The hunt for magnetic monopoles

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Abstract. A brief review of the state of the art of searches for magnetic monopoles is presented. After an introduction on the motivation for postulating the existence of monopoles and their theoretical models, detection techniques and results for direct and indirect searches are reviewed with emphasis on results from collider experiments, such as MoEDAL and ATLAS at the Large Hadron Collider, while searches from cosmic observatories targeting monopoles formed at the early Universe are reported. Future directions in the hunt for monopoles are also highlighted.

1 Introduction

The existence of isolated magnetic poles —magnetic monopoles— has fascinated physicists since the end of the 19$^{\text{th}}$ century, even though it was Dirac who put it in a modern quantum field theory concept and demonstrated that their existence is consistent with quantum theory. In this concise review, we present the state of the art of the experimental advances towards the discovery of monopoles and future plans and prospects.

The structure of the paper is the following. In Section 2, an overview of theoretical proposals involving the existence of magnetic monopoles is given. Searches for monopoles in high-energy collisions of particles and ions is presented in Section 3, with emphasis on the CERN experiments ATLAS (in Section 3.1) and MoEDAL (in Section 3.2). The results are presented according to the production process: Drell–Yan and photon-fusion processes in Section 3.3 and the Schwinger mechanism in Section 3.4. Magnetic poles of cosmic origin have been looked for through a wide spectrum of techniques, as discussed in Section 4. Lastly, in Section 5 a summary and outlook with future directions in the search for monopoles concludes the paper.

2 Theoretical motivation

The main theoretical motivations behind the hypothetical existence of magnetic monopoles are the symmetrisation of the Maxwell equations and the explanation of the charge quantisation. Dirac [1] proved that magnetic monopoles could explain the discrete nature of the electric charge, leading to the Dirac Quantisation Condition (DQC),

$$\alpha g = \frac{N}{2}e, \quad N = 1, 2, ..., \tag{1}$$

where $\alpha = \frac{e^2}{4\pi\varepsilon_0} = \frac{1}{137}$ is the fine structure constant, e is the electron charge, ε_0 is the vacuum permittivity, and g is the monopole magnetic charge in units $\hbar = c = 1$. This quantisation condition should be modified by a factor of three if quarks existed free in Nature. The monopole mass and spin are free parameters of the theory. This attractive proposal has revived a number of experimental investigations since then, with some of them highlighted here.

The existence of magnetic monopoles, characterised by their isolated magnetic charges similar to electrically charged particles, has been assumed over the years in many theoretical proposals. Moreover, dyons [2], that carry both magnetic and electric charge, offer a more involved solution leading to the DQC, which depends on the underlying theoretical scenario. Some of the theoretical scenarios predicting the existence of magnetic monopoles are listed below. A comprehensive review is given in Ref. [3].

Dirac monopole In Dirac's formulation [1, 4], magnetic monopoles are assumed to be point-like particles with quantum mechanical conditions leading to (1), establishing the discrete nature of their magnetic charge. In spite of monopoles formally symmetrising the Maxwell's equations, a numerical asymmetry emerges in the DQC: the minimum value of the magnetic charge is much larger than the smallest electric charge. Indeed, a magnetic monopole with a single Dirac charge $g_{\rm D}$ has an equivalent electric charge of $137e/2$. Hence, for a relativistic monopole the energy loss is around $68.5^2 \simeq 4,700$ times that of a minimum-ionising particle.

Monopoles in GUTs Since the Grand Unified Theory (GUT) of strong and electroweak interactions predicted the existence of magnetic monopoles [5], searches for them, in particular of cosmic origin, have been intensified substantially [6]. In 1974, 't Hooft and Polyakov [7, 8] showed that a unified gauge theory where electromagnetism is embedded in a semi-simple gauge group, such as $SU(2)$, would necessitate the existence of the monopole as a soliton with spontaneous symmetry breaking. GUT monopoles are too massive to be produced at any future accelerator, having a mass of $\mathcal{O}(10^{15})$ GeV [9].

Electroweak monopole Cho and Maison postulated the *electroweak* monopole [10–12] as a generalisation of the Dirac monopole, representing a hybrid of Dirac and 't Hooft–Polyakov monopoles that carries magnetic charge *twice* that of the Dirac monopole. The latter is due to the quotient group $SU(2) \times U_Y(1)/U_{\rm em}(1)$, where $U_{\rm em}(1)$, which is the (unbroken) group of electromagnetism instead of, e.g., the $SU(2)$ group in the Georgi–Glashow model. Recent estimates of the electroweak monopole mass indicate that it is possibly accessible at the LHC [13].

