Search for top quark flavour changing neutral currents in same-sign top quark production

Reza Goldouzian

School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM)
P.O. Box 19395-5531, Tehran, Iran
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Abstract

The presence of the anomalous top quark flavour changing neutral current (FCNC) interactions leads to the production of same-sign top quarks in proton-proton collisions. The results of a search for events with same-sign dileptons and b-jets conducted by CMS collaboration with 10.5 \( fb^{-1} \) of data collected in pp collisions at \( \sqrt{s} = 8 \) TeV are used to obtain the constraints on the strength of top quark FCNC interactions. The 95% confidence level upper limits on the branching ratios of top quark decays to a light quark \( q = u, c \) and a gauge or a Higgs boson are set to be \( BR(t \to u\gamma) < 1.27\% \), \( BR(t \to uZ) < 0.8\% \), \( BR(t \to ug) < 1.02\% \) and \( BR(t \to uH) < 4.21\% \). The sensitivity of future searches in the same-sign top quark channel is also presented.

1 Introduction

Because of the large mass of the top quark near to the electroweak symmetry breaking scale, the study of top quark properties can open a unique window to new physics [1]. In the Standard Model (SM) framework, the flavour changing neutral current (FCNC) processes are forbidden at tree level and are suppressed at the level of quantum loop corrections due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [2]. Whereas SM predicts tiny branching ratios of top quark FCNC decays to a light up type quark and a gauge or Higgs boson [3] \( BR(t \to qX) \sim 10^{-17} - 10^{-12} \) where \( q = u \) or charm quark and \( X = \) photon (\( \gamma \)) , Z boson (\( Z \)), gluon (\( g \)) or Higgs boson (\( H \)), various extensions of SM predict huge enhancement for these decays by relaxing the GIM suppression and introducing new particles contribute in quantum loops [4–7]. It indicates that observation of any sign from top quark FCNC processes will give evidence of physics beyond the SM.

Over the years, different experiments have searched for FCNC processes in the anomalous decays of top quark in \( tt \) events or anomalous productions of single top events. They have observed no clear evidence of the presence of the FCNC processes and the exclusion limits are set on the branching ratio of anomalous top decays. In table [4] the most stringent limits obtained
Figure 1: Feynman diagrams describing the production of the same-sign top quark productions (top) and same-sign top + $\bar{q}$ (bottom) representative of same-sign top + 1jet diagrams due to FCNC interactions ($q = u$ or $c$).

in hadron colliders from different sensitive channels are shown. Although the SM predicts top quark anomalous branching ratios many order of magnitude below the current experimental limits experiments are closing to the regions which are available by beyond SM.

| $BR(t \rightarrow q\gamma)$ | Exp       | $BR(t \rightarrow qZ)$ | Exp       | $BR(t \rightarrow qg)$ | Exp       | $BR(t \rightarrow qH)$ | Exp       |
|-----------------------------|-----------|-------------------------|-----------|-------------------------|-----------|-------------------------|-----------|
| $3.2 \times 10^{-2}$        | CDF [8]   | $3.7 \times 10^{-2}$    | CDF [10]  | $3.9 \times 10^{-4}$    | CDF [14]  | $8.3 \times 10^{-3}$    | ATLAS [18]|
| $1.6 \times 10^{-4}$        | CMS [9]   | $3.2 \times 10^{-2}$    | D0 [11]   | $2.0 \times 10^{-4}$    | D0 [15]   | $5.6 \times 10^{-3}$    | CMS [19]  |
| $7.3 \times 10^{-3}$        | ATLAS [12] | $3.1 \times 10^{-5}$   | ATLAS [16] | $3.5 \times 10^{-4}$    | CMS [17] |
| $5 \times 10^{-4}$          | CMS [13]  |                         |           |                         |           |                         |           |

Table 1: The most stringent experimental bounds on FCNC branching ratios obtained in Tevatron and LHC experiments.

In addition to the anomalous production or decays of top quark, the FCNC interactions can result in appearance of the same-sign top quark in hadron colliders [20,21]. Figure 1 displays the representative diagrams describing the anomalous same-sign top quark production. In spite of the fact that the diagrams with a QCD vertex contribute less to the total cross section comparing to the one without QCD vertex, their contributions are not ignorable and can improve the results. Same-sign top production followed by the leptonic decay of W boson from top decays give rise to final state with the same-sign leptons and b-jets. Despite the small cross section of the signal channels due to the presence of two anomalous vertices for tt production, this final state has proven to have very little SM backgrounds and is sensitive to new physics effects [22,23]. Therefore, same-sign dilepton final state would provide a new window for searching for FCNC interactions.

