Measurement of Transverse Single Spin Asymmetry $A_N$ in Eta Mass Region at Large Feynman $X_F$ with the STAR Forward Pion Detector

Steve Heppelmann

For STAR Collaboration
Previous observation of Single Spin Transverse Asymmetry for Forward Production of Eta Meson by FNAL Exp 704.

They reported:

1) Nominally (perhaps not significantly) larger asymmetry for Eta than Pi0.
2) Large Uncertainty in Eta $A_N$.

$$p^\uparrow + p \rightarrow M + X$$
$$\bar{p}^\uparrow + p \rightarrow M + X$$

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$\sqrt{s} = 19.4\text{GeV}$

$\langle p_T \rangle \sim 1\text{GeV} / c$

**Previous observation of Single Spin Transverse Asymmetry for Forward Production of Eta Meson by FNAL Exp 704.**

They reported:

1) Nominally (perhaps not significantly) larger asymmetry for Eta than Pi0.
2) Large Uncertainty in Eta $A_N$.

$$p^\uparrow + p \rightarrow M + X$$
$$\bar{p}^\uparrow + p \rightarrow M + X$$

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$\sqrt{s} = 19.4\text{GeV}$

$\langle p_T \rangle \sim 1\text{GeV} / c$
Should $A_N$ be larger for Eta production than Pi0 production?

- Gluons have Isospin $I=0$. Fragmentation to $I=0$ Eta mesons at large fragmentation fraction $Z$ may be enhanced for gluon jets.

- But in PQCD (both Collins or Sivers models), we expect these mesons to come from fragmentation of quark jets.

\[
I = 0 \quad \left\{ \begin{array}{l}
\eta = \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} - s\bar{s}) \\
\eta' = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} + 2s\bar{s})
\end{array} \right.
\]

\[
I = 1 \quad \left\{ \begin{array}{l}
\pi^0 = \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d})
\end{array} \right.
\]

*Assume $\eta, \eta'$ mixing angle: $\theta_p \sim -19.5^\circ$

- For Collins Effect: Asymmetry reflects transverse quark polarization through transverse momentum dependence in the fragmentation of the quark jet to a leading Pi0 or Eta meson. Differences in fragmentation could relate to:
  - Mass differences?
  - Isospin differences?
  - Role of Strangeness?
Pattern from Previous Transverse Single Spin Asymmetry Measurements of Forward Pion/Eta Production with High Energy Polarized Proton/Antiproton Beams.

1. Majority valence quark in polarized proton.
   - $u$ for proton
   - $\bar{u}$ for antiproton.

2. Minority valence quark
   - $d$ for proton
   - $\bar{d}$ for antiproton.

3. Pion containing only majority quarks gets large positive $A_N$.

4. Pion containing only minority quarks gets large negative $A_N$.

5. Pion containing both majority and minority quarks (neutral pions) have intermediate positive $A_N$.

<table>
<thead>
<tr>
<th>Polarized Beam</th>
<th>Observed Meson</th>
<th>Exp.</th>
<th>$\langle s \rangle$</th>
<th>$\langle p_T \rangle$</th>
<th>$\sim X_F$</th>
<th>$\sim A_N$</th>
<th>Comment on $A_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton $uud$</td>
<td>$\pi^+ : u\bar{d}$</td>
<td>E 704 BRAHMS</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.5 - 0.7</td>
<td>+0.15 to +0.25</td>
<td>Large Positive</td>
</tr>
<tr>
<td>Proton $uud$</td>
<td>$\pi^0 : \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$</td>
<td>E 704 STAR</td>
<td>200 GeV</td>
<td>~2.5 GeV/c</td>
<td>0.5 - 0.6</td>
<td>+0.10 to +0.15</td>
<td>Medium Positive</td>
</tr>
<tr>
<td>Proton $uud$</td>
<td>$\pi^- : d\bar{u}$</td>
<td>E 704 BRAHMS</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.4 - 0.6</td>
<td>-0.10 to -0.25</td>
<td>Large Negative</td>
</tr>
<tr>
<td>Anti Proton $\bar{u} \bar{u} \bar{d}$</td>
<td>$\pi^- : d\bar{u}$</td>
<td>E 704</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.5 - 0.7</td>
<td>0.10 to +0.20</td>
<td>Large Positive</td>
</tr>
<tr>
<td>Anti Proton $\bar{u} \bar{u} \bar{d}$</td>
<td>$\pi^0 : \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$</td>
<td>E 704</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.5 - 0.7</td>
<td>0.05 to +0.10</td>
<td>Medium Positive</td>
</tr>
<tr>
<td>Anti Proton $\bar{u} \bar{u} \bar{d}$</td>
<td>$\pi^+ : u\bar{d}$</td>
<td>E 704</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.5 - 0.7</td>
<td>-0.10 to -0.25</td>
<td>Large Negative</td>
</tr>
<tr>
<td>Proton $uud$</td>
<td>$\eta : \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} - s\bar{s})$</td>
<td>E 704</td>
<td>19.4 GeV</td>
<td>~1 GeV/c</td>
<td>0.50 - 0.60</td>
<td>0.25 ± 0.09</td>
<td>Possibly Larger than for $\pi^0$</td>
</tr>
</tbody>
</table>
STAR Forward Pion Detector (FPD)

