Event Topology Reconstruction in the CBM Experiment

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Abstract. One of the main purposes of the physics program of the future heavy ion experiment CBM (FAIR, Germany) is to understand the properties of strongly interacting matter at very high baryonic densities and to study the possibility of a phase transition to a deconfined and chirally restored phase of quark matter. The experiment will operate at high interaction rates up to 10 MHz, that requires a full event reconstruction in real time.

In order to make an efficient event selection online a clean sample of particles has to be provided by the reconstruction package called First Level Event Selection (FLES). The FLES package operates in two stages. First, particles registered in the CBM detector system are reconstructed. Then short-lived particles decayed before or inside the setup are searched based on their charged and neutral daughter particles. Since the FLES package is developed to run on many-core computer architectures, the reconstruction of particles is done in parallel that provides a possibility for a global competition between particle candidates. Such a global event topology reconstruction significantly improves suppression of a combinatorial background and provides for further physics analysis a very clean sample of particles produced at different stages of heavy ion collision.

The global event topology reconstruction procedure and the results of its application to simulated collisions in the CBM detector setup are presented and discussed.

1. Introduction

The Facility for Antiproton and Ion Research (FAIR) project is aimed to build a large international center for studying the structure and fundamental properties of matter. It is an accelerating complex of new generation which will provide unique opportunities to perform research in the most exciting fields of modern science: nuclear, hadron and particle physics, atomic and anti-matter physics, high density plasma physics, and applications in condensed matter physics, biology and bio-medical sciences [1].

In the Compressed Baryonic Matter (CBM) experiment [2] with heavy ions highest baryon densities will be created and the properties of super-dense nuclear matter will be explored in various extreme states similar, for instance, to the conditions of matter in the center of neutron stars, where the matter is at the final stage of the evolution before transition into black hole. The CBM experiment will complement the experimental heavy-ion program at the LHC accelerator.
complex at CERN where the properties of the hot matter similar to that after the Big Bang are investigated.

The scientific program of the CBM experiment includes:

- explore properties of super-dense nuclear matter;
- search for in-medium modifications of hadrons;
- search for the transition from dense hadronic matter to quark-gluon matter;
- search for the critical endpoint in the phase diagram of strongly interacting matter;
- investigate the structure of neutron stars and the dynamics of core-collapse supernovae.

The experiment will measure rare and penetrating probes such as dilepton pairs from light vector mesons and charmonium, open charm, multistrange hyperons, together with collective hadron flow and fluctuations in heavy-ion collisions at rates up to $10^7$ collisions per second.

**Figure 1.** A simulated central Au-Au collision at 25 AGeV energy with about 1000 charged particles (left), registered in the CBM detector (middle) and reconstructed by the Cellular Automaton track finder (right).

CBM is characterized by high collision rates, large amount of produced particles, non-homogeneous magnetic fields and a very complex detector system. Event reconstruction is the most complicated and time consuming task of the data analysis in modern high-energy physics experiments. It is a key part of success in the CBM experiment with up to thousand particles per central collision (Fig. 1). An additional complication in CBM is its continuous data stream represented in form of time slices. This makes the reconstruction of such 4-dimensional data with time stamps and the search for interesting physics extremely difficult. All of the above mentioned makes necessary to develop fast and efficient algorithms for data analysis and to optimize them for running on a modern high-performance computer cluster [3].

### 2. First Level Event Selection

The First Level Event Selection (FLES) package [4, 5] of the CBM experiment is intended to reconstruct online the full event topology including tracks of charged particles and short-lived particles. The FLES package consists of several modules (the block diagram is shown on Fig. 2): CA track finder, KF track fitter, KF Particle Finder and physics selection. In addition, a quality check module is implemented, that allows to monitor and control the reconstruction process at all stages. The FLES package is platform and operating system independent.

