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Production of magnetic monopoles and monopolium in peripheral collisions

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The exclusive production of magnetic monopoles and the bound states of magnetic monopoles (the monopolium) by the photon fusion is considered in different high energy processes. More specifically, we calculate the total cross sections of the ultraperipheral elastic collisions of electron-electron, proton-proton, and lead-lead in present and future colliders, comparing with the previous results found in the literature. Our results indicate that magnetic monopoles or the bound states, if both exist, can be measurable in future electron-electron colliders.

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I. INTRODUCTION

With the discovery of the Higgs boson [1,2], the last remaining unobserved particle of the Standard Model (SM) was found. Now the interest turns to the search for signals of particles not included in the SM or beyond Standard Model (BSM) particles. One of these predicted BSM particles, the magnetic monopole, was proposed by Dirac [3], giving a natural way to explain the quantization of electric charge. The magnetic monopole was also predicted in Grand Unified Theories (GUT) [4,5] (see also [6]). Unfortunately, this predicted mass is very large and, until now, several experimental searches have not confirmed its existence, giving only experimental limits on the mass and charge. Recent results on monopole charge and mass have come from MOEDAL [7,8], a dedicated experiment on highly ionizating exotic particles in the LHC [9]. For a revision of the state-of-the-art theoretical and experimental status of magnetic monopole see [10,11]; a bibliography compilation can be found in [12,13].

In this work, we analyze the production of magnetic monopoles and the bound state, the monopolium [14], by photon fusion in peripheral hadronic (proton-proton and ion-ion) collisons in present high energies at the LHC and also in electron-positron collisions expected at the CLIC (see [15]). In particular, we consider the central exclusive production where the projectiles do not dissociate and the particle is produced in the central region of rapidity of the detector, giving a clean experimental signal of this process. We compare our results with the previous ones in pp collisions [16–18] and we present a prediction for the production of pairs of monopole/antimonopole and monopolium in $Pb-Pb$ collisions at the LHC and also in electron/positron collisions in the planned CLIC.

Previous BSM particle searches with the same mechanism include the radion [19], a particle related with the Randall-Sundrum scenario of large extra dimensions, and the dilaton, a pseudo-Nambu-Goldstone boson related with spontaneous breaking of scale symmetry [20].

This paper is organized as follows. In the next session, we present an overview of the theory of magnetic monopoles with a short review of cross section production of a pair of monopoles and monopolium. In Sec. III, we present the mechanism of central production in peripheral collisions with the central system of particles created by a pair of high energy photons. The results of the calculation are shown and discussed in Sec. IV. Finally, a summary and the conclusions are presented in Sec. V.

II. MAGNETIC MONOPOLES AND MONOPOLIUM

Since the inception of Classical Electrodynamics it is clear that the Maxwell equations are not symmetric in relation to the electric charges. The possibility of existence of isolated magnetic charges, the magnetic monopoles, has interesting consequences, both at classical and quantum levels [21,22]. Probably the most important is the Dirac quantization charge relation, which established that if the magnetic charge exists, then the electric charge is quantized [3]. Meanwhile, the experimental difficulties for the experimental observation of isolated magnetic monopoles suggest the existence of a bound state of monopoles, the monopolium [23,24].

We revisit the results of production of monopoles in pp collisions at the LHC energies [16,17,25,26] and investigate the same process in ion-ion collisons at the LHC and electron collisions at the CLIC. In previous works, the production in nuclear collisions was proposed in [27,28] in the context of thermal quark-gluon plasma and in [29] the authors obtain bounds of the monopole mass from heavy ion collisions and neutron stars. Ginzburg and Schiller [25] consider the monopole pair production in electron-positron collisions for planned colliders.

One of the ingredients of the calculation is the cross section of the process of fusion of two photons into a

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monopole/antimonopole pair or a monopolium. Unfortunately, due to the high values of the coupling, a true perturbative calculation for all energies is questionable and therefore, the results presented here can be seen as an estimation for the cross sections. The coupling of the monopoles with photons can be quantified by two different forms. First, Dirac himself takes the coupling constant as $\alpha_m = g^2/4\pi$ whereas the so-called beta coupling considers $\alpha_m = (\beta g)^2/4\pi$ where β is the speed of the monopole (in natural units) [21]. We use both expressions in our results.

