Studies of track finding for long-lived particles at STCF

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Abstract

Reconstruction of the trajectories of charged particles at High Energy Physics experiments is a complicated task, in particular those of long-lived particles. At the future Super Tau-Charm Facility (STCF), long-lived particles are present in several important benchmark physics processes. A Common Tracking Software was used to reconstruct the trajectories of long-lived particles and it is shown that the track finding performance of the commonly used Combinatorial Kalman Filter for long-lived particles is limited by the seeding algorithm. This can be improved by steering the Combinatorial Kalman Filter with initial tracks provided by Hough Transform. The track finding performance of combined Hough Transform and Combinatorial Kalman Filter evaluated using the process J/ $\rightarrow \Lambda(\rightarrow p\pi-)\bar{\Lambda}(\rightarrow \bar{p}\pi+)$ at STCF is presented.

Full Text

Preamble

Studies of Track Finding for Long-Lived Particles at STCF

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Reconstruction of charged particle trajectories in high-energy physics experiments is a complex task, particularly for long-lived particles. At the future Super Tau-Charm Facility (STCF), long-lived particles appear in several important benchmark physics processes. Using a Common Tracking Software to reconstruct the trajectories of long-lived particles, we demonstrate that the track-finding performance of the widely used Combinatorial Kalman Filter is limited by its seeding algorithm for such particles. This limitation can be overcome by steering the Combinatorial Kalman Filter with initial tracks provided by the Hough Transform.

We present the track-finding performance of the combined Hough Transform and Combinatorial Kalman Filter evaluated using the process $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ at STCF.

Keywords: Track finding, Common tracking software, Hough Transform, Long-lived particles

Introduction

The Standard Model (SM) [**?**, **?**] of particle physics, which includes the unified electroweak and quantum chromodynamics theories, has successfully explained nearly all experimental results about the microscopic world. However, several fundamental questions remain, such as the baryon asymmetry of the universe, dark matter, neutrino masses, and the number of flavors. The Beijing Electron Positron Collider (BEPCII) - Beijing Spectrometer (BESIII) [**?**] is the only multi-GeV e^+e^- collider operating in the τ-charm sector, providing a unique platform for studying non-perturbative QCD and strong interactions within the SM. The Super Tau-Charm Facility (STCF) [**?**, **?**] is designed to continue and extend the physics programs at BEPCII in the near future, including probing the nature of strong interactions and hadron structure, precise tests of electroweak theories, exploring matter-antimatter asymmetry, and searching for new physics beyond the SM. STCF will operate at center-of-mass energies of 2–7 GeV with a peak luminosity above $0.5 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$ [**?**], two orders of magnitude higher than BEPCII.

Charged particle reconstruction is the most fundamental and critical step in the data processing chain of high-energy physics experiments. To achieve the physics goals and maximize the physics potential at STCF, charged particles must be reconstructed with high efficiency. This includes not only particles that decay promptly upon production but also long-lived particles [?], such as the Λ and Ξ hyperons, which are relevant for several important physics objectives at STCF. For example, the weak decays of Λ and Ξ hyperons provide promising channels for searching for new sources of CP violation [?, ?, ?]. Hyperon samples at STCF can also be used to measure time-like nucleon and hyperon form factors for Q^2 values up to $40\,\mathrm{GeV}^2$ [?]. However, reconstructing the trajectories of long-lived particle decay products is challenging because these particles may decay inside or outside the inner tracker, resulting in a very limited number of hits recorded by the inner tracker.

The Kalman Filter (KF) algorithm [?] is the most commonly used tracking algorithm in high-energy and nuclear physics [?]. The Combinatorial Kalman Filter (CKF) [?, ?] is an extended version of the KF, where measurements are progressively added to a track during propagation steered by an initial estimate of the track parameters–i.e., a seed. The effects of magnetic fields and material interactions are incorporated during track propagation, enabling CKF to resolve hit ambiguities in dense tracking environments. For this reason, CKF is deployed for track finding by several experiments, such as ATLAS [?] and CMS [?], where thousands of tracks are present in a single event. CKF is also the primary track-finding algorithm at the Belle II experiment [?]. Recently, the CKF algorithm developed by Belle II was reused to study tracking performance [?] at the Circular Electron Positron Collider (CEPC) [?]. Despite its great advantages, one downside of KF-based tracking algorithms is their dependence on the performance of the seeding algorithm, which may perform poorly for long-lived particles. Recently, a track-finding algorithm based on the Hough Transform used by Belle II [?] and BESIII [?] has been developed at STCF [?], where tracking performance for prompt particles without vertex displacement has been studied. It demonstrates promising performance, particularly good robustness against local hit inefficiency. However, tracking efficiency can deteriorate due to background hits at low transverse momentum.

