PROCEEDINGS OF SCIENCE

Super-weak force

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We summarize the current status of particle physics, collecting the established deviations from the standard model of particle interactions both at the energy and the intensity frontier as well as in cosmology. We propose a specific $U(1)$ extension of the standard model of particle interactions and discuss the possible consequences of the model concerning the observed deviations.

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1. Introduction

This conference has shown a very rich experimental program to test the standard model (SM) and search for physics beyond the standard model (BSM) at the LHC and also elsewhere. The status of the SM measurements can be summarized [1] as follows: using the large amount of data collected by the ATLAS [2] and CMS [3] experiments many important SM measurements with significantly increased precision have been carried out, proving a very robust status the SM. Detailed measurements of the properties of the Higgs boson [4] increase continuously our knowledge about its properties in accordance with the theoretical expectations. There is an even larger effort to find signs of new physics, resulting in exclusion limits so far [5, 6], without discovering new particles.

The robust status of the SM and the fruitless search for BSM physics might hint that the SM is the final theory of particle interactions. Yet there are some clear signs of new physics that call for the extension of the SM [7]: (i) We know that there is abundant cold dark matter at large scales in the universe contributing to about 25 % of the energy density. (ii) We know that neutrinos have masses as their flavours can oscillate. (iii) We know that the magnitude of the baryon–anti-baryon asymmetry in the universe cannot be understood by the amount of CP-violation in the SM. (iv) The quartic coupling of the Brout-Englert-Higgs (BEH) potential becomes negative at around 10^{11} GeV [8, 9], suggesting potential instability of the early universe. While the estimates for the tunneling time of the universe into a more stable ground state give longer time than has elapsed since the Big Bang, hence the universe is in a metastable state, such a potential instability could be fatal at early times when the characteristic energy scale of particle interactions was around 10^{10} GeV. (v) Inflation can explain the structure of the power spectrum of the cosmic microwave background radiation and the accelerated expansion of the present universe has been observed. Current efforts in theoretical particle physics are based on the hypothesis that these observations should be explained consistently by an extension of the SM.

As neutrinos in the SM are strictly massless, it is clear that neutrinos must play a key role in searching for such an extension. With non-zero masses they must feel another force apart from the weak one, e.g. Yukawa coupling to a scalar, which requires the existence of right-handed neutrinos. The simplest possible extension of the standard model gauge group $G_{\rm SM} = SU(3)_{\rm c} \otimes SU(2)_{\rm L} \otimes U(1)_Y$ is by a $U(1)_Z$ to $G = G_{\rm SM} \otimes U(1)_Z$. We propose a renormalizable gauge theory without any other symmetry assumed, but allowing all possible terms for the matter fields.

2. Definition of the model

In the fermion sector we assume three families ($f = 1$, 2 or 3) of chiral quark (ψ_q) and lepton (ψ_l) fields:

$$\psi^f_{q,1} = \begin{pmatrix} U^f \\ D^f \end{pmatrix}_{\rm L}, \quad \psi^f_{q,2} = U^f_{\rm R}, \quad \psi^f_{q,3} = D^f_{\rm R}, \quad \psi^f_{l,1} = \begin{pmatrix} \nu^f \\ \ell^f \end{pmatrix}_{\rm L}, \quad \psi^f_{l,2} = \nu^f_{\rm R}, \quad \psi^f_{l,3} = \ell^f_{\rm R} \tag{2.1}$$

where L and R denote the usual left and right-handed projections of the same field. The requirement of local gauge invariance of the Dirac Lagrangian

$$\mathscr{L}_{\rm D} = {\rm i} \sum_{f=1}^{3} \sum_{j=1}^{3} \left(\overline{\psi}^f_{q,j}(x) \not{D}_j \psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x) \not{D}_j \psi^f_{l,j}(x) \right) \tag{2.2}$$

under the extended gauge group G leads to the covariant derivatives

$$D_j^\mu = \partial^\mu + \mathrm{i}g_\mathrm{L}\boldsymbol{T}\cdot\boldsymbol{W}^\mu + \mathrm{i}g_Y y_j B'^\mu + \mathrm{i}(g'_Z z_j - g'_Y y_j)Z'^\mu \tag{2.3}$$

where the primes on the vector fields and gauge couplings indicate that the kinetic mixing between the $U(1)$ fields have been taken into account [10]. The matrices $\boldsymbol{T} = (T_1, T_2, T_3)$ are $\frac{1}{2}$ times the Pauli matrices, y_j is the hypercharge, while z_j denotes the supercharge (Z-charge) of the field ψ_j.

