Prospects for a search for gluon-mediated FCNC in top quark production using the CMS Phase-2 detector at the HL-LHC

The CMS Collaboration

Abstract

Prospects are presented for a search for gluon-mediated flavour-changing neutral currents in the top quark production via tug and tcg vertices using the CMS Phase-2 detector at the HL-LHC. The analysis uses Monte Carlo samples of proton-proton collisions at $\sqrt{s} = 14$ TeV with a full simulation of the Phase-2 upgraded CMS detector assuming an average of 200 proton-proton interactions per bunch crossing. The final state signature of the signal is similar to that for the t-channel single top quark production in the $\mu/e + \text{jets}$ final state. Bayesian and deep learning neural networks are used to discriminate the signal events against backgrounds. The 95% C.L. expected exclusion limits on the coupling strengths are $|\kappa_{\text{tug}}|/\Lambda < 1.8 \times 10^{-3}$ ($2.9 \times 10^{-3}$) TeV$^{-1}$ and $|\kappa_{\text{tcg}}|/\Lambda < 5.2 \times 10^{-3}$ ($9.1 \times 10^{-3}$) TeV$^{-1}$ for integrated luminosity of 3000 fb$^{-1}$ (300 fb$^{-1}$). The corresponding limits on branching fractions are $B(t \to ug) < 3.8 \cdot 10^{-6}$ ($9.8 \cdot 10^{-6}$) and $B(t \to cg) < 32 \cdot 10^{-6}$ ($99 \cdot 10^{-6}$) for integrated luminosity of 3000 fb$^{-1}$ (300 fb$^{-1}$). Therefore, the exploitation of the full HL-LHC data set with the upgraded CMS detector will allow to improve the current limits by an order of magnitude.
1 Introduction

Single top quark (t) production provides the opportunity to investigate aspects of top quark physics that cannot be studied with \( t \bar{t} \) events [1]. Flavour-changing neutral currents (FCNC) are absent at lowest order in the SM, and are significantly suppressed through the Glashow–Iliopoulos–Maiani mechanism [2] at higher orders. Precise measurements of various rare decays of K, D, and B mesons, as well as of the oscillations in \( K^0 \bar{K}^0 \), \( D^0 \bar{D}^0 \), and \( B^0 \bar{B}^0 \) systems, strongly constrain FCNC interactions involving the first two generations and the b quark [3]. The V–A structure of the charged current with light quarks is well established [3]. However, FCNC involving the top quark are significantly less constrained. In the SM, the FCNC couplings of the top quark are predicted to be very small (\( \sim 10^{-10} \)) and are not detectable at current experimental sensitivity. However, they can be significantly enhanced in various SM extensions, such as supersymmetry [4–6], and models with multiple Higgs boson doublets [7–9], extra quarks [10–12], or a composite top quark [13]. New vertices with top quarks are predicted, in particular, in models with light composite Higgs bosons [14, 15], extra-dimension models with warped geometry [16], or holographic structures [17]. Such possibilities can be encoded in an effective field theory through higher-dimensional gauge-invariant operators [18, 19]. Direct limits on top quark FCNC parameters have been established by the CDF [20], D0 [21], ATLAS [22], and CMS [23] Collaborations. Processes with FCNC vertices in the decay of the top quark are negligible since the current limits to the branching fractions are about \( 10^{-5} \), also the final states of such decays are difficult to distinguish from the backgrounds. This paper presents a search for FCNC interactions in the production of single top quarks. Models that have contributions from FCNC in the production of single top quarks can have sizable deviations relative to SM predictions, in particular those involving up quarks in the initial state as they profit from a large enhancement due to their parton distribution function (PDF). Also processes with charm quarks in the initial state benefit from a relative enhancement due to PDF with respect to processes initiated by bottom quarks, such as the background SM process of single top production in t channel. This is in contrast with searches for processes with FCNC vertices in the decay of the top quark where no such enhancement is present, and whose final states are difficult to distinguish from the backgrounds. The current limits on the branching ratios of the latter processes are about \( 10^{-5} \), and therefore this paper assumes negligible contribution of the FCNC decay modes to the total width of the top quark. The prospects for the search are estimated with a full simulation of the Phase-2 upgraded CMS detector with an average of 200 proton-proton interactions per bunch crossing. The Phase-2 upgrade of CMS detector is described in Technical Design Reports [24–29] and increases the angular coverage of the detector. The High Luminosity LHC regime with 3000 fb\(^{-1}\) of integrated luminosity and \( \sqrt{s} = 14 \) TeV is assumed in this study.

