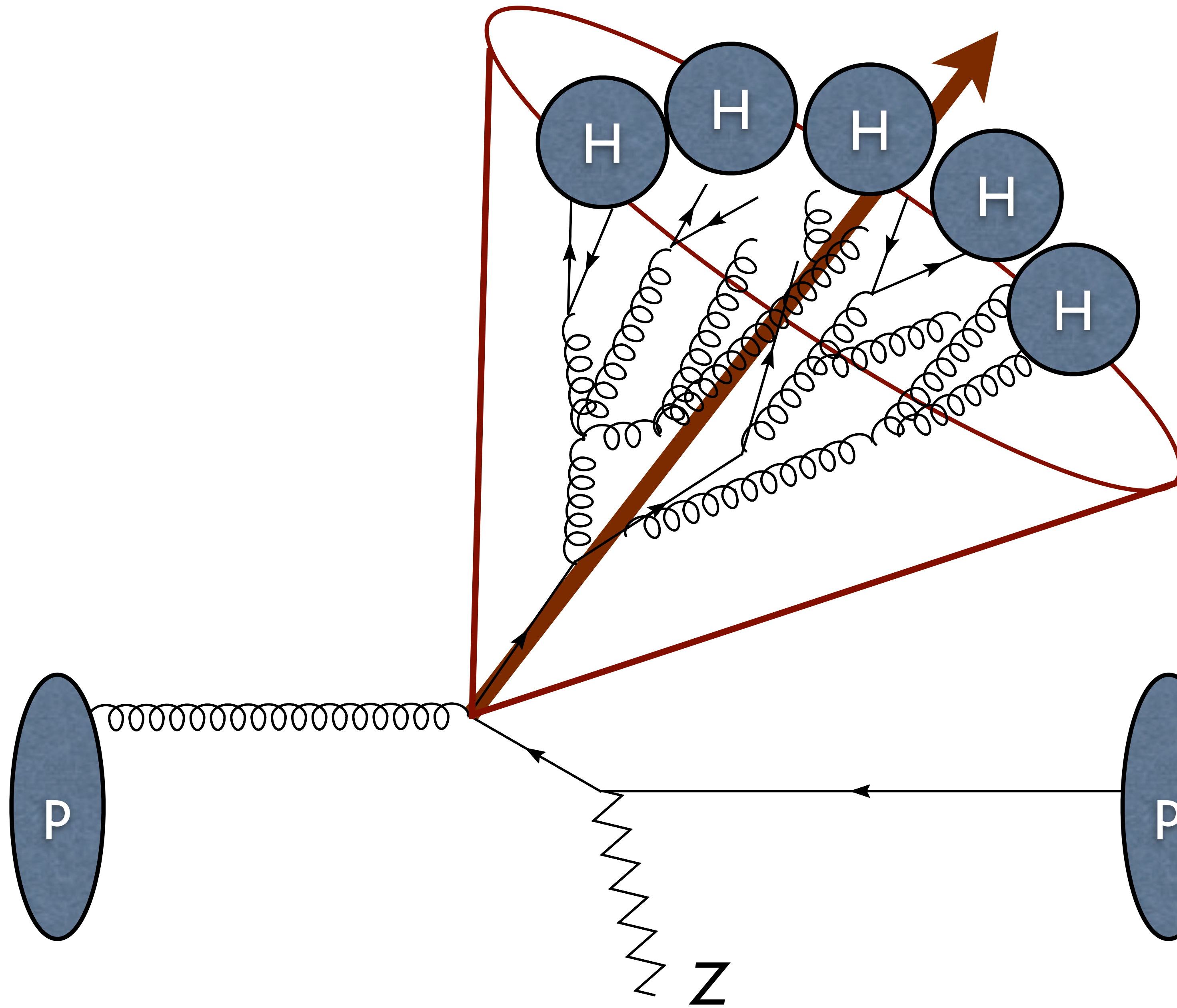
Jet Substructure

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 loose a lot of information.

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

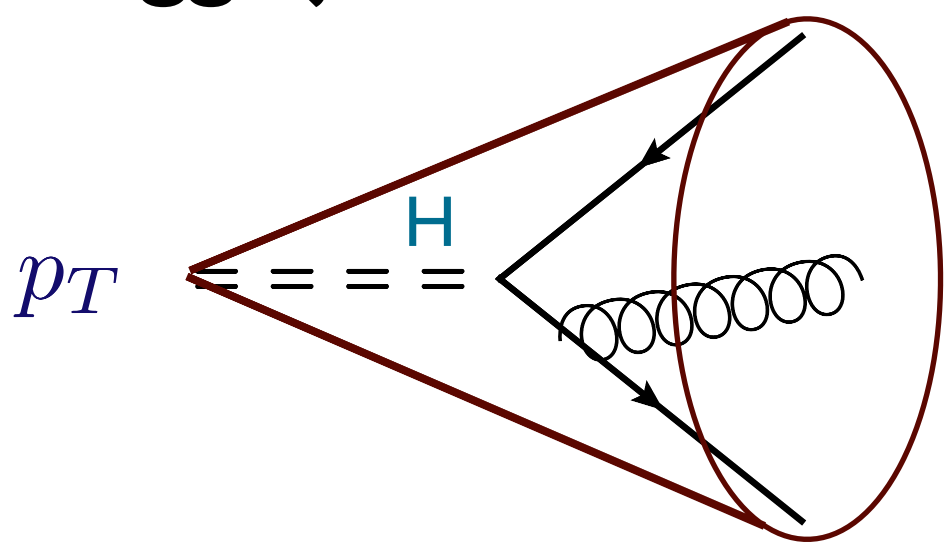
For new physics searches, it is often important to know what's inside.

Furthermore, large jets suffer from contamination from

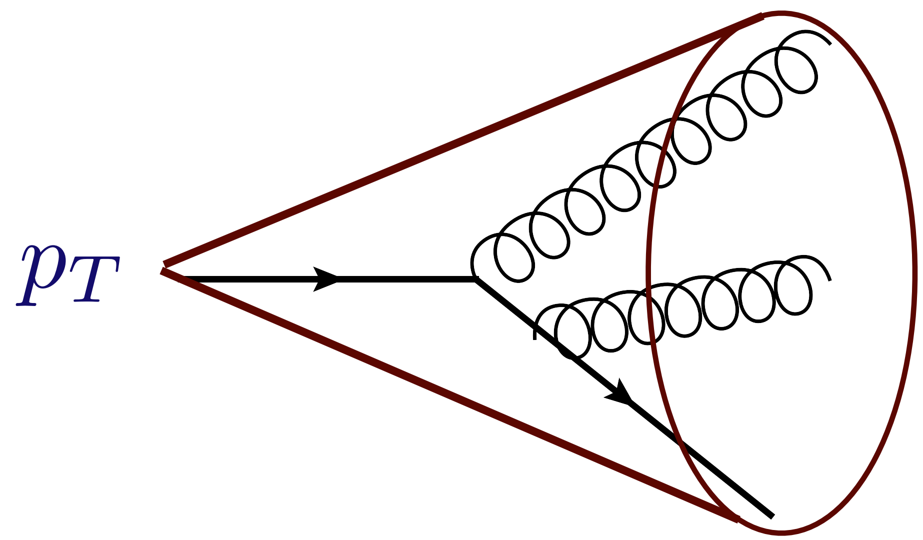
- pile-up (other collisions in the event)
- underlying event (soft radiation, ...)

