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The CERN@school Programme: A Guide to the MoEDAL Experiment

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Abstract. The MoEDAL experiment (Monopoles and Exotics Detector at the LHC) is the seventh major experiment at CERN's Large Hadron Collider. It is designed to probe the LHC's particle collisions for signs of Paul Dirac's hypothesised magnetic monopole, as well as other highly ionising signs of new physics that the other LHC experiments cannot easily look for. The Institute for Research in Schools (IRIS) is a full member of the MoEDAL Collaboration, and students associated with IRIS have access data from the MoEDAL experiment and are able to contribute to the MoEDAL Collaboration's research programme. This document aims to provide a brief guide to the history, theory, and physics of the MoEDAL experiment so that IRIS students and teachers can take full advantage of these opportunities.

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1. Introduction

CERN's Large Hadron Collider [1], know as the LHC for short, is one of the crowning achievements of humankind's quest for knowledge of our Universe. Arguably one of the largest, most complicated machines ever built, it smashes together particles at huge energies in a twenty-seven-kilometre long, colder-than-space underground ring to probe how matter works at the most fundamental level we can imagine. It has successfully found, at long last, the particle that we believe gives massive particles mass – the celebrated Higgs boson [2, 3] for which Peter Higgs and François Englert won the Nobel Prize for Physics in 2013.

The trouble is, it hasn't found anything else – yet!

Figure 1: An aerial view of Geneva showing the location of CERN's Large Hadron Collider (LHC). Image credit: J.-L. Caron/CERN 1986-2016; please contact them regarding licensing/re-use of this image.

Well, that's not fair. The four largest experiments located at the four Interaction Points (IPs) on the LHC's ring – ALICE [4], ATLAS [5], CMS [6], and LHCb [7] – have made many discoveries that have furthered our understanding of physics of the very, very small. All of these, however, pretty much fit into our current best understanding of how matter and forces work – known as the Standard Model of particle physics – of which the Higgs boson was the missing piece. In that sense, the LHC has been a huge success, and the thousands of physicists and engineers who made it work – and the public who funded it – should be immensely proud of its achievements.

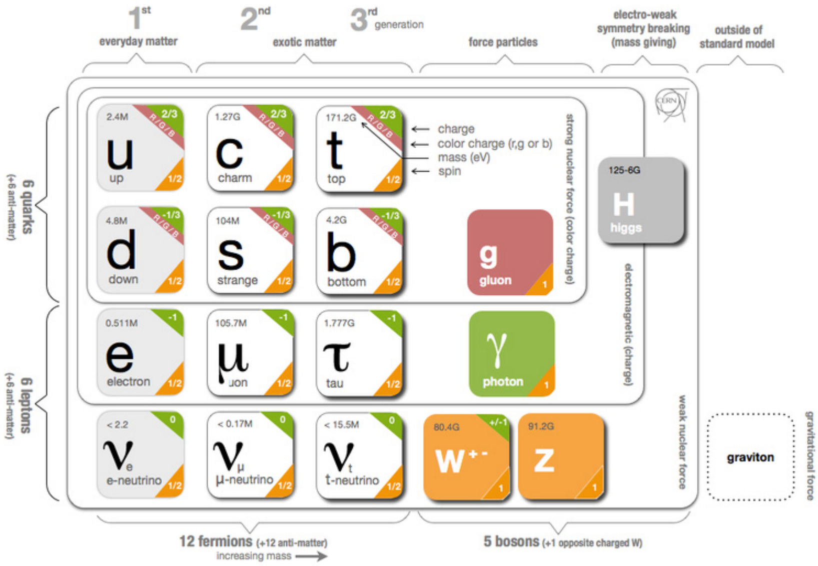

Figure 2: The Standard Model of particle physics, now completed with the Higgs boson. Image credit: D. Galbraith/C. Burgard/CERN 2012; please contact them regarding licensing/re-use of this image.

What we'd like to do, however, is go beyond the Standard Model and answer questions like:

- How did particles interact at the very beginning of the Universe?
- Can we unite all of the forces into one Grand Unified Theory?
- What is Dark Matter, the "missing fifth" of the Universe?
- Why is there more matter than antimatter?
- How can we describe gravity at very small scales?
- How many dimensions does our Universe have?
- Why do neutrinos have mass?

We can't answer these questions with the Standard Model. More research is required, and as the LHC [1] collects more data at the record-breaking 13 tera-electron volts (TeV), ALICE [4], ATLAS [5], CMS [6], and LHCb [7] will do their best to answer them. There is, however, another fundamental question about our Universe that pre-dates even the Standard Model.

1.1. A lack of symmetry: where's the magnetic charge?

When James Clerk-Maxwell unified the electric and magnetic forces into one "electromagnetic" force in 1865 [8], his famous four equations (shown in Figure 3) lacked a certain symmetry.

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e \tag{4}$$

Figure 3: Maxwell's equations of electromagnetism [8] with the electric charge and current density terms highlighted (shaded boxes). Note that these are expressed in Gaussian units (not SI) for simplicity.

Don't worry about exactly what these all mean for the moment. The terms in the shaded boxes are what we're interested in: these represent electric charge (static and moving). Electric charge is a property of matter that experiences interactions via the electromagnetic force. Electric charge can be positive or negative; like charges repel each other while opposite charges attract. The question that physicists have asked ever since – starting with Marie Skłodowska Curie's husband Pierre [9] – is is why there is no equivalent term for magnetic charge and current, which would make the equations look like those shown in Figure 4.

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e \tag{5}$$

$$\nabla \cdot \mathbf{B} = 4\pi\rho_m \tag{6}$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_m \tag{7}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e \tag{8}$$

Figure 4: Maxwell's equations of electromagnetism with additional terms representing magnetic charge and current density, as shown on the cover of the MoEDAL Technical Design Report [10]. Note that these are expressed in Gaussian units (not SI) for simplicity.

Much nicer, no? In practical terms, what these different equations would mean that some matter could have "magnetic charge". Magnetic charges would exert a force – via a magnetic field – on other matter with magnetic charge in just the same way as matter with electric charge. The problem is that we never have never seen isolated magnetic charge. The magnets we see always have a North and a South pole (the equivalent of positive and negative charge) – and so are dipoles. **Magnetic monopoles** – matter with just a North or a South pole (see Figure 5) – have not yet been seen in an experiment.

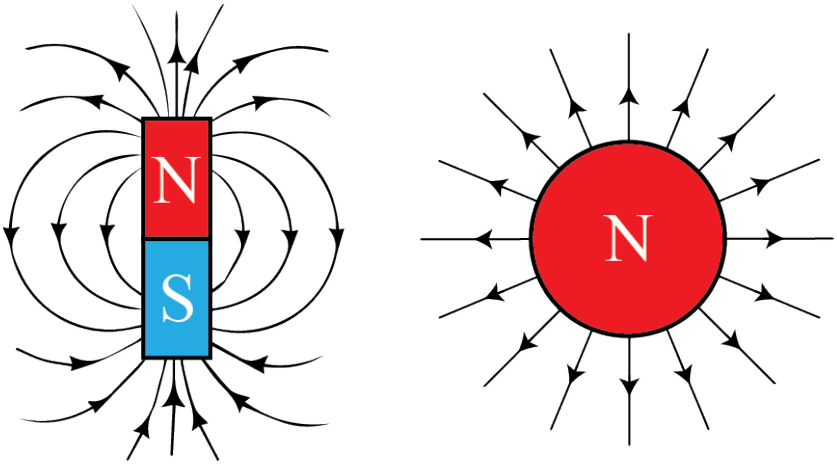

Figure 5: A magnetic dipole with North and South poles (left); a magnetic monopole, North pole only (right). Image credit: Institute for Research in Schools.

