PROCEEDINGS OF SCIENCE

Magnetic Monopoles in pp Collisions

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The aim of the study is to propose a review and establish limits for the production of the Dirac magnetic monopole and monopolium in pp collisions. The mass range used for the monopole is based on the last results of ATLAS and MoEDAL, and the simulations are made for the current LHC anergies and for the energies of the future colliders HE-LHC and FCC. The cross sections are calculated for the usual velocity dependent coupling and the more recent proposed coupling with magnetic moment dependence, and the advantages in using each of the couplings and the monopolium as an indirect measure are discussed.

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1. Introduction

In his papers of 1931[1] and 1948[2], Dirac proposed that magnetic monopoles are consistent with quantum mechanics and responsible for explaining the charge quantization by the Dirac quantization condition (DQC)

$$eq = 4\pi n, \;\; n \in \mathbb{Z}. \tag{1}$$

The Dirac's monopole does not have definite mass nor spin, and due to the DQC the magnetic coupling $\alpha_m \propto g^2$ can not be expanded perturbatively, which has lead to the development of effective models. Due to the lack of experimental comprovation of magnetic monopoles, this unknown particle was incorporated in other theories rather than only QED, such as the electroweak[3] and unification theories[4][5]. Another model[6] suggests that magnetic monopoles are not seen directly because their strong coupling forces them to form a bound state. The Monopolium, as it was called, could have a much lower mass and still be present in cosmic radiation as a relic of monopoles produced in the early universe.

The recent experiments focused in the monopole search in hadron collisions are placed at the LHC, in the ATLAS[8] and MoEDAL[7] experiments. Since there was no detection of these particles, their results give lower bounds on the monopole mass for different spin and charges, considering monopole production by photon fusion and Drell Yan in pp collisions. In this work, the monopole pair (monopole-antimonopole) production is studied for the two processes considered in the current experiments, assuming a Dirac's monopole with spin 1/2 and using two effective coupling models. The spin 0 monopolium production is investigated for the photon fusion process. The recent results concerning mass bounds are going to be considered for the estimates, combined with predictions for the future colliders HE-LHC[9] and FCC[10]. An extended version of this work can also be seen in [11].

2. Magnetic Couplings

One of the first effective couplings proposed to replace the magnetic charge, in order to treat it with perturbative methods, was the velocity dependent coupling[12]

$$\alpha_m = \frac{g^2\beta^2}{4\pi}, \tag{2}$$

with β the monopole velocity in natural units. In this model, a moving monopole is treated as an electron with charge $g\beta$ in analogy with the behavior of a moving electron producing a magnetic field. Since β assumes values from 0 to 1, the coupling can only be expanded perturbatively for slowly moving monopoles, when $\alpha_m < 1$.

A more recent model[13] proposes an addition of a magnetic moment dependence in the velocity dependent coupling. This dependence is given in terms of a parameter κ, inserted in the magnetic moment of a monopole

$$\mu_m = \frac{g\beta}{2m} 2(1 + 2\kappa m)\mathbf{S}, \tag{3}$$

where m is the monopole mass and $\mathbf{S}$ its spin, and the coupling will now be $g\beta$ plus a term proportional to κ. The main advantage in adding the magnetic moment dependence is to expand the perturbative limits of the coupling, that now are $\kappa m \gg 1$ and $\beta \ll 1$.

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3. Monopole and Monopolium production in pp collisions

The usual formalism for proton-proton collisions is presented in [15], where the cross sections are written in a factorized form containing the cross section of the subprocess and the necessary distribution functions and photon fluxes. The total cross section for a photon fusion process is written as the sum of the elastic, semielastic and inelastic contribution, while in Drell Yan the cross section is given by only one term, summed over all quark flavors. For the elastic photon flux of the proton it was used the expression in [16], and the equivalent photon spectrum of quarks for the non-elastic terms and Drell Yan is also given in [15]. For the proton structure function, it was used the Cteq6-1L parametrization [17] with scale $Q^2 = \hat{s}/4$, to compare with the results in previous works[18][19].

