Transverse Single-Spin Asymmetry for Electromagnetic (EM) Jets at Forward Rapidities at STAR in $p^+ + p$ Collisions at $\sqrt{s} = 200$ GeV

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Outline

1. Transverse Single-Spin Asymmetry ($A_N$)
2. RHIC and The STAR Experiment
3. FMS and EEMC Detectors
4. Jet Reconstruction
5. $A_N$ Extraction Status
6. Outlook
Transverse Single-Spin Asymmetry ($A_N$)

- Unexpected large transverse single-spin asymmetries ($A_N$) are observed in proton-proton collisions
- pQCD predicts $A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$

Kane, Pumplin and Repko
PRL 41 1689 (1978)

\[
A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}
\]

R. D. Klem et al., PRL 36, 929 (1976)
D.L. Adams et al., PLB 264, 462 - 466(1991)
I. Arsene et al., PRL 101, 042001 (2008)
D.L. Adams et al., PLB 261, 201(1991)
A. Adare et al., PRD 90, 012006 (2014)
E.C. Aschenauer et al., arXiv:1602.03922
Possible Mechanisms

**Sivers Mechanism:**
Correlation between proton spin and parton $k_T$

![Diagram of Sivers Mechanism](image)


Signatures: $A_N$ for jets or direct photons, $W^+/-$, $Z^0$, Drell-Yan

**Collins Mechanism:**
Transversity (quark polarization) $\otimes$ jet fragmentation asymmetry

![Diagram of Collins Mechanism](image)


Signatures: Collins effect, Interference fragmentation function (IFF), pion $A_N$

**Twist-3:**
Quark-gluon / gluon-gluon correlations and fragmentation functions. A source for Sivers function.

Relativistic Heavy Ion Collider (RHIC)

- World’s only polarized proton-proton collider
- Transverse and longitudinal polarization
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Fill-to-fill variations in spin pattern
- Polarized protons up to $\sqrt{s} = 510$ GeV
- Allows to probe hard scattering processes with control of systematic effects
The STAR Experiment at RHIC

- **Calorimetry System:**
  - Barrel Electromagnetic Calorimeter (BEMC): $-1 < \eta < 1$
  - Endcap Electromagnetic Calorimeter (EEMC): $1.1 < \eta < 2$
  - Forward Meson Spectrometer (FMS): $2.6 < \eta < 4.1$

- **Full azimuthal coverage**

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Recorded Luminosity (pb$^{-1}$)</th>
<th>Polarization Orientation</th>
<th>B/Y ($P^0$)</th>
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<tr>
<td>2009</td>
<td>200</td>
<td>25</td>
<td>Longitudinal</td>
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<tr>
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<tr>
<td>2011</td>
<td>500</td>
<td>25</td>
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<tr>
<td>2012</td>
<td>200</td>
<td>22</td>
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<tr>
<td>2012</td>
<td>510</td>
<td>82</td>
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<tr>
<td>2013</td>
<td>510</td>
<td>300</td>
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<td>51/52</td>
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<tr>
<td>2017</td>
<td>510</td>
<td>320</td>
<td>Transverse</td>
<td>55</td>
</tr>
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</table>

- **Polarized pp dataset since 2009**
**Forward Meson Spectrometer (FMS)**

- FMS is a lead-glass electromagnetic calorimeter
- Array of \( \sim 1200 \) Pb-glass cells coupled to PMTs
- Forward pseudorapidity coverage: \( 2.6 < \eta < 4.1 \)
- \( \gamma, e^-, e^+ \rightarrow \) EM shower
- Observables: \( \gamma, \pi^0, \) EM-jet
Endcap Electromagnetic Calorimeter (EEMC)

- Coverage: $1.1 < \eta < 2.0$, $0 < \phi < 2\pi$
- 12 sectors (matched to TPC sectors) $\times$ 5 subsectors $\times$ 12 $\eta$-bins = 720 towers.
- 1 tower = 24 layers, Layer 1 = pre-shower 1, Layer 2 = pre-shower 2, Layer 24 = post-shower
- SMD U and V planes at $5X_0$
- 288 SMD strips/plane/sector

![Diagram of EEMC](image-url)
**Motivation:**
- Explore potential sources of large $A_N$
- Isolate subprocess contribution (EM-jet $A_N$) to the large $A_N$
- Characterize EM-jet $A_N$ as a function of EM-jet $p_T$, energy and photon multiplicity

