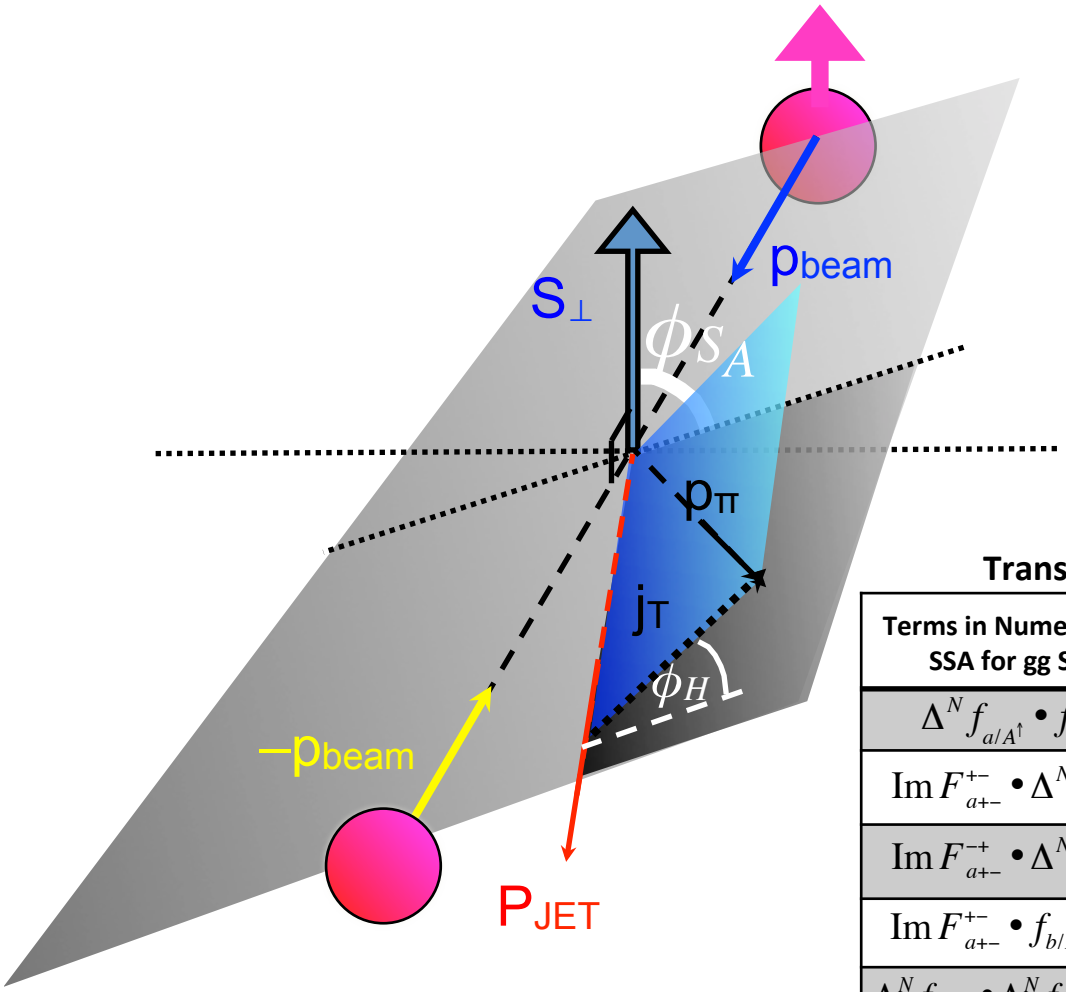

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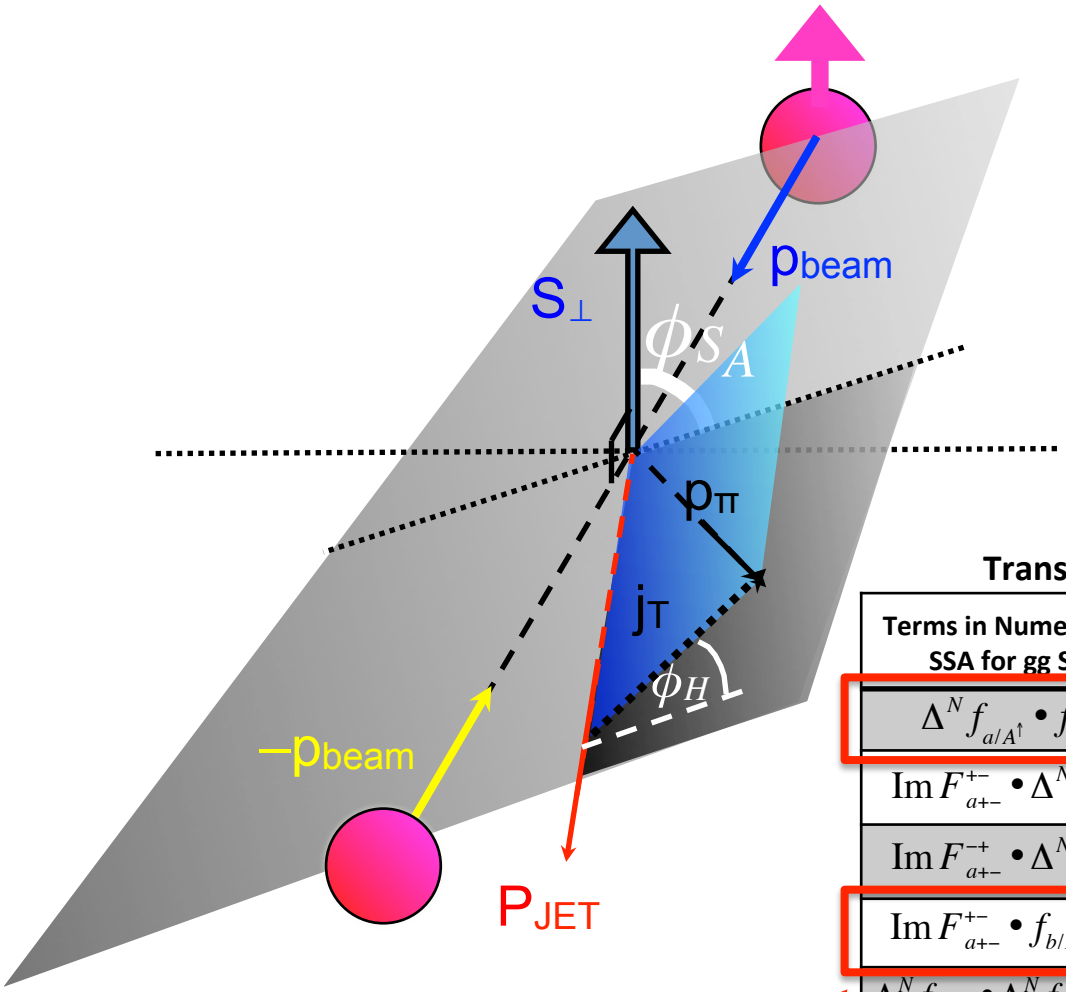

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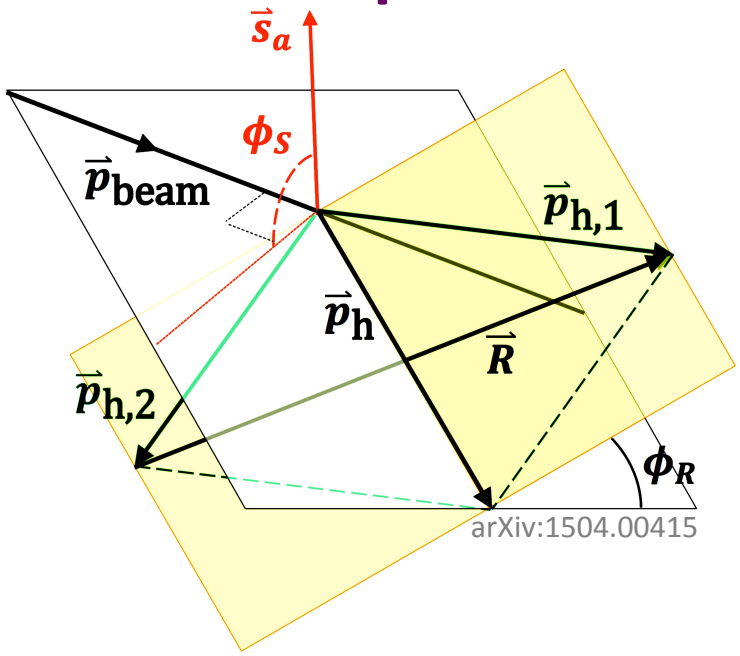
UNCONSTRAINED!

Transverse Asymmetries from Di-hadrons

Another path to transversity: Di-hadron Asymmetries



$$A_{UT}^{\sin(\phi_{RS})} \propto h_1 \otimes H_1^{\sphericalangle}$$

Survives in collinear framework

$$\phi_{RS} = \phi_R - \phi_S$$

Angle between polarization vector and di-hadron plane

—"Interference Fragmentation Function"

e.g. Bacchetta and Radici, PRD 70, 094032 (2004)

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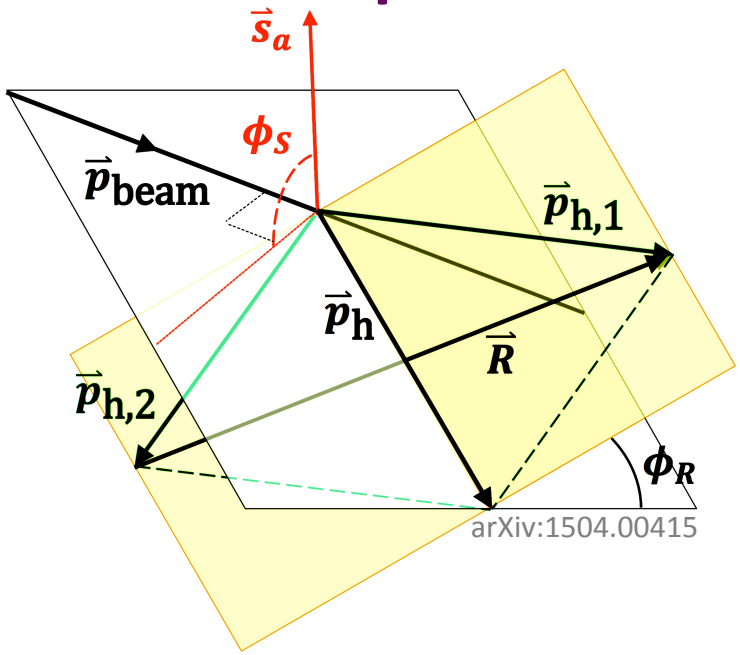

