REPORT ON THE UPDATED HECO ANALYSIS

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1. **Major Corrections:**

1. More background material
2. Updated MMT Material
3. More material on NTDs eg false positives, scanning details, etc
4. New material on systematic errors in NTDs
5. Bugs found in original calculations (due to hardwired normalization/multiplier + another bug) – giving rise to updated results
6. The Conclusion
Some changes to the introductory Material including a new figure
A small amount of material
more on the MMT detector
plus a new figure
Efficiency and False Positives for NTD detectors

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 the HIP (4) on the NTD. The connection between the threshold and the maximum angle of incidence (δ_{max}) to the normal to the NTD that the HIP can make and still be detected is expressed by the relationship: p = \frac{1}{\tan(\delta_{max})} \cdot \tan(\theta)

where θ is the angle of incidence. The larger 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 relation between δ_{max} and the REL is shown in Figure 13.

As described above, the signal for the passage of a HIP messenger of new physics passing through a MoEDAL NTD stack would be a string of etch pits in the stack where an etch pit pair is due to the ingress and egress of the HIP passing through an NTD sheet. No such signal has ever been seen in this search, or by any other HIP search employing NTDs [2]. Indeed, no candidates, or false positives as they would be classified as candidates, were seen in the 125 stacks examined (corresponding to 7.8 m²), where only the upstream sheet of the NTD stacks were examined.

The absence of false positives using the NTD technique is borne out by the astroparticle physics experiments MACRO [46] and SLIM [47], which deployed a surface area of 1263 m² and 427 m², respectively, and did not observe a single HIP candidate. It should be noted that the NTD technique employed by these experiments are essentially identical to those employed at colliders.

The lack of false positives in the NTD technique at colliders or in astroparticle physics experiments raises the question of the false negatives, or detector efficiency. This can be evaluated using the heavy ion beams that are used to calibrate NTD detectors. In the absence of beam backgrounds, the detection, or scanning, efficiency for the etch pits due to heavy-ion HIPs with ionizing power above the NTD threshold was measured to be in excess of 99%.

In order to estimate the effect of beam background on the detection efficiency of NTDs for HIPs we utilized NTD calibration stacks exposed to a relativistic lead-ion beam as described above. The stacks were comprised of sheets of Makrofol NTDs exposed to the beam backgrounds in the VELO cavern at the LHC for a year of data taking interleaved with unexposed Makrofol NTD sheets. Plastic from the same production batch was used in calibration and standard data taking.

The NTDs sheets comprising the calibration stacks were then etched in the same way as the standard NTD stacks deployed for data taking during Run-1. The individual sheets were then scanned using the same manually controlled optical scanning microscope technology employed to examine all MoEDAL NTD stacks. The relativistic lead-ion calibration beam particles penetrate the whole stack allowing the signal etch pits seen in the plastic sheet that was not previously exposed to the LHC beam - where the signal can clearly be observed with a 100% efficiency - to serve as a map. This map can be used to assess the efficiency of the scan of the adjacent NTD sheet that had been exposed to LHC beam backgrounds.

These studies indicate that the efficiency for detection above threshold was in excess of 99%. This number was determined by multiple scanning of the same sheets by different users.
The acceptance is better explained
More Material on NTDS (3)

Extra material on the etching and calibration process.
FIG. 10. Reduced etch-rate versus REL for Makrofol exposed to relativistic Lead and Xenon ion beams: (top) detectors etched in soft conditions; (bottom) detectors etched in strong conditions. The upper and lower curves are drawn through the $\pm 1\sigma$ value of the error on each $p$ value, where the error bars represent a convolution of the statistical and systematic error on each point.

FIG. 8. Reduced etch-rate versus REL for Makrofol exposed to relativistic Lead and Xenon ion beams: (top) detectors etched in soft conditions; (bottom) detectors etched in strong conditions.
8.0 radiation lengths ($X_0$) in thickness and on average around 1.4 $X_0$ [42] thick. The main contribution to the systematic uncertainty in this analysis arises from the estimate of the material in the GEANT4 geometry description. The uncertainty in the material map is modelled by two geometries which represent an excess and a deficit of material, using conservative estimates of uncertainties on material thicknesses and densities, compared to the best assessment of the material budget that is compatible with direct measurement and existing drawings.

