Cone vs. k_t, FastJet, and UE/MB jet corrections in k_t-clustering

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Jet algorithm requirements

Outline

- Cone vs. k_t

  (Since Joey "announced" it. He might not like what I'll say, though...)

  - Overview of iterative cone algorithms (& what's wrong with them)
  - Clustering algorithms
    - How they work
    - Where they've been criticised (speed, underlying-event (UE) sensitivity)

- How to solve the speed problem. Fast algorithm for k_t clustering: `FastJet`

  A brief presentation of the $\mathcal{O}(N \ln N)$ algorithm

- Underlying event and minimum bias/pile-up subtraction using `FastJet` and jet areas

  Some preliminary plots and results

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Jet algorithm requirements

What is **needed** of a jet algorithm

- Must be infrared and collinear (IRC) safe

  soft emissions shouldn't change jets

  collinear splitting shouldn't change jets

- Must be identical procedure at parton level, hadron-level

  So that theory calculations can be compared to experimental measurements

What is *nice* for a jet algorithm

- Shouldn't be too sensitive to hadronisation, underlying event, pileup

  Because we can only barely model them

- Should be realistically applicable at detector level

  Not too slow, not too complex to correct

- Should behave 'sensibly'

  e.g. don't want it to spuriously ignore large energy deposits

Jet algorithm types

Mainstream jet-algorithms

- Iterative cone algorithms (JetClu, ILCA/Midpoint, . . .)
  Searches for cones centred on regions of energy flow
  Dominant at hadron colliders
- Sequential recombination algorithms (k_t, Cambridge/Aachen, Jade)
  Recombine closest pair of particles, next closest, etc.
  Dominant at e^+e^- and ep colliders

Other approaches

- 'Optimal Jet Finder', Deterministic Annealing
  Fit jet axes (and #) so as to minimise a weight function
  [forms of 'k-means' clustering]
- . . .

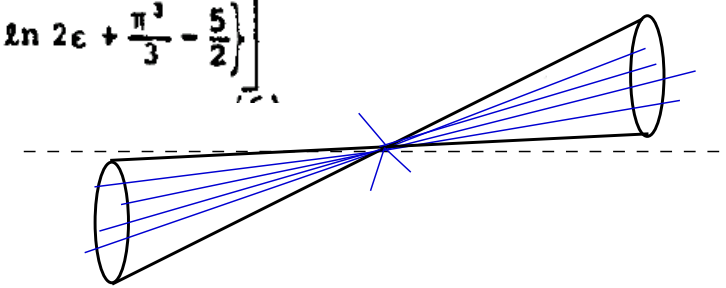
As LHC startup approaches it's important for the choice of jet algorithm to be well-motivated.

Cone Origins

First 'cone algorithm' dates back to Sterman and Weinberg (1977) — the original infrared-safe cross section:

To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\epsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\epsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line. We expect this to be measur-

$$\sigma(E,\theta,\Omega,\epsilon,\delta) = (d\sigma/d\Omega)_0 \Omega\left[1 - (g_E^2/3\pi^2)\left\{3\ln\delta + 4\ln\delta\ln 2\epsilon + \frac{\pi^3}{3} - \frac{5}{2}\right\}\right]$$



Modern cones address various issues

Where do you put the cones?

- Place a cone at some trial location
- Sum four-momenta of particles in cone – find corresponding axis
- Use that axis as a new trial location, and *iterate*
- Stop when you reach a stable axis [or when you get bored]

What are the initial trial locations?

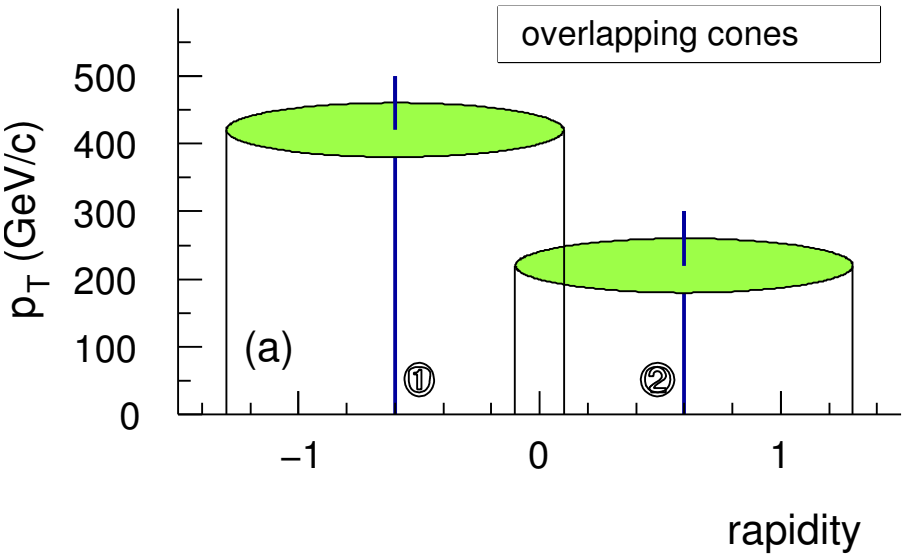
- 'Seedless' — i.e. everywhere But too slow on computer
- Use locations with energy flow above some threshold as *seeds*

  Issue: is seed threshold = parton energy, hadron energy (collinear unsafe)?

  Or calorimeter tower energy (experiment and η-dependent)?

Overlapping Jets

Jets can overlap



They are either *split* if the overlapping energy is

$$E_{\text{overlap}} < f_{\text{overlap}} E_{\text{softer-jet}}$$

otherwise they are *merged*.

NB: f_{overlap} is parameter of cone-algo

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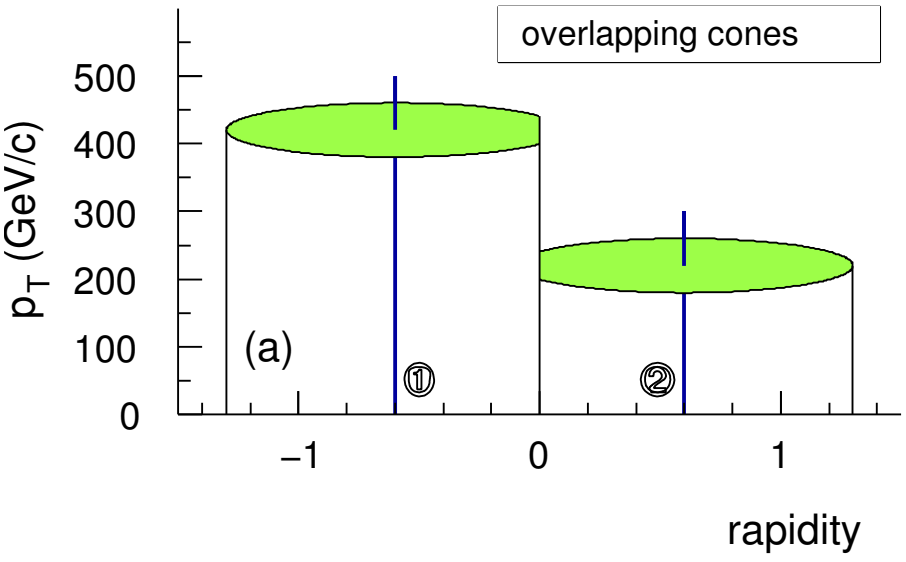

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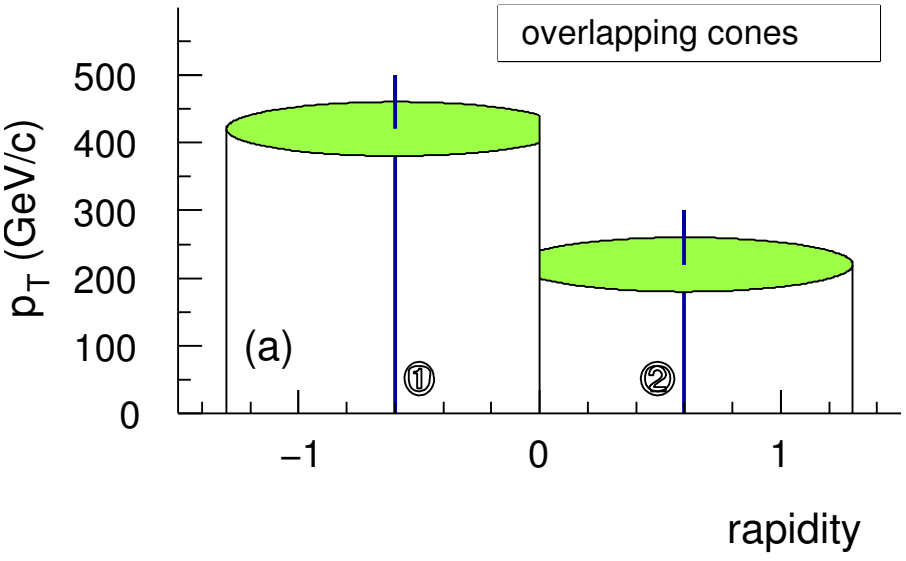

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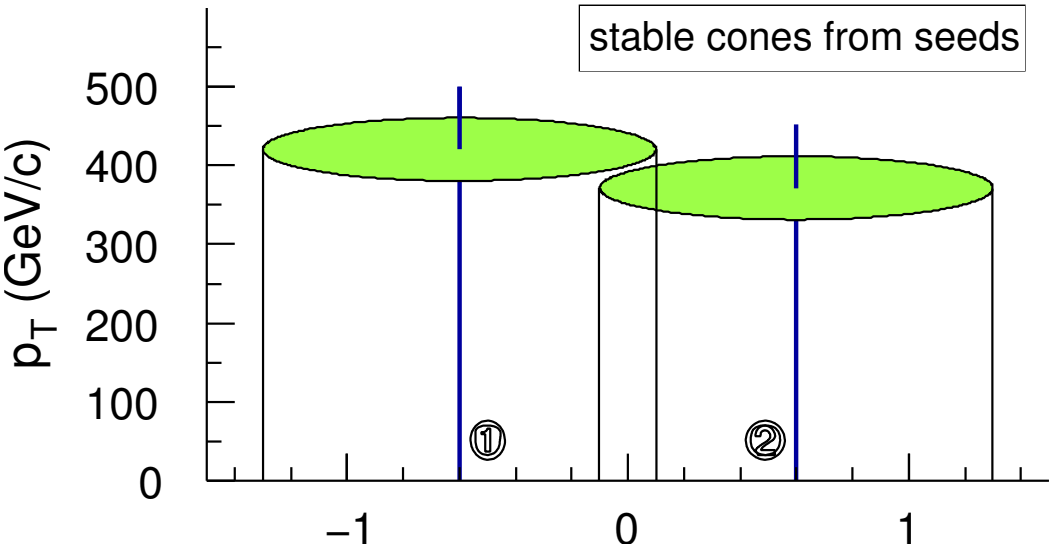
Midpoints

Use of seeds is *dangerous*



Extra soft particle adds new seed → changes final jet configuration.

This is **IR unsafe**.

Kilgore & Giele '97

Solution: add extra seeds at midpoints of all pairs, triplets, . . . of stable cones.

Seymour '97 (?)

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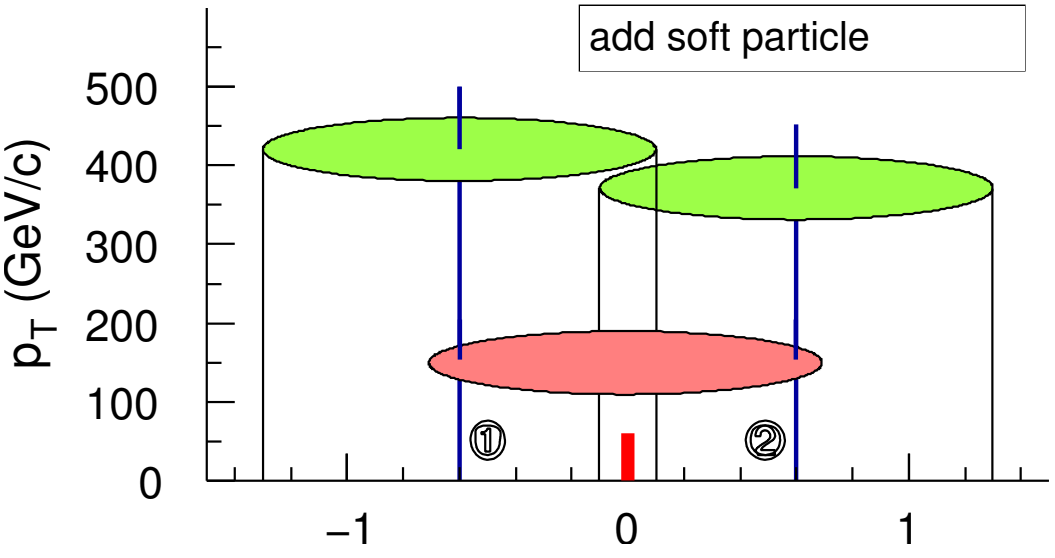

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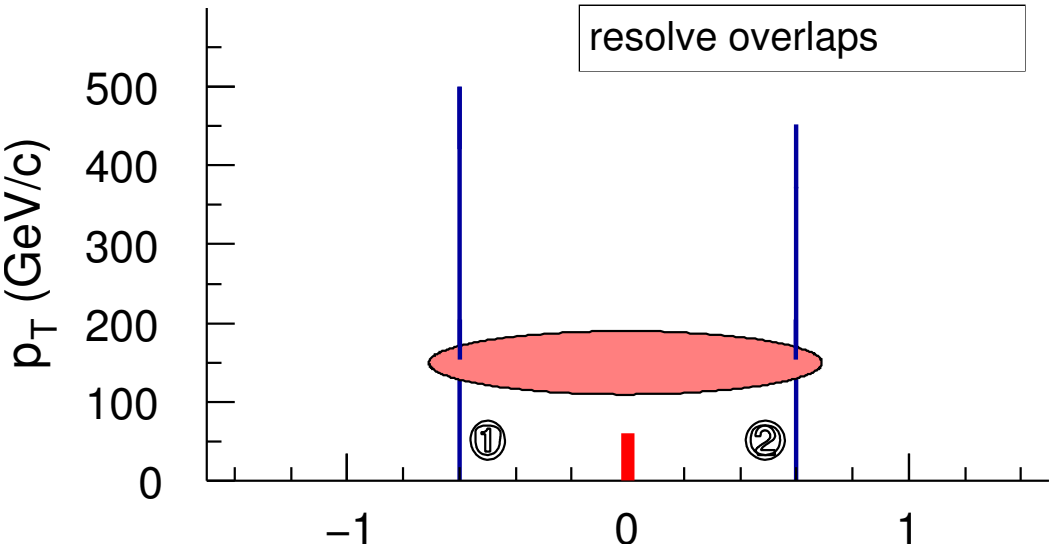

