FCNC and EFT interpretations at LHC

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on behalf of the ATLAS and CMS collaborations

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top quark decays

Dominant decay mode $t \rightarrow bW$

$BR(t \rightarrow bW)_{SM} = 9.98 \times 10^{-1}$

$BR(t \rightarrow sW)_{SM} = 1.64 \times 10^{-3}$

$BR(t \rightarrow dW)_{SM} = 7.85 \times 10^{-5}$

Flavour-changing neutral currents (FCNC) decays are forbidden at tree level.

Occur at one-loop level but are strongly suppressed by the GIM mechanism.

FCNC vertices can be probed in both production and decay modes.

~ maximum BR in several models:

<table>
<thead>
<tr>
<th>ATLAS+CMS Preliminary</th>
<th>Theory predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCTopWG</td>
<td>from arXiv:1311.2028</td>
</tr>
<tr>
<td>September 2018</td>
<td></td>
</tr>
</tbody>
</table>

Each limit assumes that all other processes are zero.

Branching ratio

$10^{-16}$ $10^{-13}$ $10^{-10}$ $10^{-7}$ $10^{-4}$ $10^{-1}$
effective field theory

model independent approach for physics beyond the SM using an effective Lagrangian:

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i + \ldots \]

- \( \Lambda \) new physics energy scale (usually set to 1 TeV)
- \( \mathcal{O}_i \) dimension 6 operators
  (59 total with lepton and baryon conservation; just 15 are relevant for top quark physics)
- \( c_i \) Wilson coefficients (WC)
  (intensity of new physics operators)
- top quark anomalous couplings can be expressed in terms of WC (or WC combinations)
- agreement in top quark community for common standards for EFT interpretation (1802.07237)
• $t\bar{t}$ production with FCNC decay and 4 $H$ decay topologies:
  - $H \rightarrow bb$
  - $H \rightarrow \tau\tau$
  - $H \rightarrow$ multileptons($WW, \tau\tau, ZZ$)
  - $H \rightarrow \gamma\gamma$

• dominant systematic (multi leptons chan.): non-prompt lepton background estimation (8%)
• combined result from simultaneous fit to distributions of the 4 analyses

• both production and decay FCNC channels with $H \rightarrow bb$
• 5 categories based on the no. jets and no. b-tagged jets
• full kinematic reconstruction for signal and background hypotheses
• BDTs to optimise signal and background discrimination
• dominant systematic: b-tagging (8–30%)
observed (expected) limits:

$$|\lambda_{tuH}| < 0.066 (0.055)$$
$$\text{BR}(t \to uH) < 1.2 \times 10^{-3} (8.3 \times 10^{-4})$$

$$|\lambda_{tcH}| < 0.064 (0.055)$$
$$\text{BR}(t \to cH) < 1.1 \times 10^{-3} (8.3 \times 10^{-4})$$
- search for single top production via FCNC (QED)
- BDT with 8 variables used to improve $W + \gamma$ discrimination
- dominant systematics: $W + \gamma$ and $W$+jets normalisations

observed (expected) limits:

$$\kappa_{t\gamma} < 0.025 \,(0.031)$$
$$\text{BR}(t \to \mu\gamma) < 1.3 \times 10^{-4} \,(1.9 \times 10^{-4})$$

$$\kappa_{tc\gamma} < 0.091 \,(0.098)$$
$$\text{BR}(t \to c\gamma) < 1.7 \times 10^{-3} \,(2.0 \times 10^{-3})$$
• $t\bar{t}$ production with $t \rightarrow qg$ decay difficult to distinguish from multijet production
• search for single top production via FCNC (strong sector)
• neural-network with 13 variables
• dominant systematics: $b$-tag, $E_T^{\text{miss}}$, background modelling

