J/ψ -meson production within improved color evaporation model with the k_T -factorization approach for $c\bar{c}$ production

Rafał Maciula,^{1,*} Antoni Szczurek,^{1,†} and Anna Cisek^{2,‡}

¹*Institute of Nuclear Physics, Polish Academy of Sciences,
Radzikowskiego 152, PL-31-342 Kraków, Poland*

²*Faculty of Mathematics and Natural Sciences, University of Rzeszów,
ul. Pigonia 1, PL-35-310 Rzeszów, Poland*

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We use a new approach for the color evaporation model for quarkonium production. The production of $c\bar{c}$ pairs is performed within the k_T -factorization approach using different unintegrated gluon distribution functions (UGDF) from the literature. We include all recent improvements to the color evaporation model. We cannot describe simultaneously midrapidity and forward rapidity data measured at the LHC when using the Kimber-Martin-Ryskin (KMR) UGDF based on the collinear MMHT2014lo parton distribution function (PDF) with the same normalization parameter. Furthermore, we get a somewhat too hard distribution in the J/ψ transverse momentum. Correcting the standard KMR-MMHT2014lo distributions for saturation effects at small values of x improves J/ψ rapidity distributions. When using CT14lo collinear PDFs a better agreement with the LHCb data can be achieved without a clear need for implementing saturation effects. We get a poor description of the large transverse momentum distributions of J/ψ with the JH-2013 Ciafaloni-Catani-Fiorani-Marchesini (CCFM)-based UGDF. Here an explicit inclusion of the $2 \rightarrow 3$ processes considerably improves the situation. Similar effects are discussed in the context of the KMR UGDF.

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I. INTRODUCTION

Inclusive production of quarkonia is one of the most actively studied topics at the LHC. The J/ψ , Ψ' , Υ , Υ' , and Υ'' are the usually measured quarkonia. The production of J/ψ is a model case. There was (still is) a disagreement related to the underlying production mechanism. There are essentially two approaches. The first one is the so-called nonrelativistic QCD (NRQCD) approach [1–4]. There are two versions of such an approach based on collinear or k_T -factorization approaches. It was shown recently that the LHC data can be explained within the NRQCD k_T -factorization approach with a reasonable set of parameters [5].

Another popular approach is the color evaporation model (CEM) [6,7]. In this approach one is using the perturbative calculation of $c\bar{c}$. The $c\bar{c}$ pair by emitting a soft radiation goes to the color singlet state of a given spin

and parity. The emission is not explicit in this approach, and everything is contained in a suitable renormalization of the $c\bar{c}$ cross section when integrating over certain limits in the $c\bar{c}$ invariant mass. It was proposed recently how to extend the original CEM, and the improved color evaporation model (ICEM) was developed [8–10]. Usually the computations of the transverse momentum dependence of J/ψ meson production within the color evaporation model are based on the collinear approach up to the next-to-leading order (NLO) [11]. Within the collinear-factorization approach in the leading-order (LO) approximation, the transverse momentum of the $c\bar{c}$ pair is equal to zero. In fact, the NLO diagrams for the inclusive c quark, such as $gg \rightarrow gc\bar{c}$ or $qg \rightarrow qc\bar{c}$, constitute the leading-order contributions for the $c\bar{c}$ -pair transverse momentum. Similarly, the next-to-next-to-leading-order (NNLO) topologies for this quantity are effectively NLO. The situation is different in the k_T -factorization approach where nonzero $c\bar{c}$ -pair transverse momentum can be obtained already at leading order within the $g^*g^* \rightarrow c\bar{c}$ or $q^*\bar{q}^* \rightarrow c\bar{c}$ mechanisms.

The leading-order approach is known to be not sufficient to describe the inclusive charm data. The NLO approach is much better in this respect [12–14]. There is even a NNLO approach [15]; however, its application to differential cross sections of charm and bottom quarks is not yet fully available. In practice, the NNLO approach is limited at

*rafal.maciula@ifj.edu.pl

†Also at University of Rzeszów, PL-35-959 Rzeszów, Poland;
antoni.szczurek@ifj.edu.pl

‡acisek@univ.rzeszow.pl

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present to the case of the inclusive distributions of the heavy top quark, due to the intrinsic instability of the numerical evaluations for masses in the few-GeV range. Moreover, in the context of the color evaporation model one needs to calculate correlation distributions such as the $c\bar{c}$ invariant mass so, in fact, the NNLO calculation in the current form cannot be used. On the other hand, the k_T -factorization with the Kimber-Martin-Ryskin (KMR) unintegrated distributions turned out to be successful in the description of the inclusive production of D mesons [16,17] as well as for some correlation observables [16,18] at the LHC. It seems therefore interesting, and valuable, to apply the k_T -factorization approach for $c\bar{c}$ production in the context of the color evaporation model for J/ψ meson production (see also Ref. [10]).

