Illuminating QCD and Nucleon Structure Through the Study of Hadrons Within Jets at STAR

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for the STAR Collaboration

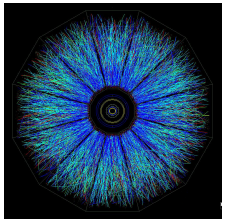
Lamar University

Fall Meeting of the APS Division of Nuclear Physics

October 27, 2017

OUTLINE

- Introduction
- RHIC and STAR
- Data and Models
- Near-term Plans
- Summary



The Fertile Field of Spin Physics

The study of spin in particle physics has unlocked doors to a deeper understanding of nucleon structure

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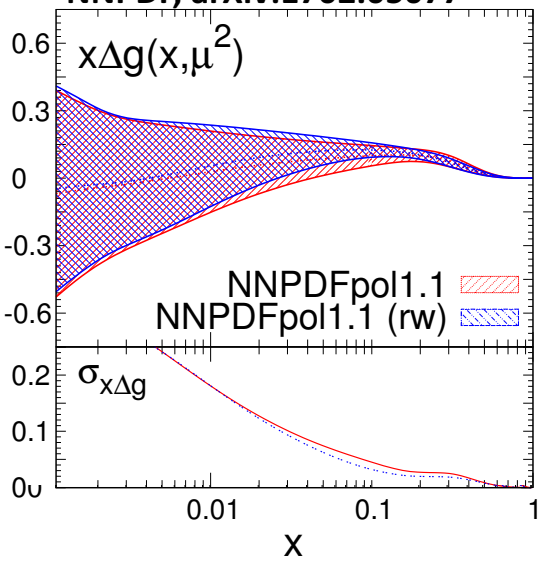
- Helicity

Recent results enable a better picture of gluon and sea-quark helicity

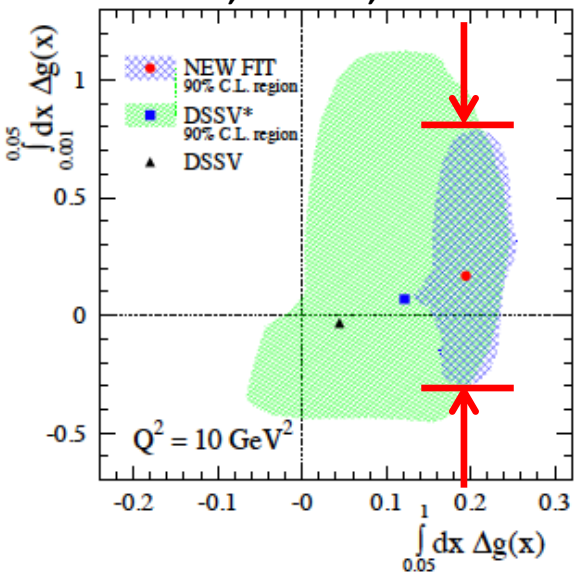
STAR data have played a key role!

e.g. Gluon Helicity

NNPDF, arXiv:1702.05077



DSSV, PRL 113, 012001



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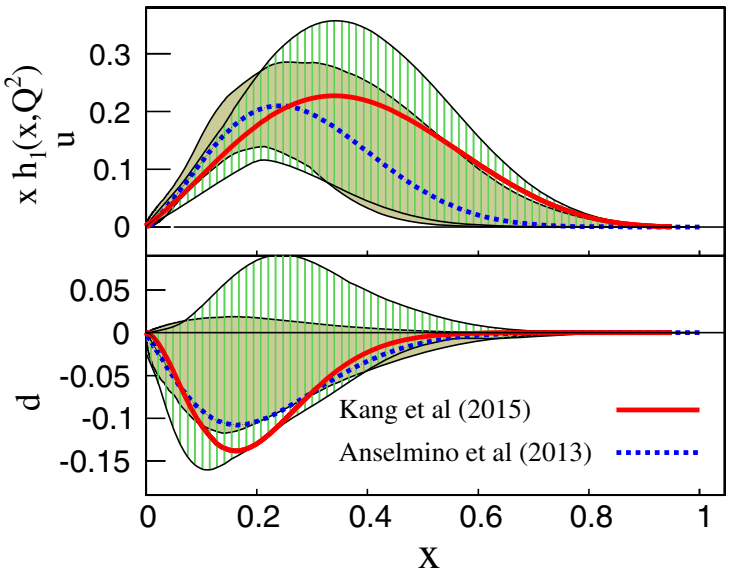
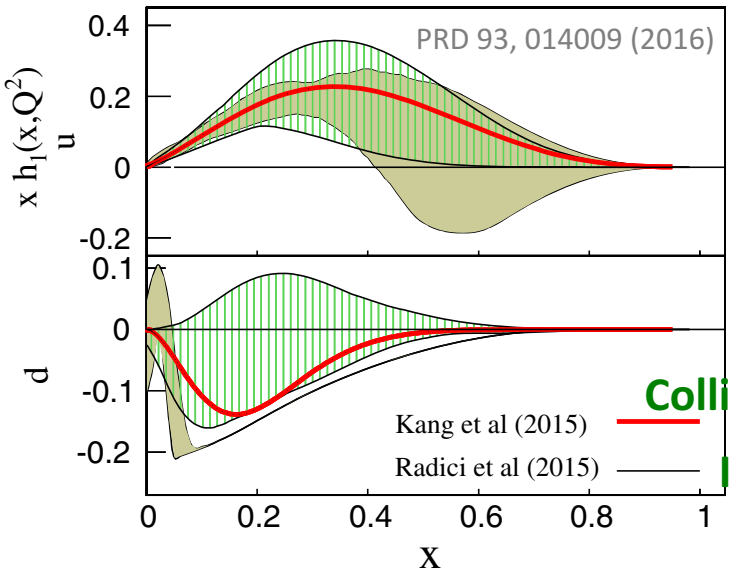
The study of spin in particle physics has unlocked doors to a deeper understanding of nucleon structure

- Helicity
- Transversity

Multiple mechanisms in play to constrain transverse spin-structure

Collins from SIDIS





Collins from SIDIS

IFF from SIDIS

(*Preliminary update at DIS2017*)

Opportunities with $p^{\uparrow} + p$***…!***

The Fertile Field of Spin Physics

Collins Effect in Hadroproduction

- Asymmetry in ***distribution of hadrons within jets*** $\sim \sin(\phi_S - \phi_H)$

Anselmino et al., PRD 73, 014020 (2006)
F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)

Transverse Momentum Dependent (TMD) Approach

Terms in Numerator of TMD SSA for qq Scattering	English Names	Modulation
$\Delta^N f_{a/A^\uparrow} \cdot f_{b/B} \cdot D_{\pi/q}$	Sivers • PDF • FF	$\sin(\phi_{S_A})$
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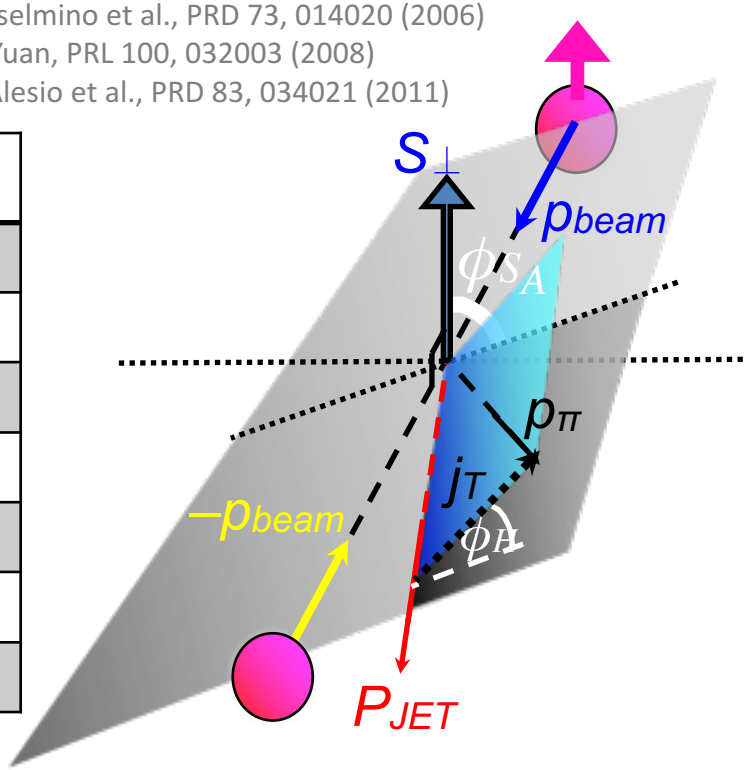

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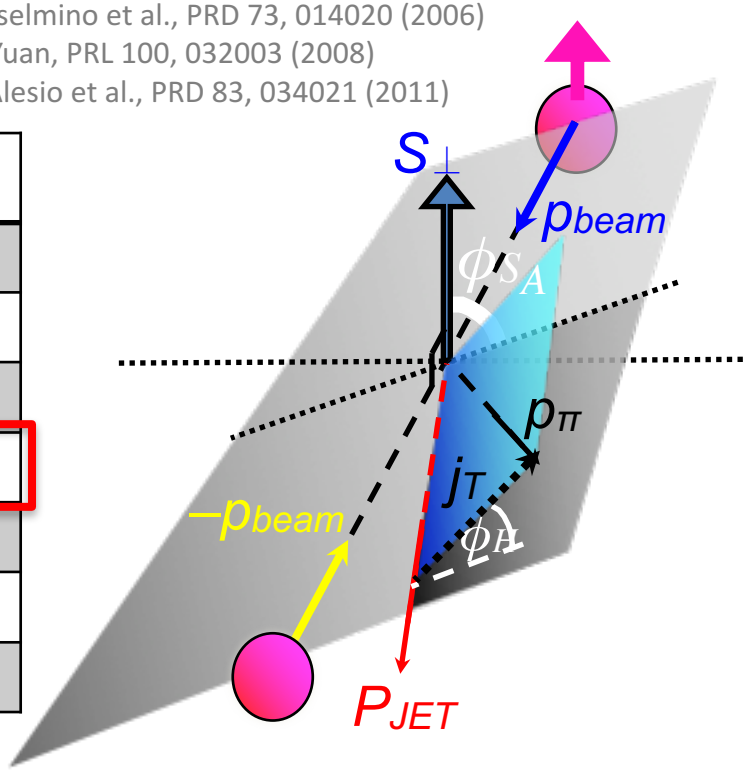
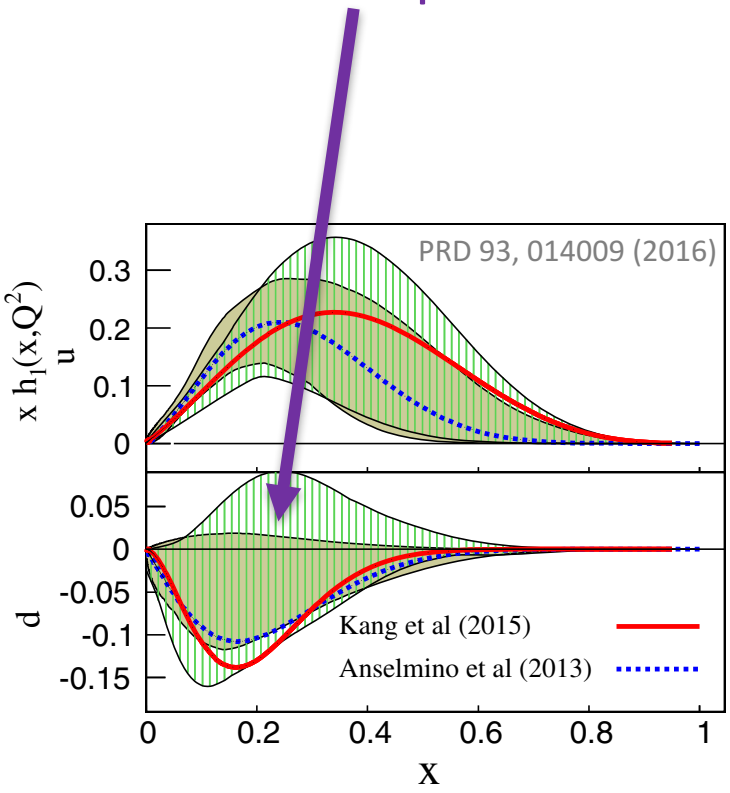


