FORSCHUNGSZENTRUM
ROSSENDORF e.V.

FZR

FZR-144
August 1996
Preprint

B. Kämpfer and O. P. Pavlenko

Thermal dilepton and open charm signals versus hard initial yields in heavy-ion collisions at RHIC and LHC energies

Forschungszentrum Rossendorf e.V.
Postfach 51 01 19 · D-01314 Dresden
Bundesrepublik Deutschland

Telefon	(0351) 260 3258
Telefax	(0351) 260 3700
E-Mail	kaempfer@fz-rossendorf.de

Thermal dilepton and open charm signals versus hard initial yields in heavy-ion collisions at RHIC and LHC energies

B. KÄMPFER[1,2], O.P. PAVLENKO[2,3]

[1]Institute for Theoretical Physics, TU Dresden, 01062 Dresden, Germany

[2]Research Center Rossendorf, PF 510119, 01314 Dresden, Germany

[3]Institute for Theoretical Physics, 252143 Kiev - 143, Ukraine

Abstract

The hard initial production of open charm and dileptons is compared with possible thermal signals in heavy-ion collisions at RHIC and LHC energies. Our approach is based on the perturbative QCD mini-jet mechanism of quark-gluon matter formation. The thermal dilepton signal is found to rise much stronger as compared to the hard Drell-Yan background with increasing collider energy and clearly dominates at LHC energy. Oppositely, open charm stems from initial hard production. A possible manifestation of gluon shadowing at RHIC and LHC energies is discussed.

PACS number(s): 12.38.Mh, 25.75+r, 12.38.Bx

key words: heavy-ion collisions, mini-jets, charm, dileptons

High-invariant mass dileptons and open charm are now widely considered as probes of the early stage of deconfined matter, which is assumed to result in ultra-relativistic heavy-ion collisions at RHIC and LHC energies. Due to the large masses, such dileptons and charm quarks are mainly created in parton matter when the momenta of secondaries (mainly mini-jets [1, 2]) are high enough and they are not yet fully thermalized. This might be used for probing the dynamics and thermalization processes in the early mini-jet plasma [3]. However, both the dilepton and charm signals face the background problem connected with the particle production via initial hard collisions of partons from different nuclei. Being a very useful tool in testing perturbative QCD (pQCD) aspects of strong interactions, initial open charm and Drell-Yan dileptons play a role of serious competitors with respect to the signals from a quark-gluon plasma. In particular at RHIC energy $\sqrt{s} = 200$ AGeV the open charm production during the equilibration of parton matter is estimated to be a small fraction of the initial fusion rate [4], unless the initial parton density and effective temperature would be very high [5]. The possible enhancement of the thermal dilepton yield over the Drell-Yan background at RHIC appears to be very sensitive against variations of the initial conditions of parton matter formation [6].

Now it is commonly believed that the increase of the energy from $\sqrt{s} = 20$ AGeV at CERN SPS up to $\sqrt{s} = 5500$ AGeV at CERN LHC leads to an increase of the energy density of the created parton matter at midrapidity. The analysis of the quark-gluon plasma formation [7], based on the recent HERA parton structure functions, confirms this expectation, indeed. Such conclusion looks as highly favorable for the probes of deconfined matter. At the same time the increase of the collider energy causes a considerable rise of the hard perturbative background. It appears therefore worthwhile to consider systematically the relative contributions from deconfined matter and initial hard collisions to the particle yields with respect to the variation of the collider energy.

The dominant lowest-order processes for charm production involve mainly gluons, while the dileptons stem from quark annihilation. Since the newer parton structure function parametrizations point to a strong increase of the gluon density at small x, one can expect a different signal-to-background ratio when increasing the collider energy from RHIC to LHC. The present note is aimed at a quantification of this expectation. We are going to consider open charm and dileptons with invariant masses $M > 1$ GeV and compare the initial hard background with a possible thermal signal. While such a goal can also be accomplished with transport simulations like the HIJING [8] or Parton Cascade Model, we would like to offer here a more transparent model which covers nevertheless the essential physical features.

