

Dielectron simulations for the CBM-TRD

Etienne Bechtel

Etienne Bechtel, Goethe University, IKF for the CBM collaboration

Abstract. This report features the simulation studies of dielectron decays with the compressed baryonic matter experiment in the regime of high net-baryon densities and moderate temperatures. The corresponding region in the QCD phase-diagram is completely unexplored with leptonic channels and could provide essential insight into potential phase transitions to a QGP-phase or chiral symmetry restoration. At CBM energies there is undisturbed access to the decay channel of prompt thermal photons into dielectron pairs in the intermediate mass range between 1.1 and 2.5 GeV/c. Due to the rare character of such electromagnetic probes, very high statistics and a powerful particle identification are crucial. With the combination of a RICH detector and the TRD, CBM will measure these signals with a sufficient significance, as will be demonstrated in this work.

1. Introduction

The comprehensive understanding of strongly interacting matter is an fundamental part of modern physics. In particular the investigation of in-medium properties in the hot and dense early stages of the fireball development in heavy-ion collisions could be of essential value. These early stages can be probed through electromagnetic decays into dielectron pairs. Due to the leptonic character of these decays, they do not interact via the strong interaction and can leave the fireball without strong influence on the information they are carrying. Also they can be used to probe a variety of fireball parameters, as such as the temperature, the pressure and the lifetime of the fireball [1][2].

Since these channels are suppressed by the electromagnetic coupling constant, their production is proportional to $(\frac{1}{137})^2$ resulting in a dielectron yield that is several orders of magnitude below the respective yield for pions. Therefore it is very hard to measure these probes with high precision. A combination of high luminosity and very good particle identification is necessary to study these decay channels, which was not yet possible in CBM's energy regime by any other experiment before [3]. In fact, CBM is supposed to surpass the rate capabilities of all the other experiments by several orders of magnitude.

Therefore CBM has enormous discovery potential, since it could deliver the very first signs for the presence of a potential 1st order phase transition from the hadron gas to the QGP or to the possible proposed state of quarkyonic matter [4]. Such a 1st order phase transition could be directly visible in the shape of the excitation function of the emitting source (see Fig. 1). In the presence of a 1st order phase transition a flattening in the temperature could be seen, because of additional energy flowing into the phase transition itself instead of the further heating of the system.

Also it would be a breakthrough to measure a chiral transition. In the vacuum chiral symmetry is spontaneously broken, which is the reason why chiral pairs do not have the same



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

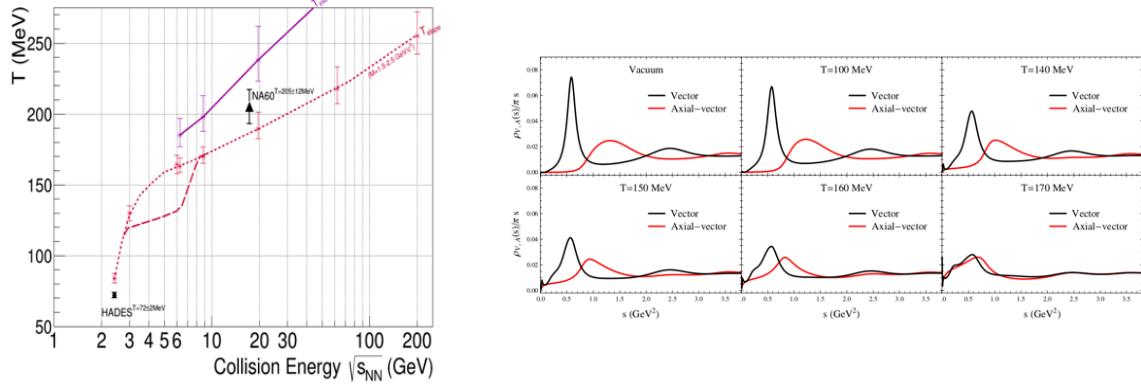


Figure 1. Left: excitation function of T of the emitting source as calculated with a coarse-graining approach [5]. The effective temperature extracted from the inverse slope parameter is shown as dotted red curve. A potential flattening in presence of a phase transition is indicated as a red dashed line. Right: Broadening scenario of the chiral pair of the ρ and the a_1 mesons from vacuum to complete chiral symmetry restoration at higher temperatures [6].

mass. In heavy-ion collisions it is possible to create extreme conditions that could lead to the restoration of the chiral symmetry, which would manifest itself via the mixing of chiral pairs. In particular the chiral pair of the ρ and the a_1 mesons are expected to be sensitive to in-medium modifications such as a "broadening" of the resonance (see Fig. 1 [6]) and would be directly accessible with CBM measurements.