To investigate the utility of the same-sign top production in searching for FCNC interactions, we make use of the results of a search for new physics in events with same-sign dilepton and b-jets performed with 10.5 $fb^{-1}$ of data collected from 8 TeV pp collisions by the CMS collaboration to estimate upper limit on the strength of the top FCNC anomalous couplings [24].


In this work, we study various processes that contribute to the same-sign top quark final state through tqX vertices with X = H, γ, Z or gluon. We limit the strength of the FCNC anomalous couplings by considering the leptonic decay of W boson from top quark decay and using same-sign dilepton experimental results.

The organization of this paper is as follows. Section 2 describes the theoretical framework used to search for FCNC processes. In Section 3 we review CMS same-sign dilepton search and the simulation details of signal samples. The results of the same-sign dilepton search are interpreted in terms of the strength of FCNC interactions in Section 4. The prediction of 95% confidence level (CL) exclusion limits at 14 TeV LHC in section 5 is followed by conclusion in Section 6.

2 Anomalous flavour changing top quark couplings

Top quark anomalous interactions can be described in a model independent way by an effective Lagrangian \([3]\). The most general effective Lagrangian describing the interactions between the top quark and a light up type quark (u or c) and a gauge or Higgs boson emerging from dimension 6 operators can be written as:

\[
- \mathcal{L}_{\text{eff}} = e\kappa_{q}\bar{q}\gamma^{\mu}q_{\nu}[\gamma_{L}P_{L} + \gamma_{R}P_{R}]tA_{\mu} + \frac{g}{2\cos\theta_{w}}\kappa_{Z}\bar{q}\gamma^{\mu}q_{\nu}[z_{L}P_{L} + z_{R}P_{R}]tZ_{\mu} + g_{s}\kappa_{g}\bar{q}\gamma^{\mu}q_{\nu}[g_{L}P_{L} + g_{R}P_{R}]T^{a}tG_{\mu} + \kappa_{H}\bar{q}[h_{L}P_{L} + h_{R}P_{R}]tH + h.c. \tag{1}
\]

Where \(e\) is the electron electric charge, \(g\) is the weak coupling constant, \(g_{s}\) is strong coupling constant, \(\theta_{w}\) is the Weinberg angle, \(P_{L,R} = \frac{1}{2}(1 \pm \gamma^{5})\), \(\sigma^{\mu\nu} = \frac{1}{2}[\gamma^{\mu}, \gamma^{\nu}]\) and the symbols \(\bar{q}\) and \(t\) represent the up (or charm) and top quark spinor fields. The parameters \(\kappa_{q}, \kappa_{Z}, \kappa_{g}\) and \(\kappa_{H}\) define the strength of the real and positive anomalous couplings for the current with photon, Z boson, gluon and Higgs boson, respectively. The relative contribution of the left and right currents are determined by \(\gamma_{L,R}, z_{L,R}, g_{L,R}\) and \(h_{L,R}\) which are normalized as \(|\gamma_{L}|^2 + |\gamma_{R}|^2 = 1, |z_{L}|^2 + |z_{R}|^2 = 1,\), etc. In the Lagrangian \(q\) is the momentum of the gauge or Higgs boson and \(\Lambda\) is the new physics cutoff by convention, is set to the top quark mass.

In the literature, there are many alternatives for normalisation of coupling constants in \(\mathcal{L}_{\text{eff}}\). Therefore, we will use top quark branching ratio for expressing our results to make it comparable with other experimental results. The tree level prediction for the top quark decay rate to the W boson and massless b-quark is \([3]\)

\[
\Gamma(t \to Wb) = \frac{\alpha}{16s_{w}^{2}}|V_{tb}|^{2} \frac{m_{t}^{3}}{m_{W}^{2}} \left[1 - 3\frac{m_{W}^{4}}{m_{t}^{4}} + 2\frac{m_{W}^{6}}{m_{t}^{6}}\right] \tag{2}
\]

