

Illuminating QCD and Nucleon Structure Through the Study of Hadrons Within Jets and Dihadron Correlations at RHIC

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Lamar University

The 22nd International Spin Symposium

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OUTLINE

- Introduction
- RHIC, PHENIX, and STAR
- Recent Developments
- Near-term Plans
- Summary



A Challenge from Transverse Single-spin Asymmetries

**Transverse single-spin asymmetries
have always presented challenges:**

- Look to higher twist
- Non-collinearity
- Non-perturbative effects

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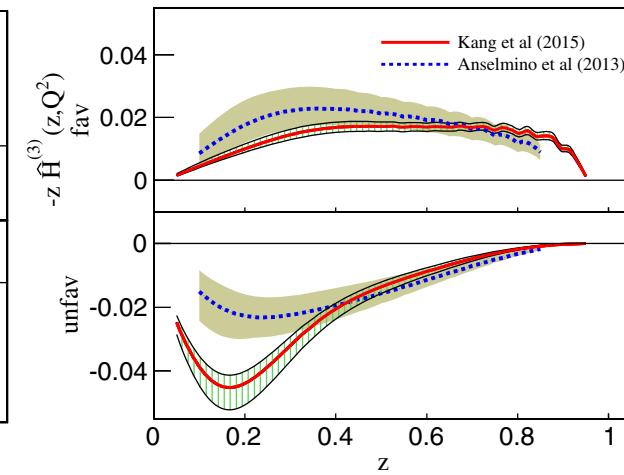
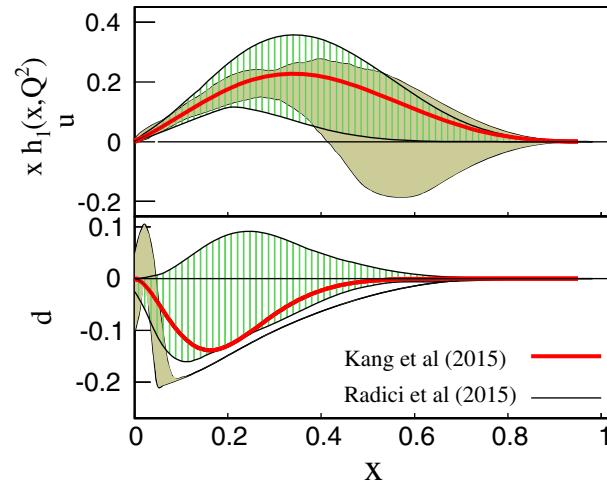
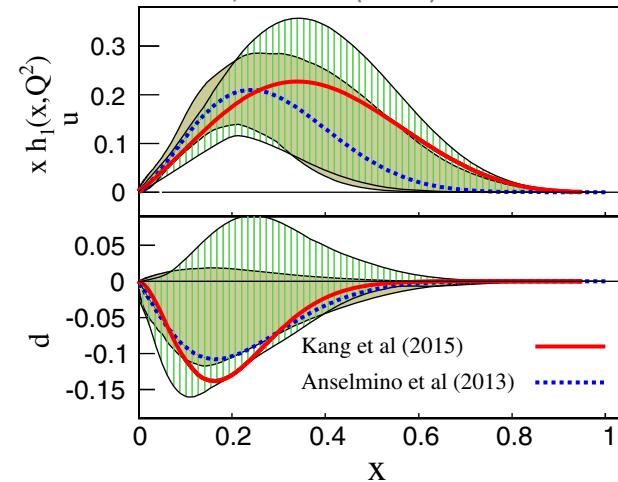
- Look to higher twist
- Non-collinearity
- Non-perturbative effects

Opportunities with $p^\uparrow + p$:

Expanded kinematics! Eliminate u -dominance! Direct sensitivity to g !

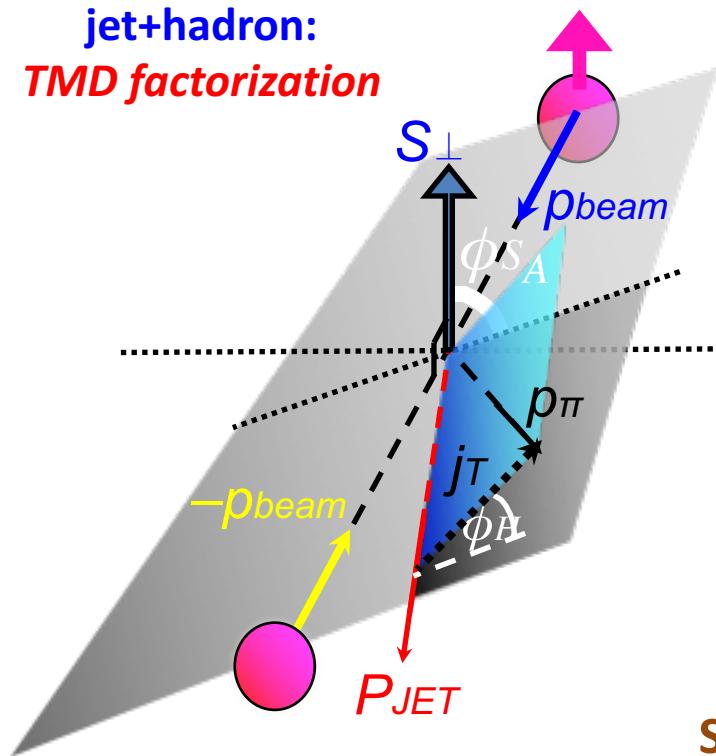
Tests of Evolution? Factorization and Universality?

PRD 93, 014009 (2016)



Asymmetry Measurements in Hadroproduction

jet+hadron:
TMD factorization



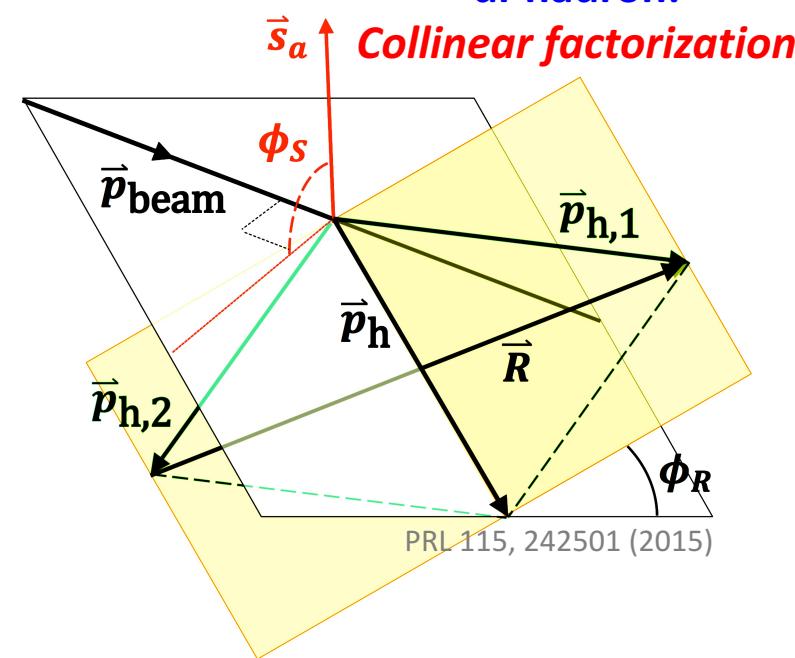
Anselmino et al., PRD 73, 014020 (2006)

F. Yuan, PRL 100, 032003 (2008)

D'Alesio et al., PRD 83, 034021 (2011)

di-hadron:

Collinear factorization

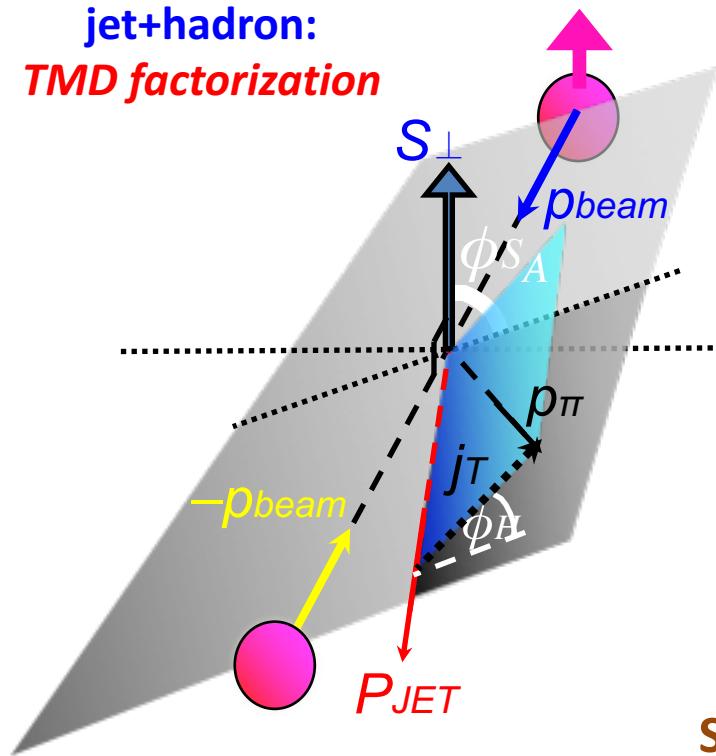


Similar to SIDIS, consider two azimuthal angles:

- ϕ_S -- between polarization vector and event plane
- ϕ_H or ϕ_R -- between event plane and pion or pair

Asymmetry Measurements in Hadroproduction

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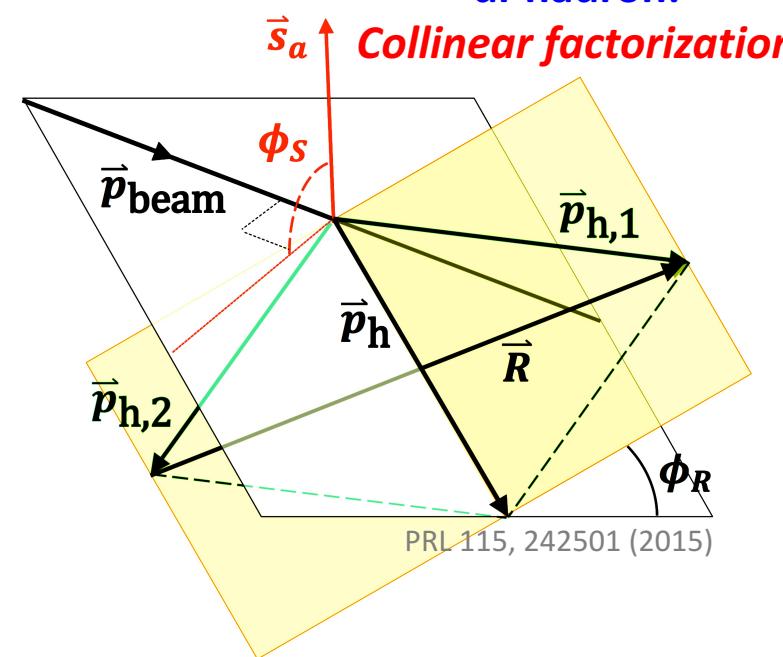


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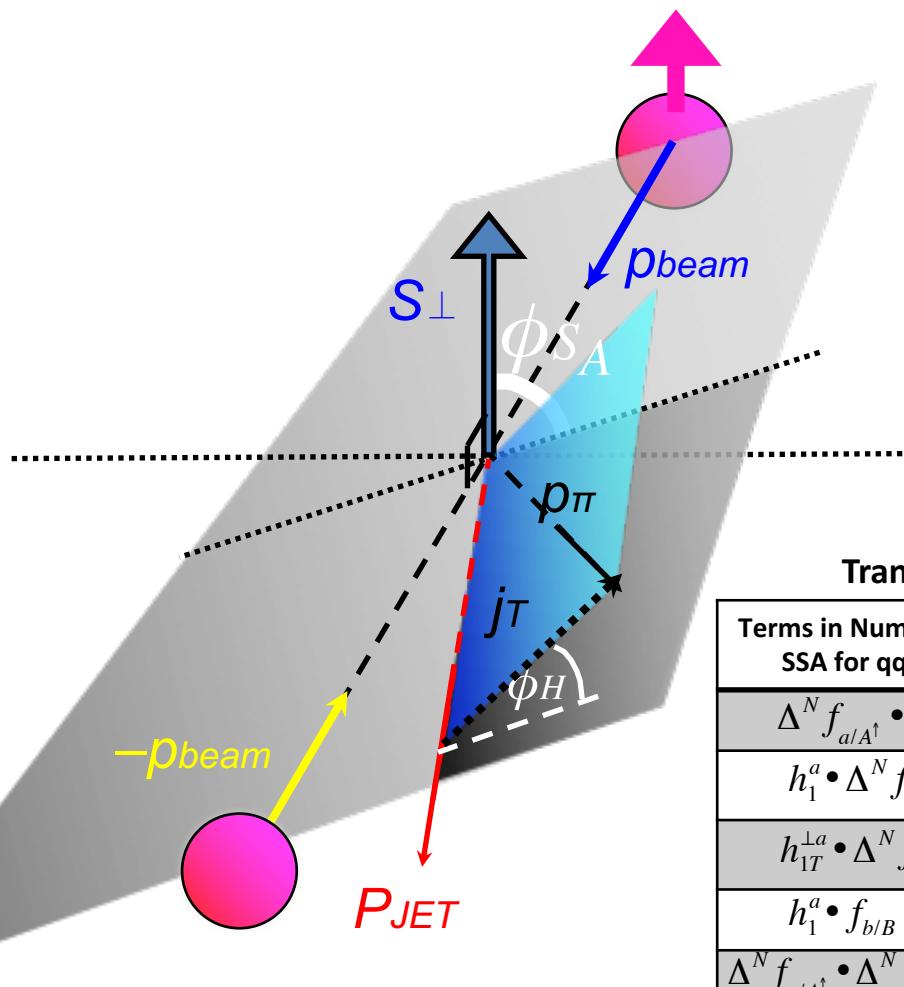
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Studying both over range of collision energy:

- **Probe evolution** of transversity and TMDs with Q^2
- **Probe open theoretical questions**, e.g. TMD factorization-breaking and universality

