Search for High Ionizing Particles in 8 TeV pp Collisions at the LHC Using the Full LHC Run-1 MoEDAL Detector

B. Acharya,[1,*] J. Alexandre,[1] P. Benes,[2] B. Bergmann,[2] J. Bernabéu,[3] A. Bevan,[4] H. Branzas,[5] P. Burian,[2] M. Campbell,[6] S. Cecchini,[7] Y. M. Cho,[8] M. de Montigny,[9] A. De Roeck,[6] J. R. Ellis,[1,10,†] M. El Sawy,[6,‡] M. Fairbairn,[1] D. Felea,[5] M. Frank,[11] J. Hays,[4] A. M. Hirt,[12] J. Janecek,[2] M. Kalliokoski,[13] A. Korzenev,[14] D. H. Lacarrère,[6] C. Leroy,[15] G. Levi,[16] P. Li,[9] A. Lionti,[14] J. Mamuzic,[3] A. Maulik,[7,9] A. Margiotta,[16] N. Mauri,[7] N. E. Mavromatos,[1] P. Mermod,[14,§] M. Mieskolainen,[13] L. Millward,[4] V. A. Mitsou,[3] R. Orava,[13] I. Ostrovskiy,[17] P.-P. Ouimet,[9,¶] J. Papavassiliou,[3] B. Parker,[18] L. Patrizii,[7] G. E. Păvălaş,[5] J. L. Pinfold,[9,**] L. A. Popa,[5] V. Popa,[5] M. Pozzato,[7] S. Pospisil,[2] A. Rajantie,[19] R. Ruiz de Austri,[3] Z. Sahnoun,[7,††] M. Sakellariadou,[1] A. Santra,[3] S. Sarkar,[1] G. Semenoff,[20] A. Shaa,[9] G. Sirri,[7] K. Sliwa,[21] R. Soluk,[9] M. Spurio,[16] M. Staelens,[9] M. Suk,[2] M. Tenti,[22] V. Togo,[7] J. A. Tuszyński,[9] A. Upreti,[17] V. Vento,[3] O. Vives,[3] and A. Wall[17]

(THE MoEDAL COLLABORATION)

[1] *Theoretical Particle Physics & Cosmology Group, Physics Dept., King's College London, UK*
[2] *IEAP, Czech Technical University in Prague, Czech Republic*
[3] *IFIC, Universitat de València - CSIC, Valencia, Spain*
[4] *School of Physics and Astronomy, Queen Mary University of London, UK*
[5] *Institute of Space Science, Bucharest - Măgurele, Romania*
[6] *Experimental Physics Department, CERN, Geneva, Switzerland*
[7] *INFN, Section of Bologna, Bologna, Italy*
[8] *Center for Quantum Spacetime, Sogang University, Seoul, Korea*
[9] *Physics Department, University of Alberta, Edmonton, Alberta, Canada*
[10] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[11] *Department of Physics, Concordia University, Montréal, Québec, Canada*
[12] *Department of Earth Sciences, Swiss Federal Institute of Technology, Zurich, Switzerland*
[13] *Physics Department, University of Helsinki, Helsinki, Finland*
[14] *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland*
[15] *Département de Physique, Université de Montréal, Québec, Canada*
[16] *INFN, Section of Bologna & Department of Physics & Astronomy, University of Bologna, Italy*
[17] *Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama, USA*
[18] *Institute for Research in Schools, Canterbury, UK*
[19] *Department of Physics, Imperial College London, UK*
[20] *Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[21] *Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[22] *INFN, CNAF, Bologna, Italy*

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A search for highly electrically charged objects (HECOs) and magnetic monopoles is presented using 2.2 fb^{-1} of p-p collision data taken at a centre of mass energy of 8 TeV by the MoEDAL detector during LHC's Run-1. The data were collected using MoEDAL's Nuclear Track Detector array and the Trapping Detector array. The results are interpreted in terms of Drell–Yan pair production of stable HECO and monople pairs with three spin hypotheses (0, 1/2 and 1). The search provides constraints on the direct production of magnetic monopoles carrying one to five Dirac magnetic charges ($5g_{\mathrm{D}}$) and with mass limits ranging from 710 GeV to 1230 GeV. Additionally, mass limits are placed on HECOs with charge in the range $10e$ to $165e$, where e is the charge of an electron, for masses between 640 GeV and 2000 GeV.

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INTRODUCTION

The quest for intrinsically highly ionizing particle (HIP) avatars of physics beyond the Standard Model has been an active area of investigation at accelerator centres for several decades [1–15]. Searches have also been performed in cosmic rays and in matter [16, 17]. Most HIP searches can be divided into two categories: the quest for magnetic monopoles (MMs) and the hunt for highly electrically charged objects (HECOs). According to the Bethe-Bloch formula [18], massive singly charged particles traversing matter can also be highly ionizing due to their low velocity, β (the particle velocity expressed as a fraction of the speed of light, c).

In 1931 Dirac formulated a consistent description of a magnetic monopole [19] within the framework of quantum physics. This monopole is associated with a line of singularity called a Dirac string. Dirac derived his Quantization Condition (DQC) in order that this string has no effect: $g_D = \frac{2\pi\hbar}{\mu_0 e} n$ where e is the electric charge of the particle probe, $\hbar$ is Planck's constant divided by 2π, g_D is the magnetic charge, μ_0 is the permeability of free space and n is an integer.