In the case of production of an antimonopole-monopole pair, the cross section can be obtained from the QED fundamental process of annihilation of a lepton pair into a pair of photons, changing the relevant physical quantities: coupling, charges, and masses. In the center of mass frame, the cross section is

$$\sigma_{\gamma\gamma\to\bar{m}m} = \frac{\pi\alpha_m^2(1-\beta^2)}{2m^2}\left[(3-\beta^4)\ln\left(\frac{1+\beta^2}{1-\beta^2}\right) - 2\beta(2-\beta^2)\right], \tag{1}$$

where m is the monopole mass. For the monopolium production, we use the known result of the cross section for the production of a massive resonance,

$$\sigma_{\gamma\gamma\to M} = \frac{4\pi}{\hat{s}}\frac{M^2\Gamma(\sqrt{\hat{s}})\Gamma_M}{(\hat{s}-M^2)^2 + M^2\Gamma_M^2}, \tag{2}$$

where $M = 2m + E_{\mathrm{bound}}$ is the monopolium mass, $\Gamma_M = 10$ GeV [24], and

$$\Gamma(\sqrt{\hat{s}}) = \frac{8\pi\alpha_m^2}{m^2}|\psi_M(0)|^2$$

is the decay width in a pair of photons with $\psi_M(0)$ being the value of the wave function in the origin of the bound system of the monopole/antimonopole. The values of $\psi(0)$ and E_{bound} are obtained through the solution of the radial Schrödinger equation for the Coulomb-type potential [24]

$$V(r) \simeq -\frac{g^2}{4\pi}\frac{1}{r}. \tag{3}$$

For this potential, the energy eigenvalues are

$$E_n = -\left(\frac{1}{8\alpha_{elm}}\right)^2\frac{m}{n^2} \tag{4}$$

and the value of wave eigenfunctions in the origin is (without angular momentum)

$$\psi_{n00} = \frac{1}{\sqrt{\pi}}\left(\frac{m}{8\alpha_{elm}n}\right)^{3/2}. \tag{5}$$

The condition of the bound state, $0 \leq 2m + E_n \leq 2m$, imposes a condition on allowed values of n. With the above eigenvalues, only values $n \geq 13$ are possible and we use $n = 13$.

Recently, the authors of [30] proposed a monopolium model with finite size based on the 't Hooft-Polyakov solution and $U(1)$ lattice gauge theory, which results in a binding potential with a linear term, similar to the Cornell potential of the quarkonium states in QCD [31]. A similar approach was also proposed in [32]. In a future work, we will consider the numerical solutions for the eigenstates of monopolium for this class of confining potentials.

Related with the above process, an experimental signal of the monopolium production is the two photon production with the monopolium being a massive ressonance state, $\gamma\gamma \to M \to \gamma\gamma$. A possible background for this process is the production of two photons by a loop of leptons/quarks, the cross section of which can be estimated by results from the Standard Model.

III. THE FORMALISM OF PERIPHERAL COLLISIONS

The process of central production of particles [33,34] has attracted much attention in recent years, especially with the start of the LHC operation and the dedicated experiments to its observations [35]. Beyond the Higgs boson, several other particles can be produced, some in expressive numbers, inside this mechanism.

The process can be described [33,34,36] as the collision of two hadrons (or leptons) that interact themselves by the gauge boson exchange (see Fig. 1). In exclusive channels, the projectiles remain intact after the interaction and the gauge bosons recombine, generating a massive state with the same quantum numbers of the vacuum, resulting in rapidity gaps in the detector.

This mechanism presents some advantages, such as, for example, a very clean experimental signature, an improved mass resolution, and a suppressed background. From another side, there exist disadvantages: the theory is not free of divergences, the measure of cross sections is laborious, requiring detectors installed away from the interaction point [37], and the experimental signal is low.

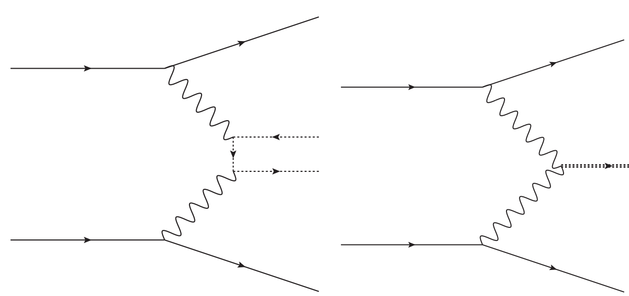

FIG. 1. Production of a monopole/antimonopole pair (left) and monopolium (right). The straight lines are the projectiles, the wavy lines, photons, and the dotted lines, monopoles or monopolium.

