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Limits on anomalous top quark gauge couplings from Tevatron and LHC data

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Abstract

We review and update current limits on possible anomalous couplings of the top quark to W gauge bosons. We consider data from top quark decay (as encoded in the W-boson helicity fractions) and single-top production (in the t-, s- and Wt-channels). We find improved limits with respect to previous results (in most cases of almost one order of magnitude) and extend the analysis to include four-quark operators. We find that new physics is constrained to live above an energy scale between 430 GeV and 3.2 TeV, depending on the form of its contribution.

Keywords: LHC, BSM physics, top quark, anomalous couplings

1. Motivations and notation

Precision studies of the interaction vertices between the top quark and the gauge bosons provide an important tool in testing the standard model (SM) against new physics contributions. Currently available measurements from the Tevatron and the LHC already allow to set stringent limits on possible deviations in the values of these couplings from their SM values. A model independent framework to study these anomalous couplings is provided by effective field theory, where the modifications are encoded into the coefficients of a set of higher dimensional operators that parametrize the effects of new physics at low energy.

The top quark has both strong and electroweak (EW) interactions. While all interactions come together in collider physics, it is possible to separate in most processes the EW from the strong part so that the anomalous vertices can be discussed separately. In this paper we concentrate on the study of the Wtb vertex. Possible deviations in the interaction between the top quark and the neutral bosons Z and γ—they enter the associated productions $t\bar{t}Z$ and $t\bar{t}\gamma$—are left out because still poorly measured.

1.1. Effective Wtb vertex

Following the literature [1], we write the effective lagrangian that describes, after EW symmetry breaking, the most general Wtb vertex as

$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^-_{\mu} \\ &\quad -\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW^-_{\mu} + \text{h.c.}\end{aligned} \quad (1)$$

where g is the $SU(2)_L$ gauge coupling, $P_{L,R}$ the chiral projectors $(1 \pm \gamma_5)/2$ and $\sigma^{\mu\nu} = i[\gamma^{\mu}, \gamma^{\nu}]/2$. The coefficients V_L, V_R, g_L and g_R are, in general, complex dimensionless constants. In this work we will restrict ourselves to the CP-conserving case and these couplings are taken to be real. In the SM the Wtb vertex in Eq. (1) reduces at the tree level to the Dirac vertex with $V_L = 1$ (after mass diagonalization, $V_L = V_{tb} \simeq 1$) and we take it to be positive. Corrections to V_L, as well as the other non-zero anomalous couplings V_R, g_L, g_R can be generated by new physics.

If the physics beyond the SM lies at an energy scale Λ that is larger than the EW scale v, then we can parametrize its effects via higher dimensional operators respecting the SM symmetries in a series suppressed by inverse powers of the scale Λ. The leading contributions

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arise at dimension six and can be written as an expansion of local operators $\{\hat{O}_k\}$

$$\mathcal{L}_{\rm SM}^{\rm dim\,6} = \sum_k \frac{c_k}{\Lambda^2}\hat{O}_k\,, \tag{2}$$

where c_k are dimensionless coefficients.

The complete list of independent dimension six SM effective operators is reported in [2] of which we follow the notation. The subset of operators that contributes to the anomalous couplings in Eq. (1) consists of the following operators

$$\begin{aligned}
\hat{O}_{\varphi q}^{(3)} &= (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_L \sigma^I \gamma^\mu q_L) \\
\hat{O}_{\varphi tb} &= i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}_R \gamma^\mu b_R) \\
\hat{O}_{tW} &= \bar{q}_L \sigma^{\mu\nu}\sigma^I t_R \tilde{\varphi} W^I_{\mu\nu} \\
\hat{O}_{bW} &= \bar{q}_L \sigma^{\mu\nu}\sigma^I b_R \varphi W^I_{\mu\nu}
\end{aligned} \tag{3}$$