The DQC indicates that if the magnetic charge exists then the electric charge is quantized in units of $e = 2\pi\hbar/(\mu_0)g_D$. The value of g_D is approximately $68.5e$. Dirac's theory did not constrain the mass or the spin of the monopole. Further, the Dirac quantization condition indicates a coupling strength much bigger than one: $\alpha_m = \mu_0 g_D^2/(4\pi\hbar c) \approx 34$. Thus, perturbation theory cannot be applied and cross-section calculations based on perturbation theory are not physically valid, although useful as a benchmark.

In 1974 't Hooft [20] and Polyakov [21] discovered monopole solutions of the non-Abelian Georgi-Glashow model [22]. This model has only one gauge symmetry, SO(3), with a three component Higgs field. The mass of the 't Hooft–Polyakov MM was predicted to be around 100 GeV. However, MMs with such a low mass were ruled out by experiment. Subsequently, Georgi and Glashow combined their electroweak theory with a theoretical description of strong nuclear forces to form a Grand Unified Theory (GUT) [23] using the single non-Abelian gauge symmetry, SU(5). In this GUT theory the MM would have a mass of $\sim 10^{15}$ GeV which is far too heavy to be directly produced at any foreseeable terrestrial collider.

Although, the Standard Model has an $SU(2) \times U(1)$ group structure that does not admit a finite-energy monopole, Cho and co-workers have modified its structure to admit the possibility of an "electroweak" monopole [24, 25] with a magnetic charge of $2g_D$. Based on this work Cho, Kim and Yoon (CKY) [26] have more recently presented an adaptation of the Standard Model, that includes a non-minimal coupling of its Higgs field to the square of its U(1) gauge coupling strength, that admits the possibility of a finite energy dyon [27].

The question of whether it is possible to create generalisations of the CKY model that are consistent with the the Standard Model was considered by Ellis, Mavromatos and You (EMY) [28]. EMY concluded that there was a possibility that an "electroweak" monopole, consistent with the current constraints on the Standard Model, may exist and be detectable at the LHC. In any case, the existence of a MM is such a theoretically well predicated and revolutionary possibility that the search for a MM has been carried out as each new energy frontier is broached.

We consider here only those models that admit a magnetic charge quantized in units of Dirac charge, g_D, or a multiple of the Dirac charge. As $g_D = 68.5e$, a relativistic monopole with a single Dirac charge will ionize $\sim$4700 times more than a relativistic proton. It is thus a prime example of a HIP.

As mentioned above electrically charged HIPs, or HECOs, have also been hypothesized. Examples of HECOs, include: dyons doubly charge massive particles [3]; aggregates of ud- [29] or s-quark matter [30], Q-balls [31], [32] and the remnants of microscopic black-holes [33].

The first searches for MMs and/or HECOs at the LHC were performed by the ATLAS and MoEDAL Collaborations in 8 TeV pp-collisions [4, 5, 8]. At this stage, the ATLAS monopole search was sensitive to singly magnetically charged ($1g_D$) monopoles, whereas the MoEDAL search was sensitive to single and multiply charged monopoles. ATLAS and MoEDAL continued the quest for HIPs at RUN2.

In the case of MMs, the ATLAS and MoEDAL searches were complementary, in the sense that ATLAS utilized the MMs highly ionizing signature [7, 14] whereas, until now, the MoEDAL experiment only exploited the induction technique to directly detect the magnetic charge [9–11]. Extensive accelerator searches for HECOs at the LHC have also been undertaken [4, 6, 7, 14]. The latest result from LHC describes the ATLAS experiment search for HECOs and monopoles using data taken during LHC's Run-2 at a centre-of-mass energy of 13 Tev [15].

In this paper we report the first use of the MoEDAL Nuclear Track Detector (NTD) System, which relies on an ionization signal to detect HIPs. The 2.2 fb^{-1} of $p-p$ collision data analyzed was obtained during LHC's Run-1 at IP8 on the LHC ring.

ENERGY LOSS OF HIPS IN MOEDAL

In the MoEDAL detector HIPs lose energy by ionization. When considering the energy loss in the MMT detector the total energy loss is computed using Bethe-Block formula. For NTDs the relevant quantity is the Restricted Energy Loss (REL) [34]. The REL is equal to the particle's total energy loss in the medium for $\beta < 10^{-2}$. At larger velocities REL is the fraction of the electronic energy loss leading to the formation of δ-rays with energies lower than a cut-off energy T_{cut}. The REL can be computed from the Bethe-Block formula restricted to energy transfers $T < T_{cut}$ with T_{cut} a constant characteristic of the medium. For Makfrofol, which is the MoEDAL NTD used for the analysis reported in this paper, $T_{cut} <= 350$ eV. The RELs for MMs and for HECOs in Makrofol are shown in Fig. 1 and Fig. 2, respectively.

