# SUPERWEAK EXTENSION OF THE STANDARD MODEL*

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The superweak force is a minimal, anomaly-free U(1) extension of the Standard Model, designed to explain the origin of *(i)* neutrino masses and mixing matrix elements, *(ii)* dark matter, *(iii)* cosmic inflation, *(iv)* stabilization of the electroweak vacuum, and *(v)* leptogenesis. In this paper, we discuss the phenomenological status of the model and provide viable scenarios for the physics of the items in this list.

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## 1. Introduction

The Standard Model (SM) of particle interactions describes the cross sections of scattering processes at high-energy colliders with high precision. The uncertainties of the measurements and predictions are usually several percent, sometimes even below the percent level [1]. This great triumph of the theoretical understanding is not matched with successes in searching for New Physics as the experiments at the LHC have not yet found any sign of beyond the Standard Model (BSM) physics yet. While exciting deviations from the SM predictions keep appearing, none of these have reached $5\sigma$ significance, and so we do not discuss those further in this presentation.

Parallel to the success of the SM, we have no doubt that some observations cannot be explained within that theory. The outstanding questions that lack answers are the following: *(i)* What does the non-baryonic dark matter (DM) consist of? *(ii)* What gives masses to the neutrinos? *(iii)* What is the origin of the matter–anti-matter asymmetry? *(iv)* How can we explain epochs of accelerated expansion of the Universe? The answers to these questions are in the realm of BSM physics. However, the lack of new particles discovered at the LHC hints that the structure of BSM physics at

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energies accessible at the LHC should be fairly simple. In fact, the addition of three right-handed neutrinos to the particle spectrum, which are sterile under the SM, may suffice [2], but the experimental confirmation of such a model is essentially impossible. The main theme of this article is to discuss whether the observations *(i)–(iv)* can be explained by a consistent, simple extension of the SM, in a way that is testable by laboratory experiments.

There are three classes of extensions of the SM studied extensively at the LHC. The Standard Model effective field theory (SMEFT) is a general approach, at the price of having 2499 dimension six operators (and even more higher-dimensional ones). The idea is that the effects of New Physics that appears as fundamental theory at high-energy scales, much above the electroweak scale, can be described by higher-dimensional operators in the Lagrangian with unknown couplings in measurements near the electroweak scale. The large number of operators and the great experimental success of the SM makes the measurement of the unknown couplings very difficult.

There are also simplified models, such as dark photon extension, or an extended scalar sector, with a reasonably easily accessible phenomenology. The dark photon extension has an explicit mass term, hence it clearly cannot be the final theory as it has to be massive. A gauge-invariant mass term for a vector field can only be generated by some form of the Brout–Englert–Higgs (BEH) mechanism, which requires the existence of at least a further complex scalar field as the degrees of freedom of the BEH field are completely used within the SM. The scalar extensions are exciting alternatives of BSM physics, but on the one hand, they predict several new particles whose traces we do not see, while on the other hand, they cannot explain all BSM phenomena simultaneously as they focus on specific aspects of New Physics.

The third class of extensions consists of ultraviolet complete models, such as the supersymmetric extension of the SM predicting the existence of many new particles. As those are not seen at the LHC, the model is becoming a less attractive solution to the BSM phenomena. In this presentation, we focus on the SuperWeak extension of the SM (SWSM) that is a phenomenological, ultraviolet complete extension, designed such that it could explain all firmly observed BSM phenomena, but not more [3].

