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

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Work in progress
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Table of contents

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

Butterworth et. al. 2008

VH production: $pp \to Wh, Zh$

- Leptons and b-jets have to be central and with sufficiently hight p_T to be tagged.
- Large background from $t\bar{t}$ to b-quarks (with energy ~ 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

Butterworth et. al. 2008

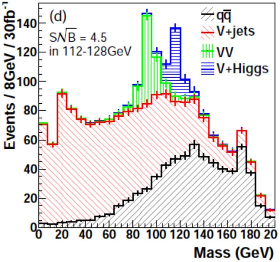
Identifying the Higgs as a single jet

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

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

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

The proposed algorithm:
Mass drop and filtering



Jet Clustering

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

$$\frac{\mathrm{d}P_{k\to i\,j}}{\mathrm{d}E_i\mathrm{d}\theta_{i\,j}} \sim \frac{\alpha_s}{\min(E_i, E_j)\theta_{i\,j}}$$

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

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

where Q is the total energy of the event.

Notice that if $\theta \ll 1$ then

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

The particles that have the min $y_{i\,j} < y_{\mathrm{cut}}$ are recombined into a single new particle (or pseudojet).

Jet Clustering

kt-algorithm

The distance

$$\min(p_{t\ i}^2, p_t^2\ )\frac{\Delta R_{ij}^2}{R^2}$$

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

antikt-algorithm

The distance

$$\min(p_{t\ i}^{-2}, p_t^{-2})\frac{\Delta R_{ij}^2}{R^2}$$

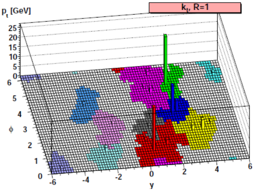
The cut value: p_{ti}^{-2}, R

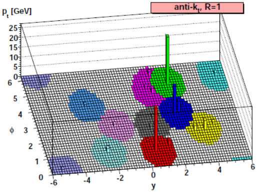
C/A-algorithm

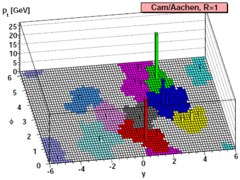
The distance

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

The cut value: R







Analyzing Jet Substructure

Grooming

- filtering
- pruning
- trimming

Taggers

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

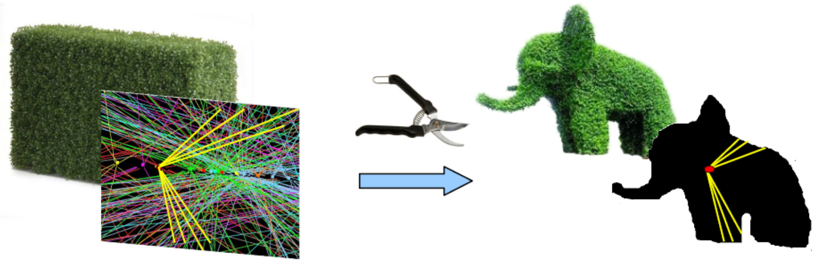
N-subjettiness

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)



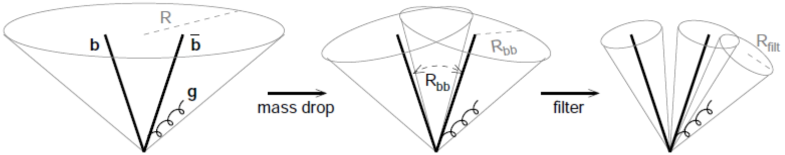
Mass drop and filtering

Butterworth et. al. 2008

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 $y = \frac{\min(p_{T\ j_1}^2, p_{T\ j_2}^2)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{cut}$, 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

Vermilion et. al. 2009

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

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

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

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

We need to systematically removes soft, large angle recombinations.
Pruning procedure: rerun the algorithm and vetoing on these recombinations

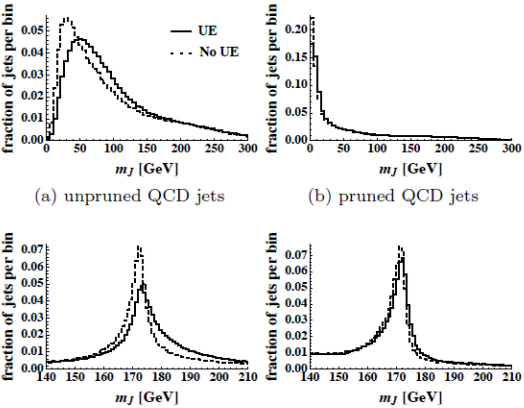
z_{cut}: how small z can be.

