Cold QCD physics with STAR at RHIC

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and the STAR Collaboration

Our group continues to play a major role in the STAR spin physics program. Over the past year, our focus has been on measurements of the Collins effect in *pp* and *p*+Au collisions. We have also continued development of trigger algorithms for the STAR Forward Upgrade.

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. Last year in *Progress in Research*, we reported on preliminary results that we have obtained for the Collins asymmetry in 200 GeV *pp* data that STAR recorded during 2015. The 2015 measurement included approximately twice the integrated luminosity as STAR recorded for a similar measurement during 2012. Since then, our post-doc Dr. Lin has developed a method to combine the STAR Collins effect measurements from 2012 and 2015, which initially were analyzed in rather different ways. Fig. 1 shows one view of the combined 2012+15 results compared to some recent model

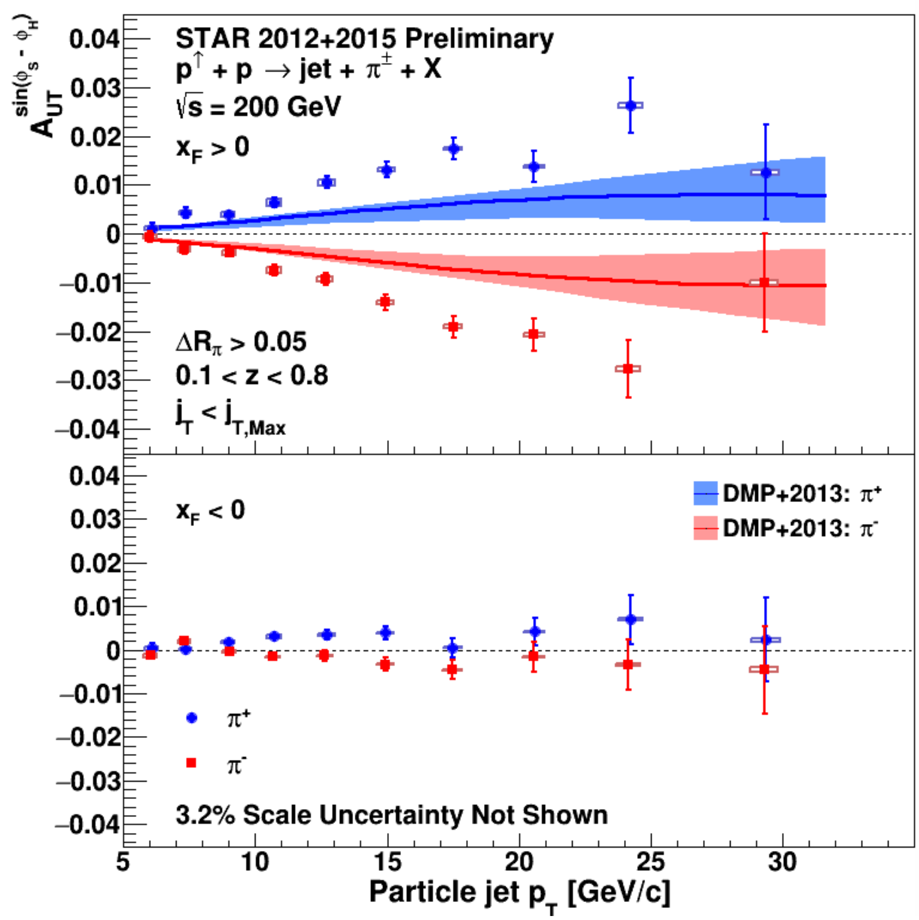

Fig. 1. STAR preliminary Collins effect measurements at mid-rapidity in 200 GeV *pp* collisions as a function of jet p_T, compared to model calculations from [1].

calculations. The final publication describing these STAR results will enter the STAR god-parent committee during the summer. Drs. Gagliardi and Lin will be principal authors, together with J.K. Adkins and R. Fatemi from University of Kentucky and J. Drachenberg of Abilene Christian

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.

Collins effect measurements depend critically on particle identification (PID). STAR primarily relies on *dE/dx* information from the Time Projection Chamber (TPC) for PID. However, in certain momentum ranges, the *dE/dx* bands of different particle types overlap. STAR utilizes time-of-flight (TOF) measurements to provide PID in those cases where *dE/dx* measurements do not suffice.

TOF consists of a start time detector – the vertex position detector (VPD), which covers about half of the solid angle in the pseudorapidity range $4.2 < |\eta| < 5$ – and a stop time detector, the barrel time-of-flight (BTOF) system that surrounds the TPC; see Fig. 2. When TOF is used for full-energy Au+Au collisions, there is high hit multiplicity on both sides of the VPD to provide good start time resolution. However, in *pp* and *p*+Au collisions, one or both sides of the VPD have a low mean hit multiplicity that results in most events having inaccurate or no start time. This led us to consider utilizing "start-less" TOF, which infers the collision time from the measured times of the observed TPC tracks, without reference to a separate start detector. Prior to our work, STAR had only used the start-less TOF mode when analyzing low-energy Au+Au collisions from the RHIC Beam Energy Scan (BES).

