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# MoEDAL-MAPP – Detectors specialised for LLP searches

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The unprecedented collision energy of the LHC has opened up a new discovery regime. The first LHC dedicated search experiment, MoEDAL, has inaugurated searches optimised for long-lived particles. MoEDAL is designed to search highly ionising avatars of new physics using proton and heavy-ion collisions at the LHC. The upgrade for MoEDAL at Run 3 — the MAPP detector (MoEDAL Apparatus for Penetrating Particles) — will extend the physics reach to include feebly interacting, long-lived messengers of physics beyond the Standard Model. This will allow the exploration of a number of models of new physics, including dark sector models, in a complementary way to that of the main LHC detectors. This paper focuses on physics results, current status and plans for the Run 3 and beyond.

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PoS(LHCP2023)011

## 1. Introduction

The Standard Model (SM) successfully describes the experimental data obtained so far. However, several SM shortcomings call for theoretical proposals of physics beyond the SM (BSM). Despite the wide spectrum of searches at the main LHC experiments, signals from BSM are still to be seen and a possible explanation involves long-lived particles (LLPs) [1], which require detectors [2–5] optimised for such manifestations of physics BSM. MoEDAL-MAPP [6] is the first of a series of such experiments, targeting highly ionising (HIPs) and feebly interacting particles (FIPs).

## 2. The MoEDAL detector and results

The Monopole and Exotics Detector at the LHC (MoEDAL) [7], the first dedicated *search* LHC experiment, is specialised in the detection of HIPs in a manner complementary to ATLAS and CMS [8]. Its main motivation is the quest for magnetic monopoles [9, 10], as well as any massive, detector-stable, slow-moving particle with single or multiple electric charge [11]. Various theoretical scenarios foresee the production of magnetic charge at the LHC [12]: (light) 't Hooft-Polyakov monopoles [13, 14], electroweak monopoles [15–19], global monopoles [20–26], monopoles in Born–Infeld theory [27–30] and monopolium [10, 31–37], a monopole-pair bound state.

The MoEDAL detector [38, 39] is deployed around interaction point 8 (IP8) in the LHCb vertex locator cavern, as shown in Figure 1. It is a unique and largely passive detector based on three different techniques, which does not require neither readout or trigger. An array of nuclear track detectors (NTD) registers the passage of a HIP by an invisible damage zone along the trajectory, revealed as an etch-pit when the plastic detector is chemically etched off-site. Aluminium magnetic monopole trappers (MMTs), which can capture magnetically charged particles, are scanned in a superconducting quantum interference device looking for isolated magnetic charges [40]. The only active sub-detector comprises TimePix devices for monitoring cavern background sources [41].

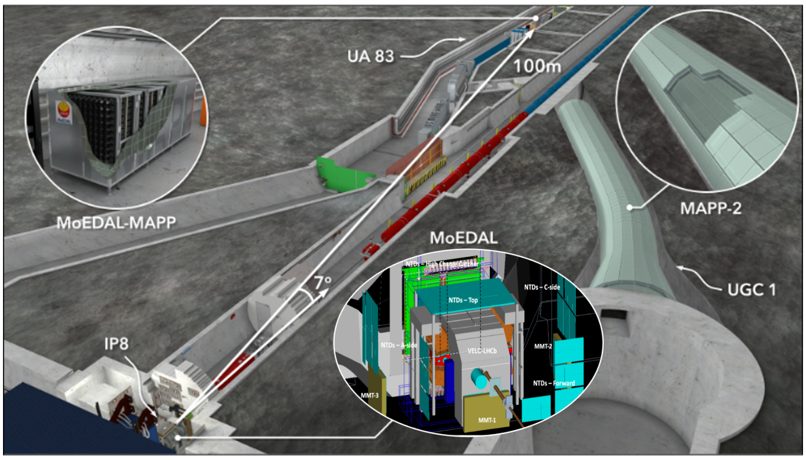


**Figure 1:** Schematic view of the MoEDAL-MAPP facility at the LHC IP8 region, depicting the location of the MoEDAL (at IP8), MAPP-1 (at UA83), and future MAPP-2 (at UGC1) detectors.

MoEDAL pioneered the quest for high magnetic charges [42–48] in several ways. It considered for the first time spin-1 monopoles [44] and the photon-fusion production mechanism [45, 49]. The



PoS(LHCP2023)011

dependency of the monopole–photon coupling on the $\beta$ parameter is being consistently considered by MoEDAL. MoEDAL also performed the first dedicated search for dyons — object arrying both electric and magnetic charge — in a collider experiment [50, 51].

MoEDAL has constrained high-electric-charge objects (HECOs) [47, 48] in the higher charge regime by analysing NTDs. Moreover, prospects for discovering particle with electric charges lower than $\sim 10e$ arising in various extensions of the SM [11], such as SUSY long-lived spartners [52–55], D-matter [56–62], radiative neutrino masses [63], among others [11, 64] look promising.

The monopoles and the HECOs coupling to the photon 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 *indicative only*. One way to resolve this problem is to use resummation techniques in monopoles [65] and HECOs [66]. Another way to evade it is the Schwinger production in heavy-ion collisions [67]. This mechanism becomes effective in the presence of strong magnetic fields and calculations rely on semiclassical techniques [68–73]. The first search for such production was conducted by MoEDAL using the MMT exposure to Pb-Pb collisions, excluding magnetic charges up to three Dirac charges and masses up to 75 GeV. This analysis provided the first lower mass limits for finite-size monopoles from a collider search [46].

