Jets: seeing quarks and gluons at the LHC

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Brief plan

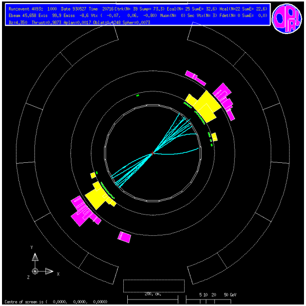
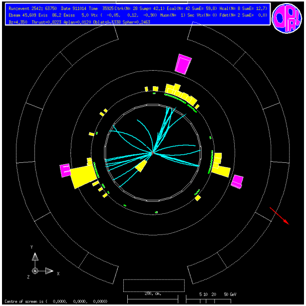
- Jets
  - concept and pre-LHC history
  - jets at the LHC
  - pileup
  - interface
- Jet substructure
  - boosted objects
  - a few examples
  - towards analytic understanding

What is a “jet”?

concept/idea

Jets

- Final-state events are pencil-like
  already observed in e^+e^- collisions:

- Consequence of the collinear divergence
  QCD (quark & gluon) branching proba: $\frac{dP}{d\theta} \propto \frac{\alpha_s}{\theta}$

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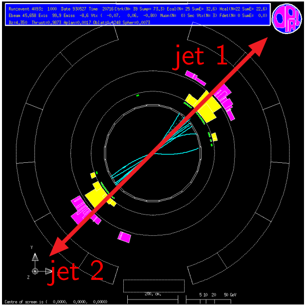

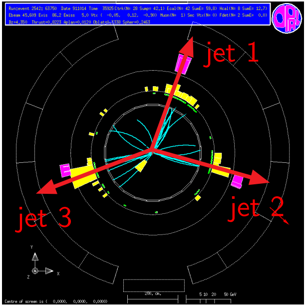

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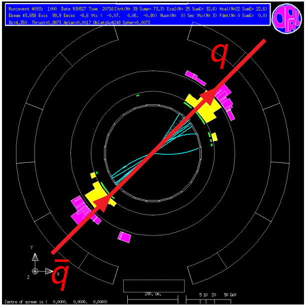

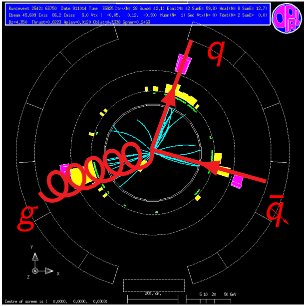

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"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

Jets and partons

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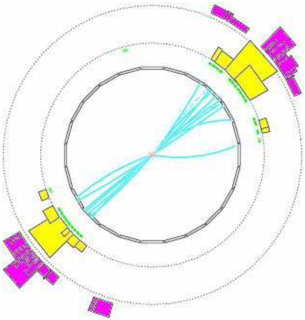
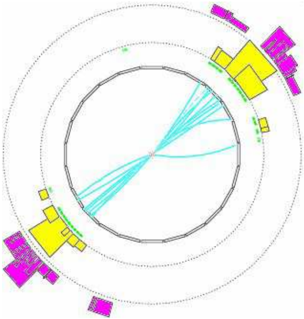
How many jets?



Jets and partons

"Jets" ≡ bunch of collimated particles ≅ hard partons

obviously 2 jets



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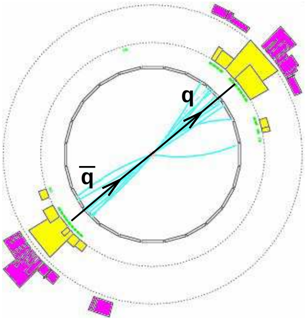

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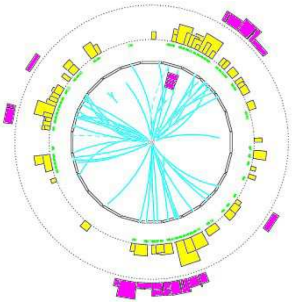

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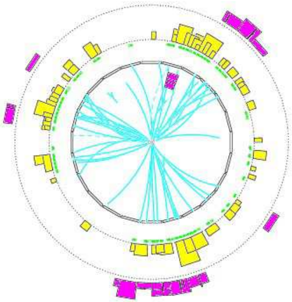
3 jets



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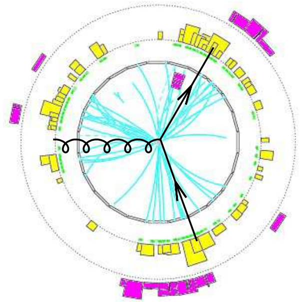

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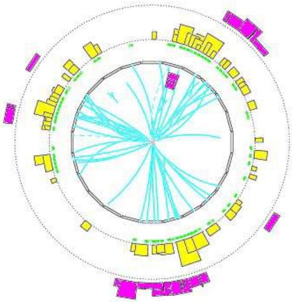
3 jets... or 4?



