Diagnostics of Quark-Gluon Plasma in Ultrarelativistic Nuclear Collisions

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Abstract

We analyze possibilities to study properties of dense QCD-matter, created in ultrarelativistic collisions of nuclei, with the different particle production processes. In recent years, a great deal of attention has been paid to the study of "hard" probes of quark-gluon plasma – heavy quarkonia, hard hadrons and jets, high mass dimuons – which do not appear as constituents of the thermalized system, but can carry information about the earliest stages of its evolution. We discuss the status of related experimental data obtained with heavy ion beams at CERN-SPS and the potential of future experiments at CERN-LHC.

1 Introduction

Experimental investigation of ultrarelativistic nuclear collisions offers a unique possibility of studying the properties of strongly interacting matter at the high energy density, when the hadronic matter is expected to become deconfined and a gas of asymptotically free quarks and gluons is formed. This is called quark-gluon plasma (QGP), in which the color interactions between partons are screened owing to collective effects (see, for example, reviews [1, 2, 3, 4]). A feature which distinguishes high energy collisions of heavy nuclei from the corresponding hadron-hadron interactions is the possibility of producing super-dense matter in volumes which are quasi-macroscopic on characteristic hadronic scales. This opens, in principle, a possibility, of using thermodynamics of strong interactions.

Significant progress attained recently in modelling of QCD systems on the lattice, in particular, inclusion of dynamical quarks, allows one to state with some certainty that the deconfinement of hadronic matter and chiral symmetry restoration must happen at sufficiently high temperatures $T_c \sim 200$ MeV and (or) baryon-chemical potential [5]. It is assumed that the conditions for realizing the quark-hadron phase transition which, according to current cosmological ideas, occurred during the first few microseconds of the evolution of the Universe, can be attained as a result of the generation of strongly excited matter in experiments at existing (AGS, SPS) and new (RHIC, LHC) heavy-ion accelerators.

Possible scenarios for production of the QGP in relativistic nucleus-nucleus collisions are still a subject of scientific discussion. In any case, when a significant fraction of the energy of the colliding nuclei is transformed into the energy of the constituents of a "thermalized" system, this energy should be sufficient for forming the QGP in a fairly large (compared to the typical hadronic scales) volume. This early, very dense state can have an energy density greater than $3 - 4$ GeV/fm^3. This creates conditions for the experimentally observed suppression of the J/Ψ's (charmonia) rate and strangeness enhancement, and begins driving the expansion of the fireball. After this, the "quark-gluon plasma" cools down and becomes more dilute, and at an energy density of 1 GeV/fm^3, quarks and gluons condense into hadrons, and the final abundances of different types of particles are fixed. At an energy density of around 50 MeV/fm^3, the hadrons stop interacting completely and the fireball freezes out. At this point, it is expanding at over half the speed of light.

At a special seminar on 10 February 2000, spokespersons from the seven experiments on CERN-SPS Heavy Ion programme (NA44, NA45, NA49, NA50, NA52, WA97/NA57, WA98) discussed compelling evidence for creation of a new state of matter, quark-gluon plasma, in central Pb-Pb and Pb-Au collisions at 158A GeV beam energy. In connection with this, professor Luciano Maiani, CERN Director General, said: "The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the Universe. We now have evidence of a new state of matter, where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical

properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider" [6].

2 Heavy quarkonium as a "colour dipole" in QCD-medium

In recent years, a great deal of attention has been devoted to the study of "hard" probes of QGP – heavy quarkonia, hard hadrons and jets, high mass dimuons – which, not forming a part of the thermalized system, carry information about the early stages of the system evolution. The predicted suppression of the Ψ-resonance yield in relativistic nucleus-nucleus collisions in the case of formation of a QGP was based on a simple and elegant idea that a bound state of $c\bar{c}$ pair (colour dipole) cannot exist if the colour screening length in the plasma r_D is smaller than the bound-state radius [7]. Another possible mechanism that governs the charmonia suppression is the dynamical dissociation of bound resonances by semi-hard deconfined gluons: if the average momentum of "thermal" gluon (which is expected to be much larger as compared to the average momentum of "confined" gluon at the same temperature) is of order of the J/Ψ binding energy, then it is sufficient for the breakup of a bound state [8].

An intriguing phenomenon has been observed in the most central Pb-Pb collisions in the NA50 experiment [9]: the "anomalously" small rate of Ψ-resonances, which is inconsistent with the conventional model of pre-resonance absorption in cold nuclear matter. Although the interpretation of this phenomenon as a result of formation of the QGP is quite plausible, some alternative explanations (like charmonia rescattering on comoving hadrons) cannot be still fully cancelled [10].

