Rare Top Quark Decays at the LHC

J. Ferrando

University of Oxford

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on behalf of:

ATLAS EXPERIMENT
Outline

1. Introduction
2. Rare decays via charged currents
3. Rare decays via flavour changing neutral currents
4. Summary
Top production @ the LHC

- SM cross section of $O(200 \text{ pb})$ @ 7 TeV for $t\bar{t}$ production at the LHC
- 10s of thousands of tops in 100 pb$^{-1}$

An ideal location to study the decays of top quarks!

Graph Produced by Akira Shibata and Ulrich Husemann
In the SM the top decays $t \rightarrow bW$ with branching fraction $\sim 1$

From the 2009 Review of Particle Physics:

$$V_{\text{CKM}} = \begin{pmatrix}
0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\
0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\
0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043}
\end{pmatrix}$$

(Assumes unitarity, 3 quark generations)

- Very few $t \rightarrow Ws, \ t \rightarrow Wd$
- No $t \rightarrow Zq, \ t \rightarrow \gamma q$ (at LO, higher orders GIM suppressed)
It is very challenging to measure $BR(t \to Wd)$ or $BR(t \to Ws)$ directly. In early data, more straightforward to measure:

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)}$$

giving sensitivity to the $Wd,s$ channels and a constraint on $|V_{tb}|$:

$$R \approx \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 \quad \text{for 3 q generations}$$

CDF$^1$ and D0$^2$: $R > 0.61$ and $R > 0.79$ respectively (95\% C.L.).

$^1$Phys.Rev.Lett.95:102002 (2005) $\rightarrow$ $|V_{tb}| > 0.78$

$^2$Phys.Rev.Lett.100:192003 (2008) $\rightarrow$ $|V_{tb}| > 0.89$
CMS have performed feasibility studies for the measurement of $R$ at $\sqrt{s} = 10$ TeV with:

- **dileptonic $t\bar{t}$ ($e\mu$), 250 $\text{pb}^{-1}$**: CMS PAS TOP-09-001
- **semi-leptonic $t\bar{t}$, 1 $\text{fb}^{-1}$**: CMS PAS TOP-09-007

Both approaches use the number of $b$-tagged jets. Probability of having a number $k$ of $b$-tagged jets, $P_k$ can be written:

$$P_k(R, \epsilon_b, \epsilon_q) = R^2 P_k(bb) + 2R(1 - R)P_k(bq') + (1 - R)^2P_k(q'q')$$

for dileptonic events, or:

$$P_k(R, B, M) = R^2 P_k(bWbW) + 2R(1 - R)P_k(bWq'W) + (1 - R)^2P_k(q'Wq'W)$$

for semileptonic events. $q' = d$ or $s$; $M$ or $\epsilon_q$ is the mistagging rate. $B$ or $\epsilon_b$ is the $b$-tagging efficiency. Depends also on $\alpha_k$ - prob. of correctly assigning $k$-jets.
### Selection

<table>
<thead>
<tr>
<th>Selection</th>
<th>Total</th>
<th>(\bar{t}t) dileptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triggered</td>
<td>((426 \pm 1) \cdot 10^6)</td>
<td>6251 (\pm 25)</td>
</tr>
<tr>
<td>(\geq 2) leptons (&gt;20 GeV/c)</td>
<td>((204.7 \pm 0.5) \cdot 10^3)</td>
<td>2595 (\pm 16)</td>
</tr>
<tr>
<td>1 e and 1 (\mu)</td>
<td>2531 (\pm 32)</td>
<td>1344 (\pm 12)</td>
</tr>
<tr>
<td>(\geq 2) jets (&gt;30 GeV)</td>
<td>1041 (\pm 12)</td>
<td>914 (\pm 10)</td>
</tr>
<tr>
<td>(E_T \geq 30) GeV</td>
<td>884 (\pm 10)</td>
<td>789 (\pm 9)</td>
</tr>
<tr>
<td>Opp. sign leptons</td>
<td>867 (\pm 10)</td>
<td>787 (\pm 9)</td>
</tr>
</tbody>
</table>

