Proceedings of the International School-seminar
"New Physics and Quantum Chromodynamics at external Conditions", pp. 104 – 106,
3-6 May 2007, Dnipropetrovsk, Ukraine

NEW (VIRTUAL) PHYSICS IN THE ERA OF THE LHC

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A simple extension of the Standard Model demonstrates that New Physics non-reachable through direct production at LHC can induce up to 10% corrections to the Standard Model value of parameter ε_K and to the frequencies of $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ oscillations.

Let us imagine the worst scenario: the only new particle found at the LHC will be the Higgs boson of the Standard Model (SM). A natural question arises: is it possible to find traces of New Physics in low energy observables without observing the production of new particles at LHC? Another facet of this question: What changes of the unitarity triangle can be produced by such particles? This is the problem we will focus on.

In order to influence the quark weak currents the new particles should be strongly interacting. The natural example would be the fourth quark-lepton family: the fourth generation quarks deform unitarity triangle into unitarity quadrangle. However since the sequential fourth generation gets masses through Higgs mechanism, its quarks cannot be heavier than 1 TeV: so, they will be directly produced at LHC. That is why the heavy particles we are looking for should get their masses from a different source. So their contributions to low energy observables decouple, being suppressed as $(\eta/M)^2$, where $\eta = 246$ GeV is the Higgs boson neutral component expectation value and M characterizes new particles masses, $M \geq 5$ TeV in order to avoid their production at LHC. These 1% corrections are too small to be detected taken into account relatively low accuracy of theoretical formulas. Nevertheless we manage to find a model where corrections are enhanced and can be detected.

Let us study the extension of SM by $SU(2)_L$ singlet heavy Dirac quark Q with electric charge $+2/3$ which mixes with the top quark. Recently the constraints from the $B \to X_s\gamma$ branching ratio and electroweak precision observables in this model have been studied [1]. Authors of [1] are interested in manifestations of rather light Q with mass just above Tevatron bound. As a consequence Q mixes strongly with the top quark in their model. So our model with much heavier Q which mixes weakly with top (see below) can be considered as complementary to [1].

The model is described by the following lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} - M\bar{Q}'Q' + \left[\mu_R \bar{Q}'_L t'_R + \frac{\mu_L}{\eta/\sqrt{2}} H^+ \bar{Q}'_R \left(\begin{array}{c} t' \\ b' \end{array}\right)_L + c.c.\right] \ , \tag{1}$$

where $\mathcal{L}_{SM}$ is the SM lagrangian, M, μ_R and μ_L are the parameters with the dimension of mass. The term proportional to M contains Dirac mass of the field Q' which is primed since it is not a state with a definite mass due to mixing with t-quark. The term proportional to μ_R describes the mixing of two $SU(2)_L$ singlets: Q'_L and t'_R, the latter being the right component of t-quark field in the Standard Model (in the absence of terms in square brackets). Finally, the term proportional to μ_L describes mixing of a weak isodoublet with Q'. An upper component of this isodoublet is the left component of the field t' which would be t-quark without the terms in square brackets:

$$t'_L = U^L_{t't''} t''_L + U^L_{t'c'} c'_L + U^L_{t'u'} u'_L \ , \tag{2}$$

where t'', c' and u' are the primary fields of SM lagrangian, while U^L_{ik} are the matrix elements of matrix U^L which transforms the primary fields c'_L and u'_L to the left-handed components of the mass eigenstates c and u and field t''_L to the field t'_L which would be the left-handed component of the top quark in the case $\mu_L = \mu_R = 0$. We do not mix $Q-$quark with $u-$ and $c-$ quarks in order to avoid FCNC which may induce too large $D^0 - \bar{D}^0$ oscillations.

