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# CKM Physics with Top

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We summarize direct measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, $V_{tb}$, using single top quark events at the ATLAS and CMS experiments and an indirect measurement of $V_{tb}$ using top quark pair events at CMS experiment of CERN LHC based on the data collected at different center-of-mass energies of 7, 8 and 13 TeV.

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## 1. Introduction

The Large Hadron Collider (LHC) at CERN is a top quark factory producing top quarks in pairs through strong interaction as well as individually via charged-current electroweak interaction. The top quark is unique in many ways compared to the other quarks. Due to its large mass it decays before fragmentating to form a hadronic bound state. According to the standard model (SM), the top quark decays through electroweak interaction to a real weak vector boson ($W$) and a bottom quark ($b$). Decay modes to lighter down-type quarks ($d$ or $s$) are allowed but highly suppressed due to observed hierarchical pattern of the flavor mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix where the diagonal element $|V_{tb}|$ is expected to be close to unity and dominant over the non-diagonal elements, $V_{tb} \gg V_{ts}, V_{td}$ if unitarity and three quark generations are assumed.

In this article, the direct measurements of the CKM matrix element $V_{tb}$ using single top quark events at the ATLAS [1, 2, 3, 4] and CMS [5, 6, 7] experiments and an indirect measurement using top quark pair events at CMS [8] are presented. A summary of these measurements from the LHC Top Working Group [9] are also provided.

## 2. Direct measurement of $V_{tb}$ using single top quark production

The production of single top quarks provides a unique testing ground for the study of electroweak processes, specifically the top-W vector boson-bottom ($tWb$) vertex, as well as for the measurement of the CKM matrix element $V_{tb}$. The study of single top quark events thereby provides probes of the electroweak sector of the SM, which predicts three production channels: the $t$ channel, the $s$ channel, and the $W$-associated or $tW$ channel (Figure 1).

The cross-sections in all the three channels are proportional to the square of the coupling at the production vertex. In the SM, the coupling is given by the CKM matrix element $V_{tb}$ multiplied by the universal electroweak coupling constant. Non-SM contributions can be encapsulated by an additional left-handed form factor $f_{\mathrm{LV}}$, assumed to be real. The sensitivity for these non-SM contributions could be enhanced for the higher center-of-mass energy, if there is new physics at high scales. All three single top quark production channels are directly related to the CKM matrix element $V_{tb}$ as mentioned above, providing a direct measurement of this SM parameter. Therefore, the cross-section is measured in each channel and can be used to extract $|f_{\mathrm{LV}}V_{\mathrm{tb}}|$.

At the LHC, the dominant production mechanism of single top quarks is the $t$-channel process. This production mode, presented in Fig. 1(left), has a very distinct signature thanks to the presence, within the detector acceptance, of a light quark recoiling against the top quark. Both the ATLAS [1] and CMS [5] Collaborations have performed measurements of this process using data collected at $\sqrt{s}$ = 13 TeV. Events are selected by requiring an isolated charged lepton (electron or muon), missing transverse momentum due to the neutrino, and two jets with high transverse momentum, exactly one of which is required to originate from the hadronization of a b quark ('b-tagged'). In both ATLAS and CMS analyses the separation between signal and background processes is achieved using a sophisticated multivariate analysis (MVA) technique. An artificial neural network is employed to construct a classifier, exploiting the discriminating power of several kinematic observables. The cross section of $t$-channel single top quark production is determined from a fit to the distribution of this single variable. The measured cross section is used to determine the absolute value of the



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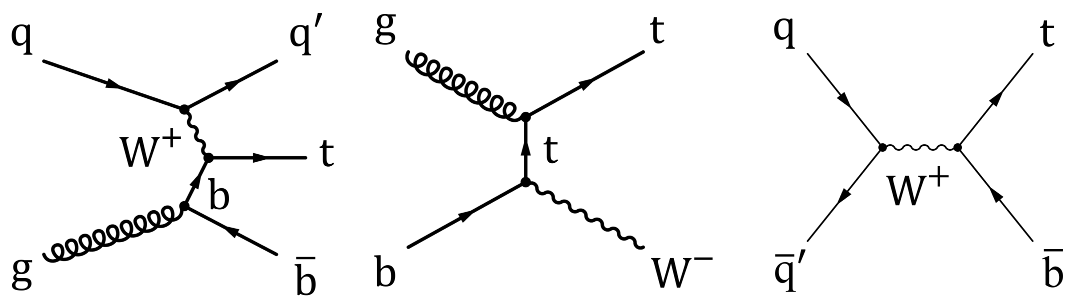


**Figure 1:** Leading-order Feynman diagram for single top quark production in the $t$ channel (left), the $top-W$ channel (middle) and the $s$ channel (right).

