Measurement of the CKM matrix elements $|V_{tb}|$, $|V_{ts}|$, and $|V_{td}|$ in single top events in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Highlight: LHCTopWG talk

LHCTopWG Open Meeting

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INFN e Università di Napoli

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Overview

Single top cross section: previous approach

In production

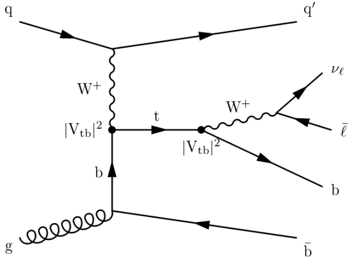
$$\sigma_{t\text{-ch.}} = \sigma_{t-\mathrm{ch.,b}} = \alpha |\mathrm{V_{tb}}|^2$$

- Only the contributions to $|\mathrm{V_{tb}}|^2$ in the production vertex cross section is considered.

In decay

$$R = \frac{|\mathrm{V_{tb}}|^2}{|\mathrm{V_{tb}}|^2 + |\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2} \sim 1$$

- The decay is fixed to the SM prediction.



Any V-A possible enhancement to $|\mathrm{V_{tb}}|$, $|\mathrm{V_{td}}|$, and $|\mathrm{V_{ts}}|$ might be altering production and decay contributions to t-channel production

Single top cross section: TOP-17-012 approach

In production...

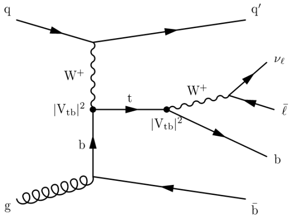
$$\sigma_{t\text{-ch.}} = \sigma_{t-\mathrm{ch.,b}} + \sigma_{t-\mathrm{ch.,d}} + \sigma_{t-\mathrm{ch.,s}} = \\ = \alpha|\mathrm{V_{tb}}|^2 + \beta|\mathrm{V_{td}}|^2 + \gamma|\mathrm{V_{ts}}|^2$$

...by adding the decay

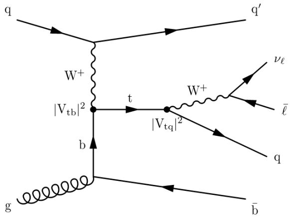
$$\sigma_{t\text{-ch.}} \times \mathrm{BR}(\mathrm{t} \rightarrow \mathrm{Wq}) \approxeq \alpha|\mathrm{V_{tb}}|^2|\mathrm{V_{tb}}|^2 + \alpha|\mathrm{V_{tb}}|^2\left(|\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2\right) \\ + \beta|\mathrm{V_{td}}|^2|\mathrm{V_{tb}}|^2 + \gamma|\mathrm{V_{ts}}|^2|\mathrm{V_{tb}}|^2$$

Three signals:

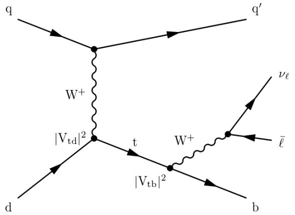
#1 $ST_{(\mathrm{b,b})}$ signal



#2 $ST_{(\mathrm{b,q})}$ signal

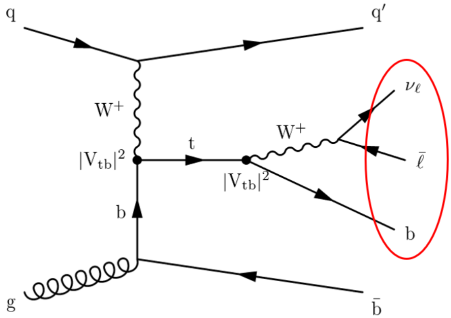


#3 $ST_{(\mathrm{q,b})}$ signal



$ST_{(b,b)}$ features

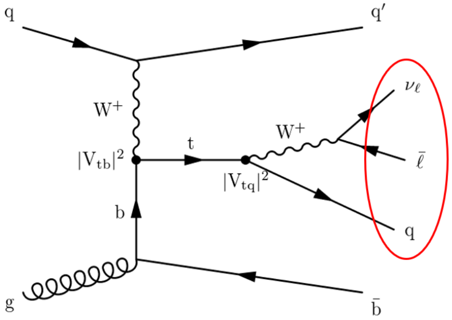
$ST_{(b,b)}$ signal: standard



- b-jet from top quark:
  - $\ell\nu b$ correct top quark candidate association
- Second b from gluon splitting:
  - if selected $\rightarrow$ 3j2t pure $|V_{tb}|^4$
  - if lost $\rightarrow$ 2j1t pure $|V_{tb}|^4$
  - if not tagged $\rightarrow$ 3j1t background to other signals