One can easily see that the lower component of the isodoublet is the combination of the down quark fields with definite masses rotated by CKM matrix V:

$$b'_L = V_{tb} b_L + V_{ts} s_L + V_{td} d_L \ . \tag{3}$$

In order to find the states with definite masses which result from t'–Q' mixing, the following matrix should

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be diagonalized:

$$(\overline{t'_L t'_R Q'_L Q'_R}) \begin{pmatrix} 0 & m_t & 0 & \mu_L \\ m_t & 0 & \mu_R & 0 \\ 0 & \mu_R & 0 & -M \\ \mu_L & 0 & -M & 0 \end{pmatrix} \begin{pmatrix} t'_L \\ t'_R \\ Q'_L \\ Q'_R \end{pmatrix} , \tag{4}$$

where m_t is the mass of t-quark in SM. For the squares of masses of the eigenstates we get:

$$\begin{aligned} 2(\lambda^2)_{t,Q} &= M^2 + \mu_R^2 + \mu_L^2 + m_t^2 \mp \\ &\mp \sqrt{(M^2 + \mu_R^2 + \mu_L^2 + m_t^2)^2 - 4M^2 m_t^2 - 4\mu_L^2\mu_R^2 + 8m_t\mu_R\mu_L M} , \end{aligned} \tag{5}$$

and the eigenstates look like (in what follows we put $m_t = 0$[1]):

$$t = t'_L + (1 - \frac{\lambda_t^2}{\mu_L^2})\frac{\mu_R\mu_L}{\lambda_t M} t'_R + \frac{\mu_L}{M}(1 - \frac{\lambda_t^2}{\mu_L^2})Q'_L + \frac{\lambda_t}{\mu_L} Q'_R , \tag{6}$$

$$\lambda_t = \frac{\mu_R\mu_L}{M}\left(1 - \frac{\mu_R^2 + \mu_L^2}{2M^2}\right) + O(\frac{1}{M^5}) , \tag{7}$$

$$Q = Q'_R + (-\frac{\lambda_Q}{M} + \frac{\mu_L^2}{\lambda_Q M})Q'_L + \frac{\mu_L}{\lambda_Q} t'_L + \frac{\mu_R}{M}\left(\frac{\mu_L^2}{\lambda_Q^2} - 1\right) t'_R , \tag{8}$$

$$\lambda_Q = -M + O\left(\frac{1}{M}\right) , \tag{9}$$

the normalization factors of the quark fields which should be taken into account when calculating Feynman diagrams are omitted.

Now we are ready to discuss the flavor changing quark transitions.

$\bar{t}_R(b_L, d_L, s_L)H^+$ transition vertex originates in our model from Q_R admixture in the t-quark wave function:

$$\begin{aligned} &\frac{\mu_L}{\eta/\sqrt{2}} \frac{\lambda_t/\mu_L}{\sqrt{\frac{\mu_L^2\mu_R^2}{\lambda_t^2 M^2}\left(1 - \frac{\lambda_t^2}{\mu_L^2}\right)^2 + \frac{\lambda_t^2}{\mu_L^2}}} \bar{t}_R b'_L H^+ = \\ &= \frac{\lambda_t}{\eta/\sqrt{2}} \frac{1}{\sqrt{1 + (\frac{\mu_L}{M})^2\left(1 - \frac{\lambda_t^2}{\mu_L^2}\right)^2}} \bar{t}_R b'_L H^+ , \end{aligned} \tag{10}$$

that is why up to the corrections $\sim (\mu_L/M)^2$ the box diagrams for $B_{d,s} - \bar{B}_{d,s}$, $K^0 - \bar{K}^0$ transitions with the intermediate t-quarks are the same as in SM[2].

How large can the term $(\mu_L/M)^2$ be? According to Eq.(1) μ_L cannot be larger than 500 GeV: in the opposite case we will be out of the perturbation theory domain and no calculations can be trusted. That is why trying to have the largest possible deviations from SM we will take $\mu_L = 500$ GeV in what follows. The smallest value of M which will prevent the production of Q-quarks at LHC is about 5 TeV, and we will use it in order to maximize deviations from SM (consequently $\mu_R = m_t M/\mu_L \approx 1.7$ TeV). At one loop level Q-quark contributes to $Z \to b\bar{b}$ decay. The analysis of the experimental data made in [1] lead to $\mu_L/M \leq 0.4$, and we are on the safe side. The constraint from $B \to X_s\gamma$ decay is even weaker. The box with two intermediate t-quarks is equal to that in SM with $(\mu_L/M)^2 \approx 1\%$ accuracy. Theoretical uncertainties in matrix elements calculations do not allow to detect 1% deviation from SM results.