D_{cut}: minimum angle of the recombination

Pruning

Vermilion et. al. 2009

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

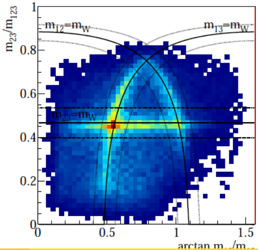


Top Tagger

T. Plehn et al. 2010

HEP top tagger

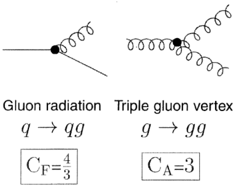
- Define a C/A fat jet with $R = 1.8$
- Identify all hard subjets using the mass drop criterion.
- Iterate through all triplets of three hard subjets and filter $R_{filt} = min(0.3, \Delta R_{jk}/2)$ $N_{filt} = 5$. Reject all the triplets outside $m_{123} \in [150.0, 200]$ GeV
- Fulfill kinematic relations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



Quark Gluon Tagger

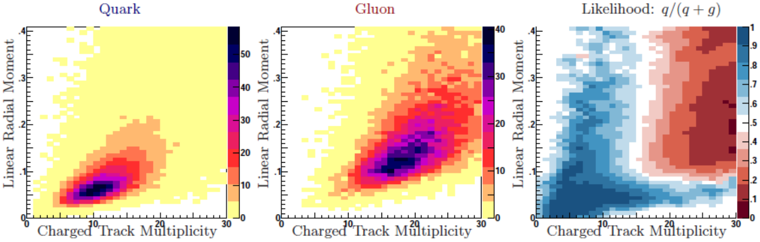
Gallichio and Schwartz 2011

The average multiplicity is sensitive to the color factors



$$\frac{< N_g >}{< N_q >} = \frac{C_A}{C_F} \quad \text{and} \quad \frac{\sigma_g^2}{\sigma_q^2} = \frac{C_A}{C_F}$$

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

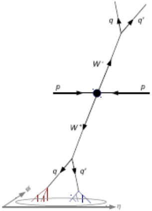
$$\tau_N = \frac{\sum_k p_{T,k} \min(\Delta \mathrm{R_{1,k}}, ..., \Delta \mathrm{R_{N,k}})}{R_0 \sum_k p_{T,k}}$$

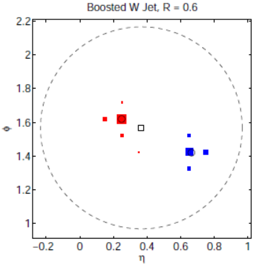
R_0 es the R parameter of the jet used for clustering.

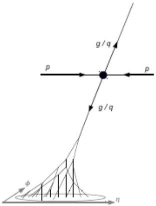
Subjet directions

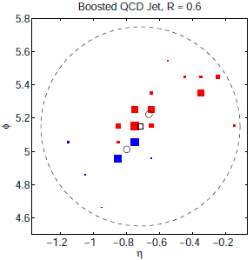
The best procedure is to use the directions that minimize the value of τ_N (computationally expensive)

The standard procedure is to run a kt-algorithm adapting ΔR to find N subjets inside the jet.