1.2. The MoEDAL experiment

The Monopole and Exotics Detector at the LHC (MoEDAL) [10] is the latest and greatest in a long line of experiments which aims to finally find evidence for the existence of magnetic monopoles. It is designed to hunt for monopoles created in particle collisions at the LHC using methods tailored to the strange properties of monopoles and other highly-ionising particles. As such it complements the searches for Beyond Standard Model (BSM) physics as performed by the other LHC experiments, providing another exciting way we can try to answer fundamental questions about our Universe.

As we'll see, one of these special techniques requires human input. Many experiments can automate their searches for new physics using computer programs because they use electronic readouts and are, generally speaking, looking for well-understood particles. The MoEDAL detector systems – and the particles they are looking for – are very different, and so require the human brain's enormous capability for image processing, decision-making, and all-round ability to spot things that are "odd". Which is where you come in – MoEDAL needs your help!

1.3. Overview of this guide

Section 2 discusses the theory behind magnetic monopoles, and presents a number of ideas that motivate the search for them. The searches that have been carried out to-date are presented in Section 3. The MoEDAL experiment is described in more detail in Section 4, and finally the ways the reader may get involved with MoEDAL is described in Section 5.

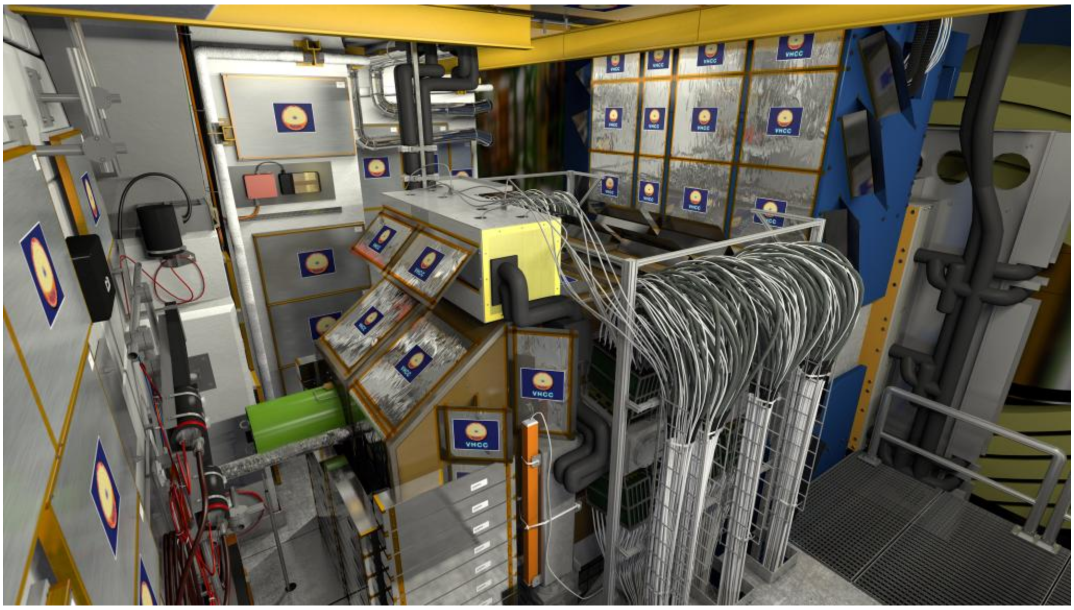

Figure 6: The MoEDAL experiment at CERN. Image credit: The MoEDAL Collaboration/CERN; please contact them regarding licensing/re-use of this image.

2. The physics of magnetic monopoles

To date there has been no solid, reproducible experimental evidence that magnetic monopoles exist. For now, magnetic charge remains an entirely theoretical concept that would, amongst other things, neaten up Maxwell's equations of electrodynamics. So why would we – *why should we* – spend time and effort looking for them? There are, in fact, some very good reasons to believe they exist and that we just haven't found them yet. One theorist has even said that they are "*one of the safest bets one can make about physics not yet seen*" [11]. In this section we look at some of these reasons – so you can decide for yourself!

2.1. Dirac's magnetic monopole

Paul Adrien Maurice Dirac (Figure 7) was a theoretical theorist who played an important part in the development of quantum mechanics. He was one of the first theoreticians to combine quantum mechanics with special relativity with his eponymous equation [12], which allowed so-called "negative energy" solutions [13]. At first Dirac interpreted these solutions, which would require the particle corresponding to the negatively-charged electron to have a positive charge, as protons. He noted in a subsequent paper [14] that, actually, the negative energy particles would need to have the same mass as the electron – the positively-charged anti-electron. He had predicted antimatter. This prediction was confirmed with Anderson's discovery of the positron [15] and the rest, as they say, is history.

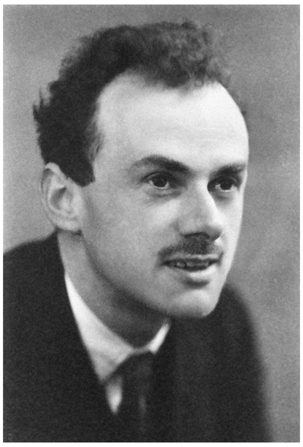

Figure 7: Paul Adrien Maurice Dirac (1902-1984) predicted the existence of antimatter [13]. Could he have been right about magnetic monopoles too? [14]. Image credit: nobelprize.org (public domain); please refer to their website regarding re-use of this image.

Funnily enough, in the same paper Dirac had made another prediction. (In fact, this prediction was the main point of the paper!) In trying to explain why there was a smallest, discrete value of the electric charge (i.e. why charge is quantised), he postulated the existence of isolated magnetic charge that would show a "*symmetry between electricity and magnetism quite foreign to current views*". He had predicted the magnetic monopole.

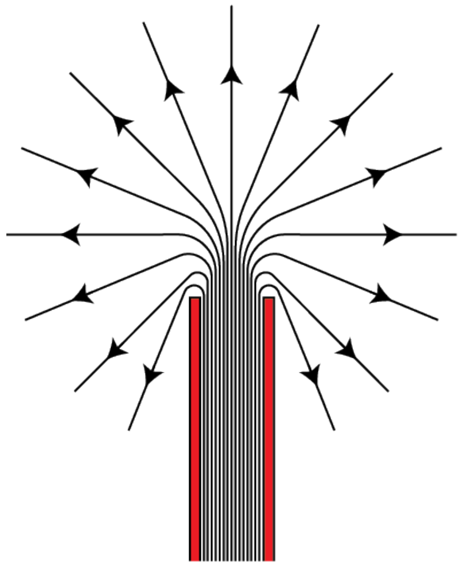

Figure 8: A schematic representation of Dirac's magnetic monopole. The monopole is imagined to be the end point of a semi-infinitely long, infinitesimally thin solenoid known as a "Dirac string", here shown from the side (red lines). The magnetic field lines (black arrows) are shown emanating from the point at the end of the string (imagine the red lines are infinitely close together). If such Dirac monopoles exist, it is the requirement that the string is undetectable that means electric charge must be quantised. Image credit: Institute for Research in Schools.

Dirac's monopole was bit of a funny object. Like a particle with electric charge, the monopole would need to exude magnetic field field lines spherically from its centre. Other magnetic charges placed in this field would experience a force exactly analogous to the Coulomb force that pushes like charges apart and pulls opposite charges together. To create such a magnetic field configuration, Dirac imagined a semi-infinitely long, infinitesimally thin solenoid (i.e. a very, very tightly-wound coil with a flowing electric current). The end of this "Dirac string" – as shown schematically in Figure 8 2 – represents the monopole.

While it is easy to imagine such a string, one might not necessarily want to get tangled up in it. Dirac showed that if such a string/monopole configuration did exist in Nature, the only way that the mathematics could work out such that the strings were undetectable by experiments was if electric charge was quantised. There is an excellent explanation of the quantum theory behind this assertion using the double slit experiment (as well as many other aspects of magnetic monopoles) in [16]. As the quantisation of charge is observed experimentally, Dirac reasoned that magnetic monopoles (and their associated strings) must exist. Unfortunately, unlike the positron, monopoles were not found a few years later.

