Top Quark Properties at HL/HE-LHC

Frédéric Déliot
CEA-Saclay

Workshop on the physics of HL-LHC and perspectives at HE-LHC, November 1st, 2017

thanks for the inputs from M. Cristinziani, M. Mangano, M. Vos
top quark statistics

- top quark samples

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>13 TeV - 30 fb⁻¹</th>
<th>13/14 TeV - 3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>30 Mevts</td>
<td>3 Gevts</td>
</tr>
<tr>
<td>( t\bar{t} ) (fiducial)</td>
<td>1.55 Mevts</td>
<td>155 Mevts</td>
</tr>
<tr>
<td>( t\bar{t} ) with ( M_{\ell\ell} &gt; 1 \text{ TeV} ) (fiducial)</td>
<td>30 kevts</td>
<td>3 Mevts</td>
</tr>
<tr>
<td>( t\bar{t} ) with ( M_{\ell\ell} &gt; 2 \text{ TeV} ) (fiducial)</td>
<td>480 evts</td>
<td>48 kevts</td>
</tr>
<tr>
<td>( t)-channel</td>
<td>6 Mevts</td>
<td>600 Mevts</td>
</tr>
<tr>
<td>( Wt)-channel</td>
<td>2 Mevts</td>
<td>200 Mevts</td>
</tr>
<tr>
<td>( s)-channel</td>
<td>300 kevts</td>
<td>30 Mevts</td>
</tr>
<tr>
<td>( ttV )</td>
<td>30 kevts</td>
<td>3 Mevts</td>
</tr>
<tr>
<td>( tZ )</td>
<td>3 kevts</td>
<td>300 kevts</td>
</tr>
<tr>
<td>( tH )</td>
<td>300 evts</td>
<td>30 kevts</td>
</tr>
</tbody>
</table>

- top quark properties: search from deviation from SM predictions
  - top couplings
  - asymmetries
  - rare process, FCNC
top-gluon coupling

- chromo-electric and magnetic dipole moments:
  - dim-6 operator: effective modification of the top-gluon coupling (dV, dA)
    \[
    \mathcal{L}_{tg} = -g_s \bar{t} \gamma^\mu \frac{\lambda_a}{2} t G^a_{\mu
u} + \frac{g_s}{m_t} \bar{t} \gamma^\mu (dV + i d_A \gamma_5) \frac{\lambda_a}{2} t G^a_{\mu
u}
    \]
  - constrain coming from the $t\bar{t}$ inclusive cross section

- enhance sensitivity by using production at high invariant mass
  - using central events $|\eta| < 2$
  - events are boosted: top tagging (12.5% efficiency, 0.03% mistag)
  - background from mistagging of top (dijet)

- expect large gain due to the statistics in the boosted regime

<table>
<thead>
<tr>
<th>Invariant mass selection</th>
<th>$\sigma_{t\bar{t}}$</th>
<th>$\sigma_{jj}$</th>
<th>$\sqrt{S + B}/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{t\bar{t}}$ (or $m_{jj}$) &gt; 1 TeV</td>
<td>1.0 pb</td>
<td>0.89 pb</td>
<td>0.004</td>
</tr>
<tr>
<td>$m_{t\bar{t}}$ (or $m_{jj}$) &gt; 2 TeV</td>
<td>16 fb</td>
<td>40 fb</td>
<td>0.047</td>
</tr>
</tbody>
</table>

normalized to 100 fb$^{-1}$
top-Z coupling

- top-Z weak magnetic and electric dipole moments:
  \[ \mathcal{L}_{ttZ} = e \bar{u}(p_1) \left( \gamma^\mu (C_{1,V}^Z + \gamma_5 C_{1,A}^Z) + \frac{i\gamma^\mu q_\nu}{M_Z} (C_{2,V}^Z + i\gamma_5 C_{2,A}^Z) \right) v(p_2) Z^\mu \]
  - \( C_{2,V}^Z \approx 10^{-4} \) at NLO, \( C_{2,A}^Z \): only at NNLO

- selection of \( ttZ \) events
  - 3 leptons
  - 4 jets, 2 b-tag

- limit settings using 2 observables with the highest sensitivity
  - \( \Delta\Phi_{ll} \) for \( C_{1}^Z \) and \( p_t Z \) for \( C_{2}^Z \)
top-Z coupling sensitivity

- Including NLO corrections improves the constraints by 20-40%
- Constraints down to 0.08
- Can go further by using $t\bar{t}Z/t\bar{t}$ ratio (and $t\bar{t}y/t\bar{t}$) to constrain 3 electroweak dipole moments (arXiv: 1603.08911)

