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The MoEDAL Experiment at the LHC—A Progress Report †

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Abstract: MoEDAL is a pioneering LHC experiment designed to search for anomalously ionizing messengers of new physics. It started data taking at the LHC at a center-of-mass energy of 13 TeV, in 2015. Its ground breaking physics program defines a number of scenarios that yield potentially revolutionary insights into such foundational questions as: Are there extra dimensions or new symmetries? What is the mechanism for the generation of mass? Does magnetic charge exist? What is the nature of dark matter? After a brief introduction, we report on MoEDAL's progress to date, including our past, current and expected future physics output. We also discuss two new sub-detectors for MoEDAL: MAPP (Monopole Apparatus for Penetrating Particles) now being prototyped at IP8; and MALL (Monopole Apparatus for very Long Lived particles), currently in the planning stage. I conclude with a brief description of our program for LHC Run-3.

Keywords: collider physics; monopoles; high ionizing particles; fractionally charged particles; massive stable charged particles; very long-lived particles

1. Introduction

MoEDAL (Monopole and Exotics Detector at the LHC) , the Large Hadron Collider's (LHC's) newest experiment [1]—which started official data taking in 2015—is totally different to other collider detectors. It is currently comprised of passive tracking, using plastic Nuclear Track Detectors (NTDs) and trapping sub-detectors that are capable of retaining a permanent direct record of discovery and even capturing new particles for further study in the laboratory. It also has a small TimePix pixel device array for monitoring beam-related backgrounds. MoEDAL is designed to only detect highly ionizing avatars of new physics and is insensitive to Standard Model physics signals. Thus, it can operate without an electronic trigger. A full GEANT4 (GEometry And Tracking platform) model of MoEDAL is now available. A visualization of this model is shown in Figure 1.

The primary aim of the General Purpose LHC Detectors (GPLDs), ATLAS and CMS, is to discover the Higgs boson and study its properties as precisely as possible. As we all know the discovery a new particle by ATLAS and CMS, which is now largely identified with the Standard Model Higgs boson, was announced on 4 July 2014 [2]. In a similar way, the main aim of the MoEDAL experiment is to search for the Magnetic Monopole. The main modern conception of the magnetic monopole is that it is a topological "excitation" in the Higgs field of the underlying theory. In this way, the main physics aims of the GPLDs and MoEDAL are complementary. Their experimental sensitivity is also complementary in that GPLDS have quite limited sensitivity to Highly Ionizing Particles (HIPs), which MoEDAL is designed to detect. On the other hand, MoEDAL cannot detect the decays of new particles into Standard Model states.

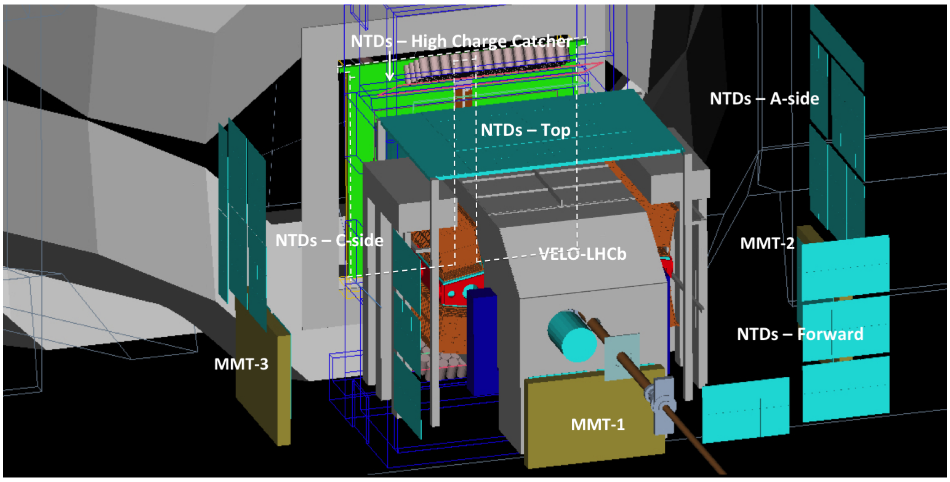

Figure 1. A visualization of the GEANT-4 simulation of the MoEDAL experiment, represented using Geant-4's PANORAMIX package.

However, MoEDAL, similar to the GPLDs, can do much more. MoEDAL is pioneering experiment designed to search for highly ionizing avatars of new physics such as magnetic monopoles or massive (pseudo-)stable charged particles [3]. Its groundbreaking physics program defines over 34 scenarios that yield potentially revolutionary insights into such foundational questions as: Are there extra dimensions or new symmetries? What is the mechanism for the generation of mass? Does magnetic charge exist? What is the nature of dark matter? How did the big bang develop from the earliest times.

