IL NUOVO CIMENTO **42 C** (2019) 85
DOI 10.1393/ncc/i2019-19085-x

Colloquia: EuNPC 2018

Perspectives of QCD phase diagram studies at high densities with the Compressed Baryonic Matter experiment at FAIR

M. Zyzak(*) for the CBM Collaboration
GSI Helmholtzzentrum für Schwerionenforschung GmbH - Darmstadt, Germany

received 5 February 2019

Summary. — The future heavy-ion experiment CBM at FAIR will operate at unprecedented interaction rates in the region of the high net baryon densities. This will provide a unique opportunity to study extremely rare probes thus increasing the sensitivity to the processes taking place in the created QCD matter. The ambitious goals of the experiment will require novel solutions in hardware, reconstruction algorithms, and their software implementation, which are currently being developed: free streaming readout electronics without hardware trigger and full event reconstruction already at the selection stage. The feasibility studies show a great potential of CBM to explore the QCD phase diagram.

1. – Introduction

The future heavy-ion experiment Compressed Baryonic Matter (CBM) [1] at FAIR [2] will study the QCD phase diagram in the region of high baryon chemical potential at relatively moderate temperatures, where complex structures are predicted by modern theories [3, 4]. In the region of small baryon chemical potential lattice QCD calculations predict a smooth cross-over between hadron gas and quark-gluon plasma phases [5, 6], while at large baryon chemical potentials a first-order phase transition takes place according to the present-day understanding [7]. In order to detect possible signatures of these structures, the physics program of the experiment includes a comprehensive study of extremely rare probes like charmed particles, dileptons, multi-strange particles, hypernuclei and their antiparticles. The multi-differential analysis of spectra, flow, collective effects will be performed even for such rare particles with unprecedented precision.

To achieve the goals the operation scenario assumes extremely high interaction rates of up to 10^7 collisions per second. To cope with such conditions the beam will have no bunch structure and CBM will operate with self-triggered front-end electronics and free streaming data. The detectors should be fast and efficient. Having no clear signatures for

(*) E-mail: `m.zyzak@gsi.de`

the hardware trigger, CBM will perform the full event reconstruction online including the stage of track and short-lived particle reconstruction. Fast and efficient reconstruction algorithms are being developed.

2. – Goals of the CBM experiment

CBM aims to investigate strongly interacting matter in the region of high baryonic densities. In the laboratory such matter can be created in the collisions of heavy-ion beams with energies $\sqrt{s_{NN}}$ = 2.7-4.9 GeV. The physics program of the experiment [8] includes the search for and a comprehensive study of:

- the hadronic-partonic phase transition in the region of high net baryon densities and the critical endpoint;
- the chiral phase transition (not necessarily the same);
- the equation of state at high densities, which is important, for instance, for studies of neutron stars;
- hypernuclei and heavy multi-strange objects;
- hadrons in dense baryonic matter and a possible modification of their properties;
- charm production at threshold beam energies and charm properties in dense baryonic matter.

Current theoretical models predict that during the evolution of the system, matter created in such collisions reaches densities up to 8 times of the saturation density ρ_0 [9]. At these densities a region of phase coexistence might be crossed. Particles created in a collision might carry the information about different stages of the collision. For instance, particles containing charm, anti-charm or anti-strange quarks are sensitive to the very first moments; Ξ^-, Ω^-, ϕ reflect processes taking place at the middle stages; bulk particles and resonance decays can provide an information about the last phases. Dileptons can be used to probe the whole evolution since they can penetrate strongly interacting matter. Thus, CBM will perform comprehensive studies of a wide range of observables including:

- particles containing strange or charm quarks (strange particles Λ, Ξ, Ω, charmed D mesons, J/ψ) — this will address such physics cases as in-medium properties of hadrons, phase transitions, hyperon-nucleon and hyperon-hyperon interactions;
- low mass vector mesons decaying into dilepton channel ($\rho, \omega, \phi \to e^+e^-$, $\rho, \omega, \phi \to \mu^+\mu^-$) — in-medium properties of hadrons, phase transitions, chiral symmetry restoration;
- hypernuclei, strange dibaryons and massive strange objects — hyperon-nucleon and hyperon-hyperon interactions;
- excitation functions of yields, spectra, and collective flow of these particles — equation of state of nuclear matter at high densities, phase transitions;
- event-by-event fluctuations of conserved quantities like baryons, strangeness, net-charge *etc.* as a function of beam energy — phase transitions and critical endpoint.

