Top quark properties at CMS and ATLAS

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On behalf of the ATLAS and CMS Collaborations

52nd Rencontres de Moriond on QCD and High Energy Interactions

March 2017
Top quark properties at the LHC

Over 30 years after its discovery, the SM top quark is well established experimentally. Many measurements on top quark mass, production cross sections in pairs: $tt^\pm X$; single: $(tW, tq$ in $t$- and $s$-channels), all agree with SM predictions within uncertainties.

LHC: precision era

>10 million top quarks produced per experiment at 8 TeV [to add: 7 TeV, 13 TeV data]  

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Use top quarks to investigate limits of the SM:

- **Go as precise as possible**: test SM comparing data to theory predictions
- Use the data to constrain **BSM theoretical predictions** (e.g.: using effective field theory)
- **Measure rare processes** involving top quarks, with much lower cross sections
- **Search directly** for signs of new physics at production or decay
Experimental take on top quark properties
(Outline of this talk)

Angular measurements
— top spin
— top polarisation (see also talk by Regina Valls)
— W polarisation in top decays

Charge and mass measurements
— charge asymmetry
— CP violation
— top width
— mass difference (talk by James Monk)

Production and decay
— EWK couplings (+top charge): e.g. ttH, tt+Z, tt+γ processes (talks by Nicolas Chanon, Lana Beck)
— FCNC couplings (searches): e.g. ggWb, tZ, tH processes

Limits on new physics
— Re-interpreting these measurements contrasting with beyond standard model physics models

Presenting latest measurements, mostly using LHC data at 8 TeV
More results can be found
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Typical top quark event selection

Focusing on final states with 1 or 2 leptons (electrons and/or muons)
Decays involving taus / full hadronic: more challenging to reach high precision

Events triggered with lepton triggers
Selection criteria mostly defined by trigger (+ detector acceptance) limitations and background rejection

Objects selection according to topology
- number of jets/b-jets
- number of isolated electrons/muons
-(additional selection criteria to reduce backgrounds, e.g. $M_{\ell^+\ell^-}$ or missing transverse energy for Z boson or non-prompt leptons rejection)

Several measurements require reconstruction of the tt system
- kinematic fit
- reconstruct missing information (e.g. neutrino pZ) from top and W masses constrains

Single top (t-channel)

Single top (tW-channel)

tt (dilepton)

tt (l+jets)
Top properties:

Angular measurements
Spin correlations and top polarisation

Angular observables: $\theta^{k,r,n}$

- $k$: helicity axis (top quark direction in $tt$ rest frame)
- $n$: transverse to the top quark production plane
- $r$: orthogonal to $k$ and $n$

Frame boosts: full $tt$ system reconstruction!

SM prediction:

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d\cos \theta^a d\cos \theta^b} = \frac{1}{4} \left( 1 + B^a_+ \cos \theta^a_+ + B^b_- \cos \theta^b_- - C(a,b) \cos \theta^a_+ \cos \theta^b_- \right),
\]

$a,b \rightarrow$ chosen axes
$+,- \rightarrow$ top charge

Polarisation: $B^a = 3 \langle \cos \theta^a \rangle$

Spin correlation between axis $a,b$: $C(a,b) = -9 \langle \cos \theta^a_+ \cos \theta^b_- \rangle$

Each top $\sim$ unpolarized (unlike EWK single top)
Top / anti-top spins are correlated
Spin correlations and top polarisation

Angular observables: data to predictions comparison

Measurements in agreement with the SM predictions

Sizeable spin correlations

SM predictions

Polarisation~0
Spin correlations and top polarisation

Angular observables: \( \theta, \phi, \varphi \)

angles defined for each lepton as

- \( \theta \): between lepton (in parent top rest frame) and top quark momentum (in tt centre of mass frame)
- \( \varphi \): between the two leptons (in their parent quark rest frame)
- \( \varphi \): azimuthal lepton angle in the lab frame ➞ no need to reconstruct full tt system!

SM prediction: 4 asymmetries ➞ 1 polarization

Polarisation:

\[
A_{P\pm} = \frac{N (\cos \theta_{\ell^+} > 0) - N (\cos \theta_{\ell^+} < 0)}{N (\cos \theta_{\ell^+} > 0) + N (\cos \theta_{\ell^+} < 0)}
\]
Spin correlations and top polarisation

Angular observables: $\theta, \phi, \varphi$

angles defined for each lepton as

$\theta$: between lepton (in parent top rest frame) and top quark momentum (in $tt$ centre of mass frame)

$\phi$: between the two leptons (in their parent quark rest frame)

$\varphi$: azimuthal lepton angle in the lab frame ➞ no need to reconstruct full $tt$ system!