- STAR forward calorimeters have gone through significant upgrades since run3.
- In run6, the original FPD remained in the east, while the west FPD was expanded to FPD++.
- The east FPD is consisted of two 7X7 Pb-glass modules, EN and ES. During run6, it was placed at x-offset~30cm, $<\eta>$~3.7.

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

$\langle x_F, <p_T> \rangle$ in $x_F$-bins

- $\triangle <\eta>=3.3$
- $<\eta>=3.7$
- $<\eta>=4.0$

*arXiv:0801.2990v1 [hep-ex]*
At $\sqrt{s}=200\text{GeV}$, $\pi^0$ cross-section measured by STAR FPD is consistent with the NLO pQCD calculation. Results at $<\eta>=3.3$ and $<\eta>=3.8$ have been included in the DSS global pion fragmentation function analysis. (Phys.Rev.D75(2007) 114010)

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \approx \frac{1}{P} \frac{\sqrt{N^{S\downarrow}} - \sqrt{S^{N\downarrow}}}{\sqrt{N^{S\downarrow}} + \sqrt{S^{N\downarrow}}}$$

We find that $A_N$ increases with $x_F$, roughly consistent with theoretical predictions. Contrary to predictions, however, $A_N$ does not fall as a function of $p_T$ at fixed $x_F$ in this kinematic region.
Acceptance and Reconstruction

7x7 FPD has limited acceptance for Eta mesons. At 40GeV, a symmetrically decaying Eta needs to point to the center of the FPD to fit in. Acceptance improves greatly at higher energy.

The reconstruction efficiency for $\pi^0$ starts to drop at $E>60$GeV, where the separation between two photons for symmetric decay becomes $\sim 1$ cell width.
Event Selection and Mass Reconstruction

Di-Photon Center of Mass Distributions

\[ \tan(\phi) \]

\begin{align*}
\text{Entries} & \quad 612759 \\
\text{Mean} x & \quad -3.691 \\
\text{Mean} y & \quad -0.001397 \\
\text{RMS} x & \quad 0.08792 \\
\text{RMS} y & \quad 0.07458
\end{align*}

\( 0.07 \text{GeV} < \eta_p < 0.3 \text{GeV} \)

\[ \langle \eta_{\text{pion}} \rangle = -3.691 \]

\[ \eta \text{ mass region with Center Cut in red} \]

\[ \tan(\phi) \]

\begin{align*}
\text{Entries} & \quad 19187 \\
\text{Mean} x & \quad -3.664 \\
\text{Mean} y & \quad 0.0005996 \\
\text{RMS} x & \quad 0.06999 \\
\text{RMS} y & \quad 0.07072
\end{align*}

\( 0.47 \text{GeV} < \eta_p < 0.62 \text{GeV} \)

\[ \langle \eta_{\text{eta}} \rangle = -3.664 \]

\[ \pi^0 \text{ mass region with Center Cut in black} \]