3. – Challenges in CBM

In order to measure rare observables CBM will operate with interaction rates up to 10^7 Hz. Since it is a fixed target experiment, the track density will be high and detector systems should combine high speed with high spatial resolution. The CBM detector

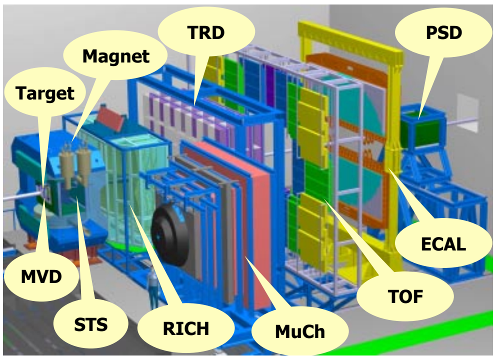

Fig. 1. – Detectors overview of the CBM experiment: tracking system consisting of MVD and STS, RICH and TRD for electron identification, MuCh for muon identification, TOF for hadron identification, PSD for event characterisation.

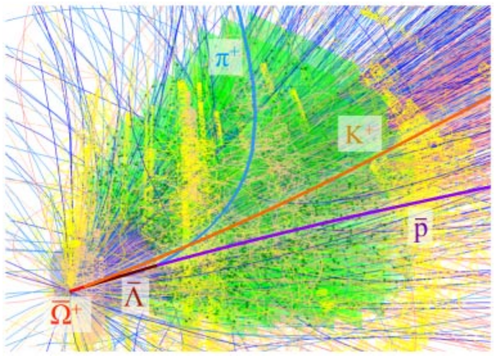

Fig. 2. – A cascade decay of $\overline{\Omega}^+ \to \overline{\Lambda} K^+$ with further $\overline{\Lambda} \to \overline{p}\pi^+$ — a typical complex signature in CBM for the online event selection. One of such decay is expected per about 1000 central collisions.

will consist of a silicon tracking system placed in the 1 T·m magnetic field followed by particle identification (PID) and event characterisation detectors [1] (see fig. 1). Most of the physics signatures will have a complex structure which do not allow to build a hardware trigger, for instance, the $\overline{\Omega}^+$ decay as shown in fig. 2. The data in CBM will be free-streaming.

Due to the high interaction rates, hits produced by particles from different collision will overlap in time. As a result, the input data will have no conventional event-like structure, they will be grouped into time slices containing large number of events, the input data will be marked with a time stamp. The time-slice structures will be reconstructed in 4D taking into account not only space coordinates (x,y,z) but also a time information t. The first version of the time based 4D Cellular Automaton (CA) track finder has been developed [10]. For the selection of events of physics interest online time based event reconstruction is required with a selection of extremely rare probes. The reconstruction algorithms will be run in real time by the First Level Event Selection (FLES) software [11] at a dedicated FLES many-core high performance computing farm. The FLES package will perform the full reconstruction including track reconstruction and

