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Quarkonium plus prompt photon and shadowing extraction

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Abstract

In this contribution we investigate the influence of nuclear effects in hadroproduction of quarkonium associated with a photon. At high energies, such processes provide a probe of the QCD dynamics as it is dependent on the nuclear gluon distribution, and could be usefull in constraining the behavior of the nuclear gluon distribution in proton-nucleus and nucleus-nucleus collisions. Here we study the influence of the shadowing effect, in the production of J/ψ (or Υ) + γ at the LHC and estimate the p_T dependence of the nuclear modification factors. The theoretical framework considered for quarkonium production is the non-relativistic QCD (NRQCD) factorization formalism.

Keywords: quarkonium production, perturbative QCD, ultrarelativistic heavy ion collisions

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1. Introduction

In the last years the study of heavy ion collisions have provided strong evidence for the formation of a quark-gluon plasma (QGP). Such extreme condition is expected to significantly influence QGP signals and should modify the hard probes produced at early times of the heavy ion collision. Since gluons are dominant, a systematic measurement of the nuclear gluon distribution is primordial to understand the parton structure of nuclei and to determine the QGP initial conditions. One of the nuclear effects which modify the behavior of the nuclear gluon distribution is the nuclear shadowing. This effect has been observed in the nuclear structure functions from deep inelastic lepton scattering (DIS) off nuclei, and can be expressed in terms of the parton content of nucleons bound in nuclei, being different from the parton content of free nucleons. Depending on the parton momentum fraction x, the nuclear parton distribution functions (nPDF) may be suppressed (shadowing) or enhanced (antishadowing) compared with the usual PDF's. There are several parametrizations of nuclear PDF's, based on different assumptions and techniques to perform a global fit of different sets of nuclear experimental data: EKS, DS, HKN, and EPS [1, 2, 3, 4], where the later include RHIC data for the first time. These nPDF's predict very distinct magnitudes for the nuclear effects. Whereas the behavior of the nuclear quark distributions is better constrained from nuclear DIS data, the nuclear gluon distribution is still an open question due to the scarce experimental data in the small-x region and for observables strongly dependent on the nuclear gluon distribution. Here our goal is to use the $J/\psi + \gamma$ processes as auxiliary observables to constrain the nuclear gluon distribution [5] (similar studies on inclusive heavy quark, quarkonium and prompt photon production in central nuclear collisions are done in [6, 7]). This processes are relatively clean because the produced large p_T quarkonium is easy to detect through its leptonic decay modes and the J/ψ's large p_T is balanced by the associated high energy photon. At LHC energies, the leading contributions are dominated by gluon induced hard processes and then the quarkonium production associated with a direct photon will be strongly dependent on the nuclear gluon distribution.

After several years of intense theoretical and experimental investigation, the mechanism for quarkonium production is still not completely understood. Basicaly, there are three types of models for quarkonium production: the color evaporation model (and more detailed soft color interaction models) [8], the color-singlet and the color-octet models [9], the later based on the nonrelativistic QCD (NRQCD) factorization formalism [10] (see [11] for comprehensive reviews and recent developments on quarkonium production). Here we study the production of associated quarkonium $+\gamma$ at large p_T within the NRQCD approach in proton-nucleus and

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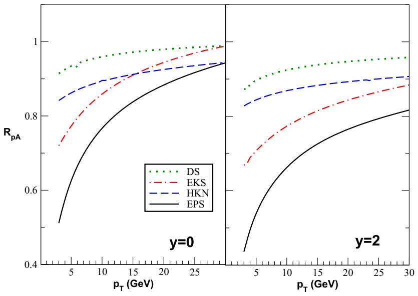

Figure 1: Transverse momentum dependence of the nuclear modification factor R_{pA} in $J/\psi+\gamma$ production in central and forward rapidities at the LHC.

nucleus-nucleus collisions. We focus on the production of a quarkonium and an isolated photon produced back-to-back, with their transverse momenta balanced. The present contribution summarizes the main results investigated in [5].

