Using substructure in boosted top quark events

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Northwest Terascale Workshop

Outline:

- Use case for boosted tops
- ATLAS boosted top jet definitions
- Comparing taggers
- What's next?
Introduction

- Sorry that this will be much more qualitative than quantitative...no new public results in the last few months

- Internally, we had an ATLAS boosted top workshop where various taggers were compared...
  - I'll tell you some conclusions
  - You tell me if you think some of them are controversial enough that you'd want to see a plot to prove it
Where we are now
Boosted tops

How many boosted tops are we talking about?

- Clean sample of boosted hadronic top events in data:
  \[\text{ttbar} \rightarrow \text{WbWb} \rightarrow l\nu q + qqq\]
- ATLAS basic event selection, + hadronic top anti-kt R=1.0 jet has \(p_T>350\) GeV and \(120<M_{\text{jet}}<220\) GeV
- expect \(\sim 1700\) ttbar (l+jets) events in 20fb-1 at \(\sqrt{s}=8\) TeV

ATLAS public results:

- \(Z' \rightarrow \text{ttbar resonance in the semi-leptonic channel}\)
- \(Z' \rightarrow \text{ttbar resonance in the fully hadronic channel}\)
Boosted tops

**lvq qqq analysis:**

- Mini-isolation for the lepton: $I_{\text{mini}}^l = \sum_{\text{tracks}} \frac{p_T^{\text{track}}}{p_T^l} < 0.05$
- Large-R jet trigger (fully efficient for R=1.0 jets with $p_T > 350$ GeV)
- 1 btag (anti-kt R=0.4)
- 1 anti-kt R=1.0 jet, $p_T > 350$ GeV, $M > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV

**qqq qqq analysis:**

- HEPTopTagger (C/A, R=1.5), $p_T > 200$ GeV
- TopTemplate tagger (anti-kt, R=1.0), $p_T > 450$ GeV
- 2 btags (anti-kt R=0.4) associated to the jets

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ATLAS-CONF-2012-136

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ATLAS-CONF-2012-102
Semi-lep ttbar resonance search

- With added boosted selection, Z' limit extended by ~800 GeV!

ATLAS-CONF-2012-136

ATLAS Preliminary

Boosted tops....we need them!
ATLAS boosted top jet definitions

- Lot of work was done to optimize grooming parameters in ATLAS
  - ATLAS-CONF-2012-065, ATLAS-CONF-2012-066

- Jets in ATLAS used for boosted tops:
  - anti-kt R=1.0 with trimming
    \( f_{\text{cut}} = 5\% \), \( R_{\text{sub}} = 0.3 \)
  - HEPTopTagger and TopTemplate
    (back to operating points later)

- We currently do not apply pileup subtraction to large-R jets

- How we optimized grooming:
  - Substructure variables vs pileup dependence (dijets only in data)
  - Mass resolution (MC) in dijets and Z' → ttbar events
  - Data/MC agreement in dijets and in boosted top enriched sample
    (though small statistics in the latter)
Trimming settings...optimized for tops?

- ...what if $R_{\text{sub}}$ is too big? or $f_{\text{cut}}$ too tight?

- $f_{\text{cut}} = 3\%$, $R_{\text{sub}} = 0.2$ seems to do pretty well in different pT ranges (orange squares, compare to default green triangles)

![Graph](image1)

(a) Trimmed anti-$k_t$: $200 \text{ GeV} \leq p_T^{\text{jet}} < 300 \text{ GeV}$

(b) Trimmed anti-$k_t$: $600 \text{ GeV} \leq p_T^{\text{jet}} < 800 \text{ GeV}$

Conclusion: looking at a few other data comparisons, $f_{\text{cut}} = 5\%$, $R_{\text{sub}} = 0.3$ is still the best (will demonstrate more quantitatively at BOOST).
Efficiency of grooming on tops

- Often we say trimming/pruning has 100% efficiency, because you always keep the jet (groomers as opposed to taggers).
- But now think of grooming on a top jet....efficiency is whether or not you can identify the jet afterwards...usually in a mass window.
  - Take a jet that has all three decay products inside R<1.0.
  - If one of the three subjets has $p_T < 5\%$ of the total top $p_T$, it gets trimmed away...need to check if $f_{\text{cut}}$ is too tight.

![Graphs showing data distributions for ungroomed and trimmed top jets with b-tagging.](image-url)
Efficiency of grooming on tops

- Turns out even at really high top pT, this can still happen, and in fact, happens more often!

Pythia8 fully hadronic top from Z'->ttbar, take MC modeling with caution!

- Luckily so far in SM ttbar events, MC seems to model data very well after trimming with $f_{cut} = 5\%$, $R_{sub} = 0.3$
Grooming optimization

- Some controversy arose over the comparison between ATLAS and CMS, where CMS found that pruning worked better than trimming
Grooming optimization

- Some controversy arose over the comparison between ATLAS and CMS, where CMS found that pruning worked better than trimming.
- ...turns out which “works better” is highly dependent on R parameter.

Point: pruning, trimming, they work (at least with pileup <30). We're sticking with akt1.0 trimmed for boosted tops. What's next?
Comparing taggers
Comparing taggers

“What's the best tagger?”

