STAR reconstruction improvements for tracking with the heavy flavor tracker

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Abstract. The reconstruction and identification of charmed hadron decays provides an important tool for the study of heavy quark behavior in the Quark Gluon Plasma. Such measurements require high resolution to topologically identify decay daughters at vertices displaced < 100 microns from the primary collision vertex, placing stringent demands on track reconstruction software. To enable these measurements at RHIC, the STAR experiment has designed and employed the Heavy Flavor Tracker (HFT). It is composed of silicon-based tracking detectors, providing four layers of high-precision position measurements which are used in combination with hits from the Time Projection Chamber (TPC) to reconstruct track candidates. The STAR integrated tracking software (Sti) has delivered a decade of world-class physics. It was designed to leverage the discrete azimuthal symmetry of the detector and its simple radial ordering of components, permitting a flat representation of the detector geometry in terms of concentric cylinders and planes, and an approximate track propagation code. These design choices reflected a careful balancing of competing priorities, trading precision for speed in track reconstruction. To simplify the task of integrating new detectors, tools were developed to automatically generate the Sti geometry model, tying both reconstruction and simulation to the single source AgML geometry model. The increased precision and complexity of the HFT detector required a careful reassessment of this single geometry path and implementation choices. In this paper we will discuss the test suite and regression tools developed to improve reconstruction with the HFT, our lessons learned in tracking with high precision detectors and the tradeoffs between precision, speed and ease of use which were required.

1. Introduction
The production of open-charm hadrons can provide important insights into the question of whether the medium created in heavy ion collisions interacts any differently with heavy quarks than with light quarks. The high-multiplicity environment in these collisions poses particular challenges for tracking. The signals of interest, such as $D^0 \rightarrow K^+\pi^-$, are swamped by large combinatorial backgrounds in $AA$ collisions. Topological reconstruction, where the daughter particles are tracked back and associated with their decay vertex, is key to suppressing these backgrounds. This demands tracking detectors which can resolve the decay vertices displaced < 100µm from the primary interaction point, and track reconstruction software capable of sufficient precision while remaining fast enough to contend with the large number of tracks to be processed. The Solenoidal Tracker at RHIC (STAR) primarily relies on a 0.5T solenoidal magnet[1] surrounding a large Time Projection Chamber[2] to identify particles and determine their momenta. The projection of the reconstructed tracks from the innermost radius of the
TPC (60 cm) to the vertex results in a DCA resolution of \( \approx 2 - 3 \) mm. To achieve the required resolution and extend the experiment’s reach into the heavy flavor sector, four layers of high-precision silicon detectors were added. STAR installed the Heavy Flavor Tracker (HFT)\cite{3} for the 2014-2016 runs, with a partial engineering run in 2013.

With the addition of the HFT geometry models in the tracking framework, a number of issues were revealed. The performance of the code, in terms of speed, was significantly degraded. Comparisons of track reconstruction with and without the HFT geometry showed more than a factor-of-two in track reconstruction speed. In addition, our standard quality assessment (QA) test suite showed problems in track reconstruction at low-\( p_T \), strongly suggesting problems with the geometry and/or track propagation engine. Tools developed to test the validity of the geometry model showed that dead material, and in some cases active layers, were being skipped in track propagation. These were questions which needed to be addressed before attempting to include HFT hits into track reconstruction. It was therefore understood that significant work would be needed to advance the performance of the tracking software to the required scale of interest without sacrificing speed.

2. Track Reconstruction in STAR

The STAR integrated tracker (Sti)\cite{4} was developed over ten years ago in order to provide a general tracking framework which could support the integration of new tracking detectors into the experimental setup. It utilizes a fairly standard track-road following algorithm, with a Kalman-filter to progressively improve the track information as new hits are discovered, followed by a Kalman-smoother. STAR has historically emphasized mid-rapidity physics using detectors with a high-degree of azimuthal symmetry. The Sti tracker leverages this, implementing a simplified, fast geometry model and track propagation engine which provides sufficient precision to enable the physics program. The Sti geometry model approximates physical volumes by cylindrical and planar surfaces, attached to concentric tracking layers. Each surface holds information about the material properties of the corresponding physical volume, including an effective (radial) thickness, and may hold a list of hits for active detectors. The surfaces are positioned in the detector subject to two restrictions – cylinders (and cylindrical arcs) must be concentric with the z-axis, and planar surfaces must lie parallel to it.

