

## 16 Conclusions

Putting all together, the lagrangian which contains the dynamics of particle physics, as described by the Standard Model, is decomposed into (not including gauge fixing terms)

$$\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_S + \mathcal{L}_Y$$

where each piece has been previously defined. If one attempts to count the number of parameters we arrive at:

- $SU(3)$  (QCD) gauge invariance: 1 coupling  $g_s$  or  $\alpha_s$  which is rather precisely determined by an enormous amount of data in deep-inelastic scattering, proton-proton, proton-antiproton or more generally hadron-hadron collisions,  $e^+ + e^- \rightarrow jets$  as well as, at low energy, hadronic  $\tau$  decays<sup>19</sup> :  $\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$  in the  $\overline{MS}$  renormalisation scheme with 5 active flavours.

- $SU(2)_L \otimes U(1)_Y$  gauge invariance: two couplings  $g, g'$ , and the weak mixing angle  $\theta_w$  : in fact one coupling  $e$ , the charge of the proton/electron and the angle because of the relation  $g \sin \theta_w = g' \cos \theta_w = e$ . One has  $\alpha = 1/(137.035999139 \pm 0.000000031)$  and  $\sin \theta_w = M_W/M_Z$  with  $M_W = 80.385 \pm 0.015$  GeV,  $M_Z = 91.1876 \pm 0.0021$  GeV.

- spontaneous symmetry breaking from  $\mathcal{L}_S$ : two parameters  $\mu$  and  $h$  or rather the vacuum expectation value  $v$  and  $h$  determined, for example, from  $v = M_W \sin \theta_w / \sqrt{\pi \alpha}$  and  $h = 0.5 M_H^2 / v^2$  with  $M_H = 125.09 \pm 0.24$  GeV<sup>109</sup>.

- Yukawa couplings in  $\mathcal{L}_Y$ : nine couplings, i.e. one coupling per lepton and quark species and four CKM parameters for the mixing between quark generations. The Yukawa couplings are determined from the masses  $m_e = 0.510998946$  MeV,  $m_\mu = 105.6583745$  MeV,  $m_\tau = 1.7768$  GeV,  $m_u = 2.2$  MeV,  $m_d = 4.7$  MeV,  $m_s = 96$  MeV,  $m_c = 1.27$  GeV,  $m_b = 4.18$  GeV,  $m_t = 173.2$  GeV. Massive neutrinos of Dirac type require seven new parameters.

There are thus 25 parameters assuming Dirac neutrinos (27 with Majorana neutrinos), most of them related to the fermions, which is not a satisfactory situation for a minimal model! However the model is strongly constrained since there are no less than 68 vertices of various types expressed in terms of the above parameters. Any persistent deviation from the predicted values in the Standard Model will indicate new physics. Checking experimentally the value of these couplings is one of the tasks of particle physicists.

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<sup>109</sup>Combined Measurement of the Higgs Boson Mass with the ATLAS and CMS Experiments, G. Aad, et al., arXiv:1503.07589.

The large number of parameters has prompted an intensive continuing search for higher hidden symmetries such as supersymmetry, for example, and Minimal Supersymmetric Standard Models and Next-to-Minimal Supersymmetric Standard Models and  $\dots$  have been constructed. The very unfortunate situation is that in such models the number of fields is more than doubled compared to the Standard Model as no supersymmetric multiplets can be filled with only known particles. Furthermore, while in principle supersymmetry breaking can in turn trigger electroweak symmetry breaking, one does not know yet how supersymmetry is dynamically broken. Thus one is led to describe it in a effective way which requires many more parameters than in the Standard Model. It seems that, at present, the remedy is worse than the disease but there are still hopes .....