THE RUN-1 MOEDAL DETECTOR

During LHC's Run-1, MoEDAL deployed a prototype detector system comprised of two sub-detector systems. The first of these was a plastic Nuclear Track Detector stack array to detect the ionization trail of HIPs. The second was a detector system comprised of 163 kg of aluminium absorber elements. This detector system was

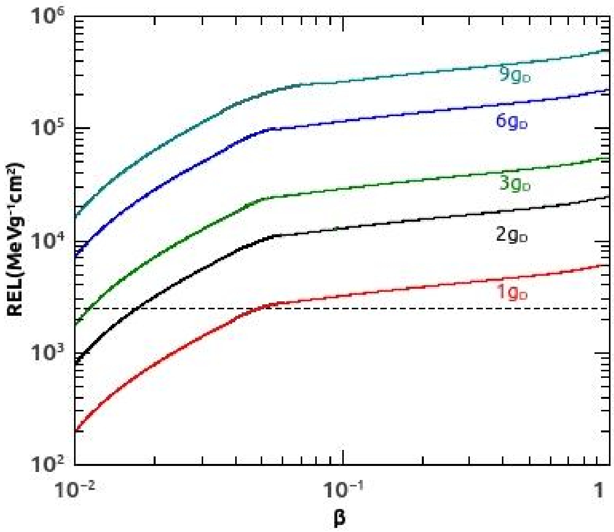

FIG. 1. Restricted Energy Loss in Makrofol for monopoles of different magnetic charge. The horizontal dotted line indicates the Makrofol detection threshold.

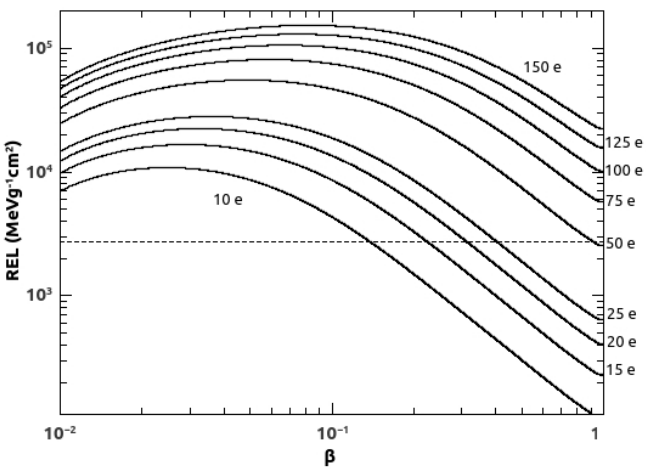

FIG. 2. Restricted Energy Loss in Makrofol for HECOs of different electric charge. The horizontal dotted line indicates the Makrofol detection threshold.

called the MMT (Magnetic Monopole Trapper) since it was used to trap HIPs with magnetic charge, that slow down and stop within its sensitive volume, for further laboratory analysis. Both of these detector systems were passive, requiring neither a trigger or readout electronics.The MoEDAL detector is described in more detail below.

The MoEDAL detector is exemplified by its ability to retain a permanent record, and even capture new particles for further study. There are no Standard Model particles that can produce such distinct signatures – thus, even the detection in MoEDAL of few HIP particle messengers of new physics would herald a discovery.

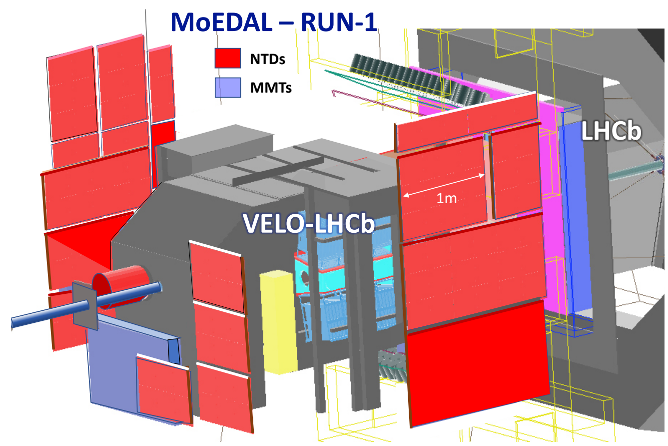

FIG. 3. The Prototype MoEDAL Detector deployed at IP8 during LHC's RUN-1.

The MMT Detector

The prototype MMT detector deployed for LHC's Run-1 was comprised of 198 aluminium rods weighing a total of 163 kg. These bars were housed in an enclosure placed just underneath the beampipe at the upstream end of LHCB's VELO detector as shown in Figure 3. After exposure the MMTs' Al rods are sent to the ETH Zurich Laboratory for Natural Magnetism. Here they are passed through a SQUID magnetometer to scan for the presence of trapped magnetic charge. A monopole will stop in the MMT detector when its speed falls below $\beta \leq 10^{-3}$. It then binds due to the interaction between the monopole and the nuclear magnetic moment[35–38] of an aluminium nucleus comprising in an MMT trapping volume.

The anomalously large magnetic moment of an aluminium nucleus gives rise to a monopole-nucleus binding energy (BE) of 0.5 - 2.5 MeV [35], comparable to the shell model splittings. In any case, it is reasonable to assume that the very strong magnetic field of the monopole will rearrange the nucleus permitting it to bind strongly to the nucleus. As reported in Ref. [35] monopoles with this BE will be bound indefinitely. It would require fields in excess of around 5T for the trapped monopole to be freed. We note that the MOEDAL experiment's MMT volumes are never subjected to such strong magnetic fields.

