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Estimates of dilepton spectra from open charm and bottom decays in relativistic heavy-ion collisions

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Abstract

The spectra of lepton pairs from correlated open charm and bottom decays in ultrarelativistic heavy-ion collisions are calculated. Our approach includes energy loss effects of the fast heavy quarks in deconfined matter which are determined by temperature and density of the expanding parton medium. We find a strong suppression of the initial transverse momentum spectrum of heavy quarks due to the energy loss at LHC conditions. Within the central rapidity covered by the ALICE detector system, the dominant contribution from bottom decays to the high invariant mass dielectron spectrum is predicted.

The production of high invariant mass dileptons in relativistic heavy-ion collisions has attracted a great deal of interest in the recent years from both the experimental and theoretical sides. Dilepton measurements are planned with the PHENIX and ALICE detector facilities at the relativistic heavy-ion collider RHIC in Brookhaven and at the large hadron collider LHC in CERN, respectively. In despite of many theoretical attempts the nature of the dominating source of dileptons, which will be measured in these detectors, is still unclear. Among the candidates that can give strong contributions in the large invariant mass continuum region near and beyond the J/ψ one can consider the following processes in which dileptons are generated: (i) hard initial quark - anti-quark collisions give rise to the Drell-Yan yield, (ii) semi-leptonic decays of heavy quarks like the charm and bottom, which are also produced dominantly in hard initial parton interactions, and (iii) the thermal dilepton radiation resulting in interactions between secondary partons or even in a locally thermalized quark-gluon plasma (QGP). The yield from (iii) is expected to serve as a direct probe from the QGP [1, 2].

It is commonly believed that, due to the large invariant mass M, at least the Drell-Yan process and the initial heavy quark production in pp and pA collisions are under reliable theoretical control by means of perturbative QCD [3, 4, 5] and, therefore, can provide a reference for the thermal dilepton signal from deconfined matter. At the same time all up to date calculations of high-M thermal dilepton rates from early parton matter contain uncertainties due to the lack of knowledge of precise initial condition parameters such as the energy density and quark-gluon phase space saturation. The parton cascade model [6] and calculations based on the HIJING event generator [7] differ nearly by an order of magnitude in predicting the thermal high-M dilepton spectra. Recent estimates [8] within the mini-jet mechanism of quark-gluon matter formation [9], with initial conditions similar to the self-screened parton cascade model [10], point to a strong competition between the Drell-Yan yield and the thermal signal in a wide range of beam energies of the colliding nuclei.

With respect to the wanted dilepton signal from the QGP the dileptons from charm and bottom decays play a rôle of substantial background [11]. The magnitude and the characteristic properties of such background is presently matter of debate. As shown by Shuryak [12] for RHIC conditions the energy loss effects of heavy quarks propagating through a medium can drastically reduce the dilepton yield from charm and bottom decays in the region of large invariant dilepton masses. Further calculations [13], including the PHENIX acceptance at RHIC, also predict a very strong suppression of dileptons from heavy quark decays, which then is partially below the Drell-Yan yield. The studies in refs.

[12, 13] are based on the approximation of a constant rate of energy loss $-dE/dx = 1$ or 2 GeV/fm. Independently of the assumed mechanism of energy loss the approximation of a constant value of dE/dx is difficult to justify for strongly expanding and cooling matter. In general, the value of dE/dx is expected to depend on the mean free path of heavy quarks in the medium which is obviously governed a time dependent density. As shown below, in particular within the gluon radiation mechanism of energy loss [14], dE/dx can depend on widely varying characteristic quantities of the parton medium formed at RHIC and LHC.

In the present paper we study the dileptons resulting from decays of correlated open charm and bottom produced initially in hard collisions and undergoing an energy loss which is determined by the temperature and the density evolution of the deconfined medium. Going beyond refs. [12, 13] we concentrate here on LHC conditions, where the energy loss appears much stronger as compared to RHIC. This leads to almost complete stopping of initial charm and bottom in deconfined matter produced at LHC. The central rapidity acceptance of ALICE will select in this case the electron pairs mainly from bottom decays. It is assumed that, due to a like-sign subtraction, the combinatoric background from uncorrelated pairs can be removed, and hence forth we focus on correlated pairs.

