Simple Standard Model Extension by Heavy Charged Scalar

E. Boos\textsuperscript{1,2}, I. Volobuev\textsuperscript{1,2}

\textsuperscript{1}Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University  
Leninskie Gory, 119991, Moscow, Russia  
\textsuperscript{2}Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory  
119991, Moscow, Russia

Abstract

We consider a Standard Model extension by a heavy charged scalar gauged only under the $U_Y(1)$ weak hypercharge gauge group. Such an extension, being gauge invariant with respect to the SM gauge group, is a simple special case of the well known Zee model. Since the interactions of the charged scalar with the Standard Model fermions turn out to be significantly suppressed compared to the Standard Model interactions, the charged scalar provides an example of a long-lived charged particle being interesting to search for at the LHC. We present the pair and single production cross sections of the charged boson at different colliders and the possible decay widths for various boson masses. It is shown that the current ATLAS and CMS searches at 13 TeV collision energy lead to the bounds on the scalar boson mass of about 400 GeV. The limits are expected to be much larger for higher collision energies and, assuming 15\,ab\textsuperscript{-1} integrated luminosity, reach about 4 TeV at future 27 TeV LHC thus covering the most interesting mass region.

1 Introduction

With the discovery of the Higgs boson at the LHC, the Standard Model (SM) was completed in the sense that all the predicted particles have been found and all the interaction structures have been fixed. However, not all the interactions in the gauge and Higgs sectors are confirmed experimentally. The Standard Model is based on the fundamental principles such as gauge invariance, the absence of chiral anomalies, unitarity and renormalizability. It is a common knowledge that the SM works extremely well explaining an enormous amount of experimental facts and results. However, because of a number of theoretical problems such as the hierarchy problem and the inability to explain the presence of Dark Matter or the nature of CP violation,
the SM is considered as a sort of effective theory describing phenomena up to the electroweak or TeV energy scale. A large number of various experimentally allowed beyond the SM models and scenarios are proposed motivating intensive searches for new physics in the terrestrial and space experiments, in particular, at the LHC. However, up to now no convincing results confirming any concrete BSM direction have been obtained.

Among various objects predicted by new physics models a special attention has been recently paid to the so-called HSCP (heavy stable charged particles) or LLP (long-lived particles). Various SM extensions predict the existence of such particles [1]-[13]. A number of searches for LLP and HSCP have been performed at the Tevatron and the LHC [14]-[19].

In this paper we discuss shortly a very simple SM extension by a charged scalar boson interacting with the $U_Y(1)$ weak hypercharge gauge boson and potentially giving an example of a long-lived charged particle. Such a model from rather different perspectives has been considered in paper [20] and quite recently in paper [21]. This SM extension by the extra charged scalar can be naturally called csSM.

Generic SM extensions by an arbitrary number of Higgs singlets and doublets were considered by P. Langacker in his famous review paper [22]. We consider in more detail one particular case with an extra complex scalar field $S$ interacting in a gauge invariant manner only with the $U_Y(1)$ weak hypercharge gauge field and with the Higgs field. The scalar field potential of the model coincides with that of the SM extension by singlet complex scalar with $U(1)$ symmetry discussed in paper [23], where this scalar field couples only to the Higgs field and is shown to give a reliable explanation of the cold dark matter. In our model we identify this $U(1)$ symmetry with the weak hypercharge $U_Y(1)$ symmetry, which makes the complex scalar electrically charged and forbids its interpretation as a dark matter particle. The model (csSM) can be viewed as a simplified variant of the Zee model [24]. The original Zee model includes an extra scalar $SU(2)$ doublet and gives rise to a number of intriguing interactions in the lepton sector, which lead to processes with lepton number violation [24] (see a recent discussion in [25]), and to radiatively induced Majorana neutrino masses [26, 27]. The parameter space of the Zee model allowed by the experimental data has been recently worked out [28] showing that the masses of the additional scalars in the range of a few hundreds GeV are possible, but they have to lie in the range below a few TeV.
## 2 The Minimal Model

The minimal part of the SM Lagrangian extended by the scalar field carrying a non-trivial representation of the $U_Y(1)$ weak hypercharge group includes the terms of dimension not greater than four. If one requires, in addition, lepton number conservation, as it takes place in the SM, the simplest model Lagrangian contains the kinetic term and the mass and self-coupling terms of the charged scalar boson field:

$$L_S = D^\mu S^* D^\nu S - V(S),$$

where the covariant derivative is given by $D_\nu = \partial_\nu - ig_1 Y_2 B_\nu$, $B_\nu$ being the SM weak hypercharge gauge field, $g_1$ is the SM $U_Y(1)$ coupling and $Y_S$ is the weak hypercharge of the new scalar field $S$.

