Multiple Event Interpretations in Jet Physics

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Outline

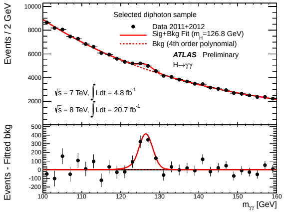
- LHC after the Higgs
  - Search for BSM physics
  - Precision measurement
  - Jet physics
- Multiple event interpretations
  - Q-jets and Q-events (jet sampling)
  - T-jets (telescoping jets)
- Demonstration: the higgs search in $ZH \to e^+e^-b\bar{b}$
  - From cut-and-count towards extended maximum likelihood fit
  - Combining and comparing T-jets with Multivariate analysis
- Results

reference :
1407.xxxx (to appear before July 4th),

Telescoping jets: 1304.5240, Jet sampling: 1304.2394, Q-jets: 1201.1914

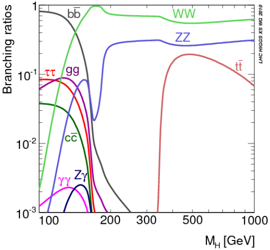
Higgs discovery on July 4, 2012

- We saw $h \to \gamma\gamma$



- Clean signal but small cross section
  - Then the LHC was shutdown in early 2013
  - Restart in early 2015

- Can we see $h \to b\bar{b}$?



Large branching fraction but also large background

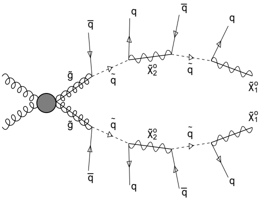
- No (Run 1), and yes (Run 2)
- Extraction of the bottom and top Yukawa couplings needs more statistics *and* better jet physics techniques

One important quest in jet physics

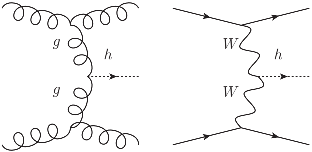
- Quark-gluon discrimination
  - Many SM and BSM signals have quark-heavy final states
  - QCD backgrounds are mostly gluon-heavy
  - Quark and gluon jets have different jet substructures

Being able to distinguish quarks from gluons is very important

- Gluino decay chain with a quark-heavy final state



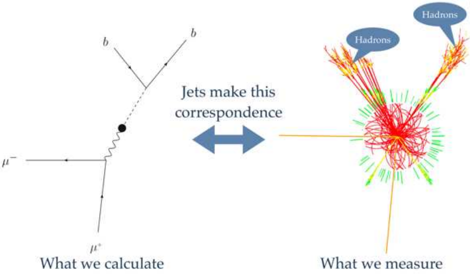
- Different higgs production mechanisms with quark or gluon jets in the final state



gluon fusion   vector boson fusion

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 measure some jet observables
  - Tools: analytic calculations and numerical simulations



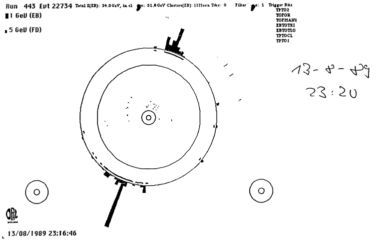
- $H(\to b\bar{b}) + Z(\to \mu\bar{\mu})$ production at parton and hadron levels

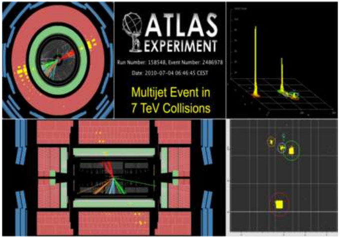
Key words

pQCD, SCET, PYTHIA, MadGraph, Herwig, FastJet, jet shape, jet substructure, jet superstructure, ...

Jets at LEP and the LHC

- Jets are distinct, localized structure in calorimeter
  - Jets can have different widths, can have substructure, ..., etc.





- The first hadronic Z decay observed at OPAL with back-to-back dijets

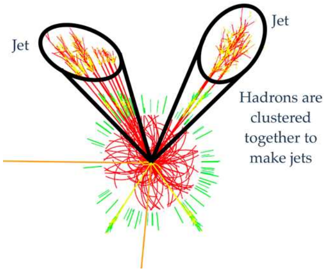
- A multi-jet event at the 7 TeV LHC

What is a jet more precisely?

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

Interrogating jets!

- With jets, we want to know all the information about them
  - which parton gives which jet? quarks v.s. gluons
  - can we measure the charge and spin of a parton?
  - what is the underlying scattering process?



