The CBM experiment at GSI/FAIR

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The heavy-ion experiment CBM, considered as one of the core projects of the future accelerator facility FAIR in Darmstadt, will investigate nucleus-nucleus collisions from 10 to 45 *A*GeV, thus exploring the QCD phase diagram in the region of highest baryon densities. High machine availability and interaction rates will give access to rare observables like charm near threshold. We discuss the physics motivation, the proposed detector system and results of feasibility studies.

1. Compressed baryonic matter

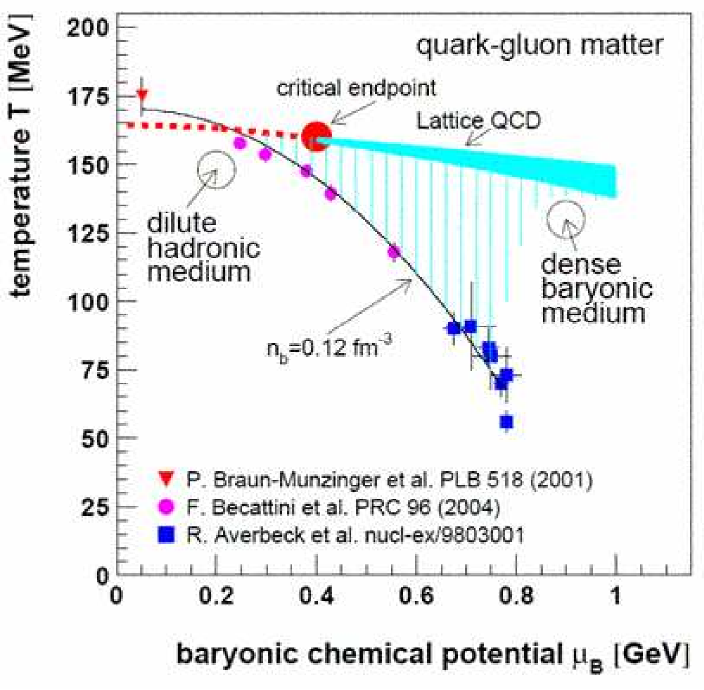

Figure 1: The QCD phase diagram as by today's knowledge (see text).

In the past decades, substantial progress in the understanding of the phase diagram of strongly interacting matter has been made, both by theoretical developments and by experimental data obtained from heavy-ion reactions at various collision energies and facilities. On the theoretical side, lattice QCD calculations have been extended to non-vanishing net baryon densities [1]. According to these results, the deconfinement phase transition at large baryochemical potential is expected to be of first order, while at lower densities, a smooth crossover from hadronic to partonic matter takes place once the temperature surpasses its critical value. Both regions are separated by a critical endpoint at $T \approx 160\,\mathrm{MeV}$ and $\mu_B \approx 400\,\mathrm{MeV}$ (see Figure 1). The experimental confirmation of the phase transition and the critical point is a prime goal for high-energy heavy-ion collision experiments.

Thermal analyses of particle yields measured in heavy-ion collisions at SIS, AGS, SPS and RHIC show that the freeze-out configurations seem to fall on a smooth curve in the $T - \mu_B$ plane, which can be described by a constant energy per particle of 1 GeV [2,3] or a constant baryon density of $0.12\,\mathrm{fm}^{-3}$ [4]. As figure 1 shows, the freeze-out curve coincides with the predicted phase boundary from top SPS energy on, indicating that no significant inelastic scattering happens after hadronisation. At higher μ_B however, the divergence of the two curves suggests the existence of a dense yet hadronic medium, which can be probed by nuclear collisions at beam energies between AGS and top SPS. Such an experimental approach is complementary to the studies of matter at high temperatures but low densities as pursued currently at RHIC and, in the near future, at LHC.

Further insight into the dynamics of nucleus-nucleus collisions is obtained by recent hydrodynamical calculations [5] of the trajectories in the $T - \mu_B$ plane (see Figure 2). According to these results, the deconfinement phase border is first reached around 10 AGeV beam energy; at 30 AGeV, the trajectory hits the critical point. At top SPS energy, the system transiently also reaches high net baryon densities, but evolves very quickly towards the low μ_B region of the phase diagram. Although the used hadronic equation of state is expected to loose its applicability above the phase boundary, these calculations suggest that phenomena connected with the onset of deconfinement and the critical point are best studied using beam energies between AGS and top SPS energy.