Calibration of the MMT Detector

A magnetic monopole captured in an MMT volume is tagged and measured as a persistent current in the SQUID coil encircling the samples' transport axis that passes through the SQUID magnetometer. The calibration of the magnetometer response is achieved using two independent techniques which are more fully recounted in Ref. [39]. These methods agree to within 10%, which is taken to be the pole strength calibration uncertainty. The magnetometer response has been determined by measurement to be charge-symmetric and linear in a range of magnetic charge 0.3 - 300 g_D.

The Nuclear Track Detector System

The MoEDAL Nuclear Track Detector is organized in modules deployed around the Point-8 intersection region of the LHCb detector, in the VELO (VErtex LOcator) cavern. The NTD system, deployed for Run-2 in 2014 comprises 186 modules. The results reported here refer to a prototype array of 135 modules. Each module comprises three layers of 1.5 mm thick CR39® polymer, three layers of Makrofol DE® and three layers of Lexan® 0.5 and 0.25 mm thick, respectively, inside Aluminium bags (Fig. 4). A sketch of the MoEDAL's prototype detector is shown in Fig. 3.

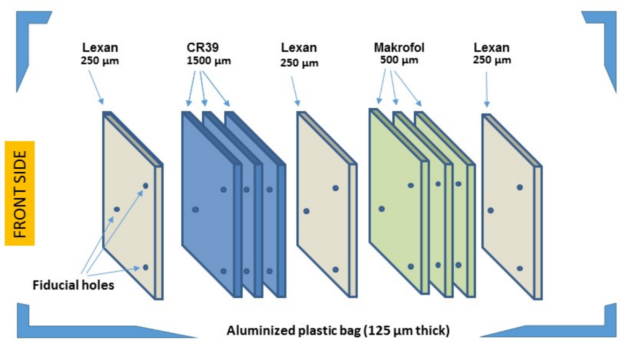

FIG. 4. NTD module composition

The etching procedure

In plastic track-etch detectors, the passage of a heavily ionizing particle can produce a permanent damage of polymeric bonds in a cylindrical region ("latent track") extending few tens of nanometer around the particle trajectory (Fig.5). By subsequent chemical etching the bulk of the material is removed at a rate v_B and at a higher rate v_T along the latent track. The damage zone is revealed under an optical microscope as a cone shaped etch–pit, called "track". Etch–pits surface openings have a circular shape for normally incident particles, otherwise they are elliptical.

A sketch of the etch-pit at different etching times is shown in Fig.5 for a normally incident particle crossing the detector at a constant energy loss. Two etching conditions were applied (Table I: the so-called "strong etching"[40] allowing faster etching and yielding larger etch-pits easier to detect under visual scanning, was applied to the top-most Makrofol foil in each module. "Soft etching" is a slower process allowing to proceed in several etching steps to follow the formation of etch-pits. Soft etching was applied to other Makrofol foils if a candidate track was found in the first layer.

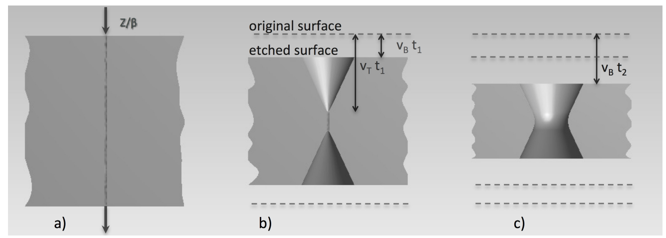

FIG. 5. Illustration of the track–etch technique: a) latent track forming along the trajectory of a high ionizing particle impinging perpendicularly on the NTD surface ; b) development of conical pits during the etching process; c) etch-pits joining after a prolonged etching, forming a hole in the detector.

Calibration of the NTD Detector

The response of the NTD is measured by the etching rate ratio p = v_T / v_B, as a function of the particle's REL. Heavy ion beams are used to determine the detector response over a large range of energy losses, as discussed in ref. [41]. The Makrofol was calibrated with 158 A GeV Pb^{82+} and 13 A GeV Xe^{54+} ion beams at the CERN SPS. The calibration set-up included a stack of Makrofoil foils placed upstream and downstream of an Aluminum target. Incoming ions undergo charge changing nuclear fragmentation along their path through the detector foils and the target. After etching the size of surface tracks was measured with an automatic scanning system providing the area, and the coordinates of the center of the etch pits. The base area distributions of incoming ions and of their fragments is shown in Fig. 7. The projectile fragments have the same velocity and approximately the same direction as the incident ions. From the base area spectrum, the charge corresponding to each nuclear fragment peak can be identified, and the corresponding REL determined. A detailed description of the calibration procedure can be found in [41].

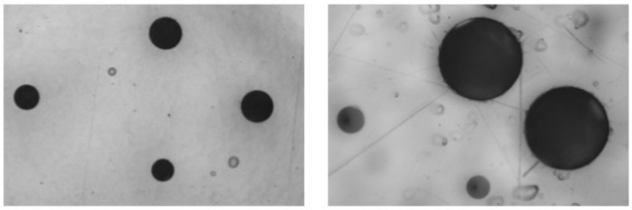

FIG. 6. Microphotographs of relativistic Pb^{82+} tracks and of nuclear fragments (Z<82) in two consecutive foils of Makrofol. Etch pits are from the same ions crossing the detector foils: (left) Makrofol foil etched in "soft consitions"; (right) Makrofol foil etched in "strong conditions".

