

The MoEDAL experiment at the LHC

Albert De Roeck*

CERN, 1211 Geneva 23 Switzerland

E-mail: deroeck@mail.cern.ch

James L. Pinfold

University of Alberta, Physics Department, Edmonton, Alberta T6G 0V1, Canada

E-mail: jpinfold@ualberta.ca

MoEDAL is a pioneering experiment designed to search for highly ionizing messengers of new physics such as magnetic monopoles or massive (pseudo-)stable charged particles. Its groundbreaking physics program defines a number of scenarios that yield potentially revolutionary insights into such foundational questions as: are there extra dimensions or new symmetries; does magnetic charge exist; what is the nature of dark matter; and, how did the big-bang develop. MoEDAL's purpose is to meet such far-reaching challenges at the frontier of the field.

The innovative MoEDAL detector employs unconventional methodologies tuned to the prospect of discovery physics. The largely passive MoEDAL detector, deployed at Point 8 on the LHC ring, has a dual nature. First, it acts like a giant camera, comprised of nuclear track detectors - analyzed offline by ultra fast scanning microscopes - sensitive only to new physics. Second, it is uniquely able to trap the particle messengers of physics beyond the Standard Model for further study. MoEDAL's radiation environment is monitored by a state-of-the-art real-time TimePix pixel detector array.

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*Speaker.

1. Introduction

In 2010 the MoEDAL experiment [1] at the Large Hadron Collider (LHC) was unanimously approved by CERN's Research Board to start data taking in 2015. MoEDAL is a pioneering experiment designed to search for highly ionizing particles such as magnetic monopoles or massive (pseudo-)stable charged particles. Its groundbreaking physics program defines over 30 scenarios [2] that yield potentially revolutionary insights into such foundational questions as: are there extra dimensions or new symmetries; and in particular does magnetic charge exist. The innovative MoEDAL detector employs unconventional methodologies tuned to the prospect of discovery physics. The largely passive MoEDAL detector, deployed at Point 8 (IP8) on the LHC ring has a dual nature. First, it acts like a giant camera, comprised of Nuclear Track Detectors (NTDs) - analyzed offline by ultra fast scanning microscopes - sensitive only to new physics. Second, it is uniquely able to trap the particle messengers of physics beyond the Standard Model for further study. MoEDAL's radiation environment is monitored by a state-of-the-art real-time TimePix pixel detector array.

2. Highly ionizing particles - messengers of new physics

One of the main objectives for MoEDAL is the state-of-the-art search for the magnetic charge carried by the monopole, just as the search for the Higgs was the prime motivation for the LHC and its general-purpose experiments.

The energy loss of a particle traversing matter is given by the Bethe-Bloch formula which in a simplified form is:

$$-\frac{dE}{dx} = z^2 \frac{KZ}{A\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e \beta^2 \gamma^2}{I} \right) - \beta^2 \right] \quad (2.1)$$

where, β is the speed of the particles expressed as a fraction of the speed of light ($\beta=v/c$) and $K = 4\pi N_A r_e^2 m_e c^2$. The properties of the medium are the atomic number Z , the atomic mass A and the mean excitation energy I . The constants are the electron mass, m_e , the classical electron radius, r_e and Avogadro's number N_A .

In proton-proton collisions at the LHC electrically charged particles can only be highly ionizing if they are massive and thus moving very slowly with $\beta\gamma < 1$, and/or multiply charged. However, there are no known massive stable or long-lived particles that are multiply charged. The only way that a Standard Model particle can be highly ionizing is if it is slowing down to stop.

A prime example of a HIP from BSM is the magnetic monopole. Interest in the existence of magnetic monopoles greatly increased when Dirac showed that electric charge quantisation could be explained as a natural consequence of angular momentum quantisation in the presence of a monopole [3]. It follows from Dirac's argument that the magnetic charge q_m carried by a monopole should be a multiple of the fundamental Dirac magnetic charge. In Gaussian units, the Dirac quantisation relation reads:

$$g = \frac{q_m}{e} = \frac{n}{2\alpha_e} = n \cdot g_D \approx n \cdot 68.5, \quad (2.2)$$

