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Looking for charged detector-stable particles at the LHC

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Many scenarios of New Physics predict meta-stable particles with electric and/or magnetic charges. Supersymmetric partners, quirks, strangelets, Q-balls, and black-hole remnants are such proposals with single or multiple electric charges, while magnetic monopoles and dyons feature magnetic charges. Their existence has been probed at the LHC directly, through virtual loops or via the bound states they may form. The MoEDAL experiment has been designed specifically to detect such highly ionising states in a way complementary to the LHC main experiments, ATLAS and CMS. Prospects for Run-3, HL-LHC and beyond are also presented.

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[*] Speaker

1. Introduction

A multitude of theoretical scenarios predicts the existence of quasi-stable singly charged particles. For instance, in supersymmetry (SUSY), such states may be the lightest SUSY partner (LSP) or the next-to-LSP (NLSP) [1]. They arise in R-parity violation [2], split SUSY [3, 4], coannihilation region [5–7], gravitino or axino LSP scenarios [8–11], anomaly-mediated supersymmetry-breaking (AMSB) models [12, 13] and compressed spectra [14–16].

In addition, many hypothetical particles characterised by multiple electric charges and long lifetime have been proposed, such as Q-balls [17, 18], micro-black-hole remnants [19, 20], quirks [21], doubly charged scalars in type-II seesaw [22–27], doubly charged higgsinos in supersymmetric left-right models [28–33], doubly charged particles in various $SU(2)_L$ additions to the Standard Model (SM) [34, 35], scalars in radiative-neutrino-mass models [36, 37], and aggregates of ud- [38] or s-quark matter [39]. Other such exotic particles include anion-like and cation-like leptons predicted by the almost-commutative model [40, 41] and technibaryons, predicted by the walking-technicolor model [42].

Moreover, magnetic monopoles [43] that carry a non-zero magnetic charge and dyons [44] possessing both magnetic and electric charge are both stable and charged. As demonstrated by the Dirac quantisation condition [45, 46] —besides symmetrising the Maxwell equations—, monopoles explain the electric charge quantisation and carry magnetic charge of integer multiples of the Dirac charge $g_{\mathrm{D}} = 68.5e$. Many theories, including grand unified theories [47, 48] and superstrings [49, 50], predict their existence. Other scenarios include the electroweak monopole [51–55], the global monopole [56–63], monopoles in Born-Infeld theory [64–67] and the monopolium [46, 68–72], a monopole-pair bound state.

Independent of their theoretical motivation, all these highly ionising particles (HIPs) can be detected by exploiting two features: (i) the high ionisation they induce in detector elements, that distinguishes them from minimum-ionising particles (MIPs); and (ii) the low, non-relativistic velocity, if they are massive enough, which makes them observable in timing-sensitive detectors through their time of flight. Besides these features, magnetic monopoles can also be probed though the induced current in a superconducting quantum interference device (SQUID) and the distinguishing track in the presence of magnetic field.

The state-of-the art in searches for such particles in experiments at the Large Hadron Collider (LHC) is presented here. The most recent searches performed by the ATLAS [73] general-purpose experiment are presented in Section 2, whereas analyses from the dedicated MoEDAL [74] experiment are described in Section 3. In Section 4, prospects for the future on HIP hunting are discussed. The paper ends with a summary in Section 5.

2. ATLAS searches

ATLAS is one of the LHC main experiments optimised for the detection of particles that decay promptly to known states. However, many analyses have been performed in the recent years targeting long-lived particles (LLPs) [75, 76]. Here, some of the most recent searches for highly ionising particles from ATLAS are highlighted. CMS [77] also forms part of this effort, albeit no newly released results were available at the time of this presentation.