where $q^T = (t\ b)$, $\tilde{\varphi} = i\sigma^2\varphi^*$ and $D_\mu\varphi = \partial_\mu\varphi + igW^I_\mu \frac{\sigma^I}{2}\varphi + ig' Y_\varphi B_\mu \varphi$. After EW symmetry breaking $\varphi = (0\,,\,(\upsilon + H)/\sqrt{2})$, $\upsilon = 246$ GeV, we can express the anomalous couplings in terms of the effective field theory coefficients as follows

$$\begin{aligned}
V_L &= V_{tb} + c_{\varphi q}^{(3)} \frac{\upsilon^2}{\Lambda^2} \simeq 1 + c_{\varphi q}^{(3)} \frac{\upsilon^2}{\Lambda^2} \\
V_R &= \frac{1}{2} c_{\varphi tb} \frac{\upsilon^2}{\Lambda^2} \\
g_L &= \sqrt{2}\, c_{bW} \frac{\upsilon^2}{\Lambda^2} \\
g_R &= \sqrt{2}\, c_{tW} \frac{\upsilon^2}{\Lambda^2}\,.
\end{aligned} \tag{4}$$

There is another operator that enters in the processes we consider, it is the four fermion operator

$$\hat{O}_{qq'}^{(3)} = \bar{q}_L \gamma^\mu \sigma^I q_L \bar{q}'_L \gamma^\mu \sigma^I q'_L\,, \tag{5}$$

where $q'^T = (u\ d)$ and, as before, $q^T = (t\ b)$. It does not give a direct contribution to the anomalous couplings but its interplay with the other operators modifies the limits. For this reason it must be included in the study and its effect parametrized by a new coefficient

$$C_{4f} = c_{qq'}^{(3)} \frac{v^2}{\Lambda^2}\,, \tag{6}$$

which can be further identified, by taking $c_{qq'}^{(3)} = 2\pi$, with the usual convention of writing four-quark operators as

$$\frac{2\pi}{\Lambda^2}\,\bar{\psi}_L \gamma^\mu \psi_L\,\bar{\psi}_L \gamma_\mu \psi_L\,. \tag{7}$$

The effect of these operators on the top-quark EW anomalous couplings can be best studied in two processes: top decay (by means of the W polarizations) and single-top production.

2. Methods

In order to study the effect of anomalous couplings on top decay rates and single top production cross sections at the LHC and Tevatron, we first use FeynRules [3] to implement our model, which has been defined to be the SM with the addition of the effective operators in Eq. (3) and Eq. (5). The dependence on these operators is encoded in the coefficients $c_i = V_L, V_R, g_L, g_R, C_{4f}$.

FeynRules provides the Universal FeynRules Output (UFO) with the Feynman rules of the model. The UFO is then used by MadGraph 5 [4] (MG5) to compute the branching ratios in the decay rates and production cross sections, which we denote by $F_{L,0}^{\rm MG5}$ and $\sigma_{\rm MG5}$, respectively.

MG5 computes the square of the amplitude for each single channel. The partonic level result thus obtained can be compared with the partonic experimental cross section that is extracted by the experimental collaborations.

We compute, using MG5, the top-quark decay width and the single-top production cross section varying the values of the anomalous couplings c_i in a range that goes from −2 to 2—except for V_L that is varied only for positive values. These different values of branching ratios $F_{L,0}^{\rm MG5}(c_i)$ and cross sections $\sigma_{\rm MG5}(c_i)$ are used to obtain limits on the coefficients by comparing the MG5 computation with the measured cross sections and helicity fractions at the LHC at the center-of-mass (CM) energies $\sqrt{s} = 7$ and 8 TeV, as discussed in the next section. By proceeding in the same way, we have also computed the rate and production cross section at the Tevatron and compared it with the measured cross section at the CM energy $\sqrt{s} = 1.98$ TeV.

Analytical expressions for the amplitudes that we study numerically can be found in [5].