• anomalous form factors:

\[ \Gamma_{\mu V}(k^2, q, \bar{q}) = -ie \left\{ \gamma_\mu \left( F_{1V}(k^2) + \gamma_5 F_{2V}(k^2) \right) + \frac{q_{\mu \nu}}{2m_t} (q + \bar{q})^\nu \left( i F_{2V}(k^2) + \gamma_5 F_{2A}(k^2) \right) \right\} \]

• selection of tty events
- 1 lepton, 4 jets, 2 b-tag
- 1 well separated photon
- main background from fake photon

• results
- constraints on the vector/axial couplings \( F_{V1} \) to 2-3%, \( F_{V2} \) to 10%

<table>
<thead>
<tr>
<th>coupling</th>
<th>30 fb(^{-1})</th>
<th>300 fb(^{-1})</th>
<th>3000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta F_{V1}^\gamma )</td>
<td>+0.23</td>
<td>+0.079</td>
<td>+0.037</td>
</tr>
<tr>
<td>( \Delta F_{V1}^A )</td>
<td>-0.14</td>
<td>-0.045</td>
<td>-0.019</td>
</tr>
<tr>
<td>( \Delta F_{V2}^\gamma )</td>
<td>+0.17</td>
<td>+0.051</td>
<td>+0.018</td>
</tr>
<tr>
<td>( \Delta F_{V2}^A )</td>
<td>-0.52</td>
<td>-0.077</td>
<td>-0.024</td>
</tr>
<tr>
<td>( \Delta F_{A2}^\gamma )</td>
<td>+0.34</td>
<td>+0.19</td>
<td>+0.12</td>
</tr>
<tr>
<td>( \Delta F_{A2}^A )</td>
<td>-0.35</td>
<td>-0.20</td>
<td>-0.12</td>
</tr>
<tr>
<td>( \Delta F_{A2}^\gamma )</td>
<td>+0.35</td>
<td>+0.19</td>
<td>+0.11</td>
</tr>
<tr>
<td>( \Delta F_{A2}^A )</td>
<td>-0.36</td>
<td>-0.24</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

## t\bar{t} charge asymmetry

### charge asymmetry small in the SM:
- \( \sim 1\% \), can be enhanced by looking at boosted channel

<table>
<thead>
<tr>
<th>14 TeV</th>
<th>QCD: ( A_{\text{C/PLD}} ) (%)</th>
<th>0.5 TeV</th>
<th>1 TeV</th>
<th>2 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A_{\text{C/PLD}} ) (%)</td>
<td>0.58 (3)</td>
<td>0.74 (3)</td>
<td>1.11 (5)</td>
</tr>
<tr>
<td></td>
<td>( A_{\text{C/PLD}} ) (%)</td>
<td>0.07 (4)</td>
<td>0.86 (5)</td>
<td>1.32 (8)</td>
</tr>
</tbody>
</table>

W. Bernreuther et al., arXiv:1205.6580

### sensitivity studies:
- for different assumptions on the scaling of the systematic uncertainties
- observation of SM asymmetry might be possible, need to improve modeling

### alternatives:
- Can also use the other asymmetries (energy or inclined asymmetry) based on t\bar{t}+jet: could be observed with 16\( \sigma \) with 3000 fb\(^{-1}\) (Berge & Westhoff, arXiv:1307.6225)
- LHCb can also measure a forward asymmetry. Might be sensitive to complementary new physics models
**ttW asymmetry**

- **ttW production**
  - like for tt: symmetric at LO, asymmetry at NLO
  - but can only occur from q̅q annihilation (no gg contribution until NNLO): larger asymmetry than for tt
  - W emission: polarizer for quark/antiquark ⇒ polarised top/antitop production (asymmetric rapidity distribution at LO)

- **asymmetry**
  - top based
  - b or lepton based

- **variation with beam energy**
  - decrease slower than the tt asymmetry

- **ttW asymmetry**
  - larger than tt asymmetry but need statistics
  - sensitive to chirality of NP

