Extraction of CKM matrix elements in the single-top *t*-channel events at 13 TeV with CMS

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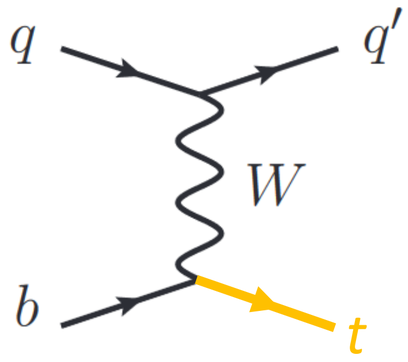
Single-top *t*-channel process

In pp collisions at the LHC, the single-top-quark production could happen in three different ways: *t*-channel, *s*-channel and tW associate production.



t-channel
Largest cross section

A light-flavour quark q from one of the colliding protons interacts with a b-quark by exchanging a space-like virtual W boson, producing a top quark (t-quark) and a recoiling light-flavour quark q', called the spectator quark.

The single top *t*-channel production process is particularly indicated to measure the Cabibbo-Kobayashi-Maskawa elements $|V_{tb}|$, $|V_{ts}|$, and $|V_{td}|$.

The cross section multiplied by the branching fraction can be written as:

$$\sigma_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\to\mathrm{Wb}) + \sigma_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\to\mathrm{Wd,s}) + \sigma_{t-\mathrm{ch.,s,d}}\mathcal{B}(\mathrm{t}\to\mathrm{Wb}) + \mathcal{O}(|V_{\mathrm{td,s}}|^4)$$

where:

$$\sigma_{t-\mathrm{ch.,q}} \propto |\mathrm{V_{tq}}|^2 \qquad \mathcal{B}(\mathrm{t}\to\mathrm{Wq}) = |\mathrm{V_{tq}}|^2 \widetilde{\Gamma}_{\mathrm{q}} \Gamma_{\mathrm{top}}$$

Motivation

In single-top *t*-channel process presence of two *tWq* vertexes

Highly sensitive to

- $|V_{tb}|$, $|V_{ts}|$, and $|V_{td}|$ — $|V_{ts}|^2 + |V_{td}|^2$ never directly measured
- New physics phenomena

Standard Model scenario: $|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$

$$\mu_{\mathrm{b}} = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}}{|V_{\mathrm{tb}}|^4} \qquad \mu_{\mathrm{sd}} = \frac{|V_{\mathrm{tb}}|^2_{\mathrm{obs}}(1-|V_{\mathrm{tb}}|^2_{\mathrm{obs}})}{|V_{\mathrm{tb}}|^2(1-|V_{\mathrm{tb}}|^2)}$$

Beyond the Standard Model scenarios

$|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 \neq 1$

$$\mu_{\mathrm{b}} = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}}{|V_{\mathrm{tb}}|^4(|V_{\mathrm{tb}}|^2_{\mathrm{obs}} + |V_{\mathrm{ts}}|^2_{\mathrm{obs}} + |V_{\mathrm{td}}|^2_{\mathrm{obs}})}$$

$$\mu_{\mathrm{sd}} = \frac{|V_{\mathrm{tb}}|^2_{\mathrm{obs}}(|V_{\mathrm{ts}}|^2_{\mathrm{obs}} + |V_{\mathrm{td}}|^2_{\mathrm{obs}})}{(|V_{\mathrm{ts}}|^2 + |V_{\mathrm{td}}|^2)(|V_{\mathrm{tb}}|^2_{\mathrm{obs}} + |V_{\mathrm{ts}}|^2_{\mathrm{obs}} + |V_{\mathrm{td}}|^2_{\mathrm{obs}})}$$