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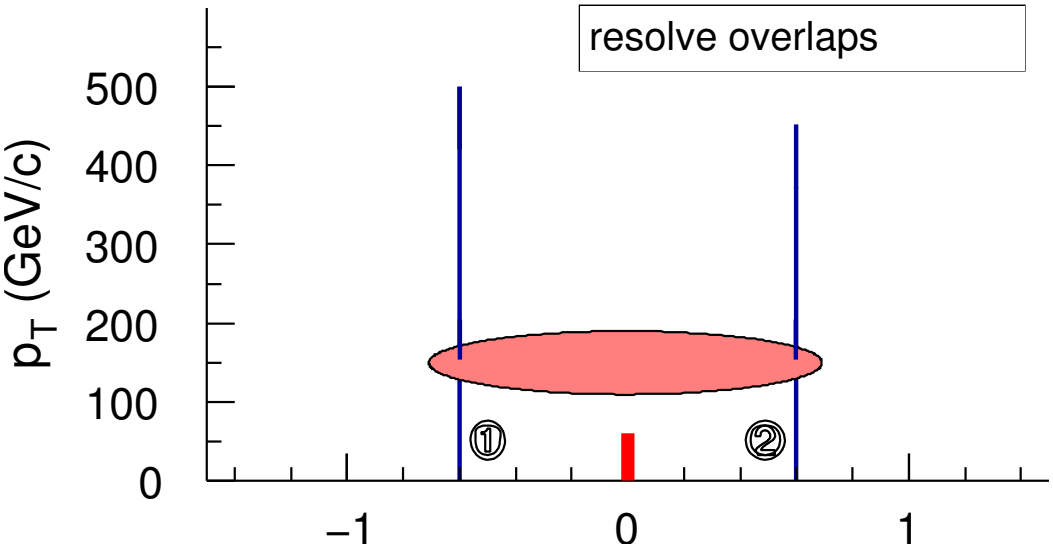

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ILCA

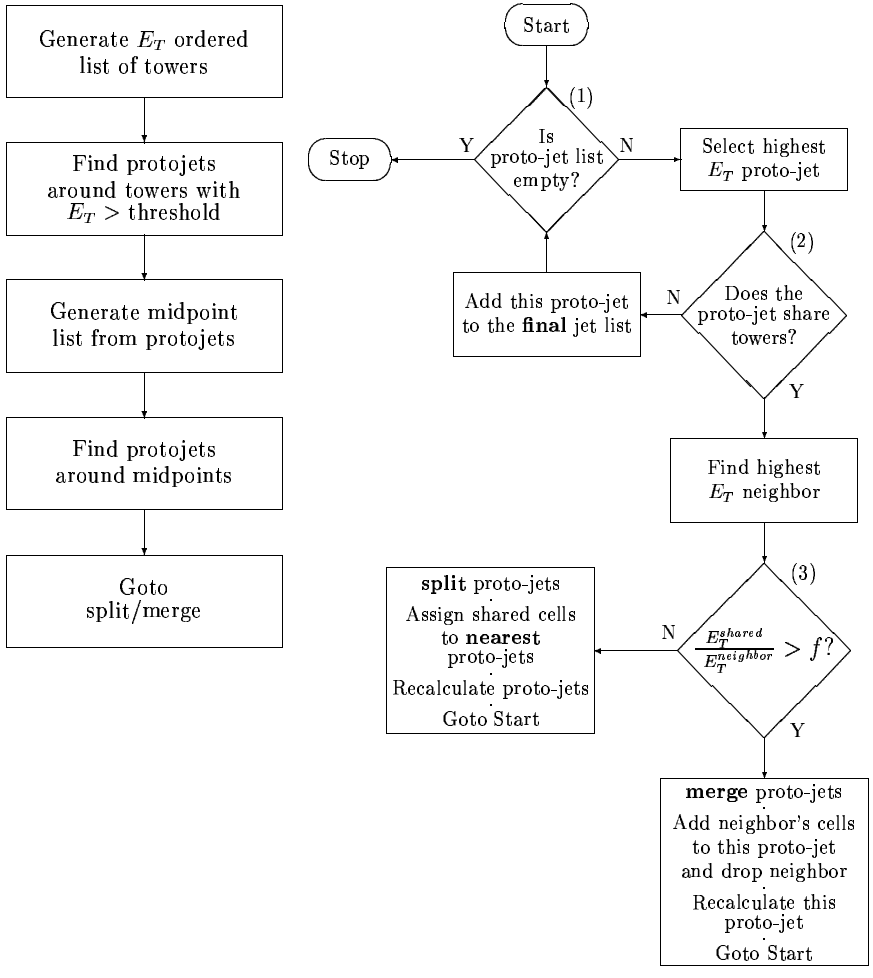
All of these considerations led recommendation of the *Improved Legacy Cone Algorithm* (ILCA), a.k.a. *Midpoint* algorithm.

hep-ex/0005012

Quite complex and has several parameters:

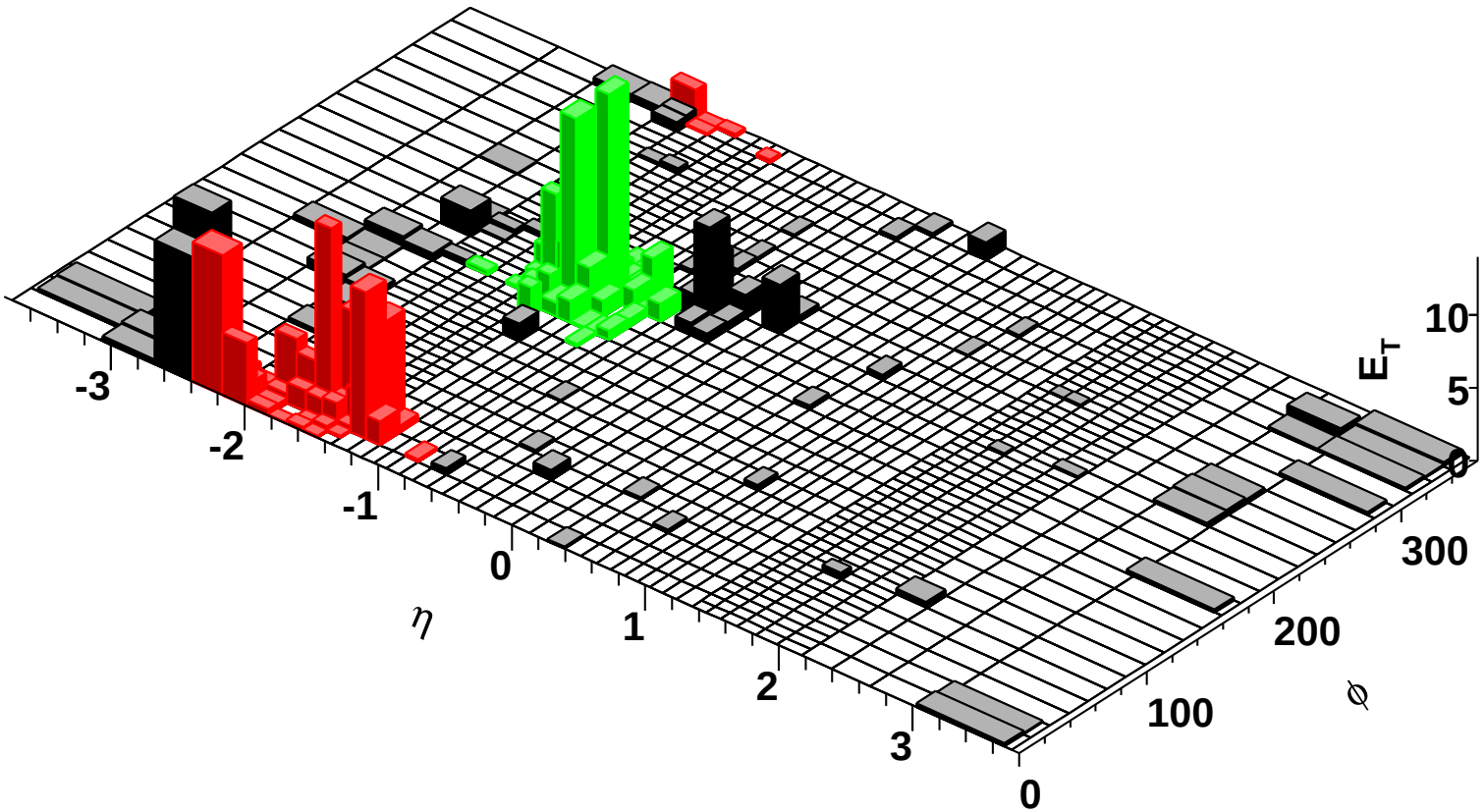
cone radius (R)
seed threshold (E_0)
f_{overlap}

Only one of these is remotely physical: R.



2/3 of ILCA flowchart

ILCA has "Dark Towers"

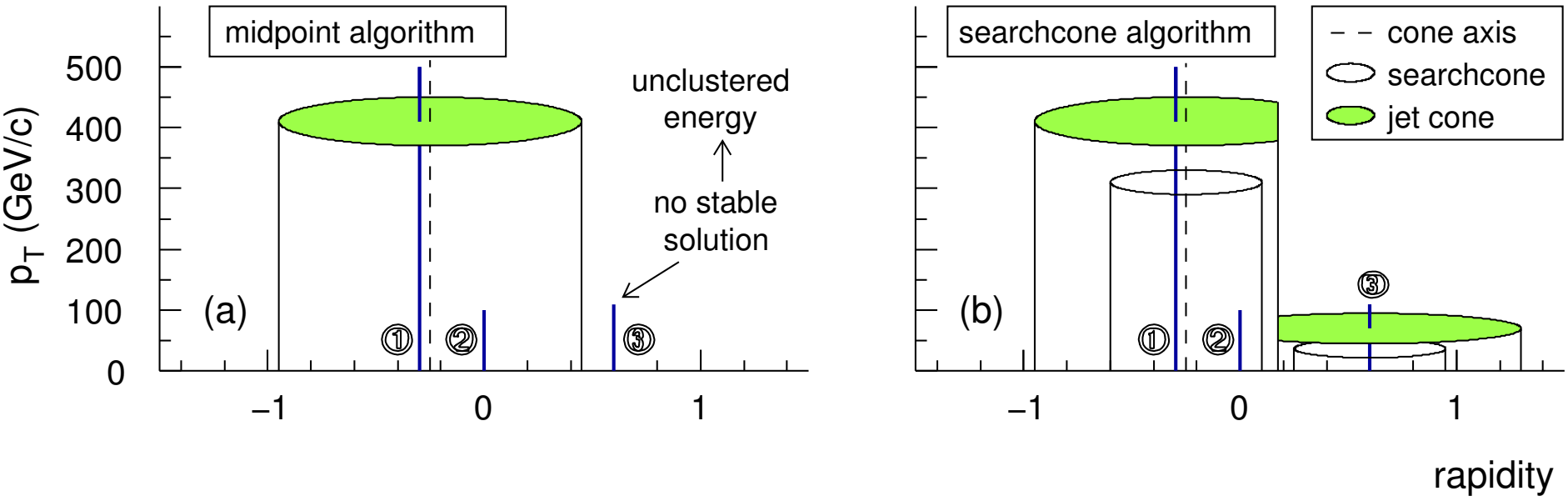


Considerable energy can be left out of jets ≡ **Dark Towers**

S. Ellis, Huston & Tönnesmann '01

Search Cone

Dark towers are consequence of particles that are never in stable cones:

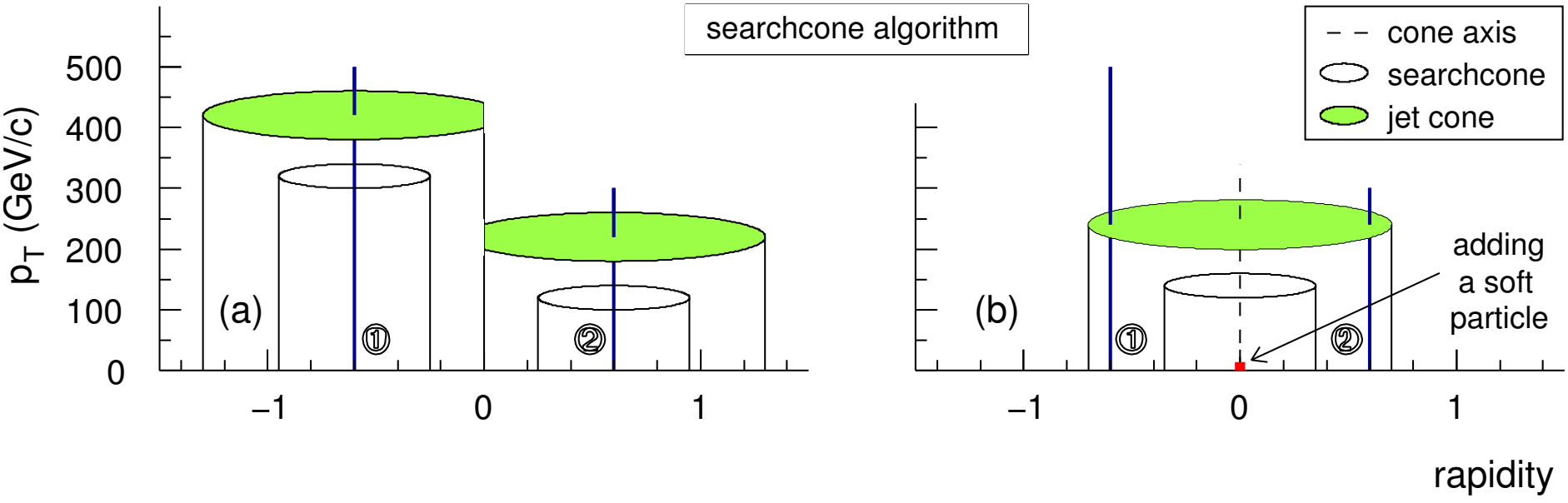


Ellis, Huston and Tönnesmann suggest *iterating a smaller 'search-cone'* and then drawing final cone around it.

