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First search for magnetic monopoles through the Schwinger mechanism

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Abstract. Magnetic monopoles are hypothetical fundamental particles predicted in several theories beyond the standard model, however they have never been experimentally detected. The Schwinger mechanism predicts that an extremely strong magnetic field would produce isolated magnetic charges, if they exist. Looking for the existence of magnetic monopoles via the Schwinger mechanism had not been attempted before, but it is advantageous, owing to the possibility of calculating its rate through semi-classical techniques without perturbation theory. This paper focuses on the first search for magnetic monopoles produced by the Schwinger mechanism in heavy-ion collisions. It was carried out by the MoEDAL experiment, whose trapping detectors were exposed to 0.235 nb^{-1} of Pb-Pb collisions with 5.02 TeV energy per collision at the LHC, that provided the strongest known magnetic fields in the universe. A superconducting quantum interference device magnetometer scanned these detectors for the presence of magnetic charge. Magnetic monopoles with 1, 2 and 3 Dirac charges and masses up to 75 GeV were excluded by the analysis. This analysis, which has been published in the journal *Nature*, provided a lower mass limit for finite-size magnetic monopoles from a collider search and greatly extended previous mass bounds.

1. Introduction

Magnetic monopoles are hypothetical fundamental particles predicted in several theories beyond the standard model (SM), however they have never been experimentally detected up to now. In collider experiments, their production through Feyman diagrams such as Drell-Yan-like or photon-fusion mechanisms has been considered in related searches. The exploration of the Schwinger mechanism as a possible means to produce them thermally in strong magnetic fields constitutes a paradigm shift. Such an analysis has been performed recently [1] by the MoEDAL experiment at the Large Hadron Collider (LHC).

The paper is structured as follows. The main features and motivation for magnetic monopole are highlighted in section 2. In section 3, the MoEDAL physics goals are reviewed and its detectors are briefly described. After an overview of the previous MoEDAL searches for monopoles in section 4, the analysis considering the Schwinger thermal production is presented in section 5. Section 6 discusses future prospects for monopole searches among other proposals envisaged by the MoEDAL Collaboration to extend significantly its physics program to monopoles and beyond. The paper concludes with a summary in section 7.

2. Magnetic monopoles

Magnetic monopoles [2] that carry a non-zero magnetic charge and dyons [3] possessing both magnetic and electric charge are among the most fascinating hypothetical particles. Even though there is no generally acknowledged empirical evidence for their existence, there are strong theoretical reasons to believe that they do exist, and they are predicted in many theories.

The theoretical motivation behind the introduction of magnetic monopoles is the symmetrisation of the Maxwell equations and the explanation of the charge quantisation [4]. Dirac showed that the mere existence of a monopole in the universe could offer an explanation of the discrete nature of the electric charge, leading to the Dirac Quantisation Condition (DQC),

$$eg = \frac{N}{2}, \quad N \in \mathbb{Z}, \tag{1}$$

where e is the electron charge and g the monopole magnetic charge. In Dirac's formulation, magnetic monopoles are assumed to exist as point-like particles and quantum mechanical consistency conditions lead to (1), establishing the value of their magnetic charge. Although monopoles symmetrise Maxwell equations in form, there is a numerical asymmetry arising from the DQC, namely that the basic magnetic charge is much larger than the smallest electric charge. A magnetic monopole with a single Dirac charge, g_{D}, has an equivalent electric charge of $e/2\alpha = 137e/2$, where α is the fine-structure constant. Thus for a relativistic monopole the energy loss is around $4,700$ times (68.5^2) larger than that of a minimum-ionising electrically charged particle. The monopole mass and spin remain free parameters of the theory.

The existence of monopoles in grand unified gauge theories (GUTs) has been proposed by 't Hooft [5] and Polyakov [6], yet in this case its mass would be near the GUT scale, therefore outside the reach of any currently operating or any future particle accelerator. Unlike the Dirac monopole, GUT-motivated monopoles are extended objects, the production of which is exponentially suppressed by a factor $e^{-4/\alpha}$. Monopoles also emerge in superstring theory [7, 8] and as self-gravitating *global monopoles* [9–15].