In the framework of perturbative QCD the number of the heavy quark - anti-quark $(Q\bar{Q})$ pairs, produced initially with transverse momenta $p_{\perp 1} = -p_{\perp 2} = p_\perp$ at rapidities y_1 and y_2, in central AA collisions can be calculated from

$$dN_{Q\bar{Q}} = T_{AA}(0)\, \mathcal{K}_Q\, H(y_1, y_2, p_\perp)\, dp_\perp^2\, dy_1\, dy_2, \tag{1}$$

where $H(y_1, y_2, p_\perp)$ is the standard combination of structure functions and elementary cross sections (see for details [8, 11])

$$\begin{aligned} H(y_1, y_2, p_\perp) &= x_1\, x_2 \Bigg\{ f_g(x_1, \hat{Q}^2)\, f_g(x_2, \hat{Q}^2) \frac{d\hat{\sigma}_g^Q}{d\hat{t}} \\ &+ \sum_{q\bar{q}} \left[f_q(x_1, \hat{Q}^2)\, f_{\bar{q}}(x_2, \hat{Q}^2) + f_q(x_2, \hat{Q}^2)\, f_{\bar{q}}(x_1, \hat{Q}^2) \right] \frac{d\hat{\sigma}_q^Q}{d\hat{t}} \Bigg\}, \end{aligned} \tag{2}$$

where $f_i(x, \hat{Q}^2)$ with $i = g, q, \bar{q}$ are the parton structure functions, $x_{1,2} = m_\perp \left(\exp\{\pm y_1\} + \exp\{\pm y_2\} \right) / \sqrt{s}$ and $m_\perp = \sqrt{p_\perp^2 + m_Q^2}$. As heavy quark masses we take $m_c = 1.5$ GeV and $m_b = 4.5$ GeV. We employ throughout the present paper the HERA supported structure function set MRS D'- [15] from the PDFLIB in CERN. The overlap function for central collisions is $T_{AA}(0) = A^2/(\pi R_A^2)$ with $R_A = 1.1 A^{1/3}$ fm and $A = 200$ in this paper. We do not include shadowing effects of nuclear parton distributions in the present paper since for heavy quark production they are expected to be not very important and can be considered separately. Our calculation procedure is based on the lowest-order QCD cross sections $d\hat{\sigma}^{Q}_{q,g}/d\hat{t}$ for the subprocesses $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$ with the simulation of higher order corrections by the corresponding $\mathcal{K}_Q$ factor. Such a procedure reproduces within the needed accuracy the more involved next-to-leading order calculations [11] for the heavy quark pair distributions with respect to their invariant mass, total pair rapidity and gap rapidity. We find the scale $\hat{Q}^2 = 4m_Q^2$ and $\mathcal{K}_Q = 2$ as most appropriate.

For the Drell-Yan production process of leptons at rapidities y_1 and y_2 and transverse momenta $p_{\perp 1} = -p_{\perp 2} = p_\perp$ we have

$$\begin{aligned} dN^{DY}_{l\bar{l}} &= T_{AA}(0)\, \mathcal{K}_{DY}\, L(y_1, y_2, p_\perp)\, dp_\perp^2\, dy_1\, dy_2, & (3) \\ L(y_1, y_2, p_\perp) &= \sum_{q,\bar{q}} x_1 x_2 \left[f_q(x_1, \hat{Q}^2)\, f_{\bar{q}}(x_2, \hat{Q}^2) + f_q(x_2, \hat{Q}^2)\, f_{\bar{q}}(x_1, \hat{Q}^2) \right] \frac{d\hat{\sigma}^{l\bar{l}}_q}{d\hat{t}}, & (4) \end{aligned}$$

with $d\hat{\sigma}^{l\bar{l}}_q/d\hat{t} = \frac{\pi\alpha^2}{3} \mathrm{ch}(y_1 - y_2)/\left(2p_\perp^4[1 + \mathrm{ch}(y_1 - y_2)]^3\right)$, $x_{1,2} = p_\perp \left(\exp\{\pm y_1\} + \exp\{\pm y_2\}\right) / \sqrt{s}$, $\alpha = 1/137$, $\hat{Q}^2 = x_1 x_2 s = M^2$ and $\mathcal{K}_{DY} = 1.1$ [3].

