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GPU-based Online Reconstruction for J/ψ TSSA at the SpinQuest Experiment

Eric Fuchey[a,†,*]

[a] *Mississippi State University, Starkville, MS, USA*

[†] *now at College of William and Mary , Williamsburg, VA, USA*

E-mail: efuchey@jlab.org

The E1039/SpinQuest experiment at Fermilab will measure the transverse single spin asymmetry (TSSA) in several processes such as J/ψ production and Drell-Yan dimuon pair production, exploiting the 120 GeV unpolarized proton beam from the Fermilab Main Injector on transversely polarized ammonia and deuterated ammonia targets. Such measurements are anticipated to provide knowledge on the Sivers function from the proton sea quarks and gluons. The importance of the Sivers function studies is based on their ability to probe the orbital angular momenta of quarks and gluons, which may contribute significantly to the nucleon spin and thus help resolve the so-called "proton spin puzzle". In pursuit of these asymmetry measurements, we have been developing and optimizing an online reconstruction algorithm exploiting the high throughput and mass parallelization capabilities of graphics processing units (GPU), which combined with adequate visualization tools will provide real-time data monitoring for the SpinQuest experiment. This talk will highlight the SpinQuest experiment and the spectrometer efficiency induced projected systematic uncertainties for the J/ψ TSSA from its first production data. The performance metrics of the GPU-based online reconstruction algorithm will also be discussed, along with the features and methods employed to reach successful real-time data visualization.

25th International Symposium on Spin Physics
September 24-29 2023
Durham, NC, USA

*Speaker

PoS(SPIN2023)131

1. Introduction

The SpinQuest/E1039 experiment at Fermilab will measure the Drell-Yan process on both polarized protons and polarized deuterons. This will allow to separate the Sivers function for the u and d quarks flavors in the "deep" sea quark region. In addition to this, SpinQuest will be able to measure the transverse single spin asymmetry in J/ψ production, which can provide the gluon Sivers function. SpinQuest will use the same spectrometer as the SeaQuest experiment [1], with the position of the target adjusted to maximize the acceptance for the Drell-Yan process (and the J/ψ production as well) in the sea quark region.
The success of this experiment relies in part on quality monitoring based on quasi-real time reconstruction using Graphics Processing Units (GPUs). In this document we present the the SpinQuest experiment and its physics motivation and program. Then we detail the algorithms and performances of the online reconstruction.

2. The SpinQuest Experiment

2.1 Sivers Function and Nucleon Spin Puzzle

The nucleon spin can be decomposed into four components: the sum of the spins of quarks, the sum of the spins of gluons, and the orbital angular momenta of quarks and gluons Measurements in deep inelastic scattering off polarized proton targets have indicated that the contribution of the quarks individual spins to the total proton spin was only ~ 30 % [2]. This is what we call the proton spin puzzle. The study Transverse Momentum distribution functions (TMDs) [3, 4] allows to evaluate contribution of the orbital momentum of the quarks and gluons. TMDs parameterize the distribution of longitudinal nucleon momentum fraction carried by the quarks, in correlation with their transverse momentum. They can be studied thanks to Drell-Yan ($pp \to \mu^+\mu^- X$), for which a diagram is shown on Figure. 1. For Drell-Yan measurements on transversely polarized target, A

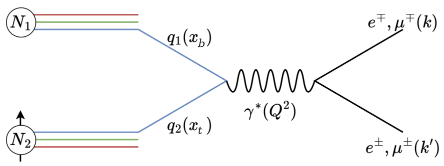

Figure 1: Feynman diagram of the Drell-Yan reaction. x_t and x_b are the parton momentum fractions from the target nucleon and the beam nucleon, respectively.

specific azimuthal modulation of the transverse target spin asymmetry provides information on the Sivers function [3], which parametrizes the transverse momentum of the quarks in a transversely polarized nucleon. The transverse momentum of the quarks in a transversely polarized nucleon being correlated to the quark orbital angular momentum, the study of the Sivers function gives a premium insight on the composition of the nucleon spin.

