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Transverse Single-Spin Asymmetries of Midrapidity Eta Mesons at PHENIX

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Transverse single-spin asymmetries (TSSAs) of proton-proton collisions have a long history of revealing the richness of QCD. Large TSSAs were originally discovered in fixed target experiments in the mid 1970s, but have been found to persist in collisions up to $\sqrt{s} = 510$ GeV and transverse momenta up to about 7 GeV/c. This is well into the perturbative regime of QCD and yet their origin remains poorly understood. The large TSSA measurements led to the development of both transverse momentum dependent descriptions and collinear twist-3 descriptions of nonperturbative spin-momentum correlations in the nucleon as well as in the process of hadronization. As hadrons, eta mesons are sensitive to both initial- and final-state nonperturbative effects for a mix of parton flavors. Their comparison to neutral pions may provide information on potential effects due to strangeness, isospin, or mass. The status of the TSSA of eta mesons at midrapidity for 200 GeV proton-proton collisions from the PHENIX 2015 data set will be shown.

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1. Introduction

Hadron transverse single-spin asymmetries study $p^{\uparrow}+p \rightarrow h+X$ collisions and measure the azimuthal asymmetry in the yields of h with the respect to the proton spin direction:

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \tag{1.1}$$

In 1978 it was shown that if these asymmetries were only caused by perturbative QCD effects they would be less than one percent [1], but TSSAs have been measured to be as large as 40% and consistent over a wide range of collision energies [2, 3, 4, 5, 6, 7]. Because the perturbative part of the calculation cannot account for the measured large spin-momentum correlations, we must reexamine the nonperturbative part.

One proposed explanation for these large TSSA are Transverse Momentum Dependent (TMD) functions. Instead of integrating over the internal parton dynamics like traditional collinear nuclear structure functions, TMD functions explicitly depend on the internal, nonperturbative transverse momentum k_T of the partons within the proton in addition to the hard scale Q. In order for TMD factorization to apply k_T^2 must me much smaller than Q^2 and so any direct measurement on a TMD functions must be a two scale process that is sensitive to both k_T and Q. For example in polarized semi inclusive deep inelastic scattering (SIDIS) ($l+p^{\uparrow} \rightarrow l'+h+X$) the hard scale Q is calculated from the lepton's final energy and scattering angle and the transverse momentum of the hadron h can be used for the soft scale (provided it is small enough). In SIDIS it is also possible to isolate the effects from particular TMD functions by measuring the angular moments. For example the Sivers functions manifests itself as a $\sin(\phi - \phi_s)$, where ϕ is the azimuthal angle of the hardron momentum $\mathbf{P}_h$ with respect to the scattering lepton plane and ϕ_s is same but for the the proton target's transverse spin $\mathbf{S}_T$. There is some indication that the Sivers asymmetry might be slightly larger for K^+ mesons than for π^+, which might indicate larger spin-momentum correlations for strange quarks in the proton [8].

Transverse single-spin asymmetries have been measured to be as large as 40% for $p^{\uparrow}+p \rightarrow \pi^0+X$ with p_T as high as 7 GeV [7], well into the perturbative regime of QCD. TSSAs in proton-proton collisions uncovered the need for a TMD framework, but unfortunately inclusive particle production in hadronic collisions is not sensitive to the soft scale k_T and only a single scale hadron p_T is available to be used as proxy for the hard scale. However, there is an alternative to the TMD framework in the higher twist functions. Traditional PDFs and FFs are twist-2 and only consider interactions with one parton in the bound state at a time. Twist-3 functions in the proton and in hadronization calculate the effects due to the quantum mechanical interference of interacting with one parton versus interacting with two partons at the same x. They can be used to describe the spin-momentum correlations and are related to k_T moments of twist-2 TMD PDFs [9] and fragmentation functions. But since they do not explicitly depend on k_T, twist-3 functions can be used to calculate spin-momentum correlation in $p^{\uparrow}+p \rightarrow h+X$ when p_T^h is sufficiently large. Twist-3 spin-momentum correlations have been shown to successfully predict the behavior of TSSA, such as in Ref. [10] where both a twist-3 polarized PDF and a twist-3 fragmentation function were use to successfully predict both the sign and approximate amplitude of the STAR forward π^0 asymmetry at $\sqrt{s} = 500$ GeV.

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2. Analysis

The Relativistic Heavy Ion Collider (RHIC) is the only collider in the world that can run polarized proton beams, allowing for TSSAs to be measured at high energies. This is made possible by the Siberian snakes that are located 180° apart along the ring that maintain the polarization in both proton beams for hours at a time. In order to avoid systematic effects, the polarization direction can switch between bunches: up to the sky or down to the ground. PHENIX is one of the large multipurpose detectors located around the RHIC ring. This analysis looks at $\eta \to \gamma\gamma$ decays and uses data from the central electromagnetic calorimeter (EMCal) which has an acceptance of $|\eta| < 0.35$ and two nearly back-to-back arms that each cover $\Delta\phi = \pi/2$ in azimuth. Six out of eight of the sectors are made of lead scintillator towers and the other two are made of lead glass and located on the bottom east side of the detector. This measurement uses the transversely polarized proton-proton data set from 2015, which had an integrated luminosity of $60pb^{-1}$ and uses a trigger that selects for high energy clusters.

Transverse single-spin asymmetries generally measure the asymmetry as a function of ϕ and then fit a sinusoid in order to extract the amplitude. But because of the limited azimuthal acceptance of the PHENIX central arms, midrapidity TSSA measurements at PHENIX generally integrate over both sides of the detector and perform an azimuthal correction:

$$A_N = \frac{1}{\langle|\cos\phi\,|\rangle}\frac{1}{P}A_N^{raw} \tag{2.1}$$

In this formula $\phi = 0$ is at a right angle to proton spin direction where the asymmetry is maximal. The acceptance correction $\langle|\cos\phi\,|\rangle$ is used to correct for the dilution to the asymmetry from being measured over such a large range in ϕ. This correction is calculated for either side of the EMCal separately and also a function of p_T. The asymmetry is also diluted by the proton bunches not being 100% polarized, and so it must be divided by the polarization of the beam P which for this data set was on average 57%.

This result uses the relative luminosity formula which measures the asymmetry in counts of photon pairs for when the beam was polarized up versus down for one side of the EMCal at a time:

$$A_N^{raw} = \frac{N_L^{\uparrow} - R\cdot N_L^{\downarrow}}{N_L^{\uparrow} + R\cdot N_L^{\downarrow}} \tag{2.2}$$

Here the up and down arrows refer to spin orientation of the beam and the subscript L refers to counts to the left of the polarized beam going direction. There is an equivalent formula for the right side, but the signs in the numerator are flipped to such that the TSSA remains a left-right asymmetry. Because the relative luminosity formula takes the ratio of counts coming from the same detector, effects from detector acceptance and efficiency cancel out. Thus this calculation only needs to be corrected for the relative luminosity of the different beam configurations: $R = L^{\uparrow}/L^{\downarrow}$. This is calculated by using the number of events that fired the minimum bias trigger from bunches where the polarization direction was spin up divided by the number of events that fired the same trigger when the bunches we spin down.

2.1 Systematic Studies

As mentioned before, proton-proton collisions at RHIC have both beams polarized and the polarization direction can be varied bunch to bunch. Thus the asymmetry can be calculated once by keeping track of the polarization direction for only the beam traveling clockwise through the PHENIX detector, effectively averaging over the polarization of the beam traveling counterclockwise. Then the asymmetry can be recalculated by considering the polarization orientation of the counterclockwise beam and averaging over the polarization of the clockwise beam. These two results are compared to verify that they are consistent, but these two separate asymmetry measurements are also statistically independent and are averaged together for the final result.

The square root TSSA formula is used as an additional cross check where effects from both relative luminosity and detector acceptance and efficiency cancel out to first order. The differences in the result between this formula and the relative luminosity formula are used as an estimate of the systematic error:

$$A_N^{raw} = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} N_R^{\uparrow}}} \tag{2.3}$$

Another cross check is to find the $\cos\phi$ modulation. Here the asymmetry is calculated as a function of ϕ (where $\phi = 0$ is at a right angle to proton spin direction) and then fit to a sinusoidal function to measure asymmetry:

$$A_N * P * \cos\phi = \frac{N^{\uparrow}(\phi) - R \cdot N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + R \cdot N^{\downarrow}(\phi)} \tag{2.4}$$

This formula is only used as a cross check because it is not an optimal way to measure this asymmetry. Even ignoring PHENIX's limited central acceptance, this asymmetry is consistent with zero and also statistically limited.

2.2 Background Correction

As shown in Figure 1, even though the diphoton invariant spectrum had a clear resonant peak for $\eta \to \gamma\gamma$ decays, there was still a significant contribution form combinatorial background. Thus the asymmetry of this background must be measured and subtracted from the peak asymmetry:

$$A_N^S = \frac{A_N^{S+B} - rA_N^B}{1-r} \tag{2.5}$$

In this formula S stands for signal and B stands for background and $r = N^B/(N^B + N^S)$ is the background fraction, the fraction of photon pairs within the invariant mass peak that come from the combinatorial background. The A_N^{S+B} asymmetry is calculated with photon pairs with invariant mass $480 < M_{\gamma\gamma} < 620$ MeV (the blue region in Figure 1) and the A_N^B asymmetry is calculated using photon pairs with invariant mass $300 < M_{\gamma\gamma} < 400$ MeV or $700 < M_{\gamma\gamma} < 800$ MeV (the red regions in Figure 1). The background fraction r is estimated from a fit to the invariant mass spectrum, using a Gaussian for the signal and a third degree polynomial to approximate the background. The background fraction is calculated as a function of p_T and also separately for each side of the EMCal.

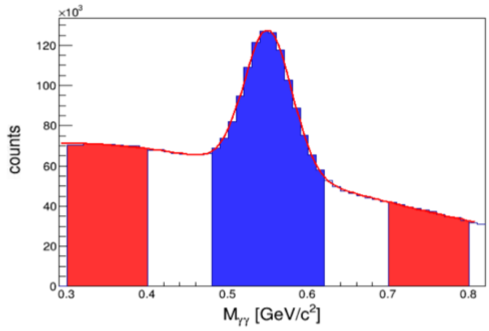

Figure 1: Example invariant mass spectrum for photon pairs in the West Arm with $4 < p_T < 5$ GeV

3. Results

The left panel of Figure 2 shows this new result plotted with the older PHENIX midrapidity TSSA η meson result from 2012 data [11]. This updated result is a factor of about 3 to 4 increase in precision. The plot of the right side of Figure 2 is this same updated result but with a smaller range on the y-axis. It shows that the asymmetry is consistent with zero to within 0.005 at low p_T, but it may indicate some hint of a trend. More data will be needed to draw more concrete conclusions.

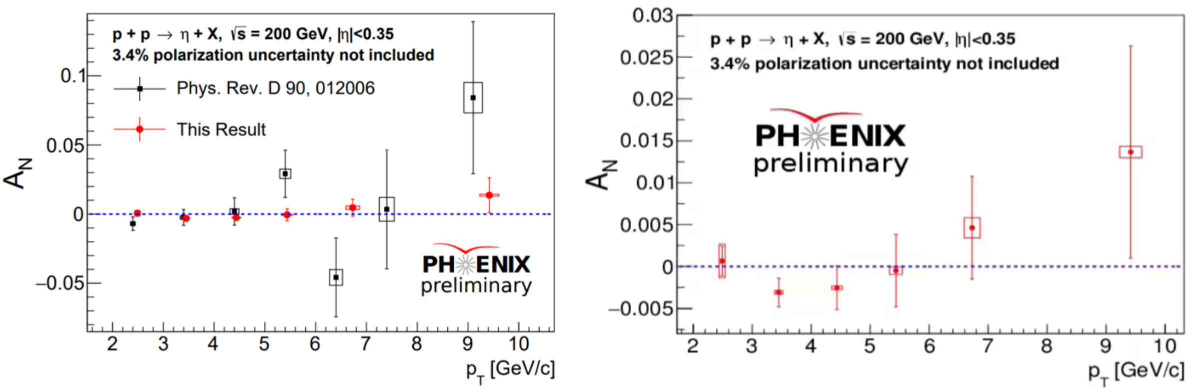

Figure 2: TSSA of midradpity η mesons at $\sqrt{s} = 200$ GeV from PHENIX 2015 data

π^0 and η mesons are both flavorless, pseudoscalars that can decay into two photons. But given the difference in quark composition: $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ and $\eta = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$, differences seen in $A_N^{\pi^0}$ and A_N^{η} can provide insights into the role that strangeness and isospin play in fragmentation. Also since the η meson is four times heavier than the π^0, differences in π^0 and η results could also point to the role of hadron mass in nonperturbative final state effects. PHENIX's most recent midrapidity results showed that $A_N^{\pi^0}$ was consistent with zero to within 10^{-4} at low p_T [12].

4. Conclusion

Transverse single-spin asymmetries probe parton dynamics in both initial- and final-state effects. Traditional twist-2 collinear nonperturbative functions cannot account for the large spin-momentum correlations that have been observed in prior experiments. Transverse momentum dependent functions study the effects from initial-state partons and final-state hadrons having some nontrivial, soft-scale transverse momentum. Twist-3 collinear functions study the quantum interference between having only one active parton per bound state versus having two. They can be more easily compared to measurements that are only sensitive to a single hard-scale energy. This document shows the η A_N PHENIX result at midrapidity and $\sqrt{s} = 200$ GeV. It is consistent with zero and when compared with the previous PHENIX result, is an improvement in and improves the precision by a factor of about 3 to 4. It will help constrain twist-3 collinear functions and is sensitive to the impact of strangeness on these functions.

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