PROCEEDINGS OF SCIENCE

Measurement of the properties of top quarks in decays with the CMS detector

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Several measurements of top quark properties are presented using data collected by the CMS experiment during the years 2011 and 2012. The top quark polarization as well as the polarization of W bosons in top quark decays are measured. The W-boson helicity fractions and angular asymmetries are extracted and limits on anomalous contributions to the Wtb vertex are determined. Furthermore, a search for flavor changing neutral currents in top quark decays is presented using a sample of top quark pair event candidates decaying via Wb and Zq into $l\nu$b and llq events. The flavor contents in top quark pair events are measured using the fraction of top quarks decaying into a W-boson and a b-quark relative to all top quark decays, R=BR(t→Wb)/∑(BR(t→Wq)). The top quark charge is measured, using the charge correlations between high-p_{T} muons from W boson decays and soft muons from B-hadron decays in b jets. First measurements of the associate production of top quark pairs with vector bosons are also presented.

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1. Introduction

With the discovery in 2012 of a new boson by both CMS and ATLAS Collaborations, strong candidate to be the Standard Model (SM) Higgs boson, a huge step was taken towards understanding the mechanism of symmetry breaking, which was one of the main goals of the entire LHC physics program. Now, very important questions are still being answered at the LHC, such as how this boson couples to other massive bosons and fermions, and whether or not physics beyond the SM can be seen at the scales being currently probed.

The physics of the top quark plays a very important role in these issues. Measuring couplings of top quarks to Higgs is essential for a deeper understanding of the SM mechanisms. On the other hand, if new physics exists, one can naively expect that it will manifest itself in final states involving top quarks, rather than in other better-exploited sectors of the SM.

Measurements of the top-quark properties, both at production and at decay, are an excellent testing ground to the SM. At the LHC, such measurements are already reaching enough precision to verify the existence of new physics. For instance, in the SM top quarks decay almost exclusively into a b quark and a W boson; couplings of new particles to the top quark would alter the properties of the Wtb vertex, and that could already be detected on LHC measurements.

The helicity of the W boson in top decays is one of these properties: it probes directly the structure of the Wtb vertex. Thus, comparisons of the W-boson helicity measurements to SM predictions can automatically constrain anomalous couplings to the vertex. Measurements of the W-boson helicity for top quark production in several final states, using the CMS detector [1], are presented in this contribution. Additional SM tests are performed using CMS data, on measurements of the Branching Ratio of top decaying to b quarks, from which an indirect measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{tb} is derived. Divergencies from these measurements to the SM expectations could be indicative of signs of fourth generation. Dedicated searches for specific top-quark decays modes, different from those predicted by the SM, are also performed: we discuss a CMS search for flavor changing neutral currents in $\mathrm{t}\rightarrow\mathrm{Z}q$ events.

The production of $\mathrm{t\bar{t}}$ associated to gauge bosons are of special interest in the LHC physics program since their cross-sections are too low to be measured with high precision at the Tevatron. Properties of $\mathrm{t\bar{t}}$ couplings to bosons can be inferred from the cross-sections and angular distributions observed in such processes. We present here measurements of associated productions of $\mathrm{t\bar{t}}$ with W and Z bosons. The search for $\mathrm{t\bar{t}}$ associated to the Higgs boson was presented in another session in this conference, and is not reported here.

2. W-boson helicity and anomalous couplings in top decays

The W-boson helicity fractions are very sensitive to the Wtb vertex couplings, and can probe signs of anomalous Wtb couplings. They can be measured from θ^*, which is defined for the top quark decay products as the angle between the down-type fermion direction and the negative b-jet direction in the W rest frame. The distribution of $\cos(\theta^*)$ is a trivial analytical function of the right, longitudinal and left-handed helicity fractions, F_R, F_0, F_L. Therefore, new helicity states can be derived from a SM-like simulated $\mathrm{t\bar{t}}$ sample by reweighting each event to new helicity configurations as a function of their generated $\cos(\theta^*)$ distributions. The measured fractions are retrieved by comparing the data to simulations with different helicity hypothesis in a likelihood fit.

