Dileptons and Charm & Bottom in Relativistic Heavy-Ion Collisions

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We study the prospects to get information about the early and hot stages of deconfined matter produced in relativistic heavy-ion collisions by analyzing dilepton and single-lepton spectra. Energy losses of heavy quarks in deconfined matter and thermalization effects in hadron matter and their influence on lepton spectra are considered.

1 Introduction

One can explore theoretically the properties of deconfined matter by employing certain numerical methods in evaluating the theory of strong interaction – Quantum Chromo Dynamics (QCD) – to get, for instance, the equation of state [1]. Phenomenological models can supplement such analyses to arrive at a more qualitative understanding of a system composed of quarks and gluons [2]. Ultimately, however, one is interested in a verification whether such a state is realized in nature. It is usually thought that central collisions of heavy ions at high energies offer the unique way to create transiently deconfined matter under laboratory conditions.

There is a fairly long list of proposals of how to measure the properties of such a novel matter state. Dileptons represent penetrating probes which are considered since a long time to be a good messenger from the early stages of the deconfined matter resulting in ultrarelativistic heavy-ion collisions. Therefore, it should be possible to get direct information about the thermodynamical parameters of the hot and dense, strongly interacting system. The problematic part about dileptons in heavy-ion collisions is that there are quite a lot of different sources. Dalitz decays dominate the low invariant mass region, while the high mass region is governed by Drell-Yan (DY) dileptons. The preferable region for a thermal signal from thermalized QCD deconfined matter is the so-called intermediate mass region between the $\phi$ and the $J/\Psi$. In the resonance region below the $\phi$ the vector meson decays provide a strong signal and also the thermal radiation from hadron matter can be probably best observed. In addition one has to be aware that, although most of heavier thermal dileptons are produced in the very early stages of the hot matter,
the production process continues during the whole evolution of the system and only the space-time integrated yield can be measured. Therefore, some efforts are needed to unfold a dilepton spectrum and to extract the wanted information.

With increasing beam energies one generally expects higher matter temperatures and therefore a stronger signal of the thermal production. At the same time, however, also other production channels for dileptons gain importance. In particular the correlated semileptonic decays of open charm and bottom mesons become strong sources. To get an idea on the various competing sources, in fig. 1 we compare the beam energy dependence of the expected thermal signal with the DY yield and the dileptons from correlated charm and bottom decays. (For the details about our modeling we refer the interested reader to [3]. Here we mention that at large beam energies we estimate the initial conditions of deconfined matter within the mini-jet model [4]. The DY process is calculated with standard procedures. \(\bar{c}c\) and \(\bar{b}b\) pairs are produced in gluon fusion processes; in lowest order the heavy quarks propagate back-to-back in the transverse plane, and the hadronization into open charm and bottom mesons can be approximated by a \(\delta\) fragmentation scheme.)

At SPS energies the charm and DY yields are of the same order of magnitude, and the thermal signal is below both ones. With increasing beam energy or \(\sqrt{s}\) the thermal signal increases stronger than the DY yield. On the other hand, the dilepton yields from charm and bottom decays increase even stronger and result in a background which is up to two orders of magnitude higher than the thermal signal. Therefore it seems to be difficult to get thermal information from the simple invariant mass spectrum. In what follows we are going to discuss whether one can find such kinematical cuts which enable one to discriminate the thermal signal from the background at very high beam energies such as envisaged at RHIC and LHC (sect. 2). We also discuss the change of the heavy quark spectra by the deconfined medium and the resulting impact on the single lepton spectra stemming from charm and bottom decays (sect. 3). And finally we consider the influence of a dense hadron

![Figure 1:](image-url)
medium on the esfinal open charm spectrum at present SPS energies and show that the dilepton spectra are correspondingly changed (sect. 4).