In the present paper we wish to study whether such a combination of elements can allow one to describe the world data for prompt J/ψ production.¹

II. THEORETICAL FRAMEWORK

In the basic step of our approach, i.e., the calculation of the cross section for $c\bar{c}$ -pair production, we follow the k_T -factorization approach. This framework was shown many times by different authors to provide a very good description of heavy quark production in proton-proton collisions at different energies. Some time ago it was successfully used for theoretical studies of the $pp \rightarrow c\bar{c}X$ reaction at the LHC, including the open charm meson [16,18], as well as the Λ_c baryon production [17]. Very recently, this approach was also applied, e.g., for $pp \rightarrow c\bar{c} + \text{jet}X$ [19], $pp \rightarrow c\bar{c} + 2\text{jets}X$ [20], and $pp \rightarrow c\bar{c}c\bar{c}X$ [21].

In principle, the k_T -factorization approach is known to be a very efficient framework for studies of correlation observables, such as $c\bar{c}$ invariant mass or $c\bar{c}$ -pair transverse momentum distributions [16,18]. Within the CEM the transverse momentum distribution of the J/ψ meson is strictly connected to the $c\bar{c}$ -pair transverse momentum. In the collinear approach, the sole graphs contributing to the production of the $c\bar{c}$ -pair with a finite pair transverse momentum are those from the $2 \rightarrow 3$ processes (see the discussion of Sec. 3.2 of Ref. [11]). In the k_T -factorization approach also the contributions from $2 \rightarrow 2$ mechanisms become available. In the present paper, we take into consideration both dominant components: $g^*g^* \rightarrow c\bar{c}$ and $g^*g^* \rightarrow gc\bar{c}$, shown schematically in the left and right panels of Fig. 1, respectively.

According to this approach, the transverse momenta (virtualities) of both partons entering the hard process are

taken into account and the sum of transverse momenta of the final c and $\bar{c}$ no longer cancels. Then the differential cross section at the tree level for the $c\bar{c}$ -pair production reads

$$\begin{aligned} & \frac{d\sigma(pp \rightarrow c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \\ &= \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2(x_1 x_2 s)^2} |\mathcal{M}_{g^*g^* \rightarrow c\bar{c}}^{\text{off-shell}}|^2 \\ & \times \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) \mathcal{F}_g(x_1, k_{1,t}^2) \mathcal{F}_g(x_2, k_{2,t}^2), \end{aligned} \quad (2.1)$$

where $\mathcal{F}_g(x_1, k_{1,t}^2)$ and $\mathcal{F}_g(x_2, k_{2,t}^2)$ are the unintegrated gluon distribution functions (UGDFs) for both colliding hadrons and $\mathcal{M}_{g^*g^* \rightarrow c\bar{c}}^{\text{off-shell}}$ is the off-shell matrix element for the hard subprocess. The extra integration is over transverse momenta of the initial partons. We keep exact kinematics from the very beginning as well as additional hard dynamics coming from the transverse momenta of incident partons. Explicit treatment of the transverse part of momenta makes the approach very efficient in studies of correlation observables. The two-dimensional Dirac delta function assures momentum conservation. The unintegrated (transverse momentum dependent) gluon distributions must be evaluated at

$$\begin{aligned} x_1 &= \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2), \\ x_2 &= \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2), \end{aligned}$$

where $m_{i,t} = \sqrt{p_{i,t}^2 + m_c^2}$ is the quark/antiquark transverse mass. In the case of charm quark production at the LHC energies, especially in the forward rapidity region, one tests very small gluon longitudinal momentum fractions $x < 10^{-5}$.

The matrix element squared for off-shell gluons is taken here in the analytic form proposed by Catani, Ciafaloni, and Hautmann (CCH) [22]. It was also checked that the CCH expression for the matrix element is consistent with those presented later in Refs. [23,24] and in the limit of $k_{1,t}^2 \rightarrow 0$, $k_{2,t}^2 \rightarrow 0$ it converges to the corresponding on-shell formula.

The calculation of higher-order corrections in the k_T -factorization is much more complicated than in the case of collinear approximation. However, the common statement is that actually in the k_T -factorization approach with tree-level off-shell matrix elements a dominant part of real higher-order corrections is effectively included. This is due to possible emission of extra soft (and even hard) gluons encoded in the unintegrated gluon densities. More details of the theoretical formalism adopted here can be found, e.g., in Ref. [16].