SM prediction: 4 asymmetries ➞ 1 polarization + 3 spin related observables

Polarisation:

$A_{P\pm} = \frac{N(\cos \theta_{\ell\pm} > 0) - N(\cos \theta_{\ell\pm} < 0)}{N(\cos \theta_{\ell\pm} > 0) + N(\cos \theta_{\ell\pm} < 0)}$

$A_{\Delta \phi} = \frac{N(|\Delta \phi_{\ell+\ell-}| > \pi/2) - N(|\Delta \phi_{\ell+\ell-}| < \pi/2)}{N(|\Delta \phi_{\ell+\ell-}| > \pi/2) + N(|\Delta \phi_{\ell+\ell-}| < \pi/2)}$

Correlated $tt$ spins:

$A_{c_1 c_2} = \frac{N(c_1 c_2 > 0) - N(c_1 c_2 < 0)}{N(c_1 c_2 > 0) + N(c_1 c_2 < 0)}$

$A_{c_1 c_2} = \frac{N(c_1 c_2 > 0) - N(c_1 c_2 < 0)}{N(c_1 c_2 > 0) + N(c_1 c_2 < 0)}$

$A_{\cos \varphi} = \frac{N(\cos \varphi > 0) - N(\cos \varphi < 0)}{N(\cos \varphi > 0) + N(\cos \varphi < 0)}$

CMS Collaboration: PRD 93 (2016) 052007

Correlated:

Uncorrelated:

PLB 725 (2013) 115
Spin correlations and top polarisation

Sizeable spin correlations
Top polarisation ~0

Angular observables: data to predictions comparison

Measurements in agreement with the SM predictions
Angular observable: $\theta^*$

angle between the down-type fermion from W decay (in top rest frame) and the reverse direction b quark from top decay (in W rest frame)

SM prediction:

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

$F_0 \sim 0.7$ $F_L \sim 0.3$ $F_R \sim 0$
W boson polarisation

Results for hadronic decay also available

$\cos \theta^*$: data to predictions comparison

$F_0 + F_L + F_R = 1 \Rightarrow$ measured fractions are correlated

Measurements in agreement with the SM predictions
Top properties:

Charge asymmetry and mass measurements
Charge asymmetry

Charge asymmetry in pp collisions: mild effect (qq diagrams)

Asymmetries observables:
event count according to top quark charge and rapidity

\[ \Delta |y| = |y_{\text{top, lepton}^+} - |y_{\text{antitop, lepton}^-}| \]

- top charge asymmetry — *requires top reconstruction*
- in dilepton channel only : lepton charge asymmetry — *direct measurement*
- also as functions of top kinematics variables

\[ A_c = \frac{N^+ - N^-}{N^+ + N^-} \]
Measurements in agreement with the SM predictions
CP violation

Commonly studied in strange and bottom quark sectors, now: also top sector!

Observables:

formed from products $v_1 \cdot (v_2 \times v_3)$ spin/p vectors of top decay products

— odd under T transformations

\[
\begin{align*}
O_2 &= \epsilon(P, p_b + p_{\ell}, p_{\ell}, p_{j_1}) \xrightarrow{\text{lab}} \alpha (\bar{p}_b + \bar{p}_B) \cdot (\bar{p}_\ell \times \bar{p}_{j_1}), \\
O_3 &= Q_\ell \epsilon(p_b, p_{\ell}, p_{\ell}, p_{j_1}) \xrightarrow{\text{CM}} Q_\ell {\bar{p}_b} \cdot (\bar{p}_\ell \times \bar{p}_{j_1}), \\
O_4 &= Q_\ell \epsilon(P, p_b - p_{\ell}, p_{\ell}, p_{j_1}) \xrightarrow{\text{lab}} \alpha Q_\ell (\bar{p}_b - \bar{p}_B) \cdot (\bar{p}_\ell \times \bar{p}_{j_1}), \\
O_7 &= q \cdot (p_b - p_{\ell}) \epsilon(P, q, p_b, p_{\ell}) \xrightarrow{\text{lab}} \alpha (\bar{p}_b - \bar{p}_B)_z (\bar{p}_{\ell} \times \bar{p}_{j_1})_z. \\
\end{align*}
\]