Global monopoles They have been proposed [14] as space-time defects allowing for the spontaneous breaking of global $SO(3)$ symmetries. They carry *no magnetic charge*, yet gravitational effects may lead to a deficit angle in space-time, that modify the scattering amplitude of ordinary background particles [15, 16]. Such *peculiar scattering patterns* may indicate indirectly the presence of a neutral global monopole in collider detectors [14, 17]. Moreover, a global monopole variant that includes axion fields and a real electromagnetic field has been proposed [18–21], resulting into axions capable of inducing electromagnetic monopole solutions with a *real magnetic charge*.

Monopolium The lack of experimental confirmation of monopoles in Dirac's proposal [1, 4] may be attributed to monopoles not being seen freely because they form a bound state called *monopolium* [22–25], confined by strong magnetic forces. Monopolium is a neutral state, however its decay into photons would make it detectable in conventional detectors [26–31].

3 Searches in collider experiments

Present and proposed future accelerators feature a centre-of-mass energy of $\mathcal{O}(10)$ TeV, thus it is practically impossible to search for GUT monopoles in these machines. Nevertheless, searches have been carried out to detect direct or indirect signals of light monopoles of mass up to a few TeV. Searches have been performed at hadron–hadron, electron–positron and lepton–hadron experiments, mostly directly using scintillation counters [32], gas chambers [33] and nuclear track detectors [34–38], taking advantage of the monopole high ionisation power. In general, any (meta)stable object either carrying magnetic and/or high electric charge, or moving with velocity less than the speed of light is highly ionising (HIP) [3, 39–41]. Other analyses focus on exposed material for trapped monopoles [42, 43] or peculiar magnetic-charge trajectories [44, 45]. In addition, virtual-monopole processes enhancing production rates of certain final states have also been considered as indirect probes for monopoles [46, 47].

Direct searches for monopoles at the Tevatron were carried out by the CDF [32] and the E882 [42, 43] experiments. CDF used a time-of-flight system with a dedicated trigger requiring large light pulses in the scintillators and an offline selection requiring large energy-loss tracks not curving in the plane perpendicular to the magnetic field to set a lower mass limit of 360 GeV under certain assumptions for the production mechanism.

The Large Hadron Collider (LHC) [48] currently in operation at CERN in the Geneva area provides the most powerful collisions of protons and heavy-ions achieved thus far and it is the testbed for many scenarios of New Physics including magnetic monopoles. Two of its experiments —ATLAS and MoEDAL— lead this effort, whereas CMS has not released any results at present.

3.1 ATLAS experiment

ATLAS is one of the LHC main experiments optimised for the detection of particles that decay promptly to known states, aiming at precise measurements of properties of the Standard Model (SM) and searches for signals from a diverse spectrum of theories beyond the SM (BSM). The discovery of the Higgs boson in 2012 [49], together with CMS [50], is its most outstanding contributions to Particle Physics up to now.

The ATLAS experiment [51] consists of an inner tracking detector [52] surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner detector comprises silicon pixel [53], silicon microstrip [54–56], and transition radiation tracking (TRT) [57–59] detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements [60] with high granularity, while a steel/scintillator-tile hadronic calorimeter in the central region and LAr calorimeters provide electromagnetic and hadronic energy measurements [61]. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each, and includes a system of precision tracking chambers and fast detectors for triggering [62].

To detect monopoles via high ionisation [63–66], ATLAS considers signals in the TRT [67, 68] and the EM calorimeter [69]. The discriminating particle characteristics are the energy dispersion in the electromagnetic calorimeter and the fraction of TRT hits passing a predefined high threshold. The lateral energy dispersion measures the fraction of the cluster energy contained in the most energetic cells of a cluster in each of the layers of the electromagnetic calorimeters.

Another approach used in heavy-ion collisions [70] exploits the straight track that a magnetic charge leaves on the plane perpendicular to the beam due to the solenoidal magnetic field unlike the curved track of any electric charge traversing the tracker. This leads to events with multiple pixel clusters [53] and no or few reconstructed charged-particle tracks [52, 60]. Allowing for at most one calorimeter-cell energy deposit [71] and requiring high transverse thrust further suppresses beam-induced background.

3.2 MoEDAL experiment

The Monopole and Exotics Detector at the LHC (MoEDAL) [72–74], the first dedicated *search* LHC experiment, is specialised in the detection of HIPs in a manner complementary to ATLAS and CMS [75]. It is sensitive to magnetic monopoles [3, 76, 77], D-matter [78–84], and (semi)stable electrically charged particles arising in various SM extensions, such as supersymmetric long-lived partners [85–87], radiative neutrino masses [88], among others [73, 89]

It is deployed around interaction point 8 (IP8) in the LHCb vertex locator cavern. It is a unique and largely passive detector based on three different techniques, which do not necessarily require either readout or trigger.

