THE PHOTON DIPOLE IN GENERIC EXTENSIONS OF THE STANDARD MODEL

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Introduction

Flavour-changing neutral current transitions (FCNC) often vanish at tree level in the Standard Model (SM) and its extensions. However with the help of extra sources of flavour violations it is possible to generate FCNC processes at loop level. Examples of this kind of sources can be $W^{\pm}$ bosons in the SM or extra heavy scalars/vectors in the SM extensions.
The high precision of the experimental measurements and the suppression within the SM make these processes ideal probe for the search of new physics. To investigate the possible theory landscape we study generic extensions of the SM, but restrict ourselves to renormalisable theory to achieve calculability. In this project we examine the γ-penguin diagrams in a generic extension of the SM.

Generic Extexsion of the SM

We consider an extension of the SM in an arbitrary number of heavy fermion, vector and physical scalar fields. In our context, heavy means particles masses are of the order of the electroweak scale or larger. Interaction part of the extended Lagrangian which is relevant to our calculations is [2]

$$\begin{aligned}\mathcal{L}_{\text{int}} = &\sum_{f_1 f_2 s_1 \sigma} y^{\sigma,abc}_{s_1 \bar{f}_1 f_2} h^a_{s_1} \bar{\psi}^b_{f_1} P_\sigma \psi^c_{f_2} + \sum_{f_1 f_2 v_1 \sigma} g^{\sigma,abc}_{v_1 \bar{f}_1 f_2} V^a_{v_1,\mu} \bar{\psi}^b_{f_1} \gamma^\mu P_\sigma \psi^c_{f_2} \\ &+ \frac{i}{6} \sum_{v_1 v_2 v_3} g^{abc}_{v_1 v_2 v_3} \left(V^a_{v_1,\mu} V^b_{v_2,\nu}\, \partial^{[\mu} V^{c,\nu]}_{v_3} + V^c_{v_3,\mu} V^a_{v_1,\nu}\, \partial^{[\mu} V^{b,\nu]}_{v_2} + V^b_{v_2,\mu} V^c_{v_3,\nu}\, \partial^{[\mu} V^{a,\nu]}_{v_1} \right) \\ &+ \frac{1}{2} \sum_{v_1 v_2 s_1} g^{abc}_{v_1 v_2 s_1} V^a_{v_1,\mu} V^{b,\mu}_{v_2} h^c_{s_1} - \frac{i}{2} \sum_{v_1 s_1 s_2} g^{abc}_{v_1 s_1 s_2} V^{a,\mu}_{v_1} \left(h^b_{s_1}\, \partial_\mu h^c_{s_2} - (\partial_\mu h^b_{s_1})\, h^c_{s_2} \right).\end{aligned} \tag{1}$$

Here, $\sigma = L, R$ denotes the chirality of the fermion field. For manipulation of unphysical scalar boson couplings the Slavnov-Taylor identities (STIs) are applied, which is well described in the Goldstone-boson equivalence theorem [3].

Slavnov-Taylor Identities

An accurate way of deriving the STIs is from the invariance of a non-Abelian gauge theory under Becchi, Rouet and Stora (BRS) transformation [5]. These identities can be used for derivation of specific sum rules, equations that impose non-trivial constraints on the couplings of physical fields. Such kind of sum rules can be useful tool for renormalization of generic loop calculations [2].
The three point couplings of unphysical fields ϕ_v with corresponding vector bosons V_v

$$g_{v_1\phi_2\phi_3} = \sigma_{v_2}\sigma_{v_3}\frac{M^2_{v_2} + M^2_{v_3} - M^2_{v_1}}{2M_{v_2}M_{v_3}} g_{v_1v_2v_3}, \qquad g_{\phi_1\phi_2 s_1} = -\sigma_{v_1}\sigma_{v_2}\frac{M^2_{s_1}}{2M_{v_1}M_{v_2}} g_{v_1v_2s_1},$$

$$g_{v_1v_2\phi_3} = -i\sigma_{v_3}\frac{M^2_{v_1} - M^2_{v_2}}{M_{v_3}} g_{v_1v_2v_3}, \qquad g_{\phi_1 s_1 s_2} = i\sigma_{v_1}\frac{M^2_{s_1} - M^2_{s_2}}{M_{v_1}} g_{v_1 s_1 s_2},$$

$$g_{v_1\phi_2 s_1} = -i\sigma_{v_2}\frac{1}{2M_{v_2}} g_{v_1v_2s_1}, \qquad g_{\phi_1\phi_2\phi_3} = 0,$$

$$y^\sigma_{\phi_1\bar{f}_1 f_2} = -i\sigma_{v_1}\frac{1}{M_{v_1}}(m_{f_1} g^\sigma_{v_1\bar{f}_1 f_2} - g^{\bar{\sigma}}_{v_1\bar{f}_1 f_2} m_{f_2}).$$

