Boosted Measurements in ATLAS+CMS

Dan Marley

*On behalf of the ATLAS & CMS collaborations*

17-22 September 2017
Motivation

• Test the Standard Model — specifically ttbar — at very high energies
  - Compare measured values with multiple SM predictions

• Complementary way to search for new physics
  - Exclude BSM physics incompatible with measurements
Challenges

• **Reconstruction** of high-\(p_T\) hadronically- and leptonically-decaying top quarks
  - Merged decay products require unique algorithms

• **Reducing systematic uncertainties** associated with boosted top quark identification

• **Modeling of top quarks** in high-\(p_T\) regime

• **Limited statistics**: fewer events available to study relative to “resolved” analyses
Reconstruction

- Large-R jets ($R \geq 0.8$) capture boosted top quark decay products
- Use jet substructure information to select pure sample of top quarks
  - Ensure “good” reconstruction of $t\bar{t}$ system ($\sim$diagonal response matrix)
- Mitigate pileup by using grooming procedures

See talks by S. Egan, G. Kasieczka, & S. Lee

Boosted top tagging is part of a much larger community! See BOOST2017
## Top Measurements

### ATLAS

<table>
<thead>
<tr>
<th>Energy</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Differential Cross Section</strong></td>
<td>( \ell + \text{jets} ) ([PRD 93 (2016) 032009])</td>
<td>( \ell + \text{jets} ) (<a href="http://arxiv.org/abs/1708.00727">arXiv:1708.00727</a>)</td>
</tr>
<tr>
<td><strong>Charge Asymmetry</strong></td>
<td>( \ell + \text{jets} ) ([PLB 756 (2016) 52])</td>
<td>All-hadronic (In preparation)</td>
</tr>
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### CMS

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<td>( \ell + \text{jets} ) (( p_T ) [PRD 94 (2016) 072002]; jet mass: <a href="http://dx.doi.org/10.1140/epjc/s10052-017-5248-0">EPJC 77 (2017) 467</a>)</td>
<td>All-hadronic (<a href="https://cds.cern.ch/record/2499944">CMS-PAS-TOP-16-013</a>)</td>
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</table>
$\ell+\text{jets}$ (13 TeV)

- **$\ell+\text{jets}$** final state with large-$R$ jet representing the hadronic top:
  - Trimmed ($f_{\text{cut}}=0.05$, $R_{\text{sub}}=0.2$), $R=1.0$ anti-$k_T$ large-$R$ jet
  - Top-tagged using $p_T$-dependent cuts on $\tau_{32}$ and large-$R$ jet mass (80% $\varepsilon$)
  - *Particle-level*: mass $> 100$ GeV; $\tau_{32} < 0.75$

See talk by M. Giannelli

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**Data**


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$m > 50$ GeV

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$300 < p_T < 1500$ [GeV]
• Good reconstruction and nearly diagonal migration matrix
  (>85% of events along diagonal in rapidity migration matrix)
• Systematic uncertainties dominated by large-R jet and ttbar modeling components
  - Total is nearly twice the magnitude uncertainties in resolved channel!
\( \ell + \text{jets (13 TeV)} \)

- Iterative Bayesian Unfolding used to obtain final result
- Resolved and boosted channels consistently show overestimation at large top \( p_T \)
**All-hadronic (13 TeV)**

- **All-hadronic** event selection: two large-R jets used to identify top quarks
  - Trimmed \((f_{\text{cut}}=0.05, R_{\text{sub}}=0.2), R=1.0\) anti-\(k_T\) large-R jet \(p_T>500\) (350) GeV
  - Top-tagged using \(p_T\)-dependent cuts on \(\tau_{32}\) and large-R jet mass (50% \(\epsilon\))

**ATLAS Preliminary**

\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)

- Data 2015+2016
- \(t\bar{t}\) (all-had)
- \(t\bar{t}\) (non all-had)
- Single top
- QCD + W/Z+jets
- Stat. Unc.

