Measurement of top quark properties at the ATLAS experiment

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Physics at the LHC 2012

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Outline

1. Introduction
2. $t\bar{t}\gamma$ cross section
3. FCNC:
   - in $t\bar{t}$ decays
   - in single top production
4. Top quark mass
5. Studies of the Wtb vertex
6. Charge asymmetry
7. Spin correlation
8. Summary
The top quark and its properties

Why is the top quark special?

➔ heaviest quark ($m_{\text{top}} = 173.2 \pm 0.9$ GeV)
➔ Yukawa coupling $\sim 1$
➔ decays before forming bound states

Why study its properties?

➔ top mass is a fundamental parameter
➔ test SM predictions
➔ look for new physics
Overview of analyses

Top mass
Wtb vertex
Charge asymmetry
$t\bar{t}\gamma$  

➔ + FCNC in $t\bar{t}$ decays, FCNC in single top production
➔ all analyses: only **leptonically decaying taus** considered in signal

$\rightarrow$ Top mass

$\rightarrow$ FCNC in $t\bar{t}$ decays, FCNC in single top production
$\rightarrow$ all analyses: only **leptonically decaying taus** considered in signal
**$t\bar{t}\gamma$ cross section**

- test EM coupling to the top quark
- search for $t\bar{t}$ + prompt photon: $E_{T,\gamma} > 15$ GeV
  - measure cross section
- prompt photons: isolated
  - distinguish from hadron fakes
- data driven bkg estimates

**Main systematics:**

ISR/FSR, JES, Photon ID eff: $\sim 0.3$ pb

**Result:**

$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.50 \text{(stat.)} \pm 0.70 \text{(syst.)} \pm 0.08 \text{(lumi)} \text{ pb}$$

$\Rightarrow$ significance: $2.7 \sigma$
FCNC in $t\bar{t} \rightarrow WbZq \rightarrow l^+l^-l'\nu_lqb$

- SM BR($t \rightarrow qZ$): $\sim 10^{-14}$ (hep-ph/0409342)
- deviation from SM: new physics
  → e.g. quark singlet model (hep-ph/0210112)
- 3 identified leptons (3ID)
- or: 2ID + track lepton (TL)
  → 22 % increase in signal acc.

<table>
<thead>
<tr>
<th></th>
<th>3ID</th>
<th>2ID+TL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ and $WZ$</td>
<td>9.5 ± 4.4</td>
<td>1.0 ± 0.5/0.6</td>
</tr>
<tr>
<td>$ttW$ and $t\bar{t}Z$</td>
<td>0.51 ± 0.14</td>
<td>0.25 ± 0.05</td>
</tr>
<tr>
<td>$t\bar{t}$, $WW$</td>
<td>0.07 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>1.7 ± 0.7</td>
<td>7.6 ± 2.2</td>
</tr>
<tr>
<td>Single top</td>
<td>0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>2+3 fake leptons</td>
<td>0.0 ± 0.2/0.0</td>
<td></td>
</tr>
<tr>
<td>Expected background</td>
<td>11.8 ± 4.4</td>
<td>8.9 ± 2.3</td>
</tr>
<tr>
<td>Data</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Signal efficiency</td>
<td>(0.205 ± 0.024)%</td>
<td>(0.045 ± 0.007)%</td>
</tr>
</tbody>
</table>

**Main systematics:**
- 3ID: ZZ+$WZ$ gen., $\sigma_{t\bar{t}}$, JES
- 2ID+1TL: $\sigma_{t\bar{t}}$, fake leptons, ISR/FSR

No evidence found, set limit (comb.):

$$\text{BR}(t \rightarrow qZ) < 0.73 \% \ (2.1 \text{ fb}^{-1})$$
FCNC in single top production

- in SM: $\text{BR}(t \rightarrow qg) \sim 10^{-13}$
- search for non-SM processes
- difficult to separate from multijet bkg: look at single top production
- $qg \rightarrow t \rightarrow W(\rightarrow l\nu)b$

Most significant variables for NN:
- $p_T^W$
- $\Delta R(\text{bjet,lepton})$
- Lepton charge