The potential $V(S)$ may have, in general, the following gauge invariant form

$$V(S) = |\mu_S|^2 |S|^2 + \lambda_S (|S|^2)^2 + \lambda_{\Phi S} |\Phi|^2 |S|^2,$$

where $|\mu_S|^2$ is a mass parameter, $\lambda_S$ is the S-boson quartic self-coupling, $\lambda_{\Phi S}$ is the coupling of the scalar S to the Higgs field. The last term has been included into the potential, because it contributes to the mass term after spontaneous symmetry breaking.

Let us stress a few points here:

- The $S$-field is a charged field, so it cannot have a nontrivial vacuum expectation value. Therefore, it cannot influence the value the SM $\rho$-parameter.

- Since the gauge boson $B$ is expressed in the SM as a linear combination of the photon and the Z-boson fields, $B_\nu = A_\nu \cos \theta_W - Z_\nu \sin \theta_W$, the S-scalar couples to the photon with the constant $\frac{e Y_2}{2}$, where the electromagnetic constant $e$ is equal to $g_1 \cos \theta_W$, as it is usual in the SM. The S-scalar is an electrically charged field. As will be shown later, the hypercharge of the $S$-field is equal to two with the electric charge being equal to one ($Q_S = Y_S/2$). Thus, we denote the $S$-field as $S^-$ and the complex conjugate field $S^*$ as $S^+$.

- The mass term parameter $\mu_S$ could be equal to zero. In this case the mass of the S-boson comes from the interaction with the Higgs field in a similar way as for the other SM particles. In this case the mass of the S-boson is equal to $M_S^2 = \lambda_{\Phi S} v^2/2$ and its natural value is of the order of hundred GeV.
If only the dimension 4 or less operators are included, there are no gauge invariant operators containing the charged scalar and the quark fields. We did not include into the Lagrangian the gauge invariant operators of dimension four, which describe the interaction of the S-scalar with the SM lepton fields giving lepton number violating vertices, they will be discussed shortly later. As a result, in this approximation the S-scalar is a stable particle.

In a simplest variant of the model the last property leads to the prediction of a stable charged scalar boson. Obviously, if the mass of the boson is of the order of a few hundreds GeV, the existence of the boson will not contradict the limits from precision electroweak measurements, in particular, the limits on S and T-parameters \[28\].

### 3 Pair Production Cross Sections

Charged scalars can be produced at the LHC in pairs via the Drell-Yan process in collisions of quark-antiquark pairs as well as in the gluon-gluon fusion. The production cross section as a function of the charged scalar mass is shown in Fig.1 for three different proton-proton collision energies \(\sqrt{s} = 13, 14, 27\) TeV.\[4\] One can see from Fig.1 that the cross section grows with the collider energy. For the Drell-Yan process initiated by the quark-antiquark collisions the cross section is about 10 \(fb\) for 200 GeV mass for the energy 13, 14 TeV. More accurately the LO cross section is about 6.8 \(fb\) and 7.6 \(fb\) at 13 TeV and 14 TeV respectively with the NNLO K-factor for the Drell-Yan quark-antiquark type of processes (Fig.1a) of about 1.18 \[31, 32, 33\]. The cross section rapidly goes down with the increase of the scalar mass. For example, for 1 TeV scalar mass the cross section is about \(5 \times 10^{-2}\) \(fb\) even for the energy 27 TeV expected for high energy (HE) regime of the LHC operation. This would lead to the production of a few hundreds charged scalar pairs in the case of a very high luminosity of about 15 \(ab^{-1}\). The production in quark-antiquark pair collisions was also discussed in paper \[21\].

