PRL **94,** 112301 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Open Charm and Beauty at Ultrarelativistic Heavy Ion Colliders

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(Received 19 November 2004; published 22 March 2005)

Important goals of BNL RHIC and CERN LHC experiments with ion beams include the creation and study of new forms of matter, such as the quark gluon plasma. Heavy quark production and attenuation provide unique tomographic probes of that matter. We predict the suppression pattern of open charm and beauty in Au + Au collisions at RHIC and LHC energies based on the DGLV formalism of radiative energy loss. A cancellation between effects due to the $\sqrt{s}$ energy dependence of the high p_T slope and heavy quark energy loss is predicted to lead to surprising similarity of heavy quark suppression at RHIC and LHC.

DOI: 10.1103/PhysRevLett.94.112301 PACS numbers: 12.38.Mh, 24.85.+p, 25.75.–q

Introduction.—BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) experiments involving nuclear collisions are designed to create and explore new forms of matter, consisting of interacting quarks, antiquarks, and gluons. One primordial form of matter, called the quark gluon plasma (QGP), is believed to have existed only up to a microsecond after the "big bang." If this QGP phase can be created in the laboratory, then a wide variety of probes and observables could be used to diagnose and map out its physical properties.

The striking discoveries [1] at RHIC of strong collective elliptic flow and light quark and gluon jet quenching, together with the decisive null control d + Au data, provide strong evidence that a strongly coupled quark gluon plasma (SQGP) is created in central Au + Au collisions at $\sqrt{200}A$ GeV with gluon densities 10–100 times greater than nuclear matter densities [2]. While there has been considerable convergence on the theoretical interpretation [3] of RHIC data, the experimental exploration of the SQGP properties beyond the discovery phase has barely begun [4]. Future measurements of rare probes such as direct photons, leptons, and heavy quarks will help to more fully map out the SQGP properties and dynamics.

Heavy quarks provide important independent observables that can probe the opacity and color field fluctuations in the SQGP produced in high energy nuclear collisions. In this Letter, we present predictions of open charm and beauty quark suppression that can be tested at both RHIC and the future LHC facilities. Together with the already established light quark and gluon jet quenching and collective elliptic flow, a future observation of a reduced heavy quark suppression (as compared to the observed pion suppression) could strengthen the current case for SQGP formation as well as test the evolving theory of jet tomography [5].

The prediction of the D and B meson suppression pattern, in principle, requires theoretical control over the interplay between many competing nuclear effects [6] that can modify the $p_\perp$ hadron spectra of heavy quarks. To study the high $p_\perp$ ($p_\perp > 6$ GeV) heavy quark suppression, we concentrate on the interplay between the two most important effects, i.e., jet quenching [5,6] and energy dependence of initial perturbative QCD (PQCD) heavy quark $p_\perp$ distribution. In addition, we explore a range of initial conditions at LHC based on extrapolating RHIC data [7] and based on color glass condensate (CGC) effective theory [8]. We note that, for lower $p_\perp < 6$ GeV spectra nonperturbative effects neglected here, for example, collective hydrodynamic flow, quark coalescence and the strong gluon shadowing in the initial CGC state, may become important [3].

Theoretical framework.—To compute the heavy quark meson suppression we apply the Djordjevic-Gyulassy-Levai-Vitev (DGLV) generalization [9] of the GLV opacity expansion [10] to heavy quarks. We take into account multigluon fluctuations as in [11]. To apply this method, we need to know the following: (1) the initial heavy quark $p_\perp$ distribution, (2) the difference between medium and vacuum gluon radiation spectrum, and (3) the heavy quark fragmentation functions.

The initial heavy quark $p_\perp$ distributions are computed in central rapidity region ($|y| < 0.5$) by using the Mangano-Nason-Ridolfi (MNR) code [12]. As in [13], we assume the charm mass to be $M_c = 1.2$ GeV and the beauty mass $M_b = 4.75$ GeV. We assume the same factorization and renormalization scales as in [13]. For simplicity, we have concentrated only on bare quark distributions ($\langle k_\perp^2 \rangle = 0\ \text{GeV}^2$), and the runs were performed by using CTEQ5M parton distributions.