2.1 Large ionisation energy loss & time-of-flight

A search has been performed in ATLAS for heavy charged LLPs with lifetimes $\tau \gtrsim 3$ ns [78], which exploits the measurement of the ionisation energy loss ($\mathrm{d}E/\mathrm{d}x$) in the pixel detector [79, 80] and the time-of-flight (ToF) measured by the hadronic calorimeter [81, 82]. The key signal characteristic is an isolated, high-momentum track with large $\mathrm{d}E/\mathrm{d}x$ measured in the pixel detector that moves significantly slower than a MIP as measured by the calorimeter ToF. The analysis uses the full Run 2 dataset and is an update of several previous searches performed by the ATLAS experiment in both Run 1 and Run 2 [83–90]. The CMS experiment has also used a combination of $\mathrm{d}E/\mathrm{d}x$ and ToF in previous searches [91–93]. In the ATLAS search that used the pixel $\mathrm{d}E/\mathrm{d}x$ only, carried out with 140 fb^{-1} of Run 2 collisions, a 3.3σ excess around a mass of 1.4 TeV was observed.

The main observable used is the mass of the particle associated to the above track. The mass is calculated via the formula $m = p/\beta\gamma$ with two independent determinations of $\beta\gamma$. One uses the Bethe-Bloch relation between $\beta\gamma$ and $\mathrm{d}E/\mathrm{d}x$ measured by the pixel detector for the candidate track. The other uses the ToF measured by a cluster of cells in the calorimeter crossed by the candidate track and their distance from the interaction point (IP). Two independent mass distributions are obtained ($m_{\mathrm{d}E/\mathrm{d}x}$ and m_{ToF}). They should be compatible with particles with unit charge and fall in the compatibility cone defined by the mass distributions. The results agree with the expected background, as shown in Figure 1, and cross-section limits for the LLP production are set.

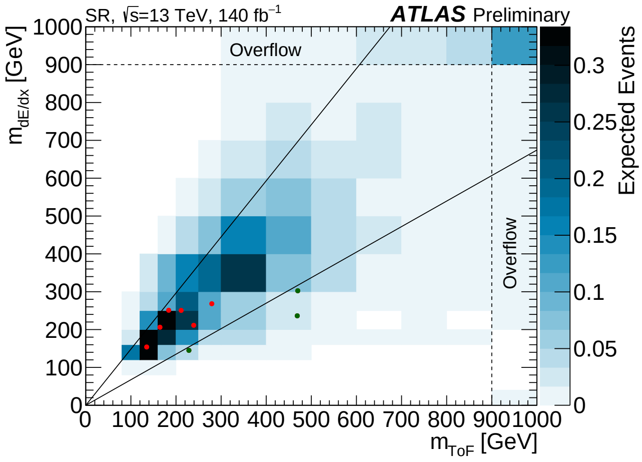

Figure 1: ATLAS $\mathrm{d}E/\mathrm{d}x$ and ToF analysis. Distribution of data and predicted background in the signal region. The observed data events are indicated as dots (red if they are inside the mass compatibility cone, blue if they are outside), while the blue area is the mass distribution of the background. Overflow background is plotted in the region $900 < m_{\mathrm{d}E/\mathrm{d}x} < 1000$ GeV or $900 < m_{\mathrm{ToF}} < 1000$ GeV. From [78].

The highest sensitivity is reached for LLPs with lifetimes exceeding 10 ns. Masses smaller than 2.3 TeV are excluded at the 95% confidence level (CL) for gluino R-hadrons with a lifetime of 30 ns and $\tilde{\chi}_1^0$ LSP mass of 100 GeV. The mass limit for compressed-scenario R-hadrons, with $\Delta m(\tilde{g}, \tilde{\chi}_1^0) = 30$ GeV and a lifetime > 200 ns, is 2.2 TeV. Masses in the range 260–440 GeV for staus are excluded for lifetimes of 10 ns. The mass limits for staus extend up to about 100 ns, with the lower mass limit staying constant in the 10–100 ns lifetime range. Moreover, these results have been recently reinterpreted considering the production of pure wino, AMSB-like charginos, improving the existing limits for lifetimes above 10 ns setting the mass limits up to 1.33 TeV [94].

