Measurements of the top quark pair production cross section in pp collisions

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Outline

- Top quark pair production and decay
- Inclusive cross sections
  - 7 TeV (dilepton, lepton+jets, fully hadronic)
  - 8 TeV (dilepton, lepton+jets, $\tau$+jets)
  - 8 TeV Combination of ATLAS and CMS
  - $\alpha_s$ extraction from $\sigma(t\bar{t})$
- Top quark pair + jets ($b\bar{b}$, $t\bar{t}$)
Top quarks: key to QCD, electroweak (EWK) and new physics

- The most massive known particle
- Decays before hadronisation: study properties of bare quark
- Essential to study Higgs properties
  - Sensitivity to Higgs through loop corrections
  - Measure top Yukawa coupling;
    Yukawa coupling to Higgs $\sim 1$

Measuring $\sigma_{t\bar{t}}$ is the first fundamental step for understanding top physics

- Huge relevance for SM and BSM:
  - In the frame of Standard Model, test QCD predictions at NNLO
  - Sensitive to New Physics Beyond the Standard Model
  - Test the presence of new production mechanisms
  - Help constraining modeling PDFs (essential ingredient in QCD calculation)
  - Determination of $m_t^{pole}$ or $\alpha_s$

- Important background for many Higgs and BSM searches at LHC
Top quark production in pp collisions at the LHC

$t\bar{t}$ production mainly by gluon fusion ($\sim80\%$ at 7-8 TeV)

### LHC Run I: Top Quark Factory
- peak inst. luminosity: $8\times10^{33}\text{cm}^{-2}\text{s}^{-1}$
- 7000 top quark pairs per hour (8 TeV)
- 20 fb$^{-1}$ (8 TeV) + 5 fb$^{-1}$ (7 TeV) recorded: $\sim6\text{M}$ top quark pairs produced at CMS

### Full NNLO+NNLL calculation\(^1\)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\sigma_{t\bar{t}}(\text{NNLO+NNLL})$(^2) [pb]</th>
<th>Scale uncert. [pb]</th>
<th>PDF+$\alpha_s$(^3) uncert. [pb]</th>
<th>Mass uncert. [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>177.3</td>
<td>+4.6 -6.0</td>
<td>+9.0 -9.0</td>
<td>+5.4 -5.3</td>
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<td>+6.4 -8.6</td>
<td>+11.7 -11.7</td>
<td>+7.6 -7.3</td>
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<td>13</td>
<td>831.8</td>
<td>+19.8 -29.2</td>
<td>+35.1 -35.1</td>
<td>+23.2 -22.5</td>
</tr>
</tbody>
</table>

\(^1\) [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO)

\(^2\) calculated using Top++(v2.0)

\(^3\) calculated following PDF4LHC prescription
Top quark decay

- Decays into W-boson and b-quark $\sim 100\%$
- Final state topology depends on W decay: "dileptons", "lepton+jets", "alljets"

**Top Pair Branching Fractions**

- "alljets" 46%
- $\tau$+jets 15%
- $\mu$+jets 15%
- $e$+jets 15%
- $\tau$+$\tau$ 1%
- $\tau$+$\mu$ 1%
- $\tau$+e 2%
- $\mu$+$\mu$ 2%
- $\mu$+e 2%
- $e$+e 0%

**Diagrams**

- Low bg: Z+jets
  - "dileptons"
- Moderate bg: W+jets
  - "lepton+jets"
- Huge bg: QCD
  - "alljets"
Typical event selection for $t\bar{t}$ analyses

Dilepton decay mode

• $\geq 2$ opposite sign isolated leptons ($p_T > 20$ GeV, $|\eta| < 2.4$)
• $\geq 2$ jets (anti-$k_T$, $R < 0.5$, $p_T > 30$ GeV, $|\eta| < 2.4$)
• $\geq 1$ b-tagged jet
• For same flavour channels QCD & Z veto ($\text{MET} > 40$ GeV, exclude $m_Z \pm 15$ GeV)

Lepton+jets decay mode

• $\geq 1$ isolated lepton (electron or muon) ($p_T > 26$, 30 GeV, $|\eta| < 2.1$, 2.5)
• $\geq 4$ jets (anti-$k_T$, $R < 0.5$, $p_T > 45$, 45, 35 and 35 GeV, $|\eta| < 2.5$)
• $\geq 1$ b-tagged jets
**tt Inclusive Cross Section at 8 TeV: Dilepton**

**JHEP 02 (2014) 024**

- Small background and clean final state
- Cut and count analysis
- Baseline MC: MadGraph+Pythia

Drell-Yan and non-W/Z background estimated from data

Dominant syst.: JES and background

\[ \sigma_{tt} = 239 \pm 2 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 6 \text{ (lum.)} \text{ pb} \rightarrow 5\% \text{ total uncertainty} \]
Inclusive Cross Section at 8 TeV: $\tau +$ leptons

**Important channel for charged Higgs boson searches**

**Selection:**
- One isolated lepton ($e$, $\mu$)
- $\geq 3$ jets (one b-tagged)
- $\tau$ decaying into hadrons
- MET

**Cut and Count method**
- Determine $\tau$ fakes from multijet
- $W+$jets from data

**Systematics dominated by fake $\tau$ and b-tag uncertainties**

$$\sigma_{t\bar{t}} = 257 \pm 3 \text{ (stat.)} \pm 24 \text{ (syst.)} \pm 7 \text{ (lum.)} \text{ pb \rightarrow 9.8\% total uncertainty}$$
Two approaches: Binned likelihood fit of signal and background to:

- Lepton and b-tagged jet invariant mass ($M_{lb}$) in data
- Mass of the 3-jet combination with the event’s highest transverse momentum ($M_3$)

QCD background shape from data

\[
\sigma_{t\bar{t}} = 228.4 \pm 9.0 \text{ (stat.)} \pm 29.0 \text{ (syst.)} \pm 10.0 \text{ (lum.)} \text{ pb} \rightarrow +14.0\% \text{ total uncertainty}
\]
Good agreement between channels, experiments and theory (systematics-limited precision)
Good agreement between data and prediction, as well as between experiments
- LHC combination at 8TeV for $e\mu$ channel: 3.5% (most precise result)
  (CMS-PAS TOP-14-016 / ATLAS-CONF-2014-054)
\( \alpha_s(M_Z) \) from Top Pair Cross Section

PLB 728 (2014) 496

- Use high precision measurements of \( \sigma(t\bar{t}) \) to:
  - determine \( \alpha_s \) for a fixed \( m_t^{pole} \) for different PDF sets
  - or determine \( m_t^{pole} \) for a fixed \( \alpha_s \)

- Most probable result from joint likelihood between theory and experiment

First \( \alpha_s \) determination from \( \sigma(t\bar{t}) \) and first result at full NNLO QCD obtained at a hadron collider →

NNPDF2.3: \( \alpha_s(m_Z) = 0.1151^{+0.0028}_{-0.0027} \) (NNPDF2.3)
Cross section ratio \[ \frac{\sigma(t\bar{t}bb)}{\sigma(t\bar{t}jj)} : e/\mu + \text{jets} \]

CMS TOP-13-016

- Irreducible non resonant background in the search for \( t\bar{t}H(b\bar{b}) \)
- Test validity of NLO QCD calculations
- Measurement of ratio \( \frac{\sigma(t\bar{t}bb)}{\sigma(t\bar{t}jj)} \): large uncertainties cancellation
  - **Selection:** one isolated lepton, \( \geq 4 \) jets, \( \geq 2 \) b-tagged jets
  - Signal extraction by fit to the measured b-tagging discriminator
  - Dominant systematic: mistag efficiency

\[ \frac{\sigma(t\bar{t}bb)}{\sigma(t\bar{t}jj)} \]

**Jet** \( p_T > 40 \text{ GeV} \)

\[ \frac{\sigma(t\bar{t}bb)}{\sigma(t\bar{t}jj)} |_{m_t = 173.5 \text{ GeV}, CT10} = 0.0109 \pm 0.0043^{+0.0046}_{-0.0026} \]

[arXiv:1403.2046]

\[ \frac{\sigma(t\bar{t}bb)}{\sigma(t\bar{t}jj)} \]

- **hardB**
  \[ = 0.0117 \pm 0.0040\text{(stat.)} \pm 0.0003\text{(syst.)} \]

- **hadronB**
  \[ = 0.0151 \pm 0.0049\text{(stat.)} \pm 0.0004\text{(syst.)} \]

*Jet flavour at gen. level defined by the flavor of the leading quark (hardB) or by the presence of a B hadron in the list of jet constituents (hadronB)
Cross section ratio $\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$: Dilepton

- Similar analysis strategy with CMS TOP-13-016
  - Selection: dilepton events with $\geq 4$ jets, $\geq 2$ b-tagged jets

- Combination of three dilepton categories $(ee, e\mu, \mu\mu)$

Jet $p_T > 40$ GeV

$\frac{\sigma(t\bar{t}b\bar{b})^{NLO}}{\sigma(t\bar{t}jj)} (m_t = 173.5 \text{ GeV}, CT10) = 0.0109 \pm 0.0043^{+0.0026}_{-0.0026}$

[arXiv:1403.2046]

$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 0.022 \pm 0.004 \text{ (stat.)} \pm 0.005 \text{ (syst.)}$
• $\sigma_{tttt}^{SM} \approx 1$ fb at 8 TeV (LO) $\rightarrow$ very low cross section!
  
  ◇ $\sim$ 9-15 times larger cross section in Run II
• Selection: 1 lepton ($e$, $\mu$), $\geq 6$ jets, $\geq 2$ b-tagged jets, $H_T > 400$ GeV, $E_T^{miss} \geq 30$ GeV
• Main background: $t\bar{t}$+jets (5 orders of magnitude larger cross section)
• Event classification scheme based on a BDT algorithm
  
  ◇ Top content, event activity and b-jet content
• Limit setting: simultaneous fit to BDT output distributions

Limits on $\sigma_{tttt}^{SM}$ at 95% C.L.:
- expected: $32 \pm 17$ fb
- observed: 32 fb
Summary and Outlook

- **LHC: Run I** \( \sim 6 \text{M top quark pairs in CMS} \)
- Many measurements available for \( \sigma_{tt} \) in different channels with increasing precision, competing with NNLO theory
- Precise measurements of the \( \sigma_{tt} \) allows to perform measurements of other interesting parameters such as \( \alpha_s \)
- **All results so far in agreement with SM predictions**
- Measurements of \( t\bar{t}b\bar{b} \) and \( t\bar{t}t\bar{t} \) (dominated by statistics)
- More 8 TeV results close to be public

- **Top community has already started looking at LHC Run II data**
  - More top quarks: \( \sigma_{tt} \) increases by a factor \( \sim 3 \)!
  - Reach higher \( m_{tt}, p_T \) ranges
  - Measurement of the ratio of \( \sigma_{tt} \) at different \( \sqrt{s} \): expected to contribute to a better knowledge of NNLO PDFs

- All CMS top public results can be found in: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
First Jet and b-jet multiplicities in the $e\mu$ channel at 13 TeV

Stay tuned!

[CMS DP-2015/019]