Our model generates extra contributions to $\Delta F = 2$ four-fermion operators due to the boxes with intermediate Q-quarks. The boxes with H^+ exchanges generate leading contributions in the limit $m_t, M \gg M_W$. The box with one t-quark substituted by Q gives coefficient $\sim G_F^2 m_t^2 (\mu_L/M)^2 \ln(M/m_t)^2$: once more the correction is damped by the factor $(\mu_L/M)^2 \approx 1\%$ relative to the SM contribution.

The largest correction comes from the box with two intermediate Q-quarks:

$$\left(\frac{|\mu_L|}{\eta/\sqrt{2}}\right)^4 \frac{1}{M^2}(\bar{b}_L\gamma_\mu d_L)(\bar{b}_L\gamma_\mu d_L) , \tag{11}$$

[1]We did it in order to simplify the formulas a bit; however this can be suggested as an explanation of heaviness of top: t-quark massless in SM gets all its mass due to mixing with heavy Q.

[2]Since H^+ is the longitudinal W^+-boson polarization its interaction is the same as that of W^+ and the square root in the denominator from (t_R, Q_R) proper normalization equals that for (t_L, Q_L) component.

where as an example we present the operator responsible for $B_d - \bar{B}_d$ oscillations. In this way we get:

$$\frac{\text{box}(QQ)}{\text{box}(tt)} \approx \frac{\mu_L^4}{m_t^2 M^2} \approx 10\% \ . \tag{12}$$

The explicit formula which takes into account (tt) and (QQ) boxes can be easily obtained from that of SM [2]:

$$\Delta m_{B_d} = \frac{G_F^2 B_{B_d} f_{B_d}^2}{6\pi^2} m_B \left[m_t^2 I\left(\frac{m_t^2}{M_W^2}\right) + M^2 \left(\frac{|\mu_L|}{M}\right)^4 I\left(\frac{M^2}{M_W^2}\right)\right] \eta_B |V_{td}|^2,$$

$$I(\xi) = \left\{ \frac{\xi^2 - 11\xi + 4}{4(\xi-1)^2} - \frac{3\xi^2 \ln \xi}{2(1-\xi)^3} \right\},$$
$$I(0) = 1; \qquad I\left(\frac{m_t^2}{M_W^2}\right) \approx 0.55; \qquad I(\infty) = 0.25. \tag{13}$$

In conclusion we have found a simple extension of SM with one additional heavy quark Q, $M_Q \approx 5$ TeV (non-reachable by direct production at LHC), in which the corrections to CP violating factor ε in $K - \bar{K}$ transitions and the values of Δm_{B_d} and Δm_{B_s} are universal and can reach 10%. We demonstrate that even with no new particles found at LHC one cannot claim that the Unitarity Triangle is universal and unambiguously extractable from different observables with the accuracy better than 10%. In our case the triangle determined by angles found from CP-asymmetries in B-decays and by one side $(V_{cb}^* V_{cd})$ has the value of side $(V_{tb}^* V_{td})$ which, being substituted into the SM expression for Δm_{B_d}, produces the number smaller than the one extracted from the measurement of the $B_d - \bar{B}_d$ oscillation frequency by ≈10%. However, to detect this discrepancy one needs to have an accuracy in the value of the product $f_{B_d}^2 B_{B_d}$ better than 10% (the present day accuracy is about 2 times worse [3]).

Heavy quark Q will lead to extra radiative corrections to electroweak observables (M_W, M_Z, Γ_Z ...). In this way the central value of the higgs mass which is extracted from the fit will be shifted. We plan to make necessary calculations in the nearest future.

In recent paper [4] the contribution to $\Delta m_{B_{d,s}}$ due to singlet heavy fermion with electric charge +2/3 has been studied. The analyzed model is motivated by a Little Higgs scenario. In this scenario our factor μ_L is substituted by $x_L \eta$, where $0 \le x_L \le 1$ [5]. That is why even for $x_L = 1$ correction to $\Delta m_{B_{d,s}}$ is damped by the factor $2^4 = 16$ compared to our value.

This talk is based on the paper [6] which originates as the answer to A. Golutvin's question.

Acknowledgements. I am grateful to V. Novikov and A. Rozanov for interesting discussions.

I am very grateful to the Conference organizers and in particular to Vladimir Skalozub for their hospitality. This work was partly supported by grants RFBR 05-02-17203, 07-02-00021 and HSh-2603.2006.2.

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