Since the energy loss of heavy quarks depends strongly on the properties of produced matter, which is propagated through, one has to specify the initial conditions and the space-time evolution of such a medium. To do this in a coherent manner we employ for the mini-jet production (which dominates the parton matter formation) the same lowest-order approximation and parton structure functions as for the initial heavy quark production. Adding a suitably parametrized soft component [8] we get the initial temperature $T_i = 1000$ (550) MeV, gluon fugacity $\lambda_i^g = 0.5$ and light quark fugacity $\lambda_i^q = \lambda_i^g/5$ of the mini-jet plasma formed at initial time $\tau_i = 0.2$ fm/c at LHC (RHIC). The space-time evolution of the produced parton matter after τ_i is governed by the longitudinal scaling-invariant expansion accompanied by quark and gluon chemical equilibration processes [16, 17]. We take for definiteness full saturation, i.e. $\lambda^g = \lambda^q = 1$ at deconfinement temperature $T_c = 170$ MeV. (Due to gluon multiplication [18] this seems to be justified, while the chemical equilibration of the quark component might be somewhat overestimated by this ansatz.) The actual time evolution is determined by $e \propto \tau^{-4/3}$ for energy density and $\lambda^{q,g} \propto \tau^2$ [17], which must be inverted to get $T(\tau)$ explicitly. This results in final pion rapidity densities (see [8]) which are in agreement with other estimates [9].

To model the energy loss effects of heavy quarks in expanding matter we assume as usual in the Bjorken scaling picture that a heavy quark produced initially at given rapidity will follow the longitudinal flow with the same rapidity. Therefore, with respect to the fluid's local rest frame the heavy quark has essentially only a transverse momentum $p_\perp(\tau)$ which depends on the proper local time τ in accordance with the energy loss in transverse direction. (Note that the transverse expansion at early times can be neglected, and we take as averaged transverse radius of parton matter $R = 7$ fm.)

To calculate the evolution of the transverse momentum $p_\perp(\tau)$ of quarks propagating the distance $r_\perp(\tau)$ in transverse direction we adopt the results of Baier et al. [14] for the energy loss of a fast quark in a hot QCD medium

$$\frac{dp_\perp}{d\tau} = -\frac{4}{3}\frac{\alpha_s k_c}{\sqrt{L}}\,(p_\perp^2 + m_Q^2)^{1/4} \ln\left(\frac{\sqrt{p_\perp^2 + m_Q^2}}{L\,k_c^2}\right), \tag{5}$$

$$\frac{dr_\perp}{d\tau} = \frac{p_\perp}{\sqrt{p_\perp^2 + m_Q^2}}, \tag{6}$$

where the parameter $k_c^2 = 2m_{th}^2(T) \equiv \frac{8}{9}(\lambda_g + \frac{1}{2}\lambda_q)\pi\alpha_s T^2$ [16, 17] is used as an average of the momentum transferred in heavy quark-parton scatterings, and the strong coupling is described by $\alpha_s = 0.3$. For the mean free path of gluons we take $L \approx (\sigma_{gg} n_g)^{-1}$ with integrated cross section $\sigma_{gg} \sim \alpha_s^2/k_c^2$ and gluon density $n_g \sim \lambda_g T^3$, resulting in $L^{-1} = 2.2\,\alpha_s T$ [16, 18]. The derivation of eqs. (5,6) relies on the assumption that the temperature changes smoothly enough in space-time so that the mean free path of heavy quarks is less than the characteristic scale of the temperature gradient. Such an approximation can be improved by considering finite size effects [19] which, however, is beyond the scope of the present paper. The r.h.s. of eq. (5) is actually the rate of energy loss dE/dx which is essentially $\propto (p_\perp^2 + m_Q^2)^{1/4}$. Due to the rapid expansion of the matter this value depends strongly on the time. For instance, at LHC conditions and initial momentum of a heavy quark of 10 GeV the stopping power $-dE/dx$ drops from 6 GeV/fm down to 0.3 GeV/fm during the expansion of deconfined matter.

