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The physics goal of the CBM experiment at FAIR

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Relativistic heavy-ion collisions enable the creation of hot and dense strongly interacting matter over a wide temperature and densities in the laboratory. The Compressed Baryonic Matter (CBM) experiment which is currently under realization at Facility for Anti-proton and Ion Research (FAIR) accelerator complex in Darmstadt, Germany aims at the investigation of the QCD phase diagram in the region of moderate temperatures and high net-baryon densities. The fundamental questions to be studied include the chiral and deconfinement phase transition at high baryon densities, the location of the critical end point, the Equation of State (EOS) of highly compressed hadronic matter and the in-medium properties of hadrons. The FAIR accelerator SIS100 will provide high-intensity heavy-ion beams up to Au ions in the beam kinetic energy range 2A GeV to 11A GeV. The CBM detector setup is designed as a universal instrument, to measure both bulk observables with large acceptance and rare diagnostic probes such as multi-strange hadrons, charmed particles (D mesons, and charmonia) and low mass vector mesons decaying into lepton pairs. The experimental challenges are high particle occupancies and data rates in the environment of unprecedented interaction rates of up to 10 MHz. Particular technological challenges are the operation of the detectors at very high particle intensities and handling of very high data rates. The foreseen contribution will discuss the major physics goals of the CBM experiment, the related observables and their physics performance studies with the designed detector setup.

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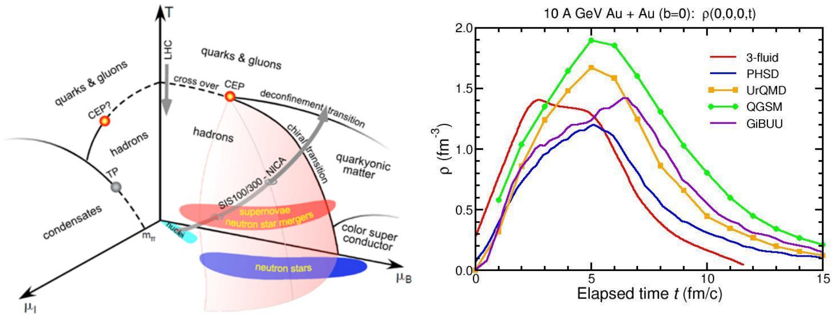

Figure 1: (left) Schematic of the conjectured QCD phase diagram in 3D representation, in terms of temperature (T), baryon chemical potential (μ_B and iso-spin chemical potential (μ_I). (right) Time evolution of the net-baryon density in the central cell of the 10A GeV central Au+Au collisions, as estimated by various transport and hydrodynamical model calculations.

1. Introduction

The fundamental theory of strong interactions, quantum chromodynamics (QCD), exhibits a rich phase structure. Fig. 1 (left panel) displays a schematic picture of the QCD phase diagram [1], described in terms of temperature (T), baryon chemical potential (μ_B) and iso-spin chemical potential (μ_I). Exploration of the QCD phase diagram and thereby gaining insights into the non-perturbative regime of strong interaction is one of major challenges in modern nuclear physics. Relativistic heavy-ion collisions are the only known experimental tool to probe the exotic states of strongly interacting matter in the laboratory. By varying the collision energy and the colliding species, nuclear matter can be produced over a wide range of temperature and net baryon densities and thus provides us the opportunity to investigate the different phases of strongly interacting matter in quantitative details. Our current understanding of the phase structure of QCD is mostly limited to the low μ_B domain. Here the state-of-the-art lattice QCD calculations provide evidence for a smooth cross-over transition from the hadronic phase to the partonic phase at a pseudo-critical temperature of $T_c \simeq 155$ MeV [2]. Experimentally this low μ_B region is well studied in heavy-ion collisions at ultra-relativistic energies at CERN-SPS, BNL-RHIC and CERN-LHC. The results indicate the formation of a deconfined phase in such collisions, a strongly coupled quark-gluon plasma (sQGP), properties of which are consistent with lattice QCD predictions. Compared to this, in the large μ_B regime, the QCD phase diagram is largely unexplored. The lattice QCD estimations are not yet applicable at these high net baryon densities whereas only a few experimental measurements mainly of bulk observables are available from first generation experiments at AGS. However this high density domain of QCD phase diagram is predicted to exhibit many interesting features. Calculations based on effective field theory (EFT) [3] suggests the existence of a first order phase transition with co-existence of hadron gas and QGP at moderate temperatures and high net baryon densities. The boundary line of first order phase transition, should end at a critical end point (CEP), where the transition is second order. As evident from the phase diagram, at high μ_B several other exotic phases are likely to exist, for example a quarkyonic phase which is confined but chirally symmetric or the color superconducting phase at almost zero temperature and extreme densities. Some of these prominent landmarks of the QCD phase diagram, if experimentally verified, would

