Physics beyond the Standard Model

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Exercise Sheet 3

Discussion: Fr, 21.11.14

Exercise 3: Flavour-changing Neutral Currents

The appearance of flavour-changing neutral currents (FCNC) poses a serious problem for 2HDMs. In this exercise, we will calculate the origin of these terms from the Lagrangian. For simplicity, we will restrict the fermion sector of the model to the leptons of the first two generations: electrons and muons and their corresponding neutrinos. The terms with fermions in the Lagrangian read

$$\mathcal{L}_f = \bar{L}_L i\not{D} L_L + \bar{E}_R i\not{D} E_R - \left(\bar{L}_L \left(\Pi_1\Phi_1 + \Pi_2\Phi_2\right) E_R + h.c.\right) \ .$$

Thereby, $L_L = (N_L, E_L)^T$ is an $SU(2)$ doublet of left-handed neutrinos and charged leptons, and in turn $E_{L,R}, N_L$ are two-vectors in flavour (generation) space, e.g. $E_L = (e_L, \mu_L)^T$ consists of left-handed electrons and muons. The Yukawa matrices $\Pi_{1,2}$ are complex 2×2 matrices in flavour space.

(a) Consider only the part of the Lagrangian which describes free fermion fields, i.e. their kinetic term and the mass term arising from the Yukawa term after spontaneous symmetry breaking.
Show that by a suitable redefinition of the fields the expression can be cast into the standard form for free Dirac particles

$$\mathcal{L}_{f,\text{free}} = \bar{N}' i\not{\partial} N' + \bar{E}' i\not{\partial} E' - M\bar{E}'E'$$

with $M = \text{diag}(m_e, m_\mu)$ and Dirac fermions E', N'. The primed basis is the basis of mass eigenstates.
Hint: singular value decomposition

(b) As next step we consider the Yukawa terms giving rise to fermion-Higgs interactions. Write down the corresponding terms and show that the interactions with the Goldstone bosons remain flavour-conserving, while the ones with the physical Higgs bosons are potentially flavour-violating.

(c) Possible solutions out of this problem are either to require that each fermion of a given charge only couples to one of the two Higgs doublets, or to require that the

two Yukawa matrices are proportional to each other: $\Pi_2 = \xi \Pi_1$, with a complex number ξ.
Show that in these cases the flavour-violating terms vanish.