To get realistic spectra of charm and bottom quarks after energy loss we use a Monte Carlo simulation with a uniform distribution of the random initial position and random orientation of $Q\bar{Q}$ pairs in the transverse plane. We integrate then eqs. (5,6) together with the above described time evolution of $T(\tau)$ and $\lambda_{q,g}(\tau)$. Eq. (6) is used to check whether the considered heavy quark propagates still within deconfined matter; if it leaves the deconfined medium it does not longer experience the energy loss according to eq. (5). (The subsequent energy loss in a possible mixed and hadron phase might be incorporated along the approach of [20].) A considerable part of heavy quarks can not escape the parton system thereby undergoing thermalization. Following [13] we consider a heavy quark to be thermalized if its transverse mass $m_\perp$ during energy loss becomes less than the averaged transverse mass of thermalized light partons at given temperature. This part of heavy quarks we assume to be distributed as $dN_Q/dm_\perp \propto m_\perp^2 \exp\{-m_\perp/T_{\rm eff}\}$ with an effective temperature $T_{\rm eff} = 150$ MeV.

The results of our calculation for transverse momentum spectra of charm and bottom quarks at midrapidity are shown in fig. 1. We obtain a strong suppression of the initial transverse momentum spectrum at large transverse momenta due to the energy loss both for charm and bottom. The bump below 3 GeV is caused by the thermal redistribution. (The rapidity integrated spectra have the same shape.) In comparison with RHIC conditions [13, 21] the suppression at LHC is found to be more pronounced due to the longer life time of deconfined matter and its higher initial temperature and density. It should be stressed that such a drastic change of the $p_\perp$ spectrum of heavy quarks in AA collisions, in comparison with pp or pA collisions, is a measurable effect which for itself can help to identify the creation of a hot and dense parton gas [7, 22].

Basing on the analysis of ref. [11] we employ a delta function like fragmentation function for heavy quark fragmentation into D and B mesons. It gives the same transverse momentum for the meson as for the parent heavy quark. The correlated lepton pairs from $D\bar{D}$ and $B\bar{B}$ decays have been obtained from a suitable Monte Carlo code which employs the single electron distributions as delivered by JETSET 7.4. The average branching ratio of $D \to l + X$ is taken to be 12%. We consider here only the so-called primary leptons [13] which are directly produced in the bottom decay $b \to l X$ with the average branching ratio 10%. The secondary leptons l' produced in further branchings like $b \to cX \to l'Y$ have much smaller energy and do not contribute to the large invariant mass region. Such simplification does not affect significantly the dielectron yield at $M > 2$ GeV as we have checked by comparison with ref. [11]. To get the dielectron spectra from charm and bottom decays at LHC we take into account the acceptance of the ALICE detector: the electron pseudo-rapidity is $|\eta_e| < 0.9$ [23] with an additional cut on the electron transverse momentum $p_\perp^e > 1$ GeV to reduce the lepton background from light hadron decays. We do not take into account the limited high-$p_\perp$ acceptance ($p_\perp^e \leq 2.5$ GeV [23]) in our simulations to demonstrate the general tendency of the spectrum in the high-M region. Our results of heavy quark decays at LHC are depicted in fig. 2 for charm (a) and bottom (b) for $M \geq 2$ GeV. Due to the strong energy loss the contribution from charm decays falls below the Drell-Yan yield in the region $2 \leq M \leq 4.5$ GeV. At the same time the contribution from bottom decays becomes dominant in this region. This can be understood also on a qualitative level. Even after strong energy loss the massive B mesons have enough energy to produce electrons with $p_\perp^e > 1$ GeV. Additionally the central rapidity cut of the ALICE detector selects electrons from charm being near midrapidity, while for bottom the corresponding rapidity region is much greater. Further one has to stress that we actually estimate a lower limit for bottom decay; as discussed above the secondary electrons contribute somewhat at not too large values of M. Therefore, at LHC the dielectron continuum region above 2 up to 4.5 GeV is expected to be dominated by bottom decays.

