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MoEDAL, MAPP and future endeavours

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The unprecedented collision energy of the LHC has opened up a new discovery frontier, however, without any signs of new physics in sight. The first LHC dedicated search experiment, MoEDAL, started data taking for Run 2. MoEDAL is designed to search highly ionising particle avatars of new physics using pp and heavy-ion collisions at the LHC. The planned upgrade for MoEDAL at Run 3 of the LHC — the MAPP detector (MoEDAL Apparatus for Penetrating Particles) — will extend MoEDAL's physics reach to include feebly interacting, long-lived messengers of physics beyond the Standard Model. This will allow the experiment to explore a number of models of new physics, including dark sector models, in a complementary way to that of conventional LHC collider experiment detectors. Furthermore, a possible astroparticle extension to MoEDAL, called Cosmic-MoEDAL, will allow the search for magnetic monopoles to be continued from the TeV scale to the GUT scale. This paper focuses on recent results and plans for the LHC Run 3.

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1. Introduction

The MoEDAL (Monopole and Exotics Detector at the LHC) [1] experiment at the Large Hadron Collider (LHC) [2] is dedicated to searches for manifestations of new physics through highly ionising particles in a manner complementary to ATLAS and CMS [3]. It is the first dedicated *search* LHC experiment to be approved among others that followed [4–6]. The principal motivation for MoEDAL is the quest for magnetic monopoles and dyons (particles with both electric and magnetic charge), as well as for any massive, stable or long-lived, slow-moving particle with the fundamental electric charge (or multiples thereof) arising in various extensions of the Standard Model (SM) [7], such as SUSY long-lived spartners [8], D-matter [9–15] among others [7, 16]. Emphasis is given here on recent MoEDAL results, based on the exposure of magnetic monopole trapping volumes to pp and heavy-ion collisions, on future prospects, including electric charges, and on the description and sensitivity of the planned MoEDAL Apparatus for Penetrating Particles (MAPP), designed to extend the LHC reach in the quest for dark matter [17, 18].

2. The MoEDAL experiment

The MoEDAL detector [19] is deployed around the intersection region at Point 8 (IP8) of the LHC in the LHCb Vertex Locator cavern. It is a unique and largly passive detector based on three different detection techniques.

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 highly ionising particle 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 in the INFN Bologna laboratory. Then the sheets of plastics are scanned looking for aligned etch pits in multiple sheets.

A unique feature is the use of magnetic monopole trappers (MMTs) to capture magnetically charged particles. The aluminium absorbers of MMTs are subject to an analysis looking for magnetically charged particles at the ETH Zurich SQUID laboratory [20].

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 allows a 3D mapping of the charge spreading effect in the silicon sensor volume, thus differentiating between different particles species from mixed radiation fields and measuring their energy deposition [21].

3. Searches for monopoles and dyons in MoEDAL

MoEDAL is designed to fully exploit the energy-loss mechanisms of magnetically charged particles [22–25] in order to optimise its potential to discover these elusive particles. Various theoretical scenarios foresee the production of magnetic charge at the LHC [7, 26]: (light) 't Hooft-Polyakov monopoles [24, 25, 27], electroweak monopoles [28–33], global monopoles [34–40], monopoles in Born-Infeld theory [41, 42] and monopolium [23, 43–47], a monopole-pair bound state. Magnetic monopoles and dyons — the latter possessing both magnetic and electric charge [48] — are fascinating hypothetical particles. Even though there is no empirical evidence for their presence, strong theoretical reasons motivate their existence and many theories, including grand unified theories [24, 25] and superstring theory [49, 50], predicted them.

Up to now, the MoEDAL physics results on monopoles are based on the scanning of the MMTs, exposed to LHC Run 1 8-TeV data [51] and to 13 TeV pp collisions [52–54]. 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 [55].

If the DY production mechanism is considered, the ATLAS bounds [56–58] are better that the MoEDAL ones for $|g| = 2g_{\rm D}$ due to the higher luminosity delivered in ATLAS and the loss of acceptance in MoEDAL for small magnetic charges, while MoEDAL is the only detector sensitive to high charges. The production cross section at the LHC energies for photon fusion is much higher than the DY [55]. Therefore MoEDAL, being the only experiment considering it, set the most stringent limits on monopoles overall [59].