2 Analysis strategy and simulation

There are two complementary strategies to search for FCNC in single top quark production. A search can be performed in the s channel for resonance production through the fusion of a gluon (g) with an up (u) or charm (c) quark, as was the case in analyses by the CDF [20] and ATLAS [22] Collaborations. However, as pointed out by the D0 Collaboration, the s-channel production rate is proportional to the square of the FCNC coupling parameter and is therefore expected to be small [21]. On the other hand, the t-channel cross section and its corresponding kinematic properties have been measured accurately at the LHC [30–32], an important feature being that the t-channel signature contains a light-quark jet produced in association with the single top quark. This light-quark jet can be used to search for deviations from the SM
prediction caused by FCNC in the top quark sector. This strategy was applied by the D0 Collaboration [21], as well as in the CMS Collaboration [23]. The FCNC tcg and tug interactions can be written in a model-independent form with the following effective Lagrangian [1]:

\[ \mathcal{L} = \frac{\kappa_{tgq}}{\Lambda} g_8 q \sigma^{\mu\nu} \lambda^a t G_{\mu\nu}^a, \]

where \( \Lambda \) is the scale of new physics (\( \gtrsim 1 \text{ TeV} \)), \( q \) refers to either the \( u \) or \( c \) quarks, \( \kappa_{tgq} \) defines the strength of the FCNC interactions in the tug or tcg vertices, \( \lambda^a/2 \) are the generators of the SU(3) colour gauge group, \( g_8 \) is the coupling constant of the strong interaction, and \( G_{\mu\nu}^a \) is a gluon field strength tensor. The Lagrangian is assumed to be symmetric with respect to the left and right projectors. Single top quark production through FCNC interactions contains 48 subprocesses for both the tug and tcg channels, and the cross section is proportional to \( (\kappa_{tgq}/\Lambda)^2 \).

Representative Feynman diagrams for the FCNC processes are shown in Fig. 1. All these features are explicitly taken into account in the Single-Top Monte Carlo (MC) generator [33] based on the COMPHEP package [34], which was used to generate the signal events.

These signal samples as well as backgrounds from \( t\bar{t} \), single top, \( W+\text{jets} \) and Drell-Yan processes are estimated from full simulation of the CMS detector with realistic Phase-2 conditions, while the multijet QCD background is estimated with Run II data-driven template owing to the lack of statistics in the corresponding MC sample. The LO MADGRAPH 5.1 [35] generator is used to simulate \( W \) boson production with up to 4 additional jets in the matrix element, sub-dominant backgrounds from Drell-Yan in association with jets, and \( WW, WZ, \) and ZZ production. The POWHEG 1.0 NLO MC generator [36] provides a model for top quark pair and single production. Given the difficulty to reliably model QCD multijet events, this study makes use of a data-driven sample of 13 TeV data collected in 2016, with an anti-isolated selection. The resulting estimation of the QCD multijet background is rescaled to the appropriate luminosity and by the theoretical cross section ratio between 13 and 14 TeV, but other factors owing to differences in pileup, detector conditions, and some of the selection criteria are taken into account by a conservative normalization uncertainty.

3 Event selection and multivariate analysis

The particle-flow event algorithm [37] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers.
Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy. Jets are reconstructed offline from particle-flow candidates clustered by the anti-\(k_T\) algorithm [38, 39]. More details are given in Section 9.4.1 of Ref. [29].

The final signature of the signal is selected by requiring to have only one isolated (\(I^\mu_{\text{rel}} < 0.15\)) muon or electron [40] with \(p_T > 25\) GeV and \(|\eta| < 2.8\). The relative isolation \(I^\mu_{\text{rel}}\) is defined as the sum of the energy deposited by long-lived charged hadrons, neutral hadrons, and photons in a cone with radius \(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4\), divided by the lepton \(p_T\), where \(\Delta \eta\) and \(\Delta \phi\) are the differences in pseudorapidity and azimuthal angle (in radians), respectively, between the lepton and the other particle’s directions. A similar definition is used for the electron isolation. Electrons in the overlap region \(1.4 < |\eta| < 1.6\) are excluded from the analyses. Events with additional muons or electrons are rejected using a looser quality requirement of \(p_T > 10\) GeV, \(|\eta| < 2.8\), and \(I_{\text{rel}} < 0.25\). The event is required to have two or three PUPPI jets [41] reconstructed using the anti-\(k_T\) algorithm with a distance parameter of \(R = 0.4\), with \(p_T > 30\) GeV and \(|\eta| < 4.7\). We require at least one b tagged jet and at least one jet that fails the b tagging criteria. A high purity b tagging working point is used based on the cMVA [42] algorithm for jets with \(|\eta| < 1.5\) and the DeepCSV [42] algorithm for jets with \(1.5 < |\eta| < 3.5\). This high-purity working point corresponds to about 68% probability to identify jets from b-quarks and a misidentification probability of about 0.1% for the light-flavor jets.