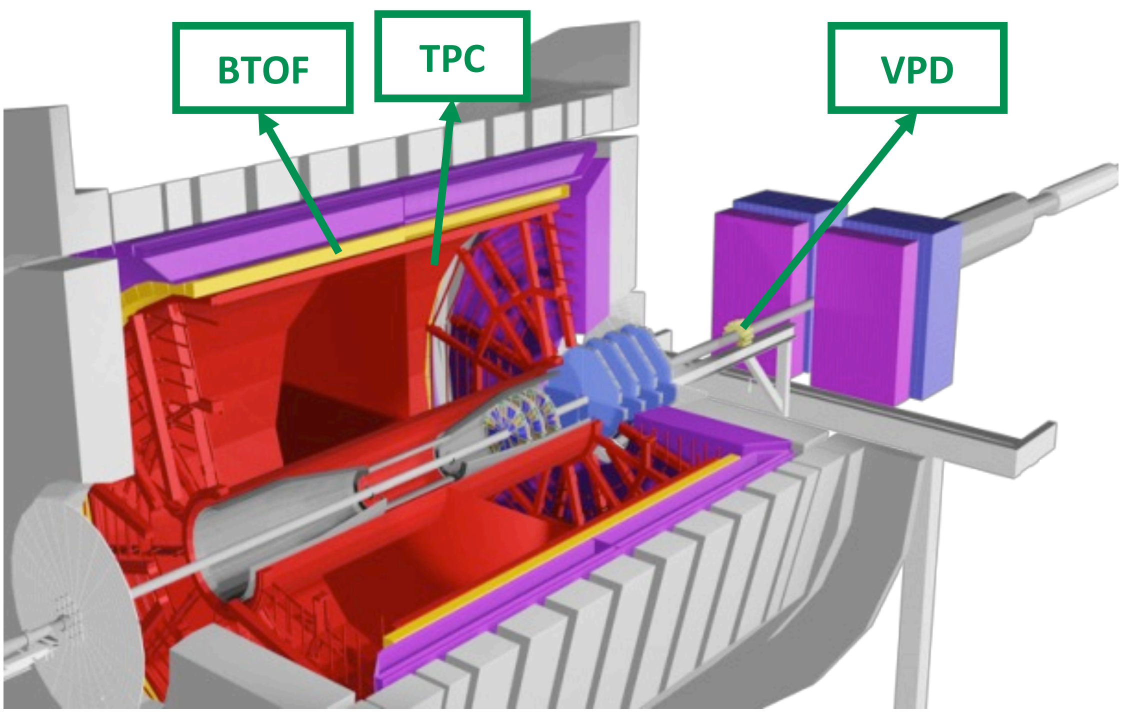

Fig. 2. View of the STAR detector, noting the subsystems that contribute to TOF measurements.

Start-less TOF uses stop times calculated by BTOF and well-identified tracks with BTOF hits to calculate the start time. Low-p_T pions end up providing the highest multiplicity of such tracks. Knowing the start and stop times, we can calculate the time-of-flight for each particle. That flight time is then combined with the path length obtained from the TPC to determine the velocity of the particle. We can obtain the momentum of the particle from the TPC and use it along with the velocity of the particle to calculate the mass of the particle and, thus, identify it.

Upon examining the default start-less TOF codes, we concluded that worthwhile optimizations could be made to multiple areas within the codes. The default start-less TOF codes consist of three main parts, "high purity" pion selection cuts, an outlier rejection algorithm to remove early or late outlier pions, and the last step is to average the start times of the pions that survive the outlier rejection algorithm to get the start time of the collision. Since then, our student B. Aboona has worked to optimize the routines.

We concluded that the default pion selection cut is too generous, so we developed a more restrictive set of cuts for pion selection that yields a higher purity pion sample. Our cuts include an extended upper limit of the momentum range, which was made possible by adding more restrictive *dE/dx* cuts. We also require the candidate pions to have higher-quality track reconstruction and *dE/dx* measurements, and include a vertex pointing accuracy cut to reduce contamination from secondary particles and decays in-flight.

When looking at the default outlier rejection algorithm, we found two main problems. The first problem was that the algorithm is a single-pass rejection loop, where the hits that are rejected depends on the order that the hits appear in the list. The second problem was that the algorithm accepts a very wide range of nominal collision times, which allows for mis-identified particles and other background tracks to make it through the rejection algorithm. In our improved outlier rejection algorithm, we address both issues. We introduce a tighter time range. We also pass iteratively over the candidate list, dropping only the grea ... allowed time dif ...