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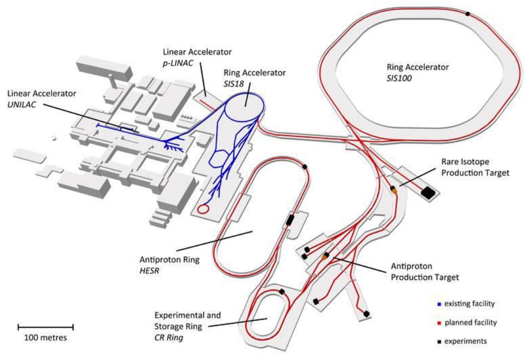

Figure 2: Schematic layout of the FAIR accelerator complex.

be a giant step forward in our efforts to understand the QCD in the non-perturbative domain.

This has triggered a renewed interest to relativistic nuclear collisions at lower energies, where incoming baryons are stopped at mid-rapidity to produce a high baryon density medium. A number of experimental programs are currently operational or under development worldwide, with a focal aim to study the properties dense baryonic matter. The Facility for Anti-proton and Ion Research (FAIR) [4] is an accelerator based international center, currently under construction in Darmstadt, Germany. The schematic layout of the facility is illustrated in Fig. 2. At FAIR, the SIS100 accelerator will deliver high-intensity heavy-ion beams up to Au ions in the beam kinetic energy range 2A GeV to 11A GeV and intensities up to 10^9 ions/s. Proton beams will be available with a maximum beam kinetic energy of 29 GeV and intensities up to 10^{11} /s. As suggested by different transport and hydrodynamic model calculations [5], relativistic heavy-ion collisions in this energy range, create baryonic matter with core density that can reach up to $8-10$ times the normal nuclear matter density ($\rho_0 \simeq 0.16$ fm^{-3}), for a relatively long duration. Such a situation is displayed in the right panel of Fig. 1. The Compressed Baryonic Matter (CBM) experiment [6] is being developed, for characterization of the baryon rich medium, anticipated in nuclear collisions at FAIR, via measurement of a large variety of observables including the multi-strange hadrons, charm and dileptons among the others.

2. Promising observable to probe dense baryonic matter

Till date there is no unique key measurement to unambiguously decode the phase structure of the hot and dense matter created in relativistic nuclear collisions. The experimental strategy of CBM is to perform systematic multi-differential measurements of a set of predicted observables as a function of beam energy and system size. In the following some of these promising observables and their relevance in the CBM research program is briefly discussed; see [7] for more details

2.1 Production of strangeness and hypernuclei

Hadrons made of strange quarks are considered useful diagnostic probes in heavy-ion collisions. An enhancement in the yields of the strange baryons is expected in nuclear collisions where high baryon densities are produced. Strange quarks are not initially present in the system, however they

PoS(CPOD2021)031

are light enough to be thermally produced inside the fireball. The thermalization status of the strange particles may be studied from the yield and phase space distribution of the multi-strange hadrons, particularly Ω baryon [8]. In a purely hadronic scenario, multi-strange baryons can be produced in a multi-step process via sequential collisions of strange hadrons like kaons and Lambdas. On the other hand thermal model calculations explain the production of multi-strange hadrons assuming the presence of a thermalized partonic medium that helps in achieving chemical equilibrium. The research program of CBM thus includes the measurement of the excitation function of multi-differential yields, flow and fluctuations of strange hadrons including multi-strange baryons and ϕ mesons for different collision centralities and varying system size.

The yields of hypernuclei will shed light on the hyperon-nucleon interactions. Their yields are governed by the interplay of two competing processes, increase in hyperon production and decreased production of light nuclei with increasing beam energy. Thermal model calculations accounting for both the effects, predict a maximum of the yield of single and double hypernuclei near the top SIS100 beam energies [9]. CBM is thus foreseen to have a major discovery potential for measuring the production of light double-Λ hypernuclei and getting deeper insights into the hypernuclei physics via studying $\Lambda - \Lambda$ and $\Lambda - N$ interactions.