2.2. Grand Unified Theories

Theorists, in the meantime, had been developing Quantum Field Theory (QFT) as a way of describing matter and forces not in terms of particles or waves but mathematical constructs called fields. (If you want to get your head around the wave-particle duality, study physics at university and take a QFT course. Your hands will thank you from all of the "hand-waving" you won't have to do.) The 1960s saw the electromagnetic and weak forces – two of the fundamental forces of Nature – united into a single electroweak force, winning Glashow, Salam and Weinberg the 1979 Nobel Prize for Physics. The 1970s then saw a great deal of interest in literally going one better – uniting the electromagnetic, weak, and strong forces into one force. Such a theory is known as a Grand Unified Theory (GUT). Figure 9 shows roughly where this "Grand Unification" might occur in terms of energy (around 10^{13} TeV) and time (about 10^{-36} seconds after the Big Bang).

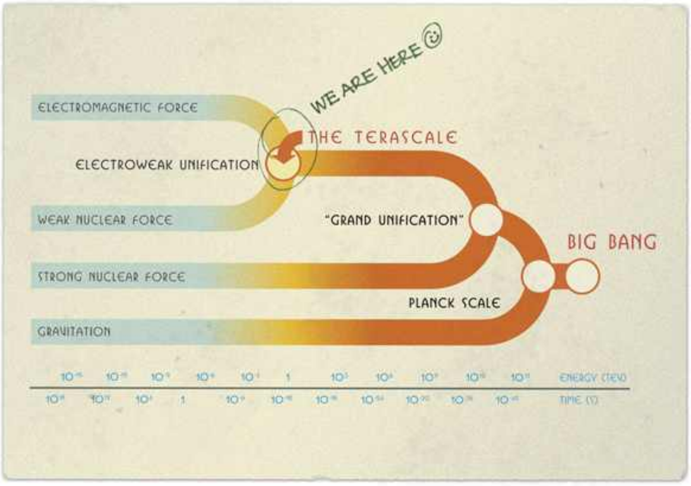

Figure 9: The unification of the four fundamental forces of Nature, as shown in this "*Postcard from the Terascale*". Image credit: Symmetry Magazine/Sandbox Illustrations; please contact them regarding licensing/re-use of this image.

What does this have to do with magnetic monopoles? Well, in the course of trying to get the mathematics to work, two theorists independently found that an inevitable consequence of bringing the three forces together was the appearance of terms in the equations that represented particles (well, fields) with magnetic charge [17, 18]. You couldn't unite the strong force with the electroweak force without magnetic monopoles†. Of course, no Grand Unified Theory has been experimentally verified, but if we believe in the ultimate unification of the fundamental forces – which, let's be honest, would be rather nice – it turns out that we *need* magnetic monopoles.

† As it happens, the monopoles appear when you squeeze the GUT to quantise the electromagnetic field into particles. So, as noted in many reviews of the magnetic monopole literature, Dirac's argument is reversed: the quantisation of the electromagnetic field necessitates the existence of magnetic monopoles.

2.3. Monopoles in the Standard Model

There is, however, one slight problem with GUT-scale magnetic monopoles. While one cannot predict the mass of the Dirac monopole, GUT monopole masses (which can be calculated) tend to be billions and billions times the energies reachable by the LHC, or indeed any physical process occurring more than a fraction of a second after the Big Bang. While we can look for "relic" monopoles in cosmic rays that reach the Earth –and [19] provides an excellent summary of the searches conducted so far – we would need something between the Dirac monopole and the GUT monopole in order to have some hope of creating magnetic monopoles in accelerators with all of the benefits that the controlled conditions of the laboratory bring.

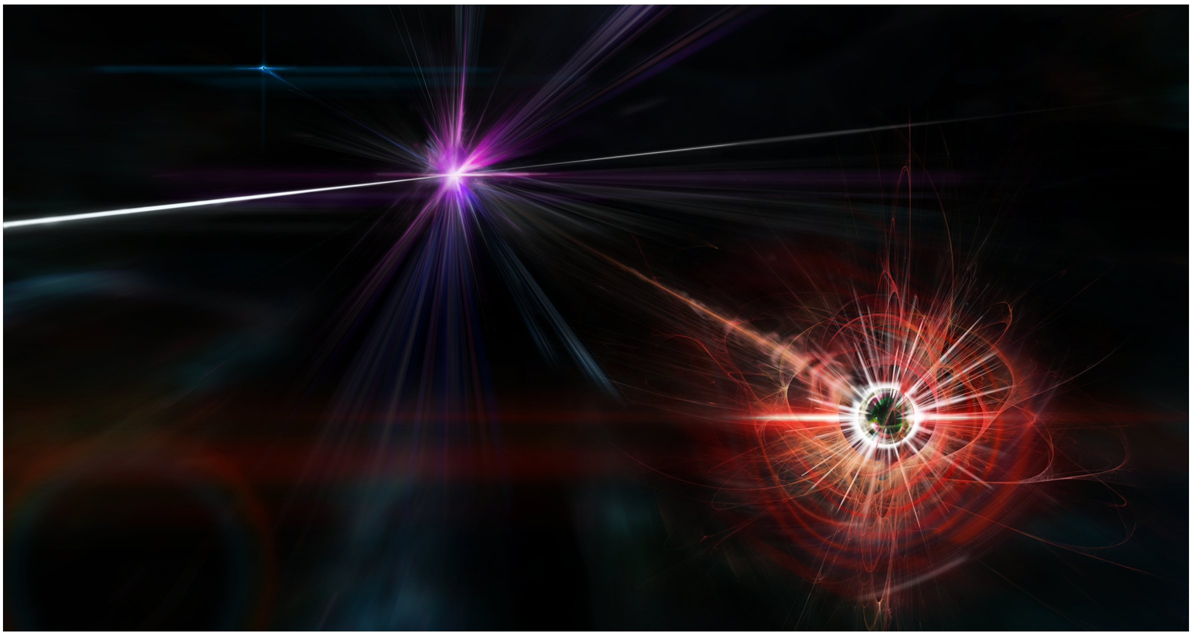

Figure 10: An artist's impression of magnetic monopole production in a proton-proton collision at the Large Hadron Collider (LHC). Image credit: The MoEDAL Collaboration/H. Valja 2015; please contact them regarding licensing/re-use of this image.

Fortunately, such a monopole has been proposed. An "**electroweak monopole**" (which, incidentally, has twice the magnetic charge of Dirac's monopole) can be made to appear in the Standard Model of particle physics by adding some extra terms to the field equations [20, 21]. In fact, the theorists behind the electroweak monopole insist that the Standard Model is incomplete without the electroweak monopole – and given that we know the Standard Model is already broken by the fact neutrinos have mass, we know that we can't just leave it at the discovery of the Higgs boson. Semantics aside, what's important is that some recent papers [22, 23] have suggested that the electroweak monopole would have a mass of below 7 TeV, putting it within tantalising reach of the Large Hadron Collider and the MoEDAL experiment. Figure 10 shows an artist's impression of monopole-antimonopole production in LHC proton-proton collisions. The question is – can Nature produce something as beautiful?

3. The search for magnetic monopoles

At the time of writing, no experimental evidence for the existence of magnetic monopoles has been recorded in the scientific literature. While MoEDAL hopes to change all of that with results from the LHC's 13TeV proton-proton collisions, for now we can only look at the results from all of the experiments that have tried so far. These searches broadly fall into two categories: looking for human-made monopoles from particle colliders ("farmed") and looking for monopoles produced by Nature ("free-range") that would be found in cosmic rays that hit the Earth.