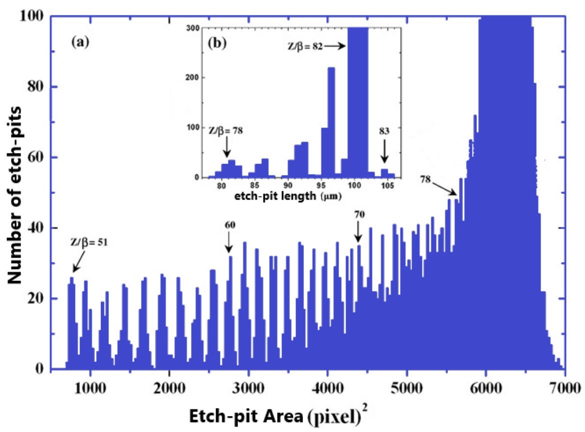

FIG. 7. Distribution of track surface areas in Makrofol exposed to 158 A GeV Pb^{82+} and etched in soft conditions [41].

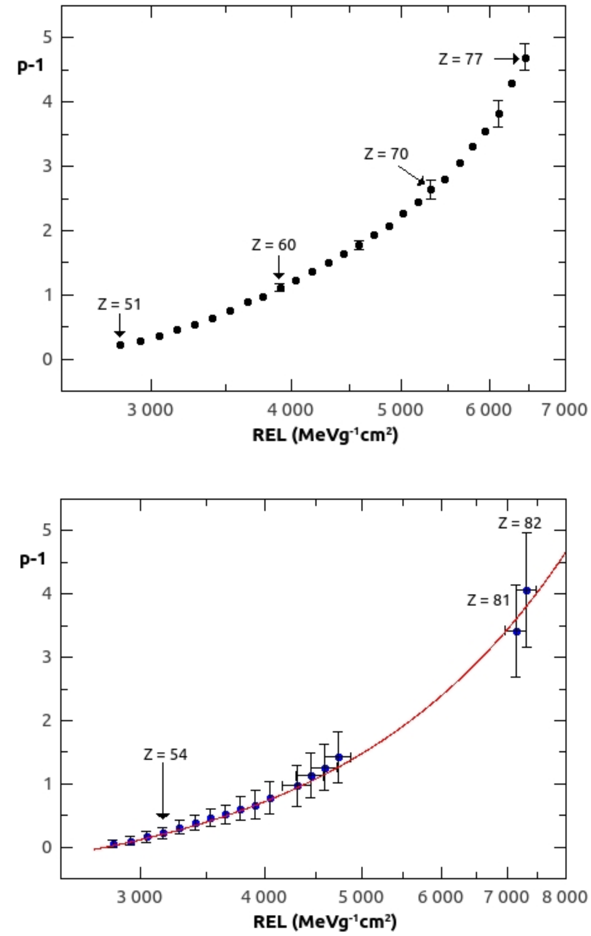

FIG. 8. Reduced etch-rate versus REL for Makrofol exposed to relativistic Lead and Xenon ion beams: (top) detectors etched in (top) soft conditions;(bottom) detectors etched in strong conditions.

Calibration data thus obtained are shown in Fig.8. The mimimum detectable relativistic charge is $Z/\beta \geq 50$, both in soft or strong etching. The detector threshold (p=1) is at REL ~ 2700 MeV $cm^{-2}g^{-1}$.

Etching and Scanning of MoEDAL NTD

After exposure in the LHC IP8 region, the MoEDAL NTD stacks were brought to the INFN etching and scanning Lab in Bologna. A global module reference system is created by drilling three holes – 2 mm diameter – on each detector module. This coordinate system provides an accuracy of 100 μm on the determination of the position of a particle track over the detector surface. The stacks are then unpacked, the detectors foils labelled and their thickness measured on a grid of points uniformly distributed over the foil surface.

For the search reported in this paper only Makrofol foils were analysed. In each exposed stack, the most upstream Makrofol layer was etched in 6 N KOH + 20% Ethyl alcohol at 65°C. After 6 hours etching etch–pits as large as 10μm would be detected under 20X magnification. An efficiency of $\sim$ 99% was estimated by scanning foils exposed to ions.

Every detected surface structure was further observed under a larger magnification microscope and classified either as material defects or particle's track. If a double etch-pit was detected it was observed at larger (100–200×) magnification. From the etch-pit size, and the bulk etching rate, the incidence angle on each surface are computed. A track was defined as a "candidate" if etch-pit sizes and incidence angles on the front and back surfaces were compatible with that of a single particle. If candidates were found in the first layer of a module, downstream Makrofol foils would be etched in 6 N KOH + 20% Ethyl alcohol at 50°C. and etch–pits' dimensions (surface diameters, area, etch-pit length) measured in order to determine the particle's direction and REL.

An accurate scan under an optical microscope with high magnification (100×) is performed in a square region of about 1 cm^2 around the candidate expected position. If a two-fold coincidence was detected, also the middle layer would be etched and analyzed.

The Detection Threshold for Makrofol

For the HIP to be detected its REL must be greater than the detection threshold of the Makrofol. The detection threshold will vary with the etching conditions. It will also vary with the angle of incidence of HIP on the NTD. The greater the angle of incidence the lower the detection threshold. The lowest threshold is obtained for a HIP impinging normally to the NTD. the curve showing the relating between angle δ_{Max} and the REL is shown in Figure 9, where δ_{Max} is the maximum angle that the HIP of a certain REL can make with the normal to the NTD plan and still be detected.