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

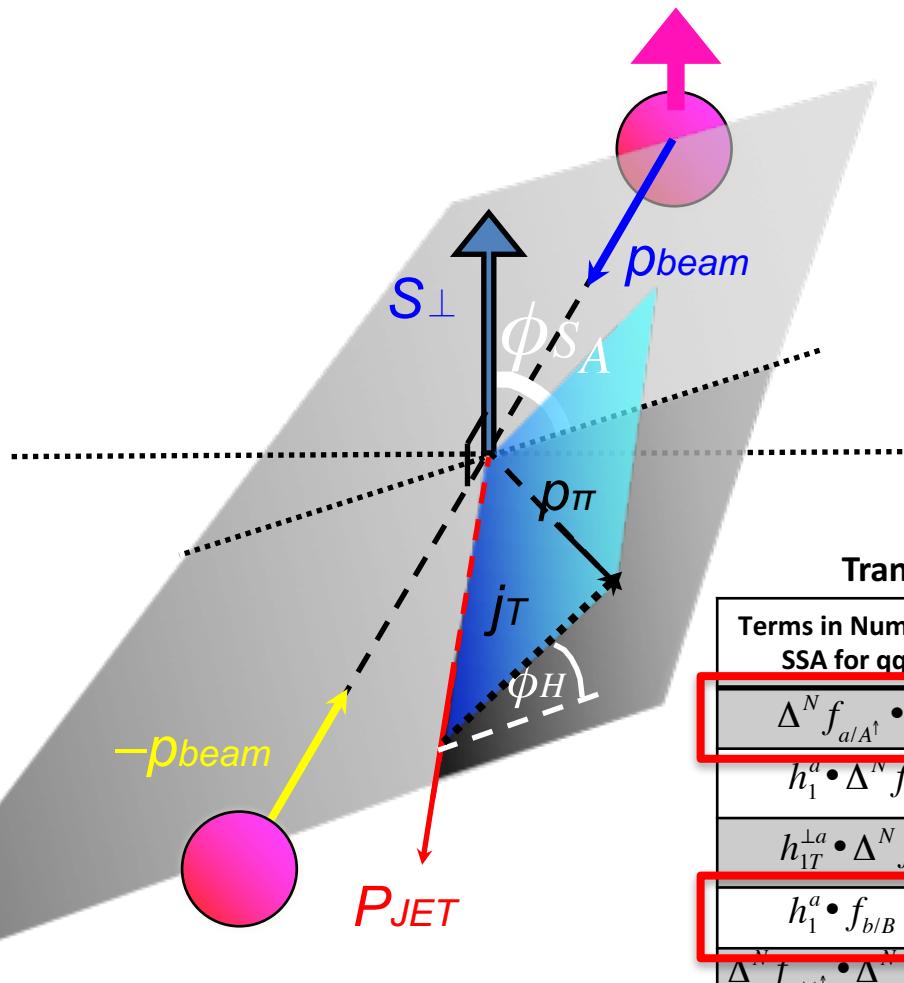
Terms in Numerator of TMD SSA for $q\bar{q}$ Scattering	English Names	Modulation
$\Delta^N f_{a/A^\dagger} \cdot f_{b/B} \cdot D_{\pi/q}$	Sivers • PDF • FF	$\sin(\phi_{S_A})$
$h_1^a \cdot \Delta^N f_{b^\dagger/B} \cdot D_{\pi/q}$	Transversity • Boer-Mulders • FF	$\sin(\phi_{S_A})$
$h_{1T}^{\perp a} \cdot \Delta^N f_{b^\dagger/B} \cdot D_{\pi/q}$	Pretzelosity • Boer-Mulders • FF	$\sin(\phi_{S_A})$
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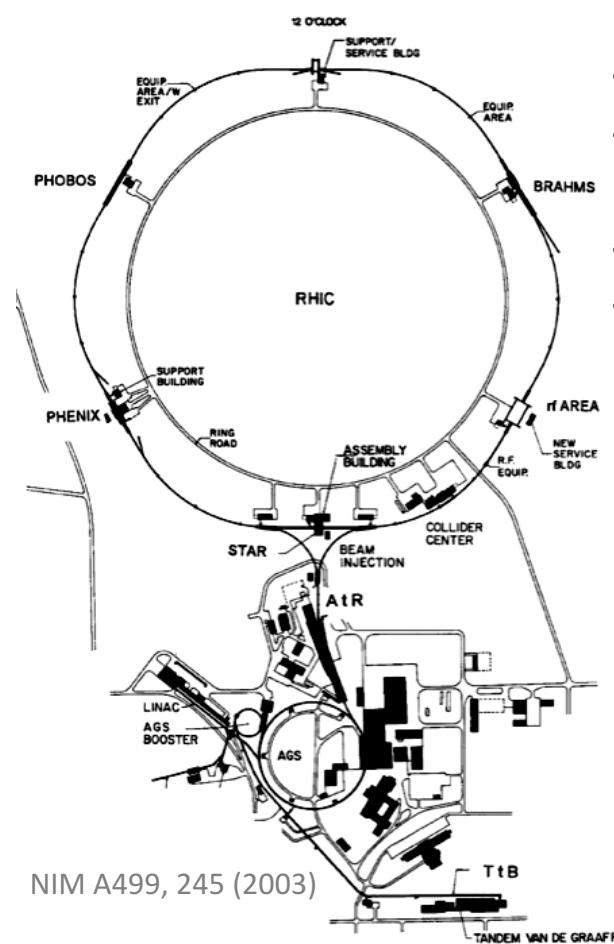
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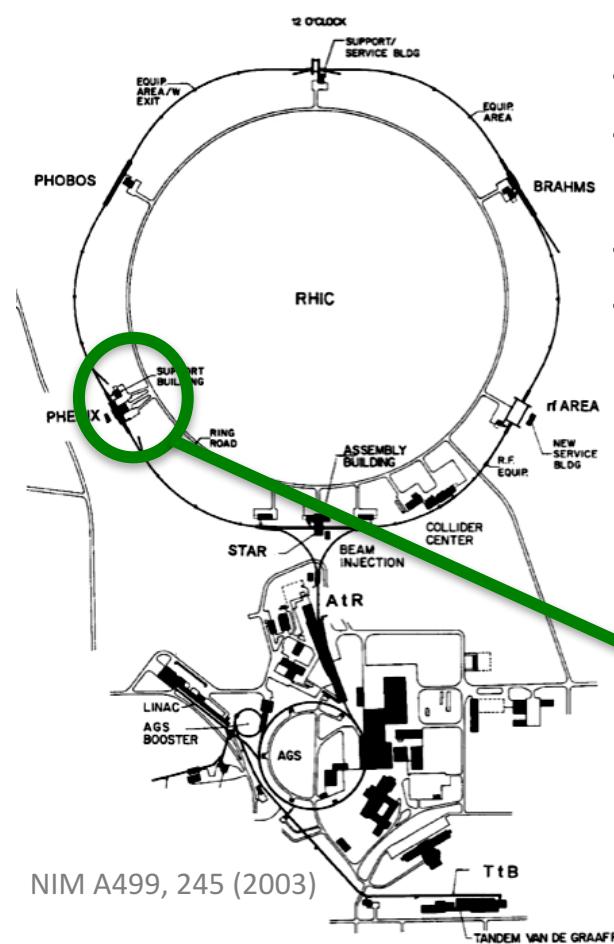
Relativistic Heavy Ion Collider



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

Pioneering High-Energy Nuclear Interaction eXperiment

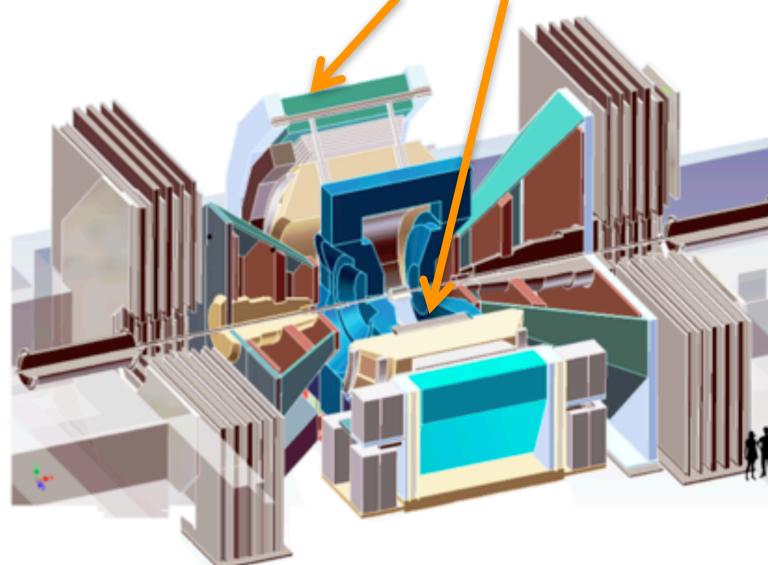


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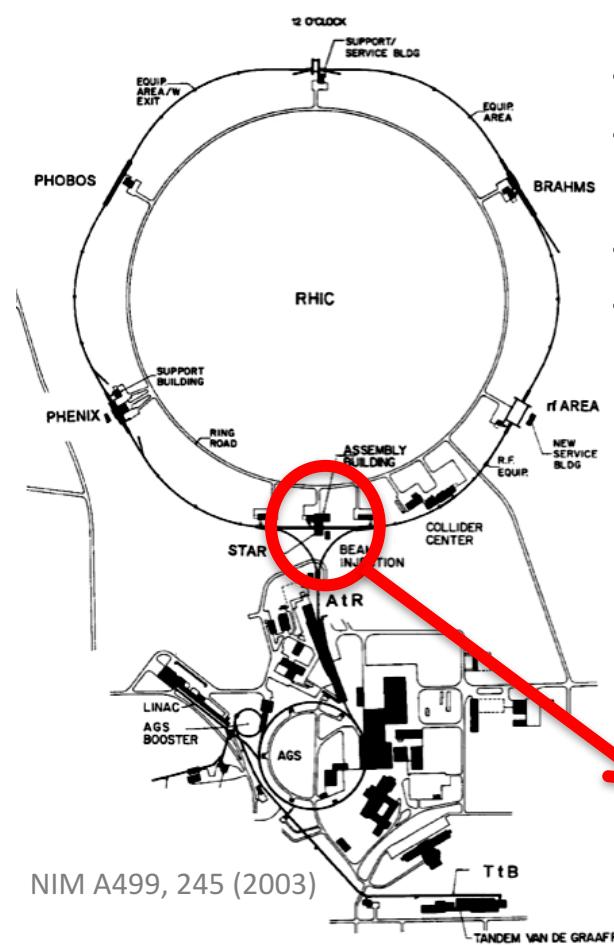
Central Arms

$$|\eta| < 0.35$$
$$|\Delta\phi| = \pi/2 + \pi/2$$



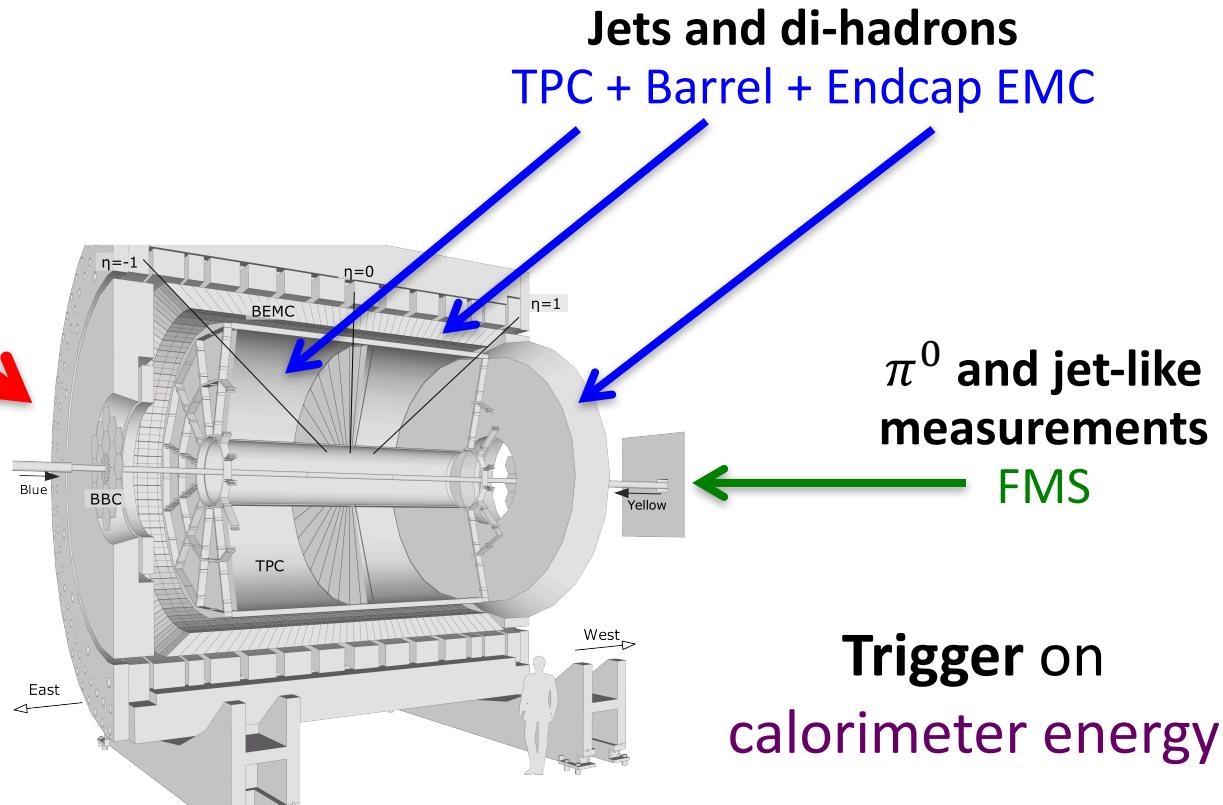
High resolution and rate capabilities

Solenoidal Tracker at RHIC



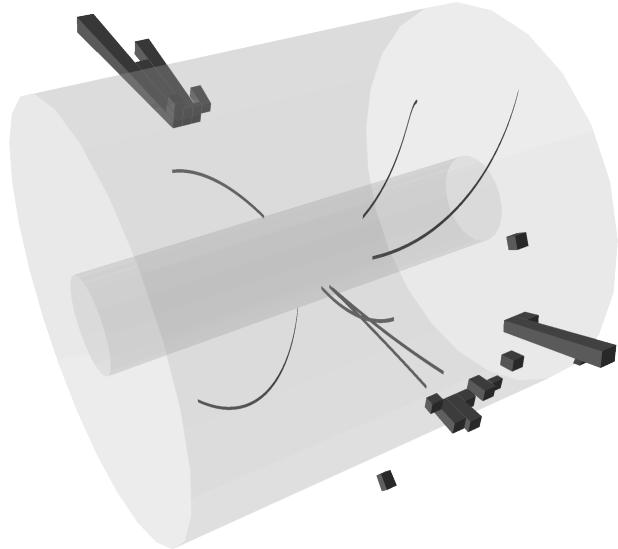
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Jet Reconstruction at RHIC

