Overview of STAR Spin Measurements

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OUTLINE

- Introduction
- Inclusive hadron production
- Jet+hadron and di-hadron production
- Summary
Contributions to Proton Spin Structure

Consider proton moving right

Proton spin $\Rightarrow$

$\Delta q(x)$ $\Rightarrow$ $\rightarrow$

$\Delta g(x)$ $\rightarrow$ $\leftarrow$

Spin sum rule: $\left\langle S_z^p \right\rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \left\langle L_z \right\rangle$

Polarized DIS: $\sim 0.3$

coming into focus:

$$\int \Delta g(x) \, dx = 0.1 \pm 0.06$$

poorly constrained

Transversity – data over limited kinematic range: $x_{Bj} \leq 0.3$
Contributions to Proton Spin Structure

Consider proton moving right

Proton spin \( \Rightarrow \)

\[ \Delta q(x) \quad \Rightarrow \quad \Delta g(x) \quad \Rightarrow \]

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coming into focus:

\[ \int \Delta g(x) \, dx = 0.1 \pm 0.06 \quad \text{arXiv:nucl-ex/1304.0079} \]

poorly constrained

Transversity – data over limited kinematic range: \( x_{\text{Bj}} \leq 0.3 \)

\[ h_1(x) \]

\[ \uparrow \quad \Rightarrow \quad \downarrow \]

STAR spin program:
Exploring components of the proton with limited constraints

STAR SpinMeasurements - Drachenberg
Concert of Facilities
• OPPIS → LINAC → AGS → RHIC

Polarized-proton Collider
• Mitigate effects of depolarization resonances with “Siberian Snakes”
• Polarization measured with CNI polarimeter
• Spin rotators provide choice of spin orientation independent of experiment

RHIC Beam Characteristics
• Clockwise beam: “blue”; counter-clockwise beam: “yellow”
• Spin direction varies bucket-to-bucket (9.4 MHz)
• Spin pattern varies fill-to-fill
Solenoidal Tracker at RHIC

Inclusive hadron measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)

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

For details on STAR hyperons, stay tuned for E. Sichtermann’s talk, coming right up!
Inclusive \( \pi^0 \) production at \( \sqrt{s} = 200 \) GeV measured over three ranges of pseudorapidity at STAR

*All in agreement with NLO pQCD predictions (DSS Frag. Func.)*

→ Important benchmark for asymmetry studies

(Inclusive jet cross section at 200 GeV also found in agreement with NLO pQCD)
STAR Longitudinal Asymmetries from Inclusive Hadrons

$A_{LL}$ for Inclusive $\pi^0$ production at $\sqrt{s} = 200$ GeV measured over three ranges of pseudorapidity at STAR

- Complementary to STAR jet measurements
- Expect $A_{LL}$ to decrease with increasing pseudorapidity
- Current statistics dominated by 2005/2006 datasets
- Higher-statistics datasets under investigation
STAR has measured sizeable transverse single-spin asymmetries for forward $\pi^0$ and $\eta$ production

At high-$x_F$, $\eta$ asymmetry may be larger than that of $\pi^0$

Asymmetries at intermediate pseudorapidity consistent with zero

Above results mostly from 2006 (6.8 pb$^{-1}$ at 55% polarization)
Current models based on fits to SIDIS and $e^+e^-$:

- “The Collins effect...is not sufficient for the medium-large $x_F$ range of STAR data, $x_F \gtrsim 0.3$”
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Theoretical questions remain about applicability to $p+p$ data of Sivers extractions from SIDIS

(e.g. Kang et al., PRD 83, 094001 (2011))
Despite expectation of $1/p_T$ scaling, STAR data from Run-3 to Run-8 show no sign of $1/p_T$ fall-off out to $p_T \sim 5$ GeV/c.

Asymmetries at intermediate-$\eta$ consistent with zero for $5 < p_T < 12$ GeV/c.
Recent measurements at $\sqrt{s} = 500$ GeV show no sign of $1/p_T$ fall-off out to $p_T \sim 10$ GeV/c (consistent across multiple $x_F$-bins).

STAR Transverse Asymmetries from Inclusive Hadrons

$\pi^0$ $A_N$ vs $p_T$ $(0.16 < |x_F| < 0.24)$ (Isolation 70 mR)

$\sqrt{s} = 500$ GeV $\pi^0$ Energy 50 GeV ($x_F \sim 0.20$)

STAR Run 11 PRELIMINARY

arXiv:nucl-ex/1304.0079
Recent models based on SIDIS fits suggest flat $p_T$-dependence for the Sivers effect out to $p_T \sim 7$ GeV/c but at a lower magnitude than data.

Particular fit within scan of acceptable fits to SIDIS.
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Similar behavior for the Collins effect in some parameterizations.

