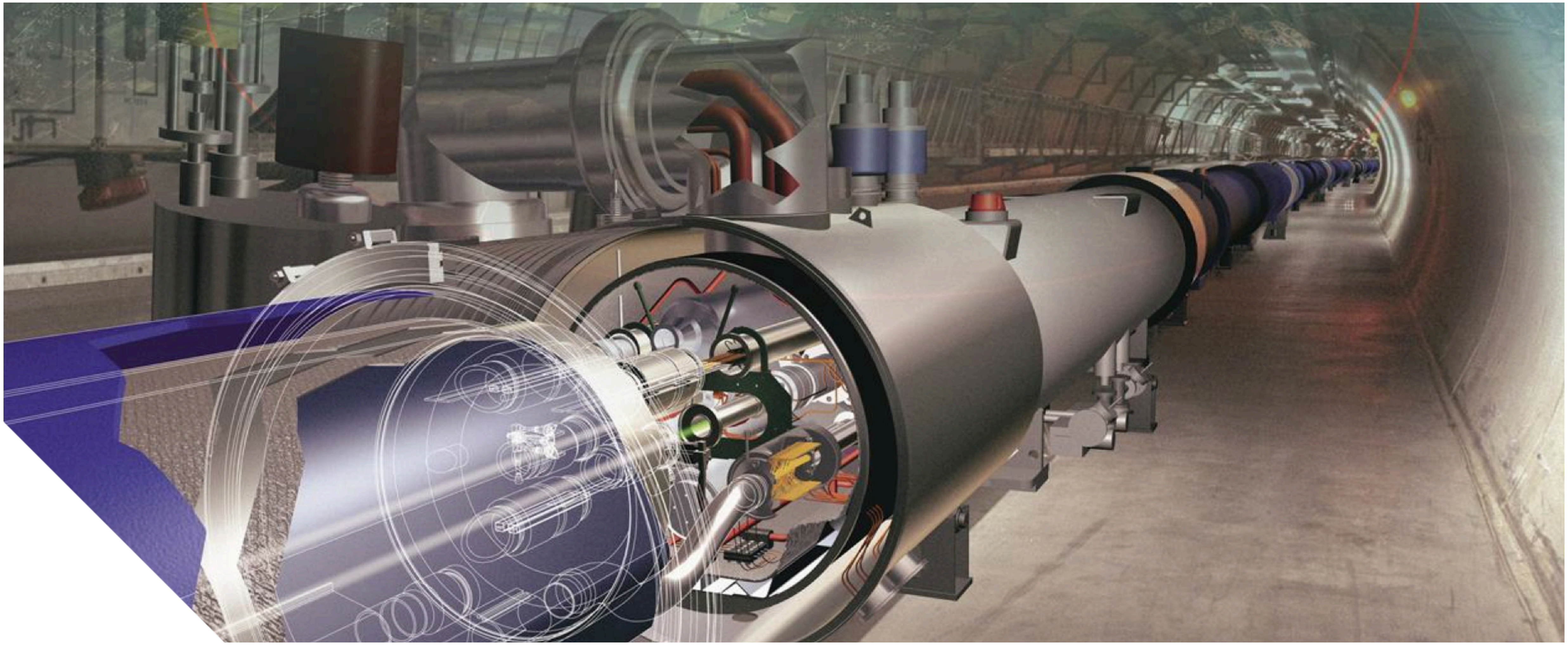
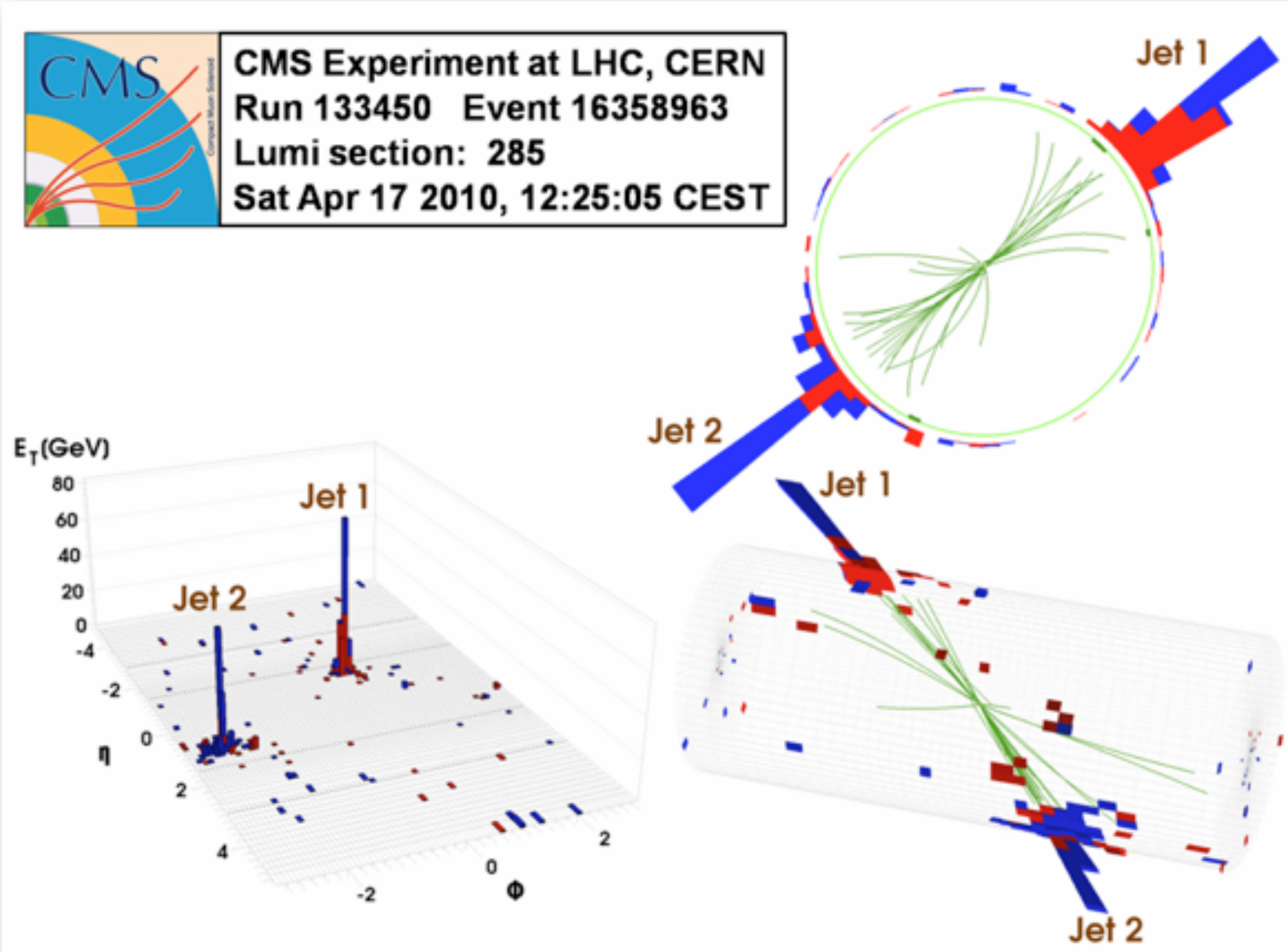