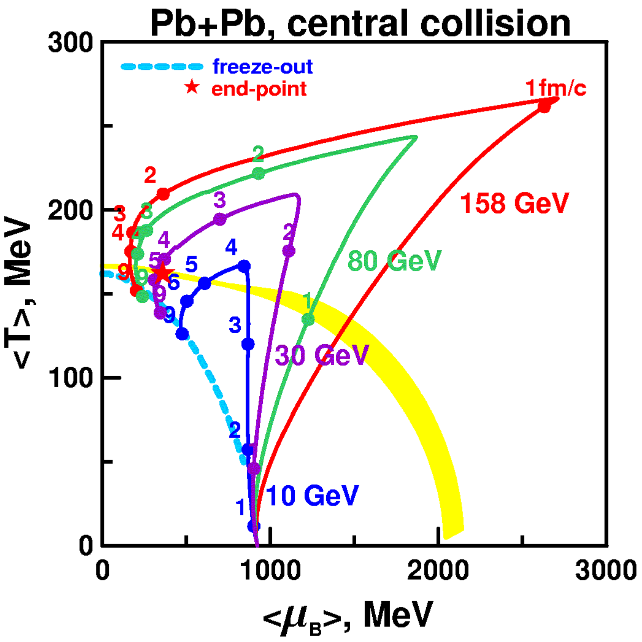

Figure 2: Trajectories of central Pb+Pb collisions calculated with a three-fluid hydrodynamical model [5]. The shaded area shows the expected deconfinement phase boundary, the dashed line the freeze-out curve. The star denotes the critical endpoint of the first-order phase transition.

Indeed, several experimental observations reported by the NA49 experiment [6] indicate an onset of deconfinement at about 30 AGeV beam energy. Among these are the sharp peak in the relative strangeness content of the final state and the constant mean transverse momenta at SPS energies, which can be interpreted as signals of a first-order phase transition [7–9]. Recently, an analysis of the pion rapiditiy distributions measured by NA49 [10] also led to the conclusion of a softest point in the equation of state around 30 AGeV [11]. Experimental signatures of the critical point, which should manifest in large dynamical event-by-event fluctuations, have been sought for, but up to now without conclusive results.

The properties of hadrons in a dense medium have also been topic of experimental and theoretical investigations. The excess of low-mass dielectrons observed by the CERES experiment in Pb+Au collisions at 158 and 40 AGeV [12,13] clearly advocates a strong in-medium modification of the ρ spectral function, but the data quality does not allow to discriminate different in-medium scenarios. At top SPS energy, high-quality data are expected from the NA60 experiment in the dimuon channel, however only for the medium size system In+In. At SIS, the HADES collaboration will provide data at 1-2 AGeV. For a better understanding of the in-medium effects, which adress the restoration of chiral symmetry in dense matter, a systematic investigation in the beam energy range where the density is expected to be highest is mandatory.

Both the theoretical and experimental results outlined above motivate an experimental programme at lower beam energies involving a dedicated next-generation experiment for a comprehensive and systematic exploration of strongly interacting matter at high baryon number densities.

