Top pair production cross-section and measurements of $t\bar{t}+X$ with the ATLAS detector

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On behalf of the ATLAS Collaboration

Outline

• Introduction

• Top-pair production cross-section
  – Inclusive and differential cross sections
  – Top quark kinematics and boosted top in TeV regime

• Measurements of $t\bar{t}+X$:
  – $t\bar{t}$ + jets
  – $t\bar{t}$+W, $t\bar{t}$+Z
  – $t\bar{t}$+γ

• Conclusion

• More Details:
  • ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
Introduction

• Top-quark was discovered at the Tevatron by CDF & D0 in 1995, the heaviest quark discovered so far: $M_{\text{top}} = 173\pm0.6$ GeV (LHC+Tevatron).

• It's the only bare quark ever observed due to a short lifetime of $5\times10^{-25}$ s.
• Top with large Yukawa coupling ($y_t \sim 1$) may play special role in EWSB.

• Top-quark pair production is well understood, consistent with NNLO.

Top-quark Pair Production at LHC

• Top-quark pair is predominately produced in gluon fusion (~90%) and $q\bar{q}$ annihilation (~10%) at LO at LHC.

• The production cross section:
  – Sensitive to gluon PDFs, $\alpha_s$, $M_{\text{top}}$.
  – Provide precision test of QCD in the TeV regime.

• Study of $t\bar{t} + X$ production provides:
  – Stringent test of higher-order QCD.
  – Probe for new physics beyond the SM.

• Main background:
  – $W$+jets, $Z$+jets, single-top, diboson, multi-jets.
Top-quark Decay in SM

- Top-quark decays into Wb with $\text{B}(t \to Wb) = 100\%$, final states determined by W decays.

- For high pT, top boosted in large-R jet (R=1):
  - Jet substructure technique by requiring 3 sub-jets ($R_{\text{sub}} = 0.2$, $f_{\text{sub}} = 0.05$) with a large mass.
Top pair-production at $\sqrt{s}=13$ TeV

• Select $e\mu + \geq 2\text{jets} + 1b, 2b$ using $3.2\text{fb}^{-1}$.

• Likelihood fit $\sigma_{\bar{t}t}$, $\varepsilon_{\text{btag}}$ simultaneously

• $\sigma_{\bar{t}t} = 818 \pm 8 \pm 27(\text{syst}) \pm 19(\text{lum}) \pm 12(\text{beam}) \text{pb}$

• Total $\sim 4.4\%$ uncertainty.

• NNLO: $832^{+20}_{-29}(\text{Scale}) \pm 35(\text{PDF} + \alpha_s) \text{ pb}$

\[\begin{array}{|c|c|c|}
\hline
\text{Event counts} & N_1 (1b) & N_2 (2b) \\
\hline
\text{Data} & 11958 & 7069 \\
\hline
\text{Single top} & 1140 \pm 100 & 221 \pm 68 \\
\text{Dibosons} & 34 \pm 11 & 1 \pm 0 \\
Z(\rightarrow \tau\tau \rightarrow e\mu) + \text{jets} & 37 \pm 18 & 2 \pm 1 \\
\text{Misidentified leptons} & 164 \pm 65 & 116 \pm 55 \\
\hline
\text{Total background} & 1370 \pm 120 & 340 \pm 88 \\
\hline
\end{array}\]

*Syst is limited by top hadronisation uncertainty.*
Differential $\sigma_{tt}$ in $e\mu$ Channel.

- Differential $\sigma_{tt}$ as function of $m_{t\bar{t}}$, $P_{T,t\bar{t}}$, $y_{t\bar{t}}$, $P_{T,t}$, $y_t$, sensitive to top processes.
  - $e\mu + \geq 2$ jets with $\geq 1$ b-jet
  - Top reconstruction using neutrino weighting technique.

- Unfolded to particle level: fid. normalised differential $\sigma_{tt}$ consistent with all ME+PS except Powheg-Box + Herwig++, deviates from data in $P_{T,t}$ and $m_{t\bar{t}}$ (p-value=1-2%).

ArXiv:1612.05220, accepted by EPJC
Differential $\sigma_{\bar{t}t}$ in lepton+jets channel

Events are divided into two regions:

- **Resolved** for low $P_T$ top-pair in $t\bar{t} \rightarrow$ lepton+>=4jets with 2bjets.
- **Boosted** for high $P_T >350$ GeV top contained in large-R jet that selected using sub-structure technique.