The FLES package is portable to different many-core CPU architectures. The package is vectorized using SIMD (Single Instruction, Multiple Data) instructions and parallelized between CPU cores. All algorithms are optimized with respect to the memory usage and the speed. Fig. 3 shows a strong scalability for all many-core systems achieving the reconstruction speed of 1700 events per second on the 80-cores server.
survive a dedicated selection based on the track length and calculated missing hit in one station is tolerated for a reconstructed track. The track candidates should to estimate the momentum of a particle, which could produce it. The triplets with two common combination of three hits on adjacent stations. The triplet structure was chosen, since it allows spacial measurements. The track finding procedure starts with combining the hits into triplets, hit measurements from the tracking detector in the form of a time-slice, which includes time and spacial coordinates. The same logic is used while constructing triplets: the first iteration only high-momentum primary tracks are reconstructed, in the second one — all other tracks.

Having found these tracks, the algorithm removes from the input information hits, which were used to construct these tracks. Thus, the combinatorics, which is higher for the iterations of the detector time precision. The resulting track reconstruction package.

2.1. 4D Cellular Automaton (CA) track finder

The 4-dimensional (4D, space and time) Cellular Automaton (CA) track finder [6] takes as input hit measurements from the tracking detector in the form of a time-slice, which includes time and spacial measurements. The track finding procedure starts with combining the hits into triplets, combination of three hits on adjacent stations. The triplet structure was chosen, since it allows to estimate the momentum of a particle, which could produce it. The triplets with two common hits are combined into track candidates. In order to take into account detector inefficiency, a missing hit in one station is tolerated for a reconstructed track. The track candidates should survive a dedicated selection based on the track length and calculated $\chi^2$-value to be accepted to the reconstructed tracks.

In order to optimize and speed up the process of track reconstruction the track finding procedure is performed in several iterations. At first the track finder algorithm is searching for the tracks, which are easier to reconstruct, for instance, high momentum and primary tracks. Having found these tracks, the algorithm removes from the input information hits, which were used to construct these tracks. Thus, the combinatorics, which is higher for the iterations when searching for low-momenta and secondary tracks gets significantly reduced. Therefore, in the first iteration only high-momentum primary tracks are reconstructed, in the second one — low-momentum primary tracks, and then — all other tracks.

Input time information is used in the algorithm to the same extent and in similar manner as it is done with the spacial coordinates. The same logic is used while constructing triplets: the hits in the triplet should belong to the same particle, therefore they should correlate not only in space, but also in time. Since the estimated time of flight between two consecutive station is negligible in comparison to the detector time precision, the hits, belonging to the same track, should coincide within $3\sigma$ of the detector time precision. The resulting track reconstruction efficiencies for the cases of event-by-event analysis (so-called 3D analysis) as well as for the 4D case (with included time measurement, as well as 3-dimensional spacial information) while reconstructing time-slices, produced out of one hundred AuAu minimum bias UrQMD events at 25 $A$GeV, are presented in Tab. 1.
Table 1. Track reconstruction efficiency performance for 100 minimum bias AuAu UrQMD simulated collisions at 25\text{AGeV} for the cases of event-by-event reconstruction, time-slice-based reconstruction at 0.1 MHz, 1 MHz and 10 MHz interaction rate, presented for different track categories.

| Track category       | E-by-E | 10^5 Hz | 10^6 Hz | 10^7 Hz |
|---------------------|--------|---------|---------|---------|
| All tracks          | 92.1   | 92.6    | 92.6    | 92.2    |
| Primary high-\(p\)  | 97.9   | 98.2    | 98.2    | 97.9    |
| Primary low-\(p\)   | 93.6   | 94.1    | 94.1    | 93.5    |
| Secondary high-\(p\)| 92.0   | 92.7    | 92.7    | 92.0    |
| Secondary low-\(p\) | 65.7   | 66.7    | 66.6    | 65.9    |
| Clone level         | 2.8    | 0.3     | 0.3     | 3.1     |
| Ghost level         | 4.9    | 3.5     | 3.5     | 4.2     |
| MC tracks found     | 145    | 146     | 146     | 145     |

2.2. Kalman Filter (KF) track fit library

High precision of the parameters of particle trajectories (tracks) and their covariance matrices is a prerequisite for finding rare signal events among hundreds of thousands of background events. Such high precision is usually obtained by using the estimation algorithms based on the Kalman filter (KF) method.

