Digluon contribution to $J/\psi$ production

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In this paper we study the contribution of the double parton distributions of gluons to the charmonium production. Despite being suppressed in the heavy quark mass limit, numerically this contribution gives a sizeable correction to the leading order $k_T$ factorization result in LHC kinematics due to enhancement of gluonic densities in the small Bjorken $x_B$ limit. This contribution is not suppressed at large $J/\psi$ momenta $p_T$ and thus presents one of the complementary mechanisms of charmonia production in this kinematics.

I. INTRODUCTION

The description of the charmonium hadroproduction remains one of the long-standing puzzles almost since its discovery. The large mass $m_c$ of the charm quark inspired applications of perturbative methods and consideration in the formal limit of infinitely heavy quark mass \[1\]. However, in reality the coupling $\alpha_s(m_c) \sim 1/3$ is not very small, so potentially some mechanisms suppressed in the large-$m_c$ limit, numerically might give a sizeable contribution.

The Color Singlet Model (CSM) of charmonia production \[2, 3\] assumes that the dominant mechanism is the gluon-gluon fusion supplemented by emission of additional gluon, as shown in the diagram 1 of the Figure \[1\]. Early evaluations in the collinear factorization framework led to incorrect results at large transverse momenta $p_T$ of charmonia and premature conclusions about the inability of CSM to describe the experimental data. The failure of the expansion over $\alpha_s$ due to milder suppression of higher order terms at large $p_T$ \[4, 5\] and co-production of additional quark pairs \[6, 7\] motivated introduction of the phenomenological color octet contributions \[8, 9\]. The modern NRQCD formulation \[10, 11, 14\] constructs a systematic expansion over the Nonperturbative Matrix Elements (NMEs) of different charmonia states which can be extracted from fits of experimental data. However, at present extracted matrix elements depend significantly on the technical details of the fit \[14\], which sheds doubts on the universality of extracted NMEs. At the same time, it was suggested that the results of the CSM evaluated in the $k_T$-factorization framework ($k_T$-CSM for short) might agree better with experimental data at large $p_T$ if the feed-down contributions from $\chi_c$ and $\psi(2S)$ decays are taken into account \[18–23\]. Inclusion of color octet contributions in $k_T$-CSM framework improves agreement with data \[24\]. However, the uncertainty of the unintegrated parton distribution function (uPDF) is large in this kinematics, and for this reason situation with NRQCD contributions still remains ambiguous \[24, 25\]. It was suggested that at large $p_T$, a sizeable contribution might come from other mechanisms, like for example gluon fragmentation into $J/\psi$ \[26, 29\].

In the aforementioned analysis it was not taken into account that in the small Bjorken-$x_B$ limit, as we approach saturation regime, the gluon densities grow rapidly, and more than one gluon from each hadron might interact with heavy quarks. In this paper we will focus on the first correction, which probes the Double Parton Distribution Function (DPDF) of gluon. According to recent theoretical \[30, 34\] and experimental \[35–43\] studies, these objects might have rich internal structure due to possible correlation between partons \[44\], and in view of various sum rules which the DPDFs should satisfy \[33\].

The DPDFs are usually studied in the double parton scattering (DPS) \[30, 32, 45–47\] and double Drell-Yann processes \[48\]. However, the DPDFs might also contribute to the single hadron production, which is usually interpreted as being due to single-gluon distributions only. In case of the charmonium production, as was noticed in \[49\], the DPDFs might contribute already in the same order over $O(\alpha_s)$, as shown in the diagram 2 of the Figure \[1\]. The relative contribution of the DPDF-induced process is growing with energy and in the LHC kinematics gives a sizeable contribution, up to twenty per cent of the theoretical prediction for the prompt $J/\psi$ hadroproduction. At large momenta this contribution is suppressed due to additional convolution of the third gluon with $k_T$-dependent gluon PDF. In this paper we suggest another mechanism, with emission of additional gluon, as shown in the diagram 3 of the Figure \[1\].

