Jets: seeing quarks, gluons and more at the LHC

Grégory Soyez

IPhT, CEA Saclay

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Brief plan

- Lecture 1: *Jets $\sim$ QCD parton*
  basic concepts
- Lecture 2: *How close is a jet to a parton?*
  Analytic estimates of perturbative and non-perturbative effects between a parton and a jet
- Lecture 3: *A jet can be something else too!*
  Boosted jets and jet substructure

What is a jet?

- Concept of a jet
- Jet algorithm/jet definition
- Fundamental requirements
- A little bit of history from LEP...
- ... to the LHC
- Practical implementation [if time permits]

Question 1

How are the hadrons distributed in a collision event?

(a) Uniformly across the event

(b) Along a few directions

(c) I do not understand the question

Question 1

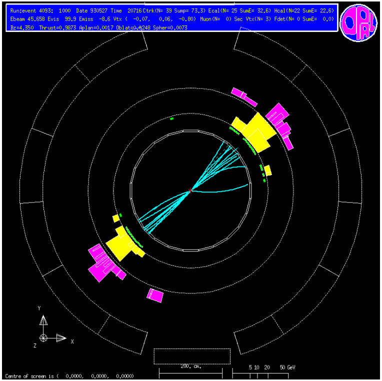
How are the hadrons distributed in a collision event?

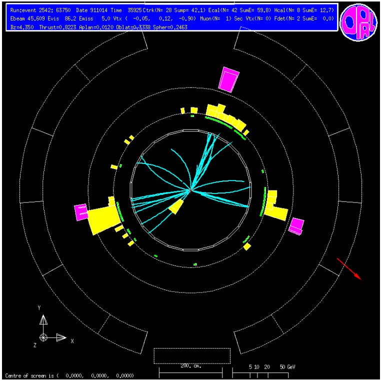
(b) Along a few directions

Jets

Final-state events are pencil-like

already observed in e^+e^- collisions:





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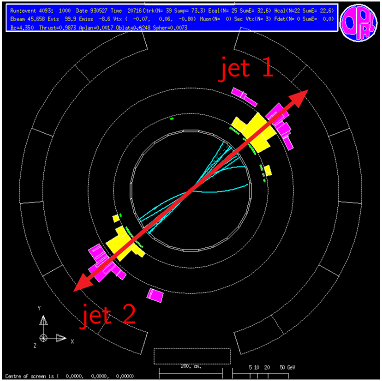

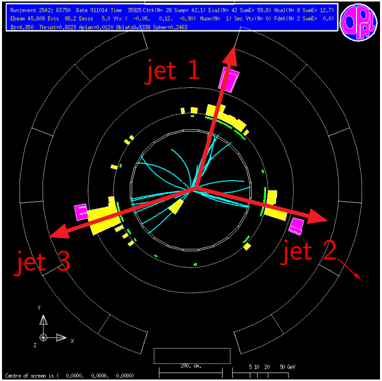

"Jets" $\equiv$ bunch of collimated particles

Jets

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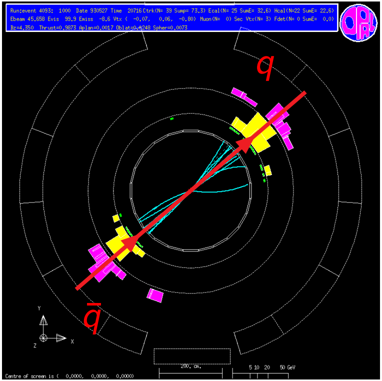
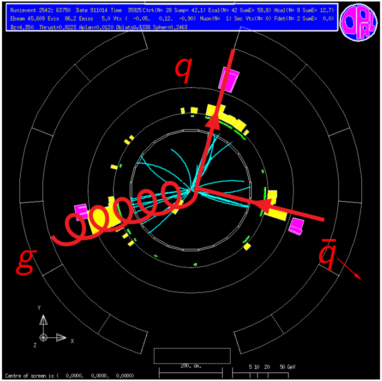




"Jets" $\equiv$ bunch of collimated particles $\cong$ hard partons

Question 2

Is that expected in QCD?

(a) Yes
(b) No
(c) What is QCD?

Question 2

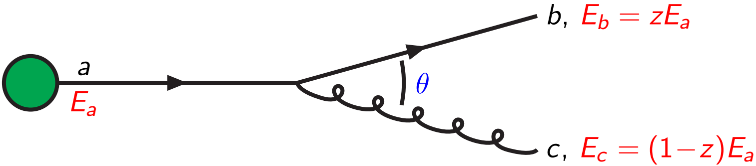
Is that expected in QCD?

(a) Yes

Origin in QCD

This is expected from QCD:

- collinear divergence: enhancement of small-angle branchings
- Same as in DGLAP/PDF evolution



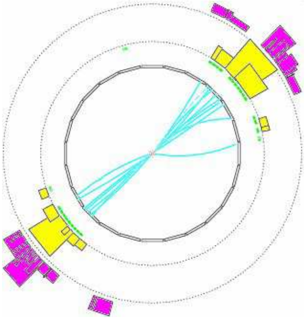
$$|\mathcal{M}_{n+1}|^2 = |\mathcal{M}_n|^2 \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2} P(z)\, dz$$

- Physical origin: as $\theta \to 0$, $p_a^2 \to 0$ (assuming b and c are massless)

Jets and partons

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

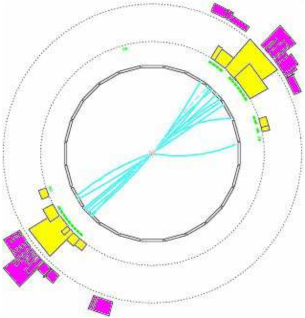
How many jets?