2.2 Multiply charged particles

This ATLAS analysis looks for heavy long-lived multi-charged particles (MCPs) in $\sqrt{s}$ = 13 TeV proton–proton collision data collected in 2015–2018 [95]. The search, conducted on a 139 fb^{-1} data sample, is performed in the MCP mass range from 500 to 2000 GeV, for electric charges $|q| = ze$, with integer charge numbers $2 \leq z \leq 7$. MCPs have been explored in the past by ATLAS [96–99] and CMS [91].

The MCPs are assumed to live long enough to traverse the entire ATLAS detector without decaying. Their identification relies on the anomalously high ionisation energy released by high-charge, muon-like particles and measured in the pixel [79, 80], the transition radiation tracker (TRT) [100, 101], and the muon drift tube (MDT) [102] subdetector systems. High dE/dx values arise from both higher electric charges and lower velocities of such particles compared to most of the SM particles produced at the LHC.

No statistically significant evidence of such particles is observed, so upper limits are derived on the cross sections using Drell-Yan (DY) and photon fusion (PF) production modes, as shown in Figure 2, and exclude muon-like MCPs with masses between 500 GeV and 1060–1600 GeV. These results supersede those of a previous search using a smaller 13 TeV data sample [99]. Apart from a data sample four times larger, improvements involve the production model (the addition of the photon-fusion production mode and the virtual Z exchange for the DY mode [103]) and to the addition of a 'late-muon' trigger. This search complements recent ATLAS searches for heavy $z = 1$ particles identifiable by their high transverse momentum, anomalously large ionisation losses and low-β discussed in Section 2.1.

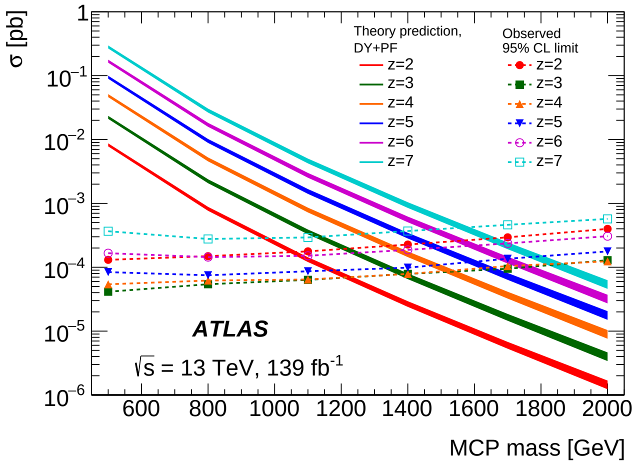

Figure 2: ATLAS MCP search. Observed 95% CL cross-section upper limits and theoretical cross sections as functions of the muon-like spin-½ MCP mass for the DY+PF production mode. Theoretical cross-section values are computed at leading order and the bands correspond to the parton-distribution-function uncertainty. From [95].

2.3 Monopoles & HECOs

In the past, the ATLAS experiment has considered highly ionising signals to probe magnetic monopoles in the range $0.5g_{\mathrm{D}} \leq |g| \leq 2g_{\mathrm{D}}$ and high-electric-charge objects (HECOs)[1] in the range $20 \leq |z| \leq 100$ in previous searches [104–106], the most recent of which used 34.4 fb^{-1} of

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[1] The name HECOs is used for charges $\gtrsim 10e$, where the HECO-γ/Z coupling is too large for perturbation to be valid, while MCP is used for lower charges.

$\sqrt{s}$ = 13 TeV pp collision data [106]. The HIP search presented here [107] uses data from 13 TeV collisions recorded by the ATLAS detector between 2015 and 2018, amounting to an integrated luminosity of 138 fb^{-1}, when custom HIP trigger was implemented.

To detect HIPs, the analysis considers the signals in the TRT [108, 109] and the electromagnetic (EM) calorimeter [110, 111]. The discriminating particle characteristics used in the search are the energy dispersion in the electromagnetic calorimeter, w, and the fraction of TRT hits passing a predefined high threshold, f_{HT}. The lateral energy dispersion measures the fraction of the cluster energy contained in the most energetic cells of a cluster in each of the layers of the electromagnetic calorimeters. The data distribution in the (w, f_{HT}) plane for the signal and control regions, as well as for a signal monopole model is presented in Figure 3.