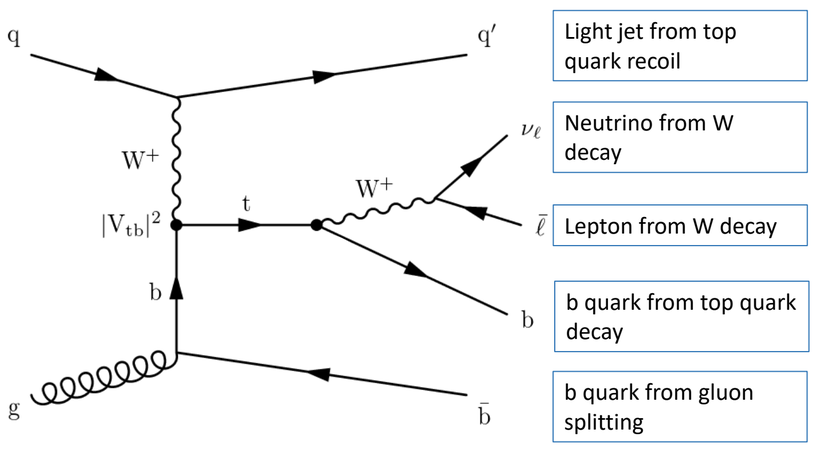
Γ_t is allowed to vary due to decay in new particles

$$\mu_{\mathrm{b}} = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}\Gamma_{\mathrm{t}}}{|V_{\mathrm{tb}}|^4\Gamma^{\mathrm{obs}}_{\mathrm{t}}}$$

$$\mu_{\mathrm{sd}} = \frac{|V_{\mathrm{tb}}|^2_{\mathrm{obs}}(|V_{\mathrm{ts}}|^2_{\mathrm{obs}} + |V_{\mathrm{td}}|^2_{\mathrm{obs}})\Gamma_{\mathrm{t}}}{|V_{\mathrm{tb}}|^2(|V_{\mathrm{ts}}|^2 + |V_{\mathrm{td}}|^2)\Gamma^{\mathrm{obs}}_{\mathrm{t}}}$$

Analysis strategy

Final state topology



Three orthogonal regions defined accordingly to the number of jets and b-jet in each event.

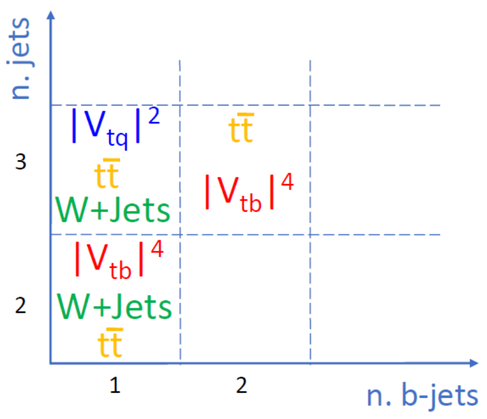
Multiple regions definitions

Signal region: 2-jets—1-tag
1 light jet in high η region
Lepton from the W boson
Missing momentum in the transverse plane (ν)
b jet from the top decay
b from the gluon splitting out of selection

Signal region: 3-jets—1-tag
1 light jet in high η region
Lepton from the W boson
Missing momentum in the transverse plane (ν)
b jet from top and non-b from gluon splitting
non-b jet from top and b from gluon splitting

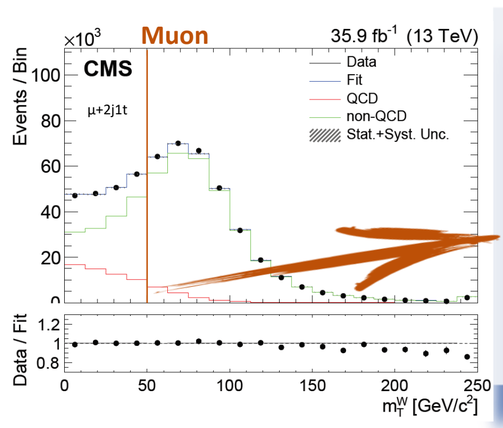
Several backgrounds present
- Top pair production ($t\bar{t}$)
- Vector boson + jets (W+Jets)
- *s*-channel
- tW associate production
- QCD multijets

The three regions are all included in the final fit for the extraction of the CKM matrix elements and to constrain the backgrounds.



Estimation QCD contribution

QCD sample from MonteCarlo simulation is not reliable. Distributions for QCD estimated from a sideband region obtained by reverting the isolation requirement on the lepton.