## 2. Superweak extension of the Standard Model

In this model, in addition to the usual SM fields, there are three right-handed neutrinos $\nu_{\mathrm{R},1}$, $\nu_{\mathrm{R},2}$, $\nu_{\mathrm{R},3}$ plus a complex scalar $\chi$ whose non-vanishing vacuum expectation value (VEV) $w$ breaks the new $\mathrm{U}(1)_z$ symmetry that is added to the SM symmetry group $G_{\mathrm{SM}}$. The model contains all dimension four renormalizable operators allowed by $G_{\mathrm{SM}} \otimes \mathrm{U}(1)_z$. We fix the new charges belonging to the new gauge interaction by requiring the cancellation of the gauge and gravity anomalies, which leaves two $z$-charges free [4]. One unknown charge can be set by the gauge=invariant Yukawa terms needed for neutrino mass generation. The second one can be set freely as it provides the normalization of the new gauge coupling $g_z$. The physical fields are shown in Fig. 1.

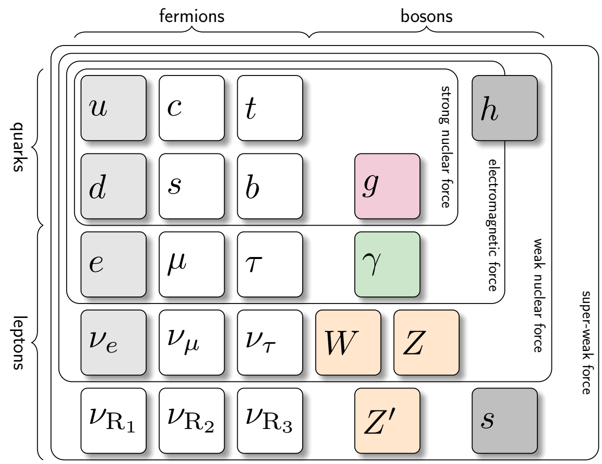


Fig. 1. Fields and interactions in the SWSM.

## 3. Gauge sector

The gauge sector of the SWSM contains three neutral gauge bosons: the SM fields $W_3^\mu$, and $B^\mu$, and the Abelian gauge field $B'^\mu$ that mix into mass eigenstates $A^\mu$, $Z^{0\mu}$ and $Z'^\mu$ by two rotations

$$\begin{pmatrix} B^\mu \\ W_3^\mu \\ B'^\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_Z & -s_Z \\ 0 & s_Z & c_Z \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix} . \tag{1}$$

We use the abbreviations $c_X = \cos\theta_X$ and $s_X = \sin\theta_X$, with $X = W$ for the weak mixing angle and $X = Z$ for the new $Z$–$Z'$ mixing. The value of $\theta_Z$ can be given in an implicit form in terms of two effective couplings $\kappa$ and $\tau$, defined in terms of the Lagrangian couplings in Ref. [3], as

$$\tan(2\theta_Z) = -\frac{2\kappa}{1-\kappa^2-\tau^2} . \tag{2}$$

The tree-level masses of the neutral gauge bosons can be expressed with the mass $M_W = \frac{1}{2}g_{\rm L}v$ of the $W$ bosons, $c_W$ and $\kappa$, $\tau$. The explicit expressions are somewhat cumbersome, but there exists a nice, compact generalization of the SM mass formula $M_W = c_W M_Z$ as follows [5]:

$$\frac{M_W^2}{c_W^2} = c_Z^2 M_{Z^0}^2 + s_Z^2 M_{Z'}^2 \,. \tag{3}$$

## 4. Scalar sector

The potential energy density of the Brout–Englert–Higgs field $\phi$ and the complex scalar $\chi$ is

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \lambda_\phi|\phi|^4 + \lambda_\chi|\chi|^4 + \lambda|\phi|^2|\chi|^2 \subset -\mathcal{L}\,, \tag{4}$$

where $|\phi|^2 = |\phi^+|^2+|\phi^0|^2$. We parametrize the scalar fields after spontaneous symmetry breaking and choosing the $R_\xi$ gauge as

