Simple standard model extension by heavy charged scalar

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(Received 14 February 2018; revised manuscript received 2 April 2018; published 15 May 2018)

We consider a Standard Model (SM) 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 scalar at different colliders and the possible decay widths for various boson masses. It is shown that the current ATLAS and CMS searches at 8 and 13 TeV collision energy lead to the bounds on the scalar boson mass of about 300–320 GeV. The limits are expected to be much larger for higher collision energies and, assuming 15 ab^{-1} integrated luminosity, reach about 2.7 TeV at future 27 TeV LHC thus covering the most interesting mass region.

DOI: 10.1103/PhysRevD.97.095014

I. 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 beyond the SM direction have been obtained.

Among various objects predicted by new physics models, special attention has been recently paid to the so-called heavy stable charged particles (HSCP) or long-lived particles (LLP). 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 [14–20].

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 [21] and quite recently in paper [22]. 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 Paul Langacker in his famous review paper [23]. 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 [24], 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

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variant of the Zee model [25]. 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 [25] (see a recent discussion in [26]), and to radiatively induced Majorana neutrino masses [27,28]. The parameter space of the Zee model allowed by the experimental data has been recently worked out [29] 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.

II. THE MINIMAL MODEL

The minimal part of the SM Lagrangian extended by the scalar field carrying a nontrivial representation of the $U_Y(1)$ weak hypercharge group includes the terms of dimension not greater than 4. 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:

$$L_S = D^*_\nu S^* D^\nu S - V(S), \qquad (1)$$

where the covariant derivative is given by $D_\nu = \partial_\nu - ig_1 \frac{Y_S}{2} B_\nu$, B_ν 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:

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

where μ_S^2 is a mass parameter, λ_S is the S-scalar quartic self-coupling, $\lambda_{\Phi S}$ is the coupling of the S-scalar to the Higgs field, which is supposed to be less than 1 in order to keep the model in the perturbative regime. 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:

(i) The S-field is a charged field, so it cannot have a nontrivial vacuum expectation value. Therefore, it cannot influence the value of the SM ρ parameter.

(ii) 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 $e\frac{Y_S}{2}$, 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 2 with the electric charge being equal to 1 ($Q_S = Y_S/2$). Thus, we denote the S-field as S^- and the complex conjugate field S^* as S^+.

(iii) The model described by Lagrangian (1) has three physically relevant parameters: the charged scalar mass squared $M_S^2 = \mu_S^2 + 1/2\lambda_{\Phi S}v^2$ which has to be positive; the coupling $\lambda_{\Phi S}$, which is assumed to satisfy the condition $|\lambda_{\Phi S}| < 1$ corresponding to the perturbative regime; and the positive self-interaction coupling λ_S. The mass term parameter μ_S can 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 and is equal to $M_S^2 = \lambda_{\Phi S}v^2/2$. Then its natural value is of the order of a hundred GeV, which, as it will be discussed below, is ruled out by the present LHC data.

(iv) 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 4, which describe the interaction of the S-scalar with the SM lepton fields giving lepton number violating vertices, they will be discussed 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 [29]. However, an important question is, whether the existence of such particles is compatible with bounds from cosmology. The production and freeze-out of S-scalars would be similar to those of cold dark matter particles and can be described by the same formulas [30]. If we consider the particle to be stable, the bounds come from the restrictions on the abundance of such scalars. Since positively charged S-scalars could form super heavy hydrogen, the abundance of S-scalars should be much less than the relative abundance of tritium, otherwise the S-scalar would have been already discovered in natural water. Estimates with the help of the MICROMEGAS program [31] show that, for the S-scalar mass 200 GeV and larger, it is possible in scenarios with low reheating temperature of the order of 4 GeV. In this case the ratio of the abundance of S-scalars to that of hydrogen is approximately 10^{-23}, which is 5 orders of magnitude less than the relative abundance of tritium about 10^{-18} (see [32]). The latest direct searches for super heavy (or anomalously heavy) hydrogen in deep sea water at 4000 m taking into account gravitational concentration gradients give the upper limit for the relative abundance of such particles about 4×10^{-17} in the mass range of 5 GeV–1.6 TeV at 95% confidence level [33].

