Review on FCNC experimental searches

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on behalf of the ATLAS and the CMS collaborations

Top LHC France
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• Introduction to FCNC interaction processes

• Experimental searches for FCNC

• Latest experimental results from ATLAS and CMS

• Conclusion
Flavour-changing neutral current (FCNC) transition is an interaction process where a fermion undergoes the change of flavour without alternation of its charge.

FCNC amplitudes at tree level are forbidden by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the Standard Model (SM).

However, highly GIM-suppressed FCNC transitions are possible in the SM in the higher orders via loop induced processes.

Some extensions of the SM could introduce FCNC decays at tree level including new particles:

- Fourth-generation models
- Extended technicolor models
- Leptoquark models
- Extra dimensions
- Extra quark models
- Supersymmetry
- Two-Higgs-Doublet models

Observation of FCNC process = new physics

Examples of FCNC non-top-quark related searches

FCNC can be studied in the decays of D, B, K-mesons - FCNC decays are highly suppressed

**K_L → µ^+µ^-**

\[ K^0 \rightarrow \mu^+\mu^- \]

Forbidden at tree level

**BR_{exp} ≈ 6 \cdot 10^{-9}**

*Phys. Rev. Lett.* 63 (1989) 2185 (AGS, BNL)

**Search for D^0 → π^+π^-µ^+µ^- at LHCb**

\[ BR_{exp} < 5.5 \cdot 10^{-7} \text{ (90\% C.L.)} \]


\[ D^0 \rightarrow \mu^+\mu^- \]

\[ \gamma/Z^0 \]

\[ u \]

\[ d \]

\[ \bar{d} \]

\[ u \]

\[ \bar{d} \]

\[ \mu^- \]

\[ \mu^+ \]

\[ \pi^- \]

\[ \pi^+ \]

\[ c \]

\[ W^+ \]

\[ W^- \]

\[ s \]

\[ d \]

\[ \bar{d} \]

\[ \nu_\mu \]

\[ u \]

\[ c \]

\[ W \]

\[ d, s, b \]

\[ \nu_\mu \]

**Search for D^0 → μ^+μ^- at LHCb**

\[ BR_{exp} < 6 \cdot 10^{-9} \text{ (90\% C.L.)} \]


**BR_{exp} ≈ 3 \cdot 10^{-9}**

LHCb-CONF-2013-12

**Observation of B_s → μ^+μ^- at LHCb and CMS**

**BR_{exp} ≈ 3 \cdot 10^{-9}**

LHCb-CONF-2013-12

**BR_{exp} ≈ 6 \cdot 10^{-9}**

**forbidden at tree level**

\[ u, c, t \]
Search for FCN(C/H) in events with top-quark is promising because of the several important properties of a top-quark:

- The formation of strong bound states occurs much slower than the decay of top-quark which results in a clean event signature.
- Yukawa coupling for top-quark is close to unity which makes it an interesting candidate to study EW symmetry breaking mechanism.
- Top-quark is the heaviest elementary particle ever discovered - sensitivity to new physics searches.
- Almost exclusively decays to b-quark and W-boson - distinctive event signature.
FCNC searches with a top-quark

\[
\mathcal{L} = \sum_{q=u,c} \left[ \sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} t^\sigma_{\mu\nu} T_a (f_{Gq}^{L} P_L + f_{Gq}^{R} P_R) q G^a_{\mu\nu} \\
+ \frac{g}{\sqrt{2}c_W} \frac{\kappa_{zqt}}{\Lambda} t^\sigma_{\mu\nu} (f_{Zq}^{L} P_L + f_{Zq}^{R} P_R) q Z_{\mu\nu} \\
- e \frac{\kappa_{\gamma q t}}{\Lambda} t^\sigma_{\mu\nu} (f_{\gamma q}^{L} P_L + f_{\gamma q}^{R} P_R) q A_{\mu\nu} \\
+ \frac{g}{\sqrt{2}} t^\sigma_{\mu\nu} (f_{Hq}^{L} P_L + f_{Hq}^{R} P_R) q H \right] + h.c.
\]
FCNC searches at Tevatron