Jets and partons

"Jets" ≡ bunch of collimated particles ≅ hard partons

obviously 2 jets



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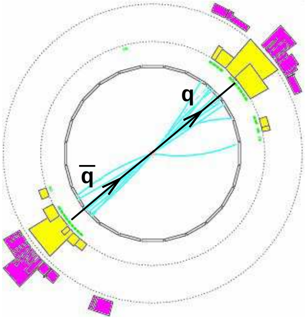

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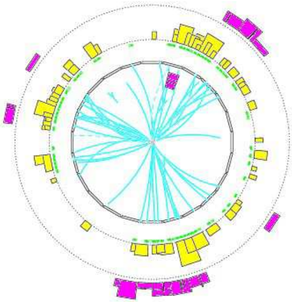

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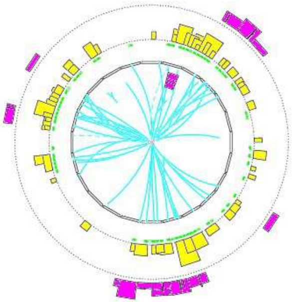
3 jets



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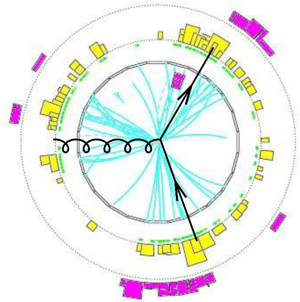

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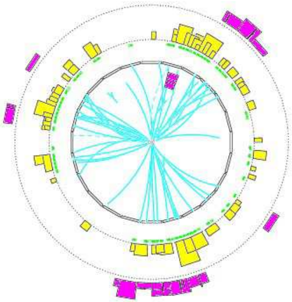
3 jets... or 4?



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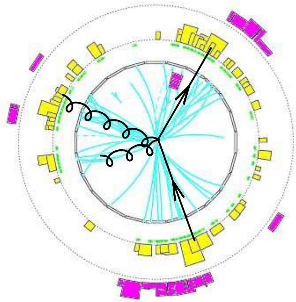

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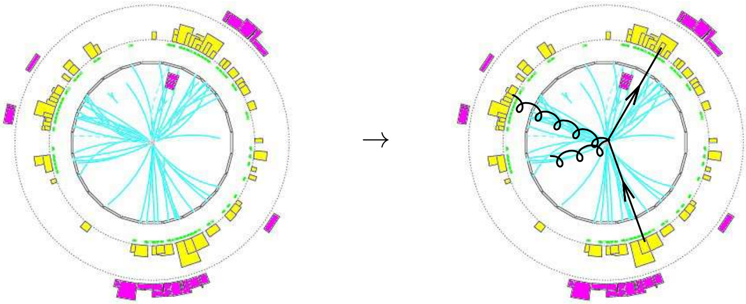
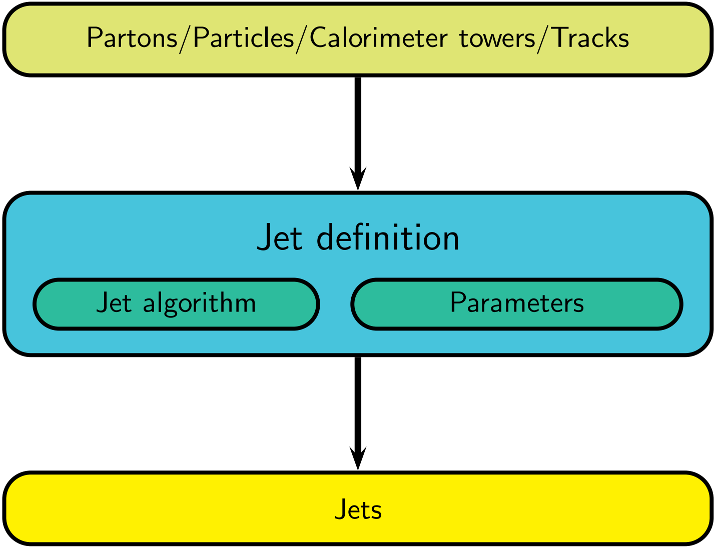


- "collinear" is arbitrary
- "parton" concept strictly valid only at LO

Jet definition



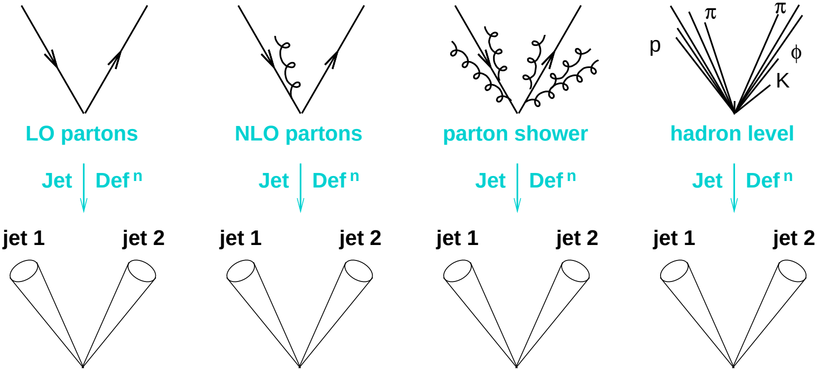
What is a "jet"?

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)



Divergences in QCD

UV divergences

- Re-absorbed into the parameters of the Lagrangian (Ψ_f, A^μ_a, g, m_f)
- QCD is a renormalisable theory
- Renormalisation-group equation e.g. $\alpha_s(\mu^2)$
- Asymptotic freedom in QCD

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IR divergences

- In the initial state: re-absorbed in the PDFs
  DGLAP evolution equation

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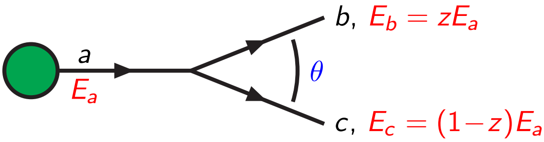
IR divergences

- In the initial state: re-absorbed in the PDFs
  DGLAP evolution equation
- what about the final-state?

