Direct measurements of $V_{tb}$ and constraints on the Wtb anomalous couplings

Nello Bruscino - University of Pittsburgh on behalf of the ATLAS & CMS collaborations
At hadron colliders, top quarks predominantly produced
* in pairs ($t\bar{t}$) via the flavour-conserving strong interaction (gtt)
* singly through the electroweak (EW) interaction (Wtb)

In $t\bar{t}$ production, Wtb vertex probed through top-quark decay
* top quarks produced unpolarised and decayed through EW interaction ($t \rightarrow Wb$)

In single top-quark production, Wtb vertex studied in production and decay
* production modes also sensitive to new physics
New effects above EWWS scale on Wtb vertex probed in a EFT approach

- the most general Wtb lagrangian, including dim-6 operators

\[ \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu \]

- CKM matrix element \( V_{tb} \approx 1 \)
- \( f_{LV} \) being a model-independent left-handed real form factor, encapsulating non-SM contributions
- \( V_R, g_L \) and \( g_R \) := complex anomalous couplings
- Imaginary parts related with CP violation!
How to probe $W_{tb}$?

Left-handed (LH) vector coupling $V_L$ measured from

- *(directly)* single top-quark production cross-section measurements
  - **assumption**: SM $W_{tb}$ vertex ($V_R = g_L = g_R = 0$)
- *(indirectly)* BR measurements in $t\bar{t}$ production (rather model dependent)

$$|V_L| := |f_{LV_{tb}}| = \sqrt{\sigma / \sigma_{th}}$$

Assumptions: $V_R = g_L = g_R = 0$

$|V_{td}|, |V_{ts}| \ll |V_{tb}|$
Anomalous couplings probed by means of top-quark related properties

- $W$ boson helicity fractions ($F_0, F_L, F_R$) in top-quark decays
- single top-quark production and decay observables (angular distributions, etc)
  - different model assumptions according to the sensitive observable

$F_i = N_i / (N_0 + N_L + N_R)$

$i = 0, L, R$ ($W$ polarizations)

Some assumptions needed:
- 2 ind. $F$, 4 (real) couplings

$A_i^T$ (ATLAS) JHEP 04 (2017) 124
$A_i^N$ (ATLAS) JHEP 04 (2017) 124
$A_i^L$ (ATLAS) JHEP 04 (2017) 124
$\sigma_i$ (CMS) JHEP 12 (2012) 035 (7 TeV)
$\sigma_W$ (ATLAS+CMS) Phys.Rev.Lett. 110 (2013) 022003 (7 TeV)
$\sigma_s$ (ATLAS) Phys.Lett.B 756 (2016) 228 (8 TeV)
$\sigma_t$ (CMS) Phys.Lett.B 772 (2017) 752 (13 TeV)
$\sigma_W$ (CMS) CMS PAS TOP-17-018 (13 TeV)
$\sigma_s$ (CDF+D0) Phys.Rev.Lett. 115 (2015) 152003
$\sigma_t$ (CDF+D0) Phys.Rev.Lett. 112 (2014) 231803

$f_0$ (CDF+D0) Phys.Rev.D 85 (2012) 071106
$f_1$ (CDF+D0) Phys.Rev.D 85 (2012) 071106

$O_{\text{theory}} - O_{\text{meas}} / \sigma_{\text{meas}}$
Anomalous couplings probed by means of top-quark related properties

- $W$ boson helicity fractions ($F_0, F_L, F_R$) in top-quark decays
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  - Different model assumptions according to the sensitive observable

$A_{\text{FB}}^i = (N_{+-}-N_{-+})/(N_{++}+N_{+-})$, $i=l,T,N$ (sensitive directions)

Assumption:
- Correlation neglected

![Graph showing observables and distributions](image-url)
How to probe $Wtb$?