Searchcone adopted by CDF (to confuse issue they still call it 'midpoint'...)

hep-ex/0505013, hep-ex/0512020

Search Cone is IR unsafe



Whether you see 1 or 2 jets depends on presence and position of a soft gluon — this is *IR unsafe (and unphysical)*. Wobisch, '06

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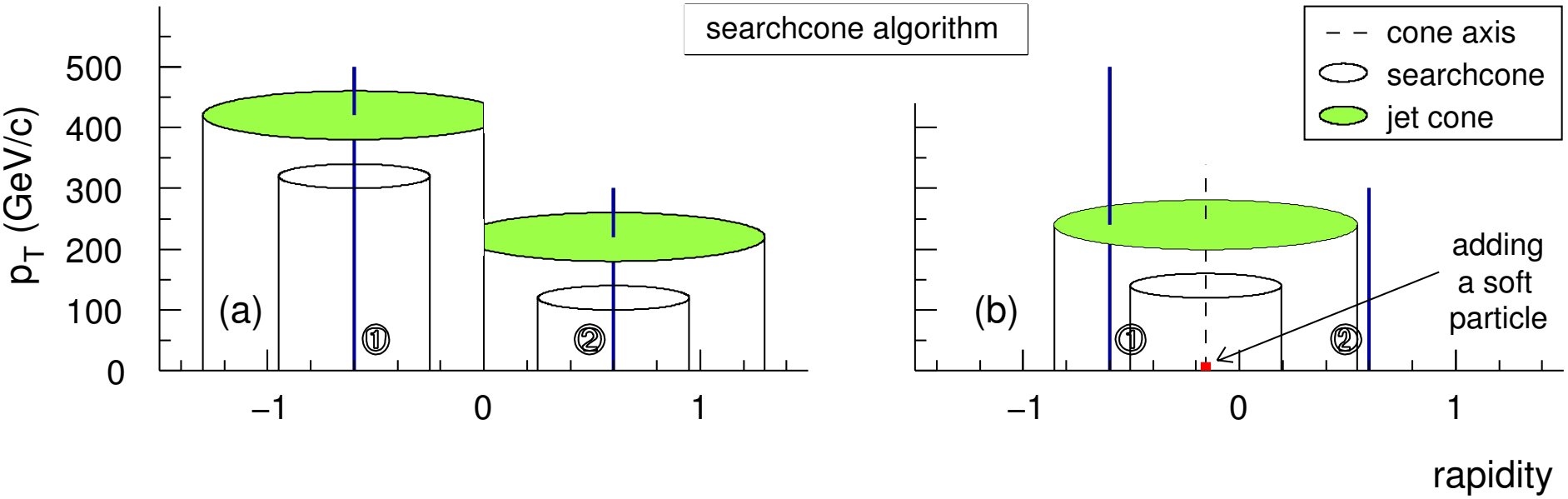

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Cone summary

- Cone algorithms are complicated beasts.
- So much so, it's often not clear *which* cone algorithm is being used!
- They often behave in unforeseen ways.
- *Patching* them makes them more complex and error-prone.

Didn't even mention the hacks people put into cone theory calculations to 'tune' them to hadron level: (cf. R_{sep}, which breaks the NLO jet X-section).

LHC experiments should be wary of cone algorithms

Sequential Recombination Algorithms

Best known is **k_t algorithm:**

1. Calculate (or update) distances between all particles i and j, and between i and beam:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = k_{ti}^2\,, \qquad \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$$

2. Find smallest of d_{ij} and d_{iB}
   - If d_{ij} is smallest, recombine i and j (add result to particle list, remove i, j)
   - if d_{iB} is smallest call i a jet (remove it from list of particles)

3. If any particles are left, repeat from step 1.

Catani, Dokshitzer, Olsson, Turnock, Seymour & Webber '91–93
S. Ellis & Soper, '93

Variant: *Cambridge / Aachen algorithm*. Like k_t with but $d_{ij} = \Delta R_{ij}^2/R^2$ and $d_{iB} = 1$. Dokshitzer, Leder, Moretti & Webber '97; Wobisch '00

Why k_t?

k_t distance measures

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

are closely related to structure of divergences for QCD emissions

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \sim \frac{\alpha_s C_A}{2\pi}\frac{dk_{tj}}{\min(k_{ti}, k_{tj})}\frac{d\Delta R_{ij}}{\Delta R_{ij}}, \qquad (k_{tj} \ll k_{ti}\,,\ \Delta R_{ij} \ll 1)$$

and

$$[dk_i]|M^2_{Beam\to Beam+g_i}(k_i)| \sim \frac{\alpha_s C_A}{\pi}\frac{dk_{ti}}{k_{ti}}\,d\eta_i\,, \qquad (k_{ti}^2 \ll \{\hat{s}, \hat{t}, \hat{u}\})$$

k_t algorithm attempts approximate inversion of branching process

One parameter: R (like cone radius), whose natural value is 1

Optional second parameter: stopping scale d_{cut} 'exclusive' k_t algorithm

k_t v. cone

k_t algorithm seems better than cone

- it's simpler, safer and better-defined (IRC safe to all orders)
- exclusive variant is more flexible (allows cuts on momentum scales)
- less sensitive to hadronization
- In MC studies k_t alg. is systematically as good as, or better than cone algorithms for typical reconstruction tasks Seymour '94
  Butterworth, Cox & Forshaw '02
  Benedetti et al (Les Houches) '06

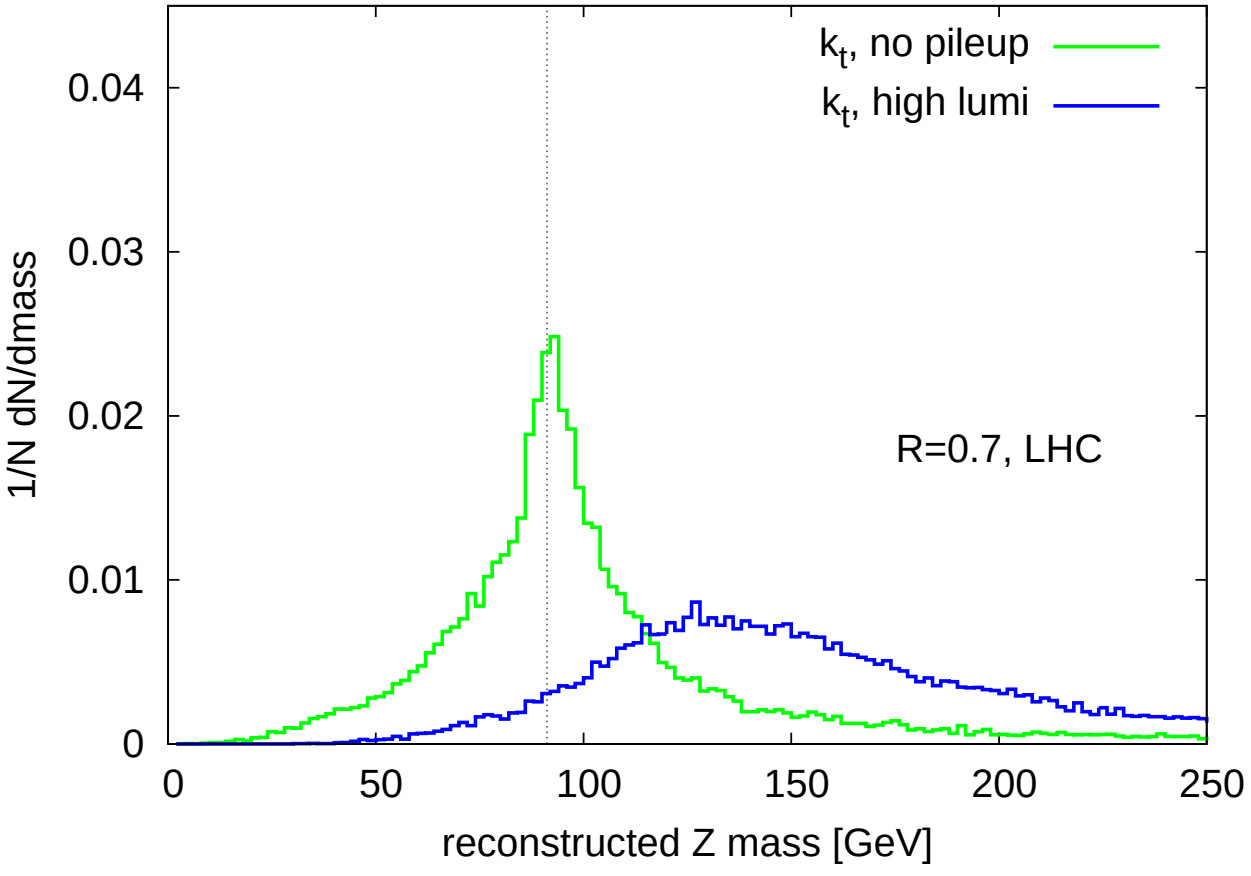
But seldom used at Tevatron. **Why?**

1. Because it's slow?
2. Because it includes more underlying event?
3. Because it's harder to understand/correct for detector effects/noise?
   But all LEP and HERA experiments managed fine
   And as of '05, CDF too

k_t v. cone: Z mass (uncorrected)

Try reconstructing M_Z from $Z \to 2$ jets [Use inv. mass of two hardest jets]

On same events, compare uncorrected k_t v. ILCA (midpoint) cone



k_t allegedly more sensitive to min-bias.
Is this true?

ILCA with standard parameters ($f_{overlap} = 0.5$) fares *very poorly*

ILCA with modified params. is no better than k_t.

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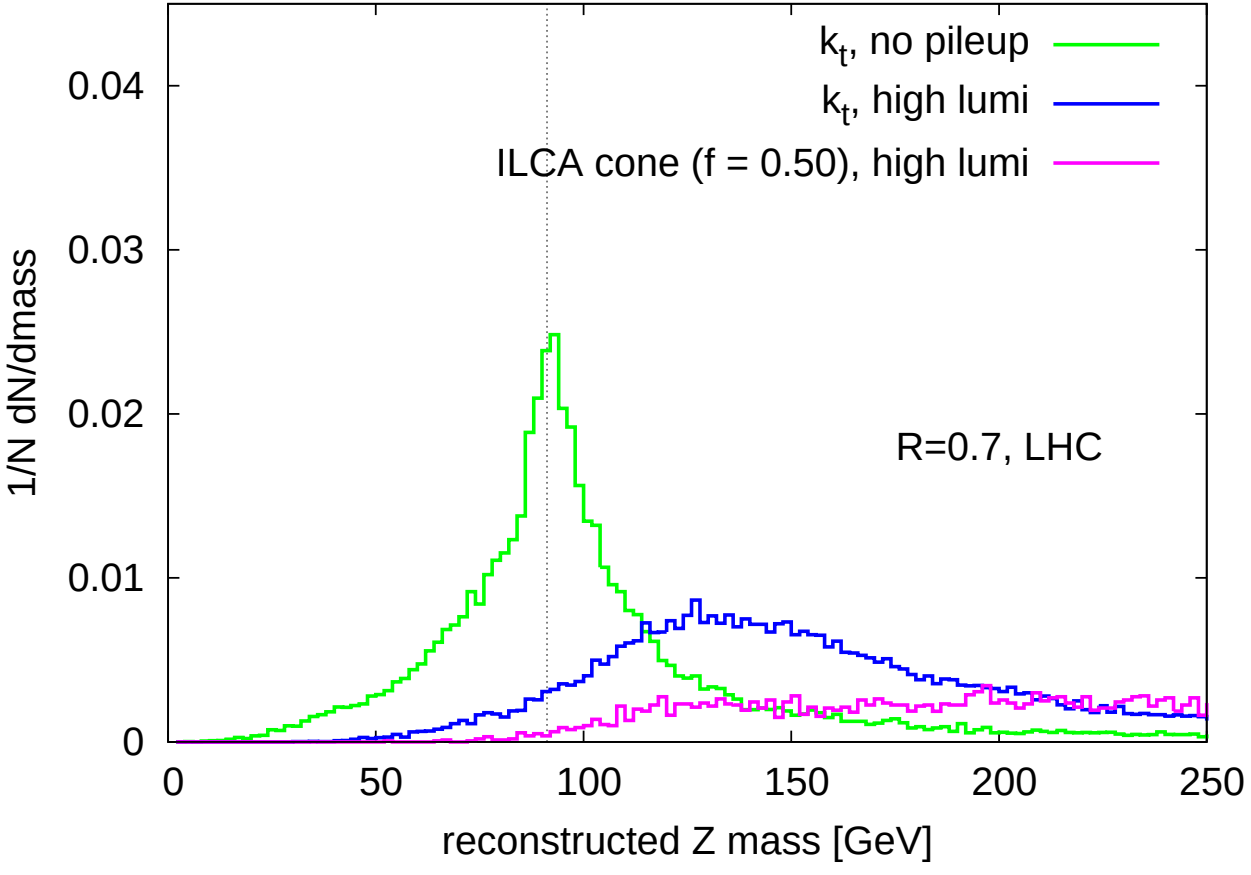

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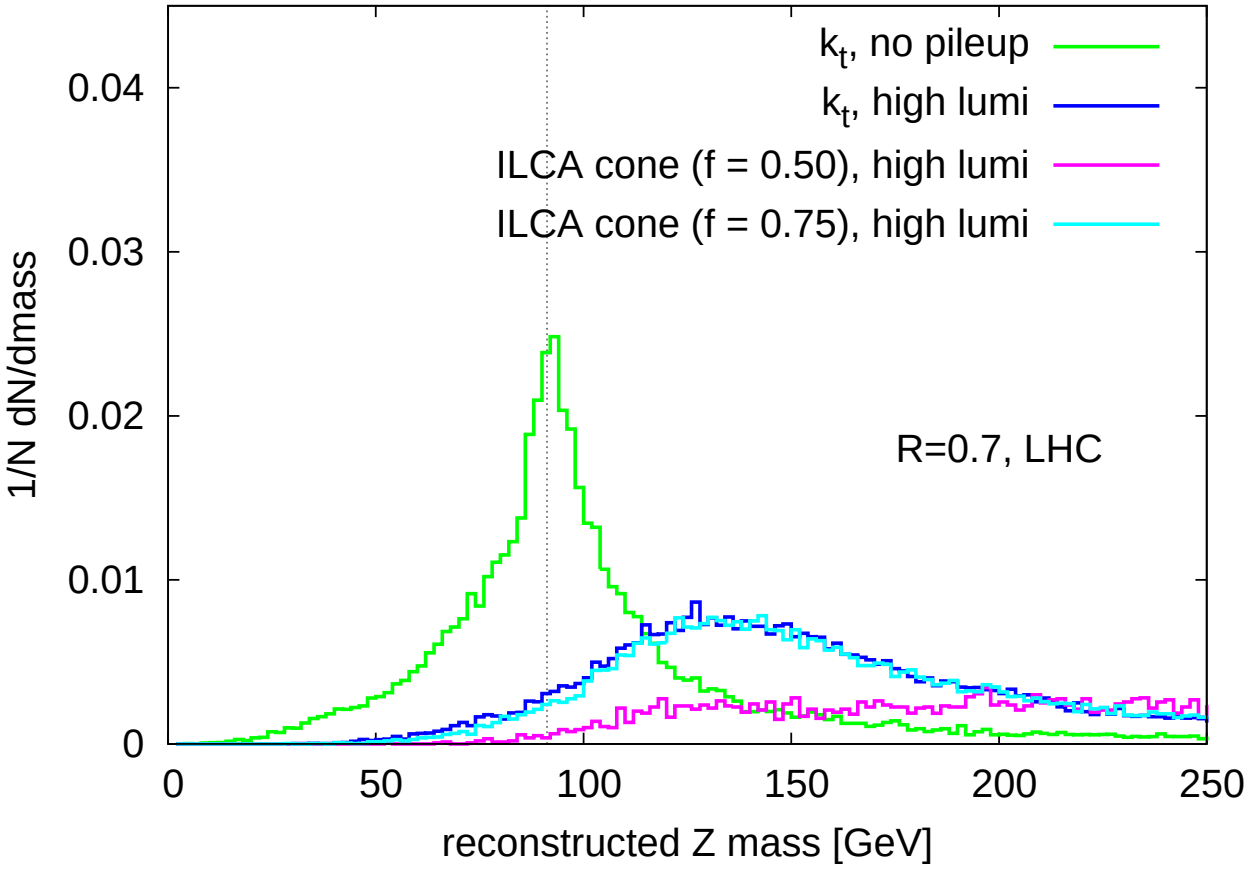