ACTS (A Common Tracking Software) [?, ?] is an emerging open-source tracking software for high-energy and nuclear physics experiments, offering a suite of detector-agnostic and framework-independent modular track and vertex reconstruction algorithms. The promising performance of KF and CKF algorithms in ACTS is underscored by their widespread adoption by experiments such as FASER [?], sPHENIX [?], and several R&D studies at STCF [?] and BESIII [?]. Notably, ACTS has demonstrated its generality across various tracking detector types [?]. However, the performance of ACTS for long-lived particles has not been investigated.

In this study, we investigate the tracking performance of STCF with a fully gaseous tracking system consisting of a μ-RWELL [?]-based inner tracker and a drift chamber, using combined Hough Transform and ACTS CKF to enhance tracking performance for long-lived particles. The manuscript is organized as follows. Section II provides a brief introduction to the STCF detector. Section III describes the track reconstruction workflow with different algorithms. Section IV focuses on tracking performance for benchmark processes with long-lived particles at STCF. Section V presents a brief conclusion.

STCF Detector

The STCF detector [?] ensures comprehensive coverage of the solid angle around the collision point, as depicted in Fig. 1 [Figure 1: see original paper]. The detector consists of a tracking system comprising an Inner Tracker (ITK) and a Main Drift Chamber (MDC), along with a Ring Imaging Cherenkov (RICH) detector [?] and a DIRC-like Time-of-Flight (DTOF) detector [?] for particle identification in the barrel and endcap regions. Additionally, it incorporates a uniform electromagnetic calorimeter (EMC) [?], a superconducting solenoid magnet generating a 1 Tesla axial magnetic field, and a Muon Detector (MUD) positioned at the outermost layer of the detector system.

To ensure optimal tracking efficiency for low-momentum charged particles, the ITK within the tracking system covers a polar angle range of 20° to 160° (i.e., $|\cos\theta| < 0.94$) and comprises three layers of low-material-budget silicon or gaseous detectors using either MAPS-based or μ-RWELL-based technology [?]. This study focuses on the μ-RWELL-based ITK, with the three layers placed at inner radii of 60 mm, 110 mm, and 160 mm, respectively, each layer having a thickness of approximately 6.5 mm. It provides a spatial resolution of about $100\,\mu$m in the r-ϕ direction and about $400\,\mu$m in the z direction. For the MAPS-based ITK, the radii of the three silicon layers are 36 mm, 98 mm, and 160 mm, respectively, with a hit resolution of $30\,\mu\text{m} \times 180\,\mu\text{m}$ assumed. Unless explicitly specified, ITK denotes the μ-RWELL-based ITK by default.

Central to the tracking system of STCF, the Main Drift Chamber (MDC) operates using a He/C_3H_8 (60/40) gas mixture and features a square cell configuration with a superlayer wire arrangement. The superlayers within the MDC alternate between stereo layers ("U" or "V") and axial layers, each containing six layers. In total, the MDC comprises eight superlayers (AUVAUVAA) and 48 layers, with inner and outer radii of 200 mm and 850 mm, respectively. The MDC provides spatial resolutions ranging between $120\,\mu$m and $130\,\mu$m.

Track Reconstruction Using Combined Hough Transform and CKF

The workflow of track reconstruction using combined Hough Transform and ACTS CKF is illustrated in Fig. 2 [Figure 2: see original paper]. The ACTS CKF is used to find track candidates through track fitting steered by initial track parameters provided by either the ACTS seeding algorithm or the Hough Transform algorithm developed within the STCF offline software.

