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Reconstruction of Λ hyperons in an inhomogeneous magnetic field with a Kalman Filter based tracking algorithm

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Abstract. The high interaction rate, fixed target experiment HADES at GSI, located in Darmstadt, Germany, investigates collisions of heavy-ion, proton and secondary pion beams with a target material. Hyperons are one of the key observables for both heavy-ion and elementary collisions [1] [2]. The challenge is to detect displaced vertices with good accuracy without having a dedicated vertex detector, by employing state-of-the-art techniques. In this contribution we discuss a newly developed tracking algorithm that uses both a Kalman Filter (KF) and the high performance KF Particle package to further boost the reconstruction performance for hyperon decays with displaced vertices [3]. With the use of the covariance matrices, which take into account effects from multiple scattering and energy loss of the particles in the material, the reconstruction performance of the tracking algorithm can be significantly improved. The KF Particle utilises these covariance matrices together with its own internal KF to reconstruct primary and secondary decay vertices.

1 Introduction

The HADES experiment (see Fig.(1)) has been designed to measure particles produced in heavy-ions collisions in fixed target geometry and at beam energies of up to $2\,A$ GeV. Tracking is accomplished by four planes of low-mass drift chambers (also known as Mini-Drift-Chambers(MDC)) arranged in front of and behind a toroidal magnetic field generated by six superconducting coils symmetrically arranged around the beam axis. Special emphasis is laid on the efficient reconstruction of rare dielectron signals originating from virtual photon emission out of the dense and hot collision system. For this, the target region is surrounded by a Ring Imaging Cherenkov Detector featuring a spherical mirror, fabricated from glassy carbon of 2 mm thickness, and a thin carbon fibre shell enclosing (0.4 mm) the mirror and the radiator volume. A carbon fibre beam pipe holding the target is placed at the symmetry axis of the spherical half-shell of the RICH. For details see [5]. As all charged particles emitted from the target region have to traverse the beam pipe, radiator volume, the mirror and shell before entering the first drift chamber, the pointing precision of charged tracks extrapolated back to the target region is hampered by multiple scattering, particularly in the mirror and shell. This affects the reconstruction of weakly decaying strange hadrons and hypernuclei, which have locally displaced vertices. In the standard reconstruction procedure, uncertainties in the calculation of decay topology parameters, due to multiple scattering in the RICH material, from the fitted track models of the daughter particles, like distance of closest approach

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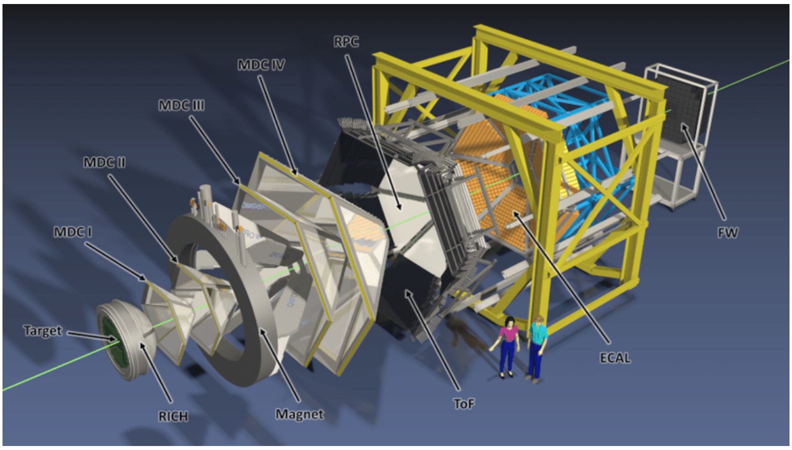


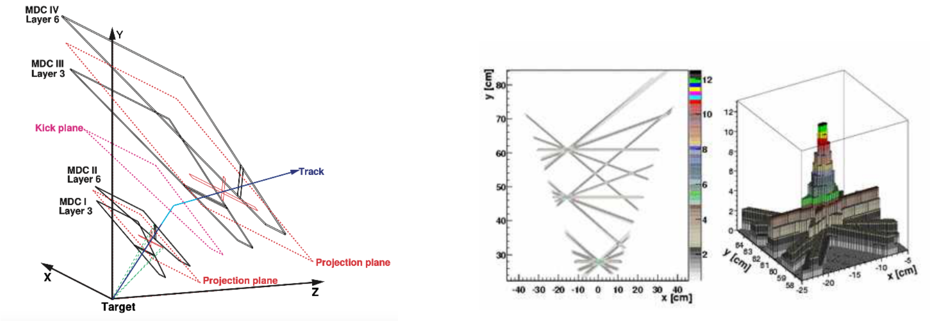
Figure 1: Expanded view of the HADES experiment with its components and the beam coloured in green

between the daughter particle tracks and of a single daughter particle track to the primary vertex, are not taken into account.

