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Unitarity analysis of FCNC top quark couplings

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Abstract. - Partial wave analysis of scattering process is one of the often used methods to constrain unknown parameters in a theory. Using this analysis, we have studied the unitarity constraint of the flavor changing neutral current (FCNC) coupling of top quarks to on-shell gauge bosons, $t \to Vq$ where $q = u, c$ and $V = \gamma, g, Z$ for elastic scattering channels; $\gamma t \to \gamma t$, $Zt \to Zt$, $gt \to gt$.

1. Introduction

Within the Standard Model (SM), the unique properties specific to top quarks can be summarized as follows: top quark has the largest mass; top quark decays without hadronization by a pure $(V - A)$ weak coupling through the major channel $t \to bW^+$. Due to large mass of the top quark, which is in the order of the Fermi scale, coupling of the top quark to symmetry breaking sector is the strongest among all other possible couplings. For this reason, it is believed that the new physics will show itself in close connection to the top quark effective interactions. Moreover, measurements of the top quark couplings to gauge bosons have not been precise enough to exclude the effects of the interactions beyond the SM.

Nonstandard interactions of the top quarks may manifest itself in quantities measured with high precision at low energy or high energy hadronic and leptonic collider experiments. In this paper, we are interested in the flavor changing neutral current (FCNC) coupling of top quarks to on-shell gauge bosons, $t \to Vq$ where $q = u, c$ and $V = \gamma, g, Z$ with using some elastic interactions;$\gamma t \to \gamma t$, $Zt \to Zt$, $gt \to gt$. In the Standard Model, FCNC interaction is possible only at loop level which is extremely suppressed. Anomalous FCNC top quark couplings can be introduced via dimension-5 effective interactions when top quark couples to photon, gluon and Z boson [1],

$$L^{eff} = L^{SM} + L^{NP} \tag{1}$$

$$L^{NP} = -g_e \sum_{q=u,c} \frac{\kappa_q^\gamma}{\Lambda}[\bar{t}\sigma_{\mu\nu}(f_\gamma + ih_\gamma\gamma_5)qA^{\mu\nu}] - g_s \sum_{q=u,c} \frac{\kappa_q^g}{\Lambda}[\bar{t}\sigma^{\mu\nu}T^a(f_g + ih_g\gamma_5)qG^a_{\mu\nu}] \quad (2)$$
$$- \frac{g_e}{\sin 2\theta_W} \sum_{q=u,c} \frac{\kappa_q^Z}{\Lambda}[\bar{t}\sigma^{\mu\nu}(f_z + ih_z\gamma_5)qZ^a_{\mu\nu}] + h.c.$$

where $A^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ and other tensors $G^a_{\mu\nu}$, $Z_{\mu\nu}$ are defined in the same way. T^a are Gell-Mann matrices. v_i, a_i, f_i and h_i are in general complex numbers which satisfy $|f_i|^2 + |h_i|^2 = 1$. Coupling strengths κ_q^i are real and positive. In the literature, Lorentz structure can also be parameterized as $(v_z - a_z\gamma_5) \to (z_L P_L + z_R P_R)$ where $P_{R,L} = \frac{1}{2}(1 \pm \gamma_5)$ and $|z_L|^2 + |z_R|^2 = 1$.

The bounds on the anomalous FCNC top quark couplings have been obtained by the analysis of the low energy processes and top quark production at present colliders; LEP, Tevatron and HERA [2, 3, 4, 5, 6]. Table (1) gives the constraints on the anomalous dim-5 $tVq(V = \gamma,\ g,\ Z$ and $q = u, c)$ couplings . In table (1) LHC estimations are included [7, 8, 9]. In some articles, definition of couplings differs by a factor of 2 and the scale Λ was assumed to be at top quark mass. Bounds in Table (1) have been corrected according to the effective lagrangian that is written above.

2. Unitarity Analysis

In an effective theory with anomalous couplings, the gauge symmetry is obviously broken, the renormalizability is spoiled, and partial wave unitarity will be violated at high energies [10]. The unitarity constraints can impose additional limits on the anomalous couplings, when the scale of new physics is as low as 2 TeV. A nonzero measurement of such anomalous coupling leads to an upper limit on the new physics scale from the unitarity condition [11]. Hence, partial wave analysis of scattering process is one the often used methods to constrain unknown parameters in a theory. The Jth partial wave amplitude is given with the scattering helicity amplitude M,

$$F^J(\lambda_1\lambda_2;\lambda_3\lambda_4) = \frac{1}{64\pi^2}\int d\Omega\ M(\lambda_1\lambda_2;\lambda_3\lambda_4,\Omega)\ d^J_{\lambda\lambda'}(\Omega) \quad (3)$$

where $d^J_{\lambda\lambda'}$ is the Wigner d-function, λ_i is the different helicity states and $\lambda = \lambda_1 - \lambda_2$, $\lambda' = \lambda_3 - \lambda_4$. Partial wave unitarity implies that $|F^J(\lambda_1\lambda_2;\lambda_3\lambda_4)| < 1$ for each amplitudes. However, the most stringiest constraints comes from small J values. We have considered only $J = 1/2$ partial waves, since it gives the stringiest constraint. In this work, we have used "+" for right-handed polarization , "−" for left-handed polarization and "L" for longitudinal polarization.

