Cold QCD physics with STAR at RHIC

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Our group continues to play a major role in the STAR spin physics program. Over the past year, our analysis efforts have focused on two measurements: the Collins effect in 200 GeV *p*+Au collisions and an investigation of the contribution from diffractive processes to the large transverse single-spin asymmetry, A_N, that is seen for forward rapidity electromagnetic jets (EM-jets) in 200 GeV *pp* collisions. In addition, the paper describing the STAR measurements of the Collins effect in 200 GeV *pp* collisions, based on data that STAR recorded during 2012 and 2015, was published [1]. Dr. Gagliardi and his former post-doc, T. Lin, carried the full responsibility for the 2015 data analysis as well as the process of merging the 2012 and '15 results together. Notably, the latter required calculation of several corrections and systematic uncertainties for the 2012 data to account for differences in the basic analysis procedures between the two years. Drs. Gagliardi and Lin were two of the five principal authors. Dr. Gagliardi also played a significant role in the preparation of the RHIC Cold QCD White Paper for input to the upcoming NSAC Long-Range Plan [2]. In addition, group members have continued to carry a wide range of administrative responsibilities for STAR.

Our graduate student B. Aboona is analyzing data that STAR recorded during 2015 to determine the size of the Collins effect in $\sqrt{s_{NN}}$ = 200 GeV *p*+Au collisions. This will provide unique insight into the possible factorization breaking that has been predicted for transverse-momentum-dependent phenomena in hadronic collisions, in addition to a spin-dependent probe of the hadronization mechanism in cold nuclear matter.

Last year's report discussed the completion of incorporating B. Aboona's improvement to start-less TOF into the data structure at STAR. The first level of data structure at STAR is called StEvent, which is then further processed into MuDst files. MuDst's can be further processed into PicoDst's or jet trees. B. Aboona's improvements were incorporated in the MuDst, PicoDst, and jet tree data structures. For the purpose of the Collins analysis, jet trees will be used as the input data structure. He also reported the completion and documentation of the quality assurance analysis of the 2015 $\sqrt{s_{NN}}$ = 200 GeV *p*+Au data set.

A very important step in the *p*+Au Collins effect analysis is to be able to perform high quality particle identification (PID). STAR primarily relies on *dE/dx* information from the Time Projection Chamber (TPC) for PID. Previous reports have discussed details of B. Aboona's improvements to the "start-less" Time of Flight (TOF) algorithm. This algorithm makes use of measurements obtained from the Barrel Time of Flight (BTOF) detector to provide complementary PID to the *dE/dx* information from the TPC. Developing a robust and high quality PID scheme requires a detailed understanding of the response of the PID quantities commonly used in STAR analyses. PID from the TPC is obtained by using a quantity known as n_σ. This quantity returns the difference between the measured and the calculated *dE/dx* of a track in units of resolution, σ. For example, a reconstructed track whose $n_\sigma(\pi)\sim 0$ is very likely to be a pion. Similarly, PID from TOF is obtained by using $n_{\sigma,TOF}$. Here, the quantity returns the difference between the measured and the calculated time of flight of a given track divided by the TOF resolution.

B. Aboona conducted a study of $n_\sigma(e)$ and $n_{\sigma,TOF}(e)$ obtained from the progeny particles of conversion photons. The results are plotted in 8 psuedorapidity (η) bins in the range $-1.33 \leq \eta < 1.33$ and 7 variable momentum bins in the range $1 \leq p < 10$ GeV/c. The left side of Fig. 1 shows the $n_\sigma(e)$ distribution for both the raw unlike-sign (US) and like-sign (LS) lepton pairs in the η and momentum bins $0.33 \leq \eta < 0.67$ and $2 \leq p < 2.5$ GeV/c, respectively. On the right, Fig. 1 shows the corrected US $n_\sigma(e)$, which is obtained by subtracting the LS $n_\sigma(e)$ distribution from the raw US $n_\sigma(e)$. The corrected US $n_\sigma(e)$