However, there is an additional contribution to the pair production cross section, which comes from the gluon-gluon fusion mechanism and which was not mentioned in \[21\]. Two gluons produce a virtual SM Higgs boson via the top loop triangle diagram and the virtual Higgs boson decays to a pair.

---

\[1\]The computations here and below have been performed by means of the CompHEP program \[29\], into which the Feynman rules obtained from the Lagrangian under consideration by means of the LanHEP code \[30\] were implemented.
Figure 1: Charged scalar pair production cross section via photon and Z-boson exchange in quark anti-quark annihilation a) and via Higgs boson exchange in gluon-gluon fusion b) at $\sqrt{s} = 13, 14, 27$ TeV as a function of its mass.

...search mechanism.

The pair production cross sections from the gluon-gluon fusion mechanism presented in Fig.1b refer to the case, where the total S-boson mass is generated by the Higgs mechanism. However, as it was noted after formula (2), there can exist a proper mass term. In this case the cross section should be multiplied by the factor $\xi^2$, $\xi = \lambda_{\Phi S} v^2 / 2 M_S^2 < 1$ denoting the part of the S-boson mass squared coming from the Higgs mechanism. Thus, the pair production cross sections presented in Fig.1b should be considered as the maximal possible for given S-boson masses. If the S-boson is discovered, measurements of its Drell-Yan production cross section will allow one to determine the value of the parameter $\xi$ and thus to find out, whether there exists another mass generation mechanism besides the SM Higgs mechanism.

Searches for stable charged particles presented in [19] at the LHC energy 13 TeV give the lowest bound on the production cross section of about $4 \, fb - 2 \, fb$ for the luminosity 2.5 $fb^{-1}$. This corresponds to 10 – 5 events...
expected for the stable charged particle production. Therefore, one gets an upper bound on the charged scalar mass of about 300 GeV and 390 GeV corresponding to 10 and 5 expected events respectively summing up the mentioned contributions from the $q\bar{q}$ and gluon-gluon sub-processes to the charged scalar production cross section.

Assuming the same lowest number of expected events from 10 to 5 one can estimate from the computed cross sections the expected upper limits on the boson mass for various cases of collision energies and luminosities. So, for the proton-proton collision energy 14 TeV and the luminosity $300 \, fb^{-1}$ the expected mass limits are calculated to be about 1000 GeV and 1150 GeV respectively. For the benchmark energy 27 TeV and the luminosity $15 \, ab^{-1}$ the limits on the charged scalar mass are expected to be 3.1 TeV and 3.4 TeV.

For completeness the production cross section in $e^+e^-$ collisions is shown in Fig.2 as a function of collision energy for the scalar mass 100 TeV, 200 TeV, and 300 GeV. The level of the cross section in Fig.2 is large enough giving good prospects to study the charged scalars in detail, if its mass is in the kinematically accessible range. Surely, if the scalar in that mass range having the specified production cross sections (Fig.1) had existed, it would have been already discovered at the LHC.

Figure 2: Charged scalar pair production cross section in $e^+e^-$ collisions as a function of collision centre of mass energy for the scalar mass $M_S = 300, 400, 500$ GeV.

4 Interactions with Leptons and Quarks

If only the above discussed terms (operators) of dimension 4 had been present in the extended SM Lagrangian, the charged scalar boson would not have had interactions leading to its decay and/or single production, and therefore
the boson would have been stable. However, gauge invariant operators of
dimension four and five involving the charged scalar field can be constructed,
which lead to decays of the boson. We will first discuss the gauge invariant
terms of dimension four involving the lepton fields.

The transformation properties of the S-scalar field under the gauge group
of the SM allow the existence of the following dimension 4 terms describing
the coupling of the S-scalar to leptons [24]:

\[ L_{S,\text{leptons}} = \left( f_{12}(\bar{\mu}_L \nu^c_e - \bar{e}_L \nu^c_\mu) + f_{13}(\bar{\tau}_L \nu^c_e - \bar{e}_L \nu^c_\tau) + f_{23}(\bar{\tau}_L \nu^c_\mu - \bar{\mu}_L \nu^c_\tau) \right) S^- + h.c., \]

