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The MoEDAL Experiment at the LHC

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Abstract. In 2010 the CERN (European Centre for Particle Physics Research) Research Board unanimously approved MoEDAL, the 7th international experiment at the Large Hadron Collider (LHC), which is designed to search for avatars of new physics signified by highly ionizing particles. The MoEDAL detector is like a giant camera ready to reveal "photographic" evidence for new physics and also to actually trap long-lived new particles for further study. The MoEDAL experiment will significantly expand the horizon for discovery at the LHC, in a complementary way. A MoEDAL discovery would have revolutionary implications for our understanding of the microcosm, providing insights into such fundamental questions as: do magnetic monopoles exist, are there extra dimensions or new symmetries of nature; what is the mechanism for the generation of mass; what is the nature of dark matter and how did the big-bang unfurl at the earliest times.

1 Introduction

MoEDAL, the 7th and newest experiment [1] is dedicated to the detection of the highly ionizing particle avatars of new physics such as the magnetic monopole and massive stable or metastable charged particles. Such particles originate from a number of beyond the Standard Model scenarios that, for example, incorporate: magnetic charge, new symmetries of nature (eg Supersymmetry); extra spatial dimensions; dark matter particles, etc. The MoEDAL detector is a largely passive detector that makes it totally unlike other collider detectors.

Essentially MoEDAL is a largely passive detector, like a giant camera ready to reveal "photographic" evidence for new physics. MoEDAL also has trapping detector volumes capable of capturing long-lived particles from beyond the Standard Model for further monitoring and study at a remote SQUID magnetometer facility and a deep underground laboratory such as SNOLAB. The MoEDAL experiment will significantly expand the horizon for discovery of the LHC, in a complementary way.

Since the MoEDAL experiment was approved by the CERN Research Board in 2010 the collaboration has doubled in size to include approximately 44 physicists from eighteen groups from around the world: Canada, CERN, the Czech Republic, Finland, Germany, Italy, Korea, Romania, Switzerland, the UK and the USA.

The MoEDAL experiment will start to take data in the Spring of 2015 when the LHC restarts at the unprecedented centre-of-mass energy of ~14 TeV.

2 The MoEDAL Detector

The MoEDAL detector shares the IP8 intersection region with the LHCb's VELO detector as shown in Figure 1. It is comprised of the largest array (~280 sqm) of CR39 and Makrofol plastic Nuclear Track Detector (NTD) stacks ever deployed at an accelerator that surrounds the intersection region at Point 8 on the LHC ring. A depiction of a MoEDAL NTD stack is given in Figure 2. Another unique feature of the detector is the use of paramagnetic trapping volumes to capture both electrically and magnetically charged highly ionizing particles. In this way we can directly measure magnetic charge and actually ensnare new particles for further study. No other LHC detector has this capability.

Over the past year MoEDAL experimenters have completed the design of two new detectors systems: the Magnetic Monopole Trapping (MMT) detectors for capturing magnetic monopole and other massive highly ionizing particles; the high threshold Very High Charge Catcher – comprised of flexible low mass NTD detectors. These add to the existing low threshold "TDR" NTD system.

A test "TDR" system - deployed in the spring of 2010 and removed at the beginning of the long LHC shutdown in the Winter of 2012 - has been calibrated and etched and is now being analyzed. In addition, a prototype MMT system exposed during 2011 was extracted and monitored for the presence of trapped magnetic charge at ETH Zurich's SQUID magnetometer facility. Results from these tests were reported elsewhere [2],[3].