Nuclear track detectors The main sub-detector system is made of a large array of CR-39, Makrofol and Lexan NTD stacks surrounding the intersection area. The passage of a HIP through the plastic detector is marked by an invisible damage zone along the trajectory. The damage zone is revealed as a cone-shaped etch-pit when the plastic detector is chemically etched. Then the sheets of plastics are scanned looking for aligned etch pits in multiple sheets. The MoEDAL NTDs have a (low) threshold of $z/\beta^\star \sim 5$, where z is the charge and $\beta^\star = v/c$ the velocity of the incident particle. Another type of NTD installed is the Very High Charge Catcher ($z/\beta^\star \sim 50$), consisting of two flexible low-mass stacks of Makrofol. It is the only NTD (partly) covering the forward region, being deployed in the LHCb acceptance between RICH1 and the Trigger Tracker.

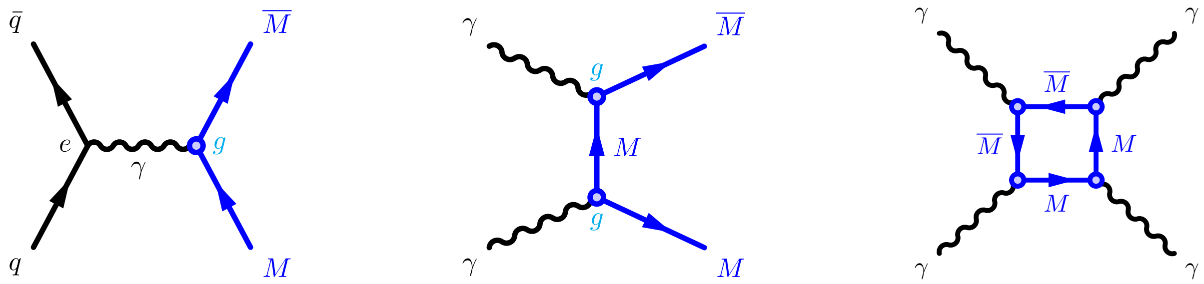
Magnetic trappers A unique feature of the MoEDAL detector is the use of paramagnetic magnetic monopole trappers (MMTs) to capture magnetically charged HIPs. The aluminium absorbers of MMTs are subject to an analysis looking for magnetically charged particles at a remote superconducting quantum interference device (SQUID) facility [90].

TimePix radiation monitors The only non-passive MoEDAL sub-detector is an array of TimePix pixel devices distributed throughout the MoEDAL cavern, forming a real-time radiation monitoring system of beam-related backgrounds. The operation in time-over-threshold mode helps differentiating between various particles species from mixed radiation fields and measuring their energy deposition [91].

MoEDAL has extended its physics program to *feebly interacting particles* that connect hidden sectors to the visible SM sector with the MoEDAL Apparatus for Penetrating Particles (MAPP) [92]. Such *portal* scenarios attempt to explain observed phenomena in particle physics and cosmology such as the non-vanishing neutrino masses, the dark matter [93,94] and the baryon asymmetry of the universe, among others [41, 95]. MAPP Phase 1 (MAPP-1) is currently being deployed in the UA83 tunnel $\sim$100 m from IP8. Its main physics goal is to detect millicharged particles of charge down to $10^{-3}e$ [96], while MAPP-2 is going to be in operation in the high-luminosity phase of the LHC (HL-LHC) and extend MAPP-1 physics reach to neutral particles [74].

3.3 Drell–Yan and photon-fusion production processes

Direct monopole pair production in colliders can proceed via two processes: a Drell–Yan-like (DY) process in photon s-channel intermediation (see Figure 1a) and a photon-fusion (PF) t-channel diagram (see Figure 1b) [97–100]. For both mechanisms, duality arguments [101, 102] justify an effective β-dependent magnetic charge in monopole-matter scattering processes, where $\beta = \sqrt{1 - 4M^2/\hat{s}}$, with M the monopole mass and $\hat{s}$ the centre-of-mass energy of the scattered partons.



(a) Drell–Yan process (b) Photon-fusion process (c) Monopole box diagram

Figure 1: Monopole M direct and indirect production diagrams in colliders: Drell–Yan (a), photon fusion (b) and light-by-light scattering through a monopole loop (c).

MoEDAL and recently ATLAS have considered both processes in their searches for monopoles of various spins; ATLAS examines monopoles of spin 0 and 1/2 only, whereas MoEDAL has studied spin 1, too. ATLAS has used the TRT and the EM calorimeter sensitivity to signals of high ionisation to constrain monopoles and high-electric-charge objects (HECOs) in proton–proton collisions at 7, 8, and 13 TeV [63–66]. The latest analyses rely on a dedicated trigger for HIPs, which makes use of two energy-loss variables based on the TRT high-threshold (HT) hits. The discriminating particle characteristics used by the offline selection are the cluster energy, the energy dispersion in the EM calorimeter, w, and the fraction of HT TRT hits, $f_{\rm HT}$. The energy dispersion measures the fraction of the cluster energy contained in the most energetic cells of a cluster in each of the EM-calorimeter layers. The variables w and $f_{\rm HT}$ are also used to estimate the background in a data-driven way. Figure 2 shows the two-dimensional distribution of w and $f_{\rm HT}$ for data and a signal with $1g_{\rm D}$ [66]. It is evident that the variables are well discriminating and data in regions B, C and D can be used to predict the number of background events in the signal region A.

