tt(±X) production in pp collisions at the LHC

Lana Beck
on behalf of CMS and ATLAS

29th March 2017 – Rencontres de Moriond QCD
Introduction

Productive Run1 and successful Run2 so far
Most results so far have not used all the available data
→ Much more to analyse!

Detailed understanding of $t\bar{t}$ xsec required in searches for new physics.
In BSM searches $t\bar{t}$ production is often the dominant background.

Outline of talk

- Inclusive $t\bar{t}$
  - $l + \text{jets}$
  - Dilepton
  - $\tau + \text{jets}$
- Differential $t\bar{t}$
  - $l + \text{jets}$
  - dilepton
  - all-hadronic
  - Jet activity
- $t\bar{t} + X$
  - $t\bar{t}W \& t\bar{t}Z$
  - $t\bar{t}b\bar{b}$
  - $t\bar{t}t\bar{t}$
Inclusive $\bar{t}t$

Lepton + jets, dilepton and $\tau$ + jets

$\sqrt{s}$ [TeV]

Inclusive $\bar{t}t$ cross section [pb]
Run 2 – Inclusive $t\bar{t}$

Dilepton

- Opposite-sign $e\mu$
- $\sigma_{t\bar{t}} = 818 (\pm 4\%)$ pb

**CMS** [EPJC 77(2017)172]  
- Opposite-sign $e\mu$
- $\sigma_{t\bar{t}} = 815 (\pm 5\%)$ pb

Lepton + jets

**CMS** [arXiv:1701.06228]  
- Likelihood fit to $M(l,b)$ (invariant mass of lepton and b-tagged jet), min $M(l,b)$ and events with 0 b-tags
- $\sigma_{t\bar{t}} = 835 (\pm 4\%)$ pb
- Top mass (pole mass) also measured to be $m_t = 172^{+2.4}_{-2.7}$ GeV, derived from cross section

Uncertainties at the level of NLO.  
All consistent with theoretical QCD calculation at NNLO.

SM prediction $\sigma_{t\bar{t}} = 832^{+20}_{-29}$(scale) $\pm 35$(PDF + $\alpha_s$) pb for $m_t = 172.5$ GeV

29/03/2017  
Lana Beck - Moriond QCD - $t\bar{t}$ (+X)
Run 1 – Inclusive $t\bar{t} - \tau +$ jets

**CMS**


$\sigma_{t\bar{t}} = 257 \pm 3$ (stat) $\pm 24$ (syst) $\pm 7$ (lumi) pb

**Theory**

$\sigma_{t\bar{t}}^{\text{SM}} = 253^{+13}_{-15}$ pb

**ATLAS**

[CERN-EP--2016--288]

- $t\rightarrow Wb\rightarrow \tau\nu_tb + t\rightarrow Wb\rightarrow q\bar{q}'b$
- Hadronic 1- and 3-prong tau decays used
- $\sigma_{t\bar{t}} = 239 \pm 29$ pb
- Consistent with theory and measurements in other $t\bar{t}$ final states
- Observed (expected) 95% CL upper limit of any non-SM process is $22(22^{+2}_{-1})$ fb
Differential $t \bar{t}$

lepton+jets, dilepton, all-hadronic + studies of jet activity
Run 2 – lepton + jets

**CMS**

- Parton level dominated by parton shower and hadronisation modelling uncertainties
- Measured cross sections slightly lower than prediction but within uncertainty on expectation

**ATLAS**

- Resolved and boosted topologies
- “None of the predictions is able to correctly describe all of the distributions”
- Powheg+Pythia8 best describes observed data for $p_T$(top)

**Discrepancy seen in other measurements**

**Tension in $p_T^{t,had}$ in Boosted Regime**
Run 2 - Dilepton

- Opposite sign $e\mu$, $\geq 2$ jets, $\geq 1$ b-tags
- Normalised cross sections in fiducial phase space region
- Consistent with all models except Powheg-Box + Herwig++
  - Which deviates in $p_t(t)$ and $m(t\bar{t})$ distributions

ATLAS [CERN-PH-2016-220]

New

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$

Fiducial phase-space

Data
Stat. Stat $\otimes$ Syst.
POWHEG Box + PYTHIA 6
POWHEG Box + HERWIG++
POWHEG Box + PYTHIA 8
SHERPA
MG5_aMC@NLO + HERWIG++
MG5_aMC@NLO + PYTHIA 8
Run 2 – All-hadronic