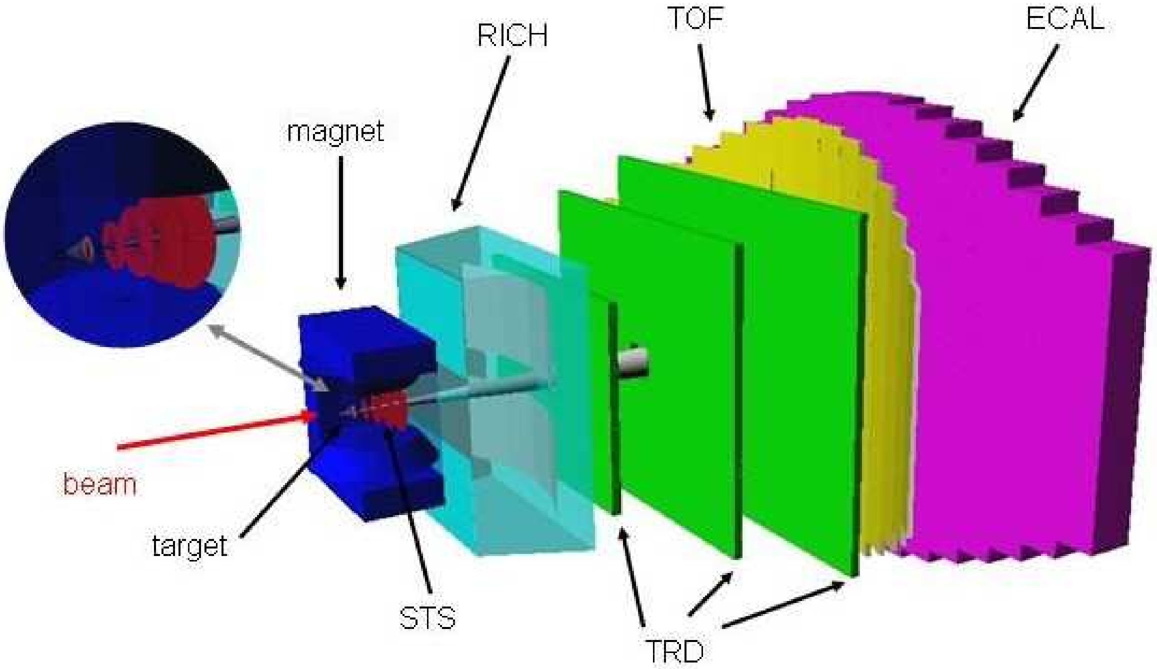

Figure 3. The CBM detector setup.

2. The CBM experiment

The future facility FAIR in Darmstadt [14] will open the possibility for such an experimental programme. It is designed as an accelerator complex serving different physics communities (such as relativistic nuclear collisions, hadron physics with antiproton beams, plasma physics with pulsed beams, atomic physics) in a highly parallel operation, thus assuring high availability for each of the programmes. The SIS300 synchroton will accelerate heavy ions up to 35 AGeV, light ions up to 45 AGeV and protons up to 90 GeV.

The high beam intensities (up to 10^9 ions per second) allow access to rarest probes like charm near threshold.

The CBM experiment [15] is being desgined to measure hadronic, leptonic and photonic observables at interaction rates up to 10 MHz. The acceptance should cover a large part of the phase space and be approximately uniform. The high interaction rates require unprecedented detector performances in terms of speed and radiation hardness, as well as a fast and efficient online event selection. The current layout comprises a high-resolution silicon tracking system (STS) placed in the field of a superconducting dipole magnet. This systems should provide momentum determination better than 1 % and the reconstruction of secondary vertices with a precision of about 50 μm . Outside of the magnetic field, a RICH detector and several stations of transition radiation detectors (TRD) will identify electrons in the momentum ranges relevant for low-mass vector meson and charmonium measurements. Hadron identification will be achieved by the time-of-flight measurement in an array of resistive plate chambers (TOF). The setup is completed by an electromagnetic calorimeter (ECAL) for identification of photons, electrons and muons. The position information from the TRDs is used for a global tracking through the detector. Figure 3 shows the layout of the planned experimental setup.

The experimental programme of CBM comprises the measurements of open and hidden charm, low-mass vector mesons in the dilepton channel, strange and multistrange hadrons, flow and event-by-event fluctuations. Some of these observables will be discussed in the following sections. All observables will be studied systematically as function of collision energy and system size, including p+p and p+A collisions.

3. Observables

3.1. Open charm

Due to the high charm quark mass, it is expected that charm is produced in the early stage of the collision. CBM will measure charm near the pp threshold, where the measured yield will be most sensitive to the production mechanism and thus to the conditions inside the fireball. Predictions of the open charm yield differ strongly between the various production scenarios [16], which systematic, high precision measurements can discriminate. Furthermore, D mesons are expected to change their masses in dense matter similar to kaons [17], which should not only reflect in their absolute yield [18] but also in the abundance of charmonium measured in the dilepton channel once the D meson threshold drops below the charmonium masses [17].