Figure 4. The KF track fitter is optimized and portable with respect to all many-core HPC architectures.

The developed Kalman filter based library for track fitting includes following tracking algorithms:

- track fit based on the conventional Kalman filter;
- track fit based on the square root Kalman filter;
- track fit based on the UD Kalman filter;
- track smoother based on the listed above approaches and
- deterministic annealing filter based on the listed above track smoothers.
High speed of the reconstruction algorithms on modern many-core computer architectures can be accomplished by: (a) optimizing with respect to the computer memory, in particular declaring all variables in single precision, (b) vectorizing in order to use the SIMD instruction set and (c) parallelizing between cores within a compute node.

Several formulations of the Kalman filter method, such as the square root KF and the UD KF, increase its numerical stability in single precision. All algorithms, therefore, can be used either in double or in single precision.

The vectorization and parallelization of the algorithms are currently done by using of: header files, Vc vector classes, Intel TBB, OpenMP, Intel ArBB and OpenCL.

The KF track fitter library is well investigated and developed to run on all many-core CPU/Phi/GPU architectures (Fig. 4).

2.3. **KF Particle Finder — a package for reconstruction of short-lived particles**

Today the most interesting physics is hidden in the properties of short-lived particles, which are not registered, but can be reconstructed only from their decay products. A fast and efficient KF Particle Finder package [7], based on the Kalman filter (hence KF) method, for reconstruction and selection of short-lived particles is developed to solve this task. A search of more than 100 decay channels has been currently implemented (Fig. 5).

![Figure 5](image-url)

**Figure 5.** Block diagram of the KF Particle Finder package. The particle parameters, such as decay point, momentum, energy, mass, decay length and lifetime, together with their errors are estimated using the Kalman filter method.

In the package all registered particle trajectories are divided into groups of secondary and primary tracks for further processing. Primary tracks are those, which are produced directly
in the collision point. Tracks from decays of resonances (strange, multi-strange and charmed resonances, light vector mesons, charmonium) are also considered as primaries, since they are produced directly at the point of the primary collision. Secondary tracks are produced by the short-lived particles, which decay not in the point of the primary collision and can be clearly separated. These particles include strange particles ($K^0_s$ and $\Lambda$), multi-strange hyperons ($\Xi$ and $\Omega$) and charmed particles ($D_0$, $D^\pm$, $D_s^\pm$ and $\Lambda_c$). After that tracks are combined according to the block diagram in Fig. 5. The package estimates the particle parameters, such as decay point, momentum, energy, mass, decay length and lifetime, together with their errors. The package has a rich functionality, including particle transport, calculation of a distance to a point or another particle, calculation of a deviation from a point or another particle, constraints on mass, decay length and production point. All particles produced in the collision are reconstructed at once, that makes the algorithm local with respect to the data and therefore extremely fast.

In addition, simultaneous reconstruction in the KF Particle Finder of different decay channels of the same particle, including also decays with a neutral particle in the final state, makes it possible to calculate the efficiency of the reconstruction of rare particles and reliably estimate their systematic errors.

The use of the Kalman filter at all stages of particle reconstruction allows in many cases to get rid almost completely of the combinatorial background and to obtain clean sets of particles, which can serve as probes of various stages of the collision (Fig. 6).

![Figure 6.](image)

**Figure 6.** The FLES package provides clean probes of various stages of the collision.

3. Discussion

Absence of a hardware trigger for selection of rare events in the CBM experiment requires the complete reconstruction of the event topology, including short-lived particles, in order to select events with rare decays, which carry important information about the process of heavy ion collision. The high interaction rate of up to $10^7$ collisions/s and a relatively low data recording speed on the storage media lead to the necessity of the online event selection stage in the FLES.
package in order to reduce the data flow by 3-4 orders of magnitude. Such high reduction ratio, as well as the need to select events with rare decays online, require the offline quality of the data processing already in real time.