- Using highly boosted tops with 2016 data
- Require two top-tagged large-R jets
  - Leading jet $p_T > 500$ GeV
  - Subleading jet $p_T > 350$ GeV
- b-tagged small-R subjets matched to top candidate
- Updated top-tagging and b-tagging
- $p_T(t\bar{t})$ and $m(t\bar{t})$ in good agreement with SM up to 2 TeV
Run 2 – All-hadronic

ATLAS

[ATLAS–CONF–2016–100]

- Using highly boosted tops with 2016 data
- Require two top-tagged large-R jets
  - Leading jet $p_T>$500 GeV
  - Subleading jet $p_T>$350 GeV
- $b$-tagged small-R subjets matched to top candidate
- Updated top-tagging and $b$-tagging
- $p_T$(tt) and $m$(tt) in good agreement with SM up to 2 TeV

CMS

[CMS–PAS–TOP–16–013]

- Resolved and boosted topologies analysed and combined
- Good agreement in overlap region, $p_T$~500 GeV
- Detector and full-partonic phase space studied
- Observed $p_T$ spectrum falls more steeply than the theory prediction with LO and NLO generators
Run2 – Jet Activity in $t\bar{t}$

- OS dilepton $e\mu$ and $\geq 2$ b-tag jets  
- Additional jets are in addition to the two highest $p_T$ b-tagged jets  
- Powheg+Pythia6 (RadHi) and MG5_aMC@NLO+Herwig++ and SHERPA perform the best  
- All predictions with Herwig7 have bad agreement with data  
  - Settings for Herwig7 will be optimised for future MC

\[ \frac{d^2 \sigma}{dN_{\ell\ell}} \]

\[ \frac{d^2 \sigma}{dN_{\ell\ell}} \]

\[ 1 \quad 10^{-1} \quad 10^{-2} \quad 10^{-3} \]

\[ 1 \quad 1.2 \quad 1.4 \quad 1.6 \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad \geq 3 \]

\[ \text{ATLAS} \quad 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]
\[ \text{add. jet } p_T \geq 80 \text{ GeV} \]

\[ \text{MC/Data} \]

\[ \text{ATLAS} \quad 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]
\[ \text{add. jet } p_T \geq 60 \text{ GeV} \]

\[ \text{MC/Data} \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad \geq 3 \]

\[ \text{Stat. uncertainty} \quad \text{Stat.+Syst. uncertainty} \]

29/03/2017  Lana Beck - Moriond QCD - $t\bar{t}$ (+X)
Run2 – Jet Activity in $t\bar{t}$

ATLAS [CERN-EP-2016-218]

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- Powheg+Pythia6 (RadHi) and MG5_aMC@NLO+Herwig++ and SHERPA perform the best
- All predictions with Herwig7 have bad agreement with data
  - Settings for Herwig7 will be optimised for future MC

- No indication that
  - any of the ME generators describe data better for all PS programs
  - or that any PS program describes data best
- Implies matching between ME and PS plays an important role
  - Requires further study
Effect of parton shower tuning in Pythia 8 in the modelling of $t\bar{t}$

Independent ME/PS/ISR/FSR variations studied

Run1 (LO) - MG 5.1.3.30 with 3 additional partons + Pythia 6.425 (Z2* tune)
  - Good except $p_T$ (top)

NLO ME generators: better modelling of signal/background and reduced systematics
  - Assessed on Run1 and used on Run2 data
Effect of parton shower tuning in Pythia 8 in the modelling of $t\bar{t}$

**CMS**

[CMS-PAS-TOP-16-021]

- Independent ME/PS/ISR/FSR variations studied
- Run1 (LO) - MG 5.1.3.30 with 3 additional partons + Pythia 6.425 (Z2* tune)
  - Good except $p_T$(top)
- NLO ME generators: better modelling of signal/background and reduced systematics
  - Assessed on Run1 and used on Run2 data

$\alpha_S$ tuned in pythia8, $h_{damp}$ tuned in powhegv2
- $t\bar{t}$ kinematics improved (except in Madgraph MLM)
- MET and $H_T$ distributions relatively unchanged
  -> searches involving MET will not be biased
- Take care(!) if searches for new physics depend on Njets, $p_T$(t$\bar{t}$) or $p_T$ of additional jets in $t\bar{t}$-like processes
- Good agreement observed in all variables except for $p_T$(top) as in Run1
Effect of parton shower tuning in the modelling of $t\bar{t}$

**ATLAS** [ATL-PHYS-PUB-2016-004]

- Tuned on 13 TeV data
- The Powheg+Herwig++ sample has more jets & much softer $p_T$ spectrum than other generators.
  → Worse description of the data than the Powheg+Pythia6 sample.
- Comparison of alternative generator setups based on aMC@NLO show smaller effects.