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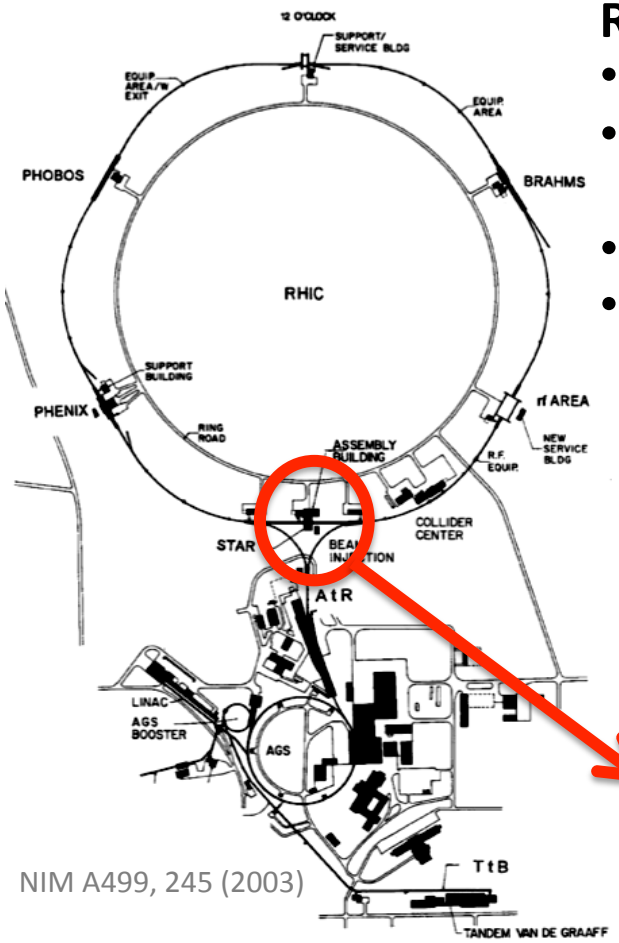
Studying both jet+hadron and di-hadron asymmetries over range of collision energy:

- ***Extend kinematic reach*** beyond existing measurements
- ***Probe evolution*** of transversity and TMDs
- ***Probe open theoretical questions***, e.g. TMD factorization-breaking and universality

Solenoidal Tracker at RHIC

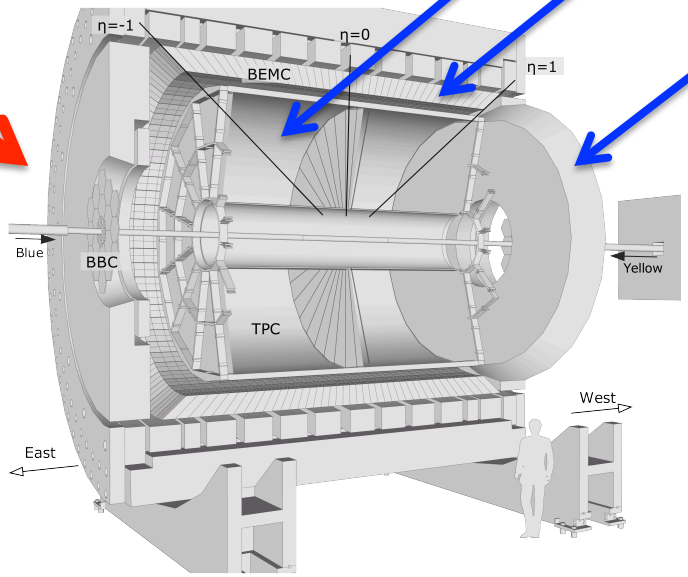


NIM A499, 245 (2003)

RHIC as Polarized-proton Collider

- "Siberian Snakes" → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Jet and di-hadron measurements:
TPC + Barrel + Endcap EMC



Jet trigger on calorimeter energy

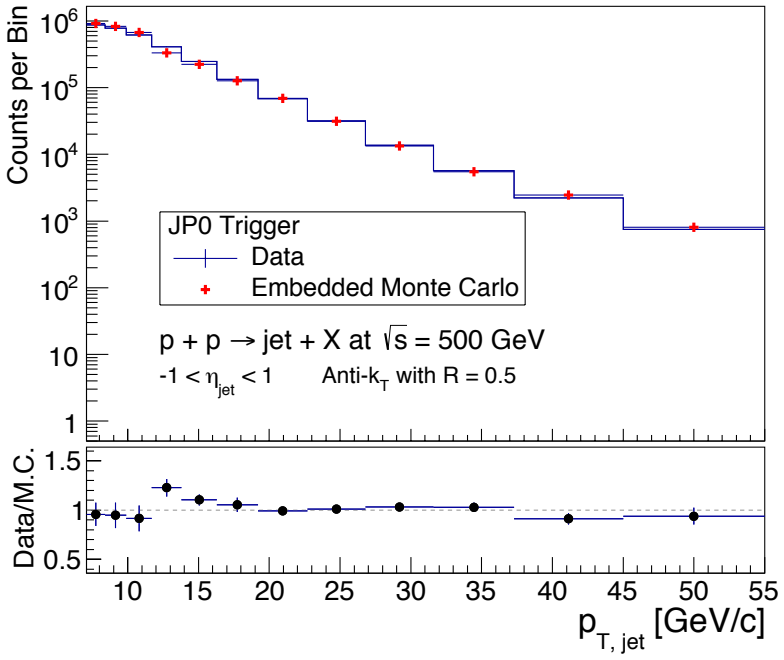
Jet reconstruction

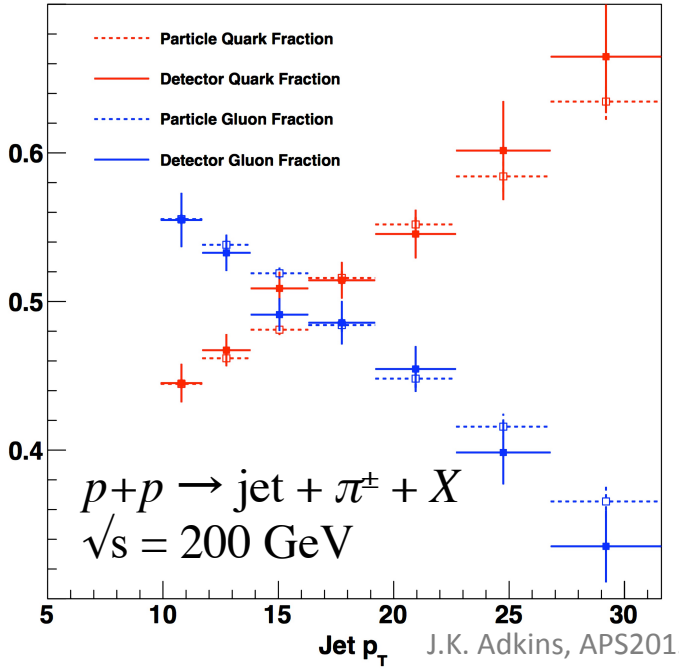
- calorimeter towers
- TPC tracks

Sources of Systematic Uncertainty

Systematic uncertainties:

- Jet+pion event kinematics corrected to PYTHIA particle level
- Energy-scale uncertainties from calorimeter gains, response, efficiencies, etc.
- Charged-particle momentum resolution
- Trigger bias: jet trigger more efficient for quark-jets than gluon
- Resolution of relevant azimuthal angles
- "leak-through" of other moments of A_{UT}
- Pion contamination from K/p and $e^{\pm}$
- Polarization uncertainty (correlated vertical scale uncertainty of 3-5%)





J.K. Adkins, APS2015

STAR Transverse Asymmetries at Central Pseudorapidity

STAR measured transverse single-spin asymmetries at central pseudorapidity from ≈2 pb^{-1} at $\sqrt{s} = 200$ GeV (2006)

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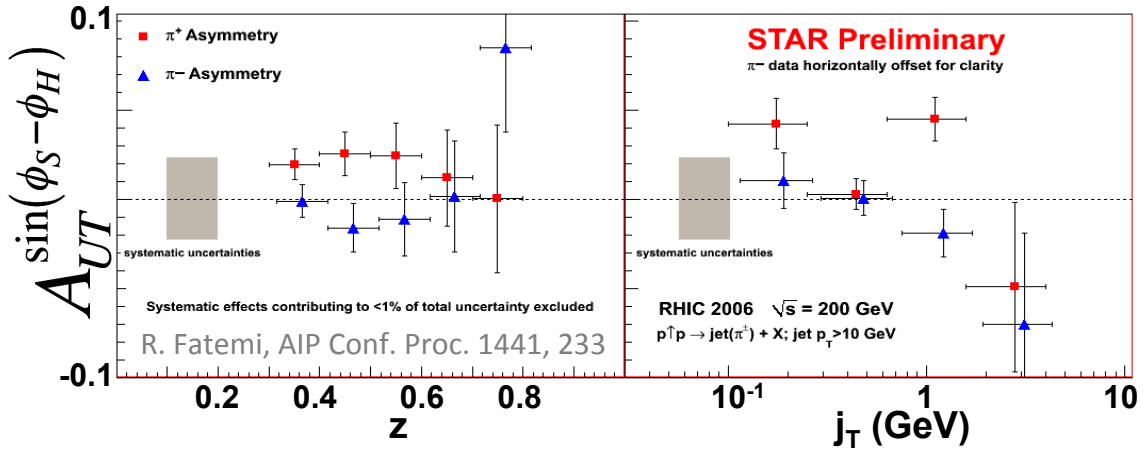

Hints of non-zero Collins asymmetry
with charge-sign dependence

Inclusive-jet and di-jet asymmetries at central psuedorapidity consistent with zero
PRL 99, 142003; PRD 86, 32006

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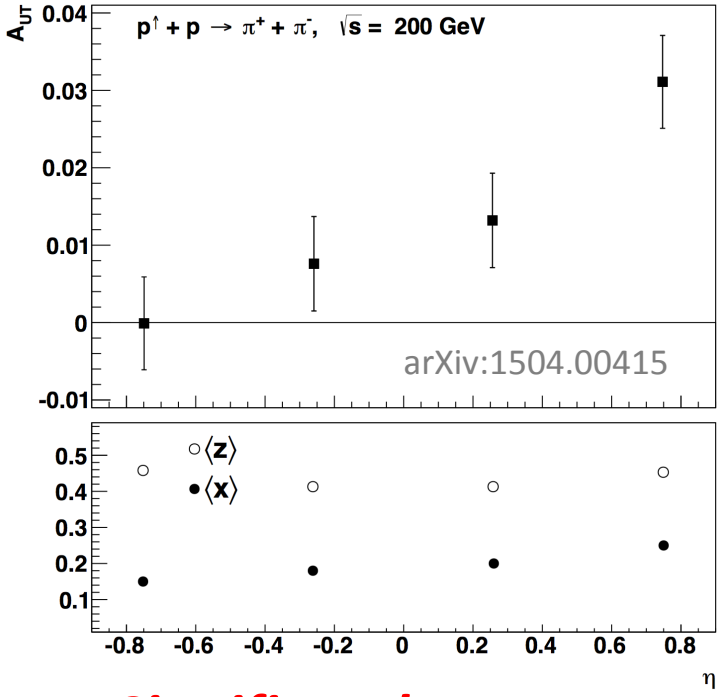