A low-quality online data processing, for example, due to poor detector alignment or the presence of uncontrolled errors in the reconstruction algorithms and in the operation of the detector system, will inevitably make all the selected and stored data useless. Therefore, use of the theoretical analysis of the reconstructed data already in real-time at the event selection stage will ensure the high quality of data processing, eliminate the possibility of irreparable loss of data and, finally, avoid the waste of the accelerator operation time.

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WWND, Guadeloupe, 28.03.2018      /18

Real-Time Physics Analysis

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E.-by-E. yield estimate incl. acceptance (Blast-Wave)
E.-by-E. impact parameter (Glauber)

Figure 7. Online extraction of properties of medium created in heavy-ion collisions.

The offline quality of the online event processing, on the other hand, allows the use of theoretical models to estimate the collision parameters [8] immediately during the collection of experimental data on the accelerator with a delay of several milliseconds after the collision itself occurred.

As it is shown in Fig. 6, within the standard thermal analysis the fit to $\pi^-/\pi^+$, $K^-/K^+$, $K^+/\pi^+$ and $p/\pi^-$, reconstructed by the KF Particle Finder, gives the temperature and $\mu_B$ on the event-by-event basis. Integrating $dN/dy$ using the blast-wave model gives the multiplicity estimate after correcting on the acceptance and the reconstruction efficiency. There are also several ways to correlate impact parameter to data: number of nucleon participants (wounded nucleons); number of spectators; number of binary collisions and charged multiplicity. At known number of participant protons the impact parameter can be estimated using the Galuber model with the accuracy up to 1 fm in the ideal $4\pi$ case.

4. Conclusion

The FLES package has been developed for the CBM experiment. It contains track finding, track fitting, short-lived particles finding and physics selection. The Cellular Automaton and the Kalman Filter algorithms are used for finding and fitting tracks, that allows to achieve a high track reconstruction efficiency up to 97% and the track parameters quality with 1% of the momentum resolution. Reconstruction of more than 100 decay channels of short-lived particles is currently implemented in the KF particle finder. The package shows a high reconstruction efficiency with an optimal signal to background ratio.

The FLES package is portable to different many-core CPU architectures. The package is vectorized using SIMD instructions and parallelized between CPU cores. All algorithms are optimized with respect to the memory usage and the speed. The FLES package shows a strong scalability on the many-core CPU systems and the processing and selection speed of 1700 events per second on a server with 80 CPU cores.
References
[1] FAIR — Facility for Antiproton and Ion Research. Green Paper. The Modularized Start Version. GSI. October 2009.
[2] CBM Collaboration, Compressed Baryonic Matter Experiment, Tech. Stat. Rep., GSI, Darmstadt, 2005; 2006 update.
[3] I. Kisel, Event reconstruction in the CBM experiment, Nucl. Instr. and Meth. A566 (2006) 85-88.
[4] I. Kisel, I. Kulakov and M. Zyzak, Standalone first level event selection package for the CBM experiment, IEEE Trans. Nucl. Sci. 60 (5) (2013) 3703-3708.
[5] V. Akishina and I. Kisel, Online 4-dimensional reconstruction of time-slices in the CBM experiment, IEEE Trans. Nucl. Sci. 62 (6) (2015) 3172-3176.
[6] V. Akishina, “4D Event Reconstruction in the CBM Experiment”, Dissertation thesis, Goethe university, Frankfurt am Main (2017).
[7] M. Zyzak, “Online Selection of Short-Lived Particles on Many-Core Computer Architectures in the CBM Experiment at FAIR”, Dissertation thesis, Goethe university, Frankfurt am Main (2016).
[8] V. Vovchenko, Theoretical description and on-line extraction of properties of medium created in heavy-ion collisions, Workshop on CBM-STAR Common Approaches in Data Reconstruction and Analysis, BNL, 10 December 2015.