Another important development is the planning and prototyping of a new MoEDAL subdetector, MAPP (MoEDAL Apparatus for Penetrating Particles). MAPP is planned for deployment for LHC's Run-3. A prototype MAPP detector is already deployed. MAPP will extend MoEDAL's physics reach by allowing the search for milli-charged particles and new very long-lived particles. A further new sub-detector, in the longer term planning phase, is MALL (MoEDAL Apparatus for extremely Long Lived Particles). This detector is aimed at the search for new massive charged particles with lifetimes that can reach the order of 10 years.

The high-risk nature of MoEDAL's extensive program is justified not only by the prospect of a revolutionary breakthrough with impact beyond the realm of particle physics, but also by its now proven ability to provide unique and wide reaching constraints on new physics. MoEDAL is now preparing a proposal to continue data taking during LHC's Run-3.

2. The MoEDAL Detector

The innovative MoEDAL detector employs unconventional methodologies tuned to the prospect of discovery physics. The largely passive MoEDAL detector is deployed at Point 8 on the LHC ring and shares the experimental cavern with the LHCb experiment, as shown in Figure 1. The innovative MoEDAL detector has a dual nature. First, it acts as a giant camera, comprised of Nuclear Track Detectors (NTDs)—analyzed offline by ultra fast optical scanning microscopes (OSMs)—that for proton–proton collisions is sensitive only to new physics. Second, it is uniquely able to trap the particle messengers of new physics for further study. MoEDAL's radiation environment is monitored by a state-of-the-art real-time TimePix pixel chip array.

2.1. The Nuclear Track Detector (NTD) Array

The MoEDAL detector consists of three detector subsystems. A depiction of part of the MoEDAL detector, showing examples of all MoEDAL sub-detector systems, is shown in Figure 2. The main NTD subsystem, referred to as the low threshold (LT) Nuclear Track Detector (NTD) array, is the largest array of (320) plastic NTD stacks (25 $\times$ 25 cm^2) ever deployed at an accelerator, comprised of CR39 (3) and MAKROFOL (3) plastic NTD sheets. A depiction of a MoEDAL LT-NTD stack is shown in

Figure 3A. The track of the HIP damages the long chain molecular bonds of the plastic, as shown in Figure 3B. Etching in a hot sodium hydroxide etchant as shown in Figure 3C reveals this damage zone. The passage of the HIP though the stack—illustrated in Figure 3D—allows it to be tracked and its characteristic ionization signature to be recognized.

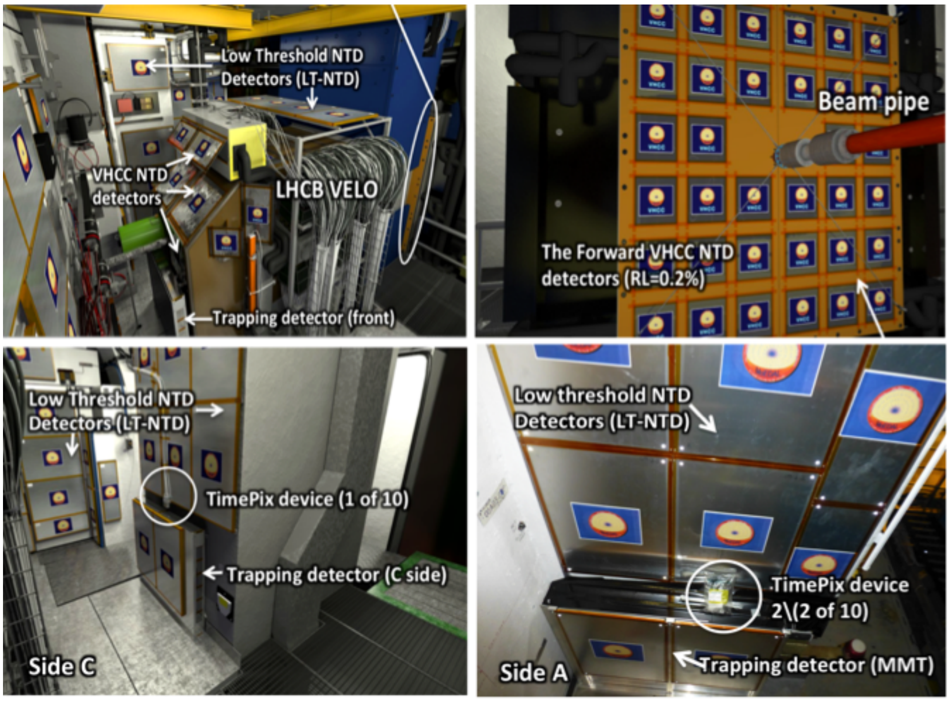

Figure 2. (**top left**) A view of part of the MoEDAL deployment showing the LHCb's VELO detector as well as various elements of the MoEDAL detector; (**top right**) the 4sqm VHCC detector plane that is deployed in the downstream acceptance of the LHCb detector; (**botton left**) part of MoEDAL's "C-side" deployment, including part of MoEDAL's NTD array, one of three MMT detector stacks and one of five TMPX devices; and (**bottom right**) "A-side" deployment.