In order to estimate the initial parameters of the parton system of secondaries formed at midrapidity in AA collisions we follow mainly the approach of ref. [2] and assume that on the pp level one can separate between a hard (mini-jet) and a soft component. The number distribution of mini-jets at rapidity y and transverse momentum $p_\perp$ produced in central AA collisions can be written as

$$\frac{dN_{jet}}{dp_\perp^2\, dy} = T_{AA}(0)\, \mathcal{K}_{jet} \sum_{i,j,k,l=q\bar{q},g} \int d\bar{y}\, x_1 f_i(x_1, Q^2)\, x_2 f_j(x_2, Q^2) \frac{d\hat{\sigma}^{ij\to kl}}{d\hat{t}}(\hat{s}, \hat{t}), \qquad (1)$$

where f_j is the parton structure function, $x_{1,2} = \frac{p_\perp}{\sqrt{s}}(\exp\{\pm y\} + \exp\{\pm \bar{y}\})$ and the integration is performed in the interval $-\ln(\frac{\sqrt{s}}{p_\perp} - \exp\{-y\}) \le \bar{y} \le \ln(\frac{\sqrt{s}}{p_\perp} - \exp\{y\})$. We employ throughout the present work the structure function MRS D-' [9] from the PDFLIB in CERN. The overlap function is $T_{AA}(0) = A^{4/3}/(\pi R^2)$ with $R = r_0 A^{1/3}$ and $r_0 = 1.1$ fm. We utilize the lowest-order partonic cross sections $d\hat{\sigma}/d\hat{t}$ for the subprocess $ij \to kl$ and simulate the higher-order corrections by a factor $\mathcal{K}_{jet} = 2$ which is appropriate for the scale $Q^2 = p_\perp^2$ [10]. The coupling parameter is $\alpha_s(Q^2) = 12\pi[(33 - 2N_f)\ln\left(\frac{Q^2}{\Lambda^2}\right)]^{-1}$ with $\Lambda = 0.2$ GeV as QCD scale parameter and $N_f = 4$ as flavor number. We use everywhere the same value of Q^2 for the renormalization and factorization scales. The energy carried by hard partons in the central rapidity slice $|y| \le 0.5$ is estimated as

$$E_{jet} = \int_{p_0}^{\sqrt{s}/2} dp_\perp\, p_\perp \int_{-0.5}^{0.5} dy\, \mathrm{ch} y\, \frac{dN_{jet}}{dp_\perp\, dy}, \qquad (2)$$

where $p_0 = 2$ GeV is the momentum cut-off needed to separate both hard and semi-hard pQCD processes from soft parton interactions.

The soft component contribution to the produced parton matter at rapidity $|y| \le 0.5$ is modelled by the cross section σ_{soft} and the average transverse energy $< E_\perp >_{soft}$ carried by soft partons. For central AA collisions the number of soft partons and their energy are $N_{soft} = T_{AA}(0)\, \sigma_{soft}$ and $E_{soft} = T_{AA}(0)\, \sigma_{soft} < E_\perp >_{soft}$, respectively. We assume that σ_{soft} and $< E_\perp >_{soft}$ at high energy $\sqrt{s} > 20$ GeV are independent of $\sqrt{s}$ and use in our calculations $\sigma_{soft} = 15$ mb and $< E_\perp >_{soft} = 1$ GeV, which are in good agreement with the data on multiplicity and transverse energy distributions of secondaries for S + Pb and Pb + Pb collisions at CERN SPS [2, 11]. Then the initial energy density of the secondary partonic system can be estimated from Bjorken's formula

$$e_i = \frac{E_{jet} + E_{soft}}{\pi R^2 \tau_i}, \qquad (3)$$

where $\tau_i = < E_\perp >_{soft}^{-1} \approx 0.2$ fm/c is the formation time of the soft component of the parton system. Since the hard component is formed somewhat earlier at $p_0^{-1} \approx 0.1$ fm/c [7] it is reasonable to approximate the earliest time where thermalization might be expected by

$\tau_i = 0.2$ fm/c. It is shown in ref. [7] that estimates, based on the use of HERA supported structure functions, could lead at LHC energy to the formation of a dense mini-jet system which thermalizes immediately after 0.1 fm/c. We do not use such extremely fast initial thermalization because even for LHC energies hard partons need some time to change their directions to arrive at an isotropic distribution in momentum space.

