η_c production within light-cone approach in pp and eA collisions

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Abstract. The charmonium state η_c is a pseudoscalar meson ($J^{PC} = 0^{-+}$). We will review the proton-proton and electron-ion reactions, where η_c can be produced through the fusion of two virtual gluons in pp collision or one virtual photon-one real photon in eA collision. The main ingredient in our light-cone approach is the space-like transition form factor with dependence on two virtualities of the particles. The idea is to construct the form factor based on the wave function of the $c\bar{c}$ state. The radial part of the wave function can be found by solving the Schrödinger equation. The transformation to the light-cone variable is performed using the Terentev prescription. We present the effects of the so-obtained form factors in the context of electron-ion collisions. Future facilities such as EIC or LHeC give the opportunity to probe the form factor dependence on the virtuality in e^-A collisions. Our results indicate that the electron-ion colliders can be considered as an alternative and provide supplementary data to those obtained in e^+e^- colliders.

1 Introduction

The process of formation and production mechanism of charmonia is still under discussion, and several approaches are available in the literature [1–3]. The electromagnetic transition form factor of a meson provides information on how photons can couple to the meson. It is known that two photons can couple to mesons with even charge parity (C =+1), in our case η_c. In our research we focus on the space-like region so that the photon's virtualities fulfil a condition $-q_i^2 = Q_i^2 \geq 0$.

In ref. [4], we have presented detailed derivation of $F_{\gamma^*\gamma^*\to\eta_c}(Q_1^2, Q_2^2)$. Here, we would like to review reaction mechanisms that lead to η_c production and emphasize the kinematics variables essential for the collisions. A significant impact on understanding the unique nature of charmonia could be provided by future colliders such as the EIC at BNL, the LHeC at CERN or the EicC in China. The characteristic features of these electron-ion colliders are centre-of-mass energies and/or high luminosities. The advantage of exclusive reactions is that the nucleus stays intact after collision and the final state is very clean, see fig. 1.

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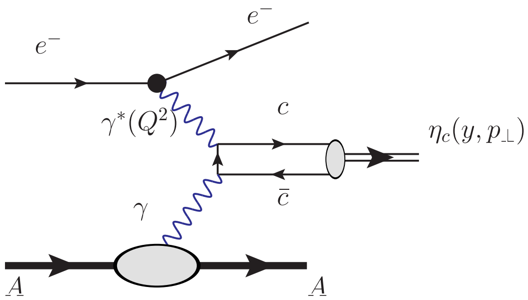

Figure 1. Illustration of possible photon(virtual)-photon(real) fusion to η_c in electron-ion collision. In particular, we consider ^{197}Au or ^{208}Pb, and the nuclear radius $R_A = r_0 A^{1/3}$, with $r_0 = 1.1$ fm.

2 Cross-section for one virtual photon

For exclusive reaction $eA \to e\eta_c A$, we can write the factorization formula in the following form

$$\sigma(eA \to e\eta_c A) = \int d\omega_e dQ^2 \frac{d^2 N_e}{d\omega_e dQ^2} \sigma(\gamma^* A \to \eta_c A)\,, \tag{1}$$

where we can express the nuclear cross-section as

$$\sigma(\gamma^* A \to \eta_c A) = \int d\omega_A \frac{dN_A}{d\omega_A} \sigma_{\mathrm{TT}}(\gamma^*\gamma \to \eta_c; W_{\gamma\gamma}, Q^2, 0)\,. \tag{2}$$

Here ω_e and ω_A are energies of photon couplings to electron and nucleus, respectively. The elementary cross-section σ_{TT}, indeed depends on one photon's virtuality $Q_1^2 = Q^2$, while the second photon is almost real $Q_2^2 \to 0$. The photon-photon center of mass energy $W_{\gamma\gamma} = \sqrt{4\omega_e\omega_A - p_\perp^2}$, where $p_\perp$ is the transverse momentum of the meson in the final state. The nuclear photon flux $dN_A/d\omega_A$, and electron-photon flux $d^2N_e/(d\omega_e dQ^2)$ in the Equivalent Photon Approximation can be found e.g. in ref. [5].