where e is the electric charge of the proton, α_e is the fine structure constant, n is an integer and g_D is the Dirac unit of magnetic charge. In SI units, the dimensionless quantity g is related to the magnetic charge q_m by the relation $q_m = gec$ where c is the speed of light in vacuo. The large value of the Dirac charge, $g_D = 68.5$, implies that the minimum coupling of a monopole to the photon should be much larger than 1, preventing reliable perturbative calculations of monopole production processes. The ionization energy loss of a magnetically charged particle can be obtained from the Bethe-Bloch formula by replacing the electric charge ze by $ng\beta$ and realizing that for magnetic monopoles the velocity dependence of the Lorentz force cancels the $1/\beta^2$ term in the Bethe-Bloch formula for charged particles:

$$-\frac{dE}{dx} = n(g/e)^2 \frac{KZ}{A} \left[\frac{1}{2} \ln \left(\frac{2m_e \beta^2 \gamma^2}{I^2} \right) - \beta^2 \right] \quad (2.3)$$

The energy loss of a singly charged ($n = 1$) very relativistic magnetic monopole ($\beta \approx 1$) is amazingly about 4700 times that of a proton.

The MoEDAL experiment detects HIPs using stacks of passive plastic Nuclear Track Detectors (NTDs). The HIP damages the plastic as it traverses the NTD stack. Etching the plastic in a hot sodium hydroxide solution can reveal this damage as two collinear etch-pits each with diameter $\sim 5 - 10\mu\text{m}$ in each of the six layers of the stack. The NTD plastic employed by MoEDAL has a threshold of around Z/β of 5 (or 5 MIPs). A HIP messenger of new physics would leave a tell tale signature of twelve tiny etch pits forming a precisely defined line pointing back to the collision. There is no known Standard Model particle that can give a trail of collinear etch pits in a MoEDAL stack.

3. Directly detecting magnetic charge

Clearly, a unique property of the magnetic monopole is that it has magnetic charge. Thus a moving magnetic monopole will be ringed by an electric field just as a moving electric charge is ringed by a magnetic field. Imagine that a magnetic monopole traverses the superconducting wire coil of a SQUID (Superconducting QUantum Interference Device). As the monopole approaches the coil it drives an electrical current within the coil that in turn creates a changing magnetic field. This changing magnetic field creates an electric field that counters the original electric field of the moving monopole. As the wire in the coil has no resistance the overall effect is to make the total electric field vanish in the coil. Meanwhile the current continues to flow in the coil because the wire is superconducting and without resistance. One can use Faraday's Law to calculate the magnitude of the current that would be generated:

$$I = -\frac{m\mu_0 q_m}{L} \quad (3.1)$$

where, L is the inductance of the coil, μ_0 is the permeability of free space and q_m is the magnetic charge. Consequently, the current induced only depends on the magnetic charge and is independent of the speed, mass or direction of the magnetic monopole.

4. A description of the MoEDAL detector

The novel MoEDAL detector is deployed at IP8 on the LHC ring, depicted in figure 1, is comprised of three key subsystems. The main component of MoEDAL's NTD subsystem consists of a low threshold (LT) NTD array - comprised of an array of (400) plastic NTD stacks ($25 \times 25 \text{ cm}^2$) each stack made up of CR39 (3) and MAKROFOL (3) NTD sheets. This is the largest NTD array ever deployed at an accelerator. The CR39 NTDs have an excellent charge resolution (≥ 0.2 of a single electric charge, based on a single measurement) and a low threshold, allowing the detection of HIPs with an ionizing power equal to or more than 5 times that of a Minimum Ionizing Particle (MIP). An illustration of the LT-NTD stack is given in figure 2 (left).