2. Results and discussions

Our starting point is the $\psi(1S)$ plus prompt photon production case. As long as $J/\psi+\gamma$ is produced at small longitudinal momentum fraction, $x_F \ll 1$, the gluon fusion channel dominates over the $q\bar{q}$ annihilation process. Therefore, at high energies and leading order, the dominant subprocesses are $g+g \to {}^{2S+1}L_J+\gamma$, where the contributing Fock-components are the color-singlet ${}^3S_1^{[1]}$ and the color-octet ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$ and ${}^3P_{0,1,2}^{[8]}$ states. The differential cross section for the process $g+g \to J/\psi+\gamma$ can be written as

$$\frac{d^2\sigma}{dy\,dp_T} = \int dx_1 g_A(x_1,\mu_F^2)\,g_B(x_2,\mu_F^2)\,J_{\rm var}\,\frac{d\hat{\sigma}}{d\hat{t}}, \quad (1)$$

$$J_{\rm var} = \frac{4x_1x_2p_T}{2x_1-\bar{x}_Te^y}, \quad (2)$$

where $\bar{x}_T = 2m_T/\sqrt{s}$, $\sqrt{s}$ is the centre of mass energy, $m_T = \sqrt{p_T^2+m_\psi^2}$, p_T is the common transverse momentum of the outgoing particles, and y is the rapidity of outgoing J/ψ with mass m_ψ. The gluon distribution $g_{A/B}$ in the hadron A/B is evaluated at factorization scale $\mu_F^2 = \mu_R^2 = (p_T^2+m_\psi^2)$. If the gluon comes from a nucleus, the nuclear PDF's are used. The variables $x_{1,2}$ are the parton momentum fractions, where $M^2/s \leq x_1 < 1$ (M is the invariant mass of $J/\psi+\gamma$ system) and $x_2 = \frac{x_1\bar{x}_Te^{-y}-2\tau}{2x_1-\bar{x}_Te^y}$, with $\tau = \frac{m_\psi^2}{s}$.

The relevant parton level differential cross sections are [12]:

$$\begin{aligned}
\frac{d\hat{\sigma}_{\rm sing}}{d\hat{t}} &= \sigma_0\left[\frac{16}{27}\left(\frac{\hat{s}^2s_1^2+\hat{t}^2t_1^2+\hat{u}^2u_1^2}{s_1^2t_1^2u_1^2}\right)\langle O_1^{J/\psi}({}^3S_1)\rangle\right],\\
\frac{d\hat{\sigma}_{\rm oct}}{d\hat{t}} &= \sigma_0\left[\frac{10}{9}\left(\frac{\hat{s}^2s_1^2+\hat{t}^2t_1^2+\hat{u}^2u_1^2}{s_1^2t_1^2u_1^2}\right)\langle O_8^{J/\psi}({}^3S_1)\rangle\right.\\
&\quad+\frac{6}{\hat{s}s_1^2m_c^2}\left(2\hat{s}+\frac{3\hat{t}\hat{u}}{4m_c^2}-\frac{4\hat{t}\hat{u}}{s_1}\right)\langle O_8^{J/\psi}({}^1P_0)\rangle\\
&\quad\left.+\frac{3}{2}\frac{\hat{t}\hat{u}}{\hat{s}s_1^2m_c^2}\langle O_8^{J/\psi}({}^1S_0)\rangle\right], \quad (3)
\end{aligned}$$

where $\sigma_0 = \pi^2e_c^2\alpha\alpha_s^2m_c/\hat{s}^2$ ($m_c = 1.5$ GeV), $s_1 = \hat{s}-4m_c^2$, $t_1 = \hat{t}-4m_c^2$, and $u_1 = \hat{u}-4m_c^2$. The Mandelstam variables become $\hat{s} = x_1x_2s$, $\hat{t} = m_\psi^2 - x_2\sqrt{s}m_Te^y$, and $\hat{u} = m_\psi^2 - x_1\sqrt{s}m_Te^{-y}$. The NRQCD matrix elements can be found in Ref. [13].

We now estimate the differential cross sections for central ($y = 0$) and forward ($y = 2$) rapidities for the pp, pA and AA collisions and compute the nuclear modification factors, which could be measured at the LHC. In Fig. 1 we present our estimates for the transverse momentum dependence of the ratio R_{pA}, defined by $R_{pA} \equiv \frac{d\sigma(pA)}{dydp_T}/A\frac{d\sigma(pp)}{dydp_T}$, in pA collisions at the LHC ($\sqrt{s} = 8.8$ TeV). The results show distinct behaviors of R_{pA} for different nPDF's. The difference between central and forward rapidities for R_{pA} comes from the kinematical x_2 range probed in the two cases. While for $y = 0$ the values of x_2 are ever larger than 10^{-3}, for $y = 2$ the minimum value could be 10^{-4}, increasing with p_T. We have that the nuclear factor is substantially suppressed in the EPS (EKS) case, going down an $0.8-0.7$ at $p_T \simeq 10$ GeV, while in the DS (HKN) case it is almost flat and equal to 0.95 (0.85) in the full p_T range. Morever, differently from the DS and HKN predictions, the EKS and EPS parametrizations lead to a strong transverse momentum dependence. Consequently, the determination of the magnitude and p_T dependence of the this nuclear modification factor at the LHC could be useful to determine the properties of the shadowing in the gluon distribution.

The production of $J/\psi+\gamma$ can also be studied in the collision of two heavy nuclei. The nuclear modification factor R_{AA} are defined by $R_{AA} \equiv \frac{d\sigma(AA)}{dydp_T}/A^2\frac{d\sigma(pp)}{dydp_T}$, in AA collisions at the LHC ($\sqrt{s} = 5.5$ TeV). In this case the nuclear effects are amplified by the presence of two nuclei in the initial state. Similarly to the pA case, we can see in Fig. 2 that the factor R_{AA} is strongly modified by the shadowing effects. For low p_T the suppression is stronger than in the pA case. Our results indicate that $J/\psi+\gamma$ production with $p_T \leq 20$ GeV can be used to

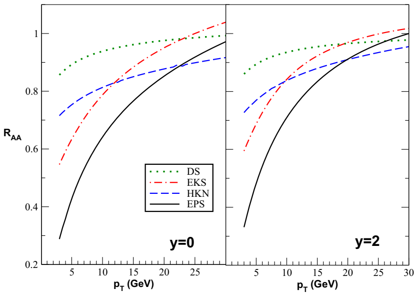

Figure 2: Transverse momentum dependence of the nuclear modification factor R_{AA} in $J/\psi+\gamma$ production in central and forward rapidities at the LHC.

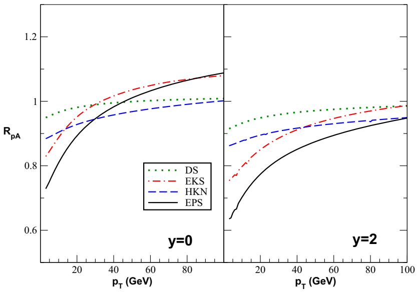

Figure 3: Transverse momentum dependence of the nuclear modification factor R_{pA} in $\Upsilon(1S)+\gamma$ production in central and forward rapidities at the LHC.

determine the gluon shadowing effect.

The production of $\Upsilon(1S)+\gamma$ can be obtained from the expression (3) above, by replacing the charm mass and charge by the bottom ones, $m_b = 4.7\,GeV$, e_b, the J/ψ mass by the $\Upsilon(1S)$ mass, and by using the corresponding color octet matrix elements. We use those values from Ref. [15]. In Fig. 3 we present our estimates for the transverse momentum dependence of the ratio R_{pA} for central and forward rapidities, in pA collisions at the LHC ($\sqrt{s}$ = 8.8 TeV) producing $\Upsilon(1S)+\gamma$. In this case the p_T range is extended to 100 GeV, since the distributions tend to be shifted to larger values of p_T due to the larger Υ mass, which makes larger values of x to be accessed, and suggests the existence of antishadowing. As in the previous cases the results show distinct behaviors of R_{pA} for different nPDF's. For central rapidities, the EKS and EPS show antishadowing for larger p_T, while this effect is absent for forward rapidities and for the other distributions. For lower p_T, the suppression is different for the different nPDFs, being stronger in the forward case. This effect could then be used to discriminate among the nuclear PDF's.

The results for the production of $\Upsilon(1S)+\gamma$ in AA collisions are shown in Fig. 4, where we present our results for the transverse momentum dependence of the ratio R_{AA} for central and forward rapidities at the LHC ($\sqrt{s}$ = 5.5 TeV). Here the nuclear effects are more pronounced than in the pA case. The EPS parameterization shows the steepest behavior, presenting shadowing (suppression) for low p_T and antishadowing (enhancement) for larger p_T and central rapidities. The EKS has a similar although less pronounced behavior, and the HKN, which presented an almost flat behavior in the J/ψ case, it now grows steeper. Thus, the HKN versus DS could be discriminated at low p_T and central rapidities, and at high p_T and forward rapidities. In the forward case, antishadowing behavior at high p_T tend to be less important for the EKS and EPS nPDF's as p_T grows. We conclude that shadowing and antishadowing effects could be tested in different p_T and rapidity regions and therefore help in discriminating among the different nuclear PDF's.

Let us now to discuss qualitatively the results and comment on the limitations of present calculations. Let us first concentrate on the pA case where cold matter effects also play an essential role. At leading order, the differential cross section is simply proportional to the product of gluon densities

$$\frac{d\sigma_{pA}}{dx_1 dx_2}(J/\psi+\gamma) \propto g_p(x_1)\,{}_A(x_2)\,\delta(x_1 x_2 s - m_\psi^2),$$

where $x_{1,2}$ are the projectile and target-parton momentum fractions. In this kinematics, the nuclear modification factor reduces to $R_{pA} \simeq R_g^A(x_2)$. In our analysis above we did not take into account the nuclear absorption. In the framework of the probabilistic Glauber model, this effect refers to the probability for the preresonant $Q\bar{Q}$ pair to survive to the propagation through the nuclear medium. Therefore, the J/ψ may be sensitive to inelastic rescattering processes in a large nuclei, which spoil the simple relationship between R_{pA} and R_g^A. Assuming the factorization between the quarkonium production process and the subsequent possible J/ψ inelastic interaction with nuclear matter, we can write the production cross section as

$$\frac{d\sigma_{pA}}{dx_2}(J/\psi+\gamma) \propto S_{\text{abs}}\,\frac{d\sigma_{\text{prod}}}{dx_2}(pA \to J/\psi+\gamma),$$

where S_{abs} denotes the probability for no interaction, or survival probability, of the meson with the nucleus target. In a Glauber model it depends on the $J/\psi - N$ inelastic cross section, $\sigma_{J/\psi N}$, and reads as (for large

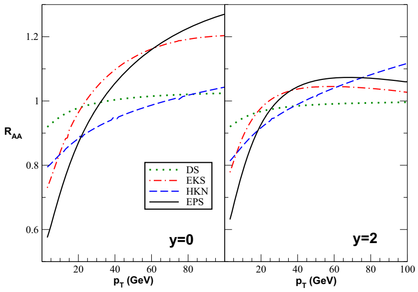

Figure 4: Transverse momentum dependence of the nuclear modification factor R_{AA} in $\Upsilon(1S) + \gamma$ production in central and forward rapidities at the LHC.

nucleus):

$$S_{\text{abs}} \simeq \frac{1}{A\sigma_{J/\psi N}} \int d^2b \left[1 - \exp\left(-T_A(b)\,\sigma_{J/\psi N}\right)\right], \quad (4)$$

with the thickness function $T_A(b)$. As $\sigma_{J/\psi N}$ is not well constrained from data, this is additional uncertainty entering on the nuclear modification factor. In a rough estimation we have $R_{pA} \simeq S_{\text{abs}}(A, \sigma_{J/\psi N}) R_g^A$. The corresponding expression for AA collision can be obtained using similar methods. We quote Ref. [16] as an example where the magnitude of these corrections has been studied for the J/ψ production in proton-nucleus and nucleus-nucleus collisions.

Concerning a nucleus-nucleus collisions, the situation is more complicated as final state effects can not be disregarded. For instance, the processes of dissociation and recombination of $c\bar{c}$ pairs in the dense medium can be computed through the co-movers interaction model [17], which also incorporates also the recombination mechanism [18]. As mentioned for pA case, nuclear effects in nucleus-nucleus collisions are usually expressed through the so-called nuclear modification factor, $R_{AB}^{J/\psi}(b)$, defined as the ratio of the J/ψ yield in AA and pp scaled by the number of binary nucleon-nucleon collisions, $N_{\text{coll}}(b)$. A similar factor can be defined in our case of $J/\Psi + \gamma$ production, having in mind that the prompt photon is insensitive to nuclear matter effects.

In summary, we have investigated the quarkonium production in association with a isolated photon in pA and AA collisions at the LHC, considering the NRQCD factorization formalism and some parameterizations of the nuclear parton distributions available in the literature. Our results show that the nuclear modification factors R_{pA} and R_{AA} are useful observables to discriminate among the different nPDF's. The nuclear effects are different at central and forward rapidities, so measuring the nuclear production of $J/\psi + \gamma$ and $\Upsilon + \gamma$ in these two regions could give additional insights about the correct nuclear gluon distribution. These complementary observables to the inclusive production are useful to understand the quarkonium production mechanism and the relative magnitude of the different nuclear effects, not fixed by present experimental data.

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