MoEDAL performed recently the first dedicated dyon search in a collider experiment by means of MMT scanning; a summary of the dyon mass limits are shown in Figure 1. Mass limits in the range 750 – 1910 GeV were set using a benchmark DY production model for dyons with magnetic charge up to $5g_{\rm D}$, for electric charge from $1e$ to $200e$, and for spins 0, ½ and 1 [60]. Moreover, an analysis for trapped monopoles in the Run 1 CMS beam pipe is currently underway [61].

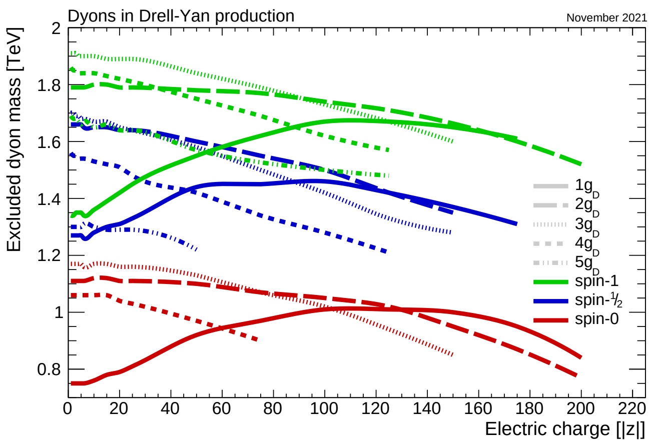

Figure 1: Dyon mass limits from MoEDAL searches [60] at $\sqrt{s} = 13$ TeV as a function of electric charge for various spins and magnetic charges, assuming Drell-Yan pair-production mechanism.

In both production processes, the monopole pair couples to the photon via a coupling that depends on $g_{\rm D}$ and therefore has a value of $O(10)$. 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 should, however, be emphasised that the upper bounds placed on production cross sections are solid and can be relied upon.

This situation is resolved if thermal Schwinger production of monopoles in heavy-ion collisions is considered [62]. This mechanism becomes effective in the presence of strong magnetic fields and calculations rely on semiclassical techniques rather than perturbation theory, therefore it overcomes these limitations [63–68]. Pb-Pb heavy-ion collisions at the LHC produce the strongest known magnetic fields in the current 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 and analysed later with a SQUID. Monopoles with Dirac charges $1g_{\rm D} \leq g \leq 3g_{\rm D}$ and masses up to 75 GeV were excluded, as seen in Figure 2. This analysis provided the first lower mass limits for finite-size monopoles from a collider search [69].

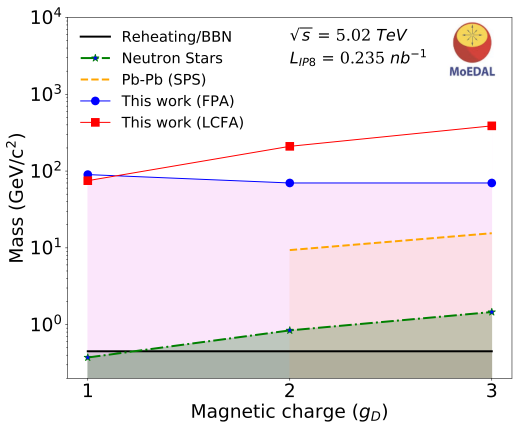

Figure 2: The magnetic-monopole exclusion region (at 95% CL) in mass and charge obtained using two different calculations of Schwinger production mechanism for Pb-Pb collisions. From [69].

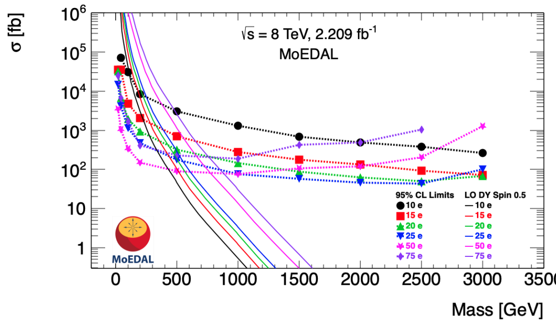

Figure 3: Cross-section upper limits (at 95% CL) for monopoles produced with a Drell-Yan pair production mechanism in 13 TeV pp collisions as a function of mass for spin-½ HECOs with electric charge $10e - 75e$. The solid lines are cross-section calculations at leading order. From [70].