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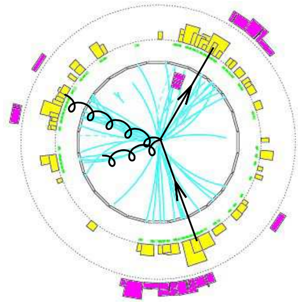

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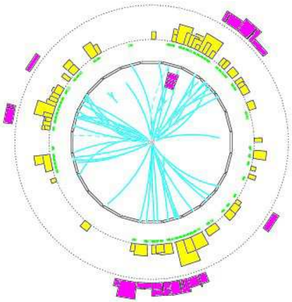

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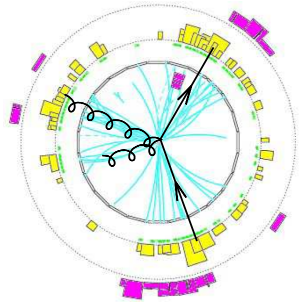
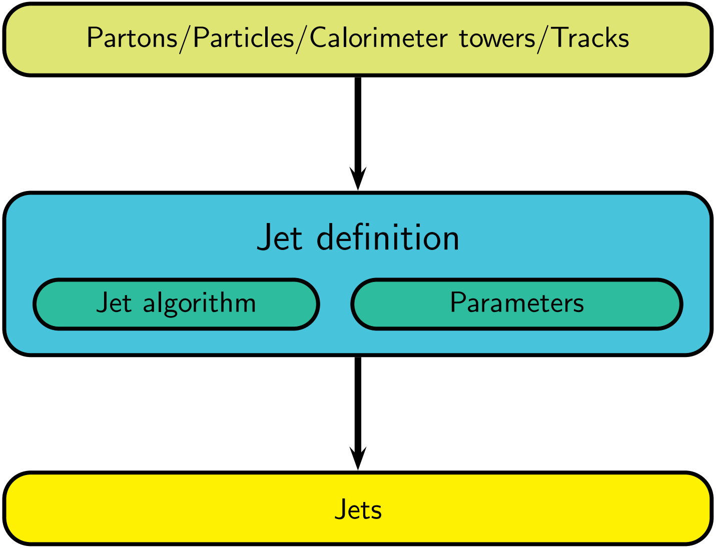


- "collinear" is arbitrary
- "parton" concept strictly valid only at LO

Jet definition



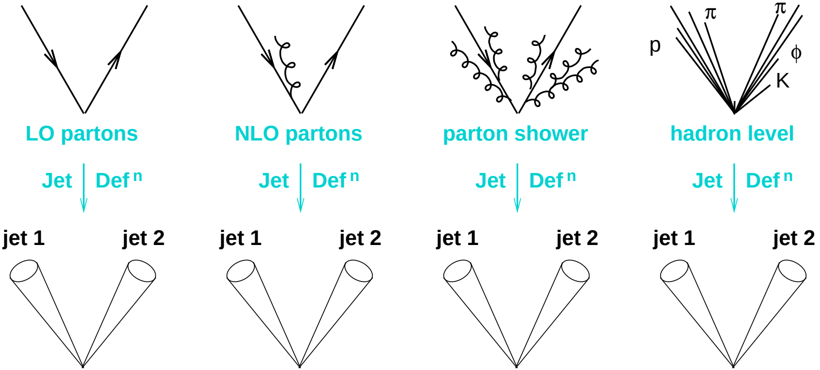
What is a "jet"?

jet definition(s)

Jet definition

A jet definiton is supposed to

- give finite jet cross sections (th)
- be fast enough (exp)
- be (as) consistent (as possible) across different view of an event (both)



Importance

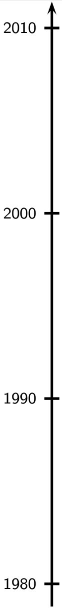
Jets are omnipresent

Jets are used in ∼60% of the LHC analyses

Jets are important

A robust jet definition is needed: it guarantees a precise access to the quarks and gluons in “hard” collisions

A brief/rough flight over the history of jets



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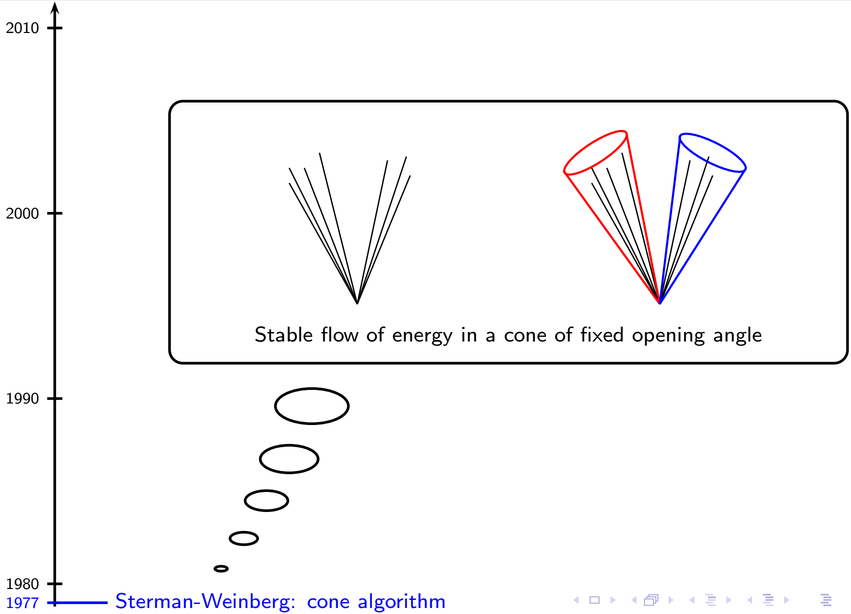

