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Top-quark physics at LHC: searches for CP violation and flavour changing neutral currents in top-quark decays

Cristina Ferro*
NCU Taipei, Taiwan
E-mail: cristina.ferro@cern.ch

Searches for CP violation and flavour changing neutral currents in top-quark decays by the ATLAS and CMS collaborations are presented, as well as tests of CPT conservation. Results are obtained using both single top and $t\bar{t}$ events produced at 7 and 8 TeV. The trigger and offline strategies are summarized for each measurement. Finally the combination of ATLAS and CMS measurements of the W-boson polarization in top-quark decays is shown. All presented results are in agreement with the Standard Model expectation and no evidence of new physics have been observed.

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*Speaker.

1. Introduction

The top quark is the heaviest particle of the Standard Model (SM) with a measured mass of $173.3 \pm 0.5(\text{stat}) \pm 1.3(\text{syst})$ [1]. Thanks to its high mass the Yukawa coupling with the Higgs field is expected to be close to one. For this reason the top quark is one of the most interesting objects to test the SM. Besides that, since the decay time of the top quark is of $\mathscr{O}(10^{-24})$, much shorter that the hadronization time scale, the top quark represents an unique possibility to study a bare quark free from hadronization effects.

The SM predicts that the top quark decays almost exclusively into a W boson plus a b jet ($V_{tb} \sim 1$), but many extensions of the SM predict the existence of another decay mode: $t \to Zq$, where $q = c, u$. This decay is a flavor changing neutral current (FCNC) decay mode, which is strongly suppressed in the SM by the GIM [2] mechanism.

In this article results on the measurements of the FCNC decay of the top quark, as well as about the searches for evidence of *CP* and *CPT* violation in top-quark physics are presented.

2. Search for FCNC decays in $t\bar{t}$ events.

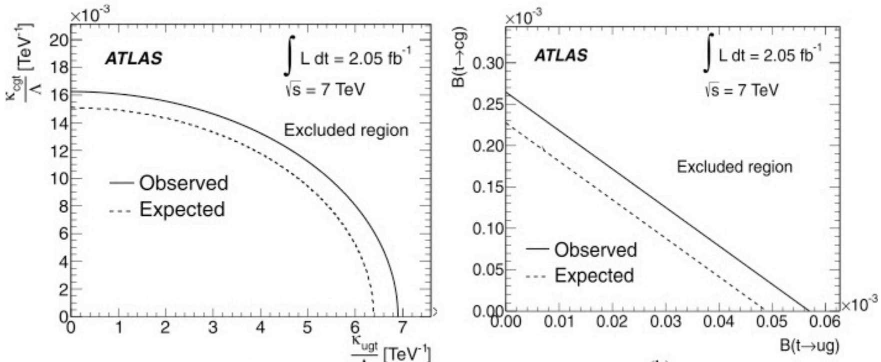
The signature that is searched for is: $t\bar{t} \to Zq + Wb \to llq + l\nu b$. At CMS [3] data were collected with a dilepton trigger while at ATLAS [4] a single lepton trigger has been used. The analyzed CMS dataset corresponds to an integrated luminosity of 5 fb^{-1}, while at ATLAS an integrated luminosity of 2.1fb^{-1} has been used. The upper limit on the $BR(t \to Zq)$ has been computed from the observed number of events, the background prediction, and the fraction of all $t\bar{t} \to Zq + Wb \to llq + lb$ expected to be selected. The observed number of events agrees with the SM prediction and no evidence for FCNC in top quark decays is found. CMS excludes a $t \to Zq$ branching fraction grater than 0.21% at the 95At ATLAS the upper limit on the $BR(t \to Zq)$ has been found to be 0.73% at 95% C.L. In the Table 1 the CMS and ATLAS results are summarized.

Table 1: Observed and expected upper limits on the $BR(t \to Zq)$. The reported results are obtained by ATLAS and CMS with data collected at $\sqrt{s} = 7$ TeV. In the rightmost column the $\pm 1\sigma$ boundaries of the limits are reported.

Experiment	Observed [%]	Expected [%]	$\pm 1\sigma$[%]
ATLAS	0.73	0.93	0.61-1.4
CMS	0.21	0.40	0.30-0.59

3. Search for FCNC decays in single-top events.

A dataset corresponding to 2.05 fb^{-1} has been used by ATLAS in order to search for evidence of the t→qg decay mode [5]. The investigated process is a gluon and a u or c quark coming from the colliding protons and interacting to produce a single top. This anomalous production of the top via 2→1 process, $qg \to t$ is preferable with respect to the $t \to qg$ since it is almost impossible to distinguish the decay of the top in a gluon plus a jet from the standard decay mode $t \to Wb$.



(a) (b)

Figure 1: Upper limits on the coupling constants k_{ugt}/Λ and k_{cgt}/Λ and on the branching fractions $\mathrm{t} \to \mathrm{ug}$ and $\mathrm{t} \to \mathrm{cg}$.

