Transverse Spin Results From STAR

Yuxi Pan

Department of Physics & Astronomy
University of California, Los Angeles

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Outline

1. STAR’s capabilities on transverse spin measurements
2. Status of STAR transverse spin analyses
3. STAR upgrades
STAR’s capabilities on transverse spin measurements

The Solenoid Tracker At RHIC (STAR)

- Full azimuthal coverage
- -1 < η < 1 coverage
- Uniform acceptance for all beam energies
- Excellent PID

Detector capabilities

- **Central Region** (−1 < η < 1): \( \pi^\pm/K/p \) ID by dE/dX and TOF, \( e^\pm/\gamma \) by EMCAL, jets
- **Mid-Forward** (1 < η < 2): \( \pi^0, \eta, \) direct \( \gamma, \) EM-jets from Endcap-EMCAL
- **Forward** (2.5 < η < 4.0): \( \pi^0, \eta, \) EM-jets by Forward Meson Spectrometer
Central Region ($-1 < \eta < 1$)
- inclusive jet $A_N$, Collins/IFF asymmetries $A_{UT}$
- $W^\pm/Z^0$ boson $A_N$

Mid-Forward ($1 < \eta < 2$)
- $\pi^0$, $\eta$, EM-jets $A_N$

Forward ($2.5 < \eta < 4.0$)
- $\pi^0$, $\eta$ $A_N$
- topology dependence of $A_N$ through EM-jet/$\pi^0$, forward-forward/forward-central correlations
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   - Mid-rapidity inclusive jet $A_N$
   - Collins/IFF Asymmetries
   - $W^{\pm}/Z^0$ boson $A_N$
   - Forward $\pi^0$/EM-jet $A_N$ on FMS

3. STAR upgrades
   - refurbished FMS + Preshower
   - Forward tracking + calorimeter for 2020
Mid-rapidity inclusive jet $A_N$

- Corresponding parton-jet $p_T$ lower by 0.6-1.4 GeV/c
- Sensitive to Sivers function

$$\Delta^N f_a/A ↑ \otimes f_b/B$$

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

- Gluon-Gluon scattering dominates due to low $x_T$

D’Alesio et al.

Phys. Rev. D 83, 034021
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Collins Asymmetries at 200 GeV

- 2-scale process described within TMD scheme by $h_1^a \otimes f_b/B \otimes \Delta D_{\pi/q \uparrow}$ assuming factorization

- 2012 STAR data provide higher precision and reduced systematic uncertainties. Preliminary results aimed for SPIN2014
Collins Asymmetries at 500 GeV

- Moments of $\sin(\phi_s - \phi_h)$ sensitive to quark Collins asymmetry

- Increased gluonic subprocess at $\sqrt{s} = 500$ GeV leads to small Collins asymmetries until large $z_h$

Phys. Rev. D83, 034021
Collins Asymmetries at 500 GeV

- Moments of $\sin(\phi_s - 2\phi_h)$ sensitive to linearly polarized gluons
- Gluon Collins-like asymmetries completely unconstrained
Asymmetries persist in collinear scheme through
\[ h_1^a/A_1 \otimes f_b/B \otimes H_{1,ot} \]

First signal of transversity in pp collisions

A. Bacchetta et al.
Phys. Rev. D70, 094032

\[ \hat{S}_B \]
\[ \hat{P}_A \]
\[ \hat{P}_C \]

\[ \phi_{s_h} \]
\[ \phi_{R_z} \]
\[ \phi_{R_{CT}} \]

\[ A_{UT}^{\sin\theta} \]

\[ A_{UT}^{\sin\theta} \]

\[ M_{inv}^{\pi^+\pi^-} \]

\[ \eta_{\pi^+\pi^-} \]
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**IFF Asymmetry projections with 2012 STAR Data @ 200 GeV**

Statistical uncertainties greatly reduced.