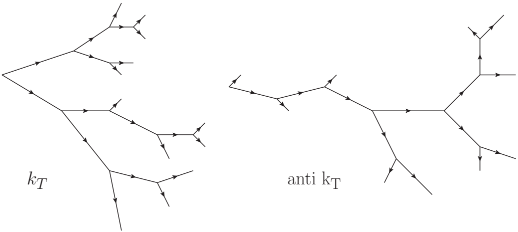
Clustering algorithms

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

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

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

β controls the merging priority in energy



- In the end we get a tree for each jet
- Different algorithms reveal different aspects of the jet structure

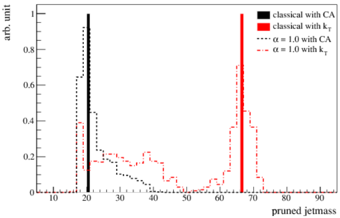
Q-jets: non-deterministic clustering algorithms (Ellis et al.)

- Idea: merge particles probabilistically according to a weight

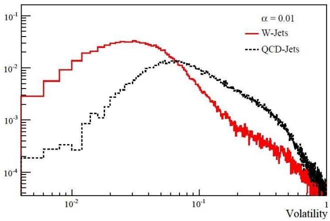
$$w_{ij}^{(\alpha)} = \exp\left\{ -\alpha \frac{d_{ij} - d^{min}}{d^{min}} \right\}, \qquad d^{min} = \min d_{ij}$$

  - There is still one single parameter R
  - α controls the deviation from the classical, deterministic clustering
  - Q-jets gives different trees and jet constituents in each reconstruction
  - Each jet observable turns from a single number to a distribution

Nice performance in boosted W-tagging with pruning



- Pruned jet mass for a single QCD-jet

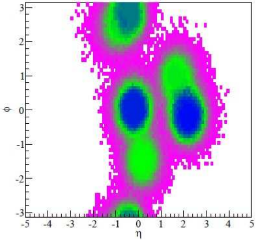


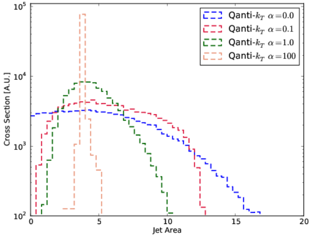
- Volatility distributions of W and QCD jets

Q-events: Q-jets applied to the whole event (Schwartz et al.)

- Each run gives a different reconstruction, or interpretation, of an event
  - Every time jets are *sampled* from the event differently

Nice performance in $pp \to \phi$, $\phi\phi$, $Z\phi$ and ZH searches using Qanti-$\mathrm{k_T}$

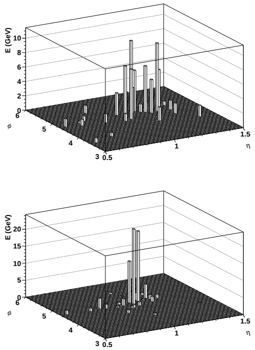




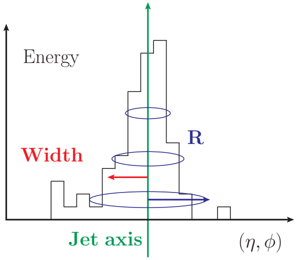
- The frequency with which a calorimeter cell is clustered into one of the hard jets in a simulated $pp \to \phi\phi \to gggg$ event at the LHC
- The jet area becomes a distribution, instead of a single number πR^2

Then why use only one fixed R for all the jets?

- There is no reason for jets to have the same size R
  - Jet formation is quantum mechanical



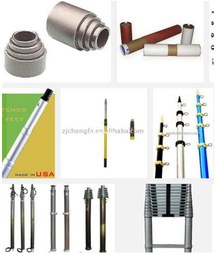
- Two b jets with the same partonic kinematics but different widths



- Distinguishing the width of the localized energy distribution of a jet from the parameter R

Telescoping jets: T-jets (Chien)

- Idea: use whatever jet algorithm you like with multiple R's
  - Each choice of R gives a distinct interpretation of an event
  - Probe the structure of an event many times with different angular resolutions
- Demonstration: the 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



T-jets recipe

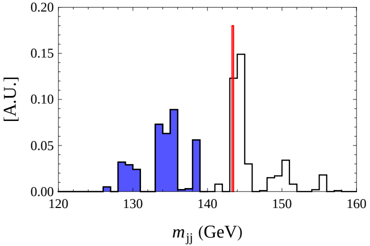
- Determine the b-jet axes n_1 and n_2: use the anti-k_T algorithm with $R_{\rm core}$ to reconstruct the cores of the two hardest jets
- Telescope around the axes: define the i-th jet to be the particles within a distance R away from n_i

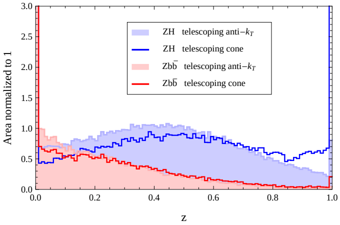
$$\text{jet}_R^i = \{\, p \mid (\eta_p - \eta_{n_i})^2 + (\phi_p - \phi_{n_i})^2 < R^2 \}$$