(3)

where \( \nu^c \) denotes the charge conjugate neutrino field. Obviously, these in-
teractions lead to lepton number violation in the S-scalar decay processes.
However, it turns out that at low energies this lepton number viola-
tion is very small due to the large S-scalar mass. Moreover, one can show with
the help of Fierz identities that the S-scalar mediated interactions of lep-
tons conserve lepton number and can be brought to the standard form
of Fermi’s four fermion interaction, which imposes constraints on the cou-
pling constants \( f_{ik} \) [35, 36]. The results of these papers with the present
day values of the Fermi constant [37, 38] and the probabilities of the de-
cays \( \tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau, \tau \rightarrow e \bar{\nu}_e \nu_\tau, \mu \rightarrow e \gamma \) [38] give \( |f_{12}|^2 < 3 \times 10^{-6} G_F M_S^2, \)
\( |f_{13}|^2, |f_{23}|^2 < 2.8 \times 10^{-2} G_F M_S^2 \). A full parameter scan of the Zee model car-
ried out in paper [28] and including a fit of the neutrino mixing angles and
mass differences gives the constraints on the coupling constants \( f_{ik} \), which
turn out to be much more stringent: \(|f_{12}|, |f_{13}|, |f_{23}| < 10^{-6}\). For these values
of the coupling constants the partial widths of the S-scalar decays to leptons
are less than 0.5 eV for the S-scalar mass up to 5 TeV.

The interaction of the S-scalar with the quark fields can take place only
due to gauge invariant terms of dimension five or larger. Here we will discuss
the gauge invariant terms of dimension five involving the quark fields. To
introduce the notations let us first recall the well-known fact that, in the SM,
the most general interaction Lagrangian of the Higgs field and the quark fields
includes a mixing of the fermion fields from various generations:

\[ L_{\text{Yukawa}} = -\Gamma_{d}^{\prime} \bar{Q}_{L}^{\prime} i \Phi d_{R}'^{j} - \Gamma_{u}^{\prime} \bar{Q}_{L}^{\prime} i \Phi C u_{R}'^{j} + h.c., \]

(4)

where \( \Gamma_{u,d} \) are generically possible mixing coefficients with up- and down-
type quark fields. The Higgs and the conjugate Higgs \( SU_L(2) \) doublet fields
in the unitary gauge are

\[ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \quad \text{and} \quad \Phi^C = i\sigma^2 \Phi^\dagger = \frac{1}{\sqrt{2}} \begin{pmatrix} v + h \\ 0 \end{pmatrix} \]

7
After spontaneous symmetry breaking Lagrangian (4) in the unitary gauge takes the following form

$$L_{Yukawa} = - \left( M_{ij}^d \bar{d}^i_L d^j_R + M_{ij}^u \bar{u}^i_L u^j_R + h.c. \right) \cdot \left( 1 + \frac{h}{v} \right), \quad (5)$$

where $M_{ij} = \Gamma_{ij}v/\sqrt{2}$ is a generic mass mixing matrix.

In order to obtain the physical mass eigenstates of quarks, the matrices $M_{ij}$ should be diagonalized by unitary transformations of the left- and right-handed quark fields:

$$d'_{L_i} = (U_{dL}^d)_{ij} d_{L_j}; \quad d'_{R_i} = (U_{dR}^d)_{ij} d_{R_j}; \quad u'_{L_i} = (U_{uL}^u)_{ij} u_{L_j}; \quad u'_{R_i} = (U_{uR}^u)_{ij} u_{R_j} \quad (6)$$

$$U_{uL}^u (U_{uL}^u)^\dagger = 1, \quad U_{uR}^u (U_{uR}^u)^\dagger = 1. \quad (7)$$

The matrices $U$ are chosen such that

$$(U_{L}^u)^\dagger M_u U_{R}^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}; \quad (U_{L}^d)^\dagger M_d U_{R}^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

As it is well known, the SM neutral currents remain the same after the above unitary transformation providing the absence of the FCNC at three level. However, after the transformation to the physical degrees of freedom

$$u' \rightarrow (U_{uL}^u)^\dagger u, \quad d' \rightarrow (U_{uL}^d)^\dagger d,$$

the charged currents get a unitary matrix in front of the down quark fields,

$$V_{CKM} = (U_{L}^u)^\dagger U_{L}^d,$$

called the Cabbibo-Kobayashi-Mascawa (CKM) mixing matrix. Similarly, after the unitary transformation of the lepton fields, one gets the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix (PMNS) in front of the massive neutrino fields in the charged leptonic currents.