The framework of the k_T -factorization is also used in the calculation of the $g^*g^* \rightarrow gc\bar{c}$ hard subprocess. The off-shell

¹When our analysis was almost finished, we found a new preprint [10] that discusses exactly the same process. The main difference is that we include the important $g^*g^* \rightarrow gc\bar{c}$ contribution to charm production. We also use different unintegrated gluon distributions.

FIG. 1. A diagrammatic representation of the $g^*g^* \rightarrow c\bar{c}$ (left) and $g^*g^* \rightarrow gc\bar{c}$ (right) mechanisms under consideration.

matrix elements for higher final state parton multiplicities at the tree level can be calculated, e.g., numerically with the help of methods of numerical Britto-Cachazo-Feng-Witten recursion [25]. We use the same numerical methods as in, e.g., Refs. [19,20]. The calculations are performed with the help of the KATIE package [26], which is a complete Monte Carlo parton-level event generator for hadron scattering processes. It can be applied to any arbitrary processes within the standard model, for several final-state particles, and for any initial partonic state with on-shell or off-shell partons.

At tree level the relevant calculations of the $g^*g^* \rightarrow gc\bar{c}$ contribution can be performed with a special treatment of minijets at low transverse momenta by multiplying the standard cross section by a somewhat arbitrary suppression factor $F_{\text{sup}}(p_T) = \frac{p_T^4}{((p_T^0)^2 + p_T^2)^2}$. This method for the regularization of the cross section is also applied in the PYTHIA Monte Carlo [27] generator for light quark and gluon $2 \rightarrow 2$ partonic processes. There, the free parameter p_T^0 of the suppression factor is fitted to the experimental data on the total cross section. In our case, the default value of the free parameter is $p_T^0 = 1.5$ GeV, which is adjusted to the exact NLO calculations of the charm production cross section at the LHC.

In the numerical calculation below we apply the KMR unintegrated gluon distributions [28,29] that were found recently to work very well in the case of charm production at the LHC [16]. As discussed also in Ref. [19] the k_T -factorization approach with the KMR UGDF gives results consistent with the collinear NLO approach. For the calculation of the KMR distribution we used here up-to-date collinear CT14 [30] and MMHT2014 [31] parton distribution functions (PDFs). For completeness of the present studies, we also use the Ciafaloni-Catani-Fiorani-Marchesini (CCFM)-based JH-2013 UGDFs [32] that were applied in the same context in Ref. [10].

The KMR prescription for UGDF allows for contributions from the region of $k_t > \mu_F$. In other words, it contains additional hard emissions from the gluon ladder. As a

consequence, calculating the $g^*g^* \rightarrow c\bar{c}$ mechanism with the KMR UGDFs one effectively includes part of higher-order diagrams with one and even two associated partons. Other models of UGDFs in the literature usually contain only soft emissions in the ladder and omit the $k_t > \mu_F$ region, which is the case of, e.g., the JH-2013 UGDFs. Within the latter case, the contributions with associated minijets or jets should be included rather in an explicit way. This difference in the construction of the UGDFs may be crucial especially for correlation observables, such as the pair transverse momentum.

In the present study the renormalization and factorization scales are set as a default to $\mu^2 = \mu_R^2 = \mu_F^2 = \sum_{i=1}^n \frac{m_{i,t}^2}{n}$ and the charm quark mass $m_c = 1.5$ GeV is used. The uncertainties related to the choice of these parameters will be discussed when presenting numerical results.

Having calculated the differential cross section for $c\bar{c}$ -pair production, one can obtain the cross section for the J/ψ meson within the framework of ICEM [8,9]. The $c\bar{c} \rightarrow J/\psi$ transition can be formally written as follows:

$$\frac{d\sigma_{J/\psi}(P_{J/\psi})}{d^3P_{J/\psi}} = F_{J/\psi} \int_{M_{J/\psi}}^{2M_D} d^3P_{c\bar{c}} dM_{c\bar{c}} \frac{d\sigma_{c\bar{c}}(M_{c\bar{c}}, P_{c\bar{c}})}{dM_{c\bar{c}} d^3P_{c\bar{c}}} \delta^3 \left(\vec{P}_{J/\psi} - \frac{M_{J/\psi}}{M_{c\bar{c}}} \vec{P}_{c\bar{c}} \right), \quad (2.2)$$

where $F_{J/\psi}$ is the probability of the $c\bar{c} \rightarrow J/\psi$ transition that is fitted to the experimental data, $M_{J/\psi}$ (or M_D) is the mass of the J/ψ (or D) meson, and $M_{c\bar{c}}$ is the invariant mass of the $c\bar{c}$ system. Using the momentum relation

$$\vec{P}_{J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}} \vec{P}_{c\bar{c}}, \quad \text{where } \vec{P}_{c\bar{c}} = \vec{p}_c + \vec{p}_{\bar{c}}, \quad (2.3)$$

one can easily calculate also the rapidity of the J/ψ meson. In the last step, in order to compare the theoretical predictions with the prompt J/ψ experimental data, we

correct the numerical results by the direct-to-prompt ratio equal to 0.62 [33].

