Top FCNC searches at HL-LHC with the CMS experiment

Petr Mandrik

on behalf of the CMS Collaboration

NRC «Kurchatov Institute» – IHEP

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The High-Luminosity LHC (HL-LHC) is the planned upgrade of the LHC:

<table>
<thead>
<tr>
<th></th>
<th>LHC Run II</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>13 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>50 fb$^{-1}$ per year</td>
<td>300 fb$^{-1}$ per year</td>
</tr>
<tr>
<td></td>
<td>300 at the end of Run III</td>
<td>3000 fb$^{-1}$ in total</td>
</tr>
</tbody>
</table>
| Pileup               | 27-36                      | 140-200                     

Top FCNC searches at HL-LHC
Phase-II Upgrade of the Compact Muon Solenoid

Significant upgrades of CMS for HL-LHC conditions:

- Radiation hardness
- Mitigate physics impact of high pileup

**Trigger/HLT/DAQ**
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

**Barrel EM calorimeter**
- New electronics
- Low operating temperature \( \approx 10^\circ \)

**Muon systems**
- New DT & CSC electronics

**New Endcap Calorimeters**
- Rad. Tolerant
- 5D measurement

**New Tracker**
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger

**Beam radiation and luminosity**
**Common systems and infrastructure**

Top FCNC searches at HL-LHC
- addition of hardware trigger capabilities
- extended acceptance of the tracker and granularity of the calorimeters (HGCAL) in the forward region:
  - inner tracker $|\eta| < 2.4 \rightarrow |\eta| < 4.0$
  - muon system $|\eta| < 2.4 \rightarrow |\eta| < 2.8$
- pileup mitigation with PileUp Per Particle approach (PUPPI) algorithm

Top FCNC searches at HL-LHC
Large number of tops @ LHC ⇒ 10x more @ HL-LHC for:

- mass, width measurement
- kinematics, asymmetry study
- (anomalous) couplings measurement
- **FCNC rare decays search**
- direct BSM search

<table>
<thead>
<tr>
<th>Process</th>
<th>14 TeV - 3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$3 \cdot 10^9$ events</td>
</tr>
<tr>
<td>$t\bar{t}$, fiducial, $M_{t\bar{t}} &gt; 1$ TeV</td>
<td>$155 \cdot 10^6$ events</td>
</tr>
<tr>
<td>$t\bar{t}$, fiducial, $M_{t\bar{t}} &gt; 2$ TeV</td>
<td>$3 \cdot 10^6$ events</td>
</tr>
<tr>
<td>$t\bar{t}$, fiducial, $M_{t\bar{t}} &gt; 2$ TeV</td>
<td>$48 \cdot 10^3$ events</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>$600 \cdot 10^6$</td>
</tr>
<tr>
<td>$tW$-channel</td>
<td>$200 \cdot 10^6$</td>
</tr>
<tr>
<td>$s$-channel</td>
<td>$30 \cdot 10^6$</td>
</tr>
</tbody>
</table>
Flavour changing neutral current in $t$–quark sector

- In the SM, top quark FCNC decays are forbidden at tree level and have much smaller BR than the dominant decay mode $t \to bW$ at one loop level.
- BSM models predict higher BR for top FCNC decays:

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>2HDM(FV)</th>
<th>2HDM(FC)</th>
<th>MSSM</th>
<th>RPV</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to Zu$</td>
<td>$7 \times 10^{-17}$</td>
<td>-</td>
<td>-</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>-</td>
</tr>
<tr>
<td>$t \to Zc$</td>
<td>$1 \times 10^{-14}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-10}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-5}$</td>
</tr>
<tr>
<td>$t \to gu$</td>
<td>$4 \times 10^{-14}$</td>
<td>-</td>
<td>-</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>-</td>
</tr>
<tr>
<td>$t \to gc$</td>
<td>$5 \times 10^{-12}$</td>
<td>$\leq 10^{-4}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-6}$</td>
<td>$\leq 10^{-10}$</td>
</tr>
<tr>
<td>$t \to \gamma u$</td>
<td>$4 \times 10^{-16}$</td>
<td>-</td>
<td>-</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-9}$</td>
<td>-</td>
</tr>
<tr>
<td>$t \to \gamma c$</td>
<td>$5 \times 10^{-14}$</td>
<td>$\leq 10^{-7}$</td>
<td>$\leq 10^{-9}$</td>
<td>$\leq 10^{-8}$</td>
<td>$\leq 10^{-9}$</td>
<td>$\leq 10^{-9}$</td>
</tr>
<tr>
<td>$t \to hu$</td>
<td>$2 \times 10^{-17}$</td>
<td>$6 \times 10^{-6}$</td>
<td>-</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-9}$</td>
<td>-</td>
</tr>
<tr>
<td>$t \to hc$</td>
<td>$3 \times 10^{-15}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-5}$</td>
<td>$\leq 10^{-9}$</td>
<td>$\leq 10^{-4}$</td>
</tr>
</tbody>
</table>