In a similar manner one can write a gauge invariant Lagrangian for the interaction of the SM fermions with the charged scalar boson:

$$L_{S, quarks} = - \frac{1}{\Lambda} Q_L \lambda_u \Phi u_R^j S^+ - \frac{1}{\Lambda} Q_L \lambda_d \Phi^C d_R^j S^+ + h.c., \quad (8)$$

where $\lambda_{u,d}$ are dimensionless matrices and $\Lambda$ is the scale of "new physics". After the substitution of the Higgs field and the transformation (6) of the quark
fields to the mass eigenstates, one gets the following interaction Lagrangian in the unitary gauge

\[ L_{S,\text{quarks}} = -\frac{1}{\Lambda} \left[ \bar{d} \cdot V_u \frac{1 + \gamma_5}{2} u \cdot S^- + \bar{u} \cdot V_d \frac{1 + \gamma_5}{2} d \cdot S^+ + \text{h.c.} \right] \cdot \left( 1 + \frac{h}{v} \right) \]

where \( V_d = V_{CKM}(U^d_L)^\dagger \mu_d U^d_R \) and \( V_u = V_{CKM}(U^u_L)^\dagger \mu_u U^u_R, \) \( \mu_d,u = \lambda_d,u v/\sqrt{2}. \)

The elements of matrices \( \mu_{d,u} \) have the dimension of mass, the matrices are not diagonal in general, they may contain complex phases leading to CP violation. Here we do not discuss such a general case.

Let us consider a simple particular case, where matrices \( \mu_{d,u} \) are proportional (or equal) to the mass matrices \( M^{ij}. \) In this case matrices \( V_{d,u} \) contain the products of the CKM matrix or its hermitian conjugated matrix and the diagonal mass matrices for the up- and down-type quarks. The interactions of the two first quark generations are therefore naturally suppressed by the corresponding quark masses allowing to overcome the FCNC constrains \([28].\) The dominating part is the interaction of the charged scalar with the top-bottom quark charged current. In fact, the interaction structure is very similar to that of the charged Higgs in the 2HDM or MSSM taken at \( \tan \beta = 1 \) (see \([39, 40, 41, 42, 43].\) However, in comparison with the 2HDM or MSSM the interaction vertices are suppressed by the factor of the order of \( v/\Lambda. \)

It is worth noting that interactions similar to those described by formulas \([8] \) and \([9] \) can exist also in the lepton sector. If the neutrinos are considered to be massless, the corresponding formulas will include only the terms similar to the second ones in formulas \([8] \), \([9] \). If the neutrinos are considered to be massive, they will be absolutely similar to formulas \([8] \), \([9] \). However, it is natural to expect the entries of the corresponding mass matrices \( \mu_{\nu,e} = \lambda_{\nu,e} v/\sqrt{2} \) to be of the order of neutrino and charged lepton masses, and in this case the contribution of these terms to the S-scalar decay processes is negligible compared with the decay to t-quark.

The dominating production channel \( pp \to t + S^- + X \) in the case of the scalar boson being heavier than the top quark is similar to the charged Higgs case with the suppression factor \( (v/\Lambda)^2 \). If the scale is not very large, the production cross section could be large enough to be interesting for searches at the LHC as shown in Fig.3. The NLO corrections make the result much more stable with respect to the factorization/renormalization scale variation while the NLO K-factor is found to vary in the range of 1.4 or less \([44].\) The single production cross section decreases quadratically with the scale and becomes smaller than the considered above pair production at the scale greater than a few tens TeV.

As was mentioned, the mass of the S-scalar in the csSM may arise from the
Figure 3: Charged scalar single production cross section at 14 TeV (a) and at 27 TeV (b) pp collision energy as a function of the scalar mass for three values of the scale $\Lambda$: 2 TeV, 6 TeV, and 10 TeV.