Fig. 1 summarises the experimental results on the "anomalous" J/Ψ suppression pattern measured in Pb-Pb collisions and "normal" suppression pattern as deduced from similar studies of experiment NA38 on collisions with lighter incident ions at the CERN-SPS [11]. Suppression is obtained from the measured cross-sections divided by the values expected from nuclear absorptions. As can be seen from the figure, in Pb-Pb interactions J/Ψ is suppressed "normally", i.e. according to pure nuclear suppression, for energy densities lower than 2.2 GeV/fm^3. The results strongly suggest that there is an onset of a new physical process for the highest density values, as it can be expected from charmonium melting due to deconfinement. The J/Ψ production rate exhibits a sudden departure form the nuclear absorption regime, the deviation form this regime being increased steadily with incr qfthep.tex easing energy density.

For heavier ($b\bar{b}$) systems, a similar suppression effect in super-dense strongly interacting matter is expected at higher temperatures than for $c\bar{c}$, which can be reached in central collisions of heavy ions at the RHIC at BNL and LHC at CERN colliders. Here the degrees of suppression of the Υ, Υ' and Υ'' quarkonia, which have different bound-state radii and binding energies, will differ.

3 Hard parton as a "colour charge" in QCD-medium

Along with the suppression of heavy quarkonia, one of the processes which may give information about the earliest stages of evolution of the dense matter formed in ultrarelativistic nuclear collisions is the passage of hard jets of colour-charged partons through the matter, pairs of which are created at the very beginning of the collision process (typically, at $\lesssim 0.01$ fm/c) as a result of individual initial hard nucleon-nucleon (parton-parton) scatterings. Such jets pass through the dense parton matter formed due to mini-jet production at larger time scales (~ 0.1 fm/c), and interact strongly with the comoving constituents in the medium, changing its original properties as a result of additional rescatterings. The inclusive cross section for hard jet production processes is still not sufficient for performing a systematic analysis at the SPS energies, but it increases fast with the energy of collided nuclei. Thus, this will play an important role in formation of the initial state at the energies of RHIC ($\sqrt{s} = 200$ GeV per nucleon pair) and LHC ($\sqrt{s} = 5.5$ TeV per nucleon pair for lead beams) colliders.

The fundamental problem arising here is behaviour of the colour charge (high-p_T parton) in the dense QCD-matter (like quark-gluon plasma) environment. Recently, possible mechanisms of the energy losses of a colour charge evolving through the QCD-matter has been studied by a number of groups: (1) radiative losses due to gluon "bremsstrahlung" induced by multiple scattering [12, 13, 14, 15, 16] and (2) collisional losses due to the final state interactions (elastic rescatterings) of high p_T partons off the medium constituents [17, 18, 19]. Since the jet rescattering intensity strongly increases with temperature,

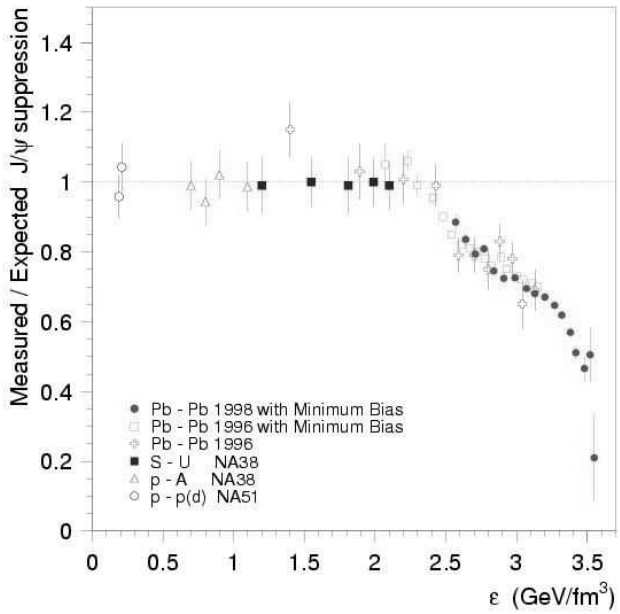

Figure 1: The J/Ψ suppression as a function of the energy density reached in the collision [11]. The cross-section expected from "normal" nuclear absorption are deduced form a fit to measurements on proton-nucleus interactions (open circles and triangles) and on S-U collisions (closed black squares).

formation of a super-dense and hot partonic matter in heavy ion collisions (with initial temperature up to $T_0 \sim 1$ GeV at LHC [20]) should result in significantly larger jet energy losses as compared with the case of "cold" nuclear matter or hadronic gas at $T \lesssim 0.2$ GeV.