D mesons can be detected via their decay into charged pions and kaons. This measurement is most challenging due to the low D multiplicity, in particular near threshold, compared to the abundant direct pions and kaons. So far, no D mesons have been found in nucleus-nucleus collisions below RHIC energies. To effectively suppress the combinatorial background, the displaced vertex of the decay ($c\tau = 127\,\mu m$) has to be measured with high precision. Simulations of the STS system of CBM, involving the high-resolution MAPS detectors and using track reconstruction inside full background events, show that a two-track vertex resolution of about 40 μm can be reached (see Figure 4). Using the D^0 multiplicity as predicted by the HSD transport model [19] and the hadronic background from UrQMD, we derive a signal-to-background ratio of about three in central Au+Au collisions at 25 *A*GeV (see Figure 5), without requiring particle identification of the secondaries. The count rate at full luminosity is approximately 10^5 per day. Similar studies are ongoing for $D^{\pm}$, D_s and Λ_C.

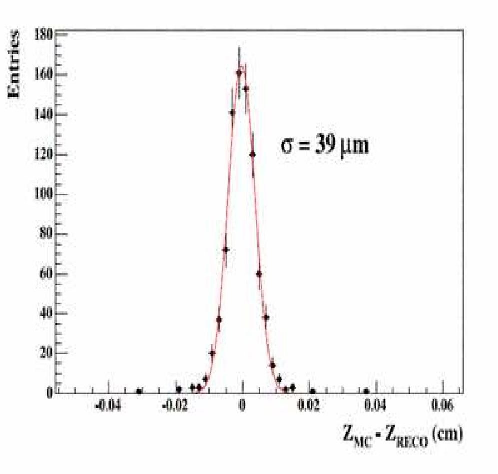

Figure 4. Residual distribution of the reconstructed z position (along the beam line) of D^0 meson decays into π^+ and K^-. The signals were embedded into full UrQMD background events (Au+Au at 25 *A*GeV).

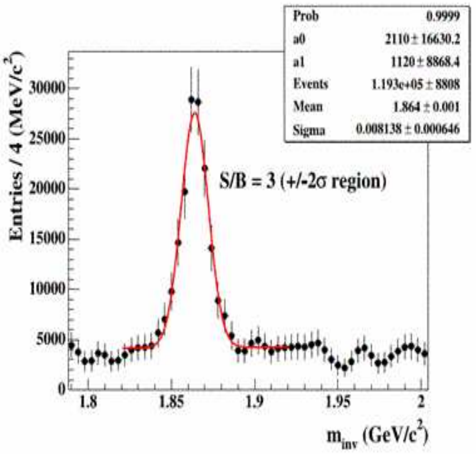

Figure 5. Simulated π^+K^- invariant-mass spectrum after cuts on D^0 from 10^{12} minimum bias Au+Au collisions at 25 *A*GeV. The statistics corresponds to three hours of data taking at 10 MHz interaction rate.

A major challenge is the implementation of the secondary vertex finding in the online event selection, which has to reduce the interaction rate to the estimated archival rate of several 10 kHz. This task requires fast yet accurate tracking algorithms implemented in a farm of programmable hardware.

3.2. Charmonium

The suppression of J/ψ mesons due to screening effects by free colour charges was predicted as an experimental signal of the quark-gluon plasma [20]. The NA50 collaboration indeed reported an anomalous suppression at top SPS energy [21], the interpretation of which is subject of an ongoing debate since hadronic scenarios seem to also explain the data. No data on J/ψ is available at beam momenta below 158 *A*GeV.

We have studied the feasibility of a $J/\psi \rightarrow e^+e^-$ measurement in CBM using electron identification from the RICH and TR detectors. The main background sources are Dalitz decays of π^0 and η, leptonic decays of ρ and D^0, γ conversions in target or detector material, and misidentified charged pions. The simulations take into account a realistic material budget and magnetic field, but not yet a full track reconstruction throughout the detector. As the background sources mainly produce soft electrons, the combinatorial background is efficiently reduced by a cut on the transverse momentum. We arrive at a signal-to-backgrond ratio of the order of unity in Au+Au at 25 *A*GeV (see Figure 6), assuming a combined pion suppression by 10^4. The measurement thus appears feasible, provided that the cuts can be implemented in the online event selection.