2.2 Collective flow

The collective flow of the produced hadrons is driven by the initial state spatial anisotropy and the resulting pressure gradients. Comparison between theoretical calculations and experimental results, on different flow harmonics, namely directed (v_1) and elliptic (v_2) flow coefficients, help to get insights about the equation-of-state (EoS) governing the evolution of the produced medium. No consistent picture is so far available at these low energies, in particular for the energy dependence of the flow coefficients of the strange hadrons. Data collected by the STAR experiment at RHIC beam energy scan (BES) indicate an increasing difference between particle and antiparticle flow with decreasing energy of the collision [10]. Analysis of AGS results indicate that Λ and K^0 have opposite sign [11]. The flow of kaons as measured by FOPI and KAOS collaborations exhibit a strong dependence on in-medium potentials [12, 13]. With the foreseen high precision measurements of the strange hadrons at CBM, we aim to bring all of this experimental observations together to a consistent outcome.

2.3 Charm production

The production and propagation of charmed hadrons close to their kinematic production threshold can be studied with proton and heavy-ion beams at SIS100. The measurement of J/ψ production in $p+A$ collisions at SIS100 energies will provide the pioneering opportunity to measure resonance-nucleon interaction cross section owing to small formation length of J/ψ mesons in the laboratory frame, and thus help to constrain different available theoretical models [14]. Additionally the SIS100 Au+Au collisions are suitable to investigate the sub-threshold charm production via a multi-step collision process, as predicted in [15]. The CBM detector setup has been optimized for the measurement of both open charm and charmonia. Hence one can in principle estimate the total charm production cross section and test the validity of the perturbative processes at low energies.

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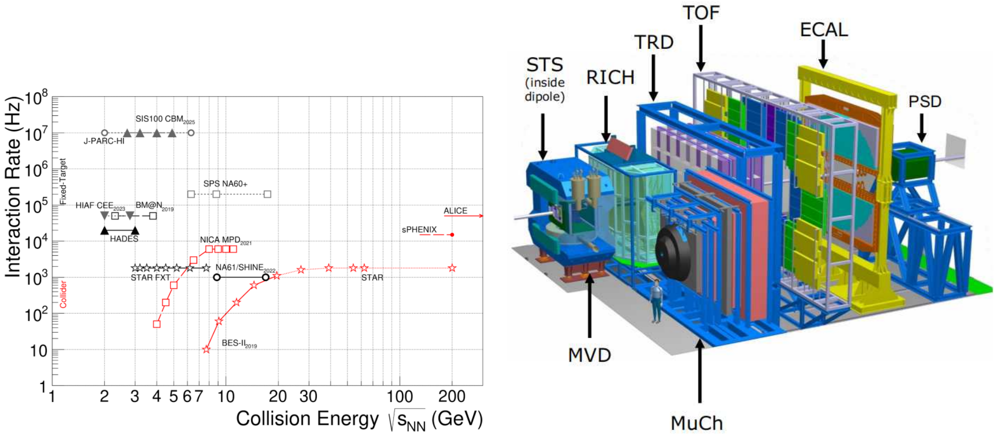

Figure 3: (left) Comparison of the highest interaction rates achieved by different running and upcoming relativistic heavy-ion experiments, as a function of collision energy. Collider geometries are shown by red symbols while black and grey symbols indicate fixed target mode. (right) The schematic picture of the CBM experimental setup at FAIR SIS100. The beam enters from the left. The sequence of detectors is: two tracking devices MVD and STS inside the superconducting dipole magnet, RICH detector, TRD, TOF, ECAL and a hadronic calorimeter (PSD) for measuring collision centrality. The muon (MUCH) detector is shown in the parking position.