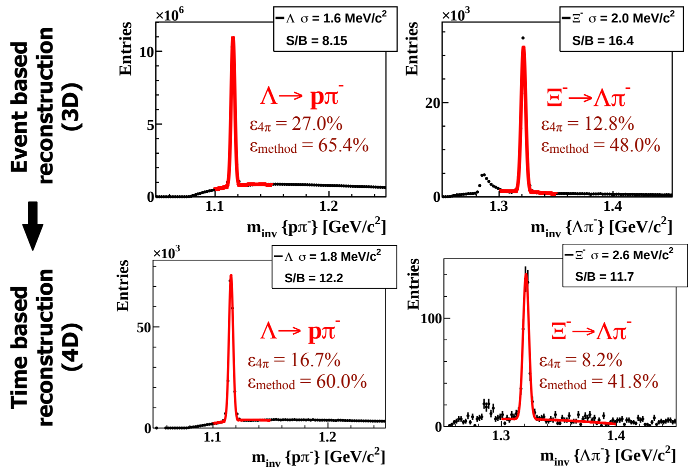

Fig. 3. – Reconstruction of short-lived particles with event-based 3D and time-based 4D approaches. 3D results were obtained with the full detector setup and realistic PID using 5M central AuAu UrQMD [12, 13] events at 10 AGeV/c, 4D — with STS only and ideal PID using 300k mbias AuAu UrQMD events at 10 AGeV/c and 10 MHz interaction rate.

reconstruction of short-lived particles. Physics events which correspond to the collisions will be defined at the last step using time and topology information.

Event based is the standard approach in High Energy Physics and Heavy Ion experiments. Development of the CBM algorithms has been started from the similar 3D reconstruction scheme, which is currently well established. The most part of feasibility studies up to now were performed using this approach.

Recently first studies using the 4D CA track finder were started with the STS detector and ideal PID. The 4D approach shows stable performance comparable to 3D. As an example reconstruction of strange particles is shown in fig. 3: efficiency and signal to background (S/B) ratio are similar, the difference is mainly due to the acceptance of the full setup and STS alone. Currently, the 4D scheme is being further extended onto PID detectors and hit reconstruction procedures. Also, the multi primary vertex reconstruction is under development for higher level of event separation.

4. – Summary and outlook

The mission of the CBM experiment is to investigate the phase diagram of strongly interacting matter in the region of the high net baryon densities ($\sqrt{s_{NN}}$ = 2.7-4.9 GeV). The key feature of the experiment which is required for the measurement of rare observables is a high rate capability. The strategy for data readout and event selection is based on free streaming front-end electronics. Having no hardware triggers, CBM will perform online reconstruction and selection of events, that will require fast and scalable algorithms. First version of the time based reconstruction in the tracking system is available. Implementation of the full time based reconstruction scheme is in progress. Performance studies for a wide set of observables show unprecedented capabilities of the CBM experiment for the exploration of highly compressed baryonic matter.

REFERENCES

[1] Friman B. *et al.*, *The CBM physics book: Compressed baryonic matter in laboratory experiments* (Springer, Berlin, Heidelberg) 2011.
[2] Gutbrod H. H. *et al.*, *FAIR Baseline Technical Report* (GSI, Darmstadt) 2006.
[3] Fukushima K. and Hatsuda T., *Rept. Prog. Phys.*, **74** (2011) 014001.
[4] Andronic A. *et al.*, *Nucl. Phys. A*, **837** (2010) 65.
[5] Aoki Y. *et al.*, *Nature*, **443** (2006) 675.
[6] Karsch F., *J. Phys. G*, **38** (2011) 124098.
[7] Fodor Z. and Katz S. D., arXiv:0908.3341 [hep-ph].
[8] Ablyazimov. T. *et al.*, *Eur. Phys. J. A*, **53 3** (2017) 60.
[9] Arsene I. C. *et al.*, *Phys. Rev. C*, **75** (2007) 24902.
[10] Akishina V. and Kisel I., *IEEE Trans. Nucl. Sci.*, **62 no. 6** (2015) 3172.
[11] Kisel I., Kulakov I. and M. Zyzak, *IEEE Trans. Nucl. Sci.*, **60 no. 5** (2013) 3703.
[12] Bass S. A. *et al.*, *Prog. Part. Nucl. Phys.*, **41** (1998) 225.
[13] Bleicher M. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **25** (1999) 1859.