The cross sections for the subprocess of monopole production, in the velocity-dependent model, are obtained by replacing $e \rightarrow g\beta$ in the usual cross sections for electron-positron production, as can be seen in [15] and [18]. Once including the magnetic term, the cross sections can be recalculated using computational resources, as done in [13]. For the monopolium, the production rate can be found by solving the Schrödinger equation with the interaction potential[14]

$$V(r) = -g^2 \left(\frac{1 - e^{-\mu r}}{r} \right), \tag{4}$$

where $\mu = 2m/g^2$ describes the interaction when $r \rightarrow 0$, and then obtaining groundstate wavefunction. The Breit-Wigner cross section takes the form as in [19].

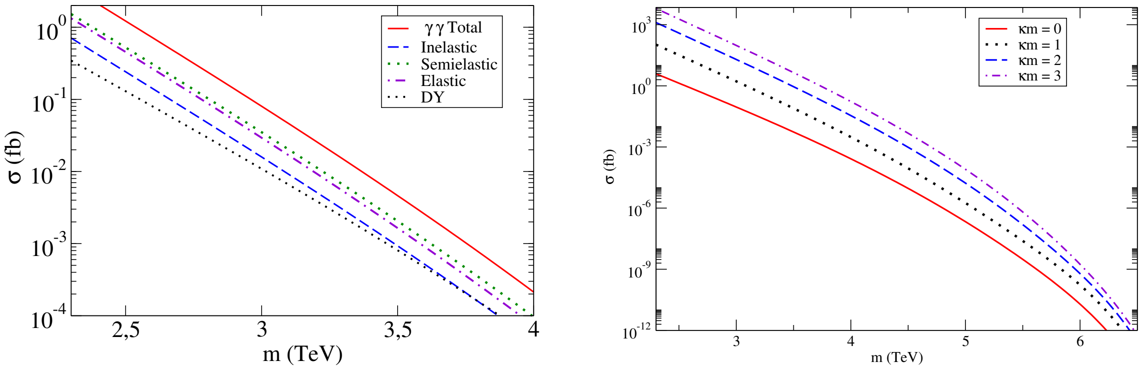
4. Results and Conclusions

In Fig. 1 are the results for monopole production at the center of mass energy $\sqrt{s} = 14$ TeV, as in the LHC. The $\gamma\gamma$ process is dominant for masses up to 5.5 TeV, and the cross sections decays rapidly for $m > 4$ TeV. The results in [13] point out that the total cross sections increase with the parameter κ, and the same behavior is achieved for the entire mass range. The cross section for $\kappa m = 3$ is up to 10^2 times higher than the one for $\kappa m = 0$ only in photon fusion and around 10 times higher in Drell Yan.

In Fig. 2 are the results for monopolium production in the LHC, and it can be seen that the cross section decreases with a lower rate when the monopolium mass is raised, compared to the monopole pair production. The production is also increased for higher values of monopole mass, supporting the results in [19] and [20].

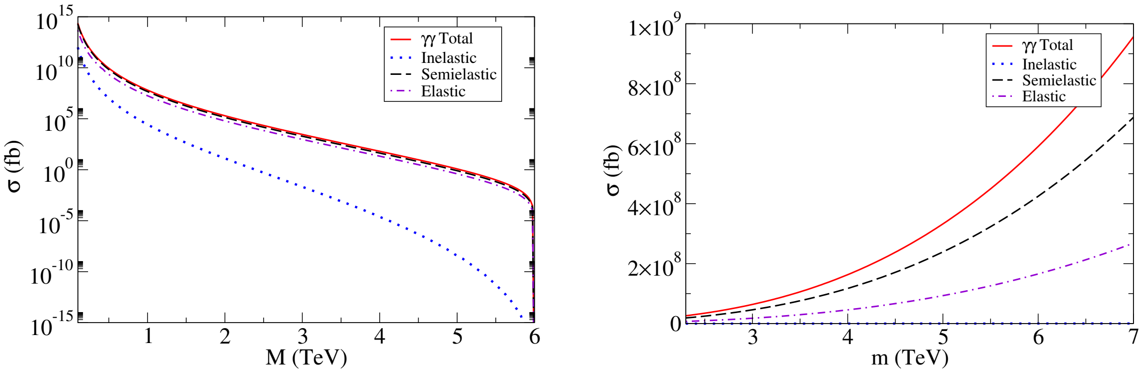
Parameters	LHC	HL-LHC	HE-LHC	FCC
Beam Energy	14	14	27	100
Peak Luminosity	1	5	16	5-30
Luminosity per year	55	350	500	250-1000

Table 1: Main parameters[9][21] of the LHC, HE-LHC and FCC colliders. The beam energy is given in TeV, the peak luminosity in 10^{-5} fb^{-1}/s, and the luminosity per year in fb^{-1}.