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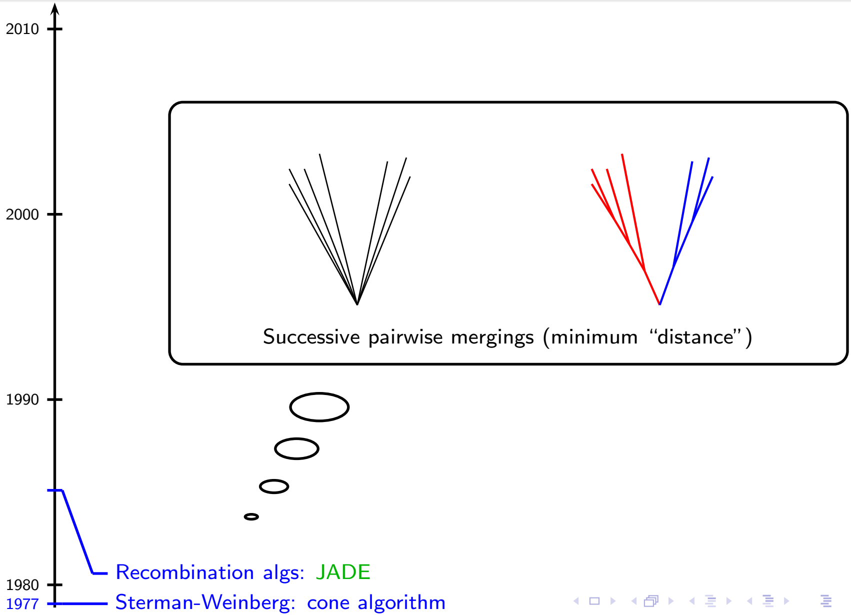

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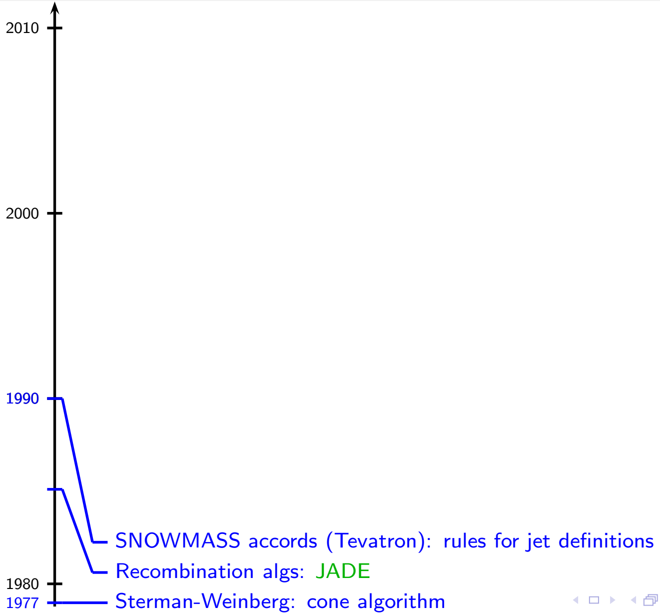

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2010

2000

90's LEP& Tevat.

- Tevatron used the cone: CDFJetClu, CDFMidPoint, D0MidPoint
  k_t and friends considered too slow

1990

- Recombination algs: JADE, Durham(k_t), Cambridge/Aachen
  Longitudinally invariant k_t
- Used at LEP (many QCD studies)

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- 2008 — Area-median background subtraction method
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A brief/rough flight over the history of jets

2010
- The LHC uses anti-k_t, FastJet and area-median subtraction

2008
- Area-median background subtraction method
  [M.Cacciari,G.Salam, 0707.1378; M.Cacciari,G.Salam,GS, 0802.1188]
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2006
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Jet v. parton

[M.Dasgupta,L.Magnea,G.Salam,08; GS, 10]

- Out-of-jet emission:

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$$\langle \delta p_t \rangle \sim -\mu_{\rm hadr} \, \frac{1}{R}$$

important for $R \lesssim 0.2$

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- Underlying Event (& PU, see below)

$$\langle \delta p_t \rangle \sim +\Lambda_{\rm UE} \, R^2$$

suggests smaller R (in the 0.4-0.8 range)

What is a "jet"?

jets at the LHC

The anti-k_t jets

- All experiments use the anti-k_t algorithm:

[M. Cacciari, G. Salam, GS, 2008]

The anti-k_t algorithm

- From all the objects, define the distances

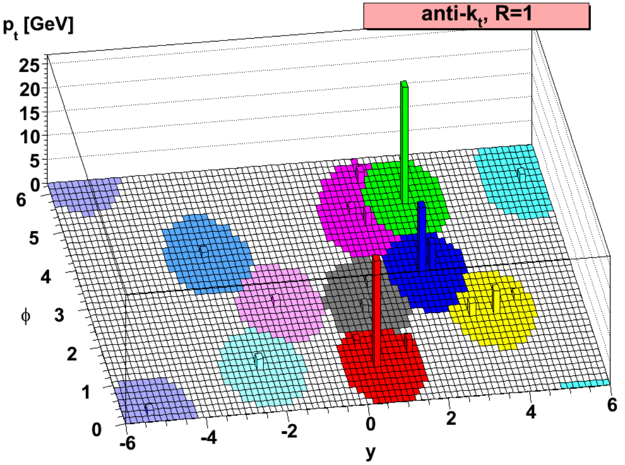
$$d_{ij} = \min(k_{t,i}^{-2}, k_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2), \qquad d_{iB} = k_{t,i}^{-2} R^2$$

- repeatedly find the minimal distance
  if d_{ij}: recombine i and j into $k = i + j$
  if d_{iB}: call i a jet

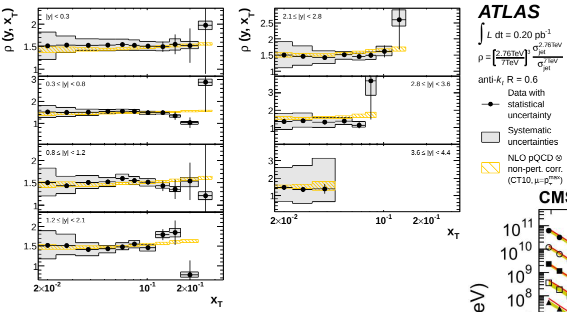
- R is a size parameter (*e.g.* CMS: 0.5,0.7, ATLAS: 0.4,0.6)

