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Long-lived highly charged particles at Run 3 and High Luminosity LHC

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We investigate the discovery prospects for scalar and fermionic particles with electric charges 1e $\leq |Q| \leq$ 8e that are singlet under SU$(2)_L$. We calculate lower mass bounds for open channel production mode coming from ATLAS/CMS and MoEDAL experiments, and limits from searches for positronium-like bound states (closed channel) decaying to two photons. Open channel searches by ATLAS and CMS are more sensitive for 1e $\leq |Q| \leq$ 5e, while closed-channel searches prevail for 6e $\leq |Q| \leq$ 8e. Sensitivity of MoEDAL is comparable to large experiments for charges 4e $\leq |Q| \leq$ 7e, and has the potential to even outperform ATLAS and CMS during the HL-LHC phase. The predicted lower mass bounds for Run 3 LHC span from 590 (940) GeV for $|Q|$ = 1e to 2190 (2320) GeV for $|Q|$ = 8e for scalars (fermions). In case of the HL-LHC limits are 630 (990) GeV for $|Q|$ = 1e to 2480 (2620) GeV for $|Q|$ = 8e for scalar (fermionic) particles.

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1. Introduction

After the discovery of the Higgs boson in 2012 at the LHC, the focus of the particle physics community has shifted towards searches for new physics, the so-called *Beyond the Standard Model (BSM)* physics. Despite many efforts, no indsputable evidence for new physics has been found at the LHC so far, which has resulted in more interest in exotic theoretic scenarios, e.g. models predicting long-lived particles (LLPs) in the final states [1]. Long lifetimes may be caused by additional symmetries making new particles stable, small couplings, narrow mass splittings or heavy mediators. In this study we focus on multi-charged long-lived particles, that is, particles with electric charge up to 8 times the charge of proton/electron. Full results are described in [2]. In this article we discuss only particles that are singlets under $\mathrm{SU(3)_C}$.

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2. Models and production mechanism

In our study we introduce scalar ϕ and fermionic ψ fields representing particles with electrical charges $1e \leq |Q| \leq 8e$. We postulate that these fields are singlets under $\mathrm{SU(2)_L}$ and $\mathrm{SU(3)_C}$, and we extend the Standard Model Lagrangian $\mathcal{L}_{\mathrm{SM}}$ as: $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \left|D_\mu \phi\right|^2 - m^2 \left|\phi\right|^2 + \ldots$ for scalar particles and $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\bar{\psi}\gamma^\mu D_\mu \psi - m^2 \bar{\psi}\psi + \ldots$ for fermions. The covariant derivative is defined as $D_\mu = \partial_\mu - i g_Y Q B_\mu$, with B_μ being the $\mathrm{U(1)_Y}$ gauge field that, after spontaneous electro-weak symmetry breaking, should be written in terms of the weak mixing angle θ_W, Z-boson (Z_μ) and photon A_μ fields: $g_Y Q B_\mu = eQA_\mu - eQ \tan\theta_W Z_\mu$. The ellipses in the above equations stand for interactions between BSM and SM fields, leading to the decay of the new particles. Without these terms new BSM particles would be stable. In our study we want to remain as general as possible, so we do not explicitly specify these interactions, we rather assume they are small enough to guarantee that new particles are *collider stable*.

Multicharged LLPs can be produced at the LHC through *open-channel mode*, in which a BSM particle-antiparticle pair is produced and propagates through the detector. Processes of this kind are: Drell-Yan (DY) production with intermediate off-shell photon or Z boson, t-channel photon fusion, and exclusively for scalars a seagul diagram involving two initial state photons. The total pair production cross section as a function of mass and charge is shown in Fig. 1, where we can see that particles with higher electric charges are more likely to be produced. This is because production processes scale as $|Q|^2$ for DY and $|Q|^4$ for photon fusion. For $Q = \pm 1e$ the DY production is dominant, but when the charge increases, the contribution from photon fusion becomes the dominant component of the production cross section, as depicted for particles with $m = 1$ TeV in Fig.2. This is an important conclusion, since the experimental searches for charged LLPs interpreted their results only for DY production [3–6], which is subdominant for large electric charges.

In addition to open-channel production mode, we also investigate the possibility to search for signatures of a positronium-like bound state composed of BSM particle-antiparticle pairs, that decays to two photons. We call it *closed-production mode*.