(a) $\kappa m = 0$ **(b)** DY + $\gamma\gamma$

Figure 1: Monopole pair production in pp collisions $\sqrt{s} = 14$ TeV: (a) production with $\kappa m = 0$, (b) production considering both Drell Yan and photon fusion for different values of κm

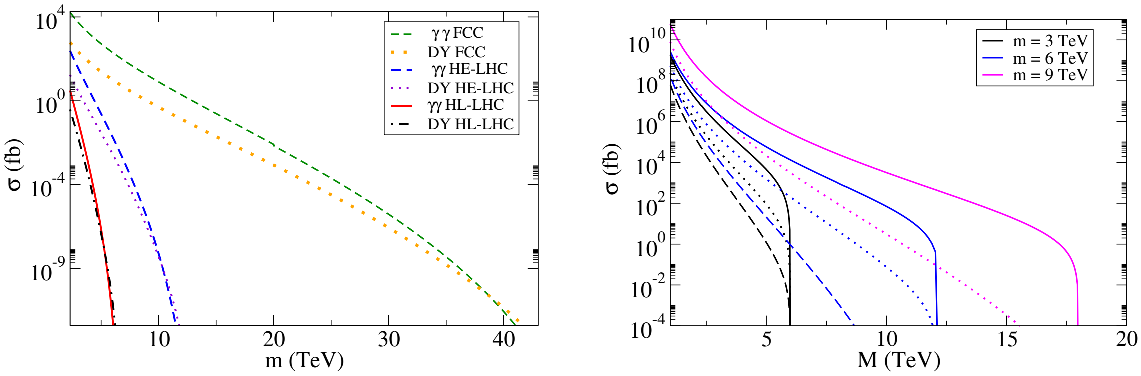


(a) $m = 3$ TeV **(b)** $M = 1$ TeV

Figure 2: Monopolium production via photon fusion in pp collisions $\sqrt{s} = 14$ TeV, for fixed (a) monopole and (b) monopolium masses.

The main parameters of the colliders considered in the simulations are shown in Table 1, and in Fig. 3 are the results for monopole and monopolium production. For $m \gtrsim 10$ TeV and $m \gtrsim 40$ TeV in the HE-LHC and FCC simulations, respectively, the Drell Yan dominates over photon fusion, as shown in Fig. 3a. Considering a minimum of 1 event per year, for the monopolium production the limits of detection in LHC are $M \lesssim 5$ TeV, for a fixed monopole mass of $m = 3$ TeV. For the HE-LHC and FCC energies and luminosities this limit is close to the maximum possible mass, $M = 6$ TeV. For a better estimate of production and detection, it is necessary to analyze the possible decay channels of the monopolium[22][23].

In Table 2 are the expected number of events for different monopole masses, considering both Drell Yan and photon fusion with the velocity dependent coupling. Considering again a limit of one event per year, the detection limits are around $m < 3$ (3.5) TeV for the LHC (HL-LHC), $m < 6$ TeV for the HE-LHC and $m < 20 - 21$ TeV for the FCC. It can be concluded that monopoles have few chances to be detected still in the LHC, and the direct detection of heavier monopoles could be made in the future accelerators. The study of the magnetic moment dependence, although preliminary, could lead to more applicability and promising predictions.



(a) $m\bar{m}$ production **(b)** Monopolium production

Figure 3: Monopole and monopolium production in different accelerators, with $\kappa m = 0$.

Mass (TeV)	LHC	HL-LHC	HE-LHC	FCC
3	< 10	< 40	$< 3 \cdot 10^4$	$< 2 \cdot 10^7$
5	$< 2 \cdot 10^{-5}$	$< 8 \cdot 10^{-5}$	< 150	$< 2 \cdot 10^6$
20	0	0	0	< 10
30	0	0	0	$< 2 \cdot 10^{-3}$

Table 2: Number of events of monopole production (Drell Yan + photon fusion) per year, for different monopole masses.

The future results given by the experiments, followed by improvements on the current models, will dictate the next steps in the search for magnetic monopoles. If the lower bounds continue to grow, this may indicate that one has to look for other possible monopole sources.

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