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>13 TeV</th>
<th>14 TeV</th>
<th>33 TeV</th>
<th>100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma (\text{pb}) )</td>
<td>( 198^{+15}_{-14} )</td>
<td>( 661^{+15}_{-13} )</td>
<td>( 786^{+14}_{-13} )</td>
<td>( 4630^{+12}_{-11} )</td>
</tr>
<tr>
<td>( A_T^c (%) )</td>
<td>( 0.72^{+0.14}_{-0.09} )</td>
<td>( 0.45^{+0.09}_{-0.06} )</td>
<td>( 0.43^{+0.08}_{-0.06} )</td>
<td>( 0.26^{+0.04}_{-0.05} )</td>
</tr>
<tr>
<td>( \sigma (\text{fb}) )</td>
<td>( 210^{+11}_{-11} )</td>
<td>( 587^{+13}_{-12} )</td>
<td>( 678^{+14}_{-13} )</td>
<td>( 3220^{+17}_{-18} )</td>
</tr>
<tr>
<td>( A_T^b (%) )</td>
<td>( 2.37^{+0.56}_{-0.38} )</td>
<td>( 2.24^{+0.43}_{-0.32} )</td>
<td>( 2.23^{+0.43}_{-0.33} )</td>
<td>( 1.95^{+0.28}_{-0.23} )</td>
</tr>
<tr>
<td>( A_T^l (%) )</td>
<td>( 8.50^{+0.18}_{-0.10} )</td>
<td>( 7.54^{+0.19}_{-0.17} )</td>
<td>( 7.59^{+0.24}_{-0.22} )</td>
<td>( 5.37^{+0.22}_{-0.30} )</td>
</tr>
<tr>
<td>( A_T^g (%) )</td>
<td>( -14.83^{+0.65}_{-0.95} )</td>
<td>( -13.16^{+0.81}_{-1.12} )</td>
<td>( -12.84^{+0.81}_{-1.11} )</td>
<td>( -9.21^{+0.87}_{-1.05} )</td>
</tr>
</tbody>
</table>

Frédéric Déliot, HL-LHC kickoff, 1-NOV-17
Top Flavour Changing Neutral Current

- ‘golden’ physics case for HL-LHC top physics
  - Forbidden at tree level in the SM, appearing only in loops but highly suppressed
  - Heavily rely on data statistics

% SM 2HDM(FV) 2HDM(FC) MSSM RPV RS
\[ t \rightarrow Zu \] \[ 7 \times 10^{-17} \] - \[ \leq 10^{-7} \] \[ \leq 10^{-6} \] -
\[ t \rightarrow Zc \] \[ 1 \times 10^{-14} \] \[ \leq 10^{-6} \] \[ \leq 10^{-10} \] \[ \leq 10^{-7} \] \[ \leq 10^{-6} \] \[ \leq 10^{-5} \]
\[ t \rightarrow gu \] \[ 4 \times 10^{-14} \] - - \[ \leq 10^{-7} \] \[ \leq 10^{-6} \] -
\[ t \rightarrow gc \] \[ 5 \times 10^{-12} \] \[ \leq 10^{-4} \] \[ \leq 10^{-8} \] \[ \leq 10^{-7} \] \[ \leq 10^{-6} \] \[ \leq 10^{-5} \]
\[ t \rightarrow \gamma u \] \[ 4 \times 10^{-16} \] - - \[ \leq 10^{-8} \] \[ \leq 10^{-9} \] -
\[ t \rightarrow \gamma c \] \[ 5 \times 10^{-14} \] \[ \leq 10^{-7} \] \[ \leq 10^{-9} \] \[ \leq 10^{-8} \] \[ \leq 10^{-9} \] \[ \leq 10^{-9} \]
\[ t \rightarrow hu \] \[ 2 \times 10^{-17} \] \[ \leq 10^{-5} \] \[ \leq 10^{-6} \] \[ \leq 10^{-5} \] \[ \leq 10^{-9} \] \[ \leq 10^{-9} \]
\[ t \rightarrow he \] \[ 3 \times 10^{-15} \] \[ 2 \times 10^{-3} \] \[ \leq 10^{-5} \] \[ \leq 10^{-5} \] \[ \leq 10^{-9} \] \[ \leq 10^{-4} \]

Snowmass, arXiv:13011.2028

- HL-LHC experimental studies
  - \( t \rightarrow Zq, t \rightarrow Hq, t \rightarrow qy \)
ATLAS t → Zq Sensitivity

- t → Zq FCNC parametrized with 4 independent couplings:

\[ L_{tZu} = - \frac{g}{2c_w} \bar{t} \gamma^\mu \left( X_L P_L + X_R P_R \right) t Z_{\mu} - \frac{g}{2c_w} \frac{i \sigma^{\mu\nu} (p_t^* - p_u^*)}{M_Z} \left( k_L P_L + k_R P_R \right) t Z_{\mu} + h.c. \]

