BOOSTED W BOSON TAGGING
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Tim Bristow
University of Edinburgh
Contents

- The LHC and ATLAS
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- What are jets?
- What does it mean if jets are boosted?
- Substructure variables and de-clustering techniques to identify boosted jets,
- Finding $W$ bosons from boosted jets,
- Results.
The Large Hadron Collider is the world's most powerful accelerator

- Centre-of-mass energy of up to $\sqrt{s}=14$ TeV,
- Circumference of 27 km and 100 m underground,
- Protons get accelerated to almost the speed of light and then collided within detectors along the circumference,
- The collisions release massive amounts of energy creating (new???) particles.

ATLAS is one of the two general-purpose detectors at the LHC

- About the size of a 6 storey building,
- Takes up to 40 million recordings of collisions per second,
- One of the experiments that announced discovery of the Higgs boson in 2012!
Run II

- We’re about to start the LHC again!
  - Running at 13 TeV for the first time,
  - Much higher energy than before (which complicates things),
  - We hope we’ll see New Physics!
  - All very exciting

- If there are new particles created, like a W’, or a heavy Higgs boson, it’s likely that they will decay into W bosons
  - These W bosons can then decay hadronically,
  - We need to make sure we can identify these new particles,
  - We need to be able to identify these W bosons anyway…
Jets

- Heavy gauge bosons, like $W/Z$ bosons, decay into quarks which get reconstructed as jets.
- Quarks and gluons from collisions hadronise due to QCD confinement,
- These leave energy deposits in the detector,
- We cluster these together (there are lots of algorithms to do this like the anti-kt algorithm) into narrow cones called jets,
  - Cone size (typically 0.4 for jets) is defined as
    \[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]
  - Generally these jets come from a single particle
- At high energies this gets more difficult
  - Multiple interactions in a short space of time produce pile-up in the detector,
  - The decay products have much more energy and momentum,
  - Decays are more collimated due to a Lorentz boost -- a boosted jet!

Anti kt algorithm: http://arxiv.org/abs/0802.1189
A boosted jet is a jet that has had a large Lorentz boost because it has a high momentum.

Multiple boosted jets can look like one single jet!

Groomers de-cluster the jets into smaller sub-jets by undoing the clustering done with the jet clustering algorithm and applying additional requirements to identify hard substructure within the jet.

Substructure within jets can be used to properly classify boosted jets or heavy boosted particles like W and Z bosons or top quarks.

Substructure can be quantified by a number of variables categorised into multiple sections: jet shapes, splitting scales,subjettiness, centre of mass jet shapes.
Boosted W boson tagging method

- Looking for a way of identifying boosted jets originating from W bosons rather than quarks or gluons --- W boson tagging,
- We simulate some collisions at 13 TeV
  - 13 TeV $qqqq \rightarrow W' \rightarrow WZ \rightarrow qqqq$
  - 13 TeV $llqq \rightarrow HVT \rightarrow VcWZ \rightarrow llqq$
  - QCD background with lots of jets
- Find jets that have been reconstructed with multiple types of groomers,
- We use a bigger cone size of 1.0 or 1.2, instead of 0.4,
- Calculate the substructure variables,
- The best configurations are chosen on their background rejection power (inverse background rejection) for each variable with a given groomer
  - 27 groomers with 10+ taggers initially,
  - Now three groomers and three potential taggers
  - Anti-$k_t$ trimming groomer is the current favourite,
- The current selection of groomers is based on Run I (8 TeV) results, but we need to see if this is good enough for Run II as well (13 TeV).
Three grooming techniques are currently used for Run II boosted $W$ boson tagging:

**Pruning** - jets are re-clustered, cutting on the angular distance between two sub-jets and the fraction of the $p_T$ carried by the lighter sub-jet. These should do well since the boson $p_T$ spectrum is expected to be symmetrical between sub-jets.

**Trimming** - Jets are un-clustered into sub-jets, where each one has a certain fraction of the total jet momentum. This uncovers hard substructure independently of pileup.

**BDRS** (or mass drop filtering) – jets are unclustered using the reverse of the initial clustering steps into 3 sub-jets. The mass drop (mass of the hardest sub-jet as a fraction of the jet’s mass) and momentum balance between the sub-jets and jet is calculated. If there is a large mass drop or the momentum balances, the sub-jet is presumed to be a hard structure and is returned as a jet.

https://cds.cern.ch/record/1577417

Jet mass

Jet mass with an anti-kT trimming groomer algorithm.