3. ATLAS and CMS searches

ATLAS and CMS have performed several open channel searches for charged LLPs. ATLAS presented results for full Run 1 data (8 TeV, 20.3 fb^{-1}) [3], then updated it with 13 TeV, 36.1 fb^{-1} [4]. CMS conducted a study using combined 7 and 8 TeV data with 5.0 and 18.8 fb^{-1} integrated luminosity, respectively [5]. The newest analysis by CMS [6] was performed for 13 TeV, 2.5 fb^{-1}.

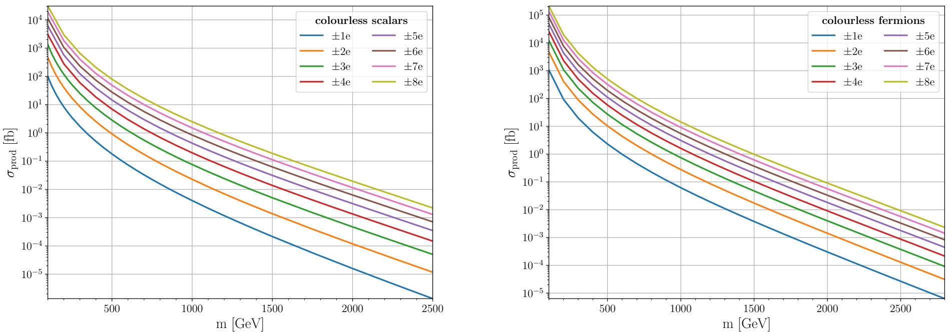

Figure 1: Pair-production cross section for scalars (left) and fermions (right), calculated at tree level.

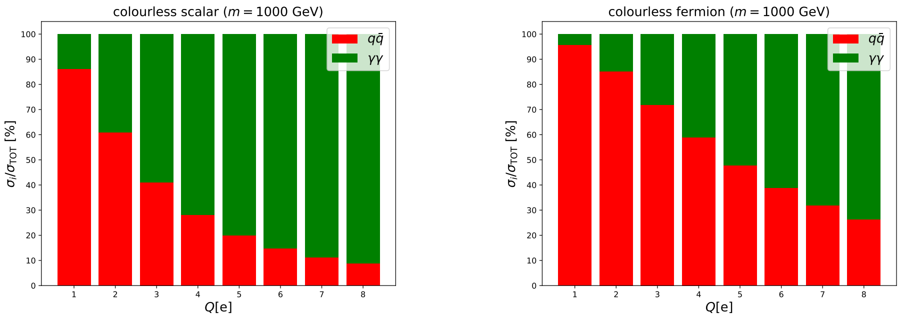

Figure 2: Contributions of the $q\bar{q}$ (green) and $\gamma\gamma$ (red) initial states to the production rate for the scalars (left) and fermions (right) with $m = 1$ TeV.

For particles with $|Q| > 2e$, the aforementioned analyses were interpreted by experimental collaborations only for colour-singlet fermions.

In our work we extend the methods of [7] and reinterpret the CMS analysis [6] to obtain lower mass bounds for both scalars and fermions, including photon fusion production processes. Our analysis is based on "Tracker + Time of Flight (TOF)" selection. We use MadGraph5 [8] with PDF set `LUXqed17`_plus_PDF4LHC15_nnlo_100 [9] for tree-level Monte Carlo generation. Next, we simulate the online selection, by imposing event selection on η and p_T of the BSM particles, taking into account that reconstruction algorithms assume $Q = \pm 1e$ resulting in underestimation of p_T for multi-charged particles. We also take care of the TOF requirement: in order to be correctly detected, the particle must move fast enough to be registered in both the Inner Detector and the Muon System before the next collision occurs. Then, we take event selection efficiency tables for offline selection provided in [10] and estimate the effective cross section. We use a procedure described in [11] to scale the experimental 95% CL limit (see e.g. citeParticleDataGroup:2010dbb, chapter 33) up to Run 3 LHC (HL-LHC) luminosity $L = 300$ fb^{-1} ($L = 3000$ fb^{-1}), we compare it with the effective cross section, and for each magnitude of the electric charge considered, we find value of the cross section that saturates the limit. It corresponds to a specific mass value, which is taken to be the lower mass bound for the considered type of BSM particles.

