Measurement of the Transverse Single-Spin Asymmetries for $\pi^0$ and Jet-like Events at Forward Rapidities at STAR in p+p Collisions at $\sqrt{s} = 500$ GeV

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ᵀransverse Single Spin Asymmetries (TSSA)

Forward Meson Spectrometer in the STAR experiment

EM-Jets in forward and central rapidity

$A_N$ measurements from RHIC Run 11 at $\sqrt{s} = 500 \text{ GeV}$
Spin-dependent transverse momentum dependent (TMD) function $S_T(Px_{k_T})$
Brodsky, Hwang, Schmidt, 02
Collins, 02, Ji, Belitsky, Yuan, 02

Twist-3 quark-gluon correlations
Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

Need 2 scales $Q^2$ and $p_t$
Remember pp: most observables one scale
Exception: DY, W/Z-production

Collinear/twist-3
$Q, Q_T \gg \Lambda_{QCD}$
$p_T \sim Q$

Intermediate $Q_T$
$Q \gg Q_T / p_T > \Lambda_{QCD}$

Twist-3 quark-gluon correlations
Efremov, Teryaev; Qiu, Sterman

Need only 1 scale $Q^2$ or $p_t$
But should be of reasonable size should be applicable to most pp observables $A_N(\pi^0/\gamma/jet)$
$$\pi^0 A_N \text{ Measurements at Forward Rapidity}$$

Inclusive $\pi^0$ production

$$p_\uparrow + p \rightarrow \pi^0 + X$$

Transverse Single Spin Asymmetry

$$A_N \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$x_F = \frac{2p_Z}{\sqrt{s}}$$

✧ Rising $A_N$ with $x_F$
✧ $A_N$ nearly independent of $\sqrt{s}$
✧ No evidence of fall in $A_N$ with increasing $p_T$
500 GeV Isolated $\pi^0$ results

$\sqrt{s} = 500$ GeV (Run 11) Transverse Single Spin $\pi^0$ Asymmetry vs $p_T$ for small and large $\pi^0$ isolation cones. (Errors shown in these are following plots are statistical)

Higher Twist or other pQCD related models suggest $A_N$ should fall at large $p_T$ with at least 1 power of $p_T$.

These plots include 2 parameter fits for $A_N$ vs $p_T$:

$$A_N(p_T) = [p_0] \times (p_T)^{p_1}$$

Fits are shown for both the 70 mRad and 30 mRad isolation cones.

✧ $A_N$ is higher with increasing isolation radius
✧ $A_N$ in increasing with $x_F$

DIS-2013 (Steven Heppelmann)
200 GeV Isolated $\pi^0$ results

$A_N$ vs. Energy, averaged over pseudo-rapidity.
Compare 3 selection criteria based on photon energy outside the cone (all with 35mR cone and no soft E cut).

- 2 track (35mr) $\pi^0$ only
- 2 track (35mr) $\pi^0$ + Away $\gamma$'s $\cos(\Delta\phi)<-0.5$
- 2 track (35mr) $\pi^0$ + Near $\gamma$'s $\cos(\Delta\phi)>0$.

For $\pi^0$'s with $X_F>0.45$:
Observation of additional Photons reduce $A_N$.

Events opposite "side photons" or "no" photons have similar $A_N$.
Same side photons lead to much reduced $A_N$.