CKM matrix element $|V_{\mathrm{tb}}|$, assuming that the other matrix elements $|V_{td}|$ and $|V_{\mathrm{ts}}|$ are much smaller than $|V_{tb}|$: $|f_{\mathrm{LV}}\ V_{tb}| = \sqrt{\sigma_{t\text{-}ch}/\sigma_{t\text{-}ch}^{\mathrm{theory}}}$.

The $tW$-channel [Fig. 1(middle)] is the mode with the second largest cross-section, behind the dominant $t$-channel mode at the LHC. With 8 TeV collision data, observations of the associated production of a single top quark and a $W$ boson were made by the CMS [6] and ATLAS [2] Collaborations, with cross-section measurements in good agreement with theoretical predictions. ATLAS has recently measured the cross section of $tW$ channel with 13 TeV data collected in 2015 [3]. The analysis is performed using the dilepton decay channels, in which the $W$ boson produced in association with the top quark and the $W$ boson from the top decay both decay leptonically into a muon or an electron, and a neutrino. All analyses use an MVA technique based on boosted decision tree, exploiting kinematic and topological differences to distinguish the $tW$ signal from the dominant $t\bar{t}$ background. The measurements are in agreement with the SM prediction.

The $s$-channel single top-quark production [Fig. 1(right)], which is least dominant production mode amongst the three, is sensitive to new particles proposed in several models of physics beyond the SM, such as charged Higgs boson or $W$ boson production. It also plays an important role in indirect searches for new phenomena that could be modeled as anomalous couplings in an effective quantum field theory. The CMS Collaboration has performed a search for single top quark production in the $s$-channel in proton-proton collisions in decay modes of the top quark containing a muon or an electron in the final state. The signal is extracted through a maximum-likelihood fit to the distribution of an MVA discriminant defined using boosted decision trees to separate the expected signal contribution from background processes. The analysis used data collected at center-of-mass energies of 7 and 8 TeV [7]. Evidence for $s$-channel single top quark production was found by ATLAS using data recorded at 8 TeV [4]. The signal is extracted using a maximum-likelihood fit of a discriminant, which is based on the matrix element method and optimized in order to separate signal events from main background contributions.

A summary of ATLAS and CMS measurements of single top cross section at different center-of-mass energies for all single top channels from the LHC Top Working Group [9] is shown in Fig. 2 while the corresponding CKM matrix element $V_{tb}$ are presented in Fig. 3.

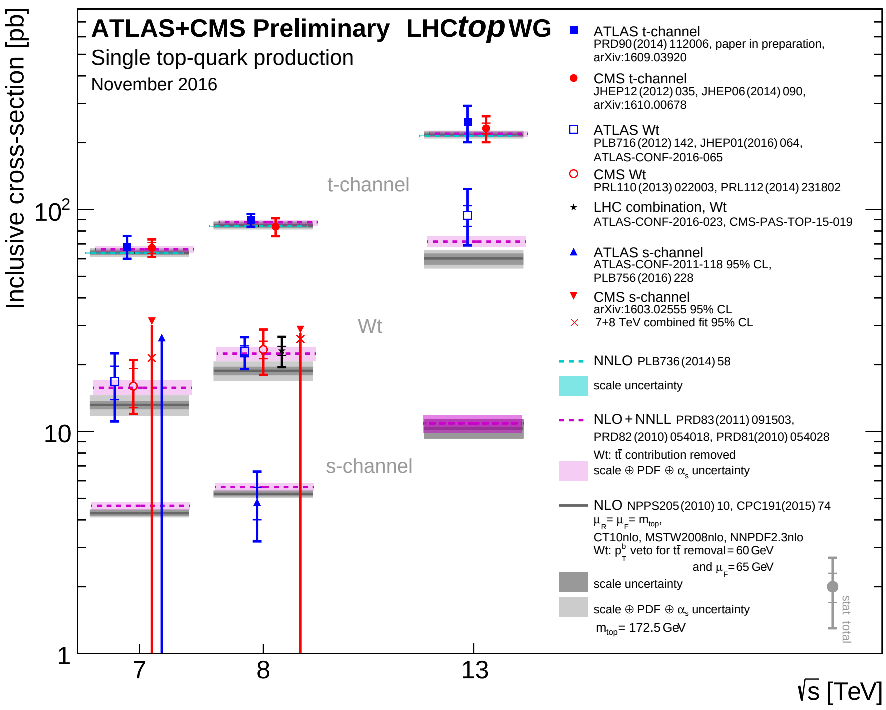


**Figure 2:** Summary of ATLAS and CMS measurements of the single top production cross-sections in various channels as a function of the center-of-mass energy [9]. The measurements are compared to theoretical calculations based on: next-to-leading-order (NLO) QCD, NLO QCD complemented with next-to-next-to-leading logarithmic (NNLL) resummation and next-to-next-to-leading-order (NNLO) QCD ($t$-channel only).