**Advantages of EM-jet:**
- Allows to investigate EM component of a full jet
- Enables us to classify EM-jet in terms of its constituent photon multiplicity

**Dataset:**
- RHIC Run 15 data
- $p^+ p$ collisions at $\sqrt{s} = 200$ GeV
- Transversely polarized protons with $<P> = 57$
- $\mathcal{L} = 52$ pb$^{-1}$
Jet Reconstruction

- Vertex z priority: TPC, VPD, BBC
- Reconstructed FMS photons / EEMC towers as input for FastJet
- Anti-$k_T$ algorithm with $R = 0.7$
- $E_\gamma > 1.0$ GeV (For FMS EM-Jet)
- Jet $p_T > 2.0$ GeV/c
- $-80\,\text{cm} < V_z < 80\,\text{cm}$

Monte Carlo

- PYTHIA 6.428 event generator
- Tune: Perugia 2012 with CTEQ6 PDFs
- GEANT based STAR detector simulation
EM-Jets in FMS and EEMC

- EM-jets from forward (FMS) and intermediate (EEMC) rapidities provide different EM-jet $E$ and $p_T$ ranges to be explored.
- Plots show EM-jet $E$, $p_T$ and photon multiplicity from data.
**EM-Jet $A_N$ Extraction**

\[
N^\uparrow = I_0^\uparrow \epsilon (1 + P A_N \cos \phi) \\
N^\downarrow = I_0^\downarrow \epsilon (1 - P A_N \cos \phi)
\]

\[
A(\phi) = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

\[
A(\phi) \approx P A_N \cos \phi + \frac{I_0^\uparrow - I_0^\downarrow}{I_0^\uparrow + I_0^\downarrow}
\]

\[
A(\phi) = P A_N \cos(\phi) + p_1
\]

\[
A(\phi) + A(\phi + \pi) \approx 2 \frac{I_0^\uparrow - I_0^\downarrow}{I_0^\uparrow + I_0^\downarrow}
\]

- Allows extraction of both physics asymmetry and beam asymmetry

\[
\chi^2 / \text{ndf} = 13.19 / 14
\]

\[
p_0 = 0.01265 \pm 0.0004955
\]

\[
p_1 = 0.0004608 \pm 0.0003489
\]

20.0 GeV < $E$ < 40.0 GeV, No. of Photons 2, 2.5 GeV/c < $p_T$ < 3.0 GeV/c
EM-Jet $A_N$ Extraction

- Cross-ratio formula to calculate $A_N$

$$\epsilon = P A_N \cos(\phi)$$

$$\epsilon \approx \sqrt{N_{\phi}^{\uparrow} N_{\phi+\pi}^{\downarrow}} - \sqrt{N_{\phi+\pi}^{\uparrow} N_{\phi}^{\downarrow}}$$

$$\sqrt{N_{\phi}^{\uparrow} N_{\phi+\pi}^{\downarrow}} + \sqrt{N_{\phi+\pi}^{\uparrow} N_{\phi}^{\downarrow}}$$

- Advantages: Cancels systematics, such as luminosity and detector effects

![Diagram of coordinate system and asymmetry calculation](attachment:diagram.png)
Corrections: Unfolding for Event Misidentification

- Solve a set of five linear equations with five variables for each energy and $p_T$ bin
- Decompose $A_N$ as a linear composition of $A_{N_i}$ corresponding to $n_i$ photons
- Use SVD for the unfolding procedure (e.g. TSVDUnfolding class)

The leading contributions come from $A_N$ for EM-jets with photon multiplicity $n < 6$
Corrections: Underlying Event and $p_T$ Corrections

- EM-jet $p_T$ values are corrected for contaminations from underlying events (UE) using off-axis cone method
- EM-jet observables are corrected to the particle level
- The asymmetry is corrected for the dilution from the background
EM-Jet $A_N$ Projection

Leading Sources of Systematic Uncertainties

- $A_N$ uncertainties:
  - Event misidentification
  - Background contamination
  - Beam polarization

- Energy or $p_T$ uncertainties:
  - Calibration
  - Energy or $p_T$ corrections
  - Effects of radiation damage
Current Status and Outlook

- We are studying $A_N$ in the subprocess: $p^+ + p \rightarrow \text{EM-jet} + X$
- Understanding the dependences of $A_N$ on photon multiplicity inside EM-jet, jet $p_T$ and jet $E$ can help further characterize large $A_N$ in the forward rapidities
- Current efforts include: improving the EM-jet simulation and better understanding of the sources of systematic uncertainties
- Expect physics results soon!