$t\bar{t}(+x)$ pair production at the LHC

Markus Seidel

CERN

on behalf of the ATLAS and CMS collaborations

March 20, 2016
Introduction

Preconditions

- Very successful LHC operation: 10M top quark pairs produced at each ATLAS and CMS
- Detectors well understood and calibrated
  - Trigger efficiencies
  - Energy measurement of jets, leptons, photons
  - Identification of jets containing B hadrons

Outline: new/updated measurements since TOP2015

- Inclusive \( t\bar{t} \) cross sections
- Global properties of \( t\bar{t} \) events
- Top quark observables
- \( t\bar{t}+V \) production
Inclusive $t\bar{t}$ cross sections

Rediscovery → precision

Run 1 measurements

**CMS**  Inclusive $t\bar{t}$ cross section at 7 and 8 TeV (dilepton)

**ATLAS**  Inclusive $t\bar{t}$ cross section at 7 and 8 TeV (dilepton)

**CMS**  Inclusive $t\bar{t}$ cross section at 7 and 8 TeV (lepton+jets)

**ATLAS**  Inclusive $t\bar{t}$ cross section at 7 and 8 TeV (lepton+jets)

Run 2 measurements

**ATLAS**  Inclusive $t\bar{t}$ cross section at 13 TeV (dilepton)

**CMS**  Inclusive $t\bar{t}$ cross section at 13 TeV (dilepton)
Select $e\mu$ events with $p_T > 20$ GeV, $|\eta| < 2.4$, no jet requirement

Binned likelihood fit in 12 categories, systematics as nuisance parameters

$$\sigma^{7 \text{ TeV}}_{t\bar{t}} = 173.6 \pm 2.1 \text{ (stat)}^{+4.5}_{-4.0} \text{ (syst)} \pm 3.8 \text{ (lumi)} \text{ pb} \left(\pm 3.6\%\right)$$

$$\sigma^{8 \text{ TeV}}_{t\bar{t}} = 244.9 \pm 1.4 \text{ (stat)}^{+6.3}_{-5.5} \text{ (syst)} \pm 6.4 \text{ (lumi)} \text{ pb} \left(\pm 3.7\%\right)$$

Largest uncertainties from trigger/lepton eff (1.2% $\oplus$ 1.5%), DY (1.3%), lumi (2.6%)

Determine $m_{t^\text{pole}} = 173.8^{+1.7}_{-1.8}$ GeV and set constraints on top squark pair production

**Result:** $\sigma^{8 \text{ TeV}}_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2$ pb (±4.3%)
Lepton+jets selection
(1 lepton, MET, 4 jets, at least one b tag)
Reconstruct top quarks, fit $M_{\ell b}$ distribution
Jet scale factor from $W \to jj$ candidates
b-tag efficiency $\epsilon_b$ from sample w/o b-tag requirement
(b-enriched $M_{\ell b} < 140$ GeV, b-depleted 140 – 240 GeV)

\[
\sigma_{t\bar{t}}^{7\,\text{TeV}} = 161.7 \pm 6.0 \, (\text{stat}) \pm 12.0 \, (\text{syst}) \pm 3.6 \, (\text{lumi}) \, \text{pb} \, (\pm 8.6\%)
\]
\[
\sigma_{t\bar{t}}^{8\,\text{TeV}} = 228.9 \pm 3.8 \, (\text{stat}) \pm 13.7 \, (\text{syst}) \pm 6.0 \, (\text{lumi}) \, \text{pb} \, (\pm 6.7\%)
\]

Largest uncertainties from signal modeling (4.4%), JES (2.2%), lumi (2.6%)
Using full 13 TeV dataset!