To demonstrate the general tendency of the relative contribution from the Drell-Yan process and heavy quark decays with the change of the collider energy we plot in fig. 3 the results of our calculations for RHIC initial conditions including the PHENIX detector acceptance for the electrons, i.e. $|\eta_e| \leq 0.35$ [24]. As above for LHC we here also employ the gate $p_\perp^e > 1$ GeV. One observes in fig. 3 a strong competition of the Drell-Yan process and correlated heavy quark decays in a wide region above $M = 2$ GeV. This confirms in part the previous estimates [13] which rely on another treatment of the energy loss. In particular, already at $\sqrt{s} = 200$ AGeV the contribution from bottom decays becomes important if energy loss effects are taken into account. As mentioned above, at higher collider energy the bottom decays happen to be the dominant dielectron source at high invariant mass if no further kinematical cuts than above mentioned are imposed.

In summary, taking into account the energy loss effects of heavy quarks we calculate the spectra of electron pairs from correlated open charm and bottom decays at LHC conditions. We obtain a measurable, strong suppression of large transverse momenta of heavy quarks due to the energy loss in the expanding deconfined matter. Our calculations predict the dominating contribution of bottom decays in the high invariant mass region of electron pairs which are planned to be measured at central rapidity in the ALICE detector.

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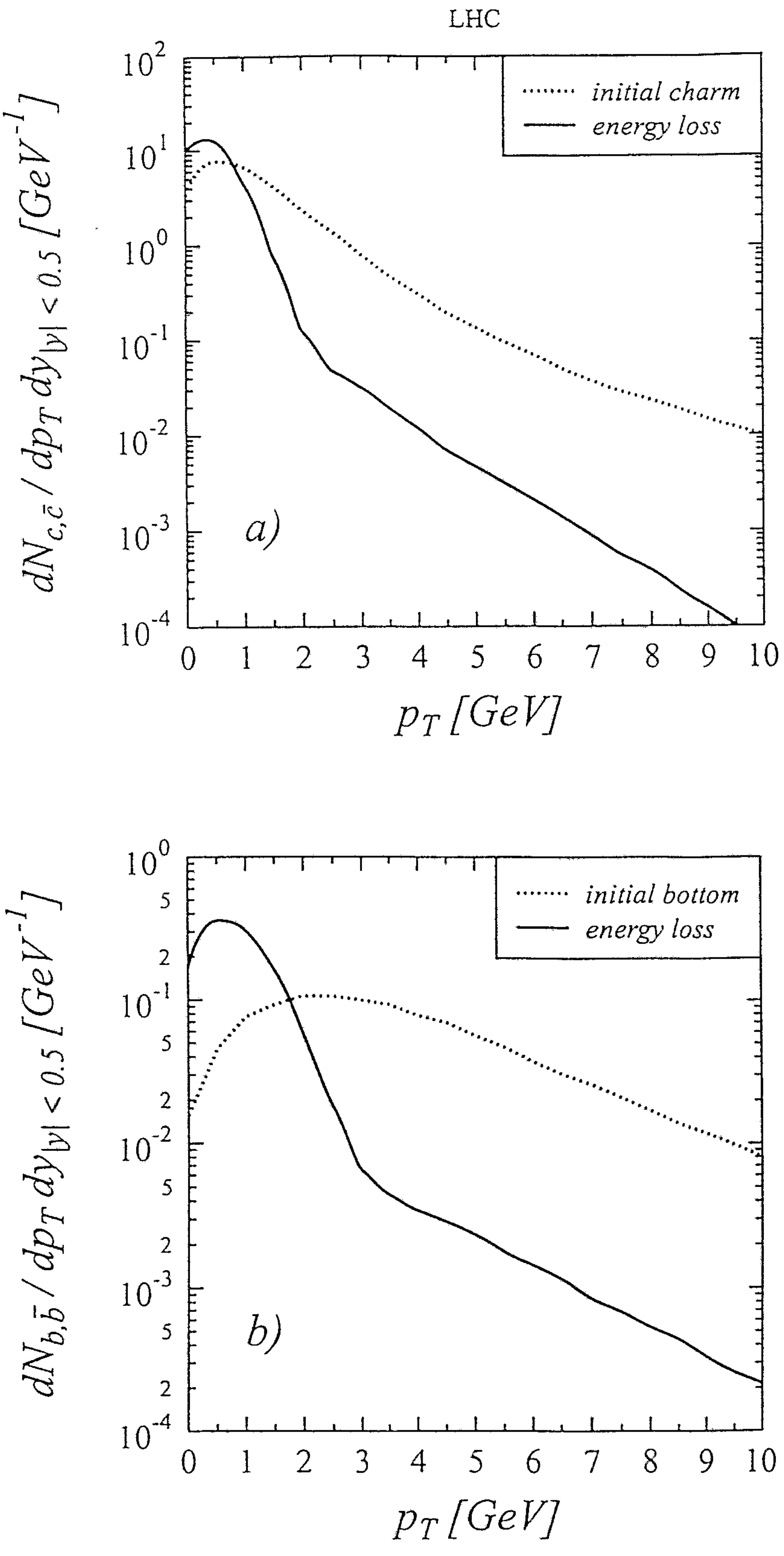

Fig. 1: The $p_\perp$ spectrum of heavy quarks ((a): charm, (b): bottom) at midrapidity in AA collisions at LHC ($\sqrt{s} = 5500$ AGeV). The dotted curves depict the initial production without energy loss, while the solid lines show our result with energy loss and $T_{\rm eff} = 150$ MeV for thermalized heavy quarks.

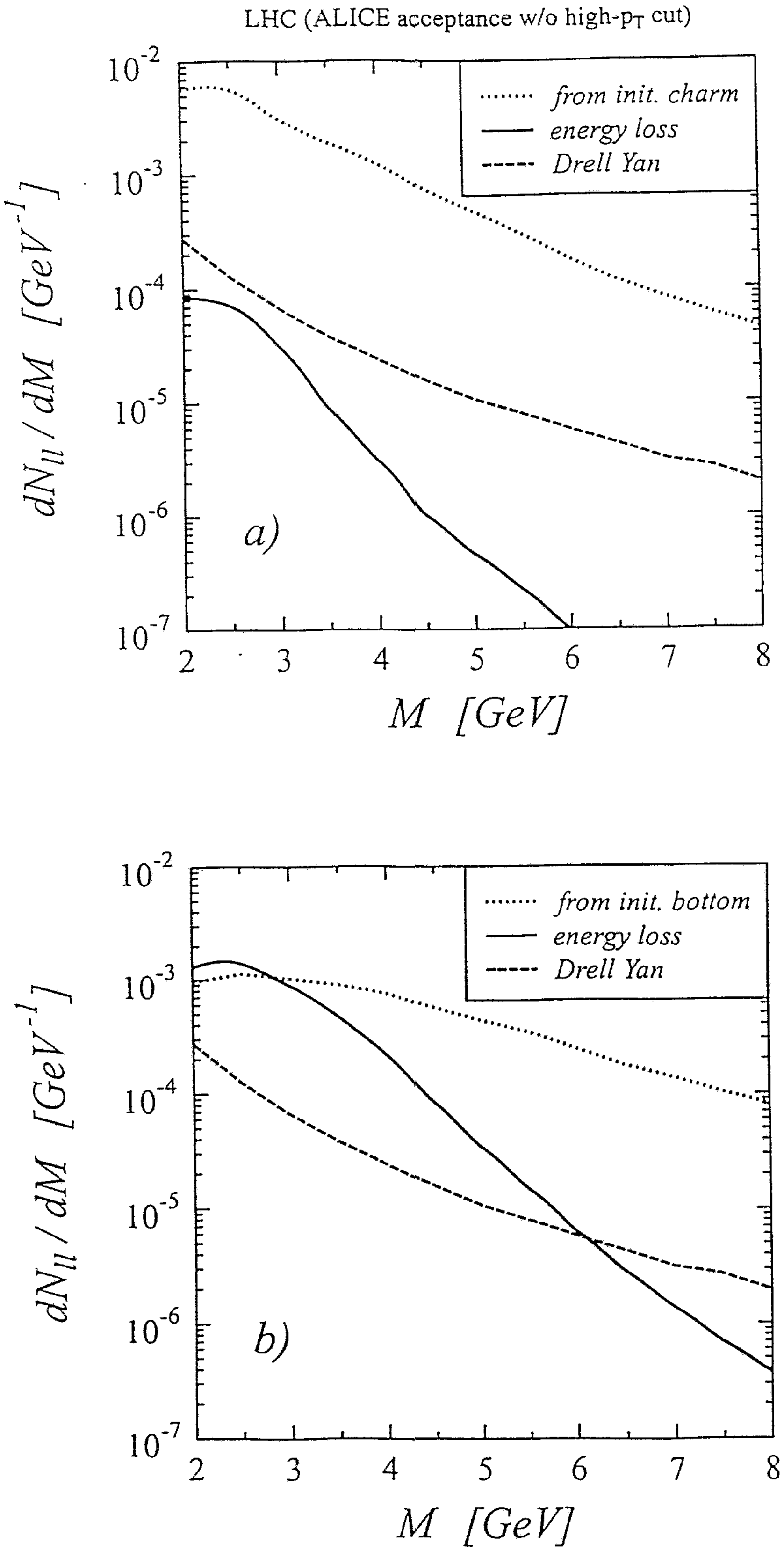