The Fertile Field of Spin Physics

Collins Effect in Hadroproduction

- Asymmetry in ***distribution of hadrons within jets*** $\sim \sin(\phi_S - \phi_H)$
- Do TMD jet(h) observables ***factorize in p+p***? [arXiv:1705.08443]
- How do TMDs evolve, e.g. with (x, Q^2)?
- Enhance d-quark sensitivity



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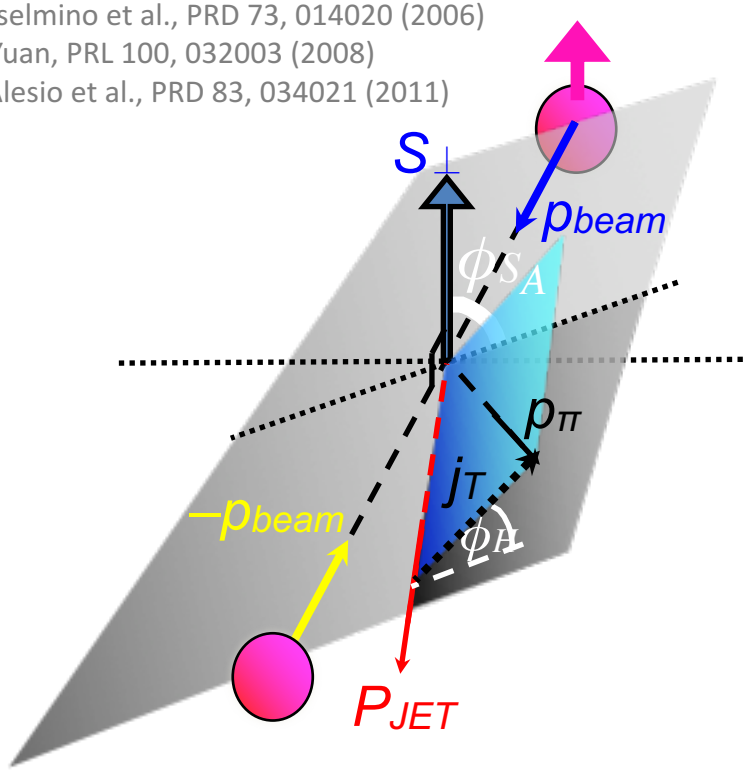
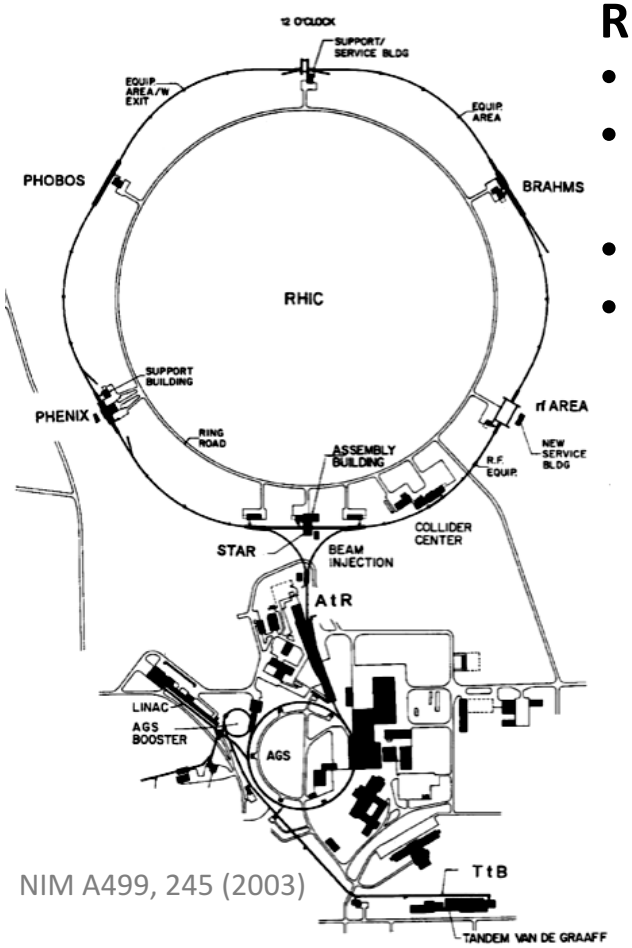


Relativistic Heavy Ion Collider

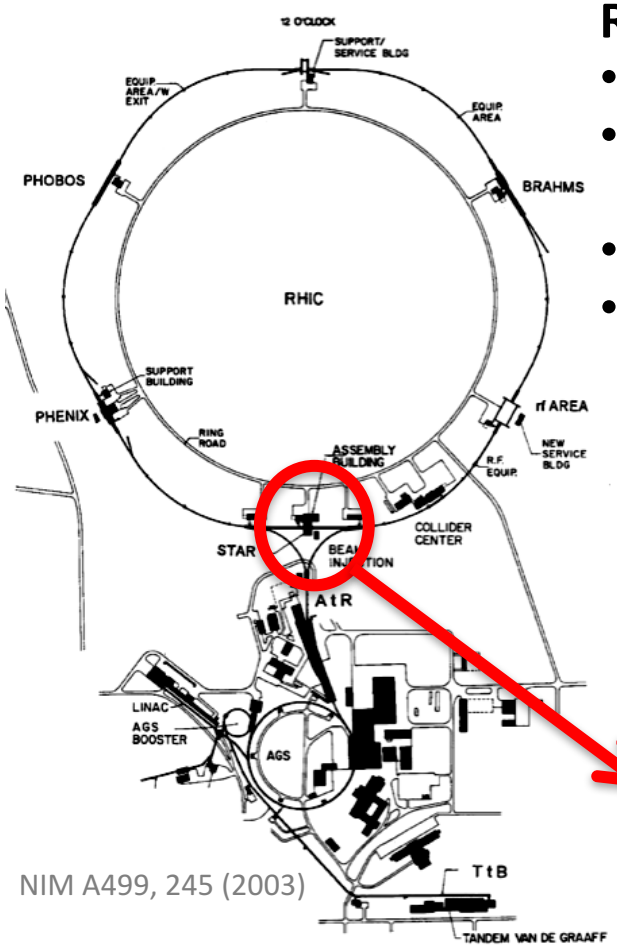


NIM A499, 245 (2003)

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

Solenoidal Tracker at RHIC



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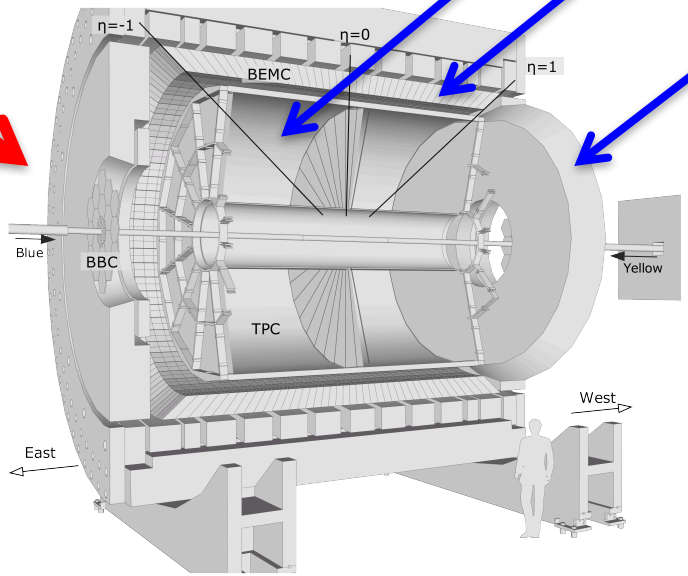
Jets, di-hadrons, weak bosons

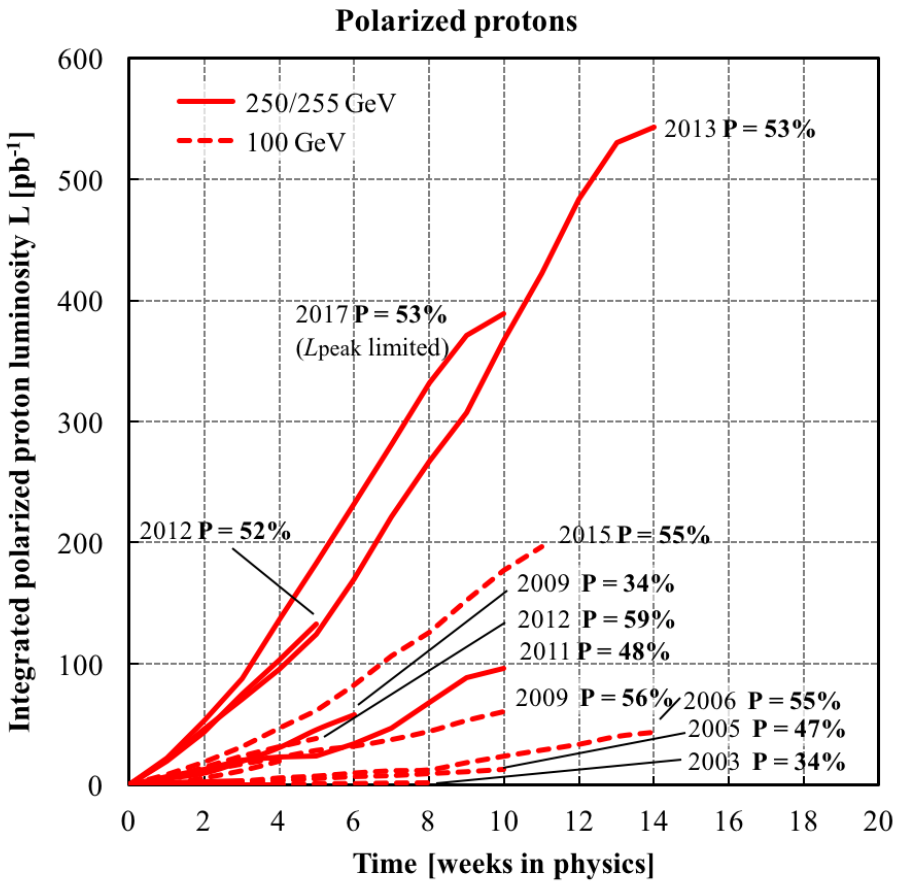
TPC + Barrel + Endcap EMC



Trigger on calorimeter energy

Polarized-proton Datasets at RHIC

Unique opportunities to probe nucleon spin structure!