No evidence found, set limit:
- $\sigma < 3.9 \text{ pb} @ 95 \% \text{ CL}$
- $\text{BR}(t \rightarrow ug) < 5.7 \cdot 10^{-5}$
- $\text{BR}(t \rightarrow cg) < 2.7 \cdot 10^{-4}$

arXiv:1203.0529
### Top mass: lepton+jets

- 2D template fit
- Hadronically decaying W: constrain JES
- Simultaneous measurement of $m_{\text{top}}$ and JSF via LH fit to data (templates from MC)

**Mass in lepton+jets channel:**

$$m_{\text{top}} = 174.5 \pm 0.6 \text{ (stat.)} \pm 2.3 \text{ (syst.)} \text{ GeV}$$

- 1D template fit with $R_{32} = \frac{m_{\text{top}}^{\text{reco}}}{m_{W}^{\text{reco}}}$ (developed at ATLAS)
- Helps to reduce JES

**Mass for 1D method:**

$$m_{\text{top}} = 174.4 \pm 0.9 \text{ (stat.)} \pm 2.5 \text{ (syst.)} \text{ GeV}$$
Top mass: all hadronic

- at least 6 jets with $p_T > 30$ GeV
- at least 5 jets with $p_T > 55$ GeV
- 2 b-tags
- reconstruction via $\chi^2$ fit
- rescale light jets with $m_W/m_{reco}$
- $f_{\text{Sig}}$ and $m_{\text{top}}$ are free parameters

Main systematics:

- ISR/FSR: 1.7 GeV
- Bkg model: 1.9 GeV
- JES: 2.1 GeV
- b-JES: 1.4 GeV

Final result:

$m_{\text{top}} = 174.9 \pm 2.1 \text{ (stat.)} \pm 3.8 \text{ (syst.) GeV}$

→ in agreement with result from lepton+jets channel
Wtb vertex

Three polarisation states:

- lepton+jets/dilepton
- observable: angular distribution of charged lepton in rest frame of W boson
- two sets of observables:
  - helicity fractions (template fit)
  - angular asymmetries (count events)
**Wtb vertex**

\[ \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_{\mu} - \frac{g}{\sqrt{2}} \bar{b} i \sigma_{\mu\nu} q_\nu \left( g_L P_L + g_R P_R \right) t W^-_{\mu} + h.c. \]

More limits (backup):
- set all but one coupling to zero
- set \( F_R = 0 \)

**Final result:**

\[
\begin{align*}
F_0 &= 0.67 \pm 0.07 \\
F_L &= 0.32 \pm 0.04 \\
F_R &= 0.01 \pm 0.05
\end{align*}
\]

- dominated by JES, fake lept., ISR/FSR
- agrees with SM expectations
- most precise measurement

arXiv:1205.2484
Charge asymmetry: lepton+jets

- expect small asymmetry:
  - $g$ radiation from IS or FS
  - interference of Feynman diagrs.

\[ A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \]

Main systematics:
- ISR/FSR, JES, Signal model $\sim 0.010$

Final result:
\[ A_C = -0.018 \pm 0.028 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \]

(MC@NLO: $0.006 \pm 0.002$)
Charge asymmetry: mass dependence

CDF result:

- measured $A_{FB}$ for $m_{ttbar} > 450$ GeV: significance: $3.4 \sigma$ (arXiv:1101.0034v1)
- possible explanations: flavour changing $Z'$

Conclusion:

- ATLAS measurement of $A_C$ is in agreement with SM
- disfavours a model with flavour changing $Z'$

$\Rightarrow$ new CDF result: still large asymmetry, but with lower significance (CDF Note 10807)
Charge asymmetry: dilepton

Two observables:

→ measure $A_{t\bar{t}}^{ll}$ as in lepton+jets

→ measure $A_{C}^{ll} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$

→ $\Delta|\eta| = |\eta_{l^+}| - |\eta_{l^-}|$

→ SM prediction: $A_{t\bar{t}}^{ll} = 0.006 \pm 0.002$

$A_{C}^{ll} = 0.004 \pm 0.001$

→ reconstruct full event using the $gg \rightarrow t\bar{t}$ matrix element

→ subtract background

→ correct distribution with calibration curves

→ main Systematics: ISR/FSR, Signal modelling, fake lepton

Lepton based asymmetry:

$A_{C}^{ll} = 0.023 \pm 0.012$ (stat.) $\pm 0.008$ (syst.)