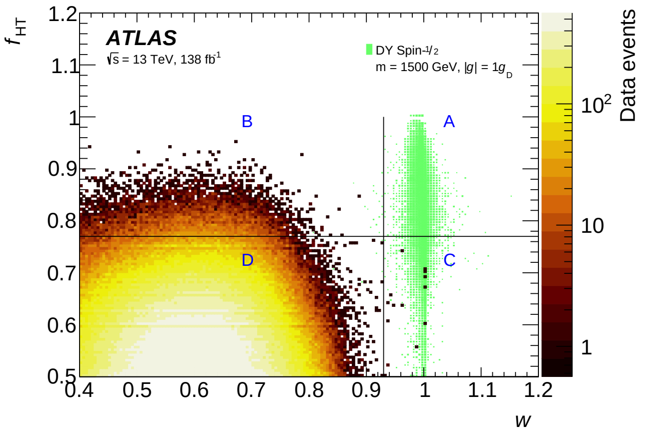

Figure 3: ATLAS monopole and HECO search. Two-dimensional distribution of the discriminators f_{HT} and w for the data and a representative signal sample (green). The signal (A) and control (B, C and D) regions are shown. From [107].

Consistent with the background expectation, no event is observed in the HIP signal region. Considering DY+PF pair production mechanisms as benchmark models, cross-section upper limits are presented for spin-0 and spin-½ magnetic monopoles of charge $1g_{\mathrm{D}}$ and $2g_{\mathrm{D}}$ and for HECOs of electric charge $20 \leq |z| \leq 100$, for masses between 200 GeV and 4000 GeV. The results supersede those of Ref. [106], benefiting from a four-fold increase in data statistics, the addition of Z exchange in the spin-½ Drell-Yan HECO production model [103], and the photon-fusion mechanism [71, 103, 112–114], which has a higher predicted cross section than that of Drell-Yan production at 13-TeV pp collisions.

3. MoEDAL searches

The Monopole and Exotics Detector at the LHC (MoEDAL) [115, 116], the first dedicated *search* LHC experiment, is specialised in the detection of HIPs in a manner complementary to ATLAS and CMS [117]. It is deployed around interaction point 8 (IP8) in the LHCb vertex locator cavern. It is a unique and largely passive detector based on three different techniques, which does not require neither readout or trigger. An array of nuclear track detectors (NTD) registers the passage of a HIP by an invisible damage zone along the trajectory, revealed as an etch-pit when the plastic detector is chemically etched off-site. Aluminium magnetic monopole trappers (MMTs), which can capture magnetically charged particles, are scanned in a SQUID looking for isolated magnetic charges [118]. The only active sub-detector comprises TimePix devices for monitoring cavern background sources [119].

MoEDAL has extended its physics program to *feebly interacting particles* that connect hidden sectors to the visible SM sector with the MoEDAL Apparatus for Penetrating Particles (MAPP) [120]. Such *portal* scenarios attempt to explain observed phenomena in particle physics and cosmology such as the non-vanishing neutrino masses, the dark matter [121, 122] and the baryon asymmetry of the universe, among others [123–125]. MAPP Phase 1 was approved by the CERN Research Board in 2021 and it is currently being deployed in the UA83 tunnel ~ 100 m from IP8. Its main physics goal is to detect millicharged particles of charge down to $10^{-3}e$ [126–128], MAPP Phase 2 is going to be in operation in HL-LHC and extend MAPP-1 physics reach [116].