Negatively charged S-scalars could form bound states with protons and deuterons, which could catalyze nuclear fusion [34]. However, the binding energy of these states would be of the order of 50 KeV, and they could not exist

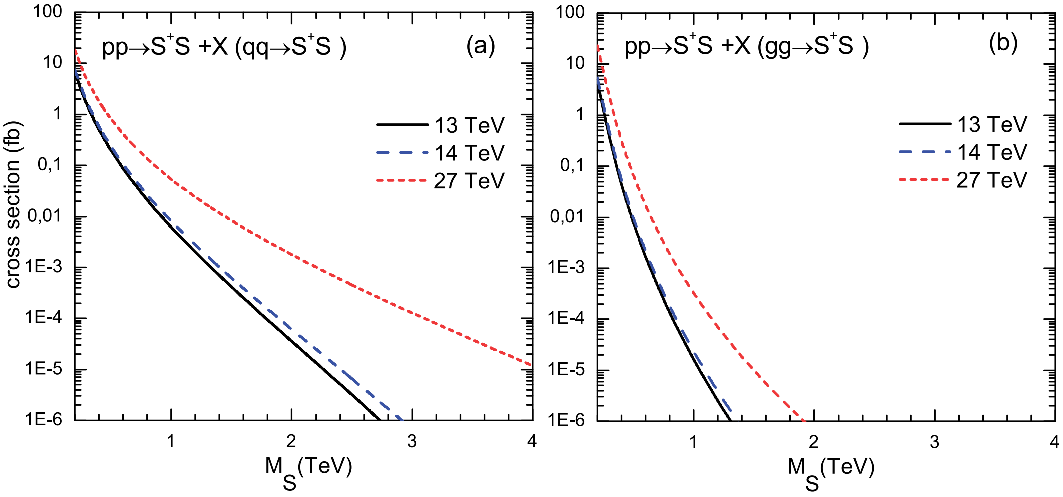

FIG. 1. Charged scalar pair production cross section via photon and Z-boson exchange in quark-antiquark annihilation (a) and via Higgs boson exchange in gluon-gluon fusion (b) at $\sqrt{s} = 13$, 14, 27 TeV as a function of its mass.

during big bang nucleosynthesis (BBN). If the S-scalar can decay, the situation is quite different and will be briefly discussed in Sec. IV.

III. 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.[1] 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 leading order cross section is about 6.8 fb and 7.6 fb at 13 and 14 TeV respectively with the next-to-next-to-leading order (NNLO) K-factor for the Drell-Yan quark-antiquark type of processes [Fig. 1(a)] of about 1.18 [37–39]. 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 5×10^{-2} fb even for the energy 27 TeV expected for the high energy 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 [22].

There is an additional contribution to the pair production cross section, which comes from the gluon-gluon fusion mechanism and was not discussed in [22]. Two gluons produce a virtual SM Higgs boson via the top loop triangle diagram and the virtual Higgs boson decays to a pair of the charged scalars. The production cross section as a function of the mass of the S-boson for the maximal boundary value of the coupling constant $\lambda_{\Phi S} = 1$, is shown in Fig. 1(b) for the collision energies $\sqrt{s} = 13$, 14, 27 TeV. For smaller values of the coupling the cross section has to be just multiplied by the factor $\lambda_{\Phi S}^2$. For the computation we have used the well-known expression for the triangle top loop diagram which was specially implemented into the CompHEP code. The cross section in Fig. 1(b) includes the NNLO K-factors as given in [40]. Since the scalar boson production via the gluon-gluon fusion is described by exactly the same diagram as the resonant SM Higgs production the K-factor is the same as for the SM Higgs with the Higgs mass equal to $2 \times M_S$. The gluon-gluon fusion cross section very rapidly decreases with the growth of the scalar boson mass. The level of the cross section is comparable with that for the Drell-Yan quark-antiquark annihilation process in Fig. 1(a) only for small masses close to 200 GeV and it becomes significantly smaller than the quark-antiquark annihilation part even for the maximum value of the coupling $\lambda_{\Phi S} = 1$. Therefore, the gluon-gluon production mode gives a practically negligible contribution to the pair production rate.