STAR Di-jet event at detector level



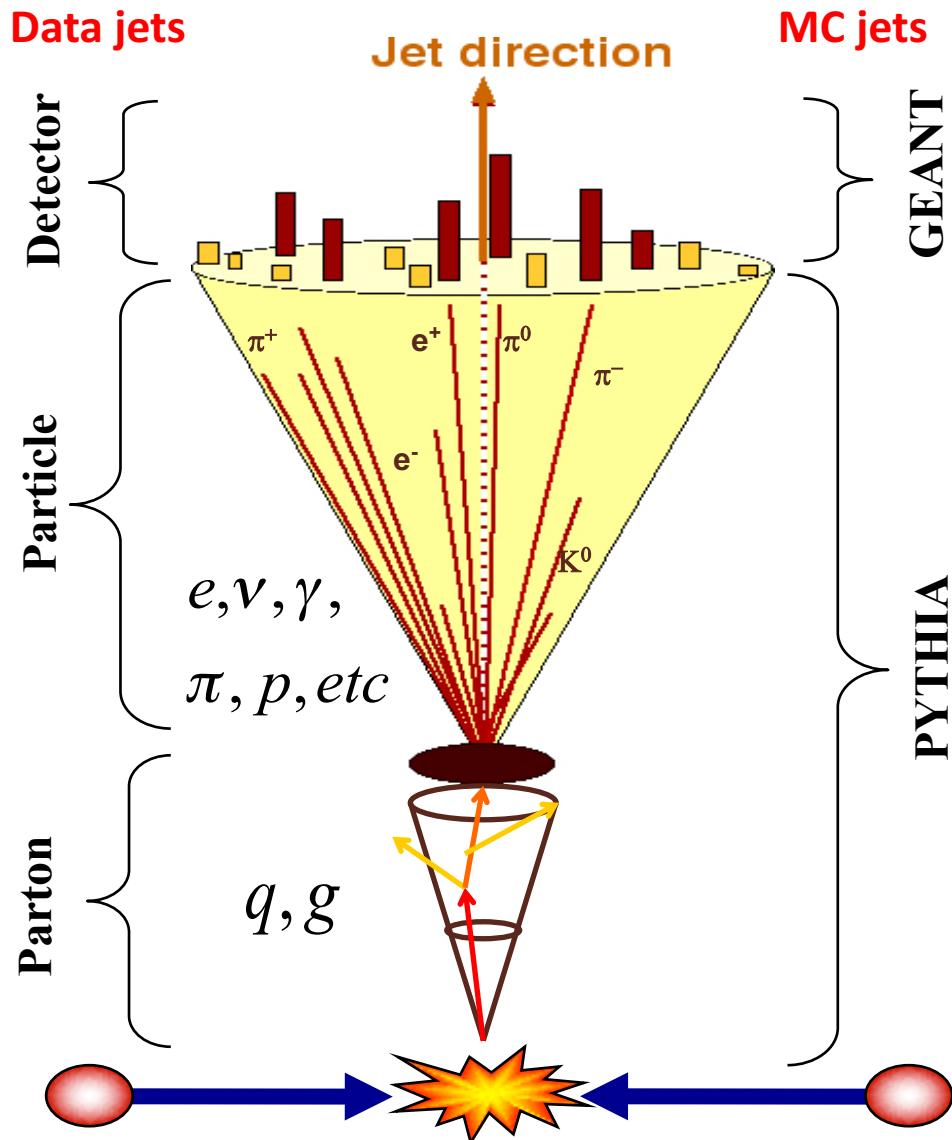
e.g. Anti- k_T algorithm

JHEP 0804, 063 (2008)

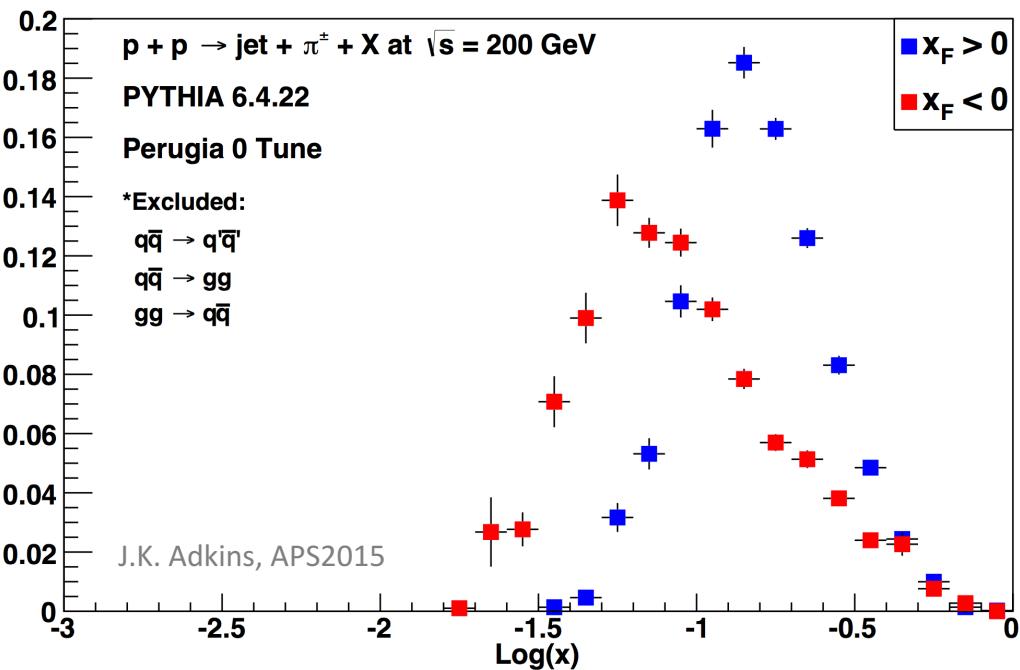
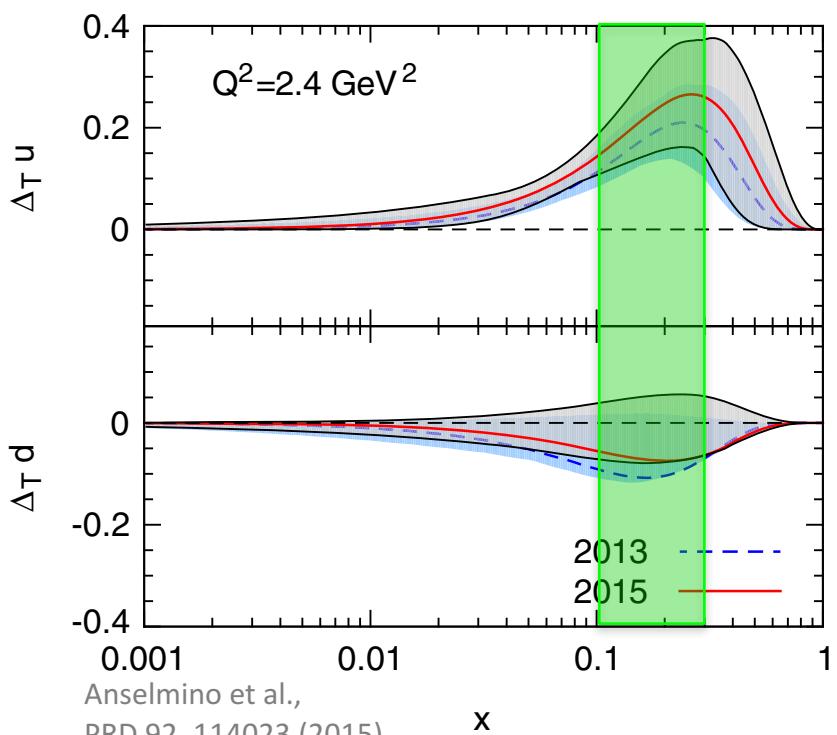
Radius parameter $R = 0.5$ or 0.6

Use PYTHIA + GEANT to
quantify detector response

π^\pm Kinematic Variables
 $z - \pi$ momentum / jet momentum
 $j_T - \pi p_T$ relative to jet axis



Sensitivity to Transversity at RHIC

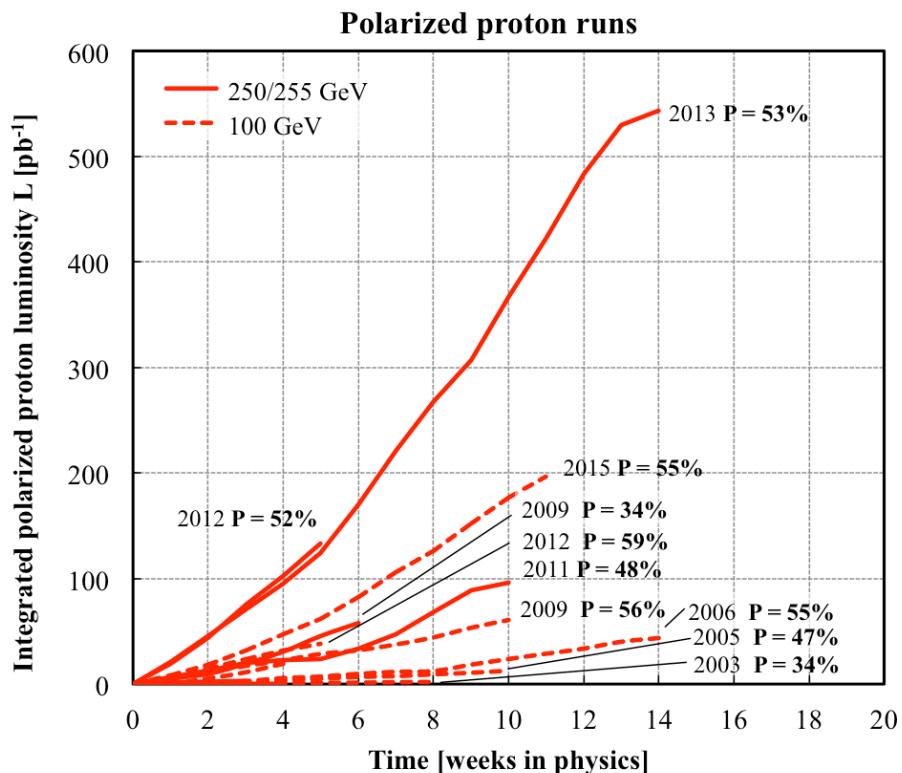


Access to transversity in interesting region!

- Limited constraints
- Potentially large effects
- *Insight into nature of Collins mechanism!*

Polarized-proton Datasets at RHIC

Unique opportunities to probe nucleon spin structure!

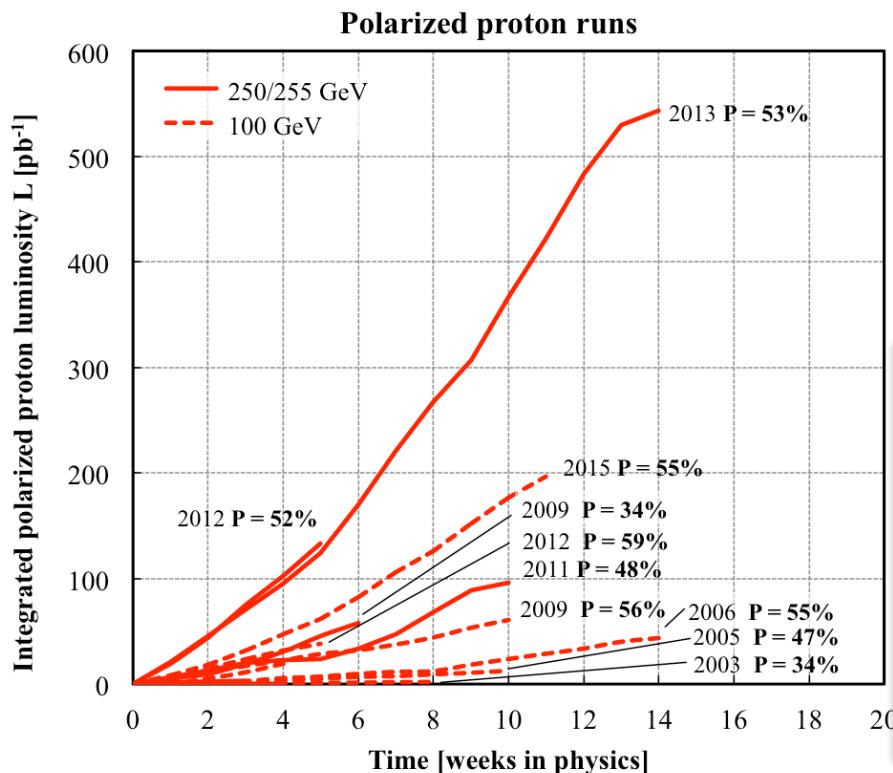


Transverse Luminosity Recorded				
Year	\sqrt{s} [GeV]	STAR	PHENIX	$\langle P \rangle$ [%]
2006	200	8.5 pb^{-1}	2.7 pb^{-1}	57
2006	62.4	0.2 pb^{-1}	0.02 pb^{-1}	48
2008	200	7.8 pb^{-1}	5.2 pb^{-1}	45
2011	500	25 pb^{-1}	--	53/54
2012	200	22 pb^{-1}	9.7 pb^{-1}	61/58
2015	200	53 pb^{-1}	52 pb^{-1}	53/57
2015	200 pAu	0.42 pb^{-1}	0.20 pb^{-1}	60
2015	200 pAl	1.0 pb^{-1}	--	54