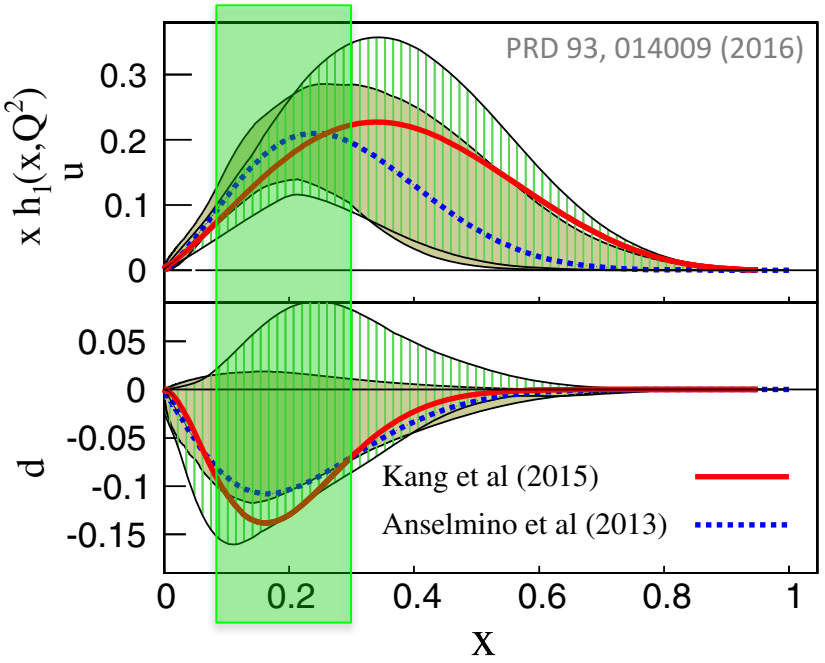


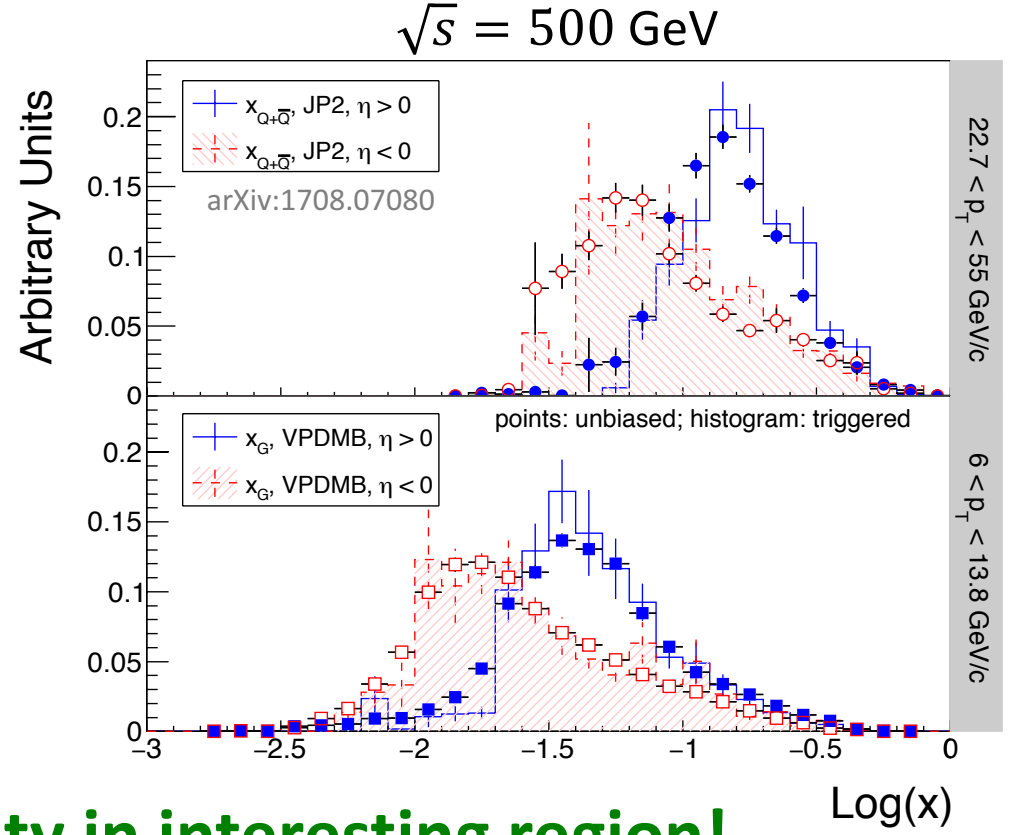
Transverse Luminosity Recorded

Year	$\sqrt{s}$ [GeV]	STAR	$\langle P \rangle$ [%]
2006	200	8.5 pb^{-1}	57
2006	62.4	0.2 pb^{-1}	48
2008	200	7.8 pb^{-1}	45
2011	500	25 pb^{-1}	53/54
2012	200	22 pb^{-1}	61/58
2015	200	53 pb^{-1}	53/57
2015	200 pAu	0.42 pb^{-1}	60
2015	200 pAl	1.0 pb^{-1}	54
2017	510	320 pb^{-1}	56

Dramatically increased figure of merit in recent years

Kinematic Sensitivity at STAR





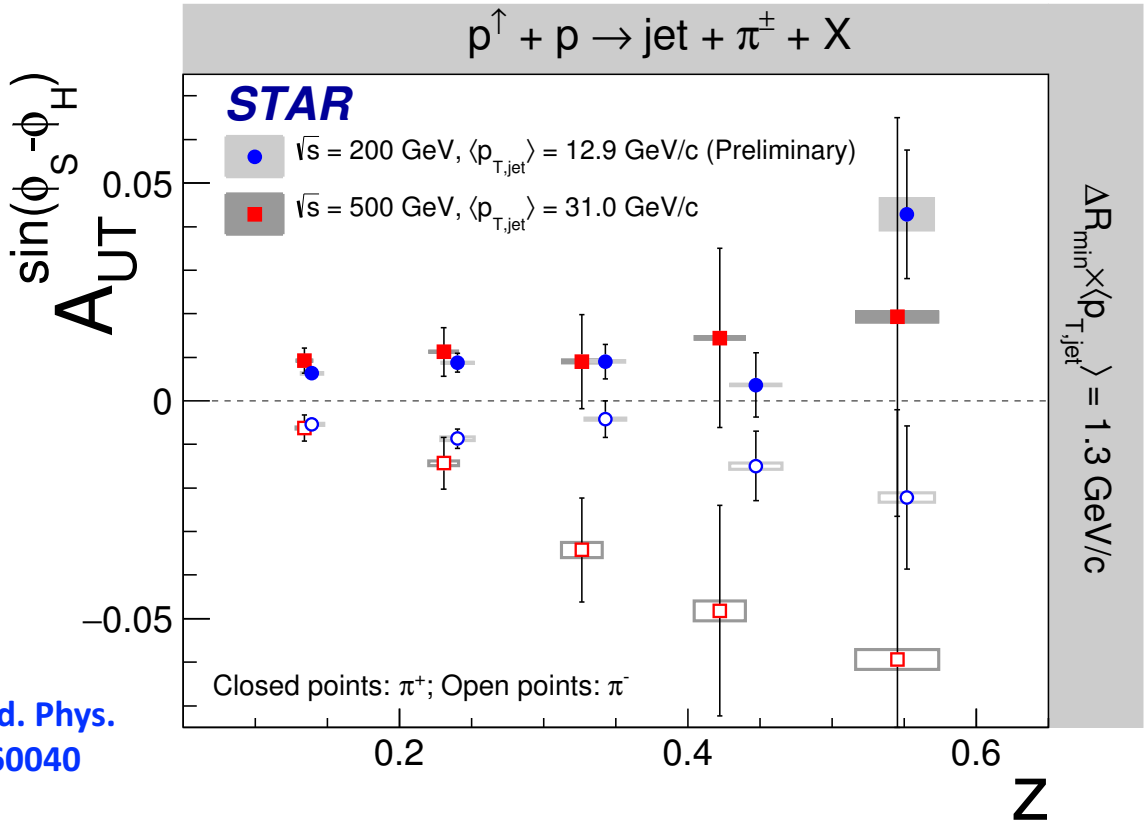
Access to transversity in interesting region!

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

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

First Collins asymmetry observations in hadroproduction!

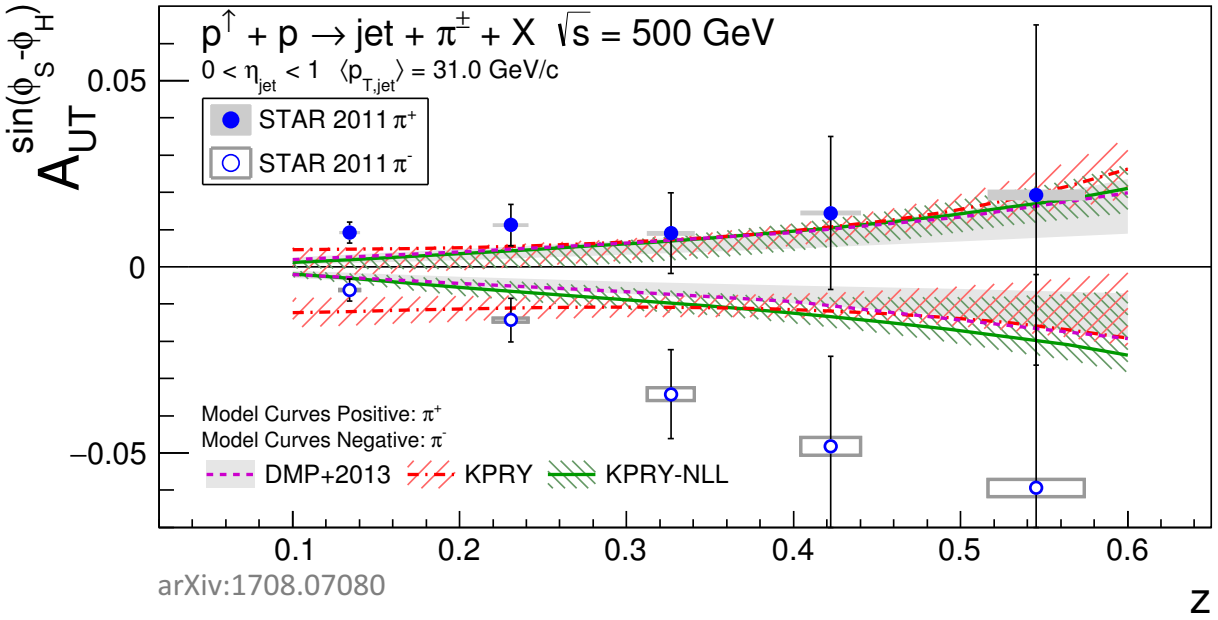
New 500 GeV Paper: arXiv:1708.07080



200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040

At the current precision, results from $p + p$ exhibit x_T scaling

Comparison to Models



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Models based on SIDIS/e^+e^-

- Assume ***universality*** and ***robust factorization***
- **DMP&KPRY: no TMD evol.**
- **KPRY-NLL: TMD evolution up to NLL**