- EvtGen shown to give generator independent b-tagging efficiencies.
- New Powheg+Pythia8 setup has been optimised that leads to an improved description of data.
- ATLAS and CMS tuning parameters consistent with each other
$t\bar{t} + X$

$X = W, Z, b\bar{b}, t\bar{t}$
**ttW and ttZ**

**Strategy** → Likelihood fit in regions defined by the number of leptons, jets and b-tagged jets

Important background for ttH searches in multilepton final states

**Observed in Run1**

- CMS
  - $\sigma_{ttZ} = 0.7 \pm 0.2$ pb
  - $\sigma_{ttW} = 0.98 \pm 0.2$ pb

- ATLAS
  - $\sigma_{ttZ} = 0.9 \pm 0.3$ pb
  - $\sigma_{ttW} = 1.5 \pm 0.8$ pb

**Theory**

- Run2
  - $\sigma_{ttZ} = 0.84 \pm 0.1$ pb
  - $\sigma_{ttW} = 0.60 \pm 0.06$ pb

Measurements currently statistically limited
ttW and ttZ

Run1

Run2

Run1

Run2
Run2 – t¯tb¯b CMS

CMS [CMS-PAS-TOP-16-010]

- OS dileptons, ≥ 4 jets, ≥ 2 b-tagged jets
- Likelihood fit to b-jet discriminator distributions for 3rd and 4th ranked jets
  - Before tuning \(\alpha_s\)
- Compatible with expectation from Powheg+Pythia8

Important background for tTH(H→bb) and tttt

<table>
<thead>
<tr>
<th>Phase Space</th>
<th>(\sigma_{t\bar{t}b\bar{b}}) [pb]</th>
<th>(\sigma_{t\bar{t}jj}) [pb]</th>
<th>(\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible</td>
<td>0.085 ± 0.012 ± 0.029</td>
<td>3.5 ± 0.1 ± 0.7</td>
<td>0.024 ± 0.003 ± 0.007</td>
</tr>
<tr>
<td>Full</td>
<td>3.9 ± 0.6 ± 1.3</td>
<td>176 ± 5 ± 33</td>
<td>0.022 ± 0.003 ± 0.006</td>
</tr>
<tr>
<td>Simulation (POWHEG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible</td>
<td>0.070 ± 0.009</td>
<td>5.1 ± 0.5</td>
<td>0.014 ± 0.001</td>
</tr>
<tr>
<td>Full</td>
<td>3.2 ± 0.4</td>
<td>257 ± 26</td>
<td>0.012 ± 0.001</td>
</tr>
</tbody>
</table>

Table 2: Summary of the systematic uncertainties from various sources contributing to \(s_{ttb}\), \(s_{ttjj}\), and the ratio \(s_{ttb}/s_{ttjj}\) for a jet \(p_T\) threshold of \(p_T > 20\) GeV in the visible phase space.
Run2 – Search for $t\bar{t}t\bar{t}$

High jet multiplicity - Select for $t\bar{t} + 1$ (2) jets for ATLAS (CMS) \[ \sigma_{tt}^{SM} = 9.2 \text{ fb} \]

Four Top decay channels

Categorisation in jets and tags and/or likelihood fit to BDT templates
Run2 – Search for $t\bar{t}t\bar{t}$

High jet multiplicity - Select for $t\bar{t} + 1\ (2)$ jets for ATLAS (CMS) $\sigma_{t\bar{t}}^{SM} = 9.2\ fb$

Four Top decay channels

Categorisation in jets and tags and/or likelihood fit to BDT templates

Intermediate BSM particle or SM Higgs → Probe top Yukawa!
Run2 – Search for $t\bar{t}t\bar{t}$

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Four Top decay channels

Intermediate BSM particle or SM Higgs → Probe top Yukawa!