Searches for stable charged particles at the LHC energy 13 TeV presented in [20] give the lowest bound on the production cross section of about 4–2 fb for the luminosity 2.5 fb^{-1} corresponding to 10–5 events as the lowest number of events expected for the stable charged particle production. This bound is found for the case of the stau leptons having the same pair production mechanism as the S-scalars. From the bound one gets the lower limit on the charged scalar mass of about 270 and 300 GeV using the cross section given in Fig. 1. The cross section limit about 0.5 fb obtained in RUN1 at the LHC energy 8 TeV

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[1] The computations here and below have been performed by means of the CompHEP program [35], into which the Feynman rules obtained from the Lagrangian under consideration by means of the LanHEP code [36] were implemented.

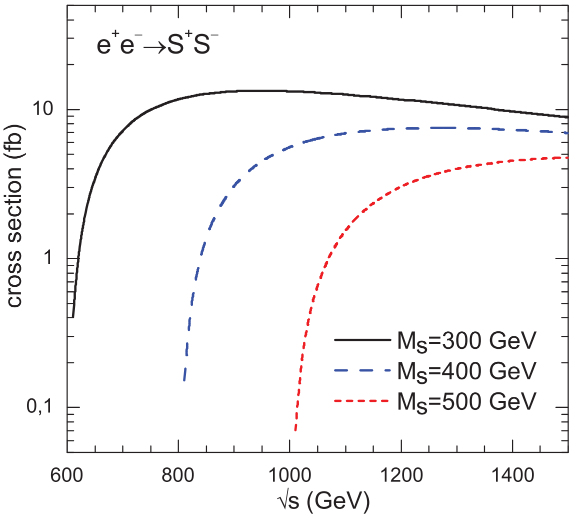

FIG. 2. Charged scalar pair production cross section in e^+e^- collisions as a function of collision center of mass energy for the scalar mass $M_S = 300$, 400, 500 GeV.

and much higher luminosity 18.8 fb^{-1} for the case of the stau lepton [17] leads to a slightly stronger lower S-scalar mass limit of about 320 GeV due to smaller cross section at 8 TeV than at 13 TeV.

Assuming the same lowest number of expected events from 10 to 5 one can estimate from the computed cross sections the expected lower 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 800 and 950 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 2.4 and 2.7 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 300, 400, and 500 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. However, the scalar in that mass range having the specified production cross sections in hadronic collisions (Fig. 1) will be, most probably, either ruled out or, in the case of luck, discovered at the LHC before an e^+e^- linear collider with a large enough energy will start to operate.

IV. 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 4 and 5 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 4 involving the lepton fields.

The left-handed lepton doublet l_a of each generation $a = 1, 2, 3$ carries the representation $\underline{2}(-1)$ of the group $SU(2)\times U_Y(1)$. The conjugate doublets $\bar{l}_a$ and the charge conjugate doublets l_b^c transform as $\underline{2}^*(1)$. Since the scalar field S^- carries the representation $\underline{1}(-2)$ of this group, the dimension 4 gauge invariant terms $\bar{l}_a\epsilon l_b^c S^-$ can be constructed, ϵ denoting the standard antisymmetric 2×2 matrix with $\epsilon_{12} = 1$. These terms give rise to the coupling of the S-scalar to leptons, which are antisymmetric in the generation indices due to the matrix ϵ. Therefore, the transformation properties of the S-scalar field under the gauge group of the SM allow the existence of the following interactions, which can be explicitly written as [25]:

$$L_{\rm S,leptons} = (f_{12}(\bar{\mu}_L\nu_e^c - \bar{e}_L\nu_\mu^c) + f_{13}(\bar{\tau}_L\nu_e^c - \bar{e}_L\nu_\tau^c) + f_{23}(\bar{\tau}_L\nu_\mu^c - \bar{\mu}_L\nu_\tau^c))S^- + \text{H.c.}, \qquad (3)$$

where ν^c denotes the charge conjugate neutrino field. These interactions lead to lepton flavor violation as well as to violation of the lepton number by two units due to the involvement of the charge conjugate fields. However, it turns out that at low energies this lepton number violation 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 leptons conserve lepton number and can be brought to the standard form of Fermi's four fermion interaction, which imposes constraints on the coupling constants f_{ik} [41,42]. The results of these papers with the present day values of the Fermi constant [43,44] and the probabilities of the decays $\tau\to\mu\bar{\nu}_\mu\nu_\tau$, $\tau\to e\bar{\nu}_e\nu_\tau$, $\mu\to e\gamma$ [44] 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 carried out in paper [29] 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 5 or larger. Here we will discuss the gauge invariant terms of dimension 5 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:

$$L_{\rm Yukawa} = -\Gamma_d^{ij}\bar{Q}'^{\,i}_{\rm L}\Phi d'^{\,j}_{\rm R} - \Gamma_u^{ij}\bar{Q}'^{\,i}_{\rm L}\Phi^C u'^{\,j}_{\rm R} + \text{H.c.}, \qquad (4)$$

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

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

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

$$L_{\text{Yukawa}} = -[M_d^{ij}\bar{d'_{\text{L}}}{}^i d'_{\text{R}}{}^j + M_u^{ij}\bar{u'_{\text{L}}}{}^i u'_{\text{R}}{}^j + \text{H.c.}]\cdot\left(1+\frac{h}{v}\right), \tag{5}$$

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:

$$d'_{\text{L}i} = (U_{\text{L}}^d)_{ij}d_{\text{L}j}; \qquad d'_{\text{R}i} = (U_{\text{R}}^d)_{ij}d_{\text{R}j};$$
$$u'_{\text{L}i} = (U_{\text{L}}^u)_{ij}u_{\text{L}j}; \qquad u'_{\text{R}i} = (U_{\text{R}}^u)_{ij}u_{\text{R}j} \tag{6}$$

$$U_{\text{L}}^{u,d}(U_{\text{L}}^{u,d})^\dagger = 1, \qquad U_{\text{R}}^{u,d}(U_{\text{R}}^{u,d})^\dagger = 1. \tag{7}$$

The matrices U are chosen such that

$$(U_{\text{L}}^u)^\dagger M_u U_{\text{R}}^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix};$$

$$(U_{\text{L}}^d)^\dagger M_d U_{\text{R}}^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}.$$

As it is well known, the SM neutral currents remain the same after the above unitary transformation providing the absence of the flavor-changing neutral current (FCNC) at tree level. However, after the transformation to the physical degrees of freedom

$$u' \to (U_L^u)u, d' \to (U_L^d)d,$$

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

$$V_{\text{CKM}} = (U_L^u)^\dagger U_L^d,$$

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 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:

$$L_{\text{S,quarks}} = -\frac{1}{\Lambda}\bar{Q}'_L\lambda_u\Phi u'_R{}^j S^- - \frac{1}{\Lambda}\bar{Q}'_L\lambda_d\Phi^C d'_R S^+ + \text{H.c.}, \tag{8}$$

where $\lambda_{u,d}$ are dimensionless matrices and Λ 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:

$$L_{\text{S,quarks}} = -\frac{1}{\Lambda}\left[\bar{d}\cdot V_u\frac{1+\gamma_5}{2}u\cdot S^- + \bar{u}\cdot V_d\frac{1+\gamma_5}{2}d\cdot S^+ + \text{H.c.}\right]\cdot\left(1+\frac{h}{v}\right), \tag{9}$$

where $V_d = V_{\text{CKM}}(U_{\text{L}}^d)^\dagger\mu_d U_{\text{R}}^d$ and $V_u = V_{\text{CKM}}^\dagger(U_{\text{L}}^u)^\dagger\mu_u U_{\text{R}}^u$, $\mu_{d,u} = \lambda_{d,u}v/\sqrt{2}$. 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.

If we assume that the minimal flavor violation hypothesis [45,46] is valid, the matrices $\mu_{d,u}$ are proportional (or equal) to the mass matrices M^{ij}. In this case the matrices $V_{d,u}$ are equal to the products of the CKM matrix or its Hermitian conjugate 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 [29]. 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 Refs. [47–51]). However, in comparison with the 2HDM or MSSM the interaction vertices are suppressed by the factor of the order of v/Λ.