**ABCD method to estimate multijet background**

\[122.5 < m < 222.5\ [\text{GeV}]\]
All-hadronic (13 TeV)

- Nearly diagonal response matrix in leading jet $p_T$
- Systematic uncertainties dominated by large-R jets and ttbar modeling
All-hadronic (13 TeV)

- Iterative Bayesian unfolding inclusively and differentially to particle-level

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Fiducial phase space

\[ \frac{1}{\sigma_{\text{fid}}} \cdot \frac{d\sigma_{\text{fid}}}{dp_T} \text{ [GeV}^{-1}] \]

Data
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

Inclusive fiducial cross-section [fb]
$\ell+\text{jets (8 TeV)}$

- **$\ell+\text{jets}$** final state: differential cross section in the jet mass
- Hadronic Top: R=1.2 C/A large-R jet with $p_T>400$ GeV
  - **No selection on jet substructure!**
    - Mass of leading jet required to be larger than sub-leading jet
- Leptonic Top:
  - high-$p_T$ lepton ($p_T>45$ GeV; $\Delta R(\ell,\text{AK5}) > 0.5$ or $p_T^{\text{rel}} > 25$ GeV) & sub-leading large-R jet ($p_T>150$ GeV): $\Delta R(\ell,j) < 1.2$

\[\text{C/A = Cambridge/Aachen}\]

See talk by A. Castro
\( \ell + \text{jets} \ (8 \text{ TeV}) \)

- Systematic uncertainties dominated by large-R jets and ttbar modeling. Significant statistical uncertainties at large values for the jet mass.
$\ell$+jets (8 TeV)

- Result unfolded to particle-level using TUnfold
- *Proof-of-concept to extract the top mass!*

![Graph](image1.png)

![Graph](image2.png)
**All-hadronic (8 TeV)**

- **All-hadronic** event selection: two C/A (R=0.8) large-R jets used to identify top quarks
- High threshold on $H_T (>750 \text{ GeV})$ and large-R jet $p_T (>400 \text{ GeV})$
  - Top tagging with mass window 140-250 GeV and $\tau_{32} < 0.55$ & $\tau_{21} > 0.1$ (for leading jet)

See talk by O. Hindrichs
**All-hadronic (8 TeV)**

- Data-driven technique using jet mass sideband and pass/fail $\tau_{32}$ regions (Alphabet method) to estimate the multijet background.
- $t\bar{t}$ yield is extracted using a maximum likelihood fit to the leading jet mass in signal enriched and depleted regions ($\tau_{32} \lesssim 0.55$).
All-hadronic (8 TeV)

- Before unfolding, ttbar yield is extracted using likelihood fit
- SVD is used to unfold the result to parton-level
- Jet and ttbar modeling systematics dominate uncertainty
Lots of on-going development in boosted top tagging!
Top tagging techniques largely developed for top vs qcd discrimination in searches (ttbar resonances, SUSY, VLQ, etc.).
For future measurements, we should expect top tagging algorithms (and boosted ttbar event selections) more tailored to measurements.
Conclusions

- Many exciting results from the LHC using boosted top quarks!

- Early 13 TeV results still suffer from significant uncertainties on the large-R jets & ttbar modeling
  - With more data being collected in 2017/2018, these results will become more precise and competitive with resolved measurements

- Upcoming boosted measurements of top properties can be used as a stronger test of the SM and complement many of the existing resolved measurements
Backup
More Info

For additional applications of boosted tops:

1. BOOST2017
   1. ATLAS
   2. CMS

TOP2017
1. ATLAS Differential X-Sections (M. Giannelli)
2. CMS Differential X-Sections (O. Hindrichs)
3. SUSY/DM (D. Guest)
4. VLQ (G. Van Onsem)
5. YSF (S. Egan)