Categorisation in jets and tags and/or likelihood fit to BDT templates

Table 1. Signatures of our simplified top-philic dark matter model.
Run2 – Search for $t\bar{t}t\bar{t}$

$\sigma^{SM}_{tt} = 9.2 \text{ fb}$

CMS

[arXiv:1702.06164] 2.6 fb$^{-1}$ New

- Combination: L+jets, OS dilepton and SS dilepton
- Observed (expected) 95% CL upper limit $\sim 7.2 (7.5) \times \sigma^{SM}_{tt}$

2.6 fb$^{-1}$ (13 TeV)

CMS

Unpublished

ATLAS


- Lepton + jets channel only
- Observed (expected) 95% CL upper limit $\sim 6.5 (9.1) \times \sigma^{SM}_{tt}$

CMS


- Same-sign dilepton
- Observed (expected) 95% CL upper limit $\sim 4.6 (3) \times \sigma^{SM}_{tt}$
Already many measurements of $t\bar{t}(+X)$ at 13 TeV

- Inclusive $t\bar{t}$ cross sections
- Differential $t\bar{t}$
- Studies on jet activity in $t\bar{t}$
- Rarer processes such as $t\bar{t}V$, $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$
  - $t\bar{t}t\bar{t}$ approaching 1*SM
- Run1 measurement of $\tau +$ jets

So far all searches have been consistent with the Standard Model Expectation
Backup
b-jet discriminator for ttbb analysis CMS
CMS-tttt-OS dilepton
1 muon, 3 jets, 2 b-tagged jets
Run 2 – Inclusive tt (l+jets)

CMS

[arXiv:1701.06228]

- 2.3 fb⁻¹
- 1 lepton (μ or e), ≥1 jet, ≥1 b-tag
- Likelihood fit to M(l,b) - invariant mass of lepton and b-tagged jet
- \( \sigma_{tt} = 835 \pm 3 \) (stat) \( \pm 23 \) (syst) \( \pm 23 \) (lumi) pb
- Top mass also measured to be \( m_t = 172^{+2.4}_{-2.7} \) GeV.

SM prediction \( \sigma_{tt} = 832^{+20}_{-29} \) (scale) \( \pm 35 \) (PDF + \( a_s \)) pb for \( m_t = 172.5 \) GeV
Run 2 – Inclusive tt (dilepton)

**ATLAS** [arxiv:1606.02699]
- 3.2 fb⁻¹
- Opposite-sign eμ
- Exactly 1 or exactly 2 b-tag regions
- Event-counting method
- \( \sigma_{t\bar{t}} = 818 \pm 8 \text{(stat)} \pm 27 \text{(syst)} \pm 19 \text{(lumi)} \pm 12 \text{(beam)} \text{ pb} \)
- Total \( \sim 4.4\% \) uncertainty

**CMS** [arxiv:1611.04040]
- 2.2 fb⁻¹
- Opposite-sign eμ
- \( \geq 2 \text{ jets, } \geq 1 \text{ b-tag} \)
- Event-counting method
- \( \sigma_{t\bar{t}} = 792 \pm 8 \text{(stat)} \pm 37 \text{(syst)} \pm 21 \text{(lumi)} \text{ pb} \)
- Total \( \sim 5.5\% \) uncertainty

Both Consistent with theoretical QCD calculation at NNLO
SM prediction \( \sigma_{t\bar{t}} = 832^{+20}_{-29} \text{(scale)} \pm 35 \text{(PDF + } a_s \text{)} \text{ pb} \) for \( m_t = 172.5 \text{ GeV} \)
Run 2 – Inclusive tt (l+jets)

- Likelihood fit to \( M(l,b) \) - invariant mass of lepton and b-tagged jet
- \( \sigma_{\text{tt}} = 835 \pm 3 \text{ (stat)} \pm 23 \text{ (syst)} \pm 23 \text{ (lumi)} \) pb
- Top mass also measured to be \( m_t = 172^{+2.4}_{-2.7} \) GeV.

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SM prediction \( \sigma_{\text{tt}} = 832^{+20}_{-29} \text{(scale)} \pm 35 \text{(PDF + } \alpha_s \text{)} \) pb for \( m_t = 172.5 \) GeV
Run 2 - Dilepton

ATLAS \[arXiv:1612.05220\]

- 3.2 fb⁻¹
- Opposite sign e\(\mu\), \(\geq 2\) jets, \(\geq 1\) b-tags
- Consistent with all models except Powheg-Box + Herwig++
  - Seen in \(p_t(t)\) and \(m(tt)\) distributions
**CMS**

[CMS-PAS-TOP-16-017] Run2

- 12.9 fb⁻¹
- **ttW**: Same-sign dilepton final state used
- **ttZ**: 3 and 4 lepton final states used
- Likelihood fit in 20 jet and b-tag regions
- \( \sigma_{ttZ} = 0.7 \pm 0.2 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ pb} \)
- \( \sigma_{ttW} = 0.98 \pm 0.2 \text{ (stat)} \pm 0.2 \text{ (syst) pb} \)

