

# Top quark couplings and polarization

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## Abstract.

Precise measurements of top quark couplings are presented. The measurements cover the single top  $tW$  cross section, the top-quark branching-fraction ratio  $R=B(t \rightarrow Wb)/B(t \rightarrow Wq)$  and the CKM matrix element  $V_{tb}$  from the single top cross sections. Top quark polarisation in the  $t$ -channel single-top quark production and dilepton  $t\bar{t}$ , and  $W$ -helicity fraction measurements along with searches of top quark anomalous couplings in lepton plus jet channel are also presented. Finally measurements of top quark pair production in association with a  $W$  or  $Z$  boson or a photon are presented.

## 1. Introduction

The top quark is the heaviest known fundamental particle. Because of its high mass, the top quark decays before hadronization and it can be thus studied as a free particle. The direct access to its bare properties provides us with a unique tool to probe the Standard Model (SM).

The top quark is produced in proton proton collisions in pairs (top,  $t$ , and anti-top,  $\bar{t}$ ), through strong processes (gluon-gluon fusion or quark-antiquark annihilation), and as a single top, through electroweak processes.

The most recent results in top quark production, couplings and properties, performed by the CMS [1] Collaboration at the Large Hadron Collider (LHC) [2] are presented here. A detailed description of the techniques is out of scope for a short conference report: we will focus on the results, while addressing to the proper documentation for the technique details.

## 2. $|V_{tb}|$ measurements

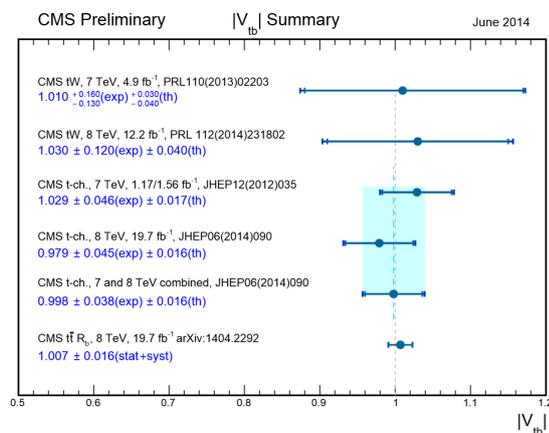
The top quark decays almost exclusively to a  $W$  boson and a  $b$  quark. The SM prediction for the Cabibbo-Cobayashi-Maskawa (CKM) matrix element  $|V_{tb}|$  is thus close to unity. The most precise measurement provided by the D0 Collaboration [3] shows some tension with the SM, raising more interest on the ongoing studies.

The CMS measurements of  $|V_{tb}|$  come from the three analysis here described. The results are summarized in figure 1.

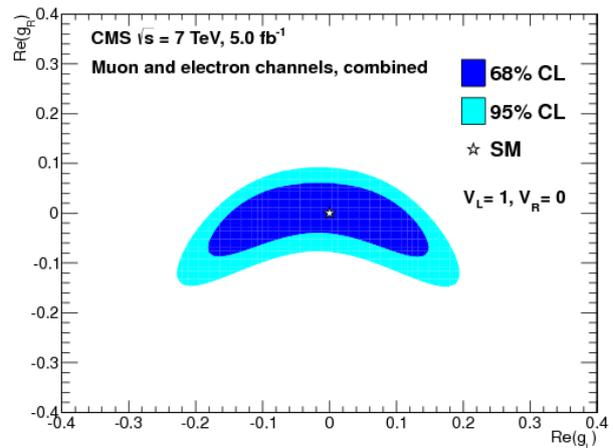
### 2.1. Measurement of the branching fraction $R=B(t \rightarrow Wb)/B(t \rightarrow Wq)$

The most sensitive analysis for a direct  $|V_{tb}|$  estimation is given by the measurement of the ratio  $R$  of the branching fractions of the top quarks decaying in  $W$  plus a  $b$  quark, and the top quarks decaying in a  $W$  plus any down type quark ( $q=b,s,d$ ). Under the assumption of the unitarity of the CKM matrix, it can indeed be shown that  $R = |V_{tb}|^2$ .