Top based asymmetry:

$A_{C}^{t\bar{t}} = 0.057 \pm 0.024$ (stat.) $\pm 0.015$ (syst.)

Combination with lepton+jets result:

$A_{C}^{t\bar{t}} = 0.029 \pm 0.018$ (stat.) $\pm 0.014$ (syst.)

→ No deviation from SM has been found.
Spin correlation

- tops decay before hadronization
- spins of tops are correlated:
  \[ A = \frac{N(↑↑)+N(↓↓)-N(↑↓)-N(↓↑)}{N(↑↑)+N(↓↓)+N(↑↓)+N(↓↑)} \]
- depends on quark/gluon fraction \( (\sqrt{s}) \)

Parton level distribution:

\[ \rightarrow \text{measure } A \text{ in helicity and in max. basis} \]

SM: \( A_{\text{hel}} = 0.31, A_{\text{max}} = 0.44 \)

**Observable:**

\[ \rightarrow \Delta \phi(\text{lepton,lepton}) \]

\[ \rightarrow \text{no full event reconstruction} \]
Spin correlation

$$A_{\text{meas}}^{\text{basis}} = A_{\text{SM}}^{\text{basis}} \cdot f_{\text{SM}}$$

- $f_{\text{SM}} < 0$: anti-correlation
- $f_{\text{SM}} = 0$: no correlation
- $f_{\text{SM}} > 1$: correlation $> \text{SM prediction}$
- SM: $A_{\text{hel}} = 0.31$, $A_{\text{max}} = 0.44$

Dominating uncertainties:

- Statistics: 0.14
- JES/JER: 0.12
- Fake lepton: $+0.16/-0.07$
- Signal modelling: 0.11

Results:

$$f_{\text{SM}} = 1.30 \pm 0.14 \text{ (stat.)} ^{+0.27}_{-0.22} \text{ (syst.)}$$

$$A_{\text{meas}}^{\text{hel}} = 0.40 \pm 0.04 \text{ (stat.)} ^{+0.08}_{-0.07} \text{ (syst.)}$$

$$A_{\text{meas}}^{\text{max}} = 0.57 \pm 0.06 \text{ (stat.)} ^{+0.12}_{-0.10} \text{ (syst.)}$$

→ First observation of spin correlation: 5.1 $\sigma$

PRL 108, 212001 (2012)
More on searches for BSM physics in top events

- $t\bar{t}$ events with large $E_T^{\text{miss}}$ (1.04 fb$^{-1}$):

- $t\bar{t}$ resonances
  - lepton+jets (2.05 fb$^{-1}$): arXiv:1205.5371v1
  - dilepton (2.04 fb$^{-1}$): ATLAS-CONF-2011-123

  ➔ Poster from Michele Petteni

  ➔ Talk by Till Eifert (Friday, 12:35 pm)

- Search for down-type fourth generation quarks
  - 1.04 fb$^{-1}$: arXiv:1202.6540
  - 1.04 fb$^{-1}$: JHEP 04 (2012) 069

  ➔ Poster from Dennis Wendland

  ➔ Talk by Till Eifert (Friday, 12:35 pm)
Summary

- thousands of top quarks have been produced at the LHC
  - precision measurements of top properties
- most analyses are limited by systematics
  - crucial to understand and reduce them
- all measurements are consistent with the SM predictions
- most precise measurement of $W$-helicity fractions
- **First observation of spin correlation!**
Backup slides
Event selection

