BSM measurements with Top at LHC : CMS sensitivity to Flavour Changing Neutral Currents

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1 Top quark and New Physics

Top quark was discovered at Fermilab in the 1995-96 [1], completing the three-families structure of the Standard Model (SM) and opening the new field of top quark physics. Since the beginning of the study phase, this object has appeared to be a very special one.

Top quark is distinguished by a large mass ($172.4 \pm 0.7\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})$GeV, [2]) that is intriguingly close to the scale of electroweak (EW) and a Yukawa coupling surprisingly close to 1. Within the Minimal Standard Model, top quark processes are known with high accuracy with no need for phenomenological parameters, decay occurs mostly through the $t \rightarrow bW$ channel and, since the top mass width is larger than the QCD scale, no top-hadrons are formed. These unique properties suggest that the top quark can be considered a very clean laboratory where to constrain the SM and to look beyond it.

Several properties of the top quark have already been examined at the $p\overline{p}$ collider Tevatron at Fermilab (up to now the only place where it is directly produced), $e^{\pm}p$ collider HERA at DESY and e^+e^- collider LEP at CERN. Despite the very important reaches and limits of these measurements, most of them suffer from the small sample of top quarks collected. It is here that the Large Hadron Collider (LHC) comes into the game.

Whereas the center-of-mass energy at LHC is seven times higher than the Tevatron, the cross section for $t\bar{t}$ production is more than a hundred times larger and amounts to $833 \pm 83\,(\mathrm{PDF}) \pm 50\,(\mathrm{stat})$ pb at next-to-leading order [3]. This large cross section, combined with the significantly enhanced single-top production, implies that during the stable low-luminosity run ($\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) a rate around 4 top quarks per second will be reached. About 800,000 events will be likely obtained after $1\,\mathrm{fb}^{-1}$,

then several millions of events can be accumulated each year. Therefore, LHC can well be renamed as a "top factory". Having a so powerful machine at hand, several top quark properties will be examined with a much better precision and entirely new measurements can be contemplated. Among the possible new couplings, the Flavour Changing Neutral Currents (FCNCs) are one of the most interesting processes.
At a fundamental level, FCNCs consist in couplings of the type tVq, where V is a neutral gauge boson ($V = \gamma, Z^0, g$) and q is a u or c quark. Since in the SM these anomalous couplings are absent at tree-level and occur only at loop level, rates for FCNC processes in the top sector are extremely small (with Branching Ratios from 10^{-14} to 10^{-14}, [5, 6]), because of the strong loop suppression and the high masses of the gauge bosons. Therefore, the top quark plays a unique role compared to the other quarks – for which the expected FCNC transitions are much larger – and *any experimental evidence for a top quark FCNC interaction would signal the existence of new physics.*
Several scenarios beyond the SM have been proposed in recent years. In many new physics models as the two Higgs Doublet Models (2HDM), the Minimal Supersymmetric Standard Model (MSSM) with and without R-parity conservation, SUperSimmetrY (SUSY) top-assisted technicolor (TC), left-right (LR) asymmetry model and quark singlets (QS), enhancements in FCNC decays can arise, either from a large virtual mass or from the couplings involved in the loop. A summary of the predicted Branching Ratios for the most promising models is in Tab. 1.

The aim of this study is to determine the sensitivity and discovery reach of the CMS experiment [14] at LHC for this channel, in both the $t \to Zq$ and $t \to \gamma q$ neutral decays ($t \to gq$ is not studied because of its very high QCD background). The strategy to reveal these signals on top of the SM background is based on a series of optimized cuts and is assessed in Sec. 2. A full set of systematic effects, originating from detector or theoretical uncertainties, are added to the simulation and their impact on the analysis is established in Sec. 3. Then a closer look is given to the relevant background and efforts are performed (Sec. 4) to find a specific control region that can be addressed in the future samples, thus allowing to measure directly

	2HDM-III [7, 8]	MSSM with R [4]	MSSM with $\not{R}$ [9]	TC2 [10]	LR [11]	QS [12, 13]
BR($t \to qg$)	10^{-4}	10^{-4}	10^{-3}	10^{-3}	10^{-5}	10^{-7}
BR($t \to q\gamma$)	$9 \cdot 10^{-4}$	10^{-6}	10^{-5}	10^{-7}	10^{-6}	10^{-8}
BR($t \to qZ$)	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-4}	10^{-4}

Table 1: Branching Ratios for FCNC top quark decays as predicted within some SM extensions. Only the order of magnitude is quoted here.

the background when data will be available. In the conclusion (Sec. 5) results are presented and comparison with current limits are showed. Full details of the work are in Ref. [15].