The SpinQuest/E1039 experiment at Fermilab will measure the Drell-Yan process on both polarized protons and polarized deuterons, which will provide a measurement of the quark orbital angular momentum in the sea quark region. It will also measure J/ψ production on polarized target, which will provide a measurement of the gluon orbital angular momentum. We will review next the experimental setup and the projected measurements.

2.2 Experimental Setup

The SpinQuest experiment is located at Fermilab. It is a polarized fixed target experiment, using the 120 GeV protons from the Fermilab main injector beamline. These protons are delivered by "spills", intense bunch of protons lasting 4 seconds, every minute. The SpinQuest spectrometer is the same as as for the SeaQuest experiment [1], combined with a polarized target of ammonia (NH_3) for tranversely polarized protons, and deuterated ammonia (ND_3) for tranversely polarized neutrons. The targets will achieve an average polarization of 78% for NH_3 and 30% for ND_3, and their spin will be flipped every eight hours. A representation of the spectrometer is shown on Figure. 2 The SpinQuest spectrometer is composed of two magnets, FMag, located between the

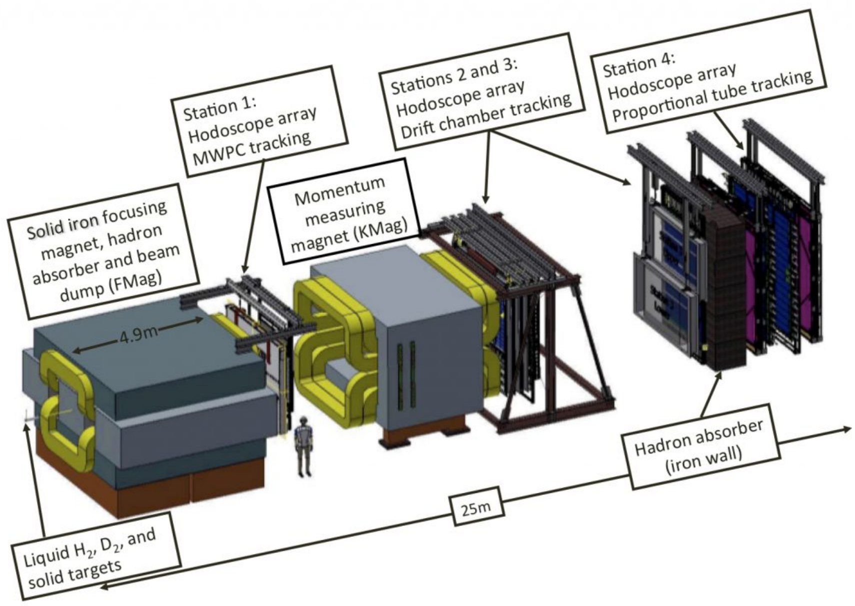

Figure 2: Drawing of the SpinQuest spectrometer, showing the magnets and the different detectors.

target and all the detectors and KMag, the momentum measuring magnet. Just behind FMag is located the tracking station 1 (which we will mention later as "station 1"), which is composed of three drift chambers, each with two planes: XX' (wires perpendicular to the spectrometer dispersive direction x), UU', VV' (wires inclined respectively +14 and -14 degrees with respect to horizontal. Station 1 also includes two planes of hodoscope, one in the x direction, and one in the y direction. Right after KMag sits tracking station 2 (which we will mention later as "station 2"), which is also composed of three drift chambers each with two planes, XX', UU' VV', as well as two planes of hodoscope, one in the x direction, and one in the y direction. Further apart from KMag, in front of the hadron absorber wall is located tracking station 3 (which we will mention later as "station 3"). Station 3 is composed of two sets of 3 drift chambers, each with two planes. One set of chamber covers the bottom part of the acceptance, while the second one covers the top part of the acceptance. Station 3 also includes one plane (divided in two subplanes) of hodoscopes in the X direction. Finally, behind the hadron absorber wall is located tracking station 4, which is composed of eight planes of proportional tubes, four in the x direction, four in the y direction, and three planes of hodoscopes (each divided in two subplanes), one in the x direction, two in the y direction.