## 3. Indirect measurement of $V_{tb}$ using top quark pair production

In the SM, top quarks in proton-proton collisions are mostly produced as $t\bar{t}$ pairs with each top quark decaying predominantly to a $W$ boson and a $b$ quark. In $t\bar{t}$ events where both $W$ bosons decay leptonically (dilepton channel), the final state contains two leptons of opposite charge, missing momentum, and at least two jets b-tagged. Owing to its purity, the $t\bar{t}$ dilepton channel is chosen for indirect measurement of $V_{tb}$ by the CMS experiment [8].

Events are selected from the data sample recorded in proton-proton collisions at $\sqrt{s}$ = 8 TeV by CMS experiment during 2012. The event selection is optimised for $t\bar{t}$ dilepton final states that contain two isolated oppositely charged leptons (electrons or muons), missing transverse energy, and at least two jets. In order to quantify purity of the signal sample, the cross section is measured by fitting the observed jet multiplicity, thereby 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 dilepton channel. Data-based strategies are used to constrain main backgrounds and the contributions of extra jets from gluon radiation in $t\bar{t}$

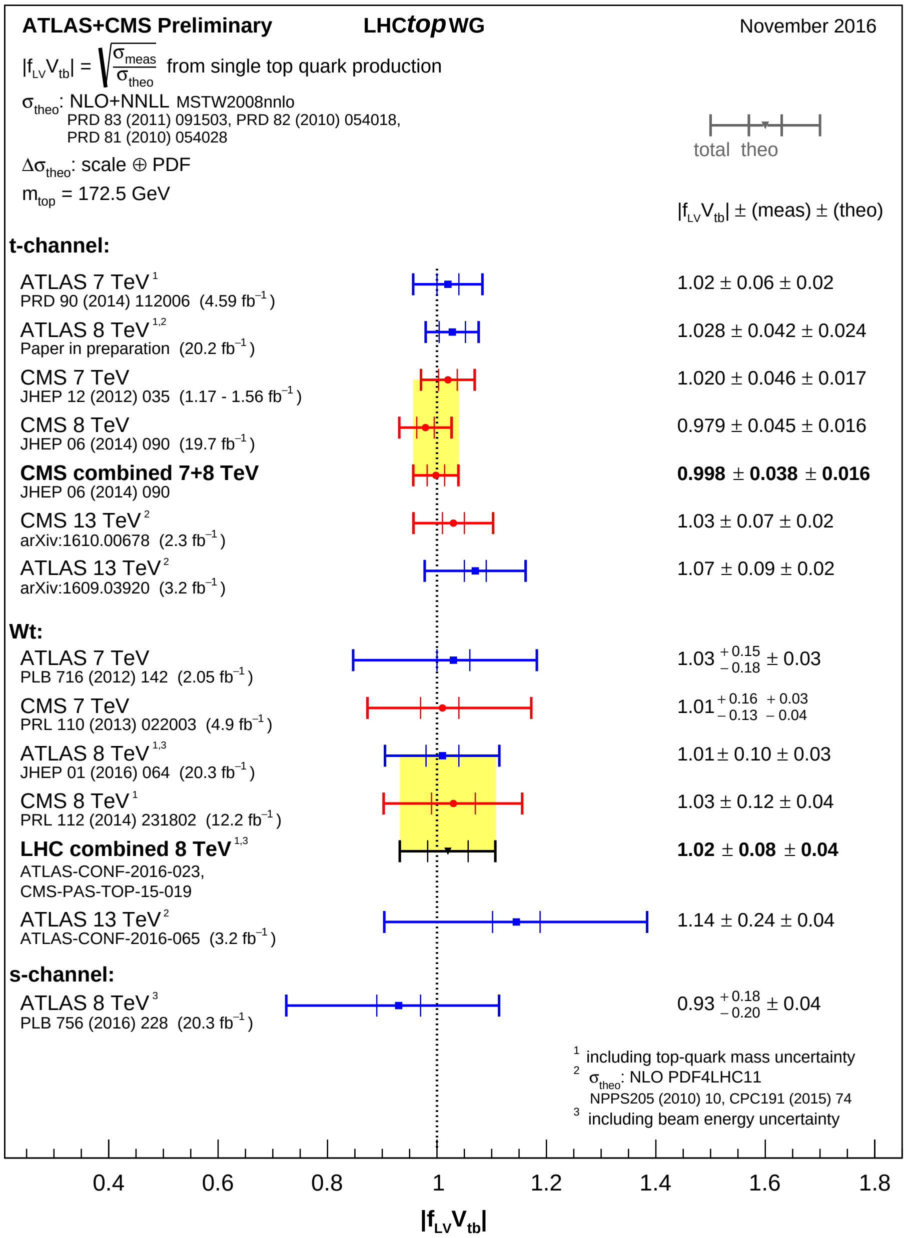


**Figure 3:** Summary of ATLAS and CMS extractions of the CKM matrix element $V_{tb}$ from single top quark measurements [9]. For each result, the contribution to total uncertainty originating from the uncertainty on the theoretical prediction for the single top production cross-section is shown along with the uncertainty of from the experimental measurement of the cross-section.

