MoEDAL-MAPP a Dedicated Detector Search Facility at the LHC

Letter of Interest for Snowmass 2021

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B. Acharya,[1,2] J. Alexandre,[1] P. Benes,[3] B. Bergmann,[3] J. Bernabéu,[4] A. Bevan,[5] H. Branzas,[6] P. Burian,[3] M. Campbell,[7] M. Campbell,[7] S Cecchini,[8] Y. M. Cho,[28], M. de Montigny,[9] A. de Roeck,[7] J. R. Ellis,[1,10] M. El Sawy,[7] M. Fairbairn,[1] D. Felea,[6] M. Frank,[11] J. Hays,[5] R. Hirosky,[30] A. M. Hirt,[29] P. Q Hung,[30] J. Janecek,[3] M. Kalliokoski,[18] D-W Kim,[13] A. Korzenev,[15] D. Lacarèrre,[7] S. C. Lee,[13] C. Leroy,[16] G. Levi,[8] A. Lionti,[15] A. S. Lobos, [9] J. Mamuzik,[4] A. Maulik,[8,9] A. Margiotta,[17] N. Mauri,[8] N. E. Mavromatos, [1] P. Mermod,[15] M. Mieskolainen,[18] L. Millward,[5] V. A. Mitsou,[4] R. Oravo,[18] I. Ostrovskiy,[19] P.-P. Ouimet,[9] J. Papavassilou,[4] B. Parker,[20] L Patrizii,[8] G. E. Păvălaş,[6] J. L. Pinfold,[9,*] L. A. Popa,[6] V. Popa,[6] M. Pozzato,[8] S. Pospisil,[3] A. Rajantie,[21] R. Ruiz de Austi,[4] Z. Sahnoun,[8,22] M. Sakellariadou,[1] A. Santra,[4] S. Sarkar,[1] G. Semenoff,[23] A. Shaa,[24] G.Sirri,[8] K. Sliwa,[25] R. Soluk,[9] M. Spurio,[8] M. Staelens,[9] M. Suk,[4] M. Tenti,[27] V. Togo,[8] J. A. Tuszynski,[9], A. Upreti,[19] V. Vento,[3] O.Vives,[4] A.Wall,[19]

[1]Theoretical Particle Physics & Cosmology Group, Physics Dept., King's College London, UK
[2]International Centre for Theoretical Physics, Trieste, Italy
[3]IEAP, Czech Technical University in Prague, Czech Republic
[4]IFIC, Universitat de Valéncia - CSIC, Valéncia, Spain
[5]School of Physics and Astronomy, Queen Mary University of London, London, England
[6]Institute of Space Science, Bucharest - Măgurele, Romania
[7]Experimental Physics Department, CERN, Geneva, Switzerland
[8]INFN, Section of Bologna, Bologna, Italy
[9]Physics Department, University of Alberta, Edmonton, Alberta, Canada
[10] Theoretical Physics Department, CERN, Geneva, Switzerland
[11]Department of Physics, Concordia University, Montréal, Quebec, Canada
[12]Physics Department, University of Muenster, Muenster, Germany
[13]Physics Department, Gangneung-Wonju National University, Gangneung, Republic of Korea
[14]Physics Department, University of Cincinnati, Cincinnati, Ohio, USA
[15]Section de Physique, Université de Genève, Geneva, Switzerland; [16]Physics Department, Universitéof Montréal, Montréal, Quebec, Canada
[17]INFN, Section of Bologna & Department of Physics & Astronomy, University of Bologna, Italy
[18]Physics Department, University of Helsinki, Helsinki, Finland
[19]Physics Department, University of Alabama, Tuscaloosa, Alabama, USA
[20]The Institute for Research in Schools, Canterbury, England
[21]Department of Physics, Imperial College London, UK
[22]Centre for Astronomy, Astrophysics and Geophysics, Algiers, Algeria
[23]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[25]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[26]Physics Department, Northeastern University, Boston, Massachusetts, USA
[27]INFN, CNAF, Bologna, Italy
[28]Physics Department, Konkuk University, Seoul, Korea
[29]Department of Earth Sciences, Swiss Federal Instituteof Technology, Zurich, Switzerland
[30]Department of Physics, University of Virginia, Charlottsville, USA

