Observation of the Higgs boson production in association with top quarks

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Invisible dark matter?
Motivation: top quark Yukawa coupling $\lambda_t$

- After the discovery of the Higgs boson ($m_H \sim 125.6$ GeV), the focus is on the precise measurement of its properties, in particular couplings to fermions and gauge bosons.

- Largest coupling to top quark (most massive elementary particle) Sensitive to New Physics

- Measurement of $\lambda_t$ from global “couplings” fit using several production & decay modes (ATLAS+CMS Run 1: $\sigma(k_t) \sim 15\%$)

  - mainly indirect constraints from loops in $ggH$ and $H\gamma\gamma$ vertices (assumes no new particles)

  - direct measurement via $tt+H$ production mode (this talk)

Extensive efforts by ATLAS & CMS to measure $tt+H$ process during LHC Run 1 and Run 2!
- After the discovery of the Higgs boson ($m_H \sim 125.6$ GeV), the focus is on the precise measurement of its properties, in particular couplings to fermions and gauge bosons.

- Largest coupling to top quark (most massive elementary particle) Sensitive to New Physics

- Measurement of $\lambda_t$ from global “couplings” fit using several production & decay modes (ATLAS+CMS Run 1: $\sigma(k_t) \sim 15\%$)

  • mainly indirect constraints from loops in ggH and Hgg vertices (assumes no new particles)

  • direct measurement via $tt+H$ production mode (this talk)

Recent results: Observation of $tt+H$ process reported by ATLAS & CMS

ATLAS: 5.8$\sigma$ (4.9$\sigma$ exp) [36-80 fb$^{-1}$@13 TeV]

4.5 fb$^{-1}$ @7 TeV + 20.3 fb$^{-1}$ @8 TeV + 36-80 fb$^{-1}$ @13 TeV

CMS: 5.2$\sigma$ (4.2$\sigma$ exp) [5 fb$^{-1}$ @7 TeV + 20 fb$^{-1}$ @8 TeV + 36 fb$^{-1}$ @13 TeV]
**Challenges:**

- low production cross section
- a priori many handles against backgrounds!

**Virtues:**

- many possible final states to consider!
- need to find the best combinations of top and Higgs decay modes to isolate the signal

\[ \sigma(ttH, 13\text{TeV}) = 507 \text{ fb}^{-1} \left[\sim 1\% \sigma(H)\right] \]

- Large variety of final states - need good understanding of all reconstructed objects 
  - \(e, \mu, \gamma\), hadronically decaying \(\tau\), jets, \(b\)-jets, MET \(\rightarrow\) requires excellent detector performance and hard work on reconstruction of objects
- Generally smaller branching ratios correspond to better signal-over-background
Challenging backgrounds

Categorization by Higgs boson decay:

- **ttH(bb)** vs. **tt+jets(bb)**
  
  *Phys. Rev. D 97 (2018) 072016*

- **tt+H(H→WW, ττ, ZZ)** vs. **tt+W/Z**
  
  *Phys. Rev. D 97 (2018) 072003*
  
  *ZZ→4l: JHEP 03 (2018) 095*

- **tt+H(H→γγ)** vs. **tt+γ(γ)**
  
  *arXiv:1802.04146*
Evidence reported few months ago (2015+2016 dataset)

Categorization by Higgs boson decay:

- \( ttH(bb) \)
- \( ttH(\text{multi-leptons}) \)
- \( ttH(\gamma\gamma) \)
- \( ttH(ZZ^{*} \rightarrow 4l) \)

- Low S/B (need MVAs)
- Clear peak (bump hunt)
- High Higgs Branching Ratios
- Low Higgs Branching Ratios

Evidence of \( tt+H \) process

4.2\( \sigma \) (3.8\( \sigma \) exp) [36 fb\(^{-1}\)@13 TeV]

- \( tt+H(H \rightarrow bb) \) vs. \( tt+jets(bb) \)

\[ \text{Phys. Rev. D 97 (2018) 072016} \]

- \( tt+H(H \rightarrow WW, \tau\tau, ZZ) \) vs. \( tt+W/Z \)

\[ \text{Phys. Rev. D 97 (2018) 072003} \]

\[ ZZ \rightarrow 4l: \text{JHEP 03 (2018) 095} \]

- \( tt+H(H \rightarrow \gamma\gamma) \) vs. \( tt+\gamma(\gamma) \)

\[ \text{arXiv:1802.04146} \]
Categorization by Higgs boson decay:

\[ \begin{array}{c|c|c|c}
\text{ttH(bb)} & \text{ttH multi-leptons} & \text{ttH(\gamma\gamma)} & \text{ttH(ZZ^* \rightarrow 4\ell)} \\
\hline
\text{Low S/B (need MVAs)} & & \text{Clear peak (bump hunt)} & \\
\text{High Higgs Branching Ratios} & & \text{Low Higgs Branching Ratios} & \\
\end{array} \]

\[ tt+H(H \rightarrow bb) \text{ vs. } tt+jets(bb) \]

\[ tt+H(H \rightarrow WW, \tau\tau, ZZ) \text{ vs. } tt+W/Z \]
ZZ \rightarrow 4\ell: arXiv:1806.00425