Although the radiative energy losses of a high energy parton have been shown to dominate over the collisional losses by up to an order of magnitude [13], a direct experimental verification of this phenomenon remains an open problem. Indeed, with increasing energy of the hard parton the maximum of the angular distribution of bremsstrahlung gluons is shifted towards the parent parton direction. This means that measuring the jet energy as a sum of the energies of final hadrons moving inside an angular cone with a given finite size θ_0 will allow the bulk of the gluon radiation to belong to the jet, and thus the major fraction of the initial parton energy to be reconstructed. Therefore, the medium-induced radiation will, in the first place, soften particle energy distributions inside the jet, increase the multiplicity of secondary particles, but will not affect the total jet energy. It was recently shown [14] that radiation of energetic gluons in a QCD medium is essentially different from the Bethe-Heitler-independent radiation pattern. Such gluons have formation times exceeding the mean free path for QCD parton scattering in the medium. In these circumstances, the coherent effects play a crucial role leading to a strong suppression of the medium-induced gluon radiation. This coherent suppression is a QCD analogue of the Landau-Pomeranchuk-Migdal effect in QED. It is important to notice that the coherent LPM radiation induces a strong dependence of the jet energy on the jet cone size θ_0 [21, 22].

On the other hand, the collisional energy losses represent an incoherent sum over all rescatterings. It is almost independent of the initial parton energy. The angular distribution of the collisional energy loss is essentially different from that of the radiative one. The bulk of "thermal" particles knocked out of the dense matter by elastic scatterings fly away in almost transverse direction relative to the hard jet axis. As a result, the collisional energy loss turns out to be practically independent of θ_0 and emerges outside the narrow jet cone. Thus the relative contribution of collisional losses would likely become significant for jets with finite cone size propagating through the QGP [21].

In a search for experimental evidence in favour of the medium-induced energy losses, a significant dijet quenching (a suppression of high-p_T jet pair yield) [23] was proposed as possible signals of dense matter formation in ultrarelativistic collisions of nuclei. Other possible signatures that could directly measure the energy losses involve tagging the hard jet opposite a particle that does not interact strongly as a Z-boson [24] (mostly $q + g \to q + Z(\to \mu^+\mu^-)$, but also $q + \bar{q} \to q + Z$) or a photon [25] (mostly

$q+g \to q+\gamma$, also $q+\bar{q} \to q+\gamma$). The jet energy losses in dense matter should result in the non-symmetric shape in P_T of the difference of the Z-boson (γ) and jetdistributions.

4 Hard jet production at LHC

At least two experiments at CERN-LHC are interested in the heavy ion program. A Large Ion Collider Experiment (ALICE) [26, 27] is specially aimed to the heavy ion physics. Besides, the general purpose detector Compact Muon Solenoid (CMS) [28, 29], which is optimized mainly for the search of the Higgs boson in proton-proton collisions, will be able to perform the accurate measurement of the characteristics of high-energy muons, photons, electrons, and hadronic jets, making it useful also for studying hard probes of the QGP in heavy ion collisions [30].

Let us consider an example, which demonstrates the sensitivity of jet production pattern to the parton rescattering and energy losses in quark-gluon plasma: distribution of high-p_T jet pair over the impact parameter of nucleus-nucleus collision [31]. The intriguing prediction associated with the coherence pattern of the medium-induced radiation is that radiative energy losses per unit distance dE/dx depend on the total propagation distance L, asymptotically as $dE/dx \propto L$ [14]. Experimentally, the dependence of energy losses on the propagation distance can be studied in different bins of impact parameter b of nuclear collision: effective transverse size of dense zone $\langle L \rangle$ averaged over all possible jet production vertices is found [31] to go down almost linearly with increasing b.

The details of the geometrical model for jet production and jet propagation through a dense matter, created in nuclear overlapping zone, can be found in our recent work [31]. In general, the intensity of rescattering and energy losses are sensitive to the initial parameters (energy density ε_0, formation time τ_0) and space-time evolution of a medium. In order to analyze the impact parameter dependence of jet quenching, we treat the medium as a longitudinally expanding quark-gluon fluid, and partons as being produced on a hyper-surface of equal proper times $\tau = \sqrt{t^2 - z^2}$ [32]. The approach is based on the accumulative energy losses, when gluon radiation is associated with each scattering in expanding medium including the interference by the modified radiation spectrum as a function of decreasing temperature $dE/dx(T)$.

