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2013 J. Phys.: Conf. Ser. 452 012011

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A Sopczak

# Measurements of new physics in top quark decay at LHC

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**Abstract.** A summary of ATLAS and CMS results on searches for new physics in top quark decay is presented. Three analysis are reported: the ATLAS and CMS searches for flavor changing neutral currents (FCNC) in top-quark decays and the CMS search for baryon number violation (BNV) in top-quark decays. ATLAS and CMS provided exclusion limits (at 95% CL) on the FCNC decay  $t \rightarrow Zq$ , using respectively  $2.1 \text{ fb}^{-1}$  and  $5.0 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  collected in 2011. Upper limits on  $B(t \rightarrow Zq)$  are respectively 0.73% and 0.24%. CMS has also set an exclusion limit (at 95% CL) on the BNV decay  $t \rightarrow lbq$  using  $5.0 \text{ fb}^{-1}$  of data. Upper limit on  $B(t \rightarrow lbq)$  is 0.67%.

## 1. Searches for Flavour Changing Neutral Currents in Top Quark Decays

In the Standard Model (SM), the top quark decays to a  $W$  boson and  $b$ -quark with a branching fraction of nearly 100%. Flavour changing neutral current (FCNC) decays, although allowed in the SM at the level of quantum correction, are highly suppressed by the GIM mechanism, with typical branching ratios (BR) of the order of  $10^{-14}$ .

However, some SM extensions predict much higher values for FCNC decays involving the top-quark. Examples are supersymmetric models with R-parity violation, quark-singlet model and topcolor-assisted technicolor models, where the BR for FCNC decays can be of the order of  $10^{-4}$  [1][2]. For this reason, direct searches for the flavor changing neutral currents in top quark decays have already been performed at Tevatron. CDF and D0 experiments set an upper limit on  $B(t \rightarrow Zq)$  of 3.7% [3] and 3.2% [4] at the 95% confidence level (CL) respectively. The same search has been performed at LHC by ATLAS [5] and CMS [6] experiments, using respectively  $2.1 \text{ fb}^{-1}$  and  $5.0 \text{ fb}^{-1}$  of  $pp$  collision at  $\sqrt{s} = 7 \text{ TeV}$ .

### 1.1. Search for the FCNC decay $t \rightarrow Zq$ with the ATLAS detector

ATLAS searched for  $t \rightarrow Zq$  in  $t\bar{t}$  events where the top (antitop) quark decayed to  $Zq$ , while the antitop (top) quark decayed to  $Wb$  [7]. Only the leptonic decays of the  $Z$  and  $W$  bosons were considered, resulting in a final state with three isolated charged leptons and at least two jets.

Two event selections were implemented, based on different requirements on the lepton candidates: in the so-called “3ID” analysis, all three lepton candidates were required to be reconstructed and identified using the full ATLAS detector (“ID” lepton candidates); in the so-called “2ID+TL” analysis, only two “ID” candidates were requested, while the third lepton candidate was required to be reconstructed using the ATLAS inner detector only (“TL” lepton candidate).



	3ID	2ID+TL
$ZZ$ and $WZ$	9.5 $\pm$ 4.4	1.0 $\pm$ $\begin{smallmatrix} 0.5 \\ 0.6 \end{smallmatrix}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 $\pm$ 0.14	0.25 $\pm$ 0.05
$t\bar{t}$ , $WW$	0.07 $\pm$ 0.02	
$Z$ +jets	1.7 $\pm$ 0.7	
Single top	0.01 $\pm$ 0.01	7.6 $\pm$ 2.2
2+3 fake leptons	0.0 $\pm$ $\begin{smallmatrix} 0.2 \\ 0.0 \end{smallmatrix}$	
Expected background	11.8 $\pm$ 4.4	8.9 $\pm$ 2.3
Data	8	8
Signal efficiency	(0.205 $\pm$ 0.024)%	(0.045 $\pm$ 0.007)%

**Table 1.** ATLAS  $t \rightarrow Zq$  search: Expected and observed yields and signal efficiencies for the 3ID and 2ID+TL selections [7].