**Electrons:**
- $E_T^\gamma > 25 \text{ GeV}$
- $|\eta| < 2.47$
- isolated
- exclude crack region

**Muons:**
- combined Muons (tracker+spectrometer)
- $p_T > 20 \text{ GeV}$
- $|\eta| < 2.50$
- isolated

**Jets:**
- AntiKt jets ($R = 0.4$)
- $p_T > 25 \text{ GeV}$
- $|\eta| < 2.5$
- at least four jets

**$b$-Jets:**
Used different methods to reconstruct secondary vertices (see backup).
$\rightarrow$ require at least one tagged jet

**$E_{miss}^T$:**
- $e$: $E_{miss}^T > 35 \text{ GeV}$
- $\mu$: $E_{miss}^T > 20 \text{ GeV}$

**Transverse W mass:**
used to reduce multijet bkg:
- $e$: $m_{W,T} > 35 \text{ GeV}$
- $\mu$: $m_{W,T} + E_{miss}^T > 60 \text{ GeV}$

For dilepton analyses:
- $\geq 2$ jets
- cuts to reduce Z+jets bkg
- larger $E_{miss}^T$ cut
Event selection

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- $E_T^e > 25$ GeV
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- at least four jets

For dilepton analyses:
- $\geq 2$ jets
- cuts to reduce Z+jets bkg
- larger $E_T^{miss}$ cut
Top reconstruction

Kinematic likelihood fit

\[
L = \mathcal{T} \left( E_{	ext{jet}_1 | \hat{E}_{\text{had}}} \right) \cdot \mathcal{T} \left( E_{	ext{jet}_2 | \hat{E}_{\text{had}}} \right) \cdot \mathcal{T} \left( E_{\text{jet}_3 | \hat{E}_{j_1}} \right) \\
\mathcal{T} \left( E_{\text{jet}_4 | \hat{E}_{j_2}} \right) \cdot \mathcal{T} \left( E_{\text{miss} | \hat{p}_{x,\nu}} \right) \cdot \mathcal{T} \left( E_{\text{miss} | \hat{p}_{y,\nu}} \right) \\
\left\{ \mathcal{T} \left( E_e | \hat{E}_e \right) e + \text{jets} \right\} \cdot \mathcal{T} \left( p_{T,\mu} | \hat{p}_{T,\mu} \right) \mu + \text{jets} \\
B \left[ m(q_1 q_2) | m_W, \Gamma_W \right] \cdot B \left[ m(\ell \nu) | m_W, \Gamma_W \right] \\
B \left[ m(q_1 q_2 b_{\text{had}}) | m_\text{top}^{\text{reco,like}}, \Gamma_\text{top} \right] \\
B \left[ m(\ell \nu b_{\ell}) | m_\text{top}^{\text{reco,like}}, \Gamma_\text{top} \right] \cdot W_{\text{btag}}.
\]

Reco via a $\chi^2$ fit (example: hadronic top mass)

\[
\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}
\]

with $\sigma_W = 10.2$ GeV, $\sigma_t = 17.4$ GeV
Event reconstr. (dilepton channel, charge asymm)

**Problem:**
- have final state with two neutrinos
- need to fully reconstruct event
- 16 equations to solve
- 22 unknowns to determine

**What do we know?**
- have 16 measured quantities
- fix W and top mass to WA
- add equations:
  - MET balance in transverse plane
  - $t\bar{t}$-$p_T$

**Idea:**
- vary 4 momentum of objects (width, resolution)
- transfer functions for b-jets: priors
- if solution: calculate weight:
  $$\frac{(2\pi)^4}{\epsilon_1 \epsilon_2^s} d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1)f_{PDF}(\epsilon_2)|\mathcal{M}(y)|^2 W(x, y) d\Phi_n$$

**Finally:**
- for each permutation of jets: phase space sampling ($10^4$-$10^5$ points, use Vegas)
- each point: calculate number of solutions
  - calculate weight $y_k = \frac{\sum_{j=1}^{N_{\text{sampl}}} \sum_{i=1}^{N_{\text{sol}}} w_{ij}^k y_{ij}^k}{\sum_{j=1}^{N_{\text{sampl}}} \sum_{i=1}^{N_{\text{sol}}} w_{ij}^k}$
- $\epsilon_{\text{reco}}$ for highest weight: 47% (rdm: 30%)
Top mass: 1D template fit