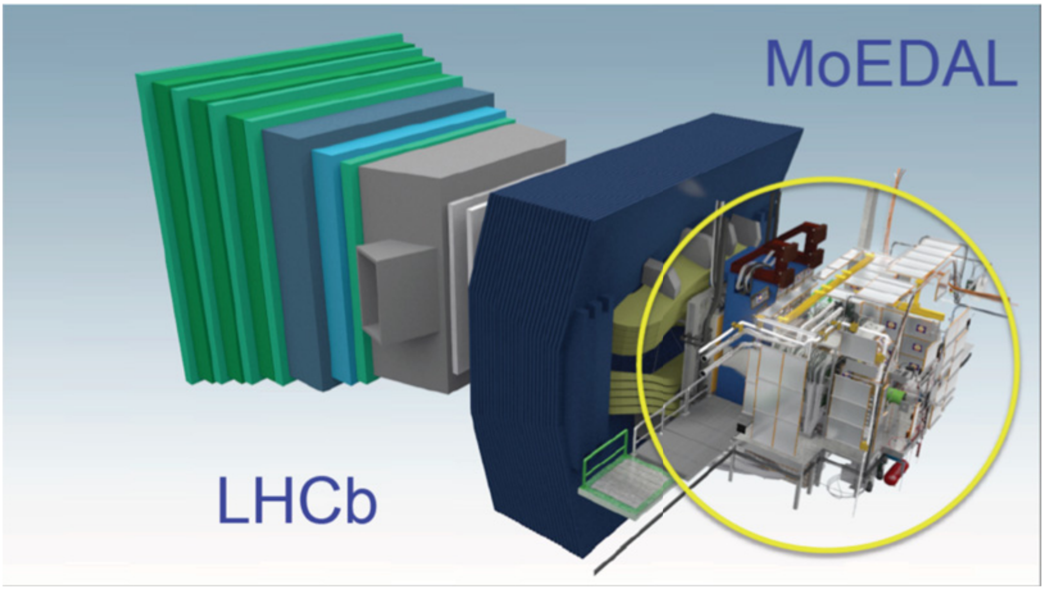

Figure 1. A depiction of the MoEDAL detector that shares the LHCb VELO cavern at Point 8 on the LHC ring

Once the NTD detectors have been exposed for a period they are removed and then etched under controlled conditions to reveal the passage of the highly ionizing particle through the NTD stack. A MoEDAL "TDR" stack is comprised of 10 sheets of CR39 and Makrofol - with thresholds of five and 50 times minimum ionizing, respectively. A depiction of etch-pit formation on a single sheet of plastic is shown in Figure 3.

The detection of, say, a candidate Magnetic Monopole event in MoEDAL would result in a string of up to 20 etch pits per stack with charge resolution of ~0.05e, and spatial resolution of ~10 μms per etch pit, with no Standard Model background. Such an event would be permanently recorded. Additionally, the detection of the magnetic field of a trapped magnetic monopole would also provide permanent record of the discovery that would be validated by corresponding evidence in the NTD detectors.

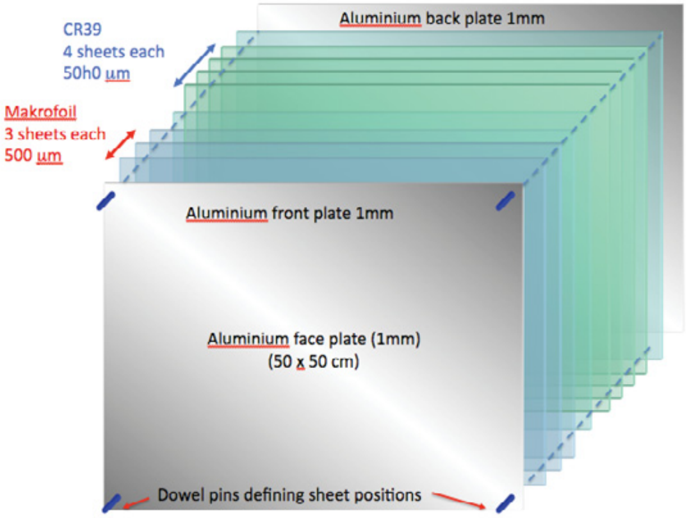

Figure 2. A depiction of the MoEDAL detector that shares the LHCb VELO cavern at Point 8 on the LHC ring

After the MMT detectors have been scanned for the presence of magnetic charge in a SQUID magnetometer facility (eg at ETH Zurich) they will be transported to an underground laboratory (eg SNOLAB) to be monitored over a long period for the decay of any other massive metastable charged and/or coloured particles that have stopped within them. The presence of trapped new physics particles also raises the possibility that the particle can be freed for direct study in the laboratory.

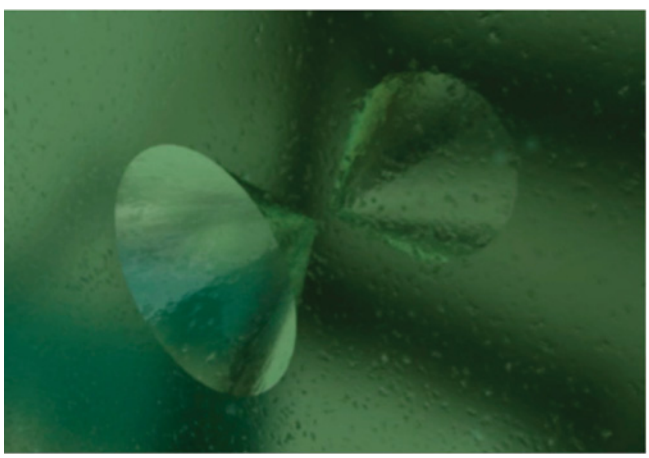

Figure 3 Etch-pit formation in a Nuclear Track Detector along the "damage trail" of a highly ionizing particle

The only non-passive MoEDAL sub-detector system is an array of TimePix pixel devices [4]. It is used to monitor the potential highly ionizing beam related backgrounds. Each pixel of the innovative TimePix chip contains a preamplier, a discriminator with hysteresis and 4-bit DAC for threshold adjustment, synchronization logic and a 14-bit counter with overflow control.

