Searches of BSM physics with boosted hadronically-decaying objects at the LHC

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Introduction

- Current bounds of new physics particles
- Looking for a heavy resonance
- Difficulty of distinguishing the decay products of top, W and Z.
- Analysis of jet substructure
The Higgs boson

**VH production**: $pp \rightarrow Wh, Zh$

- Leptons and b-jets have to be central and with sufficiently high $p_T$ to be tagged.
- Large background from $t\bar{t}$ to b-quarks (with energy $\sim 65$ GeV at top c.o.m.) and leptonically decaying $W$.

**VH production in a boosted regime**: Both bosons with large $p_T$ and back to back, only $\sim 5\%$ of the events with $p_T > 200$ GeV.

- Sufficiently large $p_T$ of the products of the Higgs.
- On-shell top-quarks can not produce a high-$p_T$ bb system.
A boosted higgs boson

Identifying the Higgs as a single jet

The strategy should flexibly adapt to the angular separation of the decay products, which vary with $p_T$ of the higgs boson.

$$R_{b\bar{b}} \approx \frac{1}{\sqrt{z(1-z)}} \frac{m_h}{p_T} \geq 2 \frac{m_h}{p_T} \quad (p_T \gg m_h)$$

Large enough $R_{bb}$ to contain QCD radiation from the Higgs decay.

The proposed algorithm:
Mass drop and filtering

Butterworth et. al. 2008
Jet Substructure

Jet Clustering

The splitting probability of a parton $k$ to go into $i$ and $j$, soft and collinear partons,

$$\frac{dP_{k\to ij}}{dE_i d\theta_{ij}} \sim \frac{\alpha_s}{\min(E_i, E_j) \theta_{ij}}$$

A distance that is essentially proportional to the squared inverse of the splitting probability

$$y_{ij} = \frac{2 \min(E_i^2, E_j^2)(1 - \cos \theta_{ij})}{Q^2}$$

where $Q$ is the total energy of the event.

Notice that if $\theta \ll 1$ then

$$2 \min(E_i^2, E_j^2) = p_T^2 \text{ of } i \text{ relative to } j$$

The particles that have the min $y_{ij} < y_{\text{cut}}$ are recombined into a single new particle (or pseudojet).
Jet Clustering

**kt-algorithm**

The distance

$$\min(p_t^2, p^2) \frac{\Delta R^2_{ij}}{R^2}$$

The cut value: $p_{ti}^2$, $R$

**antikt-algorithm**

The distance

$$\min(p_{t_i}^{-2}, p_t^{-2}) \frac{\Delta R^2_{ij}}{R^2}$$

The cut value: $p_{ti}^{-2}$, $R$

**C/A-algorithm**

The distance

$$\frac{\Delta R^2_{ij}}{R^2}$$

The cut value: $R$
Jet Substructure

Analyzing Jet Substructure

Grooming
- filtering
- pruning
- trimming

Taggers
- Top tagger (HEP top tagger)
- b-tagger
- Quark-gluon tagger

N-subjettiness

I will discuss these techniques in the context of resonances
Grooming

Get rid of underlying events or pile-up and leave the constituents of the hard scattering.

Emily Thompson talk, ATLAS collaboration (2012)
Mass drop and filtering

Cluster events using C/A algorithm.

1. Undo the last stage of clustering to get $j_1$ and $j_2$ ($m_{j_1} > m_{j_2}$).
2. If mass drop $m_{j_1} < \mu m_j$, and $y = \frac{\min(p_{T, j_1}, p_{T, j_2})}{m_j} \Delta R^2_{j_1,j_2} > y_{cut}$, then $j$ is a heavy particle.
3. Otherwise $j = j_1$ and go back to step 1.

filtering: Recluster using CA with $R_{filt} = \min(0.3, R_{b\bar{b}}/2)$
Pruning

The standard jet algorithm are base on the dominant soft and collinear physics of the QCD shower. For a recombination $1, 2 \rightarrow p$

$$z \equiv \min\left(\frac{p_{T,1}}{p_{T,p}}, \frac{p_{T,2}}{p_{T,p}}\right), \quad \theta \equiv \Delta R_{12}$$

For heavy particle decays $\Rightarrow$ final recombinations at large $\theta$

For QCD $\Rightarrow$ small $\theta$ and small-$z$

We need to systematically removes soft, large angle recombinations.