2.3 SpinQuest Measurements and Projections

The SpinQuest/E1039 experiment at Fermilab will measure the Drell-Yan process on both polarized protons and polarized deuterons, which will provide a measurement of the quark orbital angular momentum in the sea quark region. At the SpinQuest kinematics, the Drell-Yan target spin asymmetry depends on the Sivers function of the sea quarks in the polarized proton; the event for which this asymmetry will have a significant dependence on the Sivers function of the beam proton are suppressed by the SpinQuest spectrometer acceptance. Figure. 3 shows the target spin asymmetry projected uncertainties as a function of the target quark momentum x_t.

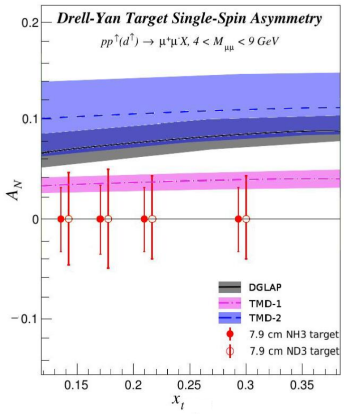

Figure 3: Projected of Drell-Yan target spin asymmetry projected uncertainties as a function of the target quark momentum x_t, for NH_3 (solid bullets) and ND_3 (hollow bullets).

During the first week of production, SpinQuest will also measure J/ψ production on polarized target. At the kinematics of SpinQuest, this process is dominated by gluon fusion [5]. The J/ψ target spin asymmetry projected uncertainties are shown in Figure. 4, for the target quark momentum x_t and x_F, the difference between beam parton momentum x_b and the target parton momentum.

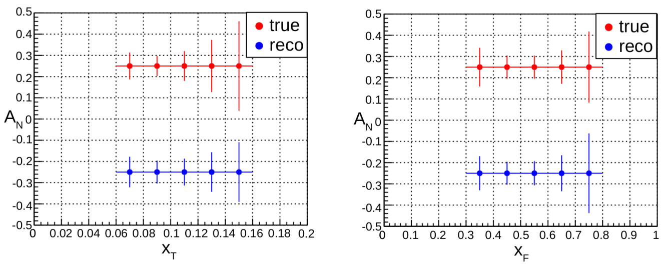

Figure 4: Projected of J/ψ target spin asymmetry projected uncertainties as a function of the target parton momentum x_t and $x_F = x_b - x_t$ (x_b being the target parton momentum). The red bullets show the projections for "true" dimuons, the blue bullets show the projections for the reconstructed dimuons.

3. GPU Based Online Reconstruction

The purpose of the Graphics Processing Unit (GPU) based Online Reconstruction (OR) is to reconstruct the tracks and dimuons from the hits recorded by the SpinQuest spectrometer, on the statistics of one proton spill, between two proton spills i.e. within less than a minute. In comparison, the official CPU-based reconstruction program for SeaQuest and SpinQuest called "kTracker" takes almost 10 minutes in the fastest multi-threaded form. To achieve this processing speed, the GPU OR program harnesses the high throughput and mass parallelization capabilities of the GPUs. This program is developed with CUDA [6] (Computer Unified Device Architecture), a proprietary C++ based language used with and developed for NVidia brand GPUs. It is also necessary for the program to minimize the transfer of data from CPU to GPU (which induces time overheads) to the strict minimum.

3.1 GPU OR Algorithms

This section describes the algorithms deployed for the GPU OR program, most of which are derived from the kTracker algorithm, with a few of those derived from the LHCb-Allen GPU reconstruction program [7].

3.1.1 Hit selection

The hits are the only information that are copied from the CPU to the GPU before the processing. The hits are filtered by the following criteria: TDC time within the data acquisition window; of two hits on a single wire, the earliest hit is kept; of two hits on neighboring wires, the hit with smaller drift distance is kept. After the hit selection, the program will flag the events as "high multiplicity" if the multiplicity in any tracking station exceeds values of 210 in station 1, 120 in station 2, and 90 in each of the subplanes of station 3. Such a multiplicity cut keeps over 50% of the statistics for a typical SeaQuest run, which shall be sufficient to detect problems.

