# 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 focus has been on measurements of the Collins effect in 200 GeV pp and p+Au collisions. In parallel, we played a substantial role in the completion, commissioning, and successful operation of the STAR Forward Upgrade during RHIC Run 22, which ran from November, 2021 to April, 2022.

The Collins effect involves the combination of the quark transversity in the proton and the Collins fragmentation function. It manifests itself as azimuthal modulations of identified hadrons about the axes of their parent jets. During the past year, we finalized the paper describing the STAR measurement of the Collins effect in 200 GeV *pp* data that were recorded during 2012 and 2015. The paper gives by far the most detailed look to date at the Collins asymmetry for pions in *pp* collisions, in addition to the first measurements ever of the Collins asymmetry for kaons and protons in *pp* collisions. Multi-dimensional binning provides the most precise determination to date of the kinematic dependence of the Collins fragmentation function. It also presents the most precise measurements to date of the Collins-like effect, which is sensitive to gluon linear polarization in transversely polarized protons, and the inclusive jet $A_N$, which at mid-rapidity is primarily sensitive to the gluon Sivers effect. The manuscript was approved by the STAR god parent committee in March. It was then submitted to *Physical Review D* in May [1] following the Collaboration review period. The principal authors are J.K. Adkins, J. Drachenberg, R. Fatemi, C.A. Gagliardi, and T. Lin.

Our graduate student B.E. 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 substantial progress made by Mr. Aboona to improve the particle identification capabilities of STAR by improving the start-less TOF algorithm. One of the improvements involved a *dE/dx* time correction for the pions used for start-time calculations. Since our report from last year, further improvements have been made to the *dE/dx* time correction. The correction now depends on the pseudorapidity of the track and the *z* location of the primary vertex for a given event. This provides a more robust correction to the start time when compared to our earlier correction, which involved only a constant factor. Notably, this modification has a substantial effect on the *pp* and *p*+Au data that STAR recorded during 2015 when the STAR Heavy Flavor Tracker (HFT) was in place.

During the past year, STAR finalized the calibrations for several energies of the Beam Energy Scan II program, which took data during 2019-21. After that, the final production to convert the data from raw hits into physics objects in micro- and pico-DSTs began. The first few beam energies are now complete, and the rest will be completed late in 2022. Mr. Bassam's start-less TOF algorithms are being used for all of these final data production passes.

After finalizing the improvement to start-less TOF, Mr. Aboona turned his focus to the initial steps in the p+Au Collins analysis. Mr. Aboona produced ROOT jet trees for the 2015 p+Au period that contain all the information needed for his Collins analysis. Prior to producing the jet trees, he made several edits to the standard jet tree routines. These edits included: making the appropriate changes to the codes to store the new start-less TOF information, adding user options that facilitate reducing the disk footprint of the jet trees by 30-40%, and fine tuning parameters for jets and particles in jets.

Mr. Aboona then performed a detailed Quality Assurance (QA) analysis of the 2015 p+Au dataset. STAR usually takes data in ~30-minute intervals; each interval is commonly referred to as a run. The QA process looked at means of various detector and physics quantities on a run-by-run basis to flag outlier runs with beam or detector issues that are difficult to simulate with the standard STAR GEANT routines. By looking at these time series plots and referring to shift log plots and notes during a given run, Mr. Aboona identified outlier runs to be excluded from the Collins analysis. As an example, Fig. 1 shows the z-coordinate of the collision vertex along the beam line as a function of run index. The plot shows three distinct jumps in the mean zvertex values. The jump at (a) corresponds to trigger configuration changes that had direct impact on zvertex. The jumps at (b) and (c) correspond to times when collider experts changed the z location of the collision point inside of STAR. Such information gained from the QA analysis will inform future steps in the Collins analysis, such as data simulations. Overall, the initial run list contained 973 runs, and the QA analysis rejected approximately 8% of the runs. Detailed notes have been made for the runs that have been rejected for future reference.