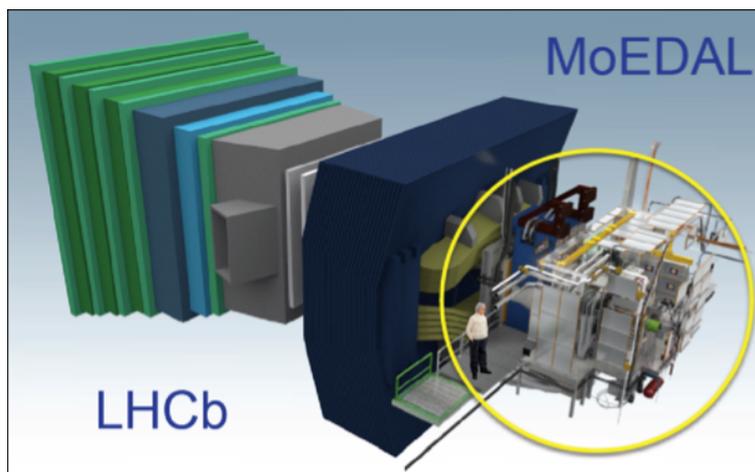


Figure 1: A view of the MoEDAL detector deployed around the LHCb's VELO detector at IP8.

The LT-NTD array has been enhanced by the Very High Charge Catcher (VHCC) subdetector, with threshold around 50 MIPs. The VHCC subdetector, comprised of two flexible low mass stacks of MAKROFOL in an aluminium foil envelope - is deployed in the forward acceptance of the LHCb experiment just after the LHCb RICH detector. The overall acceptance of the NTD system is $\sim 60\%$. The exposed NTD detectors will be etched to reveal the passage of a HIP as illustrated in figure 2 (right). The etched plastic will then be analysed using ultra-fast automated optical scanning microscopes. This enables low NTD thresholds to be maintained despite large beam related backgrounds.

The Magnetic Monopole Trapper (MMT) is the third MoEDAL sub-detector system. Its sensitive volume consists of about 800 kg of pure aluminium trapping volumes deployed around the MoEDAL cavern at IP8. Aluminium is well suited as it has an anomalously large nuclear magnetic moment. After exposure the MMT trapping volumes will be monitored at the ETH SQUID facility in Zurich for the presence of captured monopoles. A schematic description of this facility is shown in figure 3 (left). Figure 3 (right) shows the results of an exposure of a MMT test detector at IP8 on the LHC ring, as discussed below. As can be seen the SQUID can detect magnetic charges greater than one tenth of a Dirac charge.

The fourth and only active sub-detector system is the TimePix pixel device array (TMPX), consisting of ~ 8 devices distributed throughout the MoEDAL cavern at IP8. TMPX will be used

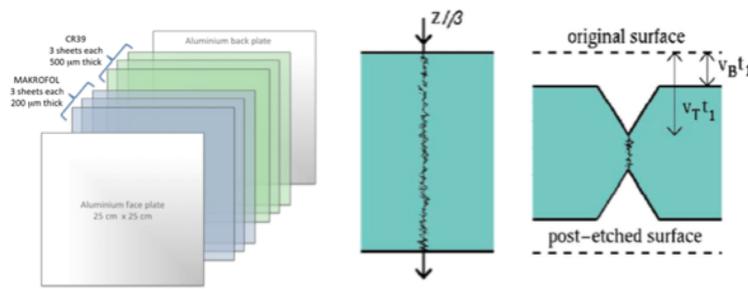


Figure 2: (Left) A MoEDAL stack comprised of CR39 and Markrofol NTD detectors. (Right) The damage zone created by the HIP that is subsequently revealed by etching in a hot NaOH solution.

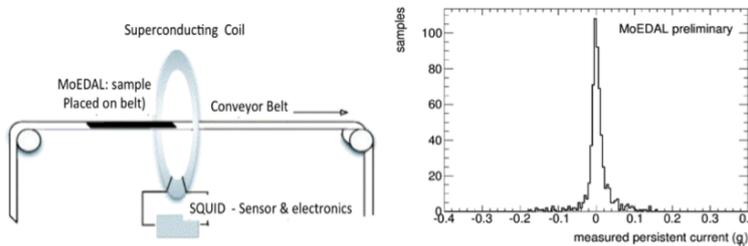


Figure 3: (Left) A schematic depiction of the use of a SQUID magnetometer to detect the presence of a trapped magnetic charge. (Right) The results of a SQUID scan of MMT elements exposed to roughly a year of LHC collisions at IP8 - as part of a MoEDAL test MMT detector deployment.

to monitor highly ionizing beam related backgrounds. Each pixel of the innovative TimePix chip contains a preamp, a discriminator with threshold adjustment, synchronization logic and a 14-bit counter. MoEDAL uses TimePix Time-over-Threshold modes where each pixel acts as an ADC for energy measurement. Effectively, the TimePix device is a tiny electronic bubble-chamber providing a real-time ‘colour’ (energy dependent) movie of the background.