Evidence of \( tt+H \) process
\( 4.2\sigma \ (3.8\sigma \ exp) \) \([36 \text{ fb}^{-1}@13 \text{ TeV}]\)

Observation of \( tt+H \) process

And with more data... \textbf{observation of } \textit{tt+H} \textbf{process}!
• Fermion-only production and decay
• Higgs boson reconstruction possible, but challenging due to multiple $b$-quarks and additional radiation in the final state
• Irreducible $tt+bb$ background: large theoretical uncertainty
**tt+H (bb): irreducible tt+bb background**

- Fermion-only production and decay 🎉
- Higgs boson reconstruction possible, but challenging due to multiple $b$-quarks and additional radiation in the final state

**Irreducible $tt+bb$ background: large theoretical uncertainty** 😞 😞

**Biggest challenge:** good and precise modelling of the $tt+HF$ ($\geq 1b$, $\geq 1c$) background

Nominal $tt$+jets sample (Powheg+Pythia8): 5-flavour scheme ($m_b=0$)
Relative contribution of $tt+\geq 1b$ subcomponents reweighted to $tt+bb$
NLO predictions by Sherpa+OpenLoops (4-flavour scheme, $m_b! =0$)
**tt+H (bb): divide and conquer**

- Fermion-only production and decay 😊
- Higgs boson reconstruction possible, but challenging due to multiple $b$-quarks and additional radiation in the final state 😞
- Irreducible $tt+bb$ background has large theory uncertainty 😞

**Analysis strategy**

**Categorization**

1 $\ell$ & 2 $\ell$ (e, $\mu$)

# of jets

$b$-tag score of jets (4 working points)

Several categories with very different fractions of backgrounds $tt+$light, $tt+\geq 1c$, $tt+\geq 1b$ and $tt+H$ signal + Boosted category (1 top quark & $H\rightarrow bb$ in two large-cone jets)
**tt+H (bb): cascade of MVAs**

- Fermion-only production and decay 😊
- Higgs boson reconstruction possible, but challenging due to multiple $b$-quarks and additional radiation in the final state 😞
- Irreducible $tt+bb$ background has large theory uncertainty 😞

**Analysis strategy - cascade of MVAs**

**Categorization**

1$\ell$ & 2$\ell$ ($e,\mu$)

- # of jets
- $b$-tag score of jets (4 working points)

**Intermediate BDT (in SRs)**

Reco BDT, matrix element & likelihood discriminants (1$\ell$)

**Final BDT**

BDT: ttH vs. bkg

**ATLAS**

|$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Single Lepton

SR$^{(i)}$

Post-Fit

10 CRs

9 SRs

**ATLAS**

|$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Single Lepton

SR$^{(i)}$

Post-Fit

Events / 25 GeV

Data / Pred.

Events / bin

Classification BDT output
Signal extraction: Binned profile likelihood fit to all signal and control regions. Normalization of \(tt+\geq 1b\) and \(tt+\geq 1c\) left free-floating in the fit.

Signal strength: \(\mu=\sigma/\sigma_{\text{SM}}\)

Dominant systematics
- Modelling of \(tt+\geq 1b\) (±0.46)
- Limited MC statistics (±0.30)
- Jet flavour tagging (±0.16)
- Jet energy scale & resolution (±0.16)

Significance: 1.4 \(\sigma\) (expected 1.6 \(\sigma\))

Systematically limited: Requires improvements from both theoretical and experimental communities!
• Targeting: $ZZ^*$, $WW^*$ and $\tau\tau$ decays combined with leptonic $tt$ decays - distinct multi-lepton signatures*

* $ttH(ZZ \rightarrow 4\ell)$ events within $H \rightarrow ZZ \rightarrow 4\ell$

• Higgs reconstruction is difficult
Observation of $tt+H$ process

**Categorization**

- Targeting: $ZZ^*$, $WW^*$ and $\tau\tau$ decays combined with leptonic $tt$ decays - distinct multi-lepton signatures*
- Higgs reconstruction is difficult

* $ttH(ZZ\rightarrow4\ell)$ events within $H\rightarrow ZZ\rightarrow4\ell$

**Main backgrounds**

- Irreducible: $tt+V$ and $VV$ → estimated from NLO MC & validated in data
- Reducible:
  - non-prompt $e$, $\mu$ and hadronic $\tau$ mainly from $tt$ prompt light leptons with misidentified charge → estimated from data

