Top Quark Couplings and Search for New Physics at the LHC

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Abstract. The search for new physics in top quark decays at the LHC is reviewed in this paper. Results from ATLAS [1] and CMS [2] experiments on top quark decays within the Standard Model are presented together with the measurements of the W boson polarizations and the study of the structure of the Wtb vertex. As a natural step forward, the experimental status on measurements sensitive to top quark couplings to gauge bosons (γ, Z, W and H) is reviewed as well as possible top quark decays Beyond the Standard Model (MSSM and FCNC).

1. Introduction

The top quark is the heaviest known quark ($m_t = 173.18 \pm 0.94$ GeV [3]) ever discovered. With a charge of $+2/3|e|$ (e is the electron charge) and spin 1/2, the top quark completes the 3 family structure of the Standard Model (SM). One of the stricking features of this quark is precisely the value of its mass, so distinctive from the other fermions, which may suggest it plays a more fundamental role in the eletroweak symmetry breaking mechanism. In the SM, top quarks are expected to decay mostly through $t \to bW$, being the branching ratios $Br(t \to sW) \leq 0.18\%$ and $Br(t \to dW) \leq 0.02\%$ diminut when compared with the dominant decay channel [4]. The lifetime, at least one order of magnitude smaller than the typical hadronization time scale $O(10^{-23})$ s, was measured to be $\tau_t = (3.29^{+0.90}_{-0.67}) \times 10^{-25}$ s [5]. This implies top quarks decay before hadronization may take place and spoil the spin information propagated to the final state decay products. Once again, top quarks show remarkable distintive features when compared to the other quarks. At the LHC, top quarks are mainly produced in pairs through gluon fusion or quark anti-quark annihilation with a predicted cross section of $164.6^{+11.4}_{-15.7}$ pb (approx. NNLO) at 7 TeV [6]. There is however a significant number of top quarks which are produced singly through the t-channel ($gq' \to qt\bar{b}$), associated production ($bg \to Wt$) and s-channel ($q\bar{q}' \to t\bar{b}$) single top production. The production cross sections are, respectively, $64.6^{+2.7}_{-2.0}$ pb [7] (NNLO+soft gluon corrections), 15.7 ± 1.1 pb [8] (approx. NNLO) and 4.6 ± 0.2 pb [9] (NNLL resummation). In this paper the experimental status of top quark measurements sensitive to gauge bosons couplings (W, γ, Z and H) and decays beyond the SM are reviewed. As most analysis described in the paper rely on the lepton+jets and dilepton final states, or variations from these, it is appropriate to shortly mention them.

In the lepton+jets channel, one isolated lepton (e or μ) is required in the event selection as well as at least 4 jets for both ATLAS [10, 11] and CMS [12, 13]. While for muons, the transverse momentum ($p_{\rm T}$) selection is similar for both experiments, selected electrons at ATLAS are harder (with transverse energy, E_{T}, above 25 GeV) than in CMS ($E_{\mathrm{T}} > 20$ GeV). Softer jets, with $p_{\mathrm{T}} > 25$ GeV, are also selected by ATLAS compared to CMS ($p_{\mathrm{T}} > 30$ GeV). The use of a transverse missing energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) cut together with the requirement that at least one jet had to be tagged as a b-jet was performed by ATLAS while CMS required at least two b-tagged jets with no $E_{\mathrm{T}}^{\mathrm{miss}}$ condition.

In the dilepton channel, events with two isolated leptons (e or μ) and two jets, from which at least one is b-tagged, are selected by both CMS [14, 13] and ATLAS [15]. While at least 2 opposite charge leptons are requested by CMS, exactly 1 pair is imposed by ATLAS. In order to reduce potential contributions from the Z+jets background, events are required to have the invariant mass of the two opposite charge leptons ($m_{\ell^+\ell^-}$) outside a mass window of at least 10 GeV around the central value of the Z mass. Both CMS and ATLAS impose $E_{\mathrm{T}}^{\mathrm{miss}}$ cuts to events and ATLAS, for the $e^{\pm}\mu^{\mp}$, requires the scalar sum of jets and leptons transverse energies (H_{T}) to be above 130 GeV.

