Illuminating Nucleon Structure Through Polarized Proton-Proton Collisions at STAR

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Lamar University

25th International Workshop on Deep Inelastic Scattering and Related Topics

April 5, 2017

OUTLINE

- Introduction
- RHIC and STAR
- Recent Developments
- 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

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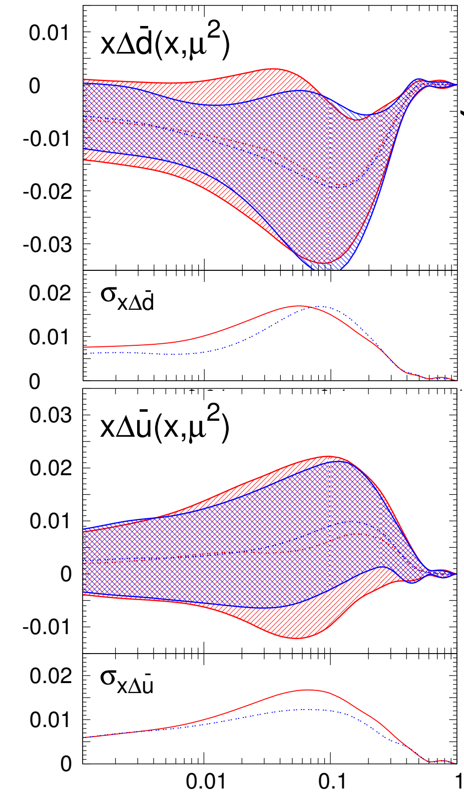
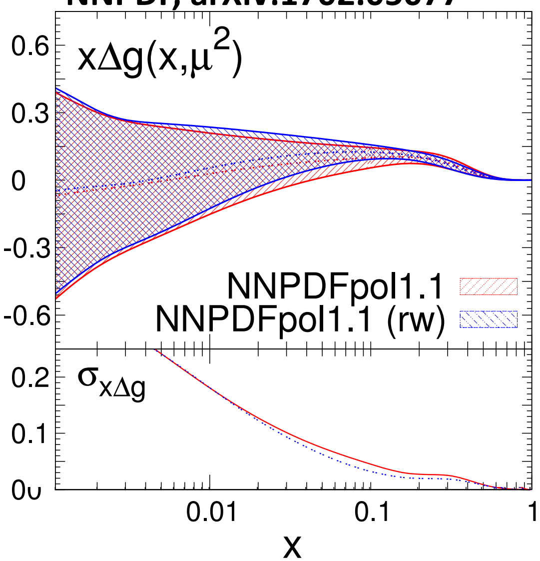
STAR data have played a key role!



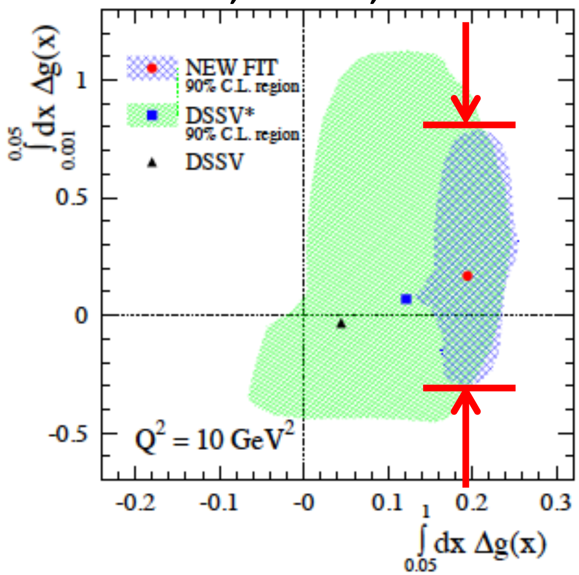
NNPDF, arXiv:1702.05077

Gluon Helicity

NNPDF, arXiv:1702.05077



DSSV, PRL 113, 012001



See talks by Q. Xu and B. Surrow

Sea-quark Helicity

The Fertile Field of Spin Physics

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- Helicity
- Transversity

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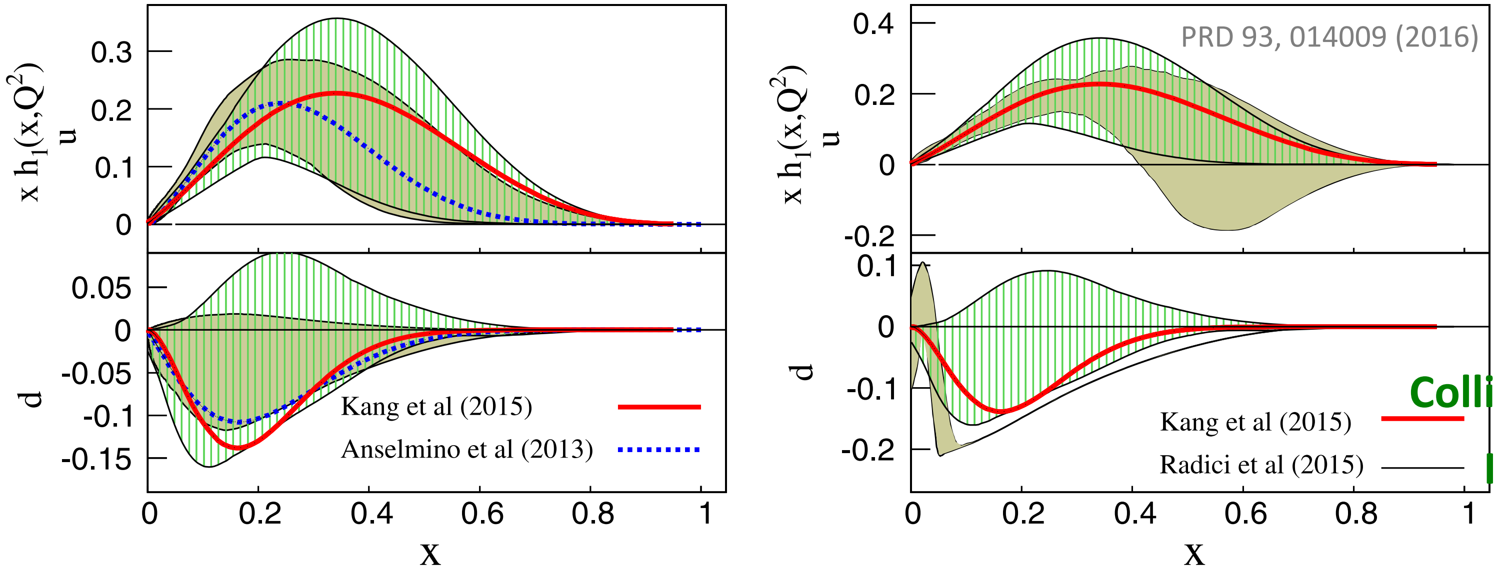
Multiple mechanisms in play to constrain transverse spin-structure

Collins from SIDIS



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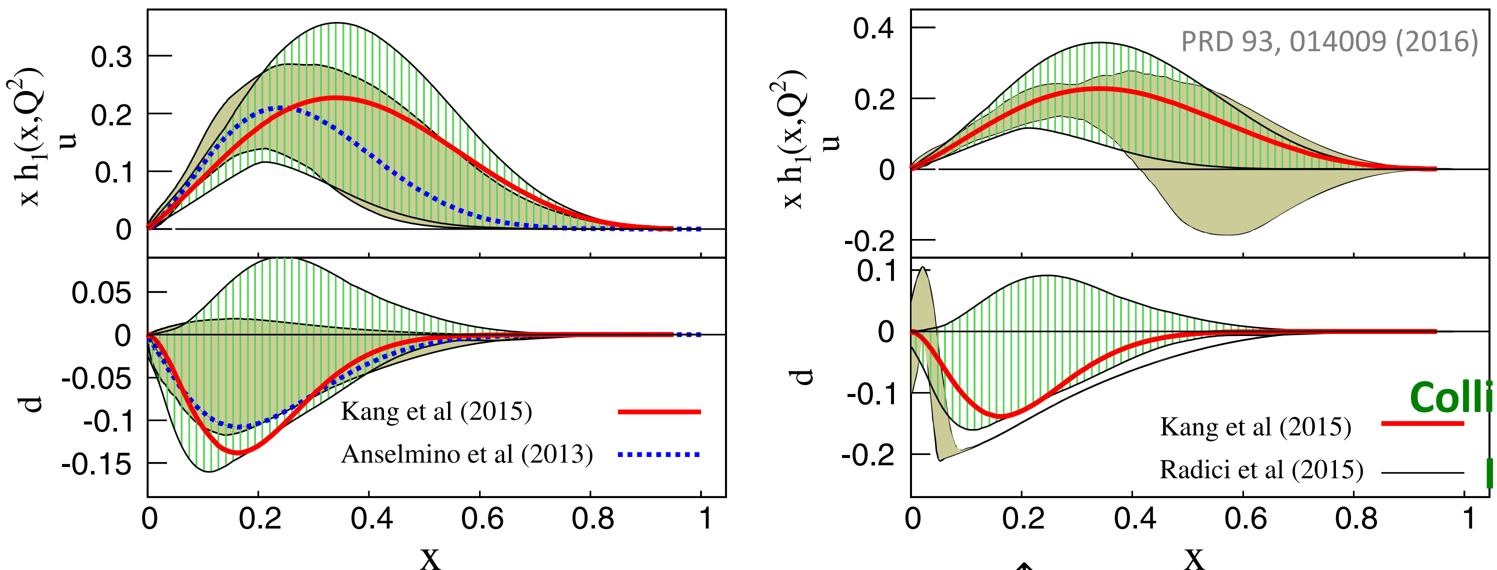

Collins from SIDIS

IFF from SIDIS

(***Preliminary update at this conference!***)

Opportunities with $p^{\uparrow}+p$:

Expanded kinematics! Eliminate u-dominance!

The Fertile Field of Spin Physics

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

- Helicity
- Transversity
- Higher dimensions

Non-collinear probes, e.g. TMDs, enable multidimensional imaging

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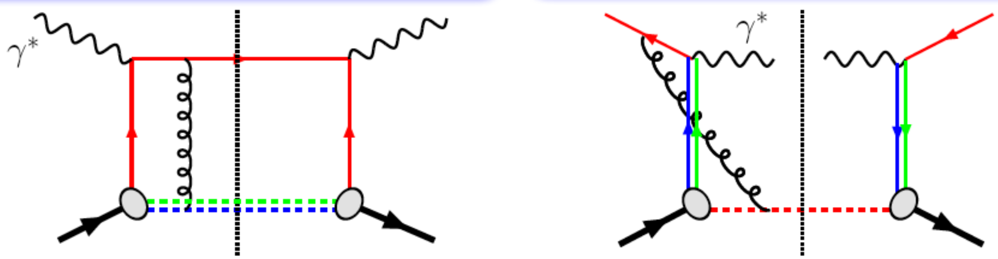
QCD:

DIS:
Final-state interaction

Drell-Yan or W:
Initial-state interaction

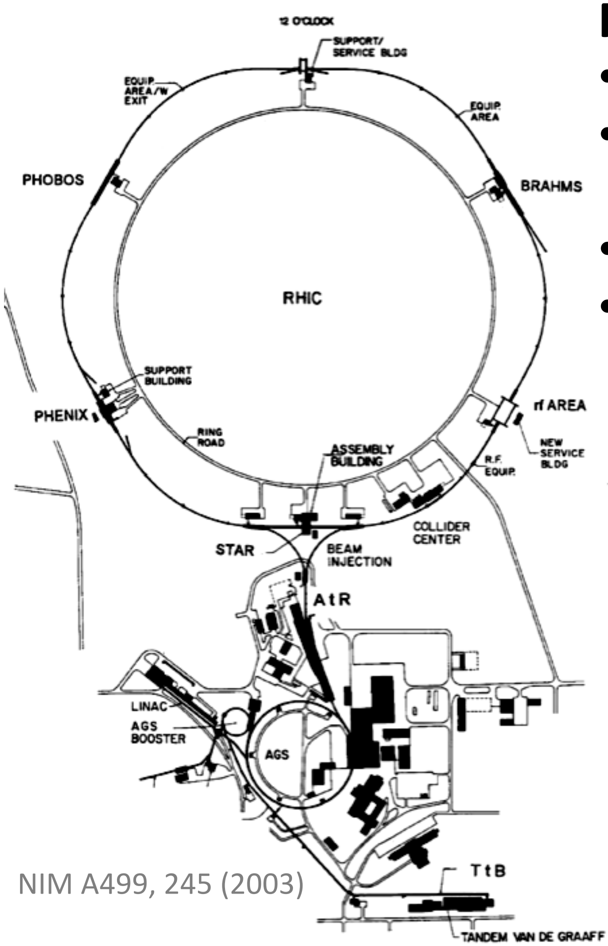


$$\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{Drell-Yan}} \text{ or } \text{Sivers}_{\text{W}}$$

Opportunities with $p^{\uparrow} + p$**:**

Tests of Evolution? Factorization and Universality?