2 Perspectives for RHIC/LHC: dilepton spectra

Since the kinematics of heavy meson production and decay differs from that of thermal dileptons, one can expect that special kinematical restrictions superimposed on the detector acceptance will be useful for finding a window for observing thermal dileptons in the intermediate mass continuum region. As demonstrated recently [3], the measurement of the double differential dilepton spectra as a function of the transverse pair momentum $Q_\perp$ and transverse mass $M_\perp = \sqrt{M^2 + Q_\perp^2}$ within a narrow interval of $M_\perp$ offers a chance to observe thermal dileptons at LHC. The key observation here is to apply also a single-electron low-$p_\perp$ cut. Fig. 2 shows the double differential spectrum for a narrow interval of $M_\perp$ around 5.5 GeV and for $p_\perp > 2$ GeV. One observes that these kinematical restrictions suppress the background at large values of $Q_\perp$, while the thermal signal obeys the so called $M_\perp$-scaling and extends nearly up to the kinematical boundary.

Another possibility to suppress the mentioned background processes is to implement only a large enough low-$p_\perp$ cut on single electrons [5]. This opens a window for the thermal signal in the invariant mass distribution. Since the energy of individual decay electrons or positrons has a maximum of about 0.88 (2.2) GeV in the rest frame of the decaying $D$ ($B$) meson, one can expect to get a strong suppression of correlated decay lepton pairs by choosing a high enough low-momentum cut $p_\perp^{\text{min}}$ on the individual leptons in the mid-rapidity region. For thermal leptons stemming from deconfined matter there is no such upper energy limit and for high temperature the thermal yield will not suffer such a drastically suppression by the $p_\perp^{\text{min}}$ cut as the decay background. The results of our lowest-order calculations of the invariant...
mass spectrum with such a $p_\perp$-cut is displayed in fig. 3 again for LHC energies. One observes that the thermal dilepton signal with a single-electron low-momentum cut-off $p_\perp^{\text{min}} = 3$ GeV exhibits an approximate plateau in the invariant mass region $2 \text{ GeV} \leq M \leq 2p_\perp^{\text{min}}$.

With both methods it is possible to extract the information about the thermodynamical parameters of the very first stages of the deconfined matter \cite{6, 7}. But due to the quite low rates, it is questionable if these cuts are experimentally feasible.

Recently, the ALICE-GSI group \cite{8} found that, via exact tracking and vertex reconstruction, one can suppress a substantial part of the open charm and bottom decay electrons in the midrapidity region. Therefore, the need of stringent cuts is relaxed somewhat and realistic count rates are to be expected. The announced heavy-ion programme of the CMS collaboration at LHC \cite{9} looks also quite interesting as it can provide complementary muon spectra in the midrapidity region.

### 3 Energy losses of heavy quarks in deconfined matter

Charm and bottom quarks traversing through deconfined matter radiate gluons \cite{10} and lose energy. As a consequence the transverse momenta of parent quarks and the resulting heavy mesons and the emerging decay leptons are diminished. Since the invariant mass of dileptons is $M^2 = 2p_\perp^+ p_\perp^- [c(y^+ - y^-) - \cos(\phi^+ - \phi^-)]$, smaller values of the $p_\perp$’s cause smaller values of $M$ ($p_\perp^+, y^\pm$ and $\phi^\pm$ are the respective transverse momenta, and rapidities, and azimuthal angles of leptons). Therefore, via energy losses the number of dileptons in the intermediate mass region is reduced. The effect is extensively studied in \cite{11} and it turns out that, with realistic estimates of the energy loss, the background is not reduced below the thermal signal. However, we would also like to point out that an explicit measurement of the inclusive
single-electron $p_\perp$-spectra from open charm and bottom decays contains valuable information \cite{3}. Namely the energy losses sufficiently change the resulting momentum distribution of the open charm and bottom mesons and, as a consequence, the decay electrons exhibit a significantly modified $p_\perp$ spectrum (for details consult \cite{3}). Since such an effect does not appear in pp collisions, the verification of a modified electron spectrum from identified charm and bottom decays would offer a hint to the creation of deconfined matter. The studies in \cite{8} demonstrate that tracking cuts offer the chance to get a ”signal”-to-background ratio of 98\%, where ”signal” means here the decay electrons from charm and bottom. Therefore, such a measurement seems to be feasible with ALICE at LHC. To illustrate the order of magnitude of the expected effect we show in fig. 4 the transverse momentum spectrum of decay electrons from open charm and bottom mesons in a lowest-order calculation as described above \cite{3}. Only electrons which seem to come from a point outside a sphere of 150 \(\mu\)m around the primary vertex are counted.