The multijet QCD background is derived from the full single muon dataset collected in Run II in 2016 by CMS detector with 13 TeV center-of-mass energy. Owing to Run II detector conditions and the purpose to produce multijet-QCD-enriched sample, the event selection is modified to require one anti-isolated (\(0.35 < I^\mu_{\text{rel}} < 1\)) muon with \(p_T > 26\) GeV and \(|\eta| < 2.4\), without veto for additional low-\(p_T\) leptons. The other requirements to select events with two or three jets are the same as in signal region described in previous paragraph. The b-tagging criteria are slightly different due to the limitation of \(|\eta| < 2.4\) with the DeepCSV algorithm in Run II. Since the lepton is not isolated, we consider only jets outside a cone \(\Delta R(\text{lepton, jet}) > 0.5\) to avoid a mismodelling in isolation-sensitive variables. The purity of the resulting QCD multijet sample is expected to be about 97% according to MC simulation in the Run II detector conditions. The normalization of the data-driven sample is obtained from the fit of multijet QCD template in 13 TeV CMS data and then rescaled to the expected luminosity of 3000 \(fb^{-1}\) and by the theoretical cross section ratio of 1.09 between 13 and 14 TeV collision energy. Other factors related to little differences in event selection, pileup, detector conditions, and some of the selection criteria are taken into account by a conservative normalization uncertainty.

Several variables in the analysis require full kinematic reconstruction of the top quark and W boson candidates. For the kinematic reconstruction of the top quark, the W boson mass constraint is applied to extract the component of the neutrino momentum along the beam direction (\(p_z\)). This leads to a quadratic equation in \(p_z\). When there are two real solutions of the equation, the smaller value of \(p_z\) is used as the solution. For events with complex solutions, the imaginary components are eliminated by modifying \(E_T^{\text{miss}}\) such that \(m_T(W) \equiv \sqrt{2p_T(\mu)E_T^{\text{miss}}(1 - \cos[\Delta \phi(\mu, \vec{p}_T^{\text{miss}})])} = M_W\), where \(M_W = 80.4\) [3].

The Bayesian Neural Network technique (BNN) and the slightly adapted FBM package [43, 44] are used to distinguish signal events from the standard model background. The input variables for each BNN are summarized in Table 1. Their choice is based on the difference in the structure of the Feynman diagrams contributing to the signal and background processes [45].

