Searches for FCNC with top quarks

Kirill Skovpen

IPHC CNRS, Strasbourg

on behalf of the ATLAS and the CMS collaborations

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**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

<table>
<thead>
<tr>
<th>Model</th>
<th>$\text{Br} (t \to Z/\gamma q)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>$\sim 10^{-12}$</td>
</tr>
<tr>
<td>SUSY</td>
<td>$\sim 10^{-6}$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 10^{-7}$</td>
</tr>
</tbody>
</table>

Observation of FCNC process = **new physics**

Why to look for FCNC with a top quark?

- Distinctive event signature of top quark decay
- Several models predict a large coupling of the new particles to the top quark = enhanced sensitivity to FCNC in the top quark sector
- FCNC in single top production is particularly interesting due to enhanced production associated with an up quark
FCNC searches with top quark

\[
\mathcal{L} = \sum_{q=u,c} \left[ \sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} t \sigma^{\mu\nu} T_{a} (f_{Gq}^L P_L + f_{Gq}^R P_R) q G_{\mu\nu}^a + \frac{g}{\sqrt{2}c_W} \frac{\kappa_{zqt}}{\Lambda} t \sigma^{\mu\nu} (f_{Zq}^L P_L + f_{Zq}^R P_R) q Z_{\mu\nu} - e \frac{\kappa_{\gamma qt}}{\Lambda} t \sigma^{\mu\nu} (f_{\gamma q}^L P_L + f_{\gamma q}^R P_R) q A_{\mu\nu} + \frac{g}{\sqrt{2}} t \frac{\kappa_{H qt}}{\Lambda} (f_{H q}^L P_L + f_{H q}^R P_R) q H \right] + \text{h.c.}
\]
FCNC searches at LEP2 and HERA

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

\[
\Delta L_{\text{eff}} = e e_t \frac{\bar{t} i \sigma_{\mu\nu} p^\nu}{\Lambda} \kappa_{\gamma} \ u \ A^\mu + \frac{g}{2 \cos \theta_W} \bar{t} \gamma_\mu \ v_Z \ u Z^\mu + \text{h.c.} \quad \Lambda = 175 \text{ GeV}
\]

\[
\kappa_{q\gamma t} \lesssim 0.4
\]
\[
\kappa_{qZt} \lesssim 0.4
\]
\[
\text{BR}(t\rightarrow q\gamma) \lesssim 4\%
\]
\[
\text{BR}(t\rightarrow qZ) \lesssim 10\%
\]


**FCNC searches at HERA in $ep\rightarrow etX$**

\[
\text{BR}(t\rightarrow q\gamma) \lesssim 0.5\%
\]
\[
\text{BR}(t\rightarrow qZ) \lesssim 4\%
\]


**H1:** Phys. Lett. B678 (2009) 450

\[\Lambda = 175 \text{ GeV}\]
**FCNC searches at TEVATRON**

**gqt**  
Search for $t \rightarrow gq$ at DØ

**Zqt**  
Search for $t \rightarrow Zq$ at CDF

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FCNC searches at the LHC

**gqt**

**ATLAS:** arXiv:1509.00294v1
**CMS:** CMS-PAS-TOP-14-007

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**Zqt**

**ATLAS:** arXiv:1508.05796v1
**CMS:** Phys. Rev. Lett. 112 (2014) 171802
**CMS:** CMS-PAS-TOP-12-021

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**γqt**

**CMS:** CMS-PAS-TOP-14-003

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**Hqt**

**ATLAS:** JHEP 06 (2014) 008
**ATLAS:** PAPER SOON!
**CMS:** CMS-PAS-TOP-14-019
**CMS:** CMS-PAS-TOP-13-017

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2015/09/17
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Event signature is the top quark decay: exactly one isolated lepton, missing $E_T$ and one b-tagged jet

**MVA approach** to discriminate signal and background events

**QCD Multi-jet** is measured in data from the missing $E_T$ template fit

$\kappa_{ug}/\Lambda < 0.58 \cdot 10^{-2}$ TeV$^{-1}$

$\kappa_{cg}/\Lambda < 1.3 \cdot 10^{-2}$ TeV$^{-1}$

$BR(t\rightarrow ug) < 0.0040$ % (obs)

