Magnetic Monopoles and Monopolium in pp Collisions

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Outlook

- The Dirac Monopole and the Quantization Condition
- Effective Couplings
- Monopolium
- Monopole production in pp collisions
  - Drell Yan pair production
  - Photon fusion pair production
  - Monopolium production by photon fusion
  - Energy distributions
- Perspectives in Future Accelerators

The Dirac Monopole and The Quantization Condition

- In 1931[1] Dirac showed that magnetic monopoles are consistent with quantum mechanics
- By arguments about the uncertainty of the wave function's phase, he proposed the quantization condition

$$eg = 4\pi n, \;\; n \in \mathbb{Z}$$

- Properties of the Dirac monopole
  - Undefined mass and spin
  - Big coupling $\alpha_m \propto g^2 \gg 1$
  - Can not be calculated perturbatively, which lead to effective models for the monopole coupling

[1] P. A. M. Dirac, Proc. Roy. Soc. Lon. A 133, 60 (1931).

Magnetic Couplings

- **Velocity-Dependent Coupling**: the moving monopole is treated as an electric charge (E/B symmetry)

  The monopole can be taken in the place of an electron in many processes by the simple replacement $e \to g\beta$

  Perturbative expansions can be made when $\beta \ll 1$

- **κ-dependent Coupling**: a magnetic moment term is added to the $g\beta$ coupling[2], with the magnetic moment given by

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

  where m and $\mathbf{S}$ are the mass and spin of the monopole.

  Perturbative methods can be used in the limit $\kappa m \gg 1$ and $\beta \ll 1$.

[2] S. Baines, N. E. Mavromatos, V. A. Mitsou, J. L. Pinfold and A. Santra, Eur. Phys. J. C **78**, no. 11, 966 (2018).

Monopolium

Theorized bound state[3] between a monopole and an antimonopole

- The coupling is just g - the monopole does not couple to photon, only to an antimonopole
- Can be described[4] by a potential of the form

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

Considering a spin 0 monopolium (the simplest case), the wave function will be (in the ground state)

$$|\psi_M(0)|^2 = \frac{1}{\pi} \left(2 - \frac{M}{m} \right)^{3/2} m^3,$$

with $M = 2m + E_{binding}$ the monopolium mass

[3] C. T. Hill, Nucl. Phys. B **224**, 469 (1983).

[4] L. N. Epele, H. Fanchiotti, C. A. Garcia Canal and V. Vento, Eur. Phys. J. C **56**, 87 (2008).

Monopole and Monopolium Production in pp Collisions

Following the factorization formalism [5] , the cross sections in pp collisions can be written in a general form

$$\sigma_{pp}(s) = \int dx_1 \dots dx_n f(x_1) \dots f(x_n) \hat{\sigma}(\hat{s} = x_1 \dots x_n), \text{ where}$$

- $\sqrt{s}$ is the center of mass energy of the protons
- $\sqrt{\hat{s}}$ is the center of mass energy of the subprocess
- x_i is the fraction of momenta carried by the particle i
- $f(x_i)$ is the distribution function inside the proton (for quarks) or the photon flux (for photons emmited by protons or quarks)
- $\hat{\sigma}$ is the cross section of the fundamental subprocess

[5] M. Drees, R. M. Godbole, M. Nowakowski and S. D. Rindani, Phys. Rev. D 50, 2335 (1994).

Photon Flux

- For elastic collisions, the photon flux used is [6]

$$f^{el}_{\gamma/p}(z) = \frac{\alpha}{2mz}[1+(1-z)^2]\left[\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right],$$

$$\text{where} \;\; A = 1 + \frac{0,71(GeV)^2}{Q^2_{min}},\; Q^2_{min} \approx m^2_{proton} z^2/(1-z)$$

and z is the fraction of energy carried by the photon

- For inelastic collisions (involving the quarks inside the proton),

$$f^{inel}_{\gamma/q}(x) = \frac{\alpha e_q^2}{2\pi}\frac{[1+(1-x)^2]}{x}\ln\left(\frac{Q_1^2}{Q_2^2}\right), \text{ where}$$

$Q_1^2 = \hat{s}/4 - m^2$, and $Q_2^2 = 1\,\text{GeV}$ are the minimum and maximum of momentum transfer

[6] M. Drees and D. Zeppenfeld, Phys. Rev. D **39**, 2536 (1989).

