Coherent photoproduction of low-$p_T$ charmonium in peripheral heavy ion collisions within the color dipole model

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Abstract

We calculate the centrality dependence for coherent photoproduction of very low-$p_T$ $J/\psi$ at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies within the impact parameter dependent saturated color dipole model. By using the large equivalent photon fluxes, we present the differential cross section of very low-$p_T$ $J/\psi$ produced by coherent photonuclear in peripheral heavy-ion collisions. The numerical results demonstrate that our calculation are agree with $J/\psi$ data in peripheral heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) energies.

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) are the most powerful collider for the central and non-central heavy ion collisions, offering a unique opportunity to study fundamental aspects of Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD). The central collisions of heavy ions provide a unique tool to create and study the strongly interacting matter, known as quark-gluon plasma (QGP) at high energy density and temperature [1, 2, 3, 4, 5, 6, 7, 8, 9]. The central collisions of heavy ions at RHIC and LHC give an opportunity to explore high-energy nuclear physics with beams of quasi-real photons [10, 11, 12, 13, 14]. The $J/\psi$ suppression in heavy ion collisions has been proposed as a signature of QGP formation [7]. The peripheral collisions of heavy ions at RHIC and LHC give an opportunity to study fundamental aspects of Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD). The strong electromagnetic fields generated by the colliding ions can be represented by a spectrum of equivalent photons, that can be used to study coherent photonuclear interactions. The quasireal photons coherently interact with the gluon field of the other nucleus to produce a $J/\psi$ with low transverse momentum.

In the present work, we investigate the coherent photoproduction of very low-$p_T$ $J/\psi$ within the impact parameter dependent saturated dipole model, that can be described by dipole-nucleus scattering amplitude. The dipole model became an important tool in investigations of deep-inelastic scattering due to the simple ansatz for the dipole cross section integrated over the phase space. The $J/\psi$ can also be produced via the strong electromagnetic fields generated by heavy ions, e.g. photon-nucleus coherent or incoherent interactions, in peripheral heavy-ion collisions [15, 16, 17, 18, 19, 20, 21]. Recently, a significant excess of $J/\psi$ yield at very low transverse momenta has been observed by the ALICE collaboration in peripheral hadronic Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at forward-rapidity [22], and by the STAR collaboration in hadronic Au-Au collisions with $\sqrt{s_{NN}} = 200$ GeV and U-U collisions with $\sqrt{s_{NN}} = 193$ GeV at mid-rapidity [23, 24], that cannot be explained within the hadronic $J/\psi$ production modified by the cold and hot medium effects. It indicates that the significant excess maybe originated from the coherent photoproduction in hadronic heavy-ion collisions ($b < 2R$). In this process, the strong electromagnetic fields generated by the colliding ions can be represented by a spectrum of equivalent photons, that can be used to study coherent photonuclear interactions. The quasireal photons coherently interact with the gluon field of the other nucleus to produce a $J/\psi$ with low transverse momentum.

2. General formalism

In peripheral nucleus-nucleus collisions, the strong interactions are heavily suppressed, and the electromagnetic interaction is expected to dominate. The differential cross-section for coherent photoproduction of very low-$p_T$ charmonium production in peripheral heavy ion collisions within the impact param-
...ependent saturated dipole model can be written as
\[ d\sigma = dN_{i}(r, \omega) d\eta_{A \rightarrow J/\psi}(r-b, x_{p}, Q_{2}^{2}, \Delta) \]
\[ = \frac{d\sigma}{dp_{T}^{2} dy} \int d^{2}r d^{2}d\omega \frac{dN_{i}(r, \omega)}{d^{2}r d\omega} \frac{d\eta_{A \rightarrow J/\psi}(r-b, x_{p}, Q_{2}^{2}, \Delta)}{d^{2}d\omega} (r-b, x_{p}, Q_{2}^{2}, \Delta), \tag{1} \]
where \( r \) and \( b \) are the impact parameter, and \( \hat{r} = -\Delta \) is the transfer momentum. The energy for the photon is \( \omega = \frac{M_{V}}{2} \exp(y) \), here \( M_{V} \) and \( y \) are the vector meson mass and rapidity, respectively. In the center-of-mass frame, the transformation \( d\tau \sim d\rho_{T}^{2} \) and \( d\omega = \omega dy \) can be performed. Therefore the differential cross section for the nucleus-nucleus collisions can be written in the terms of charmonium transverse momentum as the following
\[ \frac{d\sigma}{dp_{T}^{2} dy} = \int d^{2}r d^{2}\omega \frac{dN_{i}(r, \omega)}{d^{2}r d\omega} \frac{d\eta_{A \rightarrow J/\psi}(r-b, x_{p}, Q_{2}^{2}, \Delta)}{d^{2}d\omega} (r-b, x_{p}, Q_{2}^{2}, \Delta), \tag{2} \]
where \( x_{p} = \frac{M_{V}}{2} \exp(y) \) is the momentum fraction of the gluon probed by the photon.

