ttH measurements at LHC

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Arlington
Motivation

• Fermion masses are generated through Yukawa interaction

• Heaviest SM particle (top) expected to have largest Yukawa coupling \(y_t\) to the Higgs field.

• Indirect constraints on top Yukawa coupling possible through Higgs production through ggH and H->γγ decay processes.

• ATLAS+CMS Run-1 combination of ratio of measured coupling to SM expectation \((κ_t)\)
  - Assuming no new particles in the loop
  \[ κ_t \equiv \frac{y_t}{y_t(SM)} = 0.87 \pm 0.15 \]

\[ \text{JHEP08(2016)045} \]

• Direct measurement of top-Yukawa coupling needed to disentangle any new physics effects.

• \(ttH/tH\) production cross-section measurement is the only direct way to measure \(y_t\)
  - \(tH\) cross-section too low
Experimental challenges

- Standard Model production cross section: ~507 fb: About 1% of total Higgs cross-section.
  - Many final states
  - Tiny signal and large backgrounds

**Signal**
- \( \text{ttH}(bb) \)
- \( \text{ttH-multileptons} \)
- \( \text{ttH}(\gamma\gamma) \)

**Background**
- \( \text{tt+(HF) jets (irreducible)} \)
- \( \text{ttV} \)
- \( \text{tty} \)
Experimental challenges

- Object identification and reconstruction among multiple proton collisions (pileup)

Excellent mitigation efforts

Jet energy scale

Missing $E_T$ resolution
**ttH(bb)**

- Large $H \rightarrow b\bar{b}$ branching fraction.

**Challenges**
- Huge combinatorics in reconstructing $H \rightarrow b\bar{b}$ candidate
- Large $tt + HF$ background + theory uncertainties

**Channels**
- Leptonic (dileptonic and single leptonic)
- Hadronic
ttH(bb): dileptonic

- Exactly two opposite sign leptons
- Regions constructed for 3 and ≥4 jets.
  - SR’s constructed with high b-tag quality
  - Three SR’s: purity ranging from 1.8% to 5.4%
  - Highest signal purity in region with 3 very tight and 1 tight b-tag
- CR’s for tt+b, tt+c and tt+light to constrain uncertainties, backgrounds,

<table>
<thead>
<tr>
<th></th>
<th>none</th>
<th>loose</th>
<th>medium</th>
<th>tight</th>
<th>very-tight</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>85%</td>
<td>77%</td>
<td>70%</td>
<td>60%</td>
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<tr>
<td>Discriminant</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

b-tag working points

- Similar region splitting in single lepton category as well (backup)
In signal regions, MVA techniques are used to further separate signal and background:

- **Reconstruction BDT**: Attempts to reconstruct top quarks and H(bb)
- **Likelihood discriminant (LHD)**: $ttH$ signal vs $tt+b$ background.
- **Matrix Element discriminant (MEM)**: $ttH$ and $tt+b$ PDF estimation using Matrix Element Method

Final discriminant: Classification BDT

- Reconstruction BDT, LHD, MEM, kinematic variables
ttH(bb): Dilepton

- Events categorized based on number of jets and b-tagged jets:

  - $\geq 4j, \geq 3b$: A BDT separating signal and tt+jets background
  - $\geq 4j, \geq 4b$: Two categories based on BDT; Matrix Element Method (MEM) separating signal from tt+HF background
ttH(bb): SingleLepton

- Events categorized as number of jets and b-tagged jets

- Multi-classification Deep Neural Network per jet category:
  - 6 categories: 1 signal and 5 tt+HF categories
  - Final discriminant is the DNN output
ttH(bb) Leptonic: Results

\[ \mu = 0.84^{+0.64}_{-0.61} \]

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

\[ \mu = 0.72^{+0.45}_{-0.45} \]

significance: 1.6\(\sigma\) (expected 2.2\(\sigma\))

- Systematics:
  - Largest impact from tt+bb generator modeling
  - b-tagging
  - ATLAS considers additional tt+HF systematics (backup)
**ttH(bb) hadronic**

- Events categorized as number of jets and b-tagged jets
  - $\geq 7$ jets, $\geq 3$ b-tagged jets, $H_T > 500$ GeV, no leptons
- Dominant background is QCD-multijet
- Modeling
  - Shape from low b-tag multiplicity control region in data
  - Normalization from final fit to data
- MEM to discriminate ttH vs tt+HF

![Graph of ttH(bb) hadronic events](chart.png)

**CMS Supplementary**

<table>
<thead>
<tr>
<th>Events</th>
<th>$S/B$</th>
<th>$S/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 jets, 3 b tags</td>
<td>0.0023, 0.5878</td>
<td></td>
</tr>
<tr>
<td>8 jets, 3 b tags</td>
<td>0.0033, 0.7048</td>
<td></td>
</tr>
<tr>
<td>$\geq 9$ jets, 3 b tags</td>
<td>0.0049, 0.7874</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Events</th>
<th>$S/B$</th>
<th>$S/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 jets, $\geq 4$ b tags</td>
<td>0.0077, 0.5227</td>
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</tr>
<tr>
<td>8 jets, $\geq 4$ b tags</td>
<td>0.0095, 0.8560</td>
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</tr>
<tr>
<td>$\geq 9$ jets, $\geq 4$ b tags</td>
<td>0.0143, 0.8484</td>
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</tbody>
</table>

**CMS**

<table>
<thead>
<tr>
<th>Events</th>
<th>$\mu$ (tot) (stat) (syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7j, 3b</td>
<td>1.6 (+9.6, +2.7, +9.2)</td>
</tr>
<tr>
<td>8j, 3b</td>
<td>1.2 (+5.9, +2.2, +5.4)</td>
</tr>
<tr>
<td>$\geq$9j, 3b</td>
<td>-3.5 (+5.9, +2.4, +5.4)</td>
</tr>
<tr>
<td>7j, $\geq$4b</td>
<td>5.4 (+2.9, +1.8, +2.3)</td>
</tr>
<tr>
<td>8j, $\geq$4b</td>
<td>-0.2 (+2.8, +1.5, +2.3)</td>
</tr>
<tr>
<td>$\geq$9j, $\geq$4b</td>
<td>-0.4 (+2.1, +1.4, +1.6)</td>
</tr>
<tr>
<td>3b cats</td>
<td>-1.7 (+5.2, +1.4, +5.0)</td>
</tr>
<tr>
<td>4b cats</td>
<td>1.5 (+1.6, +0.9, +1.4)</td>
</tr>
</tbody>
</table>

**Combined**

<table>
<thead>
<tr>
<th>Events</th>
<th>$\mu$ (tot) (stat) (syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9 (+1.5, +0.7, +1.3)</td>
</tr>
</tbody>
</table>

Best fit $\hat{\mu} = \sigma/\sigma_{SM}$ at $m_H = 125$ GeV
ttH Multileptons

- Targets $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow \tau^+\tau^-$
- Events categorized based on number of light leptons and hadronic taus

Main backgrounds
- Fake leptons (heavy flavor, conversions)
- Irreducible background from $ttV$
- High lepton multiplicity reduces backgrounds
**ttHML: CMS strategy**

- Event categorization based on number of light leptons and hadronic taus.
- Final fit variables
  - MEM against $ttZ$ ($2\,l$ same-sign + $1\,\tau_h$)
  - Yields in 4-leptons
  - BDTs against $tt+$jets ($1l+2\,\tau_h$) and $tt+ V$ ($2\,l$ same-sign, 3 $l$)
**ttHML: ATLAS strategy**

<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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</thead>
<tbody>
<tr>
<td>BDT trained against</td>
<td>Fakes and t\bar{t}V</td>
<td>t\bar{t}, t\bar{t}W, t\bar{t}Z, VV</td>
<td>t\bar{t}Z / -</td>
<td>t\bar{t}</td>
<td>all</td>
<td>t\bar{t}</td>
<td>-</td>
</tr>
<tr>
<td>Discriminant</td>
<td>2×1D BDT</td>
<td>5D BDT</td>
<td>Event count</td>
<td>BDT</td>
<td>BDT</td>
<td>BDT</td>
<td>Event count</td>
</tr>
<tr>
<td>Number of bins</td>
<td>6</td>
<td>5</td>
<td>1 / 1</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Control regions</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Simultaneous fit in 12 regions (CR+SR)
  - Multiclass BDT in 3l
- Single bin used in 3l CR’s as well as low stat SR’s
  - 3l+1τ
  - 4l (z-enriched, z-depleted)
- BDT shape information used in 5 SR’s
ttHML: Results

- Measured \( \mu = 1.6^{+0.5}_{-0.4} \) with a significance with respect to background only hypothesis \( 4.1\sigma \) (expct. \( 2.8\sigma \))

- Measured \( \mu = 1.23^{+0.45}_{-0.43} \) with a significance with respect to background only hypothesis \( 3.2\sigma \) (expct. \( 2.8\sigma \))

- Limited by fake lepton estimation, tau identification JES, ttH and ttV process modeling.
- Several channels are limited by statistics.
ttH(ZZ*)

- Candidate event selection:
  - At least two opposite sign same flavor light lepton
  
- Extremely low rate (about 0.6 event expected with the statistics available); but 
clean final state with high S/B

- Dedicated ttH channel, part of the global H(ZZ*) analysis

- No candidates in a window $115 < m_{4l} < 130$
ttH(γγ)

- Clear signature from the photons
- Higgs boson can be reconstructed from the two isolated photons.
- Dedicated ttH channel part of the H(γγ) analysis.
ttH(γγ) ATLAS strategy

- Events classified into hadronic and leptonic channels based on decay topology of tt-bar system.

- BDT’s used in hadronic and leptonic channels.
  - Separating ttH from main background ttγγ and γγ background processes.

- Based on the BDT output 4 hadronic and 3 leptonic categories are defined for the fit.
  - S+B fit in each category between 105 < m_{γγ} < 160 GeV
ttH(γγ) Results

**ATLAS:** \( \mu = 1.39^{+0.48}_{-0.42} \)  
observed (expected) significance: 4.1\( \sigma \) (3.7\( \sigma \))

**CMS:** \( \mu = 2.2^{+0.9}_{-0.8} \)
ttH Combination

- Combine different decay modes assuming SM for the decay BR
- Combine also with run 1 data (lower sensitivity, 20 (5) fb\(^{-1}\) @ 8(7) TeV)

\[ \kappa_{ttH} = 1.26^{+0.31}_{-0.26} \]

<table>
<thead>
<tr>
<th>Run1+Run2</th>
<th>Run2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>6.3(\sigma) observed (5.1(\sigma) expected)</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>5.2(\sigma) observed (4.2(\sigma) expected)</td>
</tr>
</tbody>
</table>

ATLAS uses 2017 data as well for ttH(\(\gamma\gamma\)), ttH(ZZ*) analysis

\[ K_t = 1.09^{+0.15}_{-0.14} \quad \text{ATLAS} \quad 0.98^{+0.14}_{-0.14} \quad \text{CMS} \]
Conclusion and Outlook

• Both CMS and ATLAS has observed $ttH$ process at the LHC

• Leading measurement uncertainties
  • Process modeling: $tt+HF$ and $ttV$
  • Light lepton fake estimates, jet systematics

• New data (about 140 fb$^{-1}$ collected)
  • Statistically limited channels will gain sensitivity
  • Impacts statistically limited systematics: eg. fake estimates
  • Differential measurements
  • Simultaneous measurements, ratios

• HL-LHC
  • Rare decay channels become accessible eg: $ttH(\mu\mu)$, $ttH(Z\gamma)$
Backup
ttH(bb): Single lepton

Sub channels
- Exactly 1 lepton.
- Boosted Category:
  - Presence of two R=1.0 reclustered jets (for Higgs and top candidate)
  - Remove jets which have pT < 50GeV and pT>1500 GeV
- Resolved Category: Failing boosted selection
  - Require ≥5 jets and ≥2 very-tight or ≥3 medium b-tagged jets

- SR’s defined for 5 and ≥6 jets
- Boosted channel is not categorized further.
- Highest purity in 4 very tight b-tag bins (≥6 jets)
- CR’s for tt+ ≥1b, tt+ ≥1c and tt + light
### CMS ttH(bb)Leptonic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\pm \Delta \mu$ (observed)</th>
<th>$\pm \Delta \mu$ (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>$t\bar{t}+hf$ cross section and parton shower</td>
<td>+0.24/−0.28</td>
<td>+0.28/−0.28</td>
</tr>
<tr>
<td>Size of the simulated 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>
</tbody>
</table>
## CMS Combinations

| Parameter | Best fit | Stat | Uncertainty | | |
|-----------|----------|------|-------------|---|---|---|
| $\mu_{W^*W^*}$ | 1.97$^{+0.71}_{-0.64}$ | +0.42 | +0.46 | +0.21 | +0.25 |
| $\mu_{t\tau H}$ | 0.00$^{+1.30}_{-0.00}$ | +1.28 | +0.20 | +0.04 | +0.09 |
| $\mu_{t\tau H}$ | 2.27$^{+0.86}_{-0.74}$ | +0.80 | +0.15 | +0.02 | +0.29 |
| $\mu_{\gamma\gamma}$ | 0.28$^{+1.09}_{-0.96}$ | +0.86 | +0.64 | +0.10 | +0.20 |
| $\mu_{t\tau H}$ | 0.82$^{+0.44}_{-0.42}$ | +0.23 | +0.24 | +0.11 |
| $\mu_{7+8 TeV}$ | 2.59$^{+1.01}_{-0.88}$ | +0.54 | +0.53 | +0.55 | +0.37 |
| $\mu_{13 TeV}$ | 1.14$^{+0.31}_{-0.27}$ | +0.17 | +0.17 | +0.13 | +0.14 |
| $\mu_{tt H}$ | 1.26$^{+0.31}_{-0.26}$ | +0.16 | +0.17 | +0.13 | +0.15 | +0.07 | +0.11 | +0.05 |
ATLAS + CMS ttH(bb) systematics

**CMS Supplementary**

- t\(\bar{t}\)+b\(\bar{b}\) cross section (50%)
- b tagging: charm (linear)
- t\(\bar{t}\)H cross section (renorm./fact. scales)
- jet energy scale (1)
- t\(\bar{t}\)+2b cross section (50%)
- b tagging: If fraction
- b tagging: If stats (quadratic)
- \(\mu_\text{R}\) scale (If)
- PS scale: ISR (t\(\bar{t}\)+If)
- PS scale: FSR (t\(\bar{t}\)+If)
- b tagging: hf fraction
- b tagging: charm (quadratic)
- ME-PS matching (t\(\bar{t}\)+If)
- jet energy scale (2)
- \(\mu_\text{Z}\) scale (If)
- jet energy scale (3)
- PDF (gg t\(\bar{t}\)H)
- b tagging: rf stats (quadratic)
- jet energy scale (4)
- t\(\bar{t}\) cross section (renorm./fact. scales)

**ATLAS**

\(\sqrt{s} = 13\text{ TeV}, 36.1\text{ fb}^{-1}\)

- Pre-fit impact on \(\mu\):
  - \(\theta = \theta + \Delta\theta\)
  - \(\theta = \theta - \Delta\theta\)
  - Nuis. Param. Pull

- Post-fit impact on \(\mu\):
  - \(\theta = \theta + \Delta\hat{\theta}\)
  - \(\theta = \theta - \Delta\hat{\theta}\)

- 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\(\bar{t}\)H: PS & hadronization
- b-tagging: mis-tag (light) NP I
  - \(k(t\bar{t}+\geq1b) = 1.24 \pm 0.10\)
- Jet energy resolution: NP I
- t\(\bar{t}\)H: cross section (QCD scale)
- t\(\bar{t}\)+\(\geq\)1b: t\(\bar{t}\)+\(\geq\)3b normalization
- t\(\bar{t}\)+\(\geq\)1c: SHERPA5F vs. nominal
- t\(\bar{t}\)+\(\geq\)1b: shower recoil scheme
- t\(\bar{t}\)+\(\geq\)1c: ISR / FSR
- 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 (c) NP I
- \(E_t^{\text{miss}}\): soft-term resolution
- b-tagging: efficiency NP II
# ATLAS $t\bar{t}+HF$ systematics

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Description</th>
<th>$t\bar{t}$ categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ cross-section</td>
<td>Up or down by 6%</td>
<td>All, correlated</td>
</tr>
<tr>
<td>$k(t\bar{t} + \geq 1c)$</td>
<td>Free-floating $t\bar{t} + \geq 1c$ normalization</td>
<td>$t\bar{t} + \geq 1c$</td>
</tr>
<tr>
<td>$k(t\bar{t} + \geq 1b)$</td>
<td>Free-floating $t\bar{t} + \geq 1b$ normalization</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>SHERPA5F vs. nominal</td>
<td>Related to the choice of NLO event generator</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>PS &amp; hadronization</td>
<td>POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>ISR / FSR</td>
<td>Variations of $\mu_R$, $\mu_F$, $h_{damp}$ and A14 Var3c parameters</td>
<td>All, uncorrelated</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1c$ ME vs. inclusive</td>
<td>MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)</td>
<td>$t\bar{t} + \geq 1c$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ SHERPA4F vs. nominal</td>
<td>Comparison of $t\bar{t} + b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ renorm. scale</td>
<td>Up or down by a factor of two</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ resumm. scale</td>
<td>Vary $\mu_Q$ from $H_T/2$ to $\mu_{CMMPS}$</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ global scales</td>
<td>Set $\mu_Q$, $\mu_R$, and $\mu_F$ to $\mu_{CMMPS}$</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ shower recoil scheme</td>
<td>Alternative model scheme</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ PDF (MSTW)</td>
<td>MSTW vs. CT10</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ PDF (NNPDF)</td>
<td>NNPDF vs. CT10</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ UE</td>
<td>Alternative set of tuned parameters for the underlying event</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 1b$ MPI</td>
<td>Up or down by 50%</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 3b$ normalization</td>
<td>Up or down by 50%</td>
<td>$t\bar{t} + \geq 1b$</td>
</tr>
</tbody>
</table>
## ttHML: light lepton fakes

<table>
<thead>
<tr>
<th></th>
<th>$2\ell$SS</th>
<th>$3\ell$</th>
<th>$4\ell$</th>
<th>$1\ell+2\tau_{\text{had}}$</th>
<th>$2\ell$SS+$1\tau_{\text{had}}$</th>
<th>$2\ell$OS+$1\tau_{\text{had}}$</th>
<th>$3\ell+1\tau_{\text{had}}$</th>
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</thead>
<tbody>
<tr>
<td><strong>Non-prompt lepton strategy</strong></td>
<td>DD (MM)</td>
<td>DD (MM)</td>
<td>semi-DD (SF)</td>
<td>MC</td>
<td>DD (FF)</td>
<td>MC</td>
<td>MC</td>
</tr>
<tr>
<td><strong>Fake tau strategy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DD (SS data)</td>
<td>semi-DD (SF)</td>
<td>DD (FF)</td>
</tr>
</tbody>
</table>

## $2\ell$SS/3l

![Graph](image1)

## 4l

![Graph](image2)

![Graph](image3)
## ttHML: Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$ modeling (cross section)</td>
<td>+0.20, -0.09</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.18, -0.15</td>
</tr>
<tr>
<td>Non-prompt light-lepton estimates</td>
<td>+0.15, -0.13</td>
</tr>
<tr>
<td>Jet flavor tagging and $\tau_{\text{had}}$ identification</td>
<td>+0.11, -0.09</td>
</tr>
<tr>
<td>$t\bar{t}W$ modeling</td>
<td>+0.10, -0.09</td>
</tr>
<tr>
<td>$t\bar{t}Z$ modeling</td>
<td>+0.08, -0.07</td>
</tr>
<tr>
<td>Other background modeling</td>
<td>+0.08, -0.07</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.08, -0.06</td>
</tr>
<tr>
<td>$t\bar{t}H$ modeling (acceptance)</td>
<td>+0.08, -0.04</td>
</tr>
<tr>
<td>Fake $\tau_{\text{had}}$ estimates</td>
<td>+0.07, -0.07</td>
</tr>
<tr>
<td>Other experimental uncertainties</td>
<td>+0.05, -0.04</td>
</tr>
<tr>
<td>Simulation sample size</td>
<td>+0.04, -0.04</td>
</tr>
<tr>
<td>Charge misassignment</td>
<td>+0.01, -0.01</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>+0.39, -0.30</td>
</tr>
</tbody>
</table>
ttH(bb): Matrix Element method

- Calculate the likelihood of each event to originate from ttH or tt + bb
- Used in most powerful signal region 6j SR1

\[ L_i = \sum_{\text{flavor}} \int \frac{f_1(x_1, Q^2) f_2(x_2, Q^2)}{|\vec{q}_1||\vec{q}_2|} |\mathcal{M}_i(Y)|^2 T(X; Y) d\Phi_n dY \]

\text{parton distribution function} \\
\text{accounts for production mechanism} \\
\text{transfer function} \\
\text{maps detector response to diagram} \\
\text{matrix element} \\
\text{describes signal or background process}