Previous presentations:
   Top2016: (K. Kousouris)
   Top2015 (L. Skinnari)
The clouds of points in Fig. 3 correspond to a number of models in Refs. [80]; [81]: a heavy $W'$ boson exchanged in the $t$-channel, a heavy axi-gluon $G_\mu$ exchanged in the $s$-channel, and doublet ($\phi$), triplet ($\omega^4$) or sextet ($\Omega^4$) scalars. Each point corresponds to a choice of the new particle's mass, in the range between 100 GeV and 10 TeV, and of the couplings to SM particles, where all values allowed give a total cross-section for top-quark pair production at the Tevatron compatible with observations and a high-mass $t\bar{t}$ production cross-section ($m_{t\bar{t}} > 1$ TeV) at the LHC that is at most three times the SM prediction. The contribution from new physics to the Tevatron $A_{FB}$ is moreover required to be positive. The predictions of the Tevatron forward–backward asymmetry and the LHC high-mass charge asymmetry are calculated using PROTOS [83], which includes the tree-level SM amplitude plus the one(s) from the new particle(s), taking into account the interference between the two contributions. This measurement extends the reach of

[80] J. Aguilar-Saavedra, M. Perez-Victoria
Asymmetries in $t\bar{t}$ production: LHC versus Tevatron

CrossRef

[81] J. Aguilar-Saavedra, M. Perez-Victoria
Simple models for the top asymmetry: constraints and predictions
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<th>CMS</th>
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</table>
Figure 2: Values of the selection requirements in the top-tagging algorithm: (a) the lower threshold on \( m_{\text{jet}}^{\text{calib}} \) for the 50% working point; (b) the lower threshold on \( m_{\text{jet}}^{\text{calib}} \) for the 80% working point; (c) the upper threshold on \( \tau_{32} \) for the 50% working point and (d) the upper threshold on \( \tau_{32} \) for the 80% working point. The black points show the explicitly evaluated requirements, the red line shows the regularised interpolation.
# $\ell$+jets (13 TeV)

<table>
<thead>
<tr>
<th>Level</th>
<th>Detector</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>Resolved</td>
<td>Boosted</td>
</tr>
<tr>
<td>Leptons</td>
<td>$</td>
<td>d_{0}</td>
</tr>
<tr>
<td>Small-R jets</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Num. of small-R jets</td>
<td>$\geq 4$ jets $\geq 1$ jet Same as detector level</td>
<td></td>
</tr>
<tr>
<td>$E_T^{miss}, m_W^{miss}$</td>
<td>$E_T^{miss} &gt; 20$ GeV, $E_T^{miss} + m_W^{miss} &gt; 60$ GeV Same as detector level</td>
<td></td>
</tr>
<tr>
<td>Leptonic top</td>
<td>Kinematic top-quark reconstruction for detector and particle level At least one small-R jet with $\Delta R(\ell, \text{small-R jet}) &lt; 2.0$</td>
<td></td>
</tr>
<tr>
<td>Hadronic top</td>
<td>Kinematic top-quark reconstruction for detector and particle level The leading-$p_T$ trimmed large-R jet has: $</td>
<td>\eta</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>At least 2 $b$-tagged jets At least one of: 1) the leading-$p_T$ small-R jet with $\Delta R(\ell, \text{small-R jet}) &lt; 2.0$ is $b$-tagged 2) at least one small-R jet with $\Delta R(\text{large-R jet, small-R jet}) &lt; 1.0$ is $b$-tagged Ghost-matched $b$-hadron</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolved</td>
<td>Boosted</td>
</tr>
<tr>
<td>$tt$</td>
<td>$123800 \pm 10600$</td>
</tr>
<tr>
<td>Single top</td>
<td>$6300 \pm 800$</td>
</tr>
<tr>
<td>Multijets</td>
<td>$5700 \pm 3000$</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>$3600 \pm 2000$</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>$1300 \pm 700$</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
<td>$400 \pm 100$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$300 \pm 200$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$142000 \pm 11000$</td>
</tr>
<tr>
<td>Data</td>
<td>$155593$</td>
</tr>
</tbody>
</table>

# Boosted = 5% # Resolved
ℓ+jets (13 TeV)
$\ell + \text{jets}$

(13 TeV)

arXiv:1708.00727
All-hadronic (13 TeV)

