Illuminating Nucleon Structure Through Polarized Proton-Proton Collisions at STAR

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Lamar University
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OUTLINE
• Introduction
• RHIC and STAR
• Recent Developments
• Near-term Plans
• Summary
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
The Fertile Field of Spin Physics

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

- Helicity

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

**STAR data have played a key role!**

### Gluon Helicity

![Gluon Helicity Diagram](image)

See talks by Q. Xu and B. Surrow

### Sea-quark Helicity

![Sea-quark Helicity Diagram](image)
The study of spin in particle physics has unlocked doors to a deeper understanding of nucleon structure

- Helicity
- Transversity
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

Multiple mechanisms in play to constrain transverse spin-structure

Collins from SIDIS

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JFF from SIDIS
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

Opportunities with $p^+ + p$:
Expanded kinematics! Eliminate $u$-dominance!
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
The study of spin in particle physics has unlocked doors to a deeper understanding of nucleon structure:

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

**QCD:**

**DIS:** Final-state interaction

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

Sivers_{DIS} = - Sivers_{Drell-Yan or W}

**Opportunities with** $p^{↑} + p$:

Tests of Evolution? Factorization and Universality?
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
Solenoidal Tracker at RHIC

RHIC as Polarized-proton Collider
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Jets, di-hadrons, weak bosons
TPC + Barrel + Endcap EMC

$\pi^0$, photons, jet-like measurements

Trigger on calorimeter energy
Polarized-proton Datasets at RHIC

Unique opportunities to probe nucleon spin structure!

Transverse Luminosity Recorded

<table>
<thead>
<tr>
<th>Year</th>
<th>√s [GeV]</th>
<th>STAR</th>
<th>PHENIX</th>
<th>⟨P⟩ [%]</th>
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<tbody>
<tr>
<td>2006</td>
<td>200</td>
<td>8.5 pb⁻¹</td>
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PHENIX numbers for |z_{vtx}| < 40 cm
Polarized-proton Datasets at RHIC

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PHENIX numbers for $|z_{	ext{ vtx}}| < 40$ 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!**

**Spin Results at STAR - Drachenberg**
Sensitivity to Transversity at STAR

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- *Insight into nature of Collins mechanism!*

Spin Results at STAR - Drachenberg
A clear message from early results:  
**Access to transversity effects at RHIC**

\[ A_{UT} \text{ in } \pi^+\pi^- \text{ IFF} \]

- **STAR Data:**
  - PRL 115, 242501 (2015)
- **Theory:** Radici et al.
  - PRD 94, 034012 (2016)

\[ \sqrt{s} = 200 \text{ GeV} \]
Comparison of Early STAR Data to Theory

A clear message from early results:
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Compare with models based on SIDIS/\(e^+e^-\)
Band represents 68% of replicas deduced by fitting SIDIS and \(e^+e^-\) data

Overall agreement in terms of invariant mass
\[ \rightarrow \text{ Same mechanism as in SIDIS!} \]
Comparison of Early STAR Data to Theory

A clear message from early results: 
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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

\[ \sqrt{s} = 200 \text{ GeV} \]
Recent IFF Results at STAR

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

$P^+ P \rightarrow \pi^+ \pi^- + X$ at $\sqrt{s} = 200$ GeV

$A_{UT}$

STAR preliminary

K. Landry, APS 2015

“forward”

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

- Increasing with pion $p_T$
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 $p_T$

Consistent behavior when scaled for $2\langle p_T \rangle / \sqrt{s}$
Newest Collins Results at $\sqrt{s} = 200$ GeV

Anselmino et al., PRD 73, 014020 (2006)
F. Yuan, PRL 100, 032003 (2008)
D’Alesio et al., PRD 83, 034021 (2011)
Newest Collins Results at \( \sqrt{s} = 200 \text{ GeV} \)

Clear first observation of Collins asymmetry in \( p + p \)!
Newest Collins Results at $\sqrt{s} = 200$ GeV

**STRONG dependence upon** $j_T$

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

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

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 $\Delta R_{\text{min}}(j_T, \text{min})$
STAR Collins Results at $\sqrt{s} = 200$ and 500 GeV

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

Compare with models based on $\text{SIDIS/e}^+\text{e}^-$

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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!”

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**Theory:** Kang, Prokudin, Ringer, Yuan 2017 in preparation

**Data:** **STAR Preliminary**
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

$Sivers_{\text{DIS}} = -Sivers_{\text{Drell-Yan}}$ 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

**First Measurement of $A_N$ for Weak Bosons!**

**Global fit to the (unevolved) KQ prediction:**

- **solid line:** assume Sivers sign change: $\chi^2/\nu = 7.4/6$
- **dashed line:** assume no sign change: $\chi^2/\nu = 19.6/6$
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 $\sim 5$ or less

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

Forward direct-$\gamma$ at 200 GeV already in the bag!
The Near-term Future: Collins Evolution

The diagram shows the results of the reaction $p^+ + p(Au) \rightarrow \text{jet} + \pi^\pm + X$. The $A_{UT}$ (spin asymmetry) is plotted against $Z$ (proportionality factor). The data points represent different energy settings:

- $p+p$, $\sqrt{s} = 200$ GeV (Preliminary 2012)
- $p+p$, $\sqrt{s} = 500$ GeV (Preliminary 2011)
- $s^p+p$, $\sqrt{s} = 200$ GeV (Preliminary 2012)
- $s^p+p$, $\sqrt{s} = 500$ GeV (Preliminary 2011)

Closed points represent $\pi^+$; Open points represent $\pi^-$. The $x_T$ of the jet is approximately 0.13.

Preliminary 2011 and 2012 Collins asymmetries suggest $x_T$ scaling.

Implications for TMD evolution?
The Near-term Future: Collins Evolution

$\sin(\phi_S - \phi_H)$

$A_{UT}$

$p^+ + p(Au) \rightarrow \text{jet} + \pi^\pm + X$

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?*
Summary

- Spin physics is a fertile field and $p + p$ plays a critical role
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  - First observations of transversity in polarized $p + p$
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  - Investigation of Sivers/twist-3 in $W$, $\gamma$, and Drell-Yan
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Stay tuned for more new results from RHIC transverse spin!
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$^{-1}$
$\Rightarrow A_N$ for DY to $\pm 0.008$
**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 $u$ and $d$ at high $x$
  - collinear objects but more complicated evolutions than DGLAP
  - indirect constraint on Sivers fct.

\[
- \int d^2k_\perp \frac{k_\perp^2}{M} f_{1T}^q(x,k_\perp^2) |_{S\text{DIS}} = T_{q,F}(x,x)
\]

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

Assembled by E.C. Aschenauer