To parametrize the average momentum scale of the secondary partons we rely on the estimate

$$T_i = \frac{1}{2.7} \frac{E_{jet} + E_{soft}}{N_{jet} + N_{soft}} \tag{4}$$

which approximates the initial temperature of the system at $\tau = \tau_i$. This results in the associated initial gluon fugacity for baryonless matter

$$\lambda_i^g = \frac{e_i}{3a\left(1 + \frac{b}{a}\frac{\lambda_i^q}{\lambda_i^g}\right) T_i^4}, \tag{5}$$

where $a = 16\pi^2/90$, $b = 21N_f\pi^2/180$ and $\lambda_i^{q(g)}$ is the initial quark (gluon) fugacity. The pQCD analysis of the chemical composition of parton matter predicts a strong dominance of gluons [7, 12] that can be approximated by the ratio $\lambda_i^q/\lambda_i^g = 0.2$. The results of our estimates for the initial parameters of the parton matter formed at RHIC and LHC are listed in tab. 1 for $A = 200$.

The space-time evolution of the formed partonic matter at midrapidity after τ_i is governed by the boost-invariant scaling hydrodynamics accompanied by quark and gluon chemical equilibration processes [5, 6]. We assume here for definiteness full saturation (i.e., $\lambda_{q,g} = 1$) at confinement temperature $T_c = 170$ MeV. This results in a simple estimate of the life time of the deconfined, quasi-thermalized stage according to $\tau_c(T_c) = \tau_i(e_i/e_c)^{3/4}$. The secondary pion rapidity density (see tab. 1) is then $dN_\pi/dy = 0.27\pi R^2 s(T_c)\tau_c$, where $s(T)$ denotes the entropy density of the parton system. The entropy production due to chemical equilibration results in higher multiplicities as compared to ref. [7]. Nevertheless, our estimate of dN_π/dy is a lower limit since viscosity and Ohmic heating effects [13] can increase the entropy and, therefore, also the parton numbers. Note that our entropy increase estimate is independent of the actual time evolution of $\lambda_{q,g}(\tau)$ and $T(\tau)$, as long as full saturation at T_c is achieved. In our calculations we assume that the fugacities evolve quadratically with time and determine from the above equation the temperature history. Due to the work done by the particle production, the cooling is considerably more rapid that it would be the case for the slow chemical evolution in ref. [5].

The invariant mass spectrum $dN_{l\bar{l}}/dM^2\,dy$ of dileptons and the transverse momentum spectrum $dN_c/dp_\perp^2\,dy$ of open charm resulting from thermalized parton matter can be written in Boltzmann approximation as

$$\frac{dN_{l\bar{l}}}{dM^2\,dy} = \frac{R^2}{(2\pi)^3}\int_{\tau_i}^{\tau_c} d\tau\tau M^3 T K_1\left(\frac{M}{T}\right)\lambda_q^2\, 3\sum_q e_q^2\,\sigma_{l\bar{l}}(M^2), \tag{6}$$

$$\begin{aligned}\frac{dN_c}{dp_\perp^2\,dy} &= \frac{R^2}{8(2\pi)^3}\int_{\tau_i}^{\tau_c} d\tau\tau\sqrt{\frac{\pi T}{m_\perp}}\frac{m_c T}{p_\perp}\int_{4m_c^2}^{\infty} dz\exp\left\{-\frac{zm_\perp}{2Tm_c^2}\right\}\frac{1}{\sqrt{z}W}\times \\ &\quad (\exp\{\beta_+\}-\exp\{\beta_-\})[\frac{1}{2}a^2\lambda_g^2\bar{\sigma}_g + b^2\lambda_q^2\bar{\sigma}_q],\end{aligned} \tag{7}$$

where $W=\sqrt{1-\frac{4m_c^2}{z}}$, $\beta_\pm = \pm\frac{zp_\perp}{2m_c^2T}W$, $\bar{\sigma}_g = \frac{2\pi\alpha_s^2}{3}[(1+\frac{4m_c^2}{z}+\frac{m_c^4}{z^2})\mathrm{arcth}W - (\frac{7}{8}+\frac{31m_c^2}{8z})W]$, $\bar{\sigma}_q = \frac{8\pi\alpha_s^2}{27}(1+\frac{2m_c^2}{z})W$; $m_c = 1.5$ GeV denotes the charm quark mass; $\sigma_{l\bar{l}} = \frac{4\pi\alpha^2}{3M^2}$ describes the electromagnetic annihilation process and e_q stands for the electrical charges of the quarks.