2 Analysis of the FCNC signals

The features that mostly make different the FCNC signal from the background events are: the presence of an isolated, high transverse momentum charged leptons ($p_T > 10 \div 20$GeV) coming from vectorial boson decays; a high-energy isolated photon in the $t \rightarrow q\gamma$ case; large missing energy ($\not{E}_T > 30 \div 40$GeV) from undetected neutrinos in W decays; two hard jets, typically with transverse momentum $p_T > 50 \div 60$GeV, coming from the fragmentation of b and q quarks.
The anomalous top decay has been studied by simulating the production of a $t\bar{t}$ pair from gluon-gluon and quark-antiquark annihilation, then requiring the SM decay for one top ($t \rightarrow bW$) and FCNC decay for the other. The $t\bar{t}$ signal has been generated with TOPREX 4.11 [16], while PYTHIA [17] was used for modeling of quark and gluon hadronization. Only leptonic decay channels of Z and W bosons have been studied, where the lepton could be either e or μ; hadronic bosons decays as well as decays to τ leptons are not considered because of the large QCD background. Both initial and final state radiation (ISR and FSR) were simulated with CTEQ5L parton density functions (PDFs). The generated events were passed through the full detector simulation and digitization, taking into account low luminosity pile-up.
Several SM processes contributing as background have been studied: $t\bar{t}$ production with both top quarks following the standard decay, single-top quark production (t-channel), Z/W+jets, $(W/Z)(W/Z)$+jets, $Zb\bar{b}$ and QCD multi-jet production.
The off-line selected leptons have to be considered isolated when the isolation variable (defined in Ref. [14]) is less than 0.07. High-p_T jets are assumed to come from a b-jet if they have more than 2 tracks and a discriminator value (defined again in Ref. [14]) larger than 2. This choice allows to maximize the b-jet purity while containing the mis-tag with jets from u/c quarks below few percent.
For the FCNC $t \rightarrow \gamma q$ channel the main selection cuts have been optimized as: *a*) 'single electron or single muon' or 'single-photon' criteria at the first level (L1) trigger and High Level Trigger (HLT); *b*) one isolated $\mu^{\pm}$ (with $p_T > 20$GeV) or an $e^{\pm}$ (with $p_T >$30GeV), plus more than 25GeVof missing transverse energy, forming a transverse invariant mass $M_T(l\text{-}\not{E}_T) <$120GeVand a transverse momentum greater than 65GeVfor $p_T(e\text{-}\not{E}_T)$ or 50GeVfor $p_T(\mu\text{-}\not{E}_T)$; *c*) only one jet compatible with b-jet with $p_T >$50GeV, that in combination with the W candidate gives an invariant transverse mass $M_T(bW) <$220GeV; *d*) the isolated photon selected from the trigger satisfying $p_T >$90GeV; *e*) at least one jet incompatible with coming from b quark

and harder than 60GeV; f) the combination of the photon and the light jet in the range 100< $M(q\gamma)$ <250GeV. A fit of the invariant mass shape with a Gaussian and a linear+exponential function (Fig. 1, left) can be used to estimate the combinatorial background. The signal efficiency turns to be $(4.0 \pm 0.4)\%$ and the only process surviving from the SM events is the top pair inclusive decay with an isolated lepton (efficiency $(1.7 \pm 0.1) \cdot 10^{-5}$).

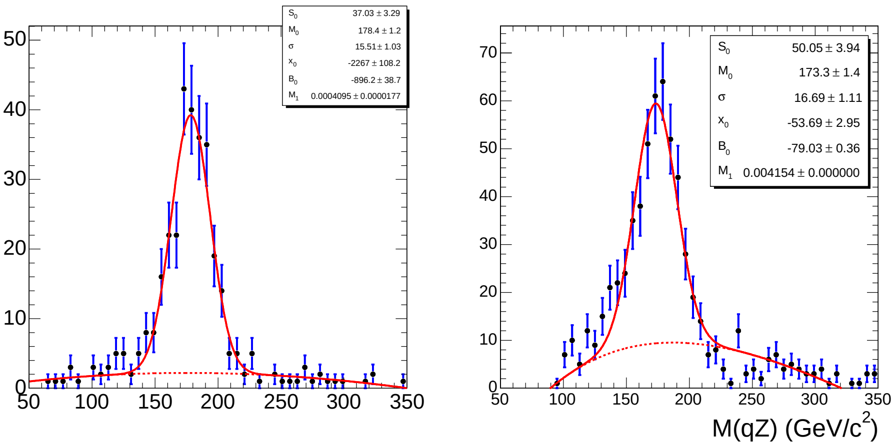

Figure 1: The result of the fit on the $t \to q\gamma$ (left) and $t \to qZ$ (right) signal distribution with a Gaussian summed to a linear plus exponential function.