In both selections, exactly three isolated lepton candidates with  $p_T > 20$  GeV ( $p_T > 25$  GeV for the leading lepton) and at least two jets with  $p_T > 25$  GeV were requested. In the 2ID+TL selection a jet consistent with originating from a  $b$ -quark was also required. The transverse missing energy of the event was requested to be greater than 20 GeV and signal-like final states were selected through a  $\chi^2$  minimization with respect to jet and lepton assignments and the neutrino longitudinal momentum ( $p_z^\nu$ ). The  $\chi^2$  definition was the following:

$$\chi^2 = \frac{(m_{j_a l_a l_b}^{reco} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_b l_c \nu}^{reco} - m_t)^2}{\sigma_t^2} + \frac{(m_{l_c \nu}^{reco} - m_W)^2}{\sigma_W^2} + \frac{(m_{l_a l_b}^{reco} - m_Z)^2}{\sigma_Z^2} \quad (1)$$

where  $j_{a,b}$  were the jets and  $l_{a,b,c}$  were the three lepton candidates. The following constraints were used on top-quark,  $W$  and  $Z$  bosons masses and resolutions:  $m_t = 172.5$  GeV,  $m_W = 80.4$  GeV,  $m_Z = 91.2$  GeV,  $\sigma_t = 14$  GeV,  $\sigma_W = 10$  GeV,  $\sigma_Z = 3$  GeV. From all combinations, the one with the smallest  $\chi^2$  was chosen. Events were retained if reconstructed top-quark,  $W$  and  $Z$  bosons masses were respectively within 40 GeV, 30 GeV and 15 GeV of their reference values.

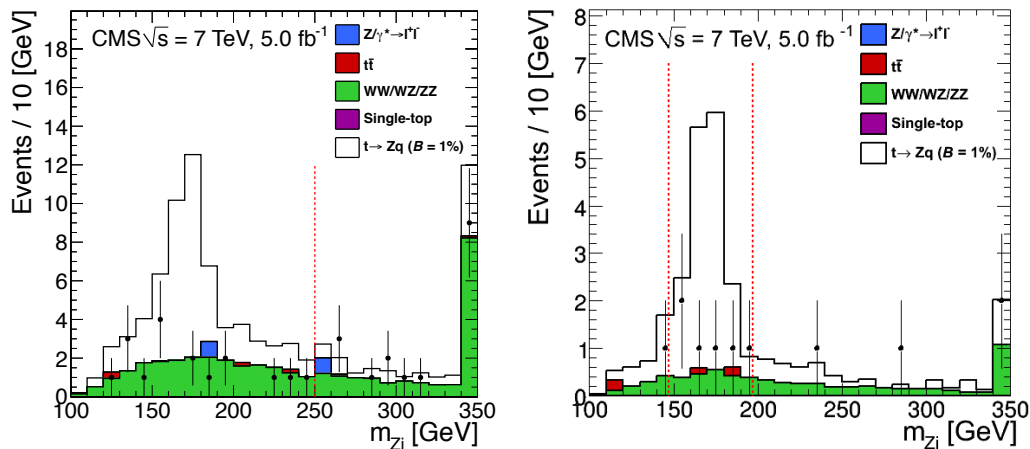
For the 3ID selection the dominant background came from events with three real leptons, whose contribution was taken from MC, while for the 2ID+TL selection the dominant background was from events with at least one fake lepton and a data-driven method was used for its estimation.

Table 1 reports data and expected yields for the 3ID and 2ID+TL selections. Good agreement between data and expectations was found, with no evidence for the  $t \rightarrow Zq$  decay mode. Upper limits at 95% CL on signal branching ratio  $B(t \rightarrow Zq)$  were derived. A number of systematic uncertainties, which could affect the expected number of signal and background events, were taken into account. In the 3ID selection, the most important sources of systematic uncertainties were the jet energy scale and the shape for  $ZZ$  and  $WZ$ . For the 2ID+TL selection, where  $\sim 90\%$  of background was estimated from data, the most important contribution was the uncertainty on the fake lepton prediction.