Similar to the mini-jets, our analysis of the initial hard production of charm and dileptons (i.e., Drell-Yan pairs) is based on the lowest-order pQCD cross sections with the simulation of higher-order corrections by the corresponding K factors [14, 15, 16]. It gives for the hard open charm production in central AA collisions

$$\begin{aligned}\frac{dN_c^h}{dp_\perp^2\,dy} &= T_{AA}(0)\mathcal{K}_c\int d\bar{y}\,x_1x_2\{f_g(x_1,Q^2)f_g(x_2,Q^2)\frac{d\sigma_g^c}{d\hat{t}} \\ &+ \sum_{q,\bar{q}}[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2)+f_q(x_2,Q^2)f_{\bar{q}}(x_1,Q^2)]\frac{d\sigma_q^c}{d\hat{t}}\},\end{aligned} \tag{8}$$

where $d\sigma_g^c/d\hat{t}$ and $d\sigma_q^c/d\hat{t}$ denote the elementary lowest-order pQCD cross sections of the subprocesses $gg\to c\bar{c}$ and $q\bar{q}\to c\bar{c}$ [14]. Here we use the scale $Q^2=4m_c^2$ and $\mathcal{K}_c = 2$ as most appropriate for the HERA supported sets of structure functions. Other choices like $Q^2 = m_c^2$ or $m_\perp^2$ do not change the rate too strongly within the accuracy needed for the comparison of thermal signals with the hard background. The variables $x_{1,2}$ and $\bar{y}$ are similar to the ones in eq. (1), but with the replacement $p_\perp \to m_\perp = \sqrt{p_\perp^2+m_c^2}$.

For the Drell-Yan production of dileptons with invariant mass M we have

$$\begin{aligned}\frac{dN_{l\bar{l}}^{DY}}{dM^2\,dy} &= T_{AA}(0)\,\mathcal{K}_{DY}\frac{\sigma_{l\bar{l}}(M^2)}{3M^2} \\ &\quad \sum_{q,\bar{q}} e_q^2 x_1x_2[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2)+f_q(x_2,Q^2)f_{\bar{q}}(x_1,Q^2)],\end{aligned} \tag{9}$$

where $x_{1,2} = \frac{M}{\sqrt{s}}\exp\{\pm y\}$, $Q^2 = M^2$, and $\mathcal{K}_{DY} = 1.1$ [9, 16].

The results of our calculations of open charm production at RHIC and LHC energies are displayed in fig. 1 for $A = 200$. Even for LHC, where the initial temperature and gluon fugacity become rather high (see tab. 1), the thermal yield is estimated to be smaller than the initial hard background. For RHIC energy the initial fusion rate overcomes the thermal one by about a factor 40. These results coincide with the earlier estimates [4] for RHIC performed with Duke-Owens structure functions and roughly with HIJING calculations [5]. It is necessary to emphasize that our model employs a short thermalization time and can be considered as an upper limit for the thermal charm signal. From this we derive a small chance to observe thermal open charm.

In contrast to the charm signal, the thermal dileptons at LHC have a dominant contribution to the invariant mass spectrum as compared to the Drell-Yan background up to $M \sim 6$ GeV (see fig. 2). At RHIC energy there is a competition between thermal production from deconfined matter and Drell-Yan background. The most favorable region for the thermal signal is around $M = 2$ GeV [6]. Unfortunately in this region the pQCD estimates of the Drell-Yan lepton pair production becomes not so reliable as for higher invariant mass, where the Drell-Yan background ultimately dominates. One should also keep in mind the importance of semi-leptonic charmed meson decays, which, when not subtracted, constitute a huge background to the signals discussed here [17]. Our model provides a simple self-consistent approach to the analysis of thermal signals versus both the initial hard Drell-Yan and charmed meson decay (not yet included here) background. We intend to perform such estimates separately since the selection of the most appropriate kinematical window to subtract the uncorrelated lepton pairs stemming from charm decays needs additional investigations.