For the FCNC $t \to qZ$ channel the main selection cuts are: a) 'double electron or double muon' trigger criteria at L1 and HLT levels; b) two isolated $e^{\pm}$ (with $p_T > 20$GeV) or $\mu^{\pm}$(with $p_T > 15$GeV), having an invariant mass ±10GeVaround the nominal Z mass; c) a third lepton with same quality cuts, which, in combination with the missing transverse energy ($\not{E}_T > 35$GeV) has a transverse mass less than 120GeV; d) only one jet compatible with b-jet with $p_T > 60$GeV; e) the invariant transverse mass of the $M_T(bW)$ <220GeV; f) at least one jet which is incompatible with coming from a b quark and satisfying $p_T > 60$GeV; g) invariant mass of this jet and the Z in the range 100< $M(qZ)$ <250GeV. The resulting distribution is presented in Fig. 1 (right), and the number of signal events corresponds to a $(4.4 \pm 0.4)\%$ efficiency. The relevant background sources are the di-leptonic $t\bar{t}$ decay and the $Zb\bar{b}$ production (both with efficiency $\sim 10^{-5}$), that may give origin to the third lepton from the decay of one b-jet.

3 Study of systematic effects

Since in this study the background will be counted in specific 'control regions', systematic effects affecting the absolute background rate have no relevance and only the variables that mark the difference between the control and the signal region are considered.
The uncertainty on the jet energy scale (considered as 3% for p_T(jet) >50GeV) is one of the most important effects, because the number of detected jets can vary in about 15% in both the light and the b-jet selection and a different occurrence of events with a single tagged jet (both light and b-tagged) is induced. Fluctuations related to tracker and muon chambers uncertainties, electromagnetic energy scale and missing energy uncertainty have been simulated and found to be below 1% in all background samples. The impact on the efficiency for b-jet is not an issue here, because the effect of asking a b-tagged object will be directly included in the control region definition.
For what concerns the theoretical description of the signal and background processes, the analysis has found to be sensitive to the description of the heavy quarks fragmentation, since changing the parameter of the Lund model (according with prescriptions in Ref. [18]) can worse the efficiency about 9% for the b-jets and 11% for the light ones. On the other hand, the fact that the main background is $t\bar{t}$ (having exactly the same initial state of the signal and a final state differing only in one jet contents) is instrumental in absorbing the impact of many theoretical uncertainties, as those on ISR/FSR, PDF and underlying event. The residual effects can be measured in a top pair-rich region and subtracted from the signal region.

4 Background estimation driven from data

When the amount of surviving background in both channels is evaluated by counting the number of event filling the last selection, several uncertainties are included, as high statistical fluctuations due to the small number of events, luminosity uncertainties, theoretical error in the cross sections. Here the problem is faced adopting the common solution, to identify specific control regions (suitable to be searched for in future data samples with the lowest systematic error) almost signal-free and rich in only one type of background process. Due to the increased background statistic, with these techniques errors from Monte Carlo are much reduced.
The $t\bar{t}$ (di-leptonic) background for the $t \to qZ$ analysis has been evaluated by requiring the double lepton ($e^{\pm}/\mu^{\pm}$), a large missing energy $\not{E}_T$ >85GeV(to minimize contamination from $Zb\bar{b}$) and one b-jet at least. These events can be used to form a region corresponding to the right side of the $M(ll)$ distribution (Fig. 2, left) where the contaminations from $Zb\bar{b}$ (blue line) and signal (upper plot) are negligible. If the

cut on missing energy is removed and at least two b-jets are required, a region around the Z peak to evaluate $Zb\bar{b}$ amount is obtained. Here the fraction of $t\bar{t}$ events under the peak is significant, but it can be derived from the data-driven estimation above. When the number of events in these control regions is rescaled to the signal one (using factors as 3^{rd} lepton and light jet efficiency, different $\not{E}_T$cut and b-jet multiplicity) the total background is $19.8 \pm 1.6\,(\text{stat}) \pm 2.7\,(\text{syst}) \pm 2.0\,(\text{theor})$ events after $10\,\text{fb}^{-1}$. The $t\bar{t} \rightarrow l + X$ process for the $t \rightarrow q\gamma$ analysis can be measured from a fit of the $M(bW)$ invariant mass shape, in a sample having high W boost ($p_T(W)$ >85GeV) and at least two hard light jets, in order not to suffer from single-top contamination. Rescaling from the different $p_T(W)$ cut and b-jet multiplicity, the top pair background in the signal region after $10\,\text{fb}^{-1}$ is $33.2 \pm 4.6\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 3.0\,(\text{theor})$ events.