In the first step of the analysis one Bayesian Neural Network is trained to filter out multijet background events. A minimal set of the simplest and well-modeled variables to distinguish
Table 1: Input variables for the BNN/DNNs used in the analysis. The symbol X represents the variables used for each particular BNN/DNN. The notations “leading” and “next-to-leading” refer to the highest-$p_T$ and second-highest-$p_T$ jet, respectively. The notation “best” jet is used for the jet that gives a reconstructed mass of the top quark closest to the value of 172.5 GeV, which is used in the MC simulation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Multijet BNN</th>
<th>tgg FCNC BNN/DNN</th>
<th>tcg FCNC BNN/DNN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(j_1)$</td>
<td>$p_T$ of the leading jet</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(j_2)$</td>
<td>$p_T$ of the next-to-leading jet</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(j_1, j_2)$</td>
<td>vector sum of the $p_T$ of the leading and the next-to-leading jet</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(j_L)$</td>
<td>$p_T$ of the light-flavour jet (untagged jet with the highest value of $</td>
<td>\eta</td>
<td>$)</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(j_{not\text{best}})$</td>
<td>$p_T$ of all jets without the one that best reconstructs the top quark</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(\text{lep})$</td>
<td>$p_T$ of the lepton</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T(\text{top}, b_1)$</td>
<td>$p_T$ of the top quark reconstructed with leading $c$ jet (the b-tagged jet with the highest $p_T$)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$H_T(j)$</td>
<td>scalar sum of the $p_T$ of the all jets</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$E_{\text{miss}}^T$</td>
<td>missing transverse energy</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$\eta(\text{lep})$</td>
<td>$\eta$ of the lepton</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$\eta(j_L)$</td>
<td>$\eta$ of the light-flavour jet</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$n_T(W)$</td>
<td>transverse mass of the W boson</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$m(j)$</td>
<td>invariant mass of the all jets</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$m(j, W)$</td>
<td>invariant mass of the W boson and all jets</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$m(\text{top}, b_1)$</td>
<td>invariant mass of the top quark reconstructed with leading $b$ jet</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$N(j)$</td>
<td>number of selected jets</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$\Delta \phi(\text{lep}, E_{\text{miss}}^T)$</td>
<td>azimuthal angle between the lepton and $E_{\text{miss}}^T$</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$\cos(\theta_{\text{lep}, j_L, \text{top}})$</td>
<td>cosine of the angle between the lepton and the light-flavour jet in the top quark rest frame, for top quark reconstructed with the leading c jet [46]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$\cos(\theta_{\text{lep}, W})$</td>
<td>cosine of the angle between the lepton momentum in the W boson rest frame and the direction of the W boson boost vector [47]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$Q(\text{lep})$</td>
<td>charge of the lepton</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
events with real W boson production from multijet QCD events are used and listed in Table 1. The input variables and the Multijet BNN discriminant distributions are shown in Fig. 2. The

Figure 2: The Multijet BNN input variable distributions: $m_{T}(W)$ (top left), $E_{T}^{miss}$ (top right), $\Delta \phi (lep, E_{T}^{miss})$ (middle left) and $p_{T}(lep)$ (middle right). Comparison of distributions of the training and testing events of the Multijet BNN (bottom left) and resulting distribution of the Multijet BNN discriminant (bottom right). The solid and dashed lines give the expected distributions for FCNC tug and tcg processes, respectively, assuming a coupling of $|k_{tug}|/\Lambda = 0.09$ and $|k_{tcg}|/\Lambda = 0.06$ TeV$^{-1}$. Both muon and electron channels are presented on the plots.

The requirement on multijet BNN output discriminant to be greater than 0.7 rejects about 95% of multijet events and about 30% of signal events, as can be seen from Table 2. This requirement makes the multijet QCD background negligible and the uncertainty, in spite of being assigned a conservative value, has a much smaller impact than other uncertainties in the analysis. The events passing the multijet BNN requirement are passed to the next level of the analysis. At the next step two networks are trained, one for each type of signal processes, since the kinematics for the tug and tcg processes are slightly different due to the different initial states. The distributions of some of the BNN input variables are shown in Figs. 3. In addition to Bayesian Neural Networks, we prepare two fully connected Deep Learning Neural Networks (DNN) to compare DNN and BNN techniques. The input set of variables for DNN and BNN are the same. Five layers with about 100 nodes each are used for DNN architecture. The DNNs are built and trained using the Tensorflow [48] and Keras [49, 50] packages. The comparison of the BNN and DNN outputs are shown in Fig. 4 for the signal and background events. The back-
ground is the properly weighted mixture of all SM processes. The comparison plots do not show a significant difference between BNN and DNN with respect to signal and background separation. However, in this analysis the BNN is used to obtain the limits for tug channel and DNN for tcg channel because of a slightly better performance in the corresponding channels.

The discriminant distributions of all SM and FCNC processes are shown in Fig. 5 for the BNN and in Fig. 6 for the DNN. All processes are normalized to their cross sections and selection efficiencies, and an integrated luminosity of 3000 fb\(^{-1}\).

The shape of the neural networks discriminants are used in the statistical analysis to estimate the expected sensitivity to the contributions from FCNC.

### 4 Statistical analysis and expected limits

The statistical analysis is performed with the Theta package \[51\]. Bayesian inference is used to obtain the posterior probabilities based on an Asimov data set of the background-only model. We assume the same systematic scenario as in \[24\] and incorporate the following systematic uncertainties in the statistical model as nuisance parameters: luminosity measurement (1%),

\[
(j - m_t) \text{(GeV)}
\]

The requirement of Multijet BNN > 0.7 is applied. The variables are described in Table 1.