3.1.2 XZ two-dimensional tracking

The "XZ" tracking is the first stage of the tracking. It reconstructs two-dimensional track candidates from which the back partial tracks and global tracks can be built upon. The algorithm pairs XX' hits in station 2 with XX' hits in station 3, fits the hits to obtain the track parameters x, x_0 (position at origin) and t_x (slope). The outside of the fiducial limits in x_0 and t_x are rejected; the track candidates are also coarsely matched with the hodoscope hits in station 2 and station 3, and with the proportional tubes, to filter out obvious false candidates. This stage is divided in 32 threads, each thread performing the tracking on a portion of the acceptance (Figure 5). Station 2 is divided in 4 bins of 28 wires each. Each chamber from station 3 is also divided in 4 bins of 29 wires average. After fitting and selection, the track candidates are then spread evenly over the threads to optimize the use of the GPU resources.

3.1.3 YZ two-dimensional tracking

The "YZ" tracking reconstructs the full back partial tracks (3D tracks in stations 2-3) from the 2D track candidates. The hits in UU', VV' are selected if they can be intersected with the XZ track candidate. For each UU'/VV' wire selected, y is evaluated as the point of intersection between the

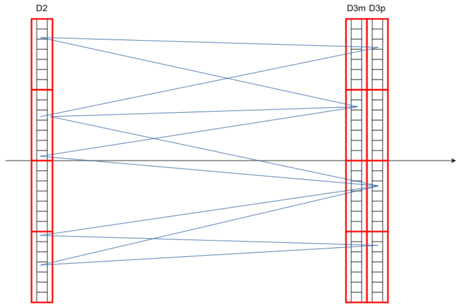

Figure 5: Scheme of tracking in XZ, associating hits from station 2 and station 3, showing the segmentation of the spectrometer acceptance for the multi-threading.

wire and the two-dimensional track candidates. Once all the hits are selected, fit the y for all the hits to obtain the y track parameters track, y_0 (position at origin) and t_y (slope). As for XZ track candidates, track candidates outside of the fiducial limits in y_0 and t_y are rejected. The back partial track candidates are also matched again with the hodoscope hits in station 2 and station 3, and with the proportional tubes, to filter out false candidates.

3.1.4 Global tracking

The global tracking reconstructs the full track in stations 1, 2, and 3, from the back partial tracks reconstructed by the previous steps. The first step for each back partial track is to select the hits using the Sagitta ratio. This ratio relates the respective distances of the hit in station 1 and the hit in station 2 to an imaginary straight track from the vertex to the hit in station 3, as illustrated in Figure. 6. For this calculation, two possible vertex origins are used: target, or dump; the hit

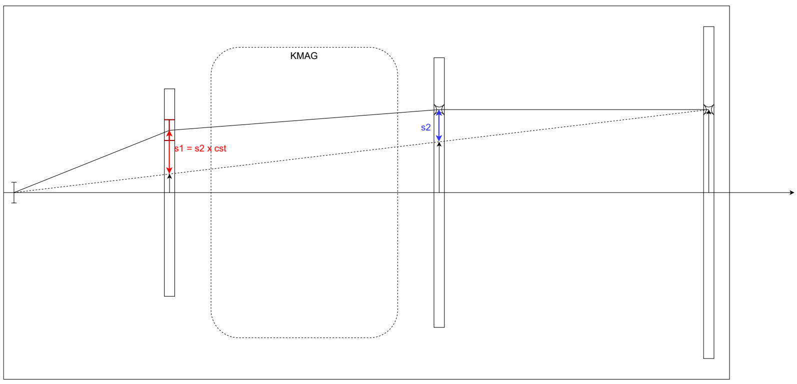

Figure 6: Illustration of the Sagitta ratio method to estimate the position of hits in station 1 from back partial tracks.

selection window is calculated for each origin, then both windows are combined to give the largest window possible. Once the hits in station 1 are selected, we evaluate X_{ip} the "point of intersection" between the reconstructed back partial track and the station 1 track segment to be reconstructed. This point is evaluated at at z_{KMag}, the point projected on Z where two track segments intersect. The station 1 track segment is obtain combining X_{ip} and with the hits in station 1 XX'. The inverse momentum $1/p$ is calculated using $\Delta p_{T,KMag}$, the total kick in momentum induced by KMag.