The total energy losses in transverse direction experienced by a hard parton are the result of averaging over the whole "nuclear geometry" (i.e. jet production vertices and azimuthal angles) at given b [31], the transfer momentum squared t in a single scattering and space-time evolution of the medium:

$$\langle \Delta E_T(b) \rangle = \left\langle \int_{\tau_0}^{\tau_L} d\tau \left(\frac{dE}{dx}^{rad}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right) \right\rangle_{"nuclear\ \ geometry"} . \qquad (1)$$

Here τ_0 and τ_L are the proper time of the plasma formation and the time of jet escaping from the dense zone respectively; $\rho_b \propto T^3$ is the density of plasma constituents of type b at temperature T; σ_{ab} is the integral cross section of scattering of the jet parton a off the comoving constituent b (with the same longitudinal rapidity y); ν and dE/dx^{rad} are the thermal-averaged collisional energy loss of a jet parton due to single elastic scattering and radiative energy losses per unit distance respectively. The formulas for collisional and radiative losses can be found in [31] (see also references therein). Let us just mark the following essential difference between collisional and radiative losses behaviour.

The collisional loss per scattering ν is independent of total distance traversed and determined by temperature, roughly $\nu \propto T$. Then total collisional energy losses integrated over the whole jet path are estimated as $\langle \Delta E_{col} \rangle \propto T_0^2 \propto \sqrt{\varepsilon_0}$. The τ_L-dependence of ΔE_{col} can be weaker than linear for expanding medium ($\Delta E_{col} \propto \tau_L$ for static matter). On the other hand, for medium-induced coherent gluon radiation in the limit of "strong" LPM effect, $\omega \gg \mu_D^2 \lambda_g$ (ω, μ_D and λ_g are the energy of radiated gluon, Debye screening mass and gluon mean free path in the medium respectively), we have [14, 22] $dE/dx^{rad} \propto T^3$ and $dE/dx^{rad} \propto \tau_L$ with logarithmic accuracy. Then total radiative energy losses $\langle \Delta E_{rad} \rangle = \int d\tau \cdot dE/dx^{rad}$ are estimated as $\langle \Delta E_{rad} \rangle \propto T_0^3 \propto \varepsilon_0^{3/4}$ and $\Delta E_{rad} \propto \tau_L^{\beta}$, where $\beta \lesssim 2$ for expanding medium.

In our calculations we used the well-known scaling Bjorken's solution [32] for temperature and density of QGP at $T > T_c$: $\varepsilon(\tau)\tau^{4/3} = \varepsilon_0 \tau_0^{4/3}$, $T(\tau)\tau^{1/3} = T_0 \tau_0^{1/3}$, $\rho(\tau)\tau = \rho_0 \tau_0$. Concretely, we used the initial conditions for the gluon-dominated plasma formation ($N_f \approx 0$, $\rho_q \approx 1.95 T^3$) expected for central

$Pb-Pb$ collisions at LHC [20]: $\tau_0 \simeq 0.1$ fm/c, $T_0 \simeq 1$ GeV. It is interesting that the initial energy density ε_0 in dense zone depends on b very slightly ($\delta\varepsilon_0 \lesssim 10\%$) up to $b \sim R_A$ [31]. Therefore the variation of impact parameter b of nucleus-nucleus collision (which can be measured using the total transverse energy deposition detected in calorimeters) up to $b \sim R_A$ gives the possibility to study jet quenching as a function of distance traversed without significant changing the initial energy density ε_0.

The observed rate of $\{ij\}$ type dijets with transverse momenta p_{T1}, p_{T2} produced in initial hard processes in AA collisions at given impact parameter b is obtained by averaging over "nuclear geometry":

$$\frac{dN_{ij}^{dijet}}{dp_{T1}dp_{T2}d^2b} = \frac{1}{\sigma_{jet}^0}\frac{d^2\sigma_{jet}^0}{d^2b} \cdot \left\langle \int dp_T^2 \frac{d\sigma_{ij}}{dp_T^2}\, \delta(p_{T1} - p_T + \Delta E_T^i(b))\, \delta(p_{T2} - p_T + \Delta E_T^j(b)) \right\rangle_{"n.g."}, \quad (2)$$