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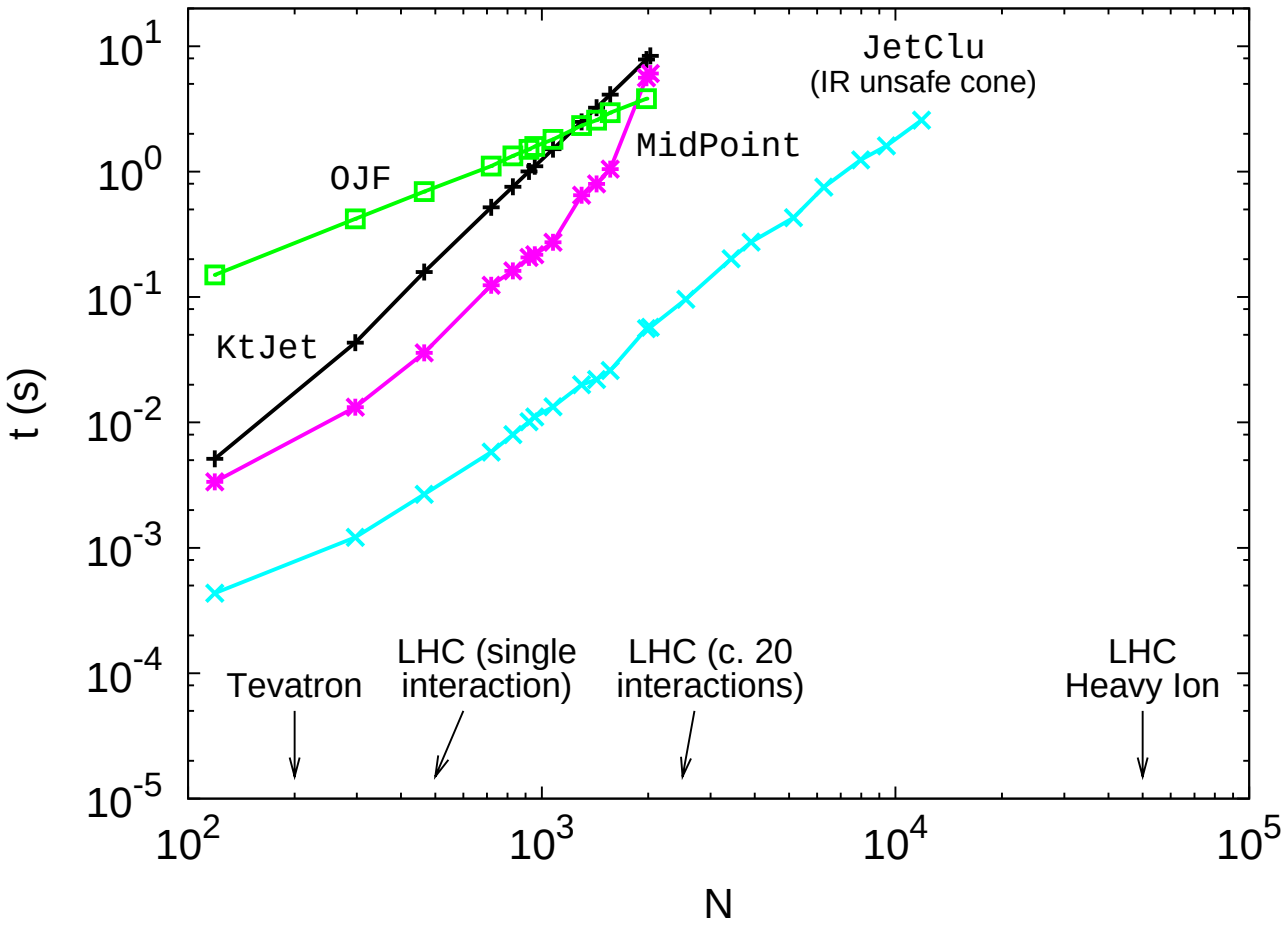

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a Pb-Pb event takes 1 day!

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Jet-clustering speed is an issue for high-luminosity pp ($\sim 10^8$ events) and Pb-Pb ($\sim 10^7$ events) collisions at LHC.

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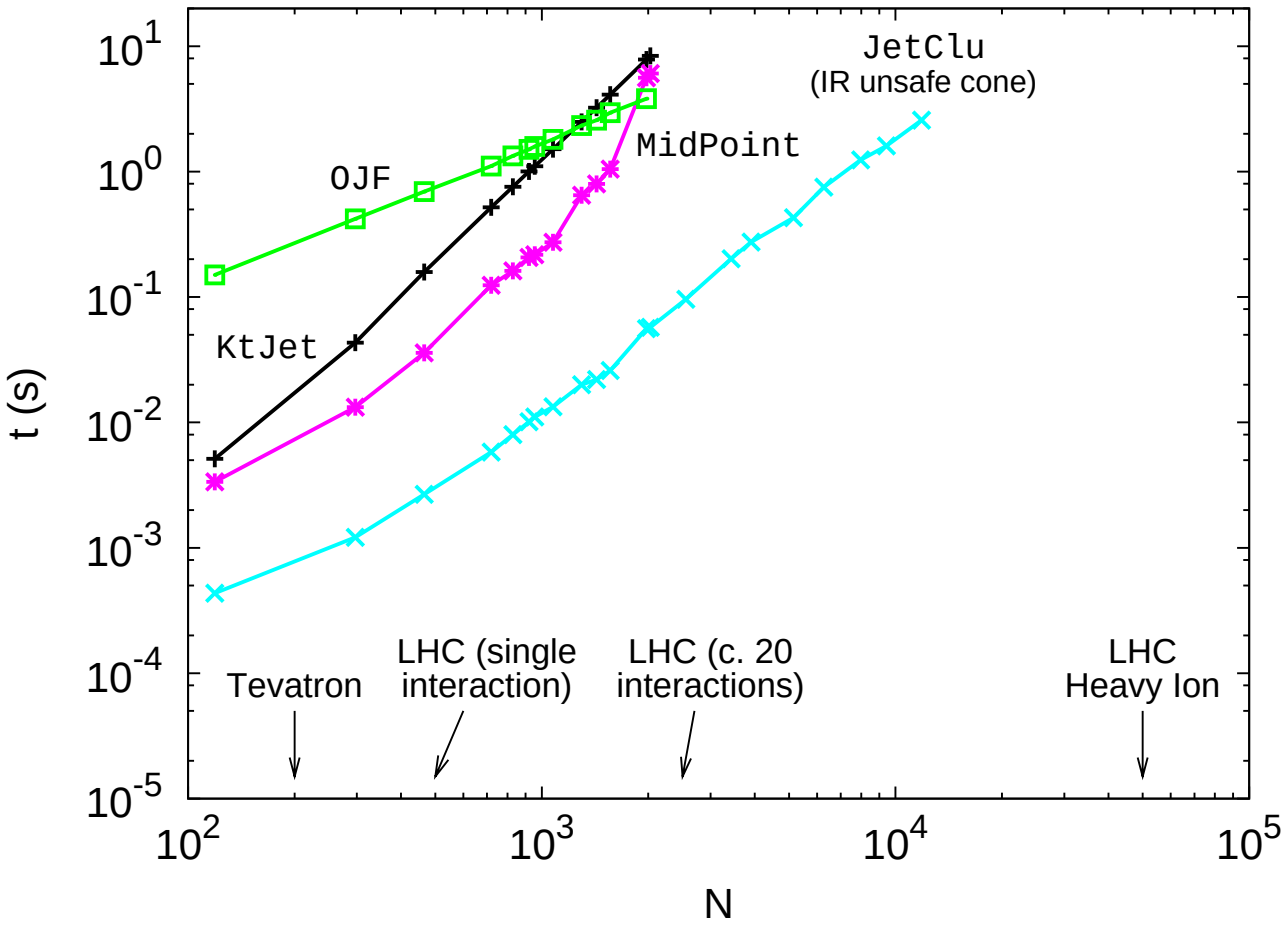

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Why is k_t an N^3 algorithm?

1. Given the initial set of particles, construct a table of all the d_{ij}, d_{iB}.
   [$\mathcal{O}\left(N^2\right)$ *operations, done once*]
2. Scan the table to find the minimal value $d_{\min}$ of the d_{ij}, d_{iB}.
   [$\mathcal{O}\left(\mathbf{N^2}\right)$ operations, done N times]
3. Merge or remove the particles corresponding to $d_{\min}$ as appropriate.
   [$\mathcal{O}\left(1\right)$ operations, done N times]
4. Update the table of d_{ij}, d_{iB} to take into account the merging or removal, and if any particles are left go to step 2.
   [$\mathcal{O}\left(N\right)$ operations, done N times]

This is the "brute-force" or "naive" method

Can we do better than N^2?

There are $N(N-1)/2$ distances d_{ij} — surely we have to calculate them all in order to find smallest?

k_t distance measure is partly *geometrical:*

- Consider smallest $d_{ij} = \min(k_{ti}^2, k_{tj}^2)R_{ij}^2$
- Suppose $k_{ti} < k_{tj}$
- Then: $R_{ij} <= R_{i\ell}$ for any $\ell \neq j$. [If $\exists\ \ell$ s.t. $R_{i\ell} < R_{ij}$ then $d_{i\ell} < d_{ij}$]

In words: if i, j form smallest d_{ij} then j is geometrical nearest neighbour (GNN) of i.

k_t distance need only be calculated between GNNs

Each point has 1 GNN $\longrightarrow$ need only calculate N d_{ij}'s

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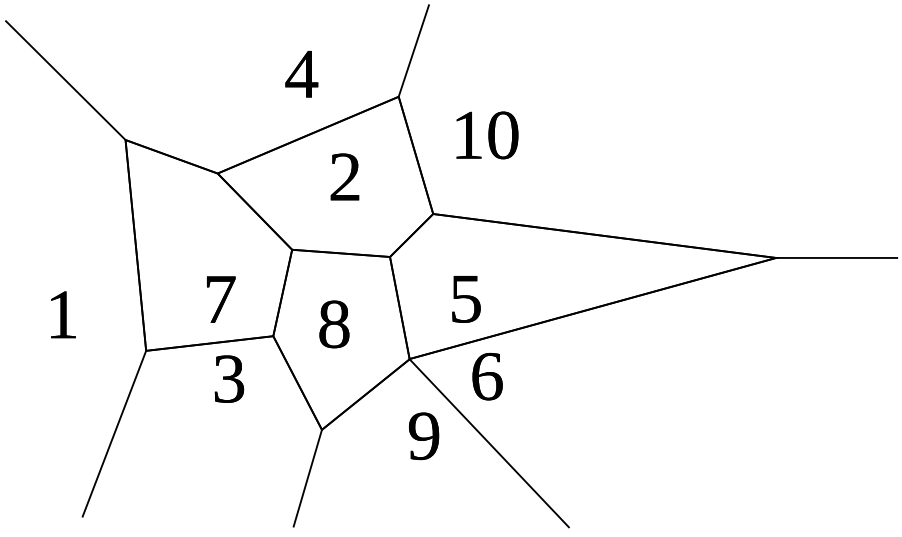

Given a set of vertices on plane (1...10) a *Voronoi diagram* partitions plane into cells containing all points closest to each vertex

Dirichlet '1850, Voronoi '1908

A vertex's nearest other vertex is always in an adjacent cell.

E.g. GNN of point 7 will be found among 1,4,2,8,3 (it turns out to be 3)

Construction of Voronoi diagram for N points: $N \ln N$ time — Fortune '88

Update of 1 point in Voronoi diagram: $\ln N$ time

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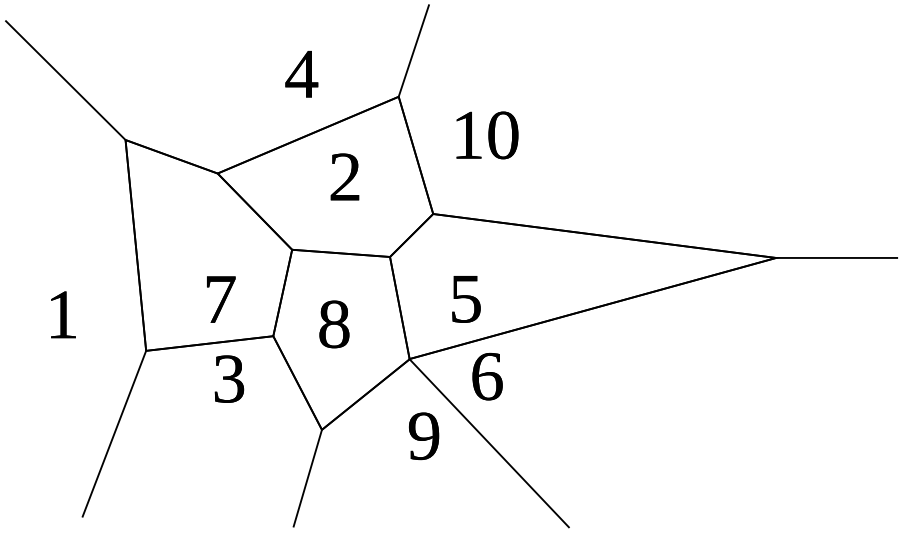

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Assembling fast k_t clustering

The `FastJet` algorithm:

Construct the Voronoi diagram of the N particles with CGAL $\mathcal{O}(\mathbf{N \ln N})$

Find the GNN of each of the N particles, calculate d_{ij} store result in a *priority queue* (`C++ map`) $\mathcal{O}(\mathbf{N \ln N})$

Repeat following steps **N** times:

- Find smallest d_{ij}, merge/eliminate i, j $\mathbf{N} \times \mathcal{O}(\mathbf{1})$
- Update Voronoi diagram and distance map $\mathbf{N} \times \mathcal{O}(\mathbf{\ln N})$

