Transverse single spin asymmetry and cross-section for forward $\pi^0$ and $\eta$ mesons at STAR

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Abstract. The STAR collaboration has reported a large transverse single spin asymmetry, $A_N$, for forward $\pi^0$ meson production. The cross-section in this region was measured up to $x_F$ of 0.55, and found to be consistent with pQCD predictions. During RHIC running in the year 2006 (6.8 $pb^{-1}$, 60% average polarization), an even larger $A_N$ was observed in the mass region of the $\eta$ meson at forward rapidity for $x_F > 0.5$. Understanding these large spin asymmetries requires information on the production cross-section. The preliminary result for the cross-section ratio between $\pi^0$ and $\eta$ up to $x_F$ of 0.75 is presented. All data were collected by the STAR Forward Pion Detector during $\sqrt{s} = 200$ GeV polarized p+p collisions at RHIC.

1. Introduction
Large transverse single spin asymmetry ($A_N$) for forward meson production has been observed in previous experiments, most notably FNAL E704 [1,2] with center of mass energy of 19.4 GeV. Over the years, several theoretical models have been developed in the framework of perturbative QCD, the best known of which are the Collins effect [3,4] and the Sivers effect [5]. Both models introduce small spin dependent transverse momentum ($k_T$) that generates the observed spin asymmetry. For the Collins effect, the extra $k_T$ comes from the transversity dependence of the jet fragmentation. The asymmetry is in the hadronization relative to the jet axis, and full jet reconstruction would suppress it. For the Sivers effect, the extra $k_T$ comes from the spin dependent initial state parton distribution function. The asymmetry is not confined to hadronic final states, and di-jets and $\gamma$-jets would not be back to back.

2. Transverse single spin asymmetry and cross-section for forward $\pi^0$ and $\eta$
STAR Forward Pion Detector (FPD) is a modular lead glass calorimeter positioned at very forward regions of the STAR wide angle hall. The main modules for each side were two 7x7 lead glass arrays positioned on both sides of the beam pipe. The distance from the modules to the beam was varied to sample a range of pseudo-rapidity points from 3.3 to 4.1.

STAR has reported both cross-section [6] and transverse single spin asymmetry ($A_N$) for forward neutral pion production [7]. Cross-section was measured at pseudo-rapidity of 3.3, 3.8, and 4.0. $A_N$ was measured at pseudo-rapidity of 3.3 and 3.7. The data were collected during RHIC run 3, 5 and 6 polarized proton runs with $\sqrt{s}$=200 GeV.
As shown in the left-hand panel of figure 1, the $\pi^0$ cross-section at $\eta=3.3$ and 3.8 were found to be in good agreement with the NLO pQCD predictions. In the same kinematic region, $A_N$ was found to be large and positive as seen in the right-hand panel of figure 1. Also shown are two QCD based theory curves, which predict the $x_F$ dependence of $A_N$ reasonably well. On the other hand, the $p_T$ dependence of $A_N$, as shown in figure 2, was found to be at odds with all current theoretical predictions. While theory in general expects $A_N$ to fall with increasing $p_T$, we found the opposite trend that was confirmed by the more recent STAR preliminary result from RHIC run 8.

In addition to the $\pi^0$, we observed $\eta$-mesons in the east FPD during RHIC run 6. Due to the relatively small physical size of the main FPD modules, ($\sim$27 cm square) acceptance

**Figure 1.** LEFT: $\pi^0$ invariant cross-section at $\sqrt{s}=200$ GeV [4]. RIGHT: Transverse single spin asymmetry ($A_N$) vs. $x_F$ for forward $\pi^0$ production [7].

**Figure 2.** Transverse single spin asymmetry ($A_N$) vs. Transverse momentum ($p_T$) for forward $\pi^0$ production. Black points have been published [7], while red points are preliminary [9]. Inner error bars are statistical errors, while outer error bars include both statistical and systematic errors.
Figure 3. Di-photon invariant mass distributions ($M_{\gamma\gamma}$) in energy bins. The upper three panels are in log scale. The bottom three panels show the corresponding distribution in linear scale to emphasize the $\eta$-meson signal.

for the $\eta$-mesons was very limited at the range of $x_F$ where previous $\pi^0$ measurements were made. ($x_F < 0.5$) However, at higher $x_F$, ($x_F > 0.5$) we found a sizable $\eta$-meson signal around the pseudo-rapidity of 3.7 through $\eta \rightarrow \gamma\gamma$ channel. These were mostly $\eta$'s that were heading towards the center of the detector, and decayed symmetrically. Figure 3 shows the di-photon invariant mass distribution in three energy bins from 40 GeV to 70 GeV. The contamination from the decays of heavier particles was minimal, as the opening angle for such decays would be too large for the FPD. With this signal, we were able to measure the single spin asymmetry for the forward $\eta$-meson production for the first time at $\sqrt{s} = 200$ GeV, up to $x_F$ of 0.7. The data were collected from RHIC run 6 transversely polarized proton collisions, with integrated luminosity of $6.8$ pb$^{-1}$. Average polarization for the projectile proton beam was 56%.

The left-hand panel of figure 4 shows the preliminary result for transverse single spin asymmetry ($A_N$) as a function of the di-photon invariant mass. There is a clear structure in $A_N$ that resembles the mass spectrum, with an asymmetry valley separating the two mass resonances. The right-hand panel of figure 4 shows the $A_N$ as a function of $x_F$ within the $\pi^0$ and $\eta$ mass regions. Despite the large statistical errors for high $x_F$ bins, the surprisingly large $A_N$ within the $\eta$ mass region makes the measurement significant. The average asymmetry for the $\eta$ mass region above $x_F=0.55$ is 4 standard deviation greater than that of the $\pi^0$. The result does not include background corrections, and therefore should be interpreted as average $A_N$ in the given mass region. Systematic errors have not been calculated, but is expected to be smaller than the statistical errors. Similar measurement had been made by FNAL E704, which found the $A_N$ for $\eta$-meson to be greater than $\pi^0$ for $x_F > 0.4$, albeit with little significance [8].

In order to better understand the large asymmetries, we need to understand the corresponding cross-sections. Previous $\pi^0$ cross-section and asymmetry measurements were made at $x_F$ less than 0.55. The reconstruction algorithm used for these analyses had been tailored to the $\pi^0$'s in this $x_F$ range, where the separation between the two photons is on average greater than
Figure 4. LEFT: $A_N$ vs. di-photon invariant mass. Shaded regions indicate the mass cuts for $\pi^0$ and $\eta$. RIGHT: $A_N$ vs. $x_F$ for the $\pi^0$ and $\eta$ mass regions, with 56% beam polarization. The dotted lines indicate weighted mean $A_N$ for $x_F > 0.55$, with the corresponding shaded area indicating the error of the mean.

In order to increase the $x_F$ reach of the previous $\pi^0$ cross-section measurement, as well as to improve the energy calibration for these high $x_F$ events, substantial reworking of the reconstruction algorithm was necessary. Significant improvements were made in position resolution for photons, energy and separation accuracy for $\pi^0$'s, and $\pi^0 - \gamma$ separation at high $x_F$.

At the time of SPIN2010, there still remained important discrepancies between data and Geant based detector simulation. First, the shower shape in Geant was broader than what was seen in the data, which limited accuracy in di-photon separation. Second, we could not reproduce in Geant the energy dependent gain shift seen in the data, which tended to shift the $\pi^0$ mass higher as the energy of the $\pi^0$ increased. These discrepancies significantly limited our confidence in energy measurement at high $x_F$, which led to large uncertainties not only in absolute calibration, but also in relative energy scale between $\pi^0$ and $\eta$. Systematic error in the cross-section ratio was dominated by the latter, and it was estimated by looking at the possible cases of severe mis-calibrations. The preliminary result for $\eta / \pi^0$ cross section ratio is shown in figure 5.

Since we produced the preliminary result, we have found that the data-simulation discrepancies can be largely resolved by an alternative method of constructing the Geant electromagnetic shower. Instead of using charged particle energy loss, the shower is formed by propagating Cerenkov photons through the Pb glass, and counting them at photo-cathode. The relativistic nature of Cerenkov process results in a narrower shower profile, while the longitudinal shifting of shower max, coupled to the attenuation of optical light, produces the energy dependent gain shift.
3. Summary
We have shown that $A_N$ for forward $\pi^0$ production continues to be large at RHIC energy, where we can rely on pQCD to describe the cross-section. Our results suggest that while QCD based models can describe the $x_F$ dependence of $A_N$, they fail to predict the observed $p_T$ dependence. We have also reported the first measurement of $A_N$ for forward $\eta$-meson production at RHIC energy, and found evidence that it is significantly larger than that of the $\pi^0$ around pseudo-rapidity of 3.7. The analysis to measure the cross-sections for $\pi^0$ and $\eta$ is in progress, and we have presented the preliminary result for $\eta / \pi^0$ cross section ratio. The systematics were driven by data-simulation discrepancies, which have since been largely resolved. We aim to measure the absolute cross-section for $\pi^0$ and $\eta$ for $x_F > 0.5$ in the near future.

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