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XIIth Quark Confinement & the Hadron Spectrum

Production of exotic charmonium in ultra-peripheral heavy ion collisions

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Abstract. We discuss exotic charmonium production in $\gamma\gamma$ interactions in heavy ion collisions and present predictions for the production cross section of several of these states in ultra-peripheral collisions of proton-proton and nucleus-nucleus beams at the CERN Large Hadron Collider energies. Our results demonstrate that the experimental study of these processes is feasible and can be used to put limits on the theoretical decay widths and yield valuable information about the structure of multiquark states.

1 Introduction

The existence of exotic hadrons has been firmly established [1–3]. These hadrons are not simply made by quark-antiquark or by three quarks. They are genuine multiquark states but we do not know yet how they are organized. Among the proposed configurations, the meson molecule and the tetraquark are the most often discussed. A tetraquark is compact and the interaction between the constituents occurs through color exchange forces whereas a meson molecule is an extended object and its constituents are weakly bound by meson exchange. It is possible that the new exotic states are charmonium-tetraquark, charmonium-molecule or tetraquark-molecule mixtures. Indeed this mixed approach has led to the best description of the $X(3872)$. In Ref. [4] the mass and strong decay width were very well reproduced assuming that the $X(3872)$ has a $c\bar{c}$ component with a weight of 97 % and a $D\bar{D}^*$ component with 3 % weight. As for the production in proton-proton collisions, both at Fermilab and at the LHC, in Ref. [5] it was shown that the best description can be achieved with a charmonium-molecule combination, i.e. $\chi'_{c1} - D\bar{D}^*$, in which the $c\bar{c}$ component is of the order of $28 - 44$ %. Even if the best description is given by a mixture it is still very important to understand the individual role played by each component.

Understanding the production of exotic particles in hadronic colliders is still an open and challenging problem. It has been shown [2, 6, 7] that it is difficult to produce molecules in p-p collisions. In a pure molecular approach the estimated cross section for $X(3872)$ production is two orders of magnitude smaller than the measured one. An attempt to explain the data in the tetraquark approach was performed in [8]. A possible way to discriminate between the two theoretical descriptions of the exotic states (R) is to measure their decay widths into two photons, i.e., $R \to \gamma\gamma$. These processes

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involve particle-antiparticle annihilation, which is sensitive to the spatial configuration of the decaying states and should be hindered if its constituents are away from each other, as it is the case in a molecular configuration. In fact, for an S-wave non-relativistic two-body system R in a state described by a wave function $\psi(r)$ the width for annihilation into $\gamma\gamma$ is given by

$$\Gamma(R \to \gamma\gamma) = \frac{2\pi\alpha^2}{M_R^2} |\psi(0)|^2 \tag{1}$$

For a loosely bound meson molecule $|\psi(0)|^2$ is much smaller than for a diquark-antidiquark compact system. As it will be seen, the width above appears in the calculation of the inverse process, i.e. $\gamma\gamma \to R$.

In this contribution we will explore the possibility of producing exotic charmonium (EC) in two-photon interactions in ultra-peripheral collisions (UPCs) with high energy protons and nuclei [9, 10]. The strong electromagnetic fields generated by these ions allow the production of a meson in photon-photon interactions. The idea of studying exotic meson production in UPCs was pioneered in [11], where the production cross section of several light and heavy well known mesons and also light exotic mesons and glueballs candidates in nucleus-nucleus collisions was computed. Later, in Ref. [12], the same formalism was applied to the production of mesons and exotic states in proton-proton collisions. In this work we revisit and update these calculations, extending them to proton-proton and nucleus-nucleus collisions at LHC energies, focusing on photon-photon production of the heavy exotic charmonium states and including $X(3915)$, $Z(3930)$ and $X(4160)$. All the ingredients of the calculation are fixed with the exception of the two-photon decay width of the exotic state. In principle, tetraquark and molecular configurations would yield quite different numbers for the decay widths, which would yield quite different production cross sections. The two-photon decay width of the exotic states has been calculated in the molecular approach in several works [13]. Unfortunately the theoretical predictions of the tetraquark model are not yet available.