Parton branching at small angle

Can be calculated explicitly (3 combinations: $q \to qg$, $g \to gg$, $g \to q\bar{q}$):



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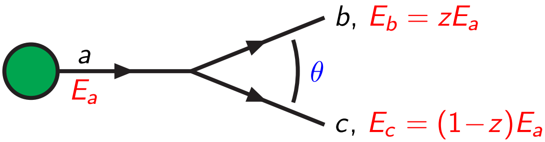
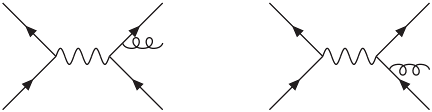


Or if you're looking for something more "concrete": $e^+e^- \to$ hadrons



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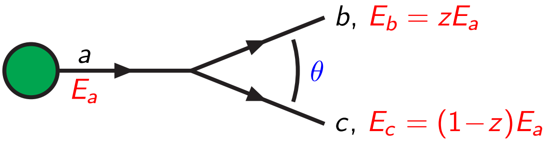

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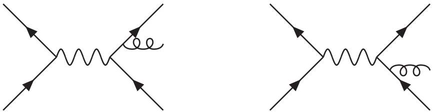

(only gives $q \to qg$)

In the end:

$$|\mathcal{M}_{n+1}|^2 = |\mathcal{M}_n|^2 \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2} P(z)\,dz, \qquad P(z) \overset{z\ll 1}{\propto} \frac{2C_R}{z}$$

At leading log: P's are the same splitting fcts as for DGLAP

Infrared-and-collinear safety

So, we have:

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Two IR divergences: collinear ($\theta \to 0$); soft ($z \to 0$)

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Kinoshita-Lee-Nauenberg/Block-Nordsieck theorem

Soft and collinear divergences cancel between real and virtual diagrams at all orders of the perturbation theory

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Infrared-and-collinear safe observables

- This cancellation must be preserved!
- Observables (e.g. jets) must be insensitive to collinear branchings and soft emissions

Question 3

How often are jets used at the LHC?

(a) Never (QCD is dirty, I live with leptons and photons)

(b) in about 20% of the analysis

(c) in about 40% of the analysis

(d) in about 60% of the analysis

(e) in about 80% of the analysis

(f) always (and I buy all QCD lecturers a beer)

Question 3

How often are jets used at the LHC?

(d) in about 60% of the analysis

Importance

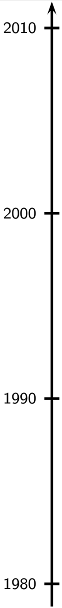
Jets are omnipresent

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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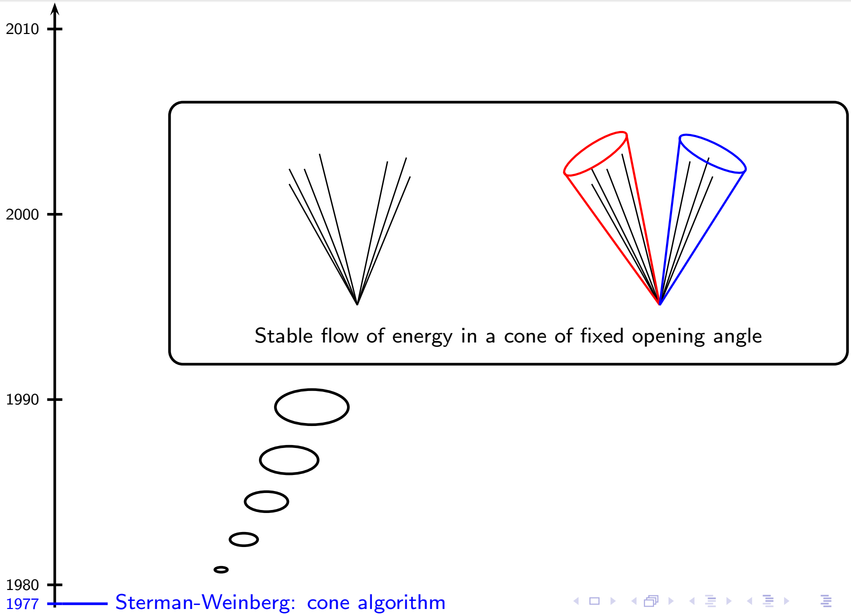

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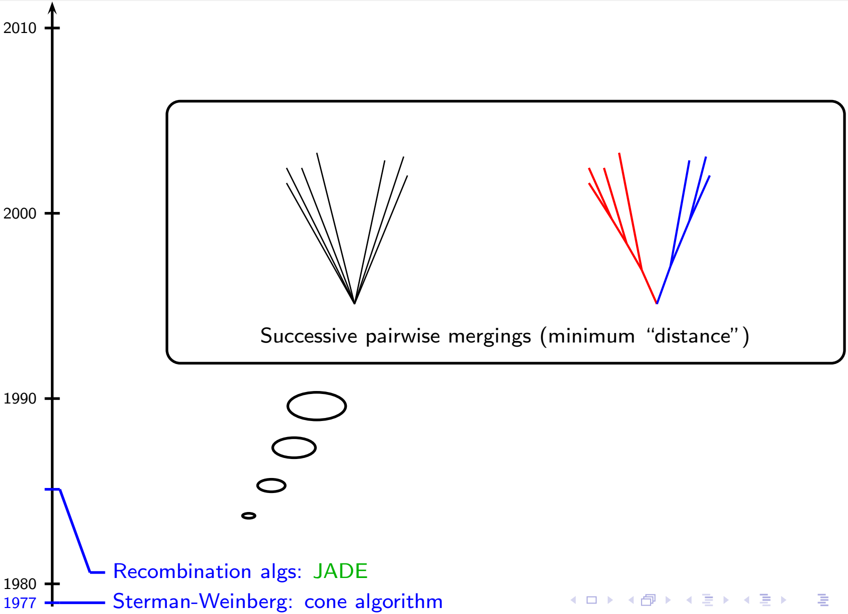