Anomalous couplings probed by means of top-quark related properties

- $W$ boson helicity fractions ($F_0, F_L, F_R$) in top-quark decays
- single top-quark production and decay observables (angular distributions, etc)

- different model assumptions according to the sensitive observable

3-differential decay, $f_l, f_{l}^{+}, f_{0}^{+}, \delta^{+}, \delta^{-}, P$

No assumption

**Direct constraints on $V_{tb}$**

**Phys. Rev. D, 97, 013007 (2017)**

<table>
<thead>
<tr>
<th>ATLAS+CMS Preliminary</th>
<th>LHCtopWG</th>
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<tbody>
<tr>
<td>$\frac{\sigma_{\text{meas}}}{\sigma_{\text{theo}}}$ from single top quark production</td>
<td>May 2018</td>
</tr>
</tbody>
</table>

$\alpha_{\text{theo}}$: NLO+NLL MSTW2008nnlo
PRD 83 (2011) 091602, PRD 82 (2010) 054018,
PRD 81 (2010) 054029

$\Delta\sigma_{\text{theo}}$: scale @ PDF

$m_{\text{top}} = 172.5$ GeV

**t-channel:**

- **ATLAS 7 TeV**
  - PRD 90 (2014) 112006 (4.59 fb⁻¹)
  - 1.02 ± 0.06 ± 0.02
- **ATLAS 8 TeV**
  - EPJC 77 (2017) 531 (20.2 fb⁻¹)
  - 1.028 ± 0.042 ± 0.024
- **CMS 7 TeV**
  - JHEP 12 (2012) 035 (1.17 - 1.56 fb⁻¹)
  - 1.020 ± 0.046 ± 0.017
- **CMS 8 TeV**
  - JHEP 06 (2014) 090 (19.7 fb⁻¹)
  - 0.979 ± 0.045 ± 0.016
- **CMS combination 7+8 TeV**
  - JHEP 06 (2014) 090
  - 0.998 ± 0.038 ± 0.016
- **CMS 13 TeV**
  - PLB 772 (2017) 752 (2.3 fb⁻¹)
  - 1.05 ± 0.07 ± 0.02
- **ATLAS 13 TeV**
  - JHEP 04 (2017) 086 (3.2 fb⁻¹)
  - 1.07 ± 0.09 ± 0.02

**Wt:**

- **ATLAS 7 TeV**
  - PLB 716 (2012) 142 (2.05 fb⁻¹)
  - 1.03 ± 0.15 ± 0.03
- **CMS 7 TeV**
  - PRL 110 (2013) 022003 (4.9 fb⁻¹)
  - 1.01 ± 0.16 ± 0.03
- **ATLAS 8 TeV**
  - JHEP 01 (2016) 064 (20.3 fb⁻¹)
  - 1.01 ± 0.10 ± 0.03
- **CMS 8 TeV**
  - PRL 112 (2014) 231802 (12.2 fb⁻¹)
  - 1.03 ± 0.12 ± 0.04
- **LHC combination 8 TeV**
  - ATLAS-CONF-2016-023,
    CMS-PAS-TOP-15-019
  - 1.02 ± 0.08 ± 0.04
- **ATLAS 13 TeV**
  - EPJC 78 (2018) 166 (3.2 fb⁻¹)
  - 1.14 ± 0.24 ± 0.04

**s-channel:**

- **ATLAS 8 TeV**
  - PLB 756 (2016) 228 (20.3 fb⁻¹)
  - 0.93 ± 0.18 ± 0.04

**Latest results from ATLAS and CMS**

- **CMS t-chan analysis at 13 TeV (35.9 fb⁻¹)**
  - TOP-17-011
  - $|f_{LVVtb}| = 1.00 \pm 0.05$ (meas) ± 0.02 (theo)
- **CMS tW analysis at 13 TeV**
  - $\mu = 0.88 \pm 0.02$ (stat) ± 0.09 (syst) ± 0.03 (lumi)
- **ATLAS tW analysis at 13 TeV**
  - EPJC 78 (2018) 186
  - $|f_{LVVtb}| = 1.14 \pm 0.24$ (meas) ± 0.04 (theo)

**Best combination at 7+8 TeV (CMS)**

- $|f_{LVVtb}| = 0.998 \pm 0.041$
- ATLAS+CMS Run I combination ongoing
W helicity fractions

