Measurements of the top-quark properties in the production and decays of $t\bar{t}$ events at CMS

Pieter David
on behalf of the CMS collaboration

DIS 2017
3–7 April 2017, Birmingham
• Only fermion with an electroweak-scale mass, more massive than W, Z, H
• $\tau_{\text{decay}} < \tau_{\text{hadronisation}}$: study a bare quark
• Interesting probe of EWSB
• Plays a prominent role in many proposed BSM theories
• The LHC is a top factory
  $\sigma(pp \to t\bar{t}) \approx 835 \text{ pb at 13 TeV}$
A variety of top quark properties measurements

• $pp \rightarrow t \bar{t}$ production and modeling
  → Juan Gonzalez, earlier today
• top properties in single top
  → Ashfaq Ahmad, later in this session
• top quark mass, $m(t) - m(\bar{t})$
  → Nataliia Kovalchuk, this afternoon
• top quark width
• angular distributions of $pp \rightarrow t \bar{t}$ production and $t \rightarrow Wb$ decay
  • $t$ polarization and spin correlations
  • $W$ helicity fractions
  • charge asymmetry
• CP violation in $pp \rightarrow t \bar{t}$ production and $t \rightarrow Wb$ decay
• FCNC decays: $t \rightarrow Hu$, $t \rightarrow Hc$, $t \rightarrow Zq$, $t \rightarrow \gamma q$, $t \rightarrow ug$, $t \rightarrow cg$
• t-H coupling $pp \rightarrow t\bar{t}H$, $pp \rightarrow tHq$
  → Georgios Krintiras, WG3
• t-V couplings: $pp \rightarrow t\bar{t}V$ ($V = \gamma, Z, W$)
Bounding the top quark width using dilepton events

- 12.9 fb\(^{-1}\) at \(\sqrt{s} = 13\) TeV
- Sensitive variable: \(m(\ell b)\)
- Distribution for various \(\Gamma_t\) obtained by reweighting between \(\Gamma_{SM}\) and \(4\Gamma_{SM}\)

- Likelihood test statistic to discriminate between \(\Gamma_{SM}\) and \(\Gamma_{alt}\)
- 95% CL bound of \(0.6 \leq \Gamma_t \leq 2.5\) GeV expected: \([0.6, 2.4]\) (\(m_t = 172.5\) GeV)
W± helicity fractions in $t\bar{t}\rightarrow$ lepton + jets

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

$$-\frac{g}{\sqrt{2}} b i\sigma^{\mu\nu} q_\nu (g_L P_L + g_R P_R) t W^-_\mu + h.c.$$ 

- Kinematic fit (using t and W mass constraints) for the reconstruction of the complete $t\bar{t}$ system
- Maximum likelihood template fit to $\cos\theta^*_\ell$ and $|\cos\theta^*_q|$ distributions (parameterized as function of helicity fractions using simulation)

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{4} (\sin \theta^*)^2 F_0$$

$$+ \frac{3}{8} (1 + \cos \theta^*)^2 F_R$$
Charge asymmetry in $pp \rightarrow t\bar{t}$

- The $t\bar{t}$ charge asymmetry can be probed through the rapidity asymmetries
  \[
  \frac{N(|\eta|_{t} > |\eta|_{t}) - N(|\eta|_{t} < |\eta|_{t})}{N(|\eta|_{t} > |\eta|_{t}) + N(|\eta|_{t} < |\eta|_{t})} \quad \text{and} \quad \frac{N(|\eta|_{\ell}^{+} > |\eta|_{\ell}^{-}) - N(|\eta|_{\ell}^{+} < |\eta|_{\ell}^{-})}{N(|\eta|_{\ell}^{+} > |\eta|_{\ell}^{-}) + N(|\eta|_{\ell}^{+} < |\eta|_{\ell}^{-})}
  \]
  in $pp$ collisions

- Valence quark effect, so SM value smaller at 13 TeV ($pp \rightarrow t\bar{t}$ dominated by $gg$)