The CR39 NTDs have an excellent charge resolution ($\sim$ 0.1e, where e is a single electric charge) and low threshold, allowing the detection of (HIPs) particles, with an ionizing power equal to more than $\sim$5 times that of a Minimum Ionizing Particle (MIP). The LT-NTD array has been enhanced by the High Charge Catcher (HCC) sub-detector—with threshold around 50 MIPS—comprised of thin low mass stacks with three MAKROFOL sheets in an Al-foil envelope applied directly inside LHCb's forward tracking system—increasing the overall geometrical acceptance for monopoles of the NTD system to 65%. The NTD detectors are calibrated at two centres. The first is the NA61 experiment at CERN where we have access to very high-energy heavy-ion beams. This year it will be lead-ions. The second is the NASA Space Radiation Laboratory (NSRL) facility at the Brookhaven National Laboratory (BNL). We have already gone through several calibration cycles at both these centres.

After exposure for one year, the NTD detectors are removed for etching under controlled conditions. The etching removes plastic preferentially along the damage trail caused by the passage of a HIP through the NTD. This process reveals etch pits on one or both sides of the plastic sheet, depending on whether the particle penetrates the sheet. The size and depth of the pit are proportional to the charge of the particle from which the pit was derived, revealing an etch pit on both sides of the plastic sheet. The etching conditions are of two kinds: strong etching and soft etching. Soft etching is used when low threshold signals are being sought otherwise strong etching is used. The etching conditions are determined from the calibration process where NTDs stacks are exposed to heavy-ion beams of known charge and energy. Etching takes place at INFN Bologna using facilities that were original developed for the MACRO [4] and SLIM [5] experiments.

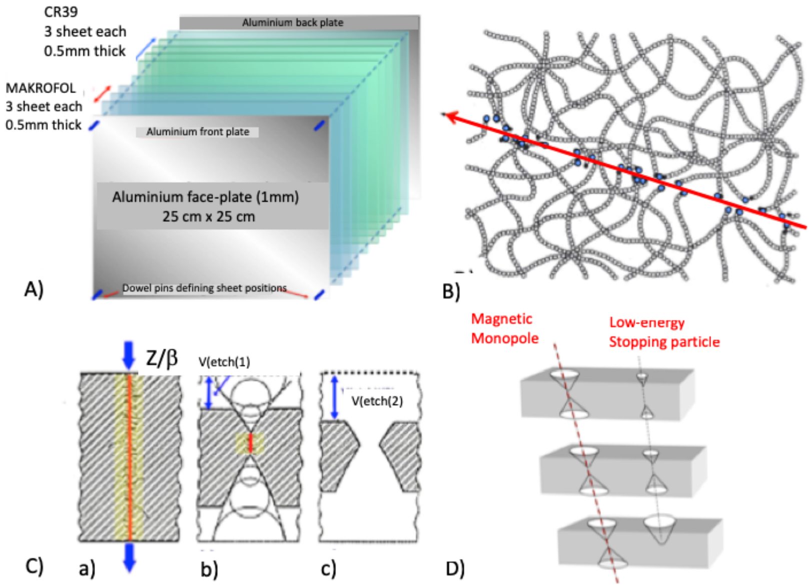

Figure 3. (**A**) A MOEDAL NTD stack; (**B**) a depiction of a HIP damaging NTD plastic as it traverses the NTD film; (**C**) the etching of the NTD plastic to reveal the passage of the particle; and (**D**) a passage of the HIP through the NTD stack defines a track of etch-pits.

After the NTDs sheets are etched, they must be scanned using optical microscopes. A computer controlled optical scanning microscope system developed at the University of Helsinki used to scan the majority of MoEDAL's NTD film exposed at IP8. This scanning system can scan NTD film at the rate of 100 cm^2 every 20 min. Considering the feature (etchpit) sizes lie in the range 20→50 microns this is extremely rapid. The INFN Bologna system consists of manual microscopes and computer assisted optical scanning microscopes that are much slower but facilitate much higher magnification by a human expert, which would be required to check candidate events. We envisage that our first publication to be based on analysis of the NTD sub-detector system will be submitted for publication by the spring of 2019. A photograph of the Helsinki scanning systems is shown in Figure 4.