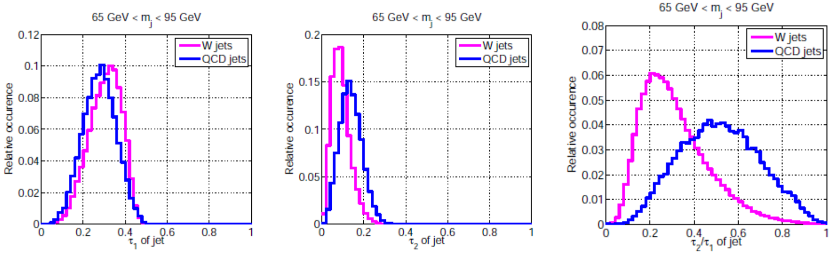






N-subjettiness

τ_1 and τ_2 are similar



The ratio is a powerful discriminator

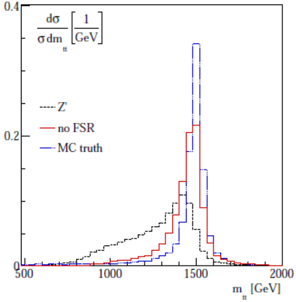
Resonance searches with Top Tagger

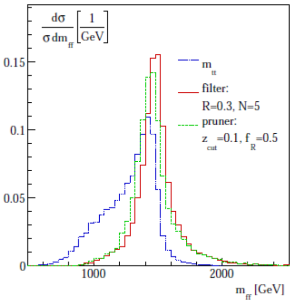
T. Plehn et al. 2015

→ Off-shell tops and final state radiation

→ Hard radiated gluons do not enter the top reconstruction

→ Asymmetric tail in m_{ff} distribution





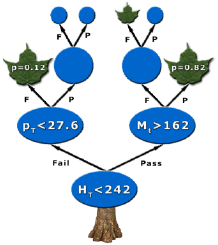
Resonance searches with Top Tagger

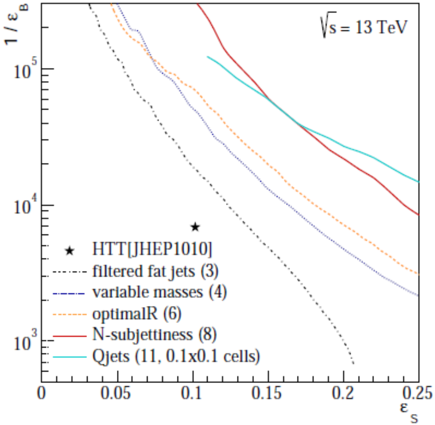
MultiVariate Analysis

T. Plehn et al. 2015

Booted decision trees

Extended cut-based selection





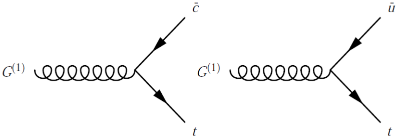
A simplified model for the gluon prime

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

$$U_L^{-1} \begin{pmatrix} g_{u\,L} & 0 & 0 \\ 0 & g_{c\,L} & 0 \\ 0 & 0 & g_{t\,L} \end{pmatrix} U_L \equiv \begin{pmatrix} \mathbf{\Gamma_{qq}}\, g_s & \Gamma_{qq'}\, g_s & \mathbf{\Gamma_{qt}}\, g_s \\ \Gamma_{qq'}\, g_s & \mathbf{\Gamma_{qq}}\, g_s & \mathbf{\Gamma_{qt}}\, g_s \\ \mathbf{\Gamma_{qt}}\, g_s & \mathbf{\Gamma_{qt}}\, g_s & \mathbf{\Gamma_{tt}}\, g_s \end{pmatrix} , \qquad \Gamma_{ij} = \Gamma_{ij\,L} = \Gamma_{ij\,R}$$



ATLAS search of resonances decaying to $t\bar{t}$ excludes $\mathbf{m_G} < \mathbf{1.62}$ TeV, arXiv:1211.2202
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

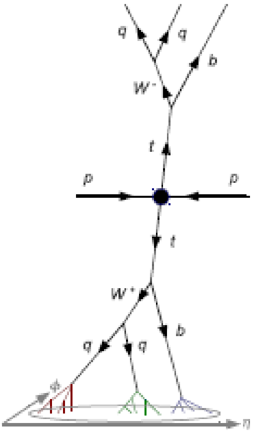
We use C/A algorithm with $R = 1.0$ to cluster the fat jets and select the two hardest ones.