Example: $pp \to$ Z+H at high p_T

Boosted fat higgs jet



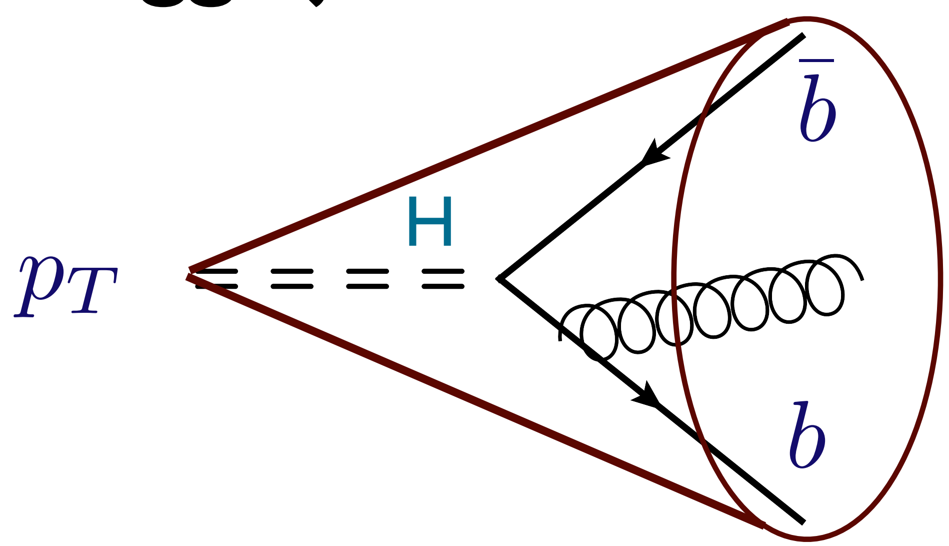
QCD jet



Difference?