![Comparison of FCNC tgc and tcg signal with the SM processes for the BNN input variables.](image)

Figure 3: Comparison of FCNC tgc and tcg signal with the SM processes for the BNN input variables. The solid and dashed lines give the expected distributions for FCNC tcg and tcg processes, respectively, assuming the couplings $|\kappa_{tug}|/\Lambda = 0.06$ TeV\(^{-1}\) and $|\kappa_{tcg}|/\Lambda = 0.09$ TeV\(^{-1}\). The requirement of Multijet BNN > 0.7 is applied. The variables are described in Table 1.
4. Statistical analysis and expected limits

Figure 4: Comparison of the BNN and DNN FCNC discriminant distributions to distinguish FCNC tug (left) and tgc (right) processes (signal) from the SM processes (background). The requirement of Multijet BNN > 0.7 is applied.

Table 2: The predicted event yields before and after the multijet BNN suppression for integrated luminosity of 3000 fb⁻¹. The estimations for tug and tgc processes assume coupling values of \(|\kappa_{\text{tg}}|/\Lambda = 0.03\) and \(|\kappa_{\text{tcg}}|/\Lambda = 0.03\) TeV⁻¹, respectively.

<table>
<thead>
<tr>
<th>Process</th>
<th>Basic selections</th>
<th>Multijet BNN &gt; 0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCNC tgc</td>
<td>646,000</td>
<td>434,000</td>
</tr>
<tr>
<td>FCNC tug</td>
<td>2,190,000</td>
<td>1,510,000</td>
</tr>
<tr>
<td>t channel</td>
<td>7,420,000</td>
<td>5,270,000</td>
</tr>
<tr>
<td>tW channel</td>
<td>1,190,000</td>
<td>846,000</td>
</tr>
<tr>
<td>t\bar{t}</td>
<td>11,000,000</td>
<td>7,970,000</td>
</tr>
<tr>
<td>W+jets</td>
<td>9,690,000</td>
<td>6,380,000</td>
</tr>
<tr>
<td>Dibosons</td>
<td>97,500</td>
<td>58,000</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>1,600,000</td>
<td>870,000</td>
</tr>
<tr>
<td>Multijets</td>
<td>3,680,000</td>
<td>226,000</td>
</tr>
</tbody>
</table>

Figure 5: The FCNC BNN discriminant distributions to distinguish FCNC tug (left) or tgc (right) processes from the SM contribution. The solid and dashed lines give the expected distributions for FCNC tug and tgc processes, respectively, assuming the couplings to be \(|\kappa_{\text{tg}}|/\Lambda = 0.06\) and \(|\kappa_{\text{tcg}}|/\Lambda = 0.09\) TeV⁻¹. The requirement of Multijet BNN > 0.7 is applied.

lepton identification and isolation (1% for electron and 0.5% for muon channel), jet energy scale (1%), b tagging (1% for b jets, 2% for c jets and 15% for light jets). The normalization of the t\bar{t} contribution is varied by 6% [52], a prior normalization uncertainty for the multijet background is estimated conservatively to be 50% while the cross section of the remaining background sources is varied through their scale uncertainties as described in [53].
The SM value for the top quark width is used in this analysis, since the influence of the FCNC parameters on the total top quark width is negligible for the allowed region of FCNC parameters. The COMPHEP package is used to simulate tug and tcg FCNC processes. The FCNC signal samples are normalized to the NLO cross sections using a K factors of 1.52 and 1.4 for $t \rightarrow ug$ and $t \rightarrow cg$ processes, respectively, for higher-order QCD corrections [54]. FCNC processes are kinematically different from any SM process. The posterior probability distributions of $|\kappa_{tug}|/\Lambda$ and $|\kappa_{tcg}|/\Lambda$ are obtained by fitting the histograms of BNN output in Fig. 5.

To obtain the individual exclusion limits on $|\kappa_{tug}|/\Lambda$ and $|\kappa_{tcg}|/\Lambda$ we assume the presence of only one corresponding FCNC parameter in the FCNC signal Monte Carlo model. These individual limits can be used to calculate the upper limits on the branching fractions $B(t \rightarrow ug)$ and $B(t \rightarrow cg)$ [55]. The expected exclusion limits at 95% C.L. on the FCNC couplings and the corresponding branching fractions are given in Table 3.