2.1. Statistical analysis

To obtain 95% confidence level (CL) limits on the coefficients c_i from the production cross sections, we use the quantity $\Delta\sigma_{\rm exp}$, defined to be the difference between the central value of the measured cross section $\bar{\sigma}_{\rm exp}$ and that of the SM theoretical value $\bar{\sigma}_{\rm th}$

$$\Delta\sigma_{\rm exp} = \bar{\sigma}_{\rm exp} - \bar{\sigma}_{\rm th}\,. \tag{8}$$

The uncertainty on $\Delta\sigma_{\rm exp}$ is given by summing in quadrature the respective uncertainties

$$\sqrt{(\delta\sigma_{\rm exp})^2 + (\delta\sigma_{\rm th})^2}\,. \tag{9}$$

Using the cross sections $\sigma_{\rm MG5}(c_i)$ calculated with MG5 we compute the value of the cross section coming from new physics as

$$\Delta\sigma_{\rm MG5}(c_i) = \sigma_{\rm MG5}(c_i) - \sigma_{\rm MG5}(0)\,. \tag{10}$$

The quantity $\Delta\sigma_{\rm MG5}(c_i)$ represents the contribution to the cross section coming from the interference between SM leading order and new physics diagrams as well as terms quadratic in the anomalous couplings.

Values of c_i for which $\Delta\sigma_{\rm MG5}(c_i)$ is more than two standard deviations from $\Delta\sigma_{\rm exp}$, namely

$$\Delta\sigma_{\rm MG5}(c_i) > \Delta\sigma_{\rm exp} + 2\,\sqrt{(\delta\sigma_{\rm exp})^2 + (\delta\sigma_{\rm th})^2} \tag{11}$$

or

$$\Delta\sigma_{\rm MG5}(c_i) < \Delta\sigma_{\rm exp} - 2\,\sqrt{(\delta\sigma_{\rm exp})^2 + (\delta\sigma_{\rm th})^2}\,, \tag{12}$$

are considered excluded at 95% CL.

To obtain limits from the branching ratios in top decay, as measured by the W-boson helicity fractions, a similar procedure is used. The experiments measure the three fractions F_0, F_L and F_R (see below for the definition). Being extracted from the same data set and from the same observable, these fractions are not independent. F_R is constrained to be equal to $1 - F_0 - F_L$ and is therefore not considered in the limit extraction. In addition, there is a correlation factor ρ different from 0 between the measured values of F_0 and F_L.

The helicity fractions $F_0^{\rm MG5}(c_i)$ and $F_L^{\rm MG5}(c_i)$ are computed within MG5, after adjusting for higher order QCD corrections, and compared to the measured values $F_0^{\rm exp}$ and $F_L^{\rm exp}$. The only uncertainties we consider are the experimental uncertainties $\delta F_0^{\rm exp}$ and $\delta F_L^{\rm exp}$, being the theoretical ones negligible.

To extract the limits, a likelihood function is defined

$$L(c_i) \propto e^{-\frac{1}{2(1-\rho^2)}\left[\chi_0^2(c_i) + \chi_L^2(c_i) - 2\rho\cdot\chi_0(c_i)\cdot\chi_L(c_i)\right]}\,. \tag{13}$$

The quantities $\chi_0(c_i)$ and $\chi_L(c_i)$ are defined to be

$$\chi_0(c_i) = \frac{F_0^{\rm exp} - F_0^{\rm MG5}(c_i)}{\delta F_0}\quad,\quad \chi_L(c_i) = \frac{F_L^{\rm exp} - F_L^{\rm MG5}(c_i)}{\delta F_L} \tag{14}$$

and ρ is the correlation coefficient.

The constrain $\int dc_i L(c_i) = 1$ is imposed and the quantity $L^{95\%}$ is defined as:

$$\int_{L(c_i)>L^{95\%}} dc_i L(c_i) = 0.95 \tag{15}$$

and values of c_i for which $L(c_i) > L^{95\%}$ are considered excluded at 95% CL.