— if CPT is valid: also under CP!

\[
A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}
\]

\[\sim 0 \text{ for SM}\]

Charge of b quark: kinematic reconstruction of top system
constrains: $m_t$ and $m_W$ : ~60% correct assignments
CP violation

Charge of b quark: soft muon from b-decay

Observables: sign (charge) relations soft/isolated $\mu$

\[ A^{ss} = r_b A_{mix}^{b\ell} + r_c \left( A_{dir}^{bc} - A_{dir}^{c\ell} \right) + r_{cc} \left( A_{mix}^{bc} - A_{mix}^{c\ell} \right) \]
\[ A^{os} = \overline{r}_b A_{dir}^{b\ell} + \overline{r}_c \left( A_{mix}^{bc} + A_{dir}^{c\ell} \right) + \overline{r}_{cc} A_{dir}^{c\ell} \]
CP violation

Commonly studied in strange and bottom quark sectors, now: also top sector!

Charge of $b$ quark: soft muon from $b$-decay

Observables: sign (charge) relations soft/isolated $\mu$

\[
A_{ss} = r_b A_{\text{mix}}^{b\ell} + r_c \left( A_{bc}^{bc} - A_{\text{dir}}^{c\ell} \right) + r_{cc} \left( A_{\text{mix}}^{b\ell} - A_{\text{dir}}^{c\ell} \right)
\]

\[
A_{os} = \bar{r}_b A_{\text{dir}}^{b\ell} + \bar{r}_c \left( A_{\text{mix}}^{b\ell} + A_{\text{dir}}^{c\ell} \right) + r_{cc} A_{\text{dir}}^{c\ell}
\]

related to $b \rightarrow \bar{b}, b \rightarrow c$

SM: all asymmetries $\sim 0$
CP violation

**ATLAS**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Data (10^{-2})</th>
<th>MC (10^{-2})</th>
<th>Existing limits (2σ) (10^{-2})</th>
<th>SM prediction (10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{ss}$</td>
<td>-0.7 ± 0.8</td>
<td>0.05 ± 0.23</td>
<td>-</td>
<td>&lt; 10^{-2}</td>
</tr>
<tr>
<td>$A^{os}$</td>
<td>0.4 ± 0.5</td>
<td>-0.03 ± 0.13</td>
<td>-</td>
<td>&lt; 10^{-2}</td>
</tr>
<tr>
<td>$A^{b}_{\text{mix}}$</td>
<td>-2.5 ± 2.8</td>
<td>0.2 ± 0.7</td>
<td>&lt; 0.1</td>
<td>[95]</td>
</tr>
<tr>
<td>$A^{c}_{\text{dir}}$</td>
<td>0.5 ± 0.5</td>
<td>-0.03 ± 0.14</td>
<td>&lt; 1.2</td>
<td>[94] [96] [95]</td>
</tr>
<tr>
<td>$A^{c}_{\text{cf}}$</td>
<td>1.0 ± 1.0</td>
<td>-0.06 ± 0.25</td>
<td>&lt; 6.0</td>
<td>[94] [95]</td>
</tr>
<tr>
<td>$A^{\text{dir}}$</td>
<td>-1.0 ± 1.1</td>
<td>0.07 ± 0.29</td>
<td>-</td>
<td>&lt; 10^{-7}</td>
</tr>
</tbody>
</table>

All asymmetries \sim 0

**CMS**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$A_{CP}^{e + jets}$ (%)</th>
<th>$A_{CP}^\mu + jets$ (%)</th>
<th>$A_{CP}^{\ell + jets}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$</td>
<td>-0.19 ± 0.61 ± 0.59</td>
<td>+0.46 ± 0.57 ± 0.65</td>
<td>+0.16 ± 0.42 ± 0.44</td>
</tr>
<tr>
<td>$O_3$</td>
<td>+0.02 ± 0.61 ± 0.59</td>
<td>-0.59 ± 0.57 ± 0.65</td>
<td>-0.31 ± 0.42 ± 0.44</td>
</tr>
<tr>
<td>$O_4$</td>
<td>-0.17 ± 0.61 ± 0.59</td>
<td>-0.10 ± 0.57 ± 0.65</td>
<td>-0.13 ± 0.42 ± 0.44</td>
</tr>
<tr>
<td>$O_7$</td>
<td>-0.38 ± 0.61 ± 0.59</td>
<td>+0.43 ± 0.57 ± 0.65</td>
<td>+0.06 ± 0.42 ± 0.44</td>
</tr>
</tbody>
</table>