Table 3: The expected exclusion 1D limits at 95% C.L. on the FCNC couplings and the corresponding branching fractions for an integrated luminosity of 300 fb$^{-1}$ and 3000 fb$^{-1}$. In addition, a comparison with statistic-only uncertainties is shown.

| Integrated luminosity | $B(t \rightarrow ug)$ | $|\kappa_{tug}|/\Lambda$ | $B(t \rightarrow cg)$ | $|\kappa_{tcg}|/\Lambda$ |
|-----------------------|------------------------|--------------------------|------------------------|--------------------------|
| 300 fb$^{-1}$         | $9.8 \cdot 10^{-6}$    | 0.0029 TeV$^{-1}$        | $99 \cdot 10^{-6}$    | 0.0091 TeV$^{-1}$        |
| 3000 fb$^{-1}$        | $3.8 \cdot 10^{-6}$    | 0.0018 TeV$^{-1}$        | $32 \cdot 10^{-6}$    | 0.0052 TeV$^{-1}$        |
| 3000 fb$^{-1}$ Stat. only | $1.0 \cdot 10^{-6}$    | 0.0009 TeV$^{-1}$        | $4.9 \cdot 10^{-6}$    | 0.0020 TeV$^{-1}$        |

The dependence of the exclusion upper limits on integrated luminosity is shown in Fig. 7 with 1 and 2 $\sigma$ bands corresponding to 68% and 95% C.L. intervals of distributions of the limits. In addition the two-dimensional contours that reflect the possible simultaneous presence of both FCNC parameters are shown in Fig. 8. In this case both FCNC couplings are implemented in the FCNC signal Monte Carlo model. The expected limits can be compared with the recent CMS results [23] for the upper limits on the branching fractions of $2.0 \times 10^{-5}$ and $4.1 \times 10^{-4}$ for the decays $t \rightarrow ug$ and $t \rightarrow cg$, respectively.

The effect of each individual systematic uncertainty on parameter of interest is calculated by fixing the corresponding nuisance parameter at $\pm \sigma$ quantiles of the posterior distributions, and performing the Bayesian inference again. The impacts for the nuisance parameters are shown in Fig. 9. The biggest contribution for both signal channels come from the uncertainties of background cross sections and in particular from multijet QCD contribution and $t\bar{t}$ cross section uncertainties.

5 Conclusions

A direct search for model-independent FCNC $|\kappa_{tug}|/\Lambda$ and $|\kappa_{tcg}|/\Lambda$ couplings of the tug and tcg interactions has been projected for HL-LHC pp collisions at $\sqrt{s} = 14$ TeV based on full Monte Carlo simulation of the CMS experiment after the Phase II upgrades. The 95% C.L. expected exclusion limits on the coupling strengths are $|\kappa_{tug}|/\Lambda < 1.8 \times 10^{-3}$ $(2.9 \times 10^{-3})$ TeV$^{-1}$ and $|\kappa_{tcg}|/\Lambda < 5.2 \times 10^{-3}$ $(9.1 \times 10^{-3})$ TeV$^{-1}$ for the integrated luminosity of 3000 fb$^{-1}$ (300 fb$^{-1}$). The corresponding limits on branching fractions for the integrated luminosity of 3000 fb$^{-1}$ are $B(t \rightarrow ug) < 3.8 \cdot 10^{-6}$ and $B(t \rightarrow cg) < 32 \cdot 10^{-6}$. These results demonstrate that about one order of magnitude improvement can be achieved with respect to existing limits [23] on the branching fractions of rare FCNC top quark decays.
5. Conclusions

Figure 6: The FCNC DNN discriminant distributions when the DNN is trained to distinguish FCNC tug (left) and tgc (right) processes from the SM processes. The solid and dashed lines give the expected distributions for FCNC tug and tgc processes, respectively, assuming a coupling of $|\kappa_{tug}|/\Lambda = 0.06$ and $|\kappa_{tgc}|/\Lambda = 0.09 \, \text{TeV}^{-1}$ on the left (right) plots. The requirement of Multijet BNN $> 0.7$ is applied.

Figure 7: The expected exclusion limits at 95% C.L. on the FCNC couplings and the corresponding branching fractions as a function of integrated luminosity.
Figure 8: Two-dimensional expected limits on the FCNC couplings and the corresponding branching fractions at 68% and 95% C.L. for an integrated luminosity of 3000 fb$^{-1}$.

Figure 9: Effect of the systematic uncertainties on the expected exclusion limits on the branching fractions for $B(t \to ug)$ (left plot) and $B(t \to cg)$ (right plot).
References