**Object level discrimination**

Isolation BDT to reduce non-prompt background, Charge misID BDT

**Event level discrimination**
### tt+H (multi-leptons): categorization & MVAs

<table>
<thead>
<tr>
<th></th>
<th>2ℓSS</th>
<th>3ℓ</th>
<th>4ℓ</th>
<th>1ℓ+2τ_had</th>
<th>2ℓSS+1τ_had</th>
<th>2ℓOS+1τ_had</th>
<th>3ℓ+1τ_had</th>
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<tbody>
<tr>
<td><strong>BDT trained against</strong></td>
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<tr>
<td>Fakes and t\bar{t}V</td>
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<td>2x1D BDT</td>
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<td></td>
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<tr>
<td>5D BDT</td>
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<td></td>
<td></td>
<td>1 / 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event count</td>
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<td></td>
<td></td>
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<tr>
<td><strong>Discriminant</strong></td>
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<td></td>
<td></td>
<td>BDT</td>
<td>BDT</td>
<td>BDT</td>
<td></td>
</tr>
<tr>
<td><strong>Number of bins</strong></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td><strong>Control regions</strong></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

#### Diagrams

- Number of Trk (tracks) vs. Event count
- Number of light leptons vs. Event count
- BDT output vs. Event count

**15/6/18**

María Moreno Llácer – Observation of tt+H process
Signal extraction: Binned profile likelihood fit to all signal and control regions.

Signal strength: $\mu = \sigma / \sigma_{\text{SM}}$

Dominant systematics

- $tt+H$ modelling (+0.20, -0.10)
- Jet energy scale/resolution ($\pm 0.17$)
- Non-prompt e/μ ($\pm 0.14$)
- Large contribution from limited CR stat.

Systematic ~ statistical unc.

New data will improve the precision on channels that are still stats. limited and help constraining $tt+Z$ & $tt+W$ background

Significance: 4.1 σ (expected 2.8 σ)
• Small rate 😞
• Higgs boson can be reconstructed as a “narrow” peak, side-bands can be used to estimate the background.

Analysis strategy (new!)
- Categorization based on $t\bar{t}$ decay: leptonic ($\geq 1\ell$) and hadronic ($0\ell$)
- Further categorization based on XGBoost BDT discriminant value: 4 hadronic and 3 leptonic categories

Input variables to XGBoost BDT:
- photons 4-vectors ($p_T/m_{yy}$), jets, $E_T^{\text{miss}}$ (both cat),
- lepton(s) (lep cat),
- b-tag (had cat)

Training $t\bar{t}+H$ (from simulation) vs. main backgrounds: $\gamma\gamma$, $t\bar{t}+\gamma\gamma$ (from data CRs), other $H$ (from simulation)
Background estimation and signal extraction performed by simultaneous unbinned fit of $m_{\gamma\gamma}$ spectra (105-160 GeV) in all 7 categories:

- Higgs signal parametrization: double-sided Crystal Ball function
- Continuous background parametrization: smooth function (power-law or exponential)

**Significance:**

$4.1 \sigma$ (expected $3.7 \sigma$)

Dominant systematics
- statistical (~29%)
- $tt+H$ parton shower model (8%)
- photon isolation, energy resolution & scale (8%)
- jet energy scale & resolution (6%)
Observation of $tt+H$ process

- Extremely low rate 🙁
- Very clean final state with high S/B 😊

Analysis strategy (new!)

- Based on $t\bar{t}$ decay
  - Hadronic
  - Leptonic

- Based on BDT output
  - Input vars: production and decay kinematics including matrix element discriminant ($t\bar{t}H$ vs. $t\bar{t}V$)

- Simultaneous fit to all regions → no events observed

Exp. significance: expected 1.2 $\sigma$

Very statistically limited

$tt+H$ ($ZZ^*\rightarrow4l$)

ATLAS
$H \rightarrow ZZ^* \rightarrow 4l$

- 13 TeV, 79.8 fb$^{-1}$
- $115 < m_{WW} < 130$ GeV

Uncertainty

Data

- $t\bar{t}H$
- $t\bar{t}$
- $ggF+bbH$
- VBF
- VH
- $ZZ^*$
- $t\bar{t}+V$, VVV
- $Z+\text{jets}$, $t\bar{t}$

New! @80fb$^{-1}$

15/6/18
María Moreno Llácerc – Observation of tt+H process
Observation of $tt+H$ process

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, \text{ 36.1 - 79.8 } fb^{-1} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttH (bb)$</td>
<td>0.79 ± 0.61 ( ± 0.29 , ± 0.53 )</td>
<td>1.6 σ</td>
</tr>
<tr>
<td>$ttH$ (multilepton)</td>
<td>1.56 ± 0.42 ( ± 0.30 , ± 0.30 )</td>
<td>4.1 σ</td>
</tr>
<tr>
<td>$ttH (\gamma\gamma)$</td>
<td>1.39 ± 0.48 ( ± 0.42 , ± 0.23 )</td>
<td>4.1 σ</td>
</tr>
<tr>
<td>$ttH (ZZ)$</td>
<td>&lt; 1.77 at 68% CL</td>
<td>0 σ</td>
</tr>
</tbody>
</table>

Significance

New! @80fb⁻¹
The observed significance of the ttH process is shown in the diagram. The significance is calculated as
\[
\frac{\sigma_{\text{ttH}}}{\sigma_{\text{SM}}}
\]
where \(\sigma_{\text{ttH}}\) is the total cross section for the ttH process and \(\sigma_{\text{SM}}\) is the cross section for the SM process.