DMP: PLB 773, 300 (2017)
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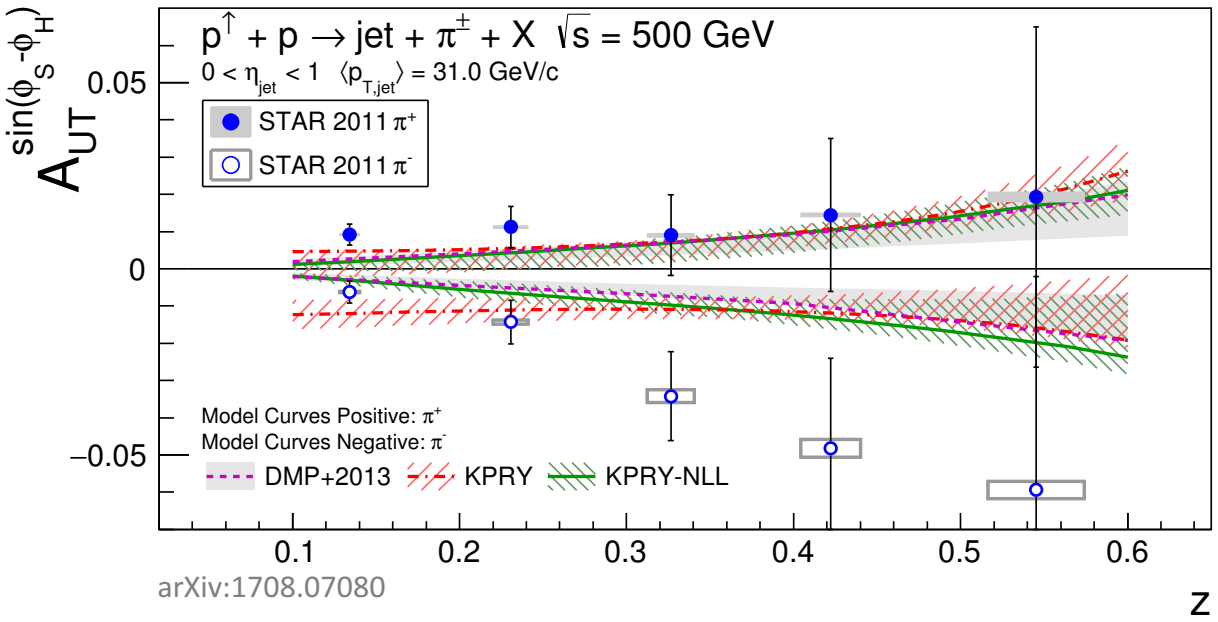

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Consistency between models and STAR data at 95% confidence level

→ Suggests robust factorization and universality

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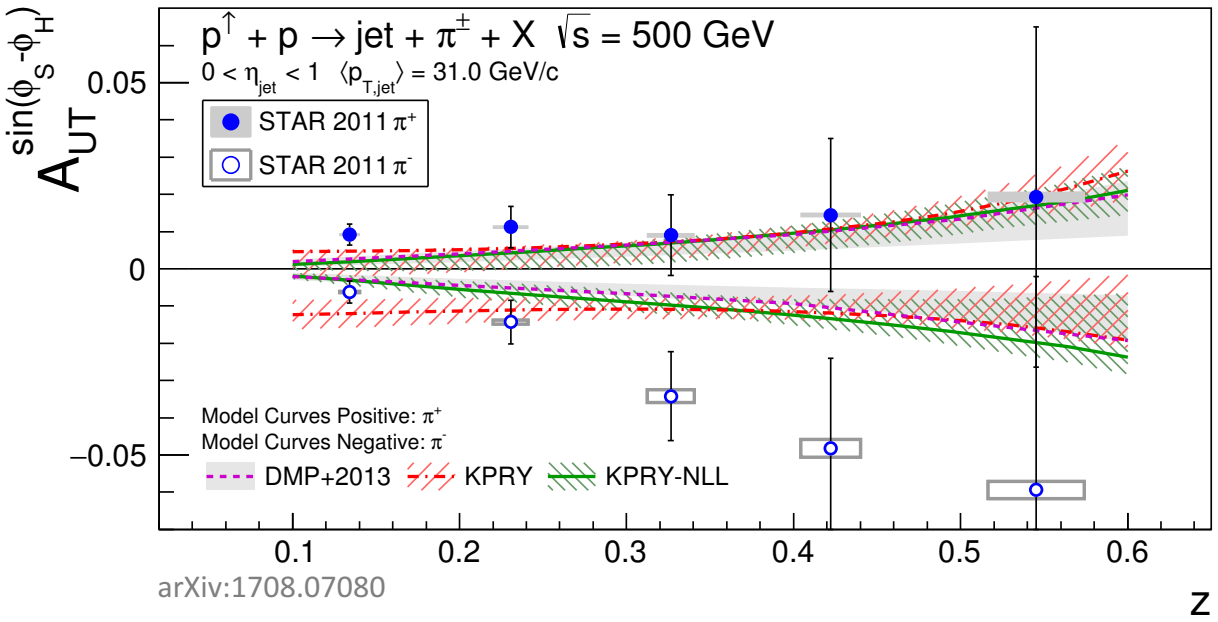

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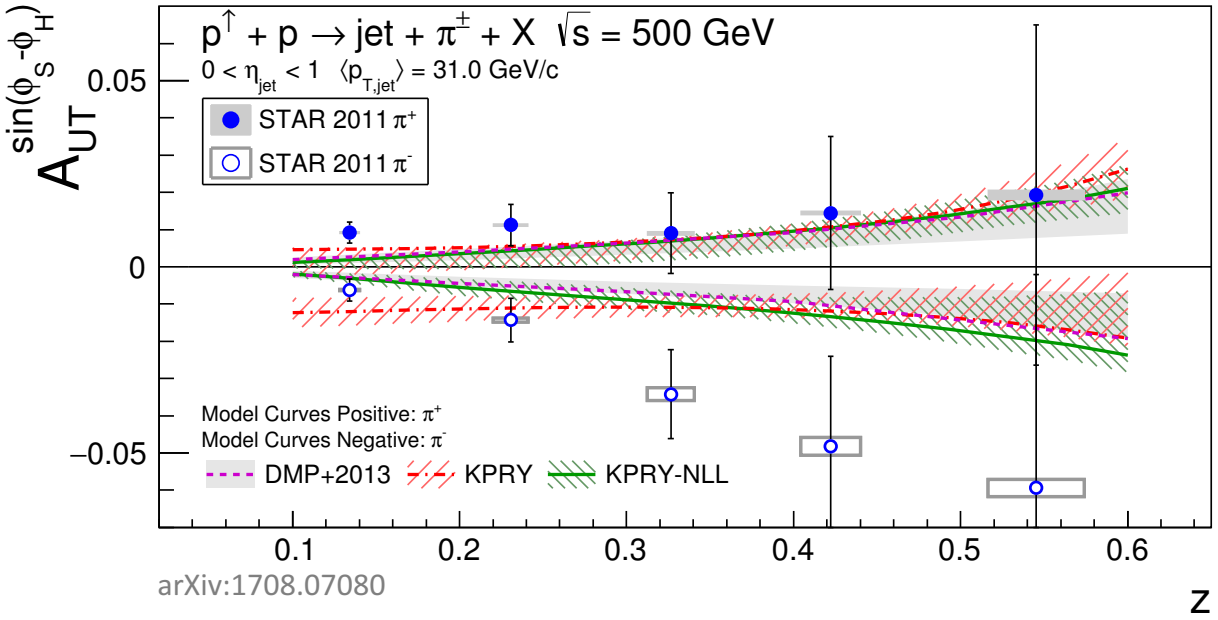

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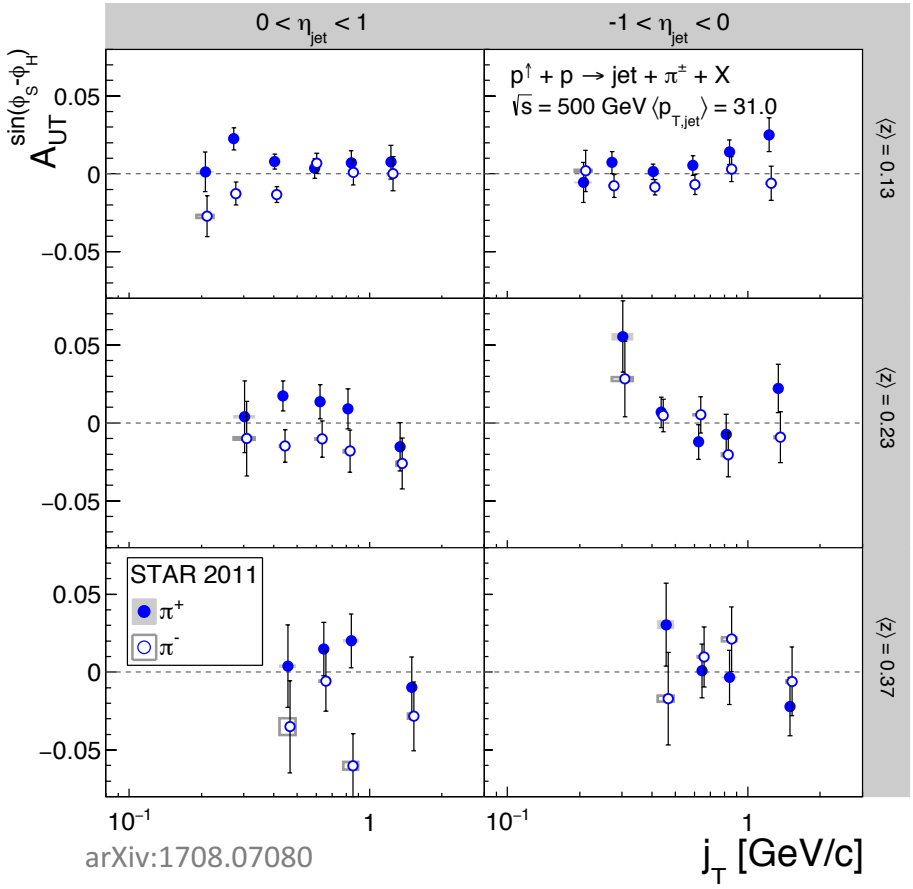
$\chi^2/\nu = 14/10$ (w/o) vs. $17.6/10$ (with)

For now, "Beauty is in the eye of the beholder!"

(a.k.a. need more data!)