Observed (expected) 95% C.L. upper limits on  $BR(t \rightarrow Zq)$  were found to be 0.81% (0.95%), 3.2% (3.31%) and 0.73% (0.61%) for the 3ID channel, the 2ID+TL channel and their combination respectively.

### 1.2. Search for the FCNC decay $t \rightarrow Zq$ with the CMS detector

Also CMS performed the search for the FCNC decay  $t \rightarrow Zq$  using the final state with three charged leptons and two jets [8]. Exactly three leptons candidates (electrons or muons) were



**Figure 1.** CMS  $t \rightarrow Zq$  search: Comparison between data and simulated events of the  $m_{Zj}$  for the “ST” (left) and “b-tag” (right) selections before the requirements on  $m_{Zj}$  and  $m_{Wb}$  [8].

required to be isolated, with  $p_T > 20$  GeV and coming from the same primary vertex. At least one opposite-sign same-flavour dilepton pair was required to have invariant mass between 60 GeV and 120 GeV. Finally events are requested to have at least two jets with  $p_T > 30$  GeV and transverse missing energy  $E_T^{miss} > 20$  GeV.

For both  $t \rightarrow Zq \rightarrow llj$  and  $t \rightarrow Wb \rightarrow l\nu$  decays, the full reconstruction of the top quark masses ( $m_{Zj}$  and  $m_{Wb}$  respectively) were possible. In the second case, the missing transverse energy was assumed as transverse component of the neutrino momentum and the invariant mass of the lepton and the neutrino ( $m_{l\nu}$ ) was constrained to the  $W$  boson mass.

CMS performed the search for  $t\bar{t} \rightarrow WbZq$  using two different selections. The first one required a minimum value of  $S_T^1$  and loose requirements on  $m_{Zj}$  and  $m_{Wb}$ . The second selection had tighter requirements on  $m_{Zj}$  and  $m_{Wb}$  and also required that one of the jets were consistent with the hadronization of a  $b$ -quark. These two selections are referred as the “ST” and “b-tag” selections in the following.

In the “ST” selection, a candidate event was required to have  $S_T$  above 250 GeV, while  $m_{Zj}$  and  $m_{Wb}$  were requested to be between 100 GeV and 250 GeV. In the “b-tag” selection, one jet was required to be identified as  $b$ -quark initiated jet and the reconstructed top-quark masses  $m_{Zj}$  and  $m_{Wb}$  were requested to be within 25 GeV and 35 GeV of the assumed top mass ( $m_t = 172.5$  GeV) respectively. Fig. 1 shows the comparison between data and simulated events of the  $m_{Zj}$  for the “ST” (left) and “b-tag” (right) selections, before the requirements on  $m_{Zj}$  and  $m_{Wb}$ . Dotted lines show the boundaries of the allowed mass region in the two selections.

Table 3 reports data and expected yields for the “ST” and “b-tag” selections. No excess beyond the SM expectations was observed and 95% CL upper limits on the signal branching ratio were derived. Many sources of systematic uncertainties were taken into account. The most important contributions came from the jet energy scale and missing energy resolution as well as the  $b$ -tagging efficiency for the “b-tag” selection.

Observed and expected 95% CL upper limits on the branching fraction  $B(t \rightarrow Zq)$  are reported in Table 3. The expected limit for the “ST” selection is more sensitive and therefore the corresponding observed limit, 0.24%, was taken as the final result.