Overall an $\mathcal{O}(\mathbf{N \ln N})$ algorithm

MC & GPS, hep-ph/0512210

`http://www.lpthe.jussieu.fr/~salam/fastjet/`

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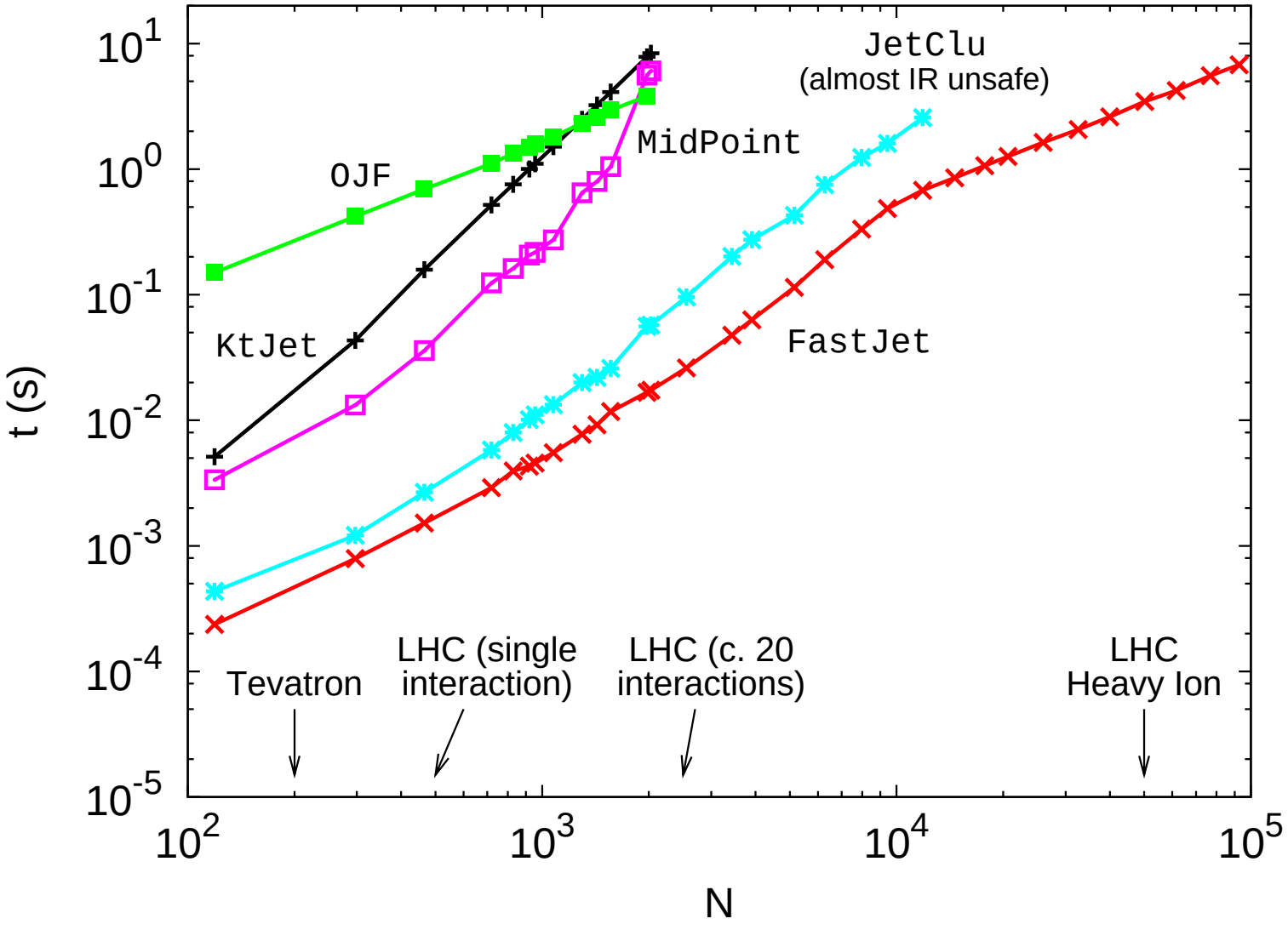
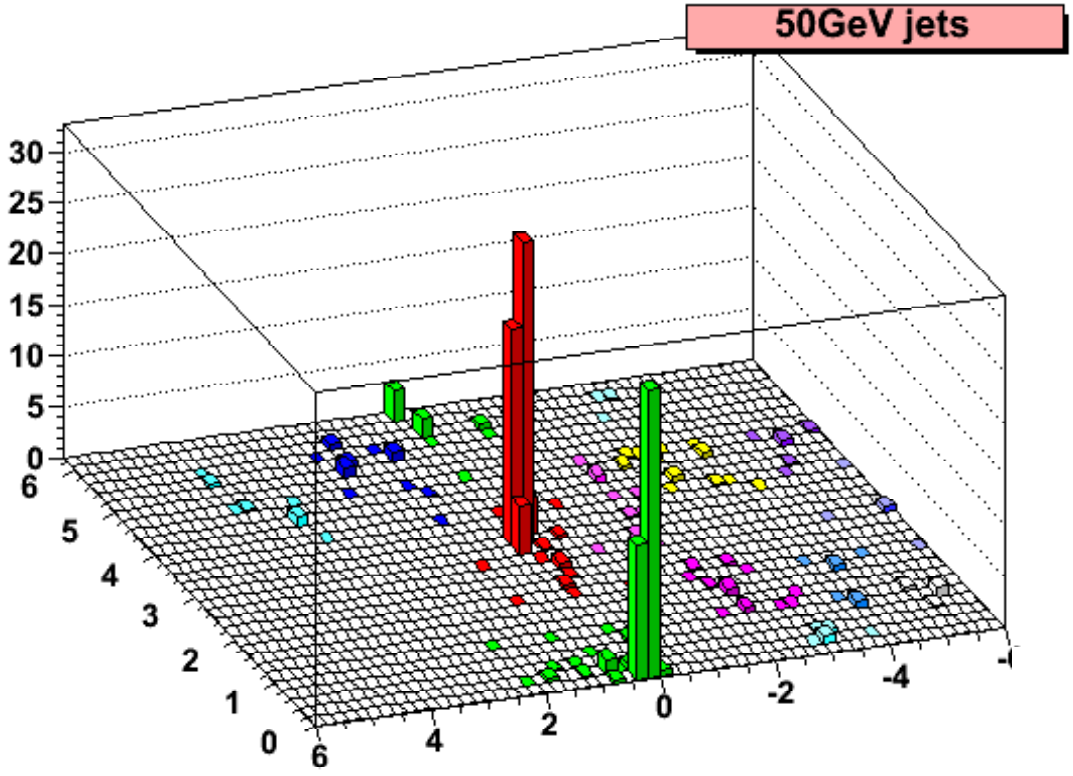
this is **NOT** a new k_t jet-finder

FastJet performance



NB: for $N < 10^4$, FastJet switches to a related geometrical N^2 alg.

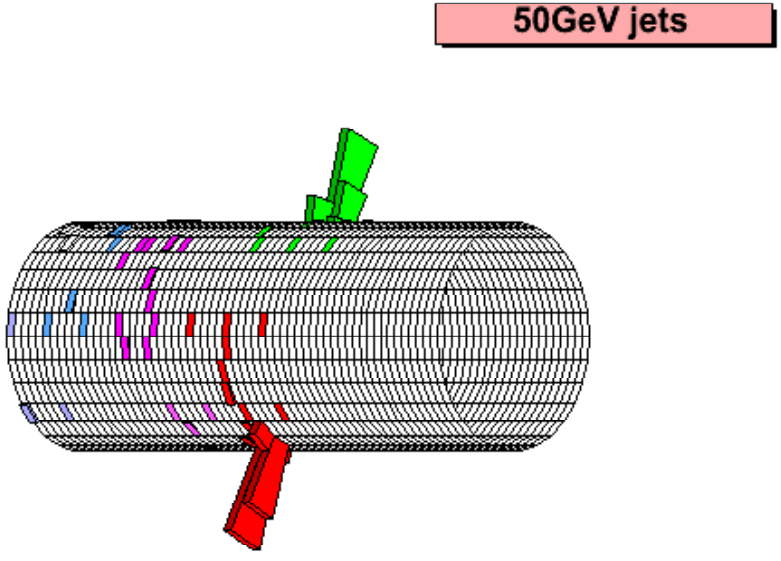
What is speed good for?



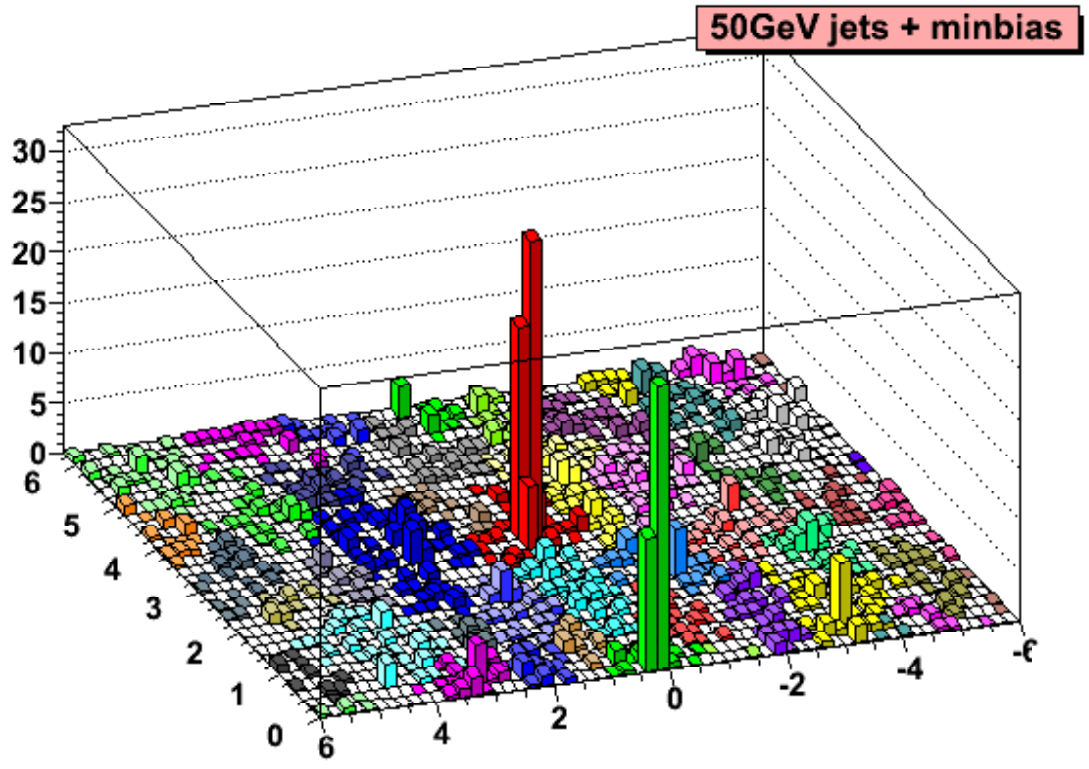
‘Standard hard’ event
Two well isolated jets

$\sim$ 200 particles

Easy even with old methods



What is speed good for?

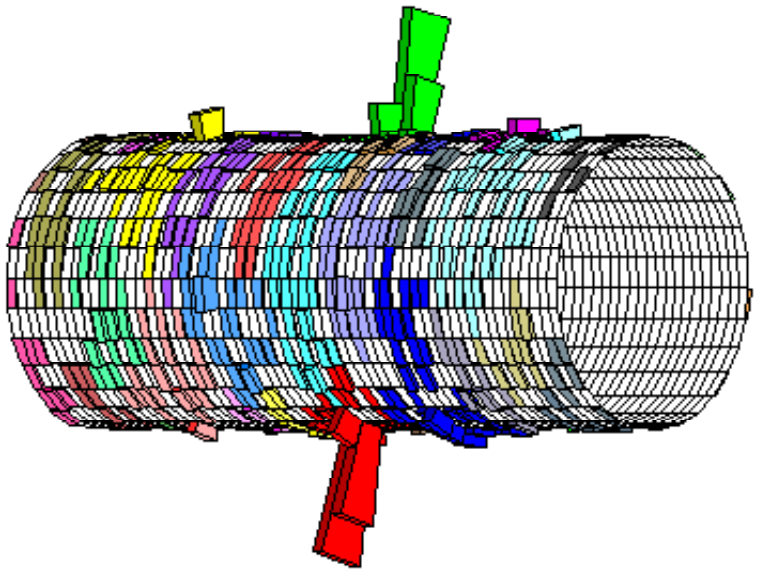


Add 10 min-bias events (moderately high lumi)

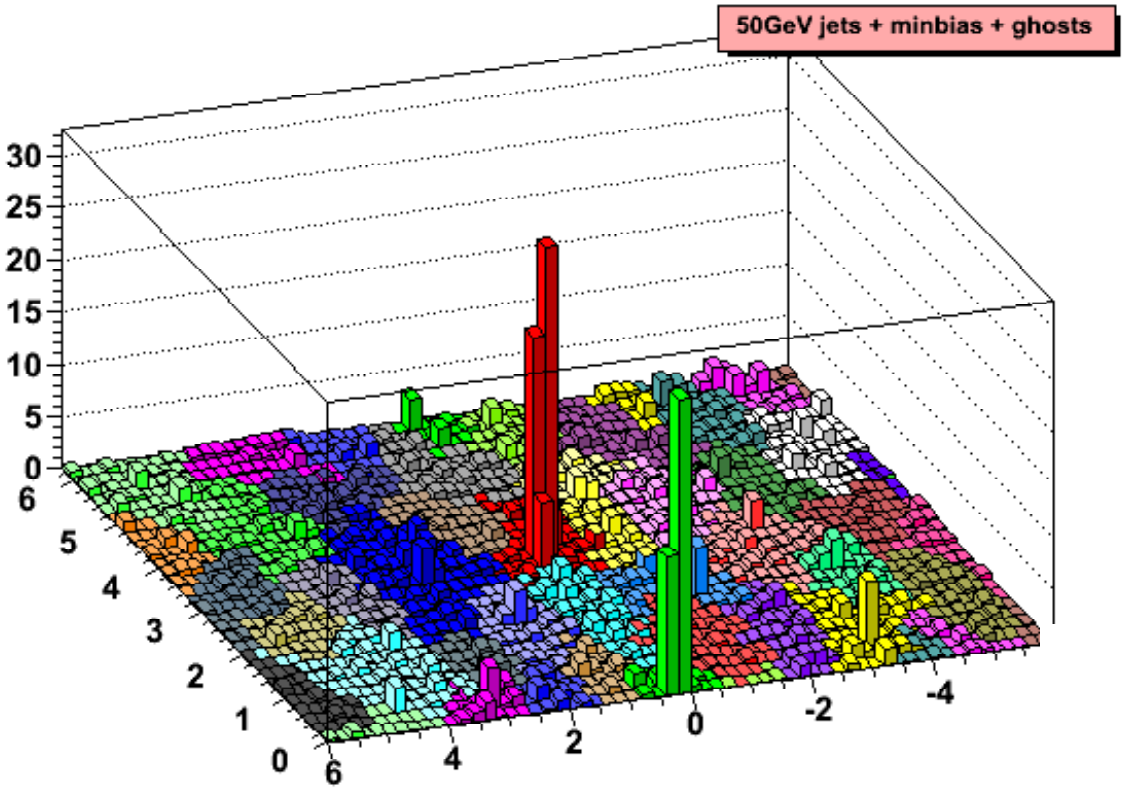
$\sim$ 2000 particles

Clustering takes $\mathcal{O}(10s)$ with old methods.

20ms with `FastJet`.



What is speed good for?