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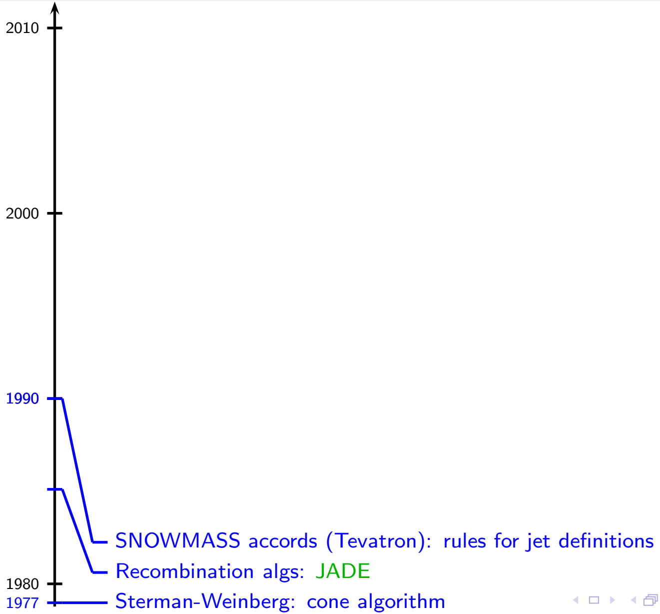

A brief/rough flight over the history of jets

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)

- SNOWMASS accords (Tevatron): rules for jet definitions
- Recombination algs: JADE

1980

1977
- Sterman-Weinberg: cone algorithm

A brief/rough flight over the history of jets

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– Getting ready for the LHC: ATLASCone, CMSIterativeCone

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2008 — (CMS)cone cured by recombinations: anti-k_t

2007 — All cones so far have divergences! ⟶ SISCone OK

2006 — k_t made fast (FastJet)

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A brief/rough flight over the history of jets

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

2010

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

2007
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Selected topics

- Cone algorithms and IRC safety
- Clustering at the LHC: the anti-k_t algorithm
- FastJet: speed and implementation
- Now is a good time to stand up if you want to hear about sth else

What is a "jet"?

Cone algorithms and IRC safety

Basic concepts

Central idea: stable cones

- A jet is a direction of stable energy flow
- Stable cone: the sum of all momenta in a cone of (fixed) radius R points in the direction of the centre of the cone

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Cone algorithms with split–merge

- find stable cones (Usually iteratively starting from a set of seeds)
- run a split–merge procedure to get rid of overlaps

CDFJetClu, CDFMidPoint, D0MidPoint, ATLASCone, SISCone

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CDFJetClu, CDFMidPoint, D0MidPoint, ATLASCone, SISCone

Cone algorithms with progressive removal

- find the hardest stable cone
  (Usually iterating from the hardest particle in the event)
- call it a jet and iterate

CMSIterativeCone, SISCone-PR

IR safety: JetClu v. SISCone

JetClu

Finds stable cones stating from all the particles in the event

SISCone

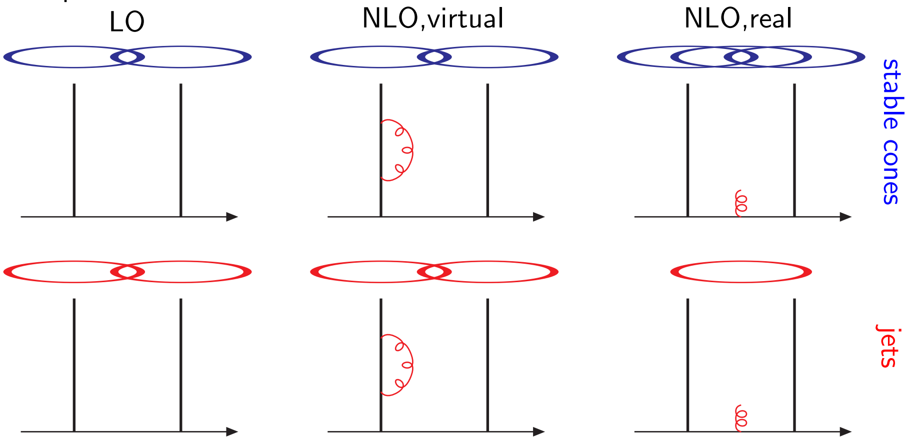
Finds ALL stable cones

Consequences

- JetClu is IR-unsafe
- SISCone is IR-safe

IR safety: JetClu v. SISCone

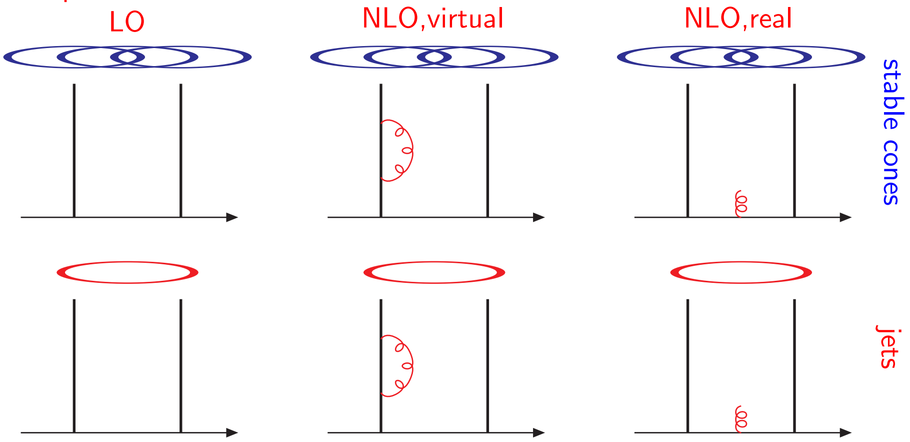
Example: JetClu



cancellation between real and virtual spoiled

IR safety: JetClu v. SISCone

Example: SISCone



Same stable cones found everywhere: all OK

Question 4

Does it matter?