W\(\bar{b}\) properties in \(t\bar{t}\) events determined by structure of weak interaction

* Helicity fractions \((F_R, F_L, F_0)\) are determined by the W\(\bar{b}\) vertex structure
  \[ F_0 + F_L + F_R = 1 \]

**Longitudinal W**

**L-handed W**

**R-handed W**

\[ F_L = 0.311 \pm 0.005 \]
\[ F_0 = 0.687 \pm 0.005 \]
\[ F_R = 0.0017 \pm 0.0001 \]

The differential decay rate of top quarks considering the angle \(\theta^*\) is given by:

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} = \frac{3}{4} \left( 1 - \cos^2 \theta^* \right) F_0 + \frac{3}{8} \left( 1 - \cos \theta^* \right)^2 F_L + \frac{3}{8} \left( 1 + \cos \theta^* \right)^2 F_R
\]

* \(F_i\) depend on (real) anomalous couplings \(\Rightarrow\) deviations as hint of BSM physics
W helicity fractions

PLB 762 (2016) 512–534

Measurement in $t\bar{t}$ topology (19.8 fb$^{-1}$, 8 TeV)

* cut-based analysis, e and $\mu$ channels
* kinematic fitting to reconstruct $t\bar{t}$ system
  ◇ leptonic side ONLY

Reweighting method:

* top events $N_{tt\bar{t}}$ reweighted according to decay function

\[ w_{\text{lep/had/single-t}}(\cos\theta_{\text{gen}}^*; \vec{F}) = \left[ \frac{3}{8} F_L (1 - \cos\theta_{\text{gen}}^*)^2 + \frac{3}{4} F_0 \sin^2\theta_{\text{gen}}^* + \frac{3}{8} F_R (1 + \cos\theta_{\text{gen}}^*)^2 \right] / \left[ \frac{3}{8} F_L^{SM} (1 - \cos\theta_{\text{gen}}^*)^2 + \frac{3}{4} F_0^{SM} \sin^2\theta_{\text{gen}}^* + \frac{3}{8} F_R^{SM} (1 + \cos\theta_{\text{gen}}^*)^2 \right] \]

* maximise a binned Poisson likelihood function

\[ \mathcal{L}(\vec{F}) = \prod_i \frac{N_{MC}(i; \vec{F}) N_{data}(i)}{N_{data}(i)!} \exp[-N_{MC}(i; \vec{F})] \]
Measurement in tt topology (20.2 fb\(^{-1}\), 8 TeV)

- cut-based analysis
- kinematic fitting to reconstruct tt system
  - leptonic and hadronic sides
  - hadronic analyser less sensitive

Template fit method:

- templates for \( F_0, F_L, F_R \) (per-lepton channel) by reweighting reco. distribution

Combined likelihood fit (8 inputs) to extract helicity fractions

**Very precise measurement!**

Leptonic analyser (\( \geq 2 \) b-tags)

\[
F_0 = 0.709 \pm 0.012 \text{ (stat.+bkg. norm.)}^{+0.015}_{-0.014} \text{ (syst.)}
\]

\[
F_L = 0.299 \pm 0.008 \text{ (stat.+bkg. norm.)}^{+0.013}_{-0.012} \text{ (syst.)}
\]

\[
F_R = -0.008 \pm 0.006 \text{ (stat.+bkg. norm.)} \pm 0.012 \text{ (syst.)}
\]
Possibility to set limits on anomalous $Wtb$ couplings with EFTFitter tool

- **limitation**: only place limits on combinations of (real) coupling pairs
  - other couplings set to their SM values ⇒ loss of generality

Allowed ranges:

- $\text{Re}[V_R] \in [-0.24, 0.31]$ @ 95% C.L.
- $\text{Re}[g_L] \in [-0.14, 0.11]$ @ 95% C.L.
- $\text{Re}[g_R] \in [-0.02, 0.06]$ and $[0.74, 0.78]$ @95% C.L.