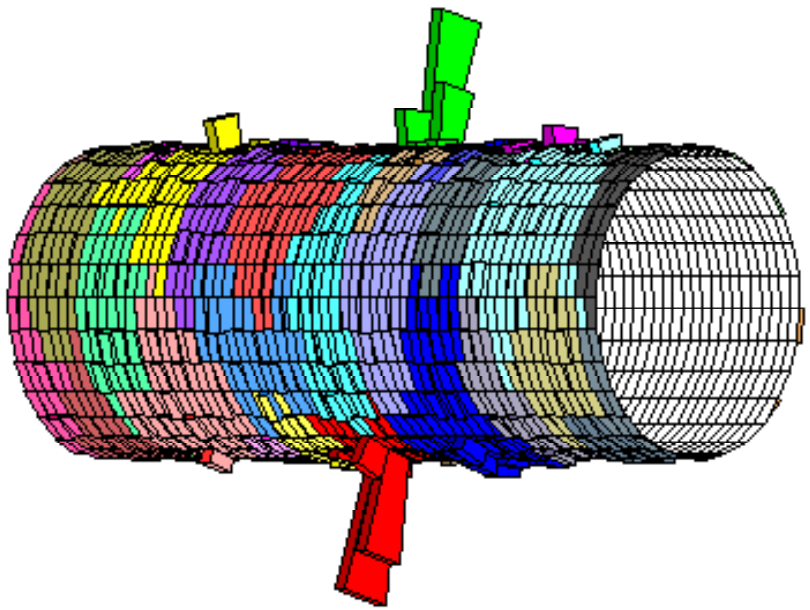
$\sim$ 10000 particles

Clustering takes $\sim$ 20 minutes with old methods.

0.6s with `FastJet`.

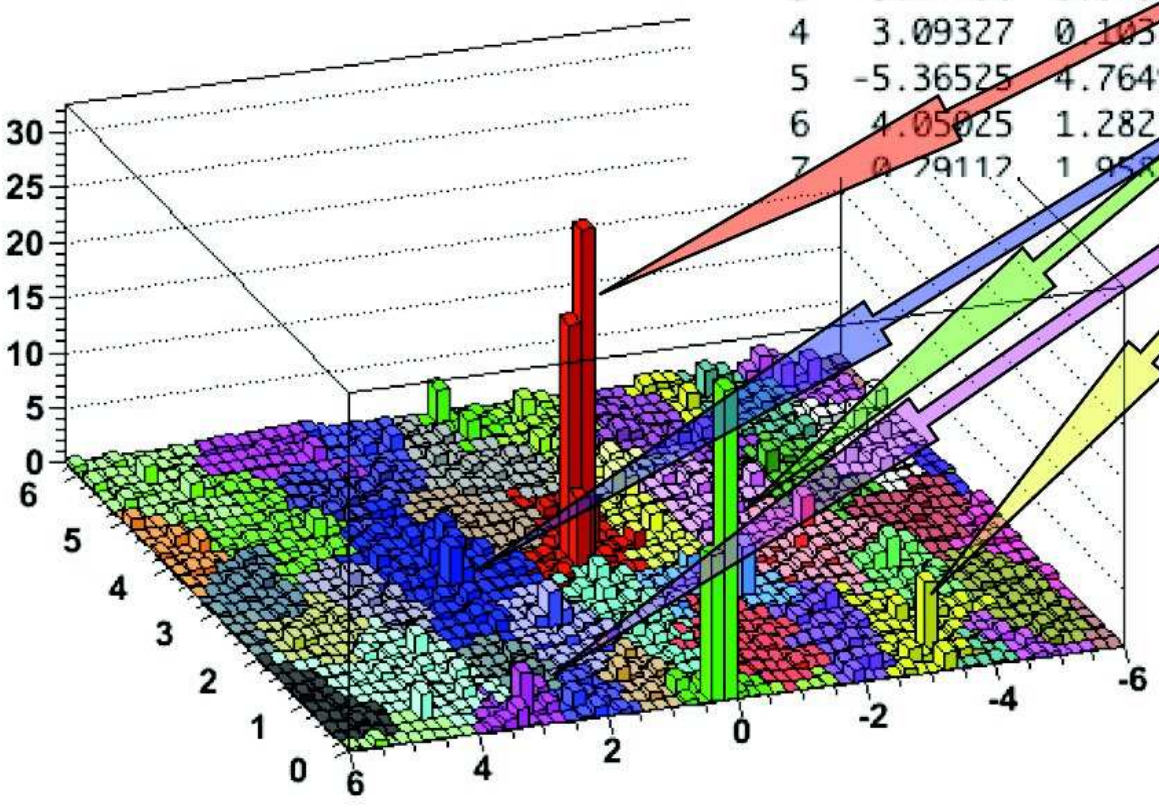
Add dense coverage of infinitely soft *"ghosts"*

See how many end up in jet to measure jet area



Jet areas

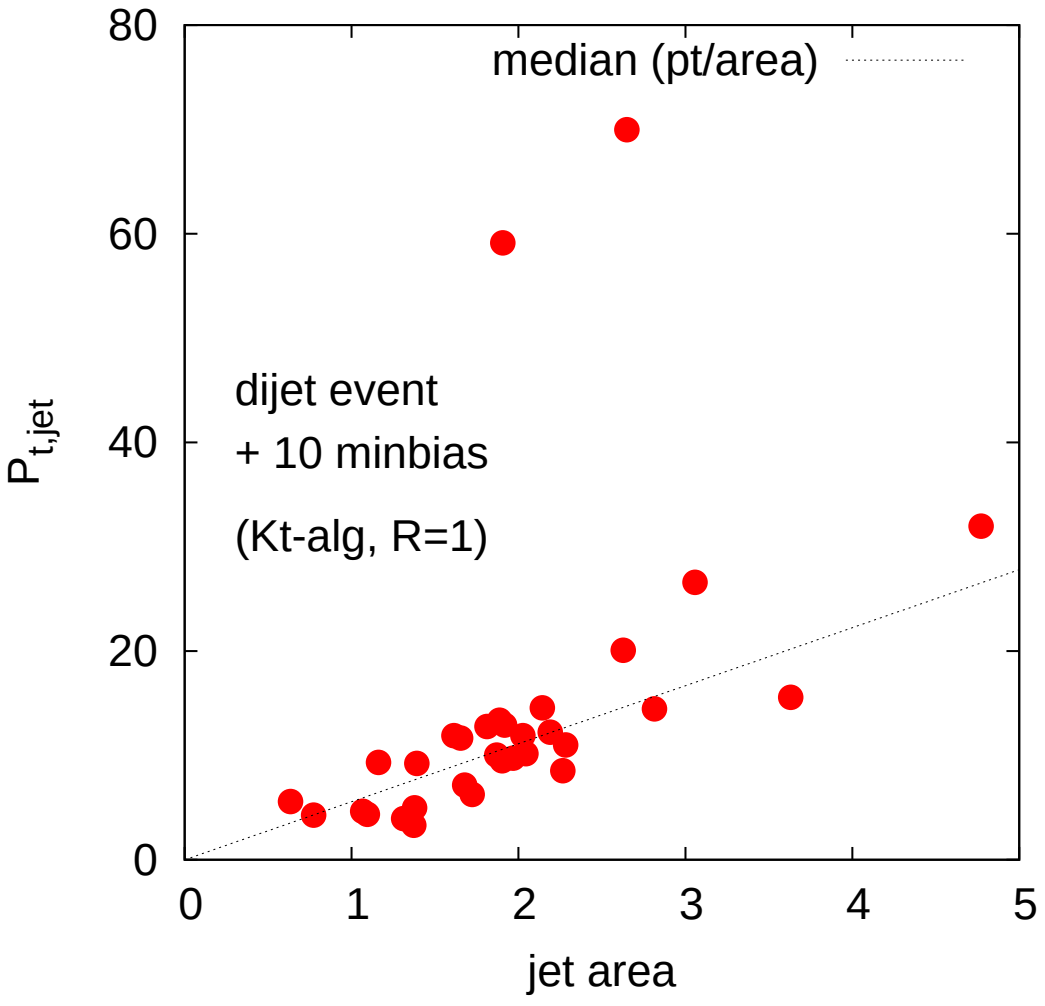
```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
Total area: 76.0265
Expected area: 76.0265
 ijet    eta       phi          Pt          area  +-    err
    0   0.15050  3.24498      69.970      2.625 +-  0.020
    1   0.18579  0.13150      59.133      1.896 +-  0.020
    2   2.33840  3.23960      31.976      4.749 +-  0.028
    3  -3.41796  0.52394      26.595      3.084 +-  0.021
    4   3.09327  0.10350      20.072      2.688 +-  0.023
    5  -5.36525  4.76491      19.583      2.780 +-  0.012
    6   4.05025  1.28278      15.361      3.592 +-  0.028
    7   0.79117  1.95835      14.566      2.114 +-  0.018
```



Approximate linear relation between Pt and area for minimum bias jets.

Can be used on an event-by-event basis to correct the hard jets

Jet areas



Jet areas in k_t algorithm are quite varied

Because k_t-alg adapts to the jet structure

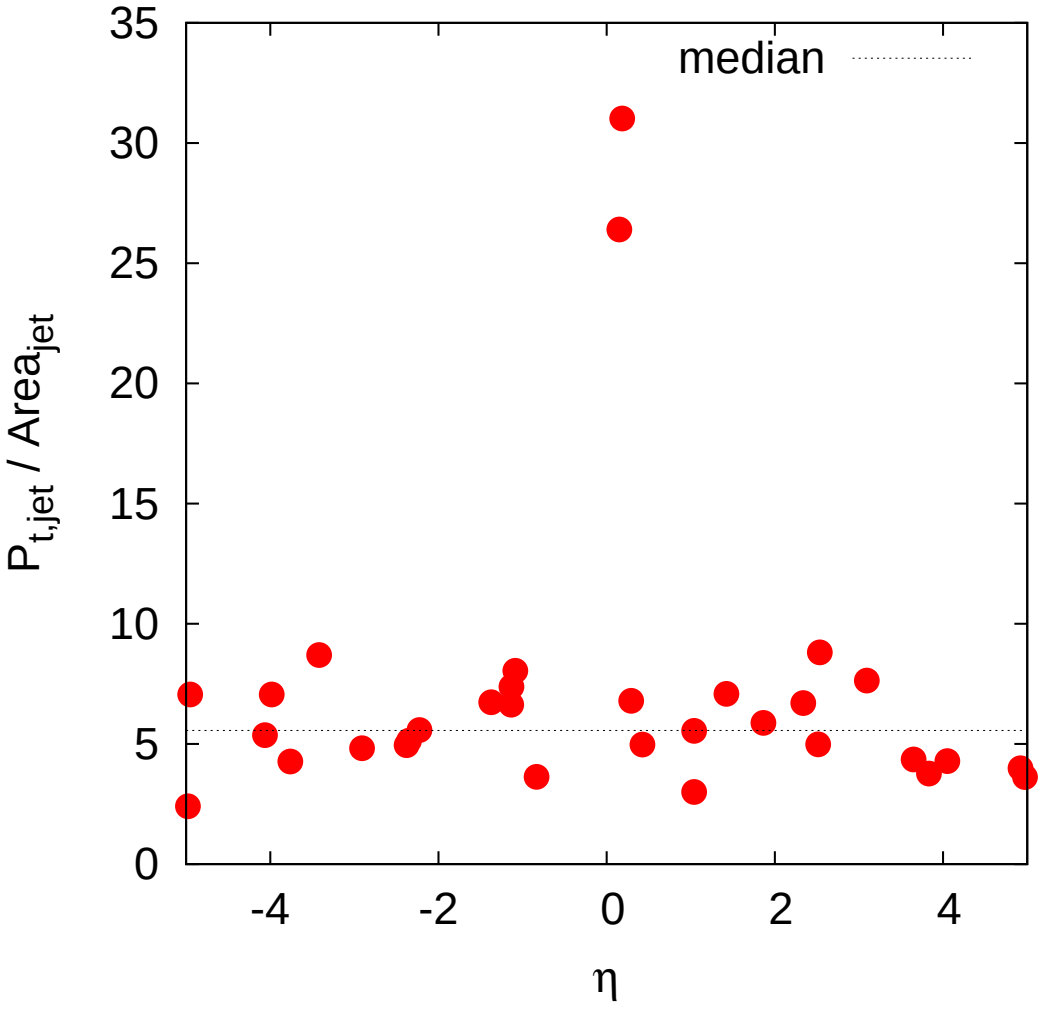
- Contamination from min-bias $\sim$ area

Complicates corrections: min-bias subtraction is different for each jet.

Cone supposedly simpler

Area $= \pi R^2$?

Subtraction using areas



Key observation: p_T/area is quite uniform, except for the hard jets

Correction procedure:

Measure area A of each jet using ghost particles

Find median $p_t/A = Q_0$

Subtract $\Delta p_t = A \times Q_0$ from each jet.

NB. This is an event-by-event correction

NB: cone much harder to correct this way — too slow to add 10^4 ghosts

UE/MB subtraction using areas

Examples of UE/MB subtraction using `FastJet` and area method

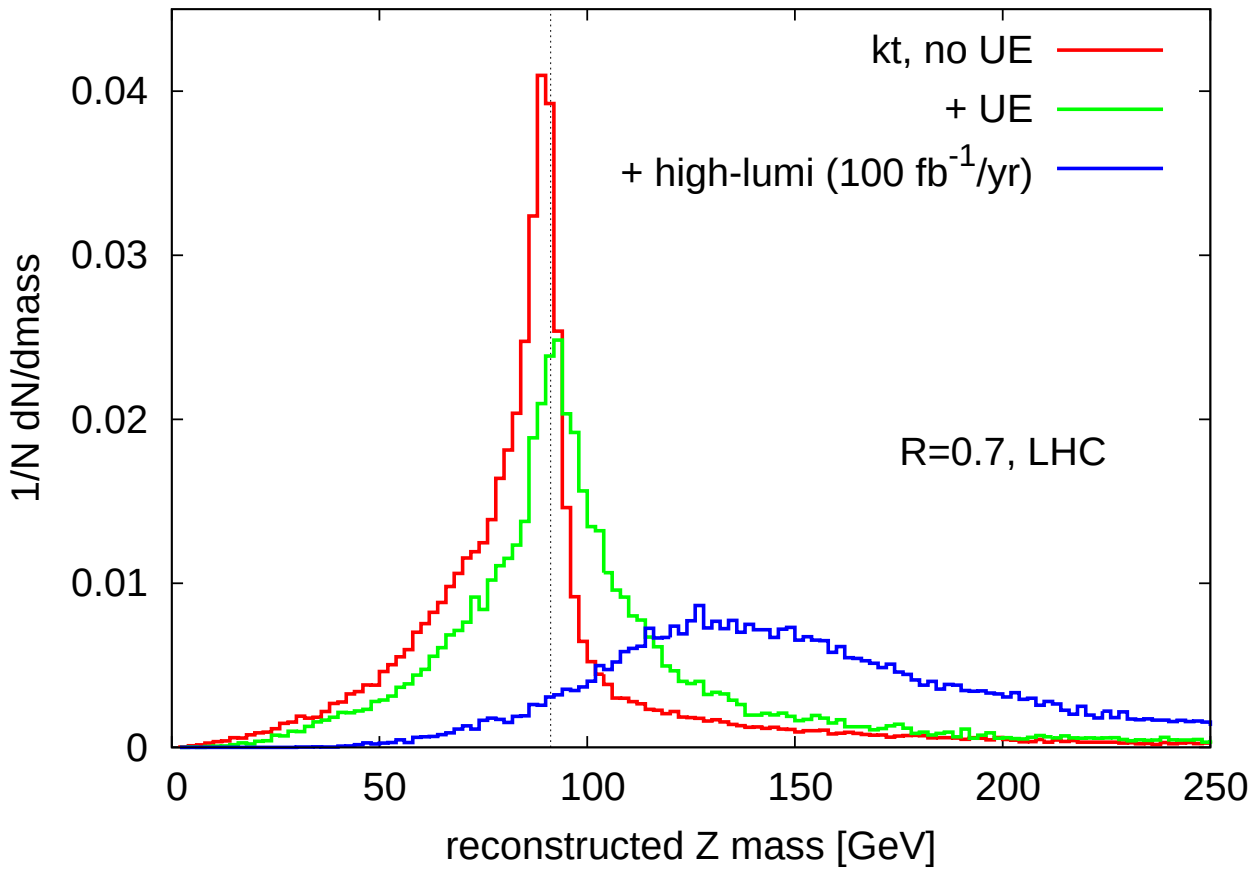
Preliminary results (MC & GPS) for

- High-lumi LHC
  - Z production
  - Z' (mass $= 2$ TeV)
  - W bosons in $t\bar{t}$ events
  - ...
- Heavy ion collisions
  - inclusive jet distribution in Pb-Pb collisions

NB. Value of these results can only be judged by comparing to similar subtractions done with other algorithms/techniques....