Finally, the hits in station 1 detectors UU' and VV' are selected and their y is calculated as the intersection between the wire and the station 1 track segment. Their y values are used to update the y_0, t_y parameters of the track. Each global track candidate outside the spectrometer fiducial acceptance is rejected. Good global tracks also have to be matched with one hit in hodoscope station 1., and their χ^2 (defined as the sum of the squared of the hits residuals divided by the resolution of the planes), is below a certain value.

3.1.5 Vertexing

The vertexing is performed once all track parameters x_0, t_x, y_0, t_y, $1/p$ are determined. The first step of the vertexing is to evaluate The position and momentum of the track at the back of FMag. From this point, we "swim" back through the FMag by back steps of length δ_{FMag} of 0.5% the length of FMag. At each step of the swimming, the energy and direction of the track is corrected and udpated based on the FMag momentum kick $\delta p_{T,FMag}$ and the dE/dx of the magnet material. This process is illustrated on Figure 7

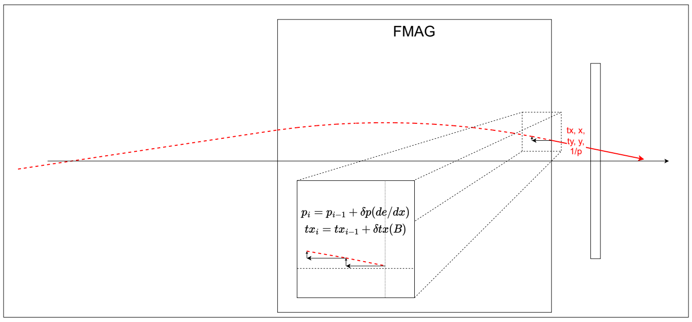

Figure 7: Illustration of the track "swimming" process through the FMag, and extrapolation to the target.

Once the swimming has gone through FMag, the track is extrapolated to the most upstream point of the target with the momentum and position obtained after swimming back through the FMag. During all the extrapolation steps, the distance of closest approach of the track to the beamline is searched. The point of distance of closest approach between the track and the beamline is used as the vertex coordinates of the track. The momentum at the distance of closest approach is selected as the momentum of the track at vertex.

3.1.6 Dimuon reconstruction

The dimuons are evaluated pairing tracks of different charge. Both tracks are swimmed back through the FMag and target, using the same procedure as described in the *vtx*, to search for the distance of closest approach between the two tracks. In the process of evaluating the distance of closest approach, the momentum of each track is updated as the momentum at the dimuon vertex, not at the track original vertex. This is susceptible to change the momentum of each track if the dimuon vertex is found in the FMag/dump area. The dimuons are then selected based on mass and other kinematic variables (including the target and beam parton momenta x_b and x_t, and $x_F = x_b - x_t$.

3.2 GPU Online Reconstruction Performance

After describing with reasonable details the GPU OR reconstruction algorithm above, we compare below the track parameters obtained with the GPU OR program with same track parameters obtained with kTracker. As we will cover, this agreement is reasonable but can be perfected. We also made a multiplicity studied which found out that as the multiplicity increases, we observe a few extra events, but the shape of the distributions are not affected significantly. A strong feature of the GPU OR program remains its processing time: it analyzes 10000 events (the typical statistics of a proton spill in SeaQuest) within less than 30 seconds, and 15 times faster than the fastest multi-threaded CPU reconstruction program based on kTracker.

3.2.1 Track Reconstruction Results

Figure. 8 show the track parameters (x_0, t_x, y_0, t_y, $1/p$) obtained by the kTracker code (which serves as our reference) in green, versus the GPU OR code in red. The agreement is overall fairly