Formally, the cross-section of this process is suppressed as $O(\alpha_s)$ compared to that of the diagram 1, however, as we will see below, it gives a sizeable contribution, on par with contribution of the diagram 2. In contrast to mechanism of \[49\], our contribution is not suppressed in the large-$p_T$ kinematics, and for this reason should be taken into account in comparison with experimental data. If one or both hadrons are polarized, the interference with leading order diagram gives rise to transverse spin asymmetries, which have been studied in detail theoretically \[50, 52\] and experimentally \[53\]. In this paper we will focus on the case of unpolarized protons for which the interference term does not contribute.

The paper is structured as follows. In the Section \[II\] we discuss the framework used for evaluations. In the Section \[III\] we introduce the parametrizations of gluon PDFs and DPDFs used for our estimates. In Section \[IV\] we present our
Figure 1. Diagram (1): A conventional Color Singlet Model (CSM) gluon-gluon fusion mechanism of $J/\psi$ production. In our evaluations we also take into account feed-down contributions from $\chi_c$ and $\psi(2S)$ decays, whose production amplitudes have similar topology (no gluon emission from quark loop in case of $\chi_c$). Diagram (2): a higher twist mechanism suggested in [49]. Diagram (3): Example of the subprocess in which diphotons may produce the same final state as CSM process (this paper, see section II for details). The two-gluon contribution may stem from either hadron. In all three diagrams summation over all permutations of gluons in heavy quark loop is implied.

II. EVALUATION OF THE AMPLITUDES

The cross-section of the charmonium production in the $k_T$ factorization framework reads as

$$d\sigma = \frac{\alpha_s^2(\mu)}{512\pi^4 s^2} \sum_{\text{polarization}} \sum_{\text{spin}} \sum_{\text{color}} |M_{gg \rightarrow gJ/\psi}(s, t)|^2 \mathcal{F}(x_1, k_{1\perp}) \mathcal{F}(x_2, k_{2\perp}) d^2k_{1\perp} d^2k_{2\perp} dy d^2p_T dy_g$$

where we introduced the shorthand notation $s = x_1 x_2 s$, the variables $(y, p_T)$ are rapidity and transverse momentum of produced charmonium, $(y_g, k_g\perp)$ are the rapidity and transverse momentum of the emitted gluon, $(x_i, k_{i\perp})$ are the light-cone fractions and transverse momenta of the incident gluons, with

$$x_{1,2} = \frac{\sqrt{M_{J/\psi}^2 + p_T^2}}{\sqrt{s}} e^{\pm y} + \frac{k_{g\perp}}{\sqrt{s}} e^{\mp y_g},$$

$$\vec{k}_{g\perp} = \vec{p}_T - \vec{k}_{1\perp} + \vec{k}_{2\perp}.$$  

$\mathcal{F}(x_i, k_{i\perp})$ in (1) are the unintegrated gluon parton distributions (uPDFs). The parton level amplitude $M_{gg \rightarrow gJ/\psi}$ in (1) is given by a sum of diagrams with all possible permutations of gluon vertices in heavy quark loop in diagram 1 of Figure (1). We fix the renormalization scale $\mu$ as $\mu = \sqrt{M_{J/\psi}^2 + p_T^2}$. For the $J/\psi$ vertex the standard approximation is to neglect the internal motion of the quarks (formally $O(\alpha_s(m_c))$ effect) and use [2–4]

$$\hat{J}(^3S_1) = \frac{g \hat{\epsilon}(S_{J/\psi})(\hat{p} + m_c)}{2}$$

where $\epsilon_{J/\psi}$ is the polarization vector of $J/\psi$ and the normalization constant $g$ is fixed from the leptonic decay width $\Gamma_{J/\psi \rightarrow e^+e^-}$,

$$g = \sqrt{\frac{3m_{J/\psi} \Gamma_{J/\psi \rightarrow e^+e^-}}{16\pi\alpha_{em} Q_c^2}}, \quad Q_c = \frac{2}{3}.$$ 