Our focus is on photon processes in peripheral collisions [38–40]. This process is described using the photon equivalent approximation. In this picture, an electric charged particle with high energy has the electromagnetic fields concentrated in its transverse region and the fields can be substituted by an equivalent photon flux. These photons interact to produce a massive state. In peripheral collisions, the impact parameter is larger than the sum of radii of the particles, avoiding frontal collisions and thus high particle multiplicities produced in the interaction.

We use the most simple model [41] for an estimation for total cross sections in all the cases: electron-electron, proton-proton, and ion-ion collisions,

$$\sigma_{\mathrm{tot}} = \int_{M_{\gamma\gamma}^2/s_{NN}}^{1} dx_1 f_A(x_1) \int_{M_{\gamma\gamma}^2/x_1 s_{NN}}^{1} dx_2 f_B(x_2)\sigma_{\gamma\gamma}(\hat{s}), \quad (6)$$

where $M_{\gamma\gamma}$ is the mass of the central produced system, s_{NN} is the center-of-mass energy of the projectiles, x_i is the fraction of the energy of the photon i, $\hat{s} = x_1 x_2 s_{NN}$, and $f(x)$ is the photon energy spectrum produced by a charged particle. The Weizsacker/Williams [42] expression for the photon spectrum (used for ion collisions) is

$$f_{\mathrm{WW}}(x) = \frac{\alpha_{elm} Z^2}{\pi}\frac{1}{x}[2YK_0(Y)K_1(Y) - Y^2(K_1^2(Y) - K_0^2(Y))], \quad (7)$$

where $Y = xM_A b_{\mathrm{min}}$, α_{elm} is the fine structure constant, Z is the atomic number of the projectile, M_A is the mass of projectiles, $b_{\mathrm{min}} = 1.2 fm A_n^{1/3}$ is the minimum impact parameter (A_n is the atomic mass number), and K_i is the modified Bessel functions. For proton collisions, we use the Dress and Zeppenfeld photon spectrum [43] given by

$$f_{\mathrm{DZ}}(x) = \frac{\alpha_{elm} Z^2}{2\pi x}[1 + (1-x)^2]\left[\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right], \quad (8)$$

where

$$A = 1 + \frac{0.71\ \mathrm{GeV}^2}{Q_{\mathrm{min}}^2}, \qquad Q_{\mathrm{min}}^2 \simeq \frac{m_p^2 x^2}{1-x}.$$

For the electron case, we use the expression of Frixione [44],

$$f_e(x) = \frac{\alpha_{elm}}{2\pi}\left\{2m_e^2 x\left[\frac{1}{q_{\mathrm{max}}^2} - \frac{1}{q_{\mathrm{min}}^2}\right] + \frac{1 + (1-x)^2}{x}\log\left(\frac{q_{\mathrm{min}}^2}{q_{\mathrm{max}}^2}\right)\right\}, \quad (9)$$

where

$$q_{\mathrm{max}}^2 = -\frac{m_e^2 x^2}{1-x}, \qquad q_{\mathrm{min}}^2 = -\frac{m_e^2 x^2}{1-x} - E^2(1-x)\theta_c^2$$

with m_e being the electron mass, E the energy beam, and $\theta_c = 30$ mrad.

Some issues should be considered for this process: the rise of the photon flux with atomic number of projectiles (Z^4), the low luminosity in ion-ion collisions, the Coulomb dissociation and excited states of projectiles [45,46], the nuclear charge form factor that modifies the photon flux, and the overlap of hadron tails in the collision.