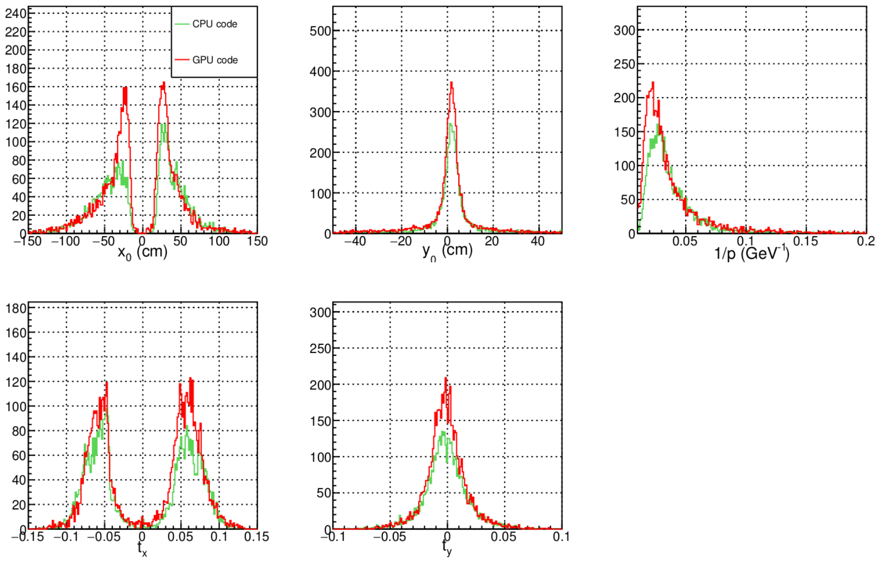

Figure 8: Track parameters reconstructed for e906 run 12525 (road 67) by the GPU online reconstruction program (red), compared to the same variables reconstructed by the e906-kTracker code (green).

good. Figure. 9 show the track vertex position and momentum at vertex obtained by the kTracker code (which serves as our reference) in green, versus the GPU OR code in red. The agreement in momentum is fairly good. The agreement with the vertex can also be perfected as the kTracker includes an extra step to fit the tracks, that will be implemented later.

3.2.2 Dimuon Reconstruction Results

Figures. 10 and 11 show respectively the dimuons variables (mass, x_F, x_t, x_b, p_T, ϕ) and the dimuons vertex position and momentum at vertex obtained by the kTracker code (which serves as our reference) in green, versus the GPU OR code in red. The agreement in momentum is fairly good. The agreement with the vertex can be improved, as those propagate the fairly loose agreement from the track vertex distributions.

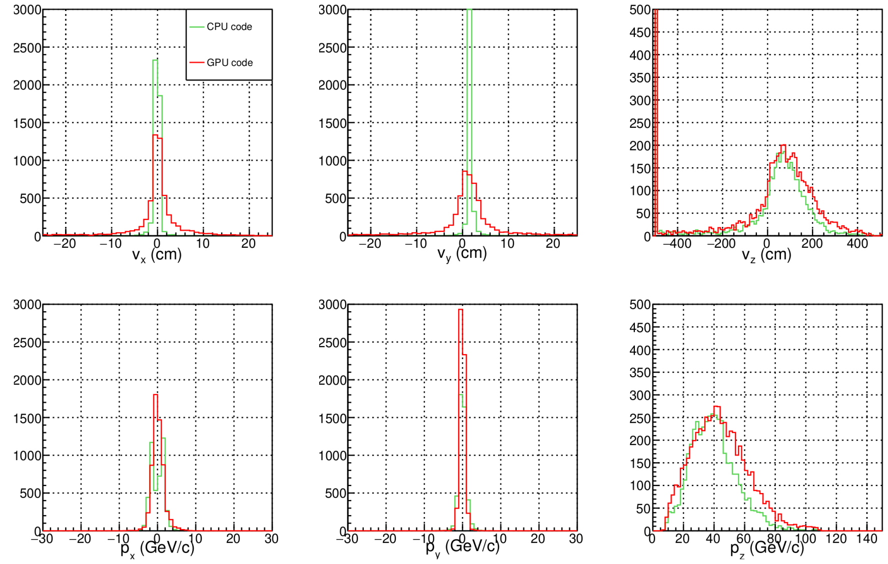

Figure 9: Track vertex position and momentum reconstructed for e906 run 12525 (road 67) by the GPU online reconstruction program (red), compared to the same variables reconstructed by the e906-kTracker code (green).