2.4 Dileptons

Dileptons emitted in relativistic nuclear collisions are believed to carry unscathed information about the early phases of the produced fireball. Being electromagnetic in nature they remain undistorted during the evolution of the medium. They are produced in large variety of processes. Depending on the selected pair mass range, dileptons provide information on the source temperature, medium modification of the vector mesons, lifetime of the fireball, baryon density due to coupling to baryonic resonances and possible restoration of chiral symmetry. In particular the mass spectrum of the thermal dileptons, once the contribution from other dilepton sources are carefully subtracted,, above 1.5 GeV/c^2 provides a direct estimate of the source temperature. Though the extracted temperature value reflects an average over the evolution history of the fireball, but the selected large mass window makes it sensitive mostly to the early high temperature phases. Moreover mass being Lorentz invariant quantity, the source temperature is not blue shifted by the collective expansion of the fireball. This method has been pioneered by the NA60 experiment at SPS to measure the fireball temperature of 205 MeV, in In+In collisions at $\sqrt{s_{NN}}$ = 17.3 GeV [16]. More recently the HADES collaboration at GSI reported a source temperature of 72 MeV extracted from background corrected di-electron spectra in 1.25A GeV Au+Au collisions [17]. In CBM, dilepton measurements as a function of collision energy between HADES and SPS offers us the unique opportunity to experimentally determine the so-called caloric curve of hot and dense QCD matter and thus experimentally finding a direct signature for a possible first order phase transition.

3. The CBM experiment at FAIR

CBM is a fixed target multi-purpose detector setup, designed to detect hadrons, electrons and muons, in order to measure their excitation functions and their dependence on collision centrality

PoS(CPOD2021)031

and system size, over the full SIS100 energy domain. The major focus of the CBM experiment is to operate at a maximum reaction rate of 10 MHz for heavy-ions. This would enable the multi-differential measurement of exotic signals like multi-strange hyperons, charm and dileptons with high precision within a reasonable beam time. The foreseen highest collision rates at CBM, is orders of magnitude higher, than the interaction rates of any other existing or upcoming heavy-ion experiments around the globe. This is schematically illustrated in the left panel of Fig. 3 [7, 18], which shows a recent compilation of the maximum interaction rates achieved by different existing and planned heavy-ion experimental facilities, as a function of centre-of-mass energy.

3.1 The CBM detector system

The schematic setup of the CBM experiment is displayed in the right panel of Fig. 3. It consists of a 250 μm thick Au target corresponding to 1% interaction length, placed inside a superconducting dipole magnet of angular aperture $\pm 25^{o}$, providing a maximum bending power of 1 Tm. Two tracking devices reside inside the magnet. The micro-vertex detector (MVD) made of four layers of silicon monolithic active pixel sensors (MAPS) is located between 5 cm and 20 cm downstream the target. It ensures high precision reconstruction of secondary decay vertices, required for detection of open charm hadrons. The silicon tracking system (STS) is the main tracking device required to measure the charged particles and their momentum. It is located between 30 cm and 100 cm downstream the target and consists of 8 layers of double-sided micro-strip silicon sensors. The material budget of the STS is kept extremely low ($\simeq$ 1%) to minimize the multiple scattering and achieve a momentum resolution of about 1.5 %. Three different strategies are adopted for particle identification in CBM. The hadrons and nuclei are identified by measuring their energy deposition in transition radiation detector (TRD) and time-of-flight (TOF) with a wall of multi-gap resistive plate chamber (MRPC) located at a distance 7 m from the target with an active area of 120 m^2. Separation of electrons (and positrons) from pions is enabled by two detectors: a ring imaging Cherenkov (RICH) counter and the TRD. Simulation studies suggest that a hadron suppression factor of the order of 10^4 can be achieved for a maximum pion momentum of 7 GeV/c, for an electron with a reconstruction efficiency of 80 - 90 %. The muon identification is provided by four high resolution gaseous detector stations, placed between hadron absorbers made of concrete (30 cm), high density graphite (28 cm) and iron blocks of variable thickness (20 cm, 20 cm, 30 cm, 100 cm). Each detector station in the muon identification setup consists of three detector layers of increasing radial size while going downstream. Due to varying particle rates incident on different detector planes, different technologies are planned to be used for detector at various stations. As per existing design, first two stations will be built of high granularity triple-gas electron multiplier (GEM) chambers, to cope up with the high incident flux. In the 3rd and 4th stations, single gap resistive plate chambers (RPC) will be used. The muon chambers (MuCh) will be operated alternatively to RICH. However the TRD will be used as the last tracking station for MuCh, after the last hadron absorber. Use of TOF information in the muon setup helps to remove the punch-through protons and pions. The determination of the reaction plane angle, required for flow measurements will be performed by a segmented hadronic calorimeter called Projectile Spectator Detector (PSD) located at 10 m downstream the target [19]. For determination for collision centrality both the methods based on charged particle multiplicity measured by STS and the energy deposited by projectile spectators in PSD will be exploited [20].