MoEDAL’s pioneering physics prospectus [2] covers more than 30 fundamentally important BSM scenarios allowing MoEDAL to significantly expand the LHC’s discovery horizon in a complementary way. This program is illustrated in the pie chart shown in figure 4.

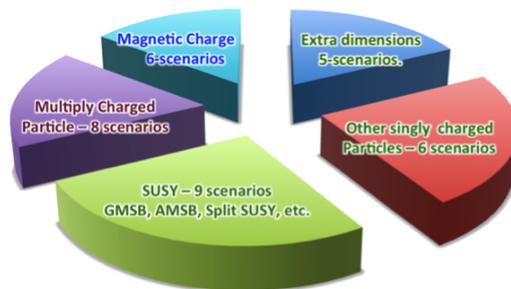


Figure 4: The MoEDAL Physics Program broken down by topic.

5. A first search for monopoles with MoEDAL prototype trapping detector

We present here the results of a search for magnetic monopoles using a 160 kg prototype MoEDAL trapping detector. The MoEDAL prototype trapping detector was exposed to 8 TeV pp collisions at IP8 between September and December 2012. Using LHCb luminosity measurements during that period, conservatively assuming a 3.5% uncertainty this corresponds to an integrated luminosity of $0.75 \pm 0.03 \text{ fb}^{-1}$. After the run was finished, the aluminium rods were retrieved and cut into samples of 20 cm length with a non-ferromagnetic saw (except one box, whose rods were cut into a mix of 10, 15, 20 and 30 cm samples for studying the sample-size dependence of the magnetometer response), for a total of 606 samples.

A DC-SQUID rock magnetometer (2G Enterprises model 755) housed at the Laboratory for Natural Magnetism at ETH Zurich was used to scan the trapping detector samples. The magnetometer calibration was performed with a convolution method applied to a dipole sample, and cross-checked using long thin solenoids that mimic a monopole of well-known magnetic charge. Two 25 cm long solenoids of different coil areas and different number of turns were used with currents varying from 0.01 to 10 μA . The magnetometer response was measured to be linear and charge symmetric in a range corresponding to $0.1 - 300g_{\text{D}}$. After calibration, the measured current is translated into units of current expected from the passage of a Dirac magnetic charge, $I_{g_{\text{D}}}$, with an estimated uncertainty of 10% in the calibration constant as obtained by comparing the different independent methods. A calibration dipole sample of well-known magnetic moment was measured at the start of each run, with current values found to be consistent within 1%, ensuring that the calibration constant remained stable. Each of the 606 aluminium samples of the trapping detector was passed at least once through the magnetometer, mostly during a measurement campaign in September 2013. Roughly every tenth measurement was performed with an empty sample holder for offset subtraction.

The SQUID magnetometer's sample holder is a long telescopic carbon-fibre tube which extends completely along the axis of the sensing coils when it is at the start position. The sample is placed at the position of maximum extension and then slowly moved back through the sensing coils to a final position of minimum extension of the sample holder arm. Magnetic dipole impurities inside the sample and the sample holder can induce currents in the coils. The monopole signature is measured in terms of the persistent current, defined as the difference between the currents measured after and before passage of the sample through the sensing coil, after adjustment for the contribution of the sample holder.

The magnetic charge measurements are made for all 606 samples of the trapping detector as measured by the first measurement — or the first subsequent measurement in the cases where a spurious offset jump was observed for the first measurement. No measurements yield values of $|g|$ beyond $0.18g_{\text{D}}$ [5].

The probability that a sample containing a magnetic monopole with $|g| \geq 0.5g_{\text{D}}$ would yield a persistent current lower than $0.25g_{\text{D}}$, and so remain undetected, was estimated from the rate of spurious jumps with values between $0.25g_{\text{D}}$ and $0.5g_{\text{D}}$ in a given direction from samples for which multiple measurements confirmed the absence of monopole. This rate was observed to be 0.25% and is assumed to be the same for samples containing magnetic charge of the order of the Dirac charge because the magnetic charge would result in a current which is small compared to

the currents induced by dipoles in the sample and sample holder, which are the main causes for spurious jumps. For monopoles with charges larger than $0.5g_D$, this number is even smaller. Thus, the presence of a monopole with $|g| \geq 0.5g_D$ is excluded at more than 99.75% confidence level.