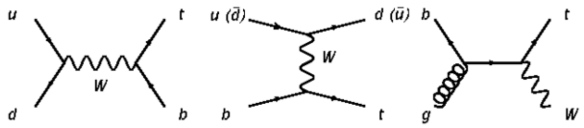

Figure 1: Tree-level diagrams for, from left to right, s-, t- and Wt-channel in top quark production.

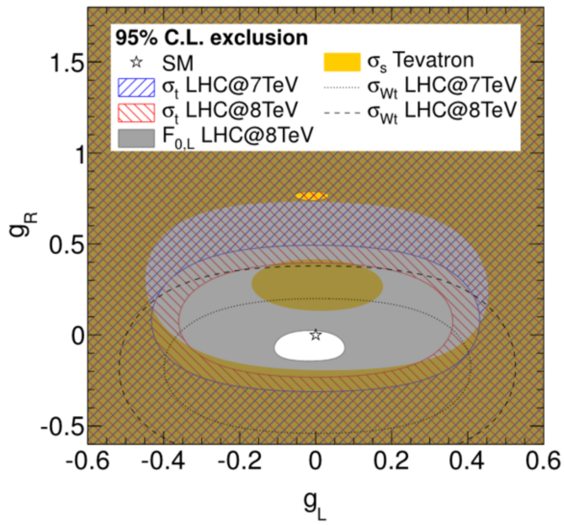

Figure 2: 95% C.L. exclusion limits on the coefficients g_R and g_L ($V_L = 1$, $V_R = C_{4f} = 0$). The full yellow, striped red, striped blue and shaded grey areas indicate the excluded regions from the s- and t-channel production cross-sections and from the helicity fractions. Brown areas result from the superposition of yellow and grey areas. The area outside the dashed (dotted) ellipses is excluded by the Wt-channel cross-section measurement at the LHC at 8 TeV (7 TeV). Region of allowed values: $-0.109 \le g_L \le 0.076$ and $-0.142 \le g_R \le 0.024$

3. Results

Top-quark decay and single-top production are the two processes where we can directly probe the top coupling to the weak bosons.

The Wbt vertex in top-quark decay is best studied by means of the helicity fractions F_0 and F_L defined, respectively, as the ratios between the rates of polarized decay of the top quark into zero and left-handed W bosons and the total decay width. In the SM they are found, neglecting m_b, to be

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} \simeq 0.7 \quad\text{and}\quad F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} \simeq 0.3\,. \tag{16}$$

The helicity fraction into right-handed W bosons is vanishingly small. These branching ratios receive corrections from the operators $\hat{O}_{tW}$ and $\hat{O}_{bW}$. The SM values at the next-to-next-to-leading order (NNLO) order in QCD are computed in [6, 7].

The best current experimental results are given by CMS [8] for data at $\sqrt{s}$ = 8 TeV (integrated luminosity 19.6 fb^{-1}) as

$$\begin{aligned} F_0 &= 0.659 \pm 0.015 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \\ F_L &= 0.350 \pm 0.010 \text{ (stat.)} \pm 0.024 \text{ (syst.)} \end{aligned} \quad (17)$$

with a correlation coefficient $\rho = 0.95$.

The single-top production occurs through t-, s- and Wt-channel (see Fig. 1). The SM NNLO cross sections have been computed in [9], [10] and [11], respectively. The corresponding experimental cross sections σ_t, σ_s and σ_{Wt} are available from the LHC and Tevatron data and we utilize the following results (in which the error includes both statistical and systematic contributions):

$$\begin{aligned} \sigma_t &= 67.2 \pm 6.1 \text{ pb} \quad \text{(LHC@7 TeV) [12]} \\ \sigma_t &= 83.6 \pm 7.7 \text{ pb} \quad \text{(LHC@8 TeV) [13]}, \end{aligned} \quad (18)$$

for single-top production in the t-channel (integrated luminosities of 1.17 and 1.56 fb^{-1} for, respectively, muon and electron final states at 7 TeV and 19.7 fb^{-1} at 8 TeV),

