Jet Substructure

Thomas Becher

Graduate course “LHC physics”, HS 2012
Clustering into large energetic jets eliminates sensitivity to small scales

- Small higher-order perturbative corrections
- Low sensitivity to hadronisation
But we also lose a lot of information.

- QCD jet? Or from decay of energetic Higgs boson, top quark or W-boson (a boosted fat jet)?

For new physics searches, it is often important to know what’s inside.

Furthermore, large jets suffer from contamination from

- pile-up (other collisions in the event)
- underlying event (soft radiation, ...)
Example: $pp \rightarrow Z+H$ at high $p_T$

Boosted fat higgs jet

QCD jet

Difference?
Example: $pp \rightarrow Z+H$ at high $p_T$

Boosted fat higgs jet

QCD jet

Difference?
Pile-up: ~ 20 collisions per bunch crossing. The additional collisions typically have low $p_T$ but contaminate jets associated with high-$p_T$ collision.
$k_T$-style jet algorithms

Recombination according to distance measure

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = k_{ti}^{2p}$$

- $p = 1$: $k_T$-algorithm
- $p = 0$: C/A algorithm
- $p = -1$: anti-$k_T$

$$\Delta R_{ij}^2 = (\phi_2 - \phi_1)^2 + (\eta_1 - \eta_2)^2$$

Animation by J. Walsh
**kT-style jet algorithms**

Recombination according to distance measure

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta R_{ij}^2 / R^2 \]

\[ d_{iB} = k_{ti}^{2p} \]

- \( p = 1 \): \( kT \) - algorithm
- \( p = 0 \): C/A algorithm
- \( p = -1 \): anti-\( kT \)

\[ \Delta R_{ij}^2 = (\phi_2 - \phi_1)^2 + (\eta_1 - \eta_2)^2 \]
Jet Properties

- Invariant mass \( m_J = \left( \sum_i p_i \right)^2 \)
- Jet shapes
- Subjets
- Flavor \((b\text{-jet, } c\text{-jet})\)
- Charge
- ...

Jet Shapes

Tracks are crowded and unresolvable, the problem will include new heavy particles which decay to different products. Most of the tops will be produced near threshold, but for highly boosted tops these studies need to assume that the lepton can be front the large dijet background to all-hadronic interactions are not always isolated from each other or from the other hadronically decaying tops. However, these studies need to assume that the lepton can be identified from light quark and gluon jets using jet substructure. The properties of QCD which control the background from features particular to the top quark. As can be seen in Figure 1, the enormous dijet background still quite large and the resulting Higgs mass peak is substructure for the clustering, like the Mercedes-Benz Tweedie filter. This avoids having to construct the enormous dijet background [21].

Our results (C/A MD-F) are compared to those for the UE so gives good resolution on the signal, however, being only slightly smaller value, does well on background rejection, but su...
Danger zone

Simplest observable is jet mass $m_J$

• sensitive to collinear radiation $k_T \sim m_{\text{Jet}}$

• and soft radiation $E_s \sim m_J^2/E_J$

For $m_J = 100$ GeV and $E_J = 1$ TeV: emission of a soft gluon of $E_s = 1$ GeV changes the $m_J$ by 20 GeV!

• Multi-scale problem: corrections enhanced $\alpha_s^n \ln^{2n} \left( \frac{E_s}{E_J} \right)$

Need to sum soft and collinear emissions to all orders

• Parton shower (only leading logs), or SCET, ...
Highway to the danger zone

Revvvin' up your engine
Listen to her howlin' roar
Metal under tension
Beggin' you to touch and go

Highway to the Danger Zone
Ride into the Danger Zone

Headin' into twilight
Spreadin' out her wings tonight
She got you jumpin' off the track
And shovin' into overdrive

Highway to the Danger Zone
I'll take you
Right into the Danger Zone
Shower Monte-Carlo programs

Generate soft and collinear emissions iteratively.