Select events with $e\mu$ pair ($p_T > 25$ GeV, $|\eta| < 2.47/2.4$)

Misidentified lepton background estimated from same-sign events with at least 1 b tag

Fit $\sigma_{t\bar{t}}$ and $\epsilon_b$ using number of b-tagged jets ($p_T > 25$ GeV, $|\eta| < 2.5$)

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N^{bkg}_1$$

$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N^{bkg}_2$$

$$\rightarrow \sigma_{t\bar{t}}^{13 \, \text{TeV}} = 803 \pm 7 \, \text{(stat)} \pm 27 \, \text{(syst)}$$

$$\pm 45 \, \text{(lumi)} \pm 12 \, \text{(beam)} \, \text{pb} \, (\pm 6.7\%)$$

Largest uncertainties:
hadronization (2.8%) and luminosity (5.5%)
Inclusive $t\bar{t}$ cross section at 13 TeV

- Published result with $42 \, \text{pb}^{-1} \rightarrow \text{full lumi}: 2.2 \, \text{fb}^{-1}$
- Select events with $e\mu$ pair ($p_T > 20 \, \text{GeV}, |\eta| < 2.4$), 2 jets ($p_T > 30 \, \text{GeV}, |\eta| < 2.4$) $\rightarrow 1$ $b$-tagged jet
- Cut-and-count: $\sigma_{t\bar{t}} = (N - N_B) / (A \times \epsilon \times L)$
  - DY background from same-flavor events
  - Non-prompt lepton background from same-sign events

published:

$\sigma_{t\bar{t}}^{13 \, \text{TeV}} = 746 \pm 58 \, \text{(stat)} \pm 53 \, \text{(syst)} \pm 36 \, \text{(lumi)} \, \text{pb} \, (\pm 11.6\%)$

$\rightarrow \text{full lumi update (preliminary)}$:

$\sigma_{t\bar{t}}^{13 \, \text{TeV}} = 793 \pm 8 \, \text{(stat)} \pm 38 \, \text{(syst)} \pm 21 \, \text{(lumi)} \, \text{pb} \, (\pm 5.6\%)$

- Main improvements: statistics, uncertainties on trigger/lepton efficiencies and luminosity (4.8% $\rightarrow$ 2.7%)
NNLO+NNLL: \( \sim 5.5\% \) precision

Experiments (\( e\mu \) channel): 4\% precision at 7 and 8 TeV, 7\% precision at 13 TeV (13 TeV dominated by uncertainty on luminosity)
Differential cross sections

Global properties of t\bar{t} events

Run1 measurements

**CMS**  \( \text{t}\bar{t} \) production with additional jet activity at 8 TeV

**ATLAS** \( \text{t}\bar{t} \) production with one or two additional b jets at 8 TeV

Run2 measurements

**ATLAS** Jets produced in \( \text{t}\bar{t} \) events at 13 TeV

**CMS** \( \text{t}\bar{t} \) cross section as a function of event variables at 13 TeV
Measure (b) jet observables: multiplicity, $p_T$, $\eta$, HT, $\Delta R_{jj}$, $m_{jj}$, and gap fractions

Additional jets must not stem from top, kinematic $t\bar{t}$ reconstruction on reco level

Disfavors extreme $g \rightarrow b\bar{b}$ scenario
Jets produced in \( t\bar{t} \) events at 13 TeV

- Select dilepton events with 2 b-tagged jets, using full 13 TeV dataset
- Measure normalized differential cross section for jet multiplicity (particle level)
- Jets other than the two leading b jets are considered additional

Different jet thresholds of 25, 40, 60, 80 GeV
- Comparison of different generator setups and radiation tunes
Select events with exactly one lepton and at least 4 jets (2 b-tagged)

Measurement of $E_T^{\text{miss}}$, $H_T$, $S_T$, $p_T^W$, jet multiplicity ($p_T > 25$ GeV), lepton $p_T/|\eta|$

Unfolded to particle level in fiducial phase space but vetoing $W \rightarrow \tau \nu_T$

Less high-jet multiplicity events in data than predicted by Run2 MC setups ($\alpha_s^{\text{ISR}}$?)
Differential cross sections