On the other hand, MoEDAL uses MMTs to capture magnetically charged particles. After exposure to high-energy collisions, these aluminium absorbers are scanned in the ETH Zurich SQUID looking for isolated magnetic charges [90]. During the scanning, the persistent current is measured before and after the passing of the sample through the superconducting loop. A consistent difference between the two currents after several passings of the same sample would provide a clear signal of a trapped monopole in the MMT volume. Such signal has not been observed in the MMT searches carried out so far [103–108].

MoEDAL also performed the first dedicated search for dyons [2] —objects carrying both electric and magnetic charge— in a collider experiment [109, 110]. Mass limits in the range 750–1910 GeV were set using a DY production model for dyons with magnetic charge up to $5g_{\rm D}$ and electric charge from $1e$ to $200e$.

Besides MMTs, MoEDAL uses plastic sheets to detect HIPs. The exposure, chemical etching and subsequent scanning of NTDs for etch-pits allows the detection not only of magnetic monopoles, but also of large electric charges, providing constraints in the highest charge regime achieved up to date [111].

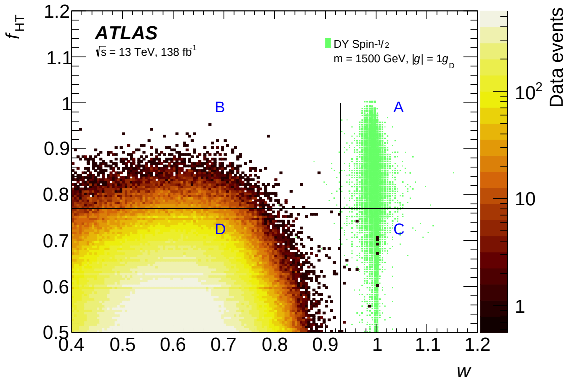


Figure 2: ATLAS HIP search. 2D distribution of discriminators f_{HT} and w for data and a signal model (green). The signal (A) and control (B, C and D) regions are shown. From [66].

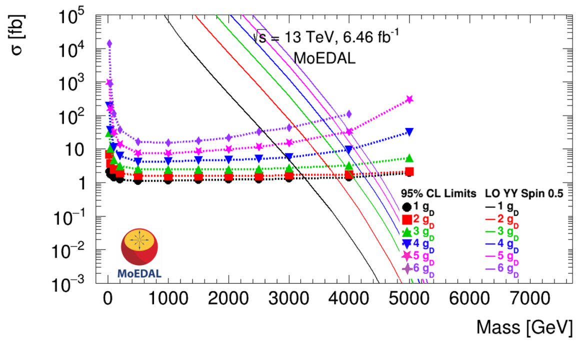


Figure 3: MoEDAL search with NTD and MMT: 95% CL upper limits on the photon-fusion production cross-section for charges in the range $1g_{\mathrm{D}}$–$6g_{\mathrm{D}}$. The solid lines denote the cross-section predictions. From [103].

MoEDAL has completed generic searches for HIPs using Makrofol NTDs exposed to *pp* collisions at 8 TeV [108] and at 13 TeV [103], without finding any candidate etch-pit indicating the passage of a HIP through the plastic foil. The 95% confidence-level (CL) cross-section upper limits compared to theoretical predictions for monopoles produced via the PF process are shown in Figure 3.

An overview of lower mass limits for monopoles at 13 TeV set by MoEDAL [103] and ATLAS [66] is presented in Figure 4. The PF cross-section is significantly larger than that of DY at LHC energies, hence the PF mass limits are higher than those assuming DY production. ATLAS, being an experiment designed to detect minimum ionising particles, has sensitivity only to low magnetic charges up to $2g_{\mathrm{D}}$. On the other hand, MoEDAL has constrained magnetic charges up to $10g_{\mathrm{D}}$, albeit with slightly less sensitivity in low charges due to loss of acceptance. Another factor affecting the comparative sensitivity between the two experiments is the lower instantaneous luminosity of MoEDAL compared to ATLAS. The combination of NTDs and MMTs has improved the sensitivity of MoEDAL with respect to MMT-only searches. Recently MoEDAL has embarked in a search for monopoles produced via photon fusion in heavy-ion collisions [112].

A note of caution is due here. In both production processes, DY and PF, the monopole pair couples to the photon via a coupling that depends on g_{D} and therefore has a value of $\mathcal{O}(10)$. This large monopole–photon coupling invalidates any perturbative treatment of the cross-section calculation and hence any mass limit based on it is *only indicative* and used merely to facilitate comparisons between experimental outcomes. However, it is stressed that the upper bounds placed on production cross sections are solid and can be relied upon.