$\rightarrow$ possible hint of Collins+Sivers effect?
Recent models based on SIDIS fits suggest flat $p_T$-dependence for **Sivers effect** out to $p_T \sim 7$ GeV/c but at **lower magnitude than data**

Similar behavior for **Collins effect** in some parameterizations

→ **possible hint of Collins+Sivers effect?**

Twist-3 models also see flat $p_T$ dependence out to $p_T \sim 15$ GeV/c

*[e.g. Kanazawa and Koike, PRD 83, 114024 (2011)]*
Recent data from 2012 suggest that asymmetries for pions with additional near-side energy deposit have lower asymmetries than those of more isolated pions.
Recent data from 2012 further suggest that asymmetries for pions with additional near-side pion have lower asymmetries than those with away-side or mid-range pion.

→ In both $\sqrt{s} = 200$ and 500 GeV isolated pions show higher asymmetry than jet-like pions.

Forward neutral-energy jet analysis of 2011 ongoing (M. Mondal, GHP2013)
Jet Reconstruction in STAR

STAR Di-jet event at detector-level

e.g. Anti-$k_T$ algorithm (2011 results)
JHEP 0804, 063 (2008)

Radius parameter $R = 0.6$

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

Data jets
MC jets

Jet direction

Detector

Particle

$e, \nu, \gamma,$
$\pi, p, etc$

$g, q$

PYTHIA

GEANT
Fragmentation in STAR Jet Reconstruction

Parton-jet Level Association with Radius = 0.6

Jet Patch 1 Trigger

Jet Patch 2 Trigger

\[ \text{Trigger Bias} = \frac{\text{subprocess trigger efficiency}}{\text{average trigger efficiency}} \]

**qq subprocess**
- more efficient than qg or gg at lower \( p_T \)
- *small fraction* of event sample in \( p_T \)-range where qq bias is significant

For anti-\( k_T \) particle-jet bias is factor
~2-3 smaller than parton-jet bias
STAR Longitudinal Asymmetries from Inclusive Jets

2009 $A_{LL} \rightarrow$ two pseudorapidity ranges

Forward jets $(0.5 < \eta < 1)$:
- Larger fraction of q-g scattering with
  - Higher $x$ quarks that are more polarized
  - Lower $x$ gluons that are less polarized
- Larger $|\cos(\theta^*)| \rightarrow$ reduced $\hat{a}_{LL}$

$A_{LL}$ falls between the predictions from DSSV and GRSV-STD

First experimental evidence of non-zero $\Delta g(x)$ in range $0.05 \leq x \leq 0.2$

$\int_{0.05}^{0.2} \Delta g(x) \, dx = 0.10^{+0.06}_{-0.07}$ with $Q^2 = 10 \text{ GeV}^2$

P. Djawotho, arXiv:nucl-ex/1106.5769
STAR Transverse Asymmetries from Inclusive Jets

\[ p^+ + p \rightarrow jet + X \]

STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and \( \sqrt{s} = 200 \ \text{GeV} \) (2006)

\[ A_{UT}^{\sin(\phi_S)} : \text{consistent with zero} \]

\[ A_{UT}^{\sin(\phi_S-\phi_h)} : \text{hints of non-zero asymmetry with charge-sign dependence} \]

Similarly, di-jet at central pseudorapidity and 200 GeV consistent with zero

PRL 99, 142003
2012 STAR data provide opportunity for higher precision and greatly reduced systematic uncertainties at $\sqrt{s} = 200$ GeV. Analysis well underway.

2011 STAR data provide opportunity for first measurements of central pseudorapidity inclusive jet asymmetries at $\sqrt{s} = 500$ GeV → Increased sensitivity to gluonic subprocesses.
Moments of Jet Asymmetries at 500 GeV

Various contributions to polarized jet+π cross section (TMD approach)

\[ d\sigma(\phi_S, \phi_h) - d\sigma(\phi_S + \pi, \phi_h) \sim d\Delta\sigma_0 \sin \phi_S \]
\[ + d\Delta\sigma_1^- \sin(\phi_S - \phi_h) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_h) \]
\[ + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_h) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_h) \]

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Negligible under \textit{maximized} scenario!
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\[ + d\Delta \sigma_2^- \sin (\phi_S - 2\phi_h) + d\Delta \sigma_2^+ \sin (\phi_S + 2\phi_h) \]

Possible non-zero contributions, expected to be quite small

e.g. Phys. Rev. Lett 99, 142003 (2007);
Phys. Rev. D 86, 032006 (2012);
Moments of Jet Asymmetries at 500 GeV

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“Collins-like” asymmetry:
Sensitive to linearly polarized gluons
Completely unconstrained!