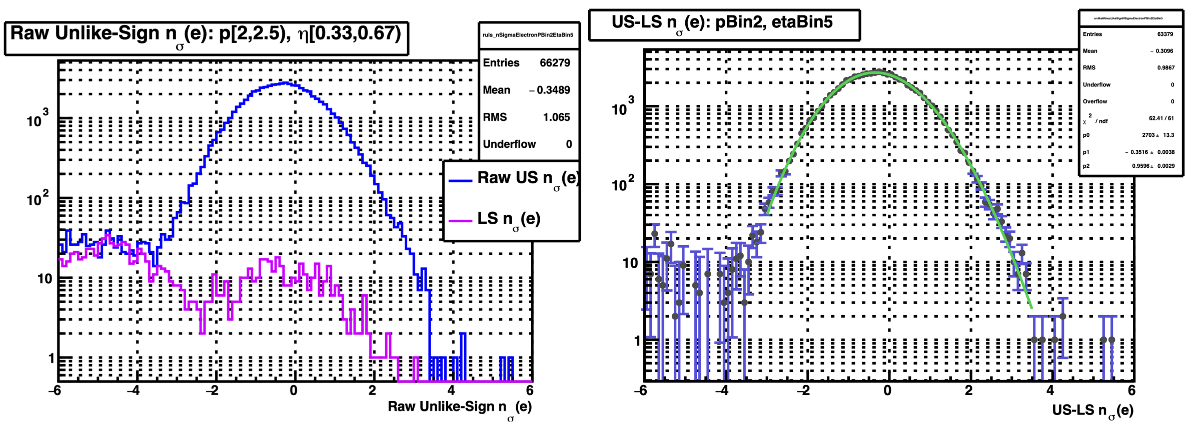

Fig. 1. The plot on the left shows the $\boldsymbol{n_\sigma(e)}$ distributions for raw unlike-sign (US) lepton pairs in blue and the like-sign (LS) lepton pairs in magenta for the momentum bin $\mathbf{2 \leq p < 2.5}$ GeV/c and $\boldsymbol{\eta}$ bin $\mathbf{0.33 \leq \eta < 0.67}$. The plot on the right shows the background-subtracted US $\boldsymbol{n_\sigma(e)}$ distribution fitted with a skewed Gaussian function over the range $\mathbf{-3 < n_\sigma(e) < 3.5}$.

is fitted with a skewed Gaussian function over the range $-3 < n_\sigma(e) < 3.5$. Equation 1 gives the functional form adopted for the skewed Gaussian. A constant value for the skew parameter, b, is found to work very well over the full momentum and pseudorapidity range. Also, the value of b that is found for electrons also works well for pions, kaons, and protons. Fig. 2 shows the same procedure for $n_{\sigma,TOF}(e)$. However, a correlated double Gaussian function of the form described in Eq. 2, where α, μ_2, and σ_2 are constants, is used to fit the corrected US $n_{\sigma,TOF}(e)$ distribution shown on the right in Fig. 2. The fit performs very well over the range $-4 < n_{\sigma,TOF}(e) < 4$.

$$f(x) = Ae^{-\frac{1}{2}\left[\frac{x-\mu}{\sigma+b(x-\mu)}\right]^2} \qquad (1)$$

$$f(x) = A_1\left[e^{-\frac{1}{2}\left(\frac{x-(\langle x\rangle-0.085)}{\sigma_1}\right)^2} + \alpha e^{-\frac{1}{2}\left(\frac{x-(\langle x\rangle-0.085+\mu_2)}{(\sigma_1+\sigma_2)}\right)^2}\right] \qquad (2)$$

B. Aboona has also made significant progress in understanding the n_σ and $n_{\sigma,TOF}$ response of pions, kaons, and protons. For this study, he utilizes two-dimensional log-likelihood fits. Since, to first order, the TPC and TOF measurements are independent, the functional form of the two-dimensional fit is then given by the product of the skewed Gaussian, Eq. 1, and the correlated double Gaussian, Eq. 2, found

