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Production of QED bound states in photon induced processes

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In this contribution we study the production of QED bound states in processes photo-induced in hadronic colliders considering RHIC, LHC and FCC energies. We analyze the pp, pA and AA collisions considering an accurate treatment of the nuclear form factor and the absorptive corrections. We estimate the total cross section for photoproduction of singlet and triplet QED bound states in ultraperipheral collisions. For singlet QED bound states, we predicted cross section considering the rapidity ranges covered by frontal and forward detectors. In the analysis of production of parapositronium we estimate the impact of the Coulomb corrections.

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[*] Speaker

1. Hadronic collider as a photon collider

Recent studies have pointed that the QED bound states are sensitive to beyond Standard Model physics, given that they are purely electromagnetic systems. As the electromagnetic interaction is very well known, any deviation of the expected results can help in the search of New Physics. Currently, we can study of QED bound states in photon induced processes present in heavy ion collisions at the Large Hadron Collider (LHC) and Relativistic Heavy Ion Collider (RHIC) [1]. The advantage of these collisions are the strong electromagnetic field produced by heavy ions, which are associated with photon fluxes proportional to Z^2, leading large production rates for QED bound states [2].

Singlet and triplet QED bound states, denoted by $(l^+l^-)_S$ and $(l^+l^-)_T$ respectively, at the Born level can be produced by fusion of two and three photons. Thus, these states can be produced in hadronic collisions with hadrons as sources of almost real photons. With the equivalent photon approximation [2] we can write the total cross section of hadronic collisions for photoproduction of singlet and triplet QED bound states as

$$\sigma_{h_1 h_2 \to h_1 (l^+l^-)_S h_2} = \int \mathrm{d}^2\mathbf{r}_1 \mathrm{d}^2\mathbf{r}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2 \, N(\omega_1, \mathbf{r}_1) \, N(\omega_2, \mathbf{r}_2) \, \hat{\sigma}_{\gamma\gamma \to (l^+l^-)_S} S^2_{abs}(\mathbf{b}) \ , \tag{1}$$

and

$$\sigma_{h_1 h_2 \to h_1 (l^+l^-)_T h_2} = \int \mathrm{d}^2\mathbf{r}_1 \mathrm{d}\omega_1 \, N_1(\omega_1, \mathbf{r}_1) \, \hat{\sigma}_{\gamma h_2 \to (l^+l^-)_T h_2} S^2_{abs}(\mathbf{b}) + (1 \leftrightarrow 2) \ , \tag{2}$$

respectively. Where $N(\omega_i, r_i)$ is equivalent photon spectrum of hadron i [2]. $\hat{\sigma}$ is the elementary cross section which we factorize the total cross section and $S^2_{abs}(\mathbf{b})$ is the absorptive factor, which exclude the overlap between the colliding hadrons and allows to disregard the frontal and peripheral collisions. The equivalent photon spectrum dependent of transverse distance is essential to apply the absorptive correction, and can be expressed as a function of the nuclear form factor [2]. For a heavy ion as source of photons, we can obtain the realistic form factor with the Fourier transform of the charge density of the ion, constrained by experimental parameterization of Wood - Saxon distribution. Moreover, for proton as source of photon we consider the proton as a dipole. The realistic and dipole form factors are expressed, respectively, by

$$F(q^2) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR) - qR\cos(qR)\right]\left[\frac{1}{1+q^2a^2}\right] \quad \text{and} \quad F(q^2) = \frac{\Lambda^4}{(\Lambda^2+q^2)^2} \ , \tag{3}$$

with $a = 0.549\,(0.535)$ fm, $R = 6.63\,(6.38)$ fm and $A = 208\,(197)$ for Pb (Au) [3], and $\Lambda^2 = 0.71\,\mathrm{GeV}^2$ [4].

Our interest in this work is the ultraperipheral collisions, thus, we need of an absorptive correction to disregard the overlap nuclear, hence, excludes the collisions that have strong interactions. The absorptive correction that we are using is given by $S^2_{abs}(\mathbf{b}) = \Theta(|\mathbf{b}| - R_{h_1} - R_{h_2})$ [5], with R_{h_i} being the hadronic radius.