Drell Yan

The cross section for monopole production via Drell Yan, for the two coupling models are [7] [8]

- Velocity-dependent

$$\hat{\sigma}_{DY}(q\bar{q} \to m\bar{m}) = \frac{\pi\eta^2\beta^3}{12\hat{s}}\left(2 - \frac{2}{3}\beta^2\right), \quad \text{where} \quad \eta = e_q/e$$

- Magnetic moment dependence

$$\hat{\sigma}_{DY}(q\bar{q} \to m\bar{m}) = \frac{\pi\eta^2\beta^3}{18\hat{s}}\left[3 - \beta^2 - (2\beta^2 - 3)\kappa^2\hat{s} + 6\kappa\sqrt{\hat{s} - \beta^2\hat{s}}\right]$$

[7] T. Dougall and S. D. Wick, Eur. Phys. J. A **39**, 213 (2009).

[8] S. Baines, N. E. Mavromatos, V. A. Mitsou, J. L. Pinfold and A. Santra, Eur. Phys. J. C78, no. 11, 966(2018).

Photon fusion

For photon fusion the cross sections for the two coupling models are [9] [10]

- Velocity-dependent

$$\sigma(\gamma\gamma \to m\bar{m}) = \frac{\pi\beta^5}{4\alpha^2\hat{s}}\left[\frac{3-\beta^4}{2\beta}\ln\frac{1+\beta}{1-\beta} - (2-\beta^2)\right].$$

- κ-dependent

$$\hat{\sigma}_\kappa(\gamma\gamma \to m\bar{m}) = \frac{\pi\alpha_m^2(\beta)}{3\hat{s}}\left\{\ln\left(\frac{1-\beta}{1+\beta}\right)\left[\beta^2\kappa^2\hat{s}(3\beta^2\kappa^2\hat{s} - 6\kappa^2\hat{s} + 6)\right.\right.$$
$$\left. + 6\beta^4 - (36\beta^2 - 72\beta)\kappa\sqrt{(1-\beta^2)\hat{s}} - 9\kappa^4\hat{s}^2 - 60\kappa^2\hat{s} - 18\right]$$
$$\left. - \beta\kappa^2\hat{s}(7\beta^2\kappa^2\hat{s}^2 + 15\kappa^2\hat{s} + 132) + 12\beta^3 - 24\beta - 36\kappa\sqrt{(1-\beta^2)\hat{s}}\right\}.$$

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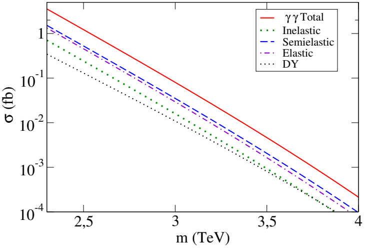
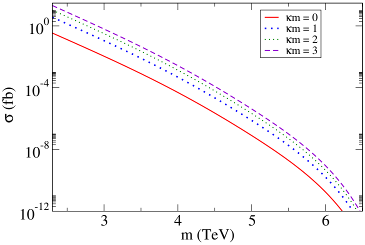
[9] T. Dougall and S. D. Wick, Eur. Phys. J. A 39, 213 (2009).

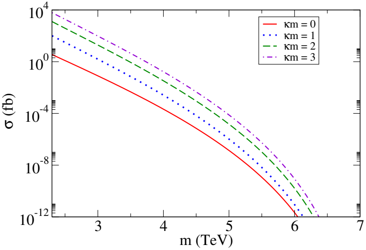
[10] S. Baines, N. E. Mavromatos, V. A. Mitsou, J. L. Pinfold and A. Santra, Eur. Phys. J. C78, no. 11, 966(2018).