Simulations of monopole propagation and energy loss in the MoEDAL experimental setup are performed using the GEANT4 toolkit[6]. The production process is assumed to be Drell-Yan, and the produced monopoles can be spin zero or spin 1/2 particles. About 10^5 events are used in each sample for DY production, for different monopole mass hypotheses. For the assessment of systematic uncertainties, the simulations are performed using four different geometries, corresponding to the baseline, minimum material, maximum material, and trapping detector position shifted by 1 cm in all three coordinates. For each event, the monopole final position is recorded to assess the acceptance of the trapping detector, or probability to trap a monopole. Once the monopoles are produced in a collision at the LHC, they will travel through the surrounding material losing energy. They will slow down and likely become trapped in matter by binding to the nucleus of an atom forming the material.

In the simulations, the final position of a monopole is the point at which its velocity falls to $\beta \leq 10^{-3}$. If that position is inside the volume of the prototype trapping detector, the monopole is considered trapped. It was verified that changing the criterion to $\beta \leq 10^{-2}$ does not change the result in any significant way. This is expected since $\beta = 10^{-2}$ corresponds to a point where a monopole in the mass range considered in this search is expected to further travel at most a few mm in aluminium. This distance is much smaller than the trapping detector dimensions. It is assumed here that the monopole binding to the aluminium trapping volumes is due to the interaction between the magnetic charge of the monopole and the magnetic moment of the nucleus. The large and positive anomalous magnetic moment of aluminium makes it a good choice for the MoEDAL trapping detector with a predicted monopole-nucleus binding energy in the range 0.5 – 2.5 MeV. The acceptance of the trapping detector is defined on an event basis as the probability that at least one of the pair-produced monopoles is trapped inside one of the aluminium bars comprising the prototype trapping detector. This acceptance is determined by propagating monopoles with GEANT4 through the geometry model defining the disposition of material comprising the prototype trapping detector and the relevant material in its vicinity.

The acceptance is highly dependent on the energy distribution predicted by the model for monopole production and on the material budget between the trapping detector and the production point. Monopoles with low charges and/or high energies tend to punch through the trapping material and are thus better captured in regions where they are slowed down by thicker upstream material. Monopoles with higher charges and/or low energies tend to range out before they reach the trapping detector, and are thus only trapped in regions of low upstream material. Also, for the same charge and the same kinetic energy, monopoles with lower masses possess a higher velocity, leading to higher dE/dx , and thus tend to lose their energy earlier. For instance, for a magnetic charge $|g| = 2g_D$, a monopole with mass 100 GeV needs about 100 GeV more kinetic energy to reach the trapping detector than a monopole with mass 1000 GeV.

No magnetically-charged particles were observed in the prototype trapping detector volumes exposed to $0.75 \pm 0.03 \text{ fb}^{-1}$ of 8 TeV pp collisions, where the assumption is made that a monopole that would range out in the aluminium material would always be captured and remain bound to a nucleus. This observation, combined with the estimate of the acceptance and its uncertainty, results