Example: $pp \to$ Z+H at high p_T

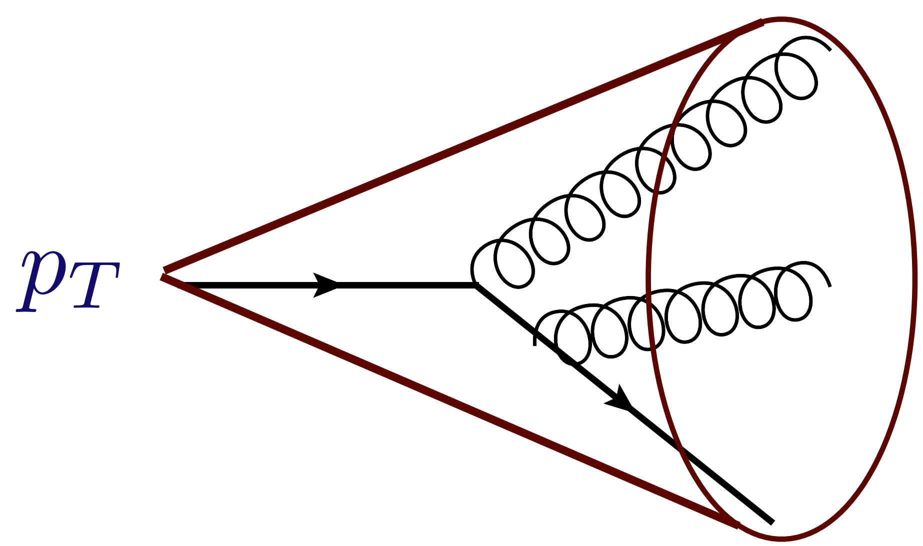
Boosted fat higgs jet



symmetric splitting

$$p_T^b \sim p_T^{\bar{b}}$$

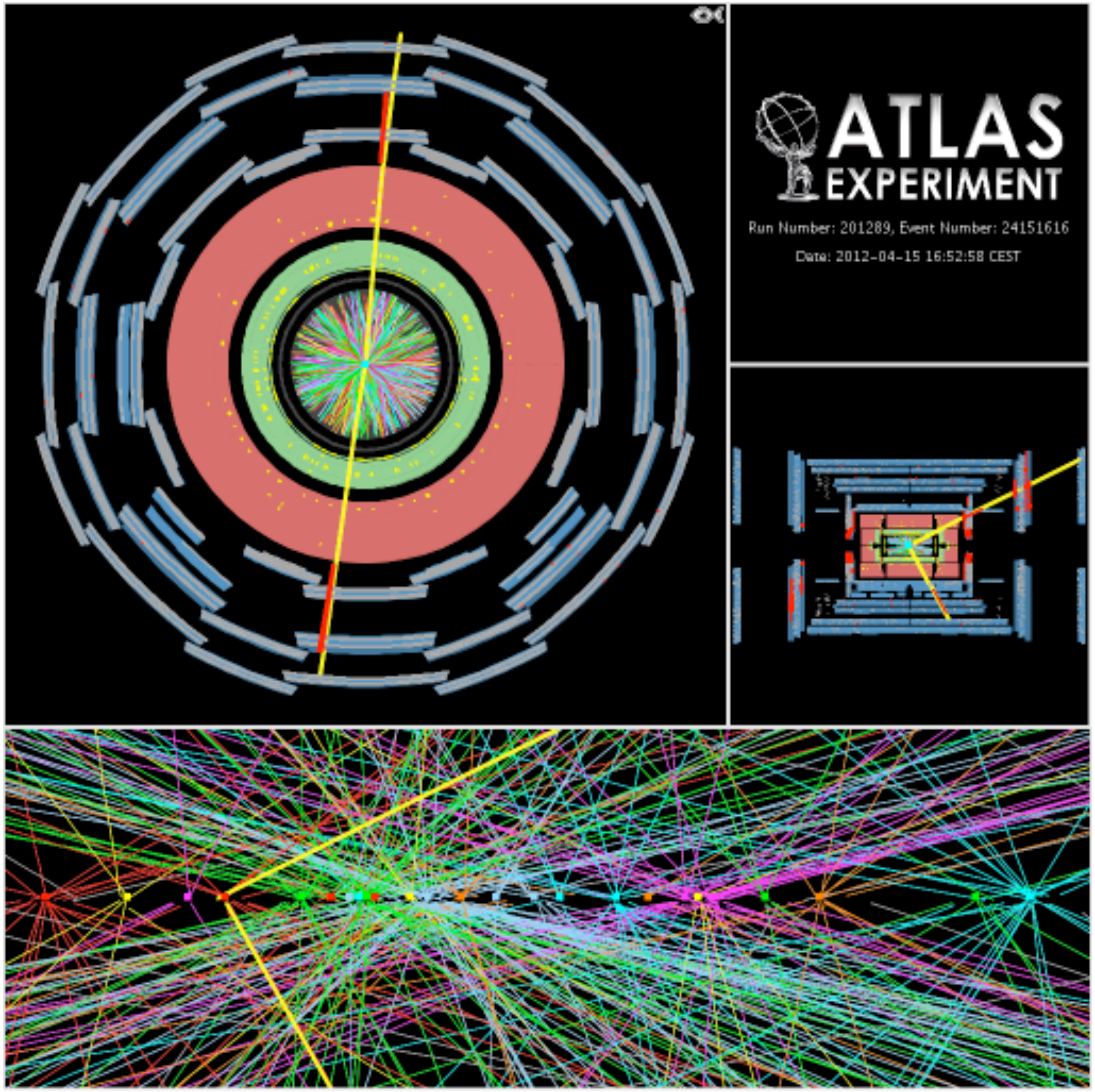
QCD jet



asymmetric splitting

$$p_T^q \gg p_T^g$$

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.