In the scalar sector besides the Brout-Englert-Higgs field ϕ, we also assume the existence of a new complex scalar field χ that transforms as a singlet under G_SM transformations. Then the gauge invariant Lagrangian of the scalar fields is

$$\mathscr{L}_{\phi,\chi} = [D_{\phi\,\mu}\phi]^* D_\phi^\mu \phi + [D_{\chi\,\mu}\chi]^* D_\chi^\mu \chi - V(\phi,\chi) \tag{2.4}$$

where the covariant derivative for the scalar s ($s = \phi,\ \chi$) is as in Eq. (2.3) with $j \to s$, and the potential energy contains also a mixed coupling term ($-\lambda|\phi|^2|\chi|^2$) of the scalar fields in the Lagrangian:

$$V(\phi,\chi) = V_0 - \mu_\phi^2|\phi|^2 - \mu_\chi^2|\chi|^2 + \left(|\phi|^2, |\chi|^2\right)\begin{pmatrix}\lambda_\phi & \frac{\lambda}{2}\\ \frac{\lambda}{2} & \lambda_\chi\end{pmatrix}\begin{pmatrix}|\phi|^2\\ |\chi|^2\end{pmatrix}. \tag{2.5}$$

The fermion masses emerge from the Yukawa Lagrangian

$$\mathscr{L}_\mathrm{Y} = -\left[c_D\bar{Q}_\mathrm{L}\cdot\phi\, D_\mathrm{R} + c_U\bar{Q}_\mathrm{L}\cdot\tilde{\phi}\, U_\mathrm{R} + c_\ell\bar{L}_\mathrm{L}\cdot\phi\,\ell_\mathrm{R} + c_\nu\bar{L}_\mathrm{L}\cdot\tilde{\phi}\,\nu_\mathrm{R} + \frac{1}{2}c_\mathrm{R}\,\overline{\nu_\mathrm{R}^c}\nu_\mathrm{R}\,\chi\right] + \mathrm{h.c.} \tag{2.6}$$

after spontaneous symmetry breaking. In Eq. (2.6) the dot product abbreviates scalar products of $SU(2)$ doublets:

$$\bar{Q}_\mathrm{L}\cdot\phi \equiv (\bar{U},\bar{D})_\mathrm{L}\begin{pmatrix}\phi^{(+)}\\ \phi^{(0)}\end{pmatrix}, \quad \bar{Q}_\mathrm{L}\cdot\tilde{\phi} \equiv (\bar{U},\bar{D})_\mathrm{L}\begin{pmatrix}\phi^{(0)*}\\ -\phi^{(+)*}\end{pmatrix}, \tag{2.7}$$

$\bar{L} \equiv \left(\bar{\nu}_\ell, \bar{\ell}\right)$, c denotes charge conjugate of the field, $\nu^c = -\mathrm{i}\gamma_2\nu^*$ and h.c. means hermitian conjugate terms. The Yukawa couplings c_D, c_U, c_ℓ, c_ν, c_R are matrices in family indices and summation over the families is understood. The Majorana term of Eq. (2.6) (the last piece in the bracket) is gauge invariant if the supercharges of the right-handed neutrinos and the new scalar are related by $z_\chi = -2z_{\nu_\mathrm{R}}$. In order to fix the supercharges of the particles, (i) we require the cancellation of gauge and gravity anomalies, resulting in charges of fermions expressed in terms of two numbers Z_1 and Z_2 as shown in in Table 1 [11]; (ii) we assume that the left- and right-handed neutrinos have opposite charges, so $Z_2 - 4Z_1 = 3Z_1$, solved by $Z_1 = Z_2/7$; (iii) and we choose $Z_2 = 7/6$ implying $Z_1 = 1/6$. The last step simply sets the scale of the new gauge coupling.

After the spontaneous symmetry breaking of the vacuum of the scalar fields the Yukawa Lagrangian leads to the following mass terms for the neutrinos:

$$\mathscr{L}_\mathrm{Y}^\nu = -\frac{1}{2}\sum_{i,j}\left[\left(\overline{\nu_\mathrm{L}}, \overline{\nu_\mathrm{R}^c}\right)_i M(h,s)_{ij}\begin{pmatrix}\nu_\mathrm{L}^c\\ \nu_\mathrm{R}\end{pmatrix}_j + \mathrm{h.c.}\right] \tag{2.8}$$

where the mass matrix $M(0,0)$ is a complex symmetric 6×6 matrix. The propagating states, obtained by the diagonalization of the matrix $M(0,0)$, will be mixtures of the left- and right-handed

Table 1: Assignments for the representations (for $SU(N)$) and charges (for $U(1)$) of fermion and scalar fields of the complete model. The charges y_j denote the eigenvalue of $Y/2$, with Y being the hypercharge operator and z_j denote the supercharges of the fields ψ_j of Eq. (2.1) ($j = 1, 2, 3$).