- No indication of FCNC transitions in $t$–quark sector:

- Powerful probe for new physics
Sensitivity to $tq\gamma$ FCNC transition

Single top quark **production** in association with photon:

$\Rightarrow$ distinctive event final-state signature of top quark decay with single muon or electron, neutrino and photon

$\Rightarrow$ enhanced FCNC production with an up-quark $\rightarrow$ differentiate between up and charm-type FCNC couplings

$\Rightarrow$ the photon is expected to have large transverse momentum, because of its recoil from the heavy top quark
Signals:

- FeynRules model in MadGraph: **TopFCNCmode**
- Official MC generation of datasets with MadGraph

Backgrounds:

- $t\bar{t}$, $t\bar{t} + \gamma$
- $W + $ jets, $W + \gamma$ + jets
- Single top, Single top + $\gamma$

Generated with 1Powheg, 2MadGraph, 3aMCatNLO. Showered and hadronized with **PYTHIA 8**.

⇒ Full simulation of the upgraded CMS detector for signals and most of the backgrounds. Fast Delphes simulation of Single top + $\gamma$

⇒ Pile-Up $< \mu > = 200$ scenario is assumed
Selections:

- **Exactly one tight lepton** ($e$ or $\mu$) with $p_T > 25$ GeV, $|\eta| < 2.8$, relative isolation $< 0.15$ (electrons in the overlap region $1.4 < |\eta| < 1.6$ are removed)

- No additional leptons with $p_T > 10$ GeV, $|\eta| < 2.8$, relative isolation $< 0.10$

- **Exactly one b-tagged jet** with $p_T > 30$ GeV, $|\eta| < 2.8$ (cMVA algorithm for $|\eta| < 1.5$, DeepCSV algorithm for $|\eta| > 1.5$, PUPPI jets clustered with anti-$k_T$ $R = 0.4$)

- **At least one photon** with $p_T > 50$, $|\eta| < 2.8$ (photons in the overlap region $1.4 < |\eta| < 1.6$ are removed)

- $E_T^{miss} > 30$ GeV

- Reconstructed t-quark mass in the range from 130 to 220 GeV
High photon $p_T$ and Energy regions are populated by signal events: combination of this distributions is used in statistical analysis for limit settings with the asymptotic $CL_S$ method.
Systematic scenario:

⇒ 1.5% luminosity uncertainty
⇒ 1% JES uncertainty
⇒ 5% b-tagging uncertainty for the used working point
⇒ Run II normalization uncertainties (Single top $+\gamma$, $t\bar{t}$)
⇒ 50% variation of the renormalization and factorization scales (rest of the backgrounds)

single top $+\gamma$ and $t\bar{t} + \gamma$ cross section uncertainties are dominated!

Limits:

• 14 TeV 3000 fb$^{-1}$ preliminary
  
  CMS-TDR-17-007
  
  $Br(t \rightarrow \gamma + u) < 1.16 \cdot 10^{-5}$
  $Br(t \rightarrow \gamma + c) < 9.12 \cdot 10^{-5}$

• 8 TeV 19.7 fb$^{-1}$
  
  JHEP 0 2 (2017) 028
  
  $Br(t \rightarrow \gamma + u) < 1.3 \cdot 10^{-4}$
  $Br(t \rightarrow \gamma + c) < 1.7 \cdot 10^{-3}$

• 14 TeV 3000 fb$^{-1}$
  (fast simulation based)
  
  CMS-PAS-FTR-16-006
  
  $Br(t \rightarrow \gamma + u) < 2.7 \cdot 10^{-5}$
  $Br(t \rightarrow \gamma + c) < 2.0 \cdot 10^{-4}$
Sensitivity to $tqZ$ FCNC transition

Top-quark pair with one top quark FCNC decay:

$\Rightarrow$ final-state signature with three isolated leptons ($\mu$ or $e$), neutrino and photon

