Telescoping Jets: Multiple Event Interpretations with Multiple R's

Yang-Ting Chien

Center for the Fundamental Laws of Nature, Harvard University

Los Alamos National Laboratory

August 27, 2013, Los Alamos

Outline

- Jet definition: jet algorithms with a parameter R
  - clustering and cone
  - deterministic and non-deterministic
- Q-jets and Q-events
- Telescoping jets: jet algorithms with multiple R's
  - Demonstration: higgs search in $ZH \to \nu\bar{\nu}b\bar{b}$
  - Statistics
- Results and conclusions

reference :

Telescoping jets: 1304.5240, Jet sampling: 1304.2394, Qjets: 1201.1914

Jets at LEP

- Jets are distinct, localized structure in calorimeter

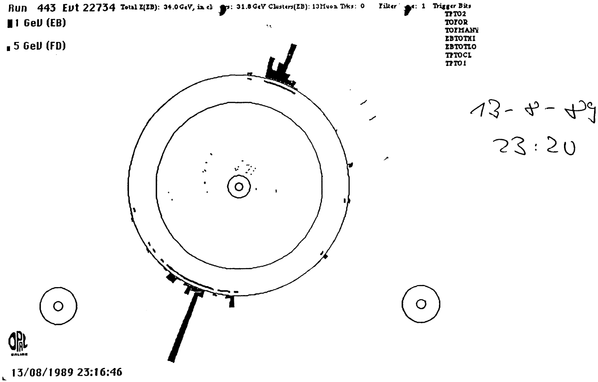


Figure: The first hadronic Z decay recorded by OPAL

Jets at the LHC

- Jets are distinct, localized structure in calorimeter

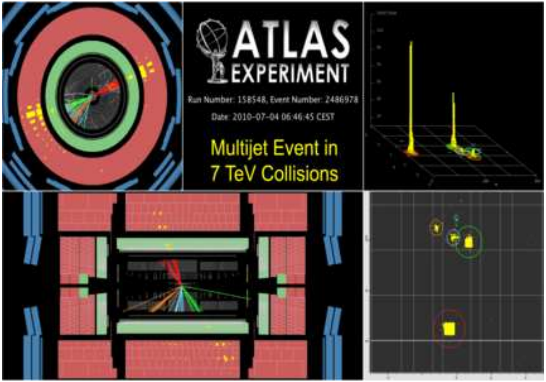


Figure: A multi-jet event at the 7 TeV LHC

Jet physics in a nutshell

- Jets are a manifestation of the underlying colored partons

Jet physics in a nutshell

- Jets are a manifestation of the underlying colored partons
  - Partons emit soft and collinear radiation
    - To reconstruct the hard process it is necessary to strip off the complication from QCD
  - Define jets and look at their properties through jet observables
  - Analytic calculations and numerical simulations

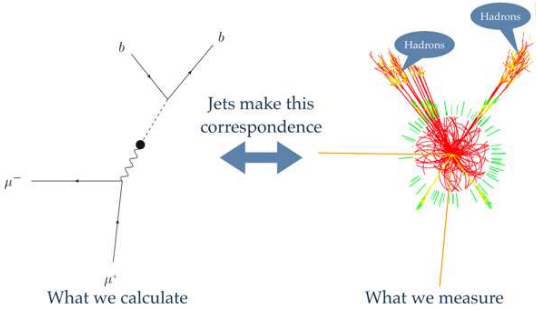


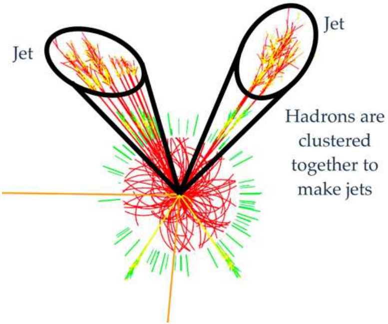
Figure: $H(\to b\bar{b}) + Z(\to \mu\bar{\mu})$ production at parton and hadron levels

What is a jet more precisely?

- Identifying (defining) jets: jet algorithms with a parameter R

What is a jet more precisely?