Let us now move to the elementary cross-section $\sigma_{\mathrm{TT}}(\gamma^*\gamma^* \to \eta_c)$, where the transition form factor is combined into the helicity amplitude $\mathcal{M}_{\mu\nu}(\gamma^*(q_1)\gamma^*(q_2) \to \eta_c)$:

$$\begin{aligned} \sigma_{\mathrm{TT}}(W_{\gamma\gamma}, Q_1^2, Q_2^2) &= \frac{1}{4\sqrt{X}} \frac{M_{\eta_c}\Gamma_{\mathrm{tot}}}{(W_{\gamma\gamma}^2 - M_{\eta_c}^2)^2 + M_{\eta_c}^2\Gamma_{\mathrm{tot}}^2} \mathcal{M}^*(++)\mathcal{M}(++)\,, && (3) \\ \mathcal{M}_{\mu\nu}(\gamma^*(q_1)\gamma^*(q_2) \to \eta_c) &= 4\pi\alpha_{\mathrm{em}}\,(-i)\varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\, F(Q_1^2, Q_2^2)\,. && (4) \end{aligned}$$

Above $\sqrt{X} = \sqrt{(q_1 \cdot q_2)^2 - q_1^2 q_2^2}$. In electron-ion collision one of the photons is almost real, which implies the limit $Q_2^2 \to 0$. Then, we can denote $Q_1^2 = Q^2$, and rewrite $\sqrt{X} = q_1 \cdot q_2 = (M_{\eta_c}^2 + Q^2)/2$. We can relate the transition form factor at the on-shell point ($Q_2^2 = Q_1^2 = 0$) to radiative decay width: $\Gamma(\gamma\gamma \to \eta_c) = \frac{\pi}{4}\alpha_{em}^2 M_{\eta_c}^3 |F(0,0)|^2$ and express the cross-section in the narrow width approximation as follows:

$$\sigma_{\mathrm{TT}}(W_{\gamma\gamma}, Q^2, 0) \approx 8\pi^2\,\delta(W_{\gamma\gamma}^2 - M_{\eta_c}^2)\frac{\Gamma_{\gamma\gamma}}{M_{\eta_c}}\Big(1 + \frac{Q^2}{M_{\eta_c}^2}\Big)\Big(\frac{F(Q^2,0)}{F(0,0)}\Big)^2\,, \tag{5}$$

where

$$\begin{aligned} F(Q^2,0) = e_c^2\sqrt{N_c}\,4\int \frac{dz d^2\vec{k}_\perp}{\sqrt{z(1-z)}16\pi^3}\Bigg\{&\frac{1}{\vec{k}_\perp^{\,2} + z(1-z)Q^2 + m_c^2}\tilde{\psi}_{\uparrow\downarrow}(z,k_\perp) \\ &+ \frac{\vec{k}_\perp^{\,2}}{[\vec{k}_\perp^{\,2} + z(1-z)Q^2 + m_c^2]^2}\Big(\tilde{\psi}_{\uparrow\downarrow}(z,k_\perp) + \frac{m_c}{k_\perp}\tilde{\psi}_{\uparrow\uparrow}(z,k_\perp)\Big)\Bigg\}\,. \end{aligned} \tag{6}$$

Above m_c is the c-quark mass, and the number of colours is denoted by N_c. The key element of the form factor is the light-front wave function of the meson $\Psi_{\lambda\bar{\lambda}}(z, \vec{k}_\perp)$.

$$\Psi_{\lambda\bar{\lambda}}(z, \vec{k}_\perp) = e^{im\phi}\tilde{\psi}_{\lambda\bar{\lambda}}(z, k_\perp), \quad \vec{k}_\perp = k_\perp(\cos\phi, \sin\phi), \quad m = \lambda + \bar{\lambda}, \tag{7}$$

$$\tilde{\psi}_{\uparrow\downarrow}(z, k_\perp) \to \frac{m_c}{\sqrt{z(1-z)}}\,\psi(z, k_\perp), \quad \tilde{\psi}_{\uparrow\uparrow}(z, k_\perp) \to \frac{-|\vec{k}_\perp|}{\sqrt{z(1-z)}}\,\psi(z, k_\perp), \tag{8}$$

and $\lambda, \bar{\lambda}$ stand for quark or antiquark spin projections. In our model, we assume that the dominant component in the light-front Fock-state expansion comes from $c\bar{c}$ pair [4]. Hence the radial part of the wave function $\psi(z, k_\perp)$ can be found by solving the Schrödinger equation with $c\bar{c}$ potential model and then "translated" to the light-front using the Terentev prescription. An alternative method to obtain directly the light-front wave function $\Psi_{\lambda\bar{\lambda}}(z, \vec{k}_\perp)$ called basis light-front quantization (BLFQ) was developed in ref. [6].

