Measurements of the top-quark mass and properties at CMS

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Abstract. Measurements of the top-quark mass and other top-quark properties are presented, obtained from the CMS data collected in 2011 and 2012 at centre-of-mass energies of 7 and 8 TeV. The mass of the top quark is measured using several methods and decay channels. The measurements of the top-quark properties include the $W$ helicity in top-quark decays, the search for anomalous couplings, and the ratio of top-quarks decaying to $bW$ over $qW$ in order to gain information on $|V_{tb}|$ using both $t\bar{t}$ and single-top quark event samples. The results are compared with predictions from the standard model as well as new physics models. The cross section of $t\bar{t}$ events produced in association with a $W$, $Z$ boson or a photon is also measured.

1. Introduction
The top-quark is the heaviest fundamental particle known in the Standard Model of particle physics (SM) and exhibits features which render it unique among quarks. Its large mass results in its decay before hadronization processes take place, hence the properties of the quark are directly accessible. After its discovery about 20 years ago at the Tevatron, studying the top-quark has been an active field of research [1, 2]. Knowledge of the precise value of its mass is of paramount importance to the understanding of the SM, as it can help constraining the SM and also plays an important role in physics beyond the standard model. Figure 1 shows an example in which a global fit on the free parameters of the SM is performed and compared in a plane of $m_{top}$ and $m_W$, the mass of the $W$ boson.

Besides measurements of its mass, some measurements of its properties are presented in the following which constitute some of the most precise measurements to date.

2. Measurements of $m_{top}$
Measuring the mass of the top-quark can be done in many different ways. The most common procedure is to construct templates from Monte-Carlo simulation and to extract the top-quark mass parameter of the simulation by interpolating between the different mass templates.

Such a technique is implemented in CMS [4] in the measurement via the so-called $m_{lb}$ variable, the invariant mass between the lepton and the $b$-tagged quark in di-leptonic $e^{\pm}\mu^{\mp}$ events. The lepton is chosen as the one which yields minimal $m_{lb}$ with the highest $p_T$ $b$-tagged jet in the
Figure 1. Comparison of a global fit to the SM with the values of the $W$ boson versus the mass of the top-quark. Direct measurements with their errors are shown as green bands while the global fit yields the blue regions [3].

The final distribution of the variable with MC templates at different top-quark masses is shown in Fig. 2. A final mass of $172.3 \pm 1.3$ GeV is extracted.

Figure 2. Distribution of $m_{tb}$ overlaid with different simulated templates at masses of 178.5 (red), 172.5 (green), and 166.5 (blue) GeV. The inlay shows the interpolated $\chi^2$ fit to the data, yielding a minimum at 172.3 GeV.

A similar approach has been taken for the most precise single measurement of $m_{top}$. Single lepton events are selected with at least four accompanying jets of which exactly two are required to be $b$-tagged. A kinematic fit to the $t\bar{t}$ hypothesis is performed along with the implementation of the ideogram method in order to extract additional information in cases where the physical objects are incorrectly assigned [6, 7]. The final measurement from fits to seven MC templates where not only $m_{top}$, but also an overall jet-energy scale factor is obtained yields a value of
172.04 ± 0.19 ± 0.75 GeV, where the first error is statistical and the second systematic. The overall jet scale factor is fit to 1.007 ± 0.002 ± 0.012 pertaining to a sub-percent correction to the jet energies. Both results are displayed in Fig. 3.

Two more measurements of the top-quark mass in CMS were presented. These are a measurement in the di-leptonic final state where a very similar technique to the one in the aforementioned single leptonic measurement was employed via the implementation of a kinematic fit with the added complication of an additional neutrino. The final presented measurement is a fully hadronic measurement in which a global jet scale factor is extracted simultaneously with $m_{\text{top}}$. The obtained values are $m_{\text{top}} = 172.47 ± 0.17 ± 1.40$ GeV for the high-statistics di-lepton measurement and $m_{\text{top}} = 172.08 ± 0.36 ± 0.83$ GeV along with a jet scale factor of 1.007 ± 0.003 ± 0.011 in splendid agreement with the previously presented measurements [8, 9]. Two pieces of these results are shown in Fig. 4, where the $\chi^2$ fit to the seven templates is shown on the left for the di-leptonic analysis, and the fitted top mass of the hadronic analysis is displayed on the right.