Figure 1 shows initial $p_\perp$ distributions for D and B mesons. By comparing $p_\perp$ distributions at RHIC and LHC case we see that RHIC distributions have significantly larger slope than the LHC ones. Since the suppression is sensitive to the slope of quark initial $p_\perp$ distribution, the decrease in the $p_\perp$ slope with the increase of collision energy will have the tendency to lower the suppression from RHIC to LHC.

Additionally, comparison between full and dashed curves in Fig. 1 shows the variation of D and B meson $p_\perp$ distributions using two different types of fragmentation function. Full curves show the meson spectrum obtained by

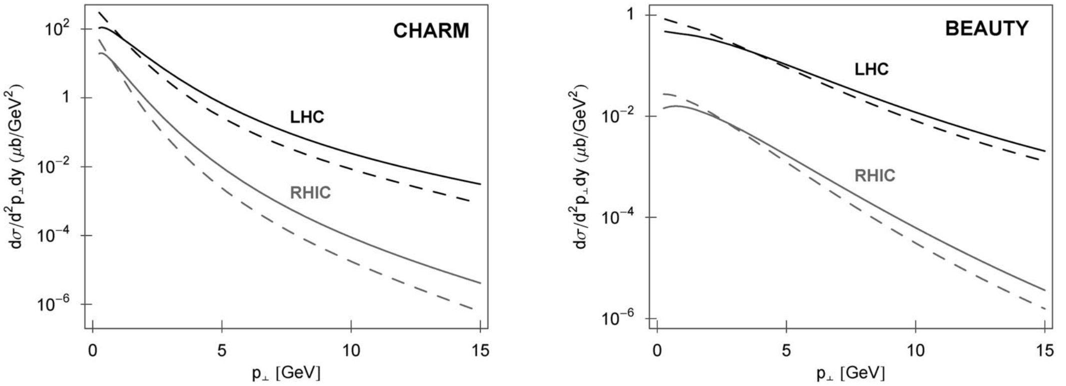

FIG. 1. Initial $p_\perp$ distributions are shown for D (left) and B mesons (right). Lower (upper) curves correspond to the RHIC (LHC) case. Solid curves are computed by assuming δ-function fragmentation, while dashed curves assume Peterson fragmentation [14]. For D (B) mesons we used $\epsilon = 0.06$ ($\epsilon = 0.006$) [13].

using δ-function fragmentation, while dashed curves show the meson spectrum obtained using the Peterson fragmentation [14]. Though the choice of fragmentation function can lead to the order of magnitude difference in the absolute $p_\perp$, we see that slopes of the curves remain quite similar. Therefore, we expect that the final suppression is insensitive to the choice of fragmentation functions. This conclusion is confirmed in Fig. 4 below, and a difference of less than 0.05 in the nuclear modification factor R_{AA} is found. (R_{AA} is the ratio of the observed yield in $A + A$ divided by the binary collision scaled yield in $p + p$.) Therefore, for clarity, we show the most results for only the δ-function fragmentation for both charm and beauty quarks.

To compute the gluon radiation spectrum, we have to include (in general) three medium effects that control heavy quark energy loss. These effects are (1) the Ter-Mikayelian, or massive gluon effect [15,16], (2) transition radiation [17] which comes from the fact that medium has finite size, and (3) medium induced energy loss [9,16], which corresponds to the additional gluon radiation induced by the interaction of the jet with the medium.

In [18] we will show that the first two effects are not important for heavy quark suppression, since their contribution is less than 10% of the final result. Therefore, in this Letter, we address only the medium induced gluon radiation spectrum which is given by [9]

$$\frac{dN^{(1)}_{\rm ind}}{dx} = \frac{C_F\alpha_S}{\pi}\frac{L}{\lambda_g}\int_0^\infty \frac{2\mathbf{q}^2\mu^2 d\mathbf{q}^2}{(\frac{4Ex}{L})^2 + (\mathbf{q}^2 + M^2x^2 + m_g^2)^2} \times \int \frac{d\mathbf{k}^2\theta[2x(1-x)p_\perp - |\mathbf{k}|]}{[(|\mathbf{k}| - |\mathbf{q}|)^2 + \mu^2]^{3/2}[(|\mathbf{k}| + |\mathbf{q}|)^2 + \mu^2]^{3/2}} \times \left\{\mu^2 + (\mathbf{k}^2 - \mathbf{q}^2)\frac{\mathbf{k}^2 - M^2x^2 - m_g^2}{\mathbf{k}^2 + M^2x^2 + m_g^2}\right\}. \tag{1}$$