2. The Wtb vertex structure

In the SM, the Wtb vertex has a $(V-A)$ structure where, V and A, are the vector and axial-vector contributions to the vertex. One way of probing the structure of the vertex, is to study top quark decays to W-bosons and b-quarks ($t \to bW$). The W bosons produced in these decays can have longitudinal, left-handed or right-handed polarizations with fractions F_0, F_{L} and F_{R}, respectively equal to 0.687 ± 0.005, 0.311 ± 0.005 and 0.0017 ± 0.0001 at NNLO [16], in the SM. The helicity fractions were extracted from a direct fit to the top quark decay products angular distribution, $\cos\theta$, using templates from simulation. Alternatively, angular asymmetries (A_+, A_- and A_{FB}), built from $\cos\theta$, were also used by ATLAS [17]. The angle θ is measured between the momentum direction of the charged lepton from the decay of the W boson, and the reversed momentum direction of the b-quark from the decay of the top quark, both boosted into the W boson rest frame. CMS [18] measured the helicity fractions to be $F_0 = 0.567 \pm 0.074(\mathrm{stat}) \pm 0.047(\mathrm{syst})$, $F_{\mathrm{L}} = 0.393 \pm 0.045(\mathrm{stat}) \pm 0.029(\mathrm{syst})$ and $F_{\mathrm{R}} = 0.040 \pm 0.035(\mathrm{stat}) \pm 0.044(\mathrm{syst})$. The correspondent measurements from ATLAS [19] are, $F_0 = 0.67 \pm 0.03(\mathrm{stat}) \pm 0.06(\mathrm{syst})$, $F_{\mathrm{L}} = 0.32 \pm 0.02(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ and $F_{\mathrm{R}} = 0.01 \pm 0.01(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. All these measurements are consistent with SM expectations. The measured fractions were used to probe the existence of anomalous Wtb couplings. Exclusion limits on the real components of the anomalous couplings g_{L} and g_{R} were set at 68% and 95% CL (Figure 1). The region of g_{R} around 0.8 in the ATLAS plot is disfavored by the current experimental measurements on the single top quark production cross sections at Tevatron and LHC. Once the limits depend on V_{tb}, it is worth mentionning the current experimental status of these measurements (Table 1) which assume the SM and negligeable decays to $t \to sW$ and $t \to dW$, when compared to the dominant channel. The current V_{tb} measurements precision is at the level of 5%-10%.

3. Top quark couplings to gauge bosons

Following the discussion on the Wtb vertex and V_{tb}, it is natural to ask what is the current LHC status on the measurements of the couplings of the top quarks to other bosons (γ,Z,W and H). Several dedicated analyses were developed by both ATLAS and CMS, relying to a great extent on the lepton+jets and dilepton channels discussed previously, with the exception that activity from the gauge bosons is expected to be present as well in the events. These are particularly challenging channels which should be improved as both CMS and ATLAS collect more data over time. ATLAS [20] looked into $t\bar{t}\gamma$ production and, by fitting the data with templates for prompt photons (well isolated) and hadron fakes, measured the cross section to $\sigma(t\bar{t}\gamma) = 2.0 \pm 0.5$ (stat) $\pm$ 0.7 (syst) $\pm$ 0.08 (lumi.) pb, for events with photons with $p_{\mathrm{T}} >8$ GeV for which the expected SM cross section is 2.1$\pm$0.4 pb (at 7 TeV). For the $t\bar{t}Z$ channel ATLAS [21] observes 1 candidate after event selection against a background of