**Figure 1.** Summary of all the  $|V_{tb}|$  measurements performed by CMS.



**Figure 2.** Limits on the real components of the anomalous couplings constants  $g_L$ ,  $g_R$  at 68% and 95% CL.

The analysis [4] is performed in the dilepton channel only, given its channel-dependent purity of 70-90%. The selected events are used to measure the  $t\bar{t}$  cross section through a likelihood fit on the jet multiplicity constraining the signal and background contributions. The b-quark content is inferred from the distribution of the b-tagged jets per event as a function of the jet multiplicity. The model accounts for correction due to the single top contribution, the fraction of events with correct jet assignment, the b-tag efficiency and mis-identification.

The analysis leads to a measured value  $R = 1.014 \pm 0.003(\text{stat.}) \pm 0.032(\text{syst.})$  which translates to  $|V_{tb}| = 1.007 \pm 0.016(\text{stat.} + \text{syst.})$ . By requiring  $R = |V_{tb}| \leq 1$  we obtain  $R > 0.955$  and  $|V_{tb}| > 0.975$  at 95% confidence level.

## 2.2. $|V_{tb}|$ in single top production

Since the single top production involves a  $Wtb$  vertex, the  $|V_{tb}|$  matrix element can be determined from the cross section measurements of several production mechanisms.

In the t-channel, the single top is produced in association with a light quark emitted at high rapidity and a soft b quark. An event is selected if a muon or an electron that originated from the top quark is present. The signal is extracted from a maximum likelihood fit to the distribution of the absolute value of the pseudorapidity of the jet originating from the light quark. The t and  $\bar{t}$  production cross section are extracted independently. The analysis is performed both for 7 TeV and 8 TeV data. Here we report the combined results [5]. Assuming the CKM matrix elements  $|V_{td}|$  and  $|V_{ts}|$  to be negligible, we obtain:

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-ch}}{\sigma_{t-ch}^{th.}}} = 0.998 \pm 0.038(\text{exp.}) \pm 0.016(\text{th.}) \quad (1)$$

where the experimental uncertainty comes from the uncertainty on the measurement of  $\sigma_{t-ch}$  while the theoretical uncertainty comes from the uncertainty on  $\sigma_{t-ch}^{th.}$ ; By requiring  $|V_{tb}| \leq 1$  we obtain  $V_{tb} > 0.92$  at 95% confidence level.

Single top can also be produced in association with a W boson (tW-channel). A clean signature is possible when both the top quark and the W have a leptonic decay: this leads to a final state with two opposite charge isolated leptons, a b-jet and missing transverse energy due to the neutrino. The CMS analysis [6], performed over 12.2 fb<sup>-1</sup> of 8 TeV

data, uses a multivariate technique exploiting the topological differences between the  $tW$  signal and the dileptonic  $t\bar{t}$  background. Using the same assumptions as in  $t$ -channel, we measure  $|V_{tb}| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$ . By requiring  $|V_{tb}| \leq 1$  we obtain  $V_{tb} > 0.78$  at 95% confidence level.

### 3. $t\bar{t}$ and $W/Z/\gamma$ associated production

The associated production of  $t\bar{t}$  pairs with  $W$ ,  $Z$  and  $\gamma$  bosons can be disentangled at LHC and the corresponding cross sections measured in order to test the internal consistence of the SM. CMS performed the cross section measurements of the three processes using 8 TeV data.

Same sign dilepton events are used for the measurement of the  $t\bar{t}W$  process, where one lepton originates from the leptonic decay of one of the two top quarks and the other from the decay of the  $W$ . Trilepton events, one lepton arising from the top quark decay and two opposite sign same flavour leptons from the vector boson, are used for the  $t\bar{t}Z$  analysis, as well as four leptons events.

The different channels are then combined in order to provide the cumulative  $t\bar{t}V$  cross section [7]. In order to solve the dependence of the measured cross section on the other  $t\bar{t}V$  process, a simultaneous fit of the cross sections using all processes is also performed, resulting in the following:

$$\sigma(t\bar{t}W) = 170_{-100}^{+110} \text{ fb} \quad (2)$$

$$\sigma(t\bar{t}Z) = 170 \pm 90 \text{ fb} \quad (3)$$

where the reported errors are  $1\sigma$  standard deviation obtained from the combination of the different channels. The  $t\bar{t}W$  and  $t\bar{t}Z$  measurements have respectively a significance of  $1.6\sigma$  and  $3.1\sigma$ . The  $t\bar{t}\gamma$  cross section [8] is instead evaluated in the context of a muon plus jets analysis, with the additional request of a high energy photon with extra angular distance requests from the  $b$  jets. The photon misidentification plays a big role in the analysis and is estimated using a template fit to the photon shower shape. The cross section is extracted from a ratio with the CMS measured cross section for the  $t\bar{t}$  events. The resulting value is:

$$\sigma(t\bar{t}\gamma) = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.}) \text{ pb} \quad (4)$$

## 4. Top Properties

### 4.1. Polarization and spin correlation in $t\bar{t}$

In the SM, top quarks are produced in proton proton interactions with a small amount of polarization. Conversely the production mechanisms results in a full spin correlation between  $t$  and  $\bar{t}$ .

