Study of QCD radiation in top quark pair events.

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On behalf of the ATLAS and CMS collaborations
Motivation.

- Most top events have additional jets at LHC energies
- Need to have good background estimation of $t\bar{t}$ with additional jets
- Improve modelling of QCD radiation in generators and reduce MC modelling uncertainties
  - Tuning of fixed order NLO calculations to ISR/FSR
  - Matching and merging in modern generators (additional jets are generated @ NLO)
Recent results.

Jet multiplicity measurements:
- $\ell^+\text{jets} @ 13 \text{ TeV} - \text{CMS-PAS-TOP-16-008}$
- Dilepton @ 13 TeV - ATLAS-CONF-2015-065
- Dilepton @ 13 TeV - CMS-PAS-TOP-16-011
- $e\mu @ 8 \text{ TeV} - \text{paper in preparation}$
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{CMS-PAS-TOP-12-016}$
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{Eur.Phys.J.C(2016)76:11}$
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{Phys.Lett.B746(2015)132 (not covered)}$

Gap fraction measurements:
- $e\mu @ 8 \text{ TeV} - \text{ATLAS-TOPQ-2015-04}$
- Dilepton @ 8 TeV - CMS-PAS-TOP-12-041

$t\bar{t} + \text{heavy flavor:}$
- Dilepton @ 8 TeV - CMS-PAS-TOP-12-041
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{CMS-PAS-TOP-13-016}$
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{Eur.Phys.J.C(2016)76:11}$
- $\ell^+\text{jets} @ 8 \text{ TeV} - \text{Phys.Lett.B746(2015)132 (not covered)}$

Other:
- $t\bar{t} + X (\mu+\text{jets}) @ 13 \text{ TeV} - \text{CMS-PAS-TOP-15-017 (not covered)}$
- Jet Pull Angle ($\ell^+\text{jets}$) @ 8 TeV - PLB 750 (2015) 475-493 (not covered)
- Comparisons of theory predictions @ 8 TeV - CMS-PAS-TOP-15-011 (not covered)
Measurement strategies.

Fiducial phase space

- Matches closely the phase space of the detector
- Detector response corrections (resolution & efficiency)

Particle level

- Based on final state particles at generator level
- Electrons and muons: prompt, origin not from a hadron decay
- Neutrinos: origin not from a hadron decay
- Jets: Clustering of all stable final state particles
- b-jets: Matching jets to b-hadrons (ghost matching)

Smaller model dependence and no extrapolation needed compared to full phase space and parton level
Jet multiplicity measurements.

- Differential cross-section as a function of jet multiplicity unfolded at particle level
- Sensitive to the production mechanism of additional jets
- Probing $p_T$ dependence of the hard emission via different $p_T$ thresholds
- Anti-$k_T$ jets with a radius of 0.4 are used (except CMS @ 8 TeV → R=0.5)
Jet multiplicity at 13 TeV.

Different phase spaces:

- Leptons: $p_T > 25$ GeV & $|\eta| < 2.5$
- b-jets: $p_T > 25$ GeV & $|\eta| < 2.5$
- Add. jets: $p_T > 25$ GeV & $|\eta| < 2.5$

- Leptons: $p_T > 20$ GeV & $|\eta| < 2.4$
- Jets: $p_T > 30$ GeV & $|\eta| < 2.4$
- Add. jets: $p_T > 20$ GeV & $|\eta| < 2.4$

Different versions & tunes for predictions → Need to have comparable results

Large uncertainties 5-40% (jet energy scale (JES) is dominant part)

Add. jets from parton shower → Tuning is important
Jet multiplicity at 13 TeV vs. 8 TeV.

- \( \eta \) region: \(|\eta| < 2.5\) vs. \(|\eta| < 4.5\)
- 13 TeV measurement uses Powheg+Pythia6 with \( h_{\text{damp}} = m_t \)

Uncertainties up to 20% @ 8 TeV (Data statistics and JES)
Consistent results with 8 TeV measurement
Powheg with Pythia8 or with Herwig++ perform reasonably well at both \( \sqrt{s} \)
Comparison to lepton+jets analysis at 13 TeV

Differential cross section:

- Absolute
- Normalized

Similar trend towards too many predicted additional jets in both analyses
Gap fraction measurement.