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -i\sqrt{2}\sigma^+ \\ v + h' + i\sigma_\phi \end{pmatrix}, \qquad \chi = \frac{1}{\sqrt{2}}\left(w + s' + i\sigma_\chi\right)\,, \tag{5}$$

where $v$ and $w$ denote the VEVs of the scalar fields. The real scalar fields $h'$ and $s'$ mix into mass eigenstates $h$ and $s$

$$\begin{pmatrix} h' \\ s' \end{pmatrix} = \begin{pmatrix} c_{\rm S} & -s_{\rm S} \\ s_{\rm S} & c_{\rm S} \end{pmatrix}\begin{pmatrix} h \\ s \end{pmatrix}. \tag{6}$$

In Eq. (6), $\theta_{\rm S}$ is the scalar mixing angle that can be given again implicitly

$$\tan\left(2\theta_{\rm S}\right) = \frac{\lambda v w}{\left(\lambda_\chi w^2 - \lambda_\phi v^2\right)}\,. \tag{7}$$

## 5. Neutrino masses

As compared to the SM, the SWSM contains the new Yukawa terms

$$\frac{1}{2}\bar{\nu_R}\boldsymbol{Y}_N(\nu_R)^c\chi + \bar{\nu_R}\boldsymbol{Y}_\nu\varepsilon_{ab}L_{La}\phi_b + \text{h.c.} \subset -\mathcal{L}\,. \tag{8}$$

The masses of the neutrinos are generated after SSB in the form of $3\times 3$ matrices

$$\boldsymbol{M}_N = \frac{w}{\sqrt{2}}\boldsymbol{Y}_N\,, \qquad \boldsymbol{M}_D = \frac{v}{\sqrt{2}}\boldsymbol{Y}_\nu\,. \tag{9}$$

We see that both Dirac and Majorana mass terms appear already at tree level, and they constitute a $6\times 6$ mass matrix of the form

$$\boldsymbol{M}' = \begin{pmatrix} \boldsymbol{0}_3 & \boldsymbol{M}_D^T \\ \boldsymbol{M}_D & \boldsymbol{M}_N \end{pmatrix}\,. \tag{10}$$

The mixing of the left- and right-handed neutrinos results in masses of the active and sterile neutrinos via a type-I see-saw mechanism. It was shown in Ref. [6] that the quantum corrections to the masses of the active neutrinos remain perturbatively small over most of the parameter space.

## 6. Free parameters

The SWSM contains numerous new couplings in the Yukawa sector, but it is more convenient to account for those as six neutrino masses, three angles, and a complex phase in the Pontecorvo–Maki–Nakawaga–Sakata matrix. (Additional Majorana phases are possible.)

There are also new gauge couplings in the Lagrangian, namely $g_z$ and $g_{yz}$, the latter characterizing the mixing of the two U(1) fields. Alternatively, we can use the effective couplings $\kappa$, $\tau$, or fiducial parameters, such as the mixing angle $\theta_Z$ and neutral gauge boson mass $M_{Z'}$.

In the scalar sector, out of the five couplings, two are constrained by the known $v$ and $M_h$, leaving three unknown. These are $\mu_\chi^2$ and the new quartic couplings $\lambda_\chi$ and $\lambda$. Of these three, one can be traded for the new VEV $w$. Again, one may choose phenomenologically more accessible parameters, such as the scalar mixing angle $\theta_{\rm S}$, new scalar boson mass $M_{\rm S}$, plus $\lambda$. The different sets have different advantages.

## 7. Possible consequences of the SWSM

The take-home messages of this paper can be summarized as follows:

1. The origin of neutrino masses and oscillations can be explained by the Dirac and Majorana neutrino mass terms that appear after SSB of the scalar fields [6, 7].
2. The lightest sterile neutrino is a natural and viable candidate for WIMP dark matter if it is sufficiently stable [8].
3. The decays and scattering processes of the Majorana neutrinos can provide sufficient leptogenesis [9, 10].
4. The scalar sector can stabilize the vacuum and cause the accelerated expansion now and inflation in the early universe [11].

A decisive test of the SWSM will be the observation of a $Z'$ gauge boson and a new scalar $S$ in the allowed region of the parameter space. Lacking such a discovery, presently we focus on the question of where the region of the parameter space lies where the listed promises are fulfilled.