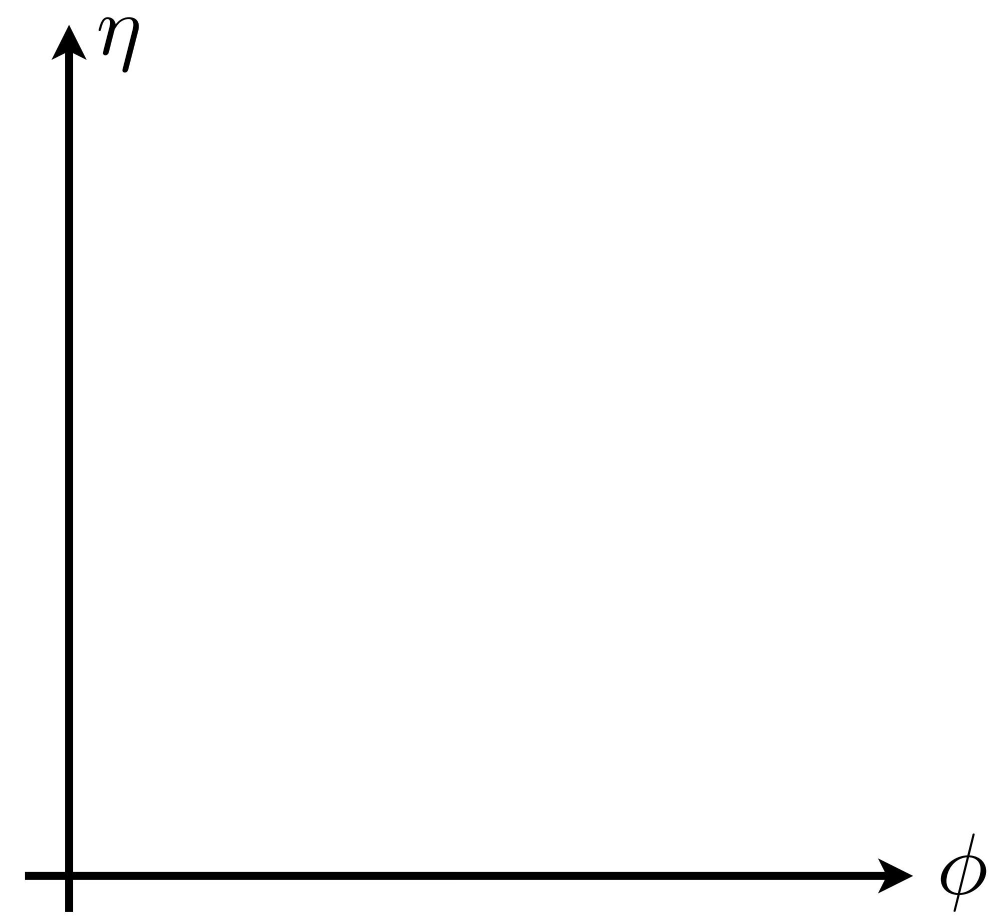
k_T-style jet algorithms

Recombination according to distance measure

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

- 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

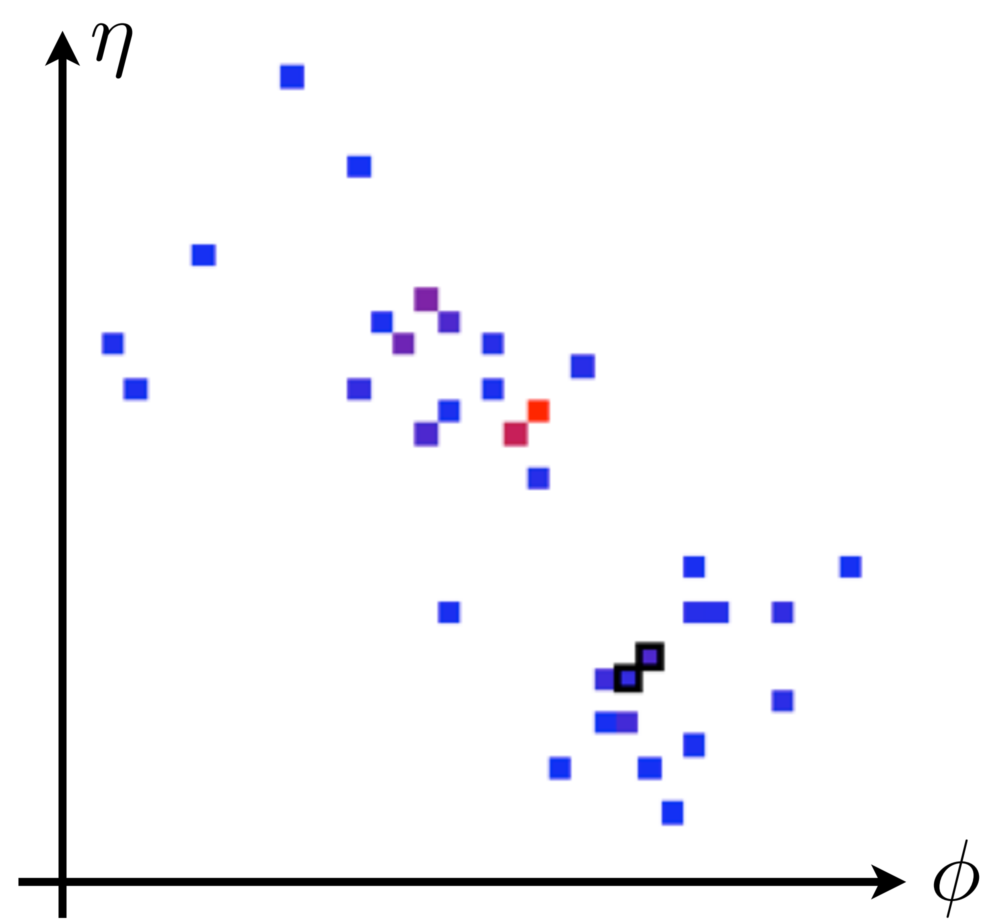
k_T-style jet algorithms

Recombination according to distance measure

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

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

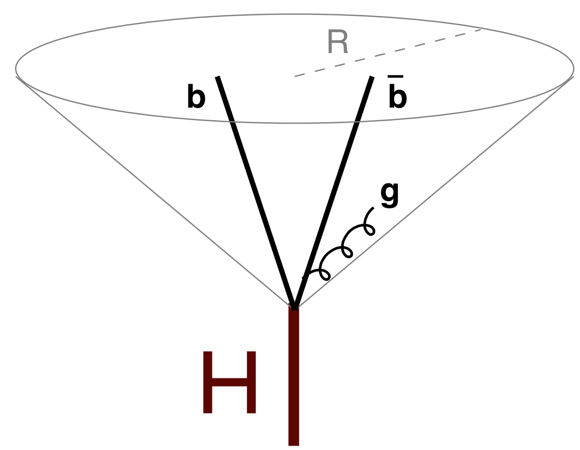
- p = 1 : k_T - algorithm
- p = 0 : C/A algorithm
- p = −1: anti-k_T

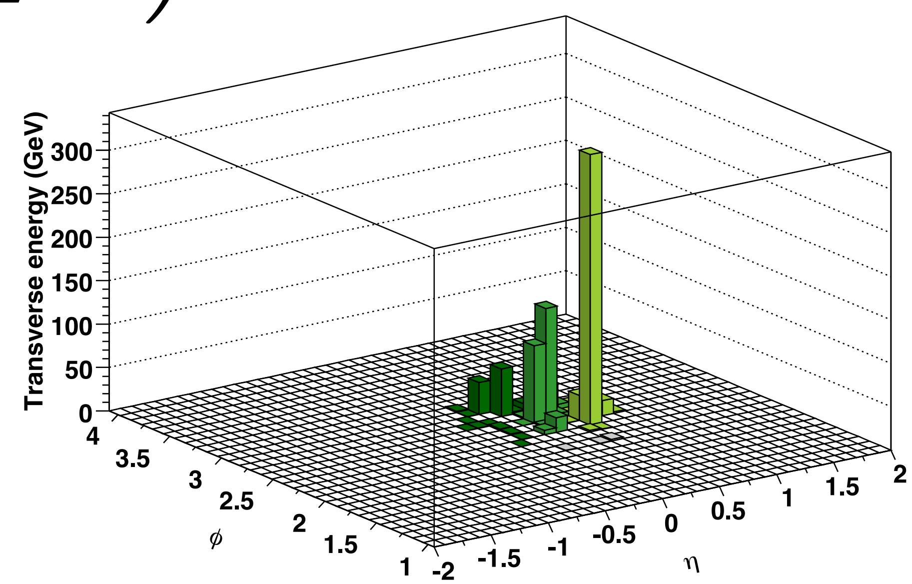


animation by J. Walsh

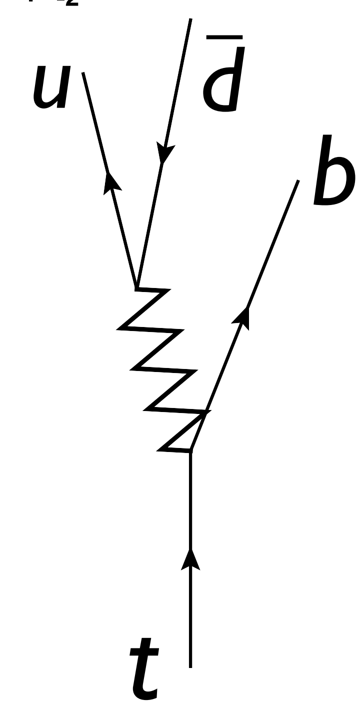
Jet Properties

- Invariant mass $m_J = \Big(\sum_i p_i\Big)^2$
- Jet shapes
- Subjets



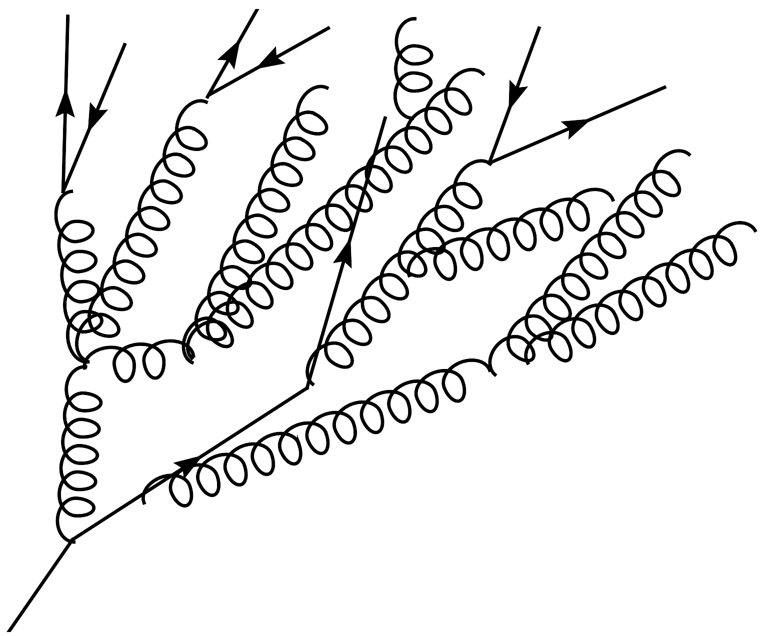


- Flavor (*b*-jet, *c*-jet)
- Charge
- ...