III. NUMERICAL RESULTS

Let us start our presentation of numerical results with the discussion of open charm meson production. Here, we concentrate ourselves on the LHCb open charm data at $\sqrt{s} = 7$ TeV in pp scattering [34]. A good description of these data will be a starting point for a construction of a theoretical framework for J/ψ -meson production within the color evaporation model at the given collision energy. In both cases, in the numerical calculations here we follow the k_T -factorization approach.

In Fig. 2 we present results of our calculations for charged D -meson production in the LHCb kinematical range of $0 < p_T < 8$ GeV and $2 < y < 4.5$. The left and right panels show the meson rapidity and transverse momentum distributions, respectively. The p_T distributions are shown for different bins in rapidity as specified in Fig. 2. Here, the dominant $g^*g^* \rightarrow c\bar{c}$ partonic mechanism is taken into account, and the running strong coupling constant α_s at leading-order is used. The top panels present the default k_T -factorization result for the three different

UGDFs: KMR-CT14lo (solid lines), KMR-MMHT2014lo (dotted lines), and JH-2013-set2 (dashed lines). Each of them leads to an overestimation of the rapidity distribution with respect to the LHCb data. The KMR-CT14lo UGDF distribution leads to results that are closest to the experimental data points. The overestimation is related to the small- p_T region (see the right-top panel). The same conclusion is relevant for the two first bins in the transverse momentum. This is the region that is very sensitive to the small- k_T behavior of the UGDF. This uncertain nonperturbative regime of the UGDFs is still not under theoretical control and can be treated only in a phenomenological way. Different models follow various theoretical assumptions and lead to quite different results, e.g., for charm production cross sections (see Ref. [16]). The situation looks much better for intermediate and larger transverse momenta of D mesons, where all of the applied UGDFs give a very good description of the data points in the considered p_T range. A small discrepancy between the data and the results of the KMR UGDFs appears at larger p_T 's when moving to the forward rapidity region. We observe that in this kinematical domain the JH-2013-set2 of unintegrated gluon density leads to a better behavior of the predicted cross section.

FIG. 2. Distributions in rapidity and transverse momentum of D meson for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization approach.

FIG. 3. Distributions in rapidity and transverse momentum of prompt J/ψ for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the ICEM for different UGDFs. The LHCb data were measured on only one side of $y = 0$. We have added them symmetrically on the other side as is often done in the literature.

In the bottom panels of Fig. 2 we illustrate how the description of the LHCb D -meson data within the KMR-MMHT2014lo UGDFs can be improved by inclusion of the saturation effects. We follow here a useful and pragmatic prescription of these effects as presented in Ref. [5]. We correct the default KMR-MMHT2014lo unintegrated gluon distribution function by assuming its saturation as follows: $\mathcal{F}_g(x, k_t^2) = \mathcal{F}_g(x, Q_s^2)$ for small initial gluon transverse momenta $k_t^2 < Q_s^2$, where the saturation scale $Q_s^2(x) = Q_0^2 \cdot (x_0/x)^\lambda$. The three free parameters Q_0 , x_0 , and λ are fitted to the LHCb charm data. As a result, we get a better description of the LHCb data for both the rapidity and the transverse momentum distributions within the KMR-MMHT2014lo UGDFs than in the case of the default calculations. The saturation effect is visible in the region of $0 < p_T < 2$ GeV and seems to be of a similar size in each of the considered bins of meson rapidity.

Let us now go to the main results of the present paper, i.e., to theoretical predictions for J/ψ -meson production within the improved color evaporation model in the version based on the k_T -factorization approach. For consistency, in the numerical calculations here when considering the $g^*g^* \rightarrow c\bar{c}$ mechanism we keep all the details and parameters as in the case of D -meson production discussed above.