SM Brought-Engler-Higgs (BEH) mechanism. In this case the natural values for the scalar mass would be in the range of the Higgs vacuum expectation value. The scale $\Lambda$ may originate from completely different physics and could be much larger. The $S$-scalar decays to the top-bottom pair with nearly 100% probability. The decay width is proportional to $M_{top}^2/\Lambda^2 \cdot M_S \cdot \beta^3$ ($\beta = \sqrt{1 - M_{top}^2/M_S^2}$) and therefore increases with the scalar boson mass and rapidly decreases with the growth of the scale $\Lambda$. This is demonstrated in Fig. 4. One can see that for the energy scale $\Lambda$ in TeV range the scalar boson

Figure 4: Charged scalar width as a function of its mass at new physics scale in TeV range (a),(b) and in GUT range (c).

decay width varies from $10^{-1}$ GeV to $10^{-4}$ GeV (left plot). However if the
scale is in the GUT range (right plot) the width becomes very small $10^{-24}$ GeV – $10^{-27}$ GeV. In this case the life time of the scalar might be 0.1 sec or more leading to a microscopic travel distance before the decay. For the case of large scales $\Lambda$ the single boson production cross section becomes negligible at colliders, and the charged scalars may be produced only in pairs. This corresponds to the case of long-lived charged particles with the discussed above current and expected limits on the charged scalar boson mass.

For rather small scales in TeV range the charged scalar may be produced either singly or in pairs with subsequent decays into top and bottom quarks. However both production cross sections are significantly smaller than the top pair and the single top cross sections. In this case a careful analysis is needed in order to estimate, whether or not a small signal of the charged scalar could be extracted from much larger backgrounds at the LHC.

5 Concluding Remarks

A simple gauge invariant extension of the SM considered in this study may provide an example of a heavy stable charged (HSCP) or long-lived (LLP) particle. The model contains, in addition to the SM fields, only the charged scalar field gauged only under the $U_Y(1)$ weak hypercharge gauge group. The model can be considered as a simple special case of the well known Zee model. In the simplest case, assuming the presence of only dimension 4 operators and lepton number conservation, the gauge invariant Lagrangian of the model contains only the gauge interaction of the charged scalar and its interaction with the SM Higgs field. Since in this case one cannot construct gauge invariant interactions of the scalar with the SM fermions, the charged scalar boson is a stable particle. The main production mode is the charged scalar Drell-Yan pair production via the photon and Z-boson exchange in quark-antiquark and via the SM Higgs exchange in gluon-gluon collisions. From the computed cross sections and the results of searches for HSCP at the LHC one can estimate the current bounds on the charged scalar boson mass to be about 400 GeV and the expected bounds at higher collision energies and larger luminosity. In particular, at future 27 GeV LHC with the luminosity of $15 \text{ ab}^{-1}$ the bound is expected to reach 3.4 TeV covering the most interesting mass regions following from the overall parameter space analysis for the Zee model as found in [28]. Allowing higher dimensional operators and violation of the lepton number one can add to the Lagrangian the interactions of charged scalar field with the SM fermions leading to decays of the scalar boson. The dimension 4 operators containing lepton fields violate lepton number conservation, and the corresponding coupling strengths


are significantly constrained by the muon decay, the neutrino mass measurements and oscillation data. The dimension 5 operators in the quark sector are naturally proportional to the fermion masses and the CKM matrix elements. The dominating decay mode of the charged scalar boson is, therefore, the decay to the top and the bottom quarks and the dominating single boson production channel is the associated production with the top quark. This is rather similar to the charged Higgs production and decay in 2HDM or MSSM at $\tan \beta = 1$, although with an additional suppression by the factor $\frac{v^2}{\Lambda^2}$. The single production cross section varies from $10^{-5} \text{ fb}$ to $10^{-5} \text{ fb}$ in the mass range between 200 GeV and 4 TeV and in the range of the scale $\Lambda$ from 2 TeV to 30 TeV. The decay width depends strongly on the scalar boson mass and the scale $\Lambda$ and for the TeV scale regions takes values from 100 MeV to 0.1 MeV or so. If the scale is much larger, say, in the GUT range, the decay width to the top and bottom quarks becomes very small. In this case the width could be dominated by lepton number violating decays, but this obviously depends on the small lepton violating coupling strengths.