[*] **Communicating Author E-mail: jpinfold@ualberta.ca**

Abstract

During LHC's Run-2 the MoEDAL experiment, the LHC's first dedicated search experiment, took over 6 fb^{-1} of data at a centre-of-mass energy (E_{cm}) of 13 TeV with 100% efficiency. The LoI of the MoEDAL Collaboration describing an exciting program to expand the search for highly ionizing particles in proton-proton and heavy-ion collisions to include feebly ionizing and long lived messengers of new physics at LHC's RUN-3 and beyond, has already been endorsed by the LHCC. This enhancement of the physics program of the MoEDAL Collaboration is made possible by the planned deployment of two new sub-detectors MAPP (the MoEDAL Apparatus for Penetrating Particles) and MALL (the MoEDAL apparatus for extremely Long Lived charged particles). MoEDAL-MAPP's physics reach is complementary to that of the general purpose detectors ATLAS and CMS.

1. Introduction. The discovery of the Higgs boson announced in 2012 by the LHC's large general purpose detectors (GPDs), ATLAS and CMS, put in place the last piece of the Standard Model (SM) puzzle. Unfortunately, evidence for physics beyond the Standard Model is still not forthcoming at the LHC. A logical possibility is that conventional collider detectors are not optimized to detect the new physics present. MoEDAL is the first of a series of "dedicated experiments" [1] planned for the LHC that is designed to provide a complementary coverage for messengers of physics beyond the

SM that the ATLAS, CMS and LHCb detectors might find it more challenging if not impossible to detect.This could be the case if the avatars of any new physics were very highly ionizing (HIPs), feebly interacting (mQP) or very long-lived weakly interacting neutral particles (LLPs). The LoI for the MoEDAL-MAPP experiment - designed to detect all three avatars of new physics: HIPs, mQPs and LLP's - has been endorsed by the LHCC, which is currently reviewing the The Technical Proposal for Phase-1 of this program.

2. The Existing MoEDAL Detector. MoEDAL officially started data taking in 2015 at a centre-of-mass energy (E_{CM}) of 13 TeV. The MoEDAL detector, positioned at Interaction Point 8 (IP8), is totally different to other collider detectors. It is currently comprised of using approximately 155 m^2 of plastic of Nuclear Track Detectors (NTDs) that can track HIPs and accurately measure their charge. Additionally, MoEDAL has roughly 800 kg of trapping volumes, forming the MMT sub-detector, that can capture HIPs for study in the laboratory. Both these detector systems would retain a direct and permanent record of discovery with no appreciable SM physics backgrounds. Importantly, the NTD and MMT detectors can easily be calibrated using heavy-ions and test coils, respectively. . The MoEDAL baseline detector is designed to only detect HIP avatars of new physics and is insensitive to SM physics signals. MoEDAL's passive detector technology allows it to operate without gas, electrical power, readout or trigger.

To date, we have already placed the world's best limits on singly and multiply charged monopole production, using detector technology that is *directly sensitive* to the magnetic charge of the monopole. Importantly, MoEDAL has extended the search to include spin-1 monopoles and monopole production via photon-fusion, for the first time at the LHC. The results of the ATLAS and MoEDAL searches for the monopole are given in detail in the following references, [2, 3, 4, 5]. We have just placed the first ever direct limits on dyon production [6] and are preparing a paper on the search for HIPs using the full MoEDAL detector - the MMT and the NTD detectors together - for the first time. We are also currently analyzing the data from a SQUID scan of the CMS central *Be* beam pipe, section that was donated to the MoEDAL Collaboration in 2019 [7].

Searches for massive singly electrically charged objects from a number of new physics scenarios involving, for example, supersymmetry and extra dimensions, described in MoEDAL's published physics program [8] are also underway. For example, a MoEDAL team of theorists and experimentalists has shown that we could make significant contributions to the search for SUSY using the enhanced luminosity of LHC's Run-3 [9]. Another exciting possibility is monopole production via the thermal Schwinger mechanism [10] in the ultrahigh magnetic fields that are fleetingly generated in heavy-ion collisions.

3. The MoEDAL-MAPP Detector for Run-3 and Beyond. The MoEDAL-MAPP detector will be deployed in three phases each of which will have its own Technical Design Report (TDR). Phase-1, the subject of this TDR, will see the reinstallation of the MoEDAL detector as far as possible as it was in Run-2, and the installation of the MAPP-mQP detector in the UGC1 gallery, adjacent to IP8. We envisage that the Phase-1 detector will be installed for the start of Run-3 data taking. Phase-2 involves the installation of a MAPP-LLP and MALL detectors alongside the Phase-1 detectors. The combination of MAPP-mQP and MAPP-LLP is called MAPP-1. The installation of MAPP-1 is planned for 2022 and the MALL detector a year later, in 2023. The final stage, Phase-3, involves the expansion of the fiducial volume of the MAPP-LLP detector to include most of the UGC1 gallery to form the MAPP-2 detector. MAPP-2 is planned for LHCs Run-4.

The MoEDAL-MAPP detector will enjoy and enhanced E_{cm} of 14 TeV and higher luminosity. For Run-3 the collision rate at IP8 (LHCb/MoEDAL's IP) will enjoy a ~5 increase in instantaneous luminosity over Run-2. In addition, there are plans for a further increase in luminosity to near that of ATLAS and CMS for the High Luminosity LHC (HL-LHC).

3.1 The Redeployed MoEDAL Baseline Detector. During Run-3 MoEDAL will be able to access the higher E_{CM} of 14 TeV. The higher energy and enhanced statistics will allow an expanded search for highly ionizing particles including electrically charged massive (pseudo-)stable electrically charged particles from, supersymmetric and extra-dimension scenarios. To advance our existing program at LHC's Run-3 we would redeploy the existing MoEDAL detector in the VELO/MoEDAL cavern in its current form, with some relatively minor changes designed to improve the sensitivity of the detector. However, our external NTD scanning facilities will be enhanced with modern automatic optical rapid scanning optical scanning microscopes with on board intelligence provided by Machine Learning (ML) code developed by the MoEDAL ML Group.

3.2 The MoEDAL-mQP Detector for Feebly ("Mini") Ionizing Particles. A major part of MoEDALs RUN-3 upgrade program will be the addition to the baseline detector of a new sub-detector called MAPP (MoEDAL Apparatus for Penetrating Particles). MAPP's purpose is to expand the physics reach of MoEDAL to include the search for feebly interacting particles like millicharged particles (mQPs) with charges as low as one thousandth the electron charge (*e*); and, weakly interacting very long-lived neutral particle (LLPs) messengers of new physics. A small prototype of the MAPP-mQP detector was deployed throughout 2018 in the UGC1 gallery some 50m from IP8. Assuming the MoEDAL-MAPP Phase-1 TP is approved this detector will be installed for the start of RUN-3 in 2022.

The MAPP-mQP detector is made up of four collinear sections, with cross-sectional area of 1.0 m^2, each comprised of 100 (10 cm $\times$ 10 cm) plastic scintillator bars each 75cm long. Each bar is readout by one low noise PMT. The detector is arranged to point towards the IP. Thus, each through-going particle from the IP will encounter 3 m of scintillator and be registered by a coincidence of 4 PMTs.

3.3 The MALL Detector for Very Long Lived Charged Particles. The MALL detector is envisaged to be installed in Phase-2 of the program. It consists of a hermetic scintillator array, to detect the decays of massive charged particles that have stopped within MoEDAL's MMT trapping detector volumes (~70 cm^3). The signal for the decay of a very long-live particle trapped in the MMT volumes would be the detection of at least one charged particle emanating from the monitored volume. The current plan is to place the MALL detector in the UGC1 gallery a few metres from MAPP.

3.4 The Phase-2 MAPP-LLP Detector (MAPP-1) for Long Lived Neutral Particles. The MAPP-LLP detector is designed to optimize as far as possible the measurement of LLPs that decay in flight within the fiducial volume of the MAPP detector. The core MAPP-mQP detector also plays a role in the identification of LLPs. The MAPP detector that is dedicated to the search for LLPs (MAPP-LLP) is deployed as three nested boxes of scintillator hodoscope detectors, in a "Russian doll" configuration, following as far as possible the contours of the cavern. Roughly speaking, the MAPP-1 detector is a trapezoidal volume with width 6m , depth 9m and height 3m. The technology employed to detect the decay products of new long-lived particles is scintillator strips in an x-y configuration or tiles readout by SiPMs.

3.5 The Phase-3 MAPP-LLP Detector (MAPP-3) for Long Lived Neutral Particles. For Phase-3 of our program we plan to extend the MAPP-LLP detector along the UGC1 gallery, the new detector is called MAPP-2. The plan at present would to utilize the same detector technology for MAPP-2 as was used for MAPP-1 detector. As one can see from the section on MoEDAL's Run-3 physics plan the physics reach of MAPP-2 is competitive and complementary with the other detectors planned for HL-LHC where a total integrated luminosity of around 300 fb^{-1} at IP8 is currently envisaged.

4. The Physics Program of MoEDAL-MAPP.

4.1 The Physics Program of the baseline MoEDAL detector. This program, designed to be sensitive to Highly Ionizing Particle (HIP) avatars of new physics, is described in detail in Ref. [8]. This program is still pertinent for LHC's Run-3 and beyond since the higher E_{CM} and higher luminosities allow the possibility of revealing new physics and/or much improved limits on physics beyond the Standard Model. This program defines over 30 new physics scenarios involving most arenas of discovery at the LHC, that involve the the search for: the electrweak monopole [11, 12, 13, 14, 15, 16, 17]; extra dimensions; new symmetries, like supersymmetry; technicolor; fourth generation particles; and, multiply charge exotic states.

4.2 The Physics Phase-1 MAPP-mQP detector. The MAPP-mQP detectors extends MoEDAL's physics reach through its sensitivity to two other messengers of new physics such as mini-charged particles (mQPs), with charge from $0.1e$ to $10^{-3}e$. An example, of a mQP arises from a hidden (dark) sector model with a new, $U'(1)$, gauge group [18]. Specifically, we consider a scenario in which the $U'(1)$ gauge group in a dark sector with a massless dark-photon A' and a massive dark-fermion (ψ), is predicted. The dark fermion is charged under $U'(1)$ field A' with a milli-charge charge e'.

4.3 The Physics Program of the Phase-2 and -3 MAPP-LLP Detector. The MAPP upgrade will also allow us to explore new physics landscapes involving models of dark matter [19, 20, 21, 22, 23, 24, 25] Hidden Valleys [26, 27, 28], and models that give rise to neutrinos with mass [29, 30, 31, 32, 33, 34, 35]. These landscapes include a promising arena of investigation for MAPP i.e. the Hidden Sector, where the hidden (or dark) sector communicates with the Standard Model via "portals" that include the vector, higgs, neutrino and axion portals [36]. Such models give rise to such new physics as dark photons, exotic Higgs decays and sterile neutrinos, that can be signified by LLPs and mQPs. The general purpose LHC detectors are not optimized to detect, HIPs, mQPs or LLPs. Hence, MoEDAL's MAPP and MALL detectors would reinforce MoEDAL's role of complementing the LHC search for new physics.

4.4 A Physics Case for MALL. An interesting example physics use case for MALL is provided by a superWIMP model for cold dark matter [37]. The massive SuperWIMP particles are naturally bequeathed the desired relic density from the late decays of metastable WIMPs. Well-motivated examples are weak-scale gravitinos in SUGRA and extra dimensional Kaluza-Klein gravitons. In this scenario a charged slepton NSLP the lifetime of a 150 GeV stau decaying to a 100 GeV gravitino is about 10^9s or around 10 years. It is remarkable that one doesn't actually need much degeneracy to get such a long lifetime! The MAPP detector would be able to detect the decays of such extremely long-lived staus and in many cases with sufficient statistics to estimate their lifetime.

5. Conclusion The MoEDAL-MAPP plan for RUN-3 and beyond presented here represents a significant enhancement of the existing MoEDAL physics program that was dedicated to searching for the HIP avatars of physics beyond the Standard Model. This plan has two main aspects. The first is to utilize the existing MoEDAL detector to exploit the prospect of enhanced luminosity and increased E_cm at IP8, to pursue the Physics Program laid out previously [8] and which was already well underway in Run-2. The second aspect involves two upgrades to the MoEDAL detector, MAPP and MALL. These two new detectors would allow MoEDAL's physics reach to be significantly expanded to include, in the case of the MAPP detector, the quest for mQPs, and weakly interacting long-lived neutral particles. The MALL detector would allow the search for LLPs to be enlarged to include extremely long-lived charged particles.

In the arena of LLPs, MAPP could provide complementary to the already approved FASER experiment [38]. To the best of our knowledge the other proposed experiments designed to search for new LLPs: CODEX-b [39], AL3X [40], MATHUSLA [41] SHIP [42] will only be deploying small test detectors, at best, during the RUN-3 period.

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