**Pruning procedure:** rerun the algorithm and vetoing on these recombinations

$z_{\text{cut}}$: how small $z$ can be.

$D_{\text{cut}}$: minimum angle of the recombination.
Pruning

For $z = 0.1$ and $D_{cut} = 0.5 \frac{m_J}{p_T,J}$

Vermilion et. al. 2009
Top Tagger

HEP top tagger

- Define a C/A fat jet with $R = 1.8$
- Identify all hard subjets using the mass drop criterion.
- Iterate through all triplets of three hard subjets and filter $R_{filt} = \min(0.3, \Delta R_{jk}/2)$, $N_{filt} = 5$. Reject all the triplets outside $m_{123} \in [150.0, 200] \text{ GeV}$
- Fulfill kinematic relations to get $m_{123}/m_{ij} = (1 \pm 0.15)m_t/m_W$

- Of all the triplets passing the criteria choose the one with $m_{123}$ closer to $m_t$. 

![Diagram](image)
Quark Gluon Tagger

Gallichio and Schwartz 2011

The average multiplicity is sensitive to the color factors

\[
\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F} \quad \text{and} \quad \frac{\sigma^2_g}{\sigma^2_q} = \frac{C_A}{C_F}
\]

No. of tracks and Linear Radial Momentum = \( \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |\Delta R_i| \) the most powerful discriminator.
N-subjettiness

Thaler and Tilburg 2011

\[ \tau_N = \frac{\sum_k p_{T,k} \min(\Delta R_{1,k}, \ldots, \Delta R_{N,k})}{R_0 \sum_k p_{T,k}} \]

\( R_0 \) es the R parameter of the jet used for clustering.

Subjet directions

The best procedure is to use the directions that minimize the value of \( \tau_N \) (computationally expensive)

The standard procedure is to run a kt-algorithm adapting \( \Delta R \) to find N subjets inside the jet.
N-subjettiness

\( \tau_1 \) and \( \tau_2 \) are similar

The ratio is a powerful discriminator
Searches of new physics using boosted objects

Resonance searches with Top Tagger

T. Plehn et al. 2015

→ Off-shell tops and final state radiation
→ Hard radiated gluons do not enter the top reconstruction
→ Asymmetric tail in $m_{ff}$ distribution
Resonance searches with Top Tagger

MultiVariate Analysis

Booted decision trees
Extended cut-based selection
A simplified model for the gluon prime

The Lagrangian of the neutral currents

$$\mathcal{L} \supset \bar{\psi}^i \gamma^\mu g_{ij} G_{\mu}^{(1)} \psi^j$$

A source of flavour violation

$$U_L^{-1} \begin{pmatrix} g_{uL} & 0 & 0 \\ 0 & g_{cL} & 0 \\ 0 & 0 & g_{tL} \end{pmatrix} U_L \equiv \begin{pmatrix} \Gamma_{qq} g_s & \Gamma_{qq} g_s' & \Gamma_{qt} g_s \\ \Gamma_{qq} g_s' & \Gamma_{qq} g_s & \Gamma_{qt} g_s \\ \Gamma_{qt} g_s & \Gamma_{qt} g_s & \Gamma_{tt} g_s \end{pmatrix}, \quad \Gamma_{ij} = \Gamma_{ij \, L} = \Gamma_{ij \, R}$$

ATLAS search of resonances decaying to $t\bar{t}$ excludes $m_G < 1.62$ TeV, for $\Gamma_{qq \, L} = \Gamma_{qq \, R} = 0.2$ and $\Gamma_{tt \, L} = 1.0$, $\Gamma_{tt \, R} = 4$
The discovery channel for Gluon prime

The ATLAS TT algorithm

We use C/A algorithm with $R = 1.0$ to cluster the fat jets and select the two hardest ones.

1. The fat jets should have $p_T > 200$ GeV and $y < 2.5$
2. One top jet [HEP Top Tagger] with $p_T > 200$ GeV
3. Two b-tagged jets [b-tagger template] jets identifies with anti-kt algorithm, $R = 0.4$

Our approach

We use C/A algorithm with $R = 1.5$ to cluster the fat jets and select the two hardest ones.