(a) Yes
(b) No
(c) I understand why I hate QCD!

Question 4

Does it matter?

(a) Yes

Seeds are bad!

Consequences of IRC unsafety

- JetClu, ATLASCone IR-unsafe for 2 (nearby) particles + 1 soft
  Trust jets only at lowest order α_s^0
- CDF/D0MidPoint IR-unsafe for 3 (nearby) particles + 1 soft
  Trust jets only at lowest order α_s^1
- CMSIterativeCone collinear-unsafe for 3 (nearby) particles + 1 soft
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- SISCone(-PR) find ALL stable cones: safe at all orders

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- IR-unsafety usually(!) beyond Tevatron precision
- Not sufficient for the LHC

What is a "jet"?

Anti-k_t and 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

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

- 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: 0.5,0.7,0.4(soon) ATLAS: 0.4,0.6)
  It determines the "angular size" of jets.

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- R is a size parameter (*e.g.* CMS: 0.5,0.7,0.4(soon) ATLAS: 0.4,0.6)
  It determines the "angular size" of jets.
- $p_t^{-2} \to p_t^{2p}$: $p = -1, 0, 1$ is anti-k_t, Cambridge/Aachen and k_t

Question 5

Are anti-kt, C/A and k_t IRC-safe?

(a) Yes

(b) No: IR-unsafe

(c) No: collinear-unsafe

(d) No: IR and collinear unsafe

Question 5

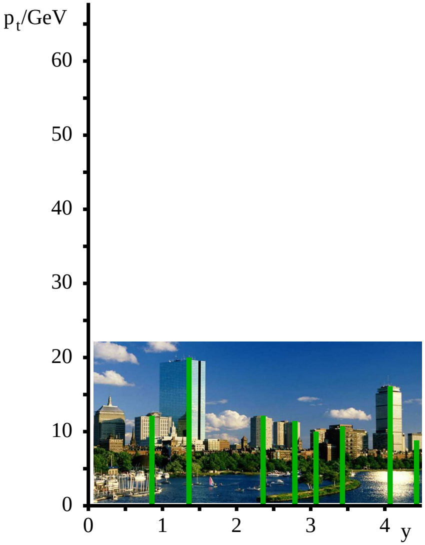
Are anti-kt, C/A and k_t IRC-safe?

(a) Yes

Clustering in action: anti-k_t ($R = 0.7$)

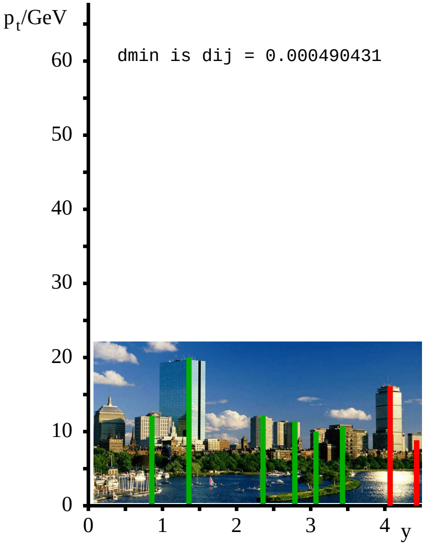
Start with your favourite picture

Clustering in action: anti-k_t ($R = 0.7$)



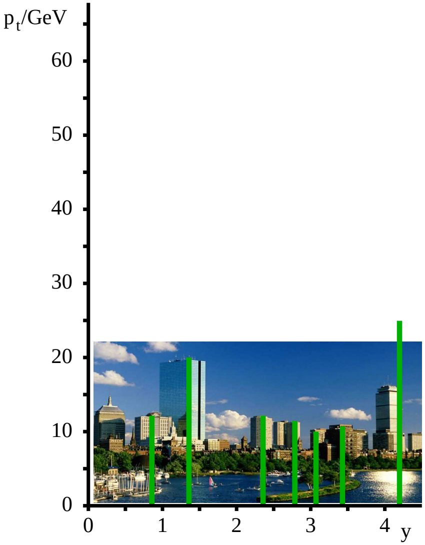
Start with your favourite ~~picture~~ event

Clustering in action: anti-k_t ($R = 0.7$)



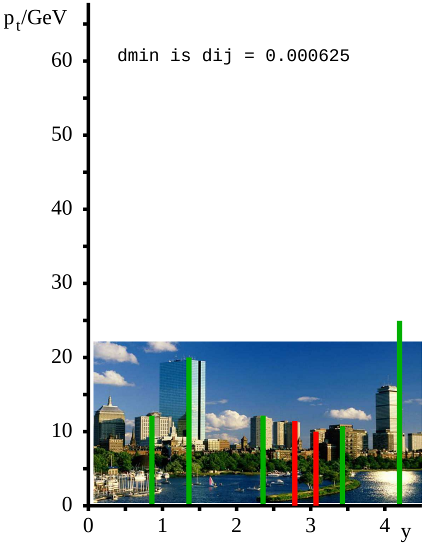
min is $d_{ij} = 4.9\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