$$\sigma_s = 1.29^{+0.26}_{-0.24} \quad \text{(CDF+D0@1.98) [14]}, \quad (19)$$

for the s-channel (integrated luminosity 7.5 pb^{-1}) and

$$\begin{aligned} \sigma_{Wt} &= 16^{+5}_{-4} \text{ pb} \quad \text{(LHC@7 TeV) [15]} \\ \sigma_{Wt} &= 25 \pm 4.7 \text{ pb} \quad \text{(LHC@8 TeV) [16]}, \end{aligned} \quad (20)$$

for the Wt-channel (integrated luminosities 4.9 fb^{-1} at 7 TeV and 12.2 fb^{-1} at 8 TeV) .

We study the effect of the operators in Eq. (3) and Eq. (5) by varying the coefficients of two of them at the time and we derive the related limits following the statistical analysis described in the previous section. The results are shown in Figs. 2, 3 and 4.

The determination of the limits on the coefficients g_R and g_L is dominated by the top-quark decay but the single-top production cross section is useful in eliminating larger values (the small area on top of Fig. 2). Accordingly, only the lower region is allowed and

$$-0.109 \leq g_L \leq 0.076 \quad \text{and} \quad -0.142 \leq g_R \leq 0.024 \,. \quad (21)$$

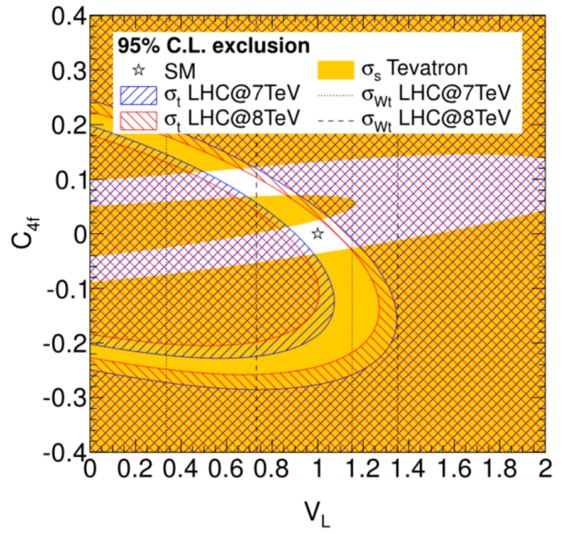

Figure 3: 95% C.L. exclusion limits on the coefficients C_{4f} and V_L ($g_L = g_R = V_R = 0$). The full yellow, striped red, striped blue and shaded grey areas indicate the excluded regions from the s- and t-channel production cross-sections and from the helicity fractions. The areas outside the dashed (dotted) vertical lines are excluded by the Wt-channel cross-section measurement at the LHC at 8 TeV (7 TeV). Region of allowed values: $0.732 \leq V_L \leq 1.145$ and $-0.037 \leq C_{4f} \leq 0.120$.

The interplay among the various channels of single-top production is crucial in delimiting the allowed region for the parameters C_{4f} and V_L in Fig 3. Unfortunately, the Wt-channel is not sensitive to V_R and C_{4f} and the remaining channels are not sufficient in completely delimiting the allowed range of the coefficients to a single region. Accordingly, the final bound is weakened when both coefficients are allowed to vary simultaneously and we find

$$0.732 \leq V_L \leq 1.145 \quad \text{and} \quad -0.037 \leq C_{4f} \leq 0.120 \,. \quad (22)$$

A future improvement in the Wt-channel measurement at the LHC could be instrumental in delimiting the range to a single region.