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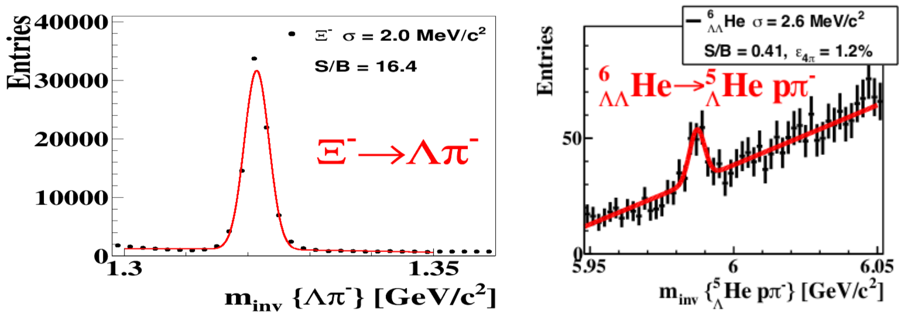

Figure 4: Invariant mass spectra of the (left) hyperons and (right) double lambda helium hyper-nuclei, reconstructed from simulations of 10 A GeV/c central Au+Au collisions using CBM software framework, based on a realistic description of geometry and response of the CBM detectors.

As CBM has to record primary and secondary reaction products of up to 10^7 heavy-ion collisions per second, the entire detector system has to be fast, radiation hard and capable of handling huge fluxes of incident particles due to the fixed target geometry. This also demands a data acquisition (DAQ) system not restricted by any trigger and readout latency on the order of (at least) several μs as introduced by a typical centrally controlled trigger hierarchy. The strategy adopted by CBM is not to employ any hardware trigger for event selection but collect data in free streaming triggerless mode. Raw hits from each subsystem, above detector-specific predefined thresholds will be recorded with a time stamp using the so-called self-trigger electronics and transferred through various FPGA-based system to a high performance computing farm in the GSI GreenIT cube [21]. The transmitted data volume from various subsystems is limited by the overall data transmission speed of 1 TB/s. Online reconstruction and selection of events including the secondary vertex search in real-time will be delivered by a high speed first level event selection (FLES) [22]. Charged particle tracks in various subsystems will be reconstructed using the corresponding hits associated with the co-ordinates and time stamp. The track momentum is provided by STS positioned inside the dipole magnet. Based on associated time information the reconstructed tracks are clustered in different groups which represent the original events.

3.2 Physics Performance studies

The CBM detector setup has been optimized to ensure the measurement of yields and phase space distributions of all promising observables over the full SIS100 energy range. Detailed feasibility studies have been performed through extensive simulations to evaluate the performance. Event generators like UrQMD [23] and transport codes like GEANT3 [24] are used for this purpose. Cellular Automation algorithm is employed for reconstruction of the charged particle tracks. A dedicated software package called KFParticleFinder, based on Kalman Filter approach [**?**] is employed to identify short-lived hadrons like hyperons, hypernuclei and charmed hadrons, from their decay topology. We present below some of the selected results of our physics performance simulations for the planned measurement of hyperons and dileptons.

Fig. 4 shows the invariant mass spectra of (left panel) Ξ^- hyperon and (right panel) double Lambda Helium hypernuclei simulated in 10 A GeV/c central Au+Au collisions, with UrQMD as event generator and reconstruction of decay topology using CBM software framework. Assuming one week of beam time, CBM expects to measure around 4×10^8 Ξ^- hyperons for a nominal reaction

PoS(CPOD2021)031

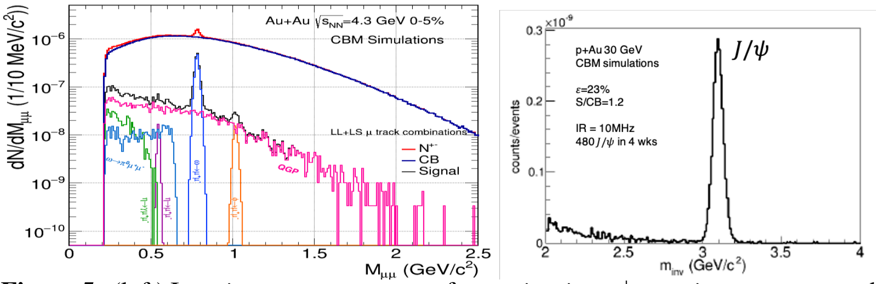

Figure 5: (left) Invariant mass spectrum of opposite sign $\mu^+\mu^-$ pairs, reconstructed from simulations, in 10A GeV/c most central ($0-5\%$) Au+Au collisions. (right) Invariant mass spectrum of J/ψ mesons reconstructed via $\mu^+\mu^-$ decay channel in 30 GeV/c p+Au collisions.