We did not discuss cosmology issues of the csSM model. This is planned to be presented in a separate study.

6 Acknowledgements

We thank Viatcheslav Bunichev, Eduard Rahmetov, and Tatiana Tretyakova for useful discussions. We are grateful to the Russian Science Foundation for support.

References

[1] G. R. Farrar and P. Fayet, “Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry,” Phys. Lett. 76B, 575 (1978).

[2] M. Drees and X. Tata, “Signals for heavy exotics at hadron colliders and supercolliders,” Phys. Lett. B 252, 695 (1990).

[3] M. Dine, A. E. Nelson and Y. Shirman, “Low-energy dynamical supersymmetry breaking simplified,” Phys. Rev. D 51, 1362 (1995).

[4] A. Kusenko and M. E. Shaposhnikov, “Supersymmetric Q balls as dark matter,” Phys. Lett. B 418, 46 (1998).
[5] P. H. Frampton and P. Q. Hung, “Longlived quarks?,” Phys. Rev. D 58, 057704 (1998).

[6] N. Arkani-Hamed and S. Dimopoulos, “Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC,” JHEP 0506, 073 (2005).

[7] G. F. Giudice and A. Romanino, “Split supersymmetry,” Nucl. Phys. B 699, 65 (2004) Erratum: [Nucl. Phys. B 706, 487 (2005)].

[8] D. Fargion, M. Khlopov and C. A. Stephan, “Cold dark matter by heavy double charged leptons?,” Class. Quant. Grav. 23, 7305 (2006).

[9] M. J. Strassler and K. M. Zurek, “Echoes of a hidden valley at hadron colliders,” Phys. Lett. B 651, 374 (2007).

[10] B. C. Allanach, M. A. Bernhardt, H. K. Dreiner, C. H. Kom and P. Richardson, “Mass Spectrum in R-Parity Violating mSUGRA and Benchmark Points,” Phys. Rev. D 75, 035002 (2007).

[11] M. Fairbairn, A. C. Kraan, D. A. Milstead, T. Sjostrand, P. Z. Skands and T. Sloan, “Stable massive particles at colliders,” Phys. Rept. 438, 1 (2007).

[12] C. W. Bauer, Z. Ligeti, M. Schmaltz, J. Thaler and D. G. E. Walker, “Supermodels for early LHC,” Phys. Lett. B 690, 280 (2010).

[13] K. Huitu, K. Kannike, A. Racioppi and M. Raidal, JHEP 1101 (2011) 010 [arXiv:1005.4409 [hep-ph]].

[14] V. M. Abazov et al. [D0 Collaboration], “Search for Long-Lived Charged Massive Particles with the D0 Detector,” Phys. Rev. Lett. 102, 161802 (2009).

[15] T. Aaltonen et al. [CDF Collaboration], “Search for Long-Lived Massive Charged Particles in 1.96 TeV pp Collisions,” Phys. Rev. Lett. 103, 021802 (2009).

[16] G. Aad et al. [ATLAS Collaboration], “Summary of the ATLAS experiments sensitivity to supersymmetry after LHC Run 1 interpreted in the phenomenological MSSM,” JHEP 1510, 134 (2015).

[17] V. Khachatryan et al. [CMS Collaboration], “Constraints on the pMSSM, AMSB model and on other models from the search for long-lived charged particles in proton-proton collisions at sqrt(s) = 8 TeV,” Eur. Phys. J. C 75, no. 7, 325 (2015).
[18] M. Aaboud et al. [ATLAS Collaboration], “Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector,” arXiv:1710.04901 [hep-ex].

[19] V. Khachatryan et al. [CMS Collaboration], “Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV,” Phys. Rev. D 94, no. 11, 112004 (2016).

[20] M. S. Bilenky and A. Santamaria, “One loop effective Lagrangian for a standard model with a heavy charged scalar singlet,” Nucl. Phys. B 420 (1994) 47.

[21] Q. H. Cao, G. Li, K. P. Xie and J. Zhang, “Searching for Weak Singlet Charged Scalar at the Large Hadron Collider,” arXiv:1711.02113 [hep-ph].