- $R_{32} = \frac{m_{\text{reco}}^{\text{top}}}{m_W}$
- less sensitive to JES
- jets for hadronic top: $p_T > 40$ GeV
- $\ln L > -50$
- reconstruction: kinematic likelihood
- template fit

Main systematics:
- ISR/FSR: 1.42 GeV
- JES: 1.23 GeV
- b-JES: 1.16 GeV

Final result:

$m_{\text{top}} = 174.4 \pm 0.9 \text{ (stat.)} \pm 2.5 \text{ (syst.)} \text{ GeV}$

→ in agreement with result from 2D method
Top mass: all hadronic

- ATLAS-CONF-2011-030
- calculate $m_{jjb}$
- perform template fit

Jet selection:
- $\geq 6(5)$ jets with $p_T > 30(55)$ GeV
- $|\eta(\text{jet})| < 4.5$, $\Delta R(\text{jet}_i, \text{jet}_j) > 0.6$
- 2 b-tags: $p_T > 55$ GeV, $|\eta| < 2.5$
- $\Delta R(b_1, b_2) > 1.2$

Procedure:
- data driven estimate for multijet bkg
- reconstruction via $\chi^2$ fit
- in reconstruction: $m_{jj} \in [50, 110]$ GeV
- rescale light jets with $m_W/m_{W}^{\text{reco}}$
Top mass: all hadronic

- fit with five templates
- binned likelihood
- $f_{\text{Sig}}$ and $m_{\text{top}}$ are free parameters
- use pseudo data for systematics

Systematic uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>0.4</td>
</tr>
<tr>
<td>Template statistics</td>
<td>0.9</td>
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<tr>
<td>MC generator</td>
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<tr>
<td>ISR/FSR</td>
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<tr>
<td>PDF</td>
<td>0.6</td>
</tr>
<tr>
<td>Background modelling</td>
<td>1.9</td>
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<tr>
<td>Jet energy scale</td>
<td>2.1</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>1.4</td>
</tr>
<tr>
<td>$b$-tag efficiency scale factors</td>
<td>0.3</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.3</td>
</tr>
<tr>
<td>Jet reconstruction efficiency</td>
<td>0.2</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Fit to data:

Final result:

$$m_{\text{top}} = 174.9 \pm 2.1 \text{ (stat.)} \pm 3.8 \text{ (syst.)} \text{ GeV}$$

→ in agreement with world average and result from lepton+jets channel
Limit on effective operator

New physics processes can be modeled by effective Langrangian $^1$:

$$\mathcal{L}_{\text{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \ldots$$

One of the six-dimension operators ($C_{uW}^{33}$) can alter the helicity fractions:

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}\text{Re}(C_{uW}^{33})v^2}{\Lambda^2 V_{tb}} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} + \frac{4\sqrt{2}\text{Re}(C_{uW}^{33})v^2}{\Lambda^2 V_{tb}} \frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

→ Assumption in model: $F_R = 0$

---

Set limit on non-SM coupling (only template method) \(^2\)

2D fit: \( F_0 = 0.66 \pm 0.05 \) (stat.+syst.)

\[
\frac{\text{Re}(C_{uw}^{33})}{\Lambda^2} \in [-0.9, 2.3] \text{ TeV}^{-2}
\]

→ No deviation from SM predictions has been found

\(^2\)arXiv:1205.2484
Set limits on $g_R$ and $g_L$:

- assumption: $V_R = 0$ and $V_L = 1$
- combined angular asymmetries
  
  \[
  A_+ = 0.53 \pm 0.02 \text{ (stat. + syst.)}
  \]
  \[
  A_- = -0.84 \pm 0.02 \text{ (stat. + syst.)}
  \]

- use helicity fractions to calculate anomalous couplings
One dimensional limits on anomalous couplings