Sub-leading Large-R Jet

<table>
<thead>
<tr>
<th>1t1b</th>
<th>0t1b</th>
<th>1t0b</th>
<th>0t0b</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>B</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>K</td>
<td>D</td>
<td>F</td>
<td>C</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>G</td>
<td>I</td>
</tr>
<tr>
<td>S</td>
<td>N</td>
<td>M</td>
<td>O</td>
</tr>
</tbody>
</table>

Leading Large-R Jet

\[
S = \frac{J \times O \cdot D \times A \cdot G \times A \cdot F \times A \cdot H \times A}{A \cdot B \times C \cdot E \times I \cdot E \times C \cdot B \times I} = \frac{J \times O \times H \times F \times D \times G \times A^3}{(B \times E \times C \times I)^2},
\]

ATLAS Simulation Preliminary $\sqrt{s} = 13$ TeV

Particle level fiducial phase-space

ATLAS Preliminary $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Fiducial phase space

prediction vs data
**ℓ+jets (8 TeV)**

- **p_{T,rel}>25 GeV**
  - (only using AK5 jets w/ pT>25 GeV)

### Data / MC vs Leading-jet p_{T} [GeV]

<table>
<thead>
<tr>
<th>Leading-jet p_{T} [GeV]</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>1</td>
</tr>
<tr>
<td>tt</td>
<td>2</td>
</tr>
<tr>
<td>W+jets</td>
<td>3</td>
</tr>
<tr>
<td>Single t</td>
<td>4</td>
</tr>
<tr>
<td>Multijet</td>
<td>5</td>
</tr>
<tr>
<td>Total unc.</td>
<td>6</td>
</tr>
</tbody>
</table>

### Data / MC vs Leading-jet \( \eta \) [GeV]

<table>
<thead>
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<th>Events</th>
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<tr>
<td>Data</td>
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<td>tt</td>
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<td>Multijet</td>
<td>5</td>
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<tr>
<td>Total unc.</td>
<td>6</td>
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### Integrated cross section [fb]

- 140–170: 12 ± 1.7
- 170–200: 42 ± 1.7
- 200–240: 27 ± 1.7
- 240–290: 18 ± 1.7
- 290–350: 1.7

### Statistical uncertainty [%]

- 140–170: 54 ± 1.3
- 170–200: 13 ± 1.3
- 200–240: 21 ± 1.3
- 240–290: 34 ± 1.3
- 290–350: 300

### Systematic uncertainty [%]

- 140–170: 40 ± 1.3
- 170–200: 9 ± 1.3
- 200–240: 16 ± 1.3
- 240–290: 20 ± 1.3
- 290–350: 25

### Model uncertainty [%]

- 140–170: 52 ± 1.3
- 170–200: 10 ± 1.3
- 200–240: 11 ± 1.3
- 240–290: 35 ± 1.3
- 290–350: 36

### Total uncertainty [%]

- 140–170: 85 ± 1.3
- 170–200: 19 ± 1.3
- 200–240: 28 ± 1.3
- 240–290: 53 ± 1.3
- 290–350: 300

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All-hadronic (8 TeV)
All-hadronic (8 TeV)

\[ L = \prod_i \prod_m \frac{N[i,m]^{n_i} e^{-N[i,m]}}{n_i!} \prod_j e^{P_j(i,m)} \prod_k e^{P_k(i,m)} \]

\[ N[i,m] = N_{tt}^{tag} \times P_{tt}(i,m) + N_{NTMJ}^{tag} \times P_{NTMJ}(i,m) + N_{tt}^{at} \times P_{tt}(i,m) + N_{NTMJ}^{at} \times P_{NTMJ}(i,m) \]