For the ttH (bb) channel, the significance is 0.79 ± 0.61 (± 0.29, ± 0.53).

For the ttH (multilepton) channel, the significance is 1.56 ± 0.42 (± 0.30, ± 0.27).

For the ttH (\(\gamma\gamma\)) channel, the significance is 1.39 ± 0.48 (± 0.42, ± 0.23).

For the ttH (ZZ) channel, the significance is < 1.77 at 68% CL.

The combined significance is 1.32 ± 0.28 (± 0.18, ± 0.21).

With Run 1, the significance is 6.3 ± 5.1.

The observed significance (Obs.) and the expected significance (Exp.) are listed in the table:

- ttH (bb): 1.6 σ, 1.4 σ
- ttH (multilepton): 4.1 σ, 2.8 σ
- ttH (\(\gamma\gamma\)): 4.1 σ, 3.8 σ
- ttH (ZZ): 0 σ, 1.2 σ
- Combined: 5.8 σ, 4.9 σ

The values are given in standard deviations (σ) with uncertainties in parentheses.
Observation of $tt+H$ production with a significance of 6.3 $\sigma$ (expected 5.1 $\sigma$)

Cross-section at 13 TeV: $\sigma_{t\bar{t}H}(13TeV) = 670 \pm 90 (stat) ^{+110}_{-100} (sys)fb$ (~20%)

Compatible with the SM prediction

NLO QCD+EW: $507^{+35}_{-50}$ fb (+7% -10%)

Analysis Integrated $t\bar{t}H$ cross section [fb] sign. sign.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$H \rightarrow \gamma \gamma$</th>
<th>79.8</th>
<th>$710^{+210}<em>{-190} (stat.) ^{+120}</em>{-90} (syst.)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow$ multilepton</td>
<td>36.1</td>
<td></td>
<td>$790 \pm 150 (stat.) ^{+150}_{-140} (syst.)$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>36.1</td>
<td></td>
<td>$400^{+150}_{-140} (stat.) \pm 270 (syst.)$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^{*} \rightarrow 4\ell$</td>
<td>79.8</td>
<td></td>
<td>$&lt;900 (68% CL)$</td>
</tr>
</tbody>
</table>

Dominant systematics

$tt+$heavy flavour modelling (10%)
$tt+H$ modelling (6%)
Non-prompt leptons (5%)
THANKS FOR YOUR ATTENTION
BACK-UP
Evidence and first cross-section measurement at 13 TeV: $590^{+160}_{-150}$ fb ($^{+27\%}_{-25\%}$)

Prediction NLO QCD+EW: $507^{+35}_{-50}$ fb ($^{+7\%}_{-10\%}$)

Observation of $tt+H$ process

Systematic uncertainties > statistical uncertainties (modelling ~ experimental unc.)
Latest $tt+H$ ($H \rightarrow \text{multilepton}$) results

For most of the channels, MVAs are used to separate $tt+H$ signal from $tt+V$ and $tt+jets$ (fakes). One of the most discriminant variables in nJets. Thus, $tt+W/Z+jets$ estimation seems relevant...

$t t + H \rightarrow 4W+2b \rightarrow 6j$ (inc. 2b)+2lSS $+E_{T,\text{miss}}$ or 4j (inc. 2b)+3l+$E_{T,\text{miss}}$ or 4j (inc. 2b)+4l+$E_{T,\text{miss}}$

$t t + V \rightarrow 2W+V+2b \rightarrow 4j$ (inc. 2b)+2lSS $+E_{T,\text{miss}}$ or 2-4j (inc. 2b)+3l+$E_{T,\text{miss}}$ or 2j (inc. 2b)+4l+$E_{T,\text{miss}}$

$t t \rightarrow 2W+2b \rightarrow 4j$ (inc. 2b)+1l+$E_{T,\text{miss}}$ or 2j (inc. 2b)+2lO$S$+$E_{T,\text{miss}}$ [1 jet fakes a lepton]
Latest \( tt+H \) \((H \rightarrow \text{multilepton})\) results

For most of the channels, MVAs are used to separate \( tt+H \) signal from \( tt+V \) and \( tt+jets \) (fakes). One of the most discriminant variables in nJets. Thus, \( tt+W/Z+jets \) estimation seems relevant…