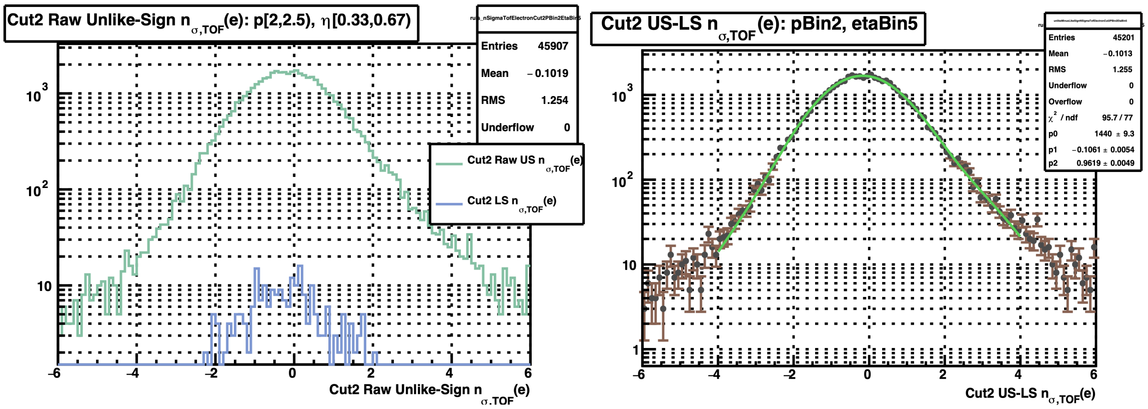

Fig. 2. The plot on the left shows the $\boldsymbol{n_{\sigma,TOF}(e)}$ distributions for raw unlike-sign (US) lepton pairs in green and the like-sign (LS) lepton pairs in blue for the momentum bin $\boldsymbol{2 \leq p < 2.5}$ GeV/*c* and $\boldsymbol{\eta}$ bin $\boldsymbol{0.33 \leq \eta < 0.67}$. The plot on the right shows the background-subtracted US $\boldsymbol{n_{\sigma,TOF}(e)}$ distribution fitted with a correlated double Gaussian function over the range $\boldsymbol{-4 < n_{\sigma,TOF}(e) < 4}$.

from his conversion photon studies. Fig. 3 shows an example of a two-dimensional fit for $n_\sigma(\pi)$ vs. $n_{\sigma,TOF}(\pi)$ in the momentum and η bins $2.8 \leq p < 2.9$ GeV/*c* and $-0.67 \leq \eta < -0.33$, respectively. Here, the pions are centered around zero on both axes, the background electrons are clustered above the pions,

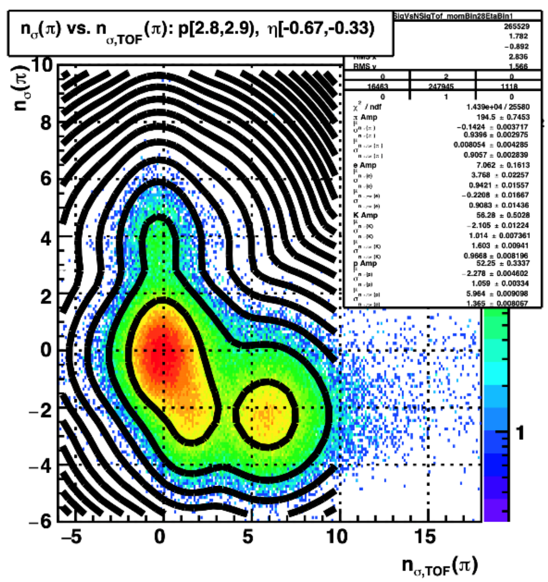

Fig. 3. An example of a two-dimensional fit for $\boldsymbol{n_\sigma(\pi)}$ vs. $\boldsymbol{n_{\sigma,TOF}(\pi)}$ in the $\boldsymbol{\eta}$ and momentum bins $\boldsymbol{-0.67 \leq \eta < -0.33}$ and $\boldsymbol{2.8 \leq p < 2.9}$ GeV/c, respectively.

the background kaons are below and slightly to the right of the pions, and the background protons are well separated on right with respect to the pions. These two-dimensional fits were done in multiple momentum bins ranging from $1 \leq p < 3.8$ GeV/*c*. A similar study is done for $n_\sigma(K)$ vs. $n_{\sigma,TOF}(K)$ and $n_\sigma(p)$ vs. $n_{\sigma,TOF}(p)$. A summary of the means of $n_{\sigma,TOF}(\pi, K, p)$ vs. *p*/m (or $\beta\gamma$) from all the momentum bins and the η bin $-1 \leq \eta < -0.67$ is shown in Fig. 4. This study has been well received by various groups in STAR and has broad impact beyond B. Aboona's analysis. The next step is to explore charge dependence in the $n_{\sigma}(\pi, K, p)$ and $n_{\sigma,TOF}(\pi, K, p)$ distributions.