0.0035 % (exp)

$BR(t\rightarrow cg) < 0.017$ % (obs)

0.015 % (exp)

---

**Main background:** $W+$jets, QCD multijet, single top, ttbar, Z+jets
Event signature: one isolated muon, missing $E_T$, $\geq 1$ b-jet, $\geq 1$ non-b-jet

Bayesian Neural Network (BNN) is used to discriminate signal and background

QCD Multi-jet is measured in data from the QCD BNN template fit

$\kappa_{ug}/\Lambda < 1.8 \cdot 10^{-2}$ TeV$^{-1}$
$\kappa_{cg}/\Lambda < 5.6 \cdot 10^{-2}$ TeV$^{-1}$
$BR(t \rightarrow u g) < 0.036$ % (obs) 0.016 % (exp)
$BR(t \rightarrow c g) < 0.34$ % (obs) 0.11 % (exp)
Search for $t \rightarrow Zq$ in $tt\bar{t}$bar events at ATLAS

Event signature: three isolated leptons, missing $E_T$, $\geq 2$ jets, of them one or two b-jets

Main background: $WZ/ZZ+$jets, fake leptons, $Z+$jets

Fake lepton background is measured in data with fake matrix method

$\text{BR}(t \rightarrow Zq) < 0.07 \%$ (obs)
$0.08 \%$ (exp)
Event signature: three isolated leptons, 
missing $E_T$, $\geq$ 2 jets of which one is $b$-jet

Main background: WW/WZ/ZZ+jets, ttbar+X

Background estimated from data

MadGraph @LO

$\mathcal{B}(t \rightarrow Zq) < 0.05 \% \text{ (obs)}$

0.09 \% \text{ (exp)}
Search for tZ events in single top at CMS

Event signature: three isolated leptons, missing \( E_T \), one b-jet

Main background: WZ/ZZ+jets, fake leptons

VV and fake lepton background measured from \( m_T(W) \) template fit in data

BDT is used to discriminate signal and background

- \( \kappa_{Zut}/\Lambda < 0.45 \text{ TeV}^{-1} \)
- \( \kappa_{Zct}/\Lambda < 2.27 \text{ TeV}^{-1} \)
- \( \kappa_{ugt}/\Lambda < 0.10 \text{ TeV}^{-1} \)
- \( \kappa_{cg}/\Lambda < 0.35 \text{ TeV}^{-1} \)
Search for $t\gamma$ events in single top at CMS

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

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

$W\gamma$+jets and $W$+jets measured from $\cos(W,\gamma)$ template fit in data

$\kappa_{u\gamma}/\Lambda < 0.028$ TeV$^{-1}$
$\kappa_{c\gamma}/\Lambda < 0.094$ TeV$^{-1}$

$\text{BR}(t\rightarrow u\gamma) < 0.02 \%$ (obs)
$0.03 \%$ (exp)
$\text{BR}(t\rightarrow c\gamma) < 0.18 \%$ (obs)
$0.26 \%$ (exp)
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

FCNH in single top

Expect a large coupling strength with a top quark?
**Search for $t \rightarrow Hq$ in $tt\bar{t}$bar events at ATLAS**

**H→γγ channel**

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

**Main background:** $γγ$+jets, $W$+jets, $tt\bar{t}$

**Background for hadronic channel estimated from $γγ$ data sample, and from $γγ(j→l)$ sample for leptonic channel**

**ProTOS @LO**

**BR($t \rightarrow qH$) < 0.79 % (obs) 0.51 % (exp)**

**$m(\text{top})$ in hadronic channel**

**$m(\text{top})$ in leptonic channel**

**$κ_{qHt} < 0.17$**
Search for $t \rightarrow Hq$ in ttbar events at CMS

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

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

**Non-resonant $\gamma\gamma$+jets background estimated from the fit to data**

$BR(t \rightarrow uH) < 0.42 \%$ (obs)
$0.65 \%$ (exp)

$BR(t \rightarrow cH) < 0.47 \%$ (obs)
$0.71 \%$ (exp)

CMS-PAS-TOP-14-019
CMS, 20 fb$^{-1}$, 8 TeV
Search for $t \rightarrow Hq$ in $tt\bar{t}$ events at ATLAS