Top quark observables

Run1 measurements

**ATLAS** Differential $t\bar{t}$ cross section at 8 TeV (lepton+jets) 
**CMS** Differential $t\bar{t}$ cross section at 8 TeV (lepton+jets and dilepton) 
**ATLAS** Differential $\times s$ of boosted top quarks at 8 TeV

**CMS** Differential $t\bar{t}$ cross section for high-$p_T$ top quarks at 8 TeV

Validation of Run2 simulation with Run1 data

**ATLAS** Simulation of $t\bar{t}$ production for the ATLAS experiment

**CMS** Comparisons of differential $t\bar{t}$ theory predictions to 8 TeV data

Run2 measurements

**CMS** Differential $t\bar{t}$ cross section at 13 TeV (lepton+jets and dilepton)
Select events with exactly one lepton and at least 4 jets (2 b-tagged)

Measure top quark observables in both fiducial (particle) and full (parton) phase space

MC simulations predict harder top $p_T$ than data, NNLO agrees well

Rapidity of top and $t\bar{t}$ system sensitive to PDFs

CMS Differential $t\bar{t}$ cross section at 8 TeV (parton level, lepton+jets and dilepton)
Select events with 1 lepton, 1 small-\(R\) jet and 1 trimmed large-\(R\) jet (1 b-tagged)

- Large-\(R\) jet is hadronic top candidate (\(p_T > 300, m > 100, \sqrt{d_{12}} > 40\) GeV)
- Large-\(R\) \(p_T\) calibrated in \(\gamma+\text{jet}\) events, full MC difference of \(\gamma+\text{jet}\) and \(t\bar{t}\) as uncertainty
Select events with 1 lepton, 1 small-$R$ jet and 1 trimmed large-$R$ jet (1 b-tagged)

- Large-$R$ jet is hadronic top candidate ($p_T > 300$, $m > 100$, $\sqrt{d_{12}} > 40$ GeV)
- Large-$R$ $p_T$ calibrated in $\gamma$+jet events, full MC difference of $\gamma$+jet and $t\bar{t}$ as uncertainty

Data level precision limited by data statistics, large-$R$ JES
- Extrapolation to parton level limited by generator uncertainties

Differential $t\bar{t}$ cross section for high-$p_T$ top quarks at 8 TeV
Validation of Run2 simulation with Run1 data

ATLAS  Simulation of \( \bar{t}t \) production for the ATLAS experiment

- 7 TeV jet multiplicity, jet \( p_T \), \( p_T \) of particle-level (pseudo) top and \( \bar{t}t \) system

CMS  Comparisons of differential \( \bar{t}t \) theory predictions to 8 TeV data

- 8 TeV parton level results corrected to particle level for generic MC comparison

\[ \begin{align*}
\text{ATLAS Data, } \sqrt{s} &= 7 \text{ TeV} \\
\text{CMS Data with stat. } &\oplus \text{ syst.}
\end{align*} \]

\( 19.7 \text{ fb}^{-1} \) (8 TeV)
Differential $t\bar{t}$ cross section at 13 TeV

- **lepton+jets (TOP-16-008)**
  - Analytic solution for neutrino momentum, find best top candidates by mass constraints
  - Measure top and $t\bar{t}$ observables at parton and particle level

- **dilepton (TOP-16-011)**
  - Kinematic reconstruction algorithm, measure top and $t\bar{t}$ observables at parton level

- In addition: jet multiplicity measured in both channels
**tt+V production**

**Top and friends**

**Run1 measurements**

- **CMS** $ttW$ and $ttZ$ production cross sections at 8 TeV
- **ATLAS** $ttW$ and $ttZ$ production cross sections at 8 TeV

**Run2 measurements**

- **ATLAS** $ttW$ and $ttZ$ production cross sections at 13 TeV
- **CMS** $tt$ production in association with a $Z$ boson at 13 TeV

**Run1 $tt+$photon (not shown, results in agreement with SM expectations)**

- **ATLAS** $tt\gamma$ production cross section at 7 TeV
- **CMS** $tt\gamma$ production cross section at 8 TeV
- Select events with jets and multiple leptons, fit 16/20 channels in total
- Non-prompt lepton background estimated from $t\bar{t}$ and $Z$+jet control regions