The partial decay width of the top quark with flavour violating interactions are given by

\[
\begin{align*}
\Gamma(t \to q\gamma) &= \frac{\alpha}{4}m_{t}^{3}\left|\kappa_{q}\gamma\right|^{2} / \Lambda^{2} \\
\Gamma(t \to qZ) &= \frac{\alpha}{32s_{w}^{2}c_{w}^{2}}m_{t}^{3}\left|\kappa_{q}Z\right|^{2} / \Lambda^{2} \left[1 - \frac{m_{Z}^{2}}{m_{t}^{2}}\right]^{2} \left[2 + \frac{m_{Z}^{2}}{m_{t}^{2}}\right] \\
\Gamma(t \to qq) &= \frac{\alpha_{s}}{3}m_{t}^{3}\left|\kappa_{q}g\right|^{2} / \Lambda^{2} \\
\Gamma(t \to qH) &= \frac{1}{32\pi}m_{t}\left|\kappa_{q}H\right|^{2} \left[1 - \frac{m_{H}^{2}}{m_{t}^{2}}\right]^{2} \tag{3}
\end{align*}
\]
For numerical calculation we set $m_t = 172.5$ GeV, $m_Z = 91.2$ GeV, $m_H = 125$ GeV, $s_{W}^{2} = 0.234$, $\alpha_s = 0.108$ and $\alpha = 1/128.92$.

3 A same-sign top production search for top quark FCN interactions

3.1 Experimental input

Same-sign dilepton searches at hadron colliders can provide a great sensitivity for probing many new physics models [25][27]. In this work we follow and use the results of the same-sign dilepton and b-jets search strategies adopted by CMS collaboration [24]. In the analysis two isolated same-sign leptons ($e$ or $\mu$) with $p_T > 20$ and $|\eta| < 2.4$ ($1.442 < |\eta| < 1.566$ is excluded for electron) are required. More criteria on the events with third lepton are applied to minimize the contribution of backgrounds with $\gamma^* \rightarrow l^+l^−$ and low mass bound state and multi boson production. In the CMS report, lepton identification efficiency, isolation cuts and detector effects are combined. The lepton selection efficiency is parametrized as [24]:

$$\epsilon = \epsilon_{\infty}erf \left( \frac{p_T - 20GeV}{\sigma} \right) + \epsilon_{20} \left[ 1 - erf \left( \frac{p_T - 20GeV}{\sigma} \right) \right]$$

with $\epsilon_{\infty} = 0.65$ (0.69), $\epsilon_{20} = 0.35$ (0.48) and $\sigma = 42$ GeV (25 GeV) for electrons (muons).

Jets are clustered using the anti-$k_t$ algorithm [28]. At least two jets with $p_T > 40$ and $|\eta| < 2.4$ are needed. B-tagging is defined using the combined secondary vertex which uses the information of secondary vertex and track based lifetime [29]. The b-tag efficiency is evaluated to be 0.71 for the b-jets with 90 $< p_T < 170$ GeV and at higher (lower) $p_T$ it decreases linearly with a slope of $-0.0004$ ($-0.0047$) GeV$^{-1}$ [24]. Candidate events are required to have at least two b-tagged jets. Finally in different signal regions different cuts are applied on the scalar sum of the transverse momenta of jets ($H_T$) and missing transverse energy ($E_{T}^{miss}$).

This search divides same-sign dilepton events into several categories, based on the charge of leptons, number of selected b-jets, number of selected jets, $H_T$ and $E_{T}^{miss}$. Table 2 shows the kinematic requirements, total number of background, observed data and upper limit on the number of new physics events of nine signal regions. Signal regions are not independent and have some overlaps with each other, so one can not combine the limits from different regions.