**NLO+PS setup used in both experiments** (MadGraph5_aMC@NLO+Pythia8)

**Interesting check:** jet multiplicity for \( tt+W/Z \) events in the high MVA region?

\[
\begin{align*}
\sigma_{ttZ} &= 0.8393 \pm 1.1.3\% \text{ (scale)} \pm 2.8\% \text{ (PDF)} \pm 2.8\% \text{ (}\alpha_s\text{)} \text{ pb} \\
\sigma_{ttW} &= 0.6008 \pm 1.1.9\% \text{ (scale)} \pm 2.0\% \text{ (PDF)} \pm 2.7\% \text{ (}\alpha_s\text{)} \text{ pb}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>( \Delta \mu / \mu ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, ( \mu ) selection efficiency</td>
<td>2–4</td>
<td>11</td>
</tr>
<tr>
<td>( \tau_h ) selection efficiency</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>b tagging efficiency</td>
<td>2–15 [57]</td>
<td>6</td>
</tr>
<tr>
<td>Reducible background estimate</td>
<td>10–40</td>
<td>11</td>
</tr>
<tr>
<td>Jet energy calibration</td>
<td>2–15 [65]</td>
<td>5</td>
</tr>
<tr>
<td>( \tau_h ) energy calibration</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Theoretical sources</td>
<td>( \approx 10 )</td>
<td>12</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>5</td>
</tr>
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</table>
Latest $tt+H$ ($H \rightarrow bb$) results

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\pm \sigma_\mu$ (observed)</th>
<th>$\pm \sigma_\mu$ (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>total experimental</td>
<td>+0.15/-0.16</td>
<td>0.19/-0.17</td>
</tr>
<tr>
<td>$b$ tagging</td>
<td>+0.11/-0.14</td>
<td>0.12/-0.11</td>
</tr>
<tr>
<td>jet energy scale and resolution</td>
<td>+0.06/-0.07</td>
<td>0.13/-0.11</td>
</tr>
<tr>
<td>total theory</td>
<td>+0.28/-0.29</td>
<td>0.32/-0.29</td>
</tr>
<tr>
<td>$tt+$hf cross-section and parton shower</td>
<td>+0.24/-0.28</td>
<td>0.28/-0.28</td>
</tr>
<tr>
<td>size of MC samples</td>
<td>+0.14/-0.15</td>
<td>0.16/-0.16</td>
</tr>
<tr>
<td>total systematic</td>
<td>+0.38/-0.38</td>
<td>0.45/-0.42</td>
</tr>
<tr>
<td>statistical</td>
<td>+0.24/-0.24</td>
<td>0.27/-0.27</td>
</tr>
<tr>
<td>total</td>
<td>+0.45/-0.45</td>
<td>0.53/-0.49</td>
</tr>
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</table>

Uncertainty source

- $\bar{t}\bar{t} + \geq 1b$ modeling: $+0.46$ $-0.46$
- Background-model statistical uncertainty: $+0.29$ $-0.31$
- $b$-tagging efficiency and mis-tag rates: $+0.16$ $-0.16$
- Jet energy scale and resolution: $+0.14$ $-0.14$
- $ttH$ modeling: $+0.22$ $-0.05$
- $tt + \geq 1c$ modeling: $+0.09$ $-0.11$
- JVT, pileup modeling: $+0.03$ $-0.05$
- Other background modeling: $+0.08$ $-0.08$
- $tt +$ light modeling: $+0.06$ $-0.03$
- Luminosity: $+0.03$ $-0.02$
- Light lepton ($e, \mu$) id., isolation, trigger: $+0.03$ $-0.04$
- Total systematic uncertainty: $+0.57$ $-0.54$
- $\bar{t}\bar{t} + \geq 1b$ normalization: $+0.09$ $-0.10$
- $\bar{t}\bar{t} + \geq 1c$ normalization: $+0.02$ $-0.03$
- Intrinsic statistical uncertainty: $+0.21$ $-0.20$
- Total statistical uncertainty: $+0.29$ $-0.29$
- Total uncertainty: $+0.64$ $-0.61$
Latest $tt+H$ ($H \rightarrow bb$) results

**CMS Supplementary**

- $tt+bb$ cross section (50%)
- b tagging: charm (linear)
- $t\bar{t}H$ cross section (renorm./fact. scales)
- jet energy scale (1)
- $tt+2b$ cross section (50%)
- b tagging: $Wf$ fraction
- $\mu_\tau$ scale ($t\bar{t}$)
- PS scale: ISR ($t\bar{t}+W$)
- PS scale: FSR ($t\bar{t}+W$)
- b tagging: charm (quadratic)
- ME-PS matching ($t\bar{t}+W$)
- jet energy scale (2)
- $\mu_\tau$ scale ($W$)
- PDF ($gg\rightarrow t\bar{t}$)
- b tagging: $Wf$ stats (quadratic)
- jet energy scale (4)
- $tt+2b+X$ cross section (renorm./fact. scales)

**35.9 fb$^{-1}$ (13 TeV)**

**Pre-fit impact on $\mu$:**
- $\theta = \theta^{+}\Delta\theta$
- $\theta = \theta^{-}\Delta\theta$

**Post-fit impact on $\mu$:**
- $\theta = \theta^{+}\Delta\theta$
- $\theta = \theta^{-}\Delta\theta$
- Nuis. Param. Pull

**ATLAS**

- $\tilde{y}_s = 13$ TeV, $36.1$ fb$^{-1}$

**ttbar syst legend**
- CMS has it
- CMS partially has it
- CMS does not have it

- $t\bar{t}+\geq 1b$: SHERPA5F vs. nominal
- $t\bar{t}+\geq 1b$: SHERPA4F vs. nominal
- $t\bar{t}+\geq 1b$: PS & hadronization
- $t\bar{t}+\geq 1b$: ISR / FSR
- $t\bar{t}N$: PS & hadronization
- $b$-tagging: mis-tag (light) NP I
- $k(t\bar{t}+\geq 1b) = 1.24 \pm 0.10$
- Jet energy resolution: NP I
- $t\bar{t}N$: cross section (QCD scale)
- $t\bar{t}+\geq 1b$: $t\bar{t}+\geq 3b$ normalization
- $t\bar{t}+\geq 1c$: SHERPA5F vs. nominal
- $t\bar{t}+\geq 1c$: SHERPA4F vs. nominal
- $t\bar{t}+\geq 1c$: PS & hadronization
- Jet energy resolution: NP II
- $t\bar{t}+light$: PS & hadronization
- Wt: diagram subtr. vs. nominal
- $b$-tagging: efficiency NP I
- $b$-tagging: mis-tag (o) NP I
- $E_T^{miss}$: soft-term resolution
- $b$-tagging: efficiency NP II

**Pull**
- $+\Delta\mu$ Impact
- $\pm\Delta\mu$ Impact
Reconstructed $tt+$jets events are classified into several categories and subcategories, based on the flavour of additional jets (at particle level) and number of hadrons in each of them.

* Only additional particle level jets above a $p_T$ threshold are considered in the classification
* Jets flavour (b, c or light) determined via $dR$ or ghost matching to hadrons (w./wo. cuts on hadrons)

### Subcategories
- “$tt+b$”: exactly 1 additional particle jet in the event which is matched to exactly 1 HF hadron
- “$tt+bb$”: 2 particle jets in the event, each of them matched to exactly 1 HF hadron
- “$tt+B/2b$” (ATLAS/CMS): 1 particle jet matched to $>1$ HF hadron ($g \rightarrow bb$ splitting)

### Treatment of uncertainties in $tt+H(bb)$

**ATLAS:** normalisation of each subcategory scaled to Sherpa 4F predictions, shape from 5F treating uncertainties as fully correlated among subcategories

**CMS:** normalisation and shapes from 5F predictions treating uncertainties as fully uncorrelated

---

<table>
<thead>
<tr>
<th>Cuts</th>
<th>ATLAS $tt+H(bb)$</th>
<th>ATLAS $tt+\geq 1b$ (8 TeV)</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructed level jets</td>
<td>(all events are classified)</td>
<td>Events in each fiducial phase-space (particle level)</td>
<td>$\geq$ 2 jets ($p_T &gt; 30$ GeV)</td>
</tr>
<tr>
<td>Particle level jets</td>
<td>15 GeV</td>
<td>20 or 25 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Hadrons</td>
<td>5 GeV, no $p_T^{hadron}/p_T^{jet}$ cut</td>
<td>5 GeV, no $p_T^{hadron}/p_T^{jet}$ cut</td>
<td>No cuts</td>
</tr>
<tr>
<td>Particle-hadron matching</td>
<td>dR&lt;0.3</td>
<td>Ghost matching</td>
<td>Ghost matching</td>
</tr>
</tbody>
</table>

Nominal $tt$: Powheg+Py8(6) 5F add. $b$-jets only from parton shower
Top coupling to Higgs boson: top Yukawa

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>Stat</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{WW}}^+$</td>
<td>$-0.64$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{Z\gamma}}^+$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{ZH}}$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{WH}}$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{ZZ}}^+$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{H} \gamma}$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{H} \gamma}$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{bb}}^+$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
<tr>
<td>$\mu_{\text{H} \gamma}$</td>
<td>$-0.34$</td>
<td>$+0.42$</td>
<td>$-0.48$</td>
</tr>
</tbody>
</table>

Uncertainty source $\Delta \mu$

- Signal theory $+0.15$ $-0.07$
  - Inclusive ttH normalisation (cross section and BR) $+0.15$ $-0.07$
  - ttH acceptance (scale, pdf, PS and UE) $+0.004$ $-0.004$
  - Other Higgs boson production modes $+0.002$ $-0.003$
- Background theory $+0.14$ $-0.13$
  - tt + bb/cc prediction $+0.13$ $-0.11$
  - tt + V(V) prediction $+0.06$ $-0.06$
  - Other background uncertainties $+0.03$ $-0.03$
- Experimental $+0.17$ $-0.15$
  - Lepton (inc. $\tau_2$) trigger, ID and iso. efficiency $+0.08$ $-0.06$
  - Misidentified lepton prediction $+0.06$ $-0.06$
  - b-Tagging efficiency $+0.05$ $-0.04$
  - Jet and $\tau_2$ energy scale and resolution $+0.04$ $-0.04$
  - Luminosity $+0.04$ $-0.03$
  - Photon ID, scale and resolution $+0.01$ $-0.01$
  - Other experimental uncertainties $+0.01$ $-0.01$
  - Finite number of simulated events $+0.08$ $-0.07$
- Statistical $+0.16$ $-0.16$
- Total $+0.31$ $-0.26$
Latest $tt+Z/W$ measurements at 13 TeV

ATLAS

CMS
Inclusive measurement, arXiv:1711.02547, submitted to JHEP (13 TeV, 35.9 fb$^{-1}$)

NLO QCD+EW  Numbers from YR4, arXiv:1610.07922

<table>
<thead>
<tr>
<th>$\sigma$ (pb)</th>
<th>8 TeV</th>
<th>13 TeV $\pm$12%</th>
<th>13 / 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt+Z$</td>
<td>0.206</td>
<td>0.839</td>
<td>3.7</td>
</tr>
<tr>
<td>$tt+W$</td>
<td>0.232</td>
<td>0.601 (±13%)</td>
<td>2.4</td>
</tr>
<tr>
<td>$tt+H$</td>
<td>0.129</td>
<td>0.5085 (±13%)</td>
<td>3.9</td>
</tr>
<tr>
<td>$tt$</td>
<td>~250</td>
<td>~830</td>
<td>3.3</td>
</tr>
</tbody>
</table>

More recent calculations in arXiv:1804.10017
**tt+Z/W: future measurements**

**tt+Z differential distributions**
- $p_T(Z)$, $m(Z)$, $\Delta\phi(Z)$, $m(tt)$ [including EFT interpretation]
- reconstruct $tt$ and $tt+Z$ systems
- with high statistics, new channels accessible
- $Z\rightarrow$ invisible, very interesting and background for SUSY searches

**tt+W differential distributions and charge asymmetry**

<table>
<thead>
<tr>
<th></th>
<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>$tt$</td>
<td>$\sigma$(pb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>198$^{+15%}_{-14%}$</td>
<td>661$^{+15%}_{-13%}$</td>
<td>786$^{+14%}_{-13%}$</td>
<td>4630$^{+12%}_{-11%}$</td>
<td>30700$^{+13%}_{-13%}$</td>
</tr>
<tr>
<td></td>
<td>$A_c^t$(%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.72$^{+0.14}_{-0.09}$</td>
<td>0.45$^{+0.09}_{-0.06}$</td>
<td>0.43$^{+0.08}_{-0.05}$</td>
<td>0.26$^{+0.04}_{-0.03}$</td>
<td>0.12$^{+0.03}_{-0.02}$</td>
</tr>
<tr>
<td>$t\bar{t}W^\pm$</td>
<td>$\sigma$(fb)</td>
<td>210$^{+11%}_{-11%}$</td>
<td>587$^{+13%}_{-12%}$</td>
<td>678$^{+14%}_{-12%}$</td>
<td>3220$^{+17%}_{-13%}$</td>
</tr>
<tr>
<td></td>
<td>$A_c^t$(%)</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></td>
<td>$A_c^b$(%)</td>
<td>8.56$^{+0.15}_{-0.10}$</td>
<td>7.54$^{+0.19}_{-0.17}$</td>
<td>7.50$^{+0.22}_{-0.22}$</td>
<td>5.37$^{+0.22}_{-0.30}$</td>
</tr>
<tr>
<td></td>
<td>$A_c^\ell$(%)</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>

**PLB 736 (2014) p.252-260**

- boosted tops improve precision of quark initiated processes
- differential spin density matrix measurements in $tt+X$ processes
- ratios: $tt+Z/tt$, $tt+Z+tt+\gamma$, $tt+H/tt+Z$
- update to MC generators versions that include EW corr.
- include NLO effect in top decay
- compare with more alternative MC generators (Powheg?)
And even access to $tZ$ coupling

$t\bar{t}+Z$ (ISR and FSR)

$t\bar{t}+W$ (ISR)

$tZq$ production probes both $tZ$ and $WWZ$ couplings

Direct measurement of top coupling to $Z$ gauge boson in $t\bar{t}+Z$ production via FSR.