Diagram above shows \(P_k(R)\), given correct jet assignment probability \(\alpha = 0.82\) and \(\epsilon_b = 0.81, \epsilon_q = 0.1\)
Several ways to fit $R$ (or $\epsilon_b$) from the $b$-tag multiplicity:

- Fit $R$ or $\epsilon_b$ - consistency check
- Choose one bin - check model consistency, select region dominated by particular systematics
- use all selected events inclusively
- Estimate $\alpha_2$ from data and leave $\alpha_0$ as a free parameter ($\alpha_1 = 1 - \alpha_2 - \alpha_0$): simultaneously fit $R$ (or $\epsilon_b$) and the background contribution
Estimating $\alpha$

- $\alpha$ can be estimated using kinematic end point of $m_{ij}$
- To first order, $\alpha_{0,1,2}$ can be parametrised as binomial combinations of $\alpha$, e.g. $\alpha_2 = \alpha^2$
Can get a good estimate of $\alpha$:

<table>
<thead>
<tr>
<th>Method</th>
<th>$\frac{N_{mis}^{M&gt;190}}{N_{mis}}$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ events from MADGRAPH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>0.21 ± 0.01</td>
<td>0.82 ± 0.04</td>
</tr>
<tr>
<td>MC truth</td>
<td>0.20 ± 0.01</td>
<td>0.80 ± 0.01</td>
</tr>
<tr>
<td>$t\bar{t}$ events from PYTHIA + TAUOLA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>0.21 ± 0.01</td>
<td>0.81 ± 0.04</td>
</tr>
<tr>
<td>MC truth</td>
<td>0.23 ± 0.02</td>
<td>0.80 ± 0.01</td>
</tr>
</tbody>
</table>

Correspondingly get good estimates of $\alpha_k$

<table>
<thead>
<tr>
<th>probability</th>
<th>MadGraph</th>
<th>Pythia + Tauola</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC truth</td>
<td>Simulated Data</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>0.63 ± 0.02</td>
<td>0.67 ± 0.07 (stat) ±0.03 (syst)</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>0.31 ± 0.02</td>
<td>0.30 ± 0.05 (stat) ±0.02 (syst)</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>0.06 ± 0.01</td>
<td>0.03 ± 0.01 (stat) ±0.01 (syst)</td>
</tr>
</tbody>
</table>
Results

- Fit $R$ with measured $\alpha$ and with $\epsilon_b$ as input
- Measurement limited by Systematic uncertainty $\sim 9\%$
- Dominated by $b$-tagging efficiency uncertainty
- This precision is comparable to current Tevatron measurements
Semi-leptonic measurement

**Selection**

- **Trigger (single lepton)**
- A single isolated high energy isolated lepton $p_T > 30$ GeV
- At least four selected jets $p_T > 40$ GeV, $|\eta| < 2.4$
- Centrality $> 0.35$
- $|m_{ij} - m_W| < \sigma(m_W)$
- $\chi^2_{\text{min}} < 4$

\[
\chi^2 = \left( \frac{m_{ijk} - m_t}{\sigma(m_{t,\text{Had}})} \right)^2 + \left( \frac{m_{l\nu p} - m_t}{\sigma(m_{t,\text{Lep}})} \right)^2
\]

Centrality $= \frac{\sum E_T}{\sqrt{(\sum E)^2 - (\sum P_Z)^2}}$

- More background ($\sim 20\%$) than dilepton ($< 10\%$)
- Requires background to be subtracted via a data-driven method
Define two different $\chi^2$:

- $\chi^2_{\text{normal}}$: as defined on the previous slide
- $\chi^2_{\text{random}}$:
  - Replace highest $E_T$ jet with new jet (same $E_T$) and random $\eta$ and $\phi$
  - calculate $\chi^2$ as before
  - distribution is similar to $\chi^2_{\text{normal}}$ for background but different for signal
Background Subtraction