For gluon polarization vectors we used the light-cone gauge $A^+ = 0$, in which the parton distributions have a simple probabilistic interpretation. The evaluation of the Feynman diagrams is straightforward in the $k_T$ factorization framework and was done with the help of \textit{FeynCalc} package [15, 16]. The code for evaluation of the cross-section (1) is available on demand.
The unintegrated double gluon distribution $F_4$ suggested in [49] (diagram 2 in the Figure 1). The diagram a feed-down contribution to gluon uPDF from digluon uPDF. The diagram 3 in the Figure 1 is a radiative correction to the process $O$. The diagram 3 in the Figure 1 is not gauge covariant on its own and should be supplemented with additional diagrams in both hadrons and contributes only if both hadrons are polarized. Diagram (3): Contribution from gluon DPDFs which gives nonzero result even if both incident hadrons are not polarized. In all diagrams summation over all permutations of gluon vertices in quark loops is implied.

The process which we study in this paper has the same final state as the CSM mechanism and may interfere with it, as shown in the diagram 1 of the Figure 2. As was discussed in detail in [50, 52], the interference contributes only if one of the incident hadrons is transversely polarized and leads to transverse spin asymmetry sensitive to the three-gluon correlators suggested in [54]. This asymmetry has been measured by PHENIX collaboration [53], and very small value compatible with zero implies that the three-gluon correlators are negligible. For the same reason we will omit the interference diagrams shown in the Figure 2: they might contribute only if both hadrons are polarized.

For the unpolarized protons, digluons should stem from the same hadron in the amplitude and its conjugate, as shown in the diagram 3 of the Figure 2. The diagram with digluon stemming from the lower proton differs from the diagram 3 in Figure 2 only by inversion of sign of rapidity in the diagram 3 of the Figure 2. The diagram with digluon stemming from the lower proton differs from the diagram 3 in Figure 2 only by inversion of sign of rapidity $y$ of $J/\psi$, so the final result has a symmetric form

$$d\sigma_{J/\psi}(y) = d\sigma_{gg+g \rightarrow J/\psi g}(y) + d\sigma_{gg+g \rightarrow J/\psi g}(-y),$$

where $\sigma_{gg+g \rightarrow J/\psi g}$ is given by

$$d\sigma_{gg+g \rightarrow J/\psi g} = \frac{\alpha_s^2(\mu)}{8192\pi^8 s^2} \sum_{\text{polarization}} \sum_{\text{spin color}} |M_{gg+g \rightarrow J/\psi}|^2 \mathcal{F}(x_{1a}, k_{1a\perp}, x_{1b}, k_{1b\perp}, \Delta_{\perp})$$

$$\times \mathcal{F}(x_{2a}, k_{2a\perp}) d^2 k_{1a\perp} d^2 k_{1b\perp} d^2 \Delta_{\perp} d^2 k_{2a} dy d^2 p_T dy dz dx_{1a}/x_{1a},$$

the unintegrated double gluon distribution $\mathcal{F}(x_{1a}, k_{1a\perp}, x_{1b}, k_{1b\perp}, \Delta_{\perp})$ which appears in (7) is defined as [30, 55]

$$\mathcal{F}(x_{1a}, k_{1a\perp}, x_{1b}, k_{1b\perp}, \Delta_{\perp}) = \int d^2 y_1 e^{i\Delta_{\perp} y_1} \int \frac{dz_1^+ dz_1^-}{2\pi} \int d^2 z_2^+ d^2 z_2^- e^{i(x_1 z_1^+ + x_2 z_2^-) p^+}$$

$$\times e^{-i k_1^+ z_1^- - i k_2^+ z_2^-} (p | O_a (0, z_1) O_a (y_\perp, z_2) | p) ,$$

$$O_a (y, z) = \Pi_a^{jj'} G^{g} \left( y - \frac{z}{2} \right) G^{g}\left( y + \frac{z}{2} \right),$$

and the matrix $\Pi_a^{jj'}$ for gluon polarization labels $a = g, \Delta g, \delta g$ is given by

$$\Pi_a^{jj'} = \delta^{jj'}, \quad \Pi_a^{jj'} = i \epsilon^{jj'}, \quad \Pi_a^{jj'} = \tau^{jj'} \delta^{jj'},$$

$$\tau^{jj'} = \frac{1}{2} \left( \delta^{ik} \delta^{jj'} k^i - \delta^{ik} \delta^{jj'} k^i - \delta^{ij'} \delta^{kk'} \right).$$