Assuming only one non-vanishing coupling:

\[
\begin{align*}
\text{Re}(V_R) \in [-0.20, 0.23] \rightarrow \frac{\text{Re}(C_{\phi\phi}^{33})}{\Lambda^2} \in [-6.7, 7.8] \text{ TeV}^{-2} \\
\text{Re}(g_L) \in [-0.14, 0.11] \rightarrow \frac{\text{Re}(C_{dW}^{33})}{\Lambda^2} \in [-1.6, 1.2] \text{ TeV}^{-2} \\
\text{Re}(g_R) \in [-0.08, 0.04] \rightarrow \frac{\text{Re}(C_{uW}^{33})}{\Lambda^2} \in [-1.0, 0.5] \text{ TeV}^{-2}
\end{align*}
\]

Conclusion for anomalous couplings:

- couplings compatible with zero

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\(^4\text{arXiv:1205.2484}\)
Dilepton selection

- single lepton trigger
- exactly two leptons, opposite charge
- $ee/\mu\mu$:
  - $m_{ll} > 15$ GeV: remove $\Upsilon, J/\Psi$
  - $E_{T}^{\text{miss}} > 60$ GeV: remove $Z/\gamma + \text{jets}, W + \text{jets}$
- $e\mu$:
  - $H_T > 130$ GeV
    $\rightarrow$ suppress $Z/\gamma \rightarrow \tau\tau$

\[\int Ldt = 2.1 \text{ fb}^{-1}\]

\begin{align*}
  &ee & 0.65 \pm 0.17 &^{+0.32}_{-0.31} \\
  &\mu\mu & 0.37 \pm 0.14 &^{+0.19}_{-0.17} \\
  &e\mu & 0.62 \pm 0.07 &^{+0.16}_{-0.15} \\
  &\text{combination} & 0.57 \pm 0.06 &^{+0.12}_{-0.10} \\
\end{align*}

\begin{align*}
  &ee & 0.46 \pm 0.12 &^{+0.23}_{-0.22} \\
  &\mu\mu & 0.26 \pm 0.10 &^{+0.13}_{-0.12} \\
  &e\mu & 0.43 \pm 0.05 &^{+0.11}_{-0.10} \\
  &\text{combination} & 0.40 \pm 0.04 &^{+0.08}_{-0.07} \\
\end{align*}
backup: Charge asymmetry

- at Tevatron: can measure $A_{FB}$
- LHC is symmetric: can measure $A_C$
- at LHC: much more gg-fusion
  $\Rightarrow$ expect only small asymmetry
Backup: $t\bar{t}\gamma$ cross section

**Templates**

- signal (from $Z \rightarrow ee$)
- hadron fakes
- electron fakes (from $Z \rightarrow ee$)
- non-$t\bar{t}$ bkg
- bkg $t\bar{t}\gamma$

**Fake rate $e \rightarrow \gamma$**

<table>
<thead>
<tr>
<th>fit parameter</th>
<th>fit value with statistical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadron fakes in the $e+$jets channel</td>
<td>21 $\pm$ 6 events</td>
</tr>
<tr>
<td>hadron fakes in the $\mu+$jets channel</td>
<td>28 $\pm$ 8 events</td>
</tr>
<tr>
<td>electrons faking photons from $t\bar{t}$ in the $e+$jets channel</td>
<td>7.4 $\pm$ 1.7 events</td>
</tr>
<tr>
<td>electrons faking photons from $t\bar{t}$ in the $\mu+$jets channel</td>
<td>10.9 $\pm$ 2.2 events</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$ background in the $e+$jets channel</td>
<td>0.2 events</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$ background in the $\mu+$jets channel</td>
<td>0.4 events</td>
</tr>
<tr>
<td>non-$t\bar{t}$ background in the $e+$jets channel</td>
<td>6.7 events</td>
</tr>
<tr>
<td>non-$t\bar{t}$ background in the $\mu+$jets channel</td>
<td>3.8 events</td>
</tr>
<tr>
<td>total number of background events</td>
<td>78 $\pm$ 14 events</td>
</tr>
<tr>
<td>total number of signal events</td>
<td>46 $\pm$ 12 events</td>
</tr>
<tr>
<td>$t\bar{t}\gamma$ signal (before selection and acceptance cuts)</td>
<td>2100 $\pm$ 500 events</td>
</tr>
</tbody>
</table>
Backup: FCNC $t \rightarrow qZ$