2. Particle identification with the Transition Radiation Detector (TRD)

Important aspects of particle identification of an experiment are not only the efficiency of the particle identification, but also its momentum coverage. For the dielectron case, the two most important identification detectors are the RICH and the TRD. While the RICH has a very good electron identification in the lower momentum region (below about $6 \text{ GeV}/c$), it can not properly separate electrons and pions at higher momenta, because the electrons do not create distinguishable rings any more. On the other hand the electron ID of the TRD is coupled to the transition radiation (TR) production [7]. The probability to produce a TR photon increases with the momentum up to its saturation value at about $3 \text{ GeV}/c$ (see Fig. 2).

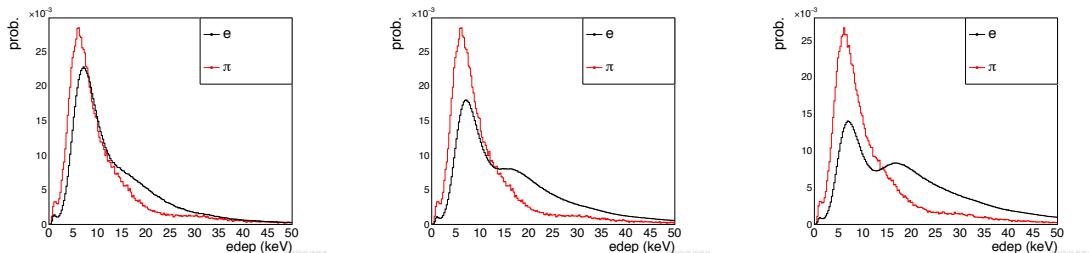


Figure 2. Simulated energy deposition spectra for electrons and pions in different momenta for the 10% most central Au+Au collisions at 8 A GeV . Left: $p = 0-1 \text{ GeV}/c$ Middle: $p = 1-3 \text{ GeV}/c$ Right: $p > 3 \text{ GeV}/c$

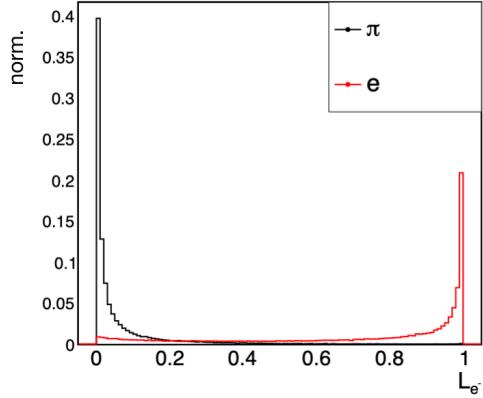


Figure 3. Electron likelihood values in the TRD for simulated electron and pion tracks normalized to unity.

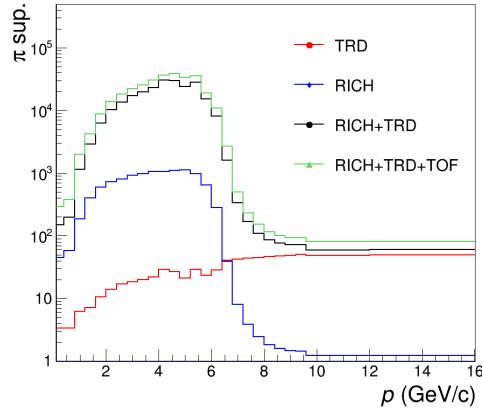


Figure 4. Pion suppression for different detector combinations from simulated central Au+Au collisions at 8 A GeV.

Spectra like these can then be used as reference to calculate the probability of an unknown charged particle to be an electron or a pion, respectively. One approach to calculate this probability is via a Likelihood ratio method, which in the one-dimensional case breaks down the identification to a simple fraction:

$$L_e = \frac{p_e}{p_e + p_\pi} \quad (1)$$

Here p_e and p_π are the probabilities read off from their corresponding spectra at the respective momentum and energy deposition in case of only one measurement. But since we have in total four TRD layers, the probability values are slightly modified as:

$$p_e = \prod_i p_{e_i} \quad (2)$$

With these multiple measurements it is far more likely to see an energy deposition with a TR contribution, which leads to a clear separation of the electron likelihood for real electron tracks (see Fig. 3) from those of pions. The combination of the different PID detectors and their momentum coverage can then be seen in the pion suppression in Fig. 4.