<table>
<tr><th></th><th>Collider-made</th><th>Cosmic rays</th><th>Trapped monopoles</th></tr>
<tr><td rowspan="2">Advantages</td><td rowspan="2">We have greater control of experimental conditions;
We know where and when to look for the monopoles.</td><td colspan="2">We could find GUT-scale monopoles.</td></tr>
<tr><td></td><td>We can recycle old collider experiment equipment!</td></tr>
<tr><td rowspan="2">Disadvantages</td><td rowspan="2">We can only find monopoles with a mass less than half of the collider's centre-of mass energy.</td><td colspan="2">We rely on Nature to throw a monopole our way.</td></tr>
<tr><td>We need large detector arrays.</td><td>We need to look through a lot of material.</td></tr>
</table>

Table 1: The advantages and disadvantages of the different search strategies employed to find experimental evidence for magnetic monopoles.

The advantage of the former approach is that we would know where and (roughly) when the monopole-antimonopole pair was produced; we have far more knowledge of the experimental conditions. We are, however, limited by the centre-of-mass energy of the collider in question. Cosmic ray-based monopole searches rely on catching a "free-range" monopole by chance – and the odds aren't great – but are capable of finding the sort of monopole required by GUTs which are far beyond what colliders could ever hope to produce.

An excellent summary all the results to-date is presented in Section 5 of L. Patrizii and M. Spurio's review paper, "*Status of Searches for Magnetic Monopoles*" [19]. You can read the arXiv preprint of this paper here[†] for free. The paper also contains sections on monopole theory, energy losses, experimental methods and what the future holds for monopole searches (including a shout-out to MoEDAL, of course!) – so it's well worth a read – but some very brief summaries are provided below for convenience.

† See http://arxiv.org/abs/1510.07125

3.1. Collider-based searches

See Section 5.1 of [19] for further information and full references.

Magnetic monopoles have been looked for whenever a particle collider has opened a new energy frontier. For electron-positron collisions, the latest results have come from experiments using the Large Electron-Positron (LEP) collider (for which the LHC's tunnel was originally constructed). OPAL (see Figure 11) and MODAL (a forerunner of MoEDAL) experiments used both the active detector systems and Nuclear Track Detector (NTD) arrays to spot monopole-antimonopole pairs. NTDs around beam interaction points were also used at the TRISTAN ring at KEK (Japan), PETRA at DESY (Germany), and PEP at SLAC (US). Likewise, the best proton-antiproton results have come from Fermilab's D0, CDF, and FNAL E710 experiments using similar techniques.

Figure 11: The Omni-Purpose Apparatus at LEP (OPAL) detector at Interaction Point 6 (IP6), which has set some of the most stringent limits on monopole production for electron-positron colliders. Image credit: CERN/Wikimedia Commons; please refer to their terms of use regarding licensing/re-use of this image.

The best proton-proton results are from the LHC's A Toroidal LHC ApparatuS (ATLAS) and Compact Muon Solenoid experiment (CMS) detectors at 8 TeV, though these are based on active (electronic) detectors. MoEDAL will ultimately produce the best NTD-based searches for magnetic monopoles – and you could part of this with Institute for Research in Schools (IRIS)!

3.2. Cosmic ray-based searches

See Sections 5.2 and 5.3 of [19] for further information and full references.

Searches for monopoles in cosmic rays typically need to take place in underground laboratories, where backgrounds from cosmic muons or background radiation can be minimised. The best results so far come from the Monopole, Astrophysics and Cosmic Ray (MACRO) observatory at the Laboratori Nazionali del Gran Sasso, Italy (Figure 12). Using a combination of liquid scintillation detectors, streamer tubes, and Nuclear Track Detectors (NTDs) – the largest ever deployed – MACRO saw only ever saw a "dummy" monopole event (used to test the detection systems). It completed its experimental run in 2001.

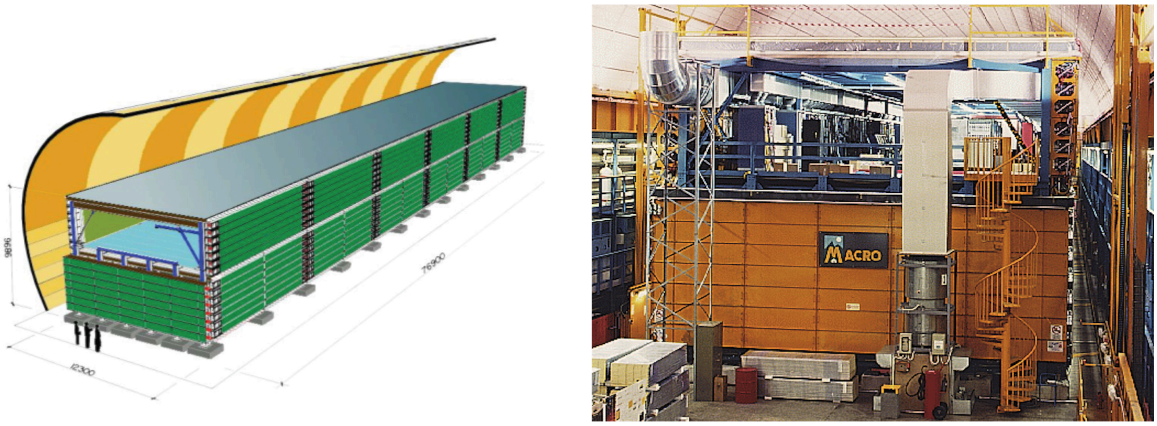

Figure 12: The MACRO (Monopole, Astrophysics and Cosmic Ray) observatory at the Laboratori Nazionali del Gran Sasso, Italy. Left – artist's impression; right – the detector itself. Image credit: The MACRO Collaboration; please contact them regarding licensing/re-use of this image.

If cosmic ray backgrounds can be accounted for, other types of searches are possible. The Search for LIght magnetic Monopoles (SLIM) experiment (Figure 13) used NTDs at an altitude of 5.2km exposed for just over four years. Searches for relativistic monopoles have been conducted with neutrino telescopes like AMANDA, ANTARES, and IceCube (See Section 5.2.2 of [19] for more information). These rely on the huge showers of Cerenkov light that monopoles would produce in the Antarctic ice, but due to the cosmic backgrounds can only look for candidates have come up all the way through the Earth. Again, these have seen nothing and the best result remains that of the MACRO experiment.

3.3. Trapped monopoles

See Sections 5.1 and 5.4 of [19] for further information and full references.

The third category of search takes a slightly different approach. Rather than record the tracks left by a magnetic monopole, one can try looking for monopoles in sample of material that might

Figure 13: The Chacaltaya Astrophysical Observatory, home of the SLIM (Search for LIght magnetic Monopoles) experiment [24, 25] which looked for magnetic monopoles in cosmic rays at an altitude of 5,230m above sea level. Image credit: Wikimedia Commons; please refer to their terms of use them regarding licensing/re-use of this image.

slow down a monopole enough to stop it and trap it. The trick is picking the right material, but the technique can be applied to both collider-produced and cosmic ray monopoles. For example, the H1 experiment at DESY, Germany cut up 60cm of its aluminium beam pipe into pieces and scanned them with a Superconducting QUantum Interference Device (SQUID) to look for magnetic monopoles produced in the electron-proton collisions of HERA (see Figure 14). Likewise, work has been carried out with material from the D0 and CDF-based Tevatron experiments (i.e. proton-antiproton collisions). Cosmic (i.e. GUT-scale) monopoles have been looked for in terrestrial, lunar and meteoric material using similar methods.

MoEDAL continues this tradition with its Magnetic Monopole Trapper (MMT) subdetector (Section 4.2), which consists of hundreds of kilograms of aluminium bars placed within the LHCb cavern. These can then be removed and replaced during the LHC shutdowns to allow SQUID scans of the bars to be made before the LHC finishes running and the ATLAS and CMS detectors are decommissioned.