Candidate events for this analysis are selected in the semileptonic top-quark decay signature. They are then classified as signal- or background-like events by using several kinematic variables as input to a neural network. No signal is observed in the neural network output distribution and a Bayesian upper limit is estimated on the production cross section. The observed upper limit on the cross-section multiplied by the $\mathrm{t} \to \mathrm{Wb}$ branching fraction is measured to be $\sigma_{\mathrm{qg}\to\mathrm{t}} \times \mathrm{B}(\mathrm{t} \to \mathrm{Wb}) <$ 3.9 pb at 95% confidence level. This upper limit is then converted using a model-independent approach into upper limits on the coupling strengths $k_{ugt}/\Lambda < 6.9 \cdot 10^{-3}$ TeV^{-1} and $k_{cgt}/\Lambda <1.6 \cdot 10^{-2}$ TeV^{-1}, where Λ is the new physics scale, and on the branching fractions $\mathrm{B}(\mathrm{t} \to \mathrm{Wb}) < 5.7 \cdot 10^{-5}$ and $\mathrm{B}(\mathrm{t} \to \mathrm{cg}) < 2.7 \cdot 10^{-4}$. In the Figure 1 the upper limits on the coupling constants k_{ugt}/Λ and k_{cgt}/Λ and on the branching fractions $\mathrm{t} \to \mathrm{ug}$ and $\mathrm{t} \to \mathrm{cg}$ are shown.

4. Search for CP violation in the single-top events.

The goal of this analysis is to search for CP violation in the decay of single top quark produced in the t-channel (Figure 2) using the lepton+jets final state, in which the top is predicted to be highly polarized. The analyzed dataset corresponds to an integrated luminosity of 4.7fb^{-1} [6], collected by ATLAS experiment using a single lepton trigger.

In the SM the couplings of the Wtb vertex are reduced to V_L =1 and $V_R = g_{R,L}$ =0 at leading order. A forward-backward asymmetry with respect to the normal to the plane defined by the W momentum and the top quark polarization, A_N^{FB}, is used to probe the complex phase of g_R. A non-zero value of this asymmetry signals a CP violating contribution to the Wtb vertex not expected in the SM. In Figure 3 the reference system in which the A_N^{FB} is computed is shown. In particular the normal direction $\vec{N}$ is defined as: $\vec{N} = \vec{s_t} \times \vec{q}$, where $\vec{s_t}$ is the polarization of the spectator quark

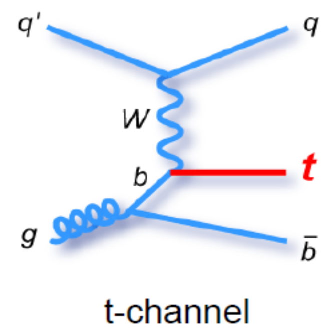


Figure 2: Feynman diagram of the t-channel single-top production.

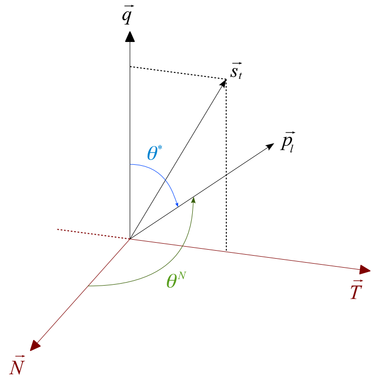


Figure 3: Definition of the two directions $\vec{N}$ and $\vec{T}$ given the direction of polarisation of the top quark, $\vec{s}_t$, and the momentum of the W boson, $\vec{q}$ in the helicity basis. The angles which are shown are defined as the angles between their reference directions and the momentum direction of the charged lepton, $\vec{p}_l$.

(labeled q in Figure 2), while $\vec{q}$ is the momentum of the W boson in the top quark rest frame. The distribution of $cos\theta^N$ is measured in the muon and electron channel respectively. In Figure 4 the obtained $cos\theta^N$ distribution is plotted for the electron and muon channel separately.

The final measured value of the asymmetry is $A_N^{FB} = 0.031 \pm 0.065$ (stat.)$^{+0.029}_{-0.031}$(syst). Taking this measurement together with the theoretical prediction of the top quark polarisation, the first experimental limits on $Im(g_R)$ are determined to be [-0.20,0.30] at 95% CL (Figure 5). Both the measurement and the limit are in good agreement with the SM.