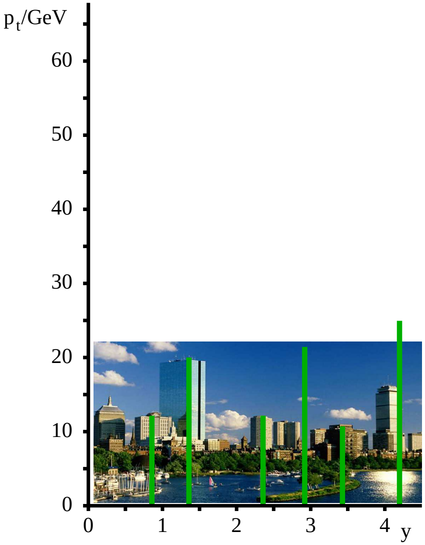
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



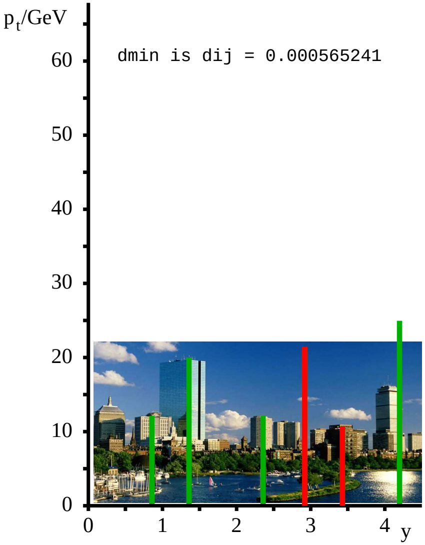
min is $d_{ij} = 6.3\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



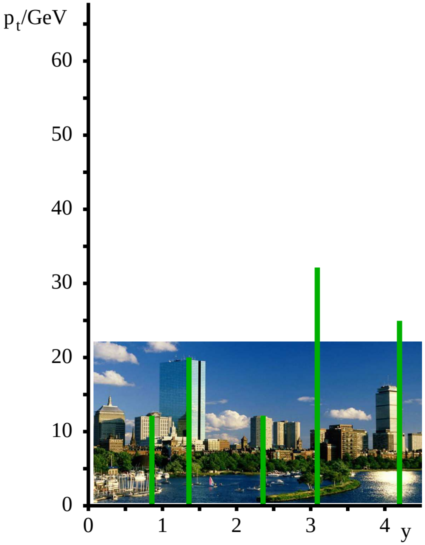
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



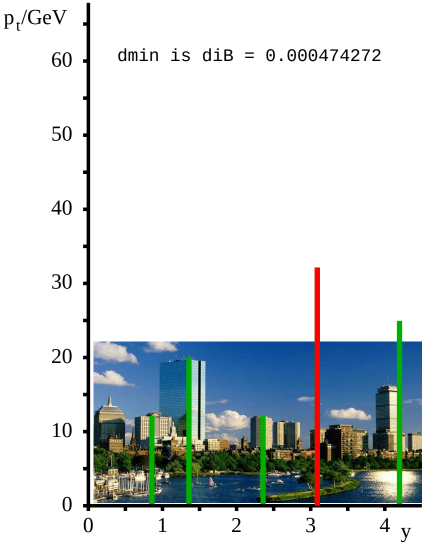
min is $d_{ij} = 5.7\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



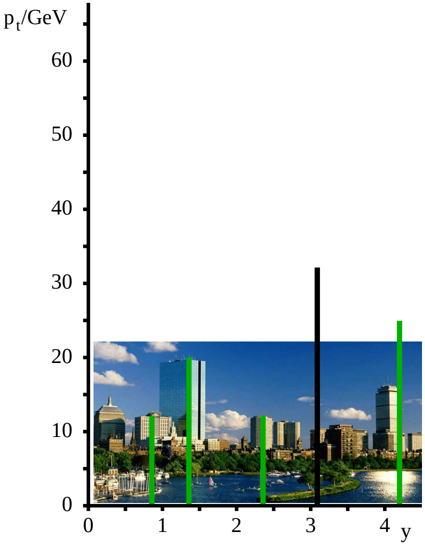
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



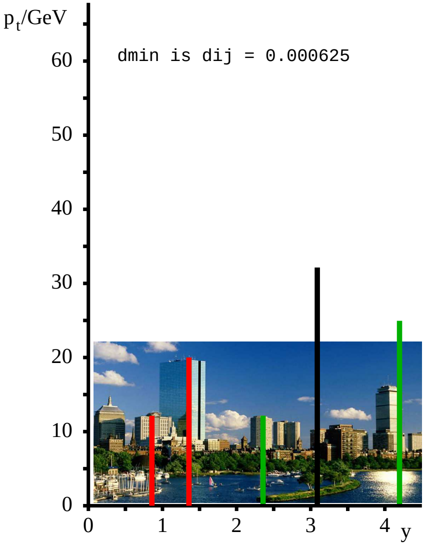
min is $d_{iB} = 4.7\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



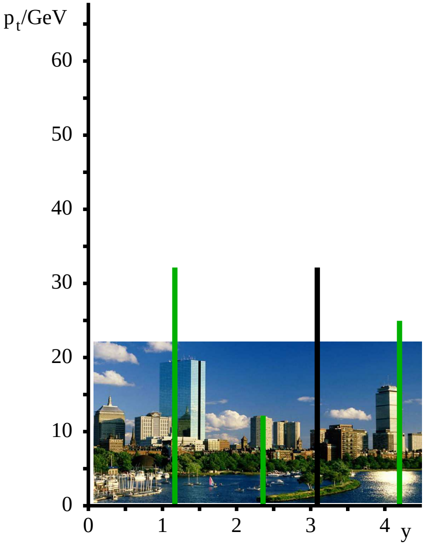
declare as a jet

Clustering in action: anti-k_t ($R = 0.7$)