Interface Between STCF Offline Software and ACTS

The Offline Software System of the Super Tau-Charm Facility (OSCAR) [?, ?] serves as the offline event processing framework for STCF. It provides common services for data processing and a suite of application tools dedicated to event generation, simulation, reconstruction, and physics analysis. For simulation purposes, OSCAR incorporates generation of τ-charm physics processes facilitated by the KKMC [?] generator, while particle decays are modeled with EvtGen as used by the BESIII experiment [?], both seamlessly integrated within the framework. The STCF detector geometry is described using the Detector Description Toolkit, DD4Hep [?], with all geometric parameters stored in compact files utilizing the eXtensible Markup Language (XML) [?]. To comprehensively simulate particle interactions with the detector, Geant4 [?] is integrated into OSCAR, ensuring sophisticated full simulation. For track reconstruction, the track-finding algorithm based on the Hough Transform is developed in OSCAR.

The interface between OSCAR and ACTS facilitates the transformation of experimental geometry, measurements, and initial track estimates into corresponding ACTS representations. Geometry plugins within ACTS are tailored to streamline the conversion of experimental geometry representations, such as DD4hep or TGeo [?], into ACTS internal geometry descriptions. For ITK, the transformation involves converting the signal readout unit tube within each μ-RWELL layer into sensitive cylinder surfaces. Similarly, for MDC, the process entails transforming each sense wire within a drift cell into a line surface. Leveraging dedicated material mapping tools within ACTS, detailed material descriptions are projected onto internal auxiliary surfaces of the ACTS geometry. For the conversion of measurements and initial track parameters, two ROOT [?]-based readers have been developed. One reader extracts simulated hits from full simulation data and converts them into ACTS measurements, taking into account the detector resolution. Another reader converts the initial estimate of track parameters provided by the Hough Transform algorithm into ACTS track parameters.

ACTS Seed Finding

The seeding algorithm in ACTS aims to find a few measurements that can provide position coordinates (x, y, z) in the global coordinate frame associated with a single particle to initiate the track-following process. Without a seed, a particle cannot be reconstructed; hence the seed-finding algorithm aims to find at least one seed for each particle in the detector acceptance region.

In a uniform magnetic field along the global z axis, the helical trajectory of a charged particle is accurately defined by three measurements, thus forming a seed. In the case of STCF, these seeds are generated by combining three compatible measurements from the ITK detector with one measurement per ITK layer, as illustrated in Fig. 3 [Figure 3: see original paper]. For each candidate seed, the curvature and center of the circle on the x-y plane are determined using the Conformal Transform [?, ?]. Subsequently, these parameters are utilized to calculate the transverse momentum and the transverse impact parameter on the x-y plane, which are required to satisfy criteria optimized for the relevant physics processes. The bending of the seed in the r-z plane is also required to be smaller than a threshold, optimized taking into account the effects of the magnetic field and multiple scattering. See Ref. [?] for a detailed description of ACTS seeding.

Track Finding with Hough Transform

The principle of Hough Transform for track finding is illustrated in Fig. 4 [Figure 4: see original paper]. With a magnetic field along the global z axis, the projection of a track in the geometrical transverse x-y plane is a circle, and the projection in the geometrical s-z plane (where s is the path length of the track in the x-y plane) is a straight line. The Conformal Transform can convert the projection of a track in the transverse x-y plane passing through the origin into a straight line, with a drift circle tangent to the projection of the track converted to another circle tangent to the straight line in the Conformal u-v space. For a displaced track with non-zero but relatively small transverse impact parameter d_0 compared to the radius of the circle projected in the geometrical transverse x-y plane (as shown in the left panel of Fig. 4), the trajectory of the transformed measurements (either a point or a drift circle) in Conformal space can be approximately parameterized using a straight line, as shown in the middle panel of Fig. 4.

The Hough Transform for track finding operates on the principle that a straight line in geometrical or Conformal space can be described by two parameters: the angle θ of its normal and its algebraic distance ρ from the origin. For a point with coordinates (u, v) on the straight line, it can be transformed into a sinusoidal curve in Hough space: $\rho = u \cdot \cos\alpha + v \cdot \sin\alpha$. For a circle with center (u, v) and radius r tangent to the straight line, it can be transformed into two sinusoidal curves in Hough space: $\rho = u \cdot \cos\alpha + v \cdot \sin\alpha \pm r$. The process of finding measurements or drift circles arising from the same track in either the Conformal u-v space or the geometrical s-z space becomes identifying curves that intersect in Hough space, as shown in the right panel of Fig. 4. Specifically, a 2D histogram with optimized binning (taking into account track parameter resolution) is filled when a curve passes through it, and the peaks of the histograms are identified, as detailed in Ref. [?]. The parameters at the intersection can be converted to track parameters describing the track projected onto either the geometrical transverse x-y plane or the geometrical s-z plane.