| No. of jets (b+jets) | SR0   | SR1   | SR2   | SR3   | SR4   | SR5   | SR6   | SR7   | SR8   |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| lepton charges      | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ | $\geq 2(\geq 2)$ |
| $E_{T}^{miss}$      | $\geq 0$ GeV | $\geq 30$ GeV | $\geq 30$ GeV | $\geq 120$ GeV | $\geq 50$ GeV | $\geq 50$ GeV | $\geq 120$ GeV | $\geq 50$ GeV | $\geq 0$ GeV |
| $H_T$               | $\geq 80$ GeV | $\geq 80$ GeV | $\geq 80$ GeV | $\geq 200$ GeV | $\geq 200$ GeV | $\geq 320$ GeV | $\geq 320$ GeV | $\geq 200$ GeV | $\geq 320$ GeV |

| No. of BG            | 40 $\pm$ 14 | 32 $\pm$ 11 | 17.7 $\pm$ 6.1 | 2.2 $\pm$ 1.0 | 8.1 $\pm$ 3.4 | 5.7 $\pm$ 2.4 | 1.7 $\pm$ 0.7 | 1.2 $\pm$ 0.6 | 8.1 $\pm$ 3.3 |
| No. of data          | 43             | 38             | 14             | 10             | 7             | 1               | 1               | 1               | 9                |
| No. of NP(30% unc.)  | 30.4           | 29.6           | 10.7           | 3.8            | 12            | 9.6             | 3.9             | 4               | 10.5             |

Table 2: A summary of the results. For each signal region (SR), the kinematic requirements, the prediction for the total background (BG) and the observed number of events are shown. The 95% CL upper limit on the number of new physics events under assumptions of 30% uncertainty on signal efficiency is shown in last row. Note that the number of jets on the first line of the table includes both b-tagged and non b-tagged jets.
3.2 Signal channels and simulation details

The presence of FCNC interactions lead to the production of $tt$ and $\bar{t}\bar{t}$ through $tuX$ or $tcX$ interactions in proton-proton collisions. The Lagrangian in Eq. 1 is implemented in FeynRules [30] and passed to MadGraph 5 [31] framework by means of the UFO model [32]. The implementation of the LO cross section calculated by MadGraph is validated for various couplings by comparing the $tX$ production cross sections calculated by PROTOS [33].

Due to the larger parton distribution function (PDF) of $u$ quark (valance quark) in proton comparing to $c$, $\bar{c}$ and $\bar{u}$ (sea quarks), the main contribution to the cross section comes from the $tt$ production through anomalous $tuX$ interaction and the contribution of other signal channels are small. In table 3 the cross section of different signal channels are compared while CTEQ6L1 is used to evaluate the parton densities.

Table 3: same-sign top production cross section due to anomalous photon, Z boson, gluon and higgs exchange at the LHC for $\sqrt{s} = 8$ TeV as a function of anomalous couplings. No cut is implemented on the final state top quarks. CTEQ6L1 is used to evaluate the parton densities while the renormalisation scale $\mu_R$ and factorization scale $\mu_F$ are fixed at $\mu_R = \sqrt{s} = \mu_F$. Note that the $(pp \rightarrow tt + jet)$ processes are not included.

In Figure 2 we plot the cross section of anomalous production of same-sign top quark for the LHC at 8 TeV against the branching ratio of the top quark FCNC decays. We show the $tt$ cross section originating from different anomalous interaction separately. The red curve corresponds to $tug$ anomalous coupling while other anomalous couplings are set to zero and so on. As we see
any bound on the production of the same-sign top quark (which is available from LHC results) immediately implies a bound on the anomalous top FCNC decays. Another interesting observation from figure 2 is the relative sensitivity of the FCNC top quark decays due to photon, Z boson, gluon and Higgs exchange to the same-sign top pair production.

Four separated samples of 100000 events are generated independently corresponding to anomalous \( tt \) production through FCNC interactions. In production of the signal events, the top quark branching ratio to a bottom quark and a W boson is assumed to be 100%. Then the W boson is required to decay only into a charged lepton (\( e, \mu \) and \( \tau \)) and neutrino in MadGraph to ensure good statistic coverage and include leptonic tau decays. Pythia \([34]\) is used to simulate the subsequent showering and hadronization effects. Detector effects are simulated using Delphes \([35]\). The Delphes card for simulating the CMS detector is modified in order to include the lepton and b-tag efficiencies calculated by the CMS collaboration as discussed in previous section.

We analyze each signal channel separately. The CMS same-sign lepton search is closely followed to determine the efficiency for FCNC signal events passing the selections. Similar cuts are applied on the selected leptons, jets, bjets, \( H_T \) and \( E_T^{miss} \) from simulated signal samples.