## 3. The MAPP detector

The MoEDAL Apparatus for Penetrating Particles (MAPP) [6, 39], an approved Phase-1 upgrade to MoEDAL, will provide competitive sensitivity to FIPs. It will be sensitive to portal interactions that connect a hidden (dark) sector and the visible sector of the SM in a complementary fashion to the LHC main experiments [74]. The Phase-1 MAPP (MAPP-1) is being installed in the gallery UA83 adjacent to the LHC ring at a distance 100 m from IP8, as shown in Figure 1. It is made of 400 plastic scintillation bars read out by low noise 3-inch photomultipliers. MAPP-1 is sensitive to particles with fractional charge as small as $0.001e$, the so-called millicharged particles (mCPs) [75]. Moreover, an Outrigger detector, composed of scintillator planks, is planned to be deployed in a circular passage joining the UA83 gallery and the beam tunnel. It will improve the acceptance of the MAPP-1 detector for heavier mCPs.

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 $\psi$ with charge much less than that of an electron as a result of kinetic mixing [76]. MAPP-1 is expected to significantly extend the sensitivity of other experiments in mCPs [77, 78]. It can also detect a heavy neutrino with large electric dipole moment considered to be a member of a fourth generation lepton doublet [79].

Another sub-detector is proposed to be deployed in the Phase-2 MAPP (MAPP-2) as several nested boxes of scintillator hodoscope detectors in a 'Russian doll' configuration, following the contours of the UGC1 cavern, depicted in Figure 1. It is designed to be sensitive to neutral long-lived particles that decay to visible particles in a decay volume of 5 m (wide) $\times$ 10 m (deep) $\times$ 3 m (high). It will be installed during the Long Shutdown 3 to be operated in the High-Luminosity LHC [6].

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 [3–5]. The projected sensitivity of MAPP-LLP is illustrated in Figure 2. Regarding their cosmological



PoS(LHCP2023)011

implications, dark Higgs bosons may mediate interactions with hidden dark matter that has the correct thermal relic density or resolves small-scale-structure discrepancies [80].

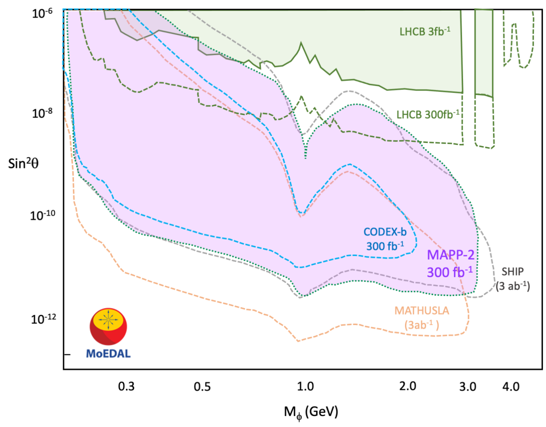


**Figure 2:** MAPP-2 sensitivity for a dark Higgs boson model in terms of its mass, $M_\phi$ and its coupling to SM particles, $\sin^2\theta$, assuming 100% detector/tracking efficiency. Comparison with the expected reach of CODEX-b, LHCb, MATHUSLA and SHiP is also provided.

In the fermion portal, right-handed long-lived heavy neutrinos can be produced in the decay of a $Z'$ boson in the gauged $B-L$ model [81]; MAPP will fill the gap left by other LHC experiments [82, 83]. Sterile neutrinos may be long-lived in neutrino-extended SM effective field theories, $\nu$SMEFT, and can be produced in decays of charmed and bottomed mesons, decaying to leptons, thus becoming detectable in MAPP [84]. In $R$-parity violating supersymmetry with light long-lived neutralinos may be produced via charm or bottom mesons and decay to charged SM particles, MAPP can cover various neutralino lifetimes [85, 86], in similar fashion as in sterile neutrinos.

## 4. Summary and future prospects

MoEDAL, the first dedicated search experiment at the LHC, extends considerably the reach for (meta)stable HIPs. It has pioneered several aspects of magnetic monopoles, such as the consideration of vector monopoles, $\beta$-dependent coupling and photon-fusion production. It is the only contender in high magnetic charges and performed the first dedicated collider search for dyons. The first search considering the Schwinger production evaded the large monopole–photon coupling and constrained finite-sized monopoles. The search for trapped monopoles in the Run 1 CMS beam pipe will be released soon [87]. Very high electric charges have been probed by analysing plastic NTDs.

The MoEDAL-MAPP experiment was established in 2021 with the addition of the MAPP-1 detector to MoEDAL. The latter has been reinstalled in an improved configuration for Run-3 data taking, while the MAPP detector adds a competitive sensitivity to FIPs. The MAPP-1 detector, which is currently being installed, is expected to take data in 2024, whereas the Phase-2 MAPP is planned to be deployed during the Long Shutdown 3, preceding Run-4 of the HL-LHC, in order to drastically improve MoEDAL-MAPP response to neutral LLPs.

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PoS(LHCP2023)011

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