**Event signature:** $\geq 4$ jets of which $\geq 3$ jets are b-jets, one lepton and missing $E_T$

**Main background:** $tt\bar{t}$+jets

**Background** and signal estimated from the likelihood fit to data

**Combination** with JHEP 06 (2014) 008 ($H \rightarrow \gamma\gamma$) and Phys. Lett. B 749 (2015) 519 ($ttH, H \rightarrow WW/\tau\tau$)

$\kappa_{uHt} < 0.13$, $\kappa_{cHt} < 0.13$

$BR(t \rightarrow uH) < 0.61\%$ (obs)

$0.64\%$ (exp)

$BR(t \rightarrow cH) < 0.56\%$ (obs)

$0.42\%$ (exp)
Search for $t \rightarrow Hq$ in ttbar events at CMS

**Event signature:** three or two same-sign leptons, one b-jet, missing $E_T$, $\geq 2$ jets

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

**Fake and charge misID lepton backgrounds estimated from data**

**AIC=$WW/ZZ/\tau\tau$ channel**

**CMS-PAS-TOP-13-017**

CMS, 20 fb$^{-1}$, 8 TeV

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$$\kappa_{qH_t} < 0.18$$

$$BR(t \rightarrow qH) < 0.93 \% \text{ (obs)}$$

$$0.89 \% \text{ (exp)}$$
## Summary on the best FCNC limits from the LHC

### $gqt$ and $Zqt$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\text{BR}(t\rightarrow u_g)$</th>
<th>$\text{BR}(t\rightarrow c_g)$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.004 %</td>
<td>0.017 %</td>
<td>arXiv:1509.00294v1</td>
</tr>
<tr>
<td>CMS</td>
<td>0.036 %</td>
<td>0.34 %</td>
<td>CMS-PAS-TOP-14-007</td>
</tr>
</tbody>
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### $\gamma qt$ and $Hqt$

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<tr>
<td>CMS</td>
<td>0.02 %</td>
<td>0.18 %</td>
<td>CMS-PAS-TOP-14-003</td>
</tr>
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<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\text{BR}(t\rightarrow u_Z)$</th>
<th>$\text{BR}(t\rightarrow c_Z)$</th>
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<th>$\text{BR}(t\rightarrow c_H)$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.45 %</td>
<td>0.46 %</td>
<td>PAPER SOON !</td>
</tr>
<tr>
<td>CMS</td>
<td>0.42 %</td>
<td>0.47 %</td>
<td>CMS-PAS-TOP-14-019</td>
</tr>
</tbody>
</table>
Summary on the best FCNC limits

**HERA:**

**LEP:**

**TEVATRON:**

**CMS:**

**ATLAS:**
An experimental review on FCNC searches with top quark was presented

All possible 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

Run II analyses are on their way

The best limits on FCNC top quark decays from the LHC:

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR(t \rightarrow u \gamma)$</td>
<td>0.02 %</td>
<td>CMS-PAS-TOP-14-003</td>
</tr>
<tr>
<td>$BR(t \rightarrow c \gamma)$</td>
<td>0.18 %</td>
<td>CMS-PAS-TOP-14-003</td>
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<tr>
<td>$BR(t \rightarrow uH)$</td>
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<td>$BR(t \rightarrow cH)$</td>
<td>0.46 %</td>
<td>ATLAS PAPER SOON!</td>
</tr>
</tbody>
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A dedicated combination effort would improve the existing limits further
Backup slides
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.

\[ K_L \rightarrow \mu^+ \mu^- \]

Forbidden at tree level.

\[ Br_{exp} \approx 6 \cdot 10^{-9} \]


Search for \( D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^- \) at LHCb

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


Observation of \( B_s \rightarrow \mu^+ \mu^- \) at LHCb and CMS

\[ Br_{exp} \approx 3 \cdot 10^{-9} \]