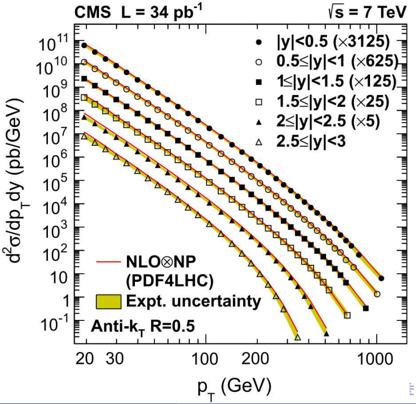
The anti-k_t jets

Main property: hard jets are circular



Examples

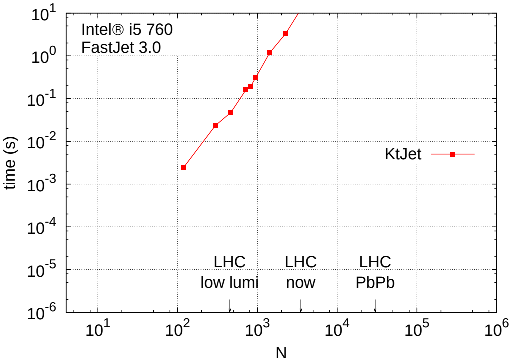

ATLAS
∫ L dt = 0.20 pb^-1
anti-k_t R = 0.6
Data with statistical uncertainty
Systematic uncertainties
NLO pQCD ⊗ non-pert. corr. (CT10, μ=p_T^max)
|y| < 0.3
0.3 ≤ |y| < 0.8
0.8 ≤ |y| < 1.2
1.2 ≤ |y| < 2.1
2.1 ≤ |y| < 2.8
2.8 ≤ |y| < 3.6
3.6 ≤ |y| < 4.4
ρ (y, x_T)
x_T


CMS L = 34 pb^-1
√s = 7 TeV
|y|<0.5 (×3125)
0.5≤|y|<1 (×625)
1≤|y|<1.5 (×125)
1.5≤|y|<2 (×25)
2≤|y|<2.5 (×5)
2.5≤|y|<3
NLO⊗NP (PDF4LHC)
Expt. uncertainty
Anti-k_T R=0.5
d²σ/dp_T dy (pb/GeV)
p_T (GeV)

Implementation

FastJet (1/2)

[M.Cacciari, G.Salam, 2005]



- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles

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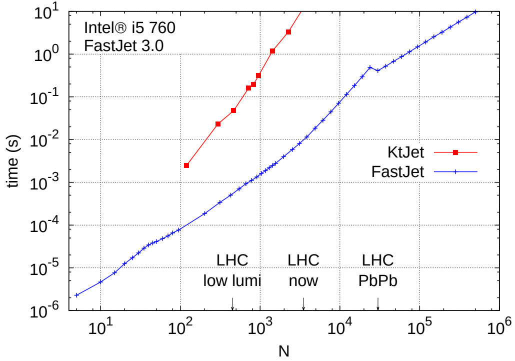


- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
- Now: (anti-)k_t very fast: $\mathcal{O}(N^2)$ or even $\mathcal{O}(N \log(N))$

FastJet (2/2)

[M.Cacciari, G.Salam, GS, 2007-2013]

- Grown way beyond just fast recombinations:
  - plugins for used jet definitions
  - jet areas and background subtraction (see below)
  - tools for manipulating jets
  - more to come...
- FastJet 3.0.6 released in October 2013
  see `www.fastjet.fr`
- Standard interface for jet physics
  for both theorists and experimentalists

FastJet contrib (since Feb 2013)

- fastjet.fr
- fastjet-contrib
- contrib svn

FastJet Contrib

The fastjet-contrib space is intended to provide a common location for access to 3rd party extensions of FastJet.

Download the current version: fjcontrib-1.011 (released 6 April 2014), which contains these contributions. Changes relative to earlier versions are briefly described in the NEWS file.

	Package	Version	Information
	ConstituentSubtractor	1.0.0	README NEWS
	EnergyCorrelator	1.0.1	README NEWS
	GenericSubtractor	1.2.0	README NEWS
	JetCleanser	1.0.0	README NEWS
2	JetFFMoments	1.0.0	README NEWS
	JetsWithoutJets	1.0.0	README NEWS
	Nsubjettiness	1.0.3	README NEWS
	ScJet	1.1.0	README NEWS
	SubjetCounting	1.0.1	README NEWS
	VariableR	1.0.1	README NEWS

- a quick and uniform access to 3rd-party code
- contributors are welcome

  (please contact us)

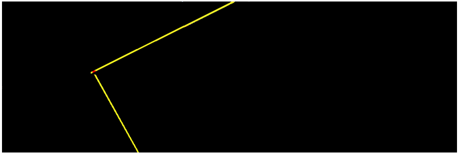
Pileup

things get more complicated

Pileup

$Z \to \ell^+\ell^-$ candidate at ATLAS

Low luminosity
(bunch population)



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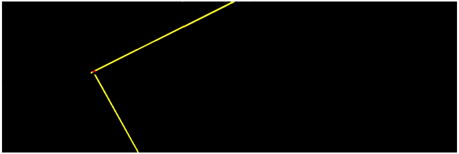

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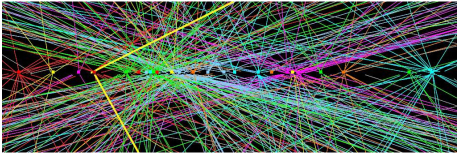