2 Two photon reactions

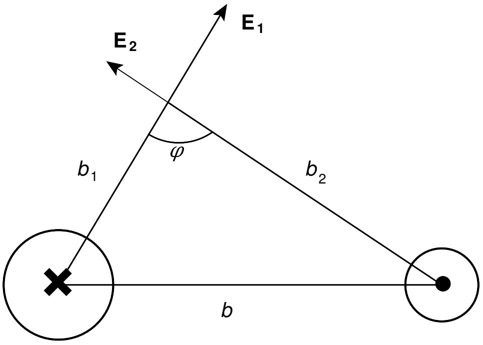


Figure 1. Ultraperipheral hadron-hadron (or nucleus-nucleus) collision. The particle on the left moves into the page and the particle on the right moves out of the page. They are separated by the impact parameter b.

The theoretical treatment of UPCs in relativistic heavy ion collisions has been extensively discussed in the literature [9, 10] and here we will only review the main formulas needed to make predictions for exotic meson production. In the equivalent photon approximation, the cross section for the production of a generic exotic charmonium state, X, in UPCs between two hadrons, h_1 and h_2, is given by [9–12]

$$\sigma(h_1h_2 \to X) = \int \mathrm{d}\omega_1 \int \mathrm{d}\omega_2 \int \mathrm{d}^2b_1 \int \mathrm{d}^2b_2\, N(\omega_1, b_1)N(\omega_2, b_2)\, \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2)\Theta[|\mathbf{b}_1{-}\mathbf{b}_2|{-}(R_1{+}R_2)]\,, \tag{2}$$

where $N(\omega_i, b_i)$ is the equivalent photon spectrum generated by proton (nucleus) i, and $\sigma_{\gamma\gamma\to X}(\omega_1, \omega_2)$ is the cross section for the production of a state X from two real photons with energies ω_1 and ω_2. Moreover, in Eq.(2), ω_i is the energy of the photon emitted by the proton (nucleus) h_i at an impact parameter, or distance, b_i from h_i. The photons, and their corresponding electric fields, interact at the point shown in Fig. 1. The constraint $\Theta[|\mathbf{b}_1 - \mathbf{b}_2| - (R_1 + R_2)]$ imposes that the distance between the ions, $b = |\mathbf{b}_1 - \mathbf{b}_2|$, must be greater than the sum of the radii $R_1 + R_2$, where R_i is a the nuclear radius assuming a sharp-cutoff matter distribution. The cross section for the production of the X state from two-photon fusion can be written in terms of the two-photon decay width of the corresponding state as

$$\sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) = 8\pi^2(2J + 1)\frac{\Gamma_{X\to\gamma\gamma}}{M_X}\delta(4\omega_1\omega_2 - M_X^2)\,, \tag{3}$$

where the decay width $\Gamma_{X\to\gamma\gamma}$ can be taken from experiment or can be theoretically estimated. Furthermore, M_X and J are, respectively, the mass and spin of the state produced. The equivalent photon flux is given by [10, 14, 15]

$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2}\frac{1}{b^2\omega}\left[\int u^2 J_1(u) F\left(\sqrt{\frac{(b\omega/\gamma)^2 + u^2}{b^2}}\right)\frac{1}{(b\omega/\gamma)^2 + u^2}\mathrm{d}u\right]^2\,, \tag{4}$$

where F is the nuclear form factor of the equivalent photon source. For nuclear projectiles (lead for LHC collisions) we use a monopole form factor of the form [10]:

$$F(q) = \frac{\Lambda^2}{\Lambda^2 + q^2}\,, \tag{5}$$

with $\Lambda = 0.088$ GeV. For proton projectiles, the form factor is assumed to be [15]

$$F(q) = 1/\left[1 + q^2/(0.71\mathrm{GeV}^2)\right]^2\,. \tag{6}$$

Another possibility is to use (for proton and nucleus) $F(q) = 1$, which implies that they are point-like particles. In this case, we need to integrate from a minimum distance $b_i = R_i$ (~ 0.7 fm for protons and $1.2A^{1/3}$ fm for nuclei) in Eq. (2), because the flux is divergent for $b = 0$ [11].