Danger zone

Simplest observable is jet mass m_J



- sensitive to collinear radiation $k_T \sim m_{Jet}$
- 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 =1GeV 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

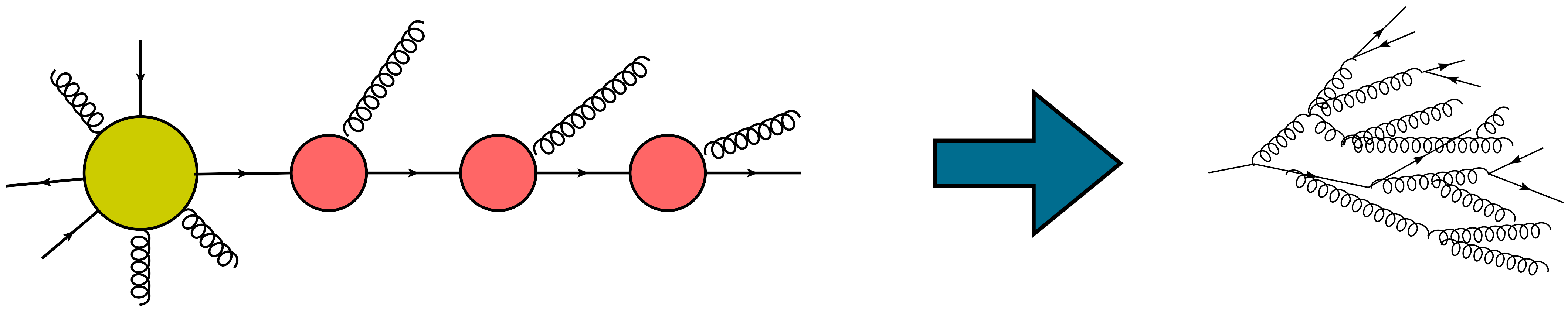
Revvin' up your engine
Listen to her howlin' roar
Metal under tension
Beggin' you to touch and go

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

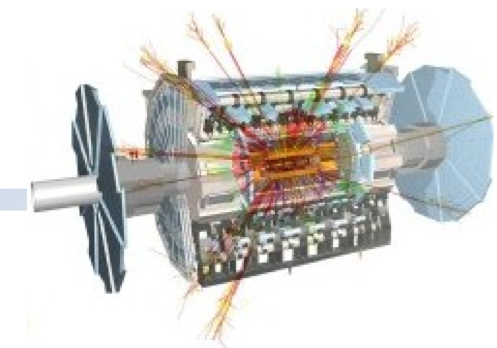
Jet grooming

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

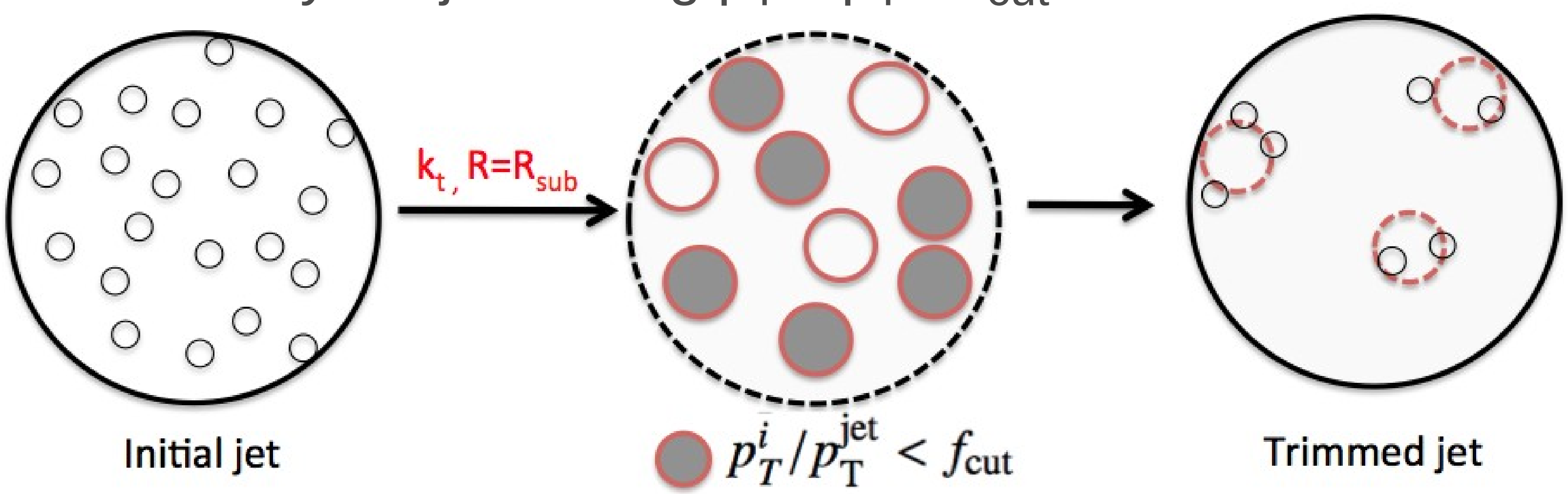
Methods

- mass drop and filtering Butterworth, Davidson, Rubin, Salam 0802.2470
- pruning Ellis, Vermilion, Walsh 0912.0033
- trimming Krohn, Thaler, Wang 0912.1342

Jet grooming

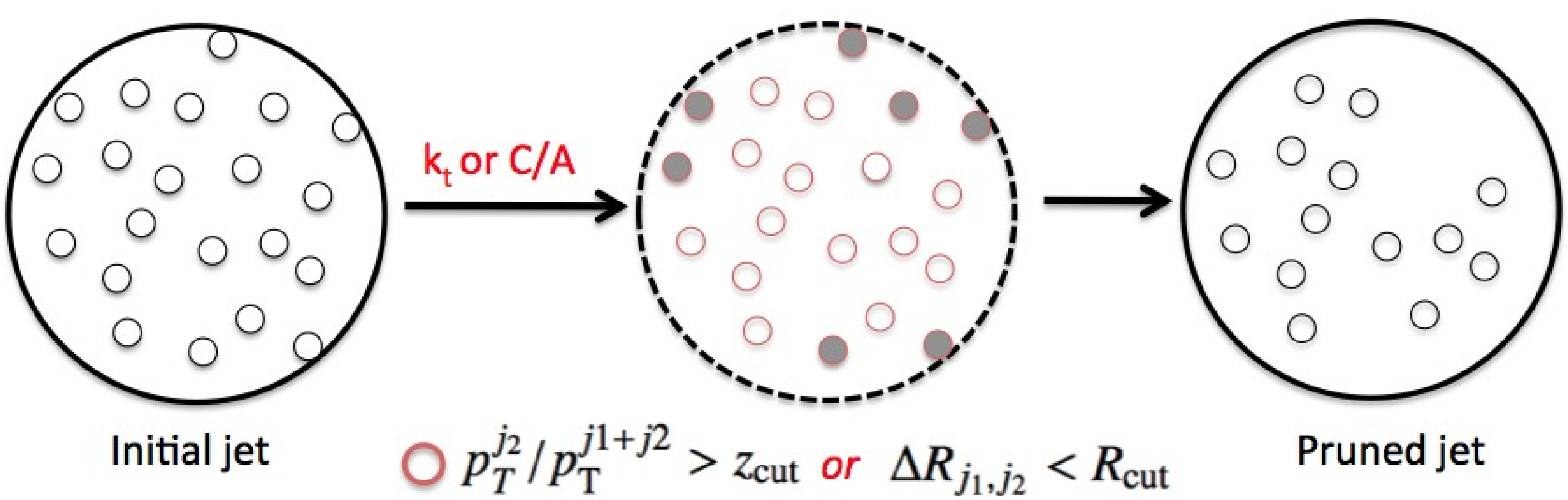


- **"Trimming"** http://arxiv.org/abs/0912.1342 (D. Krohn, J. Thaler, L. Wang)
  - uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i$ / p_T < f_{cut} are removed



