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Effects of RGE on fermion observables in SO10 models

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In the context of non-supersymmetric SO(10) models, we analyze the renormalization group equations for fermions from the GUT energy scale down to the electroweak energy scale, explicitly taking into account the effects of an intermediate energy scale induced by a Pati–Salam gauge group. To determine the renormalization group running, we use a numerical minimization procedure based on a nested sampling algorithm that randomly generates the values of 19 model parameters at the GUT scale, evolves them, and finally constructs the values of the physical observables and compares them to the existing experimental data at the electroweak scale. We show that the evolved fermion masses and mixings present sizable deviations from the values obtained without including the effects of the intermediate scale.

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1. Introduction

The lack of signals from physics beyond the Standard Model (SM) at the Large Hadron Collider (LHC) revives the question of which model constitutes the most appropriate extension of the SM and, if there is one, what is the energy scale where new features of particle interactions ought to be observed. In the present talk, we will study a non-supersymmetric extension of the SM model based on the gauge group SO(10) with the intent to check the ability to reproduce the values of fermion masses and mixings at the electroweak (EW) scale M_Z, taking into account the effects of an intermediate energy scale in the Yukawa RGE's.

We quantify the impact of using such new contributions in the renormalization group equations (RGEs) for fermion masses and mixings, considering an illustrative and simplified SO(10) model with a breaking chain given by [1, 2]:

$$\mathrm{SO}(10) \overset{M_{\mathrm{GUT}}-210_{\mathrm{H}}}{\longrightarrow} 4_{\mathrm{C}}\, 2_{\mathrm{L}}\, 2_{\mathrm{R}} \overset{M_{\mathrm{I}}-126_{\mathrm{H}}}{\longrightarrow} 3_{\mathrm{C}}\, 2_{\mathrm{L}}\, 1_{Y} \overset{M_{\mathrm{Z}}-10_{\mathrm{H}}}{\longrightarrow} 3_{\mathrm{C}}\, 1_{\mathrm{Y}}\,, \tag{1.1}$$

where the symbols are self-explanatory. The breaking of SO(10) down to the PS group at the GUT scale M_{GUT} is achieved by means of a 210_{H} representation of Higgs. In the next step, the breaking of the PS group down to the SM gauge group is performed by means of a $\overline{126}_{\mathrm{H}}$. At M_{Z}, the final step of the breaking of the SM gauge group to $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{U}(1)_{\mathrm{Y}}$ is obtained with a 10_{H}.

The output of our analysis will be the values of the elements of the Yukawa matrices at M_{GUT}, which give a reasonable fit to the fermion observables at M_{Z}. These values can directly be compared to the corresponding ones obtained from an evolution without the intermediate scale starting at M_{GUT}, thus allowing a quantification of the new effects introduced by the PS gauge group [3, 4].

2. Evolution of gauge coupling constants and Yukawas

In the PS group, the Higgs and matter fields decompose as:

$$\begin{aligned} 10_{\mathrm{H}} &= (1,2,2) \oplus (6,1,1)\,, \qquad 16 = (4,2,1) \oplus (\bar{4},1,2) \equiv F_{\mathrm{L}} + F_{\mathrm{R}} \\ \overline{126}_{\mathrm{H}} &= (6,1,1) \oplus (10,1,3) \oplus (\overline{10},3,1) \oplus (15,2,2)\,, \end{aligned} \tag{2.1}$$

where F_{L} and F_{R} are the left- and right-handed parts of the 16, respectively. At M_{GUT}, the gauge couplings are unified and the matching conditions are simply $\alpha_{4\mathrm{C}}(M_{\mathrm{GUT}}) = \alpha_{2\mathrm{R}}(M_{\mathrm{GUT}}) = \alpha'_{2\mathrm{L}}(M_{\mathrm{GUT}})$, where $\alpha_{4\mathrm{C}}$, $\alpha_{2\mathrm{R}}$, and $\alpha'_{2\mathrm{L}}$ are the coupling constants of SU(4), $\mathrm{SU}(2)_{\mathrm{R}}$, and $\mathrm{SU}(2)_{\mathrm{L}}$ above M_{I}, respectively. For $a_{4\mathrm{C}}, a'_{2\mathrm{L}}$, and $a_{2\mathrm{R}}$ between M_{GUT} and M_{I} the matching conditions are

$$\alpha_{3\mathrm{C}}(M_{\mathrm{I}}) = \alpha_{4\mathrm{C}}(M_{\mathrm{I}})\,, \qquad \alpha_{2L}(M_{\mathrm{I}}) = \alpha'_{2\mathrm{L}}(M_{\mathrm{I}})\,, \qquad \alpha^{-1}_{1\mathrm{Y}}(M_{\mathrm{I}}) = \frac{3}{5}\alpha^{-1}_{2\mathrm{R}}(M_{\mathrm{I}}) + \frac{2}{5}\alpha^{-1}_{4\mathrm{C}}(M_{\mathrm{I}})\,, \tag{2.2}$$

where $\alpha_{3\mathrm{C}}$, $\alpha_{2\mathrm{L}}$, and $\alpha_{1\mathrm{Y}}$ are the SM gauge coupling constants. Eventually, in the running from M_{I} down to M_{Z}, four Higgs representations are involved, stemming from the bidoublet of the 10_{H} and 126_{H}. The values of the mass scales obtained solving the one-loop RGE's for the gauge couplings are $M_{\mathrm{I}} = (1.5 \pm 0.2) \cdot 10^{12}$ GeV and $M_{\mathrm{GUT}} = (1.7 \pm 0.6) \cdot 10^{15}$ GeV.

For the Yukawa sector, at M_{GUT} we have the following Lagrangian:

$$L_Y = 16\,(h\,10_{\mathrm{H}} + f\,\overline{126}_{\mathrm{H}})\,16\,, \tag{2.3}$$

where h and f are unknown symmetric couplings to be determined through a fitting procedure. In the region between M_{GUT} and M_{I}, the Yukawa part of the Lagrangian is given by [5]

$$-\mathscr{L}_{\mathrm{Y}} = \sum_{i,j}\left(Y^{(10)}_{F\,ij} F^{iT}_{\mathrm{L}}\Phi F^{j}_{\mathrm{R}} + Y^{(126)}_{F\,ij} F^{iT}_{\mathrm{L}}\Sigma F^{j}_{\mathrm{R}} + Y^{(126)}_{R\,ij} F^{iT}_{\mathrm{R}}\overline{\Delta_R} F^{j}_{\mathrm{R}} + \mathrm{h.c.}\right)\,, \tag{2.4}$$

where $Y^{(10)}_F$, $Y^{(126)}_F$, and $Y^{(126)}_R$ are Yukawa couplings and we have used he short-hand notation

$$\Phi \equiv (1,2,2)\,, \qquad \Sigma \equiv (15,2,2)\,, \qquad \overline{\Delta_R} \equiv (10,1,3)\,. \tag{2.5}$$

Furthermore, at M_{GUT}, the couplings $Y^{(10)}_F$, $Y^{(126)}_F$, and $Y^{(126)}_R$ have to be matched to h and f:

$$\frac{1}{\sqrt{2}} Y^{(10)}_F(M_{\mathrm{GUT}}) \equiv h\,, \qquad \frac{1}{4\sqrt{2}} Y^{(126)}_F(M_{\mathrm{GUT}}) = \frac{1}{4} Y^{(126)}_R(M_{\mathrm{GUT}}) \equiv f\,,$$

where the numerical factors are Clebsch–Gordan coefficients needed for a correct embedding of PS into SO(10) [6]. Below this scale we are left with the SM Lagrangian with four Higgses. The resulting mass matrices, including the ones for neutrinos, can be found in [3].