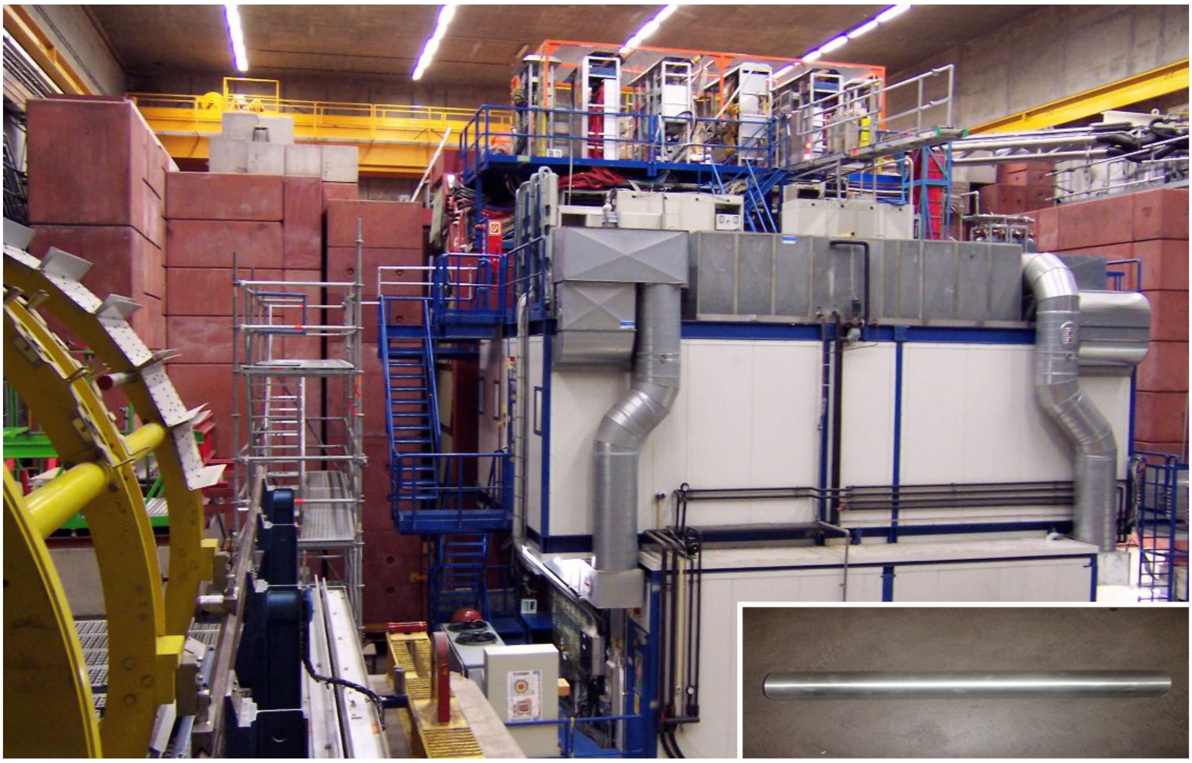

Figure 14: The H1 detector at DESY, Germany. Inset (bottom-right): a 60cm section of the H1 beam pipe used between 1994 and 1997 in a trapped monopole search. Image credit: G. Brandt/Wikimedia Commons; please refer to their terms of use regarding licensing/re-use of this image.

4. The MoEDAL experiment at CERN

In December 2009, the CERN Research Board approved the LHC's seventh experiment – the Monopole and Exotics Detector at the LHC, also known as MoEDAL [10]. Housed in the same underground cavern as the LHCb [7] experiment at Interaction Point 8 (see Figure 15), MoEDAL continues the collider-based search for magnetic monopoles at today's particle physics energy frontier: the proton-proton collisions of the LHC. Like all LHC experiments, the scientific work – installing and running the detectors, processing the data, and publishing the results – is done by the MoEDAL Collaboration. IRIS is a member of the MoEDAL Collaboration, and so – by being a member of IRIS – you are too!

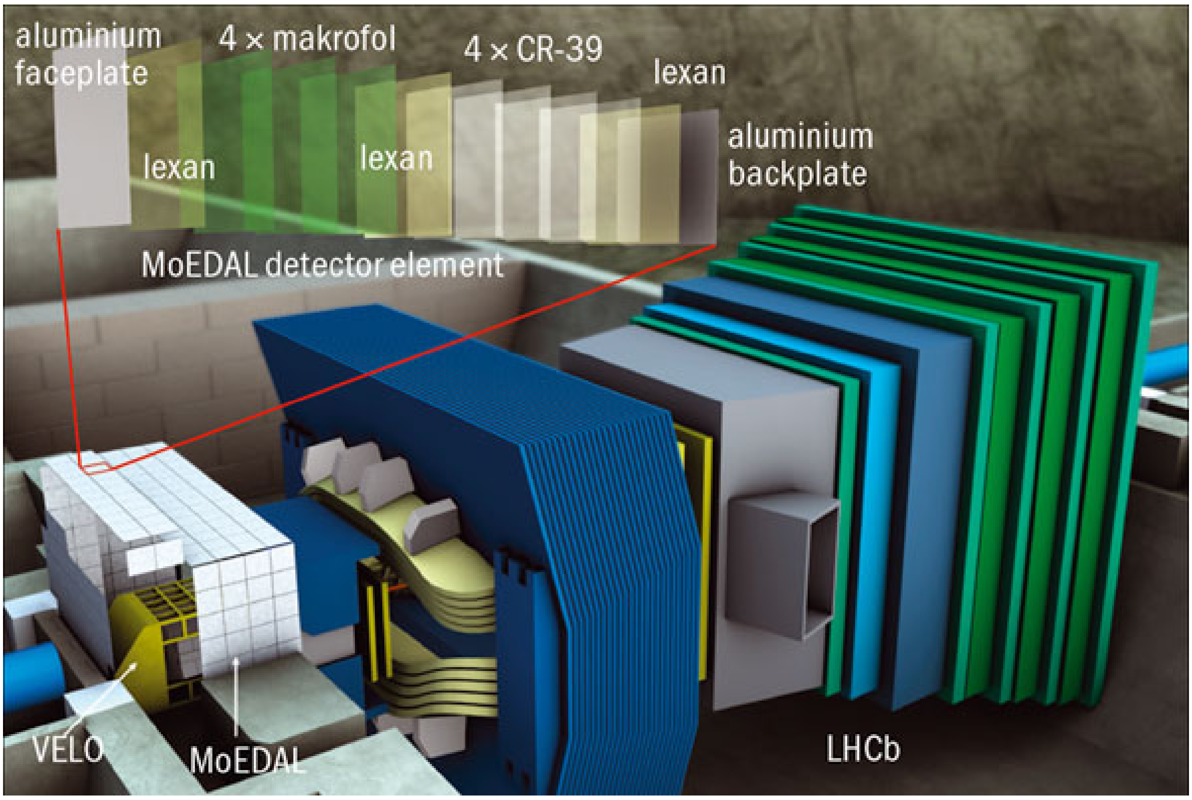

Figure 15: The MoEDAL experiment in the LHCb cavern, with the LHCb detector (and VeLo subdetector) shown for context. The structure of a MoEDAL Nuclear Track Detector (NTD) element is shown in the exploded inset image. Image credit: The MoEDAL Collaboration; please contact them regarding licensing/re-use of this image.

The first test detector elements of the MoEDAL experiments were installed in 2009, just before the LHC was restarted following its 2008 malfunction. The first full stack of Nuclear Track Detectors (NTDs – see below) were put in place in January 2011, and officially began taking data on the 3rd of June 2015. Since the publication of the MoEDAL Technical Design Report (TDR) in 2009 [10], however, the MoEDAL experiment has grown and evolved to incorporate additional subdetector systems to improve the chances of discovering a magnetic monopole (or sign of physics beyond the Standard Model). Let's take a look at these now.