Search for $t \rightarrow gq$ FCNC events at DØ

Search for $t \rightarrow Zq$ FCNC events at CDF


- DØ 2.3 fb$^{-1}$
- Cross section $t_{gu}$: 0.20 pb
- Cross section $t_{gc}$: 0.27 pb
- $\kappa_{tg}\Lambda$: 0.013 TeV$^{-1}$
- $B(t \rightarrow fg)$: $2.0 \times 10^{-4}$


- BR($t \rightarrow qZ$) $< 3.7 \times 10^{-2}$
FCNC searches at LEP2 and HERA

FCNC searches in $e^+e^-\rightarrow t\bar{q}$ at LEP2


FCNC searches at HERA in $e^+p \rightarrow e t X$

FCNC searches at the LHC

**gqt**

- ATLAS-CONF-2013-063
  - CMS-PAS-TOP-14-007

**Zqt**

- JHEP 1209 (2012) 139
  - CMS-PAS-TOP-12-021

**γqt**

- CMS-PAS-TOP-14-003

**Hqt**

- JHEP 06 (2014) 008
  - CMS-PAS-HIG-13-034
  - CMS-PAS-TOP-13-017
Search for single top production at ATLAS

\[ \kappa_{ugt}/\Lambda < 5.1 \times 10^{-3} \text{ TeV}^{-1} \]
\[ \kappa_{cgt}/\Lambda < 1.1 \times 10^{-2} \text{ TeV}^{-1} \]
\[ \text{BR}(t \rightarrow ug) < 3.1 \times 10^{-6} \]
\[ \text{BR}(t \rightarrow cg) < 1.6 \times 10^{-4} \]

Event signature is the top-quark decay: exactly one isolated lepton, missing \( E_T \) and one b-tagged jet

Main background: \( W+\)jets, QCD multijet, single top, t\( t \bar{t} \), \( Z+jets \)

MVA approach is used to discriminate signal and background events based on: \( p_T(b) \), \( p_T(W) \), \( \Delta \phi(W,\nu) \) in the top-quark rest frame, charge of the lepton, \( \eta(\ell) \), \( \Delta \phi(\ell,b) \), \( \eta(\ell\nu b) \), …

\( W+\)jets is validated with looser b-jet selection (but veto events with tight b-tagged jets)

QCD multijet events are estimated with electron-jet approach with template fit in missing \( E_T \) (electrons), and fake matrix method (muons)

Limits extracted from MVA discriminator binned likelihood fit with Bayesian approach
Search in t-channel single top at CMS

Event signature: exactly one isolated muon, missing $E_T$, at least one b-tagged jet and one non-b-tagged jet (same as for SM t-channel single top)

Bayesian Neural Network (BNN) is used to discriminate signal and background using: $p_T(b)$, $p_T(j_1j_2)$, $p_T(\mu)$, $p_T(W)$, $\Delta\phi(\mu,\nu)$, $\cos(\theta(\mu,W))$ in the W-boson rest frame, ...

QCD multijet background is estimated from a template fit using a dedicated BNN (QCD template is taken from control region with reversed lepton isolation)

Control regions of 4-jet 1-tag (ttbar) and 0-tag (W+jets) are used to validate background MC predictions

$$\kappa_{ugt}/\Lambda < 1.8 \cdot 10^{-2} \text{ TeV}^{-1}$$
$$\kappa_{cgt}/\Lambda < 5.6 \cdot 10^{-2} \text{ TeV}^{-1}$$
$$BR(t\to ug) < 3.6 \cdot 10^{-4}$$
$$BR(t\to cg) < 3.4 \cdot 10^{-3}$$
**Event signature:** exactly three isolated leptons, missing $E_T$, at least two jets