3.1 Monopoles and dyons

MoEDAL has searched for monopoles trapped in MMTs in pp collisions with Run-1 8-TeV data [129] and Run-2 13-TeV pp collisions [130–132]. The SQUID analysis yielded no observed isolated magnetic charges, leading to upper limits on monopole production cross sections. Searches involving both Makrofol NTDs and MMTs have constrained further the monopole production cross section at 8 TeV [133] and 13 TeV [134]. A summary of the lower mass limits set by MoEDAL in comparison with CDF [135] and ATLAS [105, 107] are presented in Figure 4. The ATLAS bounds are better that the MoEDAL ones for $|g| \leq 2g_D$ due to the higher luminosity delivered in ATLAS and the loss of acceptance in MoEDAL for low charges, while MoEDAL is the only detector sensitive to high magnetic charges.

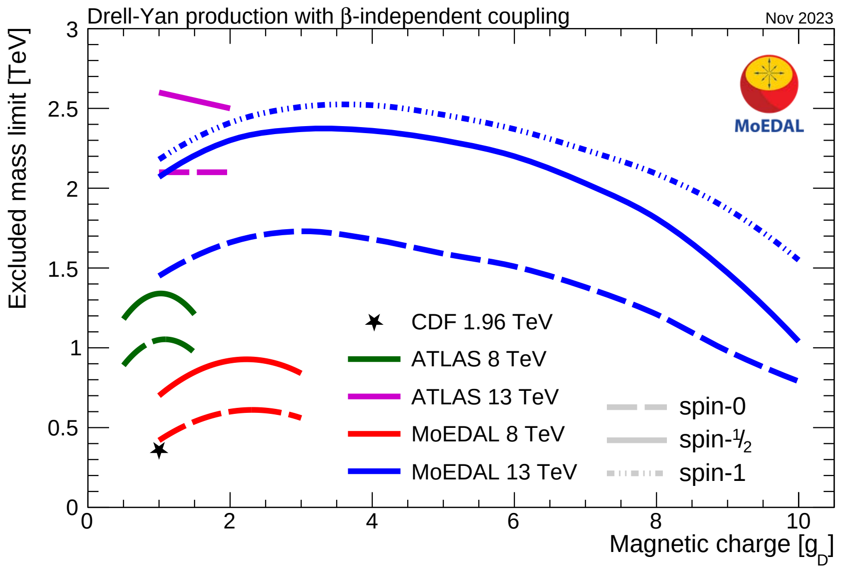

Figure 4: Magnetic monopole mass limits obtained by CDF [135], ATLAS [105, 107], and MoEDAL [129, 134] at various centre-of-mass energies as a function of the magnetic charge. Drell-Yan production with a β-independent coupling for monopoles of spin 0, ½ and 1 is assumed.

Apart from being the only contender in high charges, the MoEDAL experiment has introduced several phenomenological novelties to the results interpretation: (a) β-dependent coupling, where

$\beta = \sqrt{1 - 4M^2/\hat{s}}$, with M the monopole mass and $\hat{s}$ the Mandelstam variable, inspired by electric–magnetic duality arguments [136, 137]; (b) spin-1 monopoles, where a magnetic moment parameter κ is introduced [114]; and (c) the t-channel photon-fusion production process [71, 112–114]. As shown in Figure 5, PF gives much higher mass limits than DY due to its dominant cross section at $\sqrt{s} = 13$ TeV.