4.1. The Nuclear Track Detectors

The MoEDAL design concept was initially based only on the use of devices known as Nuclear Track Detectors (NTDs), following in the footsteps of the last monopole searches carried out in CERN's 27km underground tunnel [26]. NTDs are essentially sheets of material that, when hit with a massive, highly-ionizing particle (HIP), get damaged in such a way that we can analyse the damage and infer properties of whatever caused it. For example, in the CR-39 ® plastic used by MoEDAL, Highly Ionising Particles (HIPs) break bonds in the plastic's hydrocarbons along the path of the HIP. Careful etching with sodium hydroxide (NaOH) forms conical pits in the surface of the plastic along these paths, and by analysing the size, shape and angle of the cones we can learn more about the particle that caused them. MoEDAL uses four types of NTD material: Lexan, Makrofol, and CR-39 ®, each of which have different sensitivities to the HIP's charge and momentum. These can be seen in the exploded inset image in Figure 15 (schematic) and the top-left of Figure 16 (actual sheets). Recently, additional sheets of Makrofol have been added within the LHCb experiment itself in the form of the Very High Charge Catcher (VHCC) in order to increase the chances of spotting a monopole.

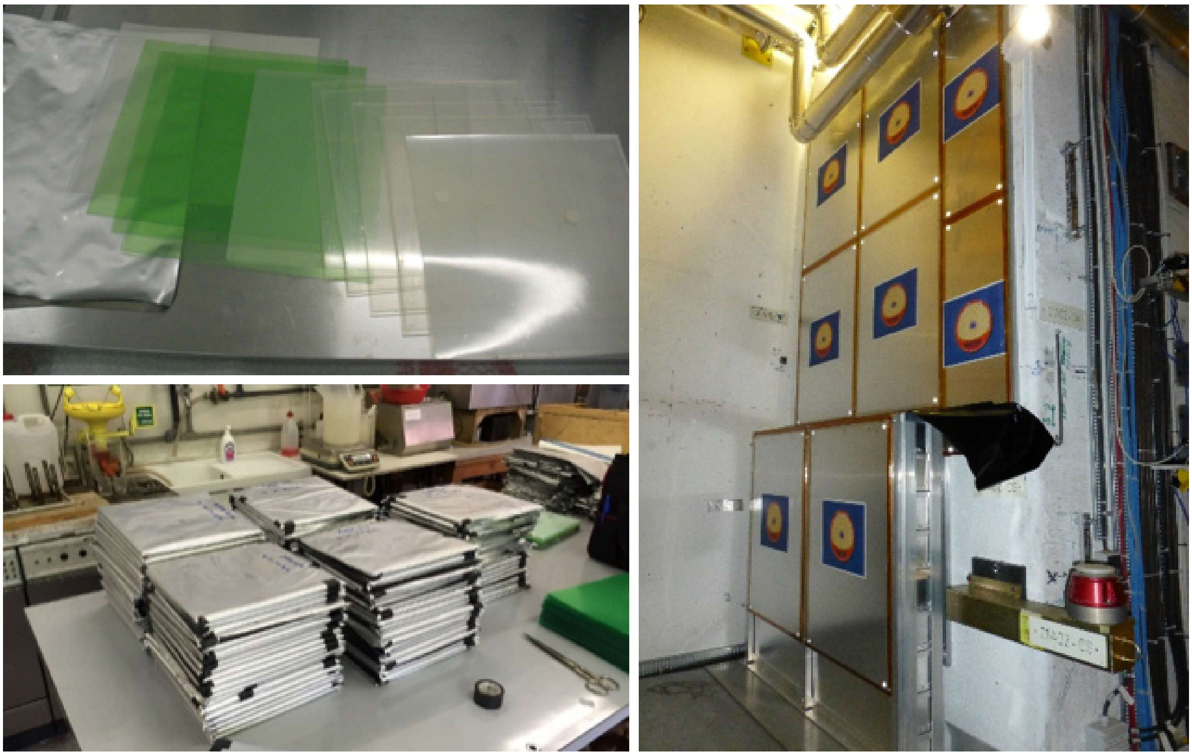

Figure 16: The component sheets of a MoEDAL Nuclear Track Detector (NTD) stack (top-left); MoEDAL NTD stacks ready for deployment in the LHCb cavern (bottom-left), and; some of the MoEDAL NTDs in situ (right). Image credit: R. Soluk/The MoEDAL Collaboration; please contact them regarding licensing/re-use of this image.

In many ways, NTDs are like the nuclear emulsions used by particle physicists in the 1950s in cosmic ray and early accelerator experiments. The use of such emulsions was pioneered by

Cecil Powell, who won the 1950 Nobel Prize for Physics for this technique and the discoveries he made with it. The passage of a charged particle through the emulsion would ionise the sensitive particles in such a way that the application of a chemical would produce a light-blocking substance along the path, making it visible. The same principle is used in film-based photography. The key thing is the sensitivity of the particles in the emulsion; Powell's silver iodide-based emulsions were great for discovering mesons in balloon flights or up mountains, but would be overwhelmed by the energy and intensity of what the LHC's collisions produce.

Luckily, magnetic monopoles are predicted to be so highly-charged that we can use something less sensitive, more stable, and a bit cheaper to record the tracks they would leave behind. While breaking hydrocarbon bonds in a plastic is a different physical process, the principles are the same – including those used in the analysis. Terabytes of digital images of the etched plastic from MoEDAL NTD stacks – like those shown in Figure 16 – need to be checked for the tell-tale tracks of the monopole. Given the unknown nature of the signal we expect (and the complexity of the proton-proton collision background), we will need help to do this – which is one of the ways you can help.

4.2. The Magnetic Monopole Trapper

The Magnetic Monopole Trapper (MMT) goes one step further than the Nuclear Track Detectors (NTDs). Rather than just recording the passage of the monopole through the material – like finding the footprints of an animal in the jungle – the MMTs literally aim to trap the monopole so that it can be taken away and studied further. The MMT is made up of many bars of aluminium packed closely together in boxes that are put in the LHCb cavern around the Interaction Point (see Figure 17). If we're lucky, magnetic monopoles passing through the aluminium would slow down, stop, and become trapped within the aluminium. We can then carefully remove the bars from the cavern and pass them through a Superconducting QUantum Interference Device (SQUID), which would detect the monopole's magnetic charge [27].

Finding a monopole this way would be particularly exciting, as with the monopole embedded in the material of the detector we would have the chance to perform all sorts of studies to find out more about the properties of magnetic monopoles. In fact, searches for trapped monopoles from collider experiments have been performed before using decommissioned detector and beam pipe elements. The beauty of MoEDAL's MMTs is that they are purpose-built for monopole trapping, and we don't have to wait for CMS and ATLAS to finish their work and throw their kit away!

4.3. The MoEDAL Timepix array

The particle collisions that take place during LHC running – with both protons and lead ions – produce a great deal of ionising radiation. For the general-purpose LHC experiments, much of this is uninteresting in the sense that we understand its properties and studying it further will

Figure 17: MoEDAL's prototype Magnetic Monopole Trapper (MMT) installed in the LHCb cavern. Each box contains several bars of aluminium (see inset image, top-right) that are later removed from the cavern and scanned using a SQUID to identify trapped magnetic monopoles. Image credit: R. Soluk/The MoEDAL Collaboration; please contact them regarding licensing/re-use of this image.

(generally speaking) not lead to new discoveries. Signatures from these particles is known as "background" to the signal and needs to be filtered out from the data. The MoEDAL NTDs and MMTs are only sensitive to highly-ionising particles (HIPs) like monopoles, and so in principle do not need to worry about this background. That said, it is important to double-check this assertion by measuring the background radiation in the LHCb cavern. To this end, a number of Timepix hybrid silicon pixel detectors [28, 29] have been installed in the vicinity of LHCb's Vertex Locator (VeLo). The location of each device is shown in Figure 18. IRIS has access to data from these detectors – which are of course the same detectors as used in the CERN@school detector network, LUCID, and the International Space Station (ISS). Discovering something like a magnetic monopole would be an extraordinary discovery, and so demonstrating that we understand any possible backgrounds would be an essential part of verifying the discovery.

