Exclusive photoproduction of heavy quarkonia pairs in ep collisions

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We present our theoretical results for the exclusive photoproduction of heavy quarkonia pairs in the kinematics of the future Electron Ion Collider (EIC). We found that in leading order over the strong coupling α_s the produced quarkonia have opposite C-parity, and predominantly are produced with oppositely directed transverse momenta. Using the Color Glass Condensate (CGC/Sat) approach, we estimated numerically the cross-section of this process for the case of J/ψ-η_c pair production, in the kinematics of the future accelerators.

Presented at DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects, Santiago de Compostela, Spain, May 2-6 2022.

I. INTRODUCTION

Exclusive production of heavy hadrons has enormous potential for precision studies of the gluonic field of the target. Up to now almost all experimental studies of exclusive quarkonia production considered only processes with single quarkonia in the final state. This preference is largely explained by the expected smallness of the cross-sections of processes which include multiple quarkonia in the final state. Nevertheless, such processes have a tremendous potential for improving our knowledge about hadronic physics and have been studied theoretically since the early days of QCD [1–4]. In fact, the interest in multiple quarkonia production has drastically increased after the discovery of all-heavy tetraquarks, which might be considered as molecular states of heavy quarkonia pair [5–15].

In LHC kinematics most of the previous studies of exclusive double quarkonia production focused on the production of $J/\psi\, J/\psi$ pair [16–21]. Due to C-parity constraints, this process gets the dominant contributions from the two-photon fusion mechanism, $\gamma\gamma \to J/\psi\, J/\psi$, and thus has a relatively small cross-sections. This mechanism also gives the dominant contribution to production of other quarkonia pairs in which both quarkonia have the same C-parity. However, in LHC kinematics the cross-section of this process might get sizable contributions from the so-called multiparton scattering contributions, which depend on the poorly known multigluon distributions, thus leading to large uncertainties in the theoretical analysis.

In electron-proton collisions the number of possible production mechanisms is significantly smaller than in hadron-hadron collisions, and for this reason the theoretical predictions have significantly less uncertainty. It is expected that the forthcoming Electron Ion Collider (EIC) [22–25] will have sufficiently high luminosity and collision energy, making it possible to study such processes with reasonable precision. In a more distant future, such processes might be also studied at the future Large Hadron electron Collider (LHeC) [26], the Future Circular Collider (FCC-he) [27–29] and the CEPC collider [30, 31]. In this proceeding we present our results for the exclusive production of heavy quarkonia pairs, $\gamma p \to M_1 M_2 p$, focusing for definiteness on the kinematics of the EIC collider. Due to C-parity constraints, it is expected that the dominant contribution to the amplitude at high energies should come from the C-even pomeron exchanges in the t-channel, which imposes the constraint that the quarkonia M_1 and M_2 should have opposite C-parities. We will consider, for the sake of definiteness, production of a $J/\psi\, \eta_c$ pair, which should have the largest cross-section. The heavy mass of the charm quark can be considered as a natural hard scale, which justifies the use of perturbative approach. In absence of other kinematic constraints, the cross-section obtains its dominant contribution from quasi-real photons of small virtuality $Q^2 \approx 0$ and very small values of Bjorken variable $x_B \ll 1$. In this domain we can describe the process in the color dipole framework (also known as Color Glass Condensate or CGC framework) [32–40].

This proceeding is structured as follows. Below, in Section II, we briefly discuss the main theoretical results for the cross-section of the process, in the CGC framework (a more complete version, which includes all derivations, might be found in our recent publication [41]). In Section III we present some numerical estimates and draw conclusions.

II. EXCLUSIVE MESON PAIR PHOTOPRODUCTION

In lepton-proton collisions the dominant contribution to heavy quarkonia pair production comes from events mediated by single-photon exchange, and for this reason the cross-section may be written as

$$\frac{d\sigma_{ep\to eM_1M_2p}}{dQ^2\, dy_1 d^2\boldsymbol{p}_1^\perp dy_2 d^2\boldsymbol{p}_2^\perp} = \frac{\alpha_{\rm em}}{\pi\, Q^2}\left[(1-y)\,\frac{d\sigma_L}{dy_1 d^2\boldsymbol{p}_1^\perp dy_2 d^2\boldsymbol{p}_2^\perp} + \left(1-y+\frac{y^2}{2}\right)\frac{d\sigma_T}{dy_1 d^2\boldsymbol{p}_1^\perp dy_2 d^2\boldsymbol{p}_2^\perp}\right], \quad (1)$$

where Q is the virtuality of the photon, y is the fraction of electron energy which passes to the photon ("inelasticity"), $(y_a, \boldsymbol{p}_a^\perp)$ are the rapidity and the transverse momenta of the produced quarkonia, and $d\sigma_L$, $d\sigma_T$ are the photoproduction cross-section for longitudinal and transverse photons respectively. For quasireal photons, which are expected to give the dominant contribution in the right-hand side of (1), the contribution of $d\,\sigma_L$ is suppressed compared to the term $d\,\sigma_T$. In case of *single* quarkonia photoproduction, experimental data from ZEUS [42] and H1 [43] suggest that the longitudinal cross-section $d\sigma_L$ constitutes less than 10% of the transverse cross-section $d\sigma_T$. For this reason it is posible to omit the contribution of $d\sigma_L$ altogether. The cross-section $d\sigma_T$ at high energies might be approximated as

$$\frac{d\sigma_T}{dy_1\, d\left|p_1^\perp\right|^2 dy_2\, d\left|p_2^\perp\right|^2 d\phi} \approx \frac{1}{256\pi^4}\left|\mathcal{A}_{\gamma_T p\to M_1 M_2 p}\right|^2 \delta\left(\frac{M_1^\perp\, e^{y_1} + M_2^\perp\, e^{y_2}}{q^+} - 1\right) \tag{2}$$

where $\mathcal{A}_{\gamma_T p\to M_1 M_2 p}$ is the amplitude of the exclusive process induced by a transversely polarized photon, and ϕ is the angle between $\boldsymbol{p}_1^\perp$ and $\boldsymbol{p}_2^\perp$ in the transverse plane. The δ-function, in the right-hand side of (2), reflects that in eikonal approximation it is possible to neglect modifications of the plus-component of the target, so the photon's plus-momentum is shared between the produced quarkonia only.

For exclusive *hadro*production $pA \to pAM_1M_2$ in ultraperipheral collisions the cross-section may be represented in a similar way, using the equivalent photon (Weizsäcker-Williams) approximation,

$$\frac{d\sigma\left(p + A \to p + A + M_1 + M_2\right)}{dy_1 d^2\boldsymbol{p}_1^\perp dy_2 d^2\boldsymbol{p}_2^\perp} = \int dn_\gamma\left(\omega \equiv E_\gamma,\, \boldsymbol{q}_\perp\right)\; \frac{d\sigma_T\left(\gamma + p \to \gamma + p + M_1 + M_2\right)}{dy_1 d^2\boldsymbol{p}_1^* dy_2 d^2\boldsymbol{p}_2^*}\bigg|_{\boldsymbol{p}_i^* = \boldsymbol{p}_i^\perp - \boldsymbol{q}_\perp} \tag{3}$$

where $dn_\gamma\left(\omega \equiv E_\gamma,\, \boldsymbol{q}_\perp\right)$ is the spectral density of the flux of photons created by the nucleus, $\boldsymbol{q}_\perp$ is the transverse momentum of the photon with respect to the nucleus, and $E_\gamma = q^+/2$ is the energy of the photon. The explicit expression for $dn_\gamma\left(\omega \equiv E_\gamma,\, \boldsymbol{q}_\perp\right)$ can be found in [44]. The distribution $dn_\gamma\left(\omega,\, \boldsymbol{q}_\perp\right)$ is strongly peaked at very small $\left\langle \boldsymbol{q}_\perp^2\right\rangle \sim \left\langle Q^2\right\rangle \sim \left\langle R_A^2\right\rangle^{-1} \lesssim \left(0.2\,\text{GeV}/A^{1/3}\right)^2$, where A is the atomic number of the nucleus and A is its radius. For this reason, it is possible to disregard the difference between $\boldsymbol{p}_i^*$ and $\boldsymbol{p}_i^\perp$ in the right-hand side of (3). We can see that both in electro- and ultraperipheral hadroproduction the cross-section depends on the same amplitude$\mathcal{A}_{\gamma_T p\to M_1 M_2 p}$. For its evaluation we may take into account that the formation time of rapidly moving heavy quarkonia is much larger than the size of the proton, and thus the quarkonia formation from heavy quarks happens far outside the interaction region. Technically, this implies that the amplitude $\mathcal{A}_{\gamma_T p\to M_1 M_2 p}$ might be rewritten as a convolution of the quarkonia wave functions with hard amplitudes, which describe the production of heavy quark-antiquark pairs in the gluonic field of the target. In leading order over the strong coupling $\alpha_s\left(m_Q\right)$, there are a few dozen Feynman diagrams which contribute to the exclusive photoproduction of meson pairs, and largely fall into two main classes, shown schematically in Figure 1. At high energies all the eikonal interactions are multiplicative in configuration space, and for this reason it is possible to factorize the hard amplitude and represent it as a convolution of the wave function of $\psi_{\bar{Q}Q\bar{Q}Q}^{(\gamma)}$, which describes the fluctuation of a photon into 4-quark state, and some linear superposition of color singlet dipole scattering amplitudes. Due to large number of contributing diagrams, the full expression for the amplitude is very lengthy and will be omitted here due to space limitations (an interested reader might find it in our paper [41]).

III. NUMERICAL RESULTS

While the framework introduced in the previous section is quite general and might be applied for any quarkonia, in what follows we will focus on $J/\psi\,\eta_c$ pair production, for which the cross-section is the largest. For the wave function of the J/ψ and η_c-mesons we will use the LC-Gauss parametrization of [45, 46], and a b-CGC parametrization for the color singlet dipole amplitudes.

In the left panel of the Figure 2 we show the dependence of the cross-section on the transverse momenta p_T of J/ψ and η_c mesons. As expected, the cross-section decreases rapidly with p_T, and the dominant contribution to the p_T-integrated observables comes from the region where both quarkonia have small transverse momenta $p_i^\perp \sim 1\,\text{GeV}$. In the right panel of the same Figure 1, we present the dependence of the yields on the azimuthal angle ϕ between the transverse momenta of the J/ψ and η_c mesons. For definiteness, we assumed that the transverse momenta $\boldsymbol{p}_{J/\psi}^\perp$, $\boldsymbol{p}_\eta^\perp$ of both quarkonia have equal absolute values. In order to facilitate the comparison of the cross-sections, which differ by orders of magnitude, we plotted the normalized ratio

$$R(\phi) = \frac{d\sigma\left(...,\, \phi\right)/dy_1 dp_1^2 dy_2 dp_2^2 d\phi}{d\sigma\left(...,\, \phi = \pi\right)/ddy_1 dp_1^2 dy_2 dp_2^2 d\phi}, \qquad R(\phi = \pi) \equiv 1 \tag{4}$$

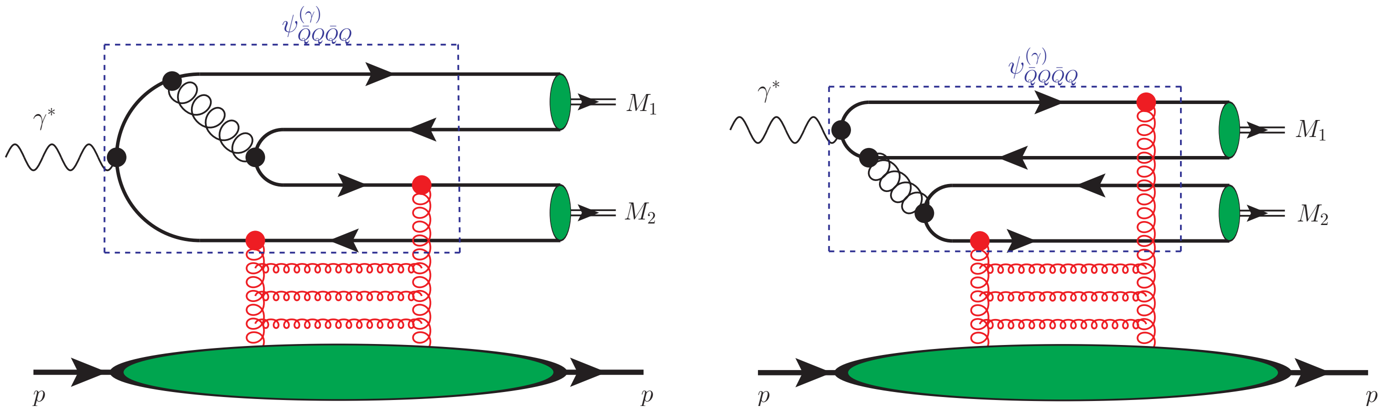

Figure 1. Examples of leading order Feynman diagrams which contribute to heavy quarkonia pair production. The eikonal interactions are shown schematically as exchanges of t-channel gluons, indicated by the red wavy lines. The full result requires summation over all diagrams which might be obtained by permutation of gluon vertices or inversion of heavy quark lines. In the right diagram the t-channel gluons must be always connected to different quark loops in order to guarantee a *color singlet* $\bar{Q}Q$ in the final state. The blue dashed rectangle in the upper left corner shows schematically part of the diagrams which contributes to the $\bar{Q}Q\bar{Q}Q$-component of the photon wave function $\psi^{(\gamma)}_{\bar{Q}Q\bar{Q}Q}$.

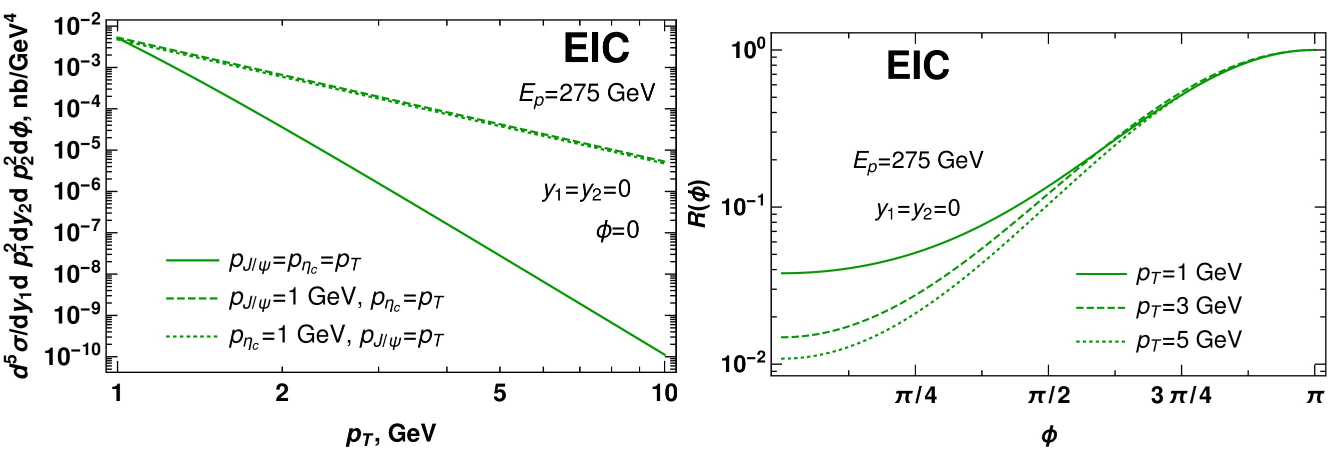

Figure 2. Left plot: The p_T-dependence of the charmonia pair photoproduction cross-section. Comparison of the case when both quarkonia have the large transverse momentum (solid line), with the cases when one of the produced quarkonia is small (dashed and dot-dashed lines). Within errors of numerical evaluation, there is no difference if the soft transverse momentum $p_T \approx 1\,\mathrm{GeV}$ is assigned to J/ψ or η_c mesons. Right plot: The dependence of the normalized ratio $R(\phi)$, defined in (4), on the angle ϕ between transverse momenta of J/ψ and η_c. The appearance of a sharp peak in back-to-back kinematics is explained in the text.

We can see that the ratio has a sharp peak in the back-to-back region ($\phi = \pi$), which happens because in this kinematics the momentum transfer to the target $|t| = |\Delta^2|$ is minimal. In contrast, for the angle $\phi \approx 0$, the momentum transfer $|t| = |\Delta^2|$ gets its maximal value, which explains a pronounced dip.

Finally, in Figure 3 we show the results for the cross-section $d\sigma_{\gamma p\to M_1 M_2 p}/dy_1 dy_2$, which is integrated over transverse momenta $\boldsymbol{p}_i^{\perp}$ of both quarkonia. As we can see from the Figure, the cross-section has a typical ridge near $y_1 \approx y_2$, *i.e*, when quarkonia are produced with approximately the same rapidities. We can observe that the cross-section in general increases as a function of rapidities, in agreement with general expectations based on energy dependence of dipole amplitudes. However, the cross-section decreases as a function of rapidity difference $|y_1 - y_2|$, which is related to the increase of the produced quarkonia invariant mass M_{12}. More detailed predictions for the EIC, as well as for other future colliders, might be found in our recent publication [41].

To summarize, our estimates show that exclusive quarkonia pair photoproduction has sufficiently large cross-section and might be studied experimentally both at the future EIC collider, and in ultraperipheral collisions at the LHC. In all cases the quarkonia are produced with relatively small oppositely directed transverse momenta, and small separation in rapidity, the kinematics which minimizes the momentum transfer to recoil proton and the invariant mass of the produced pair. The dependence of the cross-section on azimuthal angle between transverse momenta of produced quarkonia might present special interest, since it allows to test the dependence of the dipole amplitude $N(x, \boldsymbol{r}, \boldsymbol{b})$ on the relative angle between the dipole separation $\boldsymbol{r}$ and the impact parameter $\boldsymbol{b}$. Our evaluation is largely parameter-free and relies only on the choice of the parametrization for the dipole cross-section and wave functions of quarkonia.

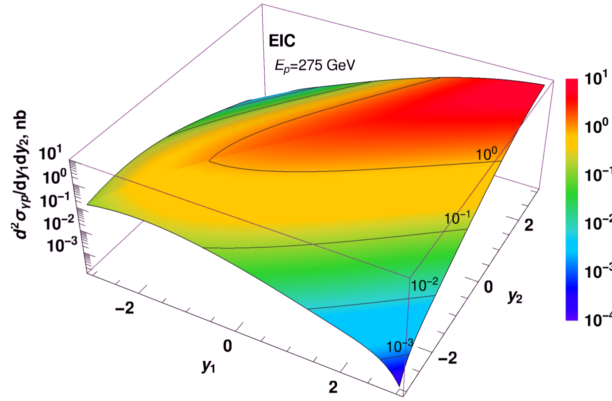

Figure 3. The dependence of the p_T-integrated photoproduction cross-section $d\sigma_{\gamma p}/dy_1 dy_2$ on rapidities y_1, y_2 of produced quarkonia. For definiteness we consider the proton with energy $E_p \sim 275$ GeV in the lab frame (EIC kinematics).

Acknowldgements: We thank our colleagues at UTFSM university for encouraging discussions. This research was partially supported by projects Proyecto ANID PIA/APOYO AFB180002 (Chile) and Fondecyt Regular (Chile) grants 1180232 and 1220242. The research of S. Andrade was partially supported by the Fellowship Program ANID BECAS/MAGÍSTER NACIONAL (Chile) 22200123. Powered@NLHPC: This research was partially supported by the supercomputing infrastructure of the NLHPC (ECM-02).

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