An extension of the Standard Model with a vectorlike forth generation

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Introduction

- In the Nature three generations of fermions are observed experimentally
- Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}$$

- Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

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- But why only three families? Other generations are not forbidden experimentally or theoretically.
- Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix} \qquad ?$$

- Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad ?$$

The Standard Model

- In the SM left-handed and right handed particles have different quantum numbers - they are chiral.

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \qquad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$d_R \qquad s_R \qquad b_R$$

- $$L_{d,Z} = \bar{d}_L \sigma^\mu \left(-\frac{g^2 + g'^2/3}{2\sqrt{g^2 + g'^2}} Z_\mu \right) d_L + \bar{d}_R \sigma^\mu \frac{g'}{3\sqrt{g^2 + g'^2}} (-g' Z_\mu) d_R$$

The model with extra vectorlike d-quarks

- d^4 is vectorlike. It means d^4_L and d^4_R have the same quantum numbers. They coincide with one's of the right-handed particles of the SM.
- The observable particles have the same quantum numbers as in the SM

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad d^4_L$$

$$d_R \quad s_R \quad b_R \quad d^4_R$$

$$L_{d,Z} = \bar{d}_L \sigma^\mu \left(-\frac{g^2 + g'^2/3}{2\sqrt{g^2+g'^2}} Z_\mu \right) d_L + \bar{d}_R \sigma^\mu \frac{g'}{3\sqrt{g^2+g'^2}} (-g' Z_\mu) d_R +$$

$$\bar{d}_{R,4} \sigma^\mu \frac{g'}{3\sqrt{g^2+g'^2}} (-g' Z_\mu) d_{R,4} - \bar{d}_{L,4} \sigma^\mu \frac{g'}{3\sqrt{g^2+g'^2}} (-g' Z_\mu) d_{L,4}$$

Quark masses in the Standard Model

- In the SM quarks have non-diagonal mass matrix

$$L_m = d_i^L m_{ij}^d d_j^R + u_i^L m_{ij}^u u_j^R$$

- They can be diagonalized by double unitary transformation

$$\begin{array}{lll} D_d = U_d m_d V_d^+ & d_m^R = V_d d_R & d_m^L = U_d^* d^L \\ D_u = U_u m_u V_u^+ & u_m^R = V_u u_R & u_m^L = U_u^* u^L \end{array}$$

- But in this case the interaction with W bosons is not diagonal

$$\begin{aligned} L_{d,u,W} &= \bar{u}_i \sigma^\mu W_\mu^+ d_i + \bar{d}_i \sigma^\mu W_\mu^- u_i \\ &= \bar{u}_{i,m} (V_{CKM})_{ij} \sigma^\mu W_\mu^+ d_{j,m} + \bar{d}_i (V_{CKM}^+)_{ij} \sigma^\mu W_\mu^- u_i \end{aligned}$$

- CKM matrix V_{CKM} is measured experimentally.

Quarks mass matrices

- In our model the mass matrices are instead

$$L_m = d^L m^d d^R + u^L m^u u^R$$

$$m^d = \begin{pmatrix} \mu_1 & 0 & 0 & \tilde{\mu}_1 \\ 0 & \mu_2 & 0 & \tilde{\mu}_2 \\ 0 & 0 & \mu_3 & \tilde{\mu}_3 \\ M_1 & M_2 & M_3 & M_4 \end{pmatrix}, \qquad m^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

- $\mu_3, \tilde{\mu}_3 \sim m_b, \tilde{\mu}_2 \sim m_s, \mu_i \leq \tilde{\mu}_i < M_i$
- The parameters can be chosen in such way that they reproduce the experimental values of quarks masses and CKM matrix

Diagonalization of d-quarks mass matrix

- $L_{m_d} = d^L m^d d^R$
- The diagonalization is made by two steps. The first

$$U_4^+ m^d V_4 = m' = \begin{pmatrix} \hat{m} & 0 \\ 0 & M \end{pmatrix}$$

- It is possible to choose

$$U_4 \approx \begin{pmatrix} 1 & \bar{u} \\ -\bar{u}^+ & 1 \end{pmatrix}$$

$$|u| << 1$$

- Then $m^d = U_4 U_3 D V_3^+ V_4^+$

$$V_3 = \begin{pmatrix} \hat{V}_3 & 0 \\ 0 & 1 \end{pmatrix} \qquad U_3 = \begin{pmatrix} V_{CKM} & 0 \\ 0 & 1 \end{pmatrix}$$