In 1986, Cho and Maison proposed the *electroweak monopole* [16, 17], a non-trivial hybrid between the (Abelian) Dirac and the (non-Abelian) 't Hooft–Polyakov monopole. Its predicted magnetic charge is $2g_{\mathrm{D}}$ and, most importantly, its mass is between 4 to 7 TeV, which is accessible even to the LHC energies [18, 19].

Monopoles can also contribute to light-by-light scattering in colliders through radiative corrections in the form of a *box diagram* [20]. Such loop effects would lead to the production of highly energetic photons, which could provide a handle to detect them indirectly in experiments such as ATLAS and CMS or in future accelerators such as the International Linear Collider and the Future Circular Collider in the context of a Born–Infeld theory [21–24]. This possibility is viable if a point-like monopole is considered; the effect is highly suppressed for finite-monopoles, in which case only the Schwinger mechanism could provide some sensitivity.

The lack of experimental confirmation of free monopoles may be due to the bound state called *monopolium* [25–27] they may form, being confined by strong magnetic forces. Monopolium is a neutral state, hence it is difficult to detect directly at a collider detector, although its decay into photons would give a rather clear signal to the ATLAS and CMS detectors [20, 28–30], unlike MoEDAL that cannot detect photons. Nevertheless, the monopolium might break up into highly ionising dyons, which subsequently can be detected in MoEDAL. Moreover, its decay via photon emission would produce a peculiar trajectory in the medium, if the decaying states are also magnetic multipoles [31]. The monopolium is also a viable dark matter candidate [32].

3. The MoEDAL experiment

The MoEDAL (Monopole and Exotics Detector at the LHC) [33] experiment at the LHC [34] is dedicated to searches for manifestations of new physics through highly ionising particles (HIPs) in a manner complementary to ATLAS and CMS [35]. It is the first dedicated *search* LHC experiment to be approved among others that followed [36–38]. The principal motivation for MoEDAL is the quest for magnetic monopoles and dyons, as well as any massive, metastable, slow-moving particle with the fundamental electric charge, or multiples thereof [39–41], arising in various extensions of the SM [31], such as SUSY long-lived spartners [42–45], D-matter [46–52] among others [31, 53].

The MoEDAL detector [54] is deployed around the intersection region at Point 8 (IP8) of the LHC in the LHCb vertex locator (VELO) cavern. A three-dimensional schematic view of the MoEDAL experiment is presented in figure 1. It is a unique and largely passive detector, which does not require neither readout or trigger, based on three different detection techniques. It provides a permanent physical register of the HIPs passage without the presence of background from SM processes.

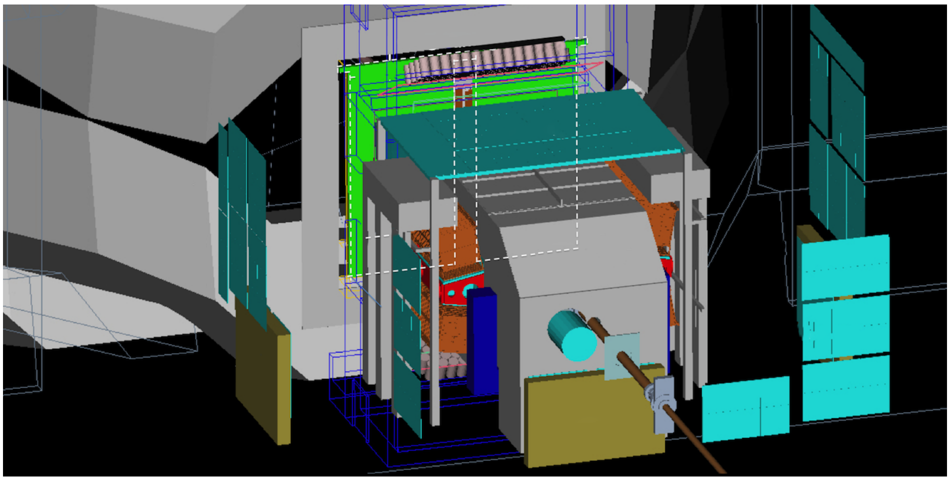

Figure 1. Geant4 visualisation of the MoEDAL experiment around the LHCb VELO region at Point 8 of the LHC.