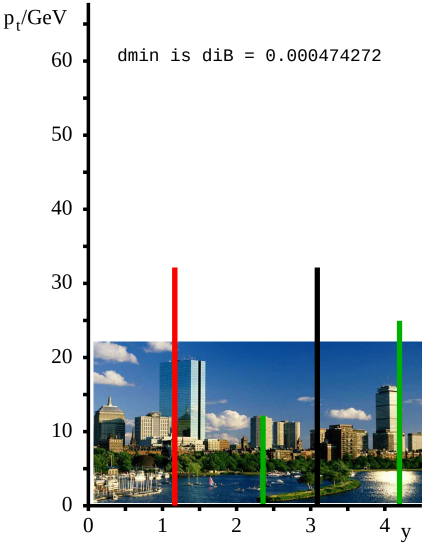
min is $d_{ij} = 6.3\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



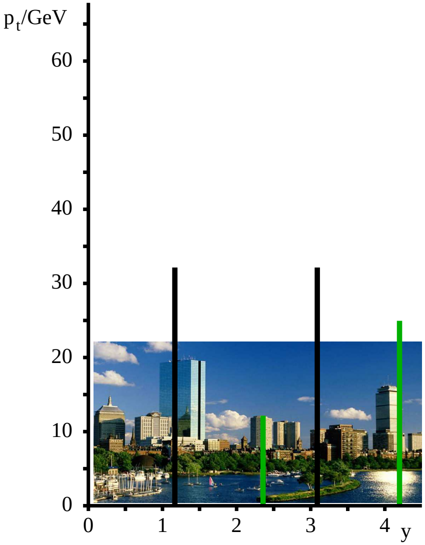
recombine them

Clustering in action: anti-k_t ($R = 0.7$)



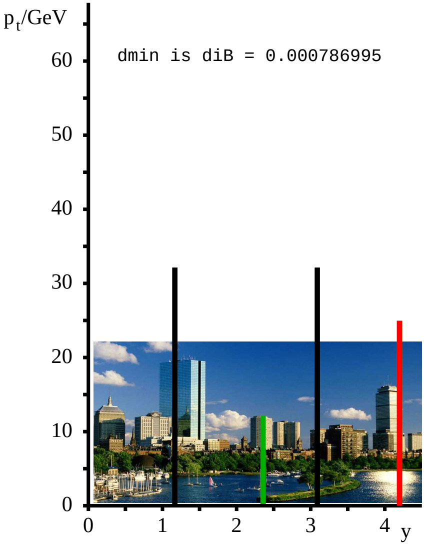
min is $d_{iB} = 4.7\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



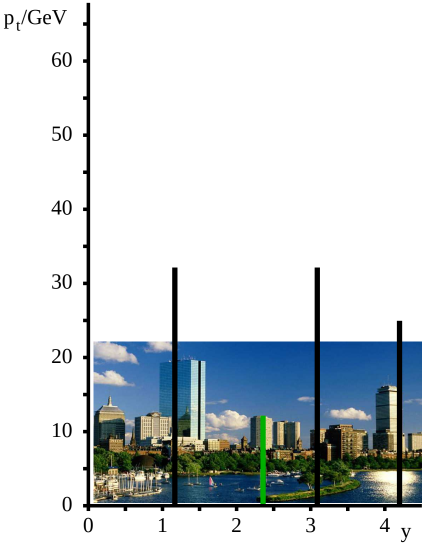
declare as a jet

Clustering in action: anti-k_t ($R = 0.7$)



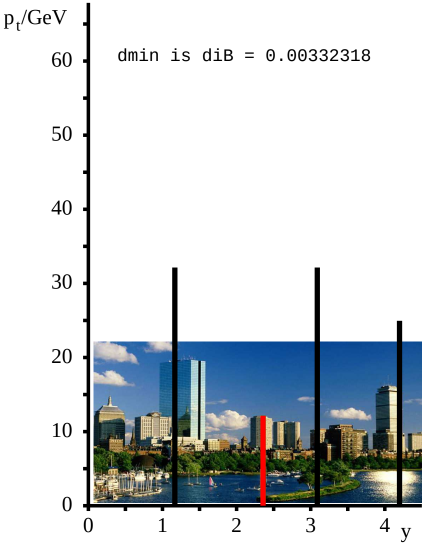
min is $d_{iB} = 7.9\,10^{-4}$

Clustering in action: anti-k_t ($R = 0.7$)



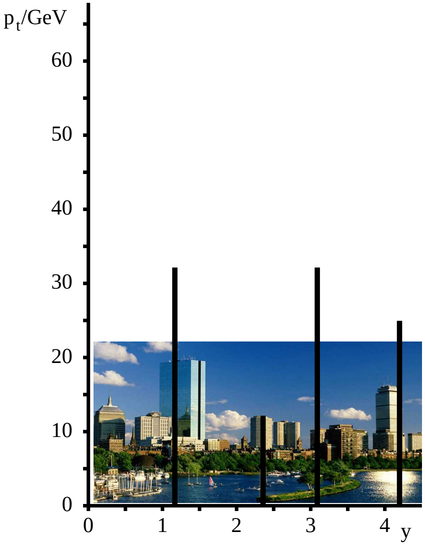
declare as a jet

Clustering in action: anti-k_t ($R = 0.7$)



min is $d_{iB} = 3.3\,10^{-3}$

Clustering in action: anti-k_t ($R = 0.7$)