We apply a 68% mass window cut to remove background.
Jet mass response

\[ p_T \, 200 - 350 \text{ GeV} \quad \text{versus} \quad p_T \, 1 - 1.5 \text{ TeV} \]

Jet mass response with an anti-\( kT \) trimming groomer algorithm.

- Jet mass response = Groomed jet mass / truth jet mass
Substructure variables

- Variables describing the substructure within a jets helps identify if boosted jets are from a single particle

- \( N \)subjettiness (\( \tau_N \)): The degree to which the substructure resembles \( \leq N \) sub-jets. This is the \( p_T \) weighted \( \Delta R \) between each constituent and its nearest sub-jet axis. The ratio \( \tau_{21}, \tau_{2/1} \), gives good two body sub-jet identification.

- Energy correlation variables (EEC): Angular separation weights are used for each sub-jet multiplied by the sum of the sub-jet momenta. Variations of ratios of these functions offer good two body identification.

\[
\tau_0(\beta) = \sum_{i \in J} p_T_i \Delta R^\beta_{i,0}, \quad \beta = 1; k \text{ over all constituents; } \Delta R \text{ is rapidity between subjet axis } a \text{ and } k; R_0 \text{ characteristic radius}
\]

\[
\tau_1(\beta) = \frac{1}{\tau_0(\beta)} \sum_{i \in J} p_T_i \Delta R^\beta_{a1,i},
\]

\[
\tau_2(\beta) = \frac{1}{\tau_0(\beta)} \sum_{i \in J} p_T_i, \text{min}(\Delta R^\beta_{a1,i}, \Delta R^\beta_{a2,i}),
\]

\[
E_{CF0}(\beta) = 1,
\]

\[
E_{CF1}(\beta) = \sum_{i \in J} p_T_i,
\]

\[
E_{CF2}(\beta) = \sum_{i<j \in J} p_T_i p_T_j (\Delta R_{ij})^\beta,
\]

\[
E_{CF3}(\beta) = \sum_{i<j<k \in J} p_T_i p_T_j p_T_k (\Delta R_{ij} \Delta R_{jk} \Delta R_{jk})^\beta.
\]


http://arxiv.org/abs/1411.0665
Energy correlation variables

\[ p_T \ 200 – 350 \text{ GeV} \quad \text{and} \quad p_T \ 1 – 1.5 \text{ TeV} \]

\[ D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3} \]

where

\[ e_2^{(\beta)} = \frac{E_{CF2}}{E_{CF1}^2} \]

\[ e_3^{(\beta)} = \frac{E_{CF3}}{E_{CF1}^3} \]

D2 is one of the ratios of the correlation functions (slide 7). Here, the angular weight, \( \beta = 1 \).
Here, the WTA indicates that a different axis was used in the calculation for the angular separation. The axis for the hardest sub-jet is used, instead of the jet’s axis (red instead of green).
Background rejection power

$\mathcal{P}_{\mathcal{T}} \, 200 - 350 \, \text{GeV}$

Higher (red) indicates better rejection power.

Top groomer (trimming) and variables

All variables are used within a 68% mass window

Background rejection power (1/ (1-signal eff))
Background rejection power

\[ p_T \ 1 - 1.5 \ TeV \]

Higher (red) indicates better rejection power.

Top groomer (trimming) and variables

All variables are used within a 68% mass window
Conclusion

- This is an important study for reconstructing boosted W bosons during Run II,
- The current selection of groomers is based on Run I (8 TeV) results, but we need to see if this is good enough for Run II as well (13 TeV).
- The Run I taggers seem to work equally well on the 13 TeV simulations and the 8 TeV data.
  - Consistently see the N-subjettiness and energy correlation variables performing well.
  - Anti-kT trimming groomer looks like the best option.
- Next step is to investigate if we benefit by combining multiple taggers into an MVA.
Backup

Filtering

Type 1 (Trimming): If $p_T$ (subjet i) / $p_T$ (jet) < $f_{cut}$: discard subjet.
Type 2: If $N_{subjets}$ ≤ $N_{min}$: discard jet.
Resulting jet is sum of subjets.

Pruning

$z = p_T(i) / p_T(i+1)$
$p_T(i) < p_T(1)$

For each step in clustering

At each step:
If $\Delta R_{ij} < d_{cut}$ OR $z > z_{cut}$
continue to next step.
Otherwise, discard object $i$. 