PHENIX numbers for $|z_{\text{vtx}}| < 40 \text{ cm}$

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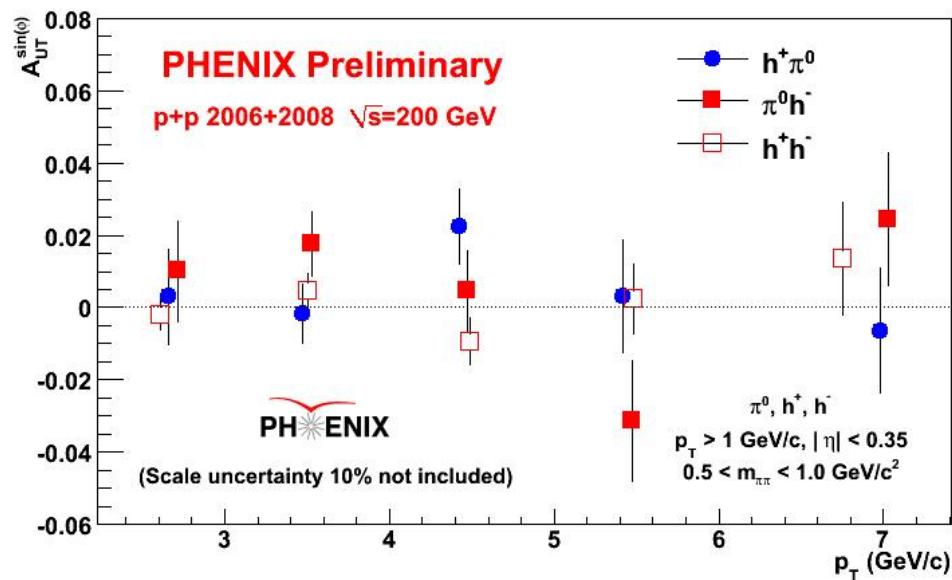
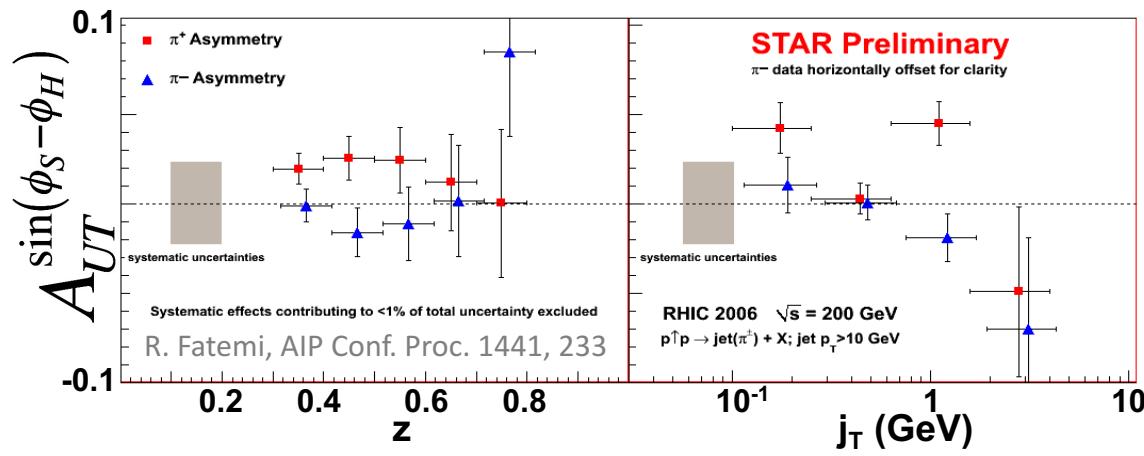
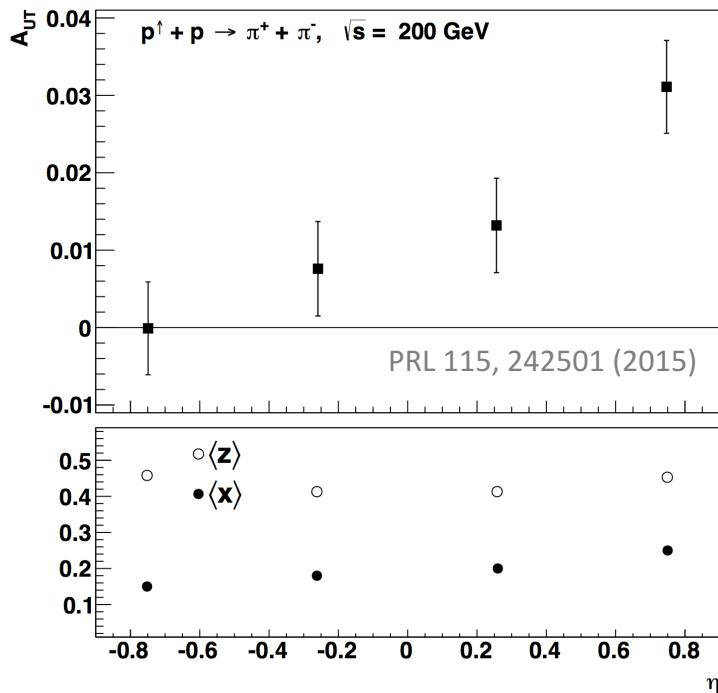
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PHENIX numbers for $|z_{\text{vtx}}| < 40 \text{ cm}$

*Dramatically increased figure of merit
in recent years*

Pioneering RHIC Measurements

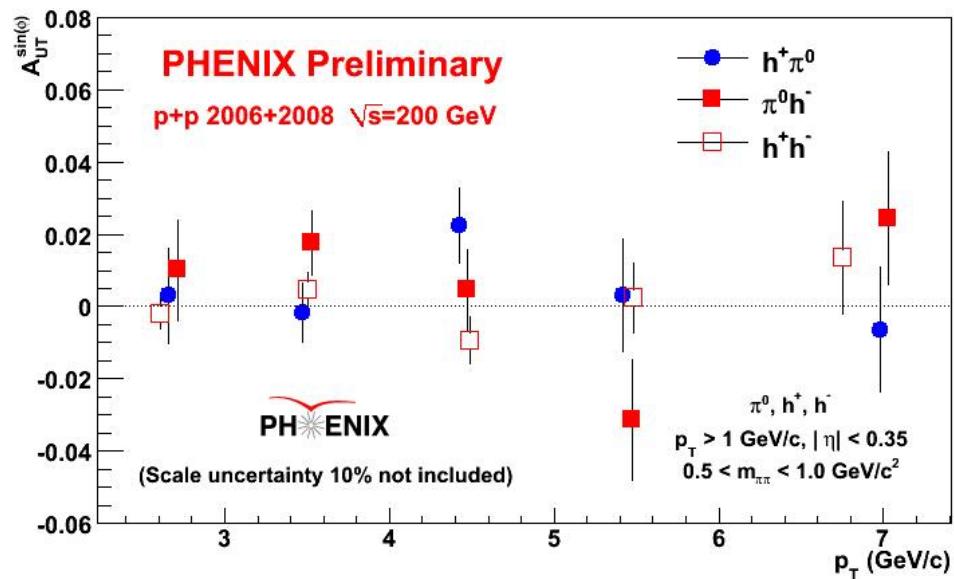
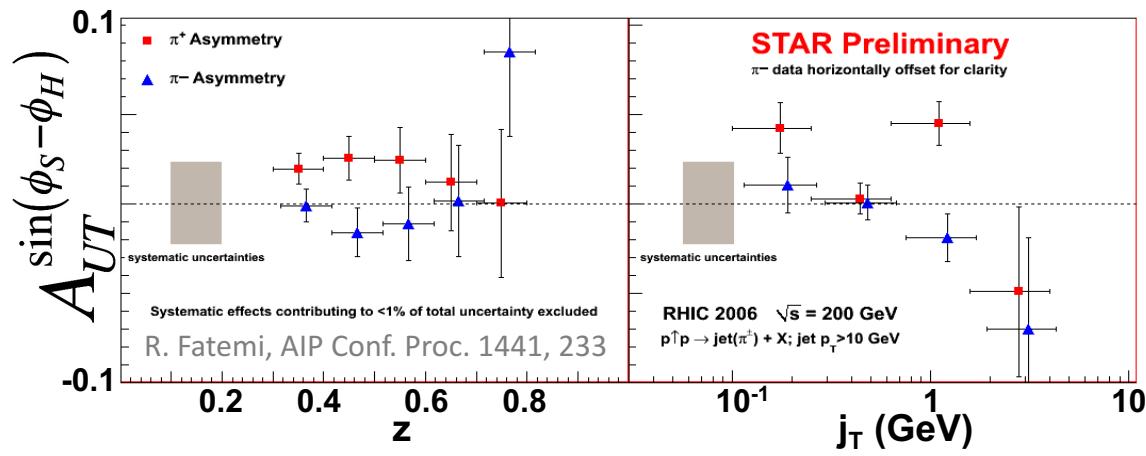
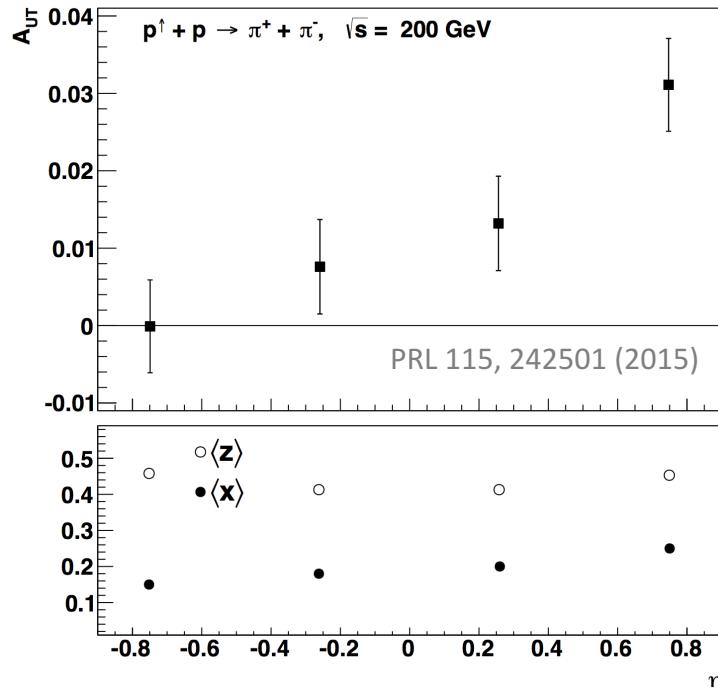
A_{UT} for $h + h$ and $jet + \pi^\pm$ for data collected in 2006 and 2008



A clear message despite limited precision of early datasets:

Pioneering RHIC Measurements

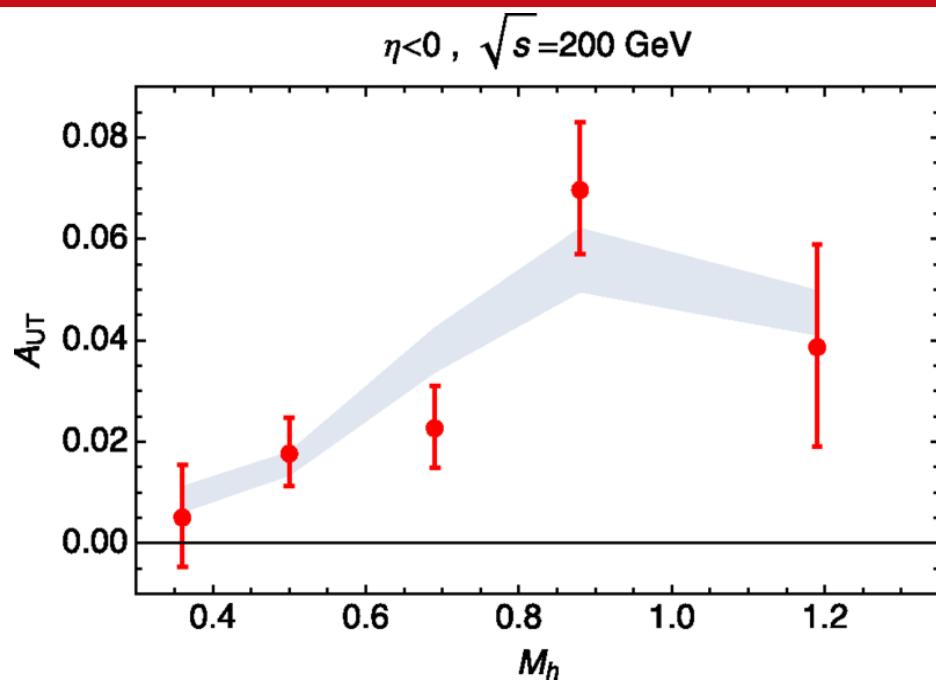
A_{UT} for $h + h$ and $jet + \pi^\pm$ for data collected in 2006 and 2008



A clear message despite limited precision of early datasets:

Access to transversity effects in charged pions at RHIC

Comparison of Early Data to Theory



Overall **agreement** in terms of
invariant mass

→ **Same mechanism as in SIDIS!**

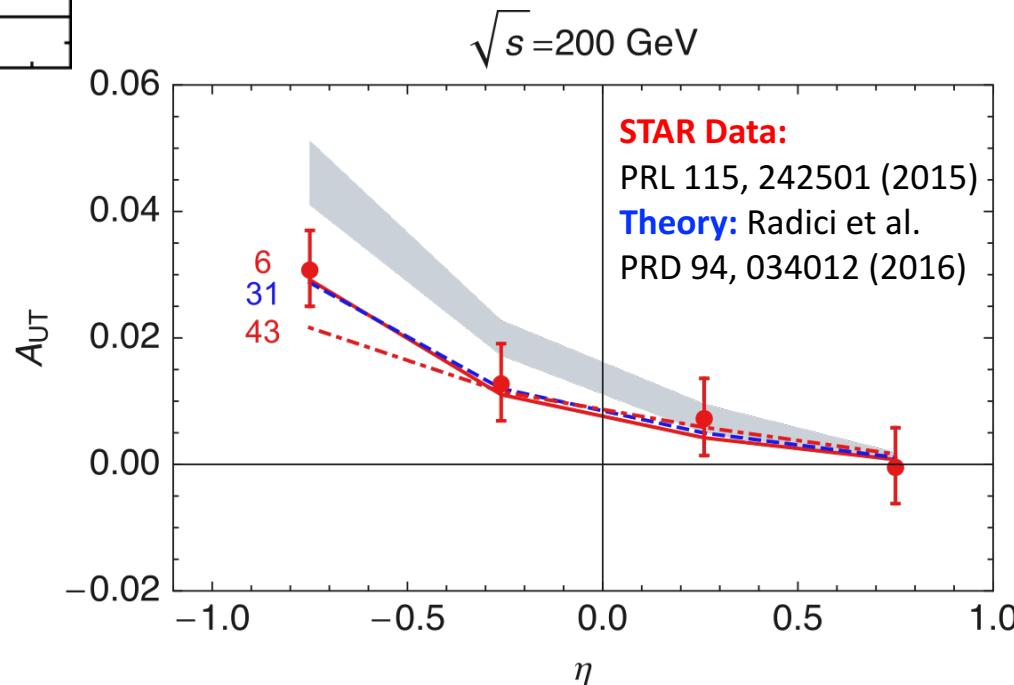
Deviation at more **forward** scattering

→ **Tension with SIDIS?**

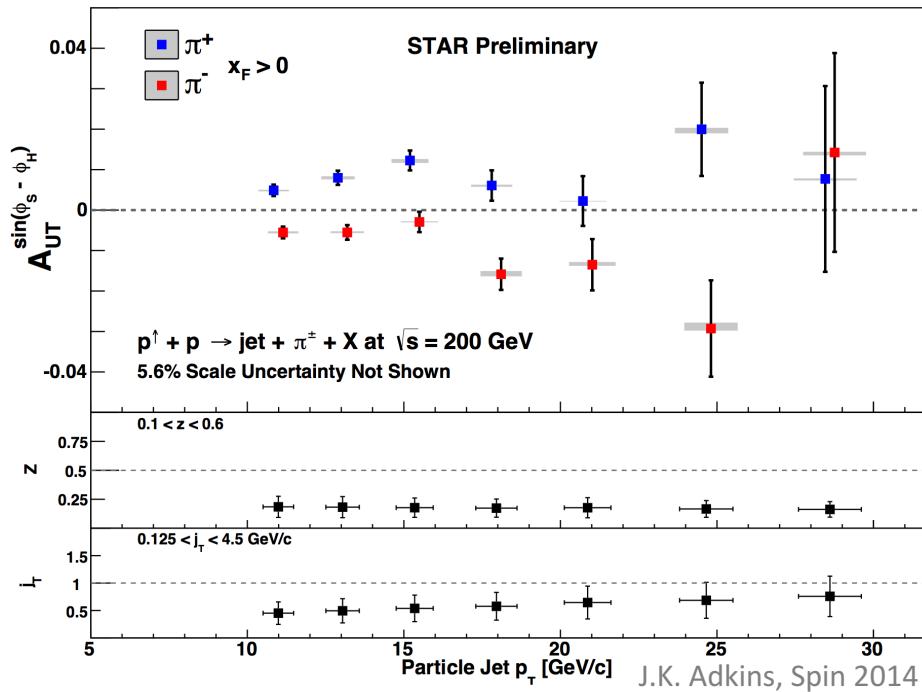
→ **More information needed on D_g^1 ?**

**Compare with models
based on SIDIS/ e^+e^-**

*Band represents 68% of replicas
deduced by fitting SIDIS and e^+e^- data*

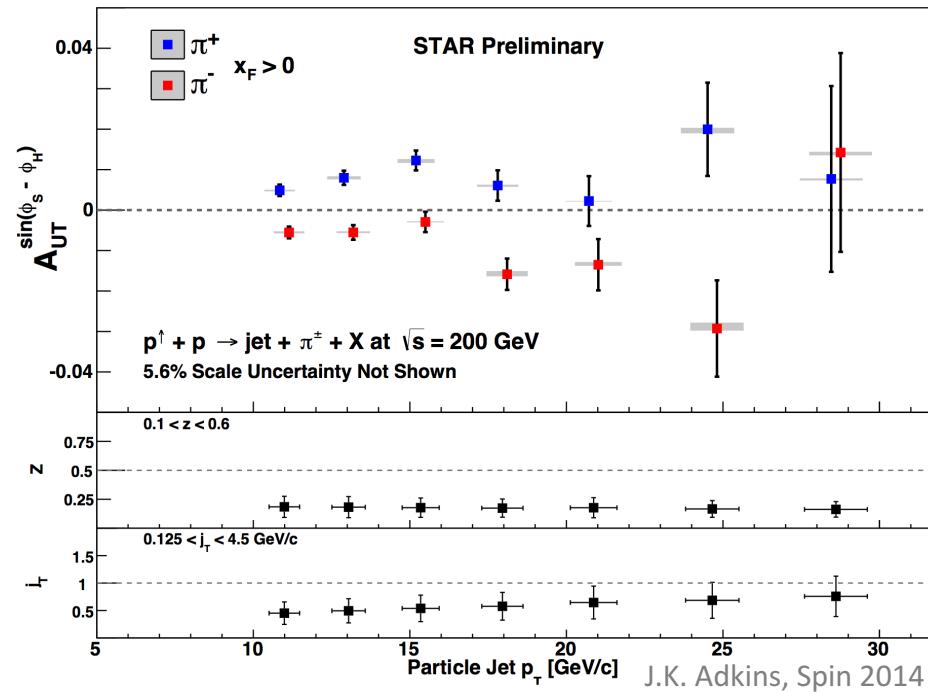
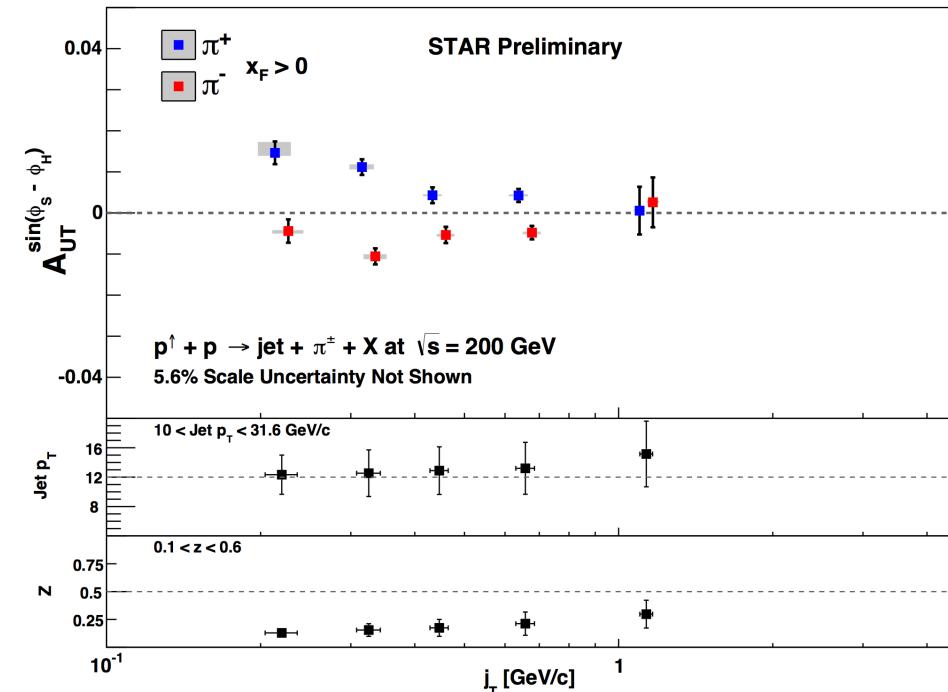


Newest Collins Results at $\sqrt{s} = 200$ GeV



Clear first observation of
Collins asymmetry in $p + p$!

Newest Collins Results at $\sqrt{s} = 200$ GeV



J.K. Adkins, Spin 2014

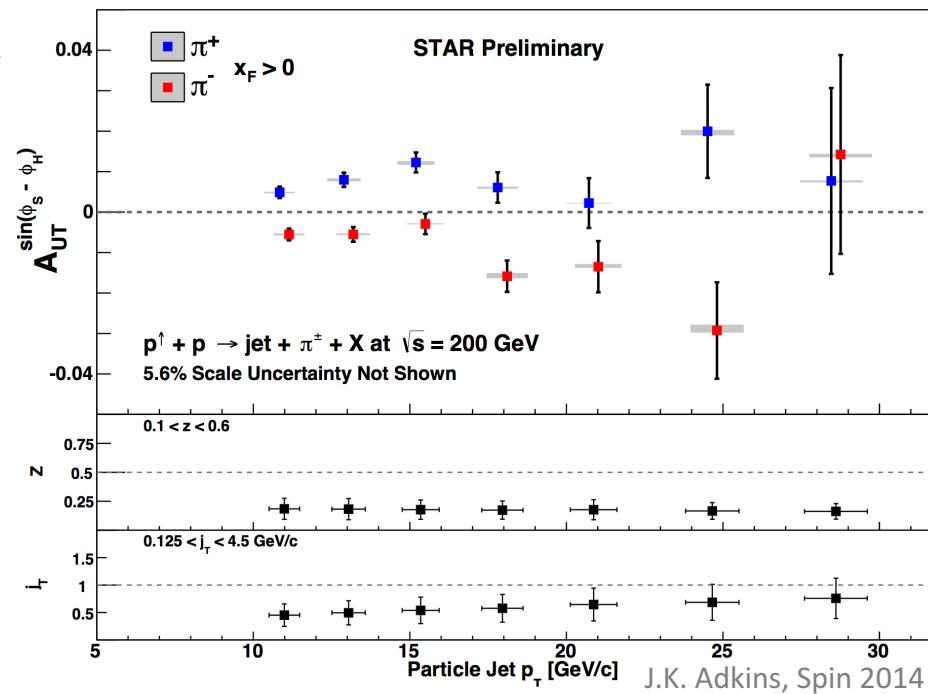
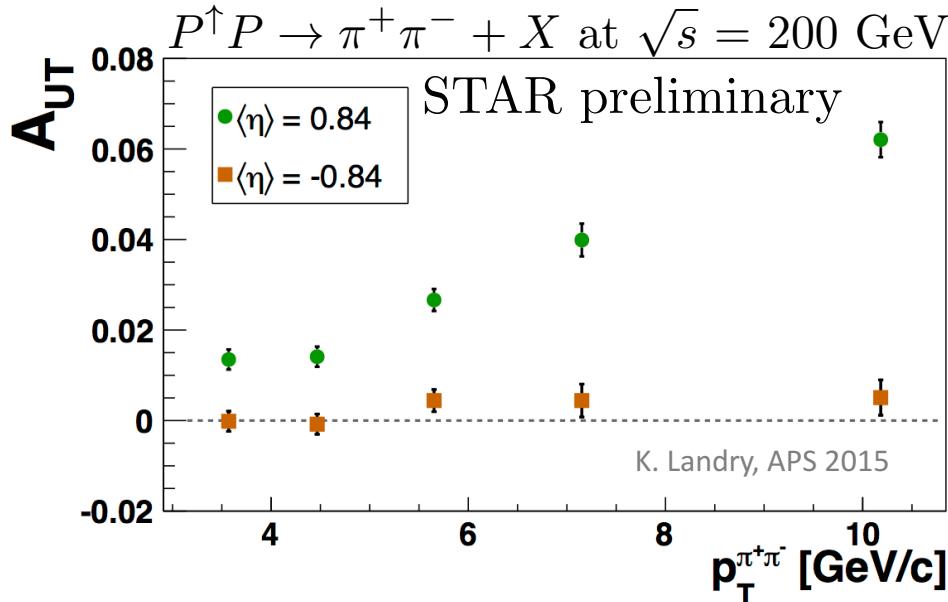
STRONG dependence upon j_T

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

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

**Clear first observation of
Collins asymmetry in $p + p$!**

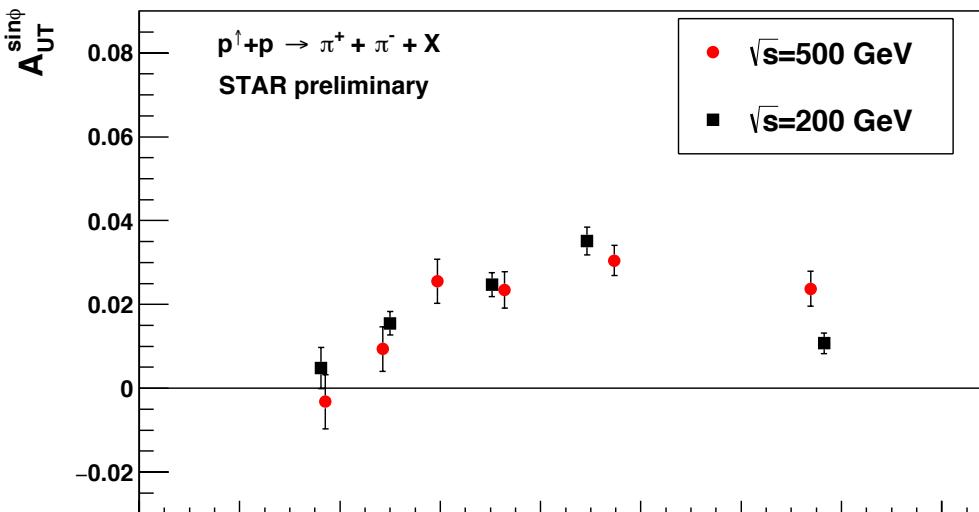
Newest Transversity Results at $\sqrt{s} = 200$ GeV