Relativistic Heavy Ion Collider

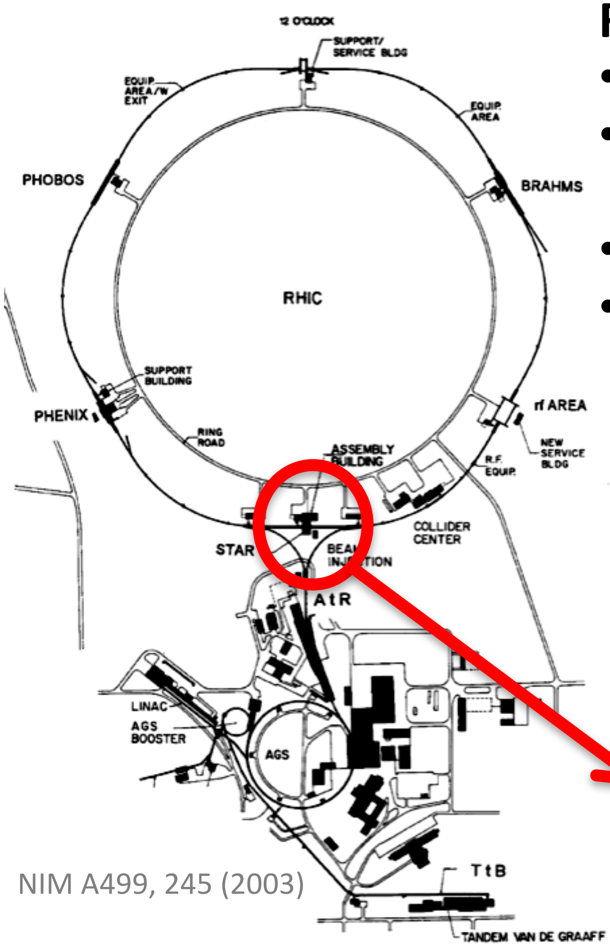


NIM A499, 245 (2003)

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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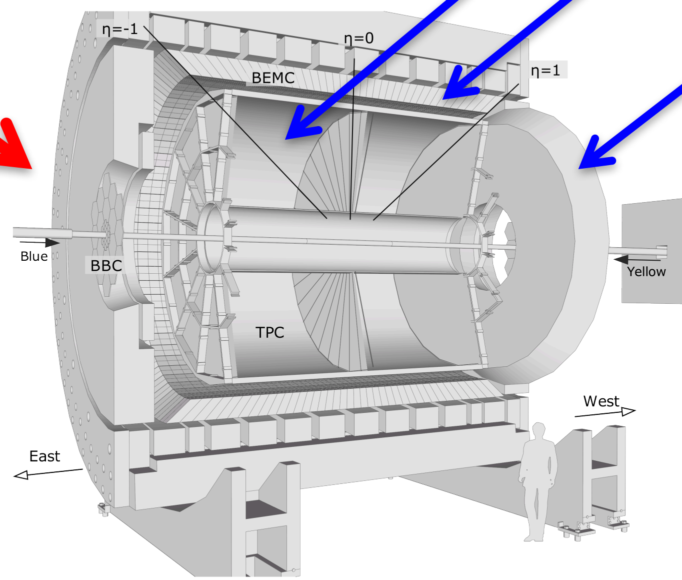
Jets, di-hadrons, weak bosons

TPC + Barrel + Endcap EMC



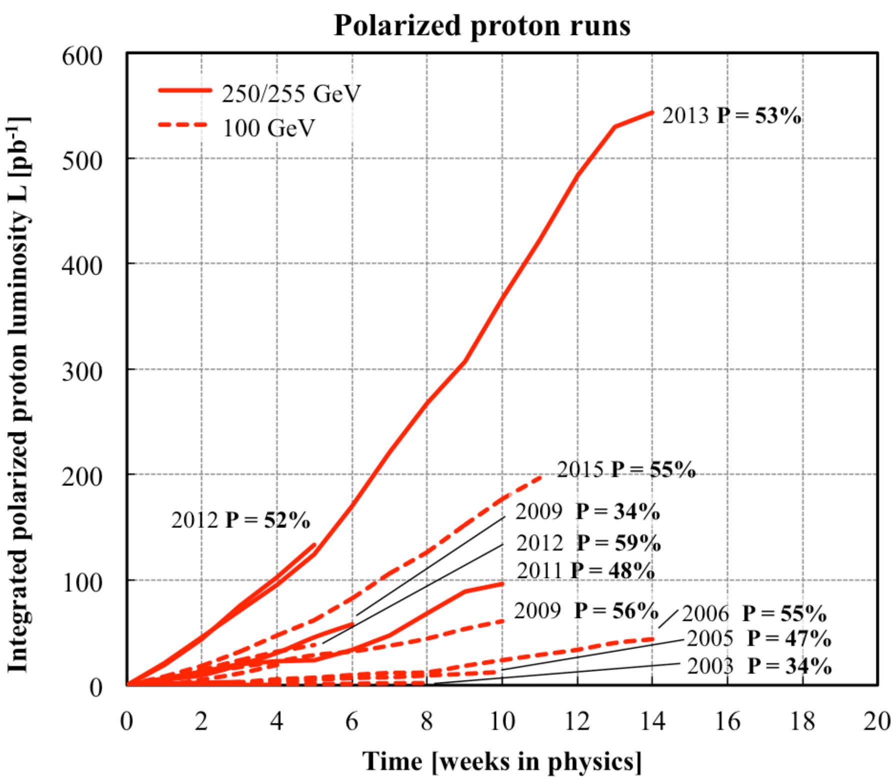
π^0, photons, jet-like measurements

FMS

Trigger on calorimeter energy

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 $|z_{vtx}| < 40$ cm

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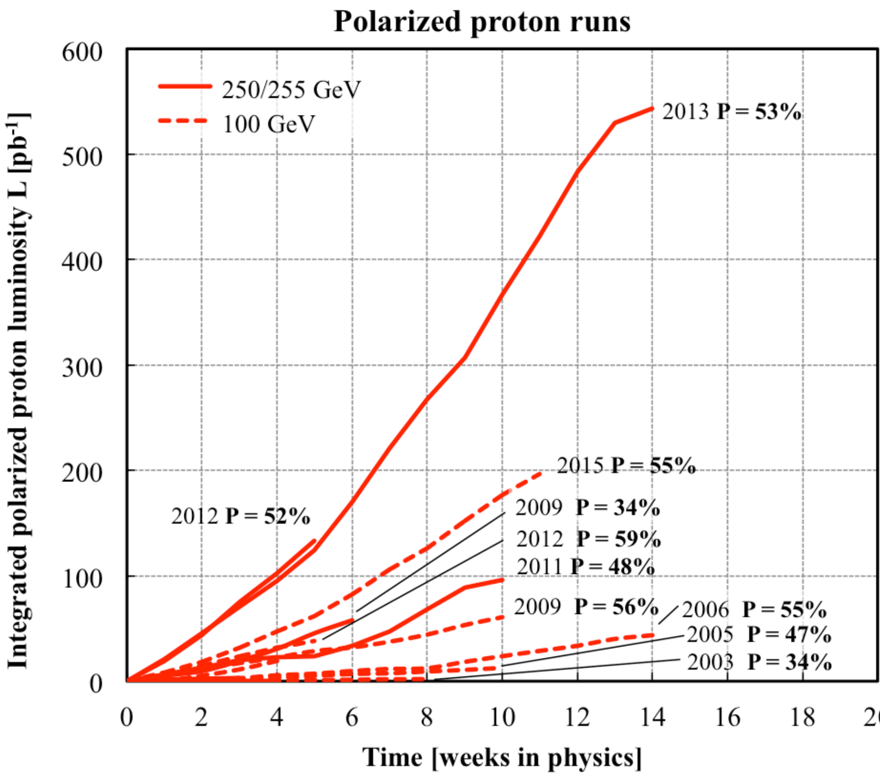

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PHENIX numbers for $|z_{vtx}| < 40$ cm

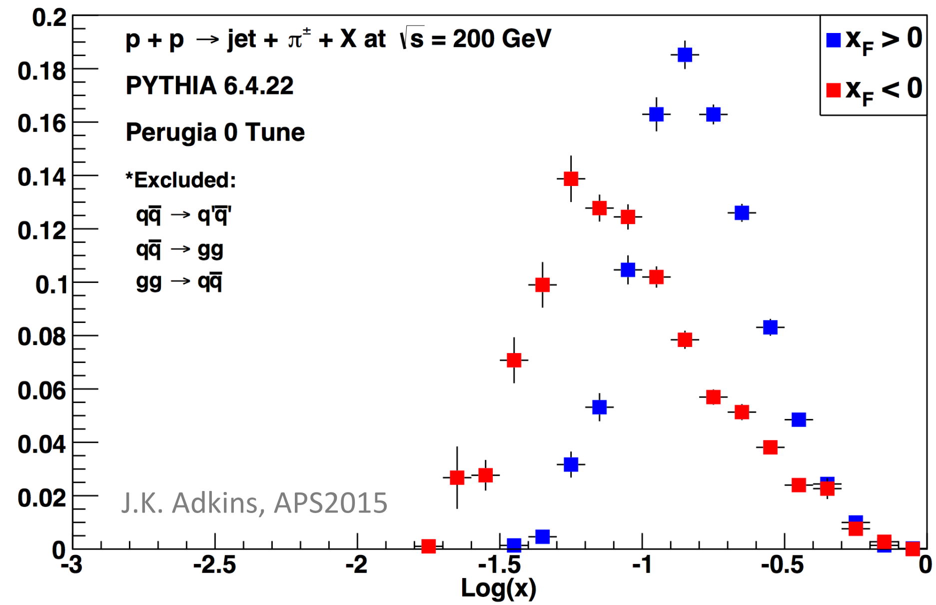
Dramatically increased figure of merit in recent years

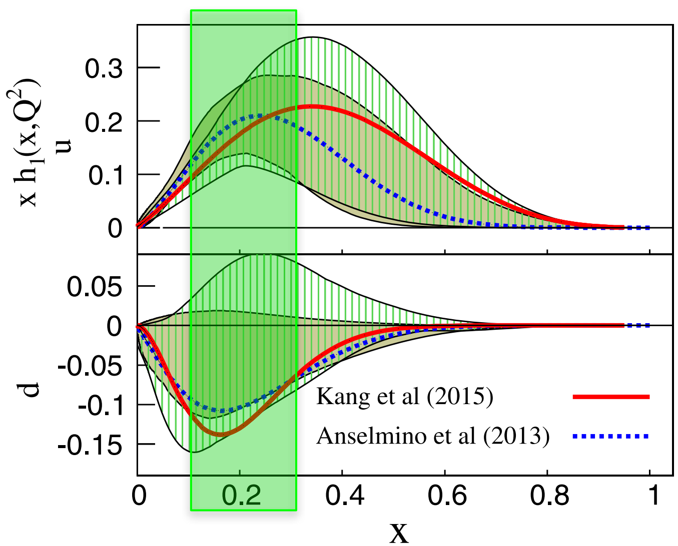
Integrating more 510 GeV data, as we speak!