field	$SU(3)_{\rm c}$	$SU(2)_{\rm L}$	y_j	z_j	z_j
$U_{\rm L}, D_{\rm L}$	3	2	$\frac{1}{6}$	Z_1	$\frac{1}{6}$
$U_{\rm R}$	3	1	$\frac{2}{3}$	Z_2	$\frac{7}{6}$
$D_{\rm R}$	3	1	$-\frac{1}{3}$	$2Z_1 - Z_2$	$-\frac{5}{6}$
$\nu_{\rm L}, \ell_{\rm L}$	1	2	$-\frac{1}{2}$	$-3Z_1$	$-\frac{1}{2}$
$\nu_{\rm R}$	1	1	0	$Z_2 - 4Z_1$	$\frac{1}{2}$
$\ell_{\rm R}$	1	1	-1	$-2Z_1 - Z_2$	$-\frac{3}{2}$
ϕ	1	2	$\frac{1}{2}$	z_ϕ	1
χ	1	1	0	z_χ	-1

neutrinos with masses m_i for the former and M_j for the latter. It is natural to assume the hierarchy $m_i \ll M_j$ when the heavy states can be integrated out and we obtain an effective operator with Majorana mass terms for the left-handed neutrinos

$$\mathscr{L}^{\nu}_{\rm dim-5} = -\frac{1}{2}\sum_i m_{{\rm M},i}\left(1+\frac{h}{v}\right)^2\left(\overline{\nu'^{c}_{i,\rm L}}\nu'_{i,\rm L} + {\rm h.c.}\right). \tag{2.9}$$

The Majorana masses $m_{{\rm M},i} = {\rm O}(m_i^2/M_i)$ can be of O(100 meV) if $m_i \sim$ O(100 keV) (as for the charged leptons) and the masses of the right-handed neutrinos are around O(100 GeV).

Similarly to the standard model, the neutral gauge fields mix. The mixing is described by the 3×3 orthogaonal matrix $O(\sin\theta_{\rm W}, \sin\theta_T)$,

$$\begin{pmatrix} W^3_\mu \\ B'_\mu \\ Z'_\mu \end{pmatrix} = O(\sin\theta_{\rm W}, \sin\theta_T)\begin{pmatrix} Z_\mu \\ T_\mu \\ A_\mu \end{pmatrix}, \tag{2.10}$$

with $\theta_{\rm W}$ being the usual weak and θ_T is a new mixing angle. In terms of the new fields the neutral current Lagrangian is the sum of the usual QED term,

$$\mathscr{L}_{\rm QED} = -eA_\mu J^\mu_{\rm em}, \quad J^\mu_{\rm em} = \sum_{f=1}^3\sum_{j=1}^3 e_j\left(\overline{\psi}^f_{q,j}(x)\gamma^\mu\psi^f_{q,j}(x) + \overline{\psi}^f_{l,j}(x)\gamma^\mu\psi^f_{l,j}(x)\right), \tag{2.11}$$

e_j being the electric charge of the field ψ_j in units of the unit charge e, and two neutral currents:

$$\mathscr{L}_Z = -eZ_\mu\left(\cos\theta_T J^\mu_Z + \sin\theta_T J^\mu_T\right) = -eZ_\mu J^\mu_Z + {\rm O}(\theta_T), \qquad \mathscr{L}_T = -eT_\mu\left(-\sin\theta_T J^\mu_Z + \cos\theta_T J^\mu_T\right). \tag{2.12}$$

The currents coupled to the massive gauge bosons can also be written as vector and axial vector currents using the non-chiral fields ψ_f

$$J^\mu_X = \sum_f \overline{\psi}_f(x)\gamma^\mu\left(v^{(X)}_f - a^{(X)}_f\gamma_5\right)\psi_f(x), \quad X = Z \text{ or } T, \tag{2.13}$$

with vector and axial vector couplings given explicitly in Ref. [10].

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3. Possible consequences and constraints on the parameter space

Our model may explain potentially the following observations: (i) If the lightest new particle is sufficiently stable, then it will be a candidate for WIMP dark matter. (ii) The Yukawa interactions involving the new right-handed neutrinos provide a possible origin of effective Majorana mass terms and the observed neutrino oscillations together with the Pontecorvo-Maki-Nakagawa-Sakata matrix in the charged current interactions of the left-handed neutrinos. (iii) The vacuum of the χ scalar has a supercharge $z_j = -1$ that may be a source of the current accelerated expansion of the universe. (iv) The second scalar together with the established BEH field can cause hybrid inflation. The credibility requirement for the model is to answer the following question: *Is there any region of the parameter space of the model that is not excluded by experimental results, both established in standard model phenomenology and elsewhere?* We shall address the many aspects of this question in separate publications.

4. Conclusions

In this contribution we have discussed the following points: (i) established observations require physics beyond SM, but do not suggest a rich BSM physics; (ii) assuming the existence of three right-handed neutrinos and a complex scalar that are neutral with respect to the standard model interactions, an extension of the standard model gauge group by a $U(1)_Z$ group has the potential of explaining all known deviations from the SM; (iii) anomaly cancellation and neutrino mass generation mechanism can be used to fix the supercharges up to reasonable assumptions; (iv) the parameter space can and need be constrained from existing experimental results (e.g. searches in missing energy events).

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