1. The fat jets should have $p_T > 400$ GeV and $y < 2.5$
2. Two top jet [HEP Top Tagger] with $p_T > 500$ GeV
3. $\tau_3/\tau_1 < 0.3$ for each top jet.
A signal of Flavour Violation

Assuming a heavy resonance has been discovered in the $t\bar{t}$ channel

$$m_{G(1)} = 2 \text{ TeV}$$

we fix $\Gamma_{G(1)} = 65 \text{ GeV}$.

**The TJ algorithm**

We use C/A algorithm with $R = 1.5$ to cluster the fat jets and select the two hardest ones.

1. The fat jets should have $p_T > 400 \text{ GeV}$ and $y < 2.5$
2. One top jet [HEP Top Tagger] with $p_T > 500 \text{ GeV}$
3. One light quark jet [Quark-gluon Tagger] identified with anti-kt ($R = 0.6$) with $p_T > 500 \text{ GeV}$.
4. $\tau_3/\tau_1 < 0.3$ for the top jet.
5. $1700 \text{ GeV} \leq M_{\text{inv}} \leq 2100 \text{ GeV}$
N–subjettiness in HEP top tagger

**N–subjettiness:**
Measures the radial distance of the particles to the closest sub-jet axes.

The direction of the pseudojets:

- $\tau_3$: $J_1, J_2, J_3 \Rightarrow p_{\text{bottom}}, p_{j_1}, p_{j_2}$ from HEP top tagger.
- $\tau_1$: $J_1 \Rightarrow$ The direction of the fat jet.

$\tau_3/\tau_1$ to distinguish Top jet from light quark-jet
parameters: $\Gamma_{qq} = 1, \Gamma_{tt} = 1, \Gamma_{\bar{t}t} = 1$

<table>
<thead>
<tr>
<th>Cut</th>
<th>QCD</th>
<th>$t\bar{t}$</th>
<th>$G \rightarrow t\bar{t}$</th>
<th>$G \rightarrow t\bar{q} (\bar{t}q)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 fat jets</td>
<td>1.61 nb</td>
<td>0.25 pb</td>
<td>2.49 pb</td>
<td>15.8 pb</td>
</tr>
</tbody>
</table>

**TT algorithm**

<table>
<thead>
<tr>
<th>Cut</th>
<th>QCD</th>
<th>$t\bar{t}$</th>
<th>$G \rightarrow t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two tops</td>
<td>31.7 fb</td>
<td>15.7 fb</td>
<td>293 fb</td>
</tr>
<tr>
<td>$\tau_3/\tau_1 &lt; 0.3$</td>
<td>3.1 fb (13)</td>
<td>8.9 fb (590)</td>
<td>131 fb (7234)</td>
</tr>
</tbody>
</table>

**TJ algorithm**

<table>
<thead>
<tr>
<th>Cut</th>
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</tr>
</thead>
<tbody>
<tr>
<td>One Top</td>
<td>4.98 pb</td>
<td>89.4 fb</td>
<td>5.38 pb</td>
</tr>
<tr>
<td>One light-quark jet</td>
<td>2.72 pb</td>
<td>11.32 fb</td>
<td>4.00 pb</td>
</tr>
<tr>
<td>$\tau_3/\tau_1 &lt; 0.3$</td>
<td>817 fb</td>
<td>7.7 fb</td>
<td>2.67 pb</td>
</tr>
<tr>
<td>1.7 TeV $&lt; M_{inv} &lt; 2.1$ TeV</td>
<td>217 fb (910)</td>
<td>2.2 fb (145)</td>
<td>2.29 pb (20115)</td>
</tr>
</tbody>
</table>
A signal of flavour violation

The required luminosity to get $5\sigma$

$$\mathcal{L}_{TT}^{5\sigma} = 4.5 \left( \frac{0.5}{\Gamma_{qq}} \right)^4 \left( \frac{0.5}{\Gamma_{tt}} \right)^4$$

$$\mathcal{L}_{TJ}^{5\sigma} = 10.4 \left( \frac{0.5}{\Gamma_{qq}} \right)^4 \left( \frac{0.2}{\Gamma_{tq}} \right)^4$$
Prospects

- Improving the algorithm
- A more realistic QCD background
- Detector effects (specially for the quark-gluon tagger)
- A multivariate analysis (MVA)