To clarify the general tendency of the competition between thermal signals and initial hard production with respect to the change of collider energy one can analyze scaled yields. The HERA supported structure functions give rise to a rapid increase of the initial hard particle production. This concerns in particular the gluon mini-jets and consequently the multiplicity of secondary hadrons. On the other hand, the thermal sources of the charm and dilepton production have at high enough temperature a dependence as $\propto (dN_\pi/dy)^2$, while the Drell-Yan like mechanism results roughly in a linear dependence. As can be seen in fig. 3 the interval of the collider energies from $\sqrt{s} = 200$ AGeV to 5500 AGeV appears to be large enough for thermal dilepton signals (with $M \sim 2$ GeV) to overcome the Drell-Yan background, even if at RHIC energies the thermal dileptons do not clearly dominate. This is not the case for open charm.

To check the importance of parton shadowing in nuclei and to find out the sensitivity of our results on the initial hard particle production we follow the standard procedure to constrain the shadowed parton distribution: $f_i^{shad.}(x, Q^2) = R_i(x, A)\, f_i(x, Q^2)$, where R_i is the component dependent modifying factor. Actually we utilize for the gluon shadowing the parametrization of ref. [18] in mini-jet production, while the parametrization of ref. [19] is used for the open charm production. Our quark shadowing employs the shadowing function of ref. [8]. The results of our calculations for the mini-jet production with structure functions $f_i^{shad.}$ are also collected in tab. 1. At LHC energies the gluon shadowing causes a considerable suppression of the number of mini-jets at midrapidity by a factor 0.5; consequently also the gluon fugacity at the beginning of a possible thermalized era is diminished, too. As result the thermal dilepton and open charm yields are also suppressed by factors 0.3 and 0.2, respectively. At the same time the important conclusion is that the signal-to-background ratio for dileptons is not affected noticeably by parton shadowing: it amounts 7.5 and 6.5 without and with shadowing at LHC energy.

Recently, Lin and Gyulassy [20] have proposed to measure the gluon shadowing at RHIC via charm identification by lepton pairs in pA reactions. One can also look at the rapidity distribution of open charm, e.g., $dN_c/d^2p_\perp dy$ vs. y in AA collisions. Indeed, for $p_\perp \approx 0$ we find at midrapidity an open charm suppression by a factor ≈ 0.5. In comparison with no shadowing the rapidity distribution is changed: shadowing causes a flatter distribution. This a consequence of maximum shadowing effect at midrapidity, where both x_1 and x_2 are small, and less shadowing in the fragmentation regions, where only x_1 is small. Possibly this effect can be used for narrowing experimentally the gluon shadowing.

In summary, using a transparent pQCD approach we compare the thermal charm and dilepton signals to be expected in heavy-ion collisions at collider energies. While the gluon dominated processes create charm at midrapidity via initial hard processes, the later quasi-thermalized partonic system can radiate brightly dileptons from quark annihilation. The signal-to-background ratio of dileptons is found rather stable with respect to parton shadowing at LHC.

Acknowledgments: Stimulating discussions with Z. Lin, V. Ruuskanen, R. Vogt, X.N. Wang, and G. Zinovjev are gratefully acknowledged. O.P.P. thanks the nuclear theory group in Research Center Rossendorf for the warm hospitality. This work is supported by BMBF grand 06DR666.

References

[1] K. Kajantie, P.V. Landshoff, J. Lindfors, Phys. Rev. Lett. **59** (1987) 847, J.P. Blaizot, A.H. Mueller, Nucl. Phys. **B 289** (1987) 847

[2] K.J. Eskola, K. Kajantie, J. Lindfors, Nucl. Phys. **B 323** (1989) 37

[3] B. Müller, in "Particle production in Highly Excited Matter", Eds. H.H. Gutbrod, J. Rafelski, Plenum Press, New York, p.11, 1993

[4] Z. Lin, M. Gyulassy, Phys. Rev. **C 51** (1995) 2177

[5] P. Levai, B. Müller, X.N. Wang, Phys. Rev. **C 51** (1995) 3326

[6] B. Kämpfer, O.P. Pavlenko, A. Peshier, G. Soff, Phys. Rev. **C 52** (1995) 2704