- Enhanced sensitivity to SM asymmetry by studying kinematic dependence, specific phase space regions, or using optimised observables
CP violation in $pp \rightarrow t\bar{t} \rightarrow \text{lepton} + \text{jets}$ at $\sqrt{s} = 8$ TeV

- asymmetry $\frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$ of T-odd triple products

\[ O_2 = \varepsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_3 = Q_\ell \varepsilon(p_b, p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{\text{b\bar{b} CM}} \propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_4 = Q_\ell \varepsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{\text{lab}} \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

\[ O_7 = q \cdot (p_b - p_{\bar{b}}) \varepsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{\text{lab}} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z \]

probes CP violation in $pp \rightarrow t\bar{t}$ production and decay to $\ell$+jets

- bounds at the 1–2% level, SM values are extremely small

\[ A'_{CP} = D A_{CP} \quad D = 1 - 2k \]

<table>
<thead>
<tr>
<th>$O_i$</th>
<th>$D$</th>
<th>$k$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$</td>
<td>$0.575 \pm 0.002 \pm 0.019$</td>
<td>$21.27 \pm 0.10 \pm 0.97$</td>
</tr>
<tr>
<td>$O_3$</td>
<td>$0.383 \pm 0.002 \pm 0.018$</td>
<td>$30.86 \pm 0.10 \pm 0.90$</td>
</tr>
<tr>
<td>$O_4$</td>
<td>$0.367 \pm 0.002 \pm 0.019$</td>
<td>$31.65 \pm 0.10 \pm 0.95$</td>
</tr>
<tr>
<td>$O_7$</td>
<td>$0.730 \pm 0.002 \pm 0.010$</td>
<td>$13.52 \pm 0.11 \pm 0.50$</td>
</tr>
</tbody>
</table>
Searches for FCNC top decays

**CMS preliminary**

February 2017


$\tau\bar{f}$, $\text{Br}(t \rightarrow Z q)$

**CMS TOP-12-039, arXiv:1702.01404 (sub. to JHEP)**

single top+$\tau\bar{f}$, $\text{Br}(t \rightarrow Z u)$

**CMS TOP-14-007, arXiv:1610.03545 (acc. by JHEP)**

single top, $\text{Br}(t \rightarrow g u)$

**CMS JHEP04(2016)035**

single top, $\text{Br}(t \rightarrow \gamma u)$

**CMS TOP-13-017, arXiv:1610.04857 (acc. to JHEP)**

$\tau\bar{f}$, $\text{Br}(t \rightarrow H u)$, $H \rightarrow WW, ZZ, \tau\tau, b\bar{b}, \gamma\gamma$

$\tau\bar{f}$, $\text{Br}(t \rightarrow H c)$, $H \rightarrow WW, ZZ, \tau\tau, b\bar{b}, \gamma\gamma$

--- 95% CL Observed Limit  green ±1σ Exp.Limit
--- 95% CL Expected Limit   yellow ±2σ Exp.Limit

--- 95% CL upper limits

Theory predictions
from arXiv:1311.2028

--- SM  green
--- 2HDM(FV)  blue
--- 2HDM(FC)  red
--- MSSM  cyan
--- RPV  magenta
--- RS  pink

--- see the talk by Ashfaq Ahmad later in this session for more details on FCNC constraints in single top production

--- Pieter David (UCLouvain-CP3)

--- Top properties @ CMS

--- DIS 2017
pp → \bar{t}t + γ cross-section at \sqrt{s} = 8 \text{ TeV}

- Fiducial region: photon $E_T > 25$ GeV, $|\eta| < 1.44$
- \bar{t}t+jets and V+γ backgrounds determined from fits to M3 (hadronic top mass) and photon isolation (with templates from data: random cone (PU) for isolated, photon η spread sideband for photons from jets)
- $e \rightarrow γ$ mis-ID rate corrected with $Z \rightarrow e^+e^-$
- $\sigma_{\text{fid}}^{\bar{t}t+γ}/\sigma_{\bar{t}t} = 5.2 \pm 1.1 \times 10^{-4} (\text{stat+syst})$
  $\sigma_{\text{fid}}^{\bar{t}t+γ} = 127 \pm 27 (\text{stat+syst}) \text{ fb}$
- photon $E_T$ and η distributions in good agreement with simulation
$pp \rightarrow \bar{t}t + \gamma$ cross-section at $\sqrt{s} = 8$ TeV