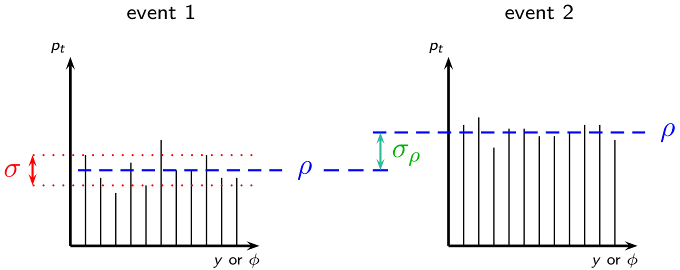
Pileup complicates things

- many (soft) *pp* interactions with the hard one (here 25)
  LHC Run I: $\sim$ 25, Run II: $\sim$ 60, upgrades: $\lesssim$ 200
- soft background in the whole detector

Basic characterisation

Pileup mostly characterised by 3 numbers (∗):

- ρ: the average activity in an event (per unit area)
- σ: the intra-event fluctuations (per unit area)
- σ_ρ: the event-to-event fluctuations of ρ



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Jet of momentum p_t and area A:

$$\text{one event:}\ \ p_t \to p_t + \rho A \pm \sigma\sqrt{A}$$

$$\text{event average:}\ \ p_t \to p_t + \langle\rho\rangle A \pm \sigma_\rho A \pm \sigma\sqrt{A}$$

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p_t shift (ρA, $\langle\rho\rangle A$)

p_t smearing ($\sigma\sqrt{A}$, $\sigma_\rho A \pm \sigma\sqrt{A}$)
resolution degradation

$^{(*)}$ valid also for the underlying event in heavy-ion collisions

Subtraction methods (correct for the shift)

one subtracts a contribution from individual jets

subtracted	PU effects kept
constant p_t ($\langle\rho A\rangle$)	both flucts + area flucts
$\langle\rho\rangle \times A$	both flucts ($\sigma\sqrt{A}$ & $\sigma_\rho A$)
$\langle\rho\rangle_{\text{per PU vertex}} \times n_{PU} \times A$	$\sigma\sqrt{A}$ and part of $\sigma_\rho A$
$\rho_{\text{event}} \times A$	only $\sigma\sqrt{A}$

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more averaged ↕ 'event-by-event'

Event-by-event determinations of the shift (are expected to) reduce the smearing effects of PU

Median-area-based subtraction

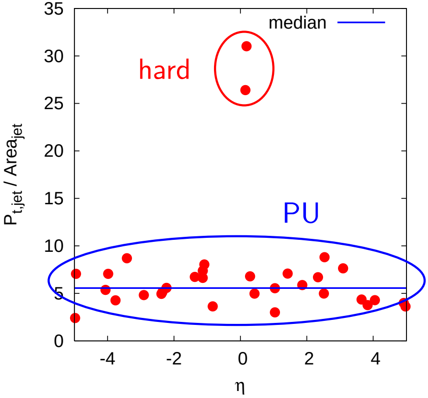
[M.Cacciari, G.P. Salam, 07; M.Cacciari, G.P. Salam, GS, 2008]

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{est}} A_{\text{jet}}$$

$$\rho_{\text{est}} = \underset{j \in \text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$

per jet

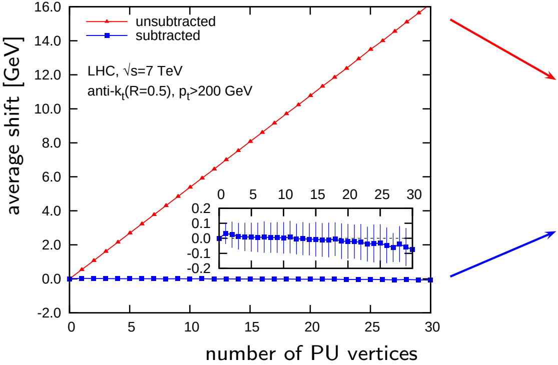
per event
(typically)



break the event in patches of similar size
e.g. cluster with k_t

Subtraction benchmarks

average p_t shift



No subtraction

area-median subtraction

corrected for shift

Subtraction benchmarks

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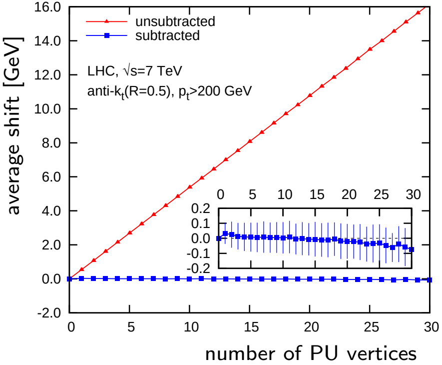
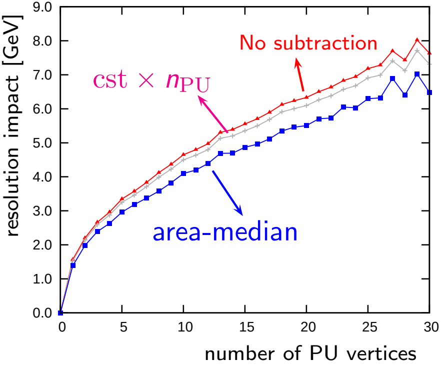