Here, $\mathbf{k}$ is the transverse momentum of the radiated gluon and $\mathbf{q}$ is the momentum transfer to the jet. M is the heavy quark mass, $\mu = 2(\rho/2)^{1/3}$ is the Debye mass, $\lambda_g = \frac{8}{9}\frac{\mu^2}{4\pi\alpha_S^2\rho}$ is the mean free path [10], $m_g = \mu/\sqrt{2}$ is the gluon mass, and $E = \sqrt{p_\perp^2 + M^2}$ is the initial heavy quark energy. We assume constant $\alpha_S = 0.3$. For central collisions we take $L = R_x = R_y = 6$ fm, and assume that ρ is given by [(1 + 1)D Bjorken longitudinal expansion [19]] $\rho = dN_g/dy\tau\pi L^2$, where $\frac{dN_g}{dy}$ is the gluon rapidity density, and τ is the proper time.

The energy loss was computed using both (1 + 1)D Bjorken longitudinal expansion and an effective *average* ρ approximation, where we replace τ by $\langle\tau\rangle = \frac{L}{2}$. Since both procedures produce similar results, in this Letter we present only the computationally simpler (average ρ) results.

We note that in Eq. (1) $k_{\rm max} = 2x(1-x)p_\perp$ instead of $k_{\rm max} = xE$ used in [9]. Numerically, there is a 20% theoretical uncertainty in R_{AA} due to the different reasonable choices of kinematical bounds.

Heavy quark suppression at RHIC and LHC.—In this section we compare suppression at RHIC and LHC as a

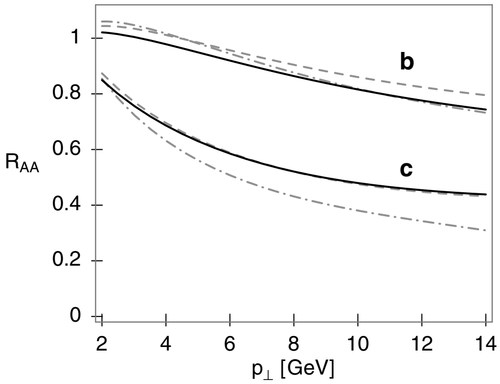

FIG. 2. The suppression ratio R_{AA} as a function of $p_\perp$ is shown for charm (lower curves) and beauty quarks (upper curves). Full curves correspond to the RHIC case ($\sqrt{s} = 200NN$ GeV), while dashed and dot-dashed curves correspond to the LHC case ($\sqrt{s} = 5.5NN$ TeV). Dashed (dot-dashed) curves correspond to PHOBOS [7] (CGC [8]) extrapolation in gluon rapidity density.

function of momentum, collision energy, and gluon rapidity density dependence. In Fig. 2 we show $R_{AA}(p_\perp)$ for both charm and beauty quarks corresponding to D and B mesons in δ fragmentation. For estimates of LHC initial conditions, we consider two cases: the PHOBOS extrapolation [7] (where gluon density is projected to be approximately 60% higher than at RHIC), and the CGC prediction [8] (where the initial gluon density is predicted to be $\sim$3 times higher than at RHIC). For the charm quark we see that there is a surprising similarity of $R_{AA}(p_\perp)$ between the RHIC and the LHC cases, if the PHOBOS extrapolation in gluon density is assumed. The similarity in suppression between these results comes from the fact that, at LHC, the enhancement in energy loss (due to the larger gluon density) is mostly compensated for by the decrease of the heavy quark distribution slopes. A slightly greater suppression is obtained with a CGC estimate of the initial gluon density, which leads to larger energy loss.