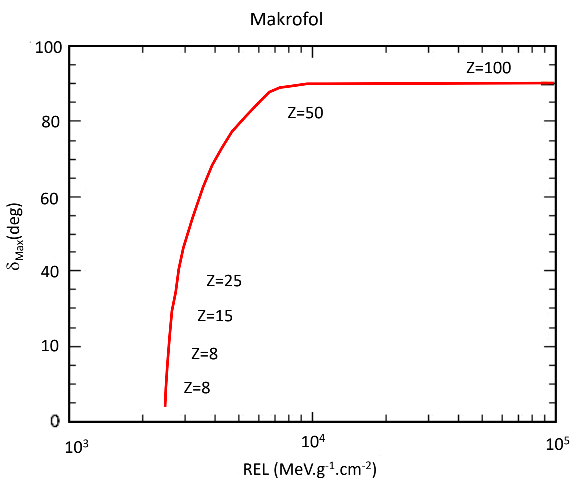

FIG. 9. The maximum angle to the normal of the NTD plane within which the HIP will be detected.

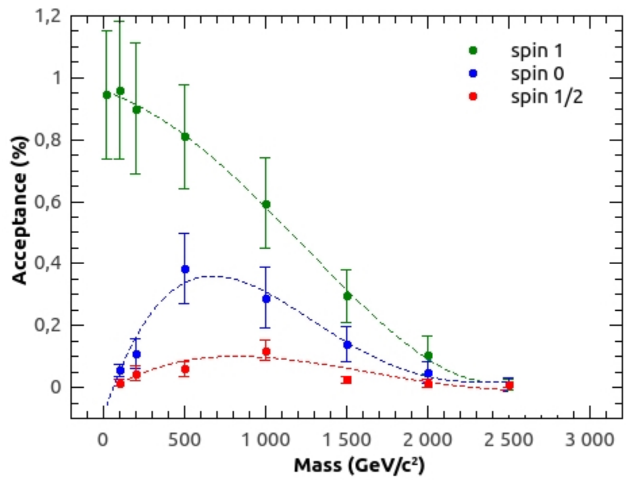

FIG. 10. Acceptance for spin-1, spin-0 and spin-1/2 HECOs with charge 125e.

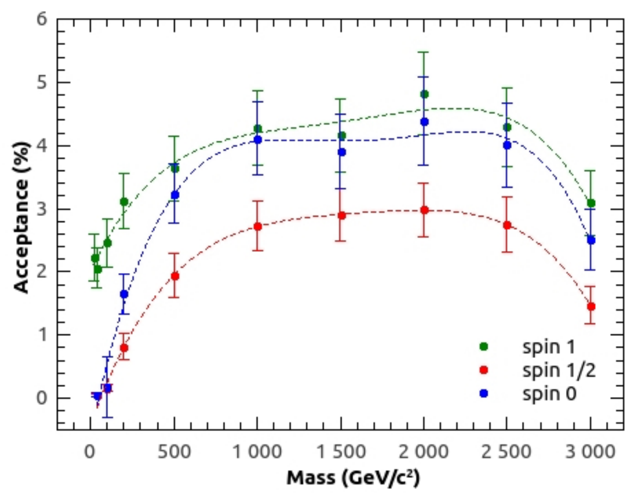

FIG. 11. Acceptance for monopole pair production with magnetic charge $2g_{\text{D}}$.

ACCEPTANCE OF THE RUN-1 MOEDAL DETECTOR

The MoEDAL detector's acceptance is defined to be the fraction of the number of events in which at least one HIP of the DY produced pair was detected in MoEDAL. The acceptance for Drell–Yan production of HECOs and magnetic monopoles is described by an interplay of the geometrical disposition of MoEDAL NTD modules and MMT detectors, energy loss in the detectors, mass of the particle and the spin-dependent kinematics of the interaction products. In the case of the HECOs, MoEDAL NTD provides the only means of detection.

For a given HIP mass and charge, the pair-production model determines the kinematics and the overall trapping acceptance obtained. The uncertainty in the acceptance is dominated by uncertainties in the material description [8–10]. This contribution is estimated by performing simulations with hypothetical material conservatively added and removed from the nominal geometry model.

An example, showing the MoEDAL NTD acceptance curves for spin-1/2, spin-0, spin-1 HECOs with charge 125e is shown in Figure 10. The acceptance curves for spin-1/2 monopoles, found using the NTD and MMT detectors, are shown in Figure 11. The acceptances shown in Figure 10 and Figure 11 refer to the prototype detector deployed for LHC's Run-1.