Three measurements are presented: firstly, samples enriched of single-top quark events are selected from 1.14 (5.3) fb^{-1} of pp collision data at 7 (8) TeV. Final states with exactly one muon and 2 jets were considered. The other two measurements use $\mathrm{t\bar{t}}$ events selected on data samples from 7 TeV pp collisions, corresponding to an integrated luminosity of approximately 5 fb^{-1}. In one of the analyses, dileptonic $\mathrm{t\bar{t}}$ decays are considered. Events with at least 2 isolated leptons and 2 jets are selected, optimized to contain $\ell\ell$+jets final states from top decays, where ℓ is an isolated electron or muon. Finally, an analysis using semileptonic $\mathrm{t\bar{t}}$ (ℓ+jets) is performed, on a sample containing events with exactly one ℓ and at least 4 selected jets.

Backgrounds from multijet (QCD), W-boson and Drell-Yan with associated jet events are rejected by requiring that at least 2 jets are b-tagged in the ℓ+jets final state measurement. The other measurements require at least one b-tag. QCD and Drell-Yan+jets events are further reduced by additional requirements either on the W transverse mass or on the transverse missing energy.

Although the selection in the first measurement is optimized for single-top events topology, a large fraction of $\mathrm{t\bar{t}}$ and W+jets events are also selected. So, in the reweight for new helicity states and likelihood fit, events from $\mathrm{t\bar{t}}$ have to be included, expanding the "signal" definition to both single-top quark and $\mathrm{t\bar{t}}$ events passing the selection criteria. In the $\ell\ell$+jets channel, the very low backgrounds, mainly from dibosons, single-top events and DY+jets, are estimated from Monte Carlo simulations. Backgrounds are larger for the ℓ+jets measurement, where the W+jets and DY+jets normalization and shape are estimated in control samples in the data.

The W-helicity fractions are measured on likelihood fits to the $\cos(\theta^*)$ distribution assuming that $F_0 + F_L + F_R = 1$. Thus, only two of the fractions are free in the fitting procedure. Additionally, the normalization of the W+jets background is left free in the likelihood fit for the single-top topology analysis, while in the others this is kept fix to the estimations, while the normalization of the $\mathrm{t\bar{t}}$ sample is a free parameter of the fit. One additional measurement is performed on ℓ+jets final state, where the right-handed helicity fraction is set to 0, corresponding to the SM prediction, within the experimental uncertainties. Only two parameters, namely F_0 and the normalization of the $\mathrm{t\bar{t}}$ sample, are free in this (2D) measurement. For this measurement, the helicity information from the hadronically decaying top ($|\cos^{\mathrm{had}}(\theta^*)|$) is also used.

The measurements are summarized in Table 1. All results are compatible with the NNLO SM predictions of $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$ and $F_R = 0.0017 \pm 0.0001$ [5].

The measurements on the ℓ+jets channel, presented for the first time in this Conference, are currently the world's most precise.

Process	F_0±(stat.)±(syst.)	F_L±(stat.)±(syst.)	F_R±(stat.)±(syst.)
Single-top topology	0.713±0.114±0.023	0.293±0.069±0.030	-0.006±0.057±0.027
$\ell\ell$+jets	0.698±0.057±0.063	0.288±0.035±0.040	0.014±0.027±0.042
ℓ+jets	0.682±0.030±0.033	0.310±0.022±0.022	0.008±0.012±0.014
ℓ+jets (2D)	0.685±0.017±0.021	0.315±0.017±0.021	fixed at 0

Table 1: Measurements of the W-boson helicity fractions in top decays by the CMS Collaboration.

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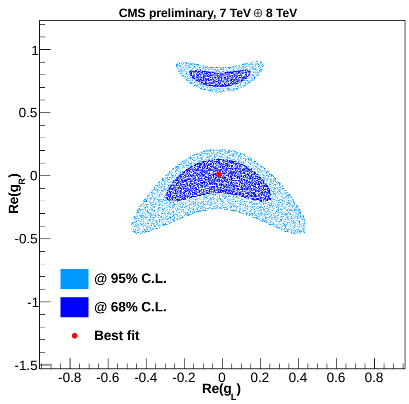
The measured fractions were used to set limits on anomalous couplings to the Wtb vertex. Using the most general 6 dimension Lagrangian, the couplings V_L, V_R, g_L and g_R are complex and =0, except $\mathrm{Re}(V_L)$, which is equal the CKM matrix element $V_{\mathrm{tb}} = 1$. Limits on the $\mathrm{Re}(g_R)$ versus $\mathrm{Re}(g_L)$ are derived from the measured fractions, setting all other couplings to their SM values. Results are presented in Fig.1 for the single-top topology and ℓ+jets analyses.