<sup>1</sup>  $S_T$  is defined as the sum of the  $p_T$  of the leptons, the  $p_T$  of the jets and the missing energy

Selection	S <sub>T</sub>	b-tag
WZ background	13.59 ± 0.20 ± 2.58	0.718 ± 0.011 ± 0.150
ZZ background	1.09 ± 0.02 ± 0.21	0.058 ± 0.001 ± 0.012
Drell-Yan and tt background	1.52 ± 0.46 ± 0.41	0.055 ± 0.017 ± 0.012
Total background prediction	16.20 ± 0.51 ± 2.62	0.83 ± 0.02 ± 0.15
Observed events	11	0
Expected limit at the 95% CL	$\mathcal{B}(t \rightarrow Zq) < 0.36\%$	$\mathcal{B}(t \rightarrow Zq) < 0.42\%$
Observed limit at the 95% CL	$\mathcal{B}(t \rightarrow Zq) < 0.24\%$	$\mathcal{B}(t \rightarrow Zq) < 0.30\%$

**Table 2.** CMS  $t \rightarrow Zq$  search: Data and expected yields, with statistical plus systematic uncertainties, for the “ST” and “b-tag” selections. Observed and expected limits at the 95% CL are also reported [8].

## 2. Search for baryon number violating top-quark decay with the CMS detector

Baryon number  $B$  is a conserved quantity in the SM though small violations can arise from non-perturbative effects. However, baryon number violation (BNV) naturally occurs in many scenarios beyond the SM, like supersymmetry, grand unified theories, and black hole physics. Baryon number violation in processes involving the top-quark production and decay have been recently investigated in [9], where it has been suggested the possibility of the BNV decays  $t \rightarrow \bar{b}\bar{c}\mu^+$  ( $\bar{t} \rightarrow bc\mu$ ) and  $t \rightarrow \bar{b}\bar{u}e^+$  ( $\bar{t} \rightarrow bue$ ), proceeding via an effective operator that makes it equivalent to a four fermion point interaction [9]. CMS searched for such decays in  $t\bar{t}$  events where just one of the two top decayed to one lepton and two jets, while the other one decayed hadronically, resulting in final state with one isolated lepton, five jets and no neutrino [10]. This search was performed using  $5.0 \text{ fb}^{-1}$  of  $pp$  collision at  $\sqrt{s} = 7 \text{ TeV}$ .

Top-quark BNV decays could appear not only in  $t\bar{t}$  events, but also in events with  $tW$  production and single top production via  $s$ - and  $t$ -channels. However, the contribution to BNV from the two latter processes was proven to be negligible and therefore they were treated as non-top backgrounds.

A “basic” selection, where to normalize the top yield to data, and a signal region, with a “tight” selection, were defined. In order to reduce the impact of some systematic uncertainties, the expected top yield in the tight selection ( $N_{top}^T$ ) was derived from quantities related to the basic selection. As results, expected total yield in the tight selection ( $N_{exp}^T$ ) was expressed as:

$$N_{exp}^T = N_{top}^T - N_{bck}^T = (N_{obs}^B - N_{bck}^B) \left[ \frac{N_{t\bar{t}}^B}{N_{t\bar{t}}^B + N_{tW}^B} \times \epsilon_{t\bar{t}}^{T|B} \frac{N_{tW}^B}{N_{tW}^B + N_{t\bar{t}}^B} \times \epsilon_{tW}^{T|B} \right] + N_{bck}^T, \quad (2)$$

where  $N_{t\bar{t}}^B$  ( $N_{tW}^B$ ) is the  $t\bar{t}$  ( $tW$ ) expected yield in the basic selection,  $N_{bck}^B$  ( $N_{bck}^T$ ) is the non-top background yield in the basic (tight) selection and  $\epsilon_{t\bar{t}}^{T|B}$  ( $\epsilon_{tW}^{T|B}$ ) is the efficiency for  $t\bar{t}$  ( $tW$ ) events to pass the tight selection once the basic selection is passed. All terms in the square brackets of Eq. 2 are functions of the signal  $BR$ .