[22] P. Langacker, “Grand Unified Theories and Proton Decay,” Phys. Rept. 72, 185 (1981).

[23] V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf and G. Shaughnessy, “Complex Singlet Extension of the Standard Model,” Phys. Rev. D 79, 015018 (2009).

[24] A. Zee, “A Theory of Lepton Number Violation, Neutrino Majorana Mass, and Oscillation,” Phys. Lett. 93B, 389 (1980) Erratum: [Phys. Lett. 95B, 461 (1980)].

[25] N. H. Thao, L. T. Hue, H. T. Hung and N. T. Xuan, “Lepton flavor violating Higgs boson decays in seesaw models: new discussions,” Nucl. Phys. B 921, 159 (2017).

[26] A. Zee, “Quantum Numbers of Majorana Neutrino Masses,” Nucl. Phys. B 264, 99 (1986).

[27] K. S. Babu, “Model of 'Calculable' Majorana Neutrino Masses,” Phys. Lett. B 203, 132 (1988).

[28] J. Herrero-Garcia, T. Ohlsson, S. Riad and J. Wirén, “Full parameter scan of the Zee model: exploring Higgs lepton flavor violation,” JHEP 1704, 130 (2017).

[29] E. Boos et al., CompHEP 4.4: automatic computations from Lagrangians to events, Nucl. Instrum. Meth. A534, 250 (2004)
[30] A. Semenov, “LanHEP: A package for automatic generation of Feynman rules from the Lagrangian. Version 3.2,” Comput. Phys. Commun. 201, 167 (2016);
A. V. Semenov, “LanHEP: A Package for automatic generation of Feynman rules in gauge models,” hep-ph/9608488.
A. V. Semenov, “Automatic generation of Feynman rules from the Lagrangian by means of LanHEP package,” Nucl. Instrum. Meth. A 389, 293 (1997).

[31] R. Hamberg, W. L. van Neerven and T. Matsuura, “A complete calculation of the order $\alpha - s^2$ correction to the Drell-Yan $K$ factor,” Nucl. Phys. B 359, 343 (1991) Erratum: [Nucl. Phys. B 644, 403 (2002)].

[32] C. Anastasiou, L. J. Dixon, K. Melnikov and F. Petriello, “Dilepton rapidity distribution in the Drell-Yan process at NNLO in QCD,” Phys. Rev. Lett. 91, 182002 (2003).

[33] S. Catani, L. Cieri, G. Ferrera, D. de Florian and M. Grazzini, “Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO,” Phys. Rev. Lett. 103, 082001 (2009).

[34] R. V. Harlander and W. B. Kilgore, “Next-to-next-to-leading order Higgs production at hadron colliders,” Phys. Rev. Lett. 88, 201801 (2002).

[35] G. C. McLaughlin and J. N. Ng, “A Study of the charged scalar in the Zee model,” Phys. Lett. B 455 (1999) 224.

[36] E. Mituda and K. Sasaki, “Zee model and phenomenology of lepton sector,” Phys. Lett. B 516 (2001) 47.

[37] T. van Ritbergen and R. G. Stuart, “On the precise determination of the Fermi coupling constant from the muon lifetime,” Nucl. Phys. B 564, 343 (2000).

[38] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.

[39] J. F. Gunion and H. E. Haber, “Higgs Bosons in Supersymmetric Models. 1.,” Nucl. Phys. B 272, 1 (1986).
[40] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, “The Higgs Hunter’s Guide,” Front. Phys. 80, 1 (2000).

[41] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, “Theory and phenomenology of two-Higgs-doublet models,” Phys. Rept. 516, 1 (2012).

[42] A. G. Akeroyd et al., “Prospects for charged Higgs searches at the LHC,” Eur. Phys. J. C 77, no. 5, 276 (2017).

[43] P. S. Bhupal Dev and A. Pilaftsis, JHEP 1412 (2014) 024 Erratum: [JHEP 1511 (2015) 147] [arXiv:1408.3405 [hep-ph]].

[44] S. Dittmaier, M. Kramer, M. Spira and M. Walser, “Charged-Higgs-boson production at the LHC: NLO supersymmetric QCD corrections,” Phys. Rev. D 83, 055005 (2011).