- event selection
  - using the detector with the full |\eta|<4 coverage
  - 3 leptons, 2 opposite signed around the Z mass
  - at least 2 jets: 1 b-tag, 1 non b-tag
  - kinematic reconstruction via a \( \chi^2 \)

\[ \chi^2 = \frac{(m_Z - m_{\text{reco}})^2}{\sigma_Z^2} + \frac{(m_W - m_{\text{reco}})^2}{\sigma_W^2} + \frac{(m_t - m_{\text{reco}})^2}{\sigma_{t \rightarrow Wb}^2} + \frac{(m_t - m_{\text{reco}})^2}{\sigma_{t \rightarrow Zq}^2} \]

reference scenario, unit normalisation

ATL-PHYS-PUB-2016-019
**t → Zq Sensitivity Results**

**ATLAS limit extraction:**
- maximum likelihood fit of the $\chi^2$ distribution

**ATLAS stat only limits**

<table>
<thead>
<tr>
<th>$\gamma^*$ $t\to Z \nu$</th>
<th>$\sigma^*$ $t\to Z \nu$</th>
<th>$\gamma^*$ $t\to Z \ell$</th>
<th>$\sigma^*$ $t\to Z \ell$</th>
<th>$\gamma^*$ $t\to Z \nu + Z \ell$</th>
<th>$\sigma^*$ $t\to Z \nu + Z \ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.3 \cdot 10^{-5}$</td>
<td>$4.3 \cdot 10^{-5}$</td>
<td>$5.6 \cdot 10^{-5}$</td>
<td>$5.8 \cdot 10^{-5}$</td>
<td>$2.4 \cdot 10^{-5}$</td>
<td>$2.5 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

**ATLAS limit with systematics:**
- Set A: 5-6 times worse limit than stat only
  - based on 8 TeV result
- Set B: 3-4 times worse limit than stat only
  - 50% improvements in the uncertainty on the data driven fake estimation
  - 10% uncertainty on the tZ/tW cross sections, 6% on the ttV cross section

**CMS projection:**
- pileup: 140
- based on the 8 TeV result
- cut and count approach
- systematic uncertainty assumption
  - signal: 20%
  - background: scaling with luminosity
    (limit to at most a factor of 4 better)

<table>
<thead>
<tr>
<th>$\mathcal{B}(t \to Zq)$</th>
<th>19.5 fb$^{-1}$ @ 8 TeV</th>
<th>300 fb$^{-1}$ @ 14 TeV</th>
<th>3000 fb$^{-1}$ @ 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. bkg. yield</td>
<td>3.2</td>
<td>26.8</td>
<td>268</td>
</tr>
<tr>
<td>Expected limit</td>
<td>&lt; 0.10%</td>
<td>&lt; 0.027%</td>
<td>&lt; 0.010%</td>
</tr>
<tr>
<td>$1 \sigma$ range</td>
<td>0.05 – 0.13%</td>
<td>0.018 – 0.038%</td>
<td>0.007 – 0.034%</td>
</tr>
<tr>
<td>$2 \sigma$ range</td>
<td>0.05 – 0.20%</td>
<td>0.013 – 0.051%</td>
<td>0.008 – 0.020%</td>
</tr>
</tbody>
</table>

Frédéric Déliot, HL-LHC kickoff, 1-NOV-17
ATLAS t → Hq Sensitivity

- **t → Zq FCNC parametrized with 2 (scalar, pseudo-scalar) couplings:**
  \[ \mathcal{L}_{\text{H}u} = -\frac{1}{\sqrt{2}} \bar{u} \left( \eta_L^R P_L + \eta_R^R P_R \right) t H + h.c. \]

- **event selection**
  - 1 lepton, at least 3 jets, 1 or 2 b-jets

- **main background**
  - t̅t+jets/soft

- **analysis strategy**
  - discriminant variable built from pdf calculated for every permutations in each signal category taking into account the reconstruction probability
  \[ p^{\text{Sig}} = M'(b_1, \ell, E_T^{\text{miss}}) \cdot M^H(b_2, b_3) \cdot M'(b_2, b_3, j) \cdot p_T(j) \]

Frédéric Déliot, HL-LHC kickoff, 1-NOV-17
ATLAS $t \rightarrow Hq$ Sensitivity Results

- **Limit extraction:**
  - maximum likelihood fit of the discriminant

- **stat only limits**
  
  \[
  \begin{array}{c|c|c|c}
  t \rightarrow Hu & t \rightarrow Hc & t \rightarrow Hu+Hc \\
  \hline
  1.2 \cdot 10^{-4} & 1.0 \cdot 10^{-4} & 0.55 \cdot 10^{-4}
  \end{array}
  \]