Although charm and bottom are of the same order of magnitude, one can fit the summed distribution by $dN_{e^-}/dp_\perp \propto \exp(-p_\perp/T_e)$ in the interval $p_\perp = 3 \ldots 5$ GeV and finds a change of the slope parameter $T_e$ from 930 MeV (without energy loss) to 790 MeV (with energy loss). This difference is approximately the same as could be expected in the PHENIX acceptance at RHIC.

One should stress that with such a measurement one can reveal the presence of a medium. Detailed information on thermodynamical state parameters are, however, difficult to extract: a variation of the initial temperature from 0.8 to 1.2 GeV causes only minor changes of the slopes of the single-electron $p_\perp$ spectra.

Figure 4: The transverse momentum spectra of single electrons from D and B meson decays in the ALICE acceptance. Displayed are the spectra without (“initial”) and with energy loss according to model II in \cite{3}. An additional vertex-cut is applied (see text).
4 Dileptons in the intermediate mass region at CERN-SPS

In present SPS experiments (\( \sqrt{s} = 15 \cdots 20 \) GeV) the CERES collaboration reports a dilepton excess over the known hadronic cocktail in S + Au and Pb + Au collisions at invariant masses \( M < 1 \) GeV \cite{12}. The order of magnitude of this excess can be attributed to a thermal source stemming mainly from pion annihilation, while the detailed shape of the spectrum is still matter of debate, e.g. it might reflect an in-medium changed \( \rho \) spectral function. Similarly, in the intermediate mass region as accessible in the acceptances of the HELIOS-3 and NA38/50 experimental set-ups, the conventional sources Drell-Yan and open charm decays, known from pp collisions, seem also not to account for the observed data, i.e. there is an excess too \cite{13, 14}.

![Figure 5: Muon pair spectra with acceptance cuts of the NA50 apparatus. Full line: open charm mesons get a thermal kick in their rest frame corresponding to a local temperature of 150 MeV; the dashed lines are for primordial open charm without any medium effect. The gray line shows a change in the fragmentation scheme.](image)

The NA50 data for central Pb-Pb collisions can be explained for an enhanced charm production \cite{14}. A possible source could be a pronounced nuclear anti-shadowing of gluons \cite{15}. On the other hand, the charmed mesons can experience a modification of their primordial spectrum via interactions with the dense hadron medium before freezing out. As a working hypothesis one can assume that the transverse open charm meson spectra in central heavy-ion collisions at CERN-SPS look like the other hadron spectra. Indeed, as shown in \cite{16} the available transverse momentum spectra of \( \pi^\pm, K^\pm, K^0_s, p^\pm, \Lambda, \bar{\Lambda}, d \) at midrapidity can be described by a unique freeze-out temperature of 120 MeV and a unique transverse flow with averaged velocity of 0.41 c. Following a suggestion of \cite{15} one can give the charm mesons a randomly oriented thermal kick, which mimics the thermalization process. As a consequence the resulting decay electron spectrum is modified as displayed in fig. 5. One observes that, due to the very acceptance of NA50 experiment, a change in the kinematical distributions of the particles can lead to an apparent ex-
cess in the measured yield. This effect deserves further studies, e.g., by analyzing the transverse dilepton spectra in the same mass region, which are presently prepared by the NA38/50 collaboration [17]. As a measure for the theoretical uncertainties we also display in fig. 5 the effect of changing the fragmentation scheme to Lund fragmentation with Peterson function ($\epsilon = 0.02$) and $m_c = 1.5$ GeV.

5 Summary

It is obvious that dileptons are very interesting and promising signals if one wants to learn about the physics of highly excited, strongly interacting matter. It is also clear that very much efforts have to be put in to unfold the spectra to get the desired information.

We show that suitable kinematical cuts can suppress the background dilepton yield. For a doubtless identification of the thermal dilepton signal, however, an explicit measurement of open charm and bottom would be preferable. In addition, in the present contribution we report studies of two in-medium effects: (i) the change of the charm & bottom quark spectra by gluon radiation in deconfined QCD matter and (ii) the change of the open charm meson spectra by thermalization in the hadron stage. Both effects are noticeable.

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