**Analysis** is performed in the channels with 3 tight lepton (3ID) and 2 tight leptons+ 1 track-lepton (2ID+TL)

**Fake lepton** background is evaluated with a data-driven method: scale factor in 3ID and fake matrix method in 2ID+TL

**Main background:** $WZ/ZZ$+jets, fakes, $Z$+jets

**Additional requirement** of a presence of $b$-jet for 2ID+TL channel

Events are tested for consistency with $t\bar{t}\rightarrow WbZq$ process by $\chi^2$ minimisation

**Reconstructed top candidate mass**

**Limits extracted using binned likelihood fit with modified Frequentist (CLs) likelihood method**

<table>
<thead>
<tr>
<th>channel</th>
<th>observed</th>
<th>$(-1\sigma)$</th>
<th>expected</th>
<th>$(+1\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ID</td>
<td>0.81%</td>
<td>0.63%</td>
<td>0.95%</td>
<td>1.4%</td>
</tr>
<tr>
<td>2ID+TL</td>
<td>3.2%</td>
<td>2.15%</td>
<td>3.31%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Combination</td>
<td>0.73%</td>
<td>0.61%</td>
<td>0.93%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

$BR(t\rightarrow Zq) < 0.73 \cdot 10^{-2}$
Search for $t \rightarrow Zq$ in ttbar events at CMS

Event signature: exactly three isolated leptons, missing $E_T$, at least two jets of which exactly one jet is b-tagged

Combinatorics is resolved by the best top quark mass reconstruction

WZ/ZZ predictions are validated in control regions in data

Drell-Yan and ttbar backgrounds are estimated from data

Limits extracted using binned likelihood fit with modified Frequentist (CLs) likelihood method

<table>
<thead>
<tr>
<th>$B(t \rightarrow Zq)$</th>
<th>8 TeV</th>
<th>7 TeV + 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected upper limit</td>
<td>&lt;0.10%</td>
<td>&lt;0.09%</td>
</tr>
<tr>
<td>Observed upper limit</td>
<td>&lt;0.06%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>1σ boundary</td>
<td>0.06–0.13%</td>
<td>0.06–0.13%</td>
</tr>
<tr>
<td>2σ boundary</td>
<td>0.05–0.20%</td>
<td>0.05–0.18%</td>
</tr>
</tbody>
</table>

$BR(t \rightarrow Zq) < 0.05 \cdot 10^{-2}$
Search for $tZ$ events in single top at CMS

**Event signature**: exactly three isolated leptons, missing $E_T$, one b-tagged jet

**WZ+jets and Z+jets (fake)** backgrounds are estimated from template fit in data using $m_T(W)$:
WZ+jets template from MC, Z+jets template from data with reversed lepton isolation

**MadGraph @LO**

**BDT** is used to discriminate signal and background using: $p_T(Z)$, $\eta(Z)$, number of jets, number of b-jets, $\Delta\phi(l_W,b)$, reconstructed top quark mass, b-tag discriminator, …

Limits extracted using profile likelihood ratio (PLR) method in modified Frequentist approach (CLs)

$\kappa_{Zut}/\Lambda < 0.45 \text{ TeV}^{-1}$
$\kappa_{Zct}/\Lambda < 2.27 \text{ TeV}^{-1}$
$\kappa_{ugt}/\Lambda < 0.10 \text{ TeV}^{-1}$
$\kappa_{cgt}/\Lambda < 0.35 \text{ TeV}^{-1}$
BR($t\rightarrow Zu$) < 0.51 $\cdot 10^{-2}$
BR($t\rightarrow Zc$) < 11.4 $\cdot 10^{-2}$
BR($t\rightarrow ug$) < 0.56 $\cdot 10^{-2}$
BR($t\rightarrow cg$) < 7.12 $\cdot 10^{-2}$
Search for $t\gamma$ events in single top at CMS

**Event signature:** exactly one isolated muon, one photon, missing $E_T$, one b-tagged jet

**Main background:** $W\gamma$+jets, $W$+jets, ttbar, $Z\gamma$+jets

$W\gamma$+jets and $W$+jets backgrounds are estimated from data with a template fit method using $\cos(\theta(W,\gamma))$: $W$+jets template taken from data with no b-jet requirement

$$\kappa_{u\gamma}/\Lambda < 0.028 \, \text{TeV}^{-1}$$

$$\kappa_{c\gamma}/\Lambda < 0.094 \, \text{TeV}^{-1}$$

$$\text{BR}(t\to u\gamma) < 0.016 \cdot 10^{-2}$$

$$\text{BR}(t\to c\gamma) < 0.182 \cdot 10^{-2}$$

Limits extracted using profile likelihood ratio (PLR) method in modified Frequentist approach (CLs)
Higgs + FCNC = ❤️?