One way to resolve this problem is to use resummation techniques in magnetic monopoles [113,114], in a manner similar to that applied for HECOs [115–117]. For monopoles, the model employs a $U(1)_{\mathrm{weak}} \times U(1)_{\mathrm{strong}}$ effective gauge field theory under which electrons and fermionic monopoles are appropriately charged. The non-perturbative quantum effects of the strongly coupled sector of the theory lead to dressed effective couplings of the monopole/dyon with the EM photon. For slowly moving monopole/dyons, such effects lead to weak coupling, thus turning the bare large non-perturbative magnetic charge into a perturbative effective β-dependent magnetic coupling. Such a treatment opens up the possibility to interpret the cross-section bounds set in collider experiments in a proper way, thus yielding sensible monopole-mass bounds, as has been the case for HECOs [115, 117].

Another possibility is the PF production for vector monopoles by using the magnetic-moment parameter κ in conjunction with the parameter β to achieve a perturbative treatment of the monopole–photon coupling [99]. Indeed, by limiting the discussion to very slow ($\beta \ll 1$) monopoles, the perturbativity is guaranteed, however, at the expense of a vanishing cross section in DY production. Nonetheless, the *photon-fusion* cross section remains finite *and* the coupling is perturbative at the formal limits $\kappa \to \infty$ and $\beta \to 0$, provided a β-dependent magnetic charge [101, 102] is assumed.

Last but not least, a third possibility to elude this non-perturbativity issue is to consider the Schwinger mechanism discussed in detail in Section 3.4.

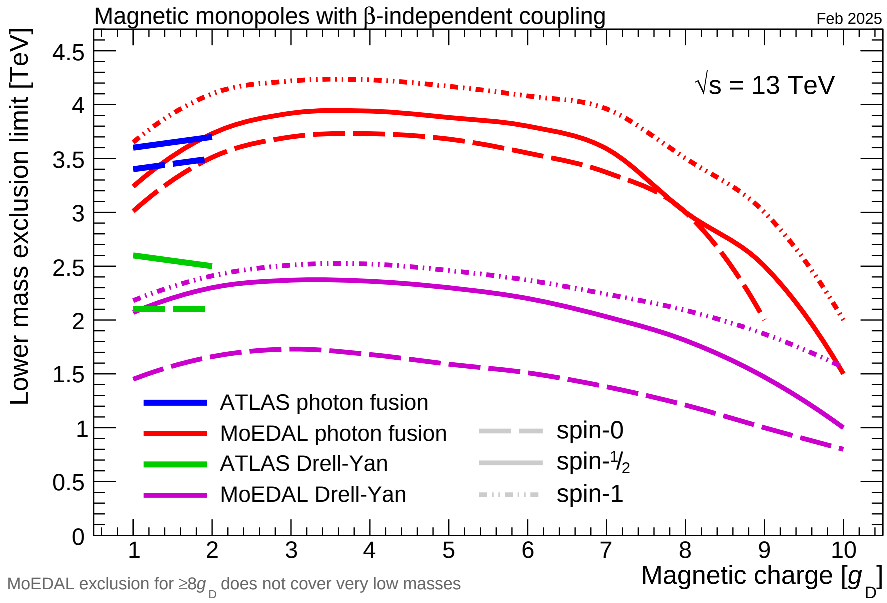


Figure 4: Magnetic monopole mass limits obtained by ATLAS [66] and MoEDAL [103] with *pp* collisions at 13 TeV as a function of the magnetic charge. Drell–Yan and photon-fusion production with a β-independent coupling for monopoles of spin 0, $^1/_2$ and 1 is assumed.

3.4 The Schwinger production mechanism

Electrically charged particles can be created in strong enough electric fields, a phenomenon known as the *Schwinger mechanism* [118]. By electromagnetic duality, a sufficiently strong magnetic field would similarly produce magnetic monopoles. The possibility of calculating its rate through semiclassical techniques [119–124] overcomes the non-perturbativity of the monopole–photon coupling.

Heavy-ion collisions at the LHC produce the strongest known magnetic fields in the Universe, and the first search for such production was conducted by MoEDAL during the 2018 heavy-ion run, during which the MMTs were exposed to 5.02 TeV/nucleon Pb–Pb collisions [125]. The strongest fields are generated in ultraperipheral collisions (UPCs), for which the impact parameters approximately twice the nuclear radius. The magnetic field strength reached 10^{16} T, which is about seven orders of magnitude greater than the critical field strength of quantum electrodynamics, and more than four orders of magnitude greater than the strongest known astrophysical magnetic fields, which are present on the surface of magnetars [126].

Two approximations in the calculation of the monopole production cross section have been considered [125].

Free-particle approximation (FPA) The spacetime dependence of the electromagnetic field of the heavy ions is treated exactly, but monopole self-interactions are neglected [124].

Locally constant field approximation (LCFA) The spacetime dependence of the electromagnetic field is neglected, but monopole self-interactions are treated exactly [122].

