Physics Letters B 736 (2014) 33–57

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Measurement of the ratio $\mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$ in pp collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration *

*CERN, Switzerland*

ARTICLE INFO

*Article history:*
Received 8 April 2014
Received in revised form 5 June 2014
Accepted 29 June 2014
Available online 3 July 2014
Editor: M. Doser

*Keywords:*
CMS
Top
CKM
Width

ABSTRACT

The ratio of the top-quark branching fractions $\mathcal{R} = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$, where the denominator includes the sum over all down-type quarks (q = b, s, d), is measured in the $t\bar{t}$ dilepton final state with proton–proton collision data at $\sqrt{s} = 8$ TeV from an integrated luminosity of 19.7 fb$^{-1}$, collected with the CMS detector. In order to quantify the purity of the signal sample, the cross section is measured by fitting the observed jet multiplicity, thereby constraining the signal and background contributions. By counting the number of b jets per event, an unconstrained value of $\mathcal{R} = 1.014 \pm 0.003$ (stat.) $\pm 0.032$ (syst.) is measured, in a good agreement with current precision measurements in electroweak and flavour sectors. A lower limit $\mathcal{R} > 0.955$ at the 95% confidence level is obtained after requiring $\mathcal{R} \le 1$, and a lower limit on the Cabibbo–Kobayashi–Maskawa matrix element $|V_{tb}| > 0.975$ is set at 95% confidence level. The result is combined with a previous CMS measurement of the *t*-channel single-top-quark cross section to determine the top-quark total decay width, $\Gamma_t = 1.36 \pm 0.02$ (stat.)$^{+0.14}_{-0.11}$ (syst.) GeV.



## 1. Introduction

Because of its large mass [1], the top quark decays before fragmenting or forming a hadronic bound state [2]. According to the standard model (SM), the top quark decays through an electroweak interaction almost exclusively to an on-shell W boson and a b quark. The magnitude of the top–bottom charged current is proportional to $|V_{tb}|$, an element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Under the assumption that the CKM matrix is unitary and given the measured values for $V_{ub}$ and $V_{cb}$ (or $V_{ts}$ and $V_{td}$), $|V_{tb}|$ is expected to be close to unity and dominate over the off-diagonal elements, i.e. $|V_{tb}| \gg |V_{ts}|, |V_{td}|$. Thus, the decay modes of the top quark to lighter down-type quarks (d or s) are allowed, but highly suppressed. The indirect measurement of $|V_{tb}|$, from the unitarity constraint of the CKM matrix, is $|V_{tb}| = 0.999146^{+0.000021}_{-0.000046}$ [3]. Any deviation from this value or in the partial decay width of the top quark to b quarks, would indicate new physics contributions such as those from new heavy up- and/or down-type quarks or a charged Higgs boson, amongst others [4]. Direct searches at the Large Hadron Collider (LHC) have set lower limits on the mass of these hypothetical new particles [5–15], and the observation of a SM Higgs boson candidate [16–18] places stringent constraints on the existence of a fourth sequential generation of quarks. These results support the validity of both the unitarity hypothesis and the 3 × 3 structure of the CKM matrix for the energy scale probed by the LHC experiments. However, other new physics contributions, including those described above, could invalidate the bounds established so far on $|V_{tb}|$ [3].

In this Letter, we present a measurement of $\mathcal{R} = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$, where the denominator includes the sum over the branching fractions of the top quark to a W boson and a down-type quark (q = b, s, d). Under the assumption of the unitarity of the 3 × 3 CKM matrix, $\mathcal{R} = |V_{tb}|^2$, and thus to indirectly measure $|V_{tb}|$. In addition, the combination of a determination of $\mathcal{R}$ and a measurement of the *t*-channel single-top cross section can provide an indirect measurement of the top-quark width ($\Gamma_t$) [19]. The most recent measurement of $\Gamma_t$ based on this approach [20] is found to be compatible with the SM predictions with a relative uncertainty of approximately 22%. The value of $\mathcal{R}$ has been measured at the Tevatron, and the most precise result is obtained by the D0 Collaboration, where $\mathcal{R} = 0.90 \pm 0.04$ (stat. + syst.) [21] indicates a tension with the SM prediction. This tension is enhanced for the measurement in the $t\bar{t}$ dilepton decay channel, where both W bosons decay leptonically and $\mathcal{R} = 0.86^{+0.041}_{-0.042}$ (stat.) $\pm 0.035$ (syst.) is obtained. The most recent measurements by the CDF Collaboration are given in [22,23].

Owing to its purity, the $t\bar{t}$ dilepton channel is chosen for this measurement. Events are selected from the data sample acquired in proton–proton collisions at $\sqrt{s} = 8$ TeV by the Compact Muon Solenoid (CMS) experiment at the LHC during 2012. The integrated luminosity of the analysed data sample is $19.7 \pm 0.5$ fb$^{-1}$ [24].

* *E-mail address:* cms-publication-committee-chair@cern.ch.

http://dx.doi.org/10.1016/j.physletb.2014.06.076

The selected events are used to measure the $t\bar{t}$ production cross section by fitting the observed jet multiplicity distribution, constraining the signal and background contributions. The b-quark content of the events is inferred from the distribution of the number of b-tagged jets per event as a function of jet multiplicity for each of the dilepton channels. Data-based strategies are used to constrain the main backgrounds and the contributions of extra jets from gluon radiation in $t\bar{t}$ events. The $\mathcal{R}$ value is measured by fitting the observed b-tagged jet distribution with a parametric model that depends on the observed cross section, correcting for the fraction of jets that cannot be matched to a $t \to Wq$ decay. The model also depends on the efficiency for identifying b jets and discriminating them from other jets. Lastly, the measurement of $\mathcal{R}$ is combined with a previously published CMS result of the $t$-channel production cross section of single top quarks in pp collisions [25] to yield an indirect determination of the top-quark total decay width.