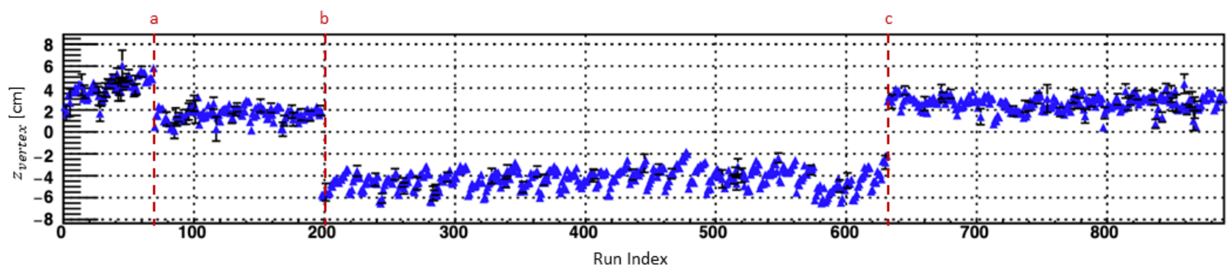


**Fig. 1**. Mean $z_{vertex}$ of the events (in cm) vs. run index for those 2015 p+Au runs that passed the QA process.

During the past year, we played a major role in the successful completion, commissioning, and data taking with the STAR Forward Upgrade during RHIC Run 22, which ran from November, 2021 to April, 2022. Dr. Gagliardi was onsite at Brookhaven for November and December, where he served as STAR Shift Leader for six weeks. During this time, he led the final cosmic ray commissioning of the Forward Silicon Tracker (FST) and small Thin Gap Chambers (sTGC). He also led the final commissioning of the FST, sTGC, and Forward Calorimeter System (FCS) with beam. STAR then took the first physics data with the Forward Upgrade during his last week on shift. Finally, he continued to monitor the entire system remotely throughout the rest of Run 22, including oversight during a number of special low-luminosity periods to optimize the gains of the FCS, determine the alignment of the FST and sTGC, and to measure minimum bias cross sections at forward rapidities. The latter will be used to tune the production of underlying event activity close to beam rapidity in Monte Carlo event generators.

Our major responsibility during the construction of the Forward Upgrade was to develop the trigger algorithms for the FCS. We identified distinct patterns of electromagnetic and hadronic calorimeter energy depositions characteristic of high-pT photons or electrons, hadrons, and jets. We also combined the calorimeter information with hits in the STAR Event Plane Detector (EPD) to distinguish electrons from photons. These various trigger primitives were then combined to produce 28 distinct triggers: 7 for jets with different pseudorapidities and pT thresholds, 2 for dijets, 3 for photons and $\pi 0$ with different pT thresholds, 3 for hadrons with different pT thresholds, 2 for Drell-Yan, 3 for J/ψ, and 8 for routine monitoring. During the run, four of the triggers were operated in "take-all" mode: the primary Drell-Yan trigger (which also provides most of the acceptance for J/ψ events in the Forward Upgrade), the highest-pT electromagnetic shower trigger, and two triggers designed to select ultra-peripheral J/ψ production where the one of the decay electrons falls within the acceptance of the Forward Upgrade and the other is detected by the STAR Endcap Electromagnetic Calorimeter. The remaining triggers were prescaled by various factors to fit into the available data acquisition bandwidth. Overall, STAR recorded slightly more than 10 billion Forward Upgrade events at an average rate of about 2 kHz, with a typical dead time of 8-10%. 1.9 billion of those events also included read-out of the STAR Time Projection Chamber.

Finally, we continue to carry various administrative responsibilities for STAR. Dr. Gagliardi served on the STAR Trigger Board for RHIC Run 22, where he had the primary responsibility for monitoring the data acquisition bandwidth allocations for all of the triggers, not just those associated with the Forward Upgrade. He also served as a member of the STAR TPC Review Panel during 2021, and is now serving as a member of the STAR TPC Data Acquisition Improvement Task Force. He served as chair of the god parent committee for a STAR spin paper [2], member of the god parent committee for a second spin paper [3], and as a member of the god parent committees for two heavy flavor papers [4,5]. Finally, he was appointed to a three-year term as a member of the RHIC Users' Executive Committee for 2021-24.

Mr. Aboona served as the Cold QCD delegate to the STAR QA Board for Run 22. During this period, STAR was collecting data from polarized pp collisions at ~510 GeV. As a QA board delegate, he developed QA analysis codes to validate the data taken by the mid-rapidity triggers during the run. He reported his weekly results to the QA Board on behalf the Cold QCD Physics Working Group. He also communicated and presented summaries to the Cold QCD group. The result of the mid-rapidity QA analysis is a compiled list of outlier runs that will serve as the first level QA for future analyses using Run 22 data.

[1] STAR Collaboration, arXiv:2205.11800.
[2] M.S. Abdallah *et al.* (STAR Collaboration), Phys. Rev. D **105**, 092001 (2022).
[3] J. Adam *et al.* (STAR Collaboration), Phys. Rev. D **103**, 092009 (2021).
[4] M.S. Abdallah *et al.* (STAR Collaboration), Phys. Rev. D **105**, 032007 (2022).
[5] M.S. Abdallah *et al.* (STAR Collaboration), arXiv:2111.14615.