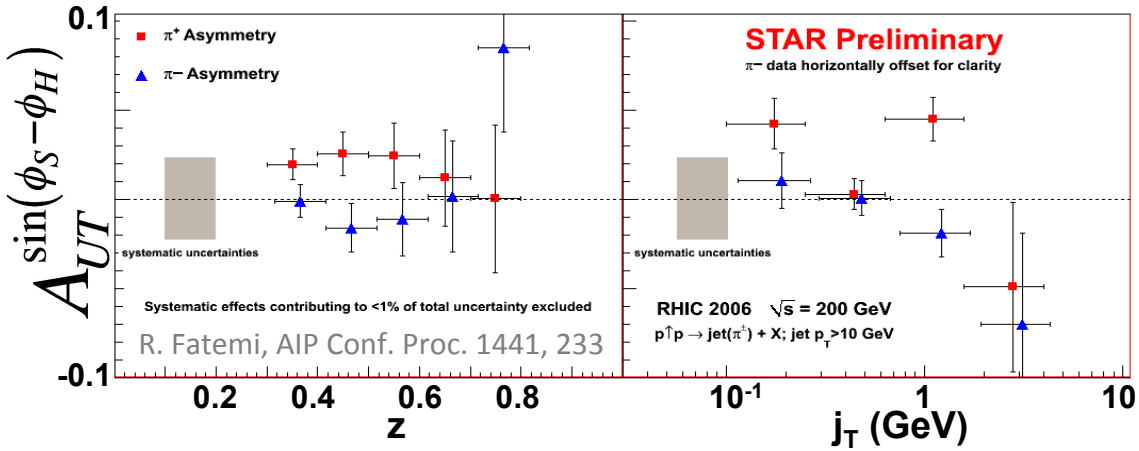

Significantly non-zero di-hadron asymmetries for charged pions at central pseudorapidity

Hints of non-zero Collins asymmetry with charge-sign dependence

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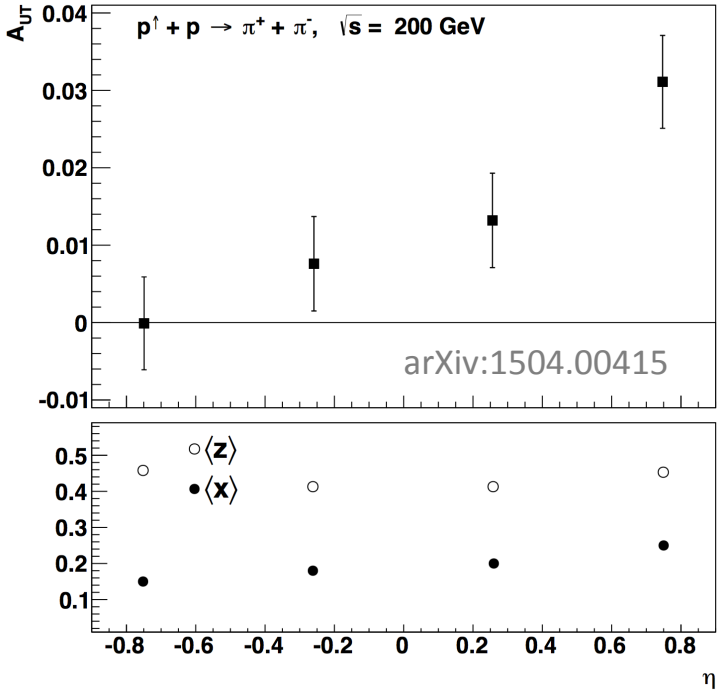
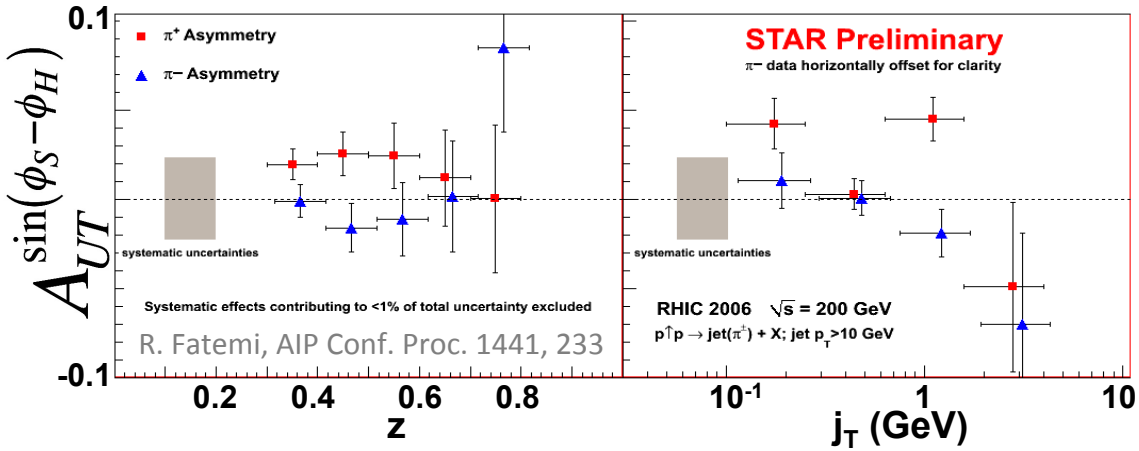




Non-zero Collins + Di-hadron Asymmetries

→ ***Access to transversity in p+p!***

Recent Polarized-proton Datasets at STAR

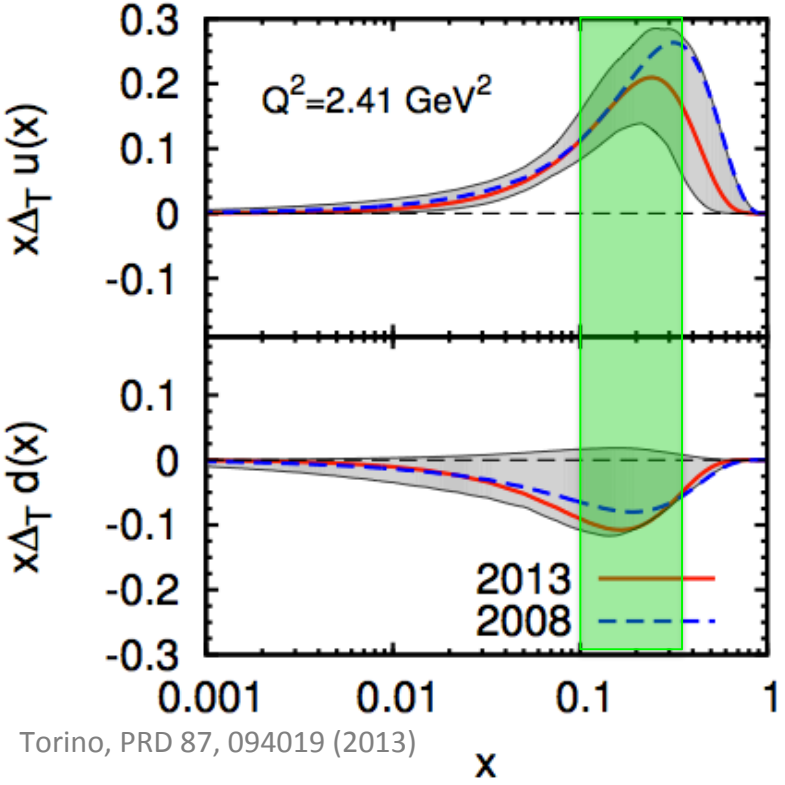
2011

- 25 pb^{-1} at $\sqrt{s} = 500$ GeV
- Average polarization = 53%

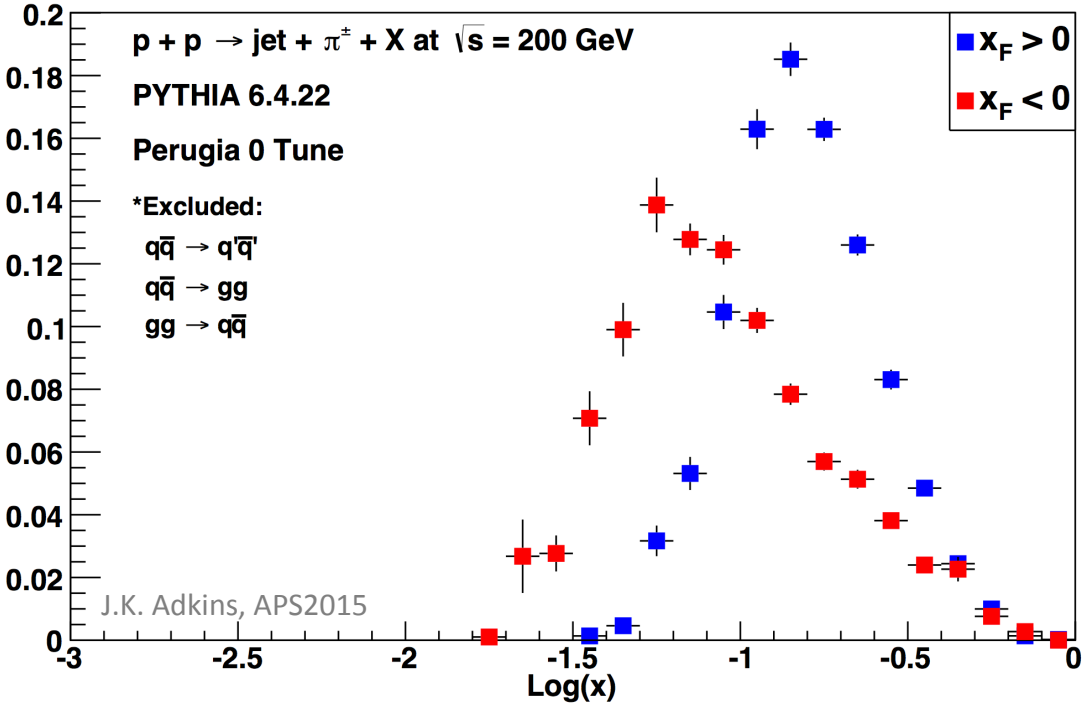
2012

- 22 pb^{-1} at $\sqrt{s} = 200$ GeV
- Avg polarization = 63%

Compare to ≈2 pb^{-1} at 57% polarization in 2006

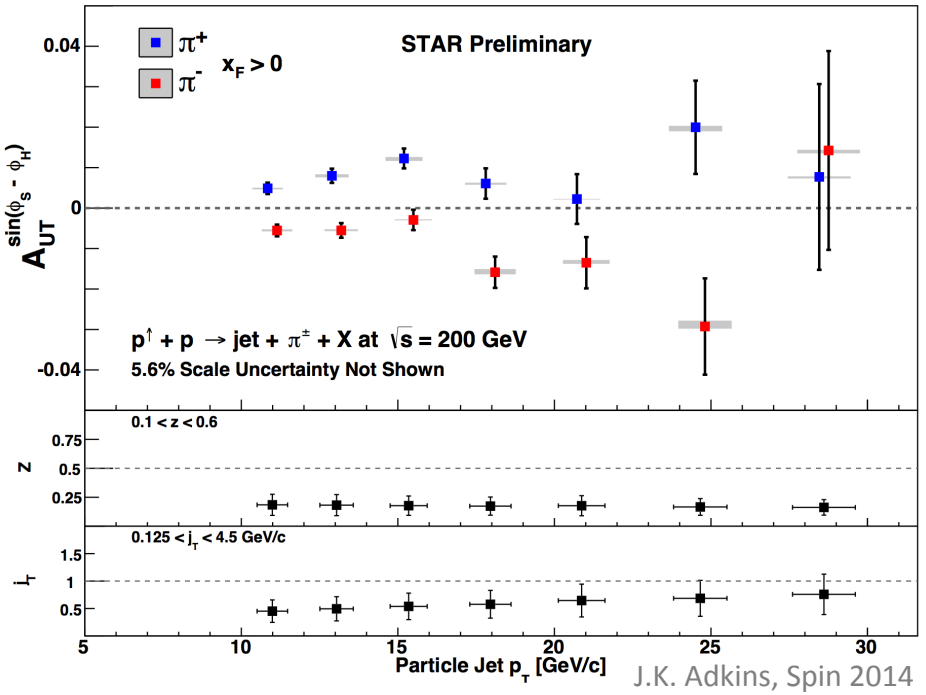


Torino, PRD 87, 094019 (2013)