This scheme allows us to represent the most significant elements of the STAR geometry to the tracker, while neglecting many of the smaller details which are unimportant to the total material budget and tracking resolution. It also permits the simplification of track propagation, and an increase in speed navigating the geometry. Instead of trying to find the distance to the next extended 3-dimensional object, as in the ROOT\cite{5} geometry package, the tracker only needs to determine which (if any) 2-dimensional surface is intersected at the next tracking layer along the path of the candidate track. When a track is determined to intersect a surface the state of the track is updated: (1) material effects are applied to the track as if it crossed the full thickness of the corresponding volume; (2) if an acceptable hit is present, it is added to the track and Kalman updates the track parameters; and (3) the track’s updated parameters are used to propagate it to the next layer. This simplified track propagation works well at midrapidity, where tracks are approximately perpendicular to the detector volumes. Tracking quality compares well between the Sti tracker and the alternate Stv tracker\cite{6}, which was developed to satisfy the demands of a planned forward physics program, and which utilizes the ROOT/TGeo geometry package to fully realize the goal of a single source for geometry information in STAR. In terms of speed, however, the Sti tracker performs significantly faster than Stv, outpacing it by more than 50% due primarily to the time spent during track navigation. Thus, the Sti tracker remains the preferred choice for track reconstruction in STAR.
3. HFT Integration
The HFT consists of three subsystems of silicon detectors, providing four layers of increasing precision as we dive from the TPC (1 mm hit resolution) to the vertex. These include: (1) The Silicon Strip Detector (SSD) [7]: fast, double-sided (stereoscopic) silicon strips at radii of $\approx 22$ cm; (2) Intermediate Silicon Tracker (IST) [3]: fast, single-sided silicon pads at radii of $\approx 14$ cm; and (3) the Pixel Detector (PXL) [8]: two layers of $20.7 \times 20.7\mu m$ Monolithic Active Pixel Sensors (MAPS) at radii of $\approx 8$ cm and $\approx 2.8$ cm. Figure 1 shows the ROOT/TGeo implementation of the HFT geometry, and the corresponding track projection resolution at each tracking layer. The HFT geometry is represented to the tracker by a semi-automated conversion routine, which translates the detailed ROOT geometry model into a simplified version based on Sti primitives. This permits us to support both simulation and reconstruction geometries from the same AgML[9] source code. The conversion routine operates on user-selected volumes, and performs different actions based on the shape, orientation and contents (if any) of the volumes. Compatible volumes, such as cylinders and boxes with no contents, are directly copied into the corresponding Sti primitive volumes. More complicated shapes are built up from multiple Sti primitives. If a volume contains daughters, then the properties of the daughters are averaged in order to obtain effective material properties for the parent volume.

3.1. Improvements to Track Propagation
Many misbehaviors of the tracker were a consequence of the choices made to optimize the tracker for speed. In particular, tracks were found to miss volumes in the HFT because of two assumptions built into the track propagation engine: volumes are thin along the radial direction, and only one volume may be crossed in each tracking layer. Figure 2 illustrates the first issue. The left panel shows two tracks propagating through a thin scatterer (black box) attached to a radial tracking layer (grey dashed line). The blue track passes through the representative surface (magenta line), and is judged by the propagator to have intercepted the material. Energy loss and multiple scattering effects are applied proportional the full thickness of the volume, as indicated by the solid blue line. The red track, which clips the edge of the material, is judged to have missed it since the track does not pass through its representative surface. The errors are small and unlikely for thin scatters oriented tangent to the tracking layer, but grow in importance as the scatterer is oriented radially, as indicated in the middle panel. Tracks which pass through the material miss the representative surface more frequently, and the amount of material which they should have passed through is larger. Furthermore, tracks judged to have crossed the material are presumed to have crossed its full thickness, leading to an overestimate of the material effects. The solution to these issues is to split radially oriented volumes into slices, and attach them to different tracking layers, as illustrated in the right panel. While adding additional tracking layers slows track reconstruction slightly, it significantly reduces the number...
Figure 2. Illustration of track propagation in the vicinity of thin scatters, and the need for finer segmentation in radially-oriented support structures. Tracks (blue and red) are judged to cross material if they pass through its representative surface (magenta). See text for more details.

of tracks which are incorrectly judged to have missed material, and improves the estimated thickness of material crossed. This was of particular importance to correctly model the PXL sector supports.

The second assumption was that tracks may cross only one volume at any given tracking layer. This was found to be too constraining, as it led to tracks missing active and/or dead layers in the setup. A typical use case is shown in figure 3. In the left panel, three planar objects are attached to a single tracking layer and tilted with respect to each other, providing overlapping coverage near the edge of each object. A track passing through the overlap region is shown. Once it is determined that a track passes through a volume in a tracking layer, the propagator proceeds to the next layer without considering other candidates. This behavior has several consequences. First, when both volumes represent dead material, this can lead to an underestimate of the material in the setup. As this was not a frequent occurrence in our geometries, we left it unaddressed. Second, when one of the two volumes is active, the track propagator may miss picking up hits because it found the track to be in the dead material. This issue was fixed by giving active layers priority in the volume search. When a surface has been crossed, the search terminates only if the corresponding volume is active. Otherwise the search continues until all candidates at that layer have been visited. Finally, when both layers are active, the propagator can only add one hit. Mitigation of this effect required a change to the geometry implementation. The active volumes were split, and assigned to separate tracking layers as illustrated in the right panel of figure 3.