- Produce samples with $\chi^2 < 4$ cuts on both normal and random $\chi^2$
- Note that the shapes of the signal and background remain similar
- Subtract the “random” distribution from the “normal” distribution
- Subtract the “random” distribution from the “normal” distribution.
- Background becomes consistent with 0.
- Subtracted probability distribution is consistent with the original signal distribution.
- $R$ is extracted similarly to the dilepton measurement.
- Procedure is more complex because now there are four jets.
- Typical uncertainty size 0.12 (stat) and 0.11 (sys).
Flavour-changing neutral current (FCNC) branching ratios in different scenarios:\(^3\):

<table>
<thead>
<tr>
<th>Decay</th>
<th>SM</th>
<th>Quark Singlet(^4)</th>
<th>MSSM</th>
<th>(\mathcal{R}) SUSY</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t \rightarrow q\gamma)</td>
<td>(\sim 10^{-14})</td>
<td>(\sim 10^{-9})</td>
<td>(\sim 10^{-6})</td>
<td>(\sim 10^{-6})</td>
</tr>
<tr>
<td>(t \rightarrow qZ)</td>
<td>(\sim 10^{-14})</td>
<td>(\sim 10^{-4})</td>
<td>(\sim 10^{-6})</td>
<td>(\sim 10^{-5})</td>
</tr>
<tr>
<td>(t \rightarrow qg)</td>
<td>(\sim 10^{-12})</td>
<td>(\sim 10^{-7})</td>
<td>(\sim 10^{-5})</td>
<td>(\sim 10^{-4})</td>
</tr>
</tbody>
</table>


\(^4\) \(Q = \frac{2}{3}, M_q \geq 300\) GeV
Experimental Limits

<table>
<thead>
<tr>
<th>BR</th>
<th>LEP</th>
<th>HERA</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow q\gamma$</td>
<td>2.4%</td>
<td>0.64% $(tu\gamma)$</td>
<td>3.2%</td>
</tr>
<tr>
<td>$t \rightarrow qZ$</td>
<td>7.8%</td>
<td>49% $(tuZ)$</td>
<td>3.7%</td>
</tr>
<tr>
<td>$t \rightarrow qg$</td>
<td>17%</td>
<td>13%</td>
<td>$2.0 \times 10^{-4}(tug)$, $3.9 \times 10^{-3}(tcg)$</td>
</tr>
</tbody>
</table>

- LEP limits on $tq\gamma, tqZ$ from single top production searches\(^5\)
- All HERA limits from searches for single top production \(^6\)
- Tevatron limits on $tq\gamma, tqZ$ from FCNC decays \(^7\)
- Tevatron limits on $tgq$ from single top production \(^8\)

\(^7\)Phys. Rev. Lett. 80 (1998) 2525
\(^8\)arXiv:1006.3575
$t\bar{t} \rightarrow Wbqg$

**Signature:**

- 3 jets: $(p_T > 40, 20, 20$ GeV$)$
- 1 lepton: $(p_T > 25$ GeV$)$
- Miss. transv. momentum: $(\not p_T > 20$ GeV$)$
- No isolated photon: $(p_T > 15$ GeV$)$

No $b$-tag, get $p_T^\nu$, assign $g, q, b$ by minimising:

$$\chi^2 = \frac{(m_t - m_{qg})^2}{\sigma^2_{m_t}} + \frac{(m_t - m_{bl\nu})^2}{\sigma^2_{m_t}} + \frac{(m_W - m_{l\nu})^2}{\sigma^2_{m_W}}$$

**Extra Selection:**

- Visible energy: $E_{vis} > 300$ GeV
- $q - g$ mass: $125 < m_{qg} < 200$ GeV
- gluon-jet $p_T$: $P_T^g > 75$ GeV