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RHIC: the world’s first and only polarized proton collider

For 2011: Average Blue Beam Polarization = 51.6% (Transverse)
Luminosity = 22 pb⁻¹
Forward Meson Spectrometer (FMS) :
-- Pb glass EM calorimeter covering $2.5<\eta<4.0$
-- Detect $\pi^0, \eta$, direct photons and jet-like events in the kinematic region where transverse spin asymmetries are known to be large.
**STAR** detector cross view

**FMS photon reconstruction:**
- towers → clusters → photon
- shower shape fitting

BEMC+EEMC towers: to find central electromagnetic jets

FMS photons: to find forward electromagnetic jets
RHIC Run 11 (2011) pp @ √s=500 GeV

Forward Electromagnetic Jets (EM-Jets)
Jet algorithm : anti-k_T
R-parameter : 0.7
p_T^{EM-Jet} > 2.0 GeV/c

Leading EM-Jets : defined as EM-Jets with highest energy.
2.8<|EM-Jet|<4.0
40 GeV < Energy^{EM-Jet} < 100 GeV
(0.16 < x_F < 0.4)

Structure in EM-Jet p_T :
-- Acceptance non uniformity in small and large tower boundary inside FMS
-- Different trigger threshold influence different p_T region

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Forward EM-Jet characteristics

No. of photons in leading EM-Jets

γγ invariant mass 2-photon EM-jets

2-photon jets are mostly π⁰
Events with more than 2 photons show jet-like energy flow
$A_N$ from fits

$A_N$ is calculated from $p_0 + P \times A_N \cos(\phi)$ fits over each fill on

$$\frac{N_{\uparrow}(\phi)-N_{\downarrow}(\phi)}{N_{\uparrow}(\phi)+N_{\downarrow}(\phi)} = p_0 + P \times A_N \cos(\phi)$$

--- $A_N$’s are corrected for polarization values from RHIC-fills
--- $A_N$ and $\chi^2$/NDF are calculated over entire fills

EM-Jet Energy = 55-57.5 GeV

For 2-photon isolated $\pi^0$

For each slice of data averaged over ~18 fills. Fits are well in control.
$A_N$ vs. EM-Jet Energy

$\pi^0$-Jets – 2γ-EM-Jets with $m_{\gamma\gamma} < 0.3$ and $Z_{\gamma\gamma} < 0.8$

EM-Jets – with no. photons >2

✧ Isolated $\pi^0$’s have large asymmetries consistent with previous observation (CIPANP-2012 Steven Heppelmann)

https://indico.triumf.ca/contributionDisplay.pycontribId=349&sessionId=44&confId=1383

✧ Asymmetries for jettier events are much smaller
$A_N$ vs. EM-Jet Energy

**STAR Preliminary**

$p+p^\uparrow$ @ $\sqrt{s} = 500$GeV

- $\pi^0$-Jets ($x_F > 0$)
- $\pi^0$-Jets ($x_F < 0$)
- EM-Jets ($x_F > 0$)
- EM-Jets ($x_F < 0$)
- 2-photon-Jets $m_{\gamma\gamma} > 0.3$ ($x_F > 0$)

- $\pi^0$-Jets – 2γ-EM-Jets with $m_{\gamma\gamma} < 0.3$
- Z$_{\gamma\gamma} < 0.8$
- 2γ-EM-Jets ($\eta +$ continuum) - with $m_{\gamma\gamma} > 0.3$
- EM-Jets – with no. photons $> 2$

✧ Isolated $\pi^0$’s have large asymmetries consistent with previous observation (CIPANP-2012 Steven Heppelmann)

https://indico.triumf.ca/contributionDisplay.pycontribId=349&sessionId=44&confId=1383

✧ Asymmetries for jettier events are much smaller
$A_N$ for different # photons in EM-Jets

<table>
<thead>
<tr>
<th>EM-Jet Energy</th>
<th>40-60 GeV</th>
<th>60-80 GeV</th>
<th>80-100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. photons</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

- 1-photon events, which include a large $\pi^0$ contribution in this analysis, are similar to 2-photon events.

- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated $\pi^0$'s.

- $A_N$ decreases as the event complexity increases (i.e., the "jettiness".

- $A_N$ for #photons >5 is similar to that for #photons = 5.