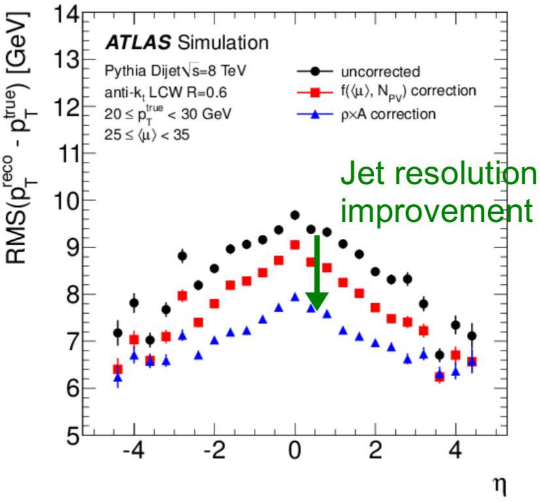
corrected for shift

impact on resolution



resolution improved

PU subtraction as seen in ATLAS



[B. Petersen, ATLAS Status report for the LHCC, 2013]

Recent developments

Improvements/extensions of the method

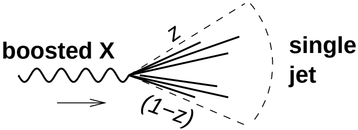
- Methods to handle positional dependence of ρ
  Directly relevant for the LHC (*e.g.* rapidity dependence)
  [M.Cacciari,G.Salam,GS,2010-2011]
- Subtraction for jet mass and jet shapes
  Important for jet tagging ("q v. g jet", b jet, top jet, $H \to b\bar{b}$)
  [GS,G.Salam,J.Kim,S.Dutta,M.Cacciari,2013]
  [P.Berta,M.Spousta,D.Miller,R.Leitner,2014]
- Subtraction of fragmentation function (moments)
  Useful for quenching in *PbPb* collisions
  [M.Cacciari,P.Quiroga,G.Salam,GS,2012]
- Recommended setup: ρ estimation from a grid with cell-size=0.55 + appropriate rescaling to handle rapidity dependence

Jet substructure

concept, importance, main ideas

Fat jets

Problem: boosted heavy objects will decay in a single jet



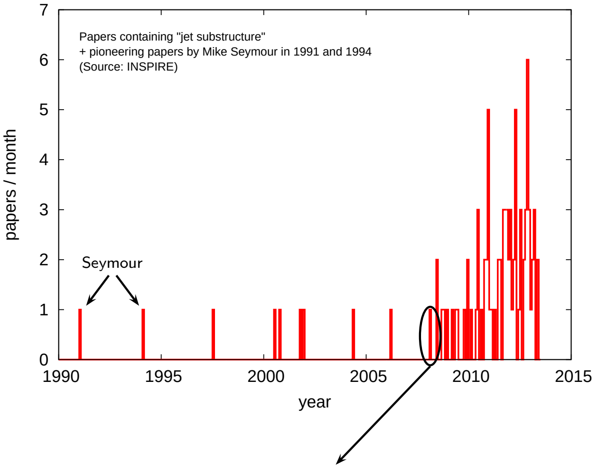
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

How to disentangle that from a QCD jet?

Increasingly important and many applications: (examples)

- 2-pronged decay: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier combinations: $t\bar{t}H$
- new physics: *e.g.* heavy SUSY $\to$ boosted top

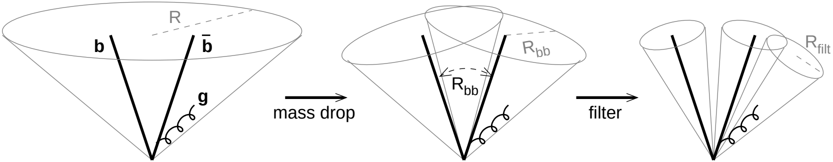
A lot of activity since 2008



Jet substructure as a new Higgs search channel at the LHC

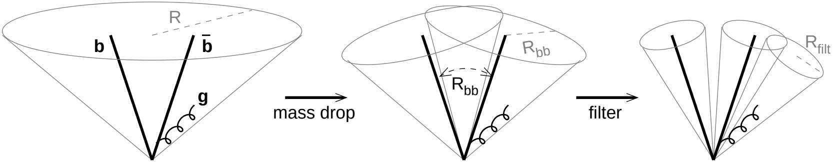
Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam, 0802.2470

Many tools



- Two major ideas:
  1. Find $N = 2, 3$ hard cores in a jet
     QCD jets typically have a single core + soft radiation
  2. constrain the radiation pattern in jets
     q/g jets radiate soft gluons differently from, *e.g.* $W \to q\bar{q}$

Many tools



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  1. uncluster the jet into subjets/investigate the clustering history
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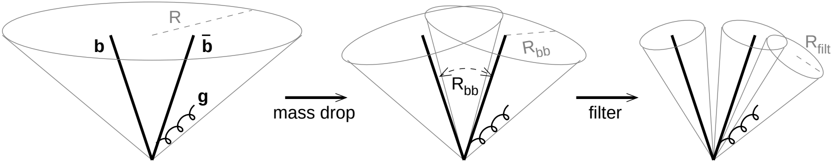
Many tools



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- Many approaches:
  1. uncluster the jet into subjets/investigate the clustering history
  2. use jet shapes (functions of jet constituents),...
- Many tools: mass drop; filtering, trimming, pruning; soft drop; N-subjettiness, planar flow, energy correlations, pull; template methods; Johns Hopkins top tagger, HEPTopTagger; ...