$ST_{(b,q)}$ features

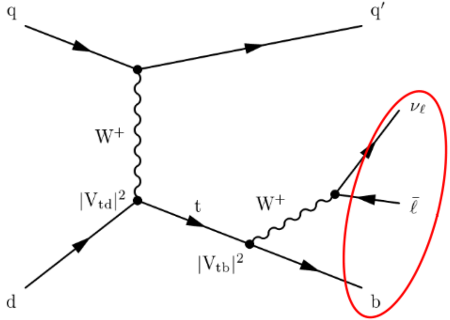
$ST_{(b,q)}$ signal: NEW



- b-jet from gluon splitting
  - $\ell\nu b$: wrong top quark candidate.
- light jet from top quark:
  - $\ell\nu q$: correct top quark candidate.
- Reconstructing the top quark with non–btagged jet gives the right kinematic variables
- Main signal region: 1 b-jet, 1 fwd jet, 1 non-b jet.

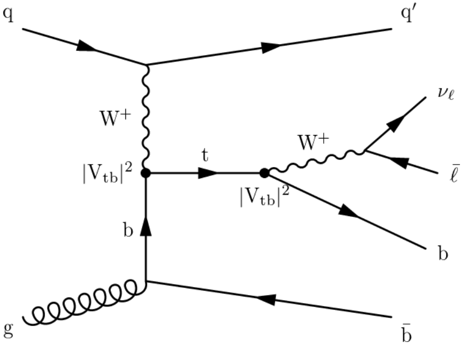
$ST_{(q,b)}$ features

$ST_{(q,b)}$ signal: NEW



- b-jet from top quark:
  - $\ell\nu b$: correct top quark candidate association.
- Main difference: PDF in the initial state.
- Main signal region: 1 b-jet, 1 fwd jet.

Baseline selection



Light jet from top-quark recoiling (j')

Lepton (e or μ) coming from W-boson decay

Neutrino (ν_e or ν_μ) coming from W-boson decay

Jet coming from top-quark decay

Jet coming from gluon splitting

Required objects

1	Tight muon	$p_T > 26$ GeV/c	$\|\eta\| < 2.4$	$I^{\mu}_{rel} < 0.06$	
0	Loose muon	$p_T > 10$ GeV/c	$\|\eta\| < 2.4$	$I^{\mu}_{rel} < 0.2$	
1	Tight electron	$E_T > 35$ GeV	$\|\eta\| < 2.1$	$I^{e}_{rel} < 0.0588$ (B)	$I^{e}_{rel} < 0.0571$ (E)
0	Veto electron	$E_T > 15$ GeV	$\|\eta\| < 2.5$	$I^{e}_{rel} < 0.2$	
2(3)	Jet	$E_T > 40$ GeV	$\|\eta\| < 4.7$		
1(2)	b-Jet	$E_T > 40$ GeV	$\|\eta\| < 2.4$	CMVA ≥ 0.9432	

Top quark reconstruction

Top quark mass reconstructed with

- jet momentum
- lepton momentum
- missing transverse momentum (neutrino)

To obtain $p_{z,\nu}$ one uses:

$$m_{\mathrm{W}}^2 = \left(E_\ell + \sqrt{\not{E}_{\mathrm{T}}^2 + p_{z,\nu}^2}\right)^2 - \left(\vec{p}_{\mathrm{T},\ell}^{\,2} + \vec{\not{E}}_{\mathrm{T}}^{2}\right)^2 - \left(p_{z,\ell}^2 + p_{z,\nu}^2\right)^2$$

So:

$$p_{z,\nu} = \frac{\Lambda \cdot p_{z,\ell}}{p_{\mathrm{T},\ell}^2} \pm \sqrt{\frac{\Lambda^2 \cdot p_{z,\ell}^2}{p_{\mathrm{T},\ell}^4} - \frac{E_\ell^2 \cdot \not{E}_{\mathrm{T}}^2 - \Lambda^2}{p_{\mathrm{T},\ell}^2}} \quad \text{where:} \quad \Lambda = \frac{m_{\mathrm{W}}^2}{2} + \vec{p}_{\mathrm{T},\ell} \cdot \vec{\not{E}}_{\mathrm{T}}$$