We first have studied the unitarity constraints from the process $\gamma t \to \gamma t$. We have obtained the helicity states for the $J = 1/2$ as follows,

$$M^{1/2}(++;++) = 8g_e^2(\frac{\kappa_q^\gamma}{\Lambda})^2 s\cos(\theta/2) = M^{-1/2}(--;--). \quad (4)$$

Here s is the Mandelstam variable which is center of mass energy and $g_e = \sqrt{4\pi\alpha}$. In equation (4) we have retained only the terms which increase with s, as they guaranteed to violate unitarity at some scale. Therefore we have neglected other helicity amplitudes. Then the coupled channel matrix found for the $J = 1/2$ as,

$$F^{1/2} = \begin{pmatrix} F_1 & 0 \\ 0 & F_1 \end{pmatrix}$$

where

$$F_1 = (\frac{\kappa_q^\gamma}{\Lambda})^2 \alpha s. \quad (5)$$

Using the equation (5) we have found the unitarity constraint for $\frac{\kappa_q^\gamma}{\Lambda}$ as follows,

$$\frac{\kappa_q^\gamma}{\Lambda} < \frac{1}{\sqrt{\alpha s}}. \quad (6)$$

Next we have examined the process $gt \to gt$. The obtained helicity amplitudes for this process is

$$M^{1/2}(++;++) = 12g_e^2(\frac{\kappa_q^g}{\Lambda})^2 s\cos(\theta/2) = M^{-1/2}(--;--) \quad (7)$$

.

Then the coupled channel matrix for $J = 1/2$ can be found as discussed above,

$$F^{1/2} = \begin{pmatrix} F_2 & 0 \\ 0 & F_2 \end{pmatrix}$$

where,

$$F_2 = \frac{3}{2}(\frac{\kappa_q^g}{\Lambda})^2 \alpha s \quad (8)$$

.

From equation (8) we have obtained unitarity constraint for $\frac{\kappa_q^g}{\Lambda}$ as follows,

$$\frac{\kappa_q^g}{\Lambda} < \frac{\sqrt{2}}{\sqrt{3\alpha s}}. \quad (9)$$

Finally we have analyzed unitarity constraints for $Zt \to Zt$ process when $J = 1/2$. Similarly, after retaining the leading terms proportional to s, the helicity states can be obtained as follows,

$$M^{1/2}(++;++) = 8(\frac{g_e}{\sin(2\theta_W)})^2(\frac{\kappa_q^Z}{\Lambda})^2 s\cos(\theta/2) = M^{-1/2}(--;--). \tag{10}$$

Initially, we expected the longitudinal polarized Z boson helicity states to give the best unitarity constraint. However, since all terms that include the s^2 term eliminated each other, $M(L+;L+)$, $M(L-;L-)$ helicity states are obtained as follows,

$$M^{1/2}(L+;L+) = 4(\frac{g_e}{\sin(2\theta_W)})^2(\frac{\kappa_q^Z}{\Lambda})^2 mz^2\cos(\theta/2) = M^{-1/2}(L-;L-), \tag{11}$$

.

$$M^{1/2}(++;L+) = 4\sqrt{2}(\frac{g_e}{\sin(2\theta_W)})^2(\frac{\kappa_q^Z}{\Lambda})^2\sqrt{s}\sin(\theta/2) = M^{-1/2}(--;L-). \tag{12}$$

.

Therefore we have neglected these helicity states. Then the coupled channel matrix have been found for this process

$$F^{1/2} = \begin{pmatrix} F_3 & 0 \\ 0 & F_3 \end{pmatrix}$$

where

$$F_3 = (\frac{\kappa_q^Z}{\sin(2\theta_W)\Lambda})^2\alpha s \tag{13}$$

.

We have found the constraint for $\frac{\kappa_q^Z}{\Lambda}$ with using partial wave unitarity as below ,

$$\frac{\kappa_q^Z}{\Lambda} < \frac{\sin(2\theta_W)}{\sqrt{\alpha s}} \tag{14}$$

We have showed the unitarity constraints of the κ_γ/Λ, κ_g/Λ and κ_z/Λ for different $\sqrt{s}$ values in table (2). As can be seen this table, current and next high energy colliders do not spoil the partial wave unitarity.

Table 1: Present constraints on the top quark anomalous dim-5 FCNC coupling tVq where V=γ, g, Z and $q = u, c$.

Collider	Mode	κ_γ/Λ	κ_g/Λ	κ_z/Λ
Low energy processes	tVc	0.28	0.95	-
LEP	tVc	1.38 (DELPHI)	-	-
LEP	tVc	1.23 (L3)	-	-
LEP	tVc	1.38 (OPAL)	-	-
Tevatron	tV(c+u)	0.77 (CDF)	0.52 (CDF)	2.22 (CDF)
HERA	tVu	0.5 (ZEUS)	0.4	-
HERA	tVu	0.77 (H1)	0.4	-
LHC	tVu	0.027	0.02	0.04
LHC	tVc	0.037	0.048	0.097

Table 2: Unitarity constraints on the top quark anomalous dim-5 FCNC coupling tVq where V=γ, g, Z and $q = u, c$.

$\sqrt{s}$(TeV)	κ_γ/Λ(1/TeV)	κ_g/Λ(1/TeV)	κ_z/Λ(1/TeV)
1	2.63	2.11	2.21
5	1.17	0.95	1.01
10	0.59	0.48	0.50
14	0.41	0.34	0.35
20	0.42	0.23	0.24
30	0.27	0.14	0.17

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