In the left and right panels of Fig. 3 we show the J/ψ -meson rapidity and transverse momentum distributions, respectively, together with the ALICE [35] and the LHCb data [36]. Here we present results for the default KMR-CT14lo (solid lines) and for the JH-2013-set2 (dashed lines) UGDFs. In this calculation the model parameter $P_{J/\psi}$ was fixed to 0.018 and to 0.0065, respectively, in order to describe the LHCb data at small transverse momenta. Within these values, we get a very good description of the experimental rapidity distribution of the prompt J/ψ meson in the case of the KMR-CT14lo UGDF. In principle, one could fit both rapidity distributions

with the same quality taking different values of $P_{J/\psi}$. However, the calculated transverse momentum distributions differ strongly, and the LHCb data prefer the result with the KMR-CT14lo UGDF. For the JH-2013-set2 UGDF, the larger values of the $P_{J/\psi}$ suggested by the rapidity spectrum would lead to a significant overestimation of the small transverse momentum data. The distributions obtained with this UGDF have a completely different p_T slope than the experimental one and falls down much faster. This observation is consistent with the results presented in Ref. [10]. There, this behavior of the quarkonium p_T distributions was, in our opinion, correctly recognized as a consequence of omitting the $k_t > \mu$ region in the UGDF. As mentioned in the previous section, only the KMR model includes this contribution explicitly. In the case of the JH-2013 UGDF additional emissions of an extra hard gluon can be taken into account by exact calculations of the $g^*g^* \rightarrow gc\bar{c}$ mechanism at the level of matrix elements.

It was shown in Ref. [16] that the KMR and CCFM-based UGDFs lead to significant differences in correlation observables for the $c\bar{c}$ pair, e.g., in the $D\bar{D}$ invariant mass and/or azimuthal angle distributions. In the case of the CCFM-based unintegrated gluon distributions, an improved description of correlation observables can be obtained once the higher-order process of gluon splitting is taken into account in an explicit way [37]. Just to illustrate the differences we show in Fig. 4 two-dimensional distributions as a function of the transverse momentum of the initial gluon k_t and the transverse momentum of the meson $p_T^{J/\psi}$. The latter observable, within the color evaporation model, in fact, represents a modified transverse momentum of the $c\bar{c}$ pair. This variable is very strongly correlated with the gluon transverse momentum k_t . We observe that the KMR and the JH-2013 UGDFs provide very different results. In the case of the KMR, we get long tails in the gluon k_t that allows for larger $p_T^{J/\psi}$'s (see the left panel). On the other hand, in the JH-2013

FIG. 4. The double-differential cross section as a function of the transverse momentum of initial gluon k_T and the transverse momentum of the meson $p_T^{J/\psi}$ for the KMR (left) and for the JH-2013-set2 (right) UGDFs.

FIG. 5. Distributions in the transverse momentum of prompt J/ψ for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the improved (solid lines) and original (dashed lines) color evaporation model.

model, the k_T distribution drops down very quickly, and therefore production of the J/ψ meson with larger p_T 's is strongly reduced as long as we consider only the $g^*g^* \rightarrow c\bar{c}$

mechanism (see the right panel). We will return to this interesting issue in a further part of this section.

In Fig. 5 we illustrate the difference between the improved (solid line) and original (dashed line) versions of the color evaporation model. We see that the improved version of the CEM leads to a slope of the $p_T^{J/\psi}$ distribution more favorable by the LHCb data points. However, the calculations with the KMR-CT14lo UGDF overshoots slightly the experimental $p_T^{J/\psi}$ distribution at larger transverse momenta, which was also observed by other authors in the collinear realization of the CEM [11]. Here, and in the following, the two sets of the LHCb data [36] correspond to the assumption of fully transversely or fully longitudinally polarized prompt J/ψ 's.

Besides the discussed uncertainties of the results related to the choice of the unintegrated gluon distributions, within the KMR model the theoretical predictions are also sensitive to the choice of the collinear PDFs used in the calculations of the KMR UGDF. In Fig. 6 we compare the results for the KMR UGDFs obtained with the help of the CT14lo, CT14nlo, and MMHT2014lo collinear gluon PDFs. We find a visible difference between the KMR-CT14lo and

FIG. 6. The same as in Fig. 3 but for different collinear PDFs used in the calculation of the KMR UGDF.

FIG. 7. The same as in Fig. 3 but for different choices of the renormalization and factorization scales specified in the figure. Here the probabilities are adjusted separately for each choice of the scale.

KMR-MMHT2014lo results at forward/backward rapidities and small transverse momenta. The LHCb experimental data prefer the theoretical predictions obtained with the KMR-CT14lo UGDF.

Now we wish to discuss uncertainties of our predictions related to the choice of the renormalization and factorization scales as well as due to the charm quark mass. In Fig. 7 we present results obtained with the four different sets of the $\mu = \mu_R = \mu_F$. For each case we are able to obtain the same quality fit for the experimental rapidity distribution only by slight changes of the $P_{J/\psi}$ parameter. In this sense, our predictions for the J/ψ rapidity spectrum seem to be not really sensitive to the choice of the scales. However, the different scales used in the calculations lead to a quite different slope of the $p_T^{J/\psi}$ distribution. Our default set of $\mu = \mu_R = \mu_F = \frac{m_T^2 + m_c^2}{2}$ provides the theoretical cross sections that are closest to the LHCb experimental data points at larger transverse momenta of the J/ψ meson. In Fig. 8 we

show the two uncertainty bands that represent the typical variation of the default set of the scales $0.5 < \frac{\mu}{m_T} < 2$ and of the charm quark mass $1.2 < m_c < 1.5$ GeV. Within these uncertainties we describe the LHCb rapidity and transverse momentum data on prompt J/ψ production in the whole considered kinematical range.

In Fig. 9 we show the uncertainty of our predictions related to the choice of the factorization scale only. There is only a little dependence of the cross section on the factorization scale for the KMR-CT14lo UGDF. On the other hand, we observe a huge sensitivity of the $p_T^{J/\psi}$ transverse momentum distribution for the case of the JH-2013-set2 UGDF. The latter observation is fully consistent with those reported in Fig. 8 from Ref. [10]. There, the authors explained that fact by a sharp cutoff for $k_t > \mu_F$ present in the JH-2013 UGDF. We agree with this statement and show its explicit confirmation for the KMR-CT14lo result where the region of $k_t > \mu_F$, responsible for additional hard emissions from the UGDF, is included. Below, we

FIG. 8. Distributions in rapidity and transverse momentum of prompt J/ψ for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the ICEM. The shaded bands represent uncertainties of our model due to the variation of the default set of the scales and of the charm quark mass. Here $P_{J/\psi}$ is kept unchanged. Details are specified in the figure.

FIG. 9. Distributions in transverse momentum of the J/ψ meson for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the ICEM for different UGDFs. Here, the shaded bands represent the uncertainty related to the choice of the factorization scale only.

present and discuss how to improve the predictions for the JH-2013 UGDFs beyond the scale variations.

The JH-2013 model for UGDFs by its construction does not include the contributions from the $k_T > \mu_F$ region and resume only soft extra emissions. Therefore, working within this model we find it necessary to include contributions with additional hard (mini)jets at the level of hard matrix elements. In regard to the lack of the NLO framework for the k_T -factorization, this can be done by adding together the $g^*g^* \rightarrow c\bar{c}$ and the $g^*g^* \rightarrow gc\bar{c}$ mechanisms. At high energies, the $2 \rightarrow 3$ channel driven by the gluon-gluon fusion is the dominant one. In Fig. 10 we present numerical results obtained within this procedure. Here, for consistency, the running coupling constant α_s is taken at the next-to-leading order, in contrast to the previous calculations. The top and bottom panels correspond to the JH-2013-set2 and the KMR UGDFs, respectively. The dotted histograms correspond to the $g^*g^* \rightarrow c\bar{c}$ mechanism, and the dashed histograms are for the $g^*g^* \rightarrow gc\bar{c}$. In the case of the KMR

FIG. 10. Distributions in rapidity and transverse momentum of prompt J/ψ for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the ICEM for different UGDFs. Here, both the $g^*g^* \rightarrow c\bar{c}$ and the $g^*g^* \rightarrow gc\bar{c}$ mechanisms are taken into account.

FIG. 11. Distributions in the transverse momentum of the prompt J/ψ at midrapidity for $\sqrt{s} = 7$ TeV together with the ALICE, ATLAS, and CMS data (left panel) and for $\sqrt{s} = 1.96$ TeV together with the CDF data (right panel). The theoretical predictions are obtained within the k_T -factorization realization of the ICeM.

predictions, here we impose a special cut $k_t < \mu_F$ to avoid double counting. We see that the presence of the $g^*g^* \rightarrow gc\bar{c}$ mechanism completely changes the picture for the JH-2013-set2 UGDF and allows for a very good description of the experimental data. The proposed procedure does not influence the predictions for the KMR UGDF. Both considered prescriptions ($2 \rightarrow 2$ with the standard KMR approach and $2 \rightarrow 2 + 2 \rightarrow 3$ with the modified KMR approach) provide a description of the experimental data of a similar quality.

Now we wish to discuss rapidity and energy dependence of our ICeM predictions based on the k_T -factorization approach. In Fig. 11 we present the results for the J/ψ transverse momentum distributions measured at midrapidity by the ALICE [35], ATLAS [38], and CMS [39] at $\sqrt{s} = 7$ TeV (left panel) and by the CDF experiment [40] at $\sqrt{s} = 1.96$ TeV (right panel). Here, the calculations are done for the $g^*g^* \rightarrow c\bar{c}$ mechanism with the KMR-CT14lo UGDF. We observe that the value of the model parameter $P_{J/\psi} = 0.018$ fitted to the forward LHCb data also leads to

a reasonable description of the experimental data from different rapidity regions and different collision energies. The midrapidity datasets allow us to study much larger transverse momenta than in the case of the LHCb. The predictions seem to slightly overestimate the large $p_T^{J/\psi}$ data at both energies. This may be related to the approximate treatment of the direct-to-prompt ratio included in the calculations here as a constant number independent of p_T . This common approximation may be too naive especially when going to larger transverse momenta where the relative contribution of the nondirect prompt J/ψ mechanisms is expected to be enhanced. In Fig. 12 we show in addition the results for the procedure with both the $g^*g^* \rightarrow c\bar{c}$ and the $g^*g^* \rightarrow gc\bar{c}$ mechanisms included. Again, within this prescription the JH-2013-set2 UGDF gives a very good description of the experimental data, at large transverse momenta even better than in the case of the KMR-CT14nlo model. The KMR calculations based on the CT14nlo PDFs need a larger value of the $P_{J/\psi}$ parameter to fit the rapidity

FIG. 12. Distributions in transverse momentum of prompt J/ψ at midrapidity for $\sqrt{s} = 7$ TeV together with the ALICE, ATLAS, and CMS data for the JH-2013-set2 (left panel) and the KMR-CT14lo (right panel) UGDFs. Here, both the $g^*g^* \rightarrow c\bar{c}$ and the $g^*g^* \rightarrow gc\bar{c}$ mechanisms are taken into account.

FIG. 13. Distributions in rapidity and transverse momentum of prompt J/ψ for $\sqrt{s} = 7$ TeV obtained within the k_T -factorization realization of the ICEM for the KMR-MMHT2014lo UGDFs modified for saturation effects.

and the low- p_T data than in the case of the CT14lo PDFs and as a result of which here a slightly larger overestimation of the large- p_T data is obtained.

Finally, we wish to check whether the conclusions from the discussion of D -meson production in the context of possible saturation effects from the beginning of this section can also be applied to the case of J/ψ -meson production. As we can see from Fig. 13 the inclusion of the saturation effects for the KMR-MMHT2014lo UGDF improves the shape of the rapidity distribution. Adjusting the normalization via modifying $P_{J/\psi}$ allows one to nicely describe the LHC rapidity data. It also improves the shape of the transverse momentum distributions in the region $0 < p_T^{J/\psi} < 4$ GeV but the higher value of $P_{J/\psi}$ parameter simultaneously leads to a larger discrepancy between the theory and experimental data at large transverse momenta of prompt J/ψ .

IV. CONCLUSIONS

In the present paper we have discussed how to extend the improved color evaporation model for the production of the J/ψ meson to be used in the framework of the k_T -factorization approach for the production of c and $\bar{c}$ pairs. The same was done independently very recently in Ref. [10]. We have included recent developments proposed recently in the literature. In our calculations we have used the KMR unintegrated gluon distributions that allow one to relatively well describe the single D -meson distributions as well as the meson correlation observables.

Rapidity and transverse momentum distributions of J/ψ mesons have been calculated and the normalization factors $P_{J/\psi}$, being a probability of $c\bar{c}$ soft transition to color singlet S wave quarkonium, have been obtained. We could not describe all the world data with exactly the same normalization when using MMHT2014lo collinear PDFs. The situation can be improved by including saturation effects in the KMR UGDF. A better agreement with both rapidity

and transverse momentum distributions in the small p_T region has been achieved with the CT14lo collinear PDFs without including saturation effects. This weakens the conclusions about the onset of gluon saturation.

Inspired by our earlier work [5] we have tried to include saturation effects that modify the KMR UGDF for small values of longitudinal momentum fractions. Including such an effect improves the agreement of the J/ψ rapidity distributions as well as those for D -meson production but generates some problems at large transverse momenta.

The CCFM-based JH-2013 UGDF leads to a rather poor agreement with the LHCb transverse momentum distributions at large p_T . Much better agreement is achieved when including explicitly extra emissions of (mini)jets. In the case of the KMR approach it is sufficient to use the standard k_T -factorization approach and allow for initial gluon k_T larger than factorization scales. A corresponding discussion has been presented.

In summary, a reasonable description of the data for J/ψ can be achieved in the improved color evaporation model supplemented for the k_T -factorization approach for production of $c\bar{c}$ pairs. Simultaneously a rather good description of the D meson production is achieved with the same UGDFs.