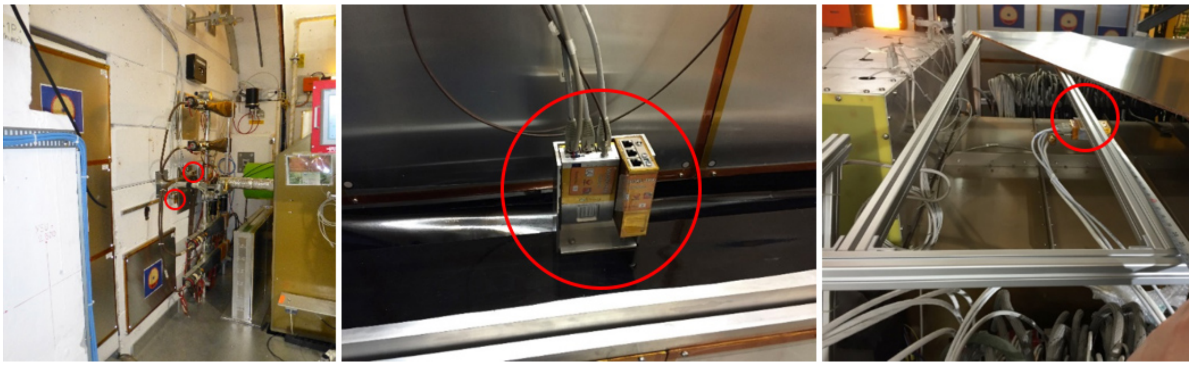

Figure 18: MoEDAL's five Timepix devices deployed around the LHCb VeLo. In the left-most image, TPX2 (TPX4) is shown in the lower-left (upper-right) red circle, where it has been installed with the sensor plane normal (parallel) to the beam pipe. In the central image, TPX1 (TPX3) is shown on the left (right) where it has been installed on the side of the VeLo enclosure with the sensor plane normal (parallel) to the beam pipe. In the right-most image, TPX5 is shown installed above the VeLo enclosure with the sensor plane normal to the beam pipe. Image credit: R. Soluk/The MoEDAL Collaboration; please contact them regarding licensing/re-use of this image.

5. Get involved!

So you want to help look for magnetic monopoles at the Large Hadron Collider? Great! This section will take you through what you need to do, how to do it, and how to get help if you need it.

5.1. Getting started

In order to give you access to the MoEDAL experiment data, and tools you'll need to analyse it, the Institute for Research in Schools has called in some help from our friends at the Zooniverse. The Zooniverse started with the Galaxy Zoo project, where people were invited to classify thousands of images of galaxies from the Sloan Digital Sky Survey. It has since evolved into the world's largest and most popular platform for people-powered research that has led to peer-reviewed publications and opened the door to many new areas of scientific research that just would not be possible otherwise. MoEDAL has created the Monopole Quest! project within the Zooniverse, and by taking part in this you'll be joining the millions of Zooniverse volunteers helping to do real science.

5.1.1. Creating a Zooniverse account

The first thing to do is to visit the Zooniverse website[†] and create a user account. You can do this on a desktop computer, a laptop, a tablet or even a smartphone (if the screen is big enough!). If you're a student, you may wish to ask your teacher to do this for you or for them to create an account for your class. You don't have to create an account to take part in Monopole Quest!, but in order for your work to be credited you need to be logged in. Always ask your teacher or your IRIS contact for advice if you need to. Creating a user account is simple – you can create a user account by filling in the online form you get when you click on the "Register" link at the top-right of the Zooniverse homepage.

5.1.2. Sign in and access the Monopole Quest! project

Once you have created an account, sign in to the Zooniverse by clicking the "Sign in" link (also at the top-right of the homepage). Then you can access the Monopole Quest! project at the following URL:

- `https://www.zooniverse.org/projects/twhyntie/monopole-quest`

After which you should see the Monopole Quest! landing page as shown in Figure 19.

Then click on the "Get started!" button and start doing some science!

[†] See http://www.zooniverse.org

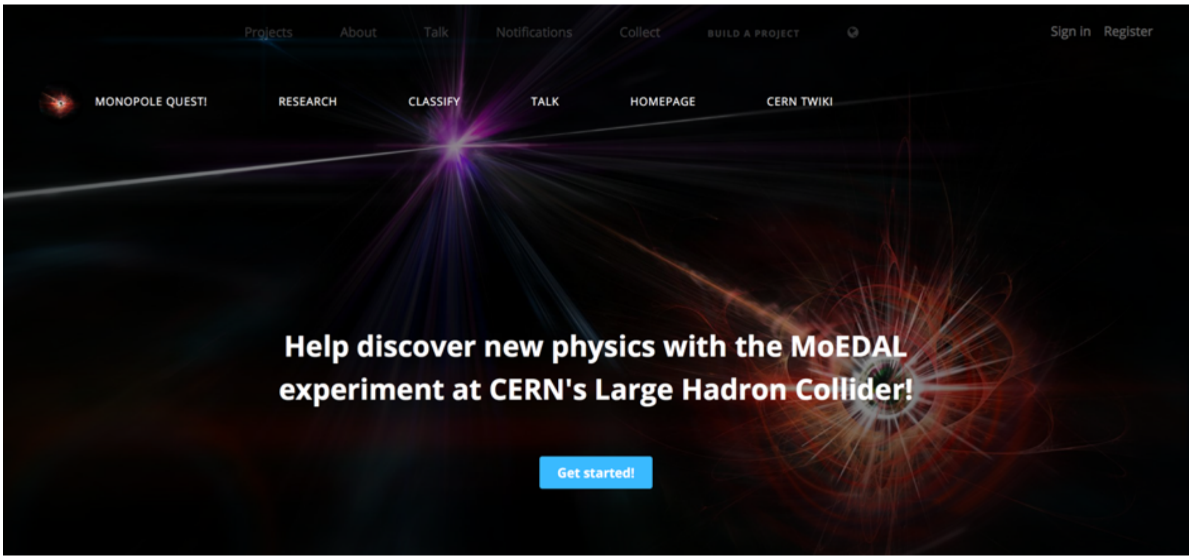

Figure 19: The Monopole Quest! landing page on the Zooniverse. From here you can get stuck into some real MoEDAL data straight away!

5.2. The Monopole Quest! project

5.2.1. What do I do?

As with all Zooniverse projects, Monopole Quest! will ask you a number of questions about an image from one or more their datasets. Your answers to these questions will result in a classification for that image – information about that data that will help scientists with some aspect of the research. For example, the first question in Monopole Quest! asks you if you can see any "blobs" in the image (see Figure 20). These blobs correspond to the etched pits in the NTD scans that may be caused by monopoles or other HIPs. So, in essence, you are being asked if you can see any potential monopole signals!

You can answer the questions by selecting the appropriate answer with your mouse (or tapping the option on a touch screen) and then pressing the "Done" button. You'll then be asked the next question or asked to perform a task, such as drawing a shape on the image. For example, if you can see a blob in the image, you'll be asked to draw around it with a circle (the "blob marking tool") in order to measure its size (see Figure 21).

5.2.2. How do I get help?

As there are many questions and tasks to do in Monopole Quest!, we have added interactive help to the questions themselves rather than list everything here. If you need help at any point, click on the "Need some help with this task?" button and a pop-up window will appear that will give you some additional guidance if you get stuck. Figure 22 shows an example of this.