Analyses of 200 GeV and 500 GeV data are ongoing

Preliminary results aimed for SPIN2014
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The sign change of Sivers function

Critical test for TMD factorization and evolutions

\[ Sivers_{SIDIS} = -Sivers_{DY} = -Sivers_{W^\pm/Z^0} \]

\[ A_N^{\gamma N} \] measures the sign change through Twist-3

\[ A_{UT}^{Sivers/SIDIS}, A_N^{DY}, \text{ and } A_N^{W^\pm/Z^0} \] together test TMD evolutions
**W± identification**

- **W±** identified via high $p_T$ isolated electrons + $p_T$ imbalance on the away-side
- 2011 500GeV $pp$ collisions, $\mathcal{L} = 25pb^{-1}$
**W± kinematics reconstruction**

- \( P_T^{W} = -P_T^{\text{recoil}} \) (MC corrected)
- \( P_Z^{W} = P_Z^{e} + P_Z^{\nu} \), neutrino \( P_Z \) calculated by
  \[
  M_W^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2
  \]
- Neutrino \( P_T \) is reconstructed from missing \( P_T \)

**Good agreement between data/MC after \( P_T \) correction**
W±/Z0 boson A_N From 2011 STAR Data

M.G. Echevarria et.al Phys. Rev. D 89, 074013
and priv. comm.

sea quark Sivers function constrained by positivity bound
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$W^\pm/Z^0$ $A_N$ Projections for 2016

AN Collins/IFF Asymmetries
$W^\pm/Z^0$ boson $A_N$
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Forward Meson Spectrometer

- Pb Glass calorimeter provides EM coverage in $2.5 < \eta < 4.0$
- small cells: $3.81 \times 3.81 cm^2$
  large cells: $5.81 \times 5.81 cm^2$
- detect $\pi^0$, $\eta$ and jet-like events
**π⁰ A_N**

- Isolated π⁰ from 2011 data shows flat $p_T$ dependence
- Analysis of inclusive π⁰ $A_N$ is ongoing
- A successful twist-3 model (initial-/final-state, or both) would have to explain SSA in $pp$ and SIDIS with the same set of parameters, plus evolutions

![Graph showing $A_N$ vs $p_T$ for π⁰](image)

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$A_N$ for forward jet-like events

- Apply Anti-$k_T$ jet finding on FMS photons, $R = 0.7$

- Isolated $\pi^0$ has larger asymmetries than jet-like events

![Graph showing $A_N$ vs EM-Jet Energy (GeV)]
$A_N$ for forward jet-like events

- Apply Anti-$k_T$ jet finding on FMS photons, $R = 0.7$
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- Study dependence of $A_N$ on number of photons and away-side jet activities
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with and without a correlated central EM-jet on the away-side $p_T^{EMjet} > 2.0$ GeV
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FMS lead glass was exposed to sunlight to recover from radiation damage
first two layers of preshower provides γ/charged-track separation and (x,y)
3rd layer of preshower separates electrons and γ from charged hadrons
Direct $\gamma A_N$ for Run15

- $p^\uparrow + p @ \sqrt{s} = 200$ GeV, $\mathcal{L} = 40 pb^{-1}$, pol. = 60%
- Track matching between FMS and layer 1 & 2 of preshower
- $E_{\text{cluster}} > 15$ GeV, $p_T > 2.0$ GeV
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**Forward Tracking & Calorimeter System for 2020**

- ECAL: W powder + scintillating filters
  \[ \sigma_E / E = 0.11/\sqrt{E} + 0.007 \]
- HCAL: Lead plates + scintillating tiles
  \[ \sigma_E / E = 0.58/\sqrt{E} + 0.007 \]
- Prototypes tested extensively at Fermilab

- Silicon micro-strip technology based on experience from STAR IST
- GEM technology from FGT design
- Still in early stage of development
Summary

- STAR continues to deliver high quality transverse spin measurements for
  - Mid-rapidity jet $A_N$ to probe gluon Sivers function
  - Mid-rapidity correlations to access transversity
  - $W^\pm/Z_0$ asymmetries to test TMD factorization & evolutions
  - $A_N$ for forward hadron/jet-like events to shed light on the origins of the large transverse spin effects

- STAR upgrades in the (near-) future will enable new exciting measurements
  - Forward direct photon
  - Forward jet, di-hadrons...

Stay tuned!
\[ \frac{d\sigma_{\text{pol}}}{d\sigma_{\text{unpol}}} = 1 + P_1 P_2 \cdot A\Sigma(\eta, p_T) + \cos(\phi) \cdot [P_1 \cdot A_N(\eta, p_T) - P_2 \cdot A_N(-\eta, p_T)] + P_1 P_2 \cdot \cos(2\phi) \cdot A_{TT}(\eta, p_T) \]