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) and (9). If the neutrinos are considered to be massive, they will be absolutely similar to formulas (8) and (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 next-to-leading order (NLO) corrections make the result much more stable

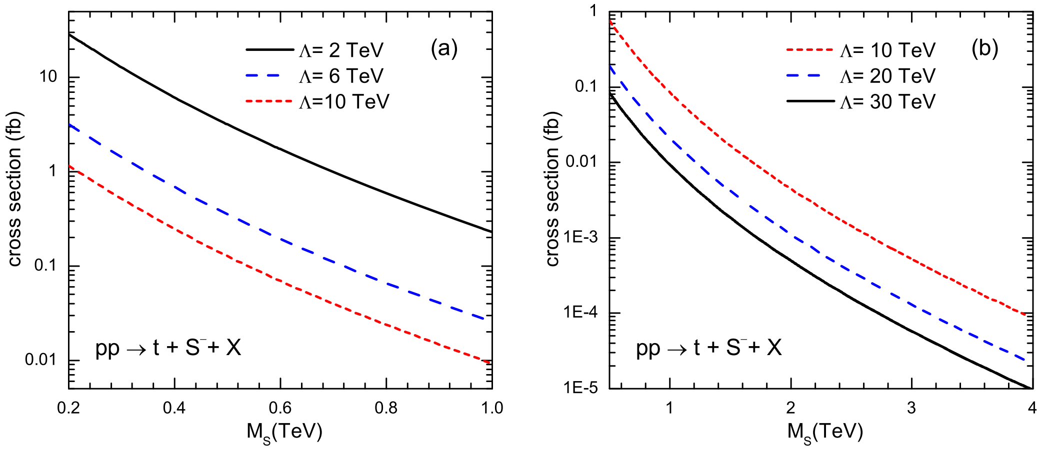

FIG. 3. Charged scalar single production cross section at 14 TeV (a) and at 27 TeV (b) pp collision energy as a function of the scalar mass for three values of the scale Λ 2, 6, and 10 TeV.

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 [52]. The single production cross section decreases quadratically with the scale and becomes smaller than the considered above pair production at some scale. In Fig. 4 the dependence of the scale Λ, corresponding to equal single and pair charged scalar production cross sections, is shown for 14 and 27 TeV collision energy as a function of the scalar boson mass for the same mass intervals as in Fig. 3. For the values of the scale above the lines in Fig. 4 the single production cross section is smaller than the pair one and vice versa, for the values below the lines the single production cross section is larger.

As was mentioned, the mass of the S-scalar in the csSM may arise from the SM Brought-Engler-Higgs mechanism.

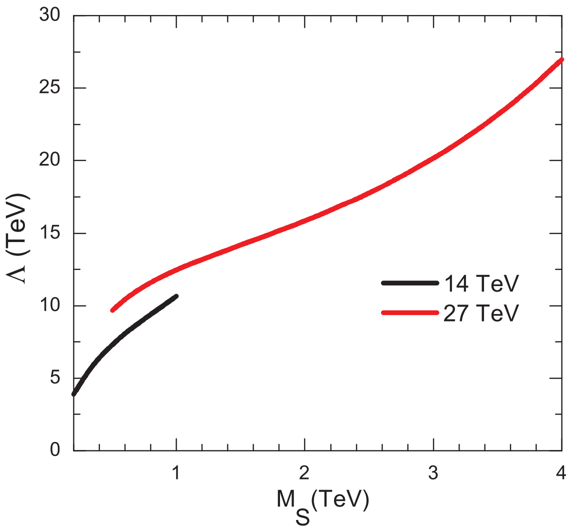

FIG. 4. The scale Λ, at which the single production cross section becomes equal to the pair production cross section at 14 TeV and at 27 TeV pp collision energy, as a function of the scalar mass.

In this case the natural values for the scalar mass would be in the range of the Higgs vacuum expectation value. The scale Λ 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 $M_{\mathrm{top}}^2/\Lambda^2 \cdot M_S \cdot \beta^3$ ($\beta = \sqrt{1 - M_{\mathrm{top}}^2/M_S^2}$) and therefore increases with the scalar boson mass and rapidly decreases with the growth of the scale Λ. This is demonstrated in Fig. 5. One can see that for the energy scale Λ in the TeV range the scalar boson decay width varies from 10^{-1} to 10^{-4} GeV (left plot). However, if the scale is in the GUT range (right plot) the width becomes very small $10^{-24} - 10^{-27}$ GeV. In this case the lifetime 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 Λ 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. The existence of such particles is compatible with cosmology, if they decay before BBN. The MICROMEGAS program [31] gives that this is the case, if $\Gamma > 10^{-24}$ GeV. Figure 5 shows that, for the S-scalar mass 200 GeV and larger, the width satisfies this restriction for all the considered values of Λ, except $\Lambda = 10^{15}$ GeV for the S-scalar mass smaller than about 700 GeV and $\Lambda = 10^{16}$ GeV for all the considered S-scalar masses.