Excluded by $t$-channel $x$-sect
Search for anomalous Wtb couplings in t-channel single top quark production (24.7 fb⁻¹, 7-8 TeV)

- one muon and two or three jets
- Bayesian Neural Network (BNN) technique to separate $V_L$ vs. $V_R$, $g_R$ and $g_L$

1-2-3D constraints on the anomalous parameters are obtained

Agreement with SM predictions
Combining x-sec, W-helicity and asymmetry to increase sensitivity to BSM

* in the EFT framework
* most recent asymmetries result from ATLAS included
* very general approach: couplings (real+imaginary) allowed to vary simultaneously
Combining x-sec, W-helicity and asymmetry to increase sensitivity to BSM

- in the EFT framework
- most recent asymmetries result from ATLAS included
- very general approach: couplings (real+imaginary) allowed to vary simultaneously

\[
V_L = 1
\]

- helic.
- helic. + \( \alpha_{t_R} \) (2 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 7 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 8 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 13 TeV) + Asym.

\[
V_L = 1
\]

- helic.
- helic. + \( \alpha_{t_R} \) (2 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 7 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 8 TeV)
- helic. + \( \alpha_{t_{WS}} \) (up to 13 TeV) + Asym.

TopFit 95% C.L. Limits

Standard Model
Combining x-sec, W-helicity and asymmetry to increase sensitivity to BSM

- in the EFT framework
- most recent asymmetries result from ATLAS included
- very general approach: couplings (real+imaginary) allowed to vary simultaneously

<table>
<thead>
<tr>
<th>$W_{hel} \oplus \sigma_{W,ls}$</th>
<th>$g_R$</th>
<th>$g_L$</th>
<th>$V_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>[−0.07, 0.08]</td>
<td>[−0.18, 0.20]</td>
<td>[−0.33, 0.41]</td>
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<tr>
<td>Im</td>
<td>[−0.23, 0.23]</td>
<td>[−0.20, 0.19]</td>
<td>[−0.39, 0.36]</td>
</tr>
<tr>
<td>$\oplus A_{FB}^L, A_{FB}^T, A_{FB}^N$</td>
<td>$g_R$</td>
<td>$g_L$</td>
<td>$V_R$</td>
</tr>
<tr>
<td>Re</td>
<td>[−0.07, 0.06]</td>
<td>[−0.19, 0.19]</td>
<td>[−0.27, 0.33]</td>
</tr>
<tr>
<td>Im</td>
<td>[−0.19, 0.13]</td>
<td>[−0.18, 0.19]</td>
<td>[−0.30, 0.30]</td>
</tr>
</tbody>
</table>

Floating $V_L$
Measurement of triple-differential angular decay rates of single top quarks produced in the t-channel (20.2 fb$^{-1}$, 8 TeV)

- 3D angular ($\theta, \theta^*, \phi^*$) decay rate using the helicity formalism
- relative phases can only be measured with polarised top quarks
- polarisation (P) can only be measured in single top-quark events.

$$
\rho(\theta, \theta^*, \phi^*; P) = \frac{1}{N} \frac{d^3N}{d \cos \theta d\Omega^*} = \frac{1}{8\pi} \left( \frac{3}{4} A_{1, \frac{1}{2}} \right)^2 (1 + P \cos \theta) (1 + \cos \theta^*)^2 
+ \frac{3}{4} A_{-1, -\frac{1}{2}}^2 (1 - P \cos \theta) (1 - \cos \theta^*)^2 
+ \frac{3}{2} \left( A_{0, \frac{1}{2}}^2 - (1 - P \cos \theta) + (1 + P \cos \theta) \right) \sin^2 \theta^* 
- \frac{3\sqrt{2}}{2} P \sin \theta \sin \theta^* (1 + \cos \theta^*) \text{Re} \left[ e^{i\phi^*} A_{1, \frac{1}{2}} A_{0, \frac{1}{2}}^* \right] 
- \frac{3\sqrt{2}}{2} P \sin \theta \sin \theta^* (1 - \cos \theta^*) \text{Re} \left[ e^{-i\phi^*} A_{-1, -\frac{1}{2}} A_{0, -\frac{1}{2}}^* \right] = 0
$$