In this way, the two approaches are complementary, with uncorrelated uncertainties. In addition, for the FPA the leading effects of monopole self-interactions have been shown to enhance the cross section, and for the LCFA the leading effects of spacetime dependence have also been shown to increase the cross section [122, 124]. Thus, while neither approximation provides a complete calculation of the production cross section, both are expected to yield conservative lower limits.

The MMT measurements were compatible with the absence of monopoles and therefore magnetic charges equal to or above the Dirac charge were excluded in all samples. Subsequently, upper limits on the production cross section at 95% CL were set for monopoles with Dirac charges up to $3g_{\mathrm{D}}$ and masses up to 75 GeV, as shown in the inset of Figure 5. In addition, this analysis provided the first lower mass limits for *finite-size* monopoles from a collider search, since the Schwinger mechanism is not subject to the exponential suppression that their cross section suffers in DY and PF processes.

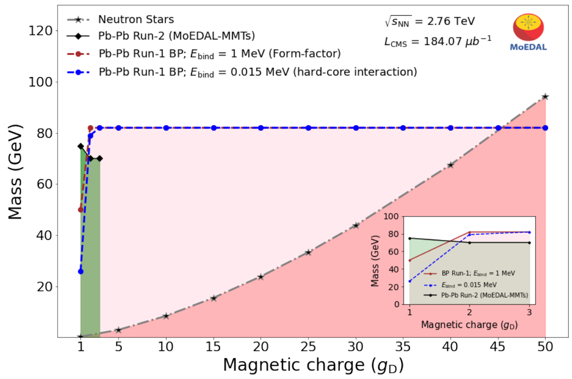


Figure 5: Exclusion region for monopole search via the Schwinger effect in the CMS beam pipe exposed to Pb–Pb collisions during LHC Run-1. The green-shaded region shows the MoEDAL MMT Run-2 limits [125]. The inset zooms in on the low-charge region. The limit from indirect searches for MMs produced by neutron stars [124] is also shown. From [127].

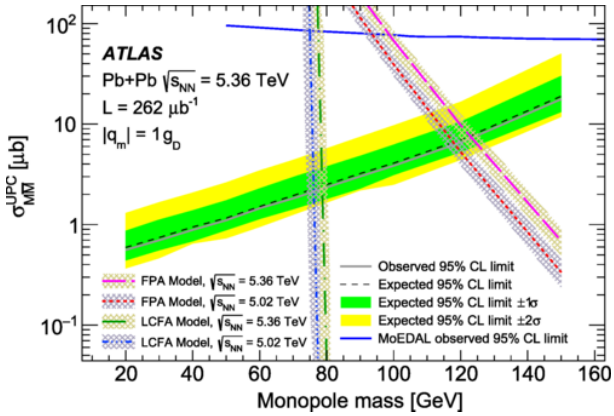


Figure 6: Upper limits on 1-g_D monopole pair-production cross-section in Pb–Pb UPC at $\sqrt{s_{NN}} =$ 5.36 TeV. The gray solid line (black dashed line) represents observed (expected) limits, whereas the darker (lighter) shaded bands are $\pm1\sigma$ ($\pm2\sigma$) intervals. The observed limits by MoEDAL at $\sqrt{s_{NN}} =$ 5.02 TeV (blue line) and the FPA and LCFA model predictions (dashed/dotted lines) for both $\sqrt{s_{NN}}$ values are also shown. From [70].

Furthermore, a search for monopoles potentially trapped in the Run-1 CMS beam pipe after exposure to 2.76-TeV Pb–Pb collisions was performed by MoEDAL using the SQUID magnetometer [127]. The use of a trapping volume very close to the collision point [75] and ultra-high magnetic fields generated during the heavy-ion run that could produce monopoles via the Schwinger effect allowed setting the first reliable, world-leading mass limits on monopoles with very high magnetic charge. In particular, the established limits are the strongest available in the range 2–45g_D, excluding monopoles with masses of up to 80 GeV, as presented in Figure 5.

ATLAS has published recently a search for monopole-pair production in UPC Pb–Pb collisions based on 5.36 TeV data recorded in 2023. Due to their high ionisation and unique trajectories in a solenoidal magnetic field, monopoles are expected to leave numerous clusters in the innermost ATLAS pixel detector without associated reconstructed charged-particle tracks or calorimeter activity, thus leading to selection criteria outlined in Section 3.1. Monopoles of magnetic charge of 1g_D in the mass range of 20–150 GeV have been excluded, as depicted in Figure 6. Both cross-section approximations, FPA and LCFA, have been considered to extract lower mass limits; a conservative mass bound of 80 GeV has been set assuming FPA production rate.

The Schwinger mechanism offers good prospects for detecting monopoles at future hadron colliders such as FCC-hh [128] and SPPC [129], expected to reach *pp* collision energy of 100 TeV and 125 TeV, respectively. The reach of such machines in detecting monopoles in Pb–Pb collisions has been studied assuming an ATLAS-like, general-purpose experiment capable of a 50% detection efficiency, and a HIP-optimised MoEDAL-like detector, both under a zero-background hypothesis. Both concepts will provide sensitivity to TeV-scale masses for monopoles of charges 1g_D or higher [130].

3.5 Indirect searches

Virtual monopoles have been suggested to mediate processes giving rise to multi-photon final states via a box diagram shown in Figure 1c [131, 132]. Photon-based searches have been carried out by D0 [46] at the Tevatron and L3 [47] at LEP.

At LHC, such searches may use forward-proton tagging to probe heavy monopoles in photon-initiated central exclusive production using effective field theory interpretations [133–135]. The direct observation of light-by-light scattering at the LHC [136] by ATLAS and CMS in heavy-ion UPCs opened up the possibility to further constrain virtual monopoles in Born–Infeld theory [137, 138]. As discussed in Section 2, the monopolium decay to photons provides an additional means to constrain monopoles [26–31].

4 Searches for cosmic monopoles

Magnetic monopoles of cosmic origin are hypothesised to have been formed shortly after the Big Bang as topological defects arising when the Universe expanded and cooled. The Schwinger effect in strong magnetic fields could also contribute to the monopole number density. The existing galactic magnetic field would accelerate cosmic monopoles, thus draining energy from the magnetic field, so its dissipation should not exceed its regeneration, should the galactic field be sustained. This requirement implies that an upper flux limit should be respected, the so-called *Parker bound* [139,140]. The *extended Parker bound*, on the other hand, also considers the survival of a small galactic seed field and lowers the flux bound [141]. Furthermore, the detection of intergalactic magnetic fields may lead to additional bounds on the monopole flux, and Parker bounds are modified in the presence of primordial fields [142–144]. As discussed below, observational constraints on the monopole flux are expressed in terms of the monopole velocity. From the study of the monopole acceleration, a speed-mass-abundance relation for the monopoles that might be detected by the terrestrial detectors may be obtained, leading to current bounds on the monopole flux be expressed in terms of the monopole mass [142–145].

Direct cosmic searches have been performed on underground, surface and balloon-borne experiments targeting GUT monopoles in a mass range of 100–10^4 TeV with a velocity spanning $\beta \sim 10^{-4}$–1. Up to now, there is no confirmed experimental evidence for cosmic magnetic monopoles [6]; only bounds on their flux as a function of velocity and mass [145].

MACRO [146], a large underground detector situated in the Gran Sasso laboratory, provided the best limits for GUT monopoles with a sensitivity that largely covers the velocity range, mostly thanks to the redundancy and complementarity of the various detector components it was comprising. MACRO set an upper limit on the monopole flux well below the Parker bound in almost all the β range for GUT monopoles [147], as shown in Figure 7.

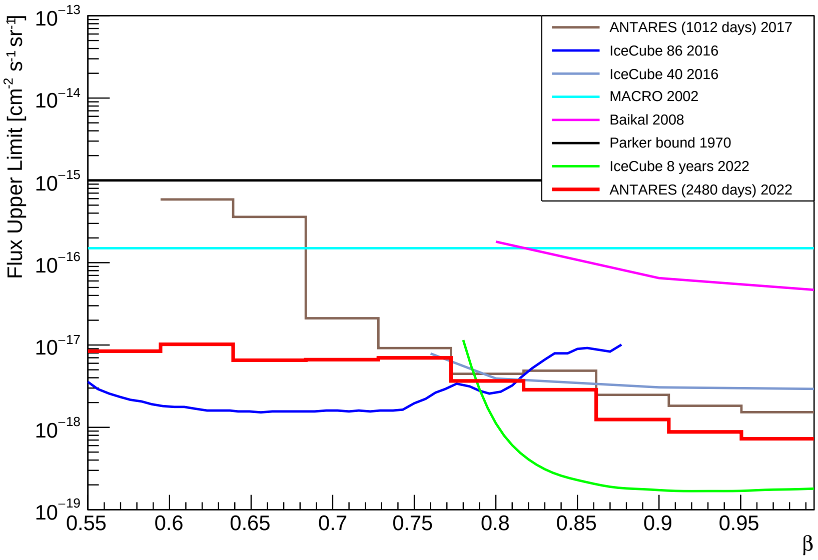


Figure 7: Summary on 90% CL monopole-flux upper limits from ANTARES 10 years [148] (red), ANTARES previous result [149] (brown), IceCube [150] (blue) and [151] (green), MACRO [147] (cyan) and Baikal [152] (magenta), as well as the theoretical Parker bound [139] (black). From Ref. [148].