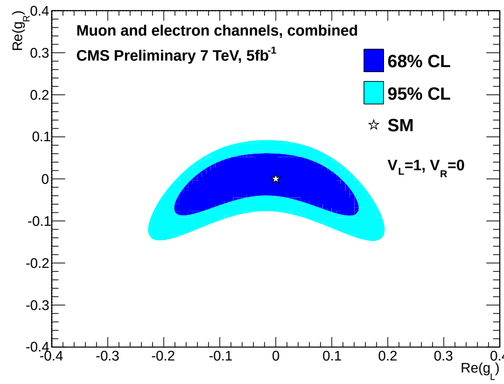


Figure 1: Limits on anomalous couplings derived from W-boson helicity fraction measured in the single-top topology (left) and ℓ+jets (right) final states.

3. Measurement of the ratio B(t→Wb)/∑(BR(t→Wq))

Using pp data at $\sqrt{s} = 8$ TeV, corresponding to 16.7 fb^{-1}, CMS has measured [6] of the ratio of the Branching Ratios (BR) R=B(t→Wb)/B(t→Wq), where B(t→Wb) is the BR of the top decaying to b quarks and B(t→ Wq) the BR of the top decaying to light quarks. A high-purity $\mathrm{t\bar{t}}$ sample in the $\ell\ell$+jets decay mode was selected.

The ratio was measured using a model based on 5 parameters: the b-tagging efficiency, the efficiency for the b-tagging criteria to accept light jets (mistags), the fractions of events with two, one or no top quarks selected and correctly reconstructed. A very important feature of this measurement is that it does not rely on the simulation as much as other analyses, since the model parameters are retrieved from the data and only verified with simulated events. Therefore, uncertainties from event modeling are reduced.

Events where none or only one top is correctly reconstructed correspond to background events or to $\mathrm{t\bar{t}}$ events where at least one of the jets is missed and the top is reconstructed with a wrong choice of jet. Single-top events correctly reconstructed also contribute to the "one top" category. The number of top quarks with misassigned jets was estimated in data using the distribution of the invariant mass of the lepton-jet pairs. Distributions of wrongly reconstructed jets were built rotating the components of the b-jet momentum, or using in the reconstruction a b-jet of another event. For top quarks correctly reconstructed, the distribution is expected to fall-off around $\sqrt{m_{\mathrm{t}}^2 - m_{\mathrm{W}}^2} = 156$ GeV/c^2; therefore, the wrongly reconstructed distribution can be normalized on the tails of the data distribution. This technique was applied in data and cross-checked in simulation, as shown in Fig. 2 (a). The two remaining parameters in the model, the efficiencies for b-tagging and mistags, were measured using a multi-jets (QCD) sample as described elsewhere [7].

The model for the observation of different b-tag multiplicities as a function of R and the multiplicities observed in the data, compared to the simulation, are shown in Fig. 2 (b) and (c), respectively. The measurement yields $R=1.023^{+0.036}_{-0.034}$, in agreement with the SM. If the requirement $R \leq 1$ is imposed, the limit $R > 0.945$ is obtained at 95% C.L. Assuming unitarity constraint on the CKM matrix, the interval for the CKM matrix element $|V_{tb}|$ as 0.972-1.000 is derived at 95% C.L.