where $d\sigma_{ij}/dp_T^2$ is the parton differential pQCD cross section. The integrated above some threshold p_T^{cut} dijet rate in AA relative to pp collisions can be studied at LHC with a reference process, unaffected by energy losses and with a production cross section proportional to the number of nucleon-nucleon collisions, such as $Z(\to \mu^+\mu^-)$ production [24]. The cross section $d^2\sigma_{jet}^0/d^2b$ for initially produced jets in AA collisions at given b can be written as [30]:

$$\frac{d^2\sigma_{jet}^0}{d^2b}(\mathbf{b}, \sqrt{s}) = T_{AA}(\mathbf{b})\sigma_{NN}^{jet}(\sqrt{s}) \left[1 - \left(1 - \frac{1}{A^2}T_{AA}(\mathbf{b})\sigma_{NN}^{in}(\sqrt{s})\right)^{A^2}\right] \quad (3)$$

where $T_{AA}(b)$ is the standard nuclear overlap function; NN collision cross section of hard process σ_{NN}^{jet} is computed with PYTHIA5_7 model [33]; inelastic non-diffractive NN cross section is $\sigma_{NN}^{in} \simeq 60$ mb.

Figure 2 shows dijet rates $\sigma_{AA}^{in} R_{AA}^{dijet} L$ ($E_T^{jet} > p_T^{cut} = 100$ GeV, CMS rapidity acceptance $|y^{jet}| < 2.5$) in different impact parameter bins for three cases: (*i*) without energy losses, (*ii*) with collisional losses only, (*iii*) with collisional and radiative losses. The rates are normalized to the expected number of events produced in Pb-Pb collisions during two weeks (1.2×10^6 s) of LHC run time, assuming luminosity $L = 10^{27}\, cm^{-2}s^{-1}$ [28]. The total initial dijet rate with $E_T^{jet} > 100$ GeV is estimated as 1.1×10^7 events ($gg \to gg \simeq 60\%$, $qg \to qg \simeq 30\%$, $qq, gg \to qq \simeq 10\%$). Since the dijet quenching is much stronger in central collisions than in peripheral ones, the maximum and mean values of dN^{dijet}/db distribution are shifted towards the larger b. The corresponding result for jets with non-zero cone size θ_0 is expected to be somewhere between (*iii*) ($\theta_0 \to 0$) and (*ii*) cases. The observation of a dramatic change in the b-dependence of dijet rates in heavy ion collisions as compared to what is expected from independent nucleon-nucleon interactions pattern would indicate the existence of medium-induced parton rescattering.

5 High mass dimuon production at LHC

Let us consider another process of interest: high invariant mass ($M_{\mu^+\mu^-} \gtrsim 20$ GeV/c^2) dimuon production. One of the main dimuon sources in this "resonances-free" mass region is the semileptonic open bottom meson decay, which is expected to be sensitive to the rescattering and energy losses of massive b quarks propagating through the dense medium [34]. The main correlated background here is the Drell-Yan muon pair production, which can be rejected using the tracker information on secondary vertex position. Since the uncorrelated part of dimuon background (random decays of pions and kaons, muon pairs of mixed origin) appears also in the like-sign dimuon mass spectra, it can be estimated from the $\mu^+\mu^+$ and $\mu^-\mu^-$ event samples and subtracted from the total $\mu^+\mu^-$ distribution.

Correct description of coherent radiation experienced by a massive quark is still not performed up to now. On the one hand, the medium-induced radiation of slow quarks, $p_T \lesssim M_q$, should be suppressed by their mass. On the other hand, the ultrarelativistic limit, $p_T \gg M_q$, corresponds to the radiation spectrum of massless quark. In our case, the main contribution in the mass region $M_{\mu^+\mu^-} = 20 \div 50$ GeV/c^2 is due to b-quarks with "intermediate" values of $p_T \gtrsim 5 \div 10$ GeV/c. In order to estimate the sensitivity of dimuon spectra to the medium-induced effects, we consider two extremal cases: (i) lower limit of medium effect with only collisional energy losses; (ii) upper limit of medium effect with collisional and radiative energy losses in the Bethe-Heitler limit of independent emissions, not taking into account the LPM coherent suppression of radiation (i.e. $dE/dx \propto E$ and does not depend on L here). We performed the Monte-Carlo simulation of the mean free path of b-quarks of mass $M_b = 5$ GeV/c^2 in QGP, formed