The main sub-detector system is made of a large array of CR39®, Makrofol® and Lexan® nuclear track detector (NTD) stacks surrounding the IP8. The passage of a HIP through the plastic sheets 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 at the INFN Bologna laboratory. Then the sheets of plastics are scanned by an automatic system looking for aligned etch pits in multiple sheets.

A unique feature of MoEDAL is the use of magnetic monopole trappers (MMTs) to capture magnetically charged particles. The aluminium absorbers of MMTs are subject to an analysis in a superconducting quantum interference device (SQUID) magnetometer looking for isolated magnetic charges [55]. During the scanning, which takes place at the ETH Zurich SQUID laboratory, 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 magnetic monopole in the aluminium volume.

The only active MoEDAL sub-detector comprises an array of several TimePix pixel devices dedicated to the monitoring of cavern background sources. Its time-over-threshold mode provides a three-dimensional mapping of the charge spreading effect in the silicon sensor volume, thus differentiating between distinct particles species from mixed radiation fields and measuring their energy deposition [56].

4. Previous searches for monopoles and dyons in MoEDAL

MoEDAL is designed to fully exploit the energy-loss mechanisms of magnetically charged particles in order to optimise its potential to discover these elusive particles. The MoEDAL physics results on monopoles are mostly based on the scanning of the MMTs, exposed to LHC Run 1 data at $\sqrt{s} = 8$ TeV [57] and to 13 TeV pp collisions [58–60]. A distribution of persistent current calibrated to magnetic charges is shown in figure 2, obtained in the Run 2 analysis with the full MMT detector [60]. The SQUID analysis yielded no observed isolated magnetic charges, leading to upper limits on monopole production cross sections. This outcome led to lower mass exclusion bounds when considering two pair production processes: (a) a Drell–Yan-like (DY) process in photon s-channel intermediation, and (b) a photon-fusion t-channel diagram [61].

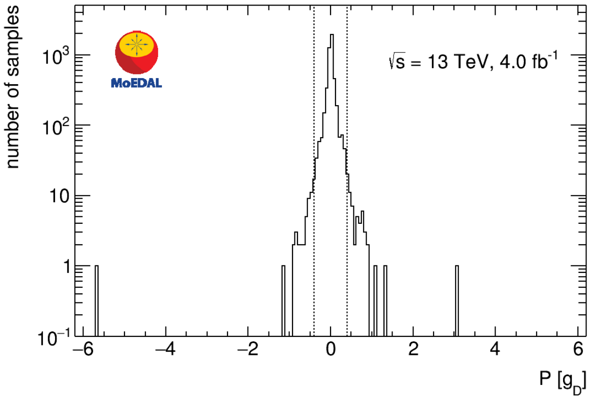

Figure 2. SQUID analysis results: Magnetic pole strength (in units of Dirac charge, $g_{\rm D}$) measured through the induced persistent current in aluminium samples of the MoEDAL trapping detectors exposed to 13 TeV pp collisions with every sample scanned twice. From [60].

MoEDAL pioneered monopole searches in several ways. It considered for the first time spin-1 monopoles [59] and the photon-fusion production mechanism [60]. The dependency of the monopole–photon coupling on $\beta = \sqrt{1 - 4M^2/\hat{s}}$ implies dependency on the centre-of-mass energy of the scattered partons, $\hat{s}$, in terms of the monopole mass, M [61]. This dependency has been consistently taken into account in the MoEDAL results interpretations.

If only the DY production mechanism is considered, the MoEDAL results complement exclusion limits obtained by the ATLAS Collaboration [62–64], which placed limits for monopoles with magnetic charge $|g| \leq 2g_{\rm D}$, as demonstrated in figure 3. The ATLAS bounds, in this case, are better that the MoEDAL ones for low charges due to the higher luminosity delivered to ATLAS than MoEDAL. The acceptance in MoEDAL for small magnetic charges is expected to be enhanced when the —sensitive to low charges— CR39 NTDs be analysed. On the other hand, higher charges are difficult to be probed in ATLAS due to the limitations of the electromagnetic-calorimeter-based level-1 trigger deployed for such searches [64]. MoEDAL is the sole detector sensitive to high magnetic charges.