*Significant, high-precision
di-hadron asymmetries*

*Clear first observation of
Collins asymmetry in $p + p$!*

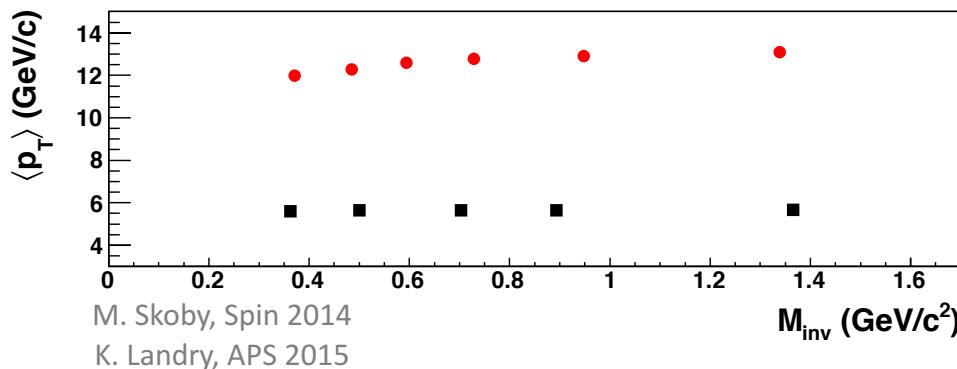
Newest RHIC IFF Results at $\sqrt{s} = 200$ and 500 GeV



*Significant non-zero
di-hadron asymmetries at*

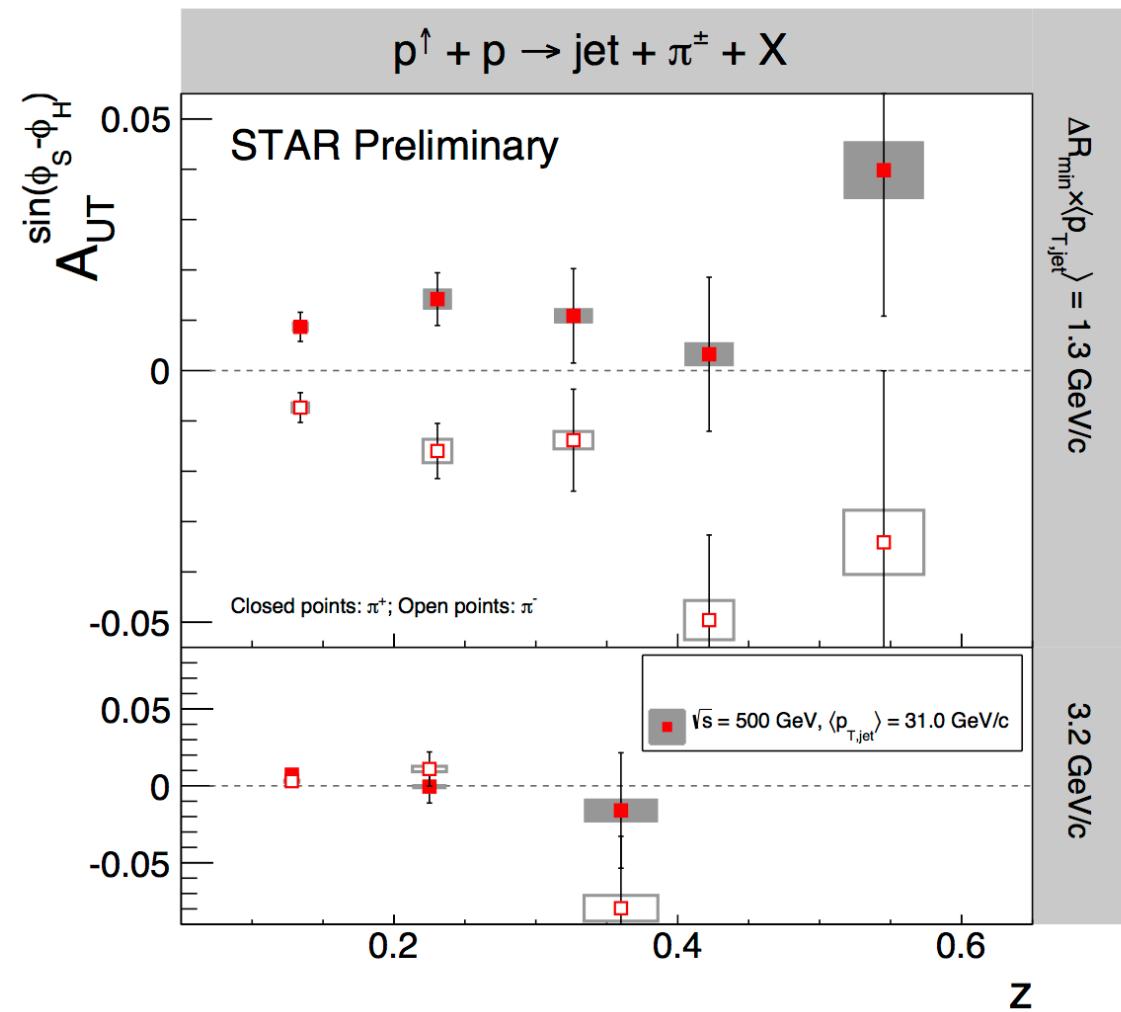
$\sqrt{s} = 500$ GeV!

- Increasing with pion p_T
- Enhanced around ρ mass



*Consistent behavior
observed in $\sqrt{s} = 200$ GeV
when scaled for $2\langle p_T \rangle / \sqrt{s}$*

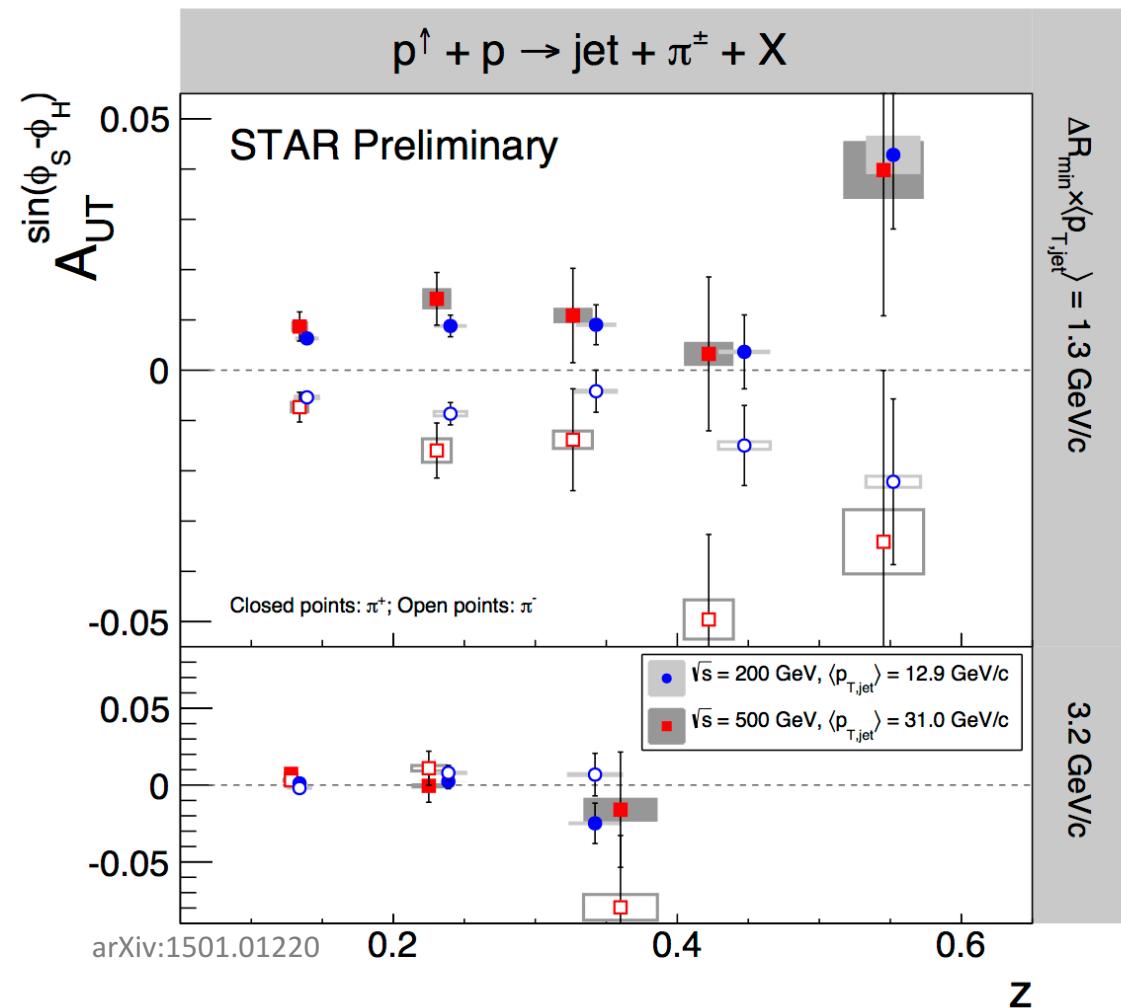
RHIC Collins Results at $\sqrt{s} = 500$ GeV



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

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

RHIC Collins Results at $\sqrt{s} = 200$ and 500 GeV



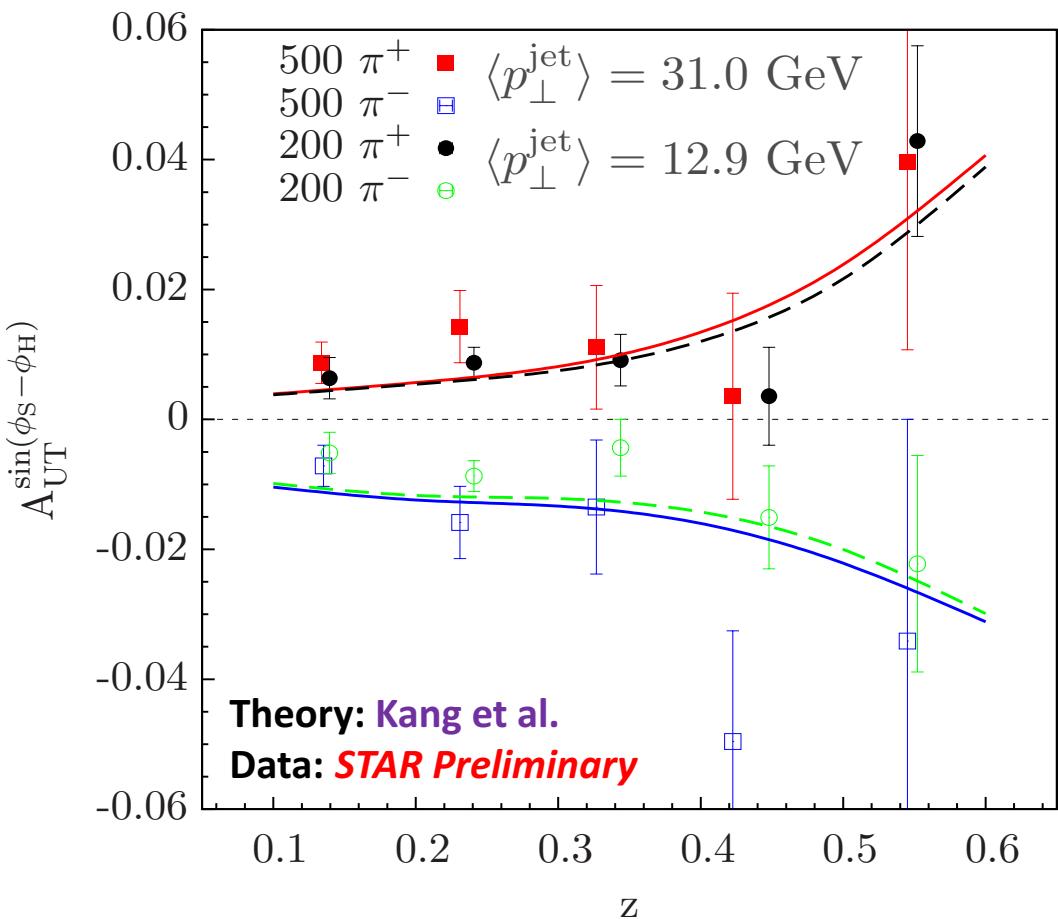
Non-zero Collins asymmetries observed

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

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

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

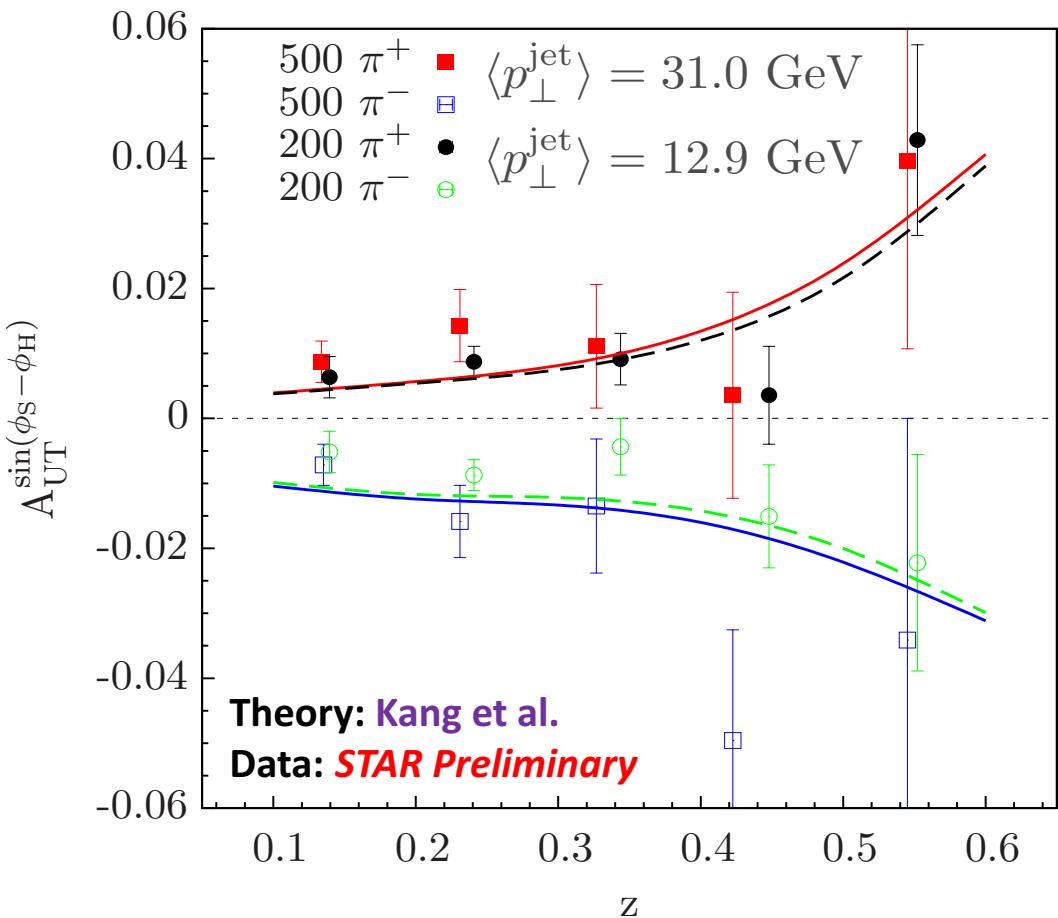
RHIC Collins Results at $\sqrt{s} = 200$ and 500 GeV