The *KF Particle* package has been developed to reconstruct secondary vertices by means of a combined fit involving all daughter track candidates and as additional constraint of the fit a line connecting the primary vertex with the reconstructed secondary vertex as proxi for the unobserved mother particle. The fit is performed with the Kalman filter method using a combined covariance matrix of all involved tracks in the fit. Based on the track model, the state vectors of each track is iteratively propagated to obtain a modified prediction of the secondary vertex. The expected mass of the mother particle can be used as an additional constraint. The ultimate goal of this work is to improve the performance of the weak decay reconstruction by including the effect of material budget in the RICH region.

2 Tracking in HADES

The track finding procedure in HADES is performed sector-wise independently. For a good approximation, the residual magnetic field in the region spanned between the inner two and outer two drift chambers can be neglected while the kick is essential produced between layer 2 and 3 (*cf.* Fig. 2 (a)). First, fired drift cells in the inner two tracking planes are evaluated to form so-called clusters, i.e. combinations matching the condition for straight tracks, called tracklets. For that, the volumes of fired drift cells are projected onto a virtual plane located between the two drift chambers of the same trapezoidal shape using a point projection with focal point in the primary vertex. Crossing wires produce local maxima in the projection plane which is searched for by applying a threshold accepting candidates for tracklets (see Fig. 2 b). In a second step, a model for a straight track is fitted using the drift time information of all wires combined to a tracklet candidate (cluster). Once all straight track candidates are found in the inner tracking layer (1+2), the same procedure is repeated for the outer two tracking layers but now using a multiple projection point given by the intersection of the extrapolated in straight tracks with the so-called Kickplane (Fig. 2 a). Next, combinations of inner and outer tracks are built to enable a track fit with the Runge Kutta method based on four hit coordinates $\vec{t_i} = [x_i, y_i, z_i]$, and respective uncertainties, which are obtained from the



(a) Projection planes

(b) MDC wire clustering

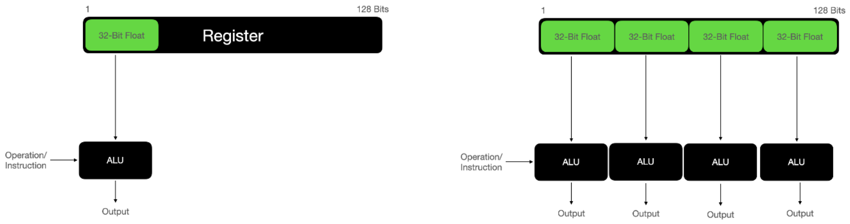
Figure 2: Two figures to illustrate the track reconstruction from the measured MDC hits. Figure(a) shows a schematic projection of track candidate search procedure with multiple projection planes
Figure(b) shows on the left side the x- and y-space projection of the cluster finding procedure and on the right a two dimensional histogram of the fired MDC wires which form a local maximum with 12 fired wires.

intersection of the straight tracks with the central plane of each drift chamber. A cubic spline fit is used to determine 50 evenly distributed space points in the field region. The resulting fit, along with a magnetic field map, is then used as input to a fourth-order Runge-Kutta method, which solves the particles equation of motion and hence delivers a good momentum reconstruction.

Finally, a Kalman Filter with subsequent Runge-Tauch-Striebel-smoothing [4] is applied on the Runge-Kutta approximated four MDC coordinates in order to gain the track uncertainties in form of covariance matrices. The calculated covariance matrices, together with other multiple track quantities, are then being used as an input for the KF Particle software package [6]. In a last iteration, the remaining particles that do not point to the silver target are assembled into potential daughter particles.

3 KF Particle package

The *KF Particle* software package was developed for highly efficient online reconstruction of short lived particles on many core computer architectures [6]. By the consequent use of SIMD (Single Instruction Multiple Data see Fig(3)) concepts and by employing a projection on a two-dimensional subspace for track extrapolation, the algorithm can avoid matrix-inversion operations and runs sufficiently fast to enable on-line event reconstruction in real time even at high-interaction rates. In the Kalman fitting procedure, all daughter particles originating from the hypothetical mother particle are added one by another to the filter process while the current estimate of the secondary vertex after step $k-1$ is filtered using the k-th track as measurement. Moreover, two constraints are imposed to the filter process by adding one-dimensional measurements with zero error. One constraint is of topological character and requests that a track connects the primary vertex with the secondary vertex. This assumptions holds for neutral particles or in cases where the characteristic decay length is short w.r.t. to the bending power of the magnetic field on that distance. Moreover, it is required that the momentum of the straight track from the primary vertex matches the momentum of the daughter particles at the secondary vertex. The second constraint is a mass constraint which



(a) SISD

(b) SIMD

Figure 3: Two figures to illustrate the data stream between register where the data is loaded into, and ALU which performs an instruction on the data. Figure(a) shows the case for a single stream and Figure(b) shows the case for a more efficient multiple data stream

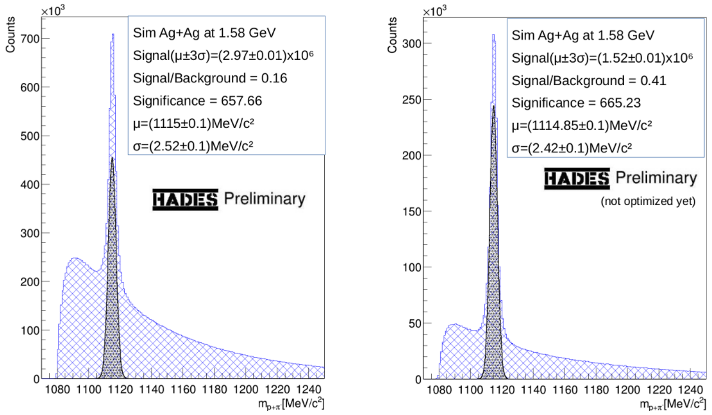
can be used if the Kalman filter test is used to identify a particular resonance, like e.g. a Λ hyperon.

4 Results

The reconstruction of Λ hyperons is extremely important because these short-lived particles can contain important information about the state of matter during the collision and thus, among other things, hint at the existence of the QGP [7]. The *KF Particle* package allows the consideration of multiple scattering, which was not taken into account to this extent with the previous reconstruction approaches. For the analysis results shown here, about $9.3x10^{7}$ UrQMD [8] Ag+Ag events at $1.58\,A$ GeV with one embedded Λ per event were used. In the first step, a differentiation is made between tracks from the event vertex (primary tracks) and tracks from displaced vertices (secondary tracks). Then, only the secondary tracks are considered and potential daughter particles of the same decay are searched for. These are then propagated with the covariance matrices along their direction of flight and the distances to other tracks are determined taking into account the errors in order to determine Λ candidates. The invariant mass spectra calculated from this, however, still contains combinatorial background, which must be subtracted from the spectrum to obtain a pure Λ signal.

In order to separate the signal (see Fig. 4) from the background, the exact position of the signal peak is first determined, to which a Gaussian distribution is then fitted. To extract the signal, points are set outside the $\pm 3\sigma$ environment, through which an exponential function is fitted, which serves as the background description. Finally, the fitted background is subtracted from the spectrum to obtain the pure signal.

Fig(4) shows the results of the Λ reconstruction. On the left side is the classical vector approach, which uses hard cuts on selected topology parameters (see Fig. (5)) to determine the λ candidates. The hard cuts applied correspond to the quantities used by [9]. On the right side are the results of the newly integrated *KF Particle* package. The signal to background ratio has increased from 0.16 (vector approach) to 0.41 (*KF Particle*) and the significance has increased from 657 to 665. Although the material budget has not yet been fully integrated into the Kalman Filter procedure, which significantly affects the performance of the *KFParticle*, it can be seen that the combinatorial background is significantly better suppressed and the significance enhanced. Once the Budget material is integrated, both significance and signal to background ratio will be significantly improved.



(a) Vector Ansatz (b) KF Particle

Figure 4: Invariant mass spectra of $\Lambda \rightarrow p + \pi^{-}$ decays of $9.3x10^{7}$ UrQmd Ag+Ag events at 1.58 GeV with one embedded Λ per event. Left plot shows the classical vector ansatz and the right plot shows the results of the new tracking algorithm

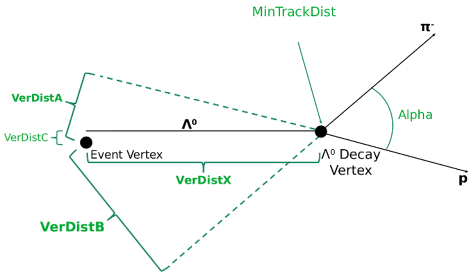


Figure 5: Decay topology parameter of $\Lambda \rightarrow p + \pi^{-}$

5 Summary and Outlook

In this contribution we have shown first results of Λ reconstruction using the integrated *KF Particle* package in the event reconstruction chain of the HADES detector system. With the help of the new tracking, the background could be controlled much better in direct comparison to the classical approach and the signal to background ratio has been significantly improved. In the current setup of the software, the parameters are not yet fully optimised and during the Kalman filter procedure, the entire material budget is not included, which affects the reconstruction possibilities of the *KF Particle* within the bounds of the errors. In the next steps, the multiple scattering will be modelled in detail using the full material budgets so that the software parameters can be fully optimised with the exact errors. Once this adjustment is complete, the software is run with measured data from the 2019 beam time with Ag+Ag at $\sqrt{S_{NN}} = 1.58\,A\,\mathrm{GeV}$.

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