4. Electrically charged particles

The MoEDAL detector is also designed to search for any massive, long-lived, slow-moving particles with single or multiple electric charge arising in many scenarios of physics beyond the Standard Model. Supersymmetric (SUSY) long-lived particles [16, 71–74], quirks, strangelets, Q-balls, and many others fall into this category [7]. A generic search for high-electric-charge objects (HECOs) using for the first time NTD data has been completed recently [70] with a prototype NTD detector exposed at 8-TeV pp collisions. Upper cross section limits on fermionic HECOs are shown in Figure 3. The limits placed on the DY production cross sections of HECO pairs vary from $\sim$ 30 fb to 70 pb, for electric charges in the range $15e$ to $175e$ and masses from 110 GeV to 1020 GeV. For comparison, ATLAS has constrained HECOs of electric charge between $20e$ to $100e$ [75].

A feasibility study on the detection of massive metastable supersymmetric partners showed that MoEDAL is mostly sensitive to slow-moving particles unlike ATLAS/CMS suitability for faster ones ($\beta \gtrsim 0.8$ [76]). However, the lower integrated luminosity for MoEDAL at IP8 remains a limiting factor for simple scenarios. Direct production of heavy fermions with large cross section (thus via strong interactions) is the most favourable scenario for MoEDAL. More complex topologies appear to be promising for detecting long-lived sleptons in phenomenologically realistic models, where MoEDAL could cover parameter space less accessible by CMS [73] and ATLAS [74]. Even for SUSY models observable by both ATLAS/CMS and MoEDAL, the added value of MoEDAL would remain, since it provides a coverage with a completely different detector and analysis technique, and thus with uncorrelated systematic uncertainties.

The prospects for detecting particles of higher electric charges in MoEDAL are also very promising. Doubly charged scalars and fermions are suggested by Type-II ($H^{\pm\pm}$) and Type-III seesaw models of neutrino masses, respectively [77]. In addition to the Type-II seesaw model, several other BSM scenarios, namely the Left-Right model, the Georgi-Machacek model, the 3-3-1 model and the little-Higgs model also predict doubly-charged scalars. Even better discovery reach is anticipated for charges of $2e$, $3e$ and $4e$, proposed in radiative neutrino mass models, which often add a discrete symmetry to the SM gauge group [77]. For such models, at least one signal event at the MoEDAL NTDs is expected for up to masses of 290, 610 and 960 GeV for scalars $S^{\pm 2}$, $S^{\pm 3}$ and $S^{\pm 4}$ in Run 3 [78]. Recent studies [79, 80] quantified the MoEDAL potential to discover generic electrically charged scalars and fermions in the range $1e$ to $6e$ in the High Luminosity LHC (HL-LHC) runs with sensitivity superior to that of ATLAS and CMS.

5. MoEDAL Apparatus for Penetrating Particles

MoEDAL proposes to deploy MAPP in a gallery near IP8 shielded by an overburden of approximately 100 m of limestone from cosmic rays [81, 82]. The Phase-1 MAPP subdetector is composed of mQP, a detector sensitive to particles with fractional charge as small as $0.001e$, the so-called millicharged particles, mCP. This MAPP first stage was approved by the CERN Research Board in December 2021. MAPP-mQP is made of plastic scintillation bars, as shown in Figure 4, and it is currently been installed in the UA82 gallery at a distance 100 m from IP8. It is expected to start taking data in 2023.

Another part of the detector, the MAPP-LLP, will be deployed in the Phase-2 MAPP as three nested boxes of scintillator hodoscope detectors, in a 'Russian doll' configuration, following as far as possible the contours of the UGC1 cavern. It is designed to be sensitive to long-lived neutral particles from new physics scenarios via their interaction or decay in flight in a decay zone of size approximately 5 m (wide) × 10 m (deep) × 3 m (high). The MAPP detector can be deployed in a number of positions in the forward direction, at at distance of $O(50\text{ m})$ from IP8. It will be installed during the Long Shutdown 3 to be operated in the HL-LHC.