The diagram 3 in the Figure 1 is not gauge covariant on its own and should be supplemented with additional diagrams which contribute in the same order in $O(\alpha_s(m_c))$, as shown in the Figure 3. The diagram 2 in the list corresponds to a feed-down contribution to gluon uPDF from digluon uPDF. The diagram 3 is a radiative correction to the process suggested in [19] (diagram 2 in the Figure 4). The diagram 4 gives nonzero contribution due to nontrivial color structure of the gauge group: the color independent part of the diagram with inverted direction of the quark loop contributes with opposite sign, for this reason the sum yields a nonzero contribution

$$\sim \text{tr} \left( t_a t_b t_c t_d \right) - \text{tr} \left( t_d t_c t_b t_a \right) = \frac{i}{8} \left[ f_{abe} d_{cd} + f_{cde} d_{abe} \right].$$
Figure 3. Diagram (1): A digluon correction to the conventional Color Singlet Model (CSM) $J/\psi$ production. Diagram (2): a contribution to the gluon PDF from digluons which contributes in the same order. Diagram (3): radiative correction to the process suggested in [49]. Sum of diagrams with emission from any of three $t$-channel gluons is assumed. Diagram (4): process without three-gluon vertex, exists due to nontrivial color group structure. In all diagrams summation over all permutations of gluon vertices in quark loop are implied.

$$V_{gggg \rightarrow J/\psi} = \sum_{P_i} \left( \begin{array}{c} J/\psi \\ J/\psi \end{array} \right)$$

Figure 4. The sum of the hard coefficient functions of the diagrams in the Figure 3 effectively correspond to four gluon-$J/\psi$ vertex $V_{gggg \rightarrow J/\psi}$. Summation over all possible permutations $P_i$ of the four gluons is implied.

The evaluation is quite straightforward and was done with FeynCalc [56, 57] package. An important technical observation which allows to simplify significantly the evaluations is that the hard coefficient functions of all the diagrams in the Figure 3 effectively reduce to the sum over the permutations of four gluons in the $V_{gggg \rightarrow J/\psi}$ vertex, as shown in the Figure 4. This allows us to perform numerically the symmetrization instead of evaluating explicitly all possible interference terms which stem from the amplitude and in its conjugate. In numerical evaluations of particular concern are the diagrams which stem from the interferences of the diagram 3 in the Figure 3: when squared (see diagram 1 in the Figure 5), in collinear limit they yield (together with the virtual corrections shown in the diagram 1’ of the same Figure) the familiar gluon splitting kernel $P_{gg}$ [58–60]. When the diagram 3 interferes with other diagrams, as shown in diagrams (2, 3) of the Figure 5, additionally it might contain collinear and soft divergencies in certain points. Special care is needed near the points where the different singularities start overlapping and pinch the integration contour: in this case individual diagrams might contain real singularities. Due to complex structure of the integrand, demonstration of analytic cancellation of singularities is challenging, for this reason we used a numerical method which will be described in the section IV below. Numerically these diagrams give a very small contribution (see e.g. the Figure 5) and could be disregarded. This happens because the average rapidities of the emitted gluons in the amplitude and in its conjugate are different, and only a very small domain in the configuration space contributes to the interference.