3 Results

We have considered all the charmonium states for which either a measurement or a theoretical estimate of the decay width is available. For the sake of comparison with the results found in [12] we consider the two possible assignments, 0^{++} and 2^{++}, for the states $X(3940)$ and $X(4140)$. The masses and decay widths were inferred from Ref.[13]. We use the following notation: $\sigma_{b_{min}}$ denotes cross sections evaluated with $F = 1$ and σ_F denotes cross sections evaluated with the form factors from Eqs.(5) and (6). The precise form of the form factor is the main source of uncertainties in our calculations and the use of the two cases mentioned above gives us an estimate of the theoretical error. In Table 1

Table 1. Cross sections for exotic meson production in PbPb collisions using the theoretical decay rates presented in Ref. [13].

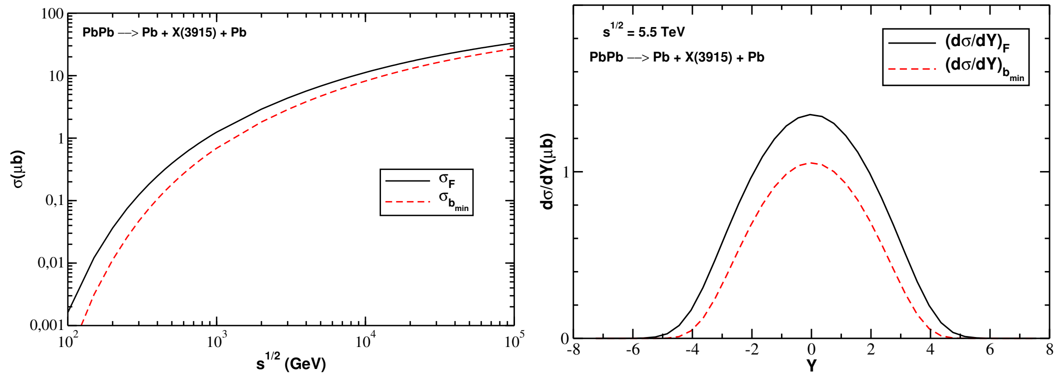
State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (μb)		σ_F (μb)	
			2.76 TeV	5.5 TeV	2.76 TeV	5.5 TeV
X(3940), 0^{++}	3943	0.33	4.2	8.2	6.5	11.8
X(3940), 2^{++}	3943	0.27	17.2	33.6	26.5	48.4
X(4140), 0^{++}	4143	0.63	6.5	12.9	10.2	18.7
X(4140), 2^{++}	4143	0.50	26.0	51.2	40.3	74.3
Z(3930), 2^{++}	3922	0.083	5.4	10.5	8.3	15.2
X(4160), 2^{++}	4169	0.363	18.4	36.4	28.6	52.7
Y_p(3912), 2^{++}	3919	0.774	50.5	98.6	77.9	142.2
X(3915), 0^{++}	3919	0.20	2.6	5.1	4.0	7.34

we present our predictions for the cross sections for the production of several exotic mesons in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.5$ TeV using both form factors. The cross section is enhanced by a factor Z^4 in Pb-Pb collisions. This is reflected in our calculations, with the cross sections ranging from a few hundred nb up to a few tens of μb. Comparing the cross sections for different form factors shows that $\sigma_F \approx 1.5\ \sigma_{b_{min}}$. This happens because $\sigma_{b_{min}}$ does not take into account meson production when $b_i < R_i$, while σ_F allows this, as long as the constraint $b > R_1 + R_2$ is respected. Since the masses of the exotic states are nearly the same (within 5%), the main sources of differences in the cross sections are the magnitude of the decay width and the spin of the produced particle. In Table 2 we present our results for the production of exotic mesons in p-p collisions at $\sqrt{s} = 7$ TeV and 14 TeV. Here we observe a smaller difference between the two choices of form factor when compared with the previous case. Moreover, in this case ($Z = 1$) we do not have any enhancement of the cross section compared with nuclear case case, leading to much smaller cross sections. Even so, these are non-negligible cross sections, of order of few pb, well within reach of present experiment detection techniques. We can calculate the rapidity distributions of mesons produced in two-photon fusion. We recall that