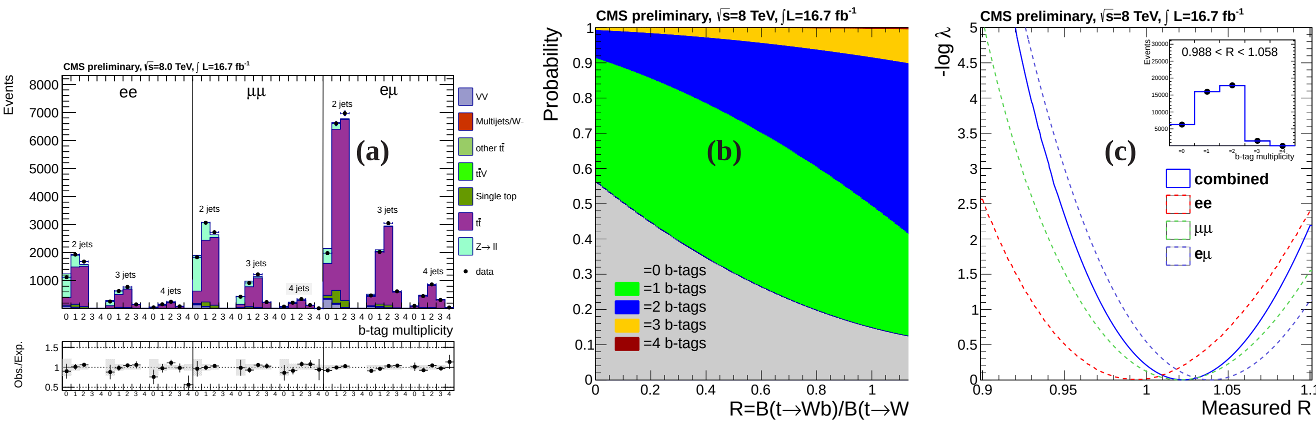


Figure 2: (a) Observed b-tag multiplicity in data and simulation. (b) Model for R as a function of the b-jet multiplicities. (c) Likelihood using the tag multiplicity model to measure the ratio in each channel.

4. FCNC in $\mathrm{t\bar{t}}$

Although allowed, top quark decays in the $\mathrm{t} \to \mathrm{Z}q$ mode is highly suppressed on the SM, being its branching fraction $\sim 10^{-14}$. However, some models beyond the SM predict a substantial enhancement of this decay, making it visible at the LHC.

The search is performed on a $\mathrm{t\bar{t}}$ sample corresponding to an integrated luminosity of 19.5 fb^{-1} of pp at 8 TeV, where one of the top quarks decays according to the SM prediction and the other one via flavor changing neutral current (FCNC), being the complete process $\mathrm{pp} \to \mathrm{t\bar{t}} \to \mathrm{Z}q\,\mathrm{Wb} \to (\mathrm{t} \to \ell\ell j)(\mathrm{t} \to \mathrm{b}\ell\nu)$, with 3 isolated leptons and at least 2 jets in the final state.

While for the signal sample exactly 1 btag was required, the expected background was estimated using control samples with similar selection criteria as the signal, but different btag multiplicity. The backgrounds from di-boson and Drell-Yan (with no b jets) and $\mathrm{t\bar{t}}$, tbZ, $\mathrm{t\bar{t}Z}$ and $\mathrm{t\bar{t}W}$ (with two b jets) are determined in these control samples, yielding 3.14 ± 5.1 events. This was verified to agree with the expected background estimated from the Monte Carlo simulated samples, 3.19 ± 2.37.

With only one event observed, the limit on the Branching Fraction for $\mathrm{t} \to \mathrm{Z}q$ is derived as 0.07% at 95% C.L.

5. Associated production $\mathrm{t\bar{t}}$+Z and $\mathrm{t\bar{t}}$+W

CMS has measured [9] the associate production $\mathrm{t\bar{t}}$+V, with V=W or Z, using two independent final states: firstly, trilepton final states with 4 jets, at least 2 of them b-tagged, and 3 leptons, at least 2 of them of the same flavor and opposite charge were considered. These requirements aimed to select events from the process $\mathrm{pp} \to \mathrm{t\bar{t}Z} \to (\mathrm{t} \to \mathrm{b}jj)(\mathrm{t} \to \mathrm{b}\ell\nu)(\mathrm{Z} \to \ell\ell)$. Secondly, a sample containing at least 3 jets, one of which b-tagged, and two leptons of same electric charge was selected. With these criteria, events from both pp$\rightarrow$t$\bar{\text{t}}$Z$\rightarrow$(t$\rightarrow$ bjj)(t$\rightarrow$bν)(Z$\rightarrow \ell\ell$) and pp$\rightarrow$t$\bar{\text{t}}$W$\rightarrow$(t$\rightarrow$bjj)(t$\rightarrow$b$l\nu$)(W$\rightarrow l\nu$) processes are selected.

Both analyses are based on 5 fb^{-1} of data. In order to guarantee statistical independence of the two analyses, events fulfilling the trilepton selection are vetoed in the dilepton analysis.

Multilepton and same-sign leptons final states are rare in the SM, so a substancial fraction of the background in both analyses originates from misreconstruction effects, such as jets misreconstructed as leptons and misidentified b-jets. The estimation of such background sources was perfomed on control samples of data with looser selection criteria and extrapolated to the fiducial region of each analysis. Other backgrounds, for instance single-top production in tW and tbZ final states for the trilepton, and diboson, tbZ, and triboson processes for the dilepton analyses, are estimated using simulation.