For rather small energy scales Λ 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. Topologies involving the top and bottom quarks in the final states have been discussed to be rather promising to search for the charged Higgs boson with mass heavier than the top

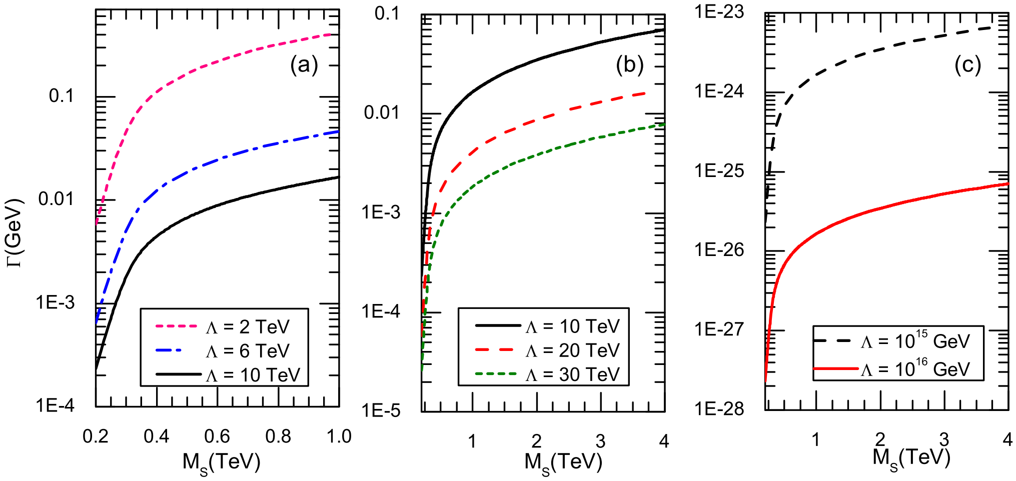

FIG. 5. Charged scalar width as a function of its mass at new physics scale in TeV range (a), (b) and in GUT range (c).

mass (see the study in [50]). Corresponding searches have been performed recently [53] and the limits on the production cross section times the decay branching to the top and bottom was found to be about 1 pb for the charged Higgs mass about 300 GeV and down to about 0.2 pb for the mass range around 1 TeV. For the case of $\tan\beta = 1$ in the 2HDM or MSSM, where the interaction of the charged Higgs boson is very similar to that of the S-scalar, the lower limit on the charged Higgs boson mass was found to be about 400 GeV. From Figs. 1 and 3 one can see that the cross sections for the S-scalar production in both pair and single production channels are expected to be significantly smaller. Therefore, in this case a special 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, in particular, in high energy and high luminosity operation regimes.

V. 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 300–320 GeV and the expected bounds at higher collision energies and larger luminosity. In particular, at future 27 GeV LHC with the luminosity of 15 ab^{-1} the bound is expected to reach about 2.7 TeV covering a significant part of interesting mass regions following from the overall parameter space analysis for the Zee model as found in [29].

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 to 10^{-5} fb in the mass range between 200 GeV and 4 TeV and in the range of the scale Λ from 2 to 30 TeV. The decay width depends strongly on the scalar boson mass and the scale Λ and for the TeV scale regions takes values from 100 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.

The estimates made with the help of the MICROMEGAs program [31] show that the existence of such a heavy stable or long-lived particle is not forbidden by cosmology in some regions of the parameter space. A more detailed study of cosmological consequences of this model will be done in a separate paper.

ACKNOWLEDGMENTS

We thank Viatcheslav Bunichev, Eduard Rahmetov, and Tatiana Tretyakova for useful discussions. Special thanks go to Alexander Pukhov for interesting discussions and help with calculations using the MICROMEGAs code. We are grateful to the Russian Science Foundation (Grant No. 16-12-10280) for support.

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