Relativistic monopoles have been sought by the emittance of Cherenkov radiation, when traveling through a homogeneous and transparent medium such as water or ice. Neutrino telescopes such as Baikal [152], AMANDA [153], ANTARES [148, 149] and IceCube [150, 151] are sensitive to visible Cherenkov light emitted by a monopole with $\beta > 0.75$ (*direct* Cherenkov). Additional light is produced by Cherenkov radiation from δ-ray electrons along the monopole path for velocities down to $\beta = 0.625$ (*indirect* Cherenkov). A summary of flux limits on magnetic monopoles are depicted in Figure 7 [148].

The SLIM detector, installed at high altitude in Bolivia at an altitude of 5,400 m, probed a region for intermediate-mass monopoles ($10^5 \lesssim M \lesssim 10^{12}$ GeV), well below the GUT scale, which do not have enough energy to penetrate the entire atmosphere. The SLIM NTDs array covered an area > 400 m^2 that, after four years of exposure, showed no signal of magnetic monopoles and set limits on cosmic monopole flux [154].

The flux of ultra-relativistic monopoles has been constrained by the Pierre Auger Observatory [155], which was sensitive to monopoles with Lorentz factor values $\gamma \sim 10^9$–10^{12}. Two other experiments exploited the radio-wave pulses from the interactions of a primary particle with ice to search for monopoles. The Radio Ice Cherenkov Experiment (RICE), consisting of radio antennas buried in the Antarctic ice, set a flux upper limit of 10^{-18} cm^{-2}s^{-1}sr^{-1} at 95% CL for intermediate-mass monopoles with $10^7 < \gamma < 10^{12}$ and a total energy of 10^{16} GeV [156]. The ANITA-II balloon-borne radio interferometer, on the other hand, set a 90%-CL flux upper limit on the order of 10^{-19} cm^{-2}s^{-1}sr^{-1} for a Lorentz factor $\gamma > 10^{10}$ at a total energy of 10^{16} GeV [157].

In the future, the hunt for cosmic monopoles may proceed in various directions. Along the lines set by SLIM, the MoEDAL collaboration is considering the deployment of a $10,000$ m^2 array of plastic NTDs at high altitude. The SLIM+ detector would enable the search for cosmic monopoles with velocities $\beta \simeq 0.1$ from the TeV scale to the GUT scale for monopole fluxes well below the Parker bound [158]. Should such a detector covering an area of $50,000$ m^2 be installed at sea level, it may explore singly charged, 1 TeV mass monopoles of Lorentz factor down to $\gamma \simeq 10$ [130].

Moreover, primordial monopoles may loose their kinetic energy in the atmosphere and drift towards the magnetic poles to eventually be trapped in ice. By scanning ice samples —such as those collected by the SPICEcore project [159]— with a SQUID magnetometer, 1-TeV monopoles of $\gamma \lesssim 6$ could be probed [130]. Lastly, earlier searches for monopoles trapped in Earth-based rocks and deep sea sediment may be revived, e.g. by passing through a SQUID a fraction of the industrially extracted ore [130].

Recently, a cosmic monopole search experiment (Search for Cosmic Exotic Particles, SCEP) has been proposed [160], utilising a hybrid approach that combines radio-frequency atomic magnetometers and plastic scintillators. Such setup would allow for the collection of both the induction and scintillation signals generated by the passage of a monopole, which provides acceptance to monopoles with velocity $\beta > 10^6$ and masses larger than $\sim 10^7$ GeV.

5 Summary and outlook

The existence of magnetic monopoles, should be confirmed experimentally, would modify our understanding of electrodynamics, rendering the Maxwell equation fully symmetric. The Dirac quantisation condition is a beautiful consequence of the existence of monopoles and therefore they represent an extremely appealing physical scenario. Various searches have beed carried out utilising diverse detection techniques in both observational facilities and experiments in colliders.

In the cosmic front, neutrino telescopes, such as IceCube and KM3NeT [161] currently, and IceCube Upgrade [162] and IceCube-Gen2 [163] in the future, may pursue the search for very fast monopoles. The deployment of a large NTD array, SLIM+, and proposals such as SCEP may probe monopoles in a wide range of velocities and masses. The search for monopoles trapped in ice and rocks through the induction technique may also be revived.

The CERN LHC, being the most powerful collider to-date, is the ideal machine to produce magnetic monopoles, if they exist. The MoEDAL experiment is the only contender in high magnetic charges and together with other LHC experiments, such as ATLAS and possibly CMS, are going to continue probing the existence of TeV-scale monopoles with HL-LHC data. MoEDAL has introduced several phenomenological novelties to the results interpretation: (a) β-dependent coupling, inspired by electric–magnetic duality arguments; (b) spin-1 monopoles, where a magnetic-moment parameter may evade the non-perturbativity problem; and (c) the t-channel photon-fusion production process, which is more abundantly produced than Drell–Yan at LHC energies. Virtual monopoles or their bound states may be probed in multiphoton events, recorded in ultraperipheral heavy-ion collisions and via forward-proton tagging.

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