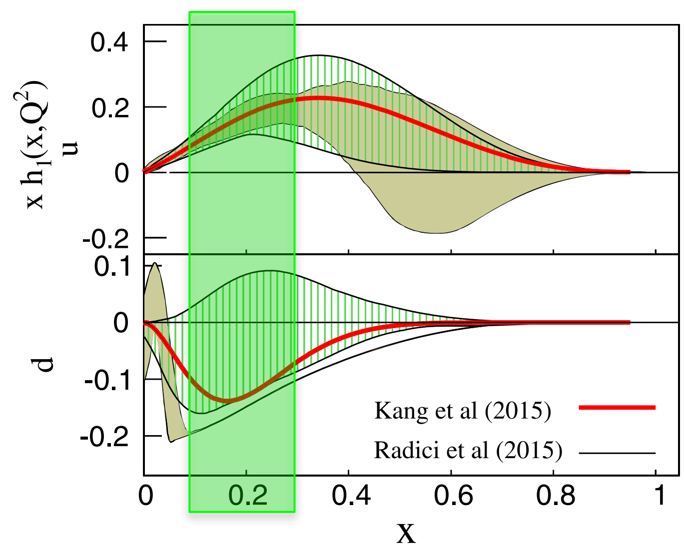
Sensitivity to Transversity at STAR

Access to transversity in interesting region!

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







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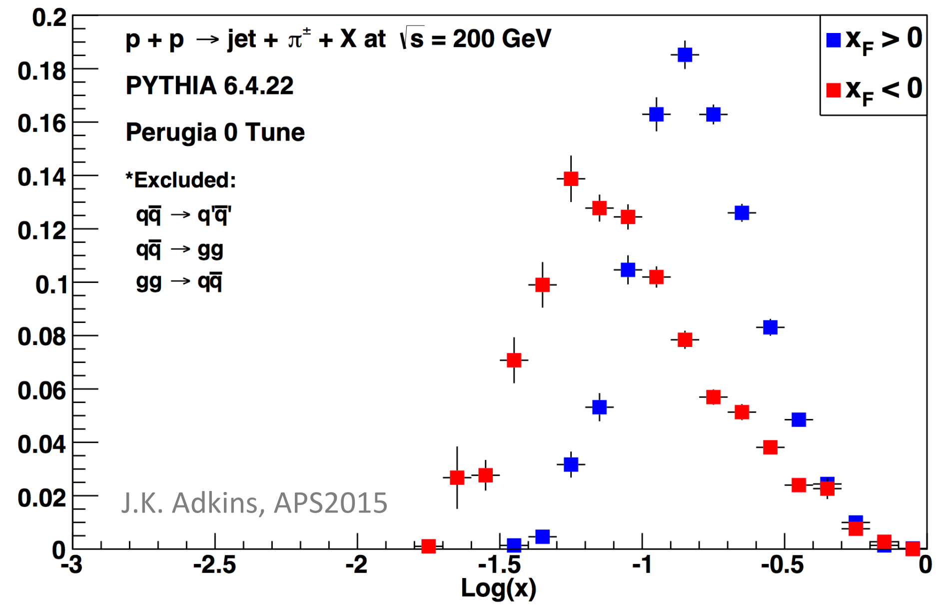
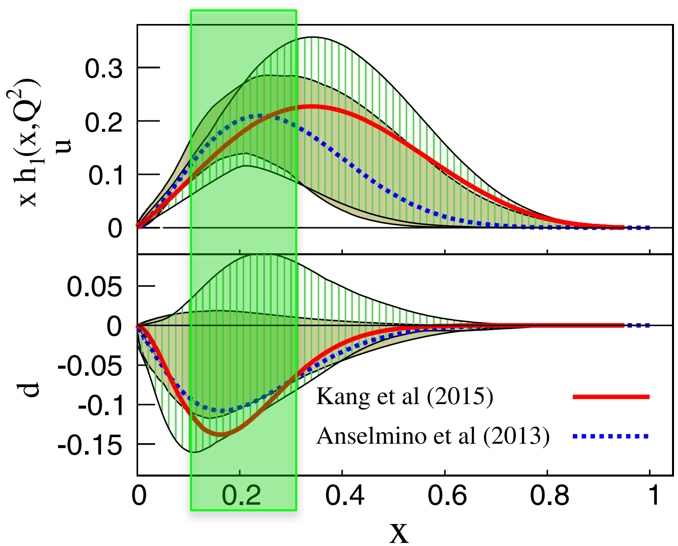
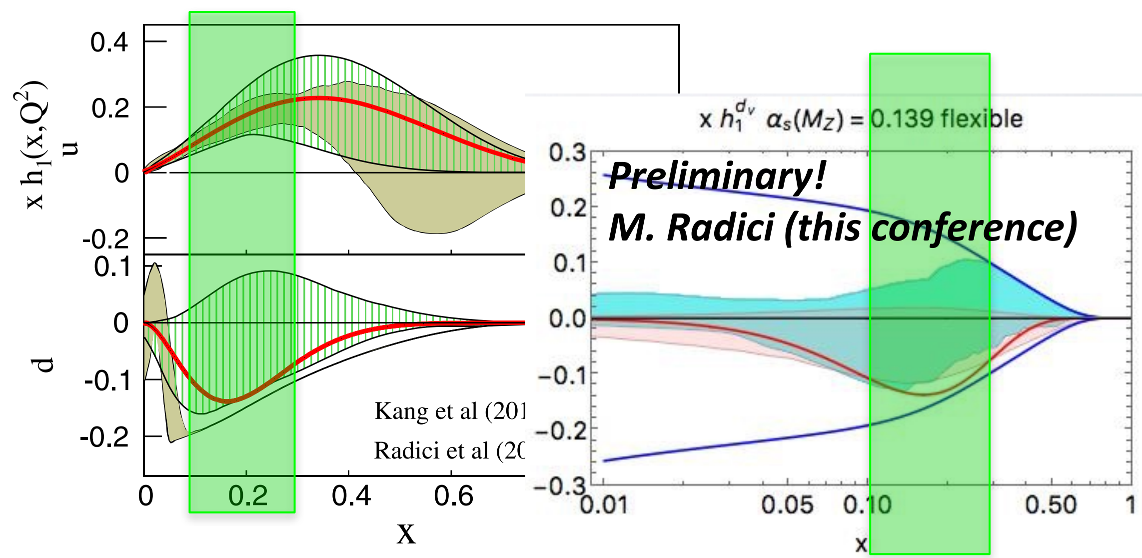




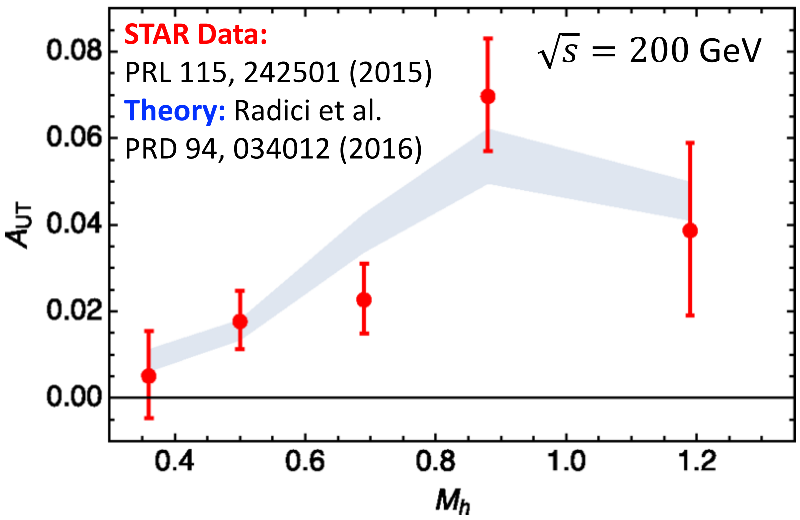


Comparison of Early STAR Data to Theory

A clear message from early results:

Access to transversity effects at RHIC

A_{UT} in $\pi^+\pi^-$ IFF



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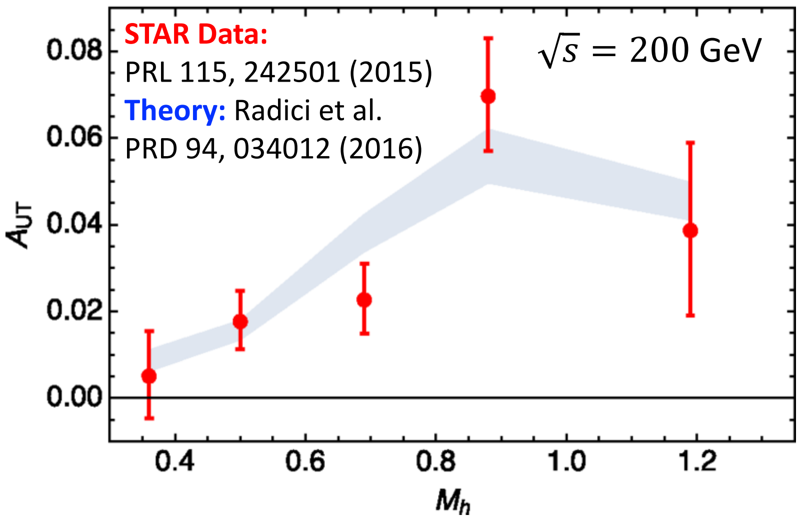

Overall ***agreement*** in terms of ***invariant mass***

→ ***Same mechanism as in SIDIS!***

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

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

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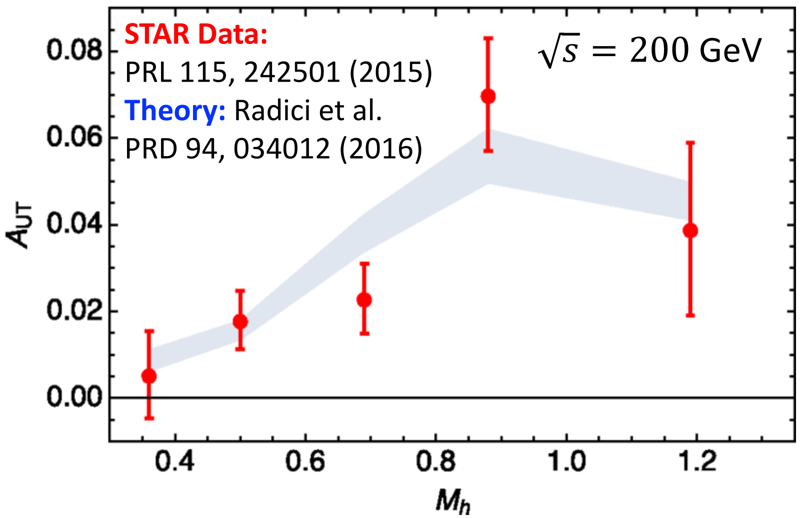

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Deviation at more ***forward*** scattering