A new particle is born

but we don’t know it very well yet …
Tight constraints on FCNH couplings to light quarks from neutral meson oscillations

Stringent limits on FCNH couplings to leptons from LFV searches

http://arxiv.org/abs/1202.5704

Is there a place for FCNH with a top quark?

FCNH in single top

FCNH in ttbar

Should we expect a large FCNH coupling strength with a top quark as in case of Yukawa interactions?
Search for $t \rightarrow Hq$ in $t\bar{t}b\bar{t}$ events at ATLAS

**Event signature:** two photons, one b-tagged jet, 3 jets (W-boson **hadronic** decays) or one isolated lepton, missing $E_T$ and one jet (W-boson **leptonic** decays)

**Main background:** $\gamma\gamma$+jets, W+jets, $t\bar{t}b\bar{t}$

**In hadronic channel** background is estimated from the data fit using non-resonant $\gamma\gamma$+jets shape. **Leptonic channel** uses transfer factor (SR/CR) with the central value measured in hadronic channel.

**Analysis** is done in $H \rightarrow \gamma\gamma$ channel

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Search for $t \rightarrow Hq$ in ttbar events at CMS

**Analysis** is done in multilepton (H→WW/ZZ/ττ) channel

**Event signature:** three or two same-sign leptons, one b-tagged jet (used for background validation in CRs), missing $E_T$, at least two jets

**Main background:** WZ+jets, ttbar+V (tri-lepton), fake leptons, charge mis-ID (same-sign dilepton)

Additional selection in **tri-lepton** channel:

Additional selection in **di-lepton** channel includes cuts on missing $E_T$ and $H_T$

Fake lepton and charge mis-ID background are estimated from data

\[ \kappa_{qHt} < 0.18 \]
\[ BR(t \rightarrow qH) < 0.93 \cdot 10^{-2} \]

Limits extracted using CLs method

PYTHIA6 @LO
Search for \( t \rightarrow Hq \) in ttbar events at CMS

Based on a combination of two analyses performed in multilepton \((H \rightarrow WW/ZZ/\tau\tau)\) and \( H \rightarrow \gamma\gamma \) channels

Multi-lepton analysis is done in the framework of the SUSY search for natural Higgsino, slepton, etc.

Several SUSY scenarios are probed, also possible to set limits on FCNH in this inclusive search:

<table>
<thead>
<tr>
<th>Higgs boson decay mode</th>
<th>Upper limits on ( B(t \rightarrow cH) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B(H \rightarrow WW^*) ) = 23.1%</td>
<td>Obs. 1.6%</td>
</tr>
<tr>
<td>( B(H \rightarrow \tau\tau) ) = 6.2%</td>
<td>7.01%</td>
</tr>
<tr>
<td>( B(H \rightarrow ZZ^*) ) = 2.9%</td>
<td>5.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

\( \kappa_{qHt} < 0.21 \)

\( BR(t \rightarrow qH) < 1.28 \cdot 10^{-2} \)

MadGraph @LO is used for FCNH generation

Di-photon analysis developed for the search for 2HDM \( H \rightarrow H_{SM} H_{SM} \) and \( A \rightarrow ZH_{SM} \)