Finally, it is the interplay between top decay and the t-channel of single-top production that provides the limit on the coefficients V_R and V_L (see Fig. 4). We find

$$0.891 \leq V_L \leq 1.081 \quad \text{and} \quad -0.121 \leq V_R \leq 0.173 \,. \quad (23)$$

Notice that all these coefficients are very much constrained by flavor physics. In particular, the coefficient

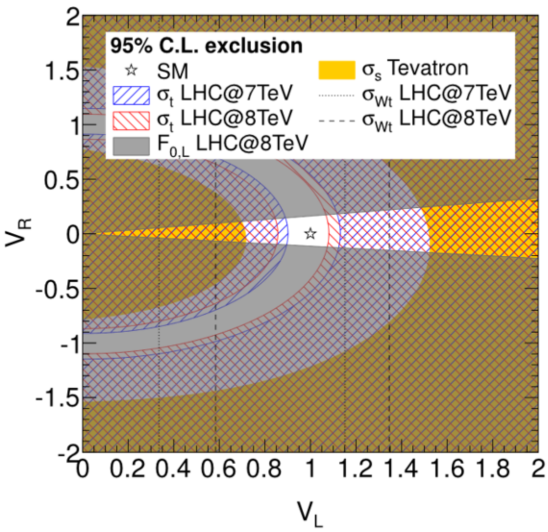

Figure 4: 95% C.L. exclusion limits on the coefficients V_R and V_L ($g_L = g_R = C_{4f} = 0$). The full yellow, striped red, striped blue and shaded grey areas indicate the excluded regions from the s- and t-channel production cross-sections and from the helicity fractions. Brown areas result from the superposition of yellow and grey areas. The areas outside the dashed (dotted) vertical lines are excluded by the Wt-channel cross-section measurement at the LHC at 8 TeV (7 TeV). Region of allowed values: $0.891 \leq V_L \leq 1.081$ and $-0.121 \leq V_R \leq 0.173$.

V_R should be [18]

$$-0.0004 \leq V_R \leq 0.0013\,. \tag{24}$$

When this limit is included, Fig. 4 should be read only along the line $V_R \simeq 0$ with a slightly improved bound

$$0.902 \leq V_L \leq 1.081\,. \tag{25}$$

Similarly, the coefficient g_L should be approximately less than 0.001 [17]. Limits comparable to those from collider physics hold for the other coefficients.

Our results are summarized in Table 1 in the case in which the various anomalous couplings are turned on one at the time.

The limits found can be interpreted in terms of the energy scale of the effective operators in Eq. (3) (see second column of Table 1). By inspection, we see that all EW limits on the coefficients are of the order of 10^{-1} which translates into a characteristic scale $\Lambda \simeq 700$ GeV (actually from 430 GeV to 1 TeV, depending on the contribution) except for the four-quark interaction which has $\Lambda \simeq 3.2$ TeV, if we follow the definition in

Table 1: Limits (95% CL) on the coefficients $c_i = V_L, V_R, g_L, g_R, C_{4f}$ and $C_{1,2}$ when they are varied independently of each other and energy scale of the corresponding effective operators.

$-0.142 \leq g_R \leq 0.023$	$\Lambda \gtrsim 780$ GeV
$-0.081 \leq g_L \leq 0.049$	$\Lambda \gtrsim 1$ TeV
$0.902 \leq V_L \leq 1.082$	$\Lambda \gtrsim 790$ GeV
$-0.112 \leq V_R \leq 0.162$	$\Lambda \gtrsim 430$ GeV
$-0.036 \leq C_{4f} \leq 0.025$	$\Lambda \gtrsim 3.2$ TeV
$-0.008 \leq C_1 \leq 0.015$	$\Lambda \gtrsim 1.3$ TeV
$-0.023 \leq C_2 \leq 0.020$	$\Lambda \gtrsim 1.5$ TeV

Eq. (6). Above these limits, there is still room for new physics.

4. Discussion

Constraints on the Wtb vertex from Tevatron and early LHC data were reported in [19]. Future limits for the LHC at 14 TeV were estimated in [20]. The bounds were obtained, as in this paper, by combining the experimental measurements of W-boson helicity fractions and single-top production and by varying two operators at the time. More recently, the measurement of the W-boson helicity fractions has been substantially improved by ATLAS and CMS in [21], [22] and [23] and limits on the coefficients g_R and g_L were extracted by the experimental collaborations based on these new measurements. Concerning the single top production, many detailed results have been released by both Tevatron and LHC experiments [12, 13, 14, 15, 16], as reported in the previous section.