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

Dependence on j_T (momentum transverse to jet)



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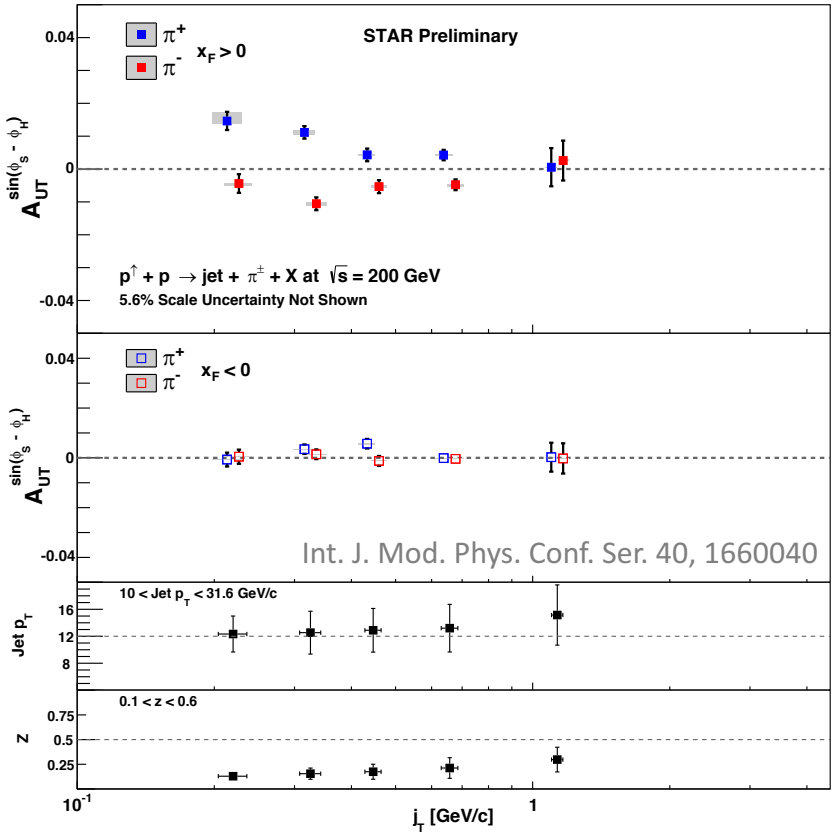
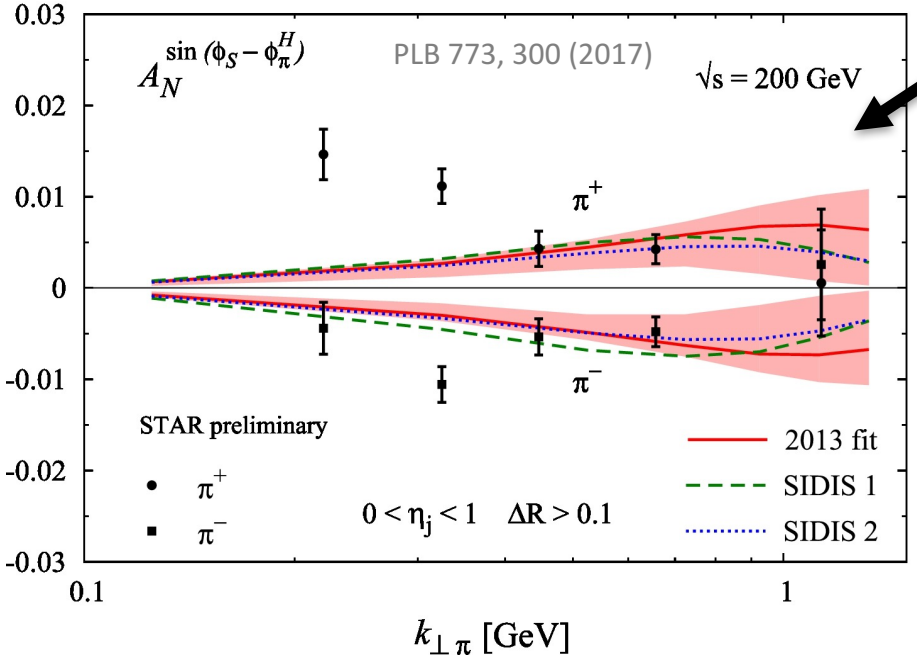


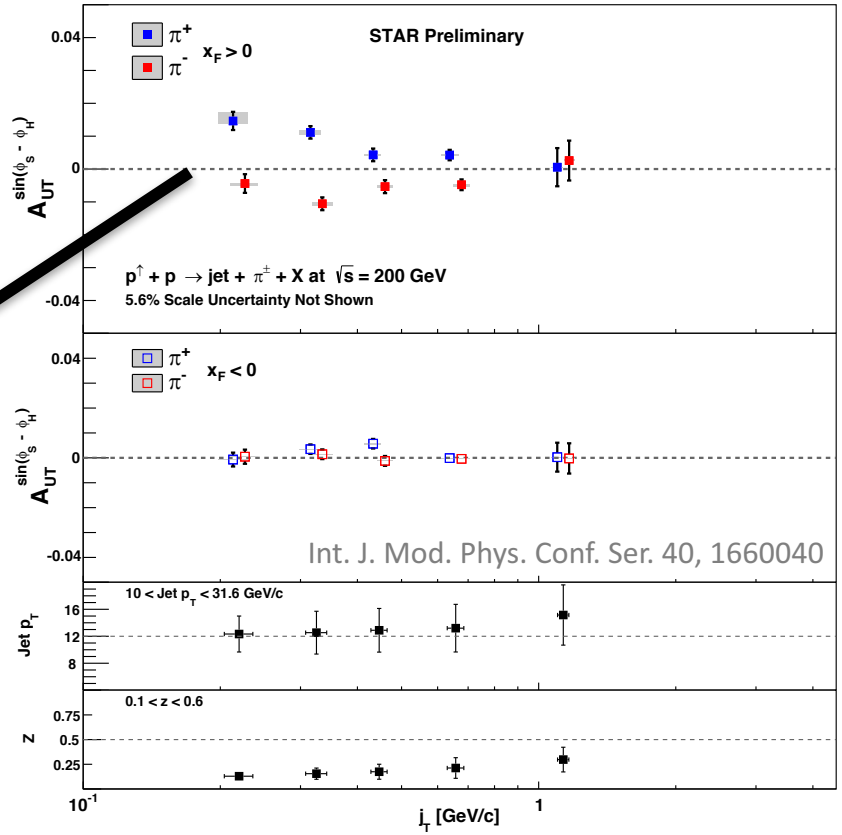
Asymmetries appear to decrease with j_T
Consistent between energies?

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

Dependence on j_T (momentum transverse to jet)

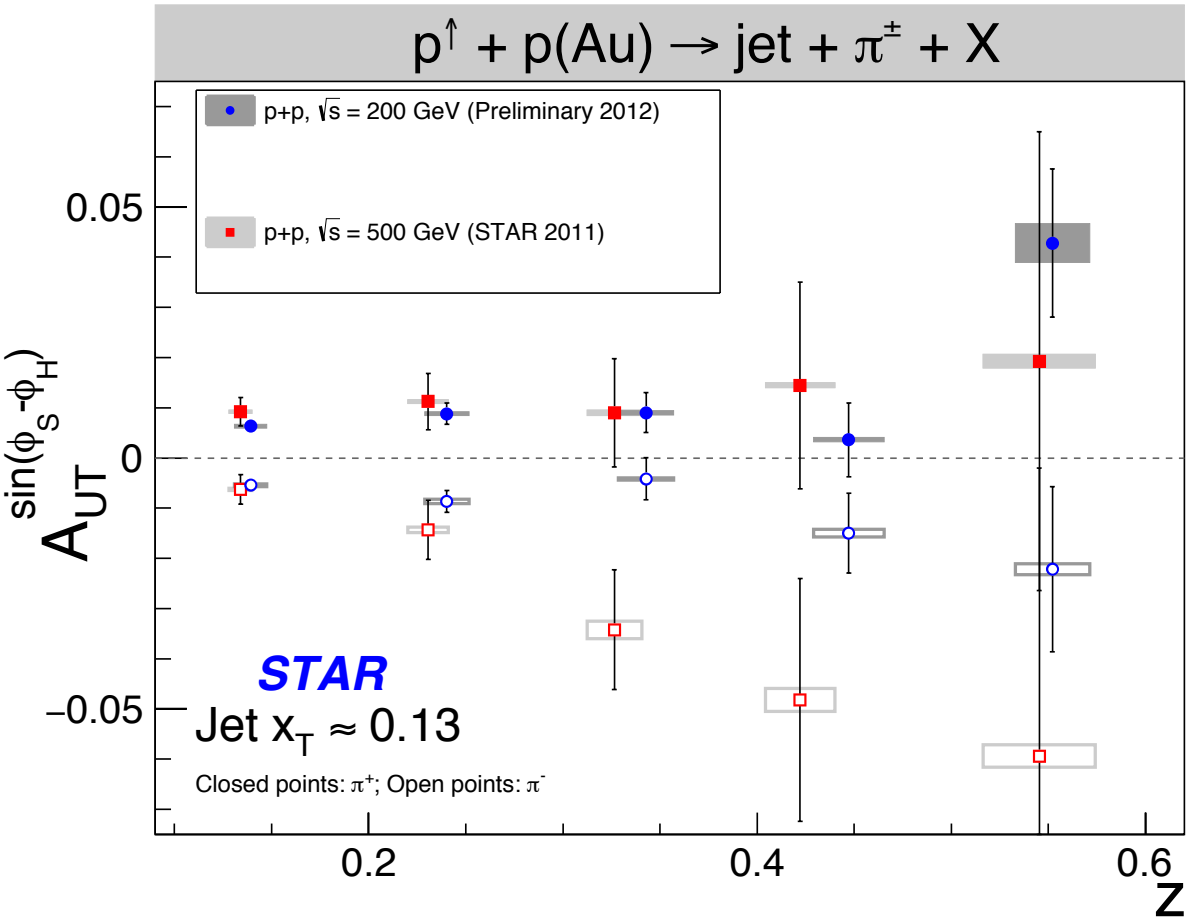
Compare to DMP models





Further investigation of low j_T region needed
e.g. unpolarized TMD data, model parameterization, etc.

The Near-term Future: Collins Evolution



2011 and Preliminary 2012 Collins asymmetries suggest x_T scaling

Implications for TMD evolution?

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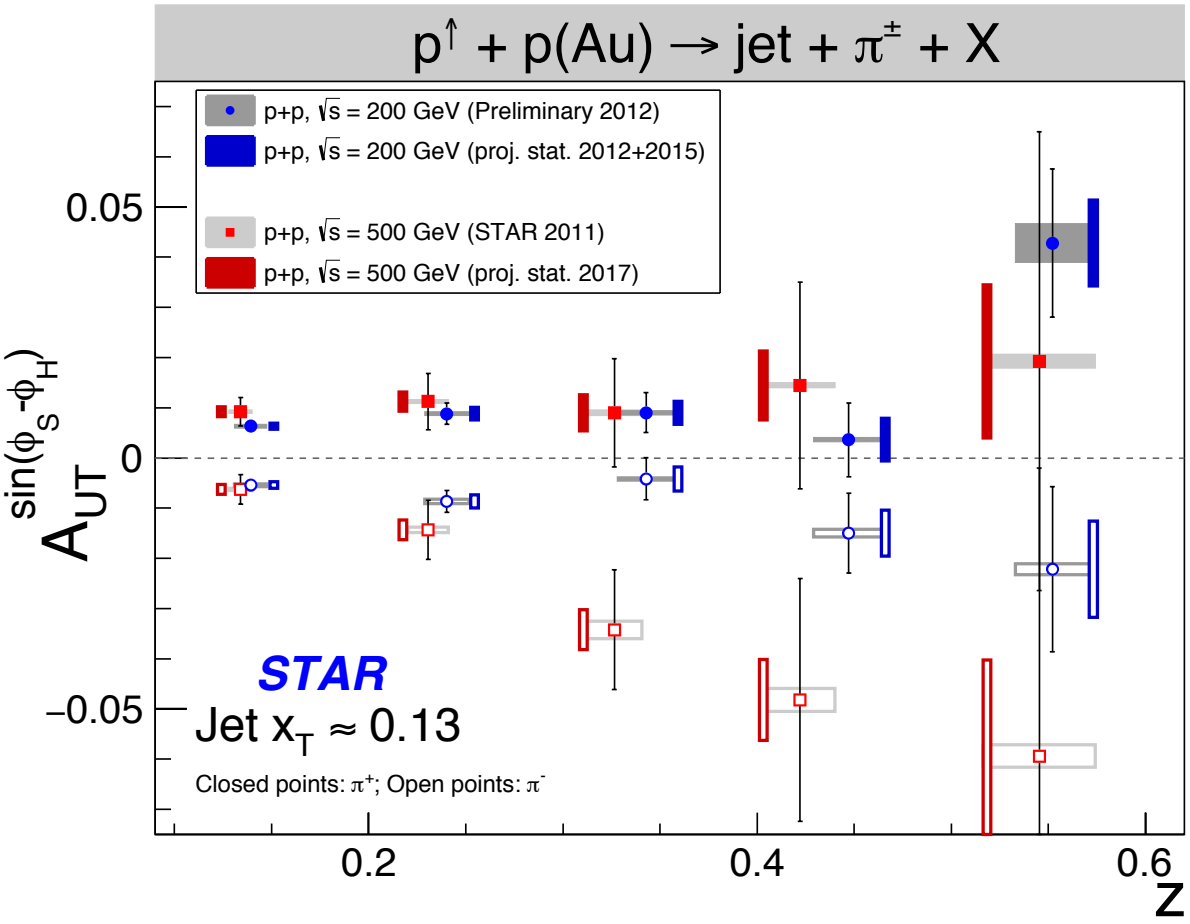

Higher precision in 2015 and 2017 will allow more precise comparison!