[7] K.J. Eskola, Nucl. Phys. **A 590** (1995) 383c

[8] X.N. Wang, M. Gyulassy, Phys. Rev. **D 44** (1991) 3501

[9] A.D. Martin W.J. Stirling, R.G. Roberts, Phys. Lett. **B 306** (1993) 145

[10] K.J. Eskola, X.N. Wang, Int. J. Mod. Phys. **A 10** (1995) 3071

[11] P. Deines-Jones et al., Phys. Rev. **C 53** (1996) 3044

[12] E.V. Shuryak, Phys. Rev. Lett. **68** (1992) 3270

[13] K.J. Eskola, M. Gyulassy, Phys. Rev. **C 47** (1993) 2329

[14] P.L. McGaughey, E. Quack, P.V. Ruuskanen, R. Vogt, X.N. Wang, Int. J. Mod. Phys. **A 10** (1995) 2999

[15] I. Sarcevic, P. Vaerio, Phys. Rev. **C 51** (1995) 1433

[16] S. Gavin, S. Gupta, R. Kaufman, P.V. Ruuskanen, D.K. Srivastava, R.L. Thews, Int. J. Mod. Phys. **A 10** (1995) 2961

[17] R. Vogt, B.V. Jacak, P.L. McGauphey, P.V. Ruuskanen, Phys. Rev. **D 49** (1994) 3345

[18] K.J. Eskola, Nucl. Phys. **B 400** (1993) 240

[19] C.J. Benesh, J. Qiu, J.P. Vary, Phys. Rev. **C 50** (1994) 1015

[20] Z. Lin, M. Gyulassy, preprint hep-ph/9510041

Table 1: Initial temperatures T_i and gluon fugacities λ_i^g and estimated pion rapidity densities dN_π/dy for RHIC and LHC energies.

	RHIC		LHC	
	w/o shad.	with shad.	w/o shad.	with shad.
T_i [GeV]	0.571	0.544	1.095	1.038
λ_i^g	0.38	0.41	0.51	0.25
$\frac{dN_\pi}{dy}$	1175	1080	10291	5204

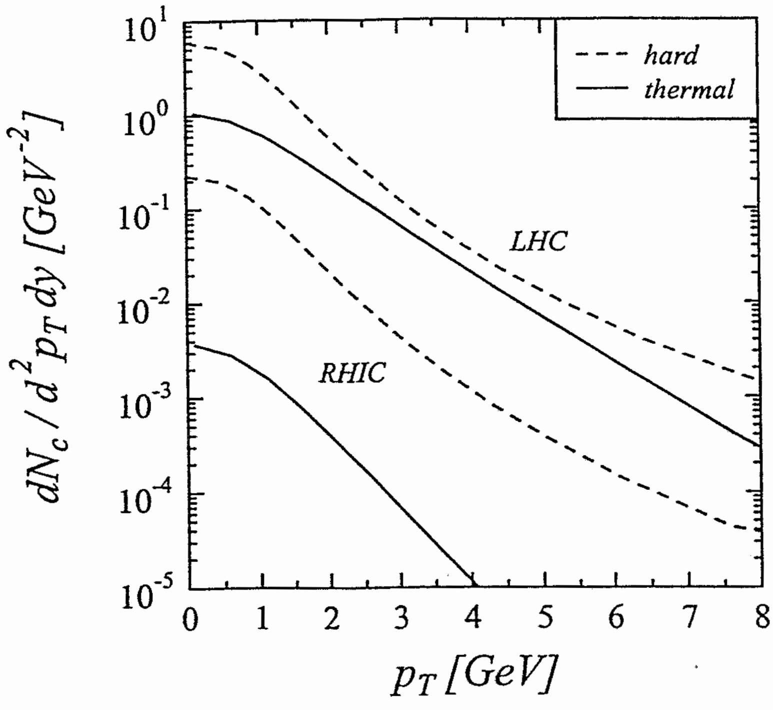

Fig. 1: Transverse momentum spectra of open charm for RHIC and LHC energies. Depicted are the hard initial and thermal yields.