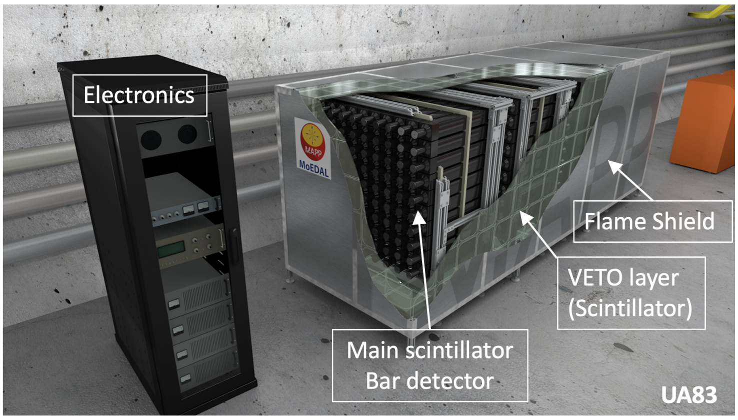

Figure 4: A schematic view of the MAPP-mQP subdetector.

mCPs arise when a new $U(1)$ is introduced to a dark sector with a massless dark photon A', coupled to the SM photon field, and a massive dark fermion ψ with charge much less than that of an electron as a result of kinetic mixing [83]. MAPP-mQP is expected to significantly extend the reach obtained by milliQan demonstrator [84]. Moreover, it has been shown that MAPP-mQP can detect a heavy neutrino with a large enough electric dipole moment considered to be a member of a fourth generation lepton doublet [85].

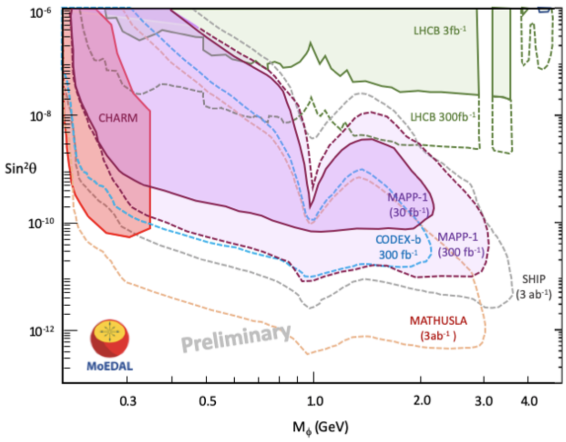

Figure 5: MAPP-LLP sensitivity with 30 and 300 fb^{-1} of pp collisions for a dark Higgs boson ϕ in terms of its mass and its coupling to SM particles.

The MoEDAL-LLP detector should be sensitive to portal interactions that connect a hidden (dark) sector and the visible sector of the SM. Scenarios beyond-the-SM that introduce a dark sector in addition to the visible SM sector are required to explain a number of observed phenomena in particle physics, astrophysics and cosmology such as the non-zero neutrino masses and oscillations, the dark matter, baryon asymmetry of the Universe, the cosmological inflation. In particular, dark Higgs bosons interact with the SM through a kinetic mixing term, thus probing one of the few possible renormalisable interactions with a hidden sector, the Higgs portal quartic scalar interaction. Such scenarios are accessible to MAPP and other future experiments [4–6]. A comparison of the projected sensitivity of MAPP-LLP with other LLP experiments is illustrated in Figure 5. Regarding their cosmological implications, dark Higgs bosons may mediate interactions with hidden dark matter that has the correct thermal relic density or resolves small-scale-structure discrepancies. Indeed, such a model with a dark Higgs inflaton strongly favoured by cosmological Planck+BK15 data is expected to leave imprints on LHC experiments, MAPP-LLP included [86].