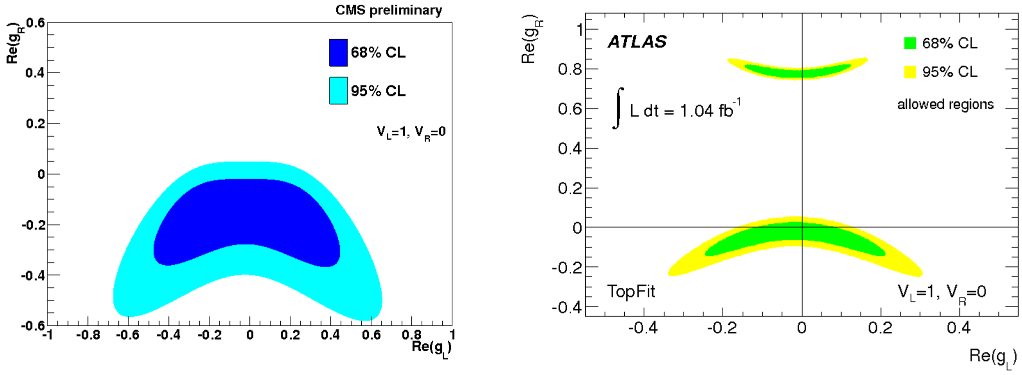

Figure 1. CMS(left) and ATLAS(right) allowed regions, at 68% and 95% CL, on the anomalous coupling plane ($g_{\rm L}$,$g_{\rm R}$), for $V_{\rm R}$=0 and $V_{\rm L}$=1.

$0.28^{+1.57}_{-0.14}$. A 95%CL limit of 0.71 pb was set on the $t\bar{t}Z$ production (which compares with a SM prediction of 0.14 pb). CMS [22] searched, in two independent channels (three and two same charge leptons), for $t\bar{t}V(V = W, Z)$. While the $t\bar{t}V$ combined cross section was measured to be $\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(stat)^{+0.05}_{-0.04}(syst)$ pb at 7 TeV, the $t\bar{t}Z$ cross section (obtained from the trilepton channel) was $\sigma(t\bar{t}Z) = 0.30^{+0.14}_{-0.11}(stat)^{+0.04}_{-0.02}(syst)$ pb (Figure 2).

Both ATLAS [23] and CMS [24] searched for $t\bar{t}H$ production using data collected at 7 TeV with a total integrated luminosity of 5 fb^{-1}. While ATLAS studied the single lepton channel, where the Higgs boson is assumed to decay to a pair of b-quarks, CMS looked into both the single and dilepton channels. As no evidence for signal was found, combined upper limits, at 95% CL, were set on cross section times branching ratio by ATLAS and CMS to $\sigma_{t\bar{t}H} \times Br(H \rightarrow b\bar{b}) \leq$13.1 pb (10.5 pb expected), $\sigma_{t\bar{t}H} \times Br(H \rightarrow b\bar{b}) \leq$3.8 pb (4.6 pb expected), respectively.

4. Top quark decays beyond the SM

In the pursuit of new physics in the top quark sector, the decays play a fundamental role. Not only they may reveal the presence of new Physics Beyond the SM, as predicted for instance by the Minimal Supersymmetric Model (MSSM) but could even show that decays with very low SM branching ratios, like Flavor Changing Neutral Currents (FCNC), non visible at tree level

Table 1. Current status of $V_{\rm tb}$ measurements from both ATLAS and CMS.