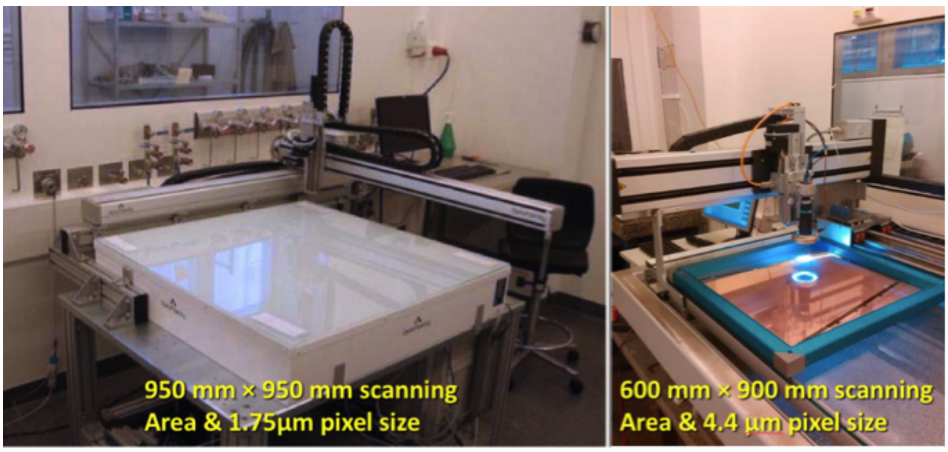

Figure 4. The Helsinki computer controlled optical scanning microscopes.

2.2. The Trapping Detector System (MMT)

The Magnetic Monopole Trapper (MMT) is another vital MoEDAL sub-detector system. Its sensitive volume consists of 1 t of aluminium trapping volumes deployed around the MoEDAL cavern at IP8. A photo of the "C-side" MMT stack is given in Figure 5A comprised of aluminium bar sections, shown in Figure 5B. The exposed bars are monitored for the presence of monopoles using the ETH SQUID (Superconducting Quantum Interference Device) magnetometer shown in Figure 5D. A fraction of the monopoles traversing the MMT detector stack will slow down, stop and be trapped by the magnetic effect of the nucleus. Al is well suited as it has an anomalously large nuclear magnetic moment. After exposure, the MMT trapping volumes will be monitored at the ETH-Zurich SQUID facility for the presence of captured monopoles. The response of the MoEDAL SQUID magnetometer, shown in Figure 5C, has a resolution of around $0.1g_d$, where g_d is a Dirac charge. The SQUID is calibrated with very long thin solenoids that are effective monopoles.

In the future, after the SQUID scan is performed, the trapping volumes will be sent to SNOLAB, to be monitored for the decays of trapped very long lived electrically charged particles. The MALL sub-detector, which is in the planning stage for future deployment, will monitor exposed MMT detector volumes for the decay of extremely long-lived massive electrically charged particles captured in the MMT volumes. One such particle could be a long-lived slepton [6]. More detail on the MMT detector will be included in below in the subsection on upgrades.

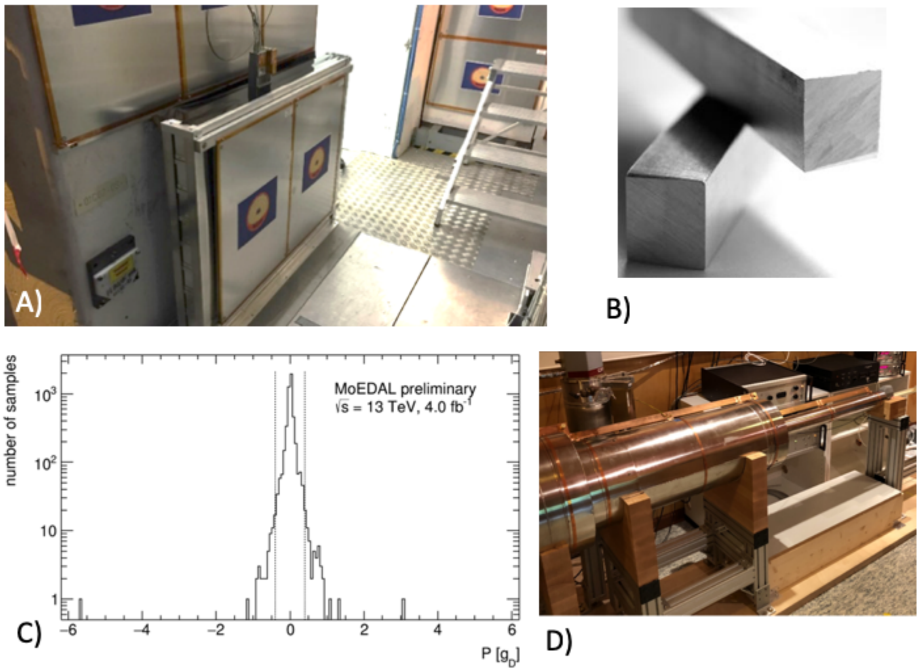

Figure 5. (**A**) The "C-side" (negative x-coordinate) MMT detector stack (with two LT-NTD detector planes attached to its front) is one of three similar arrangements; (**B**) the aluminium bars that comprise the MMT stacks; (**C**) the response of the SQUID to MMT volumes prior to exposure and presumably with no trapped magnetic charge; and (**D**) the MoEDAL SQUID facility based at ETH Zurich.