Access to transversity in region with limited constraints

New STAR Results at $\sqrt{s} = 200$ GeV



J.K. Adkins, Spin 2014

First observation of Collins asymmetry in p+p!

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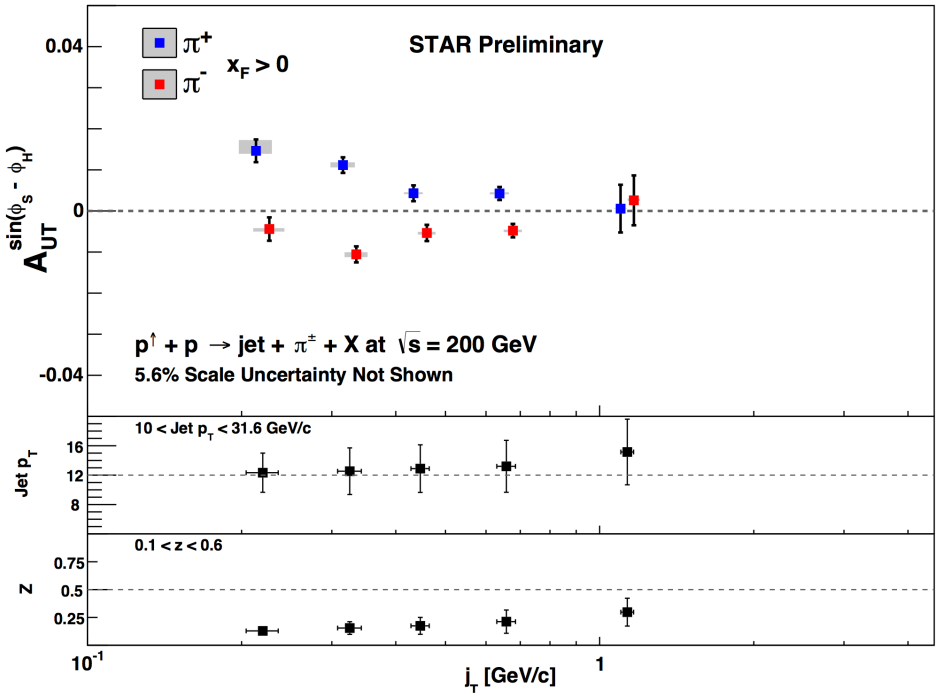

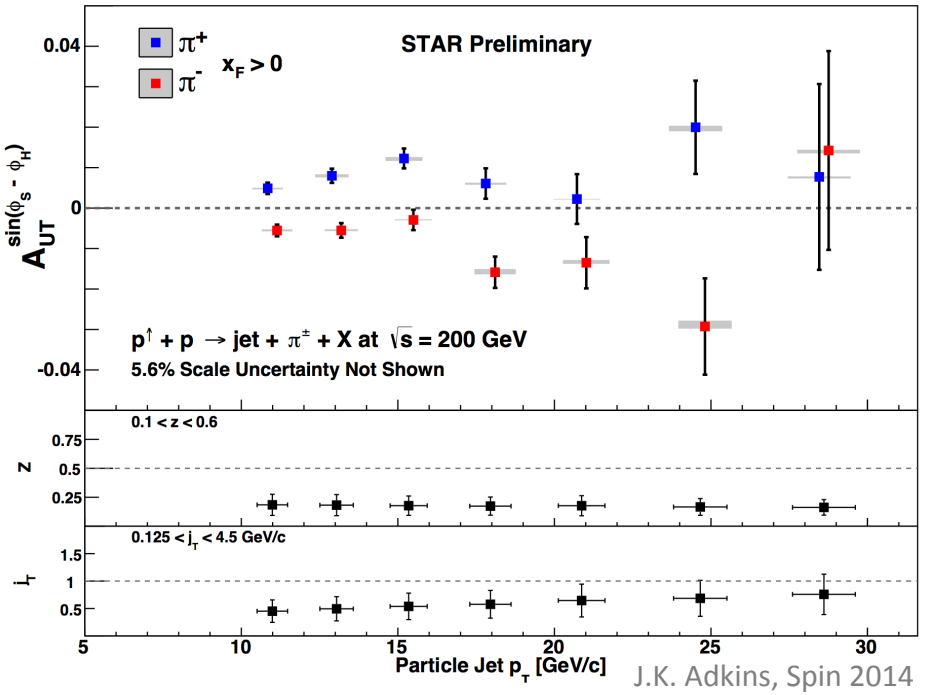

J.K. Adkins, Spin 2014

STRONG dependence upon j_T

$$j_{T,\min} \approx z \times \Delta R_{\min} \times \langle p_T \rangle,$$

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

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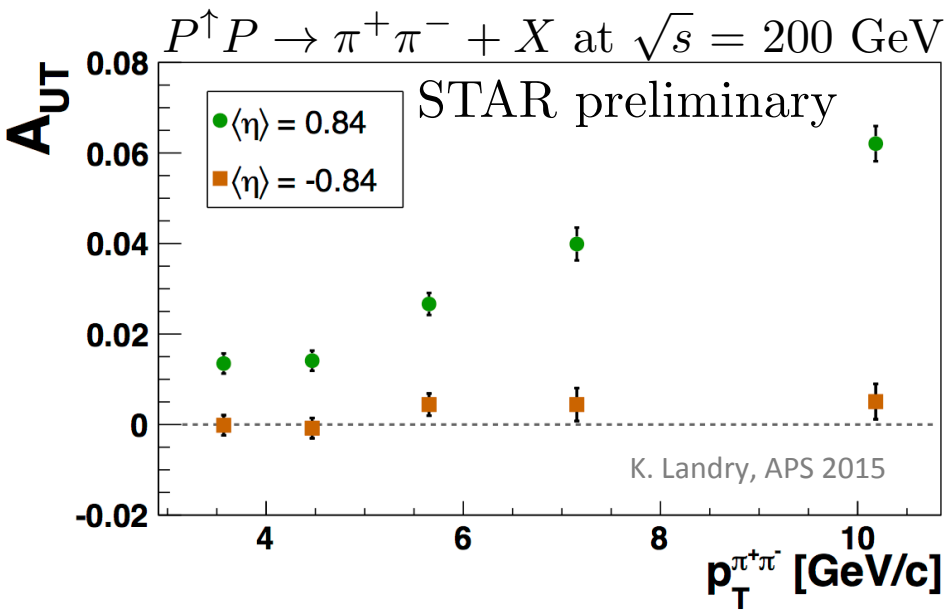
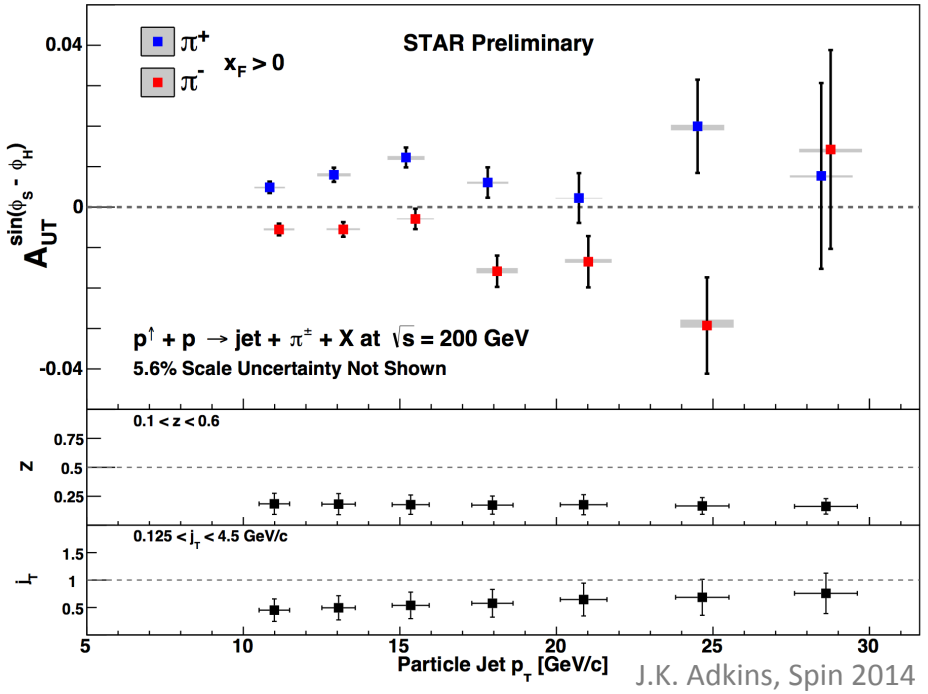


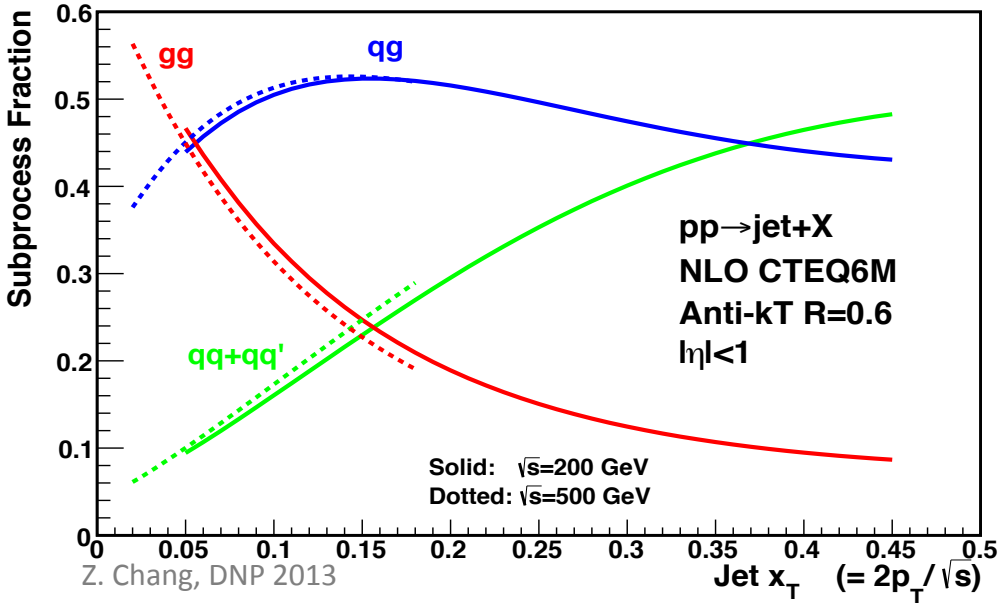


Significant, high-precision di-hadron asymmetries

First observation of Collins asymmetry in p+p!