LHCb-CONF-2013-12

Search for \( D^0 \rightarrow \mu^+ \mu^- \) at LHCb

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

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>$B(H \rightarrow WW^*)$</td>
<td>$23.1%$ Obs. $1.6%$ Exp. $1.6%$ $1\sigma$ range $(1.0-2.2)%$</td>
</tr>
<tr>
<td>$B(H \rightarrow \tau\tau)$</td>
<td>$6.2%$ Obs. $7.01%$ Exp. $5.0%$ $1\sigma$ range $(3.5-7.7)%$</td>
</tr>
<tr>
<td>$B(H \rightarrow ZZ^*)$</td>
<td>$2.9%$ Obs. $5.3%$ Exp. $4.11%$ $1\sigma$ range $(2.9-6.5)%$</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.3%$ Obs. $1.2%$ $1\sigma$ range $(0.9-1.7)%$</td>
</tr>
</tbody>
</table>

$\kappa_{qHt} < 0.21$
$BR(t \rightarrow qH) < 1.28\%$

MadGraph @LO is used for FCNH generation

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

**Combination of results**

$\kappa_{qHt} < 0.14$
$BR(t \rightarrow qH) < 0.56\%$

CMS-PAS-HIG-13-025
CMS, 20 fb$^{-1}$, 8 TeV

CMS-PAS-HIG-13-025
CMS, 20 fb$^{-1}$, 8 TeV
Search for $t\to Zq$ in $t\bar{t}$ events at ATLAS

**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 $t\bar{t}\to WbZq$ process by $\chi^2$ minimisation

Reconstructed top candidate mass

Limits extracted using binned likelihood fit

<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>

$BR(t\to Zq) < 0.73\%$ (obs)
$0.93\%$ (exp)
MVA discriminating variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T$(top)</td>
<td>Transverse mass of the reconstructed top quark</td>
</tr>
<tr>
<td>$p_T^e$</td>
<td>Transverse momentum of the charged lepton</td>
</tr>
<tr>
<td>$\Delta R$(top, $\ell$)</td>
<td>Distance in the $\eta$-$\phi$ plane between the reconstructed top quark and the charged lepton</td>
</tr>
<tr>
<td>$p_T^{b}$-jet</td>
<td>Transverse momentum of the $b$-tagged jet</td>
</tr>
<tr>
<td>$\Delta \phi$(top, $b$-jet)</td>
<td>Difference in azimuth between the reconstructed top quark and the $b$-tagged jet</td>
</tr>
<tr>
<td>$\cos \theta$(\ell, $b$-jet)</td>
<td>Opening angle of the three-vectors between the charged lepton and the $b$-tagged jet</td>
</tr>
<tr>
<td>$q^\ell$</td>
<td>Charge of the lepton</td>
</tr>
<tr>
<td>$m_T$(W)</td>
<td>W-boson transverse mass</td>
</tr>
<tr>
<td>$\eta^\ell$</td>
<td>Pseudorapidity of the charged lepton</td>
</tr>
<tr>
<td>$\Delta \phi$(top, W)</td>
<td>Difference in azimuth between the reconstructed top quark and the W boson</td>
</tr>
<tr>
<td>$\Delta R$(top, $b$-jet)</td>
<td>Distance in the $\eta$-$\phi$ plane between the reconstructed top quark and the $b$-tagged jet</td>
</tr>
<tr>
<td>$\eta^{top}$</td>
<td>Pseudorapidity of the reconstructed top quark</td>
</tr>
<tr>
<td>$p_T^W$</td>
<td>Transverse momentum of the W boson</td>
</tr>
</tbody>
</table>

- reconstructed top-quark mass,
- $\Delta \phi$(\text{1}_W - $b$), azimuthal angle between the lepton from the $W$ candidate and the $b$-jet candidate,
- $q|\eta|$, with $q$ and $\eta$ the electric charge and the pseudorapidity of the $W$ candidate, respectively,
- $p_T$ of the Z boson candidate,
- $\eta$ of the Z boson candidate,
- jet multiplicity,
- $b$-tagged jet multiplicity,
- $\Delta \phi$(\text{Z} - $E_T$), azimuthal angle between the Z candidate and the direction of the $E_T$ vector,
- CSV $b$-tagging discriminator,
- $\eta$ of the leading jet,
- $\Delta \phi$(\text{1}_W - Z), azimuthal angle between the lepton from the $W$ candidate and the Z candidate,