- Identifying (defining) jets: jet algorithms with a parameter R
  - R sets the *artificial* jet size
    - jet constituents are those particles within an angular scale R away from the jet direction
  - three angular scales: R, angles between jets and "jet widths"
    - jet width is a dynamically generated scale



Clustering algorithms

- Idea: merge the pair of particles with the shortest distance until the particles are away from one another farther than R

Clustering algorithms

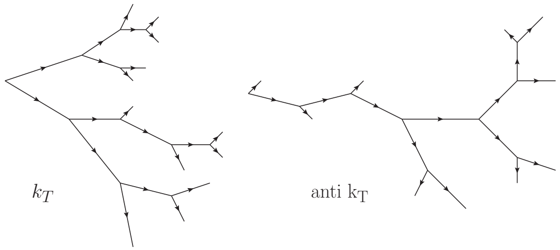
- Idea: merge the pair of particles with the shortest distance until the particles are away from one another farther than R
  - deterministic

Clustering algorithms

- Idea: merge the pair of particles with the shortest distance until the particles are away from one another farther than R
  - deterministic
- the distance measure d_{ij} between particles i and j is defined by

$$d_{ij} = \min(p_{ti}^{2\beta}, p_{tj}^{2\beta})\Delta R_{ij}^2/R^2, \quad d_{iB} = p_{ti}^{2\beta} \qquad B : \text{beam}$$

$\beta = 1$: k_T $\quad$ $\beta = 0$, Cambridge/Aachen $\quad$ $\beta = -1$, anti-k_T



Q-jets: non-deterministic clustering algorithms

- Jet formation is quantum mechanical
- Idea: merge particles probabilistically according to a weight

$$d_{ij} = \min(p_{ti}^{2\beta}, p_{tj}^{2\beta})\Delta R_{ij}^2/R^2, \quad d_{iB} = p_{ti}^{2\beta} \qquad B: \text{beam}$$

$$w_{ij}^{(\alpha)} = \exp\left\{ -\alpha\frac{d_{ij} - d^{min}}{d^{min}} \right\}, \qquad d^{min} = \min d_{ij}$$

  - there is still a parameter R
  - α controls the deviation from the deterministic clustering
  - Q-jets give different clustering trees and jet constituents in each run
- Nice performance in boosted W-tagging with pruning

Q-events

- Q-jets technique applied to the whole event
  — Nice performance in $pp \to \phi$, $\phi\phi$, $Z\phi$ and ZH searches using Qanti-$\mathrm{k_T}$

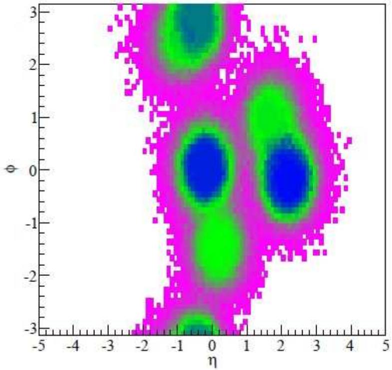


Figure: The frequency with which a calorimeter cell is clustered into one of the hard jets in a simulated $pp \to \phi\phi \to gggg$ event at the LHC. Here α=1.

Q-events

- Q-jets technique applied to the whole event
  — Nice performance in $pp \to \phi$, $\phi\phi$, $Z\phi$ and ZH searches using Qanti-$\mathrm{k_T}$

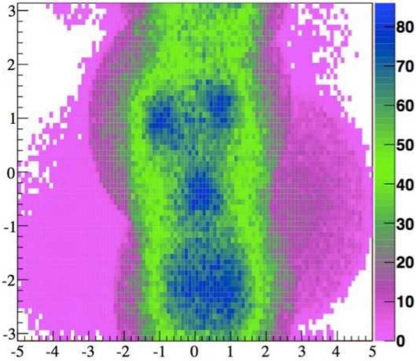


Figure: Sometimes you see this. Here α=0.1.

Jet sampling using Q-jets

- Each run gives a different reconstruction of a single event
  - — Q-jets probe around the classical clustering trees
  - — all jet observables turn from a single number to a distribution

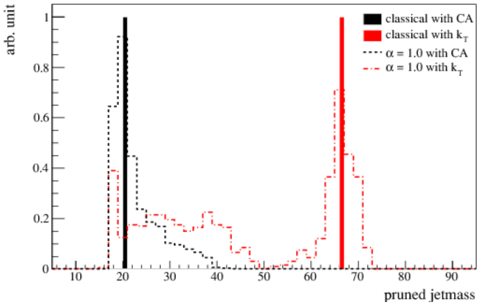


Figure: Distribution of pruned jet mass for a single QCD-jet (1201.1914)

Jet sampling using Q-jets

- Each run gives a different reconstruction of a single event
  - Q-jets probe around the classical clustering trees
  - all jet observables turn from a single number to a distribution
  - jet area changes in different reconstructions

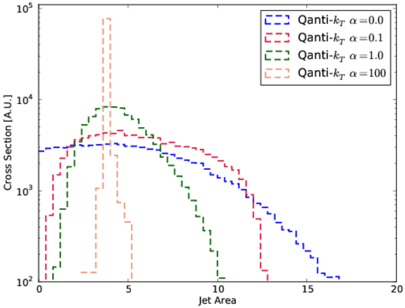


Figure: The jet area computed for the hardest jet in dijet events

Why use only one R for all jets?