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

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



Z. Chang, DNP 2013

2011 STAR Data:

first measurements

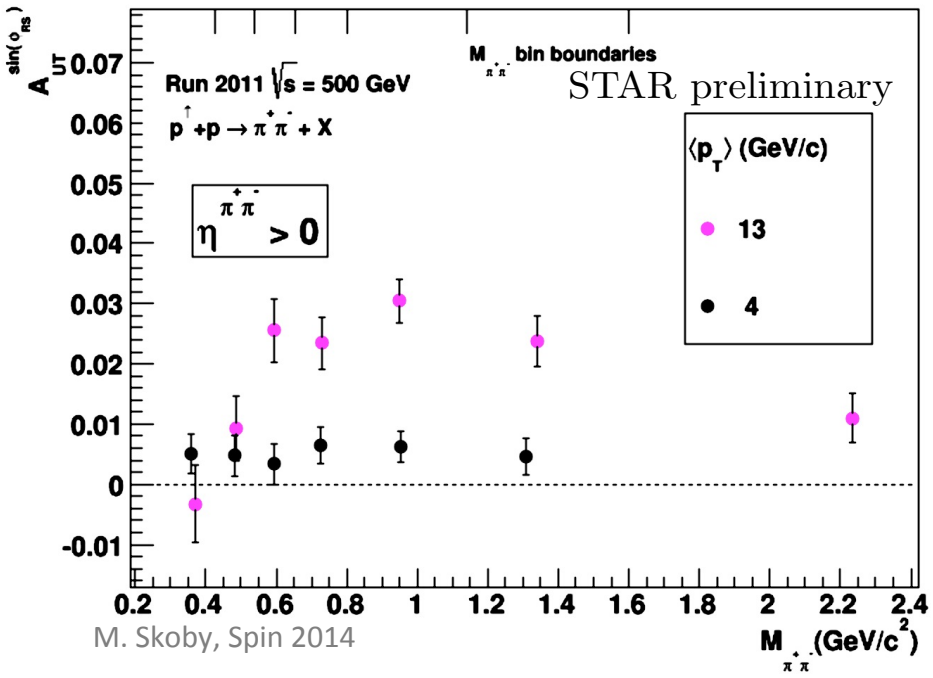
of central pseudorapidity asymmetries at $\sqrt{s} = 500$ **GeV**

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

→ ***Push to higher*** p_T ***for kinematics comparable to*** 200 ***GeV***

→ ***Probe TMD evolution?***

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

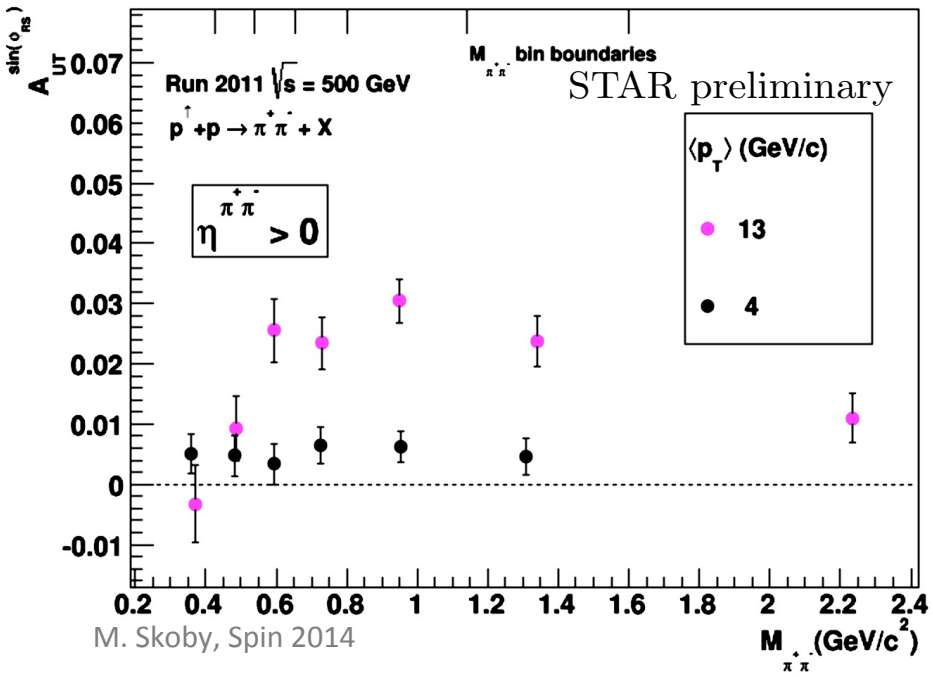


M. Skoby, Spin 2014

Significant non-zero di-hadron asymmetries at $\sqrt{s} = 500$ GeV!

- Increasing with pion p_T
- Enhanced around ρ mass

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



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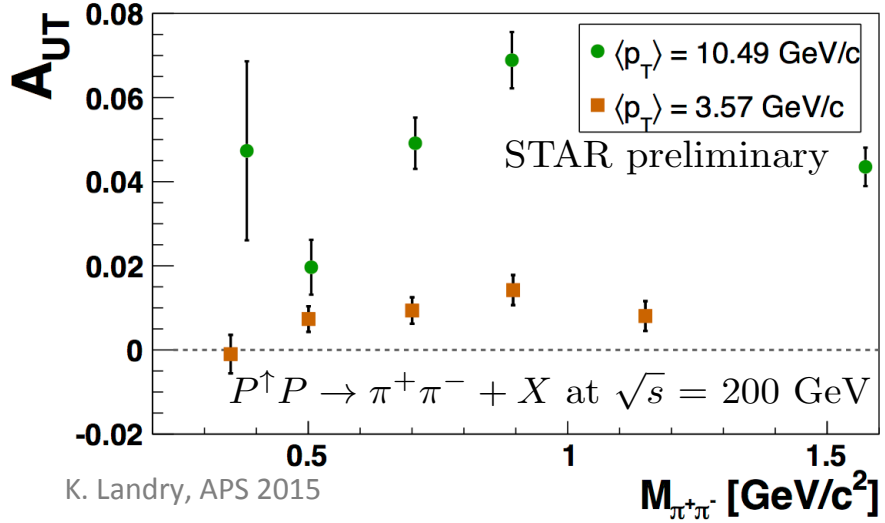


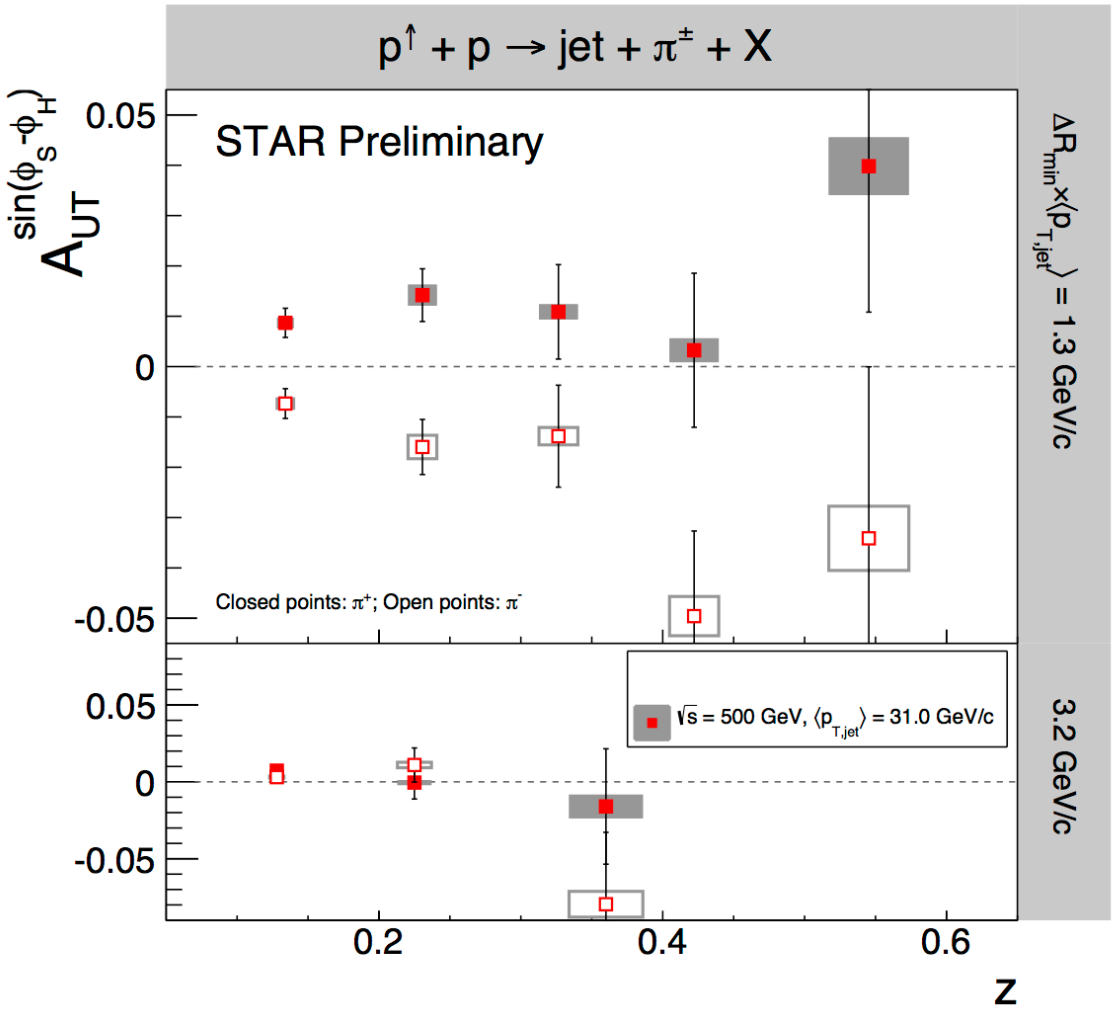
K. Landry, APS 2015

Significant non-zero di-hadron asymmetries at $\sqrt{s} = 500$ GeV!