The workflow of track finding using Hough Transform in OSCAR is shown in Fig. 5 [Figure 5: see original paper]. Initially, measurements from ITK and MDC axial wires are used to reconstruct the projections of tracks on the x-y plane (denoted as 2D tracks), followed by circle fitting to extract track parameters of the 2D tracks. This is succeeded by associating MDC stereo wire measurement candidates to the 2D tracks, where the z position and path length s of the track at the stereo wires are derived simultaneously. For each stereo wire measurement, two z position solutions can be obtained, and measurements from other tracks may be wrongly assigned to a 2D track. Therefore, a secondary application of Hough Transform is employed to find tracks in the s-z plane. More details can be found in Ref. [?].

Track Finding with ACTS CKF

Starting from a set of initial track parameters, the ACTS CKF is driven by the ACTS track propagator to search for compatible measurements at a particular surface through KF track fitting, as illustrated in Fig. 6 [Figure 6: see original paper]. This process is also known as track following. The measurement providing the best fitting quality is associated with the track and used to filter the track parameters for further track propagation.

Performance Studies

Monte-Carlo Samples

The J/ψ decay process $J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ is an important benchmark process at STCF enabling several key physics studies relevant to Λ. Signal events generated with the KKMC and EvtGen generators in OSCAR, without considering beam-related backgrounds, are used to evaluate tracking performance. The 2D distributions of $\cos\theta$ versus p_T, vertex displacement in the x-y plane V_{xy} versus p_T, and transverse impact parameter d_0 versus p_T for protons (anti-protons), denoted as $p(\bar{p})$, and pions in $J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ events are shown in Fig. 7 [Figure 7: see original paper].

Pions have low momentum with p_T below $310\,\mathrm{MeV}/c$, while $p(\bar{p})$ have p_T up to $1.1\,\mathrm{GeV}/c$. A non-negligible fraction of particles decay outside the first layer of ITK. However, most tracks have d_0 smaller than the radius of the first ITK layer, particularly for $p(\bar{p})$.

Following event generation, Geant4 simulates hits from final-state particles decaying from primary particles interacting with the STCF tracking system in a uniform 1 T magnetic field. Detector measurements are then generated by applying Gaussian smearing to the positions of simulated hits, with zero mean and widths corresponding to the detector resolutions.

Track Finding Performance

The performance of track finding, including seed finding using either the ACTS seeding algorithm or Hough Transform algorithm in the first stage, and track following using ACTS CKF in the second stage, is studied. Considering the acceptance of the STCF tracking system, only truth particles with p_T above $50\,\mathrm{MeV}$ and $|\cos\theta|$ below 0.94 are considered in performance metric evaluation, which involves identifying the primary particle [?] of a seed or track (i.e., the simulated particle contributing the most simulated hits to this seed or track).

The seeding process serves as the initial step in track finding using CKF and should ideally provide seeds for all particles. The ACTS seeding efficiency is defined as the fraction of particles in the tracking system acceptance region that have matched seeds with all three hits arising from the same particle. The seeding efficiency using Hough Transform is defined by requiring that a matched seed has at least 50% hits from its primary particle.

For ACTS seeding, it is only possible to find seeds for tracks if the particle produces hits in all three layers of ITK, indicating a vertex displacement below 66.5 mm. The comparison between efficiencies of ACTS seeding and Hough Transform as a function of particle V_{xy} is shown in the top panels of Fig. 8 [Figure 8: see original paper]. The ACTS seeding efficiency approaches 100% when the number of measurements from ITK is no less than 3. In particular, ACTS seeding provides better efficiency than Hough Transform for π with small V_{xy}. However, ACTS seeding efficiency immediately drops to zero if the number of measurements from ITK is below 3, indicating a significant limitation of the ACTS seeding algorithm, particularly for long-lived particles. The Hough Transform algorithm, functioning as a global tracking algorithm, demonstrates reduced sensitivity to the number of ITK layers particles traverse. The bottom panels of Fig. 8 show seeding efficiency as a function of particle p_T. The Hough Transform algorithm can provide efficiency above 90% for $p(\bar{p})$ with p_T above $350\,\mathrm{MeV}/c$ and above 80% for π with p_T above $85\,\mathrm{MeV}/c$, which is much improved compared to ACTS seeding.