Generic status

current status

methods are

- tested on Monte-Carlo simulations
- validated on LHC data (QCD backgrounds)

disclaimer

I cannot realistically cover everything
$\Rightarrow$ I will just show a few examples

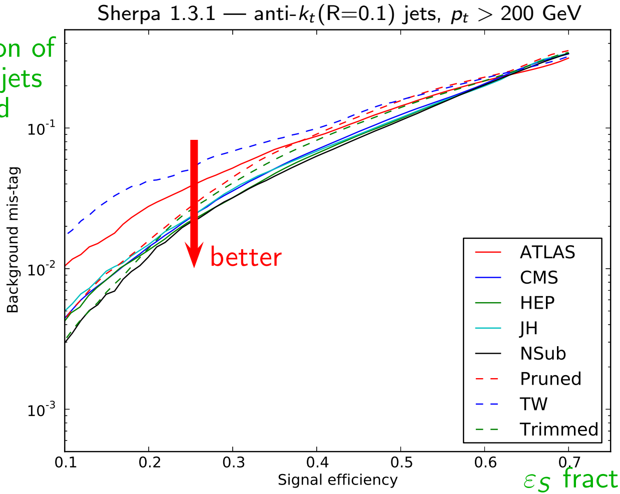
Jet substructure

A few practical examples

Example 1: top tagging MC study

[Boost 2011 proceedings]

ε_B fraction of QCD jets tagged

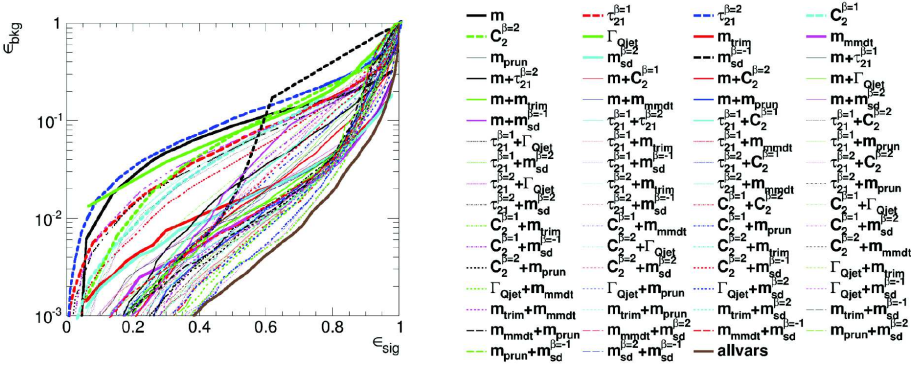


ε_S fraction of top jets tagged

Example 2: recent MC study of W tagging

[Boost 2013 WG]

W v. q jets: combination of "2-core finder" + "radiation constraint"



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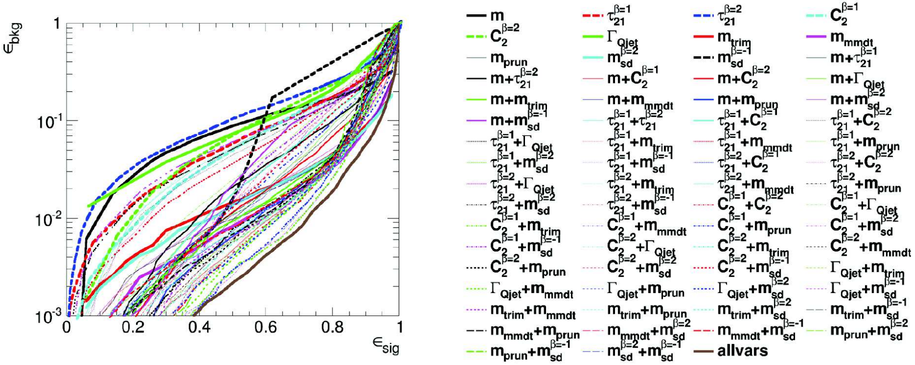
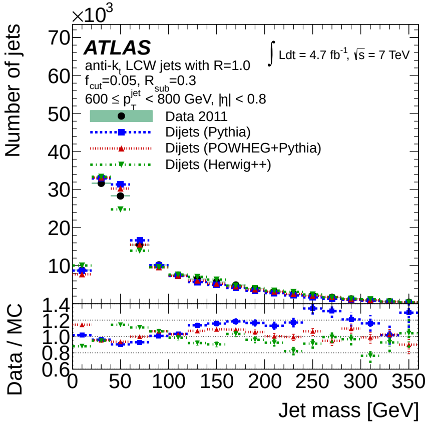


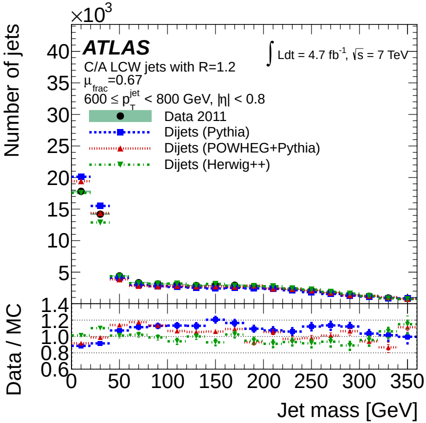
- Combination largely helps
- details not so obvious

Example 3: Monte Carlo v. data

Trimming

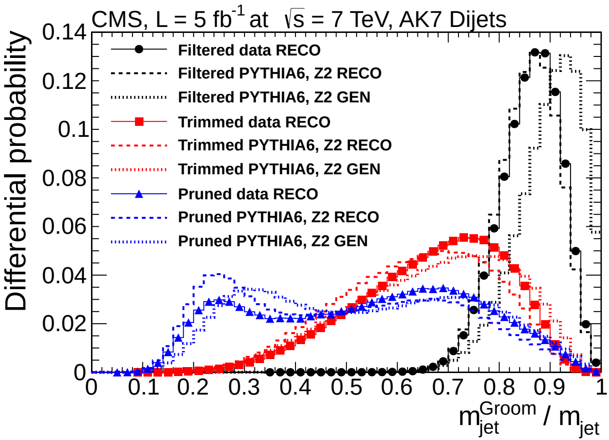


Mass-drop+filtering



Example 3: Monte Carlo v. data

("Groomed" mass)/(plain mass)