ANALYSIS RESULTS

The first Makrofol sheet of each of MoEDAL's 135 NTD modules was etched and scanned, as described

TABLE I. Etching Conditions of Makrofol

Etching Mode	Etchant	v_B(μm/hour)
Strong	6N KOH + 20% ethyl alcohol at 65°C	23±0.5
Soft	6N KOH + 20% ethyl alcohol at 50°C	3.4±0.05

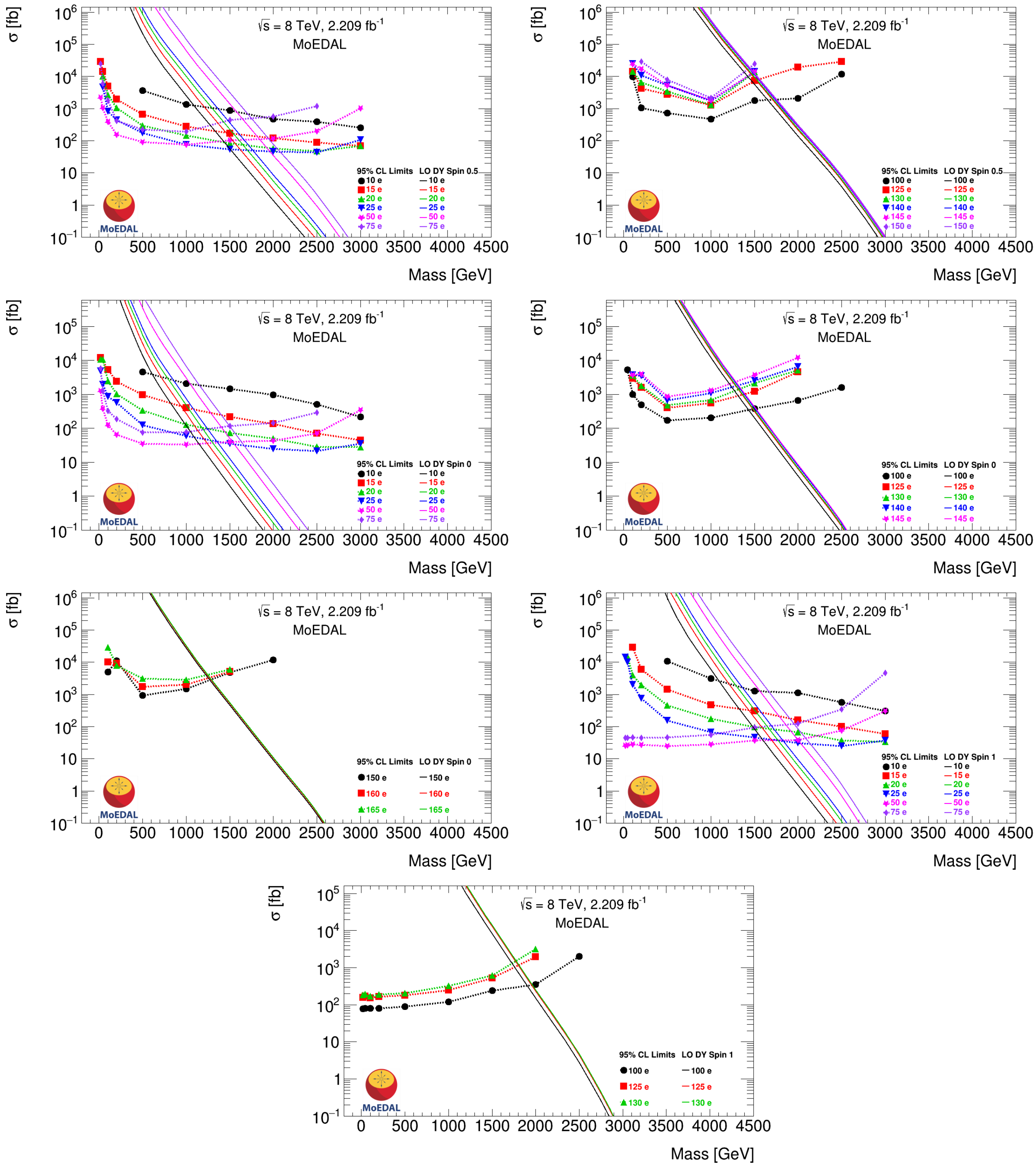

FIG. 12. 95% CL mass limits in a DY production model of spin-0, spin-1/2 and spin-1 HECO pair direct production in LHC *pp* collisions.

above, for evidence of the passage through the sheet of a highly ionizing object such as a HECO or a magnetic