**Signal Eff.:** 2.9%

**Main bkg:** $t\bar{t}$, $W$+jets
$t\bar{t} \rightarrow Wbq\gamma$

**Signature:**

- 2 jets: ($p_T > 20$ GeV)
- 1 lepton: ($p_T > 25$ GeV)
- Miss. transv. momentum: ($\not{p}_T > 20$ GeV)
- 1 isolated photon: ($p_T > 25$ GeV)

No $b$-tag, get $p_T^\gamma$, assign $q, b$ by minimising:

$$\chi^2 = \frac{(m_t - m_{q\gamma})^2}{\sigma_t^2} + \frac{(m_t - m_{bl\nu})^2}{\sigma_t^2} + \frac{(m_W - m_{l\nu})^2}{\sigma_{mW}^2}$$

**Extra Selection:**

- photon $p_T$: $P_T^\gamma > 75$ GeV

**Signal Eff.**: 7.6%

**Main bkg**: $t\bar{t}$, $W/Z+\text{jets}$
Signal Eff.: 7.6%
Main bkg: $t\bar{t}$, $Z$+jets

Signature:
- 2 jets: ($p_T > 30, 20 \text{ GeV}$)
- 3 lepton: ($p_T > 25, 15, 15 \text{ GeV}$)
- Miss. transv. momentum: ($\not p_T > 20 \text{ GeV}$)
- No isolated photon: ($p_T > 15 \text{ GeV}$)

no $b$-tag, get $P^\nu_z$; assign opposite sign, same flavour leptons to $Z, W$ by minimising:

$$
\chi^2 = \frac{(m_t - m_{l_1l_2q})^2}{\sigma_t^2} + \frac{(m_t - m_{blc\nu})^2}{\sigma_t^2} + \frac{(m_W - m_{l_c\nu})^2}{\sigma^2_W} + \frac{(m_Z - m_{l_1l_2})^2}{\sigma_Z^2}
$$
Build likelihood variables:

\[ L_S = \prod_{i}^{n} P^{\text{sig}}_i \text{ and } L_B = \prod_{i}^{n} P^{\text{bkg}}_i \]

based on probability distribution functions (\( P \)) for:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t \to qg )</td>
<td>( m_{qg}, m_{lq\nu}, m_{qb}, P_T^{b}, P_T^{q}, \alpha_{lq}, )</td>
</tr>
<tr>
<td>( t \to q\gamma )</td>
<td>( m_{q\gamma}, m_{b\gamma}, p_T^{\gamma} )</td>
</tr>
<tr>
<td>( t \to qZ )</td>
<td>( m_{qZ}, m_{ll}^{\text{min}}, p_T^{\gamma}, m_{bZ}, m_{bq}, P_T^{q}, P_T^{l3} )</td>
</tr>
</tbody>
</table>

Use the likelihood ratio:

\[ L_R = \log_{10} \left( \frac{L_S}{L_B} \right) \]

as a discriminant.
Discriminant distributions

Introduction

$t \rightarrow Wq$

FCNC

Conclusion

$t \rightarrow qg$

$t \rightarrow q\gamma$

$t \rightarrow qZ$

Results

Discriminant distributions

- Signal ATLFAST
- Signal FullSim
- Background ATLFAST
- Background FullSim

![Graphs showing discriminant distributions](image)
### Limits

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$-\sigma$</th>
<th>Expected</th>
<th>$+\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}t \to bWq\gamma$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>$4.3 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$1.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$4.5 \times 10^{-4}$</td>
<td>$8.3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\ell$</td>
<td>$3.8 \times 10^{-4}$</td>
<td>$6.8 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{t}t \to bWqZ$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3e</td>
<td>$5.5 \times 10^{-3}$</td>
<td>$9.4 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>3$\mu$</td>
<td>$2.4 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-3}$</td>
<td>$6.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>$1.9 \times 10^{-3}$</td>
<td>$2.8 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\bar{t}t \to bWqg$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$2.1 \times 10^{-2}$</td>
<td>$3.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$2.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\ell$</td>
<td>$7.2 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$1.8 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Limits obtained using the modified-frequentist likelihood method (95% C.L, in absence of any signal)