ATLAS and CMS conducted analyses that might be recasted to look for closed-channel production, out of which the di-photon searches are the most sensitive. The most recent CMS result [12], is based on 36fb^{-1} data at 13 TeV, while the newest ATLAS analysis [13] uses 139^{-1} data at 13 TeV. Since ATLAS results are based on a larger data set, we recast the latter analysis and

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adapt it to the studied model. We first calculate the effective cross section for the production of a positronium-like bound state decaying to two photons using a non-relatvistic approach, by postulating a potential $V(r) = -\alpha|Q|^2/r$, where $\vec{r}$ is the spatial separation between two BSM particles, Q is the electric charge, and α is the structure constant of electromagnetism. Putting it into the Schrödinger equation and using a narrow width approximation, we are able to calculate the desired cross section $\sigma_{pp\to\mathcal{B}\to\gamma\gamma} = \sigma_{pp\to\mathcal{B}} \cdot \mathrm{BR}_{\mathcal{B}\to\gamma\gamma}$. Next, we compare the results of our calculation to the experimental limit from [13], scaled for Run 3 and HL-LHC luminosity, and obtain lower mass bounds by finding the value of the cross section that saturates the limit, similarly to the open channel case.

4. MoEDAL search

MoEDAL is a small, mostly passive detector located in the LHCb cavern just outside the VELO detector. It was primarily designed and built to search for magnetic monopoles; however, in recent years it has been shown that MoEDAL is also able to detect charged LLPs through the open-channel mode with good sensitivity, sometimes comparable to ATLAS and CMS [14–16].

There are several reasons to include MoEDAL in this analysis: i) it is background free, which compensates for lower luminosity (10 times less than ATLAS); ii) unlike ATLAS and CMS, it is sensitive to slowly moving particles with $\beta < 0.15 * (|Q|/e)$; iii) its sensitivity always grows with the magnitude of the electric charge, while for ATLAS/CMS it decreases due to underestimation of p_T and TOF requirements.

To obtain lower mass bounds from MoEDAL we follow the approach developed in [14–16], and obtain the expected number of signal events for a given type of particle as a function of its mass and decay length. To compare with ATLAS/CMS results, we consider the quasi-stable particle limit, i.e. when the decay length is of the order of 1km. Since MoEDAL is a background-free experiment, we can calculate lower mass bounds for three very low signal thresholds: $N_{\mathrm{sig}} = 1, 2, 3$.

5. Preliminary results

The preliminary results of our study for Run 3 LHC are summarised in Tab.1. One can see that for small electrical charges, up to 5e (6e) for scalars (fermions), ATLAS/CMS open-channel searches are more sensitive than bound-state searches. Lower mass bounds span from 590 (940) GeV for charge 1e to 1240 (1710) GeV for charge 5e (6e) for scalars (fermions). Closed-channel searches provide stronger mass bounds for larger charges, 1410 (1970) GeV for charge 6e (7e) and 2190 (2320) GeV for charge 8e for scalars (fermions). There are several reasons behind the dependence of sensitivity of large LHC experiments on charge magnitude. Firstly, the signal efficiency for ATLAS and CMS peaks for particles with $|Q| = 2 - 3$e and drops for larger values, because of the TOF criterium (the particles are expected to be heavy, hence slow) and momentum underestimation. This effect is compensated by a higher production cross section, resulting in a moderate increase in sensitivity for larger charges. Bound state searches are insensitive for $|Q| < 3$e, because the probability of forming a positronium-like bound state is small, but it quickly grows for larger charges, resulting in very strong lower mass bounds: 2190 (2320) GeV for $|Q| = 8$e scalars (fermions). MoEDAL provides intermediate lower mass bounds, for small charges. For small charges they are lower than those of open-channel ATLAS/CMS analyses. For large electric charges the bounds are weaker than those of closed-channel searches. However, the sensitivity

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of MoEDAL detector always grows with charge, because its magnitude is directly connected to the detector acceptance. If particles have charges $|Q| > 6\frac{2}{3}$e, then they are no longer subject to the velocity constraint $\beta < 0.15 \cdot |Q|$. As a results for charges $5\text{e} \leq |Q| \leq 7\text{e}$, MoEDAL can a provide similar sensitivity as that of ATLAS and CMS. It is worth pointing out that the results from MoEDAL are obtained using totally a different experimental technique, hence it provides an independent BSM physics check from ATLAS and CMS.

Q	Lower mass bounds (scalar)				
	ATLAS/CMS $L = 300$ fb^{-1}		MoEDAL $L = 30$ fb^{-1}		
	open	closed	$N_{sig} = 3$	$N_{sig} = 2$	$N_{sig} = 1$
1	590	<100	<100	<100	<100
2	820	<100	210	240	300
3	990	<100	490	540	640
4	1130	370	770	840	970
5	1240	950	1010	1090	1230
6	1340	1410	1190	1270	1400
7	1440	1780	1300	1390	1540
8	1520	2190	1410	1490	1650

Q	Lower mass bounds (fermion)				
	ATLAS/CMS $L = 300$ fb^{-1}		MoEDAL $L = 30$ fb^{-1}		
	open	closed	$N_{sig} = 3$	$N_{sig} = 2$	$N_{sig} = 1$
1	940	<100	200	210	270
2	1210	<100	540	590	700
3	1400	130	880	950	1080
4	1520	640	1170	1250	1390
5	1630	1210	1390	1480	1630
6	1710	1590	1550	1640	1780
7	1800	1970	1660	1740	1890
8	1900	2320	1760	1850	1990

Table 1: Expected lower mass bounds for scalars (left) and fermions (right), recasted for Run 3 LHC [2].