3.2. Improvements to Geometry Model
The most significant issue came back to the way in which the HFT geometry was represented to the tracker. The AgML representation of the HFT is a complicated geometry, implementing
10,000 physical volumes in the IST subsystem alone. This level of detail is appropriate for simulation, but is unnecessary for track reconstruction. Figure 4 shows the AgML/ROOT model of the IST on the left, and the Sti conversion on the right. Highlighted are hundreds of small volumes created in the Sti model in order to represent the curved cooling tubes, which are far outside of the acceptance of the detector and present a negligible contribution to the material. The complexity of the IST geometry model alone accounted for most of the observed slow down. Furthermore, the automatic conversion was failing to preserve the mass of the detector. The IST model gained an acceptable 10% in mass during conversion, but the pixel and SSD detectors were off by substantially more. The reasons for this were that overlapping volumes in the AgML model resulted in double-counting of material in the Sti conversion, and the size of incompatible volumes was not preserved when they were translated to Sti primitives. While these isssues had solutions, it was also realized that the averaging procedure tended to overestimate the material budget in the regions of interest, as heavy support structures outside of the acceptance were not excluded. Fixing this would require a major revision of our AgML geometry model. It was therefore decided to implement the HFT geometry model directly in terms of Sti primitives. While this breaks the single-source goals for the STAR geometry, this compromise was deemed acceptable since the HFT geometry would not change over its limited run. This change reduced the number of Sti volumes by a factor of 100, and resulted in a doubling in the speed of the tracker. As these changes were implemented, we applied regression testing based on a comprehensive QA test suite. Figure 5 shows the mean and width of the \( \text{DCA}_{xy} \) distribution of global tracks for the 2010 geometry model (pre-HFT) on the left. A significant bias is seen at low pT when the (passive) HFT geometry model is added to the 2014 setup using the automated conversion, shown in the middle panel. At right, the \( \text{DCA}_{xy} \) is shown with the geometry implemented directly in Sti. The bias is significantly reduced, and falls below our typical 200 MeV analysis cuts.

### 3.3. Including HFT Hits in Tracking

With the quality and speed issues resolved, work could continue on utilizing HFT hits in track reconstruction in order to achieve the required tracking resolution for the physics program. Several incremental improvements were made to track fitting in order to better handle small misalignments in the HFT detectors. These included increasing the tolerance for hits displaced off of the ideally-placed volumes, nudging the hits to the detector plane before the fit, and allowing HFT hits to be reused on up to five different track candidates. The latter change was needed to ensure that pileup tracks found in the TPC could not rob real tracks of necessary hits in the HFT. Finally, we needed to address how HFT hits would be assigned to tracks. Track

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**Figure 4.** The ROOT geometry model of the IST (left), compared with its automatic translation into the Sti geometry model (right).
Figure 5. Mean and width of the $DCA_{xy}$ distributions as a function of $p_T$ for the y2010 pre-HFT geometry (left), the y2014 auto-converted HFT geometry (middle) and the y2014 native HFT geometry (right).

projection from the TPC was found to be insufficient to find hits in the pixel detector, if hits in the SSD and IST were missed. So it was decided that a track must find three hits in the four layers of the HFT in order to include them in track reconstruction. Figure 6 shows the resulting $DCA_z$ distributions for TPC-only (top-left) and TPC+HFT (top-right) as a function of eta, demonstrating that inclusion of the HFT results in $\approx 50\mu m$ pointing resolution to the vertex. The $K\pi$ invariant mass in 200 GeV AuAu collisions with HFT in tracking is shown in the bottom panel of 6, in which the $D^0$ peak is clearly visible, after suppressing the background.

Figure 6.
by more than 4 orders of magnitude by including the HFT.

4. Summary

Track reconstruction in high energy nuclear and particle physics experiments must strike a balance between speed and performance, maximizing physics impact given the available computing resources. In order to successfully integrate the HFT into tracking, STAR had to revisit the design of the Sti tracking software, and the implementation of the HFT geometry in terms of Sti primitives. The reduction of the detector descriptions used in simulation to surface-based geometry models provides a significant advantage in speed, while still being able to provide sufficient resolution for some of the most demanding applications of tracking. However, achieving that resolution requires effort on the part of the developers. Complex detectors may not be suitable for automated conversion to surface-based descriptions – care must be taken to identify where the approximations being made for track propagation break down, and ensure that the number of volumes required in the description is reduced. Tools capable of analyzing the static properties of the geometry model, and inspecting the dynamic state of the tracker during track propagation, are critically important to this task.

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References

[1] Bergsma F, et al. 2003 Nucl. Instr. and Meth. A 499 633.
[2] Anderson M et al. 2003 Nucl. Instr. and Meth. A 499 699.
[3] Qiu H et al. 2014 Nucl.Phys. A 931 1141-1146.
[4] Rose A, et al. 2003 eConf C 0303241, THLT004 [nucl-ex/0307015].
[5] Brun R, Gheata A and Gheata M 2003 Nucl. Instrum. Meth. A 502, 676.
[6] Evdokimov E et al. 2011 STAR Tracking Components Review, STAR NOTE 0552
[7] Arnold L et al. 2003 Nucl. Instr. and Meth. A 499 652.
[8] Greiner L et al. 2011 Nucl. Instr. and Meth. A 650 68.
[9] Webb J C et al. 2012 J. Phys. Conf. Ser. 396 022058.