Gluon helicity density matrix

\[ \rho = \frac{1}{2} \left( \begin{array}{cc} 1 + P_{\text{circ}} & -P_{\text{lin}} e^{-2i\phi} \\ -P_{\text{lin}} e^{2i\phi} & 1 - P_{\text{circ}} \end{array} \right) \]

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

Phys Rev. D 73, 014020 (2006)
Sivers Asymmetries at 500 GeV

Asymmetries shown as function of particle-jet $p_T$

Corresponding parton-jet $p_T$ lower by 0.6-1.4 GeV/c

Horizontal errors include uncertainties from statistics, calorimeter gains, efficiencies, track momentum, and tracking efficiency

No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s} = 500$ GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s} = 200$ GeV
Sivers Asymmetries at 500 GeV

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Corresponding parton-jet $p_T$ lower by 0.6-1.4 GeV/c

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Twist-3 Prediction
Kanazawa and Koike

Measured asymmetries shown in $\eta$-bins
No sign of sizable asymmetry
Collins Asymmetries at 500 GeV

Increased gluonic subprocesses at $\sqrt{s} = 500$ GeV lead to expectation of small Collins asymmetry until larger $z$

Present data do not have sufficient statistics at high-$z$ to observe Collins asymmetry of order 1%
Collins-like Asymmetries at 500 GeV

Model predictions shown for “maximized” effect, saturated to positivity bound

Until now, Collins-like asymmetries completely unconstrained

→ Sensitive to linearly polarized gluons
STAR Transverse Asymmetries from Di-hadrons

Another path to transversity:
**interference fragmentation functions via di-hadron asymmetries**

Advantage: *applicable in collinear framework*
STAR Transverse Asymmetries from Di-hadrons

Non-zero signal for di-hadron transverse single-spin asymmetries in 2006 data

→ Inform transversity at higher $x, Q^2$?
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→ Inform transversity at higher $x$, $Q^2$?

2012+15: opportunity for much higher precision

Analysis of 2012 data underway
Summary

• STAR measurements play a vital role in understanding nucleon spin structure
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• STAR inclusive hadron production
  - Cross-sections and $A_{LL}$ measured at three pseudorapidity ranges
  - Persistence of sizable $A_N$ at forward pseudorapidity to $p_T \sim 10$ GeV/c
  - Measurement of $\pi^0 A_N$ for the first time at intermediate pseudorapidity ($0.8 < \eta < 2$)
    $\Rightarrow$ asymmetries consistent with zero
  - Precise investigation of $A_N$ dependence of on event topology
    $\Rightarrow$ asymmetries in jet-like $\pi^0$ are smaller than asymmetries in isolated $\pi^0$
Summary

• STAR measurements play a vital role in understanding nucleon spin structure

• STAR inclusive hadron production
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• STAR inclusive jet and di-hadron production
  - Significant constraints placed on gluon polarization $\Rightarrow$ between DSSV and GRSV-STD
  - First signs of transversity at RHIC through inclusive jet and di-hadron asymmetries
  - Investigation of transverse single-spin asymmetries for the first time in inclusive jets at central pseudorapidity and $\sqrt{s} = 500$ GeV
    $\Rightarrow$ First ever measurement of “Collins-like” effect from linearly polarized gluons
    $\Rightarrow$ Stage set for analysis of $A_{UT}$-moment evolution from 200 GeV to 500 GeV
  - Analyses underway of Collins and IFF from 2012 run $\Rightarrow$ higher statistical precision and reduced systematics
Back-up Slides
Collins-like Asymmetries at 500 GeV

Measured asymmetries shown for $-1 < \eta < 1$ in $z$-bins
Consistently below 2% maximum from model
Collins-like Asymmetries at 500 GeV

Similarly, no large effect observed as a function of jet $p_T$

Measured asymmetries shown for $-1 < \eta < 1$ in $z$-bins
Collins Asymmetries

Present model predictions expect negligible effects for $A_{UT}$ vs. $j_T$ integrated over $z > 0.1$

Measured asymmetries shown for $x_F > 0$ (i.e. $0 < \eta_{jet} < 1$) in $z$-bins

No sign of non-zero asymmetry as a function of $j_T$ or jet $p_T$

Similarly, no sign of positive effect for backward region ($x_F < 0$), as expected
STAR measured $A_{LL}$ for inclusive charged pions during 2005
- $A_{LL}(\pi^+) - A_{LL}(\pi^-)$ is sensitive to the sign of $\Delta G$
- **Difficult to trigger on charged pions**
- Used the E/M calorimeter jet patch trigger as a surrogate
  $\rightarrow$ significant trigger bias (*dominates syst. error band*)
• Making lemons into lemonade
  \(\rightarrow\) **Beat the trigger bias by using it**
• Trigger and reconstruct a jet, then look for a charged pion on the opposite side
• Correlation measurement **significantly increases the sensitivity of** \(A_{LL}(\pi^+)\)
2011 provides first look at transverse-spin inclusive jets at central pseudorapidity range with $\sqrt{s} = 500$ GeV

Collins asymmetries expected to be small at $\sqrt{s} = 500$ GeV

Higher gluon participation at $\sqrt{s} = 500$ GeV allows unique sensitivity to gluon Collins-like asymmetry