ATLAS	**Measurement (SM)**
t-channel (@ 7TeV)	$\|V_{tb}\| = 1.13^{+0.14}_{-0.13}$
(arXiv:1205.3130)	$|V_{tb}| \geq$0.75 @ 95% CL ($|V_{tb}$ in [0,1])
t-channel (@ 8TeV,5.8 fb^{-1})	$\|V_{tb}\| = 1.04^{+0.10}_{-0.11}$
(ATLAS-CONF-2012-132)	$|V_{tb}| \geq$0.80 @ 95% CL ($|V_{tb}$ in [0,1])
Wt-prod. (PLB 716 (2012) 142)	$\|V_{tb}\| = 1.03^{+0.16}_{-0.19}$
CMS	**Measurement (SM)**
t-channel (@ 7TeV)	$\|V_{tb}\|$=1.02±0.046(exp)±0.017(th.)
(arXiv:1209.4533)	$|V_{tb}| \geq$0.92 @ 95% CL ($|V_{tb}$ in [0,1])
t-channel (@ 8TeV,5. fb^{-1})	$\|V_{tb}\|$=0.96±0.08(exp)±0.02(th.)
(CMS PAS TOP-12-011)	$|V_{tb}| \geq$0.81 @ 95% CL ($|V_{tb}$ in [0,1])
Wt-prod. (@ 7TeV)	$\|V_{tb}\| = 1.01^{+0.16}_{-0.13}$(exp.)$^{+0.03}_{-0.04}$(th.)
(arXiv:1209.3489)	$|V_{tb}| \geq$0.79 @ 95% CL ($|V_{tb}$ in [0,1])

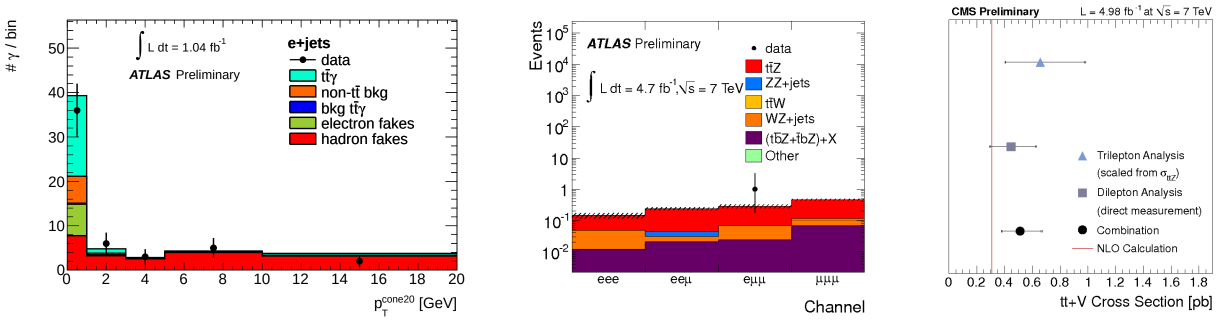

Figure 2. (left) ATLAS template fit to $t\bar{t}\gamma$ events in the electron channel; (middle) ATLAS expected and observed numbers of events for the $t\bar{t}Z$ signal region; (right) CMS measurements of the $t\bar{t}V$ production cross section.

and very much suppressed at one loop due to the GIM mechanism in the SM ($Br < 10^{-12}$), could be experimentally detected. In addition to the theorectical motivation to search for these decays, the stronger motivation is perhaps more of experimental nature: to look for signs of new physics where the SM expects essentially no contribution.

Both CMS [25] and ATLAS [26] looked for MSSM decays of top quarks to charged Higgs ($t \to H^+b$) when $m_{H^\pm} < m_t$. If $\tan\beta$ is particularly suited, it may happen the dominant decay mode of the charged Higgs is through the decay $H^+ \to c\bar{s}$. As no sign of new physics was found, best 95% CL upper limits were set on the branching fractions $Br(t \to H^+b)$ in the range 2-4% for Higgs boson masses between 80 and 160 GeV and assuming $Br(H^+ \to \tau^+\nu_\tau) = 1$.

In the SM, FCNC decays ($t \to qX, X = \gamma, Z, g, H$) are forbidden at tree level and much smaller than the dominant decay channel. ATLAS [27] and CMS [28] searched for signs of $t \to qZ$ and, as no new physics was found, observed limits at 95% CL were set on $Br(t \to qZ) \leq 0.73\%$ (ATLAS) and $Br(t \to qZ) \leq 0.27\%$ (CMS).

5. Conclusions

Top quark studies are well under way at the LHC. Although no new physics was seen yet in the top quark physics, the performance of the LHC and the ATLAS and CMS experiments has been remarkable. The LHC is entering a new era of precision studies for the top quark physics.

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6. References

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