Fig. 2: The invariant mass spectrum of dielectrons from correlated charm (a) and bottom (b) decays as well as Drell-Yan electron pairs filtered throughout the LHC acceptance, but the high-$p_\perp$ cut of 2.5 GeV is here not implemented.

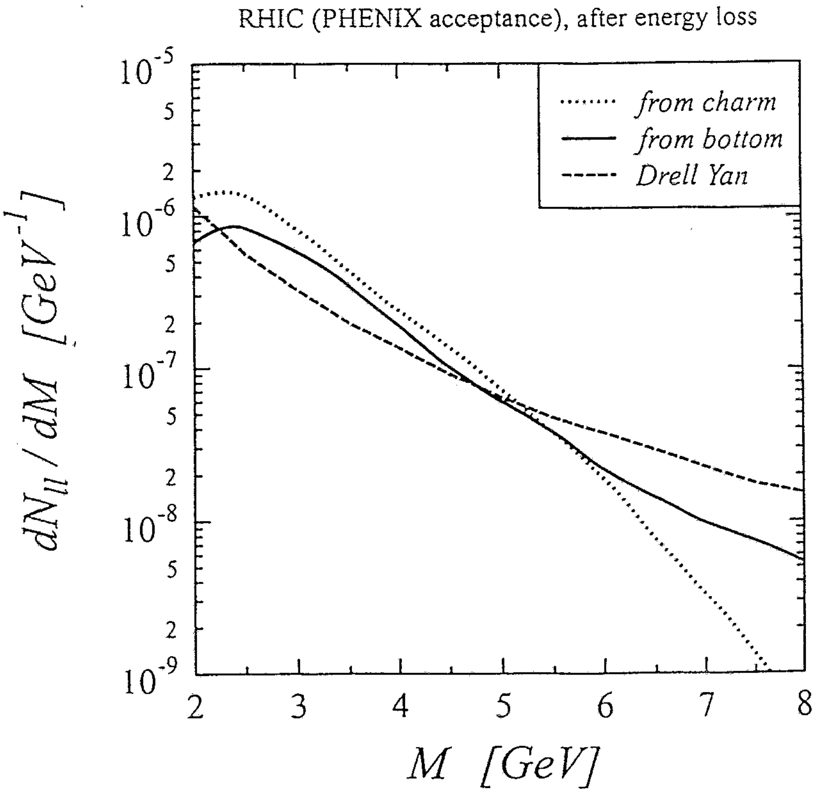

Fig. 3: The invariant mass spectrum of dielectrons from correlated charm (dotted line) and bottom (solid line) decays as well as Drell-Yan electron pairs (dashed line) filtered throughout the PHENIX acceptance.