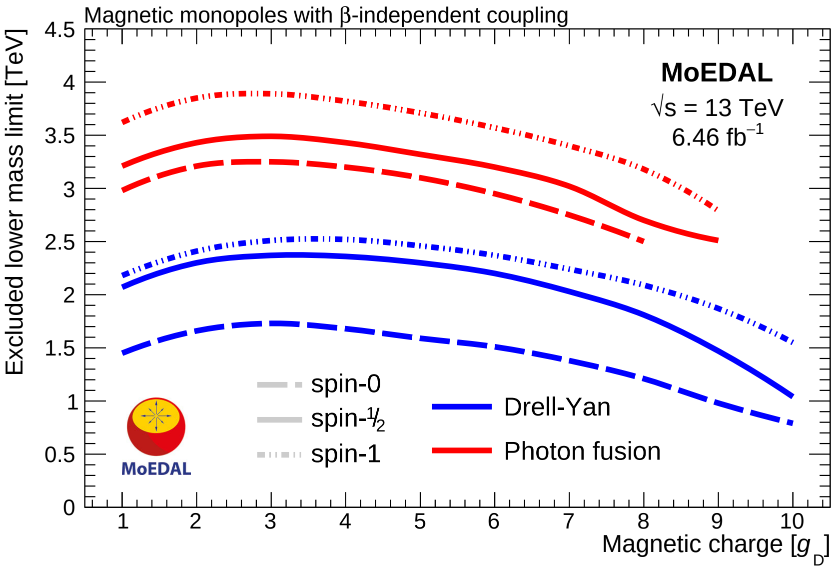

Figure 5: Magnetic monopole mass limits obtained by MoEDAL [134] at $\sqrt{s} = 13$ TeV as a function of the magnetic charge. Drell-Yan and photon-fusion production modes with a β-independent coupling for monopoles of spins 0, ½ and 1 are assumed.

MoEDAL performed the first dedicated dyon search [138] in a collider experiment by means of MMT scanning. Mass limits in the range 750–1910 GeV were set using a benchmark DY production model for dyons with magnetic charge up to $5g_{\mathrm{D}}$, for electric charge from $1e$ to $200e$, and for spins 0, ½ and 1 [139].

A note of caution is due here. In both production processes, DY and PF, the monopole pair couples to the photon via a coupling that depends on g_{D} and therefore has a value of $O(10)$. This large monopole–photon coupling invalidates any perturbative treatment of the cross-section calculation and hence any result based on it is *only indicative* and used merely to facilitate comparisons between experimental outcomes. However, it is stressed that the upper bounds placed on production cross sections are solid and can be relied upon. One way to resolve this problem is to use resummation techniques in monopoles [140] and HECOs [141, 142]. Another way to evade it for vector monopoles is the appropriate choice of the parameters κ and β in PF [114].

Last but not least, the Schwinger production mechanism in strong magnetic fields present in heavy-ion collisions [143] rely on semiclassical techniques for the cross-section calculation, thus evading the large-coupling problem [144–149]. The first search for such production was conducted by MoEDAL using the MMT exposure to ultraperipheral Pb–Pb collisions, excluding magnetic charges up to three Dirac charges and masses up to 75 GeV [150]. This analysis provided the first lower mass limits for *finite-size* monopoles from a collider search. Furthermore, a search for monopoles trapped in the Run-1 CMS beam pipe after exposure to 2.76-TeV Pb–Pb collisions was performed by MoEDAL using a SQUID magnetometer [151]. The use of a trapping volume very close to the collision point [117] and ultra-high magnetic fields generated during the heavy-ion run that could produce monopoles via the Schwinger effect allowed setting the first reliable, world-leading mass limits on monopoles with very high magnetic charge. In particular, the established limits are the strongest available in the range 2–45g_{D}, excluding monopoles with masses of up to 80 GeV.

3.2 HECOs

The exposure, chemical etching and subsequent scanning of MoEDAL NTDs allows the detection of large electric charges. MoEDAL has completed generic searches for HECOs using Makrofol NTDs exposed to pp collisions at 8 TeV [133] and recently at 13 TeV [134], without finding any candidate etch-pit indicating the passage of a HIP through the plastic sheet. In the 8-TeV search, conducted with a prototype detector, only DY production was considered, whereas both DY and PF was used in the 13-TeV analysis. The set lower mass bounds are summarised in Figure 6 for the DY process, together with limits from ATLAS and CMS searches for MCPs and HECOs [91, 95, 107]. As in the magnetic-monopole case, ATLAS has better sensitivity in small charges, while MoEDAL is the only LHC experiment that can observe electric charges $\gtrsim 100e$.