It should be further noted that ATLAS cannot differentiate monopoles from HECOs since the corresponding analysis is only sensitive to the ionisation signal.[1] In the MoEDAL NTDs, on the other hand, etch-pits from magnetic charges would be different than those from electric charges, providing a clear signal of magnetic monopoles. Limits on monopoles from other collider experiments as well as from searches in cosmic radiation are reviewed in Refs. [2, 67].

A comparison between the photon-fusion and the DY mass limits is presented in figure 4 together with bounds set by ATLAS [62–64]. The production cross section at the LHC energies for photon fusion is much higher than the DY [61]. Therefore MoEDAL, being the only experiment considering it, set the most stringent limits on monopoles overall [69].

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[1] A clear monopole-induced signal in ATLAS (or CMS) could come from an analysis based on the characteristic trajectory of a magnetically charged particle in the presence of a solenoid magnet, exploited in the past by the CLEO [65] and TASSO [66] experiments.

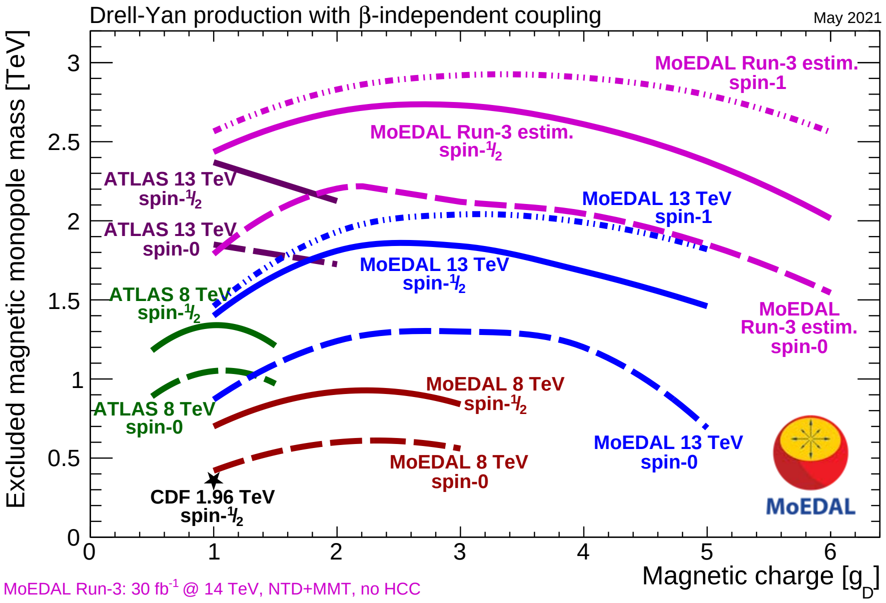

Figure 3. Magnetic monopole mass limits from CDF [68], ATLAS [63, 64] and MoEDAL searches [57, 60] as a function of magnetic charge for various spins, assuming a Drell-Yan pair-production mechanism and β-independent coupling.