4 Results

The same-sign dilepton final state coming from \( t \to Wb \to l\nu b \) in same-sign top production is associated with two b-jets and missing transverse energy from the undetected neutrinos. In addition, the signal samples are dominated by the events with positive charged leptons as discussed in previous section. Therefore, the most sensitive signal region in our search for FCNC interactions is SR2. In this category, the signal efficiency is high while the number of the SM backgrounds and their uncertainties are small comparing to other signal regions. In other words, the best significance is obtained from SR2.

As no excess above the SM expectation is observed, 95% CL upper bound on the number of new physics events are set in \([22]\). In table 2 the bounds are shown in each of nine signal regions. In order to determine more conservative upper bounds, the results from considering 30% uncertainty on signal efficiency are chosen between 10%, 20% and 30%.

The results for the signal region SR2 is used to set limit on the FCNC anomalous couplings. In the derivation of the limits, the contribution of \( tq\gamma \), \( tqZ \), \( tqg \) and \( tqH \) to the same-sign top production are considered separately. Therefore, limits are evaluated on one of the FCNC couplings, setting the other couplings to zero. The limits on the strength of FCNC anomalous couplings can be converted to limits on the anomalous top quark decays and are summarized in table 4.

| Process \((tqX)\) | \(\kappa_{uX}(\kappa_{cX} = 0)\) | \(\kappa_{cX}(\kappa_{uX} = 0)\) | \(BR(t \to uX)\)(%) | \(BR(t \to cX)\)(%) |
|------------------|----------------------|----------------------|----------------------|----------------------|
| \(tq\gamma\)    | 0.23                 | 1.28                 | 1.27                 | 38.15                |
| \(tqZ\)         | 0.20                 | 1.15                 | 0.80                 | 25.52                |
| \(tqg\)         | 0.05                 | 0.25                 | 1.02                 | 27.73                |
| \(tqH\)         | 0.39                 | 1.30                 | 4.21                 | 45.46                |

Table 4: The observed 95% upper limits on the top quark FCNC anomalous couplings and branching ratios.

Figures 3 and 4 show the 95% CL excluded region in the \((\kappa_{uX}, \kappa_{cX})\) and \((BR(t \to uX), BR(t \to cX))\) plane obtained by this analysis. Due to the PDF of proton, the LHC data are less sensitive to the \(\kappa_{cX}\) parameter than \(\kappa_{uX}\).
Figure 3: Excluded region at 95% CL in the $\kappa_{uX} - \kappa_{cX}$ plane for $X = \gamma$, $Z$, gluon and Higgs.

Figure 4: Excluded region at 95% CL in the $BR(t \rightarrow uX) - BR(t \rightarrow cX)$ plane for $X = \gamma$, $Z$, gluon and Higgs.
5 Sensitivity at 14 TeV LHC

In this section, we study the sensitivity of future searches for FCNC interactions through the same-sign top quark production. In Figure 5, the cross sections for $tt$ production induced by flavour violating top-Z, top-photon, top-gluon and top-Higgs couplings normalized to the corresponding top quark decay branching ratios are shown as a function of the center-of-mass energy. We find from Figure 5 that for a determined and equal top quark FCNC branching ratios, the anomalous $tZq$ coupling is the most sensitive coupling followed by $tqg$, $tq\gamma$ and $tqH$ in the shown range of the center of mass energy. The cross sections of all signal channels increase by increasing the center of mass energy and the cross section due to $tqH$ increase less than others.

The same-sign analysis used to constrain the top quark FCNC interactions has three sources of SM backgrounds:

- fake leptons: selected leptons not originating neither from the decay of a boson, nor from a $\tau$ lepton.
- charge flips: electron charge is mismeasured due to severe bremsstrahlung in the tracker material.
- rare SM processes: mostly from $t\bar{t}W$ and $t\bar{t}Z$.

The contribution of these three sources are reported separately in [24]. The simulation does not reproduce the contribution of the backgrounds with fake or charge flip leptons (instrumental background) properly. Therefore, data driven methods are used to estimate the instrumental background contribution from data in [24]. In addition to the considerable contribution of these backgrounds, they are the main source of uncertainties. This, however makes it impossible to predict the expected limit precisely for higher center-of-mass energies or an arbitrary luminosity.