\( H_{qt} \) combinations of results

<table>
<thead>
<tr>
<th>Higgs Decay Mode</th>
<th>observed</th>
<th>expected</th>
<th>1( \sigma ) range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow WW^* ) ( (B = 23.1%) )</td>
<td>1.58%</td>
<td>1.57%</td>
<td>(1.02-2.22)%</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau ) ( (B = 6.15%) )</td>
<td>7.01%</td>
<td>4.99%</td>
<td>(3.53-7.74)%</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* ) ( (B = 2.89%) )</td>
<td>5.31%</td>
<td>4.11%</td>
<td>(2.85-6.45)%</td>
</tr>
<tr>
<td>Combined multileptons ((WW^<em>, \tau\tau, ZZ^</em>))</td>
<td>1.28%</td>
<td>1.17%</td>
<td>(0.85-1.73)%</td>
</tr>
<tr>
<td>( H \rightarrow \gamma\gamma ) ( (B = 0.23%) )</td>
<td>0.69%</td>
<td>0.81%</td>
<td>(0.60-1.17)%</td>
</tr>
<tr>
<td>Combined multileptons + diphotons</td>
<td>0.56%</td>
<td>0.65%</td>
<td>(0.46-0.94)%</td>
</tr>
</tbody>
</table>

\( \kappa_{qHt} < 0.14 \)

\( BR(t \rightarrow qH) < 0.56 \cdot 10^{-2} \)

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### Summary on FCNC searches at the LHC

#### gqt

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BR(t→ug)</th>
<th>BR(t→cg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>3.1 $\times$ 10^{-6}</td>
<td>1.6 $\times$ 10^{-4}</td>
<td>ATLAS-CONF-2013-063</td>
</tr>
<tr>
<td>CMS</td>
<td>3.6 $\times$ 10^{-4}</td>
<td>3.4 $\times$ 10^{-3}</td>
<td>CMS-PAS-TOP-14-007</td>
</tr>
</tbody>
</table>

#### Zqt

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BR(t→uZ)</th>
<th>BR(t→cZ)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.73 $\times$ 10^{-2}</td>
<td></td>
<td>JHEP 1209 (2012) 139</td>
</tr>
<tr>
<td>CMS</td>
<td>0.05 $\times$ 10^{-2}</td>
<td></td>
<td>Phys. Rev. Lett. 112 (2014) 171802</td>
</tr>
<tr>
<td>CMS</td>
<td>0.51 $\times$ 10^{-2}</td>
<td>11.4 $\times$ 10^{-2}</td>
<td>CMS-PAS-TOP-12-021</td>
</tr>
</tbody>
</table>

#### γqt

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BR(t→uγ)</th>
<th>BR(t→cγ)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>0.02 $\times$ 10^{-2}</td>
<td>0.18 $\times$ 10^{-2}</td>
<td>CMS-PAS-TOP-14-003</td>
</tr>
</tbody>
</table>

#### Hqt

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BR(t→uH)</th>
<th>BR(t→cH)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.79 $\times$ 10^{-2}</td>
<td></td>
<td>JHEP 06 (2014) 008</td>
</tr>
<tr>
<td>CMS</td>
<td>0.56 $\times$ 10^{-2}</td>
<td></td>
<td>CMS-PAS-HIG-13-034</td>
</tr>
</tbody>
</table>
Conclusion

- An experimental review on FCNC searches was presented
- All known types of FCNC couplings are considered in the searches including various final states
- No evidence of new physics yet
- The ATLAS and the CMS experiments have significantly improved the exclusion limits for FCNC couplings with Run I data
- Looking forward to Run II analyses results from the LHC

Best limits on FCNC top quark decays from the LHC:

| BR(t→qg)  | 3.1 · 10^{-5} | ATLAS-CONF-2013-063 |
| BR(t→cg)  | 1.6 · 10^{-4} | ATLAS-CONF-2013-063 |
| BR(t→qZ)  | 0.05 · 10^{-2} | Phys. Rev. Lett. 112 (2014) 171802 |
| BR(t→uy)  | 0.02 · 10^{-2} | CMS-PAS-TOP-14-003 |
| BR(t→cy)  | 0.18 · 10^{-2} | CMS-PAS-TOP-14-003 |
| BR(t→qH)  | 0.56 · 10^{-2} | CMS-PAS-HIG-13-034 |