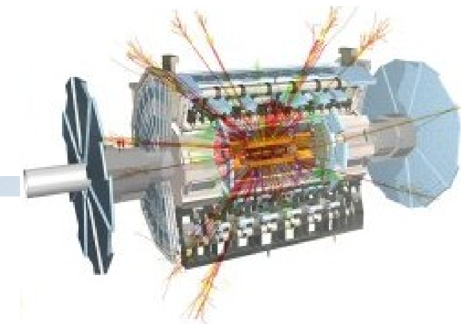
Tuned parameters: f_{cut} and R_{sub}

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



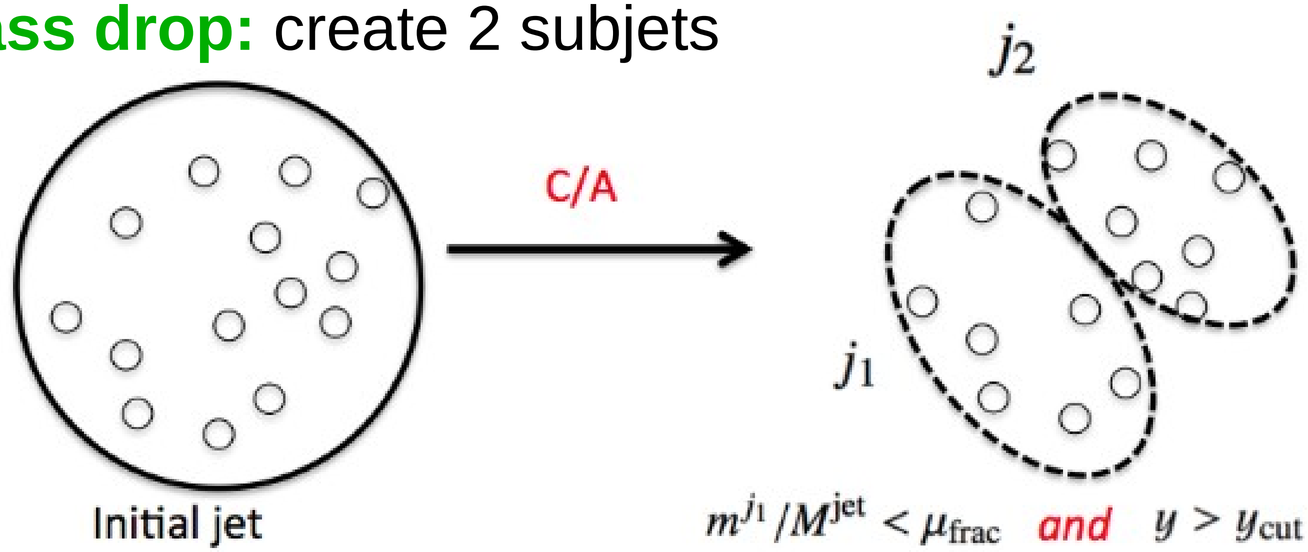
Tuned parameters: R_{cut} and z_{cut}

Jet grooming



- **“Mass drop/filtering”** 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→bb search using C/A jets...**not applied to anti-kt jets!**

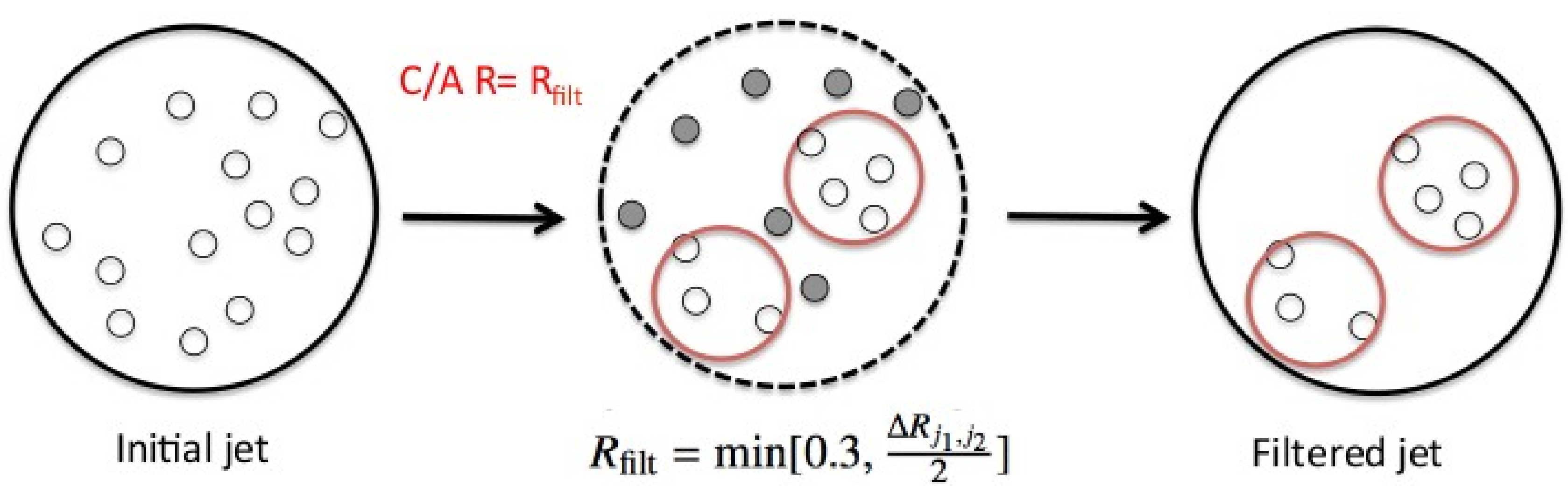
Mass drop: create 2 subjets



$$\frac{\min[(p_T^{j_1})^2, (p_T^{j_2})^2]}{(M^{\text{jet}})^2} \times \Delta R^2_{j_1,j_2} > y_{\text{cut}},$$