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

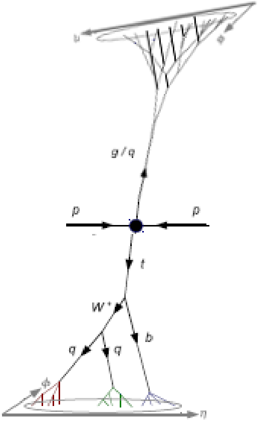
$$m_{G^{(1)}} = 2\,\mathrm{TeV}$$

we fix $\Gamma_{G^{(1)}} = 65\,\mathrm{GeV}$.

The TJ algorithm

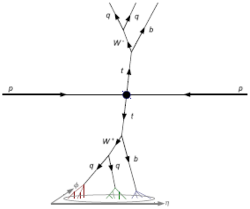
We use C/A algorithm with $R = 1.5$ to cluster the fat jets and select the two hardest ones.

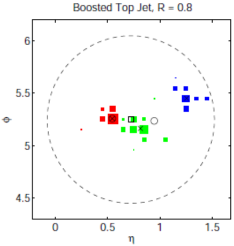
1. The fat jets should have $p_T > 400$ GeV and $y < 2.5$
2. One top jet [HEP Top Tagger] with $p_T > 500$ GeV
3. One light quark jet [Quark-gluon Tagger] identified with anti-kt ($R = 0.6$) with $p_T > 500$ GeV.
4. $\tau_3/\tau_1 < 0.3$ for the top jet.
5. 1700 GeV $\leq M_{\mathrm{inv}} \leq$ 2100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



N–subjettiness in HEP top tagger

N–subjettiness:
Measures the radial distance of the particles to the closes subjet axes.





The direction of the pseudojets:

τ_3: J_1, J_2, J_3 $\Rightarrow$ $p_{bottom}, p_{j_1}, p_{j_2}$ from HEP top tagger.
τ_1: J_1 $\Rightarrow$ The direction of the fat jet.

τ_3/τ_1 to distinguish Top jet from light quark-jet

parameters: $\Gamma_{qq} = 1$, $\Gamma_{tt} = 1$, $\Gamma_{tt} = 1$

Cut	QCD	$t\bar{t}$	$G \to t\bar{t}$	$G \to t\bar{q}\,(\bar{t}q)$
2 fat jets	1.61 nb	0.25 pb	2.49 pb	15.8 pb

TT algorithm

Cut	QCD		$t\bar{t}$		$G \to t\bar{t}$	
Two tops	31.7 fb		15.7 fb		293 fb	
$\tau_3/\tau_1 < 0.3$	3.1 fb	(13)	**8.9 fb**	(590)	**131 fb**	(7234)

TJ algorithm

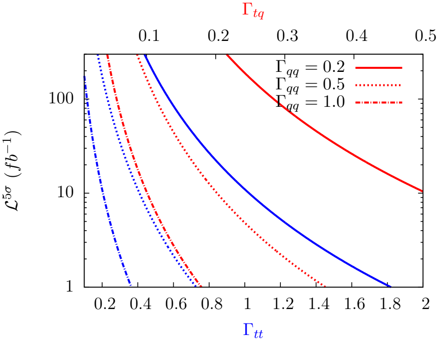
Cut	QCD		$t\bar{t}$		$G \to t\bar{q}\,(\bar{t}q)$	
One Top	4.98 pb		89.4 fb		5.38 pb	
One light-quark jet	2.72 pb		11.32 fb		4.00 pb	
$\tau_3/\tau_1 < 0.3$	817 fb		7.7 fb		2.67 pb	
$1.7\text{ TeV} < M_{\text{inv}} < 2.1\text{ TeV}$	**217 fb**	(910)	2.2 fb	(145)	**2.29 pb**	(20115)

PRELIMINARY

A signal of flavour violation

The required luminosity to get 5σ

$$\mathcal{L}^{5\sigma}_{TT} = 4.5\left(\frac{0.5}{\Gamma_{qq}}\right)^4\left(\frac{0.5}{\Gamma_{tt}}\right)^4 \qquad \mathcal{L}^{5\sigma}_{TJ} = 10.4\left(\frac{0.5}{\Gamma_{qq}}\right)^4\left(\frac{0.2}{\Gamma_{tq}}\right)^4$$



PRELIMINARY

Prospects

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