- only leading-log accuracy, but in practice very successful at modeling events
- include hadronisation models

Many substructure studies heavily rely on shower MCs.

- First SCET results during the past year
Jet grooming

Goal: remove soft radiation from pile-up and underlying event to make underlying physics visible

Methods

• mass drop and filtering Butterworth, Davidson, Rubin, Salam 0802.2470

• pruning Ellis, Vermilion, Walsh 0912.0033

• trimming Krohn, Thaler, Wang 0912.1342
**Jet grooming**

- **“Trimming”** [http://arxiv.org/abs/0912.1342](http://arxiv.org/abs/0912.1342) (D. Krohn, J. Thaler, L. Wang)
  - uses $k_t$ algorithm to create subjets of size $R_{\text{sub}}$ from the constituents of the large-$R$ jet: any subjets failing $p_T^i / p_T < f_{\text{cut}}$ are removed

- **“Pruning”** [http://arxiv.org/abs/0912.0033](http://arxiv.org/abs/0912.0033) (S. Ellis, C. Vermilion, J. Walsh)
  - Recombine jet constituents with C/A or $k_t$ while vetoing wide angle ($R_{\text{cut}}$) and softer ($z_{\text{cut}}$) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

Tuned parameters:
- **“Trimming”**: $f_{\text{cut}}$ and $R_{\text{sub}}$
- **“Pruning”**: $R_{\text{cut}}$ and $z_{\text{cut}}$
Jet grooming

- “Mass drop/filtering” [http://arxiv.org/abs/0802.2470](http://arxiv.org/abs/0802.2470)
  (J. Butterworth, A. Davidson, M. Rubin, G. Salam)

  - Identify relatively symmetric subjets, each with significantly smaller mass than their sum
  - Was optimized for $H \rightarrow \text{bb}$ search using C/A jets... **not applied to anti-kt jets!**

**Mass drop:** create 2 subjets

\[
\frac{m_{j_1}}{M_{\text{jet}}} < \mu_{\text{frac}} \quad \text{and} \quad y > y_{\text{cut}}
\]

\[
\frac{\min [ (p_T^{j_1})^2, (p_T^{j_2})^2 ]}{(M_{\text{jet}})^2} \times \Delta R_{j_1,j_2}^2 > y_{\text{cut}}.
\]

**Filtering:** constituents of $j_1, j_2$ are reclustered using C/A

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

Tuned parameter: $\mu_{\text{frac}}$
(y_{\text{cut}} set to 0.09)

from Emily Thomson, ATL-PHYS-SLIDE-2012-691
Effect of grooming

Grooming reduces invariant mass, enhances top mass peak in top jets

- Can use jet mass to distinguish top-quark light QCD jets.
Jet shapes: e.g. N-jettiness

Stewart, Tackmann, Waalewijn ’10

- Choose N different massless reference momenta \( q_1 \ldots q_N \).
  Compute
  \[
  \tau_N = \frac{2}{Q^2} \sum_k \min\{ q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k \}
  \]
- \( \tau_N \) vanishes, if all particles move along the \( N \) axes.
- SCET can systematically resum higher log’s in \( \tau_N \)
• Consider only particles inside single jet.

• \( \tau_{21} = \frac{\tau_2}{\tau_1} \) can be used to distinguish boosted W-jets from QCD jets.

• \( \tau_{32} \) for boosted top jets (with generalized \( \tau_N \) def.)

• ATLAS ’12 has measured \( \tau_{21} \) and \( \tau_{32} \)
Further reading

• Towards Jetography, G. Salam, 0906.1833

• Reports 1012.5412, 1201.0008 (and slides) from BOOST workshops

• Jet-Grooming in ATLAS, E. Thompson, ATL-PHYS-SLIDE-2012-691

Lots of activity in this area during the past few years, but “fair to say that the question of how best to use jets is still in its infancy” (G. Salam)