We confirm and improve the above limits by means of the most recent data set at 8 TeV by CMS [8] and the combined use of the helicity fractions and single-top production cross sections. The improvement is substantial, in most cases of almost one order of magnitude. As expected, the simultaneous presence of more than one anomalous coupling weaken the limits. The result for the four-fermion operator (5), and its impact on the determination of the coefficient V_L is new.

We have verified that the simultaneous variation of more than two of the coefficients does not significantly change the result. As an example, in Fig. 5, we show how the limits on the coefficients V_L vs. C_{4f} are changed by taking the two extreme values among those allowed for the coefficient g_R. For $g_R = -0.142$ we have that

$$0.753 < V_L < 1.116 \quad \text{and} \quad -0.030 < C_{4f} < 0.094\,. \tag{26}$$

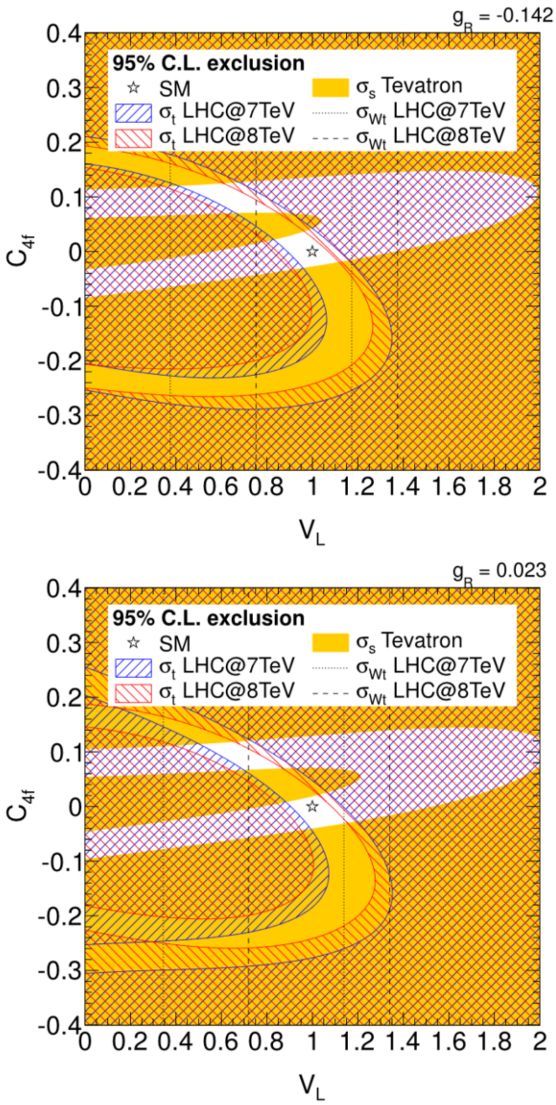

Figure 5: 95% C.L. exclusion limits on the coefficients C_{4f} and V_L ($g_L = V_R = 0$) for the two extreme allowed values of the coefficient $g_R = -0.142$ (left) and $g_R = -0.023$ (right). The full yellow, striped red, striped blue and shaded gray areas indicate the excluded regions from the s- and t-channel production cross-sections and from the helicity fractions. The areas outside the dashed (dotted) vertical lines are excluded by the Wt-channel cross-section measurement at the LHC at 8 TeV (7 TeV).

while for $g_R = 0.023$

$$0.720 < V_L < 1.138 \quad \text{and} \quad -0.041 < C_{4f} < 0.105\,. \tag{27}$$

These results show that the variation in the value of the limits is around 20%. Simultaneous variation of other subsets of coefficients, with respect to their limits as taken two at the time, are even smaller. This is explained by the dominance of different processes in the constraints for different pairs of coefficients: helicity fractions in top-quark decay dominate the limits for g_L and g_R while single-top production those of V_L and C_{4f}.

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