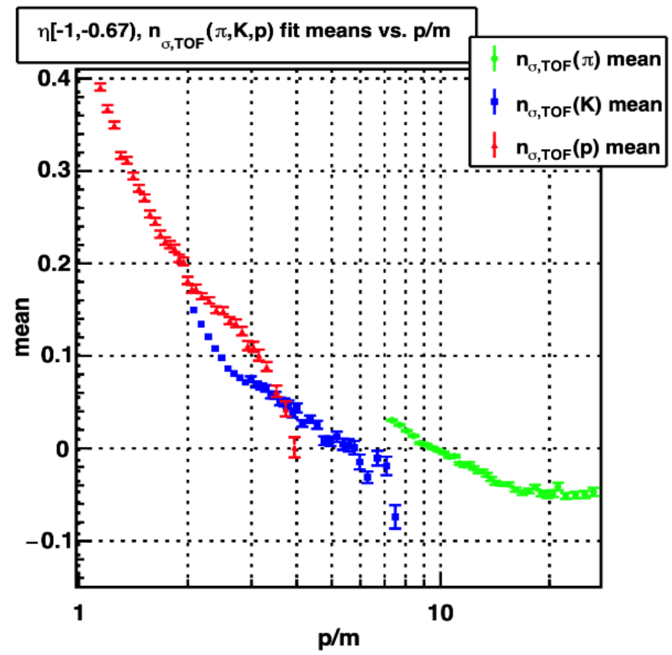

Fig. 4. Means of $\boldsymbol{n_{\sigma,TOF}(\pi, K, p)}$ vs. *p/m* (or $\boldsymbol{\beta\gamma}$) for the $\boldsymbol{\eta}$ bin $\boldsymbol{-1 \leq \eta < -0.67}$.

Recently, STAR published measurements of forward π^0 and EM-jet A_N [3] that indicate the large transverse single-spin asymmetries that have been seen for inclusive hadron production at forward rapidities are unlikely to arise from either the Collins or Sivers effects. This led to the question whether the large asymmetries might arise from diffractive processes. The UC-Riverside group began a study of EM-jets observed in *pp* data at $\sqrt{s}$ = 200 GeV that STAR recorded during 2015 to explore this question, and asked Dr. Gagliardi to join the effort. Two different diffractive processes have been investigated. In one case, A_N has been measured for the case where a moderate to high-p_T EM-jet and a low-p_T proton are both observed at forward rapidity, with the summed energy of the EM-jet and proton consistent with initial beam energy. The observed asymmetry appears to be negative, which is opposite in sign to the inclusive EM-jet asymmetry. In the other case, EM-jets that arise from single diffraction are being studied by measuring the probability that beam-like protons are seen in the opposite hemisphere. Random coincident protons make a spin asymmetry measurement difficult in this case. But it is straightforward to estimate and subtract the randoms to determine the fraction of EM-jets with a single-diffractive origin. Raw coincidence rates are now in hand. However, no physics conclusion can be drawn until detailed simulations are completed that are needed to correct the raw data for acceptance effects.

Finally, we continue to carry various administrative responsibilities for STAR. Dr. Gagliardi is a member of the STAR Trigger Board for RHIC Run 23. He also served on god parent committees for five STAR heavy ion papers. One of the five was published in EPJC [4], one is under review at JHEP [5], two are currently under Collaboration review, and one is approaching Collaboration review. In parallel, Mr. Aboona has served on the god parent committee for a STAR spin paper that was recently submitted to PRL [6].

[1] M.S. Abdallah *et al*. (STAR Collaboration), Phys. Rev. D **106**, 072010 (2022).
[2] E.C. Aschenauer *et al*., arXiv:2302.00605.
[3] J. Adam *et al*. (STAR Collaboration), Phys. Rev. D **103**, 092009 (2021).
[4] M.S. Abdallah *et al*. (STAR Collaboration), Eur. Phys. J. C **82**, 1150 (2022).
[5] STAR Collaboration, arXiv:2303.06590.
[6] STAR Collaboration, arXiv:2305.10359.