FEASIBILITY STUDY OF DETECTING FOUR TOP QUARK PRODUCTION AT CMS

Niels Van den Bossche
1 INTRODUCTION

2 RECONSTRUCTION OF HADRONIC FINAL STATES

3 SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS

4 CONCLUSIONS AND OUTLOOK
1 INTRODUCTION
   - FINAL STATES AND BACKGROUND
   - EARLIER SEARCHES

2 RECONSTRUCTION OF HADRONIC FINAL STATES

3 SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS

4 CONCLUSIONS AND OUTLOOK
**INTRODUCTION**

- Not yet observed
- Very rare process: predicted SM cross-section at 13 TeV:
  \[ \sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12.0^{+2.2}_{-2.5} \text{ fb} \]
- Only 1600 events expected in 137 fb\(^{-1}\) Run-II dataset
- Possible to probe Yukawa coupling of top quark
- Important sensitivity to EFT parameters
- New physics could have a large influence on the cross section of this process due to new bosons
**Final States**

- Final states defined by the number of leptons
- Top quark always decays as: \( t \rightarrow W + b \)
- W leads to lepton and neutrino or 2 quarks
- Pure hadronic channel: expect up to 12 jets
- Dilepton channels split up in same-sign and opposite-sign channels

**Figure**: Branching fractions for different final states
Backgrounds

Full hadronic, 1 lepton and opposite-sign dilepton (OSDL):

- QCD, $t\bar{t}$ + jets, W/Z + jets

Dominate final states but very difficult backgrounds

Figure: Branching fractions for different final states
**Backgrounds**

Same-sign dilepton (SSDL) and multilepton (ML) channels:

- **Multilepton** = 3 lepton + 4 lepton channels
- **Irreducible background**: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$
- **Reducible background**: $t\bar{t}$ with charge misidentified or non-prompt leptons

Total branching fraction of 13% but highest signal/background ratio ("golden channels")

Figure: Branching fractions for different final states
EARLIER SEARCHES

- CMS measurement in SSDL and ML channels (2020):
  - Observed (expected) significance: 2.6 (2.7) $\sigma$
  - $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}\text{fb}$
  - ArXiv:1908.06463

- ATLAS measurement in SSDL and ML channel (2021):
  - Observed (expected) significance: 4.7 (2.6) $\sigma$
  - $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 25^{+7}_{-6}\text{fb}$

- CMS measurement in single lepton and OSDL channel (2019):
  - Observed (expected) significance: 0.0 (0.4) $\sigma$
  - $\sigma_{t\bar{t}t\bar{t}} < 48\text{fb}$
  - ArXiv:1906.02805
CMS (2020): YUKAWA COUPLING MEASUREMENT

- Measurement independent of the Higgs width
- 95% CL limit: $\left| \frac{y_t}{y_t^{SM}} \right| < 1.7$
- $\bar{t}tH$-background sensitive to $y_t$ as well
1. **INTRODUCTION**

2. **RECONSTRUCTION OF HADRONIC FINAL STATES**
   - Reconstruction of full hadronic final state
   - Top tagger for leptonic channels

3. **SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS**

4. **CONCLUSIONS AND OUTLOOK**
RECONSTRUCTION OF FULL HADRONIC FINAL STATE

General idea:

- Assume all top quarks decay to 3 jets
- Make combinations of three jets
- Rate, accept and rank combinations based on invariant mass or MVA score
- Combination accepted if:
  - Invariant mass $\in [122.4 \text{ GeV}, 222.4 \text{ GeV}]$
  - BDT score > -0.1
  - MLP score > 0.5
- Find complete set of 4 compatible combinations (no common jets)
Evaluation of Reconstruction

- Evaluation using generator particles
- Generator particles linked to reconstructed jets
- Link requires $\Delta R = \sqrt{\Delta \phi^2 + (\Delta \eta)^2} < 0.4$
- Success rate in events with no leptons: 1.9%
RECONSTRUCTION OF FULL HADRONIC FINAL STATE

- BDT based reconstruction most successful:
  - At least 1 top quark correct in 80% of events
  - Mass-based and MLP sit around 50%
- MLP seems undertrained: unexpected behaviour given test results
- Failure rate generally quite low: possible to constrain acceptance requirements further

![Graph showing CMS preliminary results at 13 TeV for Mass-based, MLP, and BDT categories. Bars represent failed and correct reconstructed top quarks in arbitrary units.]
POSSIBLE IMPROVEMENTS

- Tightening acceptance requirements
- Rate set of reconstructed top quarks
  - Feedback to selection of four three-jet combinations
  - Usage of a MVA to provide this feedback
  - If set has a low rating: continue search for set of four reconstructed top quarks
- Combine with tagging of boosted top quarks

![Graph showing CMS preliminary results with MLP and BDT models for 13 TeV mass-based analysis.](image-url)
APPLICATION OF BDT AS A TOP-TAGGER

- Used in SSDL and ML channels search
- BDT scores used as an input to BDT separating signal and background
- Highest BDT scores of compatible three-jet combinations
- SSDL channel: two highest scores
- ML channel: highest score
1 INTRODUCTION

2 RECONSTRUCTION OF HADRONIC FINAL STATES

3 SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS
   ■ REPRODUCED SEARCH
   ■ MODIFIED SEARCH
   ■ EVALUATION USING 2016 & 2017 DATA

4 CONCLUSIONS AND OUTLOOK
SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON
CHANNELS

- Previous search: expected significance of $2.7\sigma$
- Backgrounds:
  - Dominant: $\bar{t}tW$, $\bar{t}tZ$, $\bar{t}tH$
  - Charge misidentified: $\bar{t}t$
  - Non-prompt leptons: $\bar{t}t$, $\bar{t}t\gamma$
  - $X\gamma$ mostly $\bar{t}t\gamma$
  - Rare: $WW$, $WZ$, $ZZ$, $VVV$, single top
  - $\bar{t}tVV$
- UGent leptonMVA for prompt lepton identification
1. INTRODUCTION

2. RECONSTRUCTION OF HADRONIC FINAL STATES

3. SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS
   - Reproduced search
   - Modified search
   - Evaluation using 2016 & 2017 data

4. CONCLUSIONS AND OUTLOOK
**OBJECT SELECTION**

- Prompt lepton identification original search:
  - Electrons: MVA
  - Muons: track quality
- Here introduce UGent leptonMVA
- Medium working point for b-tagger

<table>
<thead>
<tr>
<th></th>
<th>Leptons</th>
<th>$p_T &gt; 20 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium leptonMVA</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>$p_T &gt; 40 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>b-tagged jets</td>
<td>$p_T &gt; 25 \text{ GeV}$</td>
<td>Medium b-tag</td>
</tr>
</tbody>
</table>
EVENT SELECTION

- Leading and subleading lepton must have same charge
- Removal of low mass resonances:
  - Same-flavour lepton pair with $m_{ll} < 12$ GeV
  - Electrons: both same charge and opposite charge pairs
  - Muons: only opposite charge pairs
- Removal of Z-boson mass resonances:
  - Same-flavour opposite-charge lepton pair with $m_{ll} \in [76$ GeV, 106 GeV]
  - Suppresses $t\bar{t}Z$ background
- 2.7% of four top events selected (1.5% in original search)

\[
\begin{array}{l}
N_l \geq 2 \\
N_{jets} \geq 2 \\
N_b \geq 2 \\
H_T > 300$ GeV \\
MET > 50$ GeV
\end{array}
\]
**CONTROL REGIONS**

**CRW:**
- $N_I = 2$, $N_b = 2$, $N_{jets} < 6$
- Dominated by $t\bar{t}W$

**CRZ:**
- Inversion of Z-boson resonance veto
- Dominated by $t\bar{t}Z$

---

**Legend:**
- $t\bar{t}V$: Light blue
- Rare: Light pink
- $t\bar{t}H$: Dark brown
- Nonprompt lep.: Orange
- $t\bar{t}W$: Green
- $t\bar{t}f$: Red
- $X_\gamma$: Blue
**Cut-based Analysis**

Based on $N_l$, $N_b$ and $N_{jets}$

Generally higher event yield in reproduction

- **CMS**
  
  **Cut-based (post-fit)**

<table>
<thead>
<tr>
<th>Events</th>
<th>Data</th>
<th>$tttt$</th>
<th>Nonprompt lep.</th>
<th>$ttH$</th>
<th>$Xy$</th>
<th>Charge misid.</th>
<th>Rare</th>
<th>$ttVV$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>$10^2$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$10^1$</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^0$</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

- **CMS preliminary**

  - $ttVV$
  - $Xy$
  - Charge MisID
  - Rare
  - Nonprompt lep.

- **Signal fraction**

  - $0$
  - $0.5$
  - $1$

- **Cut**

  - $0$
  - $0.5$
  - $1$

(a) Original search

(b) Reproduction

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BDT-BASED ANALYSIS

- BDT trained on independent MC samples
- Only signal-background separation
- Same BDT variables as original search
- AUC of 0.851
- Initial overtraining issues: limited weights of $t\bar{t}(\gamma)$ events

Figure: SSDL + ML
## BDT-based Analysis

- Additional dedicated BDTs for SSDL and ML channels
- Same variables as other BDT
- SSDL AUC: 0.837
- ML AUC: 0.902
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4 CONCLUSIONS AND OUTLOOK
Object Selection

- Lowered $p_T$ threshold for jets in modified search
- $b$-tagged jets become subset of all jets in modified search
- Finer selection based on number of jets

<table>
<thead>
<tr>
<th></th>
<th>Reproduced</th>
<th>Modified</th>
</tr>
</thead>
</table>
| Leptons           | $p_T > 20$ GeV  
                    | Medium leptonMVA |
| Jets              | $p_T > 40$ GeV  
                    | $p_T > 25$ GeV    |
| $b$-tagged jets   | $p_T > 25$ GeV  
                    | Medium b-tag      |
**Event Selection**

- Aimed at maximizing four top yield

<table>
<thead>
<tr>
<th></th>
<th>Reproduced</th>
<th>Modified</th>
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</thead>
<tbody>
<tr>
<td>$N_l$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$N_{jets}$</td>
<td>$\geq 2$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>$N_b$</td>
<td>$\geq 2$</td>
<td></td>
</tr>
<tr>
<td>$H_T$</td>
<td>$&gt; 300$ GeV</td>
<td></td>
</tr>
<tr>
<td>MET</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 25$ GeV</td>
</tr>
</tbody>
</table>
EVENT SELECTION

(a) $N_{\text{jets}}$

(b) $N_b$
**EVENT SELECTION**

(a) $H_T$

(b) $p_T^{\text{miss}}$
**Event Selection**

- Aimed at maximizing four top yield
- Low mass and Z-boson resonances removed just as before
- Removed requirement for leading and subleading lepton to have the same charge in ML channel

<table>
<thead>
<tr>
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<th>Modified</th>
</tr>
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<tbody>
<tr>
<td>$N_l$</td>
<td>$\geq 2$</td>
<td></td>
</tr>
<tr>
<td>$N_{jets}$</td>
<td>$\geq 2$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>$N_b$</td>
<td>$\geq 2$</td>
<td></td>
</tr>
<tr>
<td>$H_T$</td>
<td></td>
<td>$&gt; 300$ GeV</td>
</tr>
<tr>
<td>MET</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 25$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative yield</th>
<th>Reproduced</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSDL</td>
<td>2.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>ML</td>
<td>0.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Combined</td>
<td>2.7%</td>
<td>3.7%</td>
</tr>
</tbody>
</table>
No clear motivation from background yield

Triples luminosity in ML channel
CONTROL REGIONS

CRW:

- $N_l = 2$, $N_b = 2$, $N_{jets} < 6$
- Dominated by $t\bar{t}W$

CRZ:

- Inversion of Z-boson resonance
- $N_b \geq 1$
- $N_{jets} \geq 3$
BDT-BASED ANALYSIS

- **BDT variables:**
  - Best performing of original search
  - New interesting variables selected
- **SSDL:** AUC of 0.865 (0.837 in reproduced search)
- **ML:** AUC of 0.880 (0.902 in reproduced search)
**SYSTEMATIC UNCERTAINTIES**

- Flat uncertainties used (same for all bins)
- Largest normalization uncertainties on $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}H$: 20-25%
- $t\bar{t}W$ and $t\bar{t}Z$ also big impact on cross section measurement
- Biggest impact from uncertainty on signal acting as “modelling uncertainty” with input of 15%
Both searches are capable of finding evidence and discovery.

Results surpass previous CMS search massively (2.7σ).

Modified search makes ML channel very useful.

Generally increased significance in modified search as seen in SSDL.

<table>
<thead>
<tr>
<th></th>
<th>Reproduced</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSDL</td>
<td>4.24σ</td>
<td>4.79σ</td>
</tr>
<tr>
<td>ML</td>
<td>1.76σ</td>
<td>3.35σ</td>
</tr>
<tr>
<td>Both + CRs</td>
<td>4.97σ</td>
<td>6.01σ</td>
</tr>
</tbody>
</table>
1  INTRODUCTION

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3  SEARCH IN SAME-SIGN DILEPTON AND MULTILEPTON CHANNELS
   □  REPRODUCED SEARCH
   □  MODIFIED SEARCH
   □  EVALUATION USING 2016 & 2017 DATA

4  CONCLUSIONS AND OUTLOOK
EVALUATION USING 2016 & 2017 DATA

- Corruption in compression of 2018 data
- Total dataset of 77 fb$^{-1}$
Overall agreement is very good

Fluctuations are expected
**REPRODUCED SEARCH: CONTROL REGIONS**

- Good agreement between MC and data
- Overestimation comes from 2016 MC
Generally good agreement between data and MC

**Figure:** SSDL + ML
Slight underestimation of background yields:

- 10-20% of $t\bar{t}W$ and $t\bar{t}Z$
- Allows some rescaling of the background
**MODIFIED SEARCH: CONTROL REGIONS**

Slight underestimation of background yields:

- 10-20% of $t\bar{t}W$ and $t\bar{t}Z$  
- $t\bar{t}Z$ clearly underestimated: expected from measurements on this process
Good agreement over all bins

Last bin in SSDL has no events: not unexpected given the low number of expected events
MODIFIED SEARCH: BDT-BASED ANALYSIS

- Good agreement over all bins
- Consistent underestimation of event yield at higher $N_{jets}$ could point at increased signal cross section
**Modified search: BDT-based analysis**

- Good agreement over all bins
- Consistent underestimation of event yield at higher $N_{jets}$ could point at increased signal cross section
**Results**

- Clear evidence for four top production
- Inclusion of 2018 data could provide more confidence in results
- Charge misidentification and non-prompt event yield result from MC simulations instead of data
- Flat uncertainties used instead of shape uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Reproduced search</th>
<th>Modified search</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>SSDL + ML</td>
<td>$3.46\sigma$</td>
<td>$4.44\sigma$</td>
</tr>
<tr>
<td>+ CRs</td>
<td>$3.65\sigma$</td>
<td>$5.14\sigma$</td>
</tr>
<tr>
<td>SSDL + ML</td>
<td>$4.36\sigma$</td>
<td>$4.61\sigma$</td>
</tr>
<tr>
<td>+ CRs</td>
<td>$4.50\sigma$</td>
<td>$4.91\sigma$</td>
</tr>
</tbody>
</table>

Table: Expected and observed significance in the considered channels
RESULTS: SIGNAL STRENGTH

\[ \hat{r} = \frac{\hat{\sigma}_{\text{SSDL+ML}}}{\sigma_{\text{SM}}} \]

- Measured by only fitting \( \hat{r} \)
- Maximum likelihood fit including \( \bar{t}tW \) and \( \bar{t}tZ \) normalization would be ideal
- Uncertainty clearly reduced in modified search: mostly attributed to tripled luminosity in ML

<table>
<thead>
<tr>
<th></th>
<th>Reproduced</th>
<th>Modified</th>
</tr>
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<tbody>
<tr>
<td>SSDL + ML</td>
<td>1.61 +0.72</td>
<td>1.27 +0.50</td>
</tr>
<tr>
<td>+ CRs</td>
<td>1.90 +0.69</td>
<td>1.31 +0.47</td>
</tr>
</tbody>
</table>

Table: The observed signal strength of four top production
CONCLUSIONS AND OUTLOOK

- Hadronic final state reconstruction provides promising results
- Discovery in SSDL and ML final states clearly possible
- Even with harsher uncertainties: enough room for discovery with full Run-II data
BACKUP SLIDES
REPRODUCED SEARCH: CONTROL REGIONS

(a) CRW

(b) CRZ

Large statistical errors in CRZ
Generally good agreement between data and MC

Consistent underestimation at higher $N_{jets}$ could be explained by higher $t\bar{t}t\bar{t}$ cross section

Figure: SSDL + ML
Generally good agreement between data and MC

Consistent underestimation at higher $N_{\text{jets}}$ could be explained by higher $\bar{t}t\bar{t}t\bar{t}$ cross section

Underestimation mainly at low $N_b$ points to underestimation of background instead of overestimation

Figure: SSDL + ML
**MODIFIED SEARCH: CONTROL REGIONS**

(a) CRZ: DY included

(b) CRZ: DY removed
## Input Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>Affected categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>All except nonprompt lep. and Charge MisID</td>
</tr>
<tr>
<td>Pileup</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>7</td>
<td></td>
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<tr>
<td>Lepton selection</td>
<td>5</td>
<td></td>
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<tr>
<td>Jet energy scale</td>
<td>15</td>
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<tr>
<td>Jet resolution</td>
<td>10</td>
<td></td>
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<tr>
<td>b-tagging</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Scale and PDF variations</td>
<td>15 (10 on signal)</td>
<td></td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>15</td>
<td>$t\bar{t}t\bar{t}$</td>
</tr>
</tbody>
</table>
# Input Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>Affected categories</th>
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<tbody>
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<td>Normalization</td>
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<tr>
<td></td>
<td>25</td>
<td>(t\bar{t}H)</td>
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<tr>
<td></td>
<td>20</td>
<td>Rare</td>
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<td></td>
<td>11</td>
<td>(t\bar{t}VV)</td>
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<td></td>
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<td>(X\gamma)</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>(t\bar{t}Z)</td>
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<td></td>
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<td>(t\bar{t}W)</td>
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<tr>
<td>Charge misidentification</td>
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<tr>
<td>Non-prompt leptons</td>
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<td>Nonprompt lep.</td>
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## IMPACTS

<table>
<thead>
<tr>
<th>Source</th>
<th>Input uncertainty (%)</th>
<th>Impact repr. search (%)</th>
<th>Impact mod. search (%)</th>
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</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>1.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Pileup</td>
<td>5</td>
<td>3.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>7</td>
<td>4.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>5</td>
<td>3.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>15</td>
<td>3.3</td>
<td>1.8</td>
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<tr>
<td>Jet resolution</td>
<td>10</td>
<td>7.0</td>
<td>3.8</td>
</tr>
<tr>
<td>b-tagging</td>
<td>15</td>
<td>10.7</td>
<td>5.9</td>
</tr>
<tr>
<td>Scale and PDF variations</td>
<td>15 (10 on signal)</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>15</td>
<td>28.3</td>
<td>19.5</td>
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</table>
## IMPACTS

<table>
<thead>
<tr>
<th>Source</th>
<th>Input uncertainty (%)</th>
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<tbody>
<tr>
<td>Normalization</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{t}tH$</td>
<td>25</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Rare</td>
<td>20</td>
<td>3.1</td>
<td>4.7</td>
</tr>
<tr>
<td>$\bar{t}tVV$</td>
<td>11</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>$X\gamma$</td>
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