Here the subscript ϕ_i is Goldstone boson indices and distinguishes from subscript s_i, which indicates physical scalars. The four-point STIs can be expressed in terms of three-point couplings.For instance, the Lie-algebra structure of the vector and fermion couplings is reflected by the two sum rules

$$\sum_{v_5}(g_{v_1v_2v_5}g_{v_3v_4\bar{v}_5} + g_{v_2v_3v_5}g_{v_1v_4\bar{v}_5} + g_{v_3v_1v_5}g_{v_2v_4\bar{v}_5}) = 0,$$

$$\sum_{v_3} g^\sigma_{v_3\bar{f}_1 f_2} g_{v_1v_2\bar{v}_3} = \sum_{f_3}(g^\sigma_{v_1\bar{f}_1 f_3} g^\sigma_{v_2\bar{f}_3\bar{f}_2} - g^\sigma_{v_2\bar{f}_1 f_3} g^\sigma_{v_1\bar{f}_3\bar{f}_2}).$$

Matching Conditions for Photon Penguin Diagrams in the Extended SM

The main purpose of this project is to study matching conditions for the Wilson coefficients of relevant operators for FCNC transitions in the generic extension of the SM. For our calculations we consider two down-type quark transition diagrams. In order to define generic form of Wilson coefficients, the extended SM is perturbatively matched on an effective theory containing only light degrees of freedom, i.e. particles much lighter than the electroweak gauge bosons. The photon dipole moment interactions in the low energy are mediated by effective operators with dimension five or higher.
The effective theory Lagrangian relevant to $d_i \to d_j\gamma$ is [1]

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V^*_{fd_j} V_{fd_i} \left[\sum_{k=7,9} (C_k P_k + C'_k P'_k) + \begin{bmatrix}\text{EOM-vanishing} \\ \text{operators}\end{bmatrix} \right] \tag{2}$$

where

$$\begin{aligned} P_7 &= \frac{e}{g^2} m_b\, (\bar{s}_L \sigma^{\mu\nu} b_R)\, F_{\mu\nu}. \\ P_9 &= \frac{e^2}{g^2}\, (\bar{s}_L \gamma_\mu b_L) \sum_l\, (\bar{l}\gamma^\mu l)\, . \end{aligned} \tag{3}$$

The primed operators can be obtained by changing chirality sign, $P_{L,R}$ to $P_{R,L}$. The equation of motion vanishing (EOM-vanishing) operators are operators that vanish by the QCD×QED equation of motion.