rate of 100 KHz. The accumulated statistics would be good enough to study yield and phase space distribution of the multi-strange hadrons. Assuming the predicted multiplicities in Ref. $He^{6}_{\Lambda\Lambda}$ double hypernuclei can be discovered at SIS100 energies. With an overall 4π detection efficiency of 1.2% and for the peak interaction rate of 10 MHz, around 146 $He^{6}_{\Lambda\Lambda}$ can be measured in 10A GeV/c central Au+Au collisions in 10 weeks of beam time.

CBM will perform dilepton measurements in both electron (e^+e^-) as well muon ($\mu^+\mu^-$)channels. The left panel of Fig. 5 shows the invariant mass spectrum of opposite sign $\mu^+\mu^-$ pairs simulated with top central ($0-5\%$) Au+Au collisions at a beam momentum of 10A GeV/c. The reconstruction and identification of the muon tracks is based on the available information from STS, MuCh, TRD and TOF detectors. The background is simulated with the UrQMD model. The so-called freeze-out cocktail including contributions from direct and Dalitz decays of vector mesons is simulated with a thermal model. A coarse-graining approach [26] is used to account for contributions from in-medium decay of ρ mesons and the thermal radiation from the parton plasma. Negligible contribution from Drell-Yan and correlated open charm decay processes would facilitate the extraction of thermal dilepton signals with a proper description of the combinatorial background. The results establish the feasibility of dilepton measurements with the CBM detector system at SIS100 energies, with a moderate interaction rate of 100 KHz.

The right panel of Fig. 5, displays the invariant mass spectrum of J/ψ mesons reconstructed via $\mu^+\mu^-$ decay channel in 30 GeV/c p+Au collisions. The corresponding muon tracks are reconstructed using hits from STS, MuCh and TRD detectors. The results indicate that when operated with peak interaction rate of 10 MHz, nearly 500 J/ψ mesons can be collected using CBM-MuCh setup, in 4 weeks of data taking period.

4. FAIR phase-0 activities

The civil construction for the FAIR SIS100 tunnel and the CBM building right behind it began in the year 2018. The CBM building will be ready for heavy installation by 2022. According to the current schedule, operation of the full modularized start version is foreseen in 2025. Installation and commissioning of detector subsystems is planned between 2022 to 2024. CBM will be day one experiment of SIS100. At present several CBM detector subsystems are installed, prior to their commissioning at FAIR, in several ongoing heavy-ion experiments at different accelerator facilities, commonly known as FAIR phase-0. The usefulness of such a program includes the

PoS(CPOD2021)031

substantial improvement of reconstruction performance of the running heavy-ion experiments, as well as, a thorough testing and calibration of the CBM detectors and their readout electronics well before the start of the main experiment. Several activities are being pursued in this context. 430 out of 1100 RICH multi-anode photo-multiplier tubes (MAPMT) have been installed in HADES experiment to upgrade the old RICH detector and used for physics runs [27]. 10 % of the CBM TOF detector modules including the readout chain are used by STAR experiment at the RHIC beam energy scan (BES)II program resulting substantial improvement in forward particle identification capabilities of the setup [28]. 4 STS-like tracking stations will upgrade the performance of the existing BM@N experiment at Dubna which will take data in 2022 [29]. Several PSD modules will be used by the NA61/SHINE experiment at SPS [30]. Apart from using CBM detectors in other heavy-ion experiments, a mini CBM (mCBM) experiment is currently operational at the SIS18 accelerator of GSI. This project is of ultimate importance for successful operation of the main CBM experiment. It uses detector prototypes of all CBM components in real in-beam conditions with high rate nuclear collisions. The mCBM setup has been collecting data since fall 2018. Analysis of the recorded data is useful to test and calibrate the performance of the self triggered readout, data transfer to FLES, time-based event building and online reconstruction.