This systematic uncertainty in the material map gives rise to uncertainties in the DY acceptances. For singly charged monopoles ($|g| = g_D$) the resulting relative uncertainty is of the order of 10% [8]. This uncertainty increases with electric and magnetic charge. For a doubly charged monopoles ($|g| = 2g_D$) it is of the order of 10 - 20% for intermediate masses, around 1 TeV.

Other sources of systematic error are an uncertainty due to a conservative estimate of 1 cm uncertainty in the trapping detector position. Simulations show this error lies in the range 1-17% [8]. Another source of systematics is the uncertainty in $dE/dx$ as a function of $\beta$, resulting in a 1-10% relative uncertainty in the acceptance [8].

In the case of monopoles and HECOS a systematic error on the variable $p$, due to the NTD etching and calibration process is given in Figure [10] (bottom). This error on $p$ can give rise to an error on the threshold value for detection of the plastic as well as an error on the variation of efficiency with angle of the NTD. However, these uncertainties are negligible compared to the error on the material map discussed above. All of the above sources of systematic error were added in quadrature and included in the final limit calculation.

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 [14] for HECOs. For monopoles the cross section upper limits versus mass are given in Figure [15] for spin 0, 1/2 and 1. The values of the 95% C.L. mass limits are listed in Table [1] and Table [III] for HECOs and magnetic monopoles, respectively.

**CONCLUSIONS**

Both MoEDAL’s prototype NTD system and aluminium elements of the MoEDAL MMT detector, were exposed to 8 TeV LHC collisions during LHC’s Run-1. At the end of Run-1 both detector systems were examined for the presence of magnetic monopoles and/or HECOs. 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 case of the MMT a SQUID-based magnetometer was
FIG. 8. Microphotographs of relativistic Pb$^{82+}$ tracks and of nuclear fragments ($Z<82$) in two consecutive foils of Makrofol. Each image frame measures 0.64 mm x 0.80 mm. Etch pits are from the same ions crossing the detector foils: (left) Makrofol foil etched in “soft conditions”; (right) Makrofol foil etched in “strong conditions”. Note that the microphotographs also show two clearly differentiated fragmentation products of Pb: La ($Z = 57$); and, Pm ($Z=61$).

FIG. 6. Microphotographs of relativistic Pb$^{82+}$ tracks and of nuclear fragments ($Z<82$) in two consecutive foils of Makrofol. Each image frame measures 0.64 mm x 0.80 mm. Etch pits are from the same ions crossing the detector foils: (left) Makrofol foil etched in “soft conditions”; (right) Makrofol foil etched in “strong conditions”.

MORE MATERIAL ON NTDS (3)

FIRST VERSION
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 ($E_{CM}$) of 8 TeV by the MoEDAL detector during LHC’s Run-1. The data were collected using MoEDAL’s prototype Nuclear Track Detector array and the Trapping Detector array. The results are interpreted in terms of Drell-Yan pair production of stable HECO and monopole pairs with three spin hypotheses (0, 1/2 and 1). The search provides constraints on the direct production of magnetic monopoles carrying one to four Dirac magnetic charges ($4q_D$) and with mass limits ranging from 580 GeV to 1 TeV. Additionally, mass limits are placed on HECOs with charge in the range 10e to 180e, where $e$ is the charge of an electron, for masses between 30 GeV and 1 TeV.

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

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<th>Electric charge (e)</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>130</th>
<th>140</th>
<th>145</th>
<th>150</th>
<th>160</th>
<th>170</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin: 0</td>
<td>30</td>
<td>110</td>
<td>220</td>
<td>270</td>
<td>560</td>
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<td>500</td>
<td>470</td>
<td>470</td>
<td>450</td>
<td>400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1/2</td>
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<td>270</td>
<td>420</td>
<td>550</td>
<td>770</td>
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<td>550</td>
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<td>1020</td>
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<td>940</td>
<td>920</td>
<td>910</td>
<td>890</td>
<td>870</td>
<td>850</td>
<td>840</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Magnetic charge ($q_D$)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
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<td>Spin: 0</td>
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<td>740</td>
<td>710</td>
<td>520</td>
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<tr>
<td>1/2</td>
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<tr>
<td>1</td>
<td>1030</td>
<td>1190</td>
<td>1190</td>
<td>1110</td>
</tr>
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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 monopole 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 ($5q_D$) 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.
The conclusion has changed in detail.