- **Limit with systematics:**
  - Set A: 2 times worse limit than stat only
    - based on 8 TeV result
  - Set B: 2 times worse limit than stat only
    - 2% uncertainty on the b-tagging efficiency
    - 10% uncertainty in the light fake rate

  \[
  \begin{array}{c|c|c|c}
  \text{Set} & t \rightarrow Hu & t \rightarrow Hc & t \rightarrow Hu+Hc \\
  \hline
  A & 2.4 \cdot 10^{-4} & 2.0 \cdot 10^{-4} & 1.1 \cdot 10^{-4} \\
  B & 2.4 \cdot 10^{-4} & 2.0 \cdot 10^{-4} & 1.1 \cdot 10^{-4}
  \end{array}
  \]

reduced impact of the systematic uncertainties due to profiling
strongly constrain expected with large HL-LHC control region dataset
CMS $t \rightarrow q\gamma$ Sensitivity

- **channels**
  - both single top with photon and $t\bar{t}$ with one FCNC $t \rightarrow q\gamma$ decay

- **selection**
  - 1 muon, 1 b-tag jet, 1 photon separated from the muon and the jet
  - top kinematic reconstruction using muon, b-jet, MET 4-momenta
  - not fully exploits eta coverage yet

- **main background**
  - fake photon (% taken from the 8 TeV analysis)
  - $tV$+jets, triboson

- **analysis strategy**
  - counting method

Frédéric Déliot, HL-LHC kickoff, 1-NOV-17
CMS $t \rightarrow q\gamma$ Sensitivity Results

- **systematic uncertainties in the 8 TeV analysis**
  - $t\nu\gamma / t\gamma$: 11.5 / 11 % (theory uncertainties: 4.1 % / 2.8 %)

- **extrapolation of systematics**
  - scenario 1: same as at 8 TeV
  - scenario 2:
    - theory uncertainty reduced by 50%
    - experimental uncertainties: 1% uncertainty on b-tagging, 2% on c/light misidentification, 1% on lepton/JES, 1.5% luminosity uncertainty

- **upper limits**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$B(t \rightarrow u\gamma)$</th>
<th>$B(t \rightarrow c\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.7 fb⁻¹ at 8 TeV</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>3 ab⁻¹ at 14 TeV (Scenario 1)</td>
<td>$4.6 \times 10^{-5}$</td>
<td>$3.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>3 ab⁻¹ at 14 TeV (Scenario 2)</td>
<td>$2.7 \times 10^{-5}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

CMS PAS FTR-16-006
FCNC Sensitivity Summary
4 tops

- very sensitive to New Physics
  - New resonances, e.g. color-octet/singlet vectors/scalars
  - Top compositeness
  - EFT
  - 4t operator is not constrained elsewhere

- Higgs width
  - Off-shell Higgs also contributes significantly to 4 tops

  \[
  \sigma_{SM}^{(tt\bar{t}t)}_{g+Z/\gamma} : \begin{array}{c}
  8 \text{ TeV} \\
  14 \text{ TeV}
  \end{array}
  \begin{array}{c}
  1.193 \text{ fb} \\
  12.390 \text{ fb}
  \end{array}
  \]

  \[
  \sigma_{SM}^{(tt\bar{t}t)}_{H} : \begin{array}{c}
  0.166 \text{ fb} \\
  1.477 \text{ fb}
  \end{array}
  \]

  \[
  \sigma_{SM}^{(tt\bar{t}t)}_{\text{incl}} : \begin{array}{c}
  -0.229 \text{ fb} \\
  -2.060 \text{ fb}
  \end{array}
  \]

- Experimental search:
  - SM NLO prediction: ~ 9 fb @ 13 TeV
  - current significance (30 fb^{-1}): ~ 1 sigma
    - not sure we can reach 5 sigma before HL-LHC
  - SM NLO prediction: ~ 104 fb @ 27 TeV
Other properties

- **measurements of Vts and Vtd**
  - using ratio of top decays with different b-tagging requirement and rapidity of the t-channel single top production (arXiv:1002.4718)
  - limited by systematics: overall precision down to 0.05?

- **Wtb coupling**
  - testing the anomalous tensor-like coupling using single top s-channel production at large momentum transfer (arXiv:1512.04807)
  - $|g_{A,V}| < 0.10$ with 3000 fb$^{-1}$ using $\sigma(m_{tb} > 2\text{TeV})$
Conclusion

• Top FCNC is the ‘obvious’ search that will benefit from the HL-LHC statistics
  - experimental projection done

• Studies of top couplings will also gain from statistics
  - important gain expected in constraining EFT operators

• We can go beyond that
  - asymmetries
  - other properties in the boosted regime?

• Need to develop the HE-LHC physics case for the top sector
  - 4 tops
  - ....