III. PARAMETRIZATION OF GLUON PARTON DISTRIBUTIONS

For evaluation of the unintegrated gluon parton densities $F(x, k_{\perp})$ we use Kimber-Martin-Ryskin (KMR) parametrization [61] with collinear HERAPDF NLO [62, 63] gluon density used as input. The color structure of the double gluon distribution in general case is given by [30]

$$F^{aa',bb'} = \frac{1}{64} \left[ F \delta^{aa'} \delta^{bb'} - \frac{\sqrt{8}}{3} A F \ G_{aa'} c \ G_{bb'} c + \frac{3\sqrt{8}}{5} S F \ G_{a'a'} c \ G_{b'b'} c \right]$$

(12)
Figure 5. Diagram (1): Example of a diagram which contains a double log and which after resummation contributes to gluon splitting kernel $P_{gg}$. Another contribution to $P_{gg}$ comes from virtual corrections (quark or gluon self-energy insertions into gluon lines), as shown in the Diagram (1’). Diagrams 2 and 3: examples of diagrams which possess collinear and soft divergencies. Though formally these diagrams should be taken into account, as explained in the text, numerically they give a very small contribution. In all three diagrams summation over all permutations of gluons in quark loop is implied.

Figure 6. The relative contribution of the diagram (2) from the Figure 5 to the total result.
\[
\frac{2}{\sqrt{10}} 10 F \left( t_{10}^{a',bb'} + \left( t_{10}^{a',bb'} \right)^* \right) + \frac{4}{\sqrt{27}} 27 F \left( t_{27}^{a',bb'} \right),
\]

where \( t_i \) are generators of the color group in representation \( (i = 10, \bar{10}, 27) \). In what follows, for the sake of simplicity we will consider that the color structure is given by only the first term \( \sim \delta^{a'de} \), tacitly omitting other terms with nontrivial color structure. This choice does not violate any of the positivity bounds mentioned in \[15\]. For the kinematic dependent terms, we assume that emission of both gluons is uncorrelated and use the model suggested in \[30\] with additional \( \kappa_T \)-dependence,

\[
F (x_{1a}, k_{1a\perp}, x_{1b}, k_{1b\perp}, \Delta) = F (x_{1a}, k_{1a\perp}) F (x_{1b}, k_{1b\perp}) e^{-B_g \Delta^2}
\]

where the value of the diffractive slope \( B_g \) is taken as a sum of values of gluon GPD slope [64],

\[
B_g \approx (2 \times 2.58 + 0.15 \ln (1/x_{1a}) + 0.15 \ln (1/x_{1b})) \text{GeV}^{-2}.
\]

For the case of the double parton scattering process \( pp \rightarrow h_1 h_2 X \), this parametrization leads to the so-called “pocket formula”

\[
d\sigma_{pp \rightarrow h_1 h_2 X} = \frac{d\sigma_{pp \rightarrow h_1 X} d\sigma_{pp \rightarrow h_2 X}}{\sigma_{eff}}
\]

where the cross-section \( \sigma_{eff} \) is a functional of the impact parameter profile of the parton distribution [30]. The experimental estimates of \( \sigma_{eff} \) from DPS depend on the hadrons \( h_1, h_2 \) with typical values \( \sigma_{eff} \approx 6-15 \text{nb} \) [37, 38, 65].

In the forward limit \( (\Delta \rightarrow 0) \), which is much better understood due to smaller number of variables, after integration over the transverse momenta \( k_{i\perp} \), the parametrization \[13\] yields for the collinear digluon distributions

\[
G (x_1, x_2, \mu_F^2) = G (x_1, \mu_F^2) G (x_2, \mu_F^2)
\]

Recently in [33] it was suggested a model of collinear digluon densities which takes into account all known sum rules and evolution equations. While in general their result might differ quite significantly from a factorized form \[16\], for large factorization scale \( \mu_F^2 \gtrsim M^2_{J/\psi} \) and small \( x_{1,2} \ll 1 \) the factorized form \[16\] holds within 10%. This result agrees with more general result of [32] that evolution to higher scales relevant for quarkonia production tends to wash out any correlations present at low scales.