Use jet areas to correct jet kinematics

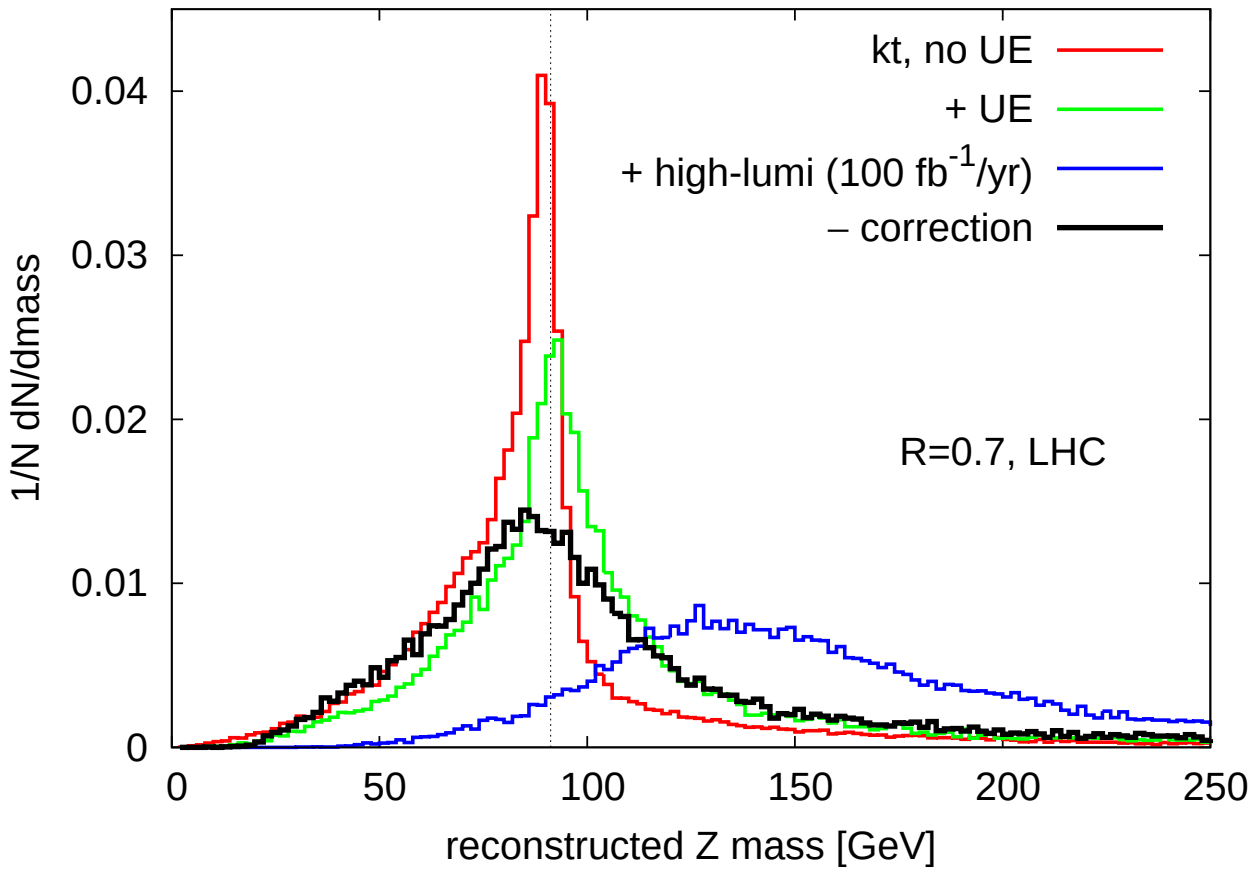
Try reconstructing M_Z from $Z \to 2$ jets, with subtraction of UE/MB



Some loss in resolution, but good value for the Z mass

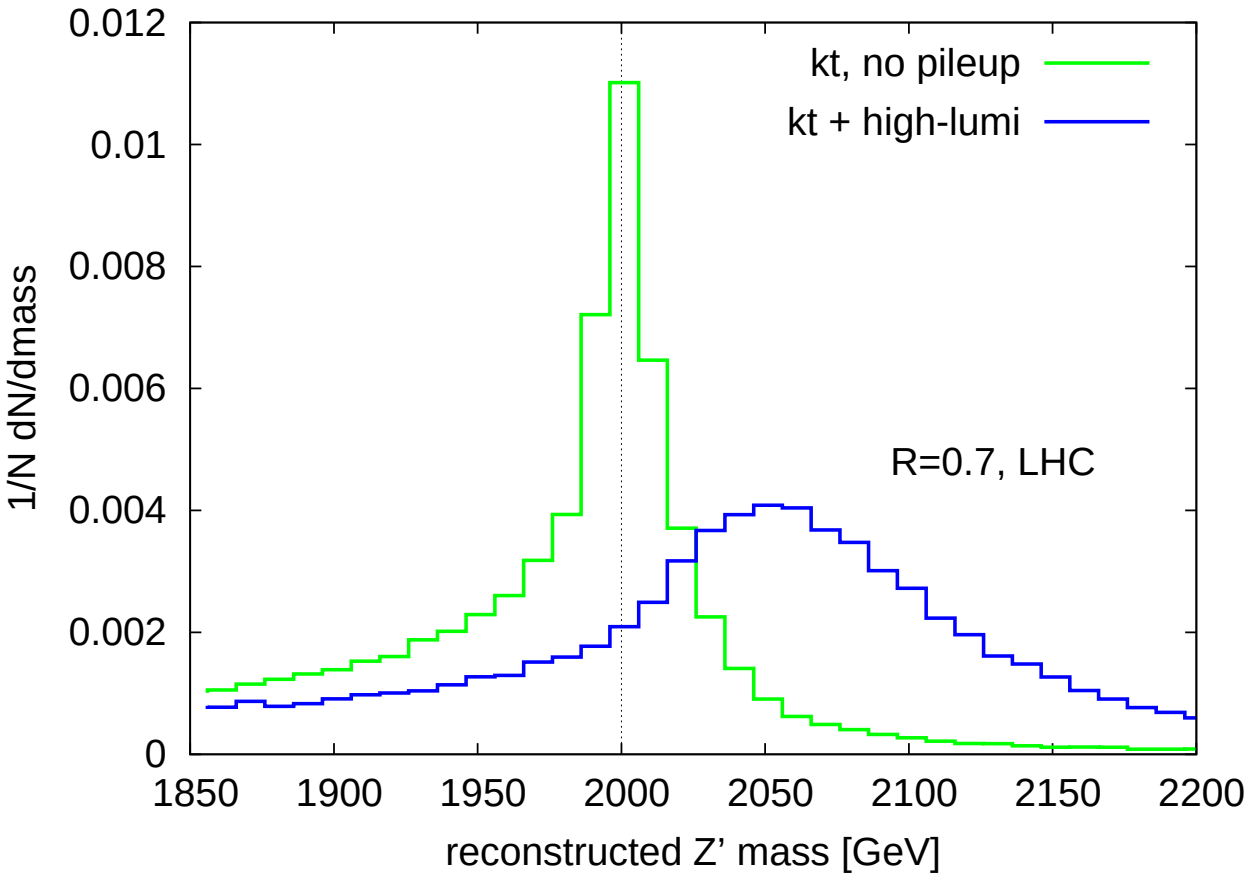
Use jet areas to correct jet kinematics

Try reconstructing M_Z from $Z \to 2$ jets, with subtraction of UE/MB



Some loss in resolution, but good value for the Z mass

Reconstruct Z' mass [2 TeV]

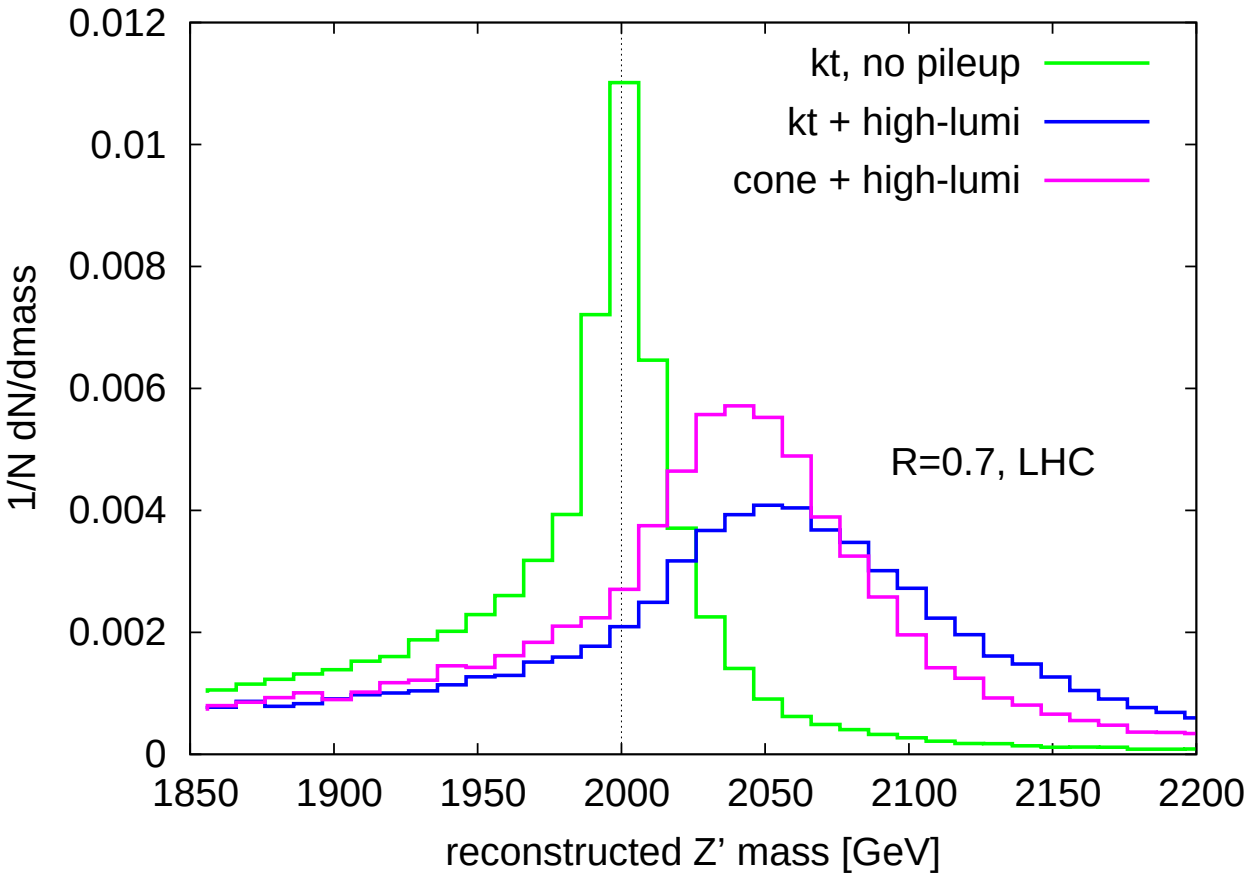


Uncorrected cone better than k_t.

Cam is intermediate ($\langle A_{cam} \rangle \simeq \langle A_{cone} \rangle$, but fluctuations larger)

Corrected Cam (and k_t) is best.

Reconstruct Z' mass [2 TeV]



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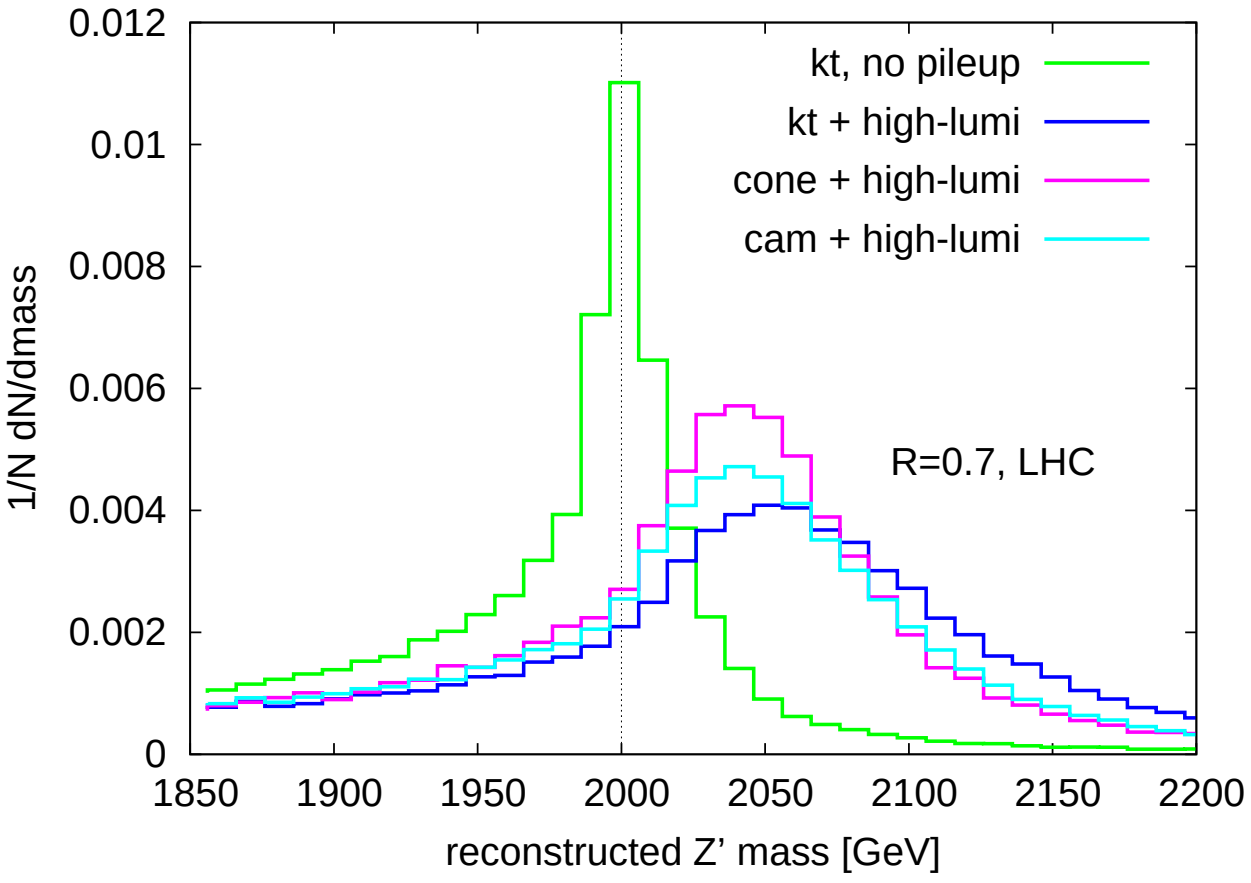