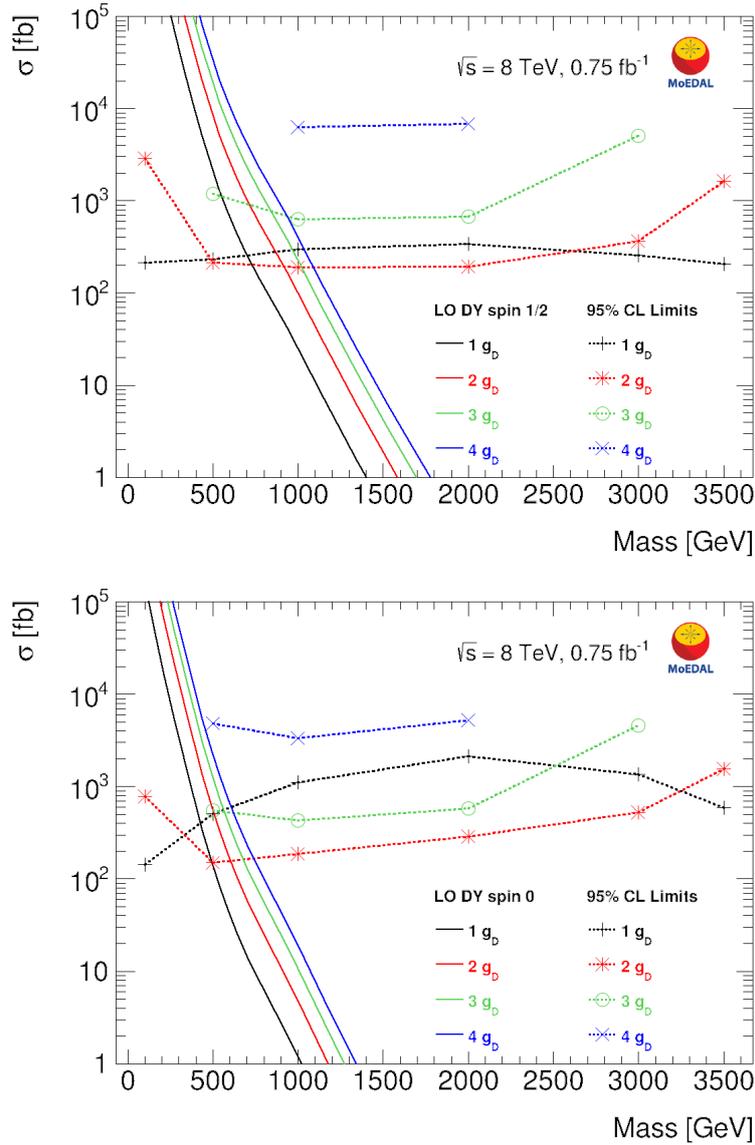


Figure 5: Cross-section upper limits at 95% confidence level for DY monopole production as a function of mass for spin-1/2 (top) and spin-0 (bottom) monopoles. The various line styles correspond to different monopole charges. The solid lines are DY cross-section calculations at leading order.

in stringent limits on the cross sections of processes with monopoles in the final state, assuming e.g. DY production.

The 95% confidence level upper limits on the monopole production cross section with the DY process are shown graphically as functions of mass in Fig. 5 and as a function of charge in Fig. 6 for spin-1/2 (top) and spin-0 (bottom) monopoles. The DY pair production cross-section calculations are performed at leading order and correspond to the DY cross sections for massive particles with a single electric charge scaled by the factor $g^2 = (n \cdot 68.5)^2$ to account for the monopole charge. These DY cross-section calculations should be viewed with caution since the monopole coupling