The polarization and spin correlation are studied at CMS in terms of angular asymmetries in the dilepton decay channel [9]. The polarization  $P$  is expressed in function of the asymmetry:

$$A_p = 2 \frac{N[\cos(\theta_l^*) - \cos(\theta_{\bar{l}}^*)]}{N[\cos(\theta_l^*) + \cos(\theta_{\bar{l}}^*)]} = 0.005 \pm 0.013(\text{stat.}) \pm 0.014(\text{syst.}) \pm 0.008(p_{Trw}) \quad (5)$$

where  $P = 2A_p$  and  $\cos(\theta_l^*)$  is the angle between the lepton and the top quark flight direction, in the top rest frame, and the major systematic uncertainties source is the top transverse momentum modeling ( $p_{Trw}$ ). The result is in agreement with the expectation.

The best estimator found for the spin correlation is instead the  $A_{\Delta\phi}$  asymmetry between the longitudinal angles  $\phi$  of the two leptons.

The result for  $A_{\Delta\phi}$  is rather precise, since it does not require any event reconstruction:

$$A_{\Delta\phi} = 0.113 \pm 0.010(stat.) \pm 0.006(syst.) \pm 0.012(p_{Trw}) \quad (6)$$

in good agreement with the fully correlated hypothesis  $A_{\Delta\phi}^{corr.} = 0.115_{-0.016}^{+0.014}$ .

#### 4.2. Polarization in single top

In the single top case, the expected polarization is close to 100%, due to the electroweak nature of the process. As in the  $t\bar{t}$  analysis, the polarization can be estimated using an asymmetry quantity. In the single top analysis the asymmetry is defined using the angle between the charged lepton and the recoiling jet in the t-channel [10], since the light quark recoiling against the top quark tends to have a direction parallel to the spin direction of the top. The measured polarization is in good agreement with the expectation:

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.) = 0.82 \pm 0.34 \quad (7)$$

#### 4.3. W helicity in $t\bar{t}$

The W-helicity fraction in the top quark decays are directly related to the V-A structure of the SM and their measurement provides great sensitivity to physics beyond the SM.

The helicity fractions of the W boson are defined as partial decay rates for a given helicity state divided by the total decay rate. In the SM, the longitudinal helicity fraction is the dominant one,  $F_0 = 0.0787 \pm 0.005$ , while the right handed is suppressed at leading order,  $F_R = 0.0017 \pm 0.0001$  [11]. The remaining left handed component is expected to be  $F_L = 0.311 \pm 0.005$ . The differential cross section connecting the three fractions can be written in terms of the  $\cos(\theta^*)$  variable, where  $\theta^*$  is the angle between the charged lepton in the W rest frame with respect to the direction of the W in the top quark rest frame. The measurement of the relative contributions is extracted through a Poisson binned likelihood on the  $\cos(\theta^*)$  variable shape.

The results from the muon analysis with 8 TeV data [12] are the world most precise estimates:

$$F_0 = 0.659 \pm 0.015(stat.) \pm 0.0023(syst.) \quad (8)$$

$$F_L = 0.350 \pm 0.010(stat.) \pm 0.024(syst.) \quad (9)$$

$$F_R = -0.009 \pm 0.006(stat.) \pm 0.020(syst.) \quad (10)$$

We also report the exclusion limits calculated for anomalous coupling with 7 TeV data [13], using both electron and muon channels in figure 2.

## 5. Conclusions

The top quark physics has been deeply investigated in the CMS experiments using the data produced by two successful LHC data taking periods at 7 and 8 TeV center of mass energy. Several measurements were reported here, focusing on the most recent results. All the measurements show a good agreement with the SM expectations. New results will come from the next LHC runs at higher center of mass energy and luminosity.

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