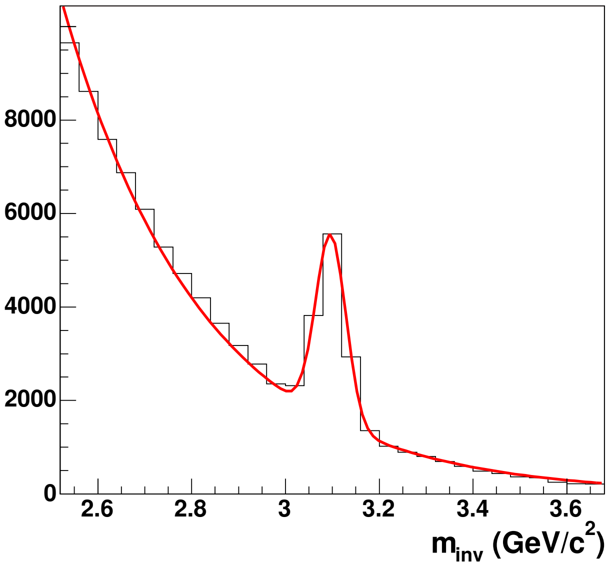

Figure 6. Simulated e^+e^- invariant-mass spectrum after a single track p_t cut at 1 GeV from $3 \cdot 10^{10}$ Au+Au collisions at 25 *A*GeV.

3.3. Low-mass vector mesons

CBM will measure the in-medium spectral functions of short lived vector mesons directly by their decay into dilepton pairs. These provide a penetrating probe of the conditions of the fireball since they are little affected by the passage through the dense matter. The difficulty of this measurement lies in the abundant background electrons, mostly from Dalitz decays and γ conversions, which cannot as conveniently be suppressed by a p_t cut as in the case of the J/ψ. Sophisticated cut strategies are being developed to optimise the sensitivity to the physics signals. Current results yield a signal-to-background ratio of about unity in the ρ mass region.

3.4. Strangeness

The results of the NA49 experiment on the energy dependence of relative strange particle yields have renewed the interest in strangeness production in heavy-ion collisions, originally proposed as signature for the QGP [22]. The observed features have not been explained so far by neither transport nor statistical models. This situation clearly calls for comprehensive studies with reduced statistical and systematic errors, in particular for multi-strange hyperons.

CBM will detect charged kaons by time-of-flight measurement, while hyperons will be measured via the topology of their decays into charged hadrons. As examples, figures 7 and 8 show that the CBM detector covers a large part of the phase space for both particle species, which will allow to derive 4π integrated yields. Figure 9 demonstrates the ability of the STS system to reconstruct Ω hyperons with small background contamination. High event statistics will enable CBM to measure not only spectra and yields, but also flow for such rare particles.

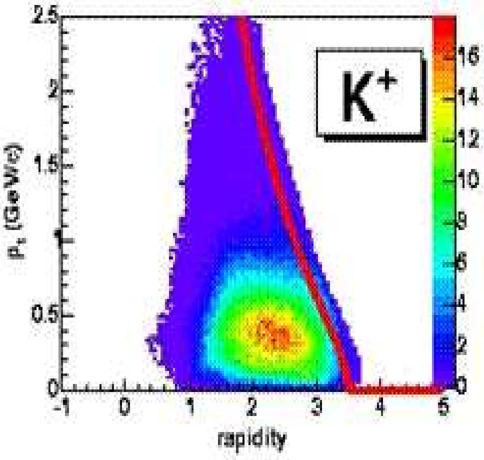

Figure 7. CBM acceptance region for K^+ identified in the TOF system. The full line shows the momentum cutoff at 6 GeV where the identification capability of the TOF measurement ceases. Midrapidity is at $y = 1.98$.

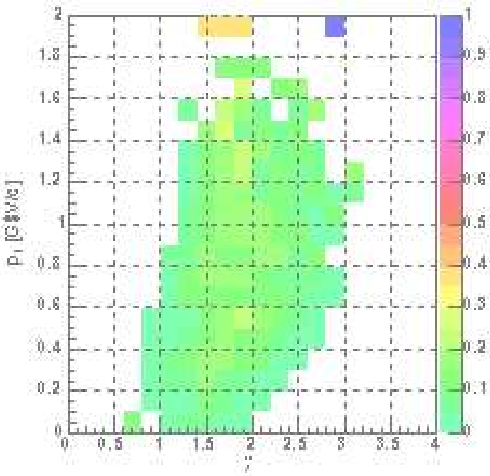

Figure 8. Phase space region of Ω baryons reconstructed in the CBM STS system after topological cuts. Midrapidity is at $y = 1.98$.

4. Detector R&D

All detector systems of the CBM experiment have to be designed to stand the extreme conditions posed by heavy-ion reactions at 35 AGeV at interaction rates up to 10 MHz, which means roughly 10^{10} tracks per seond in the CBM acceptance. Current detector technologies do largely not meet these requirements. Therefore, detector R&D programmes have been started with the emphasis on high-speed, radiation hard devices. For the STS, good position resolution and low material budget is also mandatory. Monolithic active pixel sensors (MAPS) are a promising option for the first two layers closest to the interaction point (5 and 10 cm, respectively). They provide a single point resolution of about 3 μm while being extremely thin. However, the radiation tolerance of today's prototypes needs being improved by at least an order of magnitude to cope with the CBM environment. In addition, the readout speed is limited due to the parallel columnwise readout scheme, which results in a pileup of several tenth of events in one readout frame. As an alternative, improved hybrid pixel sensors are being considered for the innermost tracking stations. The outer stations of the STS will be made of silicon strip detectors.

The RICH detector should provide a pion suppression of 100 or more for momenta below 6 GeV. The current design uses a Be glass mirrow with two vertically separated focal planes. Different choices of the radiator gas are being investigated. Detection of the Cerenkov photons will be achieved by photomultiplier tubes in the focal plane.

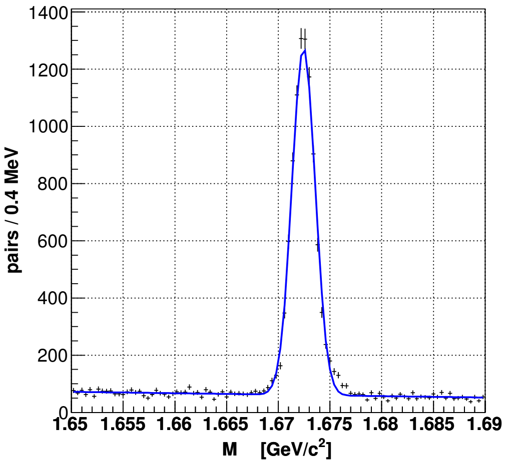

Figure 9. Invariant ΛK^- mass after topological cuts resulting from full reconstruction of simulated UrQMD events (Au+Au at 25 AGeV) in the STS.

Different options for the TRDs are being followed in parallel. One of the major issues is the rate capability, which should allow to take count rates up to 150 kHz/cm^2. Thin ALICE type prototypes read out with both wire chambers and GEMs have been tested in-beam at GSI in July 2004, showing no degradation up to 80 kHz/cm^2. Simulations of the transition radiation, employing a radiator parametrisation tuned to reproduce the ALICE protoype measurements, show that a pion suppression of the order of 100 can be achieved with nine detector layers of 3 cm radiator thickness each. The final design will be a result of further optimisation taking also into account the requirements of global tracking.

The TOF system, located at 10 m from the target, will be used for the identification of pions, kaons and protons up to 6 GeV momentum. This requires a time resolution of 80 ps or better over an area of about 120 m^2. Since the only cost-effective solution for such a system are RPCs, the rate capability is again a critical issue. Single-gap prototypes with plastic electrodes have been tested in Coimbra, showing a resolution of below 100 ps up to the required rates (25 kHz/cm^2). R&D on large-area RPCs is also ongoing at GSI in collaboration with the FOPI experiment.

The design of the ECAL is based on shashlik-type lead-scintillator modules. First prototypes will be built and tested in 2006 at ITEP Moscow.

5. Summary

We have presented the physics motivation to explore the QCD regime of high net baryon densities, adressing topics like the onset of deconfinement, the critical point and in-medium properties of hadrons. The CBM experiment will measure the relevant observables in nucleus-nucleus collisions from 10 to 45 AGeV at the future facility FAIR in Darmstadt from 2014 on. Simulations suggest that the measurements of the key observables with the planned detector setup are feasible. They require, however, the development of new, fast and radiation hard detectors as well as online event reconstruction with unprecedented speed. First steps in R&D for such detectors have already been taken.

The CBM collaboration by today consists of some 250 physicists from 38 institutes and 15 countries. A detailed review of the experiment is given in the Technical Status Report submitted in January 2005 [23]. On the basis of this report, the CBM experiment has been approved by the FAIR STI committee to work towards the Technical Design Report.

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