Reconstructed tracks are required to have at least five measurements and satisfy $|\cos\theta| < 0.94$. A reconstructed track is matched to its primary particle if the fraction of its hits from that particle (i.e., track purity) is no less than 50%; it is classified as a fake track if not matched to its primary particle. If more than one reconstructed track is matched to the same simulated particle, the track with the highest purity is classified as the real track and others are classified as duplicate tracks. Track reconstruction efficiency is defined as the fraction of particles that have matched reconstructed tracks among particles with at least five simulated hits in the detector acceptance region. The fake rate is defined as the fraction of fake tracks among reconstructed tracks. The duplicate rate is defined as the fraction of particles that have at least one duplicate track among particles with at least five simulated hits in the detector acceptance region.

Figure 9 [Figure 9: see original paper] shows tracking efficiency as a function of particle V_{xy} and p_T. As expected, tracking efficiency using ACTS seeding and CKF drops to zero when particle V_{xy} exceeds 66.5 mm, while tracking efficiency with Hough Transform and CKF is less dependent on particle V_{xy}. A tracking efficiency above 80% for $p(\bar{p})$ with p_T above $350\,\mathrm{MeV}/c$ and above 70% for π with p_T above $85\,\mathrm{MeV}/c$ is achieved using the combined Hough Transform and CKF. Figure 10 [Figure 10: see original paper] shows the fake rate and duplicate rate using the two different seeding strategies. The fake rate is less than 0.4%, with a non-negligible number of duplicate tracks found for particles with p_T below $150\,\mathrm{MeV}/c$, which have looping trajectories when traversing the detector in a magnetic field. ACTS seeding results in lower fake and duplicate rates compared to Hough Transform seeding.

The track-finding performance of the alternative MAPS-based ITK for long-lived particles is compared to that of the μ-RWELL-based ITK. Figure 11 [Figure 11: see original paper] shows the tracking efficiency, fake rate, and duplicate rate of the combined Hough Transform and ACTS CKF for the two different ITK designs. Since the first two layers of the MAPS-based ITK have smaller radii than the μ-RWELL-based ITK, the MAPS-based ITK is less robust against long-lived particles and provides slightly worse tracking efficiency than the μ-RWELL-based ITK. The occurrence of fake and duplicate tracks is at a similar level for both designs.

Conclusion

Processes with long-lived particles provide opportunities for probing CP violation, strong interactions, and other phenomena at the next-generation Tau-Charm facility, STCF. However, high-performance track reconstruction for long-lived particles is a challenging and complicated task given the STCF tracking system. CKF is one of the most commonly used track-finding algorithms at HEP experiments, with its performance subject to the corresponding seeding algorithm. For long-lived particles, CKF using traditional seeding strategies that rely on measurements from inner detectors demonstrates significant performance loss. Based on the STCF offline software and the common tracking software ACTS, we have studied for the first time the combined performance of using Hough Transform as a seeding algorithm for ACTS CKF. The performance was evaluated using $J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ events at STCF. The study shows that CKF steered by Hough Transform achieves improved efficiency compared to CKF steered by traditional seeding algorithms for particles with large vertex displacement. The tracking efficiency using combined Hough Transform and CKF is 80% for protons and anti-protons with p_T above $350\,\mathrm{MeV}/c$, and above 70% for pions with p_T above $85\,\mathrm{MeV}/c$, with negligible fake tracks. Duplicate tracks also exist, mainly arising from particles with p_T below $150\,\mathrm{MeV}/c$ that have looping trajectories. Future developments, such as extending the 2D Hough space to 3D Hough space—where a track projection on the x-y plane not passing through the origin is described by three dedicated parameters—are foreseen to further enhance tracking efficiency for long-lived particles at STCF and beyond.

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Note: Figure translations are in progress. See original paper for figures.