- If jets overlap, assign particles to the jet with the nearest jet axis

Cut-and-count with multiple event interpretations

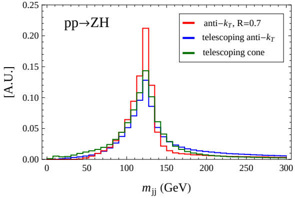
- Each event is counted by the fraction of interpretations z passing the cuts, instead of 0 or 1 in a conventional analysis
  - 110 GeV $< m_{jj} <$ 140 GeV
  - N R's ranging from R_{min} to R_{max}
- m_{jj} becomes a distribution for a single ZH event with multiple interpretations
- Signals are more robust in multiple event interpretations than backgrounds
- In general, we can count with a weight function $w(x) = \frac{\rho_S(x)}{\rho_B(x)}$ associated with the distribution $\rho(x)$ of any observable x

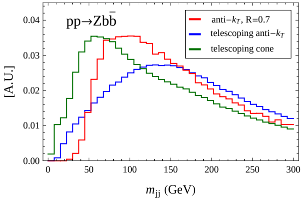




Merged m_{jj} distribution

- The signal mass peak gets broader, but the statistical stability of observables is increased so that background fluctuations shrink considerably, which is the key for $S/\delta B$ improvement





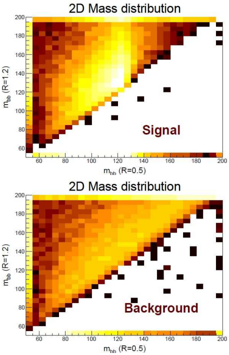
$$\frac{S}{\delta B} = \frac{\text{expected signal in the window}}{\text{fluctuation of background in the window}}$$

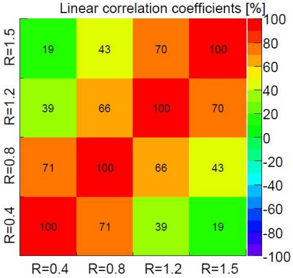
R range	N	algorithm	weight	$S/\delta B \uparrow$
0.4 and 1.0	2	cone	z	14%
0.4 to 1.0	7	cone	z	20%
0.4 to 1.5	12	cone	z	26%
0.2 to 1.5	100	anti-k_T	z	20%
0.2 to 1.5	100	cone	z	**28%**
0.4 to 1.5	12	cone	ρ_S/ρ_B	38%
0.2 to 1.5	100	cone	ρ_S/ρ_B	**46%**

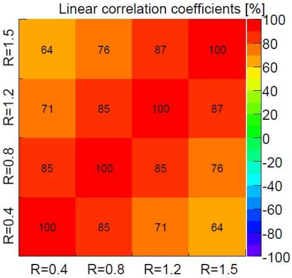
- The $S/\delta B$ improvement is significant

Extended maximum likelihood fit and multivariate analysis

- Cut-and-count pre-assumes σ_B, while EML fits σ_S and σ_B simultaneously
- We can fit the 1-D merged distribution or do the multi-dimensional fit
- The numbers of interpretations and bins can make the multi-dimensional fit impractical, and we replace the exact likelihood with boosted decision trees (BDT)







- 2-D mass distributions and correlation matrices for signals and backgrounds

Comparison to standard observables and results (preliminary)

- What extra information do we gain? Can they be equally captured by the standard kinematic variables? The answer is no.

Improvement (over R=0.5 only)	$p_T^Z < 120$ GeV		$p_T^Z > 120$ GeV	
	xs-based	EML	xs-based	EML
1 R, fraction in window	0.83	0.74	0.80	0.71
12 R's, fraction in window	0.98	0.97	0.92	0.88
1 R, $m_{b\bar{b}}$	1.00	1.00	1.00	1.00
5 R's, $m_{b\bar{b}}$ merged	0.94	1.08	0.94	1.06
4 R's, 3 bins	0.99	1.00	1.16	1.20
2 R's, full	1.10	1.14	1.35	1.38
2 R's, BDT	1.04	1.08	1.30	1.34
12 R's, BDT	1.19	1.30	1.52	1.41
12 kinematic	1.33	1.50	1.35	1.29
12 kinematic + 12 R's	1.39	1.68	1.67	1.55

- The 12 kinematic variables are the nearly optimal set in MVA (Schwartz et al.)

Conclusions and future work

- Multiple event interpretations extract more information out of an event
  – wide-angle radiation turns out to be important
- The T-jets implementation is a simple, powerful, and experiment-friendly method, which hopefully will become a standard analysis procedure
- Future work
  – Deal with the issue of pile-up
  – Analytic understanding of new observables with multiple interpretations
    e.g. correlations between observables (m_{R_1} and m_{R_2})
  – T-jets in boosted-particle tagging
  – Applications to BSM searches