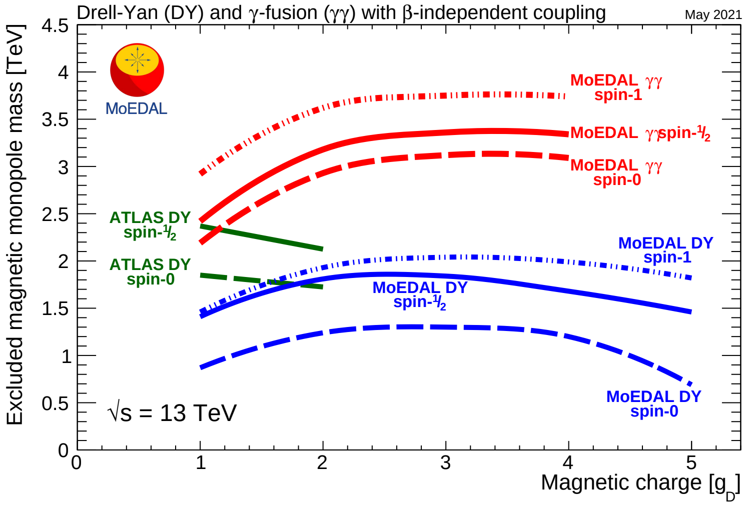

Figure 4. Magnetic monopole mass limits from ATLAS [64] and MoEDAL searches [57, 60] at $\sqrt{s}$ = 13 TeV as a function of magnetic charge for various spins, assuming β-independent coupling and two pair-production mechanism: Drell-Yan and photon fusion. From [69].

MoEDAL performed the first dedicated dyon search [70] in a collider experiment by means of MMT scanning. Mass limits in the range 750–1910 GeV were set using a benchmark DY production model for dyons with magnetic charge up to $5g_{\mathrm{D}}$, for electric charge from $1e$ to $200e$, and for spins 0, ½ and 1.

Recently a search for monopoles and for high electrically charged objects (HECOs) involving for the first time NTDs was carried out using a prototype array of Macrofol NTDs exposed to $\sqrt{s} = 8$ TeV pp collisions [71]. The limits placed on HECO pair production, which varied from $\sim$ 30 fb to 70 pb, for electric charges in the range $15e$ to $175e$ and masses from 110 GeV to 1020 GeV, were the most stringent as far as charges is concerned. For comparison, ATLAS has constrained HECOs of electric charge between $20e$ to $100e$ [64] at 13 TeV, an energy higher than that of the MoEDAL analysis. The MoEDAL result was achieved by analysing the Macrofol plastics, characterised by a high detection threshold of $z/\beta = 50$; the, not analysed yet, CR39 plastics are sensitive to charges as low as $z/\beta = 5$. Hence, MoEDAL has a much larger discovery potential, as discussed in section 6.

In both production processes, 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 result based on it is *only indicative* and used merely to facilitate comparisons between experiments. It is emphasised, however, that the upper bounds placed on production cross sections are solid and can be relied upon. One way to resolve the problem of cross-section calculations with large couplings is to use resummation techniques [72].

5. Search for monopoles produced by the Schwinger mechanism

Electrically charged particles can be created in strong enough electric fields, a phenomenon known as the Schwinger mechanism [73]. By electromagnetic duality, a sufficiently strong magnetic field would similarly produce magnetic monopoles. The possibility of calculating its rate through semi-classical techniques [74–79] 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 5.02 TeV/nucleon heavy-ion run, during which the MMTs were exposed to 0.235 nb^{-1} of Pb-Pb collisions. The strongest fields are generated in ultraperipheral collisions, for which the impact parameter b is approximately twice the nuclear radius; a schematic view of the collisions is shown in figure 5. In the 2018 heavy-ion run at the LHC, the peak magnetic field strength was $B \approx 10^{16}$ T [80]. This field strength 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 surfaces of magnetars [81].

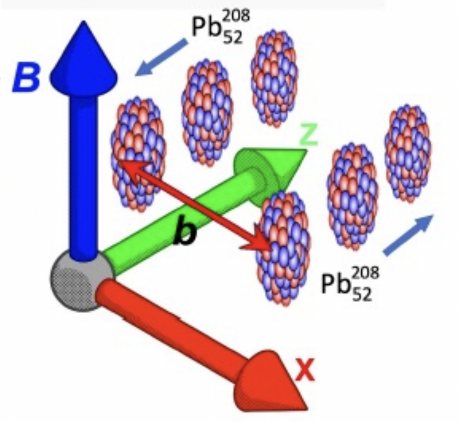

Figure 5. Peripheral Pb-Pb heavy-ion collisions produce strong magnetic fields. The 2018 Pb-Pb run with an integrated luminosity at IP8 of 0.235 nb^{-1}. B is the magnetic field of the heavy ions along the y axis, the z axis is the direction of motion of ions, and the x axis is the direction along which the impact parameter b is measured. From [1].