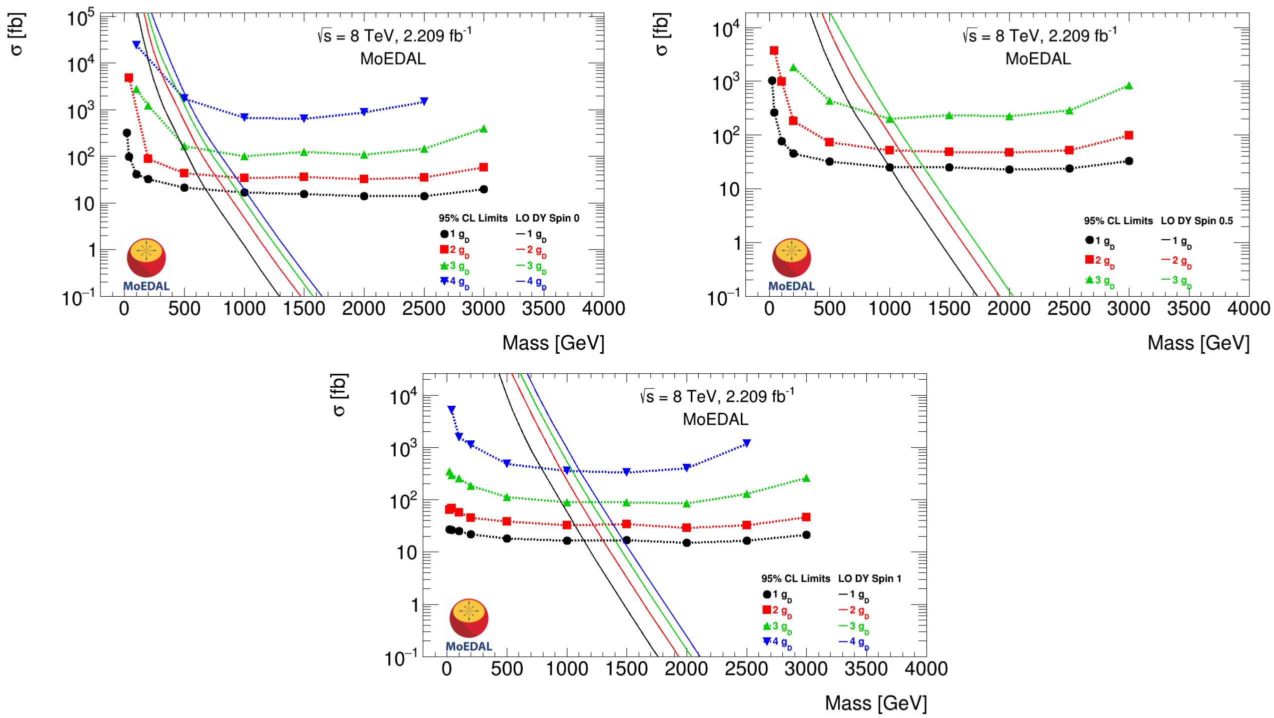

FIG. 13. 95% CL mass limits in a DY production model of spin-0, spin-1/2 and spin-1 monopole pair direct production in LHC pp collisions.

monopole. The total area of plastic analyzed was 7.8 m^2. No candidate events were observed.

The material budget preceding the MoEDAL NTD modules is due to the presence of LHCb's VELO detector. It amounts to between 0.1 and 8.0 radiation lengths X_0 of material with an average of approximately 1.4 X_0 [42]. The dominant contribution to the systematic uncertainties in this analysis arises from the estimate of the material in the GEANT4 geometry description, resulting in a relative uncertainty of $\sim$ 10% for a single charged monopole [8]. This uncertainty increases with electric and magnetic charge.

We calculated the 95% C.L. upper limits to the cross-section using as a measure a Drell–Yan model for HECO and magnetic monopole production assuming a $\beta-$independent monopole coupling and that the monopole can have a spin of $0, 1/2$ and 1. The limit curves obtained are shown in Figure 12. For HECOs the cross section upper limits versus mass are given in Figure 13 for spin $0, 1/2$ and 1. The values of the limits are listed in Table II and Table III, for HECOs and magnetic monopoles, respectively.

CONCLUSIONS

Both MoEDAL's NTD system and aluminium elements of the MoEDAL MMT detector were exposed to 8 TeV LHC collisions during Run-1 of the LHC. At the end of Run-1 both detector systems were examined for the presence of magnetic monopoles and/or HECOs. In the case of the MMT a SQUID-based magnetometer was utilized to search for the presence of trapped magnetic charge; the results were published in [8].

The NTDs were etched and scanned to reveal evidence for the passage of a magnetic monopole or a HECO using semi-automatic and manual optical microscopes.

In the final analysis no candidates for magnetic monopoles were found. Consequently, limits on the DY production of magnetic monopole pair with cross-section in the range of approximately 20 fb to 30 pb were set for magnetic charges up to $5g_{\rm D}$ and mass as high as 1.2 TeV. Additionally, no evidence was found for DY produced HECO pairs. Thus, limits were placed on the DY production of HECO pairs with cross-sections from 20 fb to 30 pb, for electric charges as much as 165e and mass up to 2 TeV. The limits on the DY production of HECOs are the strongest to date at a collider experiment [15].

ACKNOWLEDGMENTS

We thank CERN for the LHC's successful Run-2 operation, as well as the support staff from our institutions without whom MoEDAL could not be operated. We acknowledge the invaluable assistance of particu-

TABLE II. 95% CL mass limits for the HECO search.

	Electric charge/e													
	10	15	20	25	50	75	100	125	130	140	145	150	160	165
Spin	95% CL mass limits [GeV]													
0	640	950	1190	1350	1530	1500	1430	1360	1330	1310	1290	1280	1270	1260
1/2	1090	1450	1650	1770	1840	1750	1650	1520	1470	1480	1490	1450	-	-
1	1100	1440	1670	1840	2000	1960	1900	1800	1780	-	-	-	-	-

TABLE III. 95% CL mass limits for the magnetic monopole search.

	magnetic charge/g_{D}				
	1	2	3	4	5
Spin	95% CL mass limits [GeV]				
0	710	780	740	530	-
1/2	990	1090	1020	-	-
1	1150	1230	1210	1120	950

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* Also at Int. Centre for Theoretical Physics, Trieste, Italy

† Also at National Institute of Chemical Physics & Biophysics, Tallinn, Estonia

‡ Also at Dept. of Physics, Faculty of Science, Beni-Suef University, Egypt

§ Now deceased

¶ Also at Physics Department, University of Regina, Regina, Saskatchewan, Canada

** Corresponding author: jpinfold@ualberta.ca

†† Also at Centre for Astronomy, Astrophysics and Geophysics, Algiers, Algeria

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