To estimate the reach of the analysis at 14 TeV LHC, we follow the same method used in [36]. The idea is as follows. Since the signal regions contain at least two b-jets, $t\bar{t}$ is the main source of instrumental background. So one can scale the rate of these backgrounds with $t\bar{t}$ cross section approximately and predict their contributions at 14 TeV. The $t\bar{t}W$ and $t\bar{t}Z$ samples at 14 TeV are used to find the contribution of the rare SM backgrounds. The prediction of the expected backgrounds at 14 TeV is validated by calculating the ratio of the instrumental background to the rare SM backgrounds for SR6 and SR8 and comparing with the ratios calculated in [36]. The ratios are fully compatible in both regions and it is calculated to be 2.02 for SR2. To estimate the uncertainties of instrumental backgrounds no detector simulation is performed. The uncertainty obtained from 8 TeV is scaled according to the $tt$ cross section to evaluate the uncertainty at 14 TeV which leads to large uncertainty. It would make our analysis more useful if we present the results considering different uncertainties from instrumental backgrounds. In order to illustrate the uncertainty effects, we define:

$$\zeta = \frac{\text{Total background rate}}{\text{Irreducible background rate}} = 1 + \frac{\text{Instrumental background rate}}{\text{Irreducible background rate}}$$

(5)

Where both rates are calculated after all cuts. Combining the rare SM and instrumental backgrounds, the 95% predicted exclusion limits are presented in Figure 6 for all signal channels. The $\zeta$ is varied between 1 to 10 to show how the reach of the analysis would change by changing the uncertainty on the instrumental backgrounds. Using the nominal value for $\zeta = 3.02$, it can be seen that the 95% excluded region boundaries have not improved significantly at 14 TeV LHC comparing to 8 TeV LHC for $tu\gamma$, $tuZ$ and $tug$ signal channels and the reach is even worse for $tuH$. 

8
Figure 5: Anomalous top pair production cross section for the process $pp \to tt$ due to $tuX$ anomalous vertices divided by the square of the FCNC branching ratios for the decays $BR(t \to q\gamma)$, $BR(t \to qZ)$, $BR(t \to qg)$ and $BR(t \to qH)$ versus the center of mass energy.

The CMS collaboration has updated the same-sign analysis by $19.5 fb^{-1}$ of data [39]. The total uncertainties are increased in different signal regions by increasing the luminosity from $10.5 fb^{-1}$ to $19.5 fb^{-1}$. Our studies show that using updated experimental results would not change the results obtained in this analysis. This behaviour confirms that scaling the instrumental background rates and its related uncertainties to the $t\bar{t}$ cross section is a good approximation.

6 Discussion and Conclusions

In this work, we have analyzed the same-sign top-quark pair signature of the top quark flavour changing neutral interactions through photon, $Z$ boson, gluon and Higgs boson exchanges in proton-proton collisions. The experimental results conducted by CMS at 8 TeV center of mass energy are used to constrain the top quark anomalous couplings and branching ratios consequently.

Whereas the limits obtained on the the FCNC branching ratios of top quark decay are found to be non-competitive compared to recent results derived from anomalous single top quark production or anomalous decay of top quark in $t\bar{t}$ events [9,13,16,18,19,37,38], these results provide an interesting cross check of the evidences for non-presence of the top quark FCN interactions in a different physics process.

The limits could be improved if the CMS collaboration updates the same-sign dilepton search with subdividing the signal regions exclusively, so the results from different signal region could be combined.

Improvement of the lepton and b-tag efficiencies and the systematic uncertainties on the background predictions would improve the results.

Using the results of the CMS same-sign dilepton search at 8 TeV [24], we tried to predict the possible reach of 14 TeV LHC. However, the presence of the instrumental backgrounds as an important source of uncertainties makes the prediction of the analysis reach vague. We find that with selections identical to 8 TeV search no significance improvement is expected to be obtained for the top quark FCNC process through the same-sign dilepton signature at 14 TeV LHC.
Figure 6: Estimated 95% CL expected exclusion reach of flavour violating top-Z, top-photon, top-gluon and top-Higgs couplings and related top quark branching ratio through the same-sign top channel signature at the 14 TeV LHC with 100 $fb^{-1}$. Concerning the important effect of the instrumental background on the predicted results, a range is assumed for $\zeta$. $\zeta = 3.02$ is obtained by rescaling the experimental result in SR2 at 8 TeV. The theoretical prediction for the top quark FCNC branching ratios versus the anomalous couplings are also shown.
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