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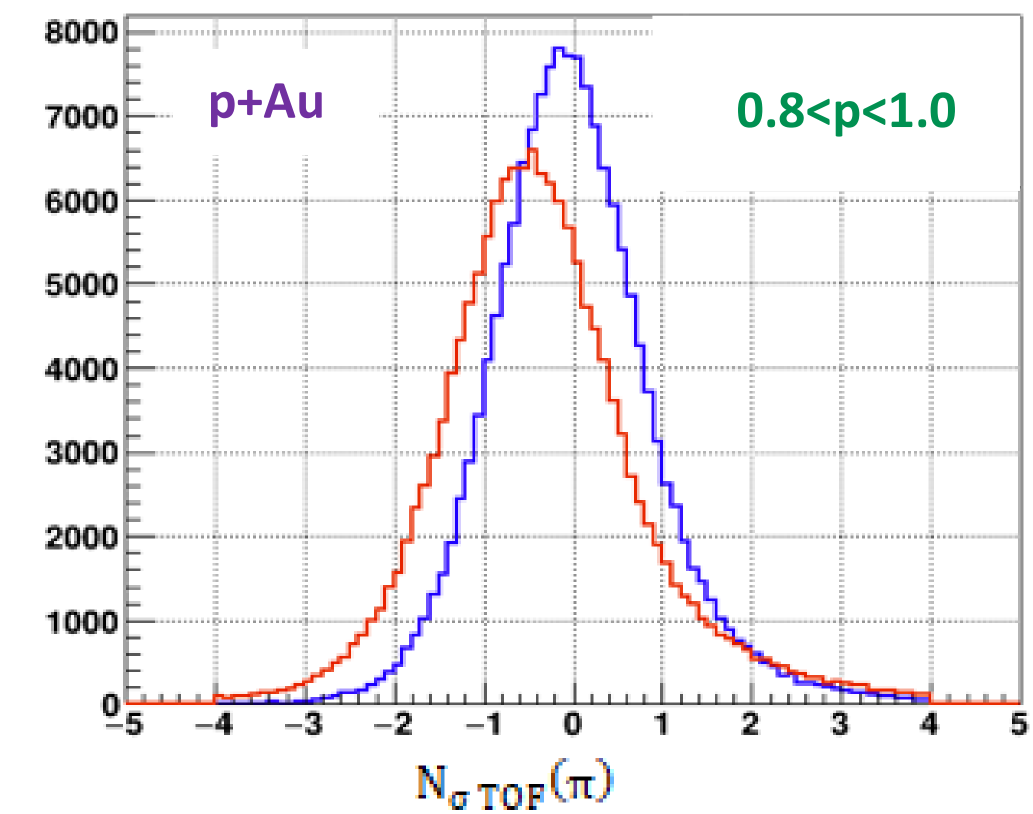

Fig. 3. Measured flight times of pions selected via dE/dx with 0.8 < p < 1.0 GeV/c, measured in units of the intrinsic time resolution. The red curve shows the results using the default start-less TOF algorithm, while the blue curve shows the results obtained when analyzing exactly the same p+Au events with our optimized algorithm.

Our original intention was to develop the optimized TOF routines only for use with *pp* and *p*+Au data from the 2015 and 2017 RHIC runs that have already been converted from raw events to MuDsts. However, during a STAR Analysis Meeting in January, heavy-ion collaborators expressed an interest in using the new routines when analyzing BES-II data. Since then, we have extended the routines so that they now perform similarly both during raw data production and when processing MuDsts. We are now optimizing the parameters for BES-II running conditions, beginning with the 19.6 GeV Au+Au data that STAR recorded during 2019.

During the past year, we have also developed a trigger algorithm for Drell-Yan dielectron events in the STAR Forward Upgrade. The challenge was to identify trigger logic that both selects Drell-Yan events with high efficiency and triggers on the orders-of-magnitude larger cross section of hadronic events at an acceptable rate for the STAR data acquisition system. The algorithm we developed provides ~85% efficiency in 510 GeV *pp* collisions for Drell-Yan events that fall within the Forward Upgrade acceptance, together with a total expected trigger rate of <1 kHz at the expected Run 22 collision rate of 5 MHz. The algorithm has now been verified to fit within the logic constraints of the FPGAs in the Forward Upgrade trigger DEP-IO boards.

Finally, we continue to carry various administrative responsibilities for STAR. Dr. Gagliardi served as one of the two conveners of the STAR Cold QCD and Spin Physics Working Group until the end of 2020. He served on the writing committee for the 2020 STAR Beam Use Request, where he was one of the three lead authors and the lead editor of the write-ups describing the proposed STAR Cold QCD physics programs for RHIC Runs 22 and 24. He also served on the god-parent committees for three different STAR papers during the past year, two from Cold QCD and one from Heavy Flavor. Dr. Lin served on the god-parent committee for a STAR Heavy Flavor paper and serves as the software coordinator for the EEMC. He also served as STAR Period Coordinator for three weeks during the current RHIC run. After completing his term as Period Coordinator, Dr. Lin left the group in Spring 2021 to take a new position as an Assistant Professor at Shandong University.

[1] U. D'Alesio, F. Murgia, and C. Pisano, Phys. Lett. B **773**, 300 (2017).