- In fact, there is no reason for jets to have the same size R — again, jet formation is quantum mechanical

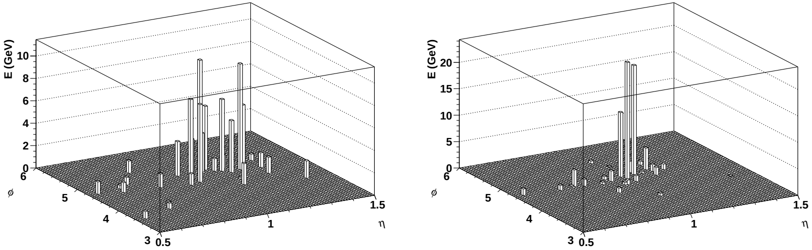


Figure: Two b jets with the same partonic kinematics but different widths

Why use only one R for all jets?

- In fact, there is no reason for jets to have the same size R — the width of the localized energy distribution in the η-ϕ plane is an independent quantity that should be distinguished from R

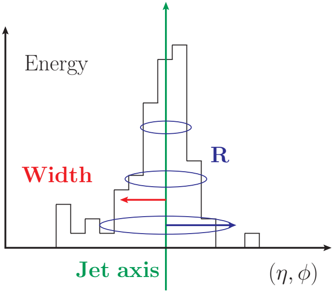


Figure: A cartoon calorimeter plot distinguishing the width of the localized energy distribution of a jet from the parameter R

Telescoping jets

- Idea: jet algorithms with multiple R's
  - each choice of R gives a distinct interpretation of an event
  - with multiple event interpretations, what can we do?

Telescoping jets

- Idea: jet algorithms with multiple R's
  - — each choice of R gives a distinct interpretation of an event
  - — with multiple event interpretations, what can we do?
- Demonstration: higgs search in ZH production with $H \to b\bar{b}$
  - — with a $p_T^Z > 120$ GeV cut
  - — perform a counting experiment with a dijet invariant mass window

Telescoping jets

- Idea: jet algorithms with multiple R's
  — each choice of R gives a distinct interpretation of an event
  — with multiple event interpretations, what can we do?
- Demonstration: higgs search in ZH production with $H \to b\bar{b}$
  — with a $p_T^Z > 120$ GeV cut
  — perform a counting experiment with a dijet invariant mass window

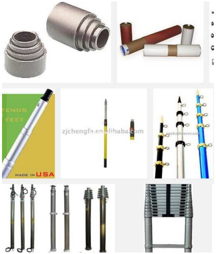


Figure: This is *telescoping*.

Telescoping cone algorithm

- Use the anti-k_T algorithm with $R = 0.4$ to reconstruct the cores of the two hardest jets and determine the jet axes n_1 and n_2
  - $R = 0.7$ is the optimal value for the classical analysis

Telescoping cone algorithm

- Use the anti-k_T algorithm with $R = 0.4$ to reconstruct the cores of the two hardest jets and determine the jet axes n_1 and n_2
  - $R = 0.7$ is the optimal value for the classical analysis
- Define the *i*-th jet to be the particles within a distance R away from n_i in the η-ϕ plane:

$$\mathrm{jet}_R^i = \{\, p \mid (\eta_p - \eta_{n_i})^2 + (\phi_p - \phi_{n_i})^2 < R^2 \}$$

Telescoping cone algorithm

- Use the anti-k_T algorithm with $R = 0.4$ to reconstruct the cores of the two hardest jets and determine the jet axes n_1 and n_2
  - $R = 0.7$ is the optimal value for the classical analysis
- Define the *i*-th jet to be the particles within a distance R away from n_i in the η-ϕ plane:

$$\mathrm{jet}_R^i = \{\, p \mid (\eta_p - \eta_{n_i})^2 + (\phi_p - \phi_{n_i})^2 < R^2 \}$$

- In the case of overlapping jets, assign particles to the jet with the closer jet axis. This step is to avoid ambiguity and is not crucial when reconstructing the invariant mass of the two hardest jets m_{jj}.

Counting

- A counting experiment with a dijet invariant mass window
  - 110 GeV $< m_{jj} <$ 140 GeV
  - N different R's ranging from 0.2 to 1.5
  - Each event is counted by the fraction of reconstructions passing the cuts, instead of 0 or 1 in a conventional analysis.