- Increasing with pion p_T
- Enhanced around ρ mass

Similar behavior observed in $\sqrt{s} = 200$ GeV

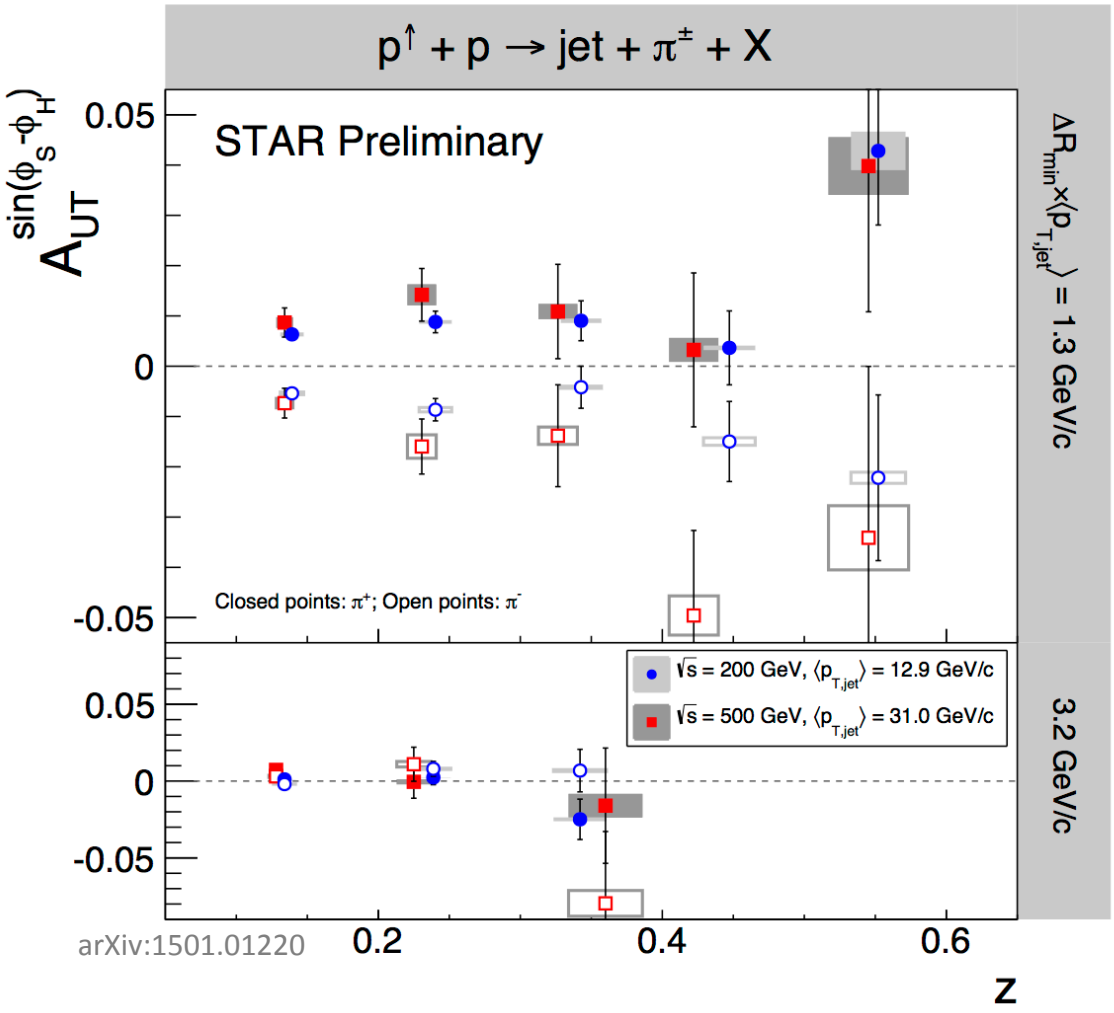
STAR Collins Results at $\sqrt{s} = 500$ GeV



Non-zero Collins asymmetries observed at $\sqrt{s} = 500$ GeV!

- Strong dependence on $\Delta R_{\min}$ ($j_{T,\min}$)

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



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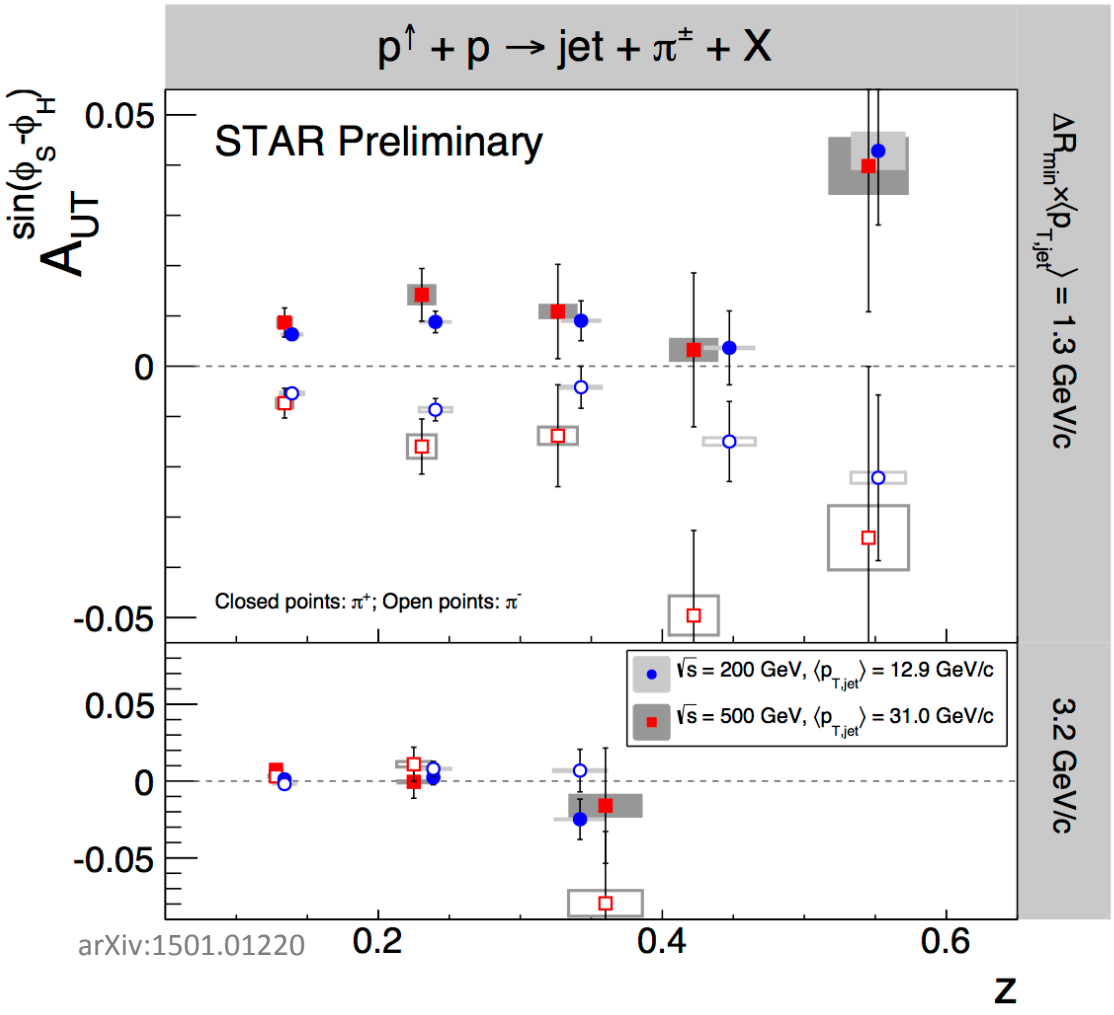
- Strong dependence on $\Delta R_{\min}$ ($j_{T,\min}$)
- Consistent with $\sqrt{s} = 200$ GeV results for consistent cuts and x_T

At the current precision, Collins results from $p+p$ appear consistent with x_T scaling

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



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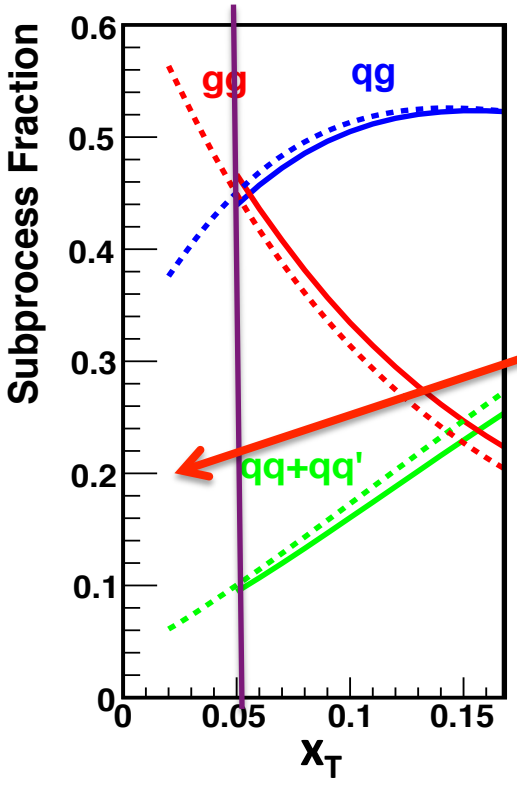
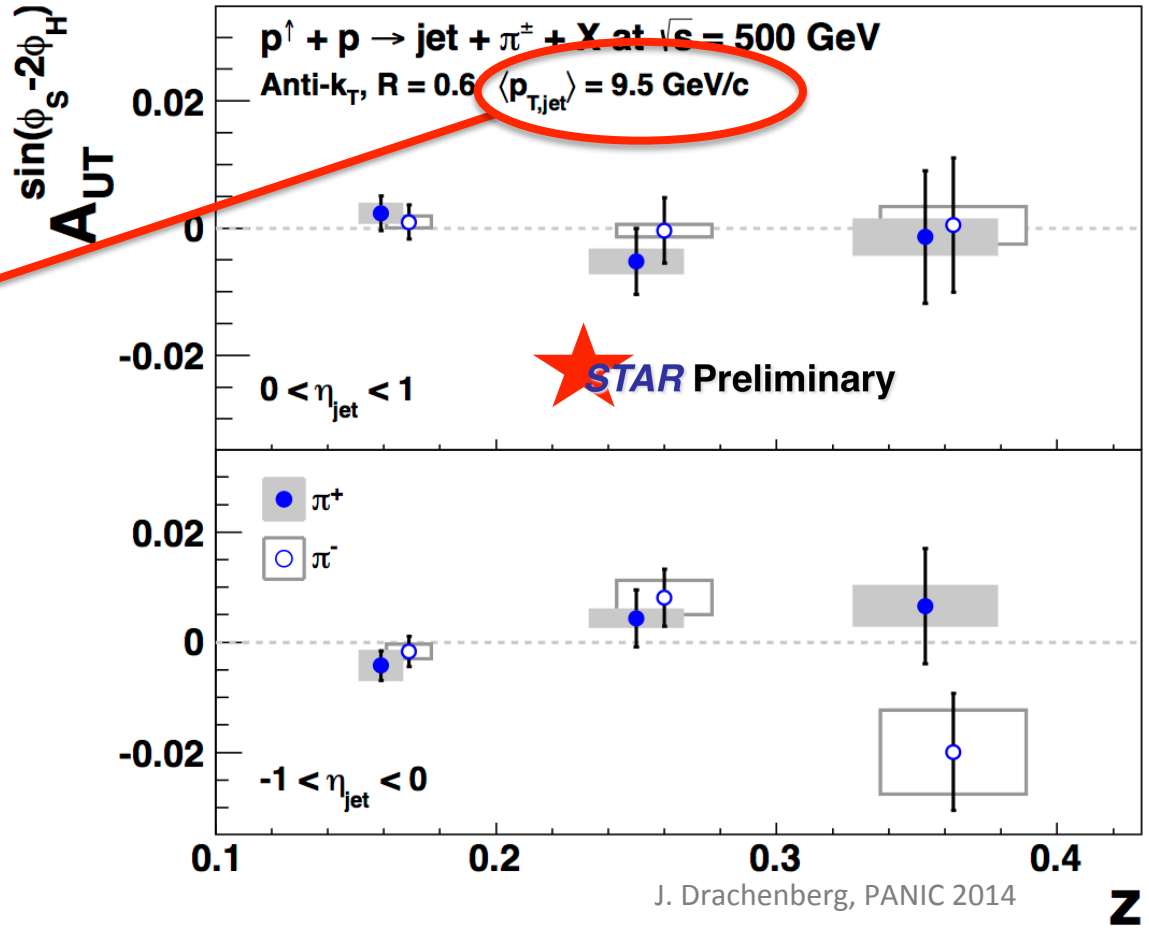
Suggestion of slow TMD evolution from 200 to 500 GeV?