CP violation observables: data to predictions comparison
Top quark width

Important property → 1/lifetime

Sensitive distribution: invariant mass (lepton, b) (which for lepton, b correctly matched to parent top drops at $M_{lb} = \sqrt{m_t^2 - m_W^2}$)

Hypotheses tested: $\Gamma_{SM}$ and wide top with $4 \times \Gamma_{SM}$

13 TeV data

CMS Collaboration: TOP-16-019

$0.6 < \Gamma < 2.5$ at 95% CL
(expected: $0.6 < \Gamma < 2.4$ GeV for $m_t = 172.5$ GeV)
Top properties:

Production and decay (couplings)
Flavour Changing Neutral Current

Tiny expected signals against (overwhelming) SM backgrounds

- Signal may be large in BSM models!
- Include more final states (e.g. several decay modes of Higgs)
- Signal / background separation: multivariate techniques (Neural Networks, Boosted Decision Trees)

Final states:

- Wb
- tHq
- tZ
- tγ

Couplings:

- \( t \rightarrow u g \)
- \( t \rightarrow c g \)
- \( t \rightarrow H c \)
- \( t \rightarrow H u \)
- \( t \rightarrow u Z, t \rightarrow c Z \)
- \( t \rightarrow u \gamma, t \rightarrow c \gamma \)

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{qg} \rightarrow t \times B(t \rightarrow Wb) &lt; 3.4, \text{pb} )</td>
<td>( B(t \rightarrow Zu) &lt; 0.022% )</td>
</tr>
<tr>
<td>( \sigma_{qg} \rightarrow t \times B(t \rightarrow Wb) &lt; 2.9, \text{pb} )</td>
<td>( B(t \rightarrow Zc) &lt; 0.049% )</td>
</tr>
<tr>
<td>( B(t \rightarrow Hc) &lt; 0.40% )</td>
<td>( B(t \rightarrow u \gamma) &lt; 0.022% )</td>
</tr>
<tr>
<td>( B(t \rightarrow Hu) &lt; 0.55% )</td>
<td>( B(t \rightarrow c \gamma) &lt; 0.049% )</td>
</tr>
</tbody>
</table>


ATLAS

CMS
Flavour Changing Neutral Current

**SM prediction**

**Upper limits**

**Graphical Representation:**
- The graph shows branching ratio on the x-axis and various processes on the y-axis.
- The graph includes SM prediction and upper limits for different processes such as $t\rightarrow Hc$, $t\rightarrow Hu$, $t\rightarrow \gamma c$, $t\rightarrow \gamma u$, $t\rightarrow gc$, $t\rightarrow gu$, $t\rightarrow Zc$, and $t\rightarrow Zu$.
- Each process is color-coded and compared against the SM prediction.
Top properties:

Beyond direct searches: limits on new physics from top properties measurements
Re-interpreting the measurements

All measurements present remarkable agreement with SM Direct/derived constrains to new physics. Examples:

Spin correlation & polarisation angles:
Effective Lagrangian for anomalous ttg interaction:

\[
\frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} = \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} \right)_{SM} + \text{Re}(\beta_t) \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} \right)_{NP}
\]

Likewise, polarisation asymmetry relates to $\hat{d}_t$:

\[
\mathcal{L}_{\text{eff}} = \frac{\mu_t}{2} \sigma^{\mu \nu} T^a G^a_{\mu \nu} - \frac{\hat{d}_t}{2} \Omega^{\mu \nu} \gamma_5 T^a G^a_{\mu \nu},
\]

\[-0.053 < \text{Re}(\mu^t) < 0.026\]
\[-0.068 < \text{Im}(\hat{d}_t) < 0.067\]

at 95% CL
Re-interpreting the measurements

All measurements present remarkable agreement with SM Direct/derived constrains to new physics. Examples:

**Spin correlation & polarisation angles:**
Effective Lagrangian for anomalous $ttg$ interaction:

\[
\frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} = \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} \right)_{\text{SM}} + \text{Re}(\beta_t) \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta \phi_{\ell+\ell^-}|} \right)_{\text{NP}}
\]

Likewise, polarisation asymmetry relates to $\delta t$:

\[-0.053 < \text{Re}(\mu^t) < 0.026\]
\[-0.068 < \text{Im}(d^t) < 0.067\]

at 95% CL

**W helicity fractions:**
Generalised $Wtb$ vertex Lagrangian:

\[
\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} b^\gamma V_{tbL} + V_{tbR} t^W - \frac{g}{\sqrt{2}} \frac{i\sigma^{\mu\nu}q_t}{M_W} (g_L P_L + g_R P_R) t^W + \text{H.c.}
\]