By comparing the charm and beauty suppressions on Fig. 2, we see that significantly less suppression is expected for beauty than for charm quarks. This is because of the following two reasons: (1) from Fig. 1 we see that beauty p_T distributions have significantly smaller slopes than the charm ones, and (2) because of the dead cone effect [20], the beauty energy loss is much smaller than the charm energy loss, as shown in Figs. 1 and 5 in [9]. This explains in large part why no significant suppression was observed for $p_\perp > 2$ GeV single electrons at RHIC [21]. In this kinematic range there is a significant beauty contribution to the single electron yields, and that component is essentially unquenched. Cronin and possibly collective flow effects in this low $p_\perp < 6$ GeV region also may play a role.

According to Fig. 2, we expect similar results for single electron suppression at both RHIC and LHC; i.e., we predict no significant suppression of single electrons at moderate p_T at LHC as well.

Our next goal is to study how the suppression is changing as a function of collision energy. For that purpose we fix the $p_\perp$ of the quark jet to 10 GeV and look at $R_{AA}(\sqrt{s})$ as shown in Fig. 3. We see that, if gluon density extrapolates according to PHOBOS, then the RHIC $\approx$ LHC conclusion from Fig. 2 is not a coincidence. It rather seems that, in this case, the high $p_\perp$ charm quark suppression is essentially independent of the collision energy. In addition, the slight beauty suppression decreases as the collision energy increases. Therefore, we see that in the PHOBOS extrapolation case, the 60% increase of the gluon density (and equivalently the increase in the energy loss) is not enough to compensate for the decrease in the $p_\perp$ slope.

A slightly different situation occurs in the case of CGC extrapolation in gluon density. In this case, at LHC, we can expect a 20% higher suppression for charm quarks and a constant suppression for beauty quarks.

Therefore, the main conclusion following from Figs. 2 and 3 is that no significant difference between the RHIC and LHC heavy quark suppression is expected. This result is surprising. To emphasize this point, we show in Fig. 3 dot-dashed curves showing a hypothetical case in which we assume that only energy loss changes with collision energy, while heavy quark initial $p_\perp$ distribution remains unchanged and fixed to the 200 GeV case. From these curves we see that, at LHC, the energy loss leads to an additional 0.1 decrease in R_{AA} for both the PHOBOS and the CGC cases.

If we compare the suppression for the PHOBOS and the CGC cases on Fig. 3, we see that at 5.5 TeV (LHC) the difference of 1000 in gluon rapidity density leads to only a ≈ 0.1 difference in R_{AA}. Since the $\frac{dN_g}{dy}$ is still unknown at LHC, in Fig. 4 we show $R_{AA}(\frac{dN_g}{dy})$ for 10 GeV D and B