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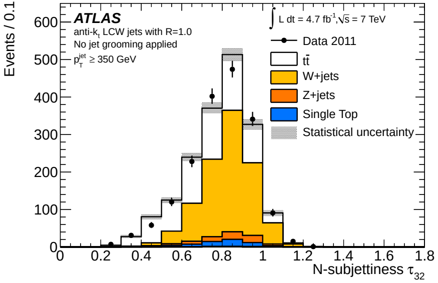

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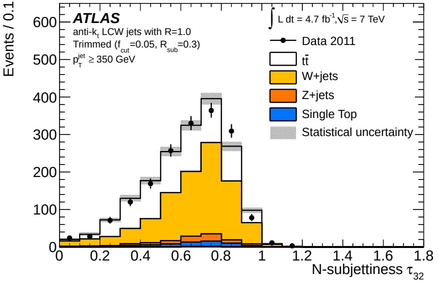

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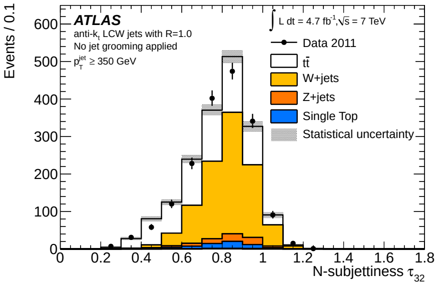

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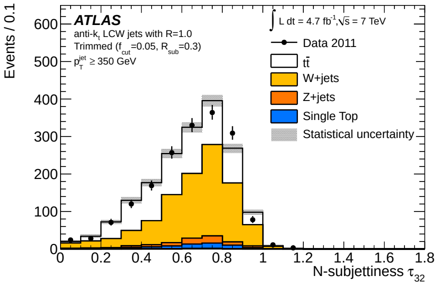


In a nutshell

- decent agreement between data and Monte-Carlo
- but some differences are observed

Jet substructure

A deeper look at a few tools

Methods for finding hard cores

(modified) mass-drop tagger

- start with a jet clustered with Cambridge/Aachen
- undo the last splitting $j \to j_1 + j_2$
- if $\max(p_{t1}, p_{t2}) > z_{\rm cut} p_t$, j_1 and j_2 are the 2 hard cores
  otherwise, continue with the hardest subjet

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08; M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

trimming

- re-cluster the jet with the k_t algorithm, $R = R_{\rm trim}$
- keep subjets with $p_t > f_{\rm trim} p_{t,\rm jet}$

[D.Krohn,J.Thaler,L-T.Wang,10]

pruning

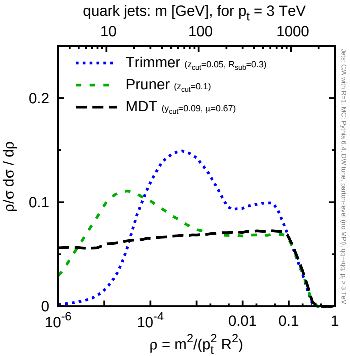
- re-cluster the jet with the k_t algorithm [S.Ellis,C.Vermillion,J.Walsh,2009]
- when recombining $j_1 + j_2 \to j$, if $\theta_{12} > R_{\rm prune} = f_{\rm prune} m/p_t$ and $\min(p_{t1}, p_{t2}) < z_{\rm prune} p_t$, keep only the hardest of j_1 and j_2.

Monte-Carlo v. analytic

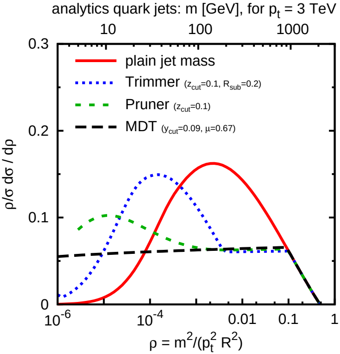
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



Analytics



- Similar behaviour at large mass/small boost (region tested so far)
- Significant differences at larger boost

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z)\, \underbrace{\Theta(z > z_{\rm cut})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

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- Focus on logarithmically enhanced terms

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \left[\log(1/\rho)\log(1/z_{\rm cut}) - \frac{3}{4}\log(1/\rho) - \frac{1}{2}\log^2(1/z_{\rm cut})\right]$$

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- All-order resummation: exponentiation!

$$P_{\text{all orders}}(<\rho) = \exp\left[-P_1(>\rho)\right]$$

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- single log in ρ!

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra "mass-drop" condition:
  no contribution at this order
- Original mass-drop tagger had an extra "filtering" step:
  no contribution at this order

Analytic example: extra notes

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- Original mass-drop tagger had an extra "mass-drop" condition: no contribution at this order
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- Original mass-drop tagger recursed into most massive branch: looses direct exponentiation!

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra "mass-drop" condition: no contribution at this order
- Original mass-drop tagger had an extra "filtering" step: no contribution at this order
- Original mass-drop tagger recursed into most massive branch: looses direct exponentiation!
- Trimming:
  - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
  - double log behaviour ($\log^2(1/\rho)$) of plain jet mass for $\rho < f_{\rm filt}(R_{\rm filt}/R)^2$

Conclusion and perspectives

- Many recent developments in use at the LHC:
  - robust and finite jet algs. In particular: anti-k_t
  - FastJet: fast and standard interface for jets
  - efficient and generic PU subtraction method
- Jet substructure:
  - lively topic of jet physics
  - many tools already available/tested (using MC)
  - first analytic results appeared...