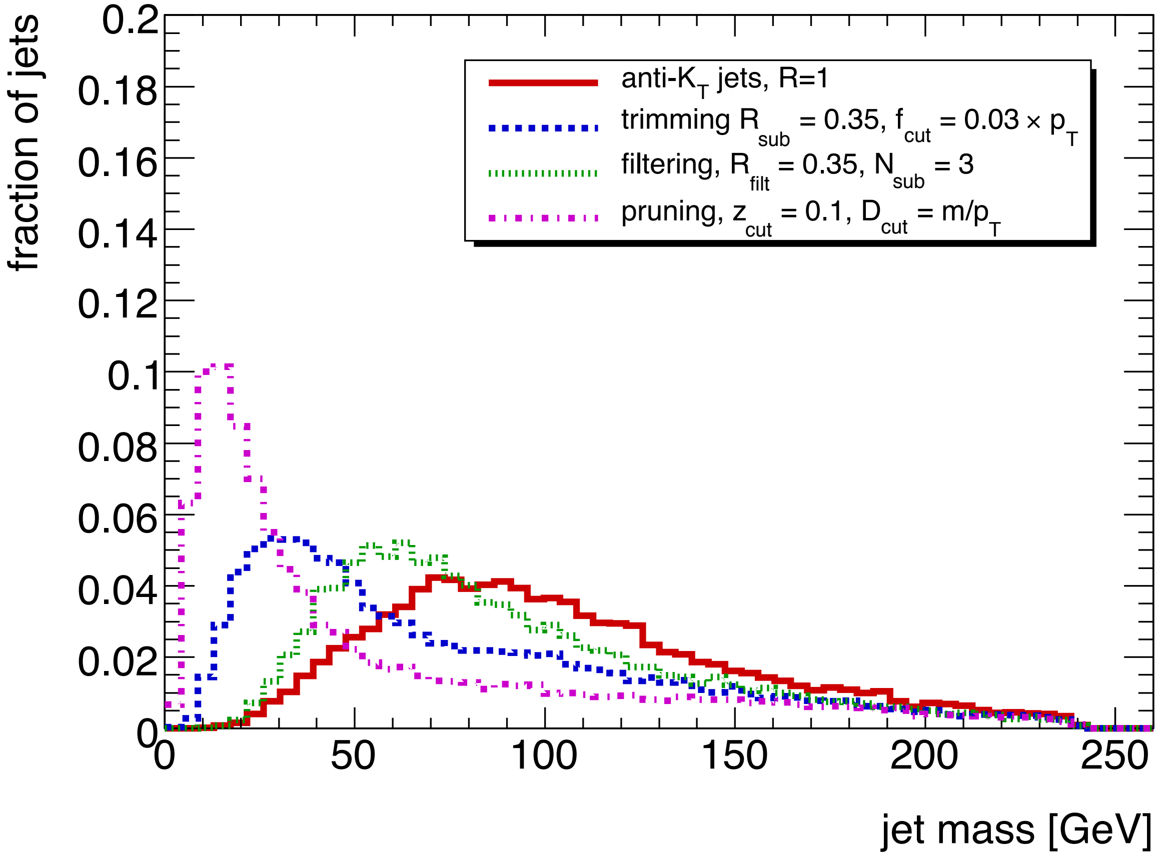
Tuned parameter: μ_{frac}
(y_{cut} set to 0.09)