## 8. Dark matter candidate

The parameter space can be constrained if the model is to provide a viable candidate for dark matter (DM). The SWSM can provide the correct relic abundance of DM both with freeze-out and freeze-in mechanisms [8], but here we discuss in detail only the former case. The latter scenario has a significantly larger parameter space than the freeze-out one due to the dark matter species not being in equilibrium at early times. In this case, there are five parameters: $M_1$, $M_{Z'}$, $g_z$, the reheating temperature $T_{\rm rh}$, and the initial abundance of neutrinos $\mathcal{Y}_{N_1}(T_{\rm rh})$. The key observation is that the observed abundance of the dark matter energy density can only be reproduced with very small values of $g_z$ ($\lesssim 10^{-10}$) [8], making this scenario possible to experimentally assess only in cosmological observations.

In both scenarios, the lightest sterile neutrino is the DM candidate, provided its mixing with the active neutrinos is negligible, making the DM candidate sufficiently stable. To observe such a particle in particle detectors of ordinary matter requires the interaction of DM with SM particles through a portal, which is the $Z'$ in the SWSM. Figure 2 shows the parameter space in the $g_z$–$M_{Z'}$ plane in the freeze-out case. Each line corresponds to a fixed value of the DM neutrino mass providing the correct DM relic

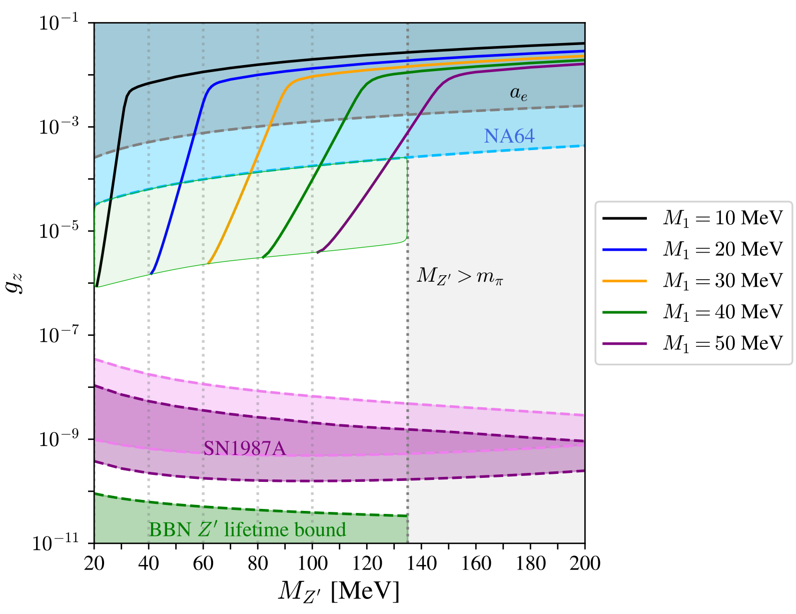


Fig. 2. Parameter space for the freeze-out scenario of dark matter production in the SWSM. The meanings of lines and shaded regions are explained in the main text.

density, while the shaded regions are excluded by the experimental results for the anomalous magnetic moment of the electron and the direct searches for dark photon by the NA64 experiment [13].

The correct DM relic density requires mostly such a large $g_z$ coupling that is already excluded by other measurements (close to horizontal slopes). The only exception is the case of *resonant annihilation* of the lightest sterile neutrinos (steep slopes) when $M_{\nu_{\mathrm{R}1}} \approx M_{Z'}/2$. The smaller the portal coupling, the earlier the freeze-out time, and hence the larger DM abundance. As a result of resonant annihilation, the probability of DM depletion can be sufficiently large with a small value of the coupling $g_z$.