3. Dielectron simulations in CBM

For the simulation of the dielectron channels in CBM we used 5 millions of the 10% most central Au+Au collisions at 8 A GeV created with the UrQMD model and with an embedded cocktail of low mass vector mesons [8] and thermal dielectron pairs from the spectral function of the in-medium ρ and the thermal radiation of the QGP itself. These last two embedded signals were calculated with a coarse-graining approach [5]. The additional signals are embedded with one pair per signal in each event. In the analysis their contributions are then weighted with the expected yields of these particles based on theory predictions. This has to be done to ensure a minimum of statistics for these signals without the need to simulate 10^{11} events. The simulated gold target has a thickness of 25 μm , which is important, because a thicker target would lead to a much larger number of photon conversions inside the target.

After we have verified the track quality with a sufficient number of hits in the detector and we have identified the electron candidates by their momentum dependent PID characteristics, we reduce the contribution of dielectron pairs from π^0 -Dalitz decays and from conversions inside

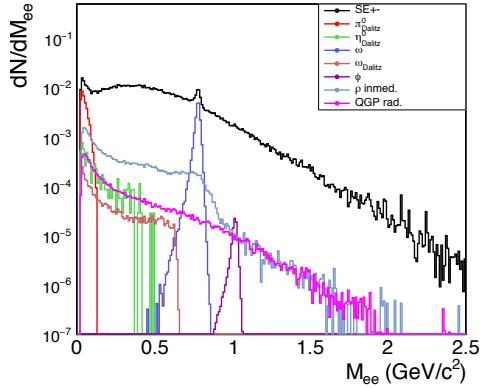


Figure 5. Invariant mass distribution of unlike-sign electron pairs identified by RICH, TRD and TOF from simulated most central (10%) Au+Au collisions at 8 A GeV. Signals are plotted with the usage of their PDG code in the respective Monte-Carlo track.

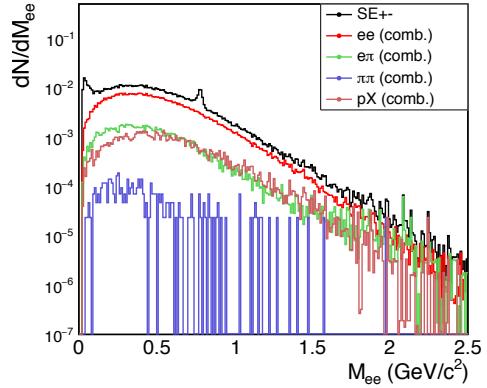


Figure 6. Invariant mass distribution of the combinatorial background contribution from simulated most central (10% Au+Au collisions at 8 A GeV). The ee (comb.) contributions contains all pairings of e^+e^- , which do not originate from the same mother particle.

the target. This is done by building all candidates of unlike-sign pairs and applying a rejection cut if their respective invariant mass is below 25 MeV/c².

Afterwards we obtain the invariant mass spectrum of unlike-sign pairs as seen in Fig. 5. The black line shows all the selected unlike-sign pairs from the same event and the colored lines show the relevant dielectron channels at this energy. The π^0 -Dalitz contribution in red is visibly constrained by the rejection of low invariant masses. The combination of the ρ spectral function and the radiation of the QGP itself build the only signal contribution in the invariant mass range from 1.1-2.5 GeV/c². With a good background description, this region can then be used to extract the shape of these thermal signals. Afterwards it is possible to fit the signal with an exponential function [1]:

$$f_T(m_{inv}) = c \cdot \frac{1}{m_{inv}^{3/2}} \cdot e^{-\frac{m_{inv}}{T}} \quad (3)$$

with c as calibration parameter and T as inverse slope parameter. In this function T corresponds to the source temperature.