2 real solutions (in $\sim 65\%$ of signal events)

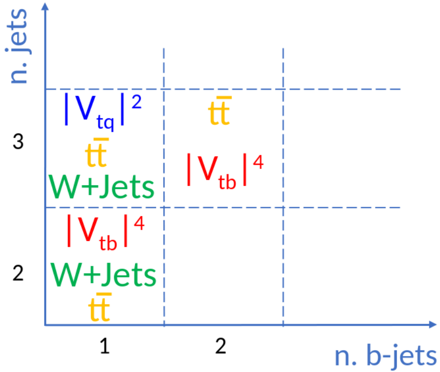
- take smaller $|p_z^\nu|$ solution

complex solutions

- $|p_{x,y}^\nu|$ pair which minimizes ΔR to the original $\not{E}_{\mathrm{T}}$

Regions categorization

- 2-jets–1-tag rich in *t*-channel $|V_{tb}|^4$
- 3-jets–1-tag rich in *t*-channel $|V_{tq}|^2$
- 3-jets–2-tags rich in $t\bar{t}$ and pure in $|V_{tb}|^4$

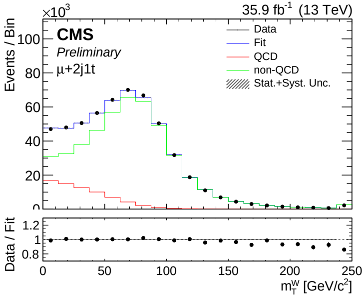


- The three regions are rich with different signal components
- All the samples taken into account in each region for both muon and electron channels.
- Simultaneous fit to extract the CKM matrix elements AND constrain the backgrounds.

QCD estimation

Large cross-section, low selection efficiency → QCD MC with large uncertainty
Extraction from the data

- Approach for 2-jets–1-tag and 3-jets–1-tag:
  - Identification of a sideband rich in QCD events
  - Yield obtained by fitting the m_T^W shape in the isolated region
    → ML fit with two components: QCD and non-QCD
  - For the 3j1t the additional scale factor for the $|\eta_{j'}| > 2.5$ region derived from data anti-iso



$$SF = \frac{N_{Data_{SB}}^{\eta_{j'}>2.5}}{N_{Data_{SB}}}$$

- Approach for 3-jets–2-tags:
  - Contribution from QCD negligible! No extra selection required.

Signal extraction overview

2-jets–1-tag

- j' defined as the non b-tagged jet
- QCD sample depleted with $m_{\mathrm{T}}^{\mathrm{W}} > 50$ GeV requirement
- BDT training: single top t-channel ($ST_{(\mathrm{b,b})}$) vs $\mathrm{t\bar{t}}$ and $\mathrm{W+jets}$

3-jets-1-tag

- j' defined as the most forward non b-tagged jet
- signal region $m_{\mathrm{T}}^{\mathrm{W}} > 50~\mathrm{GeV}$ & $|\eta_{j'}| > 2.5$
- BDT training: single top t-channel with $|\mathrm{V_{tq}}|^2$ vertex in decay ($ST_{(\mathrm{b,q})}$) vs single top t-channel ($ST_{(\mathrm{b,b})}$), standard $\mathrm{t\bar{t}}$ and $\mathrm{W+jets}$

3-jets–2-tags

- j' defined as the non b-tagged jet
- BDT training: single top t-channel ($ST_{(\mathrm{b,b})}$) vs $\mathrm{t\bar{t}}$

Fit strategy and Systematics

- Three different theoretical models used to account BSM models too
- The systematic uncertainties used are:
  - Profiled:
    - The b tagging and mis-identification efficiencies
    - Lepton trigger and reconstruction
    - The uncertainty in the average expected number of pileup interactions
    - $\mathrm{t\bar{t}}$ modelling $\rightarrow$ Q^2 scale, UE event, ME-PS matching (hdamp), ISR, FSR
    - Renormalisation and factorisation scale uncertainty ($\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$) for minor backgrounds
    - The uncertainty due to the choice of PDFs
    - MC limited size samples $\rightarrow$ Barlow-Beeston lite method
  - nonprofiled:
    - Jet energy scale (JES)
    - Jet energy resolution for the signal samples
    - The integrated luminosity is known with a relative uncertainty of 35.89 $\mathrm{cm}^{-2}\mathrm{s}^{-1} \pm$ 2.6%.
    - *t*-channel modelling $\rightarrow$ Q^2 scale, PSQ^2 scale, ME-PS matching (hdamp), PDF choice

