PROCEEDINGS OF SCIENCE

J/ψ production in hadron scattering: three-pomeron contribution

Eugene Levin[1,2], **Marat Siddikov**[*1], **and Ivan Schmidt**[1]

[1] *Departamento de Física, Universidad Técnica Federico Santa María, y Centro Científico - Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile*

[2] *Department of Particle Physics, School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Science, Tel Aviv University, Tel Aviv, 69978, Israel*

Address

E-mail: leving@tauex.tau.ac.il, Marat.Siddikov@usm.cl, Ivan.Schmidt@usm.cl

We argue that the inclusive J/ψ production in proton-proton collisions might get significant contribution from fusion of three gluons. We analyze numerically the subprocesses with direct formation of J/ψ from three gluons, and with formation of $J/\psi + g$ states. We found that numerically the three-gluon fusion gives a substantial contribution to the J/ψ production, and is able to describe the experimentally observed shapes of the rapidity, momenta and multiplicity distributions. We also demonstrate that description of rapid multiplicity growth seen in experiment presents a challenge in approaches based on gluon-gluon fusion. For this reason we believe that the available multiplicity dependence data provide a strong evidence in favor of the 3-gluon mechanism of J/ψ production.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

*Speaker.

PoS(EPS-HEP2019)298

1. Introduction

According to modern picture [1], the inclusive charmonia production in hadronic collisions proceeds via a gluon-gluon fusion. The heavy quark-antiquark pair ($\bar{Q}Q$) produced in the subprocess can form charmonium with probability controlled by the corresponding Long Distance Matrix Elements (LDMEs). The NRQCD constructs a systematic expansion over the LDMEs of different color and spin states of the $\bar{Q}Q$ pair, which are found from global fits of experimental data. However, at present the extracted LDMEs depend significantly on the technical details of the fit [2], which might be due to the large uncertainty of the unintegrated parton distribution function (uPDF) in the large-p_T kinematics [3]. However, the lack of universality of the extracted LDMEs potentially could also indicate presence of other mechanisms, beyond the gluon-gluon fusion.

A recent observation of rapidly growing multiplicity dependence [4, 5, 6, 7] in J/ψ production might present a serious challenge for descriptions based on gluon-gluon fusion, and as we will illustrate, might indicate pronounced contribution of multigluon mechanisms. While formally suppressed, in the small Bjorken-x_B limit such contributions might be important due to rapid growth of the gluon densities. In this paper we will focus on the first correction, which corresponds to fusion of three gluons (pomerons). This contribution is not suppressed neither in the heavy quark mass nor in small α_s limits, as could be seen from comparison of the diagrams 1 and 2 in the Figure 1. The analyses [8, 9] concluded that this mechanism might give a sizeable contribution to J/ψ production, though were inconclusive due to inherent model uncertainties. In this proceeding we revisit this mechanism and demonstrate that it can describe all the available experimental data, as well as recent experimental data on multiplicity dependence. We consider the latter fact as a decisive evidence in favor of multipomeron contributions. We also consider the higher order contribution mechanism shown in the diagram 3 of the Figure 1. While formally it is $\mathcal{O}(\alpha_s)$ correction, since the emitted gluon is soft, potentially it could give a numerically sizeable contribution.

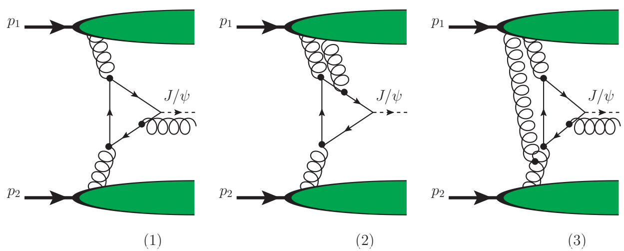

Figure 1: Mechanism (1): A conventional gluon-gluon fusion mechanism of J/ψ production. The additional feed-down contributions (from χ_c and $\psi(2S)$ decays) and color octet contributions have similar topology (in case of χ_c production and Color Octet contributions the corresponding subprocess is $g^*g^* \to \chi_c, \bar{c}c_8$, without additional gluon emission, see [3] for details).Mechanism (2): J/ψ production via 3-pomeron fusion [9]. Mechanism (3): 3-pomero fusion with the same final state as CSM process. In mechanisms (2) and (3) the two-pomeron contribution may stem from either hadron. In all three diagrams summation over all permutations of gluons in heavy quark loop is implied.

