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Proton decay in the minimal realistic $SO(10)$ GUT

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The minimal realistic $SO(10)$ model with the adjoint representation causing the GUT symmetry breaking is an appealing candidate for a realistic Grand Unified Theory. Moreover, the model allows one to make significant improvement in the proton lifetime error estimates due to the suppression of the potential gravitational effects influencing the GUT scale physics. We performed a comprehensive numerical study of the proton decay width including one-loop quantum effects mandatory in the physically relevant scenarios. The model's study was also extended by improved perturbativity constraints. We present a thorough discussion of various consistency constraints that were used to asses theory's viability.

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1. Introduction

The Grand Unified Theories (GUTs) are among the most promising approaches that extend the Standard Model (SM). Even though the new physics fields within emerge only at high energy scales (typically 10^{13}GeV – 10^{17}GeV), the phenomenological implications could be in principle observed in the present or near-future experiments. Particularly, the GUTs naturally generate non-zero neutrino masses in accordance with the experimental oscillation results. Proton is also expected not to be stable. The upcoming large volume detectors such as Hyper-K [1] or DUNE [2] aspire to observe the first proton decay. Thus one can be excited about the future experimental measurements that, eventually, will have to be matched with theoretical predictions.

2. Minimal renormalizable $SO(10)$ model

From now on we will focus on the minimal potentially realistic renormalizable $SO(10)$ model as it is one of the most intriguing candidates for a realistic GUT. The Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ is embedded into the $SO(10)$. This automatically ensures electric charge quantization as well as local quantum anomaly cancellation. The model could be regarded as an extension of the partial unifications of the Pati-Salam-like $SU(4)_c \times SU(2)_L \times SU(2)_R$ type [3] or the Georgi–Glashow $SU(5)$ [4]. The $SO(10)$ includes both these structures as possible intermediate symmetry stages that may appear during the multiple-stage spontaneous symmetry breaking.

Let us first depict the enlarged field content. One generation of the matter fermion fields with the right-handed neutrino is accommodated in the 16−dimensional spinor representation. The presence of the right-handed neutrino allows non-zero SM neutrino masses to be naturally introduced using, for example, the type-I seesaw mechanism[1]. The gauge bosons reside in the 45-dimensional vector representation containing the SM gauge fields and additional leptoquarks carrying colour and $SU(2)$ charges with masses close to the $SO(10)$ symmetry breaking scale (the so-called GUT scale). The most prominent gauge boson leptoquarks mediating proton decay transform under the SM gauge group as

$$(3, 2, -\tfrac{5}{6}) + hc., \tag{1}$$
$$(3, 2, +\tfrac{1}{6}) + hc. \tag{2}$$

The scalar sector is more elaborate in comparison with the SM. The minimal potentially realistic renormalizable setting consists of $45 \oplus 126 \oplus 10$ scalar representations. The spontaneous symmetry breaking of the $SO(10)$ down to the SM is at least two-stage. The 45−dimensional representation contains two possibly non-vanishing SM singlet VEVs

$$\langle(1, 1, 1, 0)\rangle \equiv \sqrt{3}\omega_{BL} \qquad \langle(1, 1, 3, 0)\rangle \equiv \sqrt{2}\omega_R$$

governing the $SO(10)$ symmetry breaking down to the intermediate symmetry. The transformation properties of the VEVs will always be written in the $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

[1]In addition to that, the neutrino masses can be generated by the type-II seesaw mechanism as there is a scalar $SU(2)_L$ triplet present in the 126−dimensional scalar representation [5].

language. The values of ω_{BL} and ω_R determine the GUT scale. The 126-dimensional representation controls the subsequent symmetry breaking down to the SM[2] by accommodating a non-zero SM singlet with the VEV

$$\langle(1,1,3,2)\rangle \equiv \sqrt{2}\sigma.$$

The rank is broken only at this stage. The right-handed neutrino masses are determined by the scale of $|\sigma|$ (the so-called seesaw scale). The minimal realistic choice of the scalar sector incorporates additional 10−dimensional scalar representation which helps to accommodate fermionic masses [6], [7].