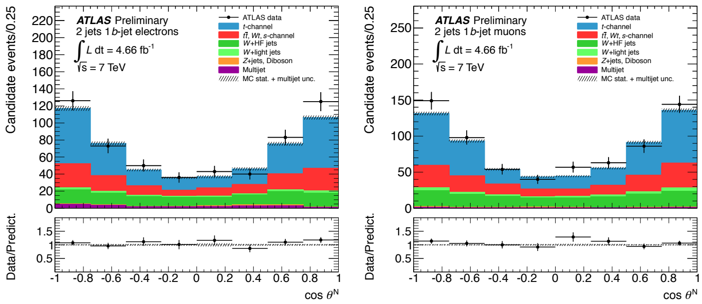


Figure 4: Reconstructed angular $cos\theta^N$ distribution obtained at selection level for electron (left) and muon (right) channels. ATLAS data, simulated signal and different background contributions are shown.

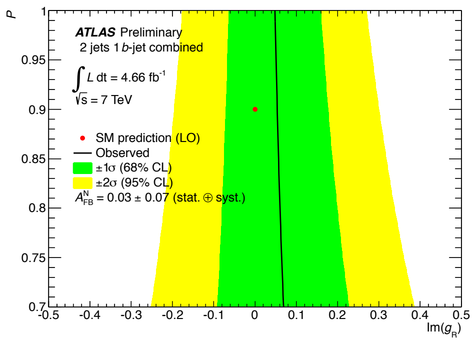


Figure 5: Constraints on the top quark polarisation versus I(g_R) from the A_N^{FB} measurement. The allowed regions at 68% and 95% CL are shown. The SM prediction at leading order ($Im(g_R)$ = 0 and P = 0.9) is also shown.

5. Measurement of the top–anti-top mass difference.

This analysis has been performed by the CMS experiment using data collected at $\sqrt{s}$ =8 TeV, for a total integrated luminosity of 18.9 fb^{-1} [7]. It represents an extension of the CMS measurement of the top anti-top mass difference using 7 TeV data [8].

The invariance of the SM under the CPT transformation predicts equality of particle and antiparticle masses. However, there are many extensions of the SM, which predict CPT-violating effects, and the large amount of top quarks produced by the LHC provide an unique opportunity to test the CPT symmetry of the heaviest particle of the SM. The semileptonic $t\bar{t}$ channel has been used for this analysis. Events were collected with a single lepton trigger. The charge of the hadronically decaying top is computed from the charge of the leptonically decaying top. The mass difference between the top quark and the antitop quark, $\Delta m_t = m_t - m_{\bar{t}}$, is measured with the Ideogram method [9] on a sample of lepton+jets $t\bar{t}$ events. The final result is: $\Delta m_t = -272 \pm 196$ (stat.) $\pm$ 122 (syst.) MeV. In Table 2 the results for the electron and muon channels are separately shown with their statistical uncertainty. This result is in agreement with the SM hypotesis of CPT conservation. This results is a factor two more precise than any of the previously published measurements [10][11].

Table 2: Top anti-top mass difference results for the muon, electron channel and their combination are presented. The uncertainty in the table is statistical only.

lepton channel	Δm_t (MeV)
electron	-325 $\pm$ 294 (stat)
muon	-230 $\pm$ 264 (stat)
combination	-272 $\pm$ 196 (stat)

6. Combination of the ATLAS and CMS measurements of the W-boson polarization in top-quark decays

The V-A structure of the Wtb vertex can be tested by measuring the polarization of W bosons produced in top-quark decays. The fractions of events containing W bosons with longitudinal, left-handed and right-handed polarization (helicity fractions), are predicted by the perturbative QCD at next to next to leading order. The helicity fractions can be measured using events in which a top-quark pair is produced taking advantage of the large $t\bar{t}$ sample. The distribution of the angle between the direction of the charged lepton and the direction opposite to the top quark, both in the rest frame of the W boson ($cos\theta^*$), is sensitive to the W polarization. By measuring this angle an estimation of the helicity fractions is possible.

Both ATLAS and CMS collaborations performed the measurements of the helicity fractions and their results have been combined [12]. Proton-proton collisions at $\sqrt{s}$ =7 TeV, collected in 2010 and 2011, have been used for this analysis. The semileptonic $t\bar{t}$ decay is used by both collaborations. The measurements are combined using the BLUE method [13]. All measurements are weighted linearly in the combination under the constraints that the total uncertainty is minimal and that the estimator is unbiased. By construction, the sum of the three observables, F_0, F_L, F_R is constrained to 1. In the current analysis, measurements of F_0 and F_L are combined while the F_R is obtained as: $F_R = 1 - F_0 - F_L$. The final combined result for the helicity fractions is: F_0 =0.626$\pm$0.034(stat.)$\pm$0.048(syst.), F_L =0.395$\pm$0.021(stat.)$\pm$0.028(syst.), F_R =0.015$\pm$0.034.

7. Conclusions

Many different measurements searching for FCNC as well as CP and CPT violation, using top quark pairs and single top events, are provided by ATLAS and CMS experiments. No evidence of new physics was found. Many other measurements are underway, using the full statistics recorded by the ATLAS and CMS experiments. Both collaborations are preparing the new data taking at 13-14 TeV which will allow them to investigate a completely new energy scenario.

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