3 Photon virtuality dependence

In fig. 2, we present predictions for differential cross-section dependence on photon virtuality. For better illustration, the differential distribution is multiplied by Q^2. We have investigated four energy ranges for three different colliders: electron-ion collider - lower energy (LE-EIC) (E_e = 2.5GeV, E_A = 41GeV), and higher energy (HE-EIC) (E_e = 18 GeV, E_A = 100 GeV), electron-ion collider in China (EicC) (E_e = 3.5 GeV, E_A = 10 GeV), the Large Hadron Electron Collider (E_e = 50 GeV, E_A = 2760 GeV). We have made predictions for the wave functions obtained from five different $c\bar{c}$ potential models. In addition, we have applied the BLFQ wave function from the data set [7], see the green dotted line.

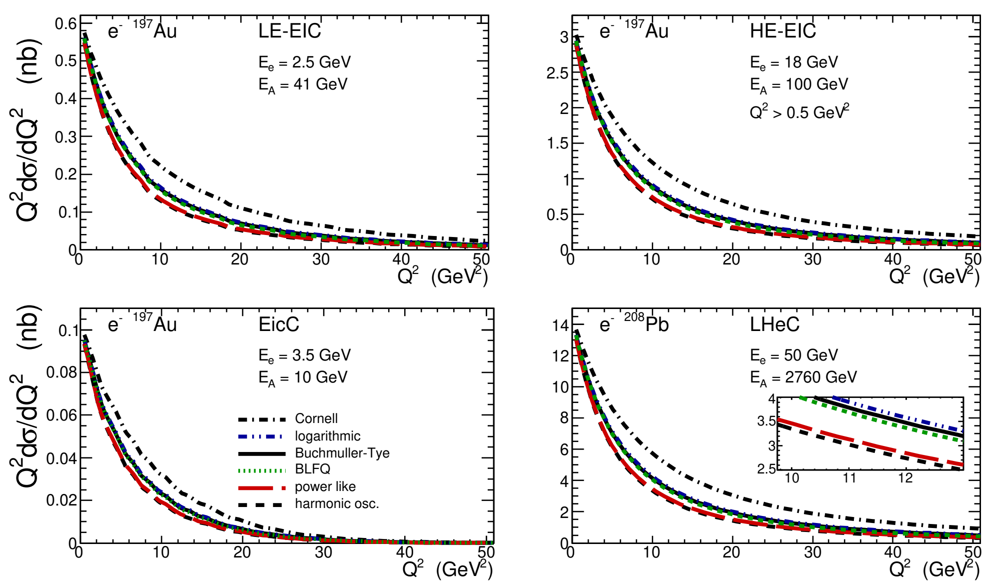

Figure 2. Differential distribution in photon virtuality times virtuality for four different energies and several potential models: Cornell, logarithmic, Buchmuller-Tye, power like, and harmonic oscillator, see [8].

Calculations have been performed for: $Q^2 > 0.5$ GeV^2. The total cross-sections are in the range 0.1 - 60 nb.

4 Proton-proton collisions

This model of the transition form factor also finds application in prompt η_c production in proton-proton collision in $k_\perp$-factorization approach, where the incoming gluons have nonzero transverse momentum. Our adopted colour-singlet approach gives a quite good de-

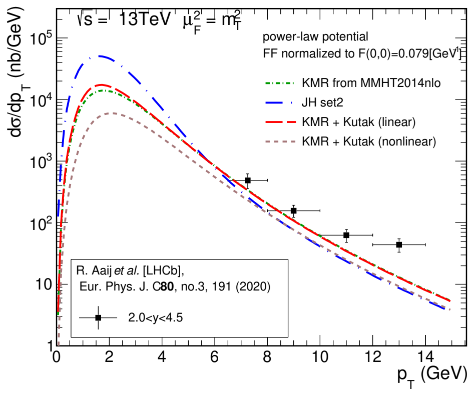

Figure 3. Differential cross-section in η_c transverse momentum at 13 TeV proton-proton center of mass energy [9]. For illustration, we have used the power-law potential model and several unintegrated gluon distribution functions, such as Kimber-Martin-Ryskin (KMR), Jung-Hautman (JH set2), and two combined Kutak's(linear/nonlinear)+KMR distributions. As a factorization scale μ_F^2 we took transverse meson mass squared. Experimental data points are LHCb prompt production data for η_c in proton-proton collision [10].

scription for three center of mass energies $\sqrt{s} = 7; 8; 13$ TeV [9]. However, we can expect, that there is an additional/different mechanism responsible for the differential cross-section at large transverse momenta at $\sqrt{s} = 13$ TeV, see the last two experimental data points in fig. 3.

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