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Charmonium production versus open charm in nuclear collisions

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Charmonium suppression in high-energy nuclear collisions is often measured with respect to the Drell-Yan continuum. We show that this leads to some difficulties when comparing data at very different incident energies, and note that in this case the use of open charm cross production provides a more reliable complementary reference.

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The suppression of quarkonium production has been proposed as a possible signal for color deconfinement in high-energy nuclear collisions [1]. It was suggested to measure this suppression relative to the Drell-Yan continuum in the dilepton spectrum from such collisions. This reference distribution seemed appropriate, since the overall Drell-Yan spectrum from minimum bias A-A collisions, once normalized to A^2, was expected to be equal to the isospin-corrected result measured in p-p collisions. The integrated Drell-Yan cross section is dominated by the α^2 quark-antiquark annihilation, with a multiplicative K factor to account for higher-order corrections. The virtual photon from q-$\bar{q}$ annihilation passes undisturbed through the strongly interacting medium produced in nuclear collisions, and hence the Drell-Yan rates should remain unaffected by the presence of any medium.

By going to higher-incident nuclear beam energies, we increase the initial energy density ϵ of the systems produced in these collisions. One way to compare the suppression at high ϵ with that at lower values is to consider data at different $\sqrt{s}$. For the ratio of quarkonium to Drell-Yan production, this makes sense only if the two rates have in p-p collisions the same dependence on incident energy, and that is, in general, not the case. The integrated rates for quarkonium production are dominated by gluon fusion, those for Drell-Yan pairs by quark-antiquark annihilation. The former are determined by gluon structure functions $g(x)$, the latter by those for quarks and antiquarks $q(x)$ and $\bar{q}(x)$; here $x \sim M/\sqrt{s}$ is the Bjorken scaling variable. Going to larger $\sqrt{s}$ thus results in smaller x, and the small-x behavior of $g(x)$, $q(x)$, and $\bar{q}(x)$ is not the same in the region of interest [2].

A second problem arises because it is known today that parton structure functions become modified in nuclei. In particular, there is shadowing at small x, and such initial-state nuclear effects have to be taken into account before discussing final-state effects in quarkonium production on nuclear targets [3]. In A-B collisions, the presently accessible range in Bjorken x is quite small, and in this range (around $x \simeq 0.1$), nuclear shadowing effects on Drell-Yan rates are negligible, providing an *a posteriori* justification for using these rates today as reference in determining suppression. The gluon-fusion dominated quarkonium production rates in p-A experiments do, however, indicate significant shadowing effects for the gluon structure functions [4]. As the incident c.m. system (c.m.s.) energy is increased significantly, both quarkonium and integrated Drell-Yan production move to much smaller x, where the relative shadowing will most likely be quite different.

These two phenomena, the functional form of the small x behavior and the difference in shadowing of quark and/or antiquark and gluon structure functions, imply that some care must be taken when studying quarkonium suppression relative to Drell-Yan production. The use of the Drell-Yan spectrum as reference is still directly possible when studying E_T variations in A-A collisions at fixed $\sqrt{s}$, and then it probably remains the best method. If, however, we want to compare data at different $\sqrt{s}$ and different A (including a comparison to p-p data), then we have to know the small-x behavior and the shadowing patterns of quarks and gluons.

It would therefore be very useful to have an alternative reference to the Drell-Yan continuum, one which is less dependent on the different behavior of quark and gluon structure functions. The aim of this Brief Report is to show that integrated open charm or beauty rates, if measurable, could play this role. The use of open quark production rates as a benchmark for quarkonium suppression has been discussed at a qualitative level earlier [5]; we will, in the following, develop this more quantitatively.