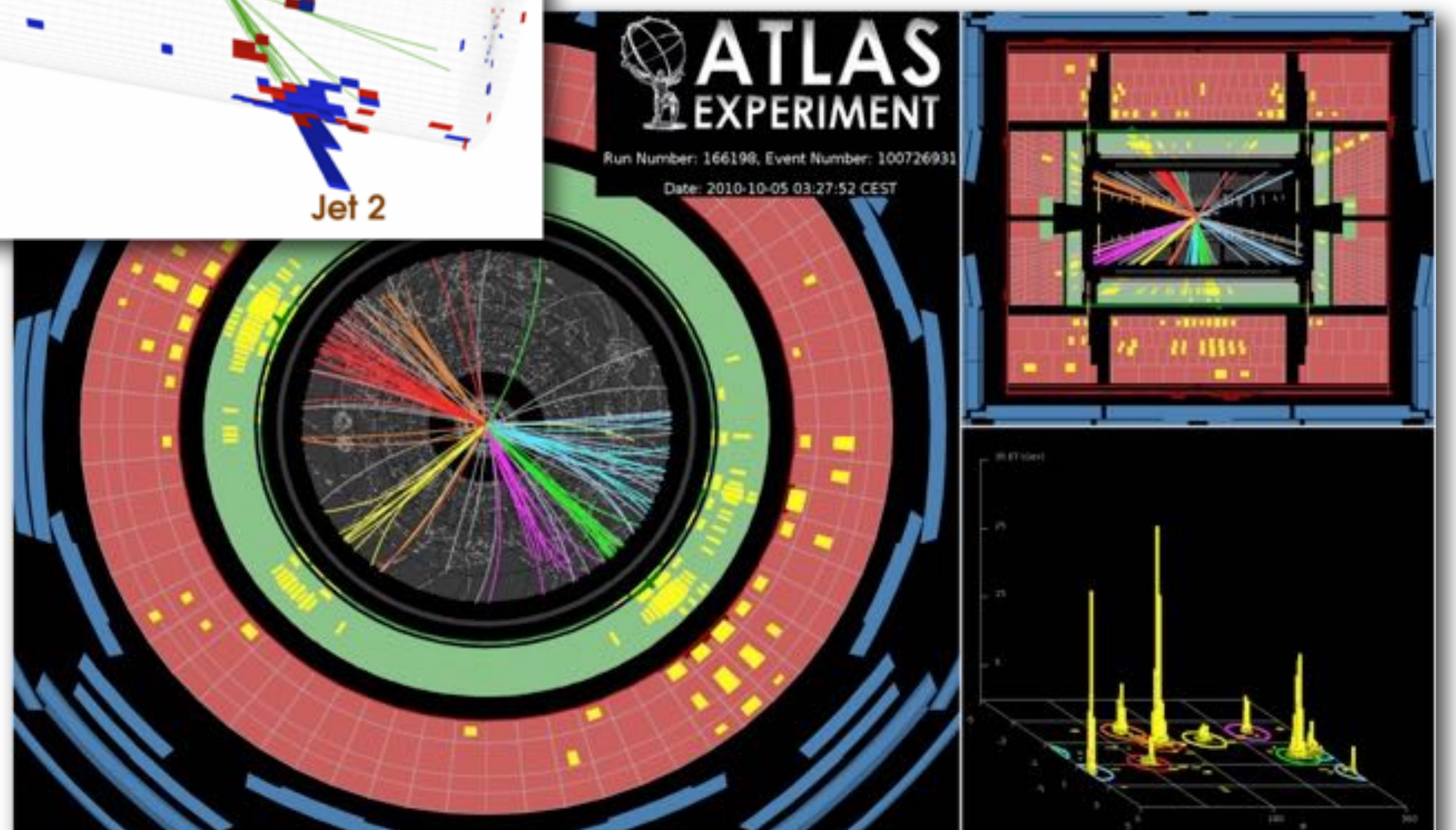