## 2. The CMS detector

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where the pseudorapidity $\eta$ is defined as $\eta = -\ln[\tan(\theta/2)]$ and $\theta$ is the polar angle of the trajectory of the particle with respect to the anticlockwise-beam direction. The tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the field of the superconducting solenoid. It provides an impact parameter resolution of $\sim$15 μm and a transverse momentum ($p_T$) resolution of about 1.5% for 100 GeV particles. The electron energy is measured by the ECAL and its direction is measured by the tracker. The mass resolution for $Z \to ee$ decays is 1.6% when both electrons are in the ECAL barrel, and 2.6% when both electrons are in the ECAL endcap [26]. Matching muons to tracks measured in the silicon tracker results in a $p_T$ resolution between 1 and 10%, for $p_T$ values up to 1 TeV. The jet energy resolution (JER) amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [27].

A more detailed description of the detector can be found in Ref. [28].

## 3. Simulation of signal and background events

The top-quark pair production cross section has been calculated at next-to-next-to-leading order (NNLO) and next-to-next-to-leading logarithmic soft gluon terms (NNLL) [29]. In proton–proton collisions at $\sqrt{s} = 8$ TeV, and for a top-quark mass of 172.5 GeV, the expected cross section is $\sigma_{\text{NNLO+NNLL}}(t\bar{t}) = 253^{+6}_{-8}$ (scale) $\pm$ 6 (PDF) pb, where the first uncertainty is from the factorisation and renormalisation scales, and the second is from the parton distribution functions (PDFs). Signal events are simulated for a top-quark mass of 172.5 GeV with the leading-order (LO) Monte Carlo (MC) generator MadGraph (v5.1.3.30) [30] matched to pythia (v6.426) [31], where the $\tau$ lepton decays are simulated with the tauola package (v27.121.5) [32]. The CTEQ6L1 PDF set is used in the event generation [33]. Matrix elements describing up to three partons, and including b quarks, in addition to the $t\bar{t}$ pair are included in the generator used to produce the simulated signal samples. An alternative simulation at next-to-leading order (NLO) based on powheg (v1.0, r1380) [34–36], using the CTEQ6M PDF set [33] and interfaced with pythia, is used to evaluate the signal description uncertainty. A correction to the simulated top-quark $p_T$ is applied, based on the approximate NNLO computation [37]: the events are reweighted at the generator level to match the top-quark $p_T$ prediction, and the full difference between the reweighted and unweighted simulations is assigned as a systematic uncertainty.

The most relevant background processes for the dilepton channel are from the production of two genuine isolated leptons with large $p_T$. This includes Drell–Yan (DY) production of charged leptons, i.e. from a $Z/\gamma^*$ decay, which is modelled with MadGraph for dilepton invariant masses above 10 GeV, and is normalised to a NNLO cross section of 4.393 nb, computed using fewz [38]. The $Z+\gamma$ process is also simulated with MadGraph and normalised to the LO predicted cross section of 123.9 pb. Single-top-quark processes are modelled at NLO with powheg [39,40] and normalised to cross sections of $22 \pm 2$ pb, $86 \pm 3$ pb, and $5.6 \pm 0.2$ pb for the tW, $t$-, and $s$-channel production, respectively [37]. The theory uncertainties are due to the variation of the PDFs and factorisation and renormalisation scales. Diboson processes are modelled with MadGraph and normalised to the NLO cross section computed with mcfm [41]. The generation of WW, WZ, and ZZ pairs is normalised to inclusive cross sections of 54.8 pb, 33.2 pb, and 17.7 pb, respectively. For WZ and ZZ pairs a minimum dilepton invariant mass of 12 GeV is required. Associated production of W or Z bosons with $t\bar{t}$ pairs is modelled with MadGraph, and normalised to the LO cross sections of 232 fb and 208 fb, respectively. The production of a W boson in association with jets, which includes misreconstructed and non-prompt leptons, is modelled with MadGraph and normalised to a total cross section of 36.3 nb computed with fewz. Multijet processes are also studied in simulation but are found to yield negligible contributions to the selected sample.

A detector simulation based on Geant4 (v.9.4p03) [42,43] is applied after the generator step for both signal and background samples. The presence of multiple interactions (pileup) per bunch crossing is incorporated by simulating additional interactions (both in-time and out-of-time with the collision) with a multiplicity matching that observed in the data. The average number of pileup events in the data is 21 interactions per bunch crossing.

## 4. Event selection and background determination

The event selection is optimised for $t\bar{t}$ dilepton final states that contain two isolated oppositely charged leptons $\ell$ (electrons or muons), missing transverse energy ($E_T^{\text{miss}}$) defined below, and at least two jets. Events in which the electrons or muons are from intermediate $\tau$ lepton decays are considered as signal events. Dilepton triggers are used to acquire the data samples, where a minimum transverse momentum of 8 GeV is required for each of the leptons, and 17 GeV is required for at least one of the leptons. Electron-based triggers include additional isolation requirements, both in the tracker and calorimeter detectors.

All objects in the events are reconstructed with a particle-flow (PF) algorithm [44,45]. Reconstructed electron and muon candidates are required to have $p_T > 20$ GeV and to be in the fiducial region $|\eta| \le 2.4$ of the detector. A particle-based relative isolation parameter is computed for each lepton and corrected on an event-by-event basis for the contribution from pileup events. We require that the scalar sum of the $p_T$ of all particle candidates reconstructed in an isolation cone built around the lepton's momentum vector is less than 15% (12%) of the electron (muon) transverse momentum. The isolation cone is defined using the