The abundance of the scalar and gauge leptoquarks leads to the possibility of baryon number violation (BNV). The most prominent perturbative BNV process is proton decay because there is no Standard Model background as proton is predicted to be stable in the SM. Moreover, proton lifetime predictions in the minimal renormalizable $SO(10)$ model are robust with respect to many types of theoretical uncertainties [8], [9]. In what follows we will present the procedure of calculating proton lifetime in this scenario.

3. Proton decay cookbook

In the current work the proton decay cookbook has been extended with theoretical consistency constraints that were improved in comparison with the previous studies [10], [11]. General theoretical and phenomenological restrictions are discussed below.

3.1 Parameter space

The analysis of the proton decay in the minimal $SO(10)$ framework starts by a detailed investigation of the parameter space with 13 real and 2 complex parameters (excluding Yukawa sector) subject to all the consistency criteria. Most of these parameters reside in the scalar potential. In addition, the GUT gauge coupling and VEVs are counted in.

3.2 Tachyonicity

The existence of non-tachyonic scalar spectrum is the crucial requirement restricting the viable parameter space. The situation is even more complicated because all the realistic scenarios involve accidentally light and often tachyonic pseudo-Goldstone scalars transforming as $(8,1,0)$, $(1,3,0)$ and $(1,1,0)$. Thus the minimal renormalizable $SO(10)$ GUT is inherently a quantum model and the complete calculation of full one-loop effective scalar mass corrections should be implemented. The interested reader can find partial analytic one-loop results for $(8,1,0)$, $(1,3,0)$ in [12].

[2] Let us note that it is possible to manage the intermediate symmetry breaking by implementing a 16−dimensional scalar spinor representation. However, the Yukawa sector cannot be renormalizable in this case as the decomposition

$$16_F \times 16_F = 10 \oplus 126 \oplus 120$$

does not contain any 16. The index F denotes fermion fields.

3.3 Perturbativity

All the calculations are carried out in the perturbative regime. Usually the scalar and Yukawa couplings are assumed to remain in the $O(1)$ domain. We aim at outlining more elaborate perturbativity criteria by exploiting the one-loop effective potential corrections. However, one should take these tests with a grain of salt as there is an unavoidable arbitrariness connected with their definitions.

Stability of the vacuum position

Positions of the one-loop and tree-level vacua are required not to be "too far away" from each other. Hence the derivative of the one-loop effective potential is assessed. Even though the positions of vacua (the field values in the vacua) are not physical quantities, the criterion restricts the size of the one-loop corrections and serves as a preliminary test. Moreover, the stability of vacuum position is tested on different renormalization scales using one-loop beta functions for all the scalar and gauge model's couplings.

Global mass perturbativity

The global mass perturbativity criterion exploits the information about the one-loop mass corrections. We require the maximal one-loop scalar mass correction to be smaller than the average tree-level mass. This test intentionally does not scrutinize the mass spectrum in too much detail as, for the sake of simplicity, it does not compare the one-loop corrections with the tree-level expressions field by field.

Last, but not least, it should be noticed that the tree-level stationary conditions contain a particular VEV structure [12]

$$\frac{\omega_{BL}\omega_R(\omega_{BL}+\omega_R)}{|\sigma|^2}. \tag{3}$$

It also proliferates to the one-loop expressions and will not vanish by zeroing out a certain set of dimensionless scalar parameters. Whenever (3) exceeds the GUT scale, distortion of the tree-level scalar mass-squares is expected as they are proportional to this VEV structure. Hence we shall adopt a bound

$$\frac{|\omega_{BL}\omega_R(\omega_{BL}+\omega_R)|}{|\sigma|^2} < \max[|\omega_{BL}|, |\omega_R|] \tag{4}$$

to restrain the VEVs. In reality, there are four possible classes of potentially viable combinations:

1. almost one-step spontaneous symmetry breaking with $\max[|\omega_{BL}|, |\omega_R|] \approx |\sigma|$,
2. (flipped) $SU(5)$ intermediate symmetry stage with $\omega_{BL} \approx \pm\omega_R$,
3. $SU(4)_c \times SU(2)_L \times U(1)_R$ intermediate symmetry stage with $\omega_{BL} \ll \omega_R$,
4. $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ intermediate symmetry stage with $\omega_R \ll \omega_{BL}$.