After exposure during November 2018, the MMTs were analysed with the SQUID at ETH Zurich. The measurements were compatible with the absence of monopoles and therefore magnetic charges equal to or above the Dirac charge were excluded in all samples [1], in a manner similar to that shown in figure 2 for a previous MoEDAL MMT analysis [60]. Subsequently, upper limits on the production cross section at 95% confidence level (CL) were set for monopoles with Dirac charges 1, 2 and $3g_{\mathrm{D}}$, as shown in figure 6.

Two approximations in the calculation of the monopole production cross section have been considered [1].

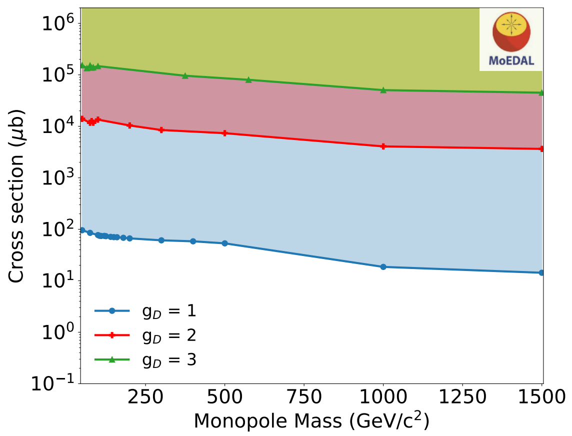

Figure 6. 95% CL exclusion regions on the cross section for monopole production via the Schwinger mechanism as functions of the monopole mass for magnetic charges $1g_{\mathrm{D}}$ (blue), $2g_{\mathrm{D}}$ (red), and $3g_{\mathrm{D}}$ (green). From [1].

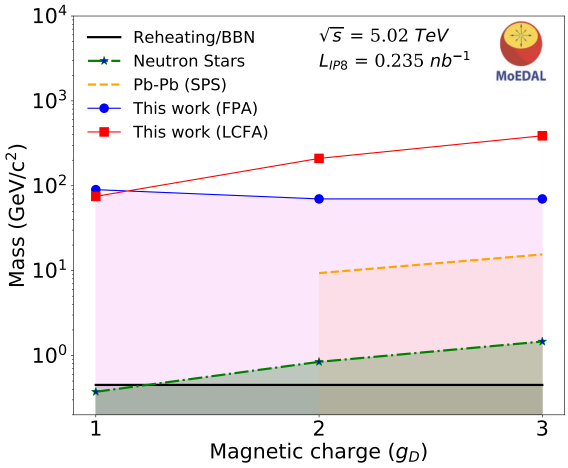

Figure 7. 95% CL excluded monopole masses obtained using the FPA (blue) and LCFA (red) calculations of Schwinger production with the conservative exclusion region shaded violet. Previous limits [74] are also shown for comparison. From [1].

Free-particle approximation (FPA) The spacetime dependence of the electromagnetic field of the heavy ions is treated exactly, but monopole self-interactions are neglected [79].

Locally constant field approximation (LCFA) The spacetime dependence of the electromagnetic field is neglected, but monopole self-interactions are treated exactly [77].

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 [77,79]. Thus, while neither approximation provides a complete calculation of the production cross section, both are expected to yield conservative lower limits. Thus, monopoles with Dirac charges $1g_{\mathrm{D}} \leq g \leq 3g_{\mathrm{D}}$ and masses up to 75 GeV were excluded, as seen in figure 7. The mass reach appears to be 20–30 times lower than the current bounds from ATLAS and MoEDAL (cf. figure 4), however, this cross-section calculation is theoretically sound. This analysis provided the first lower mass limits for finite-size monopoles from a collider search [1].

6. Future prospects

The MoEDAL Collaboration plans to continue scanning MMTs exposed to heavy-ion collisions both in the LHC Run 3 [82] and in the subsequent high-luminosity Run 4 (HL-LHC) looking for thermally produced monopoles. Assuming 2.5 nb^{-1} Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.52$ TeV and conservative theoretical assumptions, a ~ 20 GeV increase in sensitivity in HL-LHC heavy-ion run is expected, as observed in figure 8. Nuclear track detectors are not included in this projection [83].