Let us first illustrate the structure function dependence of the different processes in a qualitative way; here and in the following we consider J/ψ production as an example. The cross section for inclusive J/ψ production is given by (see Fig. 1 for the relevant diagram in lowest order of α_s)

$$\left(\frac{d\sigma_{J/\psi}}{dM^2dy}\right)_{y=0} = c_{J/\psi}\left(\frac{\alpha_s^2}{M^4}\right)\left(\frac{M}{\sqrt{s}}\right) \times[g(M/\sqrt{s})]^2F(M/M_{J/\psi}) \;, \qquad (1)$$

where $F(M/M_{J/\psi})$ is a function fixing the J/ψ mass $M_{J/\psi}$ [such as $\delta(1-M^2/M_{J/\psi}^2)$], $c_{J/\psi}$ a numerical con-

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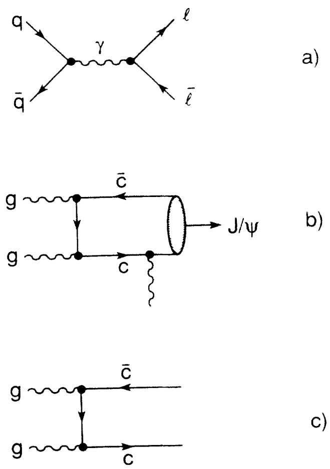

FIG. 1. Lowest-order diagrams for (a) Drell-Yan, (b) J/ψ, and (c) open charm production.

stant, and $g(x)$ the gluon structure function at $x = M/\sqrt{s}$. For the production of a Drell-Yan pair of mass M we have a very similar form:

$$\left(\frac{d\sigma_{\rm DY}}{dM^2dy}\right)_{y=0} = c_{\rm DY}\left(\frac{\alpha_s\alpha}{M^4}\right)\left(\frac{M}{\sqrt{s}}\right) \times[q(M/\sqrt{s})\bar{q}(M/\sqrt{s})] \;, \qquad (2)$$

but now containing the quark and antiquark structure functions $q(x)$ and $\bar{q}(x)$ in place of the gluon functions $g(x)$ in the charmonium case. Equations (1) and (2) apply to low transverse momenta, since the corresponding diagrams (both 2 → 1 processes) contain no (hard) P_T dependence. For the production of open charm, the lowest-order diagram is also shown in Fig. 1. It is a 2 → 2 process and hence contains an additional integral. At $P_T = 0$, this integral runs effectively over the angular orientation θ of the $D\overline{D}$ production line relaive to the collision axis. To simplify the comparison with charmonium and Drell-Yan production, we fix this angle by assuming the D and $\overline{D}$ to be emitted in a plane orthogonal to the collision axis. The cross section then becomes [6,7]

$$\left(\frac{d\sigma_{c\bar{c}}}{dM^2dyd\theta}\right)_{y=0,\theta=\pi/2} = c_{c\bar{c}}\left(\frac{\alpha_s^2}{M^4}\right)\left(\frac{M}{\sqrt{s}}\right) \times[g(M/\sqrt{s})]^2 \;, \qquad (3)$$

where M now denotes the $D\overline{D}$ invariant mass.

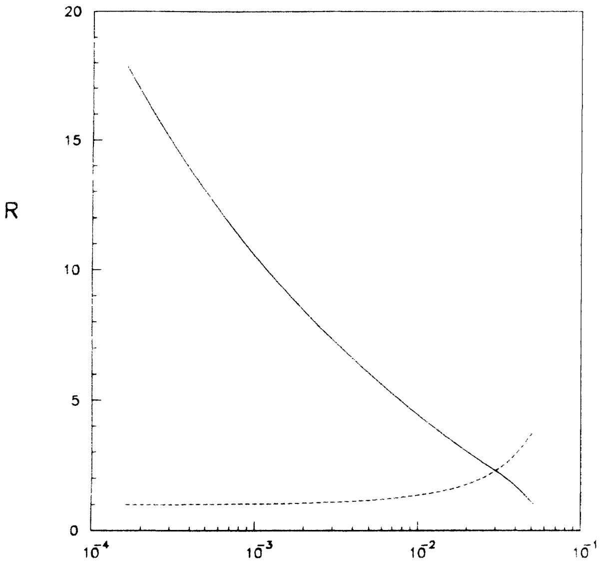

FIG. 2. The variation with incident energy $\sqrt{s}$ of the ratio of J/ψ to open charm-quark production, normalized to its value at $\sqrt{s} \to \infty$ (dashed line), and of the ratio of J/ψ to Drell-Yan production (solid line), normalized to its value at $\sqrt{s} = 20$ GeV.