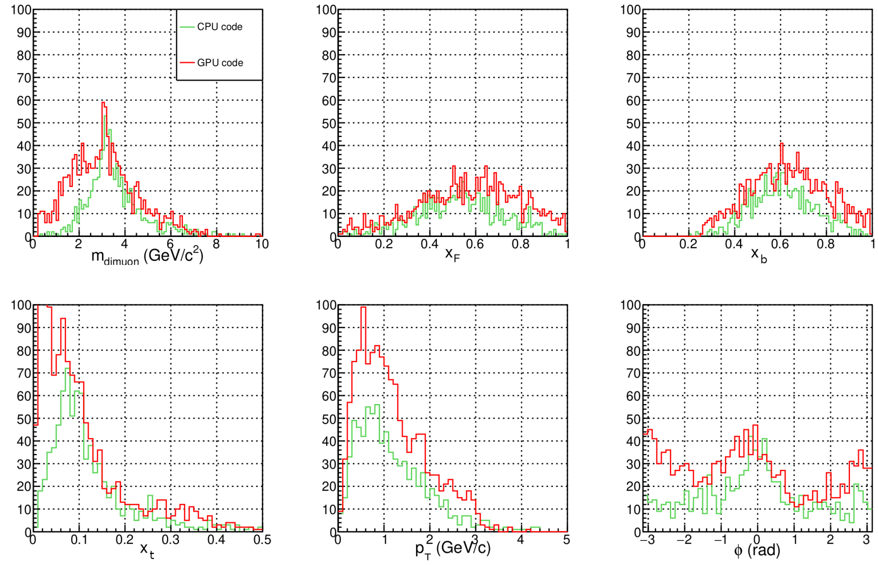

Figure 10: Dimuons variables: mass, x_F, x_t, x_b, p_T , and ϕ reconstructed for e906 run 12525 (road 67) by the GPU online reconstruction program (red), compared to the dimuons reconstructed by the e906-kTracker code (green).

4. Summary

The SpinQuest experiment at Fermilab will perform measurements of target spin asymmetry on Drell-Yan and J/ψ production to measure the Sivers function on sea quarks and gluons. Such

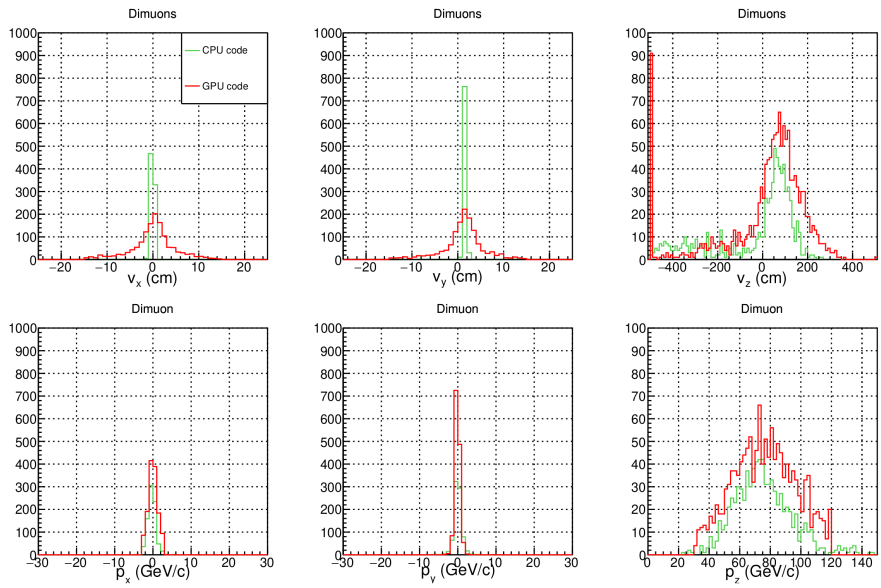

Figure 11: Dimuons vertex position and momentum reconstructed for e906 run 12525 (road 67) by the GPU online reconstruction program (red), compared to the dimuons reconstructed by the e906-kTracker code (green).

measurements will provide extremely valuable insight to solve the nucleon spin puzzle. A key to the success of the SpinQuest experiment is the real-time online data quality monitoring. This feature will be achieved using a GPU-based reconstruction program using the proprietary CUDA language developed by NVidia for their hardware. This program provides significant performance compared to the CPU-based kTracker, while offering satisfactory reconstruction accuracy. This program is being deployed for the upcoming SpinQuest data, while the development of the associated display tool is being completed.
Acknowledgement: This work is supported in part by the U.S. DOE award DE-FG02-07ER41528

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