MMTs exposed to *pp* collisions will also be analysed for the presence of monopoles during Run 3 and Run 4 assuming DY and photon-fusion production mechanisms. Likewise, NTDs will be etched and scanned looking for traces of magnetically and/or electrically charged particles. Actually, such an analysis for NTDs exposed to Run 2 collisions is currently underway, following the one presenting NTD and MMT results for Run 1 [71]. Processing CR39 plastic sheets, besides

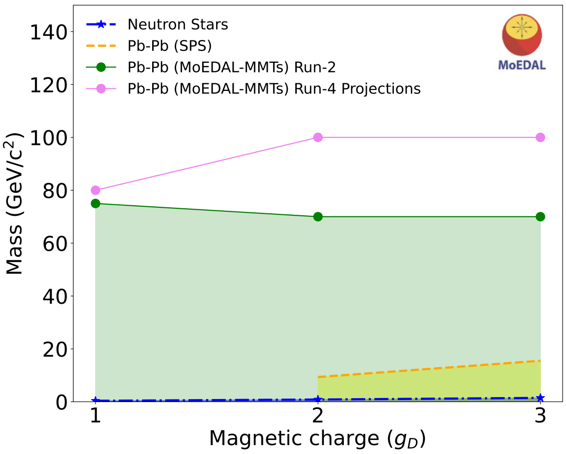

Figure 8. Projected 95% CL mass exclusion region (magenta line) expected for HL-LHC Pb-Pb runs using a conservative Schwinger cross-section calculation compared to the MoEDAL search limits (green line) [1]. From [83].

Macrofol, will allow to probe relatively *low* electric charges of less than 10e [41]. Moreover, an analysis for trapped monopoles in the Run 1 CMS beam pipe is ongoing [84].

MoEDAL plans to extend its physics program to *feebly interacting particles* that connect hidden sectors to the visible SM sector with the MoEDAL Apparatus for Penetrating Particles (MAPP) [85, 86]. Such *portal* scenarios attempt to explain observed phenomena in particle physics, astrophysics and cosmology such as the non-zero neutrino masses and oscillations, the dark matter [87, 88] and the baryon asymmetry of the universe, among others. MAPP Phase 1 was approved by the CERN Research Board in 2021 [89] and it is currently being deployed in the UA83 tunnel some 100 m from IP8, protected by cosmic rays by an overburden of ∼ 100 m of limestone [90]. MAPP Phase 2 is going to be in operation in HL-LHC and extend MAPP-1 physics reach [**?**].

Besides the search for monopoles in experiments with colliding beams, the MoEDAL Collaboration is also considering [85, 91] a *monopole telescope* sensitive to masses up to the GUT scale. This “Cosmic-MoEDAL”, which will comprise a 10,000 m^2 array of plastic NTDs deployed at high altitude, will have flux sensitivity well below the Parker limit.

7. Summary

MoEDAL, the first dedicated search experiment at the LHC, is extending considerably the reach in the search for (meta)stable highly ionising particles. It has pioneered several aspects of magnetic monopoles, such as the consideration of vector monopoles, β-dependent coupling and photon-fusion production. Thanks to its unique passive detectors, it provides sensitivity complementary to that of the LHC main detectors. It is the only contender in high magnetic charges and performed the first dedicated collider search for dyons. Very high electric charges have been probed recently by analysing plastic nuclear track detectors.

A breakthrough analysis bypassing the issue of the non-perturbativity of the monopole-photon coupling by considering the Schwinger thermal mechanism for the monopole production in strong magnetic fields has been published recently in *Nature*. It involves the monopole trappers exposure to heavy-ion LHC collisions and yielded the first theoretically robust lower mass limits for monopoles with magnetic charge up to three Dirac charges.

The search for trapped monopoles in the Run 1 CMS beam pipe is expected to be released soon. MoEDAL is also sensitive to single and multiple electric charges predicted in supersymmetric models and other exotic scenarios. Moreover, the search for HIPs can be pushed to GUT mass scales by the deployment of the Cosmic-MoEDAL array at high altitude.

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