- **Fiducial region:** photon $E_T > 25$ GeV, $|\eta| < 1.44$
- **$\bar{t}t$+jets and $V+\gamma$ backgrounds** determined from fits to $M_3$ (hadronic top mass) and photon isolation (with templates from data: random cone (PU) for isolated, photon $\eta$ spread sideband for photons from jets)
- $e \rightarrow \gamma$ mis-ID rate corrected with $Z \rightarrow e^+ e^-$
- $\sigma_{\text{tt}+\gamma}^{\text{fid}} / \sigma_{\bar{t}t} = 5.2 \pm 1.1 \times 10^{-4} \, (\text{stat}+\text{syst})$
- $\sigma_{\text{tt}+\gamma}^{\text{fid}} = 127 \pm 27 \, (\text{stat}+\text{syst})$ fb
- photon $E_T$ and $\eta$ distributions in good agreement with simulation
pp → \bar{t}t + W/Z cross-sections at $\sqrt{s} = 13$ TeV

- 12.9 fb$^{-1}$ of 2016 data
- (same-sign) dilepton, three-lepton and four-lepton categories
- Data-driven non-prompt lepton background, WZ from control region

**Figure:**

- **Top left:** Distribution of BDT values with data-driven non-prompt lepton background and WZ events from control region.
- **Top right:** Comparison of signal and background events with different jet multiplicities.

**Table:**

- | Category            | Events |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>nonprompt</td>
<td>5</td>
</tr>
<tr>
<td>charge mis-ID</td>
<td>10</td>
</tr>
<tr>
<td>ttX</td>
<td>15</td>
</tr>
<tr>
<td>WZ</td>
<td>20</td>
</tr>
<tr>
<td>rare</td>
<td>25</td>
</tr>
<tr>
<td>ttW</td>
<td>30</td>
</tr>
</tbody>
</table>

**Legend:**

- Data
- ttZ
- ttX
- WZ
- rare
- nonprompt

**Additional Notes:**

- CMS Preliminary results from 12.9 fb$^{-1}$ of data at 13 TeV.
- Focus on various lepton categories with emphasis on non-prompt and WZ backgrounds.

**References:**

- CMS PAS TOP-16-017
- Pieter David (UCLouvain-CP3)
- Top properties @ CMS
$\sigma(pp \rightarrow \bar{t}tZ) = 0.70^{+0.16}_{-0.15} \text{ (stat.)}^{+0.14}_{-0.12} \text{ (sys.) pb}$

$\sigma(pp \rightarrow \bar{t}tW) = 0.98^{+0.23}_{-0.22} \text{ (stat.)}^{+0.22}_{-0.18} \text{ (sys.) pb}$
Conclusions

• Top properties analyses allow to constrain BSM physics in various ways

• Many measurements performed by CMS with run 1 data

• $\sqrt{s} = 13$ TeV: boost in cross-section, especially interesting for rare decay modes and production processes, e.g. $t\bar{t}+X$

• 2016 dataset: 36 fb$^{-1}$, many more $t\bar{t}$ pairs than run 1

• many improved and new top properties measurements are in preparation
Additional material
References

- CMS collaboration, Bounding the top quark width using final states with two charged leptons and two jets at $\sqrt{s} = 13$ TeV, CMS-PAS-TOP-16-019, 2016.


- CMS collaboration, Search for CP violation in top quark-antiquark production and decay in proton-proton collisions at $\sqrt{s} = 8$ TeV, CMS-TOP-16-001, CERN-EP-2016-266, arXiv:1611.08931, submitted to JHEP.

- CMS collaboration, Measurement of the $t\bar{t}+\gamma$ production cross-section in pp collisions at $\sqrt{s} = 8$ TeV, CMS-PAS-TOP-14-008, 2016.