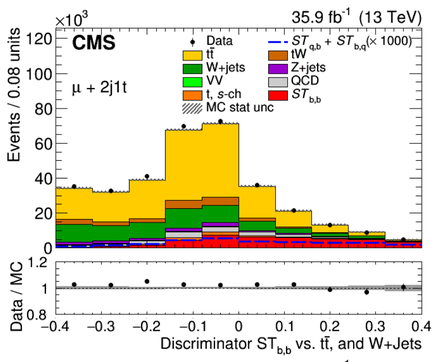
QCD multijet rejected in muon channel by requiring:

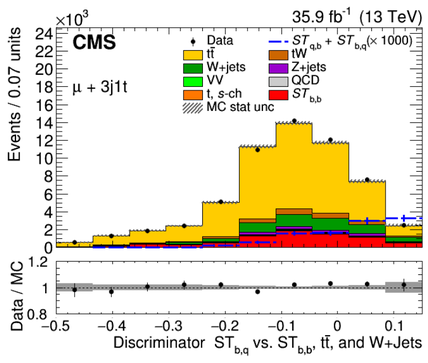
2-jets—1-tag
$m_{\mathrm{T}}^{\mathrm{W}} > 50$
$\epsilon_{non-QCD} = 68\,\%$
$1-\epsilon_{QCD} = 78\,\%$

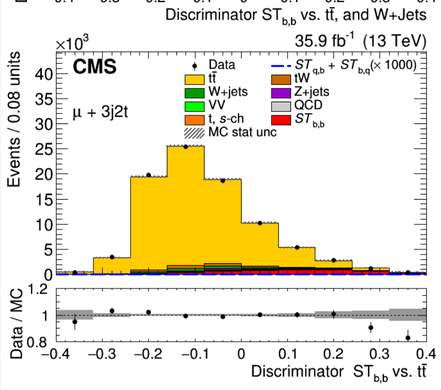
3-jets—1-tag
$m_{\mathrm{T}}^{\mathrm{W}} > 50 \& |\eta_{j'}| > 2.5$
$\epsilon_{non-QCD} = 64\,\%$
$1-\epsilon_{QCD} = 93\,\%$

Multivariate analysis and fit procedure

Signal to background discrimination:
- Several kinematic variables
- Use of Boosted Decision Trees discriminator







Finally a simultaneous fit is performed to the 6 categories: 2 lepton flavour x 3 regions.

Results

Standard Model scenario

$$|\mathrm{V_{tb}}|^2 > 0.970$$
$$|\mathrm{V_{ts}}|^2 + |\mathrm{V_{td}}|^2 < 0.057 \quad \text{at 95\% confidence level}$$

Beyond the Standard Model scenarios

Model 1

$$|\mathrm{V_{tb}}|^2 = 0.988 \pm 0.051$$
$$|\mathrm{V_{ts}}|^2 + |\mathrm{V_{td}}|^2 = 0.06 \pm 0.06$$

Model 2

$$|\mathrm{V_{tb}}|^2 = 0.988 \pm 0.024$$
$$|\mathrm{V_{ts}}|^2 + |\mathrm{V_{td}}|^2 = 0.06 \pm 0.06$$
$$\frac{\Gamma^{\mathrm{obs}}_{\mathrm{t}}}{\Gamma_t} = 0.99 \pm 0.42$$

Comparison with previous measurements

The results are more precise than the last measurement of $|\mathrm{V_{tb}}|$ performed by CMS [2]:

$$|f_{\mathrm{LV}}V_{\mathrm{tb}}| = 0.98 \pm 0.07\,(\mathrm{exp}) \pm 0.02\,(\mathrm{theo})$$

The results are in agreement with value obtained from the combination of all the single-top-quark production cross section measurements with the full Run-I data [3]:

$$|f_{\mathrm{LV}}V_{tb}| = 1.02 \pm 0.04\ (\mathrm{meas.}) \pm 0.02\ (\mathrm{theo.})$$

References

[1] **CMS Collaboration**, "*Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at* $\sqrt{s} = 13$ TeV", *Phys.Lett.B* 808 (2020) 135609.
[2] **CMS Collaboration**, "*Measurement of the single top quark and antiquark production cross sections in the t-channel and their ratio in proton-proton collisions at* $\sqrt{s} = 13$ TeV", *Phys.Lett.B* 800(2019) 135042.
[3] **The ATLAS and CMS Collaborations**, "*Combinations of single-top-quark production cross-section measurements and* $|f_{\mathrm{LV}}V_{\mathrm{tb}}|$ *determinations at* $\sqrt{s} = 7$ *and* 8 TeV *with the ATLAS and CMS experiments*", JHEP 05 (2019) 088.