The difference between the signal pairs and the black line contains combinatorial, uncorrelated pairs, which can be seen in Fig. 6. These contributions have to be minimized and well understood to achieve the most precise measurement of the inverse slope parameter. Since they are uncorrelated contributions, it is possible to describe their yield with the combinations of like-sign pairs. The combinatorial background is then described via:

$$CB_{same}^{+-} = 2 \cdot \sqrt{N^{++} \cdot N^{--}} \quad (4)$$

where N^{++} and N^{--} are the total yield of like-sign pairs. Another important method of background estimation is for example the mixing of electron candidates from different events to generate a reference sample of uncorrelated pairs. The event mixing method also brings the additional advantage of very high statistics, depending on the amount of different events mixed, which is mostly only a question of computing power. An example of this method can be found

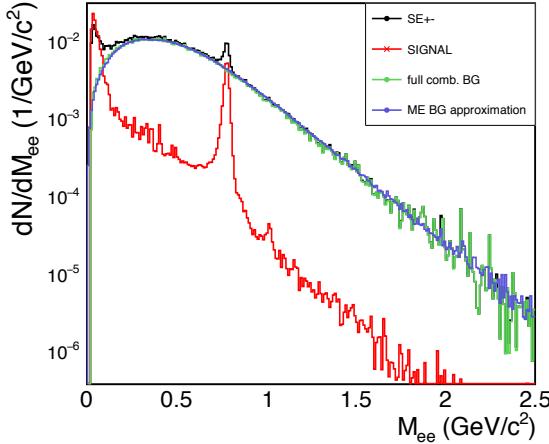


Figure 7. Background description via mixing of uncorrelated electron candidates.

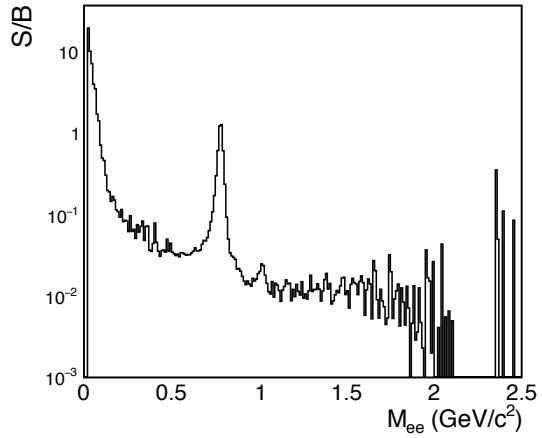


Figure 8. Signal-to-background ratio for simulated Au+Au collisions at 8 A GeV.

in Fig. 7. There the total yield of reconstructed unlike-sign pairs is again shown in black. The sum of all signal contributions over the full invariant mass region is plotted in red and the total contribution of all combinations of uncorrelated electron candidates is shown in green. So the green line shows the total sum of background, that has to be subtracted to get clean signal access. The distribution of all the mixed pairs from different events is shown in blue. The blue and the green line agree very well and it is even visible that due to the low yields in the intermediate mass range (IMR) the amount of 5 million events is not yet sufficient to achieve a smooth description of this mass region, while the blue mixed event spectrum already shows far less fluctuations.

The final signal-to-background ratio can be found in Fig. 8. With the ratio of 0.01 in the IMR a realistic running scenario at 1 MHz mean interaction rate would be estimated to need about 60h of measurement to reach a significance ($S/\sqrt{S+B}$) of more than 10 for the extraction of the thermal contributions.

4. Summary and outlook

The results of these simulations show the potential of a precision measurement of dielectron channels with CBM. It was also shown, that the TRD is a crucial detector to allow for a study of these observables. The next steps contain the investigation of other energies in the CBM energy range, the increase of statistics via computational optimization and afterwards the extraction of the inverse slope parameter.

References

- [1] NA60 Collab., Chiral 2010, AIP Conf. Proc. (2010) 1322
- [2] R. Rapp, H. van Hees, PLB 753 (2016) 586
- [3] T. Abylyazimov et al. Challenges in QCD matter physics –The scientific programme of the Compressed Baryonic Matter experiment at FAIR. Eur. Phys. J., A53(3):60, 2017
- [4] A. Andronic et al. Hadron Production in Ultra-relativistic Nuclear Collisions: Quarkyonic Matter and a Triple Point in the Phase Diagram of QCD. Nucl. Phys., A837:65–86, 2010
- [5] T. Galatyuk et al., Eur. Phys. J. A52 (2016) 131
- [6] P.M. Hohler and R.Rapp, Phys Lett. B731
- [7] The TRD working group , Technical Design Report for the CBM - Transition Radiation Detector
- [8] W. Cassing et al., Nucl. Phys. A691 (2001) 753