3. Numerical parameter-fitting procedure and results

We adopt the procedure of considering the entries of the couplings h and f as well as the vacuum expectation values of the fields in 2.5 as our free parameters and evolving them down to the EW scale M_{Z}, where the values of masses and mixings of quarks, charged leptons, and neutrinos are known. There are in total 19 free parameters at M_{GUT} which need to be determined (including one Higgs self-coupling at M_{I}, not discussed here). To evolve the Yukawa's we first randomly generate the values of the parameters at M_{GUT}, according to some prior distribution; then, we evolve them down to M_{Z} after solving the RGEs; next, at M_{Z}, we construct the observables and compare them to the experimental data. The procedure is repeated with new randomly sampled parameter values from a reduced parameter space and the result is given when convergence on the point with largest likelihood occurs, *i.e.* on the best-fit point.

For the sampling procedure, we used the software MultiNest, which is based on nested sampling normally used for calculation of the Bayesian evidence [7]. The experimental values of the quark and charged lepton masses are taken from Ref. [8], the quark mixing parameters from Ref. [9], and the neutrino mass-squared differences and the leptonic mixing angles from Ref. [10].

The effect of M_{I} on the RG running is appreciated by comparing such values with the ones obtained from RG running without M_{I}. For the up and down-type quarks, this is reported in Fig. 1. In the case of the model with M_{I}, we observe that the slope of the RG running of the quark masses changes direction at M_{I}: from M_{GUT} down to M_{I}, it decreases monotonically, whereas from M_{I} down to M_{Z}, it increases monotonically. The reason for this change of direction in the evolution can be deduced from the change of sign in front of the gauge coupling terms, which dominate the β-functions in the RGEs that are given in [3]. As expected, in the case of the model without M_{I},

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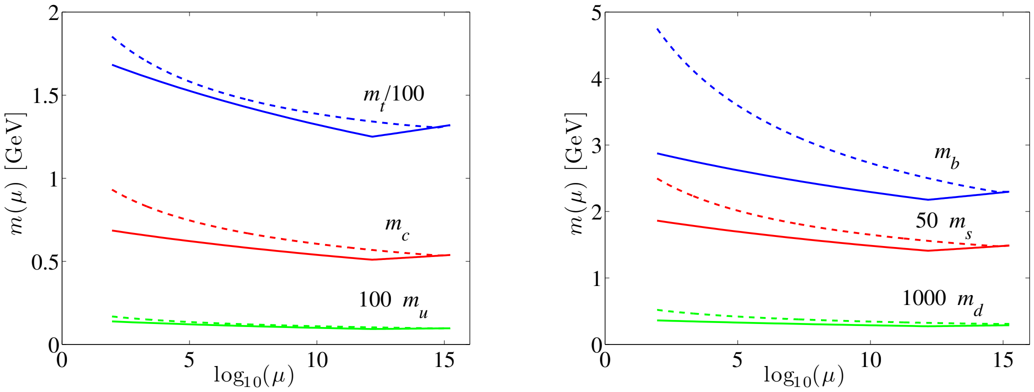

Figure 1: *The RG running of the up-type (left plot) and down-type (right plot) quark masses, with (solid curves) and without (dashed curves) the intermediate energy scale $M_{\rm I}$ as functions of the energy scale μ.*

i.e. the SM case, the RG running from $M_{\rm GUT}$ down to $M_{\rm Z}$ increases monotonically. Thus, at the $M_{\rm Z}$, the quark masses in the two cases will differ, and they will be larger in the SM case than in the model with $M_{\rm I}$. The smallest difference is for the top quark mass, which is 10 % larger at $M_{\rm Z}$, whereas the largest difference is for the bottom quark mass, which is 65 % larger.

4. Summary and conclusions

In conclusion, we have explored the effects of an intermediate energy scale on the evolution of the fermion masses and mixings in an SO(10) model with a Pati–Salam intermediate gauge group. The effects have been compared to the evolution from the GUT scale down to the EW scale in a SM-like model with two Higgs doublets. We have found that the solutions to the RGEs, *i.e.*, the values of the fermion observables, at the EW scale in the SM, disagree compared to the SO(10) model well beyond experimental uncertainties, which are at the level of 30 % for the quark masses.

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