Jettier events

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$A_N$ with midrapidity activities

**Midrapidity EM Jets**

- **Jet algorithm**: anti-$k_T$, $R = 0.7$
  - $p_T^{\text{EM-Jet}} > 2.0$ GeV/c, $-1.0 < \eta^{\text{EM-Jet}} < 2.0$
- **Inputs for central EMJets**: towers from BEMC and EEMC
- **Leading central EM-Jets**: Jet with highest $p_T$

- **Case-I**: having no central jet
- **Case-II**: having a central jet

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Characteristics of Coincident Central EM-Jets (case-II)

For Central EMJets

**p_T distribution**

Energy forward EMJet (GeV)

- 40-60
- 60-80
- 80-100

**Energy flow within central EMJets**

$\Delta R_{Jet,Towers}$

- Mean: 0.25
- RMS: 0.16

**p_T balance (di-jet like)**

Mean: 0.79
RMS: 0.39

**Energy sharing (asymmetric scatterings)**

- Mean: 0.07
- RMS: 0.04

Forward-central correlations

**p_T balance**

$E_{EMJet-Central}/E_{EMJet-Forward}$

Mean: 0.79
RMS: 0.39

**Energy sharing**

$E_{EMJet-Central}/E_{EMJet-Forward}$

Mean: 0.07
RMS: 0.04

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Δφ correlation between forward and central EMJets

Correlation is stronger for more N_photon Jets
Correlation grows stronger for higher EMJets energy.
An EM-jet in the central rapidity region reduces the asymmetries for the forward isolated π⁰
$A_N$ for the central jet: near and away in $\phi$ to the forward jet

Near and away side

Uncorrelated central EM-Jet is separated out

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$A_N$ for **correlated central jets** and **no central jet cases**

Asymmetries for the forward isolated $\pi^0$ are low when there is a correlated away-side jet.
EM-jets are reconstructed from photons detected in the FMS at STAR.

Jets with isolated $\pi^0$ have large asymmetry.

Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated $\pi^0$’s.

$A_N$ decreases as the event complexity increases (i.e., the "jettiness").

Isolated $\pi^0$ asymmetries are smaller when there is a correlated EM-jet at mid-rapidity.

Both of these dependences raise serious question how much of the large forward $\pi^0$ $A_N$ comes from $2 \rightarrow 2$ parton scattering.
Transverse Single-Spin Asymmetry and Cross-Section for $\pi^0$ and $\eta$ Mesons at Large Feynman-$x$ in $p^+ + p$ Collisions at $\sqrt{s} = 200$ GeV

STAR $p^+ + p \rightarrow \pi^0, \eta + X$ at $\sqrt{s} = 200$ GeV

- $\pi^0$ no center cut, $<p_T>$=3.7  
  - $\pi^0$ center cut, $<p_T>$=3.68  
- $\eta$ center cut, $<p_T>$=3.68

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Systematics arising from intermixing of event classes
No EM-jet within $-1 < \eta < 2$ ($p_T > 2.0 \text{GeV/c}$)

EM-Jet Energy = 40-60 \hspace{1cm} 60-80 \hspace{1cm} 80-100 \text{ GeV}

- no central jet
- isolated-
- 3-photon
- $x_F > 0$
- $x_F < 0$

$A_N$ vs $p_T^{EMJet}$ (GeV/c)

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With a EM-jet with $-1 < \eta < 2$ ($p_T > 2.0 \text{GeV/c}$)

**Diagram Description:**

- **EM-Jet Energy = 40-60**
- **60-80**
- **80-100 GeV**

- $p_T^{\text{EMJet-central}} > 2.0 \text{GeV/c}$
- $-1.0 < \eta^{\text{EMJet-central}} < 2.0$

**Graph Elements:**

- $A_N$
- $x_F > 0$
- $x_F < 0$

**Legend:**

- **isolated-$\tau^0$**
- **3-photon**
- **\ (>3-photon)**

**Axes:**

- $p_T^{\text{EMJet}}$ (GeV/c)
- $A_N$

**Note:**

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