In the fermion portal, right-handed long-lived heavy neutrinos N_i can be pair produced in the decay of an additional Z' boson in the gauged $B-L$ model, which also contains a singlet scalar field that spontaneously breaks the extra $U(1)_{B-L}$ gauge symmetry [87]. In this model, MAPP will fill the gap left by other LHC experiments [88]. Sterile neutrinos may be long-lived in neutrino-extended SM Effective Field Theories, νSMEFT. Intermediate-mass can be produced in leptonic and semi-leptonic decays of charmed and bottomed mesons, decaying to leptons via neutral and charged weak currents, thus becoming detectable in MAPP-LLP [89]. R-parity violating supersymmetry also predicts LLPs, such as light long-lived neutralinos $\tilde{\chi}_1^0$ decaying via λ'_{ijk} couplings to charged particles. Benchmark scenarios related to either charm or bottom mesons decaying into $\tilde{\chi}_1^0$ have been considered, in similar fashion as in sterile neutrinos, showing that the MAPP can cover various $\tilde{\chi}_1^0$ lifetimes [90].

6. The Cosmic-MoEDAL

The MoEDAL collaboration is considering [81, 91] an astroparticle extension to the MoEDAL experiment that will enable the search for magnetic monopoles of mass of up to the Grand Unification (GUT) scale. The detector technology for the "Cosmic-MoEDAL" will be the same as its LHC counterpart, namely based on NTDs. SLIM was the first experiment to use this approach to search for highly ionising particles of cosmic origin [92, 93]. SLIM was necessarily deployed at high altitude at the Mt Chacaltaya laboraatory in Bolivia with an elevation of 5,400 m. However, its modest size (400 m^2) precluded it from the search for a flux of cosmic monopoles below the Parker Bound.

Cosmic-MoEDAL is proposed as a 10,000 m^2 array of plastic NTDs (CR39®) deployed at high altitude. Such an array would be able to take the search for cosmic monopoles with velocities $\beta \gtrsim 0.1$ from the TeV scale to the GUT scale for monopole fluxes well below the Parker Bound, as shown in Figure 6.

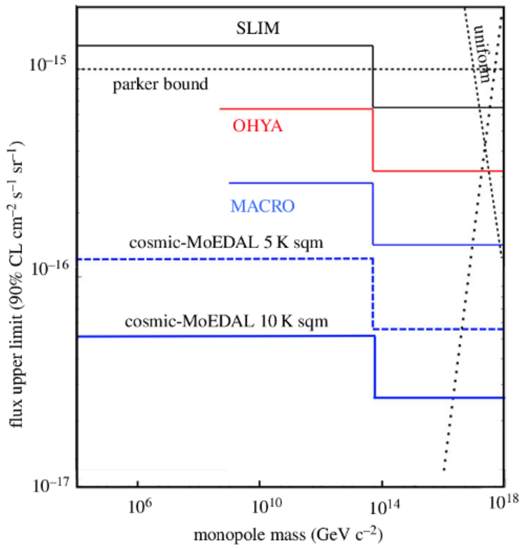

Figure 6: Flux upper limits for cosmic magnetic monopoles of charge $1g_D$ and $\beta > 0.05$ versus monopole mass. The figure shows the 90% CL limits obtained by the SLIM [92], MACRO [94] and OHYA [95] experiments. From [81].

7. Summary and outlook

MoEDAL, the first dedicated *search* experiment at the LHC, is extending considerably the LHC reach in the search for (meta)stable highly ionising particles. The latter are predicted in a variety of theoretical models and include magnetic monopoles, SUSY long-lived spartners, D-matter, quirks, strangelets, Q-balls, etc. MoEDAL is optimised to probe precisely all such long-lived states, unlike the other LHC experiments, by combining different detector technologies: plastic nuclear track detectors, trapping volumes and pixel sensors. It provides the best limits for high magnetic charges.

The latest highlights in MoEDAL results include the first search for dyons at the LHC, the first search for monopoles produced via the Schwinger mechanism and the first search with NTDs constraining electrically charged particles. The search for trapped monopoles in the Run 1 CMS beam pipe is expected to be announced soon. MoEDAL is also sensitive to single and multiple electric charges predicted in supersymmetric models and other exotic scenarios. Moreover, the search for HIPs such as Q-balls, nuclearites and magnetic monopoles can be pushed to GUT mass scales, and below the Parker Bound, by the deployment of the Cosmic-MoEDAL array at high altitude.

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