Unfolded to particle level in fid.: No MC describes data in $P_{t,had}<350$ GeV well.
Differential $\sigma_{tt}$ in all-hadronic channel

- Selecting: two large-R jets: $P_T > 500, 350$ GeV and top candidates are separated from the multi-jet QCD using substructure technique.

- Unfolded to particle level: $\sigma_{tt}^{\text{fid}} = 373^{+111}_{-92}$ fb, limited by jet energy scale.
  - normalised differential cross-section are consistent with MC predictions.

![Graphs showing differential cross-sections for leading and sub-leading top quark transverse momenta](image-url)
• $\sigma_{tt}/\sigma_Z$ is driven by gluon (quark) in PDF.

• Ratio of cross sections is more sensitive to PDF where luminosity and some systematic would cancel.

• Ratios, double rations measured at Run1 and Run2 that compared to NNLO with different PDF sets.
  
  – Data are more precise than PDFs and can be used to constrain gluon content at large x region.
Study of $\bar{t}t$ + jets activity in $e\mu$ channel

arXiv:1610.09978, accepted by EPJC

• Important to tune PS modelling $\rightarrow$ Powheg+Pythia6(Rad-hi/Rad-lo)

• Selecting: $\bar{t}t \rightarrow e\mu + 2$ bjets. $\rightarrow$ MG5_aMC@NLO+Herwig++; SHERPA v2.2.

• Count for additional jets. $\rightarrow$ Powheg+Herwig7 describes data poorly.

• Unfolded to particle-level in fid.: normalised differential $\sigma_{\bar{t}t}$ compared to MCs.
Measurement of $\sigma_{ttW}$ and $\sigma_{ttZ}$ at $\sqrt{s}=13$ TeV

- Run2 $\sigma_{ttZ} (\sigma_{ttW})=0.84\pm0.1 (0.60\pm0.06)$ pb (NLO QCD, 1610.07922) increased significantly, sensitive to BSM.
- Select: $t\bar{t}V \rightarrow 2SS, 3, and 4$ leptons in final states.
- Likelihood fit in signal and control regions (WZ, ZZ).
- Important background to $t\bar{t}H$ in Multi-lep channel.

Run2 data: $\sigma_{ttW}=1.5\pm0.8; \sigma_{ttZ}=0.9\pm0.3$ (pb)
• Select isolated $\gamma$(pT>20GeV) in lep+jets.
• Sensitive to Top-$\gamma$ coupling, BSM physics.
• Likelihood Fit $P^\text{iso}_t(\gamma)$ to extract signal and backgrounds that gives 5.3σ observation.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Electron chan.</th>
<th>Muon chan.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$52 \pm 14$</td>
<td>$100 \pm 28$</td>
<td>$152 \pm 31$</td>
</tr>
<tr>
<td>Hadrons</td>
<td>$38 \pm 26$</td>
<td>$55 \pm 38$</td>
<td>$93 \pm 46$</td>
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<tr>
<td>Prompt photons</td>
<td>$41 \pm 5$</td>
<td>$65 \pm 9$</td>
<td>$106 \pm 10$</td>
</tr>
<tr>
<td>Total background</td>
<td>$79 \pm 26$</td>
<td>$120 \pm 39$</td>
<td>$199 \pm 47$</td>
</tr>
<tr>
<td>Total</td>
<td>$131 \pm 30$</td>
<td>$220 \pm 48$</td>
<td>$351 \pm 59$</td>
</tr>
<tr>
<td>Data candidates</td>
<td>140</td>
<td>222</td>
<td>362</td>
</tr>
</tbody>
</table>

$P^\text{iso}_t(\gamma) = \sum P^\text{trk}_t(>1\text{GeV})$ in $\Delta R=0.2$

Syst uncertainty dominated by jet energy scale.
Conclusion

• Top-pair production at LHC:
  – Most are precisely measured, limited by systematic and luminosity uncertainties.
  – Ratio of $\sigma_{\bar{t}t}/\sigma_{Z}$ is more sensitive to PDFs.
  – Studies of $\bar{t}t+$jets, $\bar{t}tV$, $\bar{t}t\gamma$ can further constrain the higher-order corrections.

• Results are consistent with SM.

• Much more data available, stay tuned!