**ATLAS**

[arXiv:1609.01599] Run2

- 3.2 fb⁻¹
- Likelihood fit to 8 signal and 2 control regions
- \( \sigma_{ttZ} = 0.9 \pm 0.3 \text{ pb} \)
- \( \sigma_{ttW} = 1.5 \pm 0.8 \text{ pb} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>( \bar{t}t ) decay</th>
<th>Boson decay</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t}W )</td>
<td>((\ell^\pm \nu b)(\ell' \bar{\nu} b))</td>
<td>( \mu^\pm \nu )</td>
<td>SS dimuon</td>
</tr>
<tr>
<td></td>
<td>((\ell^\pm \nu b)(\ell' \bar{\nu} b))</td>
<td>( \ell^\pm \nu )</td>
<td>Trilepton</td>
</tr>
<tr>
<td>( t\bar{t}Z )</td>
<td>((\ell^\pm \nu b)(\ell' \bar{\nu} b))</td>
<td>( \ell^\pm \ell^- )</td>
<td>Tetralepton</td>
</tr>
</tbody>
</table>
Run2 – Search for $tttt$

High jet multiplicity - Select for $tt + 1 \ (2)$ jets for ATLAS (CMS) \( \sigma_{tt}^{\text{SM}} = 9.2 \text{ fb} \)

CMS

[arXiv:1702.06164] 2.6 fb\(^{-1}\)
- Combined across l+jets, OS dilepton and SS dilepton
- Observed (expected) 95% CL upper limit = 66 (69\(^+37\)\(^{-23}\) ) fb

ATLAS

[CONF-2017-016] 36 fb\(^{-1}\)
- Uses lepton + jets channel only
- Observed (expected) 95% CL upper limit = 193 (147\(^+212\)\(^{-110}\) ) fb

29/03/2017

Lana Beck - Moriond QCD - $tt \ (+X)$
Effect of parton shower tuning in Pythia 8 in the modelling of tt

CMS [TOP-16-021]

• Independent ME/PS/ISR/FSR variations studied
• Run1 : (LO) MG 5.1.3.30 with 3 additional partons + Pythia 6.425 using Z2* tune
  • Good except \( p_T \) (top)
• NLO ME generators: better modelling of signal/ background and reduced systematics
  • Assessed on Run1 and used on Run2 data

\( \alpha_s \) and \( h_{\text{damp}} \) tuned in powhegV2 and powheg8 respectively.

• Improves tt kinematics
• Consistent with values obtained by ATLAS
• MET and \( H_T \) distributions unchanged
  - \( \rightarrow \) searches involving MET will not be biased
• Care must be taken if searches for new physics depend on Njets, \( p_T \) (tt) or \( p_T \) of additional jets in tt-like processes.
Run2 – Jet Activity in \( \text{tt} \)

**ATLAS** [arXiv:1610.09978]

- Select OS dilepton emu and \( \geq 2 \) b-tag jets
- Additional jets are in addition to the two highest \( p_T \) b-tagged jets
- Powheg+Pythia6 (RadHi) and MG5\_aMC@NLO+Herwig++ and SHERPA perform the best
- All predictions with Herwig7 have bad agreement with data

![Diagram](image1)

- No indication that any of the ME generators describe data better for all PS programs
- No indication that any PS program describes data best
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- Care must be taken if searches for new physics depend on Njets, $p_T$ (tt) or $p_T$ of additional jets in tt-like processes.
Run2 – ttbb CMS

CMS [CMS-PAS-TOP-16-010]

- OS dileptons, ≥ 4 jets, ≥ 2 b-tagged jets
- Likelihood fit to b-jet discriminator distributions for 3rd and 4th ranked jets
  - Before tuning $\alpha_S$

Full phase space

$\sigma_{ttbb} / \sigma_{ttjj} = 0.022 \pm 0.003$ (stat) $\pm 0.006$ (syst)

$\sigma_{ttbb} = 3.9 \pm 0.5$ (stat) $\pm 1.3$ (syst) pb

$\sigma_{ttjj} = 176 \pm 5$ (stat) $\pm 33$ (syst) pb

- Compatible with expectation from Powheg+Pythia8

Important background for $ttH(H\rightarrow bb)$ and $tttt$