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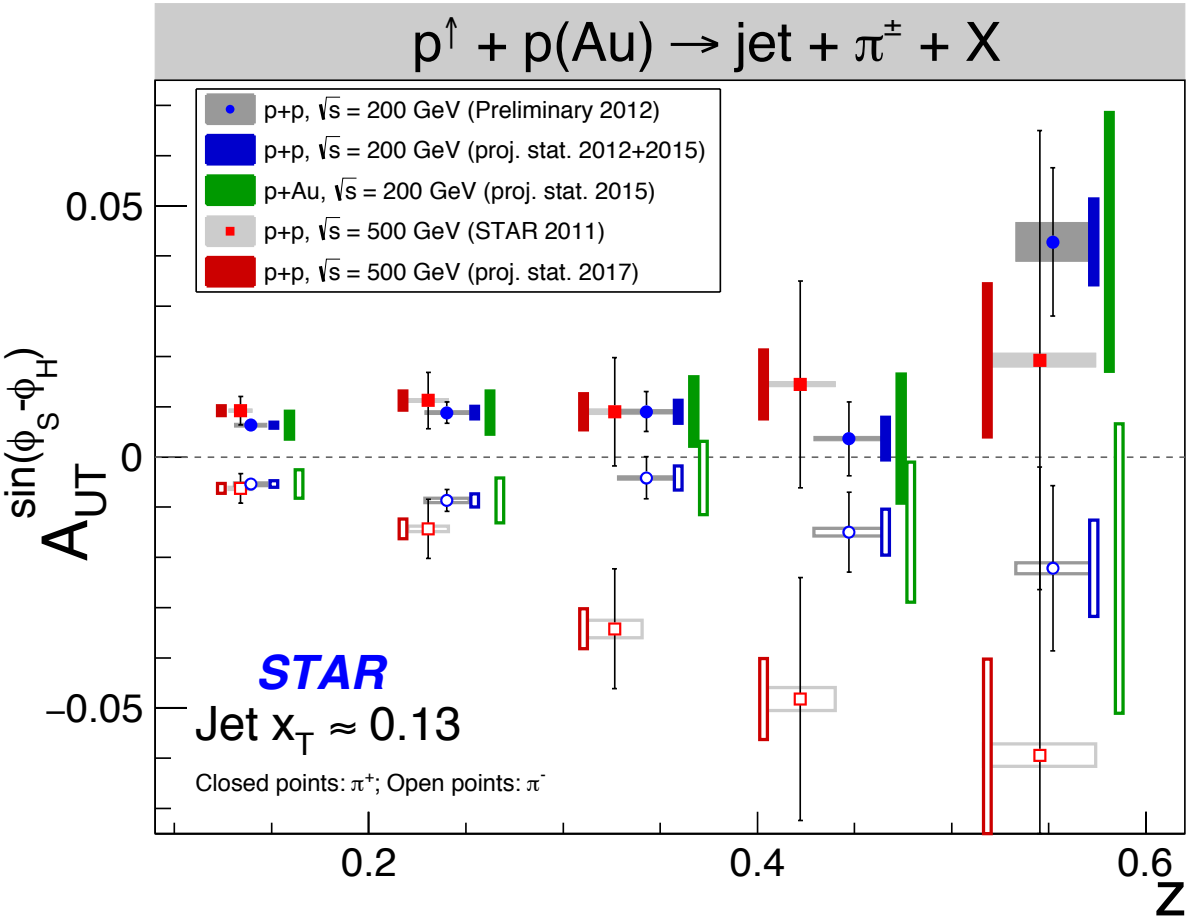
The Near-term Future: $p + A$ Collins



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**

2011 and Preliminary 2012 Collins asymmetries suggest x_T scaling

Implications for TMD evolution?

Summary

- **Spin physics is a fertile field and $p + p$ plays a critical role**

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- First observations of Collins effect in polarized $p + p$
  - Possible x_T scaling
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  - Evolution effects slow (more precise data needed to quantify)

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- **Recent and near-future runs offer even more potential**
  - Substantially increased precision for Collins at 200 and 510 GeV
  - First investigation of Collins in $p + A$

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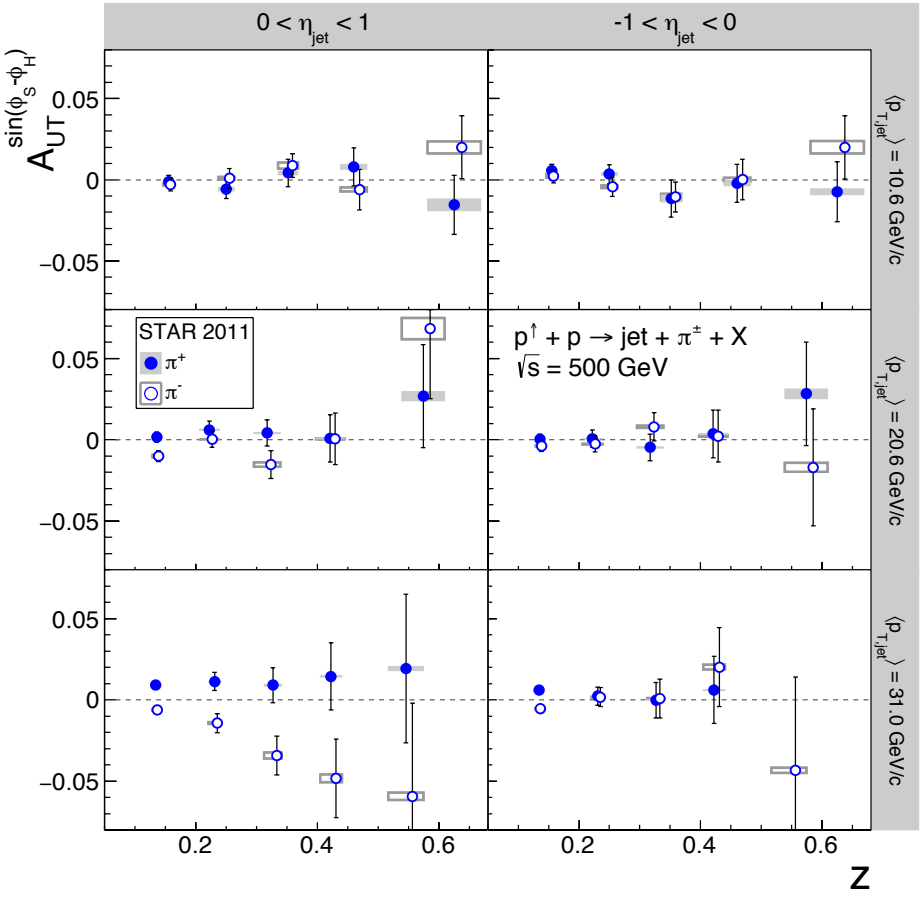
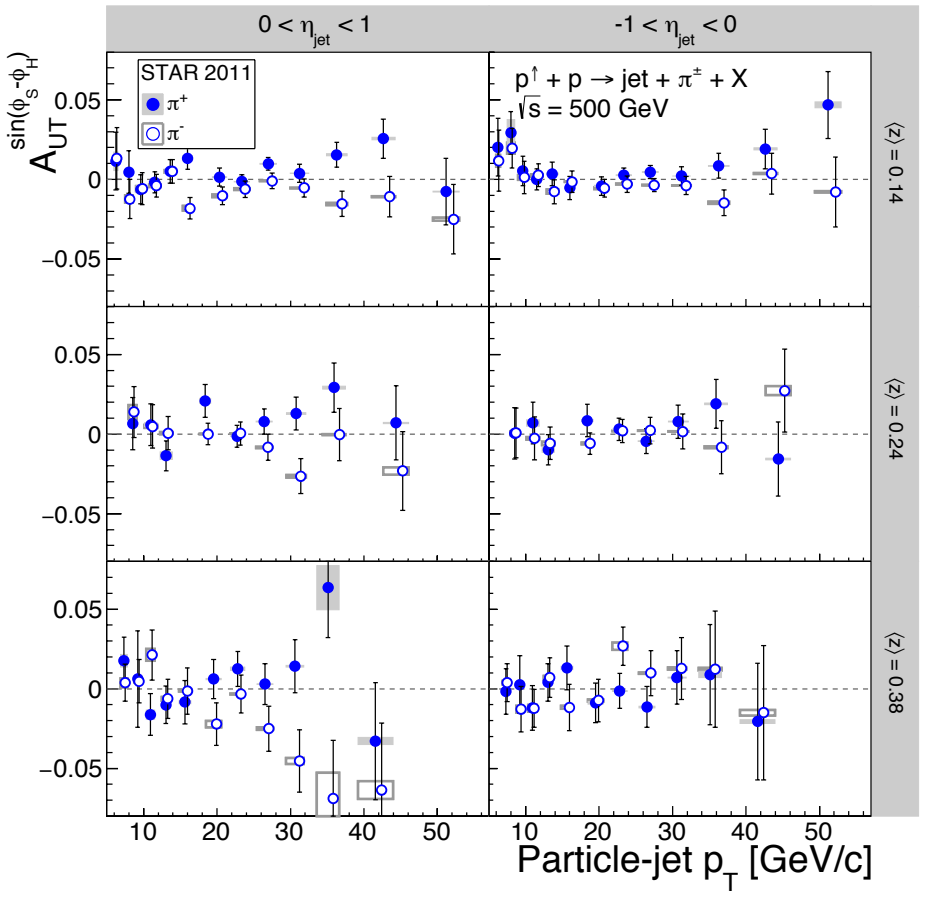
Stay tuned for more new results from STAR!