STAR Collins-like Asymmetries at $\sqrt{s} = 500$ GeV





J. Drachenberg, PANIC 2014

Gluon helicity density matrix

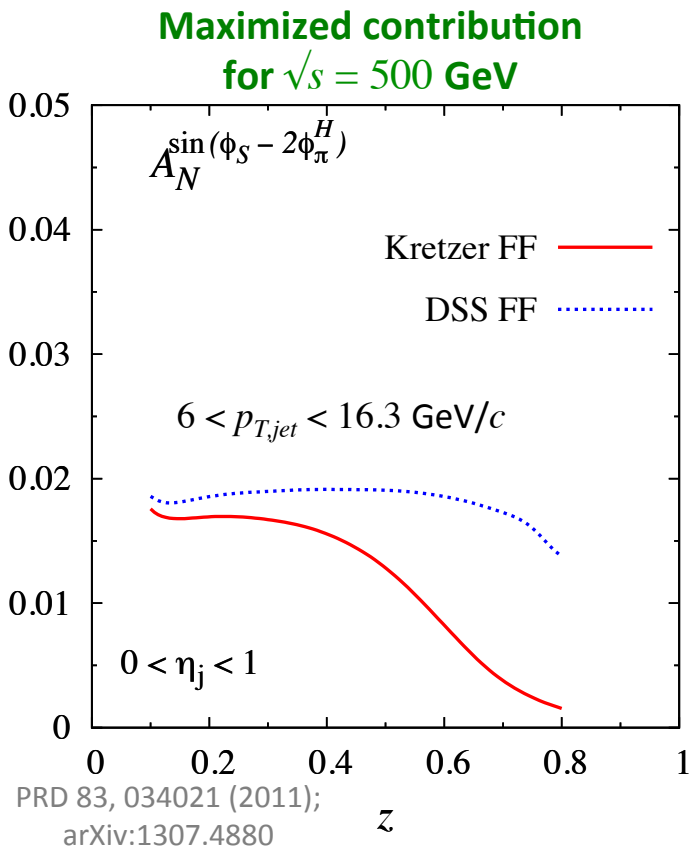
$$\rho = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & -P_{lin}e^{-2i\phi} \\ -P_{lin}e^{2i\phi} & 1-P_{circ} \end{pmatrix}$$

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

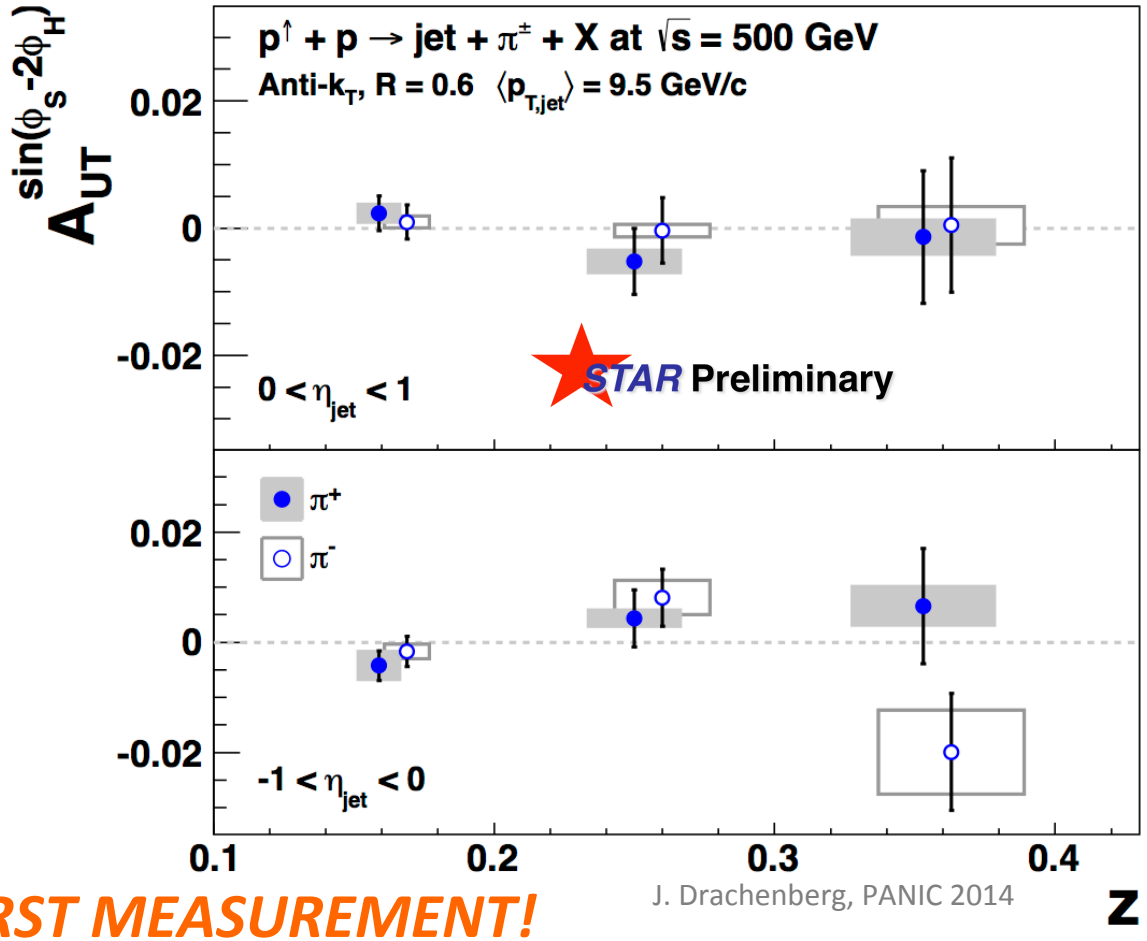
Phys Rev. D 73, 014020 (2006)

500 GeV provides opportunity to probe effects (e.g. gluon linear polarization) with ***enhanced sensitivity to gluonic subprocesses***

STAR Collins-like Asymmetries at $\sqrt{s} = 500$ GeV



PRD 83, 034021 (2011);
arXiv:1307.4880



J. Drachenberg, PANIC 2014

FIRST MEASUREMENT!

Present data sit well below maximized contribution of ~2% at low z

Present data should provide first constraints on Collins-like effect

(sensitive to linearly polarized gluons)

Summary

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    - ***Very small inclusive jet*** A_{UT}**:** further limits on gluon Sivers?
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Stay tuned for more new STAR jet and di-hadron results from the 2015 RHIC Run!