→ ***Tension with SIDIS?***

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

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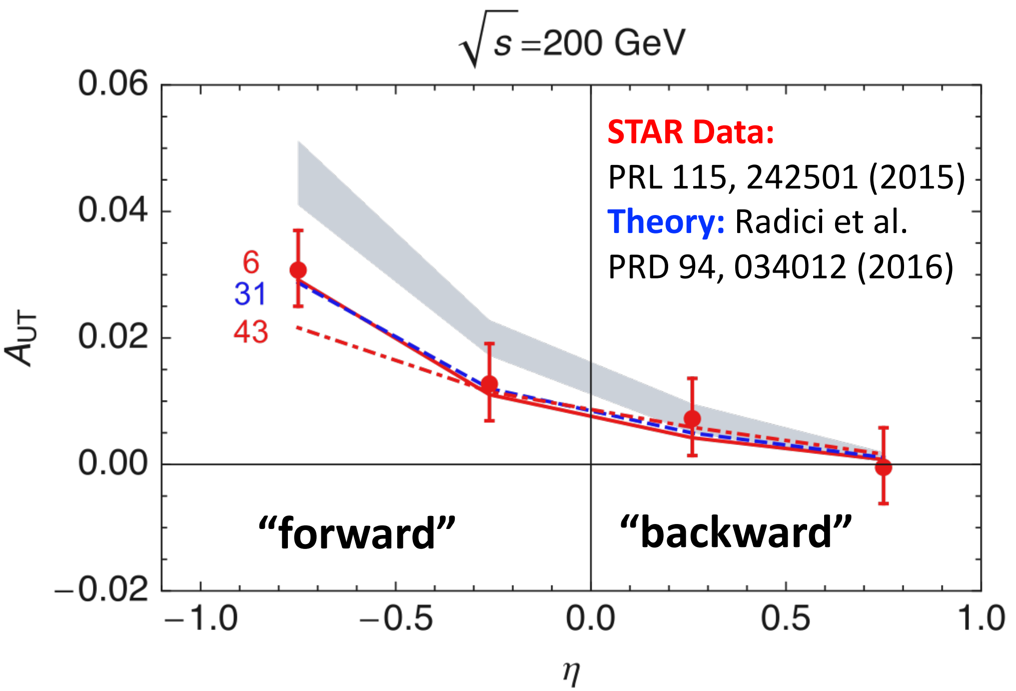
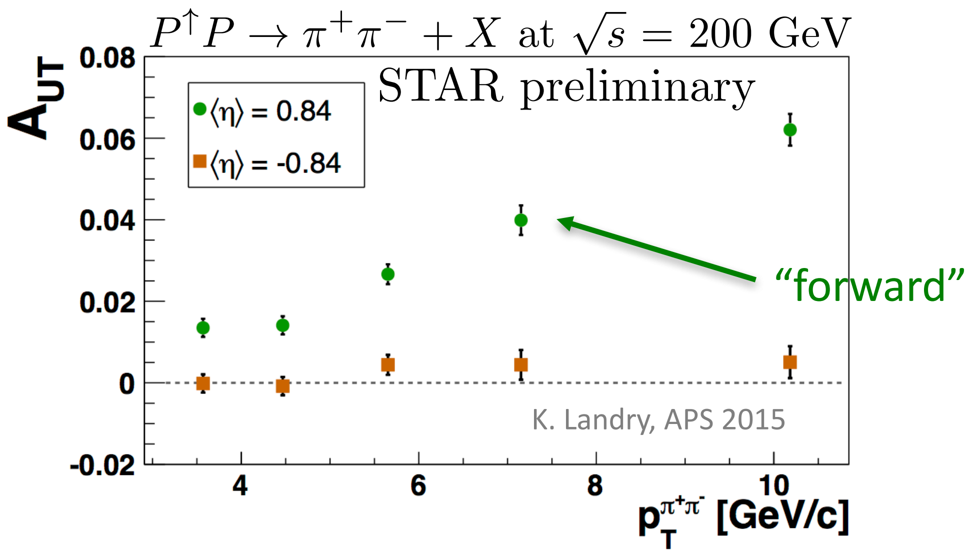


Recent IFF Results at STAR

Much larger datasets collected at 500 and 200 GeV in 2011 and 2012



Significant non-zero di-hadron asymmetries at $\sqrt{s} = 200$ **and** 500 ***GeV!***

- Increasing with pion p_T

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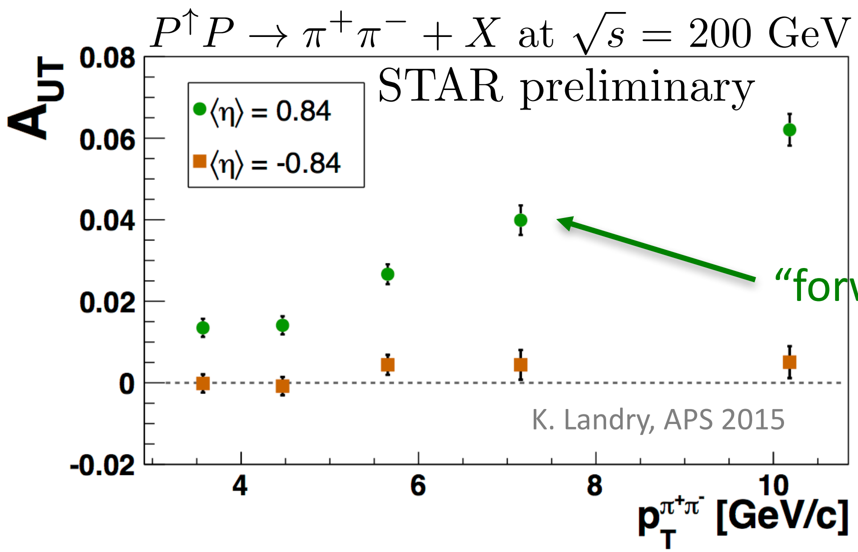
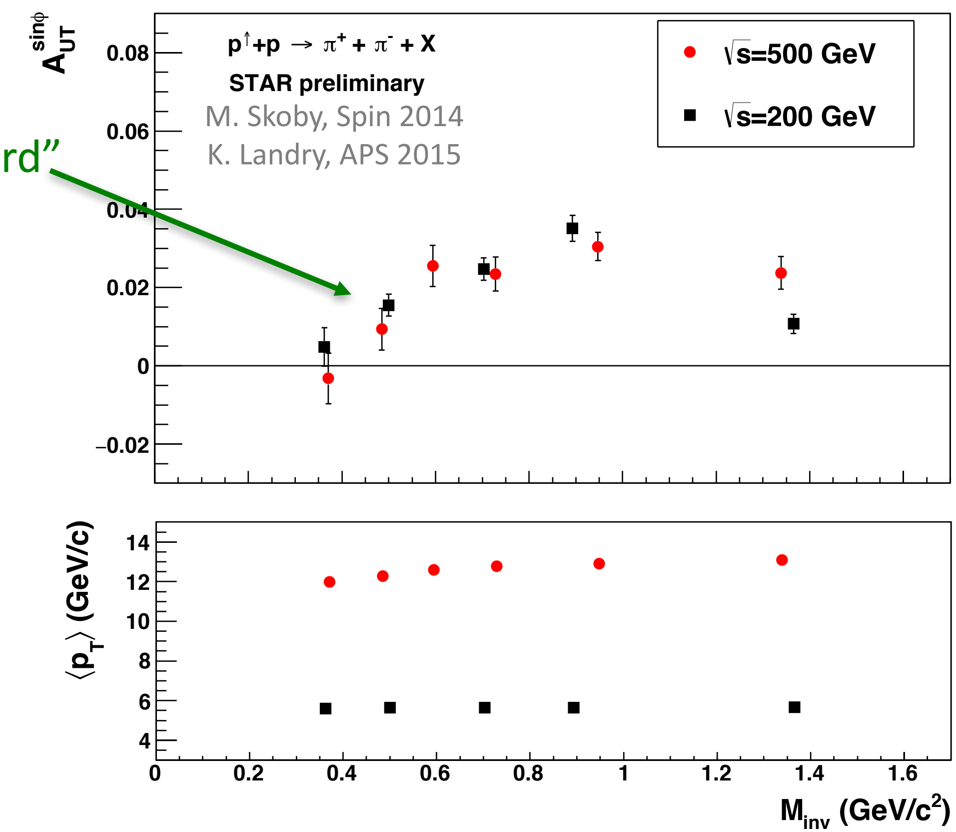


"forward"

Consistent behavior when scaled for $2\langle p_T\rangle/\sqrt{s}$



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

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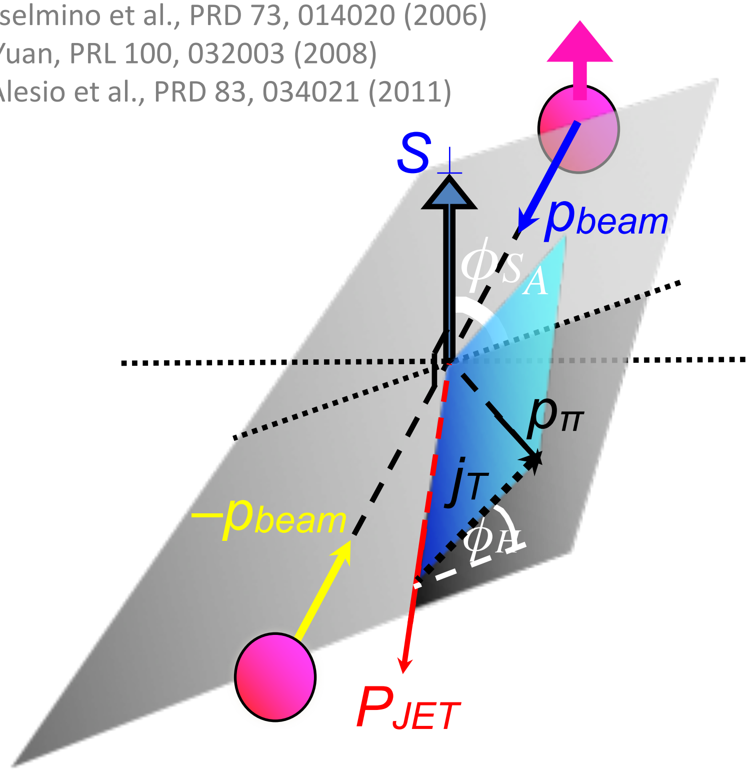
F. Yuan, PRL 100, 032003 (2008)
D'Alesio et al., PRD 83, 034021 (2011)



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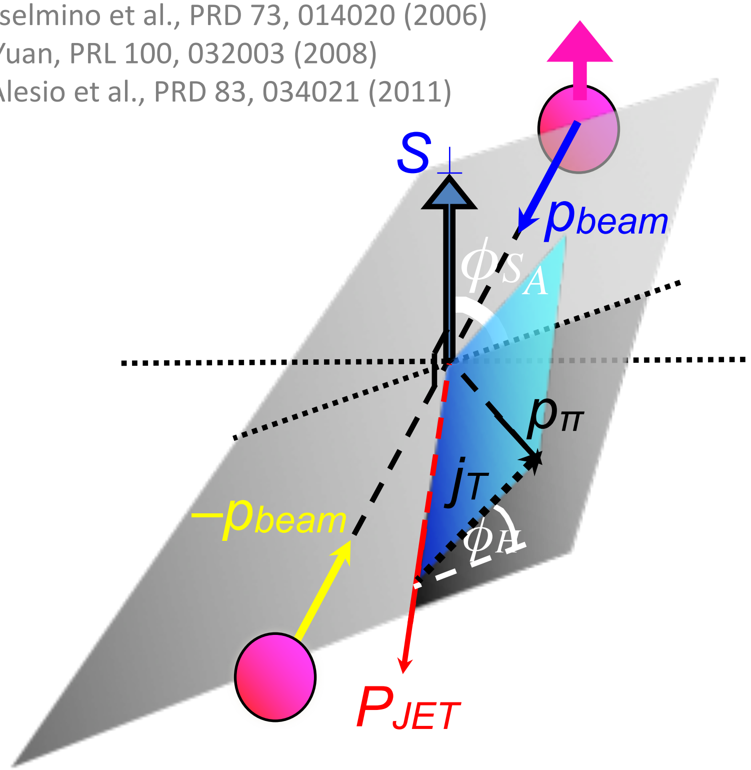