So far, only inclusive cross-sections of these processes have been measured; not the $tZ$ vertex.
**Observation of $tt+\gamma$ Process**

**(fiducial and differential, already at Run-I)**

Photon can be emitted from:

A) Production (emission before top goes on-shell): ISR+off-shell tops

B) Decay: on-shell top quarks and its decay products

- Current analysis, aim to measure cross-section: selection enhances photons emitted by top quark.

$tt+\gamma$ has a large asymmetry

$$A_{tt\gamma}^{FB} = \begin{cases} 
-17\% & \text{LO,} \\
-11\% & \text{NLO} 
\end{cases}$$

- strongly dependent on
  - $gg$ vs. $qq$ production
  - photon emission in production vs. decay
  - anomalous couplings
- studies to suppress radiative top quark decays

*arXiv:1601.08193*
ttH, tH, tWH processes

**ttH (5F scheme)**

![Diagram of ttH process]

**tHjb (4F scheme)**

![Diagram of tHjb process]

**tWH (5F scheme, DR)**

![Diagram of tWH process]

→ For ttH, tWH, tHjb and other SM production modes, NLO normalisation from YellowReport4
• Similarly, model-independent measurements of the Higgs self-coupling will require precise knowledge of the top-Higgs interactions.

• Higher-dimension operators that involve the top and Higgs fields:
  • are little tested so far, and
  • are particularly sensitive to New Physics associated with EWSB.
• Effective top-Higgs Yukawa coupling can deviate from SM prediction due to contributions from dimension-6 operators.

Example: $\sigma(ttH)$ at $\sqrt{s}=14$ TeV:

\[
\frac{\sigma(pp \rightarrow t\bar{t}h)}{fb} = 611^{+92}_{-110} + [457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10}c_G] \frac{(\text{TeV})^2}{\Lambda} + 147^{+55}_{-32}c_{HG} - 67^{+23}_{-16}c_y
\]
\[
+ [543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232}c_G^2 + 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.7} c_y^2]
\]
\[
+ 233^{+81}_{-144} \Re c_{hg} c_{HG} - 50^{+16}_{-14} \Re c_{hg} c_y
\]
\[
- 3.2^{+8}_{-8} \Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG} \frac{(\text{TeV})^4}{\Lambda}
\]

Complementary to $\sigma(gg \rightarrow H)$ and $\sigma(tt)$ measurements, which are sensitive to a different combination of operators.
One has to pay attention to which operators contribute each process:

<table>
<thead>
<tr>
<th>Process</th>
<th>$O_{tG}$</th>
<th>$O_{tB}$</th>
<th>$O_{tW}$</th>
<th>$O^{(3)}_{Q}$</th>
<th>$O^{(1)}_{Q}$</th>
<th>$O_{\phi t}$</th>
<th>$O_{t\phi}$</th>
<th>$O_{4f}$</th>
<th>$O_{G}$</th>
<th>$O_{\phi G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to bW \to bl^+\nu$</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$pp \to t\bar{q}$</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$pp \to tW$</td>
<td></td>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$pp \to t\bar{t}$</td>
<td></td>
<td>L</td>
<td>L</td>
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</tr>
<tr>
<td>$pp \to t\bar{t}\gamma$</td>
<td></td>
<td>L</td>
<td>L</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>$pp \to t\bar{t}Z$</td>
<td></td>
<td>L</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$pp \to t\bar{t}h$</td>
<td></td>
<td>L</td>
<td>L</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$gg \to H, H \to \gamma\gamma$</td>
<td>N</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- $O_{\phi t}, O_{\phi Q^3}, O_{\phi Q^1} - t\bar{t}Z$ vertex
- $O_{tW}, O_{tB} - t\bar{t}Z$ and $t\bar{t}\gamma$ vertices
- $O_{tG} - t\bar{t}g$ vertex
Towards a global fit at the LHC
Monte Carlo Event Generators used to simulate events in High Energy Physics and other applications

Cross sections for a scattering process $ab \to n$ at hadron colliders

$$
\sigma = \sum_{a,b} \int_0^1 dx_a dx_b \int f_{a_1}^{h_1}(x_a, \mu_F) f_{b_1}^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \to n}(\mu_F, \mu_R) \\
= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_{a_1}^{h_1}(x_a, \mu_F) f_{b_1}^{h_2}(x_b, \mu_F) \\
\times \frac{1}{2\delta} |M_{ab \to n}|^2(\Phi_n; \mu_F, \mu_R),
$$

First Principles
- Hard Scatter
- Beam remnants
- Parton Shower
- ISR+FSR
- Multi-Parton Interaction
- Colour Reconnection
- Hadronization
- Decays

Tunable
- Monte Carlo Event Generator
- Hadron Decays
- Final State Radiation
- Hard scatter
- Beam Remnants
- Underlying Event
- Initial State Radiation

15/6/18
María Moreno Llácer – Observation of $tt+H$ process