The paper is structured as follows. In Section 2 we briefly discuss the framework used for evaluations. In Section 3 we present our numerical results and draw conclusions. Due to space limitations, in this proceeding we omitted some technical details which might be found in [10, 11].

2. Cross-section of the three-pomeron mechanism

At high energies the evaluation of the mechanisms (2) and (3) in the Figure 1 might be simplified due to suppresison of many contributions. For example, the interference of the diagram (3) in the Figure 1 with the CSM mechanism (diagram 1) ends up with odd number of gluons attached to the same hadron. Similarly, the diagram (2) includes interferences of contributions with two gluons connected to different hadrons in amplitude and its conjugate. As was discussed in detail in [12, 13], such interference terms contribute to transverse asymmetries, yet cancel for unpolarized hadrons. In the BFKL picture, such contributions are negligible due to smaller intercept of 3-gluon configuration. Due to space limitations, here we will focus on evaluation of the mechanism (2). The cross-section of this mechanism in the color dipole approach is given by

$$\frac{d\sigma\left(Y,Q^{2}\right)}{dy\,d^{2}q_{T}} = K\,x_{g}G\left(x_{g},M_{J/\psi}\right)\int_{0}^{1}dz\int_{0}^{1}dz'\int\frac{d^{2}r}{4\pi}\,\frac{d^{2}r'}{4\pi}\,d^{2}b\,e^{-i\mathbf{q}_{T}\cdot(\mathbf{b})}\times \tag{2.1}$$

$$\times\left\langle \Psi_{g}\left(r,z\right)\Psi_{J/\psi}\left(r,z\right)\right\rangle \left\langle \Psi_{g}\left(r',z'\right)\Psi_{J/\psi}\left(r',z'\right)\right\rangle \left(N\left(y;\mathbf{b}-\frac{1}{2}\left(\mathbf{r}-\mathbf{r}'\right)\right)\right.$$

$$\left.\times+N\left(y;\mathbf{b}+\frac{1}{2}\left(\mathbf{r}-\mathbf{r}'\right)\right)-N\left(y;\mathbf{b}+\frac{1}{2}\left(\mathbf{r}+\mathbf{r}'\right)\right)-N\left(y;\mathbf{b}-\frac{1}{2}\left(\mathbf{r}+\mathbf{r}'\right)\right)\right)^{2}+\left(y\to-y\right)$$

where y is the rapidity of produced quarkonia, z and z' are the light-cone momentum fraction carried by c-quark in the amplitude and in its conjugate, $\mathbf{r}$ and $\mathbf{r}'$ and the transverse sizes of the dipole, $\Psi_{J/\psi}$ is the light-cone wave function of the quarkonium and Ψ_g is the wave function of the gluon fluctuating into the heavy quark-antiquark pair, $N(y;\mathbf{r}_i)$ are the dipole scattering amplitudes related to the solutions of the BK equation as $N(y;\mathbf{r}_i)=\int d^2b'\,N(y;\mathbf{r}_i,\mathbf{b}')$, and the variable $\mathbf{b}$ is a difference of the impact parameters of the dipole in the amplitude and its conjugate. The gluon density xG is taken at the scale of charmonium mass. The numerical coefficient K in the first line of (2.1) is an artefact of modelling the multipomeron (multigluon) distribution. In what follows we fix K from diffractive charmonia photoproduction data [14, 15].This is possible due to similar structure of the dipole amplitudes, coincidence of the $\bar{Q}Q$-wave functions of the photon and gluon in the leading order over $\mathcal{O}(\alpha_s)$ [11] and expected energy independence of the parameter K.

3. Results and discussion

For numerical estimates we used the phenomenological CGC model with built-in saturation [17]. As we discussed in the previous Section 2, the unknown coefficient K was fixed from HERA data. From the Table 1, we can see that the suggested mechanism gives a significant contribution to the observed J/ψ yields. In what follows in order to avoid ambiguity related to the constant prefactor K, we will work with the cross-sections normalized to the total cross-section, which reflect the *shapes* of distributions.

As we can see from the Fig. (2), the mechanism provides reasonable description of the shapes of the q_T- and rapidity dependencies, in agreement with experimental data from [20, 21]. As we demonstrated in [11], the asymptotic large-q_T behaviour of the cross-section is $\sim 1/q_T^{4+4\gamma}$, for this

	Theoretical estimates	Experiment
$\sqrt{s} \approx 1.96$ TeV	2.1-2.6 μb	2.38 μb [18]
$\sqrt{s} \approx 7$ TeV	3.8-5.6 μb	5.8 μb [19]

Table 1: Comparison of the theoretical estimates with experimental data for the cross-section $d\sigma/dy$ at central rapidities. Theoretical estimates correspond to values of parameter $\lambda \in (0.2, 0.3)$ (lower and upper values respectively). In the last column we've quoted the data on *prompt* J/ψ production. The cross-section $d\sigma/dy$ at Tevatron was extracted dividing the total cross-section $\sigma_{\rm tot}(|y| < 0.6)$ by the width of the bin.

reason for the sake of reference we added two brown curves, $\sim 1/\left(q_T^2 + \Lambda_c^2\right)^{2+2\bar{\gamma}}$ with parameter $\Lambda_c \approx (1-2)\, M_{J/\psi}$.

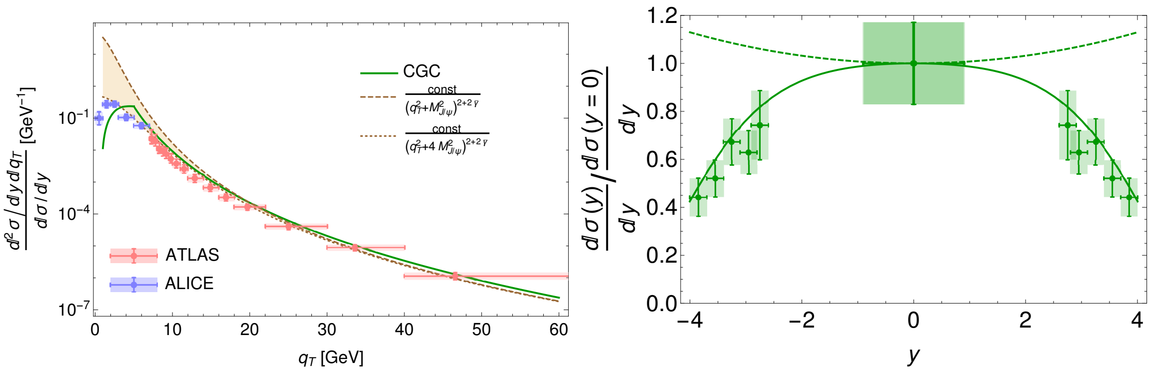

Figure 2: (color online) **Left:** Comparison of the *shapes* of the transverse momentum dependence (solid green curve) with experimental data. **Right**: Rapidity distribution of produced J/ψ. The dashed curve corresponds to evaluation with BFKL-style energy (rapidity) dependence of the dipole amplitude, the solid line takes into account $\sim (1-x)^5$-endpoint factor per each pomeron in order to have correct endpoint behaviour of the gluon densities in the $x \to 1$ limit [22]. The data are taken from [20, 21].

The mechanism (3) provides similar *shapes* for the rapidity and q_T distributions. Numerically its contribution to J/ψ yields is approximately three times smaller than the contribution of mechanism (2) due to additional suppression by $\mathscr{O}(\alpha_s)$ [10].

Finally, we would like to discuss multiplicity distributions of processes shown in diagrams (1-3). As was shown in [23], the number of particles per unit of rapidity is given by $\langle dN_{\rm ch}/d\eta \rangle \approx 6.5$, and the typical width of the interval of rapidity used for study of multiplicity is $\Delta y \approx \pm 1$. For this reason we may neglect the fragmentation of soft gluon in the process (3) and assume that both mechanisms (2) and (3) have the same multiplicity distributions. In the events with elevated multiplicity $n = (dN_{\rm ch}/d\eta)/\langle dN_{\rm ch}/d\eta \rangle \gtrsim 1$ we assume that saturation scale and gluon densities increase as [16]

$$Q_s^2\,(y, n) \; = Q^2\,(y, n = 1)\, n, \qquad xG\,(x_g, n) \; = xG\,(x_g)\, n^{\bar{\gamma}} \tag{3.1}$$

which affects the dipole amplitude in (2.1). This elevated saturation scale should be taken into account only for pomerons which contribute to the observed elevated multiplicity. In the Figure 3 we plot the self-normalized multiplicity distribution evaluated with (2.1) and saturation scale adjusted according to (3.1). We can see that agreement with experimental data from ALICE [4] is reasonable. In the same plot we also have shown for reference the estimates obtained in the limit of small saturation effects, with the dipole amplitude approximated as $N \sim \left(Q_s^2 r^2\right)^{\bar{\gamma}}$, both for the two-gluon and three-gluon fusion mechanisms. As was demonstrated in [11], in this limit we may obtain for the n-dependence of the two-gluon mechanism we would get a mild dependence $\sim n^{\bar{\gamma}}$, whereas for the three-gluon mechanism we get

$$\frac{\left.\frac{d\sigma_{J/\Psi}}{dy}\right|_{\mathrm{fixed\,n}}}{\left.\left\langle\frac{d\sigma_{J/\Psi}}{dy}\right\rangle\right|_{\mathrm{average\,over\,n}}} = \frac{1}{1+\kappa}\left(\kappa n^{\bar{\gamma}} + n^{2\bar{\gamma}}\right) \tag{3.2}$$

where the coefficient $\kappa = \left(Q_s^2(-y)/Q_s^2(y)\right)^{\bar{\gamma}} \approx 1$ at central rapidities and the parameter $\bar{\gamma} \in (0.67, 0.76)$. We can clearly see that the two-gluon fusion mechanism significantly underestimates the multiplicity dependence, whereas the three-gluon fusion mechanisms qualitatively agrees with experimental data.

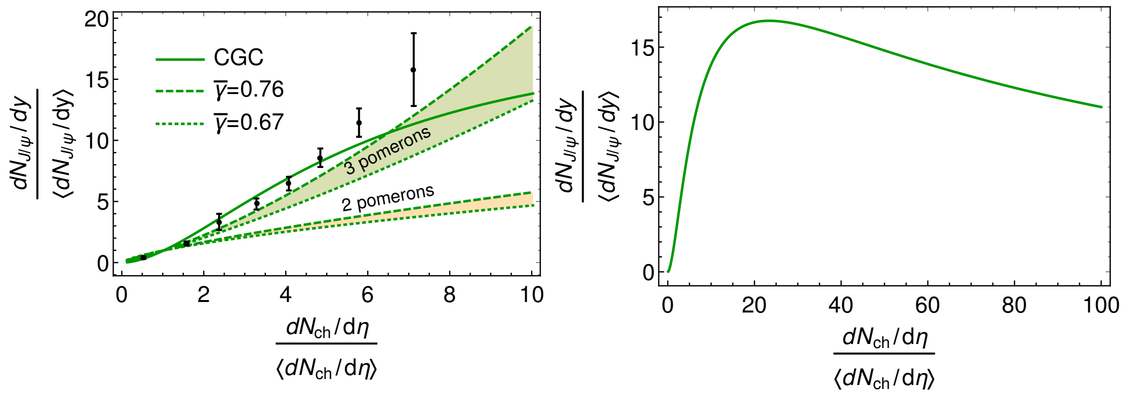

Figure 3: Left: Comparison of the multiplicity distribution with the experiment [4]. Solid line with label "CGC": multiplicity dependence of (2.1) as explained in the text. The bands marked "2 pomerons" and "3 pomerons" stands for the 2- and 3-pomeron contributions evaluated with approximate dipole amplitude (3.2) and values of $\bar{\gamma}$ varied in the range $\bar{\gamma} \in (0.67, 0.76)$, as implemented in phenomenological parameterizations.. **Right**: large-multiplicity behaviour of the 3-pomeron contirbution (solid curve from the left plot).

To summarize, in this paper we evaluated the cross-section of the three-pomeron fusion mechanism of J/ψ hadroproduction. We demonstrated that this mechanism gives a large contribution to the total cross section of J/ψ production, however, inherent uncertainties related to the model of multiparton distributions preclude more precise estimates of its fraction. The suggested mechanism describes correctly the shapes of the transverse momenta, rapidity and multiplicity distributions. The experimental data [4] on multiplicity distributions of co-produced charged particles clearly favor this mechanism over conventional gluon-gluon fusion. We *predict* that the rapid growth seen in experimental data should saturate an even start decreasing at $n = (dN_{\rm ch}/d\eta)/\langle dN_{\rm ch}/d\eta\rangle \gtrsim 20$, which could be a decisive evidence in favor of this mechanism.

Acknowledgments

We thank our colleagues at UTFSM university for encouraging discussions. This research was supported by the BSF grant 2012124, by Proyecto Basal FB 0821(Chile), and by Fondecyt (Chile) grants 1180118 and 1180232.

References

[1] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011) [arXiv:1010.5827 [hep-ph]].

[2] Y. Feng, J. P. Lansberg and J. X. Wang, Eur. Phys. J. C **75**, no. 7, 313 (2015) [arXiv:1504.00317 [hep-ph]].

[3] S. P. Baranov and A. V. Lipatov, Phys. Rev. D **96**, no. 3, 034019 (2017) [arXiv:1611.10141 [hep-ph]]; Eur. Phys. J. C **75**, no. 9, 455 (2015) [arXiv:1508.05480 [hep-ph]].

[4] D. Thakur [ALICE Collaboration], *"J/ψ production as a function of charged-particle multiplicity with ALICE at the LHC,"* arXiv:1811.01535 [hep-ex].

[5] B. Abelev et al. [ALICE Collaboration], Phys. Lett. B **712** (2012), 165.

[6] B. Trzeciak [STAR Collaboration], J. Phys. Conf. Ser. **668**, no. 1, 012093 (2016) [arXiv:1512.07398 [hep-ex]].

[7] R. Ma [STAR Collaboration], Nucl. Part. Phys. Proc. **276-278**, 261 (2016) [arXiv:1509.06440].

[8] V. A. Khoze, A. D. Martin, M. G. Ryskin and W. J. Stirling, Eur. Phys. J. C **39**, 163 (2005), [hep-ph/0410020].

[9] L. Motyka and M. Sadzikowski, Eur. Phys. J. C **75**, no. 5, 213 (2015) [arXiv:1501.04915 [hep-ph]].

[10] I. Schmidt and M. Siddikov, J. Phys. G **46**, no. 6, 065002 (2019) [arXiv:1801.09974 [hep-ph]].

[11] E. Levin and M. Siddikov, Eur. Phys. J. C **79**, no. 5, 376 (2019) [arXiv:1812.06783 [hep-ph]].

[12] X. D. Ji, Phys. Lett. B **289**, 137 (1992).

[13] Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **78**, 114013 (2008) [arXiv:0810.3333 [hep-ph]].

[14] C. Alexa *et al.* [H1 Collaboration], Eur. Phys. J. C **73**, no. 6, 2466 (2013) , [arXiv:1304.5162 [hep-ex]]; A. Aktas *et al.* [H1 Collaboration], Eur. Phys. J. C **46**, 585 (2006), [hep-ex/0510016].

[15] S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **24**, 345 (2002), [hep-ex/0201043]; S. Chekanov *et al.* [ZEUS Collaboration], Nucl. Phys. B **695**, 3 (2004), [hep-ex/0404008].

[16] E. Levin and A. H. Rezaeian, Phys. Rev. D **82** (2010) 014022, [arXiv:1005.0631 [hep-ph]].

[17] A. H. Rezaeian and I. Schmidt, Phys. Rev. D **88** (2013) 074016, [arXiv:1307.0825 [hep-ph]].

[18] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71** (2005) 032001 [hep-ex/0412071].

[19] B. Abelev *et al.* [ALICE Collaboration], JHEP **1211**, 065 (2012) [arXiv:1205.5880 [hep-ex]].

[20] G. Aad *et al.* [ATLAS Collaboration], Nucl. Phys. B **850** (2011) 387, [arXiv:1104.3038 [hep-ex]].

[21] K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. B **704** (2011) 442 Erratum: [Phys. Lett. B **718** (2012) 692] , [arXiv:1105.0380 [hep-ex]].

[22] S. J. Brodsky, M. Burkardt and I. Schmidt, Nucl. Phys. B **441** (1995) 197 , [hep-ph/9401328].

[23] J. Adam *et al.* [ALICE Collaboration], Phys. Lett. B **753** (2016) 319, [arXiv:1509.08734 [nucl-ex]].

PoS(EPS-HEP2019)298