The number of observed events compared to background predictions in each channel is shown in Fig. 3(a) and (b) for the trilepton and dilepton selections, respectively. The measured cross sections compared with NLO predictions is shown in Fig. 3(c). With the trilepton selection, 9 events were observed, over the expected background of 3.2$\pm$0.8 events, yielding a t$\bar{\text{t}}$+Z cross section of $0.28^{+0.14}_{-0.11}$(stat)$^{+0.06}_{-0.03}$(syst) pb, with a significance of 3.3 standard deviations, compatible with the NLO prediction [10] of $0.137^{+0.012}_{-0.016}$ pb. In the same-sign dilepton channel, with 13 events observed and 9.2$\pm$2.6 expected background, the measured t$\bar{\text{t}}$+V cross section (where V=Z or W) was $0.43^{+0.17}_{-0.15}$(stat)$^{+0.09}_{-0.07}$(syst) pb, with a significance of 3.0 standard deviations from the background hypothesis. The NLO predicts $0.306^{+0.031}_{-0.053}$ pb for this channel.

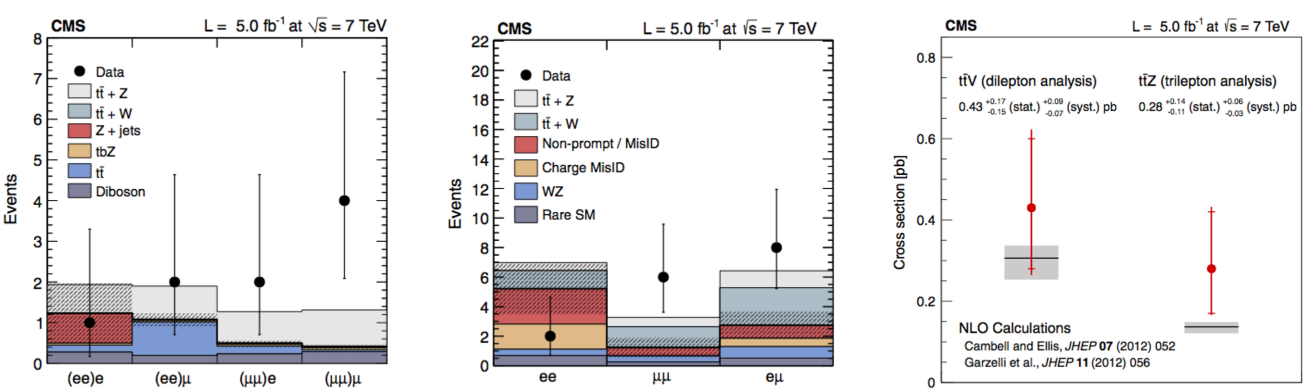


Figure 3: Number of events observed and predicted using (a) the trilepton and (b) the dilepton selection criteria. (c) Summary of the t$\bar{\text{t}}$+V cross section measurements, compared to the NLO prediction.

6. Conclusions

The most precise measurement of the W-boson helicity fractions in top decays to this date was presented for the first time in this conference. The measurement was based on events from semileptonic $\mathrm{t\bar{t}}$ decays selected on pp collision data at 7 TeV. Measurements in dileptonic $\mathrm{t\bar{t}}$ decays and single-top quark final states were also presented. The helicity fractions were used to impose stringent limits on anomalous couplings on Wtb vertex.

Two other CMS measurements tested the SM hypothesis of top quarks decaying almost exclusively into Wb: the ratio of the branching ratios of t$\rightarrow$Wb and t$\rightarrow$Wq was measured using a technique heavily based on data, reducing the dependency of the modeling. Also, a search for FCNC in the $\mathrm{t\bar{t}}\rightarrow$Wb Zb channel was performed, with no excess observed above the expected background.

The low number of associated $\mathrm{t\bar{t}}$+Z events in 2011 data does not yet allow careful experimental study of the structure of the electroweak couplings to top quarks. In spite of the large uncertainties, the measurement is still of interest in top physics, since they pave the way for more precise measurements in the near future. Moreover, $\mathrm{t\bar{t}}$+Z, as well as $\mathrm{t\bar{t}}$+W, whose contribution was measured as the summed $\mathrm{t\bar{t}}$+V cross section, are important backgrounds on searches for new physics, as for instance SUSY searches, and to the measurement of associated $\mathrm{t\bar{t}}$+Higgs production.

No signs of new physics were seen in CMS measurements so far. Rather, SM properties of the top quarks are being measured with unprecedented precision.

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