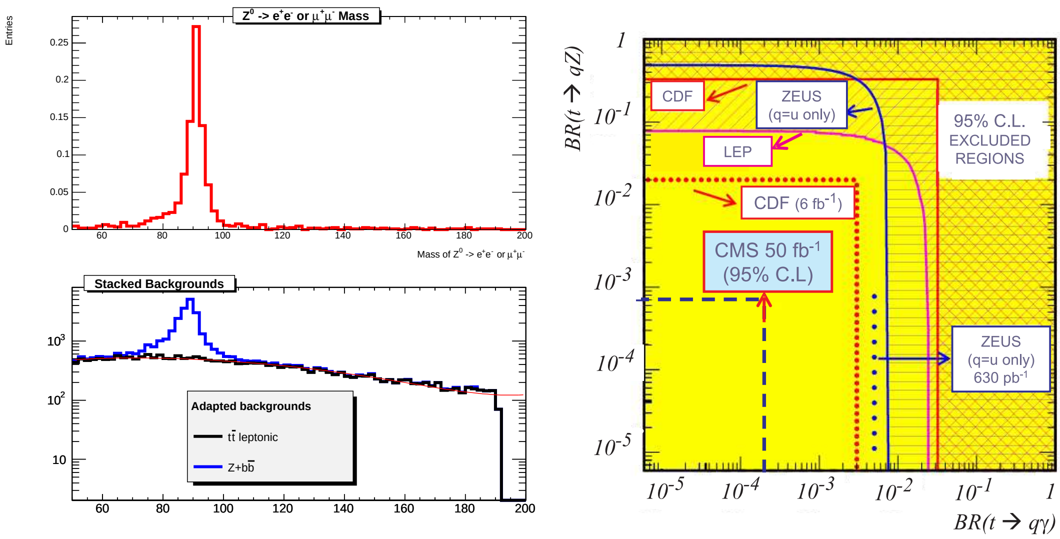

Figure 2: Left: Invariant mass of two same-sign opposite-flavour leptons in the control region defined in the text. A polynomial fit is superimposed to the $t\bar{t}$ background. Right: The 95% C.L. exclusion plot of the analysis after $50\,\text{fb}^{-1}$, compared with the current limits to $t \rightarrow q\gamma$ and $t \rightarrow qZ$ branching ratios.

5 Sensitivity estimation and conclusions

To evaluate the sensitivity reach of the analysis, the S_{12} function [19] is adopted as a significance estimator and corrections from statistical and theoretical errors are included as in Ref. [20]. For a given significance (or confidence level C.L.) and integrated luminosity L, a minimum number N_{min} of $t \rightarrow qZ/\gamma$ events is obtained from that estimator. The related Branching Ratio BR_{FCNC} comes from the formula

$N_{min} = L \cdot \epsilon_S \sigma(t\bar{t}) \cdot BR_{SM} \cdot BR_{FCNC}$, where BR_{SM} is the SM decay from the other top quark and signal efficiency ϵ_S is optimized in the analysis procedure for each cut. After $50\,\mathrm{fb}^{-1}$, a $t \to q\gamma$ ($t \to qZ$) decay can be discovered at 3σ if BR is larger than $1.65(10.4) \cdot 10^{-4}$, while the 95% C.L. exclusion limit is $1.19(7.6) \cdot 10^{-4}$. When these results are compared with the current limits as depicted in Fig. 2 (right), an improvement larger than one order of magnitude can be appreciated. It is worth to observe that even after $1\,\mathrm{fb}^{-1}$, 95% C.L. limits for the $t \to qZ(\gamma)$ will be about $1.0 \cdot 10^{-2}(8.4 \cdot 10^{-4})$, exceeding the sensitivity expected from CDF at the end of Tevatron life ($6\,\mathrm{fb}^{-1}$) and falling below the bounds determined from CP and EW observables. For integrated luminosities larger than some tens of fb^{-1}, constraints firstly on 2HDM and then on top-color and R-violating models can be obtained. Due to the fact that different theories predict different orders of enhancement, the measurements of such processes at the LHC will not only shed light on new physics, but also may indicate some favor for a specific model.

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