Direct searches for dark photons (such as that shown in the figure with the line marked 'NA64') and cosmological measurements can constrain the portal coupling. The theory of BBN does not allow for a significant contribution to the creation of light mesons during BBN. As the $Z'$ in the SWSM interacts with the quarks, its mass should be below the pion threshold, shown by the vertical gray exclusion region in the figure. Other cosmological bounds were found not to influence the parameter space relevant for the freeze-out scenario.

## 9. Constraints from the scalar sector

Collider experiments have always been searching for new scalars. The exclusion limits for the value of the scalar mixing angle as a function of the new scalar mass $M_{\mathrm{S}}$ was measured at the LHC in the mass range above the Higgs mass up to 1 TeV as shown in Fig. 3 by the shaded region, which still leaves ample parameter space for the SWSM. As mentioned in Section 6,

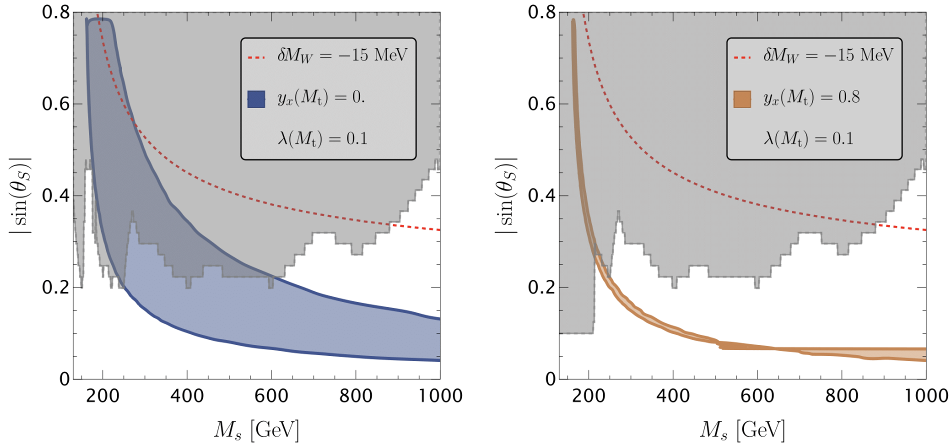


Fig. 3. Excluded region of the scalar mixing angle as a function of the new scalar mass. The meanings of lines and shaded regions are explained in the main text.

there are three free parameters in the scalar sector, of which we fix the mixing coupling $\lambda$ at the electroweak scale $M_t$ to 0.1 as benchmark value. The parameters of the SM are standard values specified in Ref. [11].

The banana-shaped strips correspond to the region where the SWSM vacuum remains perturbatively stable up to the Planck mass computed at two-loop accuracy in perturbation theory at vanishing Majorana-type Yukawa couplings $y_x$, considered equal in this example (left). Increasing the latter, the region becomes narrower and vanishes for values slightly above $y_x = 0.8$ (right). The region above the dashed line is excluded by the precision measurements for the mass of the $W$ bosons.

## 10. Constraints from the gauge sector

The results of direct searches for dark photons by the BaBar [12], NA64 [13], FASER [14], and the BelleII [15] experiments can be translated to exclusion limits in the $M_{Z'}$–$s_Z$ plane. We refer to [16] for details.

## 11. Conclusions

Established observations require physics beyond SM, but do not suggest rich BSM physics. The superweak extension has the potential of explaining all known results beyond the SM. In this model, neutrino masses are generated by SSB at tree level, and one-loop corrections to the tree-level neutrino mass matrix are found to be small (below 1‰) in the parameter space relevant in the SWSM. The lightest sterile neutrino is a candidate DM particle in the [10,50] MeV mass range for the freeze-out mechanism with resonant enhancement, which predicts an approximate mass relation between the vector boson and the lightest sterile neutrino. In the scalar sector, we find non-empty parameter space for $M_{\mathrm{S}} > M_h$. Contributions to EWPOs (*e.g.* $M_W$, lepton $g-2$) are negligible in the superweak region. A systematic exploration of the parameter space is ongoing.

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