Figure 3. Fitted $m_{\text{top}}$ (left) after event selection and a goodness-of-fit requirement as well as the final fit to the jet scale (right).

Figure 4. $\chi^2$ fit to the seven MC templates with best fit value for the di-leptonic analysis (left) as well as the top mass as extracted from the kinematic fit of the fully hadronic analysis.
2.1. Combination of \( m_{\text{top}} \) measurements

Combinations of different measurements of \( m_{\text{top}} \) from CMS and some global combinations are presented as well. Many measurements from both the \( \sqrt{s} = 7 \) TeV and 8 TeV datasets collected by CMS enter in the combination procedure [10]. In total eight different analyses are combined by measure of the BLUE (Best Linear Unbiased Estimator) [11] where correlations among these measurements and their associated theoretical and experimental uncertainties are treated consistently. Of the order of 25 uncertainties are investigated and combined with the central values into a combined best estimate of the top-quark mass of CMS at \( m_{\text{top}} = 172.38 \pm 0.10 \pm 0.65 \text{ GeV} \). This represents the most accurate experimental measurement to date and improves upon the preceding world average published by the CDF, D0, ATLAS, and CMS collaborations in early 2014 [12].

Summaries of all the measurements going into the CMS combination as well as the averages of the Tevatron experiments and the world average are presented in Fig. 5.

![Figure 5. Summary of the eight input measurements from 2010 through 2012 from CMS and the resulting combined measurement. Markers indicate the central values with the statistical errors in thick red lines and the systematic uncertainties in thin red lines. Also given are the Tevatron combination and the world average.](image)

3. Top-quark properties

As briefly stated before, the top-quark is the only quark which does not hadronize. Thus, its spin relation and many other quantities are relatively directly observable. A short selection of measurements of such properties is given, including the decay ratio \( R = t \rightarrow Wq \) and the helicity of the \( W \) boson from single-top events leading to limits on anomalous couplings. Additionally, some rare process cross-sections are presented.
The measurement of the decay ratio \( R = t \rightarrow Wb \) can be interpreted as a measurement of the \( |V_{tb}| \) element of the CKM matrix with the ratio \( R \) being the square of \( V_{tb} \). Previous measurements performed at D0 indicate some tension with the constraints derived from the unitarity of the CKM matrix of \( |V_{tb}| = 0.999146^{+0.000021}_{-0.000046} \) [13, 14]. Di-leptonic (\( e \) or \( \mu \)) events are selected and the spectra of the number of \( b \)-tagged jets is analyzed. Systematic uncertainties are dominated by the uncertainties of the experimental tagging efficiency [15]. By fitting the final distributions a ratio of \( R = 1.015 \pm 0.003 \pm 0.031 \) is extracted, corresponding to a central value of \( |V_{tb}| \) of 1.007. This is very consistent with the expectations of unitarity of the CKM matrix and can not confirm the observed tensions observed by the D0 collaboration. The results of the fit as well as the distributions are shown in Fig. 6.

**Figure 6.** Spectrum of \( N_{b-jets} \) as a function of the number of jets and the flavor of the di-leptonic events from which the ratio \( R \) is extracted (left). The \( \chi^2 \) of the flavor dependent fit as well as the combined fit is shown on the right.