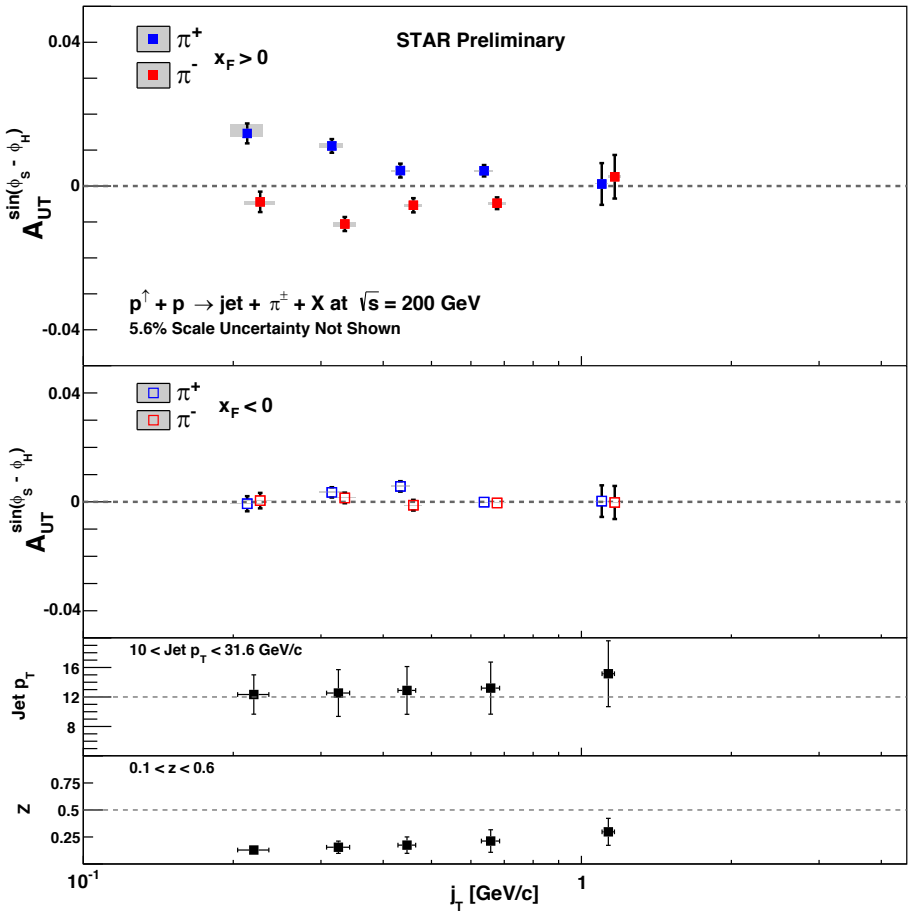
Back-up Slides

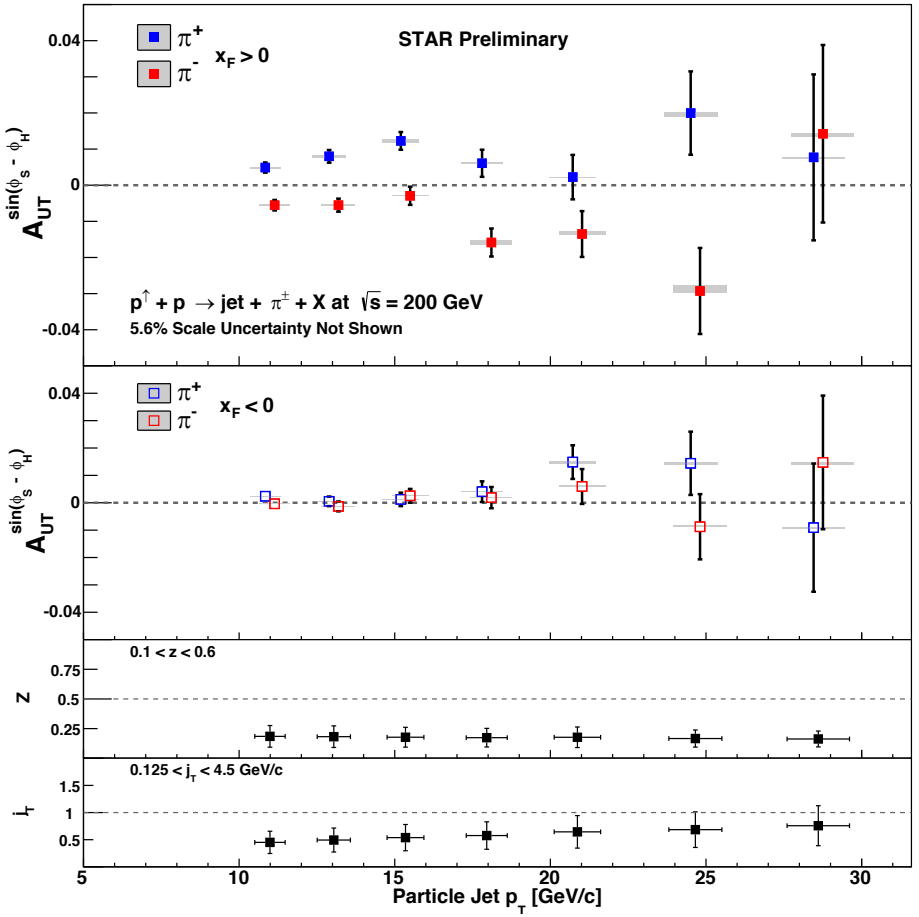
STAR Results at $\sqrt{s} = 500$ GeV



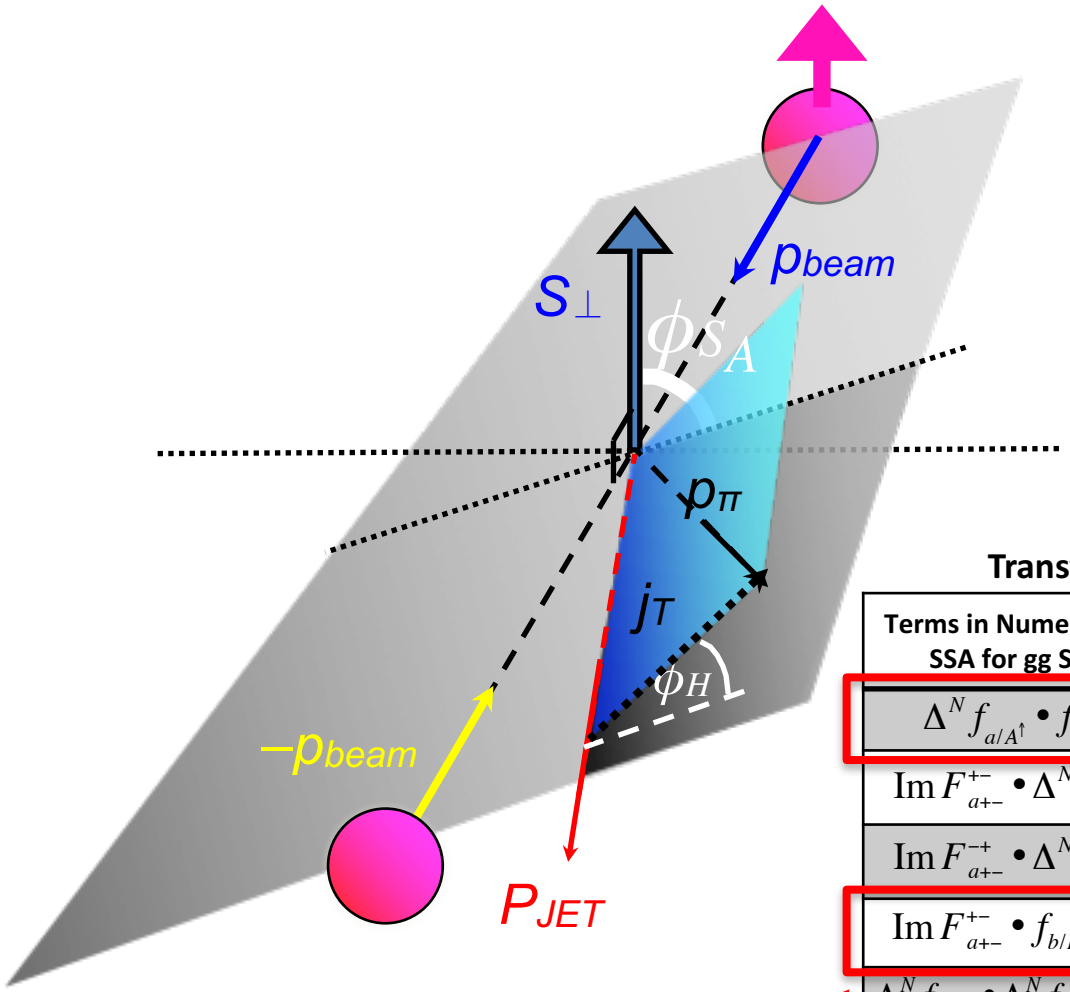


STAR Results at $\sqrt{s} = 200$ GeV





Transverse Asymmetries for Gluon 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)

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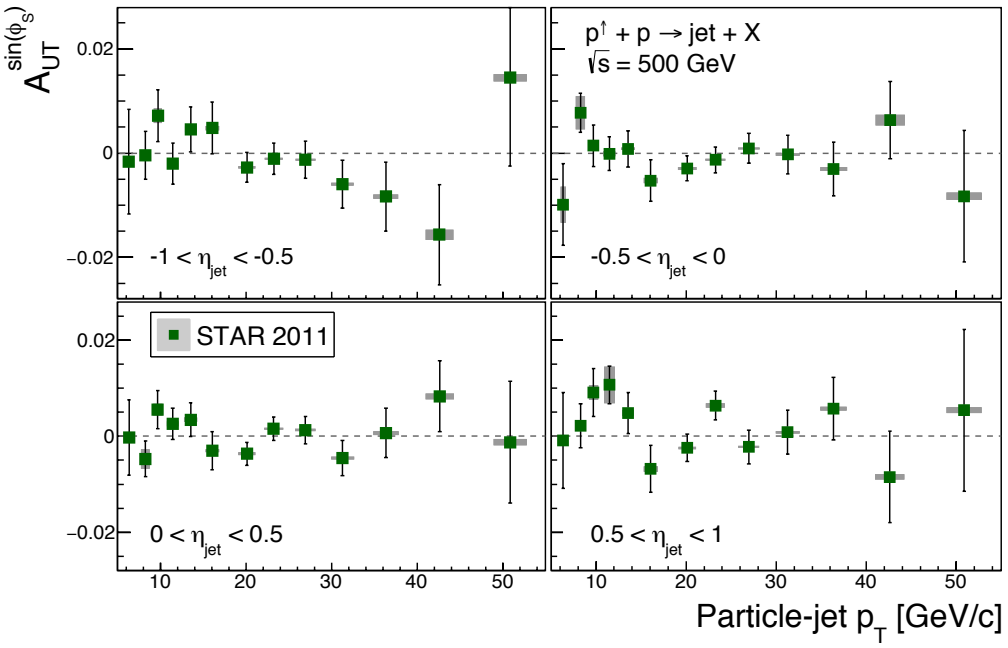
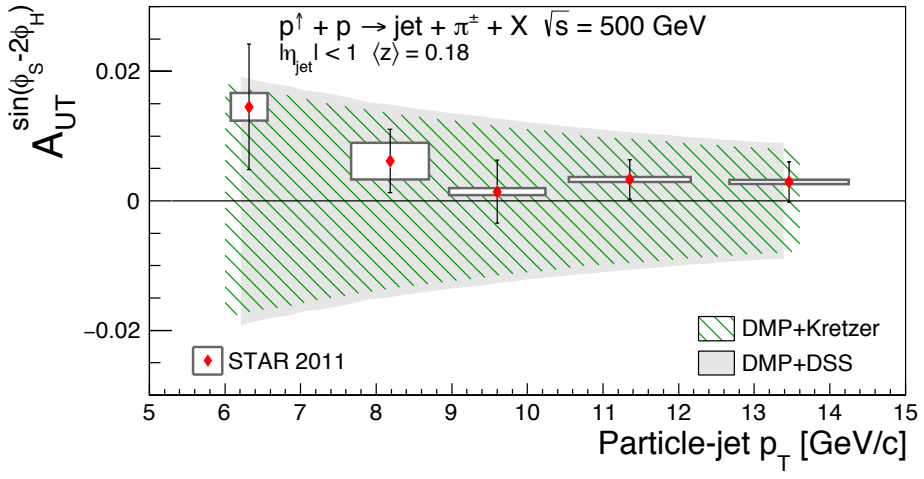
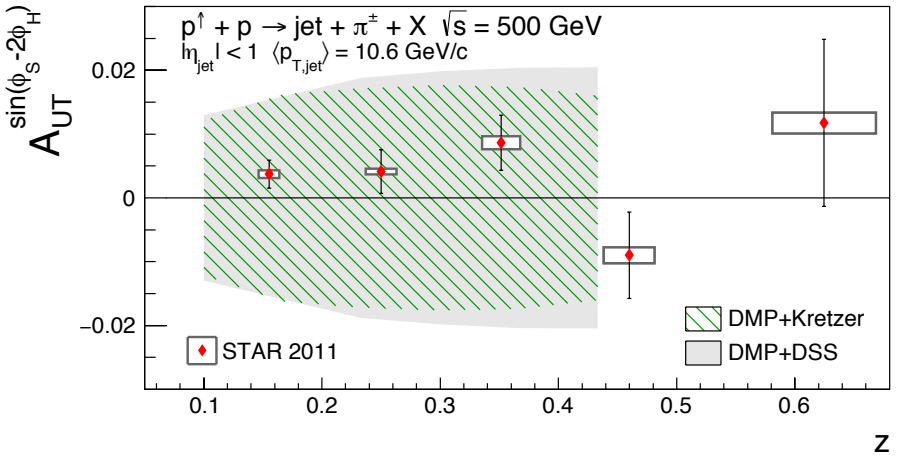
UNCONSTRAINED!

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

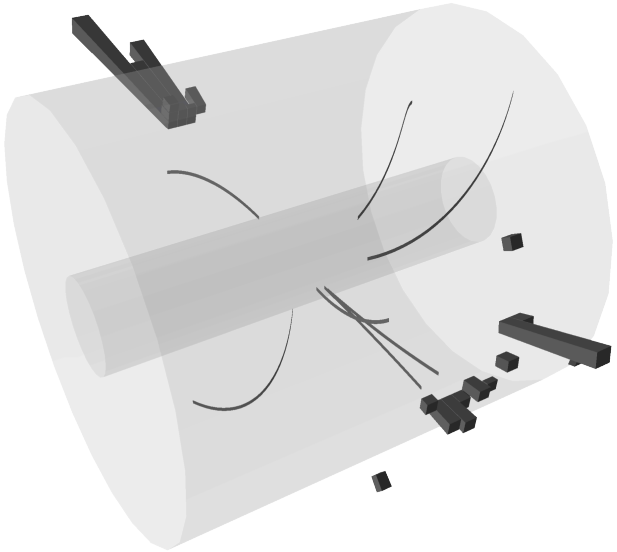






Jet Reconstruction at RHIC

STAR Di-jet event at detector level



e.g. Anti-k_T algorithm

JHEP 0804, 063 (2008)

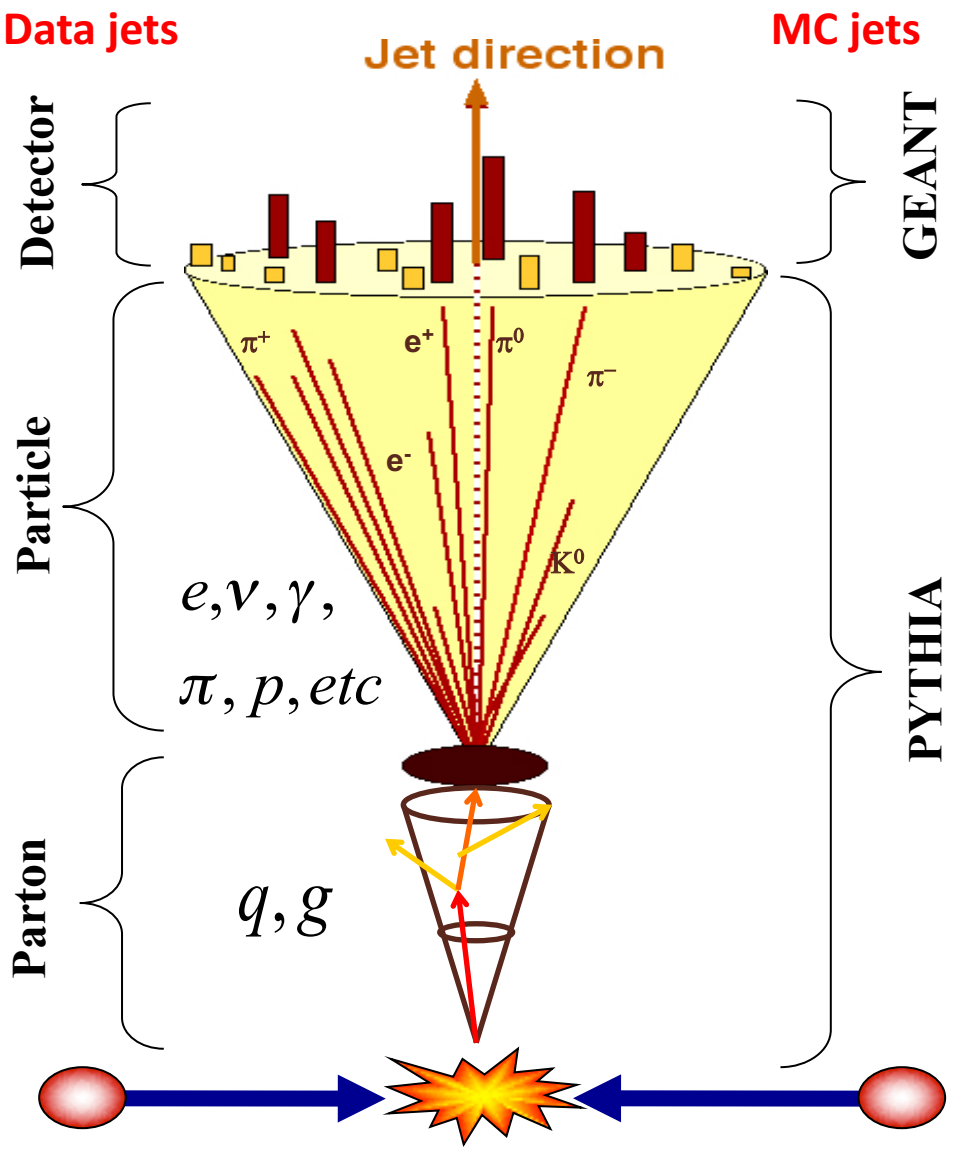
Radius parameter $R = 0.5$ or 0.6

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

$\pi^{\pm}$ Kinematic Variables

$z - \pi$ momentum / jet momentum

$j_T - \pi$ p_T relative to jet axis

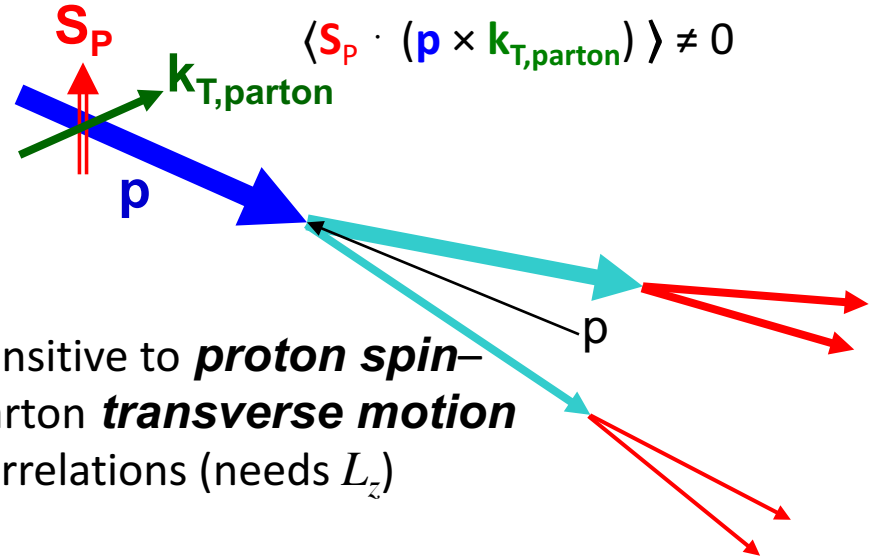


Formalisms for Transverse Single-spin Asymmetries

Transverse Momentum Dependent (TMD) PDFs and FFs

Sivers mechanism: asymmetry in e.g. jet or γ *production*

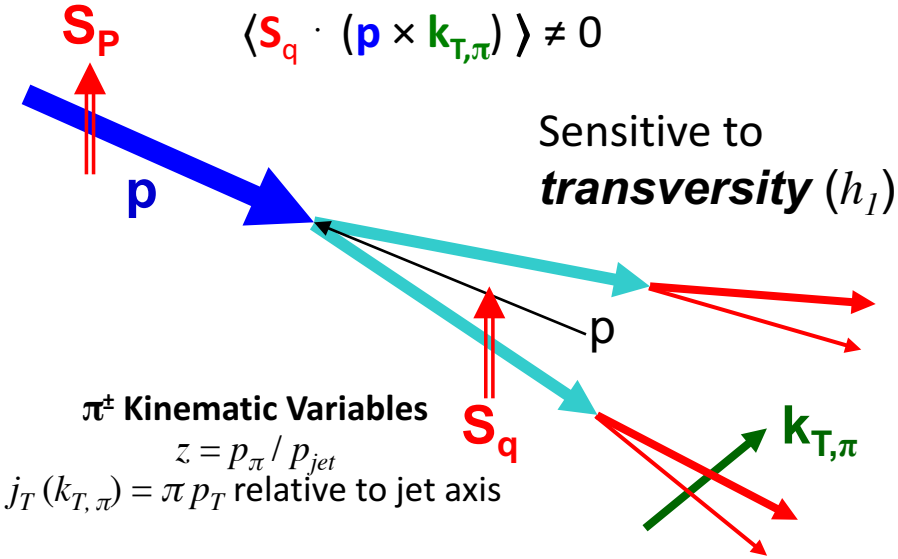
D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)



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

Collins mechanism: asymmetry in the jet *fragmentation*

J. Collins, NP B396, 161 (1993)



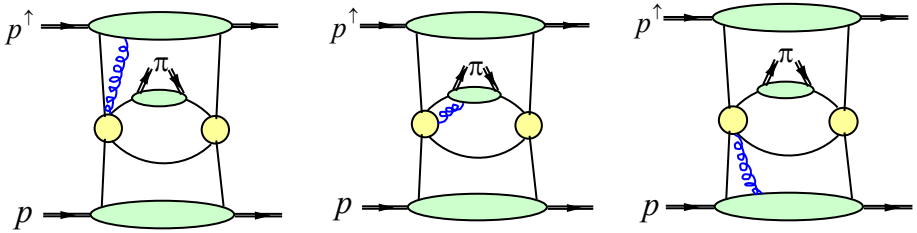
Sensitive to ***transversity*** (h_1)

$\pi^{\pm}$ Kinematic Variables

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

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

Collinear Twist-3 Correlators



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)