*Compare with models
based on SIDIS/ e^+e^-*

- Assume ***universality*** and ***robust factorization***
- Assume ***no TMD evolution***

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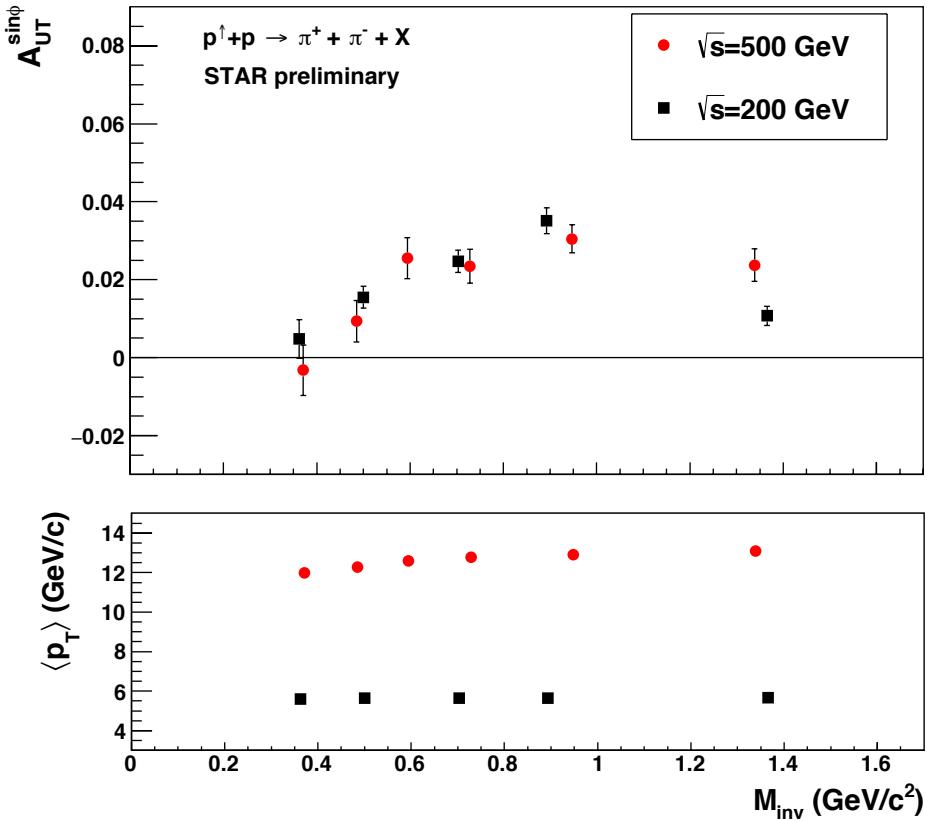
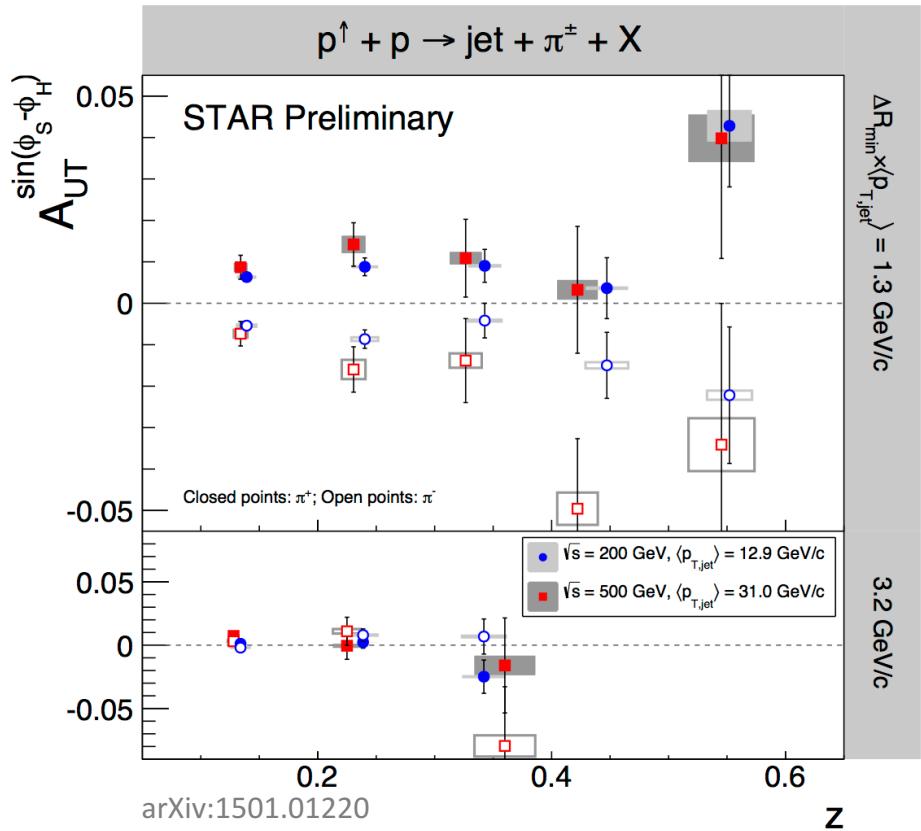


*Compare with models
based on SIDIS/ e^+e^-*

- Assume **universality** and **robust factorization**
- Assume **no TMD evolution**

*Suggest universality of Collins function!
Suggest slow or mitigation of TMD evolution!*

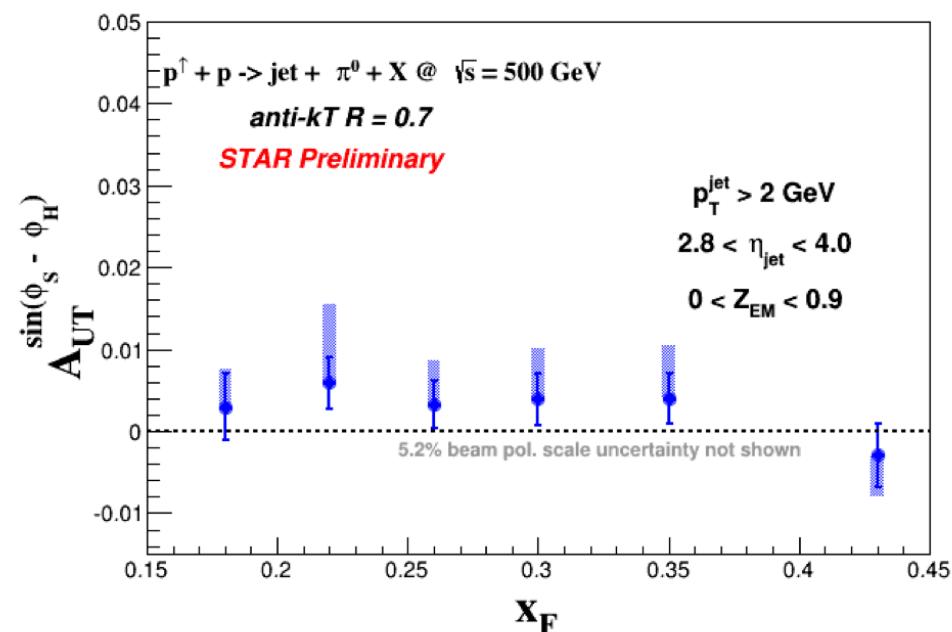
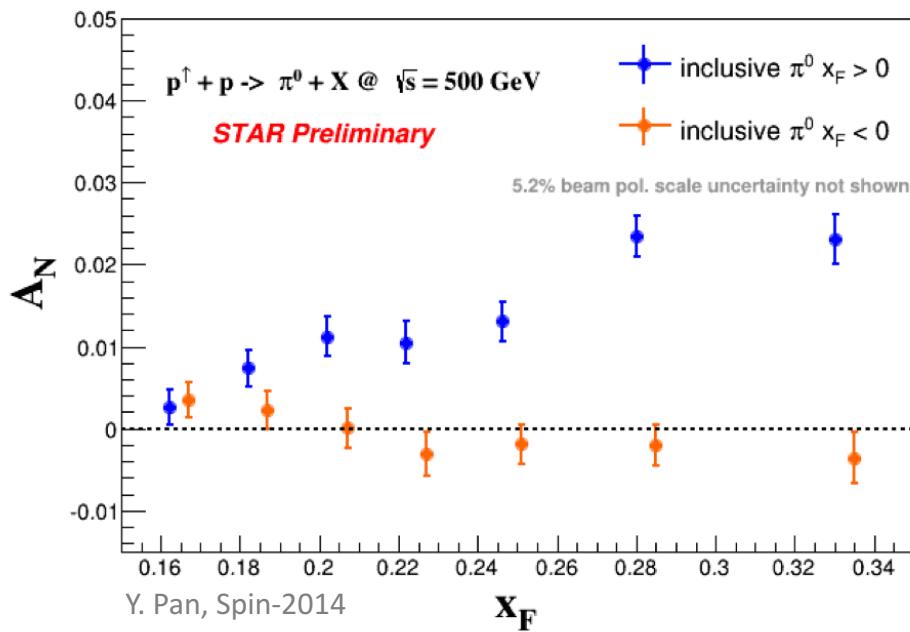
RHIC Results at $\sqrt{s} = 200$ and 500 GeV



STAR Collins and IFF results

- Consistent with x_T scaling
- Consistent with expectations based on SIDIS/ e^+e^-
- Obey very different evolution rules:
Collins—TMD vs. IFF—collinear

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

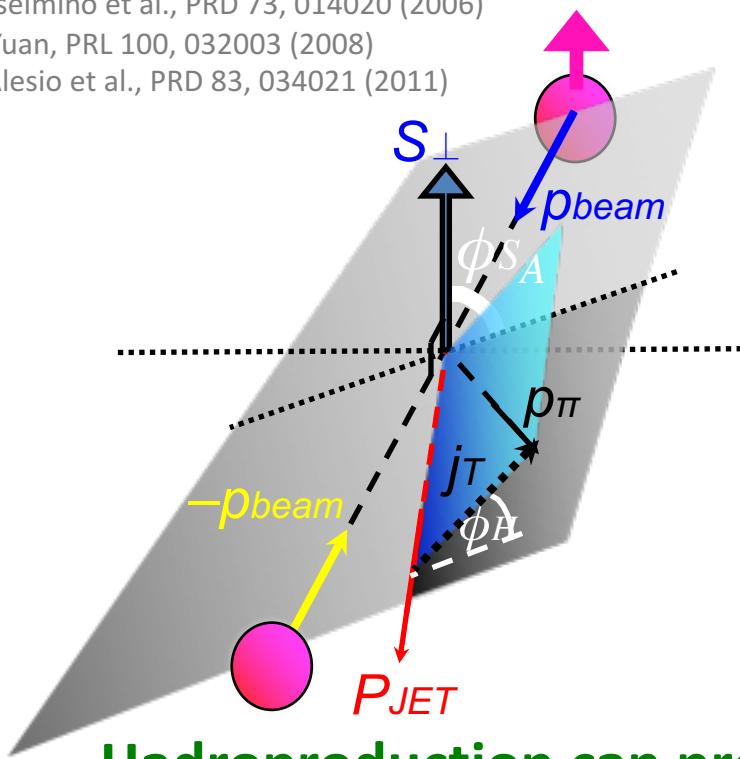


π^0 *Collins asymmetry possibly nonzero?*

Insufficient to describe large inclusive asymmetries at high x_F

Additional Modulations

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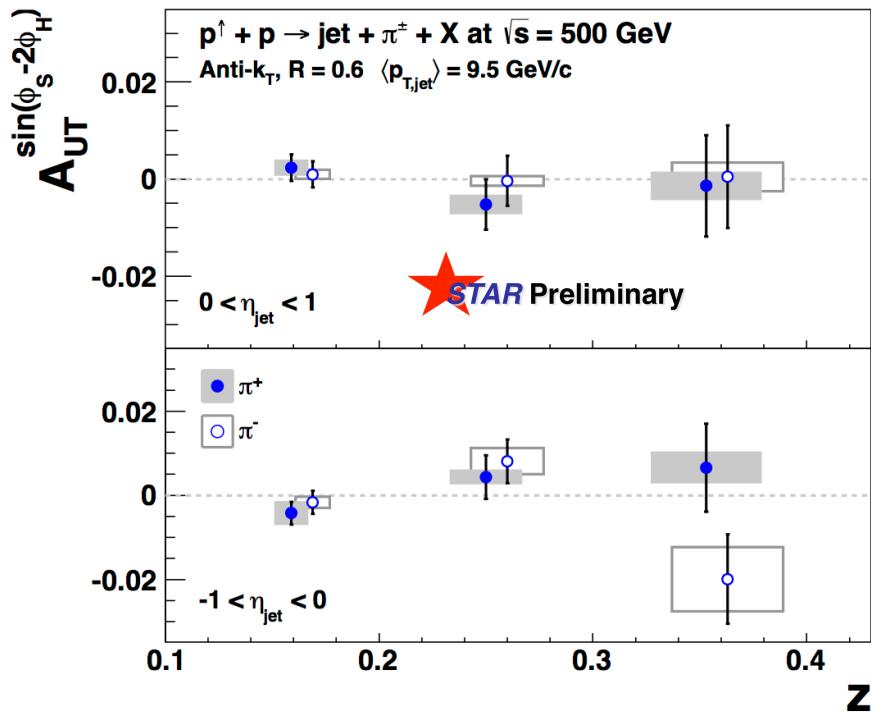
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$\text{Im } F_{a+-}^{-+} \bullet \Delta^N f_{T_1^b/B} \bullet D_{\pi/g}$	Pretzelosity-like • Boer-Mulders-like • FF	$\sin(\phi_{S_A})$
$\text{Im } F_{a+-}^{+-} \bullet f_{b/B} \bullet \Delta^N D_{\pi/T_1^g}$	Transversity-like • PDF • Collins-like	$\sin(\phi_{S_A} - 2\phi_H)$
$\Delta^N f_{a/A^\uparrow} \bullet \Delta^N f_{T_1^b/B} \bullet \Delta^N D_{\pi/T_1^g}$	Sivers • Boer-Mulders-like • Collins-like	$\sin(\phi_{S_A} - 2\phi_H)$
$\text{Im } F_{a+-}^{-+} \bullet f_{b/B} \bullet \Delta^N D_{\pi/T_1^g}$	Pretzelosity-like • PDF • Collins-like	$\sin(\phi_{S_A} + 2\phi_H)$
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UNCONSTRAINED!