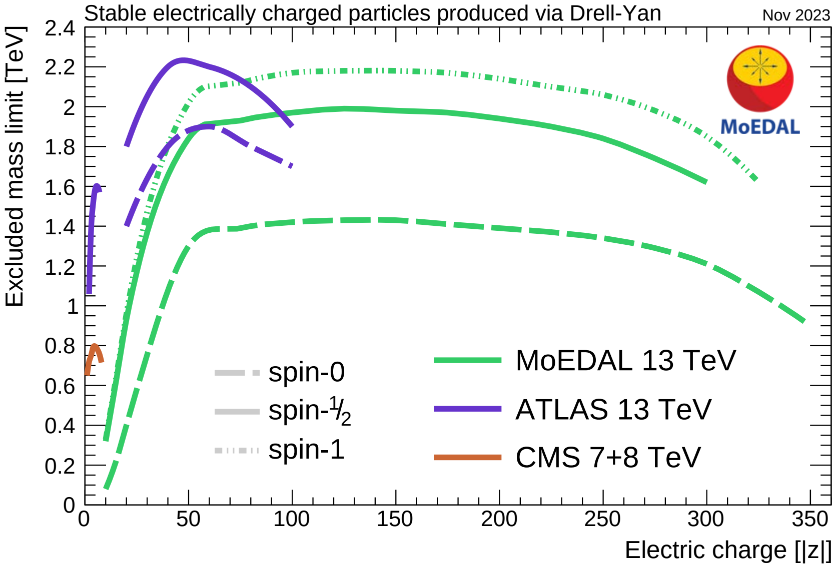

Figure 6: HECO mass limits obtained by ATLAS [95, 107], CMS [91] and MoEDAL [134] at various centre-of-mass energies as a function of the electric charge. Drell-Yan production for HECOs of spins 0, ½ and 1 is assumed.

4. Future prospects

The quest for quasi-stable charged particles in colliders continues throughout LHC Run 3, which is currently under way, colliding protons to protons at 13.6 TeV with several analyses in progress by ATLAS, CMS and MoEDAL. The latter also plans to search for exotic states in the form of D-matter [152–158]. Feasibility studies on the discovery potential for magnetic monopoles and MCPs are presented in the following subsections for Run 3, High-Luminosity LHC (HL-LHC) and beyond.

4.1 LHC Run 3 and HL-LHC

MoEDAL is mostly sensitive to slow-moving particles unlike ATLAS/CMS suitability for faster ones ($\beta \gtrsim 0.8$). However, the lower integrated luminosity for MoEDAL at IP8 remains a limiting factor for simple scenarios. Direct production of heavy fermions abundantly produced via the strong interaction is the most favourable scenario for MoEDAL. In SUSY, complex topologies appear to be promising for sleptons in phenomenologically realistic models, where MoEDAL could cover parameter space less accessible by CMS [159] and ATLAS [160] in Run 3. Even for SUSY models observable by both ATLAS/CMS and MoEDAL, the latter's added value remains, thanks to the completely different detector and analysis techniques, involving uncorrelated systematic uncertainties.

The prospects for detecting MCPs in MoEDAL are also very promising. Doubly charged scalars and fermions are suggested by Type-II ($H^{\pm\pm}$) and Type-III seesaw models of neutrino masses, respectively, and masses up to ~ 1.1 TeV can be reached by MoEDAL in Run 3 [161]. Good discovery reach is anticipated for charges of $2e$, $3e$ and $4e$, proposed in radiative neutrino mass models, which often add a discrete symmetry to the SM gauge group [36]. For such models, at least one signal event at the NTDs is expected for up to masses of 290, 610 and 960 GeV for scalars $S^{\pm 2}$, $S^{\pm 3}$ and $S^{\pm 4}$ in Run 3 [37]; see also Figure 7. Feasibility studies have quantified the MoEDAL potential to discover generic electrically charged scalars and fermions in the range $1e$ to $8e$ in Run 3 and HL-LHC [162, 163]. The sensitivity of MoEDAL is superior to that of ATLAS and CMS for charges 2–$6e$ in HL-LHC, as shown in Figure 8.