Table 2 contains preliminary results for HL-LHC. The overall picture is similar, for charges 1-5e limits from the ATLAS/CMS open-channel analyses are more sensitive than those of the closed-channel searches, providing 630 (990) GeV lower mass bounds for 1e, and 1310 (1690) GeV for charge 5e for scalar (fermionic) particles. For larger charges, the lower mass bound provided by the closed-channel searches are the strongest, spanning from 1710 (1880) GeV for charge 6e, up to 2480 (2620) GeV for charge 8e, for scalars (fermions). For charges 3e and 7e MoEDAL has a comparable sensitivity as the LHC experiments. Interestingly, for charges 4-6e, MoEDAL becomes even more sensitive than ATLAS and CMS, e.g. for scalar particles with charge 5e, the limit from MoEDAL is 1490 GeV for $N_{sig} = 3$, while for open and closed searches at ATLAS/CMS the limits are 1310 GeV and 1270 GeV, respectively. With the increase of total luminosity, not only the signal but also the SM background is enhanced, which constrains the rise of sensitivity to BSM Physics. However, since MoEDAL is background free, it is not influenced by this effect. Nevertheless, we stress that our results for HL-LHC are more speculative, because we assume Run 3 detector setup.

6. Conclusions and outlook

In our study we considered very general models of BSM particles that assumed only their quantum numbers and long lifetime. We considered scalar and fermionic particles with electric charges ranging from $\pm 1e$ to $\pm 8e$ that are singlets under SU(2)$_L$. In this article we described SU(3)$_C$ singlet particles, analysis for coloured particle will be included in the final article [2].

We studied both open and closed channel production modes, where the latter mean production of positronium-like bound states. We have recasted ATLAS and CMS analyses for $L = 300$ fb^{-1} and $L = 3000$ fb^{-1}, and performed simulation of MoEDAL for Run 3 LHC ($L = 30$ fb^{-1}) and HL-LHC ($L = 300$ fb^{-1}).

Q	Lower mass bounds				
	ATLAS/CMS $L = 3000$ fb^{-1}		MoEDAL $L = 300$ fb^{-1}		
	open	closed	$N_{SIG} = 3$	$N_{SIG} = 2$	$N_{SIG} = 1$
1	630	<100	<100	<100	120
2	870	<100	430	480	580
3	1060	160	850	930	1070
4	1190	770	1210	1300	1460
5	1310	1270	1490	1580	1740
6	1410	1710	1670	1760	1910
7	1510	2070	1790	1890	2050
8	1600	2480	1910	2000	2170

Q	Lower mass bounds				
	ATLAS/CMS $L = 3000$ fb^{-1}		MoEDAL $L = 300$ fb^{-1}		
	open	closed	$N_{sig} = 3$	$N_{sig} = 2$	$N_{sig} = 1$
1	990	<100	380	420	540
2	1280	<100	900	990	1130
3	1470	220	1340	1430	1580
4	1590	920	1660	1750	1900
5	1690	1430	1890	1980	2130
6	1780	1880	2040	2120	2280
7	1880	2250	2160	2240	2390
8	1980	2620	2260	2350	2500

Table 2: Expected lower mass bounds for scalars (left) and fermions (right), recasted for HL-LHC [2].

For charges 1-5e, ATLAS/CMS open-channel searches are more sensitive than closed-channel analyses, while for charges 6-8e the latter prevails. The sensitivity of MoEDAL always grows with the magnitude of electric charge, and remains inferior for small and large values. However, for intermediate charges, e.g. 5-7e (3-7e) for Run 3 (High Lumi) LHC, the sensitivity of MoEDAL becomes comparable to that of ATLAS and CMS. HL-LHC MoEDAL has a chance to outcompete large experiments, e.g. the MoEDAL limit for fermions with $|Q| = 6e$ is 2040 GeV for $N_{sig} = 3$, while the best ATLAS/CMS limit is 1880 GeV. If we require less signal events at MoEDAL, the difference becomes even larger. However, in our analysis for HL-LHC we assume unchanged detector setups, which makes the result more speculative.

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