Definition

\[ f(p_T) = \frac{N(p_T)}{N_{\text{total}}} \]

- \(N(p_T)\): number of events with no additional jet above a \(p_T\) threshold within the (pseudo-)rapidity interval (veto region)
- \(N_{\text{total}}\): total number of selected events

- Sensitive to the leading \(p_T\) emission accompanying the \(t\bar{t}\) system
- Inclusive measurement, which allows an insight to the parton showering
- Measured for different veto regions (e.g. \(|y| < 0.8\)
Gap fraction at 8 TeV.

- Veto region: $|y| < 0.8$
- Anti-$k_T$ jet: $R = 0.4$

Paper in preparation

Overall nice consistency between results
- Up to 1.5% uncertainty (again JES is dominant)
- Generator agreement is comparable (even with different tunes)

ATLAS Preliminary
\[ s = 8 \text{ TeV}, \text{20.3 fb}^{-1} \]

Veto region: $|y| < 0.8$

$|\eta| < 0.8$

$R = 0.5$

$\mathbf{NEW}$

19.7 fb$^{-1}$ (8 TeV)

arXiv:1510.03072
Measurement of $t\bar{t} +$ heavy flavor.

- Measurement of ratio $t\bar{t}+bb/t\bar{t}+jj$ at parton level
  - Irreducible background for $t\bar{t}H (H \rightarrow bb)$ analysis $\Rightarrow$ Constrain $g \rightarrow bb$ fragmentation

- Jet flavor at generator level defined by:
  - Flavor of leading quark ($hardB$) $\rightarrow$ parton level
  - Presence of a B-hadron in the list of jet constituents ($hadronB$) $\rightarrow$ particle level

- Caveat: different phase spaces used $\Rightarrow$ Only separate comparisons

### CMS-PAS-TOP-13-016

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{ttbb}/\sigma_{ttjj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hardB:</strong></td>
<td></td>
</tr>
<tr>
<td>this analysis</td>
<td>$0.012 \pm 34%$</td>
</tr>
<tr>
<td>theory NLO\textsuperscript{[4]}</td>
<td>$0.011 \pm 39%$</td>
</tr>
<tr>
<td>MADGRAPH + PYTHIA</td>
<td>$0.007 \pm 10%$</td>
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<tr>
<td><strong>hadronB:</strong></td>
<td></td>
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<tr>
<td>this analysis</td>
<td>$0.015 \pm 32%$</td>
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<tr>
<td>CMS dilepton\textsuperscript{[3]} \textsuperscript{CMS-PAS-TOP-13-010}</td>
<td>$0.022 \pm 29%$</td>
</tr>
<tr>
<td>MADGRAPH + PYTHIA</td>
<td>$0.009 \pm 14%$</td>
</tr>
</tbody>
</table>

- Uncertainties are statistics dominated
- Systematics mostly from b-tagging and JES

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**ATLAS**

\[ \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1} \]

- Measurement result
- stat. $\oplus$ syst. $\ominus$ stat.

- MadGraph+Pythia
- Pythia8 (wgtq3)
- Pythia8 (wgtq5)
- Pythia8 (wgtq6, sgtq=0.25)
- Powheg+Pythia6 (inclusive tt)


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Christoph Eckardt (DESY) | Study of QCD radiation in top quark pair events | 10/12
Fiducial cross section of $\ttbar + b(b)$.

- Test of NLO QCD calculations of $\ttbar + b(b)$
- QCD-only results: $\ttbar V/H$ prediction is subtracted (simulation)
- aMC@NLO with two different functional forms for renormalization & factorization scales
- Pythia8 calculations with three different options for the $g \rightarrow b\bar{b}$ splitting

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Conclusion.

- Consistent results between 8 and 13 TeV measurements

- Many different kinematic regions related to QCD radiation in top pair events have been measured

- Results show discrimination power between MC models and tuning parameters
  → Important input for top pair modelling at 13 TeV

- Need to move to NLO generators for higher jet multiplicities, where the emission of additional jets is not dependent on the tuning
Backup.
Tuning of $\alpha_S$.

CMS data 19.7 fb$^{-1}$ (8 TeV)
arXiv:1510.03072

Data Uncertainty

$\alpha_{ISR}^S = 0.115$
$\alpha_{ISR}^S = 0.096$
$\alpha_{ISR}^S = 0.137$

$1/\sigma_{vis} d\sigma_{vis}/dN_{jets}$

$N_{jets}$ [$p_T > 30$ GeV]
Study of QCD radiation in top quark pair events

$p_T$ of additional b-jets.