MoEDAL uses TimePix Time-over-Threshold modes so that each pixel can act as an ADC that can supply an energy measurement. A photograph of a TimePix pixel chip is shown in Figure 4. The online TimePix radiation monitoring system will be accessed via the web. Thus, it is not necessary to run shifts even though the TimePIx array is a real-time MoEDAL detector system.

Some 10-20 TimePix1 silicon pixel imaging devices will be deployed. Each Timepix detector is essentially a little electronic bubble chamber capable of imaging complete spallation events in its 300 μm thick silicon sensitive volume. Data readout and event display produced is provided by the “PixelMan" software developed by the IEAP-CTU MoEDAL team.

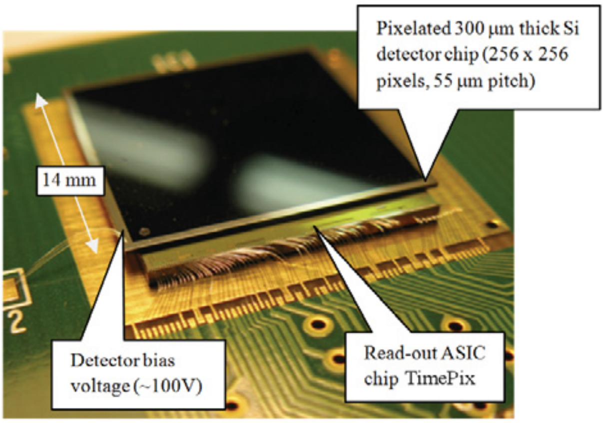

Figure 4. A photograph of TimePix chip with its main features indicated.

3 The MoEDAL Physics Program

MoEDAL's main physics motivation is the search for magnetic charge carried by, for example, monopole and monopole-like structures in electroweak theory. We also consider the possibility of monopolium formation and its detection by MoEDAL. We then move to the consideration of singly electrically charged Massive (Meta-)Stable Particles from a number of scenarios involving, for example: new symmetries of nature (eg supersymmetry); extra spatial dimensions; technicolour; a 4th generation; and, dark matter production. We also consider as a separate case the search for doubly charged news physics particles from several beyond the Standard Model physics arenas as well as multiply electrically charged excitations such as Q-balls, strangelets and quirks. A discovery in any of the above-mentioned areas will be of revolutionary significance for particle physics. A review of the physics program of the MoEDAL experiment is presented elsewhere [5]

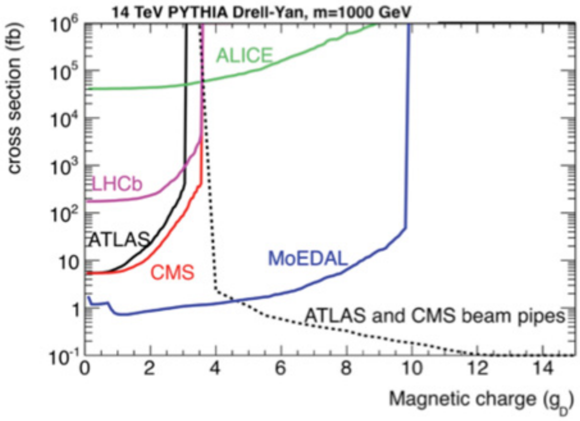

Figure 5. Comparison of the sensitivity of MoEDAL for the detection of magnetically charged particles compared with that of the other LHC detectors

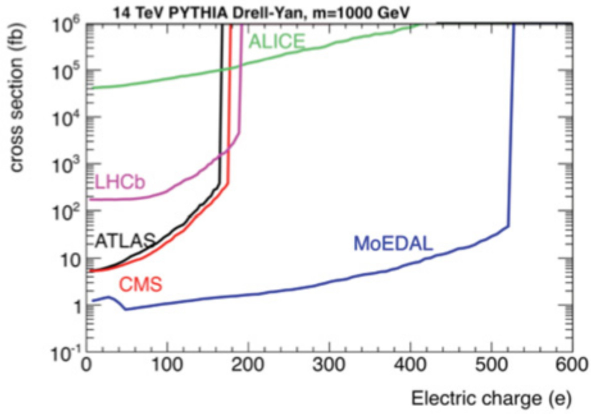

Figure 6. Comparison of the sensitivity of MoEDAL for the detection of electrically charged particles compared with that of the other LHC detectors