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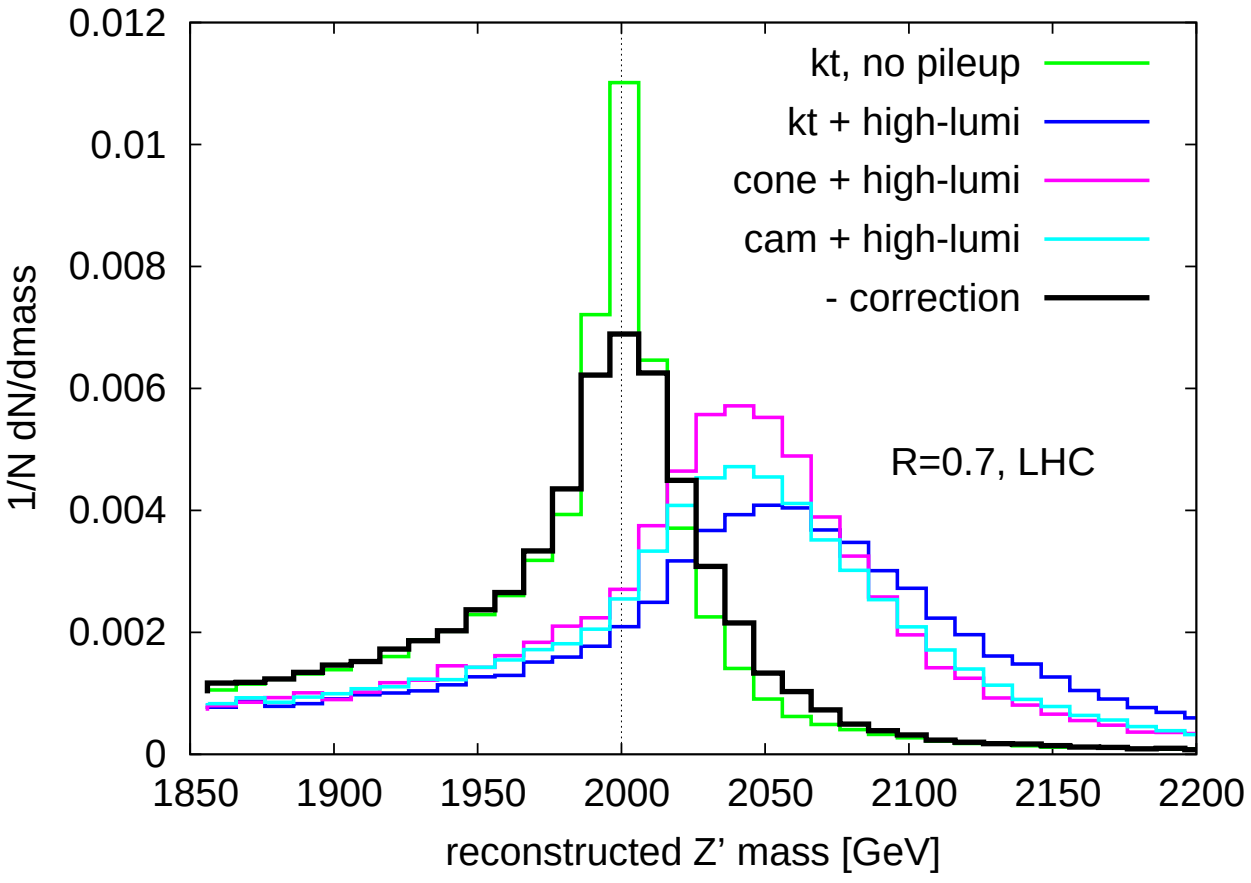

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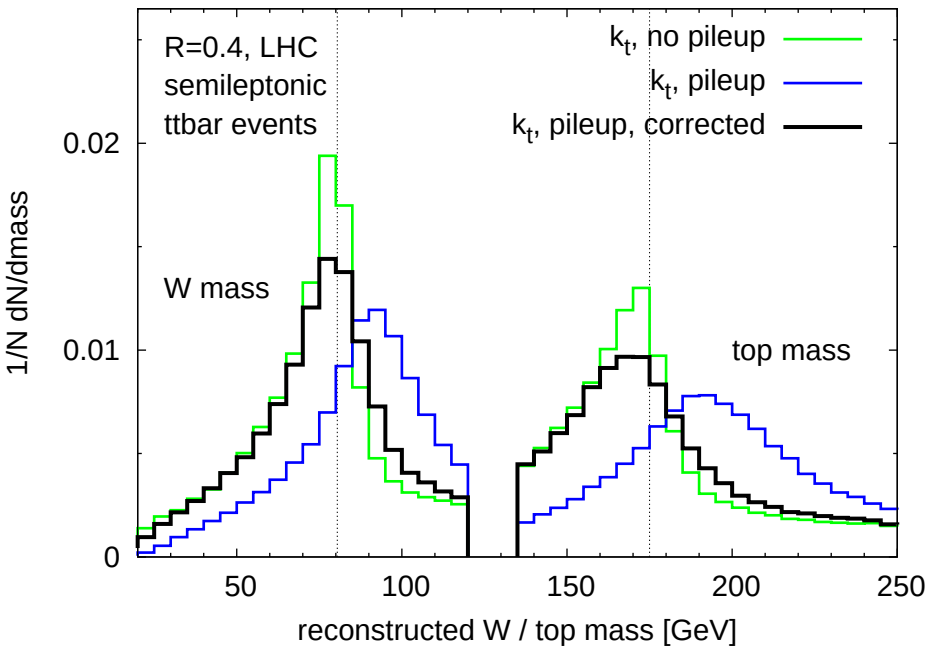
Corrected Cam (and k_t) is best.

$t\bar{t}$ at LHC

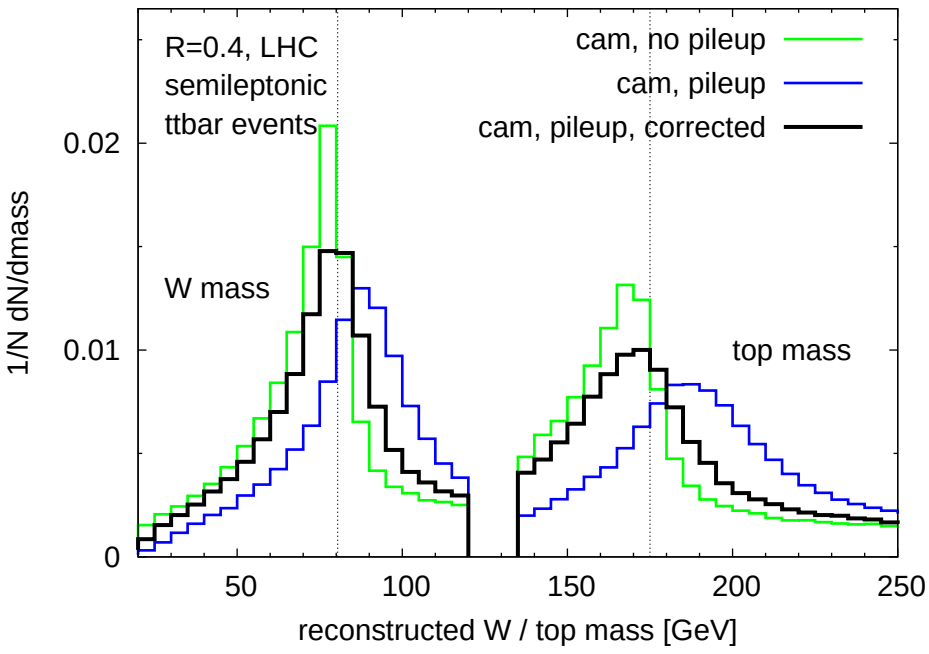
$t\bar{t}$ production in high-lumi pp collisions at LHC

W mass reconstruction via dijet mass in semileptonic decay with b-tagging

k_t



Cambridge



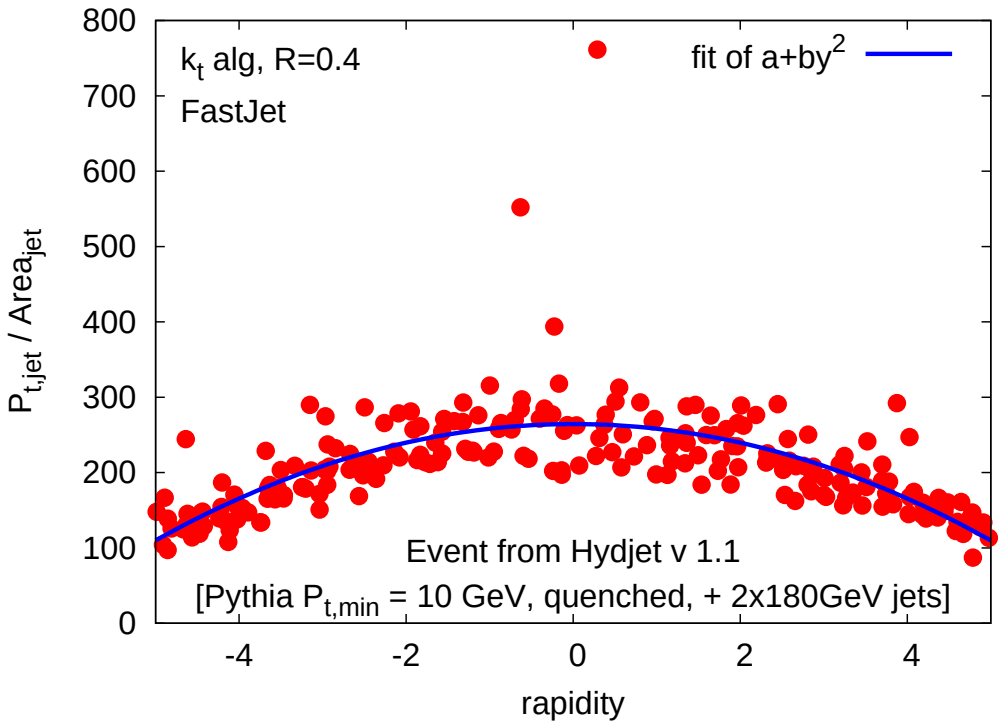
Heavy ions at LHC

At LHC one expects $\sim$ 30000 particles per Pb-Pb collisions

Very few will be hard (e.g. a dijet event), most will be very soft (10 GeV or less).

Easy way of decluttering the event: a minimum p_T cut. However, this is not an infrared safe procedure, and the result must then be artificially corrected back to the 'real' one.

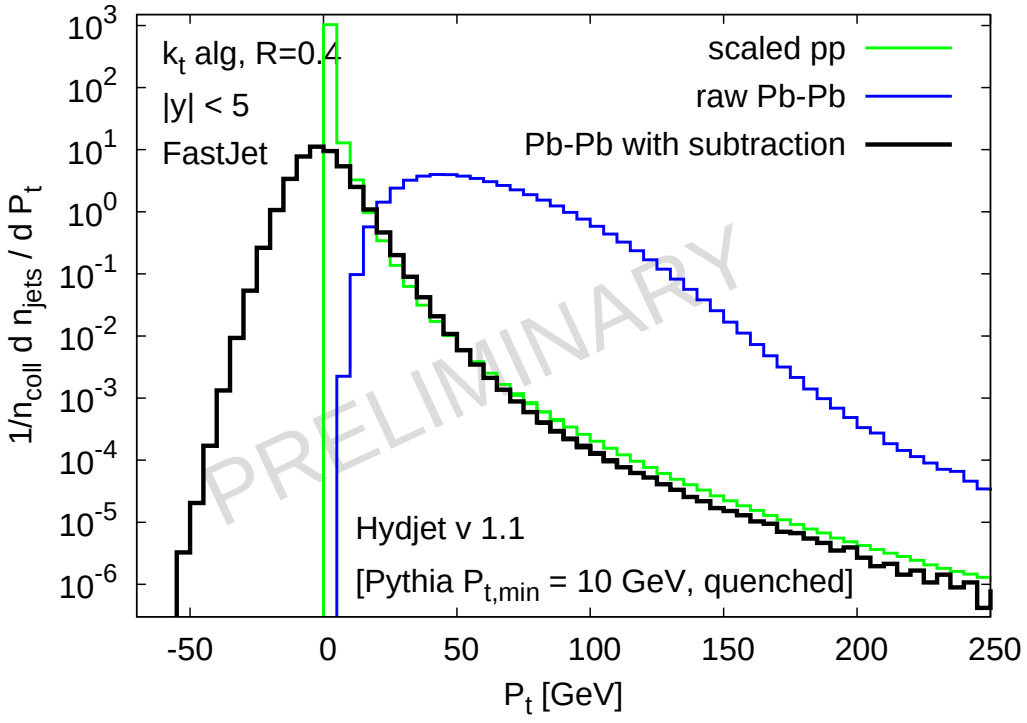
Alternative: same kind of subtraction used in high-lumi pp events



NB: the simulation of a heavy ions collision suggests a parabolic fit of the background

Inclusive jets in Pb-Pb collisions

The subtraction procedure allows one to recover the *pp* single inclusive jet distribution from Pb-Pb collisions



Good agreement with 'hard' distribution after subtraction of huge background

The jets can apparently be measured down to low p_T. Interesting for studying quenching effects.

k_t summary

- k_t alg. can be **fast** — key observation is geometrical reformulation
  Get code from `http://www.lpthe.jussieu.fr/~salam/fastjet`
- Jet areas ($\longrightarrow$ min. bias. contributions) do fluctuate
  Some aspects of areas amenable to analytical calculations
- But areas can (should) be **measured** and **used for correction** on jet-by-jet basis.
  Preliminary studies seem promising
  Next version of `FastJet` will include the subtraction
- k_t is part of a class of algorithms — other example deserving more attention is *Cambridge/Aachen* alg.
  It too can be made fast

http://hepforge.cedar.ac.uk/hepjet/