In the basic selection, events were requested to have exactly one isolated muon (electron), with  $p_T > 35 \text{ GeV}$  and  $|\eta| < 2.1$  (2.4), and at least five jets, with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.4$ . To reduce the contribution of non-top background, at least one jet consistent with originating from a  $b$ -quark was also required. In addition to the previous requirements, in the tight selection the transverse missing energy was requested to be less than 20 GeV and signal-like final states were selected by a  $\chi^2$  minimisation with respect to the jet assignment. The  $\chi^2$  was defined as:

Dataset	Cross section (pb)	Tight - Yield	Dataset	Cross section (pb)	Tight - Yield
$t\bar{t}$	$157.5 \pm 24.4$	$584 \pm 81$	$t\bar{t}$	$157.5 \pm 24.4$	$497 \pm 72$
W+jets	$31310 \pm 1560$	$76 \pm 42$	W+jets	$31314 \pm 1558$	$88 \pm 35$
Z+jets	$3048 \pm 132$	$36 \pm 20$	Z+jets	$3048 \pm 132$	$82 \pm 33$
WW	$43.0 \pm 1.5$	$0.97 \pm 0.53$	WW	$43.0 \pm 1.5$	$0.80 \pm 0.32$
WZ	$18.2 \pm 0.7$	$0.92 \pm 0.51$	WZ	$18.2 \pm 0.7$	$1.10 \pm 0.44$
ZZ	$5.9 \pm 0.1$	$0.32 \pm 0.18$	ZZ	$5.9 \pm 0.1$	$0.37 \pm 0.15$
tW	$15.7 \pm 0.8$	$12.8 \pm 1.8$	tW	$15.7 \pm 0.8$	$14.6 \pm 2.1$
t-ch	$64.6 \pm 3.4$	$2.3 \pm 1.3$	t-ch	$64.6 \pm 3.4$	$3.2 \pm 1.3$
s-ch	$4.63 \pm 0.19$	$0.26 \pm 0.14$	s-ch	$4.63 \pm 0.19$	$0.30 \pm 0.12$
ttW	$0.16 \pm 0.02$	$2.0 \pm 1.1$	ttW	$0.16 \pm 0.02$	$1.77 \pm 0.71$
QCD	-	$9.0 \pm 9.0$	QCD	-	$109 \pm 54$
Total Exp.	-	$724 \pm 39$	Total Exp.	-	$798 \pm 66$
Data	-	$796 \pm 28$	Data	-	$843 \pm 29$

**Table 3.** CMS  $t \rightarrow lbq$  search: Adopted cross section values, expected and observed yields in the tight selection for the muon channel (left) and electron channel (right). Uncertainties are statistical plus systematic [10].

$$\chi^2 = \sum_i \frac{(x_i - \bar{x}_i)^2}{\sigma_i^2}, \quad (3)$$

where the  $x_i$  were the reconstructed invariant mass of the  $W$  boson from the hadronically decaying top-quark, the reconstructed invariant mass of the hadronically decaying top-quark and the reconstructed invariant mass of the BNV decaying top-quark. Events with minimised  $\chi^2 > 20$  were rejected.

Table 4 left (right) reports the expected and the observed yields in the “tight” selection, after the  $t\bar{t}$  and  $tW$  normalisation, for the muon (electron) channel. No significant excess beyond the SM expectations was observed and 95% CL upper limits on the signal branching ratio were derived in both channels as well as their combination. Many sources of systematic uncertainties were taken into account. The dominant contribution came from the jet energy scale and from the uncertainty on the ISR/FSR modelling in the MC samples.

The observed 95% CL limits on signal  $BR$  were derived to be 0.76% and 0.72% for the muon and electron channel, while the expected limits were 0.44% and 0.54% respectively. Results from the muon and electron channels were also combined by maximising the product of the two likelihood functions, assuming a common value of  $BR$  for the two channels. The resulting observed 95% CL upper limit on signal  $BR$  was 0.67% (expected limit was 0.41%) and it was taken as final result.

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