Table 2. Cross sections for exotic meson production in pp collisions using the theoretical decay rates presented in Ref. [13].

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (pb)		σ_F (pb)	
			7 TeV	14 TeV	7 TeV	14 TeV
X(3940), 0^{++}	3943	0.33	0.98	1.3	1.0	1.5
X(3940), 2^{++}	3943	0.27	4.0	5.6	4.1	5.7
X(4140), 0^{++}	4143	0.63	1.6	2.2	1.6	2.2
X(4140), 2^{++}	4143	0.50	6.2	8.7	6.4	8.9
Z(3930), 2^{++}	3922	0.083	1.2	1.7	1.3	1.8
X(4160), 2^{++}	4169	0.363	4.4	6.1	4.5	6.3
Y_p(3912), 2^{++}	3919	0.774	11.7	16.3	12.0	16.7
X(3915), 0^{++}	3919	0.20	0.60	0.84	0.62	0.86

$$\omega_1 = \frac{M_X}{2}\exp(Y), \quad \text{and} \quad \omega_2 = \frac{M_X}{2}\exp(-Y)\ . \tag{7}$$



(a) (b)

Figure 2. a) Cross section of the process $Pb\,Pb \to X(3915)$ as a function of the energy $\sqrt{s}$. $\sigma_{b_{min}}$ denotes cross sections evaluated with $F = 1$ and σ_F denotes cross sections evaluated with the form factors from Eqs. (5) and (6). b) Rapidity distribution of the produced $X(3915)$ with the same definitions as in a).

where ω_1 and ω_2 are the photon energies and M_X and Y are the mass and rapidity of the produced meson. In order to illustrate the behavior of the cross section with the collisions energy $\sqrt{s}$ we take the state $X(3915)$ as example. In Fig. 2a, we present the behavior of the production cross section in Pb-Pb collisions with $\sqrt{s}$ from 10 GeV to 100 TeV. In particular, this result shows us that we can reach large values of the cross sections at energies covered by the future colliders such as the FCC (Future Circular Collider) and the CEPC - SPPC (Circular Electron Positron Collider - Super Proton Proton Collider). In Fig. 2b, we show the rapidity distribution of the $X(3915)$ in Pb-Pb collisions at $\sqrt{s} = 5.5$ TeV. The width of the rapidity distributions and the total cross sections are the most useful quantities to be compared with theoretical predictions of particle production in UPCs in relativistic heavy ion collisions. This is attested by recent experimental results obtained at RHIC and at the LHC for the production of J/Ψ mesons [15]. Here we propose to extend these measurements beyond the production of well-established mesons and use UPCs to asses new and revealing information on exotic mesons and constrain theoretical predictions.

4 Conclusions

We have calculated the production cross sections of exotic mesons in UPCs at LHC energies due to two photon fusion. We have found large values for the cross sections in Pb-Pb and non-negligible values in p-p collisions. In the formalism used here the cross sections are directly proportional to the two-photon decay width. We have used the widths obtained for molecular configurations. If the exotic charmonium states are tetraquarks their production cross sections would be much larger and their detection much easier. In [16] we have extended this study to *pA* collisions. Our predictions for the rapidity distributions can also be of relevance for testing the theoretical models used in the calculations. We conclude that the experimental study is worth pursuing and that it can be useful to constrain decay widths evaluated theoretically and, ultimately, it can help in determining the configuration of the considered multiquark states.

Acknowledgments

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