Abstract

This thesis summarises four years of research aiming at revealing the prospects for detection of long-lived particles at the LHC. It contains results of four projects, which have been published as independent articles.

In the first project, the possibility to utilise the MoEDAL detector to search for charged long-lived particles is considered for the first time. MoEDAL is a small effectively background-free and mostly passive detector located at the IP8 of the LHC. It can detect a particle with charge Q, if its decay length is of the order of $\mathcal{O}(1\text{ m})$ and its velocity β satisfies $\beta \lesssim 0.15 \cdot |Q/e|$. This makes MoEDAL complementary to major general-purpose LHC experiments, i.e. ATLAS and CMS, which are sensitive only to particles with $\beta \gtrsim 0.5$. As a demonstration of the capabilities of the MoEDAL detector, a particular supersymmetric model is considered, in which a pair of gluinos ($\tilde{g}$) is produced, each of them decays to SM jets and a long-lived neutralino ($\tilde{\chi}_1^0$), which subsequently decays to a metastable stau ($\tilde{\tau}$) and an off-shell tau. Schematically: $pp \to \tilde{g}\tilde{g} \to \left(\tilde{\chi}_1^0 jj\right)\left(\tilde{\chi}_1^0 jj\right) \to (\tilde{\tau}_1 \tau^* jj)\,(\tilde{\tau}_1 \tau^* jj)$. For the considered scenario, it has been revealed that Run 3 MoEDAL ($L = 30\text{ fb}^{-1}$) can test regions in the gluino mass ($m_{\tilde{g}}$) vs. neutralino decay length ($c\tau_{\tilde{\chi}_1^0}$) parameter plane, which are beyond the reach of ATLAS. This interesting result inspired a whole series of studies.

In the second project, various pair-produced long-lived supersymmetric particles are studied: gluino $\tilde{g}$, stop $\tilde{t}$, five light-flavour squarks $\tilde{q} = (\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{b})$, wino- and higgsino-like charginos $\widetilde{W}, \tilde{h}$, and sleptons $\tilde{l}$. Moreover, doubly charged ($Q = \pm 2e$) scalars and fermions, transforming under $SU(2)_L$-singlet and triplet representations, are also considered. Except for $SU(2)_L$-triplet fermions, the MoEDAL detector is found to have worse sensitivity than ATLAS and CMS, mainly because of the lower amount of data available. However, the limits that MoEDAL can provide are complementary to the ones by ATLAS and CMS, due to completely different detector design and uncorrelated systematic uncertainties.

In the third project, a particular 1-loop radiative neutrino mass model is considered, which predicts the existence of long-lived scalar particles. Two versions of the model are studied, in the uncoloured version all BSM fields are singlets under $SU(3)_C$, while in the coloured version, they are promoted to colour-(anti)triplets. In the uncoloured version there are long-lived scalars $S^{\pm 2}$, $S^{\pm 3}$, and $S^{\pm 4}$, with charges $\pm 2e$, $\pm 3e$, and $\pm 4e$, respectively. There are also triply charged fermions, $F^{\pm 3}$, however, they are short-lived. The coloured version of the model also contains long-lived scalars: $S^{\pm 4/3}$, $S^{\pm 7/3}$, and $S^{\pm 10/3}$, with charges $\pm 4/3e$, $\pm 7/3e$, and $\pm 10/3e$, respectively. Possibility to detect long-lived particles in Run 3 and HL-LHC MoEDAL have been estimated and compared with the available limits from ATLAS and CMS collaborations. In the first part of the analysis, a model-independent detection reach of MoEDAL for multiply charged LLPs is obtained, where the lifetimes of BSM particles are treated as free parameters. It have been found that most of the parameter space accessible to Run 3 MoEDAL is already excluded by large general-purpose experiments. On the other hand, MoEDAL has a chance to detect multiply charged LLPs during the HL-LHC data-taking phase, but ATLAS is expected to provide better sensitivity. The second part of the analysis targets the possibility to constrain parameters of the specific radiative neutrino mass model considered in the project. In particular, the impact of the dimensionless coupling λ_5, responsible for lepton number violation, is studied. It have been found that for $\lambda_5 \sim 10^{-5}$ MoEDAL achieves the highest sensitivity, which roughly corresponds to the longest lifetime of $S^{\pm 4}$ ($\tilde{S}^{\pm 10/3}$).

The fourth project aims at providing a comprehensive overview of possibilities to detect charged LLPs at the LHC. Four types of particles are studied: scalars and spin-1/2 fermions transforming under the $SU(3)_C$ gauge group as singlets or triplets. All particles are assumed to be $SU(2)_L$-singlets and have integer electric charges, Q, in the range

$1e \leq |Q| \leq 8e$. Three different BSM search methods are considered: (i) large dE/dx searches for detector-stable charged LLPs in ATLAS and CMS, (ii) searches for charged LLPs in MoEDAL, (iii) diphoton resonance searches by ATLAS and CMS, targeting diphoton decays of positronium/quarkonium-like bound states formed by the new BSM particles. The sensitivity of MoEDAL is estimated with the procedure established during the previous three projects, i.e. by varying the mass and lifetime of BSM particles and calculating the expected number of signal events for Run 3 ($L = 30$ fb^{-1}) and HL-LHC ($L = 300$ fb^{-1}). In the case of ATLAS and CMS searches, the most recent analyses are recast in order to obtain 95% CL upper cross section limits, which are compared with theoretical calculations. A projection for Run 3 ($L = 300$ fb^{-1}) and HL-LHC ($L = 3$ ab^{-1}) is also made.

It has been found that large dE/dx searches are most sensitive for smaller electric charges $|Q| \lesssim (3-4)e$, depending on the type of the BSM particle, while for larger charges, $|Q| \gtrsim (4-5)e$, diphoton resonance searches provide the strongest detection reach. The sensitivity of Run 3 MoEDAL is found to be in between the expected bounds of the aforementioned two types of ATLAS/CMS searches. However, for the intermediate charges, $3e \lesssim |Q| \lesssim 7e$, MoEDAL might provide better sensitivity than major general-purpose experiments at the end of the HL-LHC phase, thanks to the background-free nature of MoEDAL's detector design.

The fourth project includes also an important discussion about the impact of photon-induced production processes on the correct interpretation of experimental results. It has been shown that for particles with $|Q| \gtrsim 4e$ photon fusion (and photon-gluon fusion for coloured particles) production cross section becomes comparable to that of the Drell-Yan process. This is an important result since the ATLAS and CMS collaborations did not take this effect into account, which resulted in an underestimation of experimental limits for multiply charged particles.