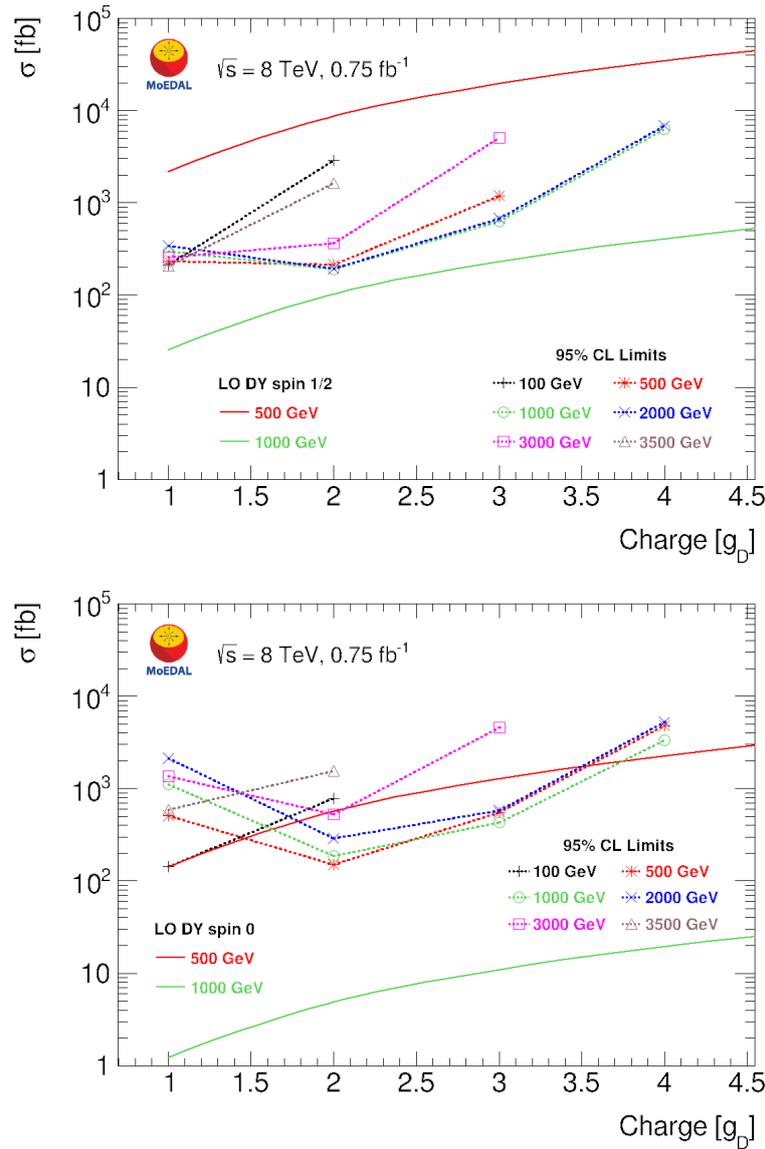


Figure 6: Cross-section upper limits at 95% confidence level for DY monopole production as a function of charge for spin-1/2 (top) and spin-0 (bottom) monopoles. The various line styles correspond to different monopole masses. The solid lines are DY cross-section calculations at leading order.

to the photon is too large for perturbative calculations to converge. However, they are useful as a benchmark by which the present results can be compared with those of other experiments.

6. Summary and Conclusion

The MoEDAL experiment has a pioneering design to search for new physics in the form of highly-ionising particles such as magnetic monopoles or massive (pseudo-)stable charged particles. The largely passive MoEDAL detector, deployed at Interaction Point 8 on the LHC ring, has a

dual nature. First, it acts like a giant camera, comprised of nuclear track detectors sensitive only to new physics. Secondly, it is uniquely able to trap particle messengers of physics beyond the Standard Model for further study. The results of a search for magnetic monopoles utilising a prototype MoEDAL trapping detector exposed to 0.75 fb^{-1} of 8 TeV pp collisions in 2012 — and subsequently removed and monitored at a remote site by a SQUID magnetometer — are presented here. This is the first time that a dedicated scalable and reusable trapping array has been deployed at an accelerator facility.

No monopole candidates with magnetic charge $\geq 0.5g_D$ were found in any of the trapping detector samples. Under the assumption of monopole capture by aluminium nuclei, this results in 95% confidence level cross-section limits ranging from 100 fb to 6000 fb in models of DY monopole pair production for charges up to $4g_D$ and masses up to 3500 GeV. Previous LHC constraints for pair production exist only for $|g| \leq 1.5g_D$ and $m \leq 2500$ GeV. Under the assumption of a DY cross section at leading order, mass limits are obtained for magnetic charges up to $3g_D$. A model-independent 95% confidence limit of 10 fb is also set for monopoles with charges up to $6g_D$ produced in specific ranges of energy and direction.

Despite a small solid angle coverage and modest luminosity, MoEDAL's prototype monopole trapping detector probes ranges of charge, mass and energy which could not be accessed by other LHC experiments. Furthermore, this technique can potentially make a discovery very quickly and allow for an unambiguous background-free assessment of a signal, providing a direct measurement of a monopole magnetic charge based on its magnetic properties only. Importantly, trapping detectors allow the possibility of studying directly captured magnetic monopoles in the laboratory. A new, larger — roughly 800 kg — trapping detector array was deployed in 2015 downstream of the LHCb VELO vessel as well as on its sides and exposed to pp collisions at 13 TeV centre-of-mass energy. The analysis of this and other MoEDAL runs will be presented in future publications.

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