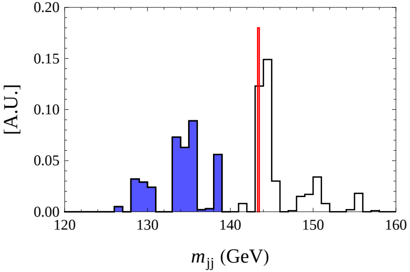
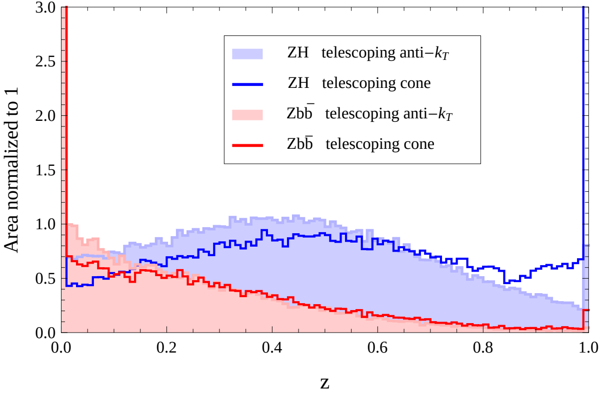


Figure: m_{jj} distribution of a ZH event with multiple interpretations

Signal and background z distributions

- z is the fraction of the reconstructions of an event passing the cuts



m_{jj} distribution

- Using multiple event reconstructions gives a wider signal Higgs mass peak, but it reduces the statistical fluctuations of the m_{jj} distributions

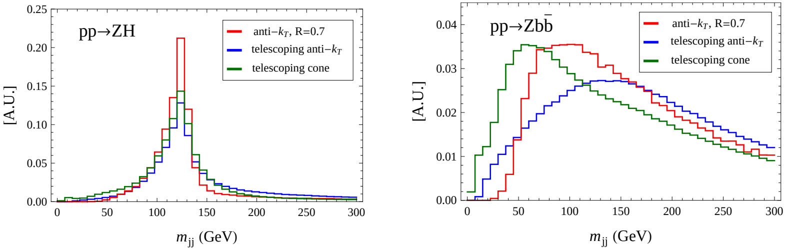


Figure: m_{jj} distribution of all event reconstructions

Goal

- Increase the statistical significance

$$\frac{S}{\delta B} = \frac{\text{expected signal in the mass window}}{\text{fluctuation of background in the mass window}}$$

- Using multiple event reconstructions increases the statistical stability of observables so that background fluctuations shrink considerably, which is the key for $S/\delta B$ improvement

Statistics and results

$$\frac{S}{\delta B} = \frac{N_S \ \epsilon_S}{\sqrt{N_B(\epsilon_B^2 + \sigma_B^2)}} \qquad \text{or} \qquad \frac{N_S}{\sqrt{N_B}} \sqrt{\int_0^1 \frac{\rho_S^2(z)}{\rho_B(z)} dz}$$

- N_S and N_B are the expected numbers of signal and background events
- ϵ and σ^2 are the mean and variance of the z distribution
- Results:

R range	N	algorithm	weight	$S/\delta B \uparrow$
0.4 and 1.0	2	cone	z	14%
0.4 to 1.0	7	cone	z	20%
0.4 to 1.5	12	cone	z	26%
0.2 to 1.5	100	anti-k_T	z	20%
0.2 to 1.5	100	cone	z	**28%**
0.4 to 1.5	12	cone	ρ_S/ρ_B	38%
0.2 to 1.5	100	cone	ρ_S/ρ_B	**46%**

Table: $S/\delta B$ improvements

Conclusions and future work

- Reconstructing each event using multiple R's extracts more information – wide-angle radiation turns out to be important

Conclusions and future work

- Reconstructing each event using multiple R's extracts more information – wide-angle radiation turns out to be important
- Using multiple interpretations increases the statistical stabilities of observables

Conclusions and future work

- Reconstructing each event using multiple R's extracts more information – wide-angle radiation turns out to be important
- Using multiple interpretations increases the statistical stabilities of observables
- Telescoping jets leads to remarkable improvement in the significance of a refined counting experiment

Conclusions and future work

- Reconstructing each event using multiple R's extracts more information
  – wide-angle radiation turns out to be important
- Using multiple interpretations increases the statistical stabilities of observables
- Telescoping jets leads to remarkable improvement in the significance of a refined counting experiment
- Work in progress and future work
  – combine with other jet substructure and superstructure observables
  – combine with likelihood-ratio test and multivariate analysis
  – deal with the issue of pile-up
  – analytic calculation of new observables with multiple interpretations
  e.g. correlations between observables (m_{R_1} and m_{R_2})