IV. RESULTS

We calculate the cross section as a function of the mass of the central system at fixed center-of-mass energies corresponding to different colliders. We also consider the

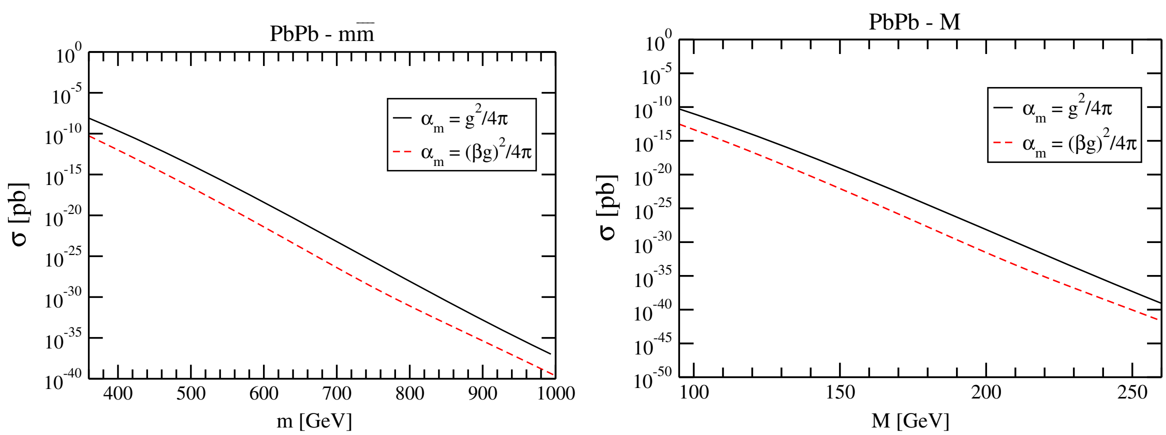

FIG. 2. Total cross section for the production of monopole antimonopole (left panel) and monopolium (right panel) in lead-lead collisions at the LHC energies as a function of the mass of monopole/monopolium. The (black) solid line is the result with Dirac coupling and the (red) dashed line is with the beta coupling.

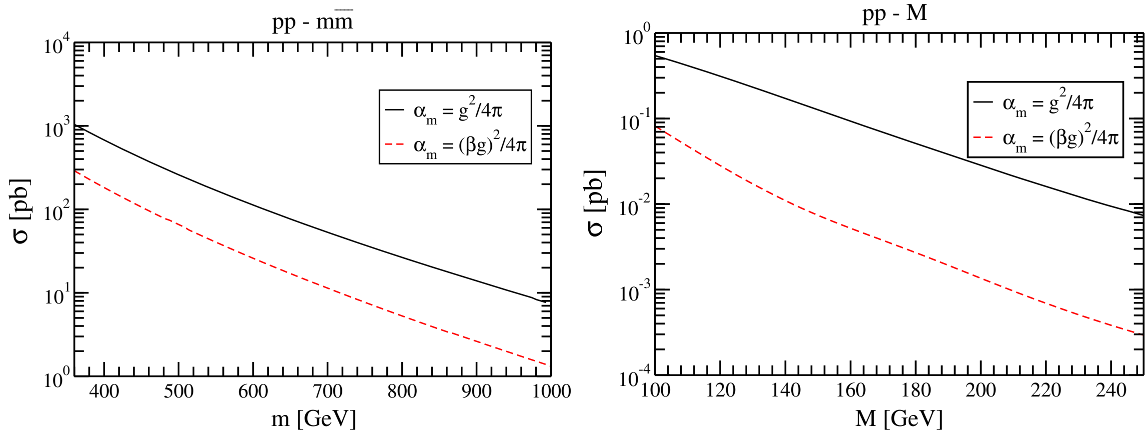

FIG. 3. Total cross section for the production of monopole antimonopole (left) and monopolium (right) in proton-proton collisions at the LHC energies as a function of the mass of monopole/monopolium. The (black) solid line is the result with Dirac coupling and the (red) dashed line is with the beta coupling.

two different magnetic coupling constants, the Dirac one, $\alpha_m = g^2/4\pi$, and the beta one, $\alpha_m = (\beta g)^2/4\pi$. First, we present in Fig. 2 the results of lead-lead collisions at the LHC energy ($\sqrt{s} = 5.5$ TeV) for the production of monopole/antimonopole pairs and monopolium. As expected, the cross section decreases with the increase of the mass and the values are very low, except for the enhancement in atomic number (Z^4) in the photon luminosity of the projectiles. As the massive central system requires a great amount of energy, there are very few energetic photons produced by an ionic projectile, diminishing the cross section.

Next, we calculate the same quantity for proton-proton collisions in the LHC energy ($\sqrt{s} = 14.0$ TeV) and display the results in Fig. 3. The general features of the above result are the same as in the lead-lead collision case, except that the cross section in this case is greater than the previous one. Comparing different produced particle scenarios, the monopolium has a cross section III orders of magnitude smaller. In comparison with the previous results [16–18], the present one agrees with the listed previous results for both produced particles.

At last, we present in the Fig. 4, the results of the cross section for the production of monopoles and monopolium at electron-positron collisions at future CLIC energies [15] ($\sqrt{s} = 3.0$ TeV). Again, in comparison with the results from hadron projectiles, we obtain the same behavior as a function of the central produced system but with a significantly larger cross section. As in previous cases, due to the large mass of monopolium, this cross section is smaller than the monopole/antimonopole case.

For all cases considered above, the cross section is quite sensitive to the expression of the magnetic coupling, being that the Dirac coupling is greater by a difference of about 1 order of magnitude in all the cases.

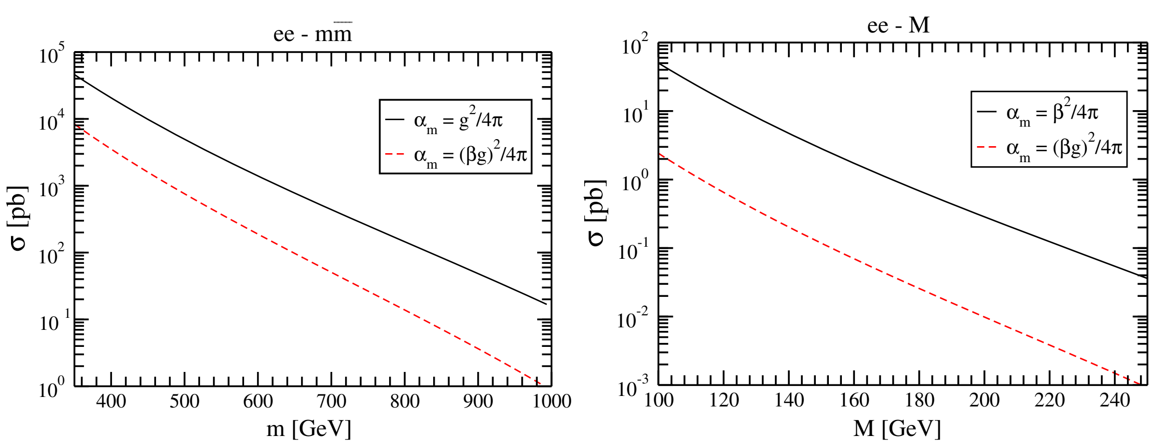

FIG. 4. Total cross section for the production of monopole antimonopole (left) and monopolium (right) in electron-electron collisions at planned CLIC energies as a function of the mass of monopole/monopolium. The (black) solid line is the result with Dirac coupling and the (red) dashed line is with the beta coupling.

V. SUMMARY AND CONCLUSIONS

In this work, we consider the central exclusive production of (Dirac) magnetic monopoles and the bound state of a monopole and antimonopole, the monopolium, for hadronic and eletronic collissions at the LHC and (planned) CLIC energies. We present a prediction for the cross sections for lead-lead collisions and electron-electron collisions and, for the proton case, a comparison with the previous results.

In the treatment of the production of magnetic monopoles there exist several drawbacks. One of them is the strong coupling with photons, which does not justify a perturbative calculation. Another problem is the absence of direct experimental observation of magnetic monopoles. In the literature, only estimation of mass and charge can be found. Another disadvantage is the large mass of the central state, already delimited by the experimental results available. In the present formalism, the production of the central states is disfavored due to the very small number of equivalent photons with required energy to produce these particles. In the heavy ions case, we have large projectile radii and, as we are interested in exclusive processes, the number of photons diminishes quickly, nullifying the gain in atomic number Z in comparison with proton collisions and also in this case, we have a low luminosity in the collider.

However, besides the above issues, the results are promising in the case of electronic and proton collisions. In particular, the production in an electron-electron collider will be measurable with a significant rate of events, even in the case of exclusive production, based on the planned luminosity of the CLIC collider and the above results for the cross section, for a large gap of monopole mass values. Comparing the proton and electron processes, the first one could include inclusive and inelastic processes, which raises the total cross section, while the electron collisions only have the process considered in this work, which gives a very clean experimental signal.

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