• search for single top production via FCNC in $t$-channel topology
• different $b$-tagged jets and light jets CRs
• neural-network with 4 variables used to reduce QCD
• neural-network with 9 (10) variables used to define $tug$ ($tcg$) region
• dominant systematics: PDF (5%), signal generator (5%)
observed (expected) limits:

\[ \kappa_{tug}/\Lambda < 5.8 \times 10^{-3} \text{ TeV}^{-1} \]
\[ \kappa_{tcg}/\Lambda < 1.3 \times 10^{-2} \text{ TeV}^{-1} \]
\[ \text{BR}(t \to ug) < 4.0 \times 10^{-5} \]
\[ \text{BR}(t \to cg) < 2.0 \times 10^{-4} \]
- 3 leptons ($e$, $\mu$), 2 jets (1 $b$-tag), $E_T^{\text{miss}}$
- event reconstruction through $\chi^2$ minimisation
- simultaneous fit to 6 distributions in SR and CR
- dominant systematics: event modelling, jets

- search for $tqZ$ vertex in production and decay
- BDTs improve signal/background separation
- simultaneous fit to five SRs/CRs
- dominant systematics: non-prompt leptons
$tqZ$

<table>
<thead>
<tr>
<th>$\mathcal{B}(t \to uZ)$</th>
<th>$\mathcal{B}(t \to cZ)$</th>
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</thead>
<tbody>
<tr>
<td>Observed</td>
<td>$1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Expected $-1\sigma$</td>
<td>$1.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Expected $+1\sigma$</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Expected $2\sigma$</td>
<td>$3.4 \times 10^{-4}$</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Operator</th>
<th>Observed</th>
<th>Expected</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>C_{uB}^{(31)}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(31)}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>C_{uB}^{(32)}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(32)}</td>
<td>$</td>
</tr>
</tbody>
</table>

$\mathcal{B}(t \to uZ) < 2.4 \times 10^{-4}$ ($1.5 \times 10^{-4}$) \quad \mathcal{B}(t \to cZ) < 4.5 \times 10^{-4}$ ($3.7 \times 10^{-4}$)
Each limit assumes that all other processes are zero.
• $\sigma(t\bar{t}Z)$ and $\sigma(t\bar{t}W)$ simultaneously measured
• 2 (SS, OS), 3 and 4 lepton final states
• measured $\sigma(t\bar{t}Z)$ used to constrain four operators ($C^{(1)}_{\phi Q}$ set to zero):

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
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<tbody>
<tr>
<td>$O_{\phi Q}^{(3)}$</td>
<td>$(\phi^+ i \gamma^\mu \phi)(\bar{Q}g^\mu \tau^I Q)$</td>
</tr>
<tr>
<td>$O_{\phi Q}^{(1)}$</td>
<td>$(\phi^+ i \gamma^\mu \phi)(\bar{Q}g^\mu Q)$</td>
</tr>
<tr>
<td>$O_{\phi t}$</td>
<td>$(\phi^+ i \gamma^\mu \phi)(\bar{t}g^\mu t)$</td>
</tr>
<tr>
<td>$O_{tW}$</td>
<td>$(\bar{Q}\sigma^{\mu \nu} \tau^I t)\phi W_{\mu \nu}$</td>
</tr>
<tr>
<td>$O_{tB}$</td>
<td>$(\bar{Q}\sigma^{\mu \nu} t)\phi B_{\mu \nu}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$C_{\phi Q}^{(3)}/\Lambda^2$</th>
<th>$C_{\phi t}/\Lambda^2$</th>
<th>$C_{tB}/\Lambda^2$</th>
<th>$C_{tW}/\Lambda^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous indirect constraints at 68% CL</td>
<td>$[-4.7, 0.7]$</td>
<td>$[-0.1, 3.7]$</td>
<td>$[-0.5, 10]$</td>
<td>$[-1.6, 0.8]$</td>
</tr>
<tr>
<td>Previous direct constraints at 95% CL</td>
<td>$[-1.3, 1.3]$</td>
<td>$[-9.7, 8.3]$</td>
<td>$[-4.0, 3.5]$</td>
<td>$[-0.2, 0.7]$</td>
</tr>
<tr>
<td>Expected limit at 68% CL</td>
<td>$[-2.1, 1.9]$</td>
<td>$[-3.8, 2.7]$</td>
<td>$[-2.9, 3.0]$</td>
<td>$[-1.8, 1.9]$</td>
</tr>
<tr>
<td>Expected limit at 95% CL</td>
<td>$[-4.5, 3.6]$</td>
<td>$[-23, 4.9]$</td>
<td>$[-4.2, 4.3]$</td>
<td>$[-2.6, 2.6]$</td>
</tr>
<tr>
<td>Observed limit at 68% CL</td>
<td>$[-1.0, 2.7]$</td>
<td>$[-2.0, 3.5]$</td>
<td>$[-3.7, 3.5]$</td>
<td>$[-2.2, 2.1]$</td>
</tr>
<tr>
<td>Observed limit at 95% CL</td>
<td>$[-3.3, 4.2]$</td>
<td>$[-25, 5.5]$</td>
<td>$[-5.0, 5.0]$</td>
<td>$[-2.9, 2.9]$</td>
</tr>
</tbody>
</table>
- $\sigma(t\bar{t}Z)$ measurement in 3 and 4 lepton final states
- differential cross sections ($dp_T^Z$ and $d\cos\theta^*_Z$) are also measured
- constraints on anomalous $ttZ$ couplings and on four operators:

$$
c_{tZ} = \text{Re} \left( -\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)} \right)
$$

$$
c_{tZ}^{[I]} = \text{Im} \left( -\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)} \right)
$$

$$
c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)}
$$

$$
c_{\phi Q}^- = C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)}
$$

- limits from reweighting procedure based on MC implementation of EFT at LO:
\(d\sigma_{t\bar{t}}\)

- differential \(\sigma(t\bar{t})\) measured as function of 14 observables (at parton and particle level) and 19 observables (at particle level only)
- anomalous top quark chromomagnetic dipole moment (CMDM) constrained from the absolute differential \(t\bar{t}\) cross section as a function of \(\Delta\phi(\ell^+, \ell^-)\) at particle level

**spin correlations**

- CMDM can also be studied from the measurement of the \(t\bar{t}\) production spin density matrix
- \(\chi^2\) fit to 20 distributions unfolded to parton level
- systematics from theoretical sources are estimated separately

\[-0.07 < C_{tG}/\Lambda^2 < 0.16\text{ TeV}^{-2}\]
• search for new physics in dilepton final states of $t\bar{t}$ and $Wt$ events
• first time constraining EFT in an experimental analysis directly
• first search for new physics that uses the $Wt$ process
• neural networks used to discriminate between signals and background
• constraints on 6 operators (one at a time)
• 2 operators also allow to derive limits of FCNC BRs

$BR(t \to u g) < 1.2 \times 10^{-3}$ ($2.2 \times 10^{-3}$) $BR(t \to c g) < 5.3 \times 10^{-3}$ ($1.05 \times 10^{-2}$)
- search for the SM production of four top quarks ($pp \rightarrow t\bar{t}t\bar{t}$)
- single-lepton and OS dilepton channels
- BDT to discriminate signal events from $t\bar{t}$ background

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected $C_k/\Lambda^2$ (TeV$^{-2}$)</th>
<th>Observed (TeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{tt}^1$</td>
<td>$[-1.5, 1.3]$</td>
<td>$[-2.1, 2.0]$</td>
</tr>
<tr>
<td>$O_{QQ}^1$</td>
<td>$[-1.5, 1.3]$</td>
<td>$[-2.2, 2.0]$</td>
</tr>
<tr>
<td>$O_{Qt}^1$</td>
<td>$[-2.4, 2.4]$</td>
<td>$[-3.5, 3.5]$</td>
</tr>
<tr>
<td>$O_{Qt}^8$</td>
<td>$[-5.6, 4.3]$</td>
<td>$[-7.9, 6.6]$</td>
</tr>
</tbody>
</table>
• ATLAS and CMS searches for rare / anomalous top quark couplings
• FCNC with $H$, $\gamma$, $g$ and $Z$ bosons covered
• no evidence for new physics found
• 95% CL limits on BR / couplings / WC derived
• EFT interpretations are becoming more frequent
• different approaches are being explored
• stay tuned for more!