Theoretical values for BR for SM and beyond SM scenarios

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM</th>
<th>FC 2HDM</th>
<th>MSSM</th>
<th>R SUSY</th>
<th>TC2</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \rightarrow u\gamma$</td>
<td>$3.7 \times 10^{-16}$</td>
<td>$7.5 \times 10^{-9}$</td>
<td>---</td>
<td>---</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>---</td>
<td>$\sim 10^{-11}$</td>
</tr>
<tr>
<td>$t \rightarrow uZ$</td>
<td>$8 \times 10^{-17}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>---</td>
<td>---</td>
<td>$2 \times 10^{-6}$</td>
<td>$3 \times 10^{-5}$</td>
<td>---</td>
<td>$\sim 10^{-9}$</td>
</tr>
<tr>
<td>$t \rightarrow ug$</td>
<td>$3.7 \times 10^{-14}$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>---</td>
<td>---</td>
<td>$8 \times 10^{-5}$</td>
<td>$2 \times 10^{-4}$</td>
<td>---</td>
<td>$\sim 10^{-11}$</td>
</tr>
<tr>
<td>$t \rightarrow c\gamma$</td>
<td>$4.6 \times 10^{-14}$</td>
<td>$7.5 \times 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
</tr>
<tr>
<td>$t \rightarrow cZ$</td>
<td>$1 \times 10^{-14}$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-5}$</td>
</tr>
<tr>
<td>$t \rightarrow cg$</td>
<td>$4.6 \times 10^{-12}$</td>
<td>$1.5 \times 10^{-7}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-8}$</td>
<td>$8 \times 10^{-5}$</td>
<td>$2 \times 10^{-4}$</td>
<td>$\sim 10^{-4}$</td>
<td>$\sim 10^{-9}$</td>
</tr>
</tbody>
</table>

Experimental limits on BR @ 95 % C.L. (without CMS result)

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>HERA</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR(t \rightarrow q\gamma)$</td>
<td>2.4% [25–29]</td>
<td>0.64% ($t\nu\gamma$) [30]</td>
<td>3.2% [31]</td>
</tr>
<tr>
<td>$BR(t \rightarrow qZ)$</td>
<td>7.8% [25–29]</td>
<td>49% ($t\nu Z$) [32]</td>
<td>3.2% [33]</td>
</tr>
<tr>
<td>$BR(t \rightarrow qg)$</td>
<td>17% [34]</td>
<td>13% [32, 35, 36]</td>
<td>$2.0 \times 10^{-4}$ ($tug$), $3.9 \times 10^{-3}$ ($tcg$) [37]</td>
</tr>
</tbody>
</table>
Backup: FCNC in single top production

Most significant variables for neural network

Further variables:
- $m_{\text{top}}$, $m_{\text{bjet}}$, $\eta_{\text{bjet}}$
- $\Delta \Phi(W,\text{bjet})$, $p_T^{\text{lep}}$, $p_T^{\text{bjet}}$
- $\cos \Theta^*$, $\Delta R(W,\text{bjet})$

Reconstruction:
- exactly one jet
- neutrino $p_z$ from constraint on $m_W$
- two results: take smallest value
Reducing ISR/FSR uncertainties

How was it evaluated in 2011 analyses?

- user AcerMC+Pythia, using Perugia HARD/SOFT tunes for ISR/FSR
  → not based on LHC data
- six samples: ISR up/down, FSR up/down, ISR & FSR up, ISR & FSR down
- take half of the largest difference between two samples

What was changed for 2012 (2011 data)?

- now: set ISR/FSR parameters based on LHC data
- ISR: constrain variation using jet gap fraction info in dil. events
- FSR: tune parameters → describe jet shapes in QCD events
- have two samples with more/less parton shower activity (AcerMC+Pythia)