### IV. NUMERICAL RESULTS

As was discussed in Section [11] the amplitude might contain soft and collinear divergencies in certain points. It is quite challenging to demonstrate analytically that such cancellation indeed happens, for this reason we use a numerical method suggested in [60, 67] and implemented in SecDec package [68–70] widely used for numerical multiloop evaluations. This method consists in treating the Feynman regularizer \( +i\delta \) as a finite parameter,

\[
S(p) = \frac{\hat{p} - m}{\hat{p}^2 - m^2 + i\delta}.
\]

Similarly, we treat \( +i\delta \) as a finite parameter in the gluon propagator complemented with Mandelstam-Leibbrandt prescription [71, 72]

\[
\frac{1}{k^+} \rightarrow \frac{k^-}{k^+ k^- + i\delta}.
\]

As was discussed in [66, 67], the infrared and collinear singularities in individual diagrams translate into poles in \( \delta \), which however should eventually cancel in the infrared stable result. In the Figure [7] we plot the ratio

\[
R(\delta) = \frac{d\sigma(\delta)}{d\sigma (5 \times 10^{-3})}
\]

as a function of parameter \( \delta \). Stability of the result for small \( \delta \) ensures that the result is free of any infrared divergencies.

In the Figure [8] we compare contribution of our mechanism with \( k_T \)-CSM results for prompt \( J/\psi \) production. As we can see, the contribution is enhanced at large \( p_T \) and for \( p_T \gtrsim 50 \text{ GeV} \) at forward rapidities presents a
sizeable contribution to the total result. However, in the $p_T$-integrated cross-section, which is dominated by small-$p_T$ domain, the considered contribution is small ($\lesssim 20$ per cent even at forward rapidities), and by the order of magnitude agrees with mechanism $[49]$. For the sake of definiteness, we fixed the renormalization and factorization scales as $\mu_R = \mu_F = \sqrt{p_T^2 + M_{J/\psi}^2}$ and estimate the higher order loop corrections varying the scale in the range $(0.5, 2)\sqrt{p_T^2 + M_{J/\psi}^2}$, in agreement with $[73]$. However, we would like to mention that for three-gluon vertex this prescription might be not very accurate since the effective scale in this case is controlled by the smallest virtuality $[74]$ (which means that loop corrections could be large).

V. CONCLUSIONS

In this paper we studied the contribution of the double parton gluon densities to the $J/\psi$ production. Though formally suppressed in the heavy quark mass limit, the suggested mechanism is significant and constitutes up to twenty per cent of the produced $J/\psi$, on par with the the contribution suggested in $[49]$. The suggested mechanism is not suppressed at large quarkonia momenta $p_T$, and for this reason presents one of the possible mechanisms of charmonia production in this kinematics.

The considered contribution grows with energy, and we expect that similar trend holds for higher order multigluon contributions. At sufficiently small $x_B$, eventually we approach the saturation regime, which is usually described by the phenomenological small-$x_B$ models with built-in saturation, like dipole model $[75, 78]$ or CGC $[79, 80]$. These models can describe the $J/\psi$ production $[81, 83]$, however the relation of the nonperturbative dipole cross-section to single and multiple gluon distributions in the DGLAP framework might be not straightforward and rely on model-dependent assumptions $[73, 78, 84]$. In case when the model admits interpretation in terms of the gluon distributions, usually the multigluon distributions are hard-coded in the underlying model, frequently being a simple product of single-gluon uPDFs in the impact parameter space $[76]$. At the same time, recent theoretical $[30, 54]$ and experimental $[35, 43]$ studies suggest that gluon DPDFs might be much more complicated objects due to possible correlation between partons $[44]$, and in view of various sum rules which the DPDFs should satisfy $[33]$. In contrast to the small-$x$ models, the suggested approach does not use eikonal approximation and can be used with arbitrary gluon DPDFs extracted from DPS experiments.
Figure 8. (color online) Top: Cross-section of prompt $J/\psi$ production (sum of direct and feed-down contributions) evaluated in CSM framework (upper red band) and digluon correction (lower blue band). The errorbars illustrate uncertainty due to higher order loop corrections and are estimated varying the renormalization scale $\mu_R$ in the range $\mu_R \in (0.5, 2) \times \sqrt{p_T^2 + M_{J/\psi}^2}$. Experimental points (green boxes) are from ATLAS [38]. Bottom: Ratio of our mechanism to the Color Singlet Mechanism as a function of $J/\psi$ transverse momentum $p_T$.

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