Event Cuts

- 2 photon events
- \( E_{\text{total}} > 25 \text{GeV} \)
- Hardware threshold nominally at 25GeV
- “Center Cut” for \( 2\gamma \) CoM defined as
  \[ (\eta - 3.65)^2 + \tan(\phi)^2 < (0.15)^2 \]
- \( m_{\gamma\gamma} = E_{\text{tot}} \sqrt{1 - (Z_{\gamma\gamma})^2} \frac{\sin \theta}{2} \)
  - Etot: Detector summed energy
  - \( Z_{\gamma\gamma} \) and photon separation: Fitted photon energy/locations
- Reconstructs on the entire FPD
- Vertex set at zero for all events
$\eta$ and $\pi^0$ Energy Sharing ($Z_{\gamma\gamma}$) Distribution

$$Z_{\gamma\gamma} = \frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}}$$

$\pi^0$ mass region with Center Cut

Energy Sharing Distribution, $0.085 < M_{\gamma\gamma} < 0.185$, Center Cut

$p_{T}$, $p_{T}$

Events

$10^4$

$10^3$

$10^2$

$10$

$0$

$0.1$

$0.2$

$0.3$

$0.4$

$0.5$

$0.6$

$0.7$

$0.8$

$0.9$

$1$

$Z_{\gamma\gamma}$

Eta mass region with Center Cut

Energy Sharing Distribution, $0.48 < M_{\gamma\gamma} < 0.62$, Center Cut

$p_{T}$, $p_{T}$

Events

$10^3$

$10^2$

$10$

$0$

$0.1$

$0.2$

$0.3$

$0.4$

$0.5$

$0.6$

$0.7$

$0.8$

$0.9$

$1$

$Z_{\gamma\gamma}$
Observation of Eta Signal

Di-Photon Invariant Mass Spectra in 3 Energy Bins

- Center Cut
- 3 columns for 3 energy bins
- Each column shows a single plot in log and linear scale.

$\pi^0$ Mass Cut

$0.085 \text{ GeV} < M_{\gamma\gamma} < 0.185 \text{ GeV}$

Eta Mass Cut

$0.48 \text{ GeV} < M_{\gamma\gamma} < 0.62 \text{ GeV}$

$A_N(x_F)$ will be reported for di-photon events in these two shaded mass regions. We will not here separate possible contributions from backgrounds under the Eta and $\pi^0$ peaks.
Mass Dependence of $A_N$

$\sqrt{s} = 200 \text{GeV}$

$p^+ + p \rightarrow M + X\hspace{1cm} M \rightarrow \gamma + \gamma$

1. $N_{\text{photon}} = 2$
2. $E_{\text{total}} > 40 \text{GeV}$
3. No Center Cut
4. Average Yellow Beam Polarization = 56%

- Yellow beam asymmetry clearly reveals the shape of two mass resonances.

- There is an “asymmetry valley” in between $\pi^0$ and $\eta$ mass regions.
$A_N(x_F)$ in $\pi^0$ and Eta Mass Regions

1. $N_{\text{photon}} = 2$
2. Center Cut ($\eta$ and $\phi$)
3. Pi0 or Eta mass cuts
4. Average Yellow Beam Polarization = 56%

For $0.55 < X_F < 0.75$, the asymmetry in the $\eta$ mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the $\pi^0$ mass region.

$\langle A_N \rangle_\eta = 0.361 \pm 0.064$
$\langle A_N \rangle_\pi = 0.078 \pm 0.018$
Summary

1. Previously, the STAR Forward Pion Detectors at RHIC (Brookhaven National Laboratory) have been used to successfully measure the forward single spin asymmetry, $A_N$, for $\pi^0$ meson in $<\eta>=3.3~4.0$ region.

2. In RHIC run 6, during $\sqrt{s}=200$ GeV $p+p$ collisions, $\pi^0$ and Eta mesons were observed in the east FPD. We measured and compared the single spin asymmetry in the $\pi^0$ and the Eta mass regions, at $<\eta>\sim3.65$ and $x_F$ above 0.4.

3. $A_N$ as a function of the invariant mass reveals $\pi^0$ and Eta resonance peaks.

4. From 55GeV to 75GeV, ($x_F=0.55~0.75$) the average transverse single spin asymmetry in the Eta mass region was measured to be $A_N = 0.361 \pm 0.064$, about 4 standard deviations greater than the average $A_N$ in the $\pi^0$ mass region.

5. Preliminary estimates of possible systematic effects show that the systematic uncertainties are considerably smaller than the statistical uncertainties.