Finite series of orthonormal $M$-functions

$$
= \sum_{k=0}^{2} \sum_{l=0}^{2} \sum_{m=-l}^{l} a_{k,l,m} M_{k,l}^m (\theta, \theta^*, \phi^*)
$$
Detector effects deconvolved from data by measuring differential rates using Fourier techniques (OSDE)

* The generalised helicity fractions (three independent: \( f_1, f_1^+, f_0^+ \)) and phases \( (\delta_+, \delta_-) + P \) (nuisance) are determined \textit{simultaneously, including all correlations}

\[\diamond \text{possibility to separate } f_0 \text{ into two components (+ and -)}\]

\[
\varrho(\theta, \theta^*, \phi^*; P) = \frac{1}{dN / d \cos \theta d \Omega^*} = \frac{1}{8\pi} \left( \frac{3}{4} A_{1, \frac{1}{2}}^2 (1 + P \cos \theta) (1 + \cos \theta^*)^2 
+ \frac{3}{4} A_{-1, -\frac{1}{2}}^2 (1 - P \cos \theta) (1 - \cos \theta^*)^2 
+ \frac{3}{2} (A_{0, \frac{1}{2}}^2 - P \cos \theta) + (A_{0, -\frac{1}{2}}^2 (1 + P \cos \theta) \sin^2 \theta^* 
- \frac{3\sqrt{2}}{2} P \sin \theta \sin \theta^* (1 + \cos \theta^*) \Re\left[e^{i \phi^* A_{1, \frac{1}{2}} A_{0, \frac{1}{2}}^*}\right] 
- \frac{3\sqrt{2}}{2} P \sin \theta \sin \theta^* (1 - \cos \theta^*) \Re\left[e^{-i \phi^* A_{-1, -\frac{1}{2}} A_{0, -\frac{1}{2}}^*}\right] \right) = \\
= \sum_{k=0}^{2} \sum_{l=0}^{2} \sum_{m=-l}^{l} a_{k,l,m} M_{k,l}^m(\theta, \theta^*, \phi^*)
\]

\textit{Finite series of orthonormal M-functions}
Helicity fractions & phases determined w/o assumptions on other parameters

- distributions (profiles and contours) from numerical calculations of the likelihood function
- interpretation in terms of anomalous couplings $V_L, V_R, g_R$ and $g_L$
- overall normalisation $V_L$ set by cross-section measurements

In agreement with SM predictions
3-angle analysis

JHEP 1712 (2017) 017

Limits @95% C.L.:

- \(|V_R/V_L| < 0.37 \quad |g_L/V_L| < 0.29\)
- tighter limits from \(b \rightarrow s \gamma\) and \(W\) helicity with assumptions on other parameters

- \(\text{Re}[g_R]/V_L \in [-0.12, 0.17] \quad \text{Im}[g_R]/V_L \in [-0.07, 0.06]\)

In agreement with SM predictions

[ N. Bruscino | Direct measurements of \(V_{tb}\) and constraints on the \(W_{tb}\) anomalous couplings | CKM18 | 18-Sep-2018 ]
Conclusions

Wtb vertex carefully probed during Run I in top-quark production and decay
- BSM effects on Wtb vertex probed in the EFT framework

Left-handed vector coupling $V_L$ extracted from single top-quark cross-sections
- most precise combination $|f_{LV}V_{tb}| = 0.998 \pm 0.041$, Run I combination ongoing
- assumption: $V_R = g_L = g_R = 0$

Wtb anomalous couplings probed in W-helicity measurements
- assumption: 2 independent $F$, 4 (real) couplings

Wtb vertex probed through global fit (x-sec+helicity+asymmetries)
- ATLAS+CMS(+CDF+D0), quite general EFT approach
- competitive constraints when $V_L = 1$

Wtb vertex tested via triple-differential angular decay rates
- most general approach, ability to separate $F_0$ into two components ($f_0$ and $f_0^+$)
- no assumptions on anomalous couplings
All measurements consistent with the SM predictions

* dominated by systematic uncertainties
* no sign of new physics BSM so far

Run II data being studied nowadays → even more interesting results soon!

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