(a) $\kappa = 0$, $\sqrt{s} = 14$ TeV



(c) DY, $\sqrt{s} = 14$ TeV



(b)$\gamma\gamma$, $\sqrt{s} = 14$ TeV

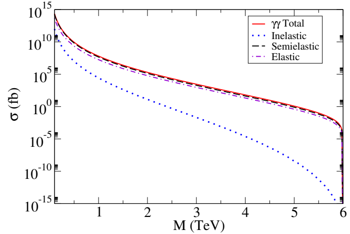
- $\gamma\gamma$ has higher cross sections for $m \lesssim 5$ TeV
- Limit for LHC detection $m \lesssim 3$ TeV
- Higher values of κ give higher cross sections

- Spin 0 monopolium production by photon fusion[11]

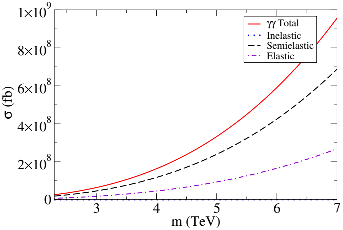
$$\hat{\sigma}_{\gamma\gamma} = \frac{2\sqrt{2}[R(R-1)]^{3/2}}{\alpha^2\epsilon^6 M^2}\frac{\bar{\Gamma}_M(\epsilon^2-1)^2}{(\epsilon^2-1)^2+\bar{\Gamma}_M^2}$$

($R = 2m/M$, $\bar{\Gamma}_M = \Gamma_M/M$ and $\epsilon = \sqrt{\hat{s}}/M$)

- The production is increased for higher values of monopole mass



(a) Fixed monopole mass $m = 3$ TeV

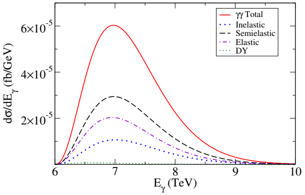


(b) Fixed monopolium mass $M = 1$ TeV

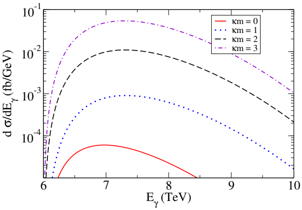
[11] L. N. Epele, H. Fanchiotti, C. A. G. Canal and V. Vento, Eur. Phys. J. C 62, 587 (2009).

Energy Distributions

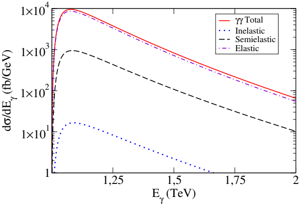
The derivatives are taken in respect to the center of mass energy of the subprocess $E_\gamma = \sqrt{\hat{s}}$



(a) $m\bar{m}$ production, $m = 3$ TeV, $\kappa = 0$



(b) $\gamma\gamma$ $m\bar{m}$ production, $m = 3$ TeV



(c) Monopolium production, $m = 3$ TeV, $M = 1$ TeV

Monopoles in Future Accelerators

Detection limit $N = \sigma l > 1/\text{year}$

- LHC (HL-LHC): $\sqrt{s} = 14$ TeV, $L = 55\,(350)$ fb^{-1} /year

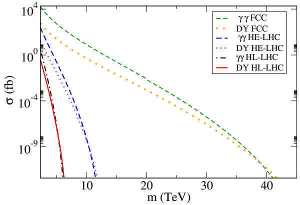
  Detection limit $m \lesssim 3$ (3.5) TeV

- HE-LHC: $\sqrt{s} = 27$ TeV, $L = 500$ fb^{-1} /year

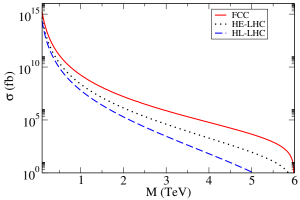
  Detection limit $m \lesssim 6$ TeV

- FCC: $\sqrt{s} = 100$ TeV, $L = 150 - 1000$ fb^{-1}/year

  Detection limit $m \lesssim 20 - 21$ TeV



(a) $m\bar{m}$ production, $\kappa = 0$



(b) Monopolium production, $m = 3$ TeV

Conclusions

- The cross sections are only indicative: they rely on perturbative methods
- For the current lower limits given by the MoEDAL[12] and ATLAS[13] experiments, $m \gtrsim 2$ TeV, monopoles have few chances to be detected in LHC
- For heavier monopoles, the detection could be made in future accelerators (direct detection) and indirectly for the monopolium
- The κ-dependent coupling can increase the cross sections up to 10^2 times and the limits of detection (for LHC) up to $m \lesssim 4$ TeV

Work published on [14]

[12] B. Acharya *et al.* (MoEDAL Collaboration), Phys. Rev. Lett. **123**, 021802 (2019)

[13] G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **124**, 031802 (2020)

[14] Gay Ducati M.B. and Carlos B. Magnetic Monopoles in pp Collisions. PoS(ICHEP2020)245 (2021)

Thank You!