- backgrounds: $t\bar{t} + jets$, $t\bar{t} + Z/W + jets$, $t + Z/W + jets$, $Z/W + jets$, $WW/WZ/ZZ + jet$
- fast Delphes simulation for signals and backgrounds
- pile-up $< \mu > = 140$ scenario is assumed

$\Rightarrow$ signals and backgrounds events are generated with MadGraph 5, showering and hadronization with Pythia 6,
Selections:

- Three isolated leptons with $p_T > 30$ GeV, $|\eta| < 2.5$ for electron and $|\eta| < 2.4$ for muon
- Invariant mass of two opposite-signed leptons $\in [78, 102]$ GeV
- At least two jets with $p_T > 50$ GeV, $|\eta| < 2.4$, one b-tagged jet
- $E_T^{\text{miss}} > 30$ GeV
- Reconstructed t-quark mass from SM decay $\in [137.5, 207.5]$

The expected number of events after selections:

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section (pb)</th>
<th>Expected @ 3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>top FCNC signal</td>
<td>1.91</td>
<td>578 ± 13</td>
</tr>
<tr>
<td>vector boson + jet</td>
<td>$338 \times 10^3$</td>
<td>&lt; 55</td>
</tr>
<tr>
<td>di-boson + jets</td>
<td>412</td>
<td>40 ± 31</td>
</tr>
<tr>
<td>top pair + jets</td>
<td>954</td>
<td>70 ± 57</td>
</tr>
<tr>
<td>single top + jets</td>
<td>323</td>
<td>&lt; 8</td>
</tr>
<tr>
<td>boson + top + jets</td>
<td>97.3</td>
<td>15 ± 15</td>
</tr>
<tr>
<td>boson + top pair + jets</td>
<td>3.97</td>
<td>144 ± 14</td>
</tr>
</tbody>
</table>
Reconstructed $m_{Zj}$ and $m_{Wb}$ distributions of the simulated signal and background events for an integrated luminosity of 3000 fb$^{-1}$:

The open histogram is the expected $Br(t \rightarrow Zq)$ is equal to 0.1%. The statistical uncertainties of these simulated background events are shown as shadowed area.
Systematic scenario:

- based on the study done with 8 TeV CMS-PAS-TOP-12-037
- rescaled as $\sqrt{19.5 \text{ fb}/\mathcal{L}}$ by 0.25

→ Simple counting experiment using the number of events after selections
→ Modified frequentist approach ($CL_s$ method)

<table>
<thead>
<tr>
<th>Uncertainty (%)</th>
<th>3000 fb$^{-1}$ @ 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>3.4</td>
</tr>
<tr>
<td>$E_T$ resolution</td>
<td>3.2</td>
</tr>
<tr>
<td>MC Statistics</td>
<td>1.3</td>
</tr>
<tr>
<td>$\sigma(tqZ)/\sigma(V\bar{t})$</td>
<td>0.8</td>
</tr>
<tr>
<td>b-tagging</td>
<td>4.2</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\mathcal{B}(t \to Zq)$</th>
<th>19.5 fb$^{-1}$ @ 8 TeV</th>
<th>300 fb$^{-1}$ @ 14 TeV</th>
<th>3000 fb$^{-1}$ @ 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. bkg. yield</td>
<td>3.2</td>
<td>26.8</td>
<td>268</td>
</tr>
<tr>
<td>Expected limit</td>
<td>&lt; 0.10%</td>
<td>&lt; 0.027%</td>
<td>&lt; 0.010%</td>
</tr>
<tr>
<td>1 $\sigma$ range</td>
<td>0.06 – 0.13%</td>
<td>0.018 – 0.038%</td>
<td>0.007 – 0.014%</td>
</tr>
<tr>
<td>2 $\sigma$ range</td>
<td>0.05 – 0.20%</td>
<td>0.013 – 0.051%</td>
<td>0.005 – 0.020%</td>
</tr>
</tbody>
</table>
Conclusions:

- The High-Luminosity LHC will deliver up billions of tops → great opportunity to challenge the SM by searching for FCNC with upgraded CMS detector.
- Search for FCNC in $t \rightarrow q\gamma$ and $t \rightarrow qZ$ events are projected into the HL-LHC conditions and shows the possibility of improving existing constraints on the branchings by about one order of magnitude.
- Several studies for different FCNC in top quark sector are in an ongoing state:
  1. $tqg$ transition in a single top quark production in association with $u$ or $c$ quark
  2. $tHq$ and $tqZ$ transition based on a full detector simulation
- Systematic uncertainty will play a dominant role in such analyzes → efforts to improve the accuracy of calculations of the cross sections of processes.