The \( W \)-boson helicity can be measured directly through the angle between the \( W \)-boson in the top-quark rest frame and the momentum of the down-type decay fermion in the rest-frame of the \( W \)-boson. This angular distribution contains contributions from left-handed, right-handed, and longitudinal partial decay widths of the \( W \)-boson and can be put formally into a probability density function

\[
\rho(\cos \theta^*_l) = \frac{3}{8}(1 - \cos \theta^*_l)^2 F_L + \frac{3}{4} \sin^2 \theta^*_l F_0 + \frac{3}{8}(1 + \cos \theta^*_l)^2 F_R, \tag{1}
\]

where \( F_i \) are the partial decay widths. In this measurement, the goal is to quantify the helicity from single-top events. A single lepton is selected with exactly two jets accompanying it of which one is required to be \( b \)-tagged. The final event selection is not very pure in the single-top process, but most of the contamination stems from \( t\bar{t} \) events, which contain the same information to begin with. Therefore, this measurement represents an orthogonal analysis to the \( W \)-helicity measurement of \( t\bar{t} \) events [16, 17]. The results for the \( F_i \) are 0.298(43), 0.720(54), and -0.018(22) for the left-handed, longitudinal, and right-handed partial decays widths, respectively. The negative value for the right-handed fraction originates from the constraint \( \sum F_i = 1 \) imposed in the fit on the angular distribution. This compares well with the theoretical prediction of 0.311(5), 0.687(5), and 0.0017(1). These results are then interpreted in terms of anomalous \( tWb \) couplings \( g_L \) and \( g_R \), which are predicted to vanish at tree level in the SM. Both the angular distribution of \( \cos \theta^*_l \) and the limits on the anomalous couplings are shown in Fig. 7.
Finally, results on the rare SM processes of $t\bar{t} + W/Z/\gamma$ are presented. The cross-sections of the $t\bar{t}$ plus massive boson production is measured in leptonic final states combining the same-sign di-lepton, tri-lepton and quadri-lepton final states in an exclusive manner. A simultaneous fit to the observed data is then performed in the cross-sections of $t\bar{t} + W$ and $t\bar{t} + Z$ to extract the values for the cross section from a simple counting experiment. The results of $\sigma_{ttW} = 170^{+110}_{-90}$ fb and $\sigma_{ttZ} = 200^{+90}_{-90}$ fb agree well with the respective SM theoretical expectations of $\sigma_{ttW}^{\text{theory}} = 206^{+21}_{-23}$ fb and $\sigma_{ttZ}^{\text{theory}} = 197^{+22}_{-25}$ fb, albeit with large uncertainties due to the limited statistics of this measurement [18]. The results of the simultaneous fit is compared with the SM expectation in the left part of Fig. 8.

The cross-section of the $t\bar{t} + \gamma$ process is investigated in the single muonic decay mode of $pp \rightarrow W^{+}W^{-}b\bar{b}\gamma$, where the $\gamma$ is required to have at least 20 GeV of $p_T$. At least four jets of which one is required to be tagged as originating from a $b$-quark are selected in the final state to suppress non $t\bar{t}$ backgrounds. A maximum likelihood method is introduced to estimate the fraction of real, prompt emissions of photons and the ratio $R = \sigma_{tt+\gamma}/\sigma_{tt}$ is extracted with a $t\bar{t}$ cross-section measurement of CMS as an input [19]. It is evaluated to $(1.07 \pm 0.07 \pm 0.27) \times 10^{-2}$ yielding a final estimate for the cross section of $\sigma_{tt+\gamma} = 2.4 \pm 0.2 \pm 0.6$ pb [20]. This is in good agreement with the SM expectation of $\sigma_{tt+\gamma}^{\text{theory}} = 1.8 \pm 0.5$ pb.

4. Concluding remarks
A number of different measurements on the top-quark mass were presented along with the CMS combination of said quantity. The precision of single measurements has arrived at the sub-percent level due to the large dataset and advances in both theoretical and experimental understanding. The relative error of the CMS combination of 0.38% stands as the most precise value to date.

Some select properties of the top-quark were presented as well, including the ratio $bW/qW$, the helicity of the $W$-boson in the top-quark decay as well as measurements on the $t\bar{t} +$-boson processes. These latter processes suffer from large statistical and systematic uncertainties, though greater precision is expected to be achieved at higher center-of-mass energy in Run...
Figure 8. Simultaneous fit to the cross-sections of the $t\bar{t}+W$ and $t\bar{t}+Z$ processes as observed in leptonic final state.

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