5. Summary

The CBM experiment at FAIR is part of the global mission to experimentally study the QCD phase diagram and the corresponding EoS in the region of high net-baryon densities. The uniqueness of CBM is the peak interaction rate, which is orders of magnitude higher than any present or future worldwide heavy-ion experiment. Such unprecedented rates will enable CBM to measure rare diagnostic probes like multi-strange hadrons, dileptons and charm with high precision. Such unique measurements will offer the possibility to experimentally resolve many fundamental physics issues unsettled till date, like nuclear EoS of the baryon rich QCD matter, existence of phase transitions and possible novel phases or medium induced modification of the spectral properties of hadrons among the others. The major experimental challenges include the development of radiation tolerant fast detectors, free streaming read out electronics, online reconstruction and event selection based on parallelized, fast and scalable algorithms running on the GSI high-performance computing nodes. Extensive physics performance simulations based on realistic detector geometries and response functions have established the feasibility of envisaged hadron and dilepton measurements, with optimized experimental setup. The ongoing activities of FAIR phase-0 program at different experimental facilities are extremely useful to understand the operation of different detector components, and test the reconstruction and physics analysis software by analyzing the collected data. As per ongoing schedule, CBM will be ready to take beams from FAIR accelerators in 2025.

References

[1] A. Bracco, G. E. Koerner, B. Krusche *et. al.*, NuPECC Long Range Plan 2017 Prespective in Nuclear Physics, Technical report, European Science Foundation, 2017.

[2] M. D'Eilia, Nucl. Phys. A982 (2019) 99, arXiv:1809.10660 [hep-lat]; HotQCD Collaboration, A. Bazavov *et. al.*, Phys. Rev. D90 (2014) 094503, arXiv:1407.6387 [hep-lat].

PoS(CPOD2021)031

[3] K. Fukushima and T. hatsuda, Rept. Prog. Phys. 74 (2011) 014001, arXiv:1005.4814 [hep-ph].

[4] M. Durante *et. al.*, Phys. Scr. 94 (2019) 033001.

[5] I. C. Arsene *et. al.*, Phys. Rev. C 75 (2007) 034902.

[6] S. Chattopadhyay for the CBM Collaboration, Euro. Phys. J. ST 30 (2021) 689.

[7] T. Ablyazimov *et. al.* [CBM collaboration], Eur. Phys. J. A. 53 (2016) 60.

[8] P. Braun-Munzinger, J. Stachel and C. Wetterich, Phys. lett. B 596 (2004) 61.

[9] A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stocker, Phys. lett. B 697 (2011) 201.

[10] L. Adamczyk *et. al.* [STAR collaboration], Phys. Rev. Lett. 110 (2013) 142301.

[11] P. Chung *et. al.* [E895 collaboration], Phys. Rev. Lett. 85 (2000) 940.

[12] V. Zinyuk *et. al.* [FOPI collaboration], Phys. Rev. C 90 (2014) 025210.

[13] Y. Shin *et. al.* [KAOS collaboration], Phys. Rev. Lett. 81 (1998) 1576.

[14] P. P. Bhaduri, M. Deveaux and A. Toia, J. Phys. G **45** (2018) no.5, 055103 doi:10.1088/1361-6471/aab27e [arXiv:1712.05951 [hep-ph]].

[15] J. Steinheimer, A. Botvina and M. Bleicher Phys. Rev. C 95 (2017) 014911.

[16] R. Arnaldi *et. al.* [NA60 collaboration], Eur. Phys. J C59 (2009) 607.

[17] J. Adamczewski-Musch *et. al.* [HADES Collaboration] Nature Physics 2019.

[18] T. Galatyuk,Nucl. Phys. A **982** (2019), 163-169; updated in 2021.

[19] See article by O. Golosov, this proceedings.

[20] See article by I. Segal, this proceedings.

[21] J. de Cuveland and V. Lindernstruth [CBM Collaboration], J. Phys:Conf. Ser. 331 (2011) 022006.

[22] I. Kisel, Eur. Phys. J. Web Conf. 95 (2015) 01007.

[23] S. A. Bass *et. al.*, Prog. Part. Nucl. Phys. 41 (1998) 255.

[24] R. Brun *et. al.* 1987 CERN Report CERN-DD-EE-84-01.

[25] I. Kisel, I. Kulakov and M. Zayak, IEE Transactions on Nuclear Science 60 (2013) 5, 3703.

[26] T. Galatyuk *et. al.* Eur. Phys. J. A 52 (20160 131.

[27] See article by Sz. Harabasz, this proceedings.

[28] See article by N. Risa, this proceedings.

[29] See article by P. Senger, this proceedings.

[30] See article by S. Kowalski, this proceedings.

PoS(CPOD2021)031