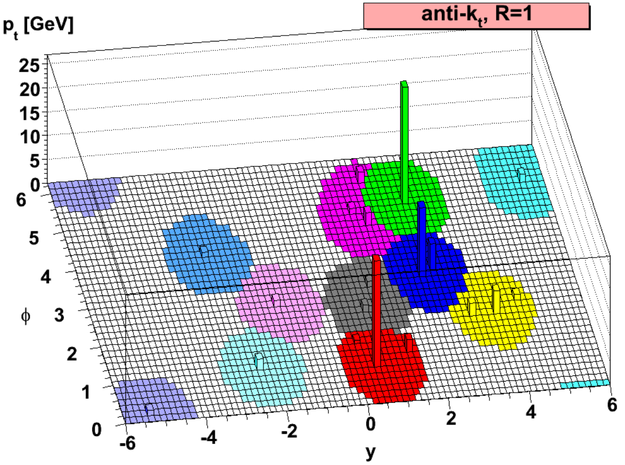
declare as a jet

Question 6

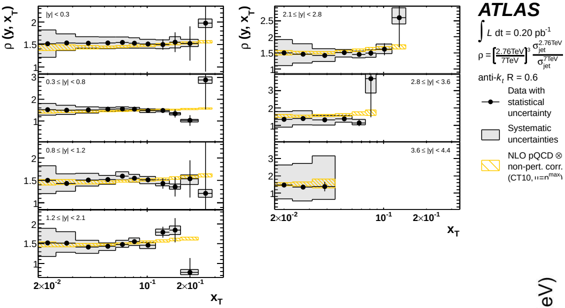
Why anti-k_t?

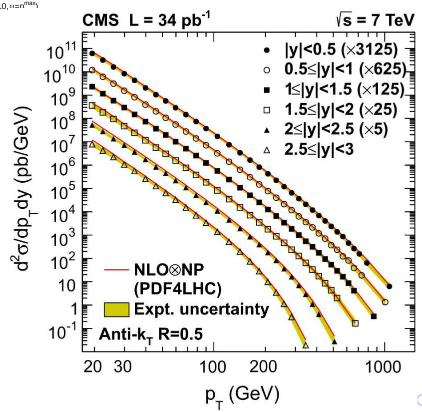
The anti-k_t jets

Main property: hard jets are circular



Examples





- Agreement between QCD & data
- Much more in Murilo's lectures:
  - Measurement
  - Calibration
  - Pileup
  - ...

Implementation and speed

Question 7

What complexity to cluster N particles?

(a) $\mathcal{O}(N)$
(b) $\mathcal{O}(N^2)$
(c) $\mathcal{O}(N^3)$
(d) $\mathcal{O}(\exp(N))$

Question 7

What complexity to cluster N particles?

(c) $\mathcal{O}(N^3)$

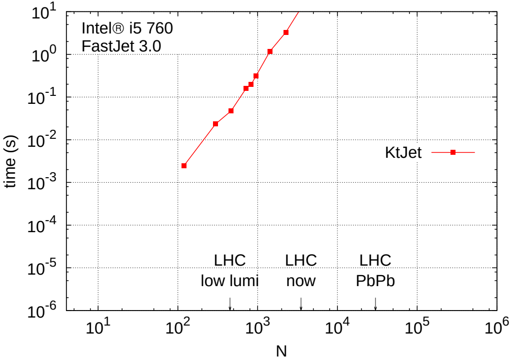
Naively:

- Compute all pairwise distances to find the minimum: $\mathcal{O}(N^2)$
- Do that $\sim N$ times

FastJet (1/2)

[M.Cacciari, G.Salam, 05]

Before 2005: k_t deemed too slow by the Tevatron

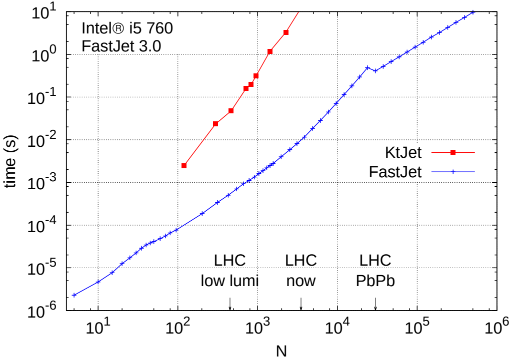


- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
  Cone preferred (easier calibration too)

FastJet (1/2)

[M.Cacciari, G.Salam, 05]

2005: FastJet: a fast implementation of k_t

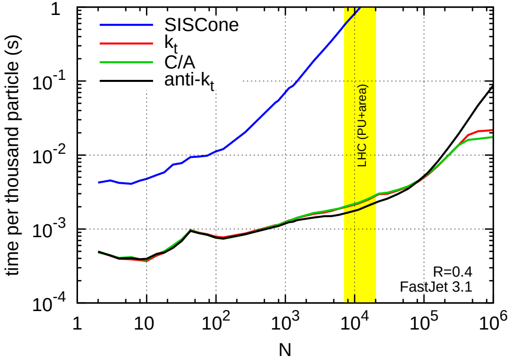


- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
  Cone preferred (easier calibration too)
- Realistic timing for the LHC! ($\mathcal{O}(N^2)$ or even $\mathcal{O}(N \log(N))$)

FastJet (1/2)

[M.Cacciari, G.Salam, 05]

2014: FastJet timings for various algorithms



- Tevatron era: k_t too slow: $\mathcal{O}(N^3)$ for N particles
  Cone preferred (easier calibration too)
- Realistic timing for the LHC! ($\mathcal{O}(N^2)$ or even $\mathcal{O}(N\log(N))$)
- The situation today: 10-50ms for $R = 0.4$ (including pileup and areas)

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
  - tools for manipulating jets
  - more to come...
- FastJet 3.1.0 released in September 2014
  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
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)

The FastJet lemma

It (i, j) is the pair that minimize the k_t distance and $k_{t,i} < k_{y,j}$, then j is i's nearest neighbour

Proof: assume it is not, then $\exists k$ s.t. $\Delta R_{ik} < \Delta R_{ij}$ and

$$\begin{aligned} \min(k_{t,i}^2, k_{t,l}^2)\Delta R_{il}^2 &\le k_{t,i}^2 \Delta R_{il}^2 \\ &\le \min(k_{t,i}^2, k_{t,j}^2)\Delta R_{il}^2 \\ &< \min(k_{t,i}^2, k_{t,j}^2)\Delta R_{ij}^2 \end{aligned}$$