QCD lecture 8: jets

Gavin Salam, Oxford, February 2020
as part of Claire Gwenlan's QCD PhD course

(with extensive use of material by
Matteo Cacciari and Gregory Soyez)





JETS
Collimated,
energetic bunches
of particles

Find all papers by ATLAS and CMS
2106 records found

reportnumber:CERN and (collaboration:ATLAS or collaboration:CMS) | Brief format | Search | Easy Search | Advanced Searc

find j "Phys.Rev.Lett.,105*" :: more

Search on INSPIRE beta

Sort by: latest first | desc. | - or rank by -

Display results: 25 results | single list

HEP **2,106** records found 1 - 25 jump to record: 1

1. **Measurement of the cross section for electroweak production of a Z boson, a photon and two jets i TeV and constraints on anomalous quartic couplings**
   CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Feb 23, 2020.
   CMS-SMP-18-007, CERN-EP-2020-007
   e-Print: **arXiv:2002.09902** **[hep-ex]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 1$**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Feb 18, 2020. 44 pp.
   CERN-EP-2019-273
   e-Print: **arXiv:2002.07546** **[hep-ex]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server; ADS Abstract Service; Link to ATLAS News article
   Detailed record

3. **A measurement of the Higgs boson mass in the diphoton decay channel**
   CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Feb 15, 2020.
   CMS-HIG-19-004, CERN-EP-2020-004
   e-Print: **arXiv:2002.06398** **[hep-ex]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server; ADS Abstract Service
   Detailed record

Pull out those that refer to one widely used jet-alg

1289 records found

reportnumber:CERN and (collaboration:ATLAS or collaboration:CMS) and refersto:recid:779080 | Brief format | Search | Easy Search | Advanced Search

find j "Phys.Rev.Lett.,105*" :: more

Search on INSPIRE beta

Sort by: latest first | desc. | - or rank by -

Display results: 25 results | single list