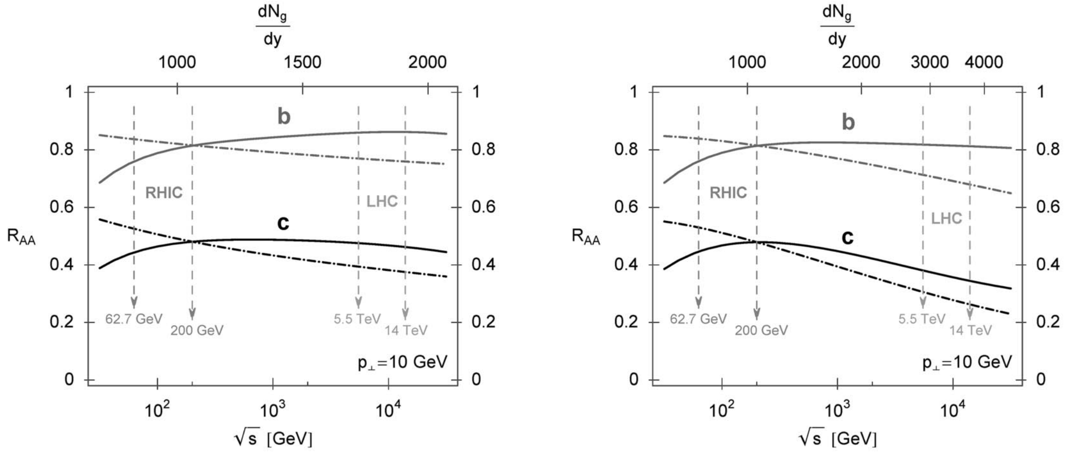

FIG. 3. The suppression ratio R_{AA} as a function of $\sqrt{s}$ is shown for 10 GeV charm (lower curves) and beauty quarks (upper curves). Left (right) panel corresponds to the PHOBOS (CGC) extrapolation in gluon rapidity density. The upper x axis shows the gluon rapidity density that corresponds to $\sqrt{s}$ for both PHOBOS and CGC scenarios. Full curves represent the case where both energy loss and initial quark $p_\perp$ distribution change with $\sqrt{s}$. Dot-dashed curves correspond to the case where only energy loss is changing with $\sqrt{s}$, while initial quark $p_\perp$ distribution is fixed at 200 GeV.

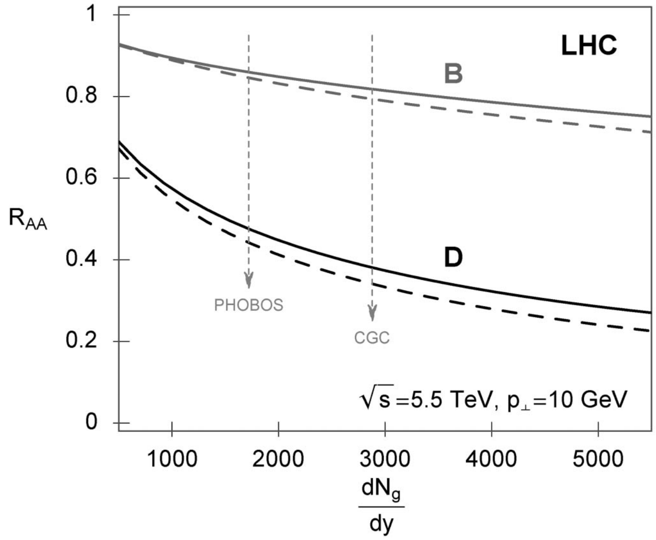

FIG. 4. The suppression ratio R_{AA} as a function of gluon density is shown for D (lower curves) and B (upper curves) mesons. Solid curves are computed by assuming δ-function fragmentation, while dashed curves assume Peterson fragmentation [14]. For D (B) mesons we used $\epsilon = 0.06$ ($\epsilon = 0.006$) [13].

mesons. We see that both D and B meson suppression falls slowly with the increase of the initial gluon rapidity density.

Conclusions.—In this Letter we predicted the nuclear modification factor $R_{AA}(p_T, M_Q, \sqrt{s}, \frac{dN_g}{dy})$ for charm and beauty quark production in central Au + Au reactions with $\sqrt{s} = (200\text{–}5500)A$ GeV. We predict a rather weak $\sqrt{s}$ dependence in this range due to the compensation of the increasing energy loss in the more opaque SQGP and the kinematic reduction of the p_T slope. Of course, it is still straightforward to deconvolute these competing effects to determine the growth of the initial density with $\sqrt{s}$ and therefore differentiate between different predictions, such as CGC, of those initial conditions.

By comparing our heavy quark predictions to the suppression patterns for the neutral pions in Ref. [6] (light quark and gluon case), we expect a striking difference in the suppression pattern between light and heavy mesons. This is because the much more strongly quenched gluon jet component of light hadrons does not play a role in D and B production. The light hadron quenching pattern is therefore expected to have a stronger collision energy dependence [6].

We expect a moderate D meson suppression $R_{AA} \approx 0.5 \pm 0.1$ for the $\frac{dN_g}{dy} \approx 1000 \pm 200$ inferred from π^0. A similar suppression is expected at LHC for 1.5–3 times larger $\frac{dN_g}{dy}$. Our high $p_\perp > 6$ GeV predictions are robust within our approach, and significant experimental deviations would pose a serious challenge to the PQCD based theory of radiative energy loss in SQGP matter. Future D meson data on 200 GeV d + Au and Au + Au and eventually at LHC will thus enable critical consistency tests of the theory and the tomographic inferences drawn from the observed jet quenching patterns.

The authors thank R. Vogt for her help with the MNR code and for valuable discussions about the heavy quark production. This work is supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Grant No. DE-FG02-93ER40764.

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