$$d^L_{mass} = U_3^T U_4^T d^L \qquad d^R_{mass} = V_3^+ V_4^+ d^R$$

Interaction between left-handed d-quarks and Z boson

- In the Standard Model

$$L_{d_L,Z} = \bar{d}_L \sigma^\mu Z_\mu d_L$$

- In our theory

$$\begin{aligned} L_{d_L,Z} &= \bar{d}_L^{mass} \sigma^\mu Z_\mu \left(-\frac{g^2 + g'^2/3}{2\sqrt{g^2+g'^2}} \right) \begin{pmatrix} 1 & V_{CKM}^T u^* \\ u^T V_{CKM}^* & 0 \end{pmatrix} d_L^{mass} \\ &+ \bar{d}_L^{mass} \sigma^\mu Z_\mu \frac{g'^2}{3\sqrt{g^2+g'^2}} \begin{pmatrix} 0 & -V_{CKM}^T u^* \\ -u^T V_{CKM}^* & 1 \end{pmatrix} d_L^{mass} \end{aligned}$$

- So in this model there is tree level Flavour changing neutral current which does not exist in the SM.

Interaction between d-quarks and Higgs

- In the Standard Model

$$L_{H,d} = \sum_{i=1}^{3} H_a Q_i^{L^a} h_{ij} d_j^R$$

- In our model

$$L_{H,d} = \sum_{i=1}^{3} H_d^a \epsilon_{ab} Q_i^{Lb} h_{ii} d_i^R + \sum_{i=1}^{3} H_d^a \epsilon_{ab} Q_i^{Lb} \frac{g_i^d v_N}{M*} d_4^R + \sum_{i=1}^{3} d_L^4 f_i v_N d_i^R + d_4^L M_d d_4^R$$

- Not all masses derive from interaction with Higgs

FCNC in case of interaction with Higgs

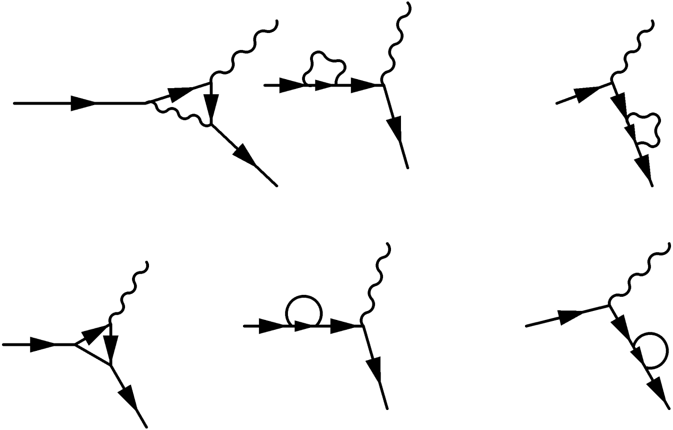
- In case of interaction between d-quarks and Higgs field there is also Flavour changing neutral current

$$H_d = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} + \begin{pmatrix} 0 \\ H_d^0 \end{pmatrix}$$

$$L_{H,d} = d^L_{mass} D^d d^R_{mass} + d^L \frac{H_d^0}{v_1} \begin{pmatrix} m_d & 0 & 0 & -M(V^+_{CKM}u)_1 \\ 0 & m_s & 0 & -M(V^+_{CKM}u)_2 \\ 0 & 0 & m_b & -M(V^+_{CKM}u)_3 \\ 0 & 0 & 0 & 0 \end{pmatrix} d^R$$

Phenomenology. A decay $b \to s/d\gamma$

The fermion b changes its flavour and finally turns into s or d by emitting and absorbing Z or Higgs boson. Also it emits a photon:



Conclusions

- The parameters of the theory can be selected in such way that observable values for the lighter three generations are in agreement with experimental data
- A theory with extra vectorial quarks predicts an existence of tree level Flavour Changing Neutral Current (In the SM FCNC exists only at loop level).
- FCNC contributes to some processes such as $b \to s/d\gamma$ which are measured experimentally. Experimental data can be applied to find constraints on the d^4 mass and their mixing with the other three generations.
- Also there are corrections to some other processes: $B_0 - \bar{B}_0$ mixing, decay$Z \to \bar{d}_\alpha d_\beta$ etc.

references

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