A relatively good description obtained within the improved color evaporation model does not prove that we have understood the underlying mechanism. A similar quality of agreement with experimental data can be obtained within the k_T -factorization NRQCD approach applied directly to J/ψ production [5]. Production of pairs of quarkonia may provide further tests.

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- [1] C. H. Chang, *Nucl. Phys.* **B172**, 425 (1980).
- [2] E. L. Berger and D. L. Jones, *Phys. Rev. D* **23**, 1521 (1981).
- [3] R. Baier and R. Ruckl, *Phys. Lett.* **102B**, 364 (1981).
- [4] E. Braaten and S. Fleming, *Phys. Rev. Lett.* **74**, 3327 (1995).
- [5] A. Cisek and A. Szczurek, *Phys. Rev. D* **97**, 034035 (2018).
- [6] H. Fritsch, *Phys. Lett.* **67B**, 217 (1977).
- [7] F. Halzen, *Phys. Lett.* **69B**, 105 (1977).
- [8] Y.-Q. Ma and R. Vogt, *Phys. Rev. D* **94**, 114029 (2016).
- [9] V. Cheung and R. Vogt, *Phys. Rev. D* **96**, 054014 (2017).
- [10] V. Cheung and R. Vogt, *Phys. Rev. D* **98**, 114029 (2018).
- [11] J. P. Lansberg and H. S. Shao, *J. High Energy Phys.* **10** (2016) 153.
- [12] P. Nason, S. Dawson, and R. K. Ellis, *Nucl. Phys.* **B303**, 607 (1988).
- [13] W. Beenakker, H. Kuijf, W. L. van Neerven, and J. Smith, *Phys. Rev. D* **40**, 54 (1989).
- [14] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, *J. High Energy Phys.* **10** (2012) 137.
- [15] M. Czakon and A. Mitov, *Nucl. Phys.* **B824**, 111 (2010).
- [16] R. Maciuła and A. Szczurek, *Phys. Rev. D* **87**, 094022 (2013).
- [17] R. Maciuła and A. Szczurek, *Phys. Rev. D* **98**, 014016 (2018).
- [18] A. Karpishkov, V. Saleev, and A. Shipilova, *Phys. Rev. D* **94**, 114012 (2016).
- [19] R. Maciuła and A. Szczurek, *Phys. Rev. D* **94**, 114037 (2016).
- [20] R. Maciuła and A. Szczurek, *Phys. Rev. D* **96**, 074013 (2017).
- [21] R. Maciuła and A. Szczurek, *Phys. Rev. D* **87**, 074039 (2013).
- [22] S. Catani, M. Ciafaloni, and F. Hautmann, *Nucl. Phys.* **B366**, 135 (1991).
- [23] J. C. Collins and R. K. Ellis, *Nucl. Phys.* **B360**, 3 (1991).
- [24] R. D. Ball and R. K. Ellis, *J. High Energy Phys.* **05** (2001) 053.
- [25] M. Bury and A. van Hameren, *Comput. Phys. Commun.* **196**, 592 (2015).
- [26] A. van Hameren, *Comput. Phys. Commun.* **224**, 371 (2018).
- [27] T. Sjstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *Comput. Phys. Commun.* **191**, 159 (2015).
- [28] M. A. Kimber, A. D. Martin, and M. G. Ryskin, *Phys. Rev. D* **63**, 114027 (2001).
- [29] G. Watt, A. D. Martin, and M. G. Ryskin, *Eur. Phys. J. C* **31**, 73 (2003).
- [30] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C.-P. Yuan, *Phys. Rev. D* **93**, 033006 (2016).
- [31] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, *Eur. Phys. J. C* **75**, 204 (2015).
- [32] F. Hautmann and H. Jung, *Nucl. Phys.* **B883**, 1 (2014).
- [33] S. Digal, P. Petreczky, and H. Satz, *Phys. Rev. D* **64**, 094015 (2001).
- [34] R. Aaij *et al.* (LHCb Collaboration), *Nucl. Phys.* **B871**, 1 (2013).
- [35] B. Abelev *et al.* (ALICE Collaboration), *J. High Energy Phys.* **11** (2012) 065.
- [36] R. Aaij *et al.* (LHCb Collaboration), *Eur. Phys. J. C* **71**, 1645 (2011).
- [37] H. Jung, M. Kraemer, A. V. Lipatov, and N. P. Zotov, *J. High Energy Phys.* **01** (2011) 085.
- [38] G. Aad *et al.* (ATLAS Collaboration), *Nucl. Phys.* **B850**, 387 (2011).
- [39] S. Chatrchyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **02** (2012) 011.
- [40] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. D* **71**, 032001 (2005).