3. Physics Results

In August 2016, MoEDAL published its first physics analysis paper [7] on the search for magnetic monopoles based on data taken at a center-of-mass energy (E_{cm}) of 8 TeV. In this paper, MoEDAL placed the best limits in the world in the search for magnetic monopoles with Dirac magnetic charge greater than or equal to $2g_d$. In February 2017, we published the results of our first paper on LHC RUN-2 data taken at an E_{cm} of 13 TeV [8]. In this paper, we were still the only LHC experiment placing limits on $g_d > 1$. Additionally, we pushed the direct search for multiple magnetically charged particles to $5g_d$, with masses up to 6 TeV, for the first time ever. Using a Drell–Yan (DY) model for monopole-pair production with spin-1/2 monopoles, this translates into monopole mass limits exceeding 1 TeV, the strongest to date at a collider experiment [9] for charges ranging 2–4 times g_d.

These last two papers placed limits on spin-0 and spin-1/2 monopole production, as is usual for searches at accelerators. Our latest paper [10] was published in July 2018. In this paper, we pushed the search to spin-1 magnetic monopoles for the first time at a collider experiment. In addition, we placed limits for both β-dependent and β-independent monopole couplings, another first for direct searches for monopoles. The results of our last three papers are summarized in Figure 6 and compared with our only competition (so far) at the high-energy frontier, coming from the ATLAS experiment [11]. Additionally, we placed monopole-pair direct production cross-section upper-limits in the range 40–105 fb for magnetic monopole charges up to $5g_D$ and monopole masses up to 6 TeV.

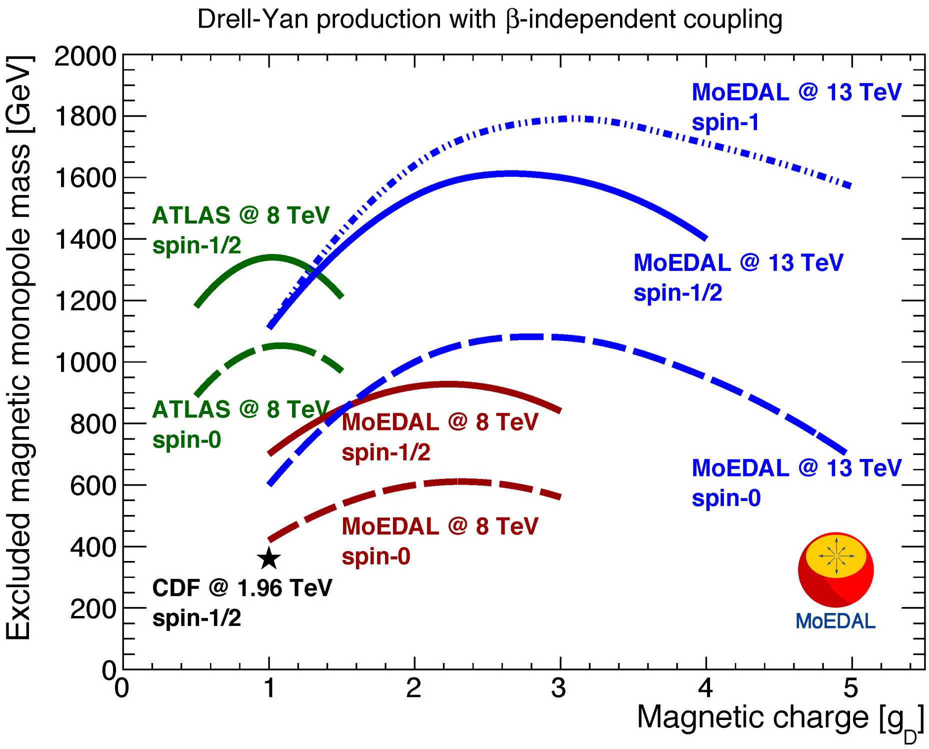

Figure 6. A summary plot of the mass limits placed on Monopole-pair production by MoEDAl, ATLAS and CDF.

We a currently have two papers in preparation and due to be published to the archive in early 2019. The first to be completed details the search for monopole-pair production via photon-fusion, and DY production. This paper follows on from a detailed theoretical study of these process carried out by MoEDAL authors [12]. In this paper, we have employed duality arguments to justify an effective monopole-velocity-dependent magnetic charge in monopole-matter scattering processes. Based on this, we conjecture that such β-dependent magnetic charges might also characterize monopole production. In addition, we introduced a magnetic-moment term proportional to a new phenomenological parameter κ describing the interactions of these monopoles with photons for spins 1/2 and 1. The lack of unitarity and/or renormalizability is restored when the monopole effective theory adopts a SM form.

The other paper that is in-progress reports a search using, for the first time, our NTD (the previous results used our trapping arrays) system to search for highly electrically charged particles. In this case we are searching for highly electrically charged particles, rather than magnetically charged particles. To date, the only LHC limit we can find comes from the ATLAS Collaboration [11] where they placed limits on electrically charged particles with charge (Z) in the range: $10e < Z < 60e$. We envisage that we will be able to place a much better limit on highly electrically charged particle production.