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events. The ratio of the top quark branching fractions $\mathscr{R} = B(t \to Wb)/B(t \to Wq)$, where $q$ can be a $d$, $s$, or $b$ quark, is measured in the $t\bar{t}$ dilepton final state. Under the assumption of unitarity of the $3 \times 3$ CKM matrix, $\mathscr{R} = |V_{tb}|^2$ , and thus one can indirectly measure $|V_{tb}|$.

For the measurement of $\mathscr{R}$, a binned-likelihood function is constructed using a parametric model that depends on the observed b-tagging multiplicity in events with two, three, or four observed jets in the different dilepton channels. A total of 36 event categories, corresponding to different permutations of three lepton-flavour pairs, three jet multiplicities, and up to four observed b-tagged jets are used. Figure 4 (left) shows the results obtained by maximising the profile likelihood. The combined measurement of $\mathscr{R}$ in the different dilepton channels gives $\mathscr{R}$ = 1.014 $\pm$ 0.003(stat.) $\pm$ 0.032 (syst.), in good agreement with the SM prediction. Assuming unitarity of the CKM matrix and by performing the fit in terms of $|V_{\rm tb}|$, a value of $|V_{\rm tb}|$ = 1.007 $\pm$ 0.016(stat.+syst.) is measured. If the condition $\mathscr{R} \leq 1$ is imposed, we obtain $\mathscr{R} > 0.955$ at the 95% CL. By constraining $|V_{\rm tb}| \leq 1$, we obtain $|V_{\rm tb}| > 0.975$ at the 95% CL. A summary of $V_{tb}$ determinations by the CMS experiment, from single top and BR($t \to b$) [10] is shown in Fig. 4 (right).

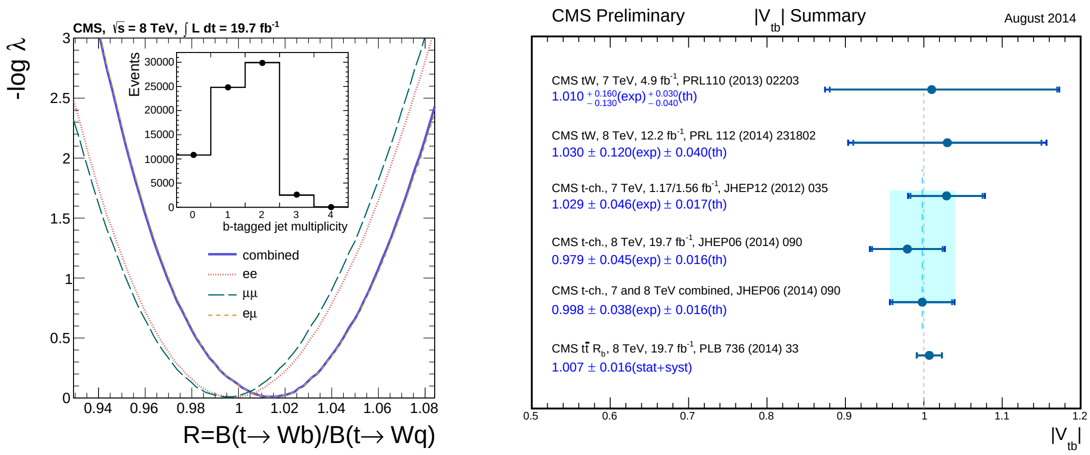


**Figure 4:** (Left) Variation of the profile likelihood used to extract $\mathscr{R}$ from data. The variation observed in the exclusive dilepton channels is depicted by the dashed lines. The inset shows the inclusive $b$ tag multiplicity distribution and the result of the fit. (Right) Summary of $V_{tb}$ determinations by CMS, from single top and BR($t \to b$) [10].

## 4. Summary

We have reviewed the results obtained by the ATLAS and CMS experiments on the direct measurement of the CKM matrix element $V_{tb}$ using single top quark production. In addition we have presented the CMS measurement of the ratio of the top quark branching fractions, extracted from $t\bar{t}$ dilepton events which leads to an indirect determination of $V_{tb}$.

## References

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[9] LHC Top Working Group Summary Plots: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

[10] Top Quark Physics Summary Figures: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures