Track reconstruction performance optimization using machine learning for the upgrade of the ALICE experiment

Anaëlle Chalumeau

- Sorbonne Université/LPNHE, Paris, France; anaelle.chalumeau@lpnhe.in2p3.fr

- 2023 CERN/ALICE summer student; Supervisor: Pavel Larionov and 2nd supervisor: Matteo Concas

Abstract

With the preparation of the future ALICE3 detector planned for the LHC Run 5 and 6, the use of new reconstruction algorithms, more adapted to its new geometry and more efficient, is needed. This project is about optimizing the performances for the charged particle track reconstruction in high-multiplicity Pb-Pb collision environment, in particular, for the particles with low transverse momenta, utilizing the machine learning based Optuna optimization framework to auto-tune the input parameters of the Combinatorial Kalman Filter algorithm within the ACTS track reconstruction software.

Keywords

CERN summer student project report; ALICE experiment; ALICE3 future detector; ACTS software; Machine learning; Hyper-Parameter Optimization

1 ALICE3 project

The ALICE detector was built to study heavy-ion collisions in order to explore the properties of the quark-gluon plasma using heavy ion collisions. Despite the progress expected in the current decade, several key questions in this area will remain unanswered and the aim is to reach a unified description of the rich phenomenology of QCD matter, connecting parton energy loss, collective flow, hadronisation and electromagnetic radiation. The ALICE3 experiment will enable an extensive program to fully exploit the LHC for the study of the properties of the quark-gluon plasma, see details in the Letter of Intent of the ALICE3 experiment [1]. This program relies on a novel and unique compact detector with high readout rate capabilities, great pointing resolution and excellent tracking and particle identification over a large acceptance. The ALICE3 cross-view is shown in Fig.1. To follow up with those new performances, the use and optimization of new reconstruction algorithms are therefore needed.

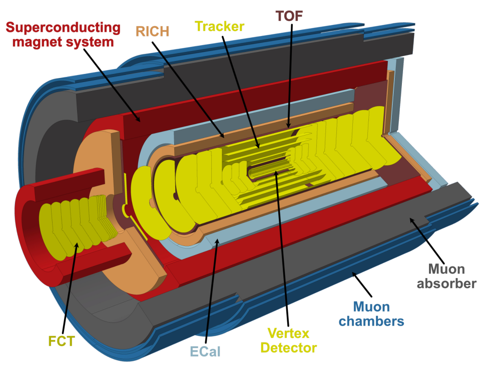

Figure 1: ALICE3 detector concept, from [1].

2 Track reconstruction with ACTS

2.1 Framework

A Common Tracking Software (ACTS) [2] is an open source framework providing high-level track reconstruction modules designed to be usable for any tracking detector. In this project we used the ACTS reconstruction software configured for the ALICE3 tracking geometry. The track reconstruction algorithms are complex and computationally expensive, especially in heavy ion collisions, where the number of produces particles is very high, thus creating an extremely challenging tracking environment.

Another complexity comes from the fact those algorithms need to be configured with many parameters for each specific detector geometry. Then the goal is to find the best set of parameters which will give the best reconstruction performances. To reach high performances, an automatic optimization of those input parameters appears as a better solution than hand tuning them, since it is difficult to determine manually the configuration which can produce the best performances. To do so, numerous optimization algorithms exist, as this problem comes down to the same as hyper-parameter optimization in machine learning. Following previous work for the ACTS generic detector as well as ATLAS inner tracker ITk, we will be using two different machine learning based optimization frameworks: Optuna [3] and Orion [4] which are already supported inside the ACTS project. Both are derivative-free approaches and integrate many different optimization algorithms.

2.2 Combinatorial Kalman Filter and Seeding algorithms of ACTS

The part of the reconstruction chain that was optimized in this project is the Combinatorial Kalman Filter (CKF) algorithm, which performs track finding and track fitting simultaneously and includes the seeding algorithm. These algorithms differ from the global ones as they evaluate individual combinations of space points (SP). The SPs in the specified detector layers are projected on a rectangular grid of configurable granularity. The seeding algorithm attempts to find triplets of SPs from increasing radii which are likely to belong to the same track. It achieves this by iterating the over the combinations of the SPs and applying cuts to filter the seeds based on their quality. The search for seed starts by selecting SPs in the middle detector layer and then matching SPs are searched in the inner and outer layers. The goal is to obtain the optimal parameters for the seeding algorithm which result in high track reconstruction performance, especially in Pb-Pb simulation at low transverse momenta.

3 Tuning of the space point finder

We established as well a manual binning for middle SP search in z and $r = \sqrt{x^2 + y^2}$ selected for our geometry as displayed in Fig.2. This configuration was found to give compatible reconstruction performance with respect to the automatic configuration for the middle SP range with lower total number of seeds.

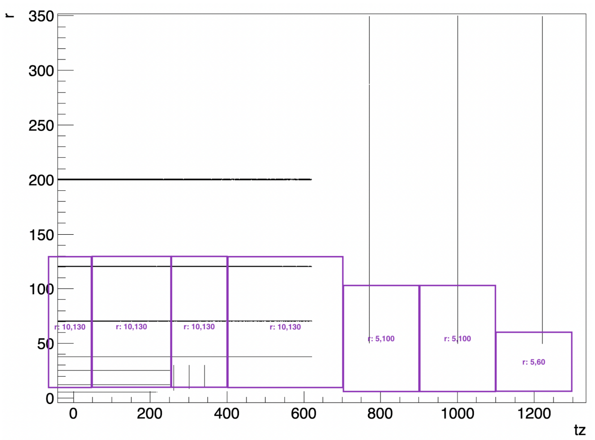

Figure 2: Manual binning for the middle SP search defined for the ALICE3 geometry.

4 Auto-tuning of the CKF input parameters

The CKF algorithm needs many input parameters which depends on several factor such as the detector geometry and pseudo-rapidity. Usually those parameters are defined based on prior experiences and tuned manually, but this approach is time consuming and not very flexible to changes. As opposed to this, automatic tuning of those parameters relying on machine learning hyper-parameter optimization techniques are more efficient, less time consuming and easily adaptable.

4.1 Approach

Following the ACTS auto-tuning on the generic and ITk detectors [5], eight parameters of the track seeding algorithm were chosen to be tuned using the optimization frameworks and their performance have been studied on CKF and compared to the hand-tuned approach.

4.2 Performance estimators

We are interested in mainly 4 quantities:

– the tracking efficiency, defined as the fraction of generated particles which have made at least 7 measurements on the traversed detector layers and are associated with tracks,
– the fake rate which is the fraction of reconstructed tracks that are not associated with any truth particle,
– the duplicate rate, fraction of reconstructed tracks associated with same truth generated particle,
– the run time of the CKF reconstruction algorithm.

4.3 Tuned parameters

The following geometry and pseudo-rapidity dependent parameters were chosen for the optimization

– `cotThetaMax`: cotangent of the maximum angle between two space points to be considered compatible,
– `maxSeedsPerSpM`: the maximum number of seeds for which one SP can be the middle SP,
– `sigmaScattering`: number of sigma of scattering angle should be considered,
– `impactMax`: maximum value of the impact parameter,
– `maxPtScattering`: the upper limit on the transverse momentum p_{T} for scattering calculation,
– `radLengthPerSeed`: the average radiation lengths of material on the length of a seed.

4.4 Implementation

We have implemented the optimization setup where the parameter tuning algorithm supplies the input parameter vector to the ACTS reconstruction framework based on the developments by [5]. In order to obtain the optimized parameters in the selected pseudo rapidity intervals the η ranges in the Seeding Algorithm of the CKF were set as following: $[-4, -3], [-3, -2], [-2, -1], [-1, 0], [0, 1], [1, 2], [2, 3], [3, 4]$. In the reconstruction chain the pseudo rapidity range is also set in the propagation engine based on Fast Track Simulation [6]. No cut in pseudo-rapidity was applied at the particle propagation step keeping the full detector acceptance range of $\eta = [-4, 4]$. The tuning framework computes a score value based on the track reconstruction performance and executes a parameter estimation method to evaluate a set of the input parameters and supply them to the ACTS framework. At the end of the optimization run the algorithm provides the set of parameters corresponding to the highest score.

4.5 Score function

We were running the Optuna optimization algorithm for 100 trials using a score function defined as: score $=$ efficiency $-$ (fakeRate $+$ duplicateRate$/7$).

5 Results

The track reconstruction efficiency and the duplicate rate as a function of the truth particle η are presented in Fig.3 and Fig.4, respectively. The results were obtained using the simulated Pb-Pb events of $\sqrt{s_{NN}} = 5$ TeV from the Pythia8 event generator and utilizing the ACTS reconstruction chain for the ALICE3 detector geometry. As a function of p_{T} the resulting efficiency in $[2,3]$ is shown in Fig.5 and compared to non-optimized parameters. A clear improvement in the reconstruction performance is observed with the optimised parameters over the entire ranges of pseudo-rapidity and p_{T}.

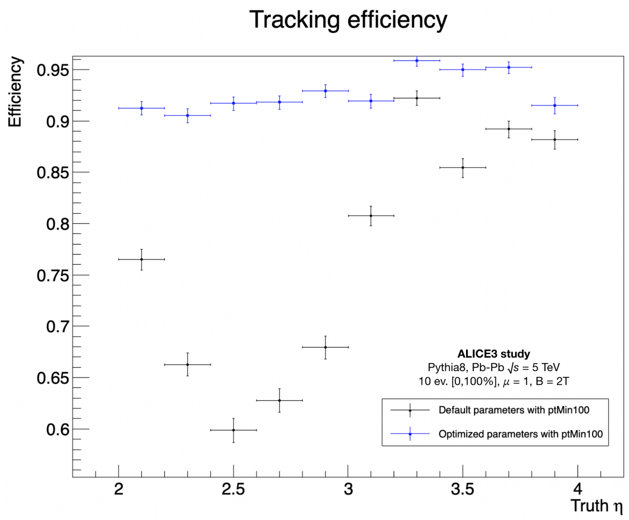

Figure 3: CKF tracking efficiency as a function of η in the $[2,4]$ range. In $[2,3]$ and $[3,4]$ the optimal parameters found are not the same.

We can also apply those optimized parameters found on $[3,4]$ for $[-4,-3]$ and it does show a similar improvements. Therefore running the optimization on only the positive η segments is enough.

6 Conclusion

In this project we have established the optimization procedure for the track reconstruction performance of the ALICE3 tracker using the ACTS reconstruction framework. We have obtained the optimal parameters for the Combinatorial Kalman Filter algorithm in the selected pseudorapitiy intervals using the Optuna optimization

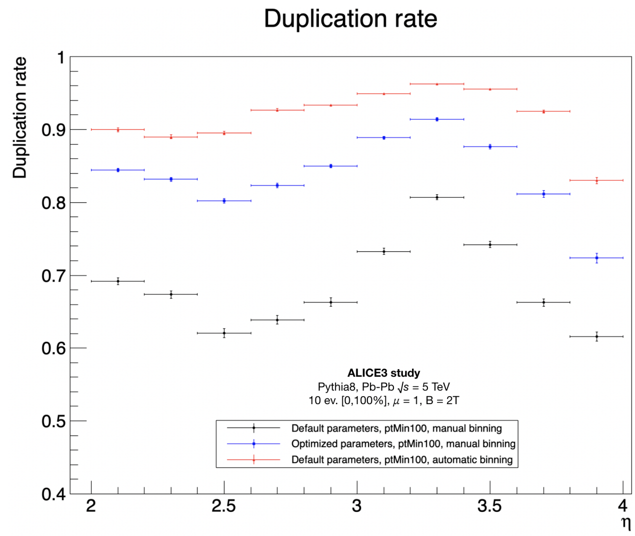

Figure 4: CKF duplication rate as a function η in the $[2,4]$ range. In red we add the comparison with the initial automatic binning, which means an equidistant binning on z by default and no cuts on r are applied.

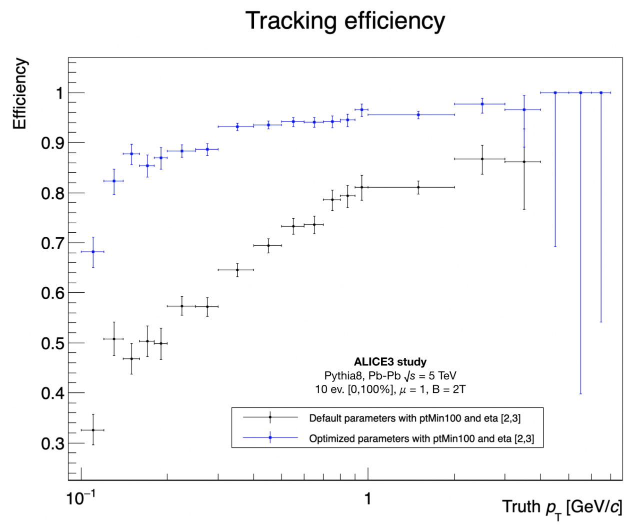

Figure 5: CKF tracking efficiency as a function of p_{T} in the low momenta region of interest for $\eta = [2,3]$. In black is the run with default hand-tuned parameters and in blue is with the optimized one.

framework that result in higher reconstruction efficiency and lower duplication rate with respect to the default hand-tuned parameters. Using the obtained parameters and by performing the further tuning of the seeding algorithm configuration we were able to successfully lower the minimum transverse momentum range for the reconstruction of Pb-Pb events within ACTS down to 100 MeV/c which provides important input for the performance studies of the ALICE3 tracker.

	time (min)	efficiency (=nMatchedParticles/ nTrueParticles)	# total seeds
	47	0.8403	451 357
	46	**0.9210**	**740 288**
	50	0.9437	1 072 746

Figure 6: Comparison table with execution time, tracking efficiency and total number of seeds from the run on $\eta = [3, 4]$ and for the 3 configurations in Fig.4.

Bibliography

[1] ALICE-Collaboration, "Letter of intent for ALICE 3: A next-generation heavy-ion experiment at the LHC." `https://cds.cern.ch/record/2803563`, 2022.

[2] X. Ai, C. Allaire, *et. al.*, "A common tracking software project." `https://github.com/acts-project/acts.git`, 2021.

[3] T. Akiba, S. Sano, T. Yanase, T. Ohta, and M. Koyama, *Optuna: A next-generation hyperparameter optimization framework*, in *Proceedings of the 25th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (2019)

[4] X. Bouthillier, C. Tsirigotis, *et. al.*, *Epistimio/orion: Asynchronous Distributed Hyperparameter Optimization*, 2023.

[5] R. B. Garg, E. Hofgard, L. Tompkins, and H. Gray, *Exploration of different parameter optimization algorithms within the context of ACTS software framework*, 2023.

[6] J. Mechnich and (on behalf ofthe ATLAS Collaboration), *Fatras - the atlas fast track simulation project*, *Journal of Physics: Conference Series* **331** (2011) 032046.