A comparison of the reach of the MoEDAL detector for magnetic and electric charge compared with the general purpose LHC experiments ATLAS and CMS is shown in Figure 5 and Figure 6, respectively [6]. Note that we have assumed it will take ~100 events in ATLAS and/or CMS to be able to claim a discovery. However, as MoEDAL has no Standard Model backgrounds only the observation of one event is necessary for us to be able to claim the discovery of an observation of physics beyond the Standard Model.

4 Concluding remarks

Standard collider detectors are not optimized for the detection of highly ionizing particles such as magnetic monopoles and massive long-lived or stable charged particles. The difficulties in these searches come from the fact that the sub-detectors of general-purpose experiments are designed to detect minimum-ionizing particles moving near to the speed of light.

Effects arising from the particles low velocity and high density of the energy deposition, such as electronics saturation, light quenching in scintillators, and adjacent hits from delta electrons, are extremely challenging to deal with. Indeed, in some cases it may be impossible to make an accurate measurement of the effective charge of the particle. For example, the resulting dead time as a result of electronics saturation may be of the order of the bunch crossing time.

In addition highly ionizing particles will be absorbed very quickly within the mass of the standard collider detector. Indeed, extremely ionizing particles may be absorbed before they penetrate far into the inner tracking detectors.

In order for stable or long lived massive particles (SMPs) to be detected in general purpose collider detectors they need to be detected and triggered on in a sub-detector system, or group of sub detectors systems, and be associated to the correct bunch crossing. This detection and triggering must happened within Δt ns - where Δt is the time between bunch crossings (nominally 25ns at the LHC with E_{cm} =14 TeV) - after the default arrival time of a particle travelling at the speed of light.

Later arrival would require detection and triggering within the next crossing time window. The typically large size of the general-purpose collider detectors results in this being an important source of inefficiency in detecting SMPs. For example, it is only possible to reconstruct the track of a slowly moving SMP in the ATLAS central muon chambers within the correct bunch crossing window if $\beta > 0.5$

The response of each of the general-purpose experiment's subdetectors to HIPs cannot be calibrated directly, and consequently signal efficiency determination relies heavily on simulations. This point is exemplified by an ATLAS search for which the dominant source of uncertainty arises from the modeling of the effect of electron-ion recombination in the liquid-argon calorimeter in the case of a large energy loss. Last, but not least, the extremely high background from Standard Model particles at, say, the High Luminosity LHC in a detector with non-optimal granularity can give rise to backgrounds from, for example, multi-particle occupancy.

The MoEDAL-LHC detector is designed to optimize the search for highly ionizing particles and magnetic charge in a way that is complementary to the reach of the general purpose LHC detectors and largely overcomes the experimental difficulties suffered using general purpose collider detectors mentioned above. The MoEDAL NTD detector system is light, thin - around 1 cm thick - with a detector density around 1.2 g/cm^3. Thus, little material is added to the relatively small amount of existing material comprising the LHCb vertex detector (VELO) around LHC intersection Point IP8. The measurement of the passage of highly ionizing particles - with $Z/\beta \geq 5$ - is accomplished using a plastic NTD system that can be easily calibrated using heavy-ion beams.

In addition, one can also stop HIPS in MoEDAL's dedicated trapping detectors with delayed detection of their presence in a remote detector system. In the case of Monopoles one can use a SQUID magnetometer to detect trapped magnetic charge. The SQUID magnetometer is calibrated for a monopole's magnetic field using a very long solenoidal coil. One can monitor the decay of stopped long-lived massive electrically charged particles in underground facilities such as SNOLAB.

Backgrounds from Standard Model particles that can simulate the signals of HIPs in MoEDAL are non-existent. Thus only one event is enough to establish the presence of new physics. However, in the case of general-purpose collider detectors the experimental shortcomings, and backgrounds from the very large flux of Standard Model particles, described above require significantly more signal particles to be recorded before a discovery can be claimed.

We estimate that in standard collider detectors between 10-100 HIP particles will need to be registered before a discovery can be claimed. A comparison of the sensitivity of MoEDAL to Highly Ionizing particles with that of the other LHC detectors - assuming that ATLAS and CMS need to detect a conservative minimum of 100 events to claim discovery whereas MoEDAL only one – are shownin Figures 5 and 6. These Figure arise from an initial study of the detection of highly ionizing particles at the LHC [6].

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