Master formulas

The following signal strengths can be defined:

$$\mu_b = \frac{\sigma^{\text{obs}}_{t-\text{ch.,b}} \mathcal{B}(\text{t} \to \text{Wb})^{\text{obs}}}{\sigma_{t-\text{ch.,b}}(\mathcal{B}(\text{t} \to \text{Wb}))}$$

$$\mu_{sd} = \frac{\sigma^{\text{obs}}_{t-\text{ch.,b}} \mathcal{B}(\text{t} \to \text{Wd,s})^{\text{obs}} + \sigma^{\text{obs}}_{t-\text{ch.,s,d}} \mathcal{B}(\text{t} \to \text{Wb})^{\text{obs}}}{\sigma_{t-\text{ch.,b}} \mathcal{B}(\text{t} \to \text{Wd,s}) + \sigma_{t-\text{ch.,s,d}} \mathcal{B}(\text{t} \to \text{Wb})}$$

In the general case $\mathcal{B}(\text{t} \to \text{Wq}) = \Gamma_q / \Gamma_{\text{top}}$

$$\mu_b = \frac{|\text{V}_{\text{tb}}|^4_{\text{obs}} \Gamma^{\text{obs}}_q \Gamma_{\text{top}}}{|\text{V}_{\text{tb}}|^4 \Gamma_q \cdot \Gamma^{\text{obs}}_{\text{top}}}$$

$$\mu_{sd} = \frac{|\text{V}_{\text{tb}}|^2_{\text{obs}} (|\text{V}_{\text{ts}}|^2 + |\text{V}_{\text{td}}|^2)^{\text{obs}} \Gamma^{\text{obs}}_q \Gamma_{\text{top}}}{|\text{V}_{\text{tb}}|^2 (|\text{V}_{\text{ts}}|^2 + |\text{V}_{\text{td}}|^2) \Gamma_q \Gamma^{\text{obs}}_{\text{top}}}$$

Unconstrained case

- Within the SM the following relations hold:

$$\Gamma_{\rm top} \sim \Gamma_b \qquad \rightarrow \quad \mathcal{B}(\mathrm{t} \rightarrow \mathrm{Wq}) = R_q = \frac{|\mathrm{V_{tq}}|^2}{|\mathrm{V_{tb}}|^2 + |\mathrm{V_{ts}}|^2 + |\mathrm{V_{td}}|^2}$$

- No unitarity relation imposed! Unconstrained case.
- In this assumption, two fits are performed

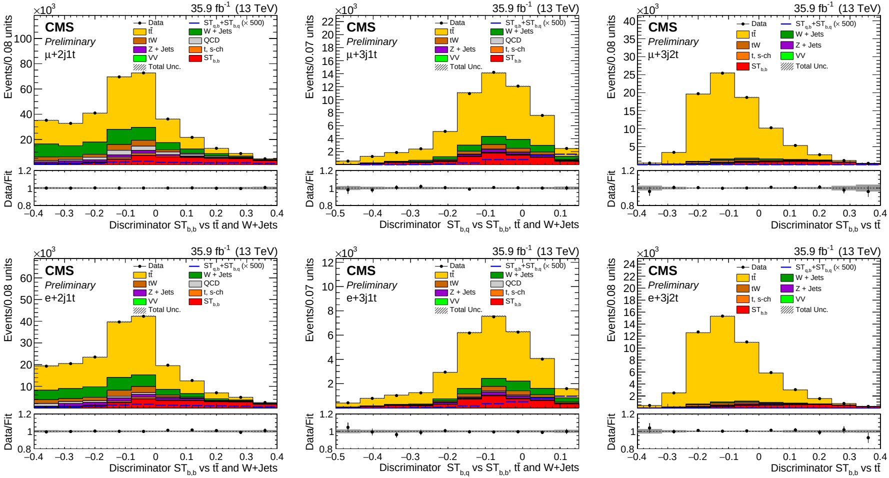
  μ_b (Max Likelihood) μ_{sd} (Asymptotic).