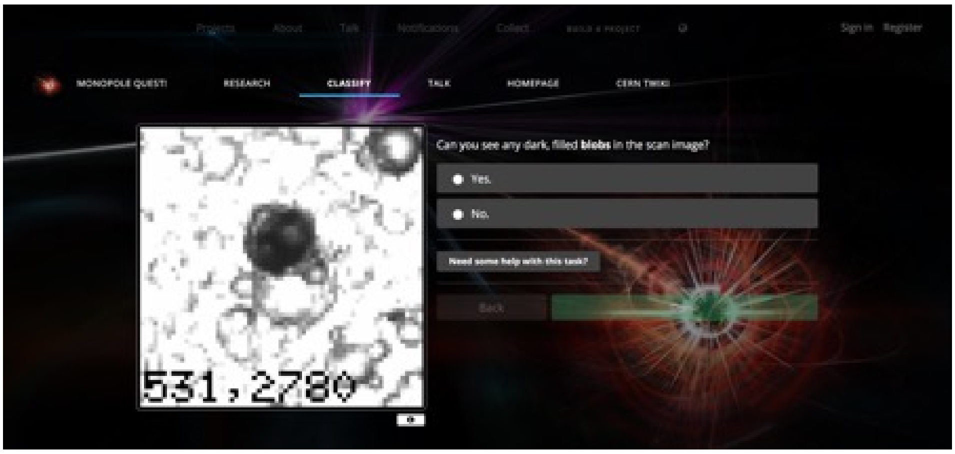

Figure 20: The first question from the Monopole Quest! Zooniverse project (Jan. 2017).

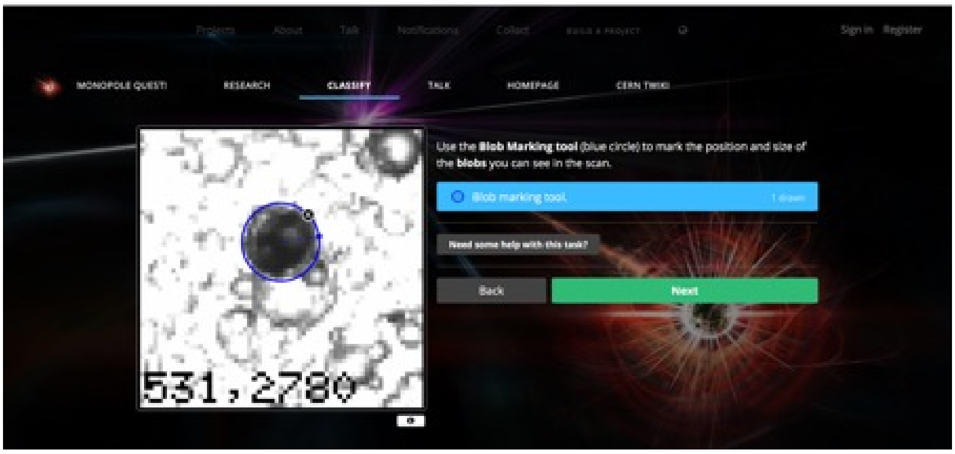

Figure 21: An example drawing task in the Monopole Quest! project (Jan. 2017).

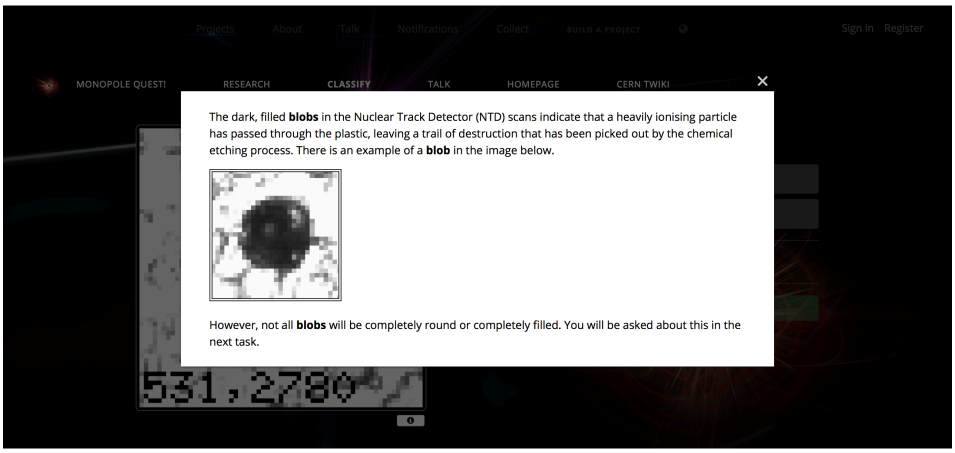

Figure 22: An example help pop-up message in Monopole Quest! (Jan. 2017).

5.2.3. What am I looking at?

The data used in Monopole Quest! comes from scans of plastic from the MoEDAL NTDs. All of it is real data from the experiment, but some images were made using plastic exposed to different environments and scanned in different laboratories:

(i) Some plastic was exposed to LHC collisions at 8 TeV centre-of-mass energy;

(ii) Some plastic was exposed to LHC collisions at 13 TeV centre-of mass energy;

(iii) Some plastic was exposed to a heavy ion test beam (see Figure 23);

(iv) Some plastic was exposed to both LHC collisions and a heavy ion test beam.

Figure 23: MoEDAL NTD samples being exposed to a heavy ion test beam at the NASA Space Radiation Laboratory (SRL), Brookhaven National Laboratory (BNL). Exposing NTD plastic to heavy ions from test beams allows us to see what monopole-like signals might look like and put our analysis procedures through their paces. Image credit: R. Soluk/the MoEDAL Collaboration; please contact them regarding licensing/re-use of this image.

Analysis of plastic exposed to these different conditions is necessary to provide control samples and to test our analysis procedures (including Monopole Quest!) with monopole-like signals from the heavy ions. As a Zooniverse volunteer, we won't tell you which sample type you are looking at (as this might bias your answers). However, all data and classifications are useful to the MoEDAL science programme, so please do as many as you can!

5.2.4. What happens next? Continuing your MoEDAL journey

Your classifications are stored by Monopole Quest! for further analysis by the MoEDAL science team – which could include you! As you and your school get further involved with IRIS, data based on the user classifications (including yours) can be made available for individual or group research projects. Contact the IRIS team with your Zooniverse usernames (so we can verify how many classifications you have made) and project ideas to find out more. Then, as with all IRIS research, the aim is to publish results based on the data and analysis in peer-reviewed scientific journals. You can see the many examples of Zooniverse-powered publications on their website – and with the support of CERN@school through IRIS and the MoEDAL Collaboration, you should be able to add to this.

What can *you* do with MoEDAL and IRIS?

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7. Acronyms

ALICE A Large Ion Collider Experiment

AMANDA Antarctic Muon and Neutrino Detector Array

ANTARES Astronomy with a Neutrino Telescope and Abyss environmental RESearch project

ATLAS A Toroidal LHC ApparatuS

BNL Brookhaven National Laboratory

BSM Beyond Standard Model (physics)

CDF Collider Detector at Fermilab

CERN Organisation Européen pour la Recherche Nucláire

CMS The Compact Muon Solenoid experiment

DESY Deutsches Elektronen-SYnchrotron (Germany)

GUT Grand Unified Theory

HERA Hadron- Elektron-Ring-Anlage (Hadron Electron Ring Facility)

HIP Highly Ionising Particle

IRIS The Institute for Research in Schools

ISS International Space Station

KEK The High Energy Accelerator Organisation (Japan)

LEP Large Electron-Positron collider

LHC Large Hadron Collider

LHCb The Large Hadron Collider Beauty experiment

MACRO Monopole, Astrophysics and Cosmic Ray observatory (Italy)

MMT Magnetic Monopole Trapper

MODAL MOnopole Detector at LEP

MoEDAL Monopole and Exotics Detector at the LHC

NASA National Aeronautics and Space Administration (US)

NTD Nuclear Track Detector

OPAL Omni-Purpose Apparatus at LEP

PEP Positron Electron Project (SLAC, US)

QFT Quantum Field Theory

SLAC Stanford Linear Accelerator Center (US)

SLIM Search for LIght magnetic Monopoles experiment

SQUID Superconducting QUantum Interference Device

SRL The NASA Space Radiation Laboratory (US)

TDR Technical Design Report for, e.g. the MoEDAL experiment

TeV tera-electron volts

VeLo Vertex Locator (LHCb subdetector system)

VHCC Very High Charge Catcher

8. Acknowledgements

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Version History

Table 2: Version history.

Version	DOI	Description	Author
1.0	10.5281/zenodo.248615	Initial version.	TW

† http://www.gridpp.ac.uk