V’s and g’s: couplings directly related to helicity fractions
Re-interpreting the measurements

All measurements present remarkable agreement with SM Direct/derived constrains to new physics. Examples:

**Spin correlation & polarisation angles:**
Effective Lagrangian for anomalous $ttg$ interaction:

$$\frac{1}{\sigma \, d|\Delta \phi_{\ell+\ell^-}|} = \left( \frac{1}{\sigma \, d|\Delta \phi_{\ell+\ell^-}|} \right)_{\text{SM}} + \text{Re}(\beta_t) \left( \frac{1}{\sigma \, d|\Delta \phi_{\ell+\ell^-}|} \right)_{\text{NP}}$$

Likewise, polarisation asymmetry relates to $\tilde{d}$

$$-0.053 < \text{Re}(\mu^t) < 0.026$$
$$-0.068 < \text{Im}(\tilde{d}^t) < 0.067$$

at 95% CL

**W helicity fractions:**
Generalised Wtb vertex Lagrangian:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} b \gamma_{\mu} (V_L P_L + V_R P_R) t W_{\mu}^- - \frac{g}{\sqrt{2}} \frac{i \sigma^{\mu \nu} q_t}{M_W} (g_L P_L + g_R P_R) t W_{\mu}^- + \text{H.c.}$$

**Charge asymmetry:**
Comparison with BSM models

V's and g's: couplings directly related to helicity fractions
Conclusions
Conclusions

Latest LHC measurements in top quark properties, mostly at 8 TeV, were presented

Several aspects of top production scrutinised
  angular distributions, charge asymmetries, production and decay

8 TeV measurements confirm SM predictions
  no signs in direct searches, limits on new physics using EFT

Large datasets, several measurements already limited by systematic uncertainties

New data at 13 TeV being analysed
  Now, focus in improving analyses techniques and beating systematic uncertainties
Top properties:

Backup slides
Typical uncertainties

**Experimental**

**Leptons**
- Reconstruction, ID **Width**
- momentum scale, resolutions

**Jets**
- Reconstruction, ID **Width**
- momentum scale, resolutions **Pol, SpinCorr WPol**
- b-tagging/mistag **CP, WPol**

**Data taking**
- pileup
- luminosity, etc **Width**

**Background determination** **WPol**
- shape and normalizations
- modelling (MC)
- data-driven methods

**Theory (modelling)**

**MC generation**
- Generator choice
- hadronization model **Pol**
- underlying event
- inputs to theory:
  - $Q^2$ scales, PDF, top mass, etc
  - potential mis-modelling of top dynamics (e.g. top $p_T$ distribution) **SpinCorr**

**Analysis-dependent**
- unfolding procedure, etc

**Statistical** **ChAsym**
- data integrated luminosity
- limited amount of Monte Carlo

**Dominant for ATLAS**
**Dominant for CMS**
FCNC: typical BDT/NN variables and uncertainties

Example: bjet+single lepton final state

- the invariant masses $m_{tH}$ and $m_{tH_j}$ of the reconstructed top quarks,
- the energy of the $u$ or $c$ jet from the $t \rightarrow qH$ in the rest frame of its parent top quark,
- the azimuthal angle between the reconstructed top quarks directions,
- the azimuthal angle between the reconstructed $W$ boson and the associated $b$ jet directions,
- the azimuthal angle between the Higgs boson and the associated jet directions,
- the azimuthal angle between the directions of the $b$ jets resulting from the Higgs boson decay.