Mistag vs efficiency for optimized parameters, Herwig++ ttbar and dijets (BOOST 2011)

(a) all $p_T$, optimised

(b) $p_T$ 500–600 GeV, optimised
Comparing taggers

- Larger R parameter works better at low pT (obviously)

- HEPTopTagger used C/A R=1.5, TopTemplating used anti-kt R=1.0

- Different R-size changes optimization
  - Use variable-R jets?

- Hard to compare details, but in the end, different algorithms seem to give the same results at higher pT
Comparing taggers in ATLAS

- Standard ATLAS large-R jet selection for boosted tops (Z'):
  - anti-kt R=1.0, trimmed with $f_{\text{cut}}=5\%$ and $R_{\text{sub}} = 0.3$
  - $\sqrt{d_{12}} > 40 \text{ GeV}$
  - $M > 100 \text{ GeV}$

- Another attempt to optimize info from substructure:
  - anti-kt R=1.0, trimmed with $z_{\text{cut}}=5\%$ and $R_{\text{sub}} = 0.3$
  - $\sqrt{d_{12}} > 40 \text{ GeV}$
  - $\tau_{32} < 0.7$ and $0.4 < \tau_{21} < 0.85$

- HEPTopTagger (C/A, R=1.2):

<table>
<thead>
<tr>
<th></th>
<th>Default</th>
<th>Tight</th>
<th>Loose</th>
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</thead>
<tbody>
<tr>
<td>$m_{\text{cut}} [\text{GeV}]$</td>
<td>30</td>
<td>30</td>
<td>70</td>
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<tr>
<td>$R_{\text{jet}}$</td>
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<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>$N_{\text{subjet}}$</td>
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<td>4</td>
<td>7</td>
</tr>
<tr>
<td>$f_{W} [%]$</td>
<td>15</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>
Comparing taggers

- $Z' \rightarrow \text{ttbar signal, QCD background, leading jet } p_T > 150 \text{ GeV}$

- At some point, correlations between substructure variables limit how well you can do (there is only so much information)
How to choose?

- Substructure variables have been optimized to discriminate something with substructure vs something without
  
  → need to go more top-specific

- We have to go to the analysis
  
  • High efficiency? or better background rejection?

- ...but most importantly, **systematics**!!!
Scale uncertainty derivation

- **Double ratio method:**

  \[ r^m_{\text{track jet}} = \frac{\text{calo jet}}{\text{track jet}} \]

  Take mean of \( r^m_{\text{track jet}} = R_{\text{data}} \) or \( R_{\text{MC}} \)

- Compute \( R_{\text{data}} / R_{\text{MC}} \)

- Systematic is deviation from 1, taking the statistical uncertainty of the calo-to-track jet ratio into account

  - weighted average (\( w_{\text{bin}} \) is the stat uncertainty):

    \[
    \langle \delta_{\text{MC}} \rangle = \frac{\sum_{\text{bins}} w_{\text{bin}} (R^m_{r\text{track-jet}} - 1)}{\sum_{\text{bins}} w_{\text{bin}}}
    \]

  - Take the larger of either the Pythia or POWHEG or Herwig++ comparison

  - This works for any substructure observable!
Mass scale uncertainty with $W$

- Use $t\bar{t}b$ selection with lower $p_T$ in order to see the hadronic $W$ in top events
- Allows us to study the scale using a particle with known mass
- anti-$k_t$ with trimming: $(0.5 \pm 1.2\text{(stat)} \pm 2.7\text{(sys)})\%$

![Graph showing mass scale uncertainty with $W$.](image)

**ATLAS Preliminary**

Events containing $W \rightarrow \mu \nu$
- anti-$k_t$, LCW jets with $R=1.0$
- Trimmed with $p_T > 200 \text{ GeV}$

**ATLAS Preliminary**

- Trimmed with $f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.3$
- For $|\eta| < 1.2$ and $200 < p_T < 1000 \text{ GeV}$

\[
\int L \, dt = 4.7 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}
\]
How to choose?

- Eg: N-subjettiness \((\beta = 1)\)
  - Looks great in a few different metrics
    - dijet rejection vs boosted top
    - less correlated with mass (unlike \(\sqrt{d12}\))

- However,
  - Can't use \(\tau_{32}\) with grooming unless we are ok with a larger fake rate (but maybe some pileup correction)
  - Doesn't work against \(W+\)jets background in semi-lep case

- Poor MC modeling (except Herwig++) without trimming \(\rightarrow\) larger acceptance systematic
btagging alternatives?

- Problem: b-tagging is much easier with low pT (<100 GeV), isolated b-jets

- Work is also ongoing to solely use substructure, but b-tagging still wins getting rid of W+jets background

- Turn to b-tagging with track jets?
What are we getting ready for?
More boost!

- From Gavin:
More boost!

- From Gavin:

  - Taggers need to be tested over a broad pT range

**In boosted regime**

Use output of a 3-pronged tagger when checking for consistency with the top mass

Use the original fat jet as an input to the di-“top” mass spectrum in searches
Summary

- Substructure in boosted tops increases efficiency at high pT
- Taggers need to be tested over a broad pT range
- We're now at the point where taggers need to be optimized in each individual analysis
  - Different backgrounds
  - Different pT-ranges
  - Different event topologies (not just ttbar resonances!)
  - Different “important” systematics (eg: searches v measurements)
- Pileup effects are reduced with grooming, but soon (already 2012 data) we'll need to also apply pileup subtraction to large-R jets