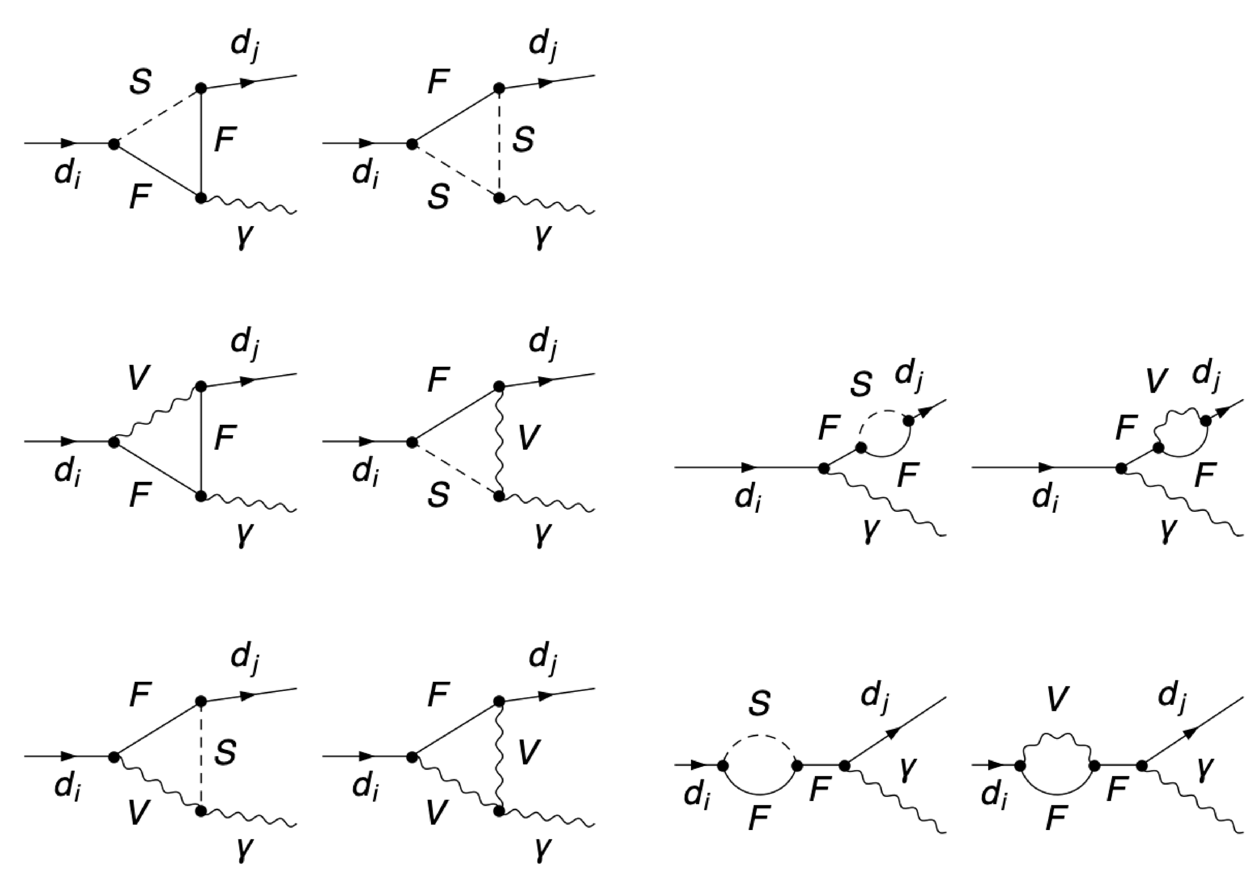

Fig. 1: The one-loop diagrams contributing to the photon penguin.

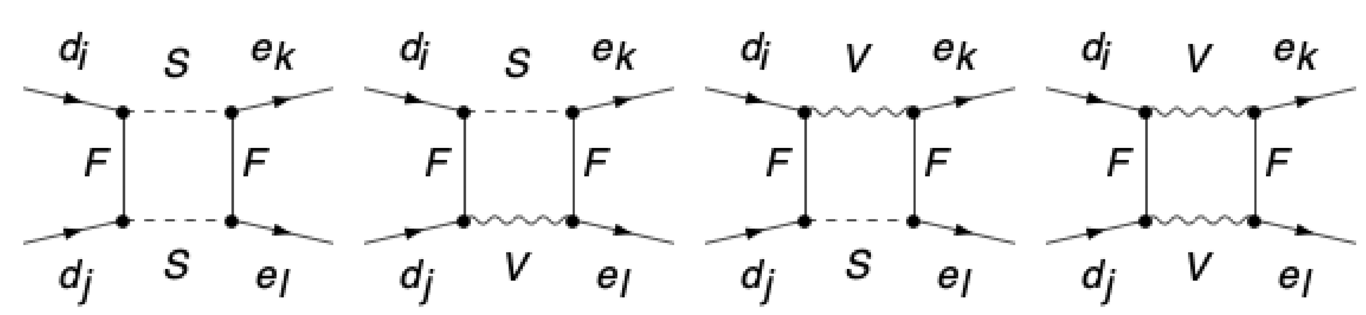

Fig. 2: The box diagrams for $d_i d_j \to l_k l_l$.

Calculational Details

The calculations of the diagrams (Fig.1) are performed off shell, in the R_ξ gauge. For renormalisation, we use the $\overline{MS}$ scheme with the renormalisation scale μ_0 that is assumed to be of the same order as the heavy masses. Before performing the momentum integration, we expand the integrands up to second order (external momenta)/(heavy masses). All the spurious IR divergences arising in this procedure are regularized dimensionally. The divergent integrals become finite because of the GIM mechanism and adding self energy diagrams of external fermion fields.
For completeness of the calculation the box diagrams (Fig.2) should be included too. Further, it will be useful for cancellation of the gauge dependency [4].
In order to obtain generic form of the Wilson coefficients, we require equality of the 1PI Green's functions calculated in the effective theory and in the extended SM.
The Wilson coefficients can be perturbatively expanded as following [1]

$$\mathcal{C}_i(\mu_0) = \mathcal{C}^{(0)}_i(\mu_0) + \frac{\alpha_s(\mu_0)}{4\pi}\mathcal{C}^{(1)}_i(\mu_0) + \ldots, (i = 7, 9). \tag{4}$$

Their values can be written as linear combinations of various functions of

$$x = (m_F/m_{V/S})^2.$$

Conclusion

We will evaluate one-loop matching conditions for all the operators, including EOM ones, relevant to the photonic penguin diagrams in the generically extended SM with arbitrary gauge. The matching procedure gives a gauge independent result for P_7 operator which agrees with the SM calculations.
The result of the current project calculations is not necessarily in the domain of flavour physics, it also can be applied to study dark matter and collider phenomenology.

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