Hadroproduction can probe additional asymmetry modulations
 (e.g. sensitive to *linearly polarized gluons*)

Additional Modulations



Transverse Momentum Dependent (TMD) Approach		
Terms in Numerator of TMD SSA for gg Scattering	English Names	Modulation
$\Delta^N f_{a/A^\uparrow} \bullet f_{b/B} \bullet D_{\pi/g}$	Sivers • PDF • FF	$\sin(\phi_{S_A})$
$\text{Im } F_{a+-}^{+-} \bullet \Delta^N f_{T_1^b/B} \bullet D_{\pi/g}$	Transversity-like • Boer-Mulders-like • FF	$\sin(\phi_{S_A})$
$\text{Im } F_{a+-}^{-+} \bullet \Delta^N f_{T_1^b/B} \bullet D_{\pi/g}$	Pretzelosity-like • Boer-Mulders-like • FF	$\sin(\phi_{S_A})$
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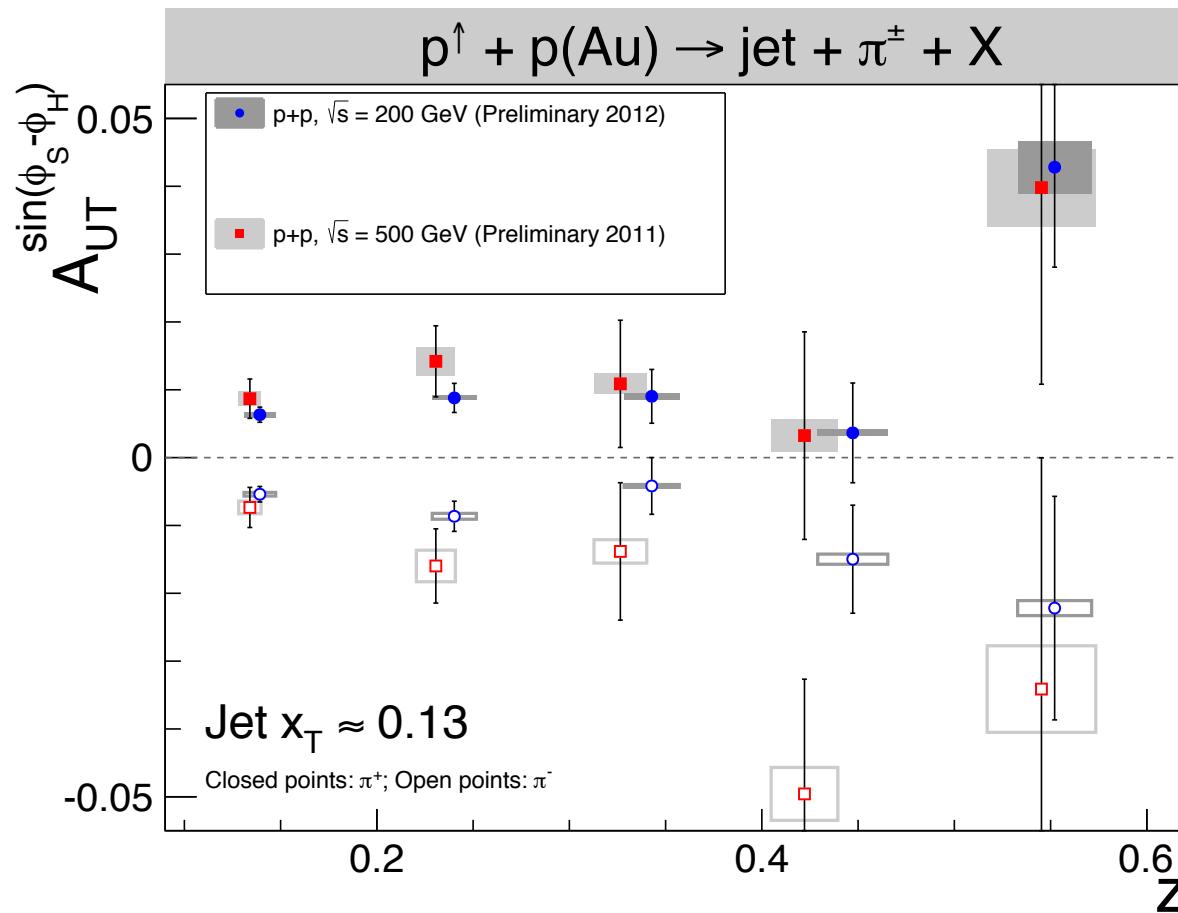
Hadroproduction can probe additional asymmetry modulations
(e.g. sensitive to *linearly polarized gluons*)

FIRST MEASUREMENT!

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

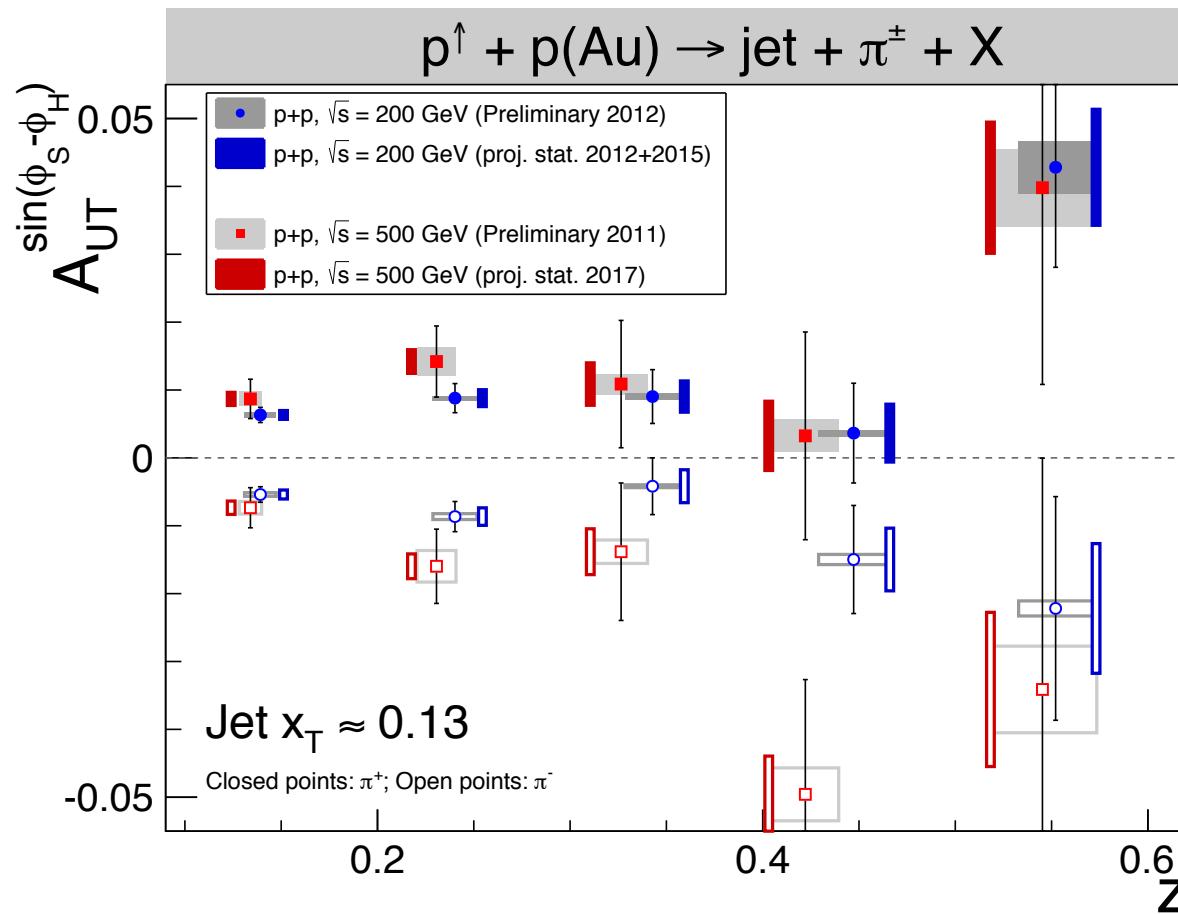
Present data should provide first constraints on Collins-like effect

The Near-term Future: Collins Evolution



Preliminary 2011 and 2012 Collins asymmetries suggest x_T scaling
Implications for TMD evolution?

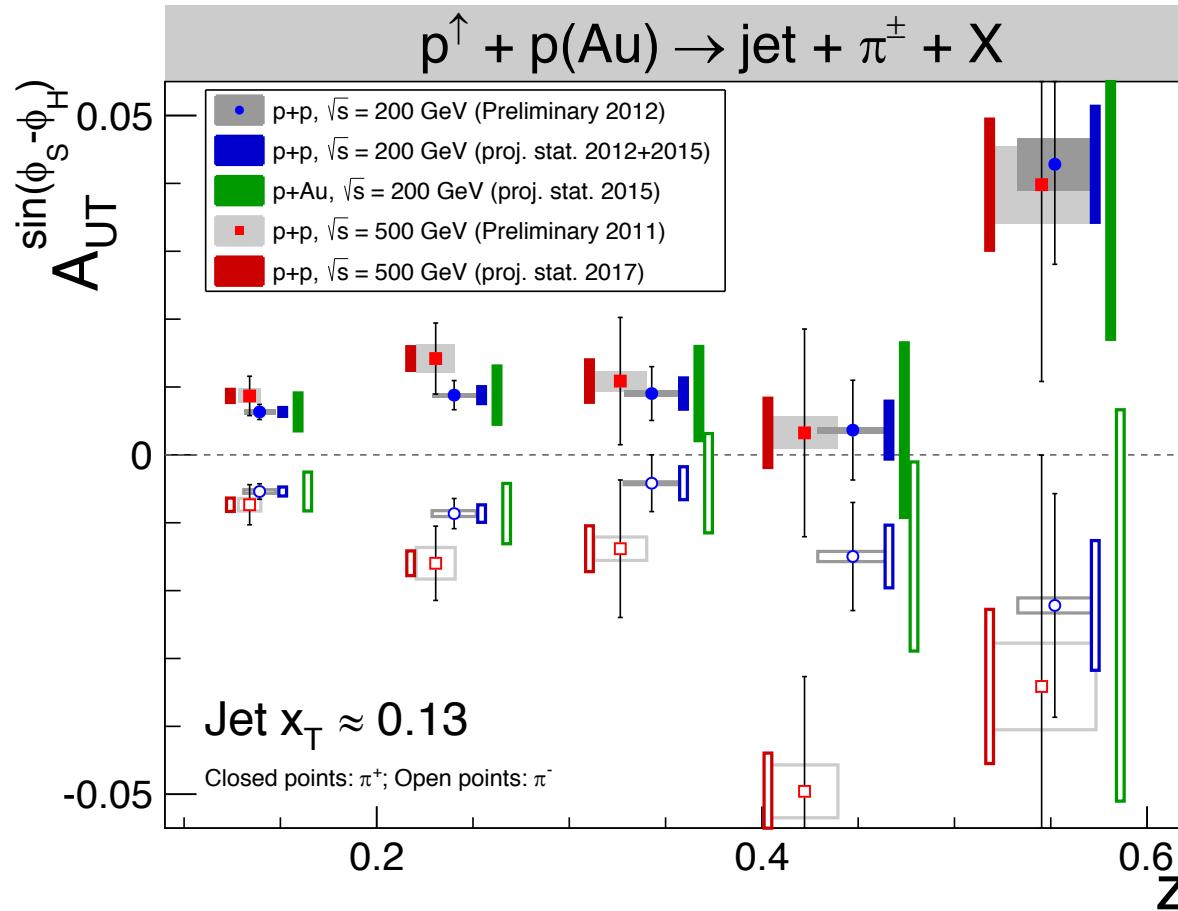
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*Higher precision in 2015
and 2017 will allow more
precise comparison!*

Preliminary 2011 and 2012 Collins asymmetries suggest x_T scaling
Implications for TMD evolution?

The Near-term Future: $p + A$ Collins



*Higher precision in 2015
and 2017 will allow more
precise comparison!*

First $p^\uparrow + Au$ run!
*Should allow for first
glimpse of Collins in $p + A$
→ Explore hadronization*

Preliminary 2011 and 2012 Collins asymmetries suggest x_T scaling
Implications for TMD evolution?

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Stay tuned for more results from RHIC transverse spin!