<table>
<thead>
<tr>
<th>8 TeV NLO</th>
<th>$\sigma (t\bar{t}W)$</th>
<th>$\mu$</th>
<th>$[\sigma]$</th>
<th>$\sigma (t\bar{t}Z)$</th>
<th>$\mu$</th>
<th>$[\sigma]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JHEP 1211(2012) 056</td>
<td>$203^{+20}_{-22}$ fb</td>
<td>5.0</td>
<td>5.0</td>
<td>$206^{+19}_{-24}$ fb</td>
<td>4.2</td>
<td>4.8</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$369^{+86}_{-79}$ (stat) ± 44 fb</td>
<td>$1.88^{+0.66}_{-0.56}$</td>
<td>$176^{+52}_{-48}$ (stat) ± 24 fb</td>
<td>$242^{+65}_{-55}$ fb</td>
<td>$1.18^{+0.35}_{-0.29}$</td>
<td>6.4</td>
</tr>
<tr>
<td>CMS</td>
<td>$382^{+117}_{-102}$ fb</td>
<td>4.8</td>
<td>4.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- CMS Constraints on axial/vector components of $tZ$ coupling and dimension-six operators
**ATLAS**

**ttW and ttZ production at 13 TeV**

- **ttW**: select events with (b) jets and 2 or 3 leptons (one same-sign pair)
- **ttZ**: select events with (b) jets and 3 or 4 leptons (one \(Z \rightarrow \ell^+\ell^-\) candidate)
- Diboson backgrounds from control regions:
  - **WZ**: 3 leptons, 1 \(Z\) candidate, 3 untagged jets / **ZZ**: 4\(\ell\), 2 \(Z\) candidates, low MET

---

### Table of Results

<table>
<thead>
<tr>
<th>Energy</th>
<th>(\sigma (ttW))</th>
<th>(\sigma (ttZ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 TeV</td>
<td>(0.57 \pm 0.06) fb</td>
<td>(0.76 \pm 0.08) pb</td>
</tr>
<tr>
<td>aMCatNLO</td>
<td>(1.38 \pm 0.70) (stat) (\pm 0.33) (syst) pb</td>
<td>(0.92 \pm 0.30) (stat) (\pm 0.11) (syst) pb</td>
</tr>
</tbody>
</table>

---

Markus Seidel (CERN)  
**tt(\(+x\)) pair production at the LHC**  
March 20, 2016  
20 / 22
CMS t\(\bar{t}\) production in association with a Z boson at 13 TeV

- Select events with 3 or 4 leptons and at least 2 jets from full 13 TeV dataset
- Data-driven estimates for non-prompt leptons, control regions for WZ and ZZ
- Binned likelihood fit to all categories, including nuisance parameters

<table>
<thead>
<tr>
<th>13 TeV</th>
<th>(\sigma(\text{t}\bar{t}Z))</th>
<th>(\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aMCatNLO</td>
<td>0.76 ± 0.08 pb</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>0.92 ± 0.30 (stat) ± 0.11 (syst) pb</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>1.065^{+0.352}<em>{-0.313} (stat)^{+0.168}</em>{-0.142} (syst) pb</td>
<td>1.27^{+0.42}<em>{-0.37} (stat)^{+0.20}</em>{-0.17} (syst) 3.6\sigma</td>
</tr>
</tbody>
</table>
Summary

Inclusive cross sections
- $t\bar{t}$ cross section measured at 7, 8, 13 TeV
- Experimental precision matches the theory prediction, excellent agreement
- Production of additional $W/Z$ in agreement with SM (but $t\bar{t}W$ keeps looking interesting)

Differential cross sections
- Measured at 7, 8, 13 TeV, as a function of final-state objects and reconstructed tops
- Particle level results and Rivet implementations for generator validation/tuning with $t\bar{t}$ data
- Parton level results for comparison to theory calculations