Top-quark + heavy-flavour measurements at CMS

Results from the Run I data

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for the CMS collaboration
Outline

1. Top-quark production and decay

2. Inclusive measurements
   • dileptonic
   • semileptonic

3. Differential measurements
   • dileptonic
Top-quark production

The heaviest SM particle: \( m_t = 172.33 \pm 0.49 \text{ GeV} \) \textit{(CMS combination)}

Life time \((10^{-25}s)\) shorter than hadronisation time scale \((10^{-24}s)\)

bare quark properties accessible: mass, \(|V_{tb}|\), spin, charge,

Top-quark pairs \((tt)\): via QCD interactions \textbf{dominant at LHC}

\[
\begin{align*}
gg & \quad \text{fusion (85\%)} \\
qq & \quad \text{annihilation (15\%)}
\end{align*}
\]

Single top quarks: via EWK interactions \textbf{not in this talk}
Almost exclusively decays: $t \rightarrow bW$

$W$ decay defines the $tt$ final state

- **Full hadronic**
  - $W^+\rightarrow \bar{u}d$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow c\bar{s}$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow e^+$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow \mu^+$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow T^+$ (jets, $e\mu$, $\mu\mu$)

- **Semileptonic**
  - $W^+\rightarrow \bar{u}d$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow c\bar{s}$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow e^+$ (jets, $e\mu$, $\mu\mu$)
  - $W^+\rightarrow \mu^+$ (jets, $e\mu$, $\mu\mu$)

- **Dileptonic**
  - $W^+\rightarrow \bar{u}d$ ($e\mu$, $\mu\mu$)
  - $W^+\rightarrow c\bar{s}$ ($e\mu$, $\mu\mu$)
  - $W^+\rightarrow e^+$ ($e\mu$, $\mu\mu$)
  - $W^+\rightarrow \mu^+$ ($e\mu$, $\mu\mu$)

$W^{-}\rightarrow \bar{u}d$ (jets, $e\mu$, $\mu\mu$)

**Bkg:**
- Full hadronic: $QCD$ multijet, large $\text{BR} \sim 56\%$
- Semileptonic: $W+\text{jets}$, small $\text{BR} \sim 37\%$
- Dileptonic: $DY+\text{jets}$, $\text{BR} \sim 7\%$

**Full hadronic**
- $W^+\rightarrow \bar{u}d$
- Jets, $e\mu$, $\mu\mu$

**Semileptonic**
- $W^+\rightarrow \bar{u}d$
- $e\mu$, $\mu\mu$

**Dileptonic**
- $W^+\rightarrow \bar{u}d$
- $e\mu$, $\mu\mu$

**Top-quark cross-section measurements with CMS**

Nazar Bartosik
Higgs boson

Gives mass to SM particles via coupling to the $H$ boson
- fermion coupling proportional to mass: $Y_f \propto m_f$ < to be tested
- couples most to the top quark

Dominant decay channel: $H \rightarrow bb$
- typical final state in QCD processes
- $\sigma(pp \rightarrow H \rightarrow bb) \ll \sigma(pp \rightarrow bb)$
- very challenging to measure

$H \rightarrow bb$ associated by top quarks ($ttH$)
- smaller $\sigma$ of background processes
- vital test for consistency with SM:
  $$\sigma \propto Y_t^2 Y_b^2$$
- the only direct way to measure $t-H$ coupling
tt+bb INCLUSIVE CROSS SECTIONS

- half of $tt$ pairs accompanied by jets ($p_T > 30$ GeV)
- main background to $ttH(H \rightarrow bb)$ production
  - important for $ttH$ searches
- background to new physics
**ttbb as background to ttH(H→bb)**

Distinctive and complex final state (dileptonic channel)

Large irreducible background

$$\sigma(ttbb) \approx 15 \times \sigma(ttH)$$

b-jet $p_T > 20$ GeV

Must be known precisely

$\#$ events
Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: analysis

Absolute $\sigma_{ttjj}$, $\sigma_{ttbb}$, $\sigma_{ttbb}/\sigma_{ttjj}$: additional (b) jet $p_T > 40$ GeV, $|\eta| < 2.5$

Dileptonic final states: $ee$, $e\mu$, $\mu\mu$ including $\tau \rightarrow e/\mu$

Stable top quarks. Parton-level additional jets

- Jet clustering on partons: $e$, $\mu$, $\tau^{\text{had}}$, $g$, $u$, $d$, $c$, $s$, $b$
- Additional b-jets: $\Delta R(b$-quark, jet) < 0.5

Simultaneous template fit to extract $ttbb/ttjj$ cross-section ratio

- ordered by b-tagging discriminant value
- 2 leading assumed from top-quark decay
  $\leftarrow$ corrected by fit results
Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: results

Additional (b) jet $p_T > 40$ GeV, $|\eta| < 2.5$ (full $tt$ phase space)

CMS

$\sigma_{ttbb}/\sigma_{ttjj} = 0.022 \pm 0.006^{\text{total}}$

$\sigma_{ttbb} = 0.36 \pm 0.13^{\text{total}}$ pb

NLO

$\sigma_{ttbb}/\sigma_{ttjj} = 0.011 \pm 0.003^{\text{total}}$

$\sigma_{ttbb} = 0.23 \pm 0.05^{\text{total}}$ pb

$R = \frac{\sigma_{tt}}{\sigma_{ttjj}} - \sqrt{s} \ [\text{TeV}]$

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NLO

HELAC-NLO

$\mu_{\text{top}} = 173.5$ GeV

$|p_T_j| > 40$ GeV

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CMS

CMS $8$ TeV

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$\sigma_{ttbb}$ vs $\sigma_{ttbb}/\sigma_{ttjj}$

- b tagging
- JES & JER
- $ttbb/ttjj$
- ttcc fraction
- lepton ID
- luminosity
- pileup
- bkg. modelling
- ME generator
- PDF
- $\mu_F$, $\mu_R$ scale
- ME$\leftrightarrow$PS scale
- Total syst.

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EXPERIMENTAL

THEORETICAL

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$\rightarrow$ compatible within $1\sigma$

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22% 28%
Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: analysis

Absolute $\sigma_{ttjj}$, $\sigma_{ttbb}$, $\sigma_{ttbb}/\sigma_{ttjj}$: additional (b) jet $p_T > 40$ GeV, $|\eta| < 2.5$

Semileptonic final states: $\ell/\mu$ including $\tau\rightarrow e/\mu$

Jets clustered from stable particles excluding $\nu$

Ghost $b$-hadrons and $b$-quarks clustered for flavour definition:

- **hardB**: flavour of leading quark
- **hadronB**: presence of $b$ hadron

Simultaneous template fit to extract $ttbb/ttjj$ cross-sections ratio

- Kinematic reconstruction + MVA classifier ($N_j \geq 6$)
- 14 templates in total: $N_j, N_{b^{\text{add}}} \times 2$ ($e, \mu$)

← corrected by fit results
### Inclusive $\sigma_{ttbb}/\sigma_{ttjj}$: results

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma_{ttbb}/\sigma_{ttjj}$</th>
<th>$\sigma_{ttbb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronB</td>
<td>$0.015 \pm 0.005^{\text{total}}$</td>
<td>$0.35 \pm 0.13^{\text{total}} \text{ pb}$</td>
</tr>
<tr>
<td>hardB</td>
<td>$0.012 \pm 0.004^{\text{total}}$</td>
<td>$0.27 \pm 0.11^{\text{total}} \text{ pb}$</td>
</tr>
<tr>
<td>NLO</td>
<td>$0.011 \pm 0.003^{\text{total}}$</td>
<td>$0.23 \pm 0.05^{\text{total}} \text{ pb}$</td>
</tr>
</tbody>
</table>

**Effect of parton shower:** hardB $\rightarrow$ hadronB

hadronB results consistent with dileptonic channel:

<table>
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<th>$\sigma_{ttbb}/\sigma_{ttjj}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>dilep.</td>
<td>$0.022 \pm 0.006^{\text{total}}$</td>
<td>$0.36 \pm 0.13^{\text{total}} \text{ pb}$</td>
</tr>
</tbody>
</table>

Dominant systematic uncertainties:

- b-tagging, JES/JER
- $top$-quark $p_T$ reweighting, PDF, MC generators
**tt+bb** DIFFERENTIAL CROSS SECTIONS

- stringent test of QCD
- better sensitivity to $ttH(H \rightarrow bb)$
Differential \( \sigma_{tt} + \text{jets} \): results

**Absolute \( \sigma_{tt} \) vs** \( N_{\text{jets}}, \ H_T, \ m, \ dR_{jj}, \ p_T, \ |\eta|_{jj1, j2} \)**

Kinematic reconstruction of the \( tt \) system: dileptonic channel

**Predictions normalised to data:** shapes reasonably described

**Absolute \( \sigma_{tt} \) underestimated:** as seen from inclusive measurements

**Dominant uncertainties:** JES, \( \mu_R, \mu_F \), hadronisation model

- model dependence of the measurement needs to be reduced

\( \text{arXiv:1510.03072} \)
**Absolute $\sigma_{tt}$ vs $m$, $dR$, $p_T$, $|\eta|$**

B-jet assignment to the $tt$ system by a BDT: **dileptonic channel**

Non-trivial signal definition: many $b$ jets in the final state

Clustering stable particles to jets: excluding $\nu$, and $e/\mu$ from $W$ decay

Overlapping $b$ jets identified: $\geq 1$ $b$ hadron in jet

Jet origin identified by analysing particle chain

- jet $\rightarrow b$ hadron $\rightarrow b$ quark $\rightarrow g/t/H/Z$

**ttjj components constrained by template fit:**

- **ttbb**
- **ttb**
- **tt2b**
- **tt other**

**ttjj** components not in acceptance
Identification of additional $b$ jets at reconstruction level:

All $b$-tagged jets - $2 \cdot b^{t\rightarrow b}$ = additional $b$ jets: ordered by $\downarrow p_T$

$b^{t\rightarrow b}$ identified using MVA: based on TMVA BDT

- trained on $ttH(H\rightarrow bb)$ simulations
- avoiding bias towards $ttH$

![Graphs showing differential $tt + bb$ analysis](image-url)
Differential $tt + bb$: analysis
dileptonic

\[
d \frac{d \sigma}{d X_i} = \frac{\sum_j A_{ij}^{-1} \left[ N_{j}^{\text{data}} - N_{j}^{\text{bkg}} \right]}{\varepsilon \cdot \mathcal{L} \cdot \Delta x_i}
\]

- subleading: $p_T, |\eta|$
- 2 leading: $\Delta R_{b\bar{b}}, m_{b\bar{b}}$

# data events
# background events
correction for migrations

Regularised SVD unfolding
- binning optimised to have $\geq 40\%$ events reconstructed in the correct bin
Differential $t\bar{t} + bb$: results

**Leading additional $b$ jet:** $p_T > 20$ GeV, $|\eta| < 2.4$

**MC predictions normalised to Data**

**Limited by statistical uncertainty**

**Well described by the considered MC predictions**
Subleading additional $b$ jet: $p_T > 20$ GeV, $|\eta| < 2.4$

**MC predictions normalised to Data**

Even larger statistical uncertainty

Can’t discriminate between different predictions yet

arXiv:1510.03072
Differential $t\bar{t} + b\bar{b}$: results

Pair of additional $b$ jets: $p_T > 20$ GeV, $|\eta| < 2.4$

MC predictions normalised to Data

$m_{bb}$ well described. Not much difference between predictions

$\Delta R_{bb}$ affected by migrations due to wrong $b$-jet assignments
Differential $tt + bb$: results

Pair of additional $b$ jets: $p_T > 20$ GeV, $|\eta| < 2.4$

**Compared to a full NLO calculation:** identical process definitions

**Shapes and normalisations compared**

**Normalisation uncertainty on the NLO prediction:** $\sim 30\%$
Differential $tt + bb$: results

dileptonic

Precision limited by systematic (statistical) uncertainty in $tt+jj$ ($tt+bb$)

Typical uncertainties: median of bins $\rightarrow$ average over variables

- B tagging
- JES
- Bkg. estimate
- JER
- ME$\leftrightarrow$PS scale
- Underlying event
- Hadronisation
- $\mu_F, \mu_R$ scale

Systematic
- 4%
- 13%
- 21%

Statistical
- 44%

Total
- 48%

Significant improvement expected with more data from $\sqrt{s}=13$ TeV
Summary

Top-quark production with heavy-flavour jets is an important process to study, especially in view of $ttH$ searches.

Inclusive measurements performed in dileptonic and semileptonic decay channels:

- consistent results, compatible with NLO predictions
- cross-section increase due to Parton Shower evaluated
- modelling uncertainties comparable to experimental

Differential measurement performed in dileptonic channel:

- important side-band region for $ttH(H \rightarrow bb)$ searches
- comparison to NLO $ttbb$ calculation shows good agreement
- limited by available statistics from Run I data

Many improvements expected in Run II: statistics, b-tag, theory, …
Thank you for attention