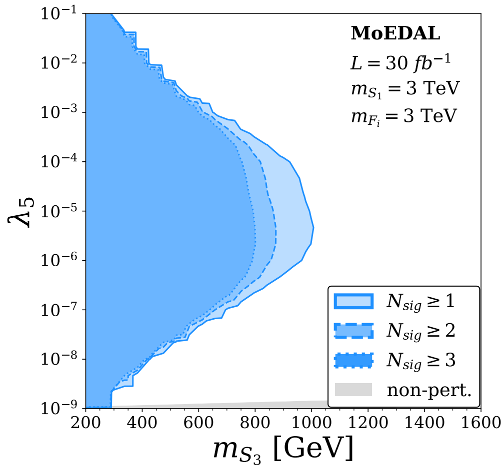

Figure 7: Radiative neutrino models. MoEDAL detection sensitivity in the (m_{S_3}, λ_5) plane for Run 3. In the regions inside the solid, dashed and dotted contours, more than 1, 2 and 3 events will be observed, respectively. From [37].

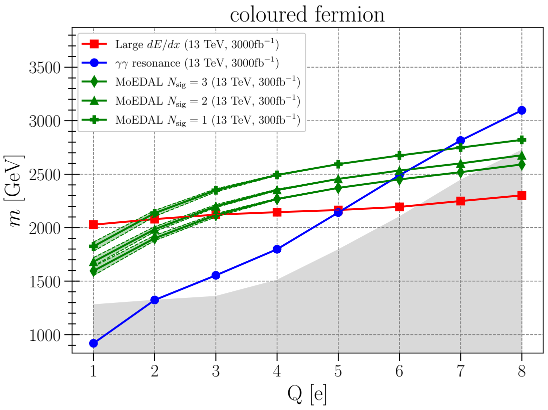

Figure 8: Generic MCP prospects. Expected lower mass limits on coloured fermions for HL-LHC for 3 ab^{-1} in ATLAS/CMS and 300 fb^{-1} for MoEDAL. Green bands around MoEDAL limits express the hadronisation-model uncertainty. For open channel ATLAS/CMS searches uncertainty is too small to be visible. From [160].

The MoEDAL Collaboration plans to continue scanning MMTs exposed to heavy-ion collisions both in the LHC Run 3 and in the subsequent HL-LHC Run 4 looking for thermally produced monopoles. Assuming 2.5 nb^{-1} of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.52$ TeV and conservative theoretical assumptions, a ~20 GeV increase in sensitivity in HL-LHC heavy-ion run is expected [164].

4.2 MEDICI at FCC-hh

CERN is envisaging building a Future Circular Collider (FCC-hh) facility that will deliver 100 TeV pp collisions using a 100 km tunnel [165]. The Monopole and Exotics Detector Infrastructure for Colliding Ions (MEDICI) at the FCC-hh aspires to carry on the program of the MoEDAL-MAPP experiment at $\sqrt{s} = 100$ TeV. The MEDICI HIP detector takes the form of a polyhedral with radius 1 m equipped with the same passive detector technology as that used in MoEDAL with the important feature that no other material intervenes between the IP and the detector. Assuming DY monopole-pair production and applying the analysis procedures, parameters and calibration as for MoEDAL, monopoles with mass up to 25 TeV can be reached with for 3 ab^{-1} at the 100 TeV FCC-hh machine [116].

5. Summary

Highly ionising particles are predicted in various scenarios of New Physics with either single or multiple electric charges or even with isolated magnetic charges. There is a growing interest in searching for these states in LHC experiments, combining energy loss and time-of-flight information. The MoEDAL experiment, specialised in HIP detection, operates in a complementary way to the ATLAS and CMS detectors towards this direction. Customised triggers, track reconstruction algorithms and other tools have being developed to enhance the efficiency to HIPs in the LHC main experiments. Several studies show promising prospects for experiments to explore 'low' charges $\lesssim 10e$ in the ongoing Run 3 and the future HL-LHC runs.

Acknowledgments

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