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>500-600</td>
<td>2.51</td>
<td>0.251</td>
<td>10.0</td>
<td>0.510</td>
<td>20.3</td>
<td>0.487</td>
<td>19.4</td>
<td>0.75</td>
<td>29.8</td>
</tr>
<tr>
<td>600-700</td>
<td>0.789</td>
<td>0.108</td>
<td>13.7</td>
<td>0.335</td>
<td>42.5</td>
<td>0.055</td>
<td>7.0</td>
<td>0.357</td>
<td>45.2</td>
</tr>
<tr>
<td>700-800</td>
<td>0.266</td>
<td>0.051</td>
<td>19.0</td>
<td>0.062</td>
<td>23.2</td>
<td>0.025</td>
<td>9.3</td>
<td>0.084</td>
<td>31.4</td>
</tr>
<tr>
<td>800-1200</td>
<td>0.042</td>
<td>0.001</td>
<td>23.5</td>
<td>0.013</td>
<td>31.3</td>
<td>0.008</td>
<td>19.7</td>
<td>0.018</td>
<td>43.8</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T$ [GeV ]</th>
<th>Data ± Tot. Unc.</th>
<th>POWHEG</th>
<th>MC@NLO</th>
<th>MADGRAPH</th>
<th>SemiLep</th>
<th>CT14</th>
</tr>
</thead>
<tbody>
<tr>
<td>500-600</td>
<td>2.51 ± 0.75</td>
<td>3.20</td>
<td>2.63</td>
<td>3.64</td>
<td>2.74</td>
<td>2.52</td>
</tr>
<tr>
<td>600-700</td>
<td>0.789 ± 0.357</td>
<td>0.972</td>
<td>0.754</td>
<td>1.11</td>
<td>0.786</td>
<td>0.733</td>
</tr>
<tr>
<td>700-800</td>
<td>0.266 ± 0.083</td>
<td>0.322</td>
<td>0.238</td>
<td>0.363</td>
<td>0.254</td>
<td>0.233</td>
</tr>
<tr>
<td>800-1200</td>
<td>0.042 ± 0.018</td>
<td>0.049</td>
<td>0.030</td>
<td>0.050</td>
<td>0.036</td>
<td>0.031</td>
</tr>
</tbody>
</table>
Jet Clustering

\[ d_i = p_{T_i}^{2a} \]

- \( a = 1 : k_T \)
- \( a = 0 : C/A \)
- \( a = -1 : \text{anti-}k_T \)

\[ d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \min(p_{T_i}^{2a}, p_{T_j}^{2a}) \]
Jet Clustering

1. Define the splitting scales for each input and pairs of inputs (Topoclusters or PF objects).

2. Find min\{d_{q}\}, where d_{q} includes all of the distance scales d_{i} and d_{ij}

3.(a) If min is a d_{ij}: redefine as d_{k}.

\[
pT_k = pT_i + pT_j
\]
\[
\eta_k = (pT_i \eta_i + pT_j \eta_j)/pT_k
\]
\[
\phi_k = (pT_i \phi_i + pT_j \phi_j)/pT_k
\]

3.(b) If min is a d_{i}: Remove from list and move to JET list

4. Repeat until all JETs formed
Jet Grooming

Pruning

Initial jet

Pruned jet

\[ p_T^{j_2} / p_T^{j_1 + j_2} > z_{cut} \text{ or } \Delta R_{j_1,j_2} < R_{cut} \]

Filtering

Initial jet

Filtered jet

\[ R_{filt} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}] \]

Trimming

Initial jet

Trimmed jet

\[ p_T^{i} / p_T^{jet} < f_{cut} \]
\[ \tau_N = \frac{1}{d_0} \sum_i p_T \times \min(\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}). \] (1)

Here \( \Delta R_{j,i} \) is the angular distance between the subjet axis \( j \) and the candidate jet \( i \). The normalization constant \( d_0 \) takes \( p_T \) into account, with \( d_0 = \sum p_T R_0 \), and \( R_0 \) is the distance parameter used in the jet clustering algorithm (here \( R_0 = 0.8 \)). If a jet is \( N \)-pronged, then \( \tau_N \) is small, whereas \( \tau_{N-1} \) and lower moments are all larger. This analysis primarily makes use of \( \tau_{32} \) defined as \( \tau_3 / \tau_2 \).