<table>
<thead>
<tr>
<th>Channel</th>
<th>SS dilepton</th>
<th>Trilepton</th>
<th>$\gamma\gamma$ hadronic</th>
<th>$\gamma\gamma$ leptonic</th>
<th>b jet + lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
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<tr>
<td>Pileup</td>
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<td>1.0</td>
<td>0.3</td>
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<td>0.2-3.0</td>
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<td>5.0</td>
<td>5.0</td>
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<td>5.0</td>
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<td>$t\bar{t}$ cross section</td>
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<td>Jet energy scale</td>
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<td>Signal PDF</td>
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<td>6.0</td>
<td>5.9</td>
<td>5.2</td>
<td>&lt;1-9.0</td>
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<tr>
<td>Top quark $p_T$ correction $E_T^{miss}$</td>
<td>4.0</td>
<td>4.0</td>
<td>1.4</td>
<td>3.2</td>
<td>0.8-4.3</td>
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<td>Trigger efficiency</td>
<td>1.0-2.0</td>
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<td>1.0</td>
<td>1.0</td>
<td>0.2-2.5</td>
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<td>Identification and isolation</td>
<td>—</td>
<td>—</td>
<td>0.3</td>
<td>0.01-0.04</td>
<td>&lt;0.1-0.2</td>
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<tr>
<td>- muon</td>
<td>1.0-2.0</td>
<td>1.0-3.0</td>
<td>—</td>
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<td>—</td>
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<tr>
<td>- electron</td>
<td>2.0-4.0</td>
<td>2.0-6.0</td>
<td>—</td>
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<td>ttW normalization</td>
<td>11.0</td>
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<td>Lepton misidentification</td>
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<td>- muon</td>
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<td>Charge misidentification</td>
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<td>5.2</td>
<td>5.2</td>
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<tr>
<td>Photon identification efficiency</td>
<td>—</td>
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Uncertainties in %
CP violation in tt (CMS)

Optimal variables (example)

\[
\mathcal{O}_2 \xrightarrow{\text{lab}} \sqrt{S} \left[ (p_b + p_{\bar{b}}) \cdot (p_{\mu^+} \times p_{j1}) + (p_{\mu^-} \times p_{\bar{j}1}) \right]
\]

\[
\xrightarrow{\text{CP}} (-)\sqrt{S} \left[ (p_b + p_{\bar{b}}) \cdot (p_{\mu^-} \times p_{\bar{j}1}) + (p_{\mu^+} \times p_{j1}) \right]
\]

j1 -> hardest jet from W decay

** observable doesn't depend on b quark charge **

If CP is conserved, \[
\vec{p}_{j1} \xrightarrow{\text{CP}} -\vec{p}_{\bar{j}1}
\] that is

Probability of a jet (q) from a \(W^+\rightarrow j1j2\) to be the hardest = Probability of a jet (qbar) from a \(W^-\rightarrow j1j2\) to be the hardest
Systematic uncertainties

"Dilution factor" estimated from control sample:
- estimated in side bands (no b-tag)
- dominant syst uncertainty: statistical uncertainty on the side band

“Dilution factor” may make up real asymmetries:
- measure both $A_{CP}$ and $A'_{CP}$
**Optimal variables in detail:**

In terms of probabilities:

\[ A^{ss} = \frac{P(b \rightarrow \ell^+) - P(\bar{b} \rightarrow \ell^-)}{P(b \rightarrow \ell^+) + P(\bar{b} \rightarrow \ell^-)}, \quad A^{os} = \frac{P(b \rightarrow \ell^-) - P(\bar{b} \rightarrow \ell^+)}{P(b \rightarrow \ell^-) + P(\bar{b} \rightarrow \ell^+)} \]

In terms of nr of positive/negative lepton charges:

\[ A^{ss} = \frac{N^{++} - N^{--}}{N^+ - N^-}, \quad A^{os} = \frac{N^{+-} - N^{-+}}{N^+ + N^-} \]

In terms of CP asymmetries:

\[ A^{ss} = r_b A_{mix}^{b\ell} + r_c \left( A_{dir}^{bc} - A_{dir}^{c\ell} \right) + r_{cc} \left( A_{mix}^{bc} - A_{dir}^{c\ell} \right), \]
\[ A^{os} = \bar{r}_b A_{dir}^{b\ell} + \bar{r}_c \left( A_{mix}^{bc} + A_{dir}^{c\ell} \right) + \bar{r}_{cc} A_{dir}^{c\ell} \]

\[ r_b = \frac{N_{rb}}{N_{rb} + N_{rc} + N_{rcc}}, \quad \bar{r}_b = \frac{N_{rb}}{N_{rb} + N_{rc} + N_{rcc}}, \]
\[ r_c = \frac{N_{rc}}{N_{rb} + N_{rc} + N_{rcc}}, \quad \bar{r}_c = \frac{N_{rc}}{N_{rb} + N_{rc} + N_{rcc}}, \]
\[ r_{cc} = \frac{N_{rcc}}{N_{rb} + N_{rc} + N_{rcc}}, \quad \bar{r}_{cc} = \frac{N_{rcc}}{N_{rb} + N_{rc} + N_{rcc}}. \]