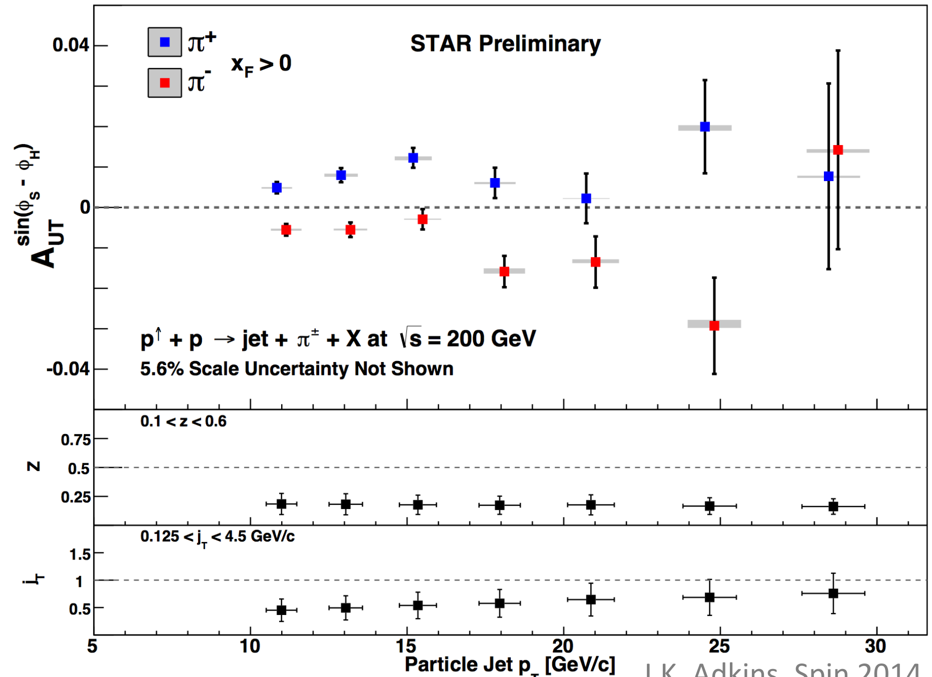

J.K. Adkins, Spin 2014

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

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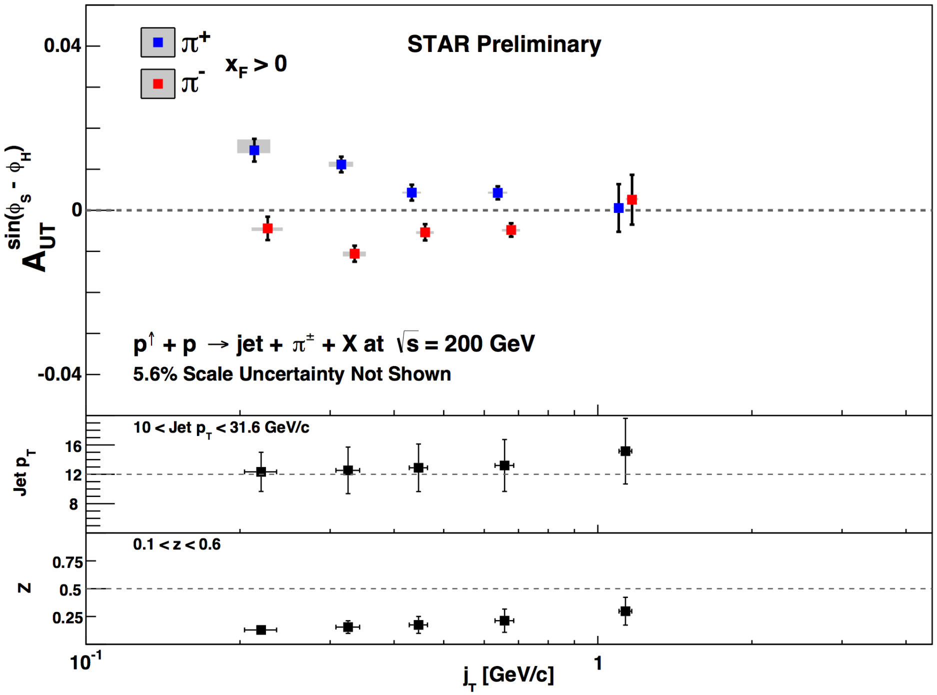

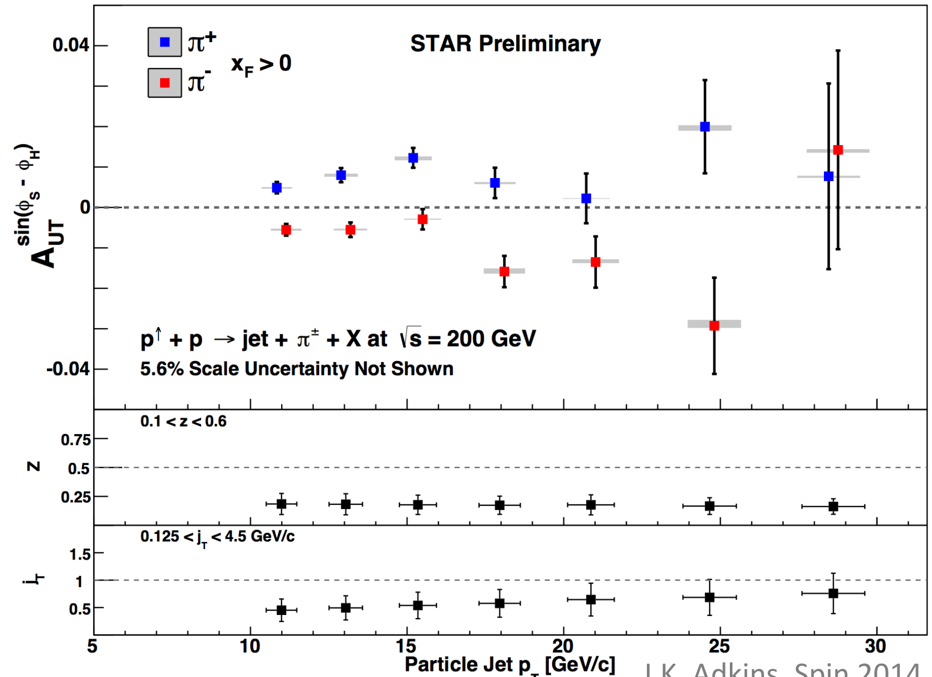

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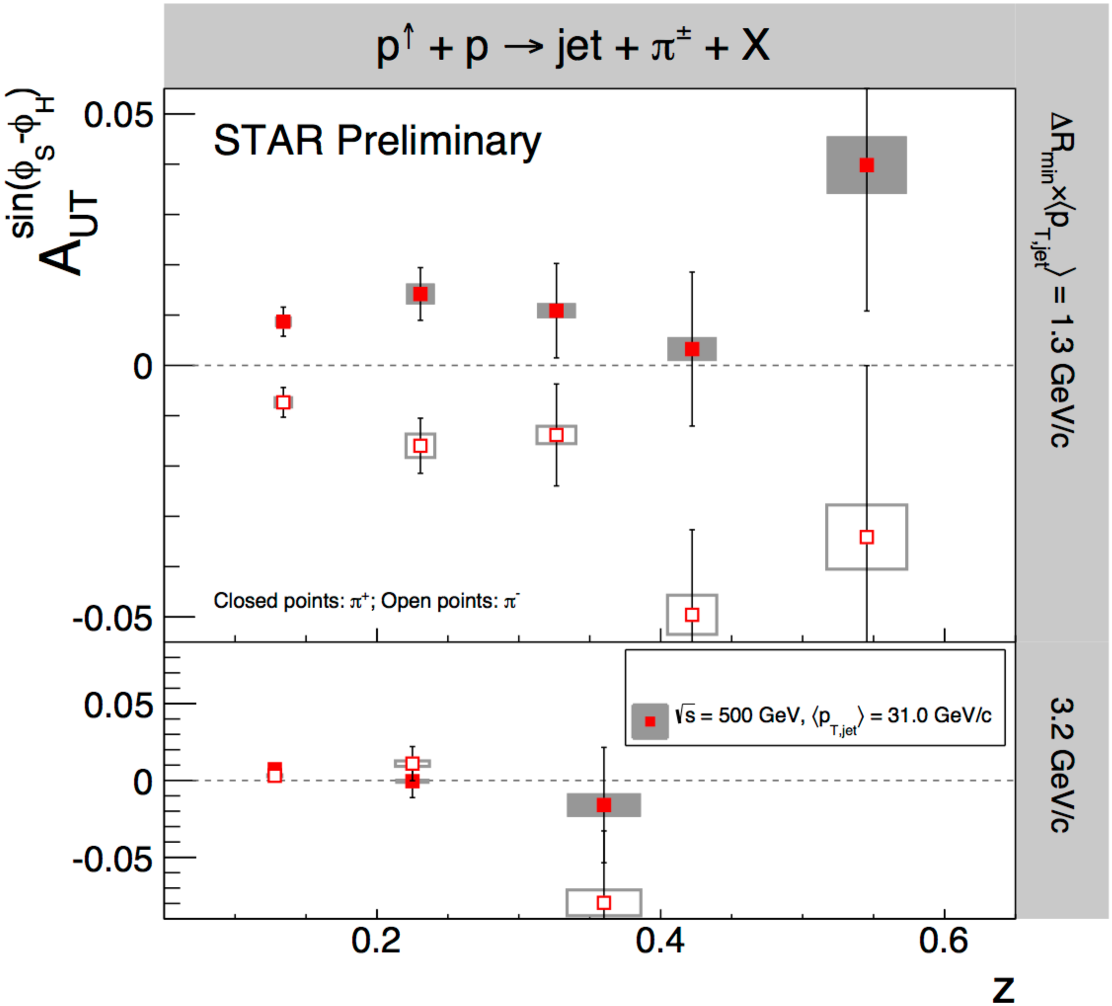
STRONG dependence upon j_T

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

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

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

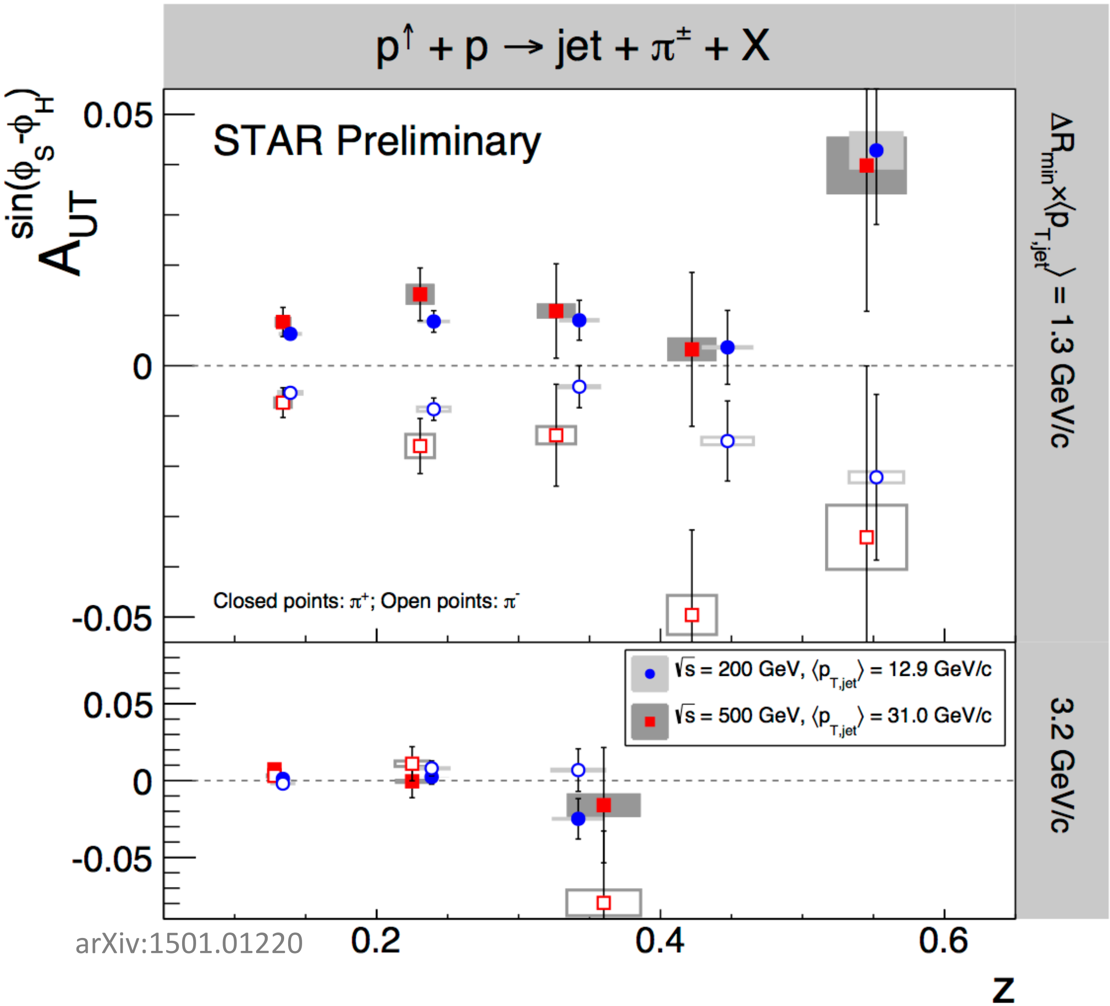
STAR Collins Results at $\sqrt{s} = 500$ GeV



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

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

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



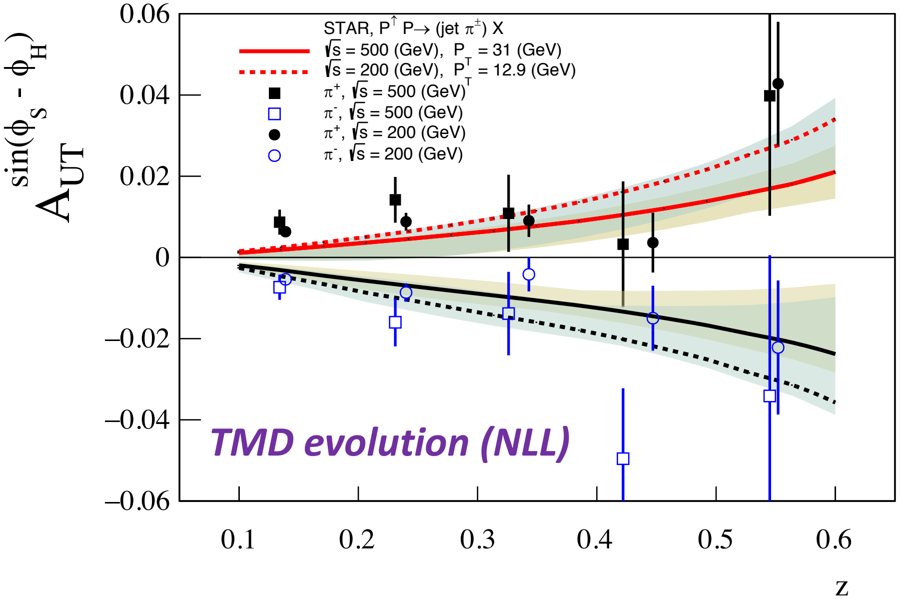
arXiv:1501.01220

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

- 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 $\sqrt{s} = 200$ and 500 GeV

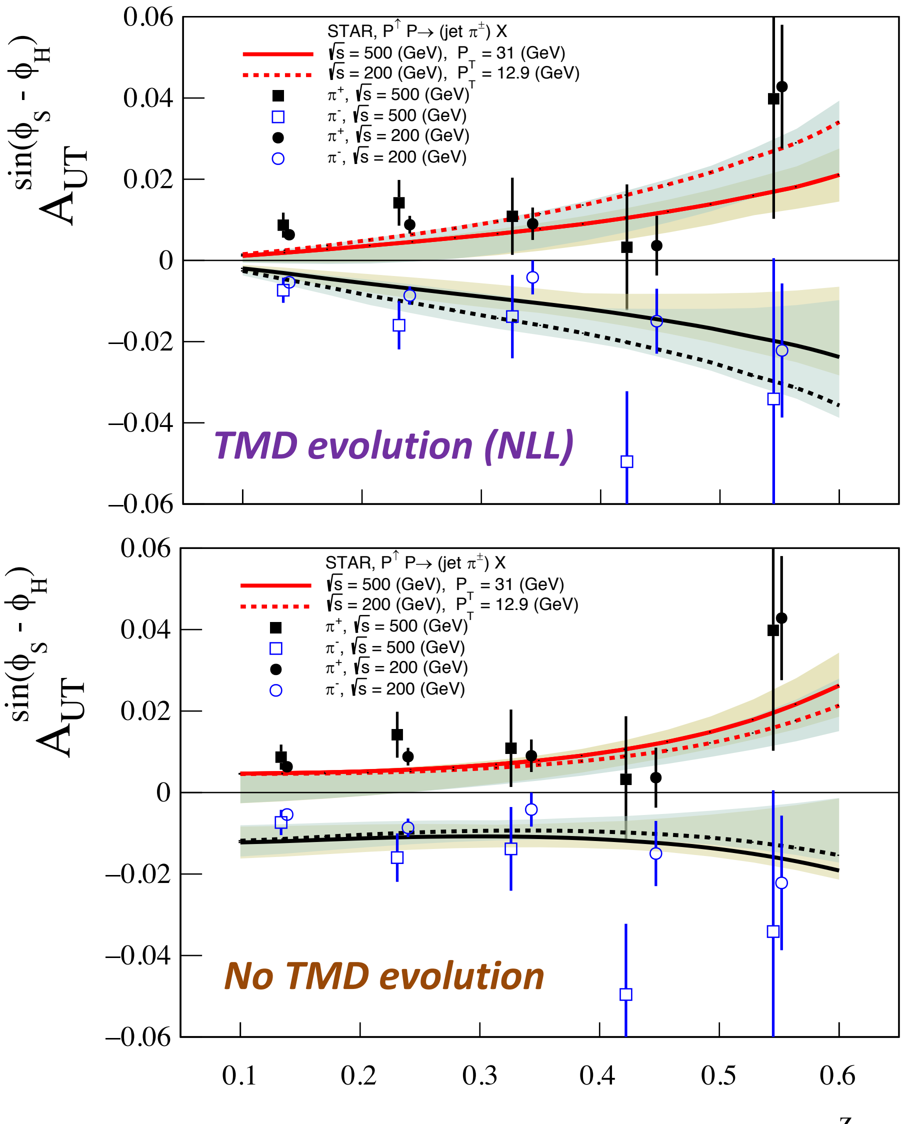


Compare with models based on SIDIS/e^+e^-

- Assume ***universality*** and ***robust factorization***
- ***One model with TMD evolution up to NLL***

Theory: **Kang, Prokudin, Ringer, Yuan 2017 in preparation**
Data: ***STAR Preliminary***

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



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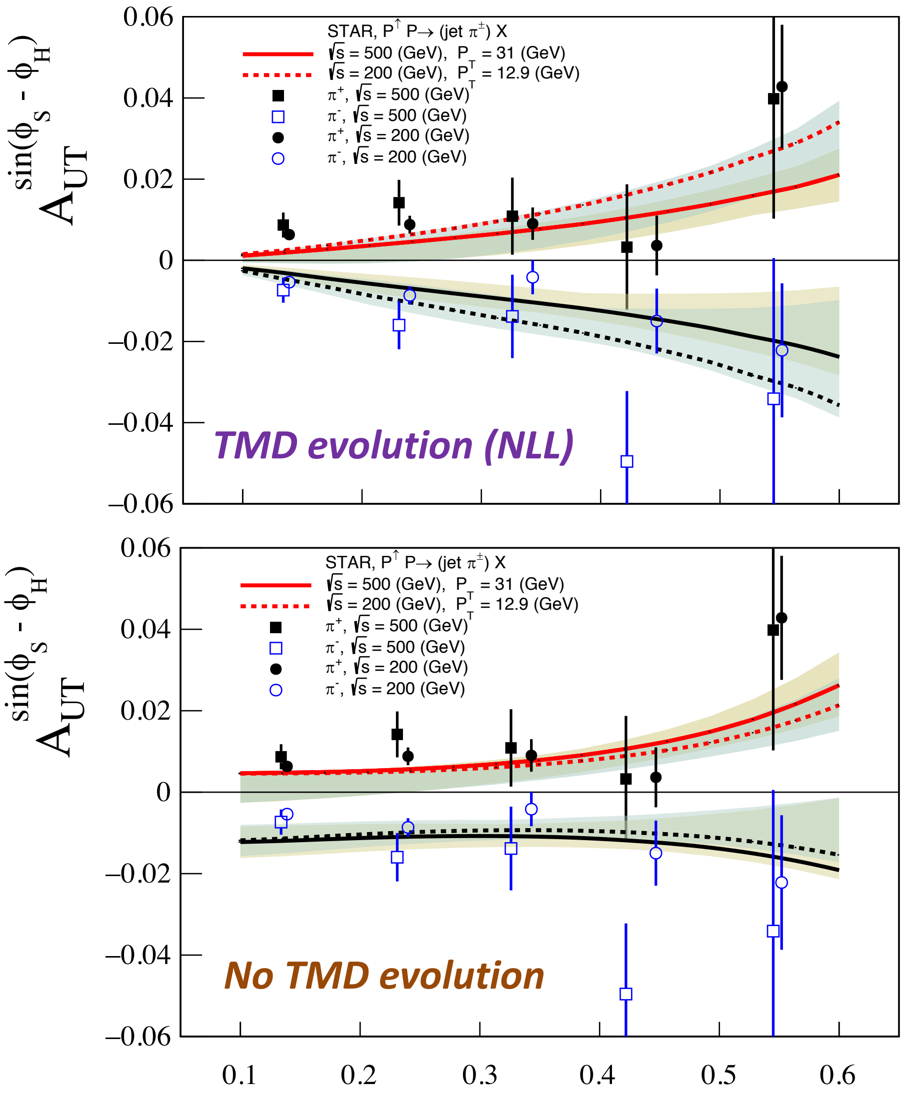

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Compare with models based on SIDIS/e^+e^-

- Assume ***universality*** and ***robust factorization***
- ***One model with TMD evolution up to NLL***
- ***One model without TMD evolution***

Generally decent agreement between models and STAR data!

Slight preference for no evolution?

"Beauty is in the eye of the beholder!"

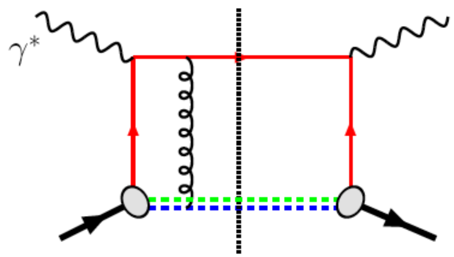
Weak Boson Asymmetries at $\sqrt{s} = 500$ GeV

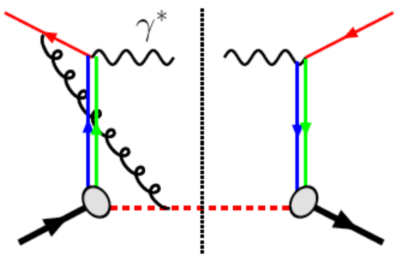
Color interactions in QCD

Non-universality of the "Sivers" function

QCD:

DIS: Final-state interaction	**Drell-Yan or W:** Initial-state interaction





$\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{Drell-Yan}}$ or Sivers_{W}

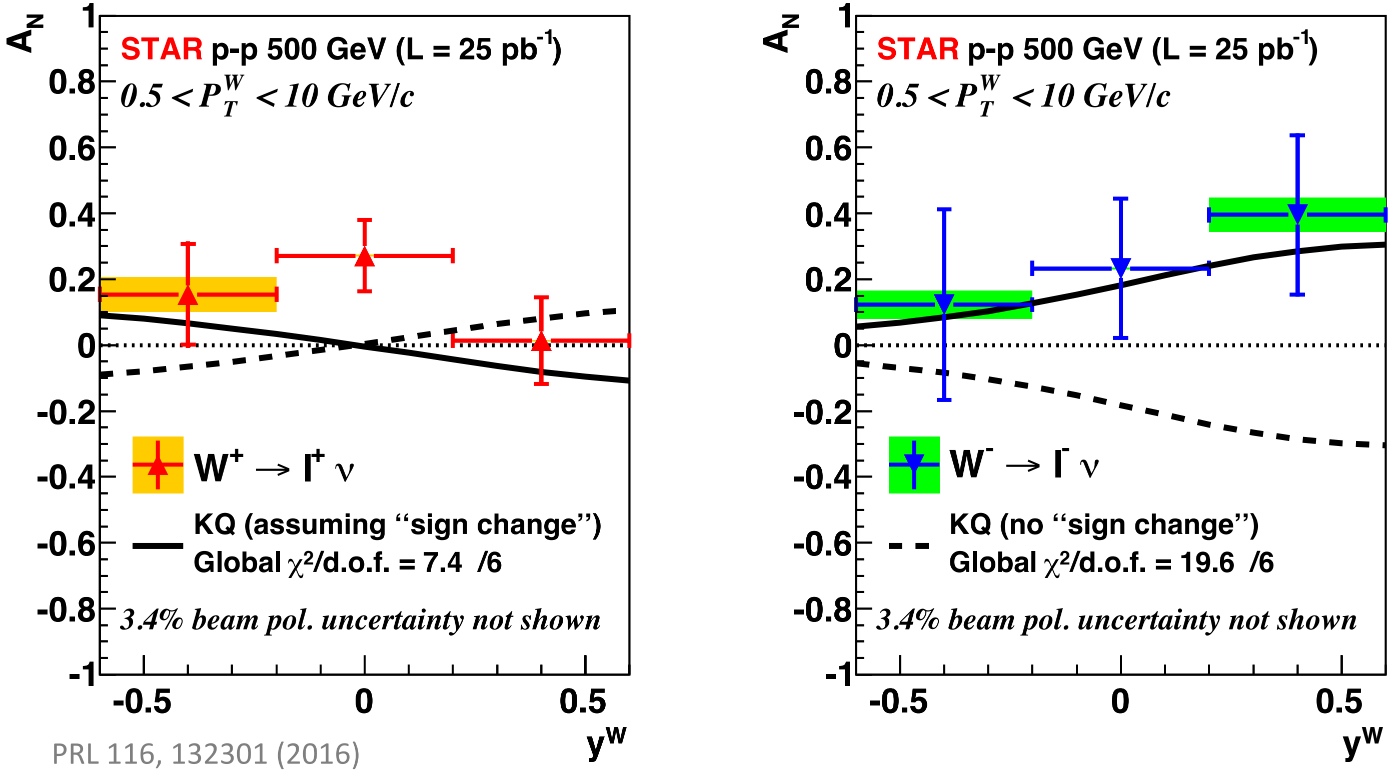
A_N **for direct photon also has a closely related sign change**

Opportunity to see the repulsive interaction between like color charges for the first time!

Can explore all of these observables in 500 GeV $p + p$ collisions at RHIC!

Weak Boson Asymmetries at $\sqrt{s} = 500$ GeV

Exploratory Measurement from a small dataset



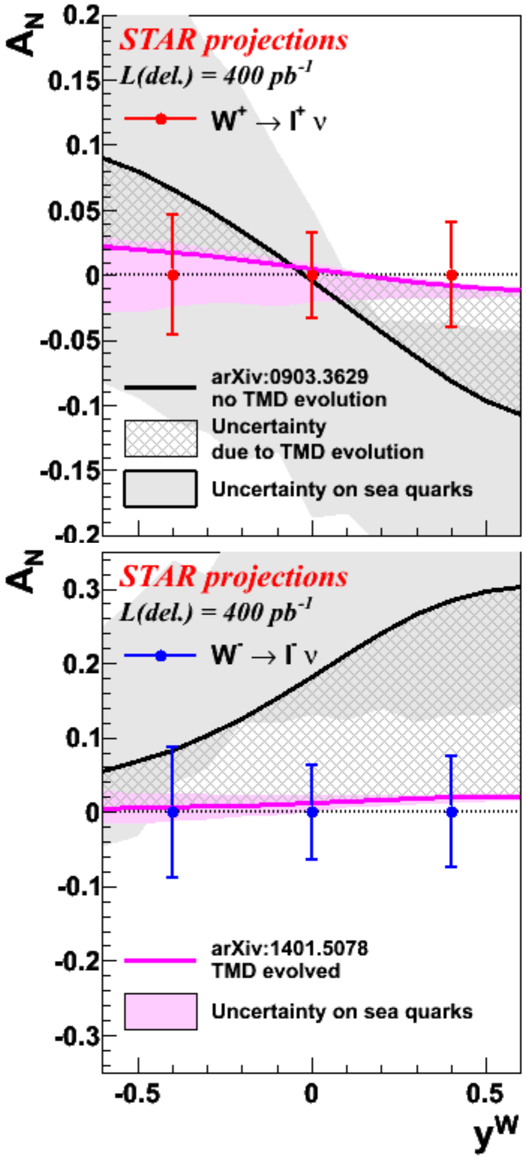
PRL 116, 132301 (2016)

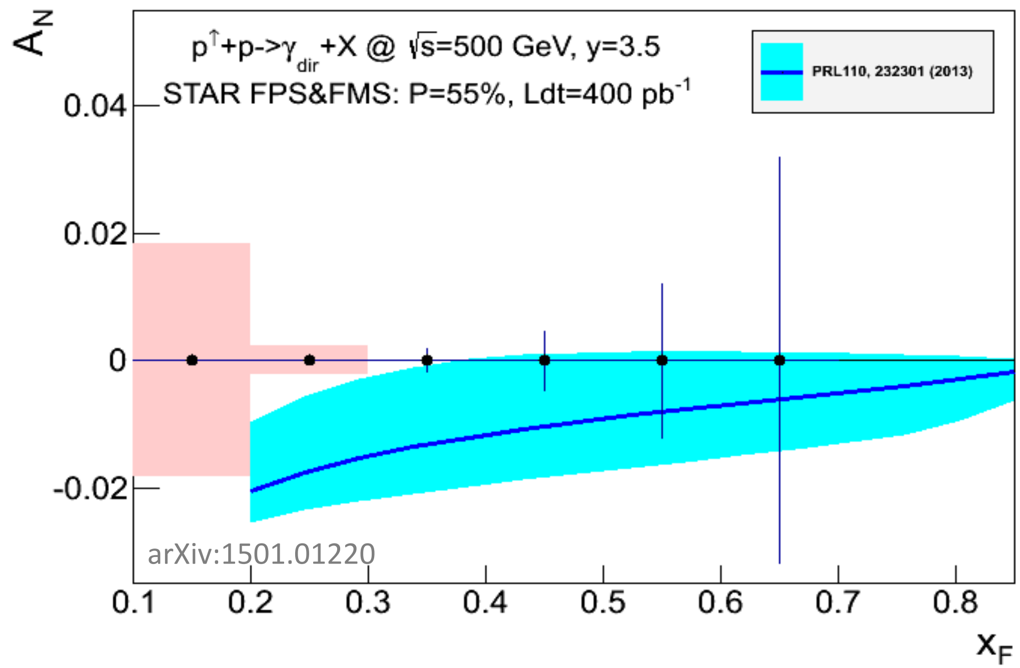
First Measurement of A_N for Weak Bosons!

Global fit to the (unevolved) KQ prediction:

- **solid line:** assume Sivers <u>sign change</u>: $\chi^2/\nu = 7.4/6$
- **dashed line:** assume <u>no sign change</u>: $\chi^2/\nu = 19.6/6$

The Near-term Future: Sivers Sign-change+Evolution





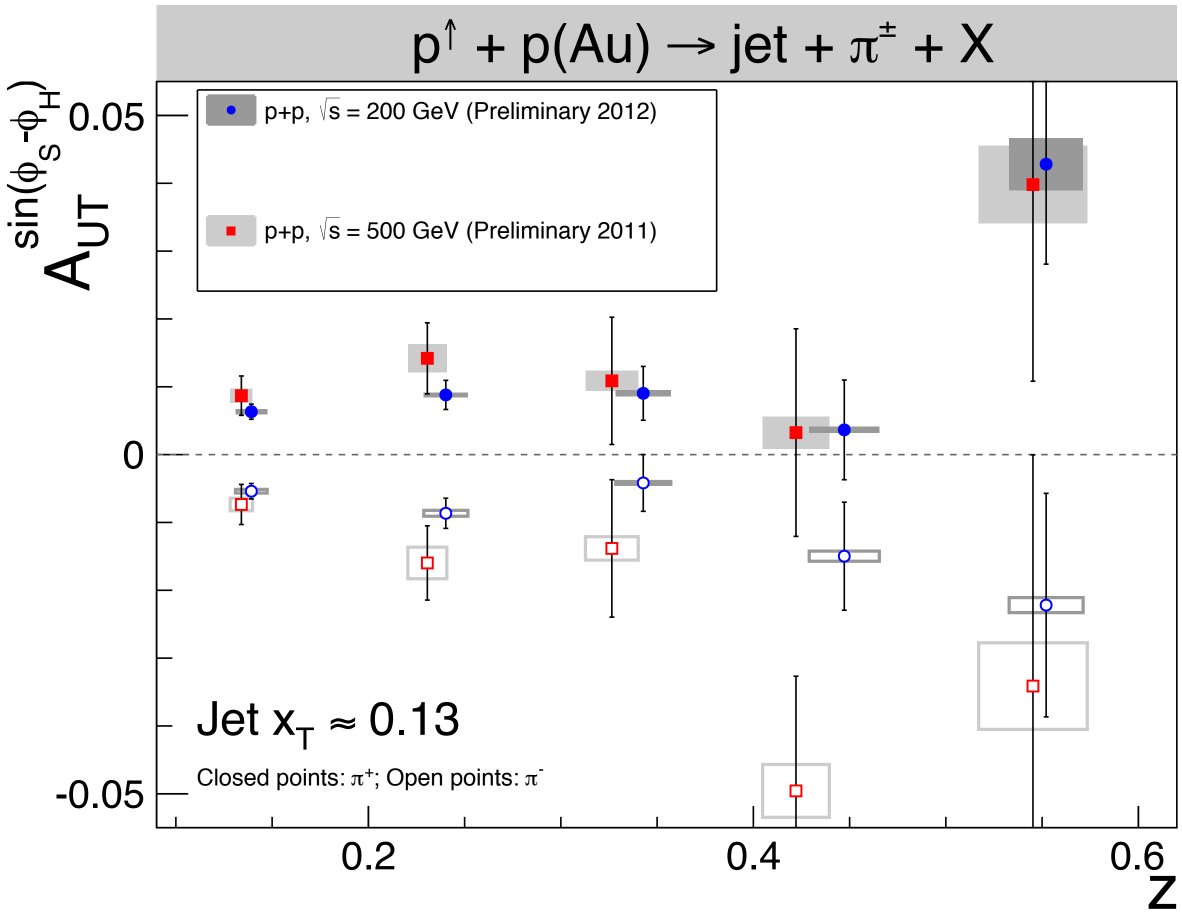
STAR currently taking data at $\sqrt{s} = 510$ GeV!

$W^{\pm}$ A_N can be sensitive to Sivers sign-change if TMD-evolution suppression factor ~ 5 or less

Evaluate sign-change+evolution through $W^{\pm}/Z$, forward direct-γ (twist-3), and forward Drell-Yan

Forward direct-γ at 200 GeV already in the bag!

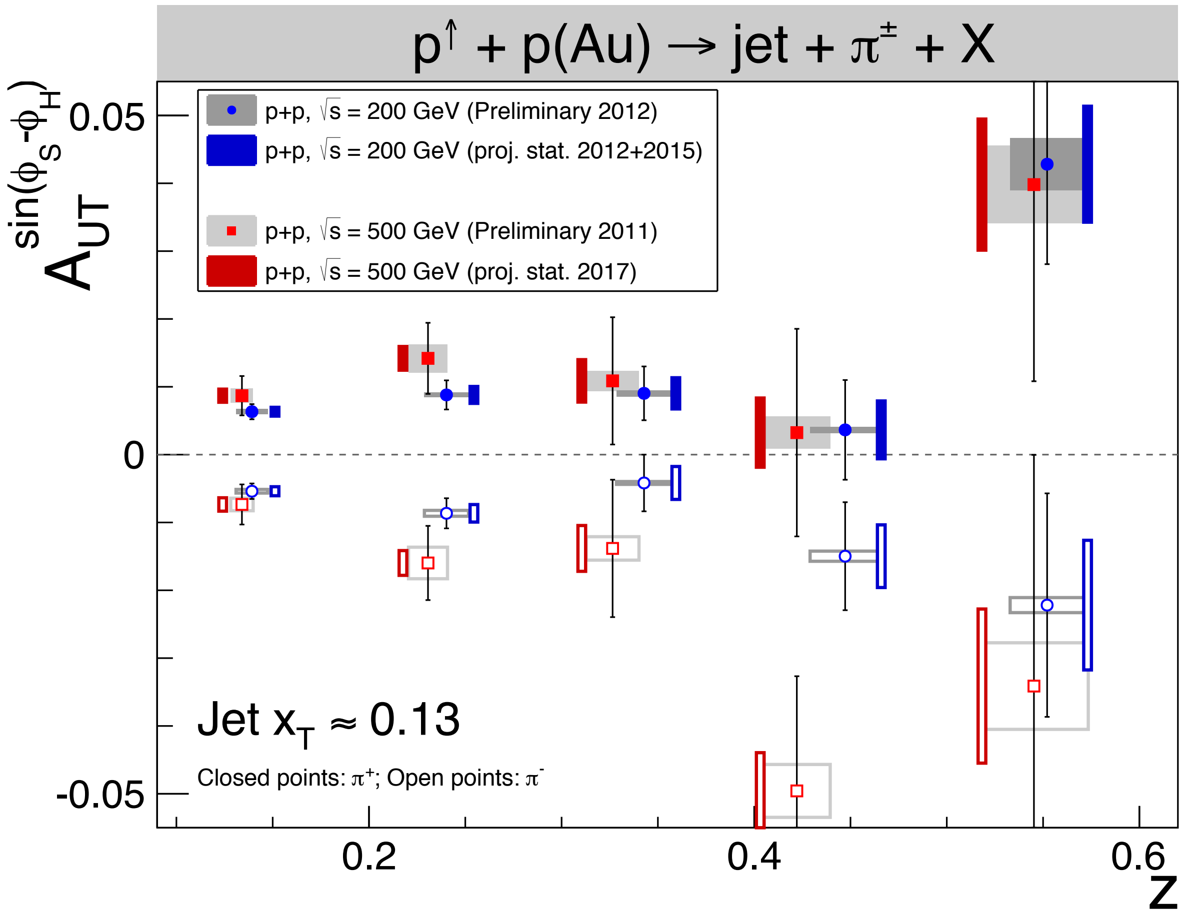
The Near-term Future: Collins Evolution



Preliminary 2011 and 2012 Collins asymmetries suggest x_T scaling

Implications for TMD evolution?

The Near-term Future: Collins Evolution



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

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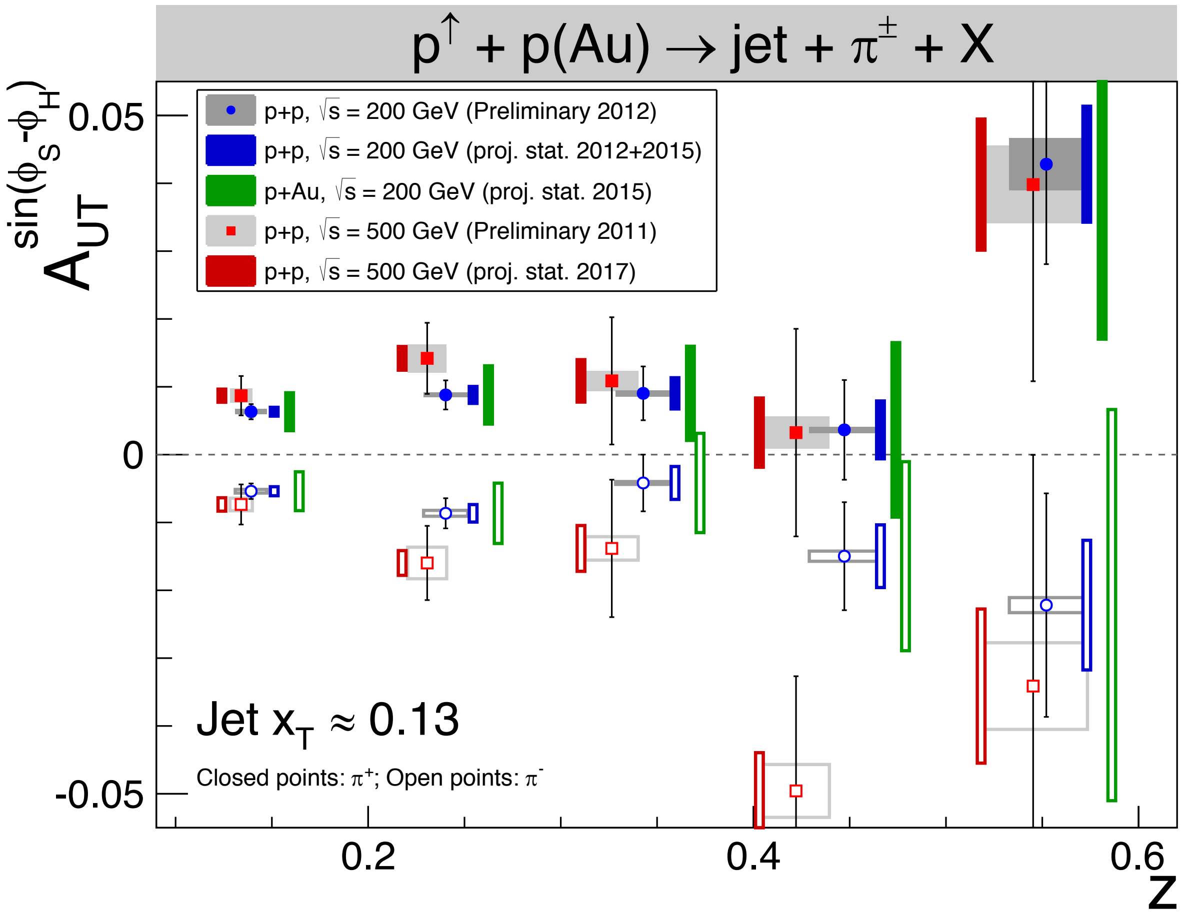
The Near-term Future: $p + A$ Collins



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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?

Summary

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

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- **Recent STAR measurements shed light on new opportunities**
  - First observations of transversity in polarized $p + p$
  - Possible x_T scaling for Collins and IFF asymmetries
  - First investigation of Sivers effect in weak boson production

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  - Possible x_T scaling for Collins and IFF asymmetries
  - First investigation of Sivers effect in weak boson production
- **Recent and near-future runs offer even more potential**
  - Investigation of Sivers/twist-3 in W, γ, and Drell-Yan
  - Substantially increased precision for Collins and IFF at 200 and 510 GeV
  - First investigation of Collins in $p + A$

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  - Possible x_T scaling for Collins and IFF asymmetries
  - First investigation of Sivers effect in weak boson production
- **Recent and near-future runs offer even more potential**
  - Investigation of Sivers/twist-3 in W, γ, and Drell-Yan
  - Substantially increased precision for Collins and IFF at 200 and 510 GeV
  - First investigation of Collins in $p + A$

Stay tuned for more new results from RHIC transverse spin!

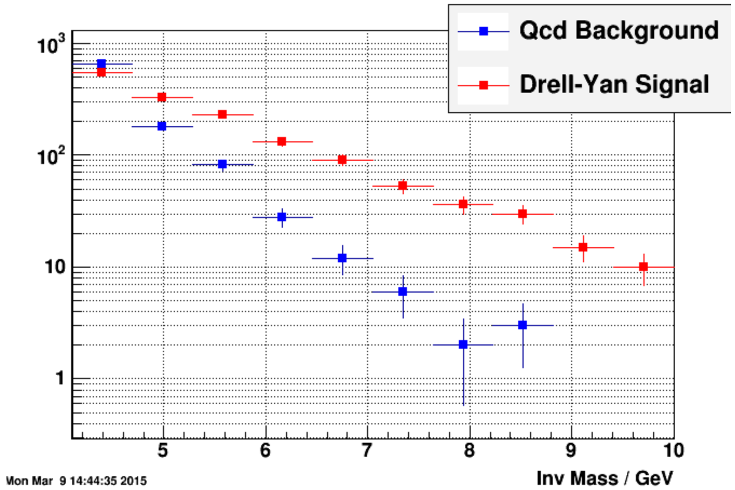
Back-up Slides

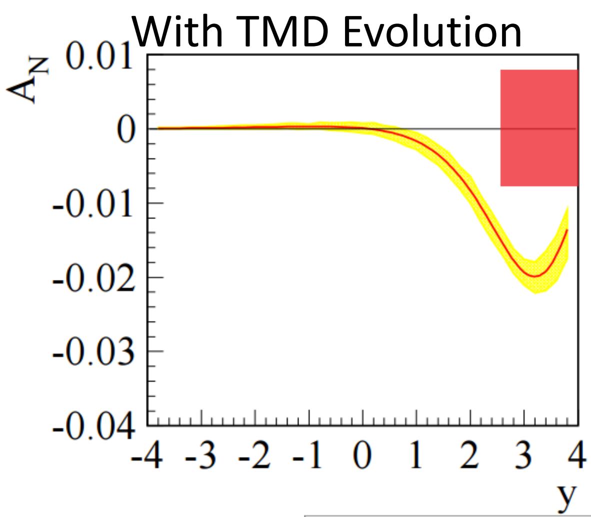
Drell-Yan at STAR For 500 GeV

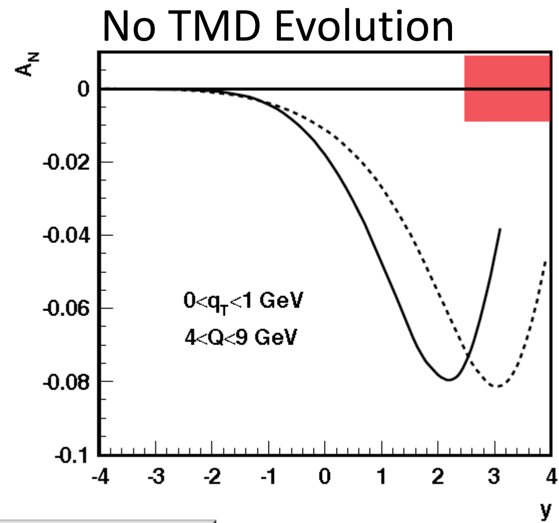
Kinematics:

DY e^+e^- in $2.5 < \eta < 4.0$ $\quad 4.0 < M_{e^+e^-} < 9.0$ GeV$/c^2$

After analysis $2.5 < \eta < 4.0$:



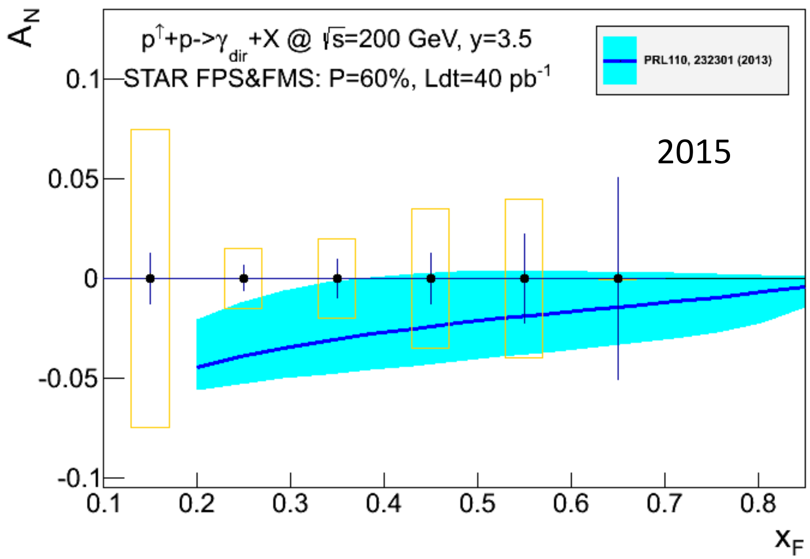


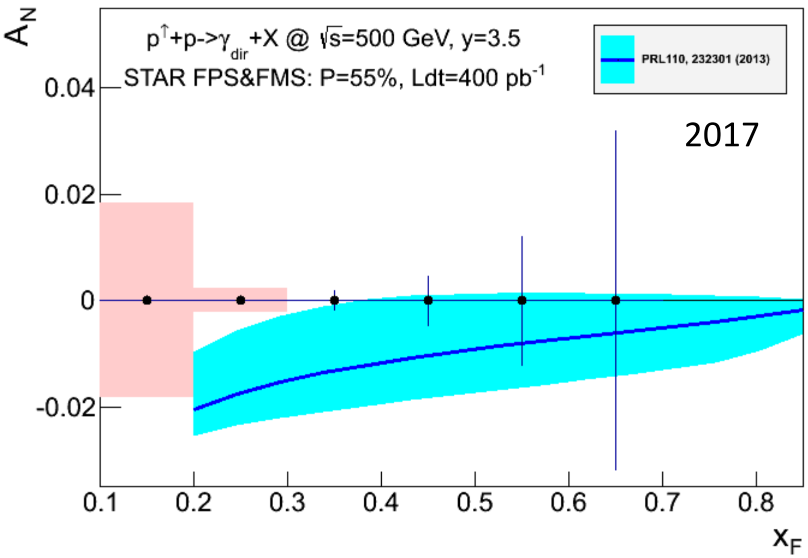


Run-17 $\int L_{\text{del}} = 400$ pb^{-1}
→ A_N for DY to ± 0.008

Assembled by
E.C. Aschenauer

Complementary Channel: A_N direct photon





A_N for direct photon production:

- sensitive to sign change, but in TWIST-3 formalism
- not sensitive to TMD evolution
- no sensitivity to sea-quarks; mainly u_v and d_v at high x
- collinear objects but more complicated evolutions than DGLAP
- indirect constraint on Sivers fct.

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Not a replacement for $A_N(W^{+/-}, Z^0, DY)$ measurement but an important complementary piece in the puzzle

Assembled by E.C. Aschenauer