Filtering: constituents of j1, j2 are reclustered using C/A

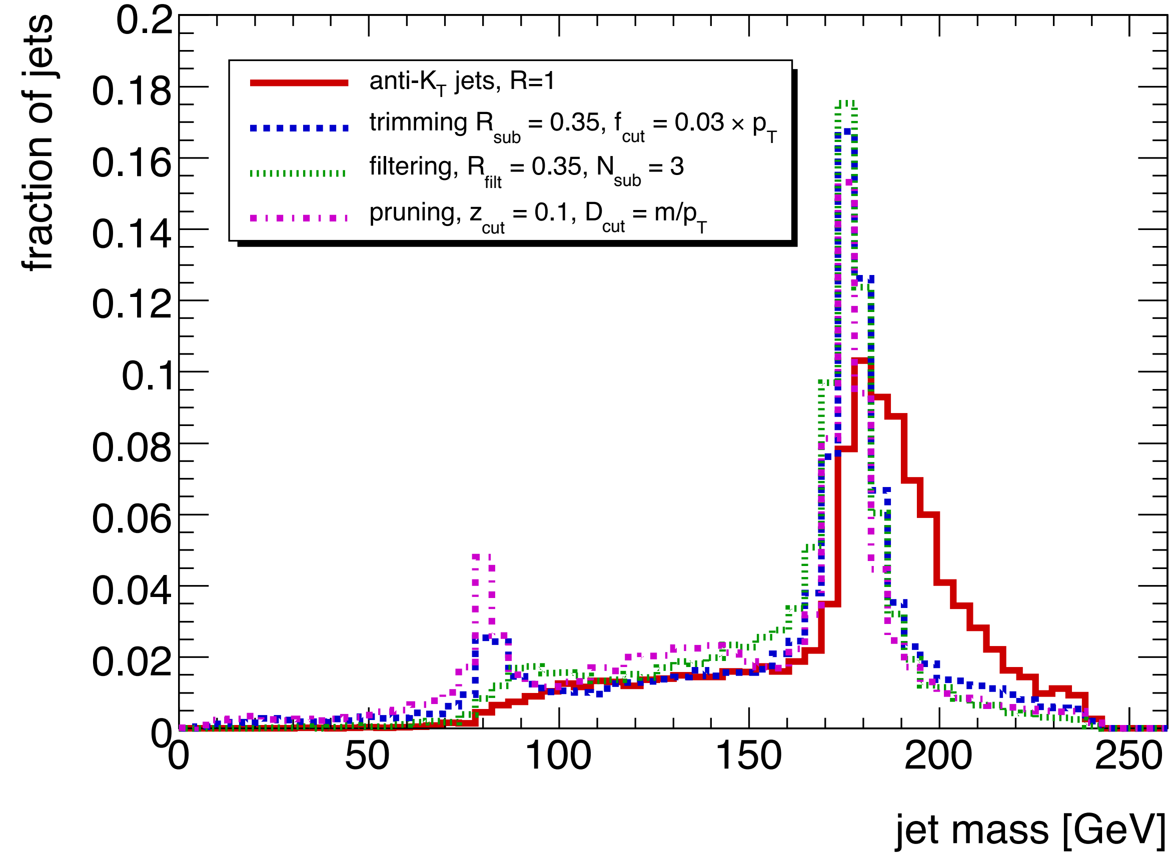


from Emily Thomson, ATL-PHYS-SLIDE-2012-691

Effect of grooming



(a) dijets, 500–600 GeV



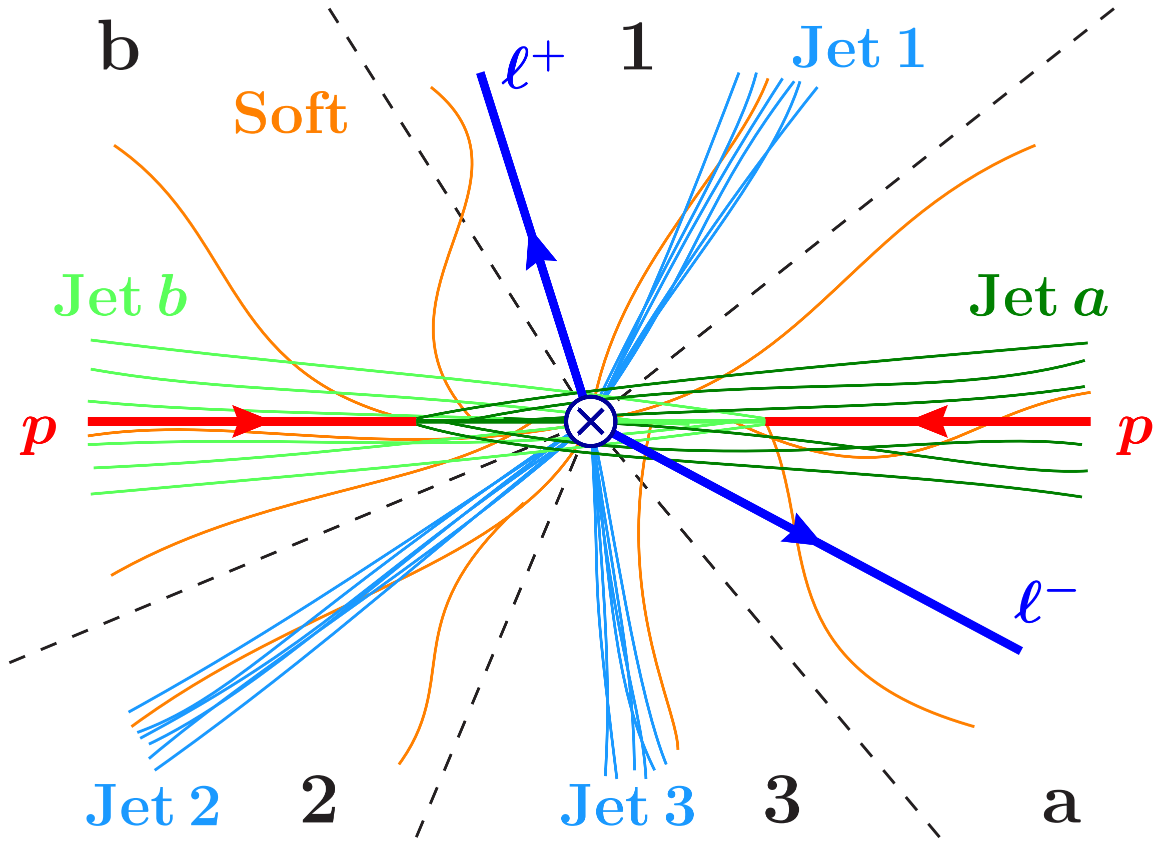
(b) $t\bar{t}$, 500–600 GeV

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

$$\tau_N = \frac{2}{Q^2} \sum_k \min\{q_a \cdot p_k,\, q_b \cdot p_k,\, q_1 \cdot p_k,\, \ldots,\, q_N \cdot p_k\}$$

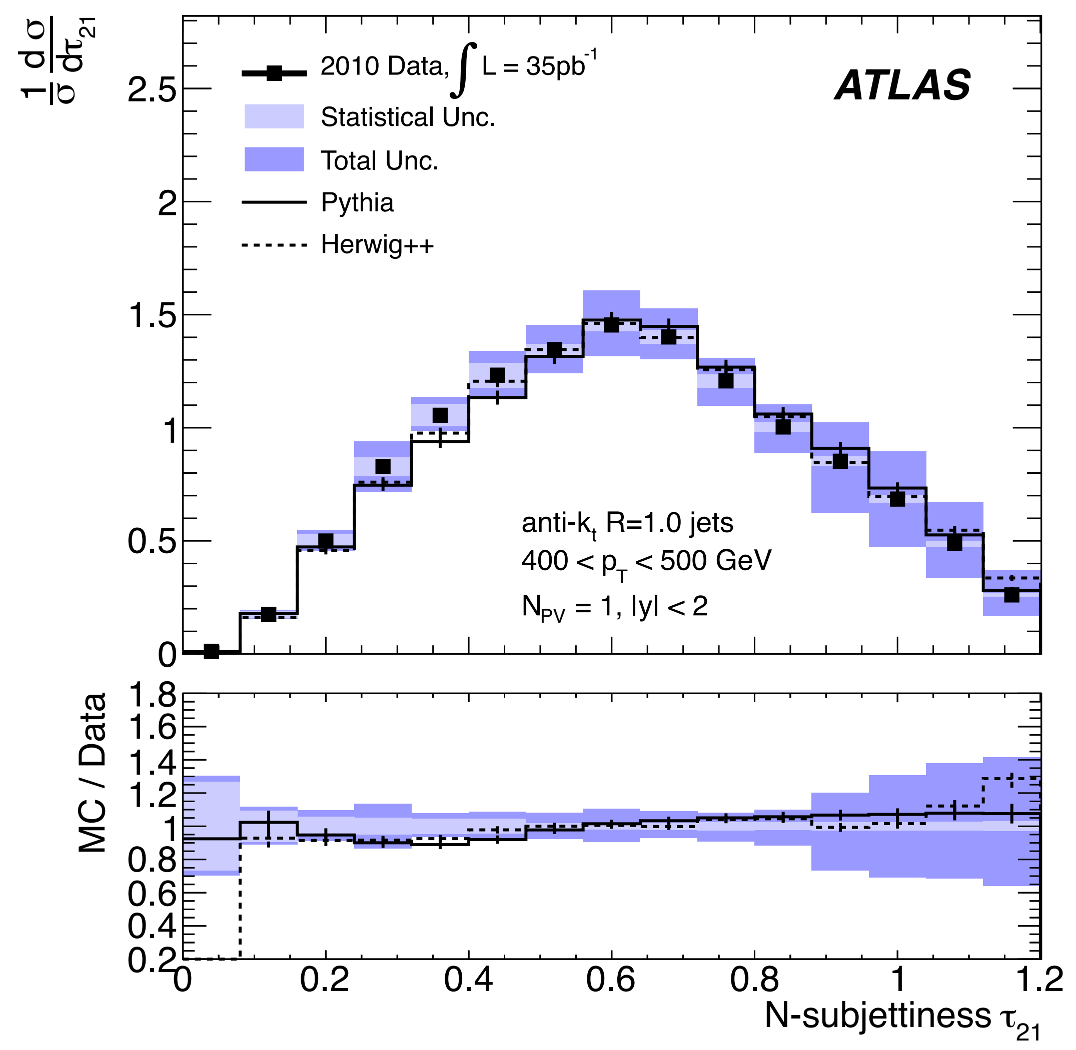
incoming hadron momenta

- τ_N vanishes, if all particles move along the N axes.
- SCET can systematically resum higher log's in τ_N

N-subjettiness

Thaler and Tilburg '11 '12

- Consider only particles inside single jet.
- $\tau_{21} = \tau_2/\tau_1$ can be used to distinguish boosted *W*-jets from QCD jets.
- τ_{32} for boosted top jets (with generalized τ_N def.)
- ATLAS '12 has measured τ_{21} and τ_{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)