Back-up Slides

Inclusive Jet Asymmetries at 500 GeV

Jets corrected to particle-jet p_T

Corresponding parton-jet p_T lower by 0.3-1.2 GeV/c

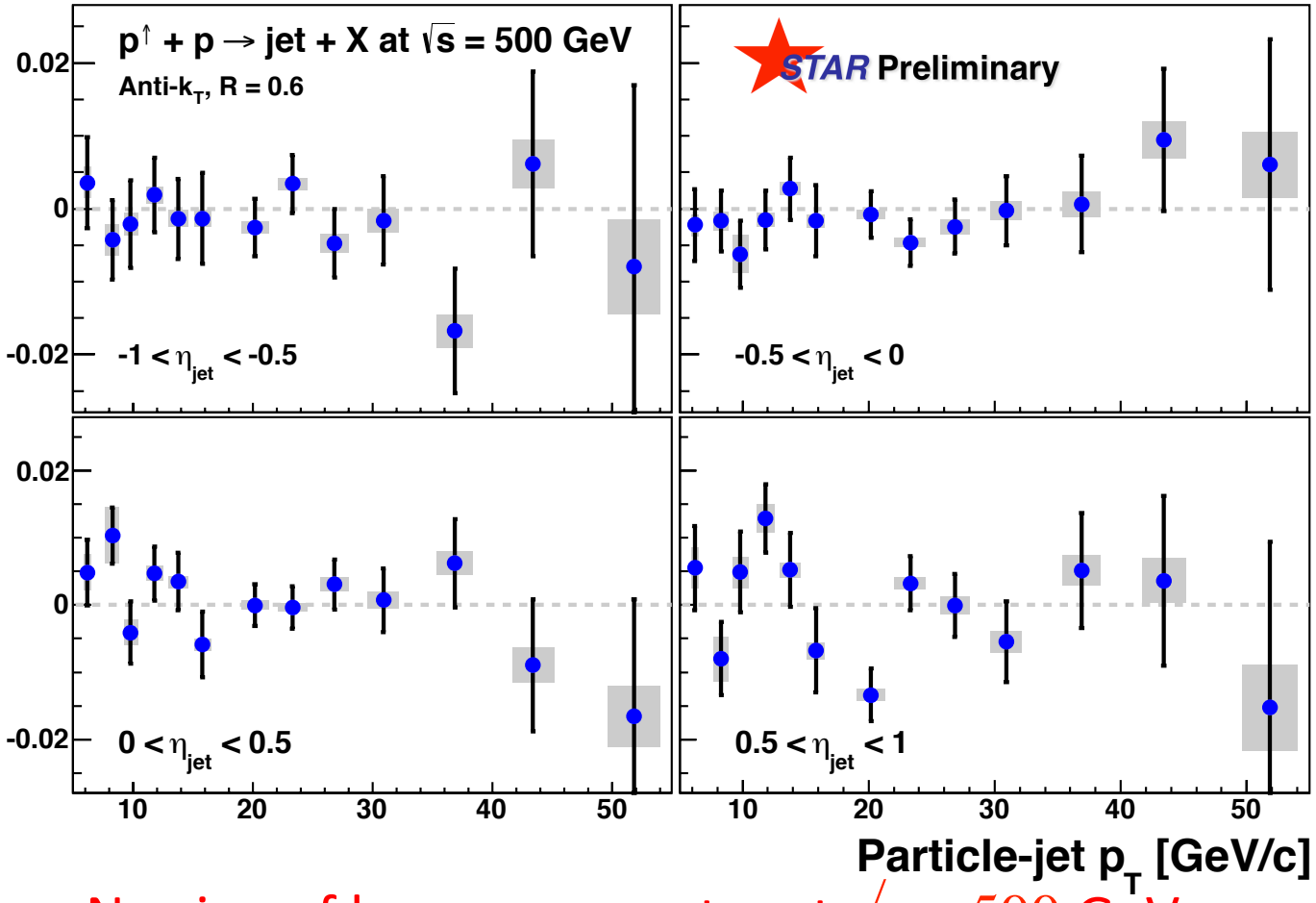
Anti-k_T, R = 0.6

Horizontal Systematics:

- M.C. statistics
- calorimeter gains
- efficiencies
- track momentum
- tracking efficiency

Vertical Systematics:

- Parton-jet matching
- Trigger bias
- Acceptance-related distortions



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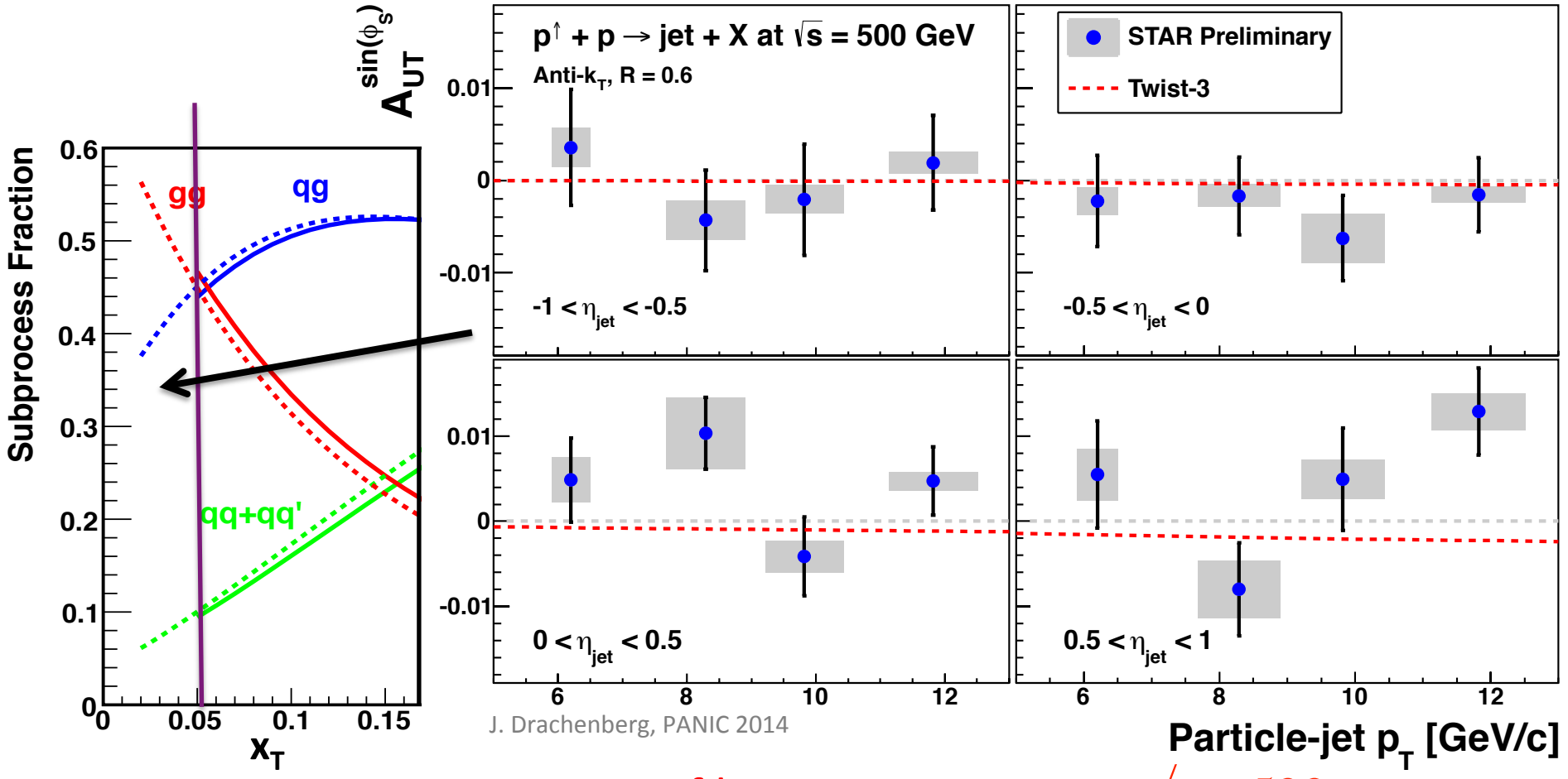
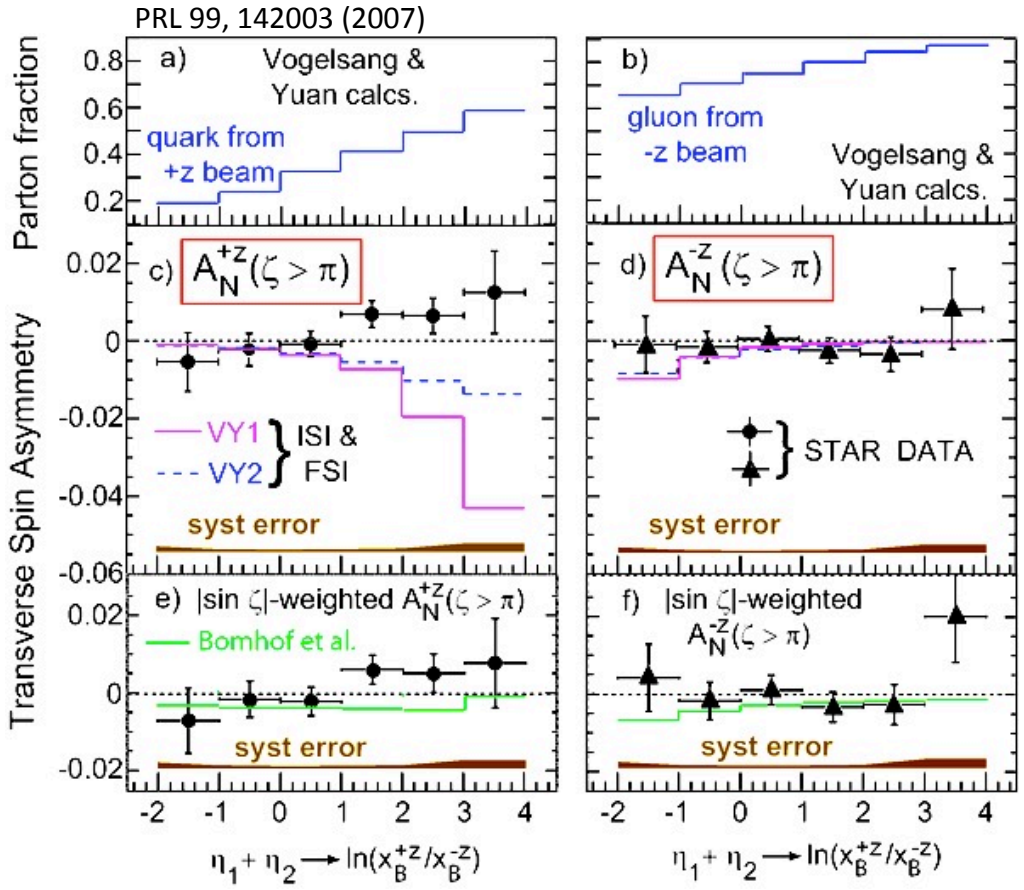


No sign of large asymmetry at $\sqrt{s} = 500$ GeV

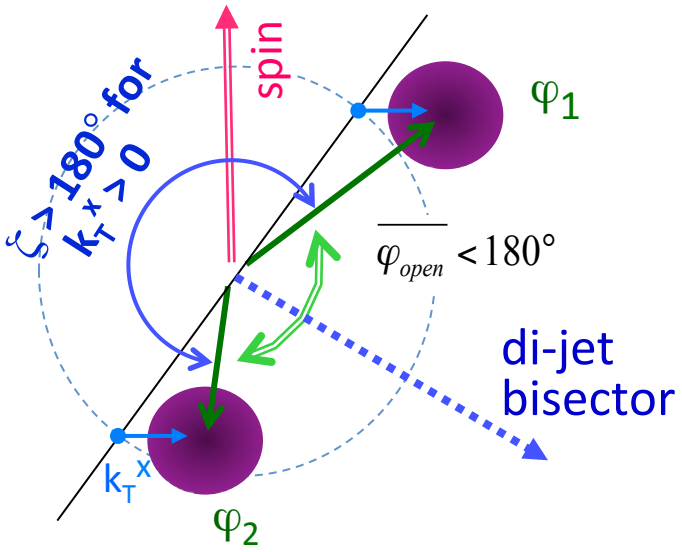
- *Consistent with measurements at $\sqrt{s} = 200$ GeV*
- *Enhanced sensitivity to gluonic subprocesses*
- *Theory predictions expect small effects*

e.g., Kanazawa and Koike PLB 720, 161 (2013) shown in red

STAR Transverse Asymmetries at Central Pseudorapidity



Sivers effect in di-jet production



- Spin-dependent sideways boost to di-jets
- Measure di-jet opening angle as function of proton spin
- *Requires parton orbital angular momentum*

Observed di-jet asymmetries much smaller than observed at SIDIS

→ ***Cancellation of initial vs. final state interactions, u vs. d quark effects, and small gluon Sivers effect?***