These three equations immediately illustrate our point. The ratio of charmonium signal to Drell-Yan continuum

$$\left(\frac{d\sigma_{J/\psi}}{dM^2dy}\right)_{y=0} \Big/ \left(\frac{d\sigma_{\rm DY}}{dM^2dy}\right)_{y=0} = \text{const} \times \frac{[g(x)]^2}{q(x)\bar{q}(x)} \qquad (4)$$

is determined by the gluon to quark structure function ratio; increasing $\sqrt{s}$ from the CERN Super Proton Synchrotron (SPS) energy (20 GeV) to the proposed value at the CERN Large Hadron Collider (LHC) (6 TeV) changes the Bjorken variable $x = M/\sqrt{s}$ from $x = 1.6 \times 10^{-1}$ to 5.2×10^{-4} in the case of J/ψ production. To estimate the resulting variation in the ratio (4), we fit the recently proposed Martin-Roberts-Stirling set S0′ (MRS S0′) structure functions [8] by the functional form

$$xf(x) = Ax^a(1-x)^b(1+cx+dx^2) \;;$$

we then use these fits to obtain the $\sqrt{s}$ dependence of the structure function ratios. For the ratio J/ψ/ (Drell-Yan) given by Eq. (4) this results in an increase by a factor 20 between SPS and LHC. On the other hand, the ratio of J/ψ to open charm production remains essentially

$$\left(\frac{d\sigma_{J/\psi}}{dM^2dy}\right)_{y=0,M=M_{J/\psi}} \Big/ \left(\frac{d\sigma_{c\bar{c}}}{dM^2dy\,d\theta}\right)_{y=0,\theta=\pi/2,M=2M_D} = \text{const} \times \left(\frac{g(M_{J/\psi}/\sqrt{s})}{g(2M_D/\sqrt{s})}\right)^2 \qquad (5)$$

we then get only a variation (decrease) by a factor 1.6, which is due to the difference between the J/ψ mass and the open charm threshold. Analogous arguments hold for bottomonium and open-quark production. Moreover, any shadowing effects caused by nuclear targets essentially cancel out in Eq. (5), since the average mass of the $D\overline{D}$ pair does not vary much with $\sqrt{s}$. In Eq. (4), on the other hand, differences in shadowing for quark and gluon functions remain an uncertainty factor.

For a more physical estimate, we consider the comparison between charmonium production and the open charm cross section integrated over the mass and production angle at $y = 0$. Using directly the mentioned MRS S0′ structure functions [8], we obtain the results shown in Fig. 2. Both the J/ψ and the open charm cross sections become constant for $s \to \infty$; we have therefore normalized the ratio of J/ψ to open charm production to its asymptotic value. The ratio of J/ψ to Drell-Yan production increases over the entire range here considered; to obtain an estimate of this increase, we have normalized the ratio to its value at the SPS energy $\sqrt{s} = 20$ GeV. The results shown confirm our qualitative considerations: while the ratio $J/\psi/$(Drell-Yan) increases by a factor 20 between SPS and LHC energies, the ratio of J/ψ to open charm production varies by less than a factor 4. Moreover, at high energies the ratio of J/ψ to open charm quickly becomes constant, with very little variation above the energy reached at the BNL Relativistic Heavy Ion Collider (RHIC). The ratio of J/ψ to Drell-Yan production, on the other hand, continues to increase strongly, and in nuclear collisions it suffers in addition from the noted uncertainties due to differences between quark and gluon shadowing.

We have in Fig. 2 considered ratios of ratios. This procedure largely eliminates K-factor effects; both Drell-Yan [9] and charm-quark production [10] K factors vary little with incident energy, if the mass of the produced system remains constant or does not change much. We conclude that the use of open charm- or b-quark production can provide an excellent complementary reference for quarkonium suppression in high-energy nuclear collisions.

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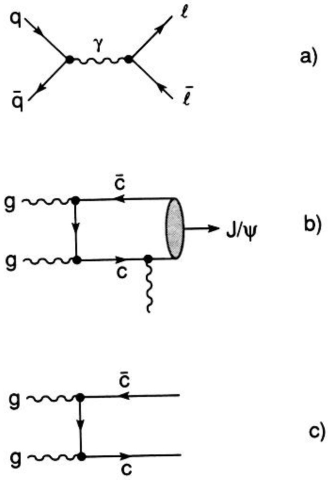

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