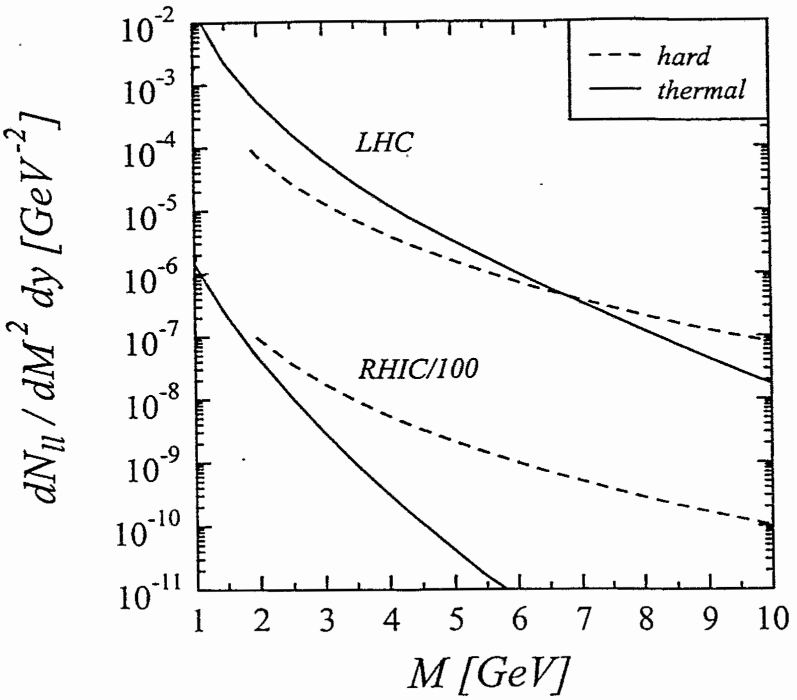

Fig. 2: Dilepton spectra for RHIC and LHC energies. Depicted are the Drell-Yan (hard) and thermal yields. The curves for RHIC are down-scaled by a factor 100. Note that the down-extrapolation of the Drell-Yan yield is not very reliable.

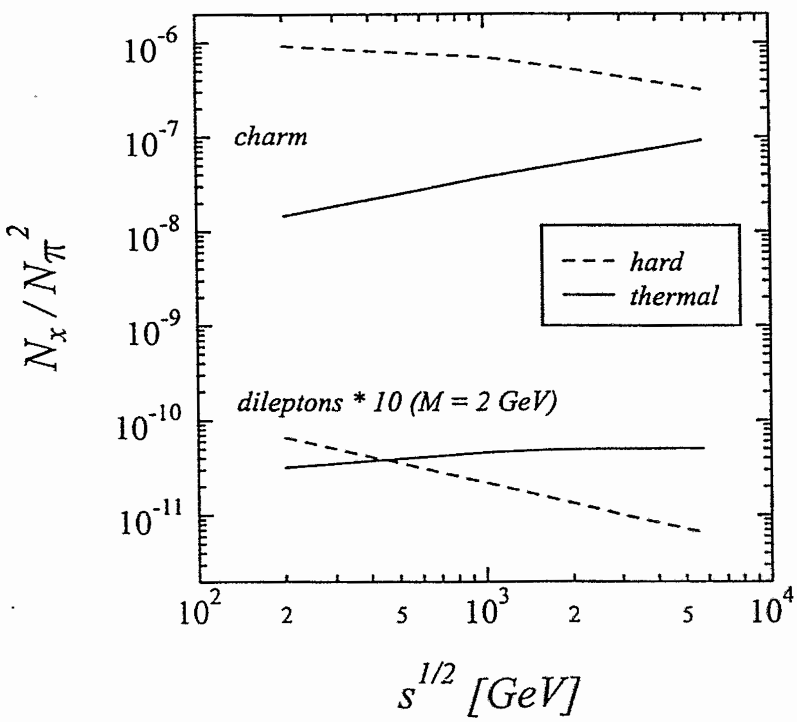

Fig. 3: Ratios of open charm $N_c/N_\pi^2 \equiv (dN_c/dy)/(dN_\pi/dy)^2$ (upper curves) and dileptons $N_{l\bar{l}}/N_\pi^2 \equiv (dN_{l\bar{l}}/dM^2\,dy)/(dN_\pi/dy)^2$ (lower curves, up-scaled by a factor 10, at $M =$ 2 GeV) to the squared pion rapidity densities.