The results obtained are:

$$\mu_b = 0.99 \pm 0.03(\text{profiled}) \pm 0.12(\text{nonprofiled})$$
$$\mu_{sd} < 86 \text{ at } 95\% \, \mathrm{C.L}$$

Unconstrained case: Post fit plots

Muon



Unconstrained case: Interpretation

The fit result for the standard t-channel, events with $|V_{tb}|^4$ vertexes, is converted in terms of $|\mathrm{V_{tb}}|^2$ by exploiting the following relation:

$$\frac{\sigma^{\mathrm{obs}}_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\rightarrow \mathrm{Wb})^{\mathrm{obs}}}{\sigma_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\rightarrow \mathrm{Wb})} = \frac{(|V_{\mathrm{tb}}|^4)^{\mathrm{obs}}}{|V_{\mathrm{tb}}|^4}$$

$$|\mathrm{V_{tb}}|^2 = 0.99 \pm 0.02 \pm 0.06$$

$$|\mathrm{V_{tb}}| = 1.00 \pm 0.01 \pm 0.03$$

The fit result for the non-standard t-channel decays, events with a $|\mathrm{V_{td}}|^2$ or $|\mathrm{V_{ts}}|^2$ vertex, is:

$$\frac{\sigma^{\mathrm{obs}}_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\rightarrow\mathrm{Wd,s})^{\mathrm{obs}}}{\sigma_{t-\mathrm{ch.,b}}\mathcal{B}(\mathrm{t}\rightarrow\mathrm{Wd,s})} + \frac{\sigma^{\mathrm{obs}}_{t-\mathrm{ch.,s,d}}\mathcal{B}(\mathrm{t}\rightarrow\mathrm{Wb})^{\mathrm{obs}}}{\sigma_{t-\mathrm{ch.,s,d}}\mathcal{B}(\mathrm{t}\rightarrow\mathrm{Wb})} = \frac{(|\mathrm{V_{td}}|^2+|\mathrm{V_{ts}}|^2)^{\mathrm{obs}}(|\mathrm{V_{tb}}|^2)^{\mathrm{obs}}}{|\mathrm{V_{td}}|^2+|\mathrm{V_{ts}}|^2|\mathrm{V_{tb}}|^2}$$

$$|\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2 < 0.17\,\mathrm{at}\,95\%\,\mathrm{C.L.}$$

Constrained SM case

By assuming the SM the unitarity relation holds.

SM costraint

$$|\mathrm{V_{tb}}|^2 + |\mathrm{V_{tb}}|^2 + |\mathrm{V_{td}}|^2 = 1$$

Master formulas

$$\mu_b = \frac{|\mathrm{V_{tb}}|^{4\,\mathrm{obs}}}{|\mathrm{V_{tb}}|^4}$$

$$\mu_{sd} = \frac{|\mathrm{V_{tb}}|^{2\,\mathrm{obs}} \cdot (1 - |\mathrm{V_{tb}}|^{2\,\mathrm{obs}})}{|\mathrm{V_{tb}}|^2 \cdot (1 - |\mathrm{V_{tb}}|^2)}$$

In this case $|\mathrm{V_{tb}}|$ directly fitted.

Results:

$$|\mathrm{V_{tb}}| = 0.980^{+0.014}_{-0.011}(\mathrm{stat.} + \mathrm{syst.}) \pm 0.031(\mathrm{nonprofiled})$$

$$|\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2 = 0.040^{+0.023}_{-0.028}(\mathrm{stat.} + \mathrm{syst.}) \pm 0.059(\mathrm{nonprofiled})$$

BSM scenario 1

New physics effects:

- enhancement of $|V_{tb}|^2$, $|V_{ts}|^2$, or $|V_{td}|^2$ in production, in decay, or in both.
- existence of new particles $\rightarrow |V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2 \neq 1$
- modification of the total top decay width

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

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

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

Free parameters: $|V_{tb}|$ and $|V_{td}|^2 + |V_{ts}|^2$

Results:

$$|V_{tb}| = 0.988 \pm 0.027(\mathrm{stat} + \mathrm{syst}) \pm 0.043(\mathrm{nonprofiled})$$

$$|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.05(\mathrm{stat} + \mathrm{syst})^{+0.04}_{-0.03}(\mathrm{nonprofiled}).$$

BSM scenario 2

Second case: $\Gamma_{\mathrm{top}}^{\mathrm{obs}} \neq \Gamma_{\mathrm{top}}$

$$\mu_b = \frac{|V_{\mathrm{tb}}|^4_{\mathrm{obs}}\Gamma_{\mathrm{top}}}{|V_{\mathrm{tb}}|^4\Gamma_{\mathrm{top}}^{\mathrm{obs}}}$$