The motivation behind our introduction of the concept of the magnetic-moment of the monopole introduced above is to enrich the monopole phenomenology with the (undefined) correction terms to the monopole magnetic moment to be treated as free parameters potentially departing from those prescribed for the electron or $W^{\pm}$ bosons in the SM. As we lack a fundamental microscopic theory of magnetic poles, such an addition appears reasonable. This creates a dependence of the scattering amplitudes of processes on this parameter, which is passed on to the total cross sections and, in some cases, to kinematic distributions. Therefore, the parameter is proposed as a new tool for monopole searches that can be used to explore different models.

Estimates from our above paper [12] indicate that photon fusion production is the leading mechanism for direct monopole searches at the Large Hadron Collider (LHC). We expect our analysis of this production mechanism, using MoEDAL data, will be the first to be published at the LHC. In addition, our analysis will provide the world's best mass limits for monopole production, for a spin-1, 1/2 and 1 monopole, via photon-fusion. For example, the most recent limit on photon-fusion, carried our nearly ten years ago, was made using CDF data with the result that the monopole mass must be greater than 370 GeV [13]. Previously, roughly 13 years ago, the H1 Collaboration at HERA carried out a search, based on monopole-pair production via photon fusion [14]. Upper limits on the monopole pair production cross-section were set for monopoles with magnetic charges from $1g_d$ to $6g_d$ or more and up to a mass of 140 GeV.

4. The Program for LHC's LS2 and RUN-3

The luminosity delivered to IP8 during LHC's Run-2 is shown in Figure 7. The average luminosity delivered per year over the four years of Run-2 to MoEDAL is 1.7 fb^{-1}. The luminosity available over the at IP8 will increase substantially to 25–30 fb^{-1} over the three years of Run-3, an increase in the average luminosity taken per year at IP8 by roughly a factor of five.

To push the search for new physics to higher E_{cm} (14 TeV) and also to take advantage of the expected significantly higher luminosity available at Point 8 during Run 3, the MoEDAL Collaboration is requesting to take data as part of the LHC's Run-3 program. This future physics program involves two additional features: a greater stress on high luminosity searches, to ∼30 fb^{-1} and beyond, and also the exploitation of the new sub-detectors MAPP and MALL. Good examples of high luminosity studies are searches for new massive long-lived/pseudostable electrically charged particles. Several candidates for such new particles can be found within the arena of supersymmetry: long-lived sleptons within the Gauge-Mediated symmetry-breaking (GMSB) framework; R-hadrons within Split Supersymmetry that contain supersymmetric gluino(s); and long-lived charginos, for example from Anomaly-Mediated Symmetry Breaking (AMSB).

This extension of data taking will also allow us to exploit two new planned sub-detectors MAPP (the MoEDAL Apparatus for Long Lived Particles) and MALL (the MoEDAL apparatus for extremely Long Lived particles) to expand the physics reach of the MoEDAL experiment and allow the search for fractionally charged and long-lived particle messengers of new physics.

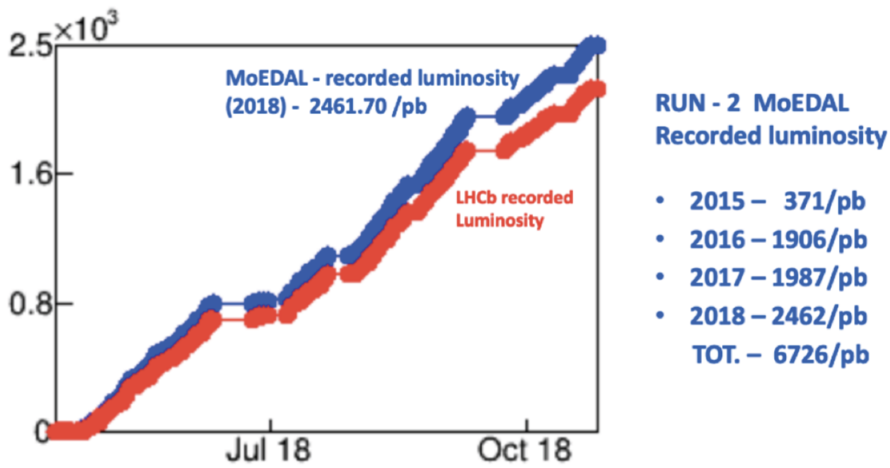

Figure 7. A plot of the luminosity delivered to MoEDAL and LHCb at IP8.

4.1. The MAPP Subdetector

The main element of MoEDAL's upgrade plans for LHC's RUN-3 is the addition of the MAPP sub-detector to the experiment. The existing baseline detector will continue to run as usual. As discussed above, the MAPP detector is designed to search for milli-charged particles (with charge as small as 0.001e, where e is the electric charge) and new long-lived neutrals.

A sketch of the MAPP detector that will be deployed during the long shutdown is shown in Figure 8. The detector will be deployed in the UGC8 gallery adjacent to MoEDAL's intersection point IP8 during the second long LHC shutdown (LS2), some 30 m to 50 m from IP8 (depending on where in the tunnel MAPP is placed), as shown in Figure 9. The MAPP detector is protected from Standard Model backgrounds from IP8 by approximately 30 m of rock. A prototype of MAPP, corresponding to 1/10th of the from compartment of the full MAPP detector, took data in UGC8 throughout 2018.

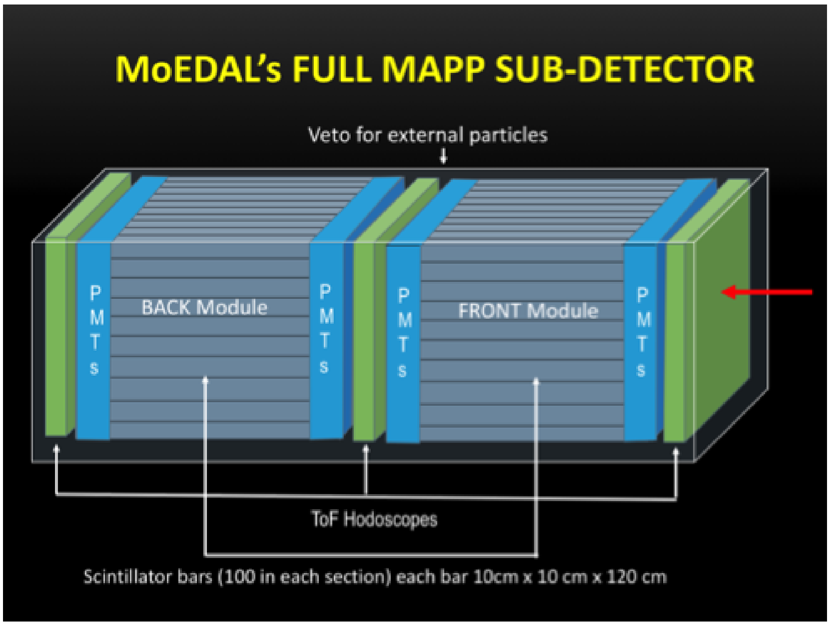

Figure 8. A sketch of the MAPP sub-detector.

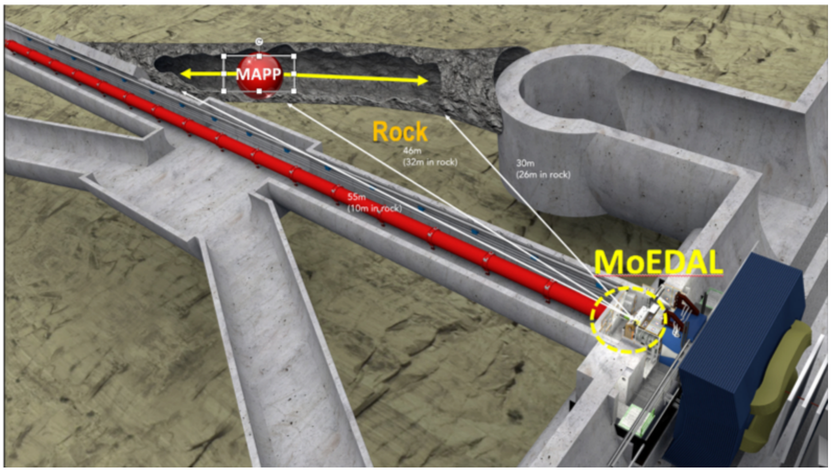

Figure 9. An artists' impression of the deployment of the MAPP detector in the UGC8 gallery adjacent to the main MoEDAL detector.

The detector is comprised two arrays of 100 (10 cm $\times$ 10 cm $\times$ 100 cm) high light yield scintillator bars, where each bar is readout by two low noise PMTs. These two sections are sandwiched between three ToF hodoscopes. Thus, a milli-charged particle would see 200 cm of plastic scintillator readout by four low noise PMTs, in coincidence. The whole device is protected by a hermetic veto system. MAPP would be calibrated using muons, from p–p collisions at MoEDAL's intersection point (IP8) that penetrate the intervening rock.

Additionally, the MAPP detector has a decay zone of 6–10 m in front of the detector (7–11 m to the midpoint of the detector) that makes it possible to measure the decay of new neutral particles in flight at large distances from the IP. Thus, with MAPP we can search for new long-lived neutral states. In addition, we have designed the ToF hodoscopes to have a timing resolution of ∼100 ps to further increase MAPP's sensitivity to new physics.

4.2. The MALL Subdetector

The MALL subdetector, which is in its planning phase, is intended to push the search for the decays of new charged, massive and very long-lived long-lived particles, with lifetimes well in excess of a year. This is achieved by monitoring the MoEDAL Trapping volumes, contained within the central portion of an hermetic scintillator array, for the decays of trapped particles. A sketch of the MALL sub-detector is shown in Figure 10. Remarkably, this detector will not be positioned at IP8 on the LHC but rather in a remote deep underground laboratory, such as SNOLAB. In this way, cosmic ray backgrounds can be reduced to a minimum.

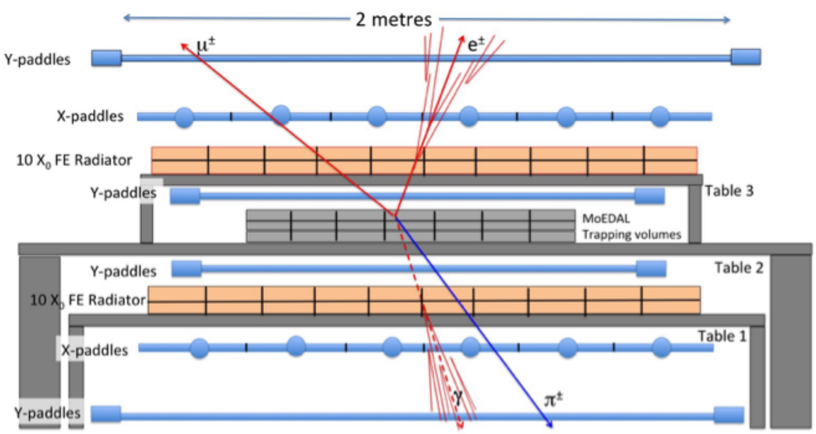

Figure 10. A sketch of the MALL sub-detector proposed for MoEDAL.

5. Beam-Pipe Searches

The MoEDAL collaboration in cooperation with the CMS collaboration will be examining the central section of CMS' beryllium beam-pipe deployed for Run-1 running and removed in the first long shutdown of the LHC (LS1), for the presence of trapped monopoles. A photograph of the removal of the beam-pipe in question is shown in Figure 11. The beam-pipe will be cut into pieces and passed through a SQUID magnetometer in the same way that MoEDAL trapping detector volumes are examined for the presence of trapped magnetic charge. Such a charge is sensitive to high magnetic charges of $6g_d$ and above, where g_d is the Dirac charge. This make the beam-pipe search complementary to MoEDAL searches which are sensitive to magnetic charges up to $6g_d$–$7g_d$. However, it should be noted that the issue of whether or not monopoles would be trapped in Be is not settled [15,16].

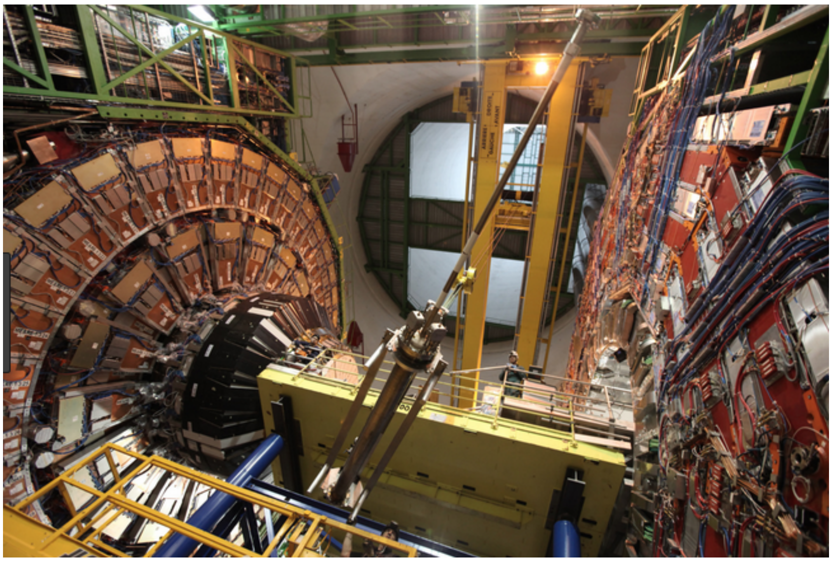

Figure 11. A photograph of the CMS beam-pipe being removed.

6. Conclusions

The MoEDAL experiment has already placed the world's most stringent limits on magnetic monopole production. It is now pushing the search for highly ionizing particles to lower charge thresholds, where it is sensitive to new physics scenarios involving, for example, supersymmetry and extra dimensions. Importantly, MoEDAL will be seeking to continue data taking during LHC's Run-3. This will enable MoEDAL to continue the search for highly ionizing avatars of new physics to smaller cross-sections and higher energy. In addition the deployment of the new MAPP sub-detector will enable MoEDAL to expand its physics horizons to include the search for fractionally charged particles and new very long-lived neutral particles.

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Conflicts of Interest: The authors declare no conflict of interest.

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