The one-step symmetry breaking in option 1 is not favourable because phenomenology prefers the seesaw scale controlling neutrino masses to be lower than the GUT scale. Moreover, option 2. runs into the problem with proton stability due to very light proton-decay-mediating gauge leptoquarks (1)-(2) [12]. Thus the only viable options turn out to be classes 3. and 4.

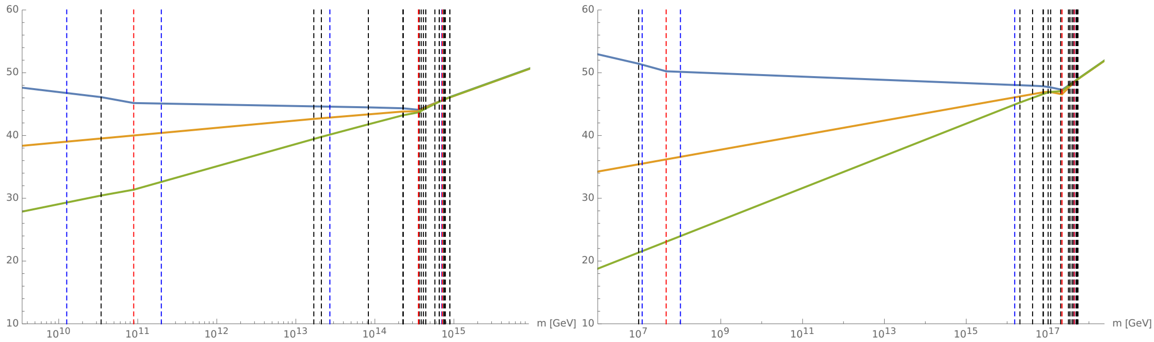

Figure 1: Gauge unification pattern for sample points in the limiting cases $\omega_{BL} \ll \omega_R$ (left) and $\omega_R \ll \omega_{BL}$ (right). The blue, orange and green colours denote $\alpha_1^{-1}, \alpha_2^{-1}$ and α_3^{-1} running gauge couplings, respectively. **Black** dashed lines mark non-singlet scalar thresholds, red dashed lines indicate non-singlet gauge boson thresholds and blue dashed lines stand for Standard Model singlets.

3.4 Unification

Successful gauge coupling unification also serves as a criterion to narrow down the viable parameter space. Robust proton lifetime estimates have to involve a two-loop gauge coupling running calculation to extract the scale of unification. Figure 1 depicts two examples of typical unification patterns in the limiting cases $\omega_{BL} \ll \omega_R$ and $\omega_R \ll \omega_{BL}$ obtained by the analysis using one-loop beta functions. Note that these results are consistent with the previous studies based on the minimal survival hypothesis [13].

4. Conclusions

The $SO(10)$ Grand Unified Theory is an appealing framework extending the Standard Model and predicting new (yet-to-be-observed) phenomena. The smoking-gun signal is expected to be proton decay. Hence the process will be heavily searched in the advanced near-future large volume facilities. The progress of experimental measurements has to be followed by precise theoretical predictions. We focus on the minimal potentially realistic renormalizable $SO(10)$ model where the proton lifetime prediction turns out to be rather robust with respect to the main theoretical uncertainties. The detailed discussion of various consistency constraints imposed on the model was presented. This will be eventually used to perform a comprehensive analysis of the theory and the proton decay width. Results of the study will be presented in upcoming papers.

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