2. Photoproduction of QED bound states

At the Born level, the cross section for photoproduction of singlet QED bound states can be estimated by two distinct ways: with the Low's formula [6], given by

$$\hat{\sigma}_{\gamma\gamma\to(l^+l^-)_S}(\omega_1,\omega_2) = 8\pi^2(2J+1)\frac{\Gamma_{(l^+l^-)_S\to\gamma\gamma}}{M}\delta(4\omega_1\omega_2 - M^2)\,, \quad (4)$$

and with the Breit - Wigner's formula, expressed by

$$\hat{\sigma}_{\gamma\gamma\to(l^+l^-)_S}(\omega_1,\omega_2) = \frac{8\pi^2}{M^2}\frac{\Gamma^2_{(l^+l^-)_S\to\gamma\gamma}}{4(M-4\omega_1\omega_2)^2+\Gamma^2_{(l^+l^-)_S\to\gamma\gamma}}\,. \quad (5)$$

Both equations are written in terms of the two-photon decay width $\Gamma_{(l^+l^-)_S\to\gamma\gamma}$ and lead to the same result. The equivalence between Equations (4) and (5) can be shown integrating both equations in the spectrum of the invariant mass ($W = 4\omega_1\omega_2$), and is valid in the limit where $M \ll \Gamma_{(l^+l^-)_S\to\gamma\gamma}$, with $M = 2m_l$. An estimate for decay of singlet QED bound state is obtained in the non - relativistic limit, where $\Gamma(n^1S_0) = \alpha^5 m_l/2n^3$.

The cross section for the production of triplet QED bound state in nuclei ($\hat{\sigma}_{\gamma h}$) was obtained by [7] in the limit of high energy of incident photon, and can be expressed by

$$\hat{\sigma}_{\gamma h\to(l^+l^-)_T h}(W^2_{\gamma h} = 2\omega\sqrt{s_{NN}}) = 4\nu^2\sigma_0\zeta(3)B(\nu)\,, \quad (6)$$

where $\nu = Z\alpha$, $\sigma_0 = \pi\nu^2\alpha^4/m_l^2$ and the function $B(\nu)$ is a constant dependent on target nuclei.

3. Results

With the Equations (1) and (2) we estimate the total cross section at the Born level for photoproduction of singlet and triplet QED bound states. We analyze considering RHIC, LHC, HE-LHC and FCC energies in heavy ion collisions. The results of the total cross section are shown in Table 1. We predicted a large number of events (in parentheses) assuming the integrated luminosity per year in RHIC/LHC being 10 nb^{-1} and 110 nb^{-1} in the FCC. We shown that the production of singlet QED bound state is greater than the triplet QED bound state by factor of 14/14/2080 for positronium/muonium/tauonium in LHC energies. Thus, we have a motivate for an analysis more detailed of singlet states. With the change variables $(\omega_1,\omega_2) \to (Y, W_{\gamma\gamma})$ obtained in reference [8], we obtain a rapidity distribution for production of singlet QED bound states at the Born level, expressed by

$$\frac{d\sigma_S}{dY} = \int d^2\mathbf{r}_1 d^2\mathbf{r}_2 dW_{\gamma\gamma}\frac{W_{\gamma\gamma}}{2}\,\hat{\sigma}\left(\gamma\gamma\to(l^+l^-)_S;W_{\gamma\gamma}\right)N\left(\omega_1,\mathbf{r}_1\right)N\left(\omega_2,\mathbf{r}_2\right)S^2_{abs}(\mathbf{b})\,. \quad (7)$$

With the Equation (7), we estimate the rapidity distribution for production of singlet QED bound states at the Born level in heavy ion collisions, shown in Figure 1. Moreover, the Equation (7) allows obtain rapidity cuts for cross section considering frontal (-2.5 ≤ Y ≤ 2.5) and forward (2.0 ≤ Y ≤ 4.5) ranges. The cross section with rapidity cuts is shown in Table 2 for pp, pA and AA collisions for production of singlet states.

	Parapositronium	**Paramuonium**	**Paratauonium**
AuAu ($\sqrt{s_{NN}}$ = 0.2 TeV)	112.1×10^{12} (11.2×10^{8})	150.0×10^{6} (1.5×10^{3})	3.8×10^{3} (0.04)
PbPb ($\sqrt{s_{NN}}$ = 5.02 TeV)	333.2×10^{12} (33.3×10^{8})	1297.0×10^{6} (12.9×10^{3})	832.7×10^{3} (8.3)
PbPb ($\sqrt{s_{NN}}$ = 10.6 TeV)	400.3×10^{12} (40.0×10^{8})	1796.0×10^{6} (17.9×10^{3})	1450.0 ×10^{3} (14.5)
PbPb ($\sqrt{s_{NN}}$ = 39.0 TeV)	537.6×10^{12} (59.1×10^{9})	2945.0×10^{6} (32.4×10^{4})	3142.0×10^{3} (345.6)
	Orthopositronium	**Orthomuonium**	**Orthotauonium**
AuAu ($\sqrt{s_{NN}}$ = 0.2 TeV)	6.7×10^{12} (0.67×10^{8})	21.2×10^{6} (0.22×10^{3})	0.02×10^{3} (0.19×10^{-3})
PbPb ($\sqrt{s_{NN}}$ = 5.02 TeV)	23.3×10^{12} (2.3×10^{8})	90.8×10^{6} (0.91×10^{3})	0.40×10^{3} (4.1×10^{-3})
PbPb ($\sqrt{s_{NN}}$ = 10.6 TeV)	27.9×10^{12} (2.8×10^{8})	110.5×10^{6} (1.1×10^{3})	0.56×10^{3} (5.6×10^{-3})
PbPb ($\sqrt{s_{NN}}$ = 39.0 TeV)	37.0×10^{12} (4.0×10^{8})	150.9×10^{6} (1.6×10^{3})	0.89×10^{3} (98.3×10^{-3})

Table 1: Total cross sections in fb (Event rates per year) for the production of singlet and triplet QED bound states in heavy ion collisions.

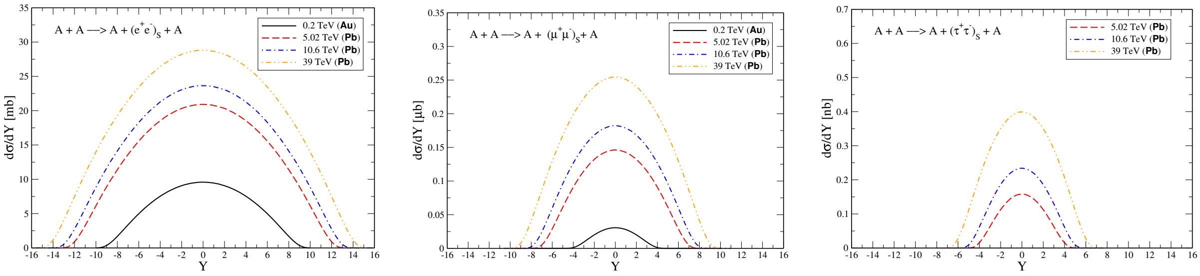

Figure 1: Rapidity distributions for the photoproduction of singlet QED bound states in AA collisions.

	Parapositronium		**Paramuonium**		**Paratauonium**	
	$-2.5 \leq Y \leq 2.5$	$2.0 \leq Y \leq 4.5$	$-2.5 \leq Y \leq 2.5$	$2.0 \leq Y \leq 4.5$	$-2.5 \leq Y \leq 2.5$	$2.0 \leq Y \leq 4.5$
pp ($\sqrt{s_{NN}}$ = 0.5 TeV)	2.2×10^{6}	1.0×10^{6}	13.7	5.2	11.9 ×10^{-3}	2.0 ×10^{-3}
pp ($\sqrt{s_{NN}}$ = 14 TeV)	3.6×10^{6}	1.7×10^{6}	34.0	15.3	57.7 ×10^{-3}	22.8 ×10^{-3}
pp ($\sqrt{s_{NN}}$ = 27 TeV)	3.9×10^{6}	1.9×10^{6}	39.0	17.8	70.4 ×10^{-3}	29.1 ×10^{-3}
pp ($\sqrt{s_{NN}}$ = 100 TeV)	4.6×10^{6}	2.2×10^{6}	50.0	23.3	99.1 ×10^{-3}	43.5 ×10^{-3}
pPb ($\sqrt{s_{NN}}$ = 8.8 TeV)	19.4×10^{9}	9.7×10^{9}	157.0×10^{3}	78.6×10^{3}	206.3	105.6
pPb ($\sqrt{s_{NN}}$ = 18.8 TeV)	21.4×10^{9}	10.7×10^{9}	184.7×10^{3}	92.9×10^{3}	273.4	139.0
pPb ($\sqrt{s_{NN}}$ = 63 TeV)	25.7×10^{9}	12.9×10^{9}	248.4×10^{3}	124.8×10^{3}	431.1	217.8
AuAu ($\sqrt{s_{NN}}$ = 0.2 TeV)	46.6×10^{12}	20.4×10^{12}	125.5 ×10^{6}	19.7 ×10^{6}	3.8 ×10^{3}	3.6
PbPb ($\sqrt{s_{NN}}$ = 5.02 TeV)	103.1×10^{12}	48.2×10^{12}	693.9 ×10^{6}	269.3 ×10^{6}	671.0 ×10^{3}	130.2 ×10^{3}
PbPb ($\sqrt{s_{NN}}$ = 10.6 TeV)	116.7×10^{12}	55.0×10^{12}	874.5 ×10^{6}	359.4 ×10^{6}	1044.0 ×10^{3}	280.0 ×10^{3}
PbPb ($\sqrt{s_{NN}}$ = 39.0 TeV)	142.5×10^{12}	67.9×10^{12}	1236.0 ×10^{6}	539.9 ×10^{6}	1867.0 ×10^{3}	663.1 ×10^{3}

Table 2: Cross sections (in fb) for the photoproduction of singlet QED bound states in pp, pA and AA collisions considering the central and forward rapidity ranges.

The Equation (1) allows analyze the cross section at Born level. Here we estimate higher orders corrections of parameter $\nu = \alpha Z$, which is ≈ 1 for gold and lead. One estimate for Coulomb corrections for production of parapositronium is developed in references [7, 9]. The rapidity distributions with an estimate for Coulomb corrections is presented in Figure 2 for pA and AA collisions.

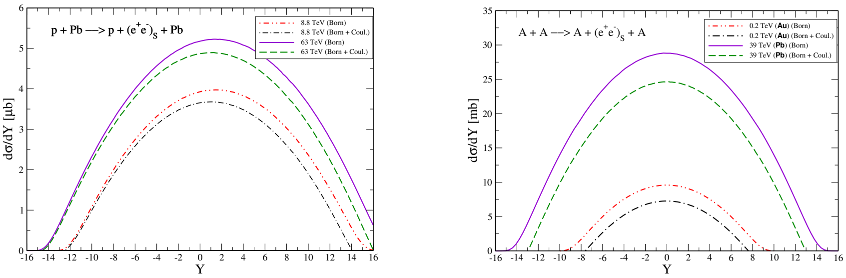

Figure 2: Rapidity distributions for the photoproduction of parapositronium in pPb (left) and heavy ion (right) collisions calculated at the Born level and including the Coulomb corrections.

4. Conclusion

In this work we analyze the photoproduction of QED bound states in pp, pA and AA high energy collisions. We shown that the production rates are of the order of $10^9/10^4/10^0$ per year for $(e^+e^-)_S/(\mu^+\mu^-)_S/(\tau^+\tau^-)_S$ in heavy ion collisions at LHC, being possible a future experimental analysis for $(e^+e^-)_S$ and $(\mu^+\mu^-)_S$. We also presented that the Coulomb corrections for photoproduction of parapositronium is very important, being responsible by decrease the total cross section in $\approx 22\%$ (13%) in heavy ion collisions at RHIC (FCC) energies, and $\approx 7\%$ (5%) in pPb collisions at LHC (FCC) energies. The future experimental analysis can be useful to valid this model for Coulomb corrections, and observe the muonium for the first time.

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