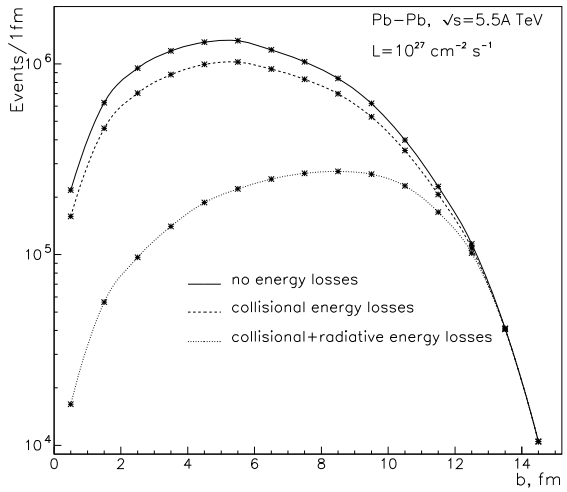

Figure 2: The distribution of dijets with $E_T > 100$ GeV over impact parameter: without energy losses (solid curve), with collisional losses (dashed curve), with collisional and radiative losses (dotted curve).

in nuclear overlapping zone (see the model described in the previous chapter). The nuclear shadowing effect (which is of order of 15% in the kinematic region of interest, i.e. $\sigma^{b\bar{b}}_{Pb-Pb} \approx 0.85 \cdot (207)^2 \sigma^{b\bar{b}}_{pp}$) and transverse momentum kicks obtained by b-quark per rescattering have been taken into account.

Figure 3 presents the $\mu^+\mu^-$ invariant mass spectra from b-decays for cases without and with energy losses of b-quarks at CMS acceptance: $p^{\mu}_T > 5$ GeV/c, $|\eta^{\mu}| < 2.4$. The rates are normalized again to the expected number of events produced in Pb-Pb collisions during two weeks of LHC run time. The total initial rate of dimuons at $M_{\mu^+\mu^-} = 20 \div 50$ GeV/c^2 is estimated with PYTHIA5_7 and CTEQ2L parton distribution function as 2.8×10^4, and it can be reduced by factor $\sim 1.6 \div 4$ due to rescattering and energy losses of b-quarks in QGP. The absolute rates here, of course, depend on the PDF choice, B-meson fragmentation scheme, next-to-leading order corrections, etc. Thus, the high mass dimuon spectra measurements with proton or deuterium beams with the same energy per nucleon are requested.

6 Conclusions

The recent data obtained at CERN-SPS with heavy ion beams give an indication on some of new physics and cannot be explained using "conventional" hadronic interaction scenarios. Many of the observations (charmonium suppression, strangeness enhancement) are consistent with the predicted signatures of a quark-gluon plasma. However, we do not yet know the properties of the deconfined state which has been reached, even though it looks like the expected quark gluon plasma. The coming heavy ion experiments at RHIC at Brookhaven and LHC at CERN will certainly shed light on the properties of relatively long-living state of "hot" quark-gluon matter. In connection with this, the subject of particular interest in nuclear collisions is the hard QCD-production processes, so-called "hard" probes: "colour dipoles" – heavy quarkonia (Ψ, Υ) and "colour charges" – high-p_T partons (jets). Since such objects are created at the very beginning of the nuclear collision process, they propagate through the dense matter formed at larger time scales, and interact strongly with constituents in the medium. This results in the change of the original properties of observable spectra of quarkonia, jets and high-mass dimuons.

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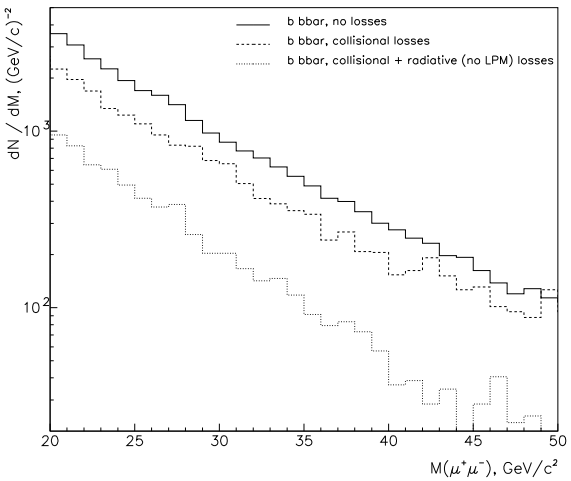

Figure 3: Invariant mass distribution of $\mu^+\mu^-$ pairs, $p_T^\mu > 5$ GeV/c: no energy losses (solid histogram), with collisional losses (dashed histogram), with collisional and radiative losses (dotted histogram).

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