**Systematic uncertainties:**

- $t \to qg \sim 27\%$
- $t \to q\gamma \sim 32\%$
- $t \to qZ \sim 27\%$

mainly ($m_t$, ISR/FSR, pile-up, $\sigma_{bkg}$, generator effects)
Sensitivity Comparison

**ATLAS 1 fb⁻¹**

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR (1 fb⁻¹)</th>
<th>Expected (1 fb⁻¹)</th>
<th>+1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}t \rightarrow bWqγ$</td>
<td>4.3 × 10⁻⁴</td>
<td>1.1 × 10⁻³</td>
<td>1.9 × 10⁻³</td>
</tr>
<tr>
<td>$\bar{t}t \rightarrow bWqZ$</td>
<td>5.5 × 10⁻³</td>
<td>9.4 × 10⁻³</td>
<td>1.4 × 10⁻²</td>
</tr>
<tr>
<td>$\bar{t}t \rightarrow bWqg$</td>
<td>1.3 × 10⁻²</td>
<td>2.1 × 10⁻²</td>
<td>3.0 × 10⁻²</td>
</tr>
<tr>
<td>$\bar{t}t \rightarrow bWqZ$</td>
<td>1.9 × 10⁻³</td>
<td>2.8 × 10⁻³</td>
<td>4.2 × 10⁻³</td>
</tr>
</tbody>
</table>

**Results**

**Sensitivity Comparison**

**CMS 5σ discovery reach Vs L**

N.B. A 95% C.L. limit in absence of signal unlike CMS (5σ discovery).

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR 5σ (10 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow qγ$</td>
<td>8.4 × 10⁻⁴</td>
</tr>
<tr>
<td>$t \rightarrow qZ$</td>
<td>1.5 × 10⁻³</td>
</tr>
</tbody>
</table>

CERN-LHCC-2006-021
With 1 fb$^{-1}@\sqrt{s} = 14$ fb$^{-1}$, expected limits from ATLAS on $t \rightarrow q\gamma$ and $t \rightarrow qZ$ comfortably outstrip:

- Exisiting and prospective limits from the Tevatron
- Existing limits from single top production at LEP
- Existing and prospective limits from HERA

More details: arXiv:0901.0512
Feasibility studies show good potential at the LHC for rare top decay studies

For $R = \frac{t \to Wb}{t \to Wq}$:
- With $\mathcal{O}(250 \text{ pb}^{-1})$ (@10 TeV) competitive measurements to those at Tevatron
- From top cross section would expect something similar for $\mathcal{O}(500 \text{ pb}^{-1})$ @7 TeV

For FCNC:
- Excellent prospects for sensitivity beyond current limits
  - Far better sensitivity for $1 \text{ fb}^{-1}$ @14 TeV
  - Would expect that sensitivity is still better for $1 \text{ fb}^{-1}$ @7 TeV from the top cross section.
### FCNC Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$t \rightarrow q\gamma$</th>
<th>$t \rightarrow q\ell$</th>
<th>$t \rightarrow q\ell$</th>
<th>$t \rightarrow q\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e</td>
<td>$\mu$</td>
<td>$\ell$</td>
<td>e</td>
</tr>
<tr>
<td>Jet energy calibration</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>9%</td>
<td>8%</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>7%</td>
<td>7%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Backgrounds $\sigma$</td>
<td>6%</td>
<td>10%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>21%</td>
<td>18%</td>
<td>17%</td>
<td>6%</td>
</tr>
<tr>
<td>Pile-up</td>
<td>37%</td>
<td>21%</td>
<td>22%</td>
<td>30%</td>
</tr>
<tr>
<td>Generator</td>
<td>34%</td>
<td>18%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>5%</td>
<td>0%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>Total</td>
<td>56%</td>
<td>36%</td>
<td>32%</td>
<td>32%</td>
</tr>
</tbody>
</table>