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

Free parameters: $|V_{\mathrm{tb}}|^2$, $|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2$, and $\Gamma_{\mathrm{top}}^{\mathrm{obs}}/\Gamma_{\mathrm{top}}$

Results:

$$|V_{\mathrm{tb}}| = 0.988 \pm 0.011(\mathrm{stat+syst}) \pm 0.021(\mathrm{nonprofiled})$$

$$|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 = 0.06 \pm 0.05(\mathrm{stat+syst}) \pm 0.04(\mathrm{nonprofiled})$$

$$\frac{\Gamma_{\mathrm{top}}^{\mathrm{obs}}}{\Gamma_{\mathrm{top}}} = 0.99 \pm 0.42(\mathrm{stat+syst}) \pm 0.03(\mathrm{nonprofiled}).$$

Summary

- First direct measurements of CKM matrix elements
- single top events $\rightarrow$ 1 lepton + 2/3 jets (1/2 b-tagged)
- QCD multijets template from sideband by inverting the lepton selection criteria
- Three regions defined and three BDTs, one for region:
  - single top *t*-channel vs $\mathrm{t\bar{t}}$ and $\mathrm{W + jets}$ in 2j1t
  - single top *t*-channel with $|\mathrm{V_{tq}}|^2$ vertex in decay vs single top *t*-channel, standard $\mathrm{t\bar{t}}$ and $\mathrm{W + jets}$ in 3j1t
  - single top *t*-channel vs $\mathrm{t\bar{t}}$ in 3j2t

The results obtained are:

Unconstrained case

$$|\mathrm{V_{tb}}| = 1.00 \pm 0.01 \pm 0.03$$

$$|\mathrm{V_{tb}}|^2 = 0.99 \pm 0.02 \pm 0.06$$

$$|\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2 \leq 0.17 \,\mathrm{at}\, 95\% \,\mathrm{C.L.}$$

Constrained case

$$|\mathrm{V_{tb}}| = 0.980^{+0.014}_{-0.011} \pm 0.031$$

$$|\mathrm{V_{td}}|^2 + |\mathrm{V_{ts}}|^2 = 0.040^{+0.023}_{-0.028} \pm 0.059$$

BACKUP

MC samples

Monte Carlo samples used:

- Standard single top:
  - NLO precision in POWHEG 2.0 4FS
- Non standard production and decay for single top: $[|V_{td}|,|V_{ts}|]$
  - NLO precision in POWHEG 2.0 5FS
- Associate production tW:
  - NLO precision in POWHEG 1.0 5FS
- $t\bar{t}$:
  - NLO precision in POWHEG 2.0 5FS
- $W + \text{jets}$, single top *s*-channel and dibosons events:
  - NLO precision in aMC@NLO
- Multi-jet QCD:
  - Derived from data by reverting the isolation cuts on the lepton
  - Cross check with MADGRAPH

All standard MC used reported in back up slides.

Standard objects selection

- Data:
  - 2016 Dataset Run-BCDEFG
- Triggers
  - μ: `HLT_IsoMu24v*` or `HLT_IsoTkMu24v*`
  - e: `HLT_Ele32_eta2p1_WPTight_Gsfv*`
- 1 Lepton (Tight):
  - μ: $p_T > 10$ GeV, $|\eta| < 2.4$ and $I_{rel}^{\delta\beta\text{-coor.}} < 0.06$
  - e: $p_T > 35$ GeV, $|\eta| < 2.1$, $I_{rel}^{\rho\text{-corr.}} > 0.2$
  - Trigger, ID, Isolation SF for electron and muon derived privately and validated by MUON and EGamma POGs
- No additional Lepton (Loose):
  - μ: $p_T > 10$ GeV, $|\eta| < 2.4$ and $I_{rel}^{\delta\beta\text{-coor}} > 0.2$
  - e: With Veto ID, $p_T > 15$ GeV, $|\eta| < 2.5$
- Jets:
  - CHS anti-k_T jets with Loose PF ID, $p_T > 40$GeV, $|\eta| < 4.7$
  - Lepton-jet disambiguation by ΔR(Lep, jet) > 0.4
  - b-tagged with CMVAT tight working point, $|\eta| < 2.4$
- Corrections and scale factors: b-tagging reshaping; pileup reweighting ($\sigma_{pp} = 69$ mb); Summer16_23Sep2016V4 JEC; Summer16_25nsV1 JER, pre-firing.

QCD depletion

QCD normalized to fit results.
Other processes normalized to the expected cross sections.