The equivalent photon spectrum for nucleus can be obtained from the semiclassical description of high-energy electromagnetic collisions. A relativistic nucleus with \( Z \) the electric charge moving with a relativistic factor \( \gamma_{L} \gg 1 \) with respect to develop an equally strong magnetic field component hence it resembles a beam of photons, where the number of photons can be expressed as \([25, 26, 27]\)
\[ \frac{dN_{i}(r, \omega)}{d^{2}r d\omega} = \frac{Z^{2} \rho_{1}^{2}}{r^{2} \omega} \left( K_{1}(\eta) + \frac{1}{\gamma_{L}} K_{0}^{2}(\eta) \right), \tag{3} \]
where \( \eta = \omega \gamma_{L} \), \( \omega \) is the photon momentum, \( K_{0}(x) \) and \( K_{1}(x) \) are the Bessel function, and \( \alpha \) is the electromagnetic coupling constant.

The differential cross section for the quasielastic coherent vector meson photoproduction in nucleus-nucleus collisions can be written as \([28, 29]\)
\[ \frac{d\sigma}{d\Omega d\hat{r}} = \frac{R_{s}^{2}(1+\beta_{s})^{2}}{16\pi} \left| A_{V A}^{A \rightarrow VA}(r-b, x_{p}, Q_{2}^{2}, \Delta) \right|^{2}, \tag{4} \]
with
\[ R_{s} = \frac{2z^{2+3}}{\sqrt{\pi}} \frac{\Gamma(\delta + 5/2)}{\Gamma(\delta + 4)}, \beta_{s} = \tan(\pi \delta), \delta = \frac{\partial \ln A_{V A}^{A \rightarrow VA}(r-b, x_{p}, Q_{2}^{2}, \Delta)}{\partial \ln \left(1/x_{p}\right)}, \tag{5} \]
the elementary amplitude \( A_{V A}^{A \rightarrow VA}(r-b, x_{p}, Q_{2}^{2}, \Delta) \) which is defined such that the elastic differential cross section for the quark-antiquark color dipole scattering on the nucleus is given by
\[ A_{V A}^{A \rightarrow VA}(r-b, x_{p}, Q_{2}^{2}, \Delta) \int d^{2}z \frac{d\Omega}{4\pi} d\hat{r} e^{-i[r-b]z^{2}/2 + i\hat{r} \cdot \Delta} \times (\hat{\Psi}_{\psi}^{*} \hat{\Psi}_{\psi})(r-b, r_{d}, x_{p}), \tag{6} \]
here \( A \) is the nucleon number, the overlap between the photon and the vector meson wave functions can be written as \([28]\)
\[ (\hat{\Psi}_{\psi}^{*} \hat{\Psi}_{\psi}) = \hat{e} \hat{\phi}_{\psi} N_{c} \pi \beta f_{\psi}(r_{d}, z) \]
\[ = \sqrt{z^{2} + (1-z)^{2}} K_{1}(\beta f_{\psi}(r_{d}, z) \]
\[ = \int d^{2}z \frac{d\Omega}{4\pi} d\hat{r} e^{-i[r-b]z^{2}/2 + i\hat{r} \cdot \Delta} \times (\hat{\Psi}_{\psi}^{*} \hat{\Psi}_{\psi})(r-b, r_{d}, x_{p}), \tag{7} \]
where \( N_{c}, \beta f_{\psi}, \pi \beta f_{\psi}(r_{d}, z) \), and \( \Delta \) are the coefficients A and B are determined uniquely by matching of the two parts of dipole amplitude and their logarithmic derivatives at \( r_{d} Q_{s} = 2 \).
and the free parameters $\sigma_0$ and $N_0$ were determined by a fit to Hadron Electron Ring Accelerator (HERA) $F_2$ data \cite{28}.

The saturation scale $Q_s$, which depends on the impact parameter is given by

$$Q_s = Q_s(x, b) = \left( \frac{x_0}{x} \right)^{1/2} \exp\left( -\frac{b^2}{B_{GGC}} \right) 1/2 \lambda_s,$$

(14)

where the value of $B_{GGC} = 5.5 GeV^{-2}$ is derived by the $t$ distribution of the exclusive diffractive processes at Hadron Electron Ring Accelerator (HERA) \cite{29}.

3. Numerical results

In order to present our results in a way that can be compared with STAR data from RHIC, we will study the invariant yield of very low-$p_T$ $J/\psi$ production as the following

$$B_{r,\psi} \frac{dN}{dp_T^2 dy} = \frac{B_{r,\psi}}{\sigma_{total}} \frac{d\sigma}{dp_T^2 dy}$$

(15)

where $B_{r,\psi} = 5.97\pm0.03\%$ is the branching ratio for $J/\psi$ decay into electron-position pair ($J/\psi \rightarrow e^+ e^-$) \cite{48}, $\sigma_{total} = 4\pi R_T^2$ is the total cross section for nucleon-nucleus collisions \cite{49}, $R_T = 1.2 A^{1/3} fm$ is the transverse radius of the nucleus, and $A$ is the nucleon number of the nucleus.

From Fig. 11 we plot the spectra of low-$p_T$ $J/\psi$ produced by coherent photoproduction processes in Au-Au collisions with $\sqrt{s_{NN}} = 200 GeV$ and U-U collisions with $\sqrt{s_{NN}} = 193 GeV$ at RHIC, as well as Pb-Pb collisions with $\sqrt{s_{NN}} = 5.02 TeV$ at LHC.

4. Conclusion

In summary, We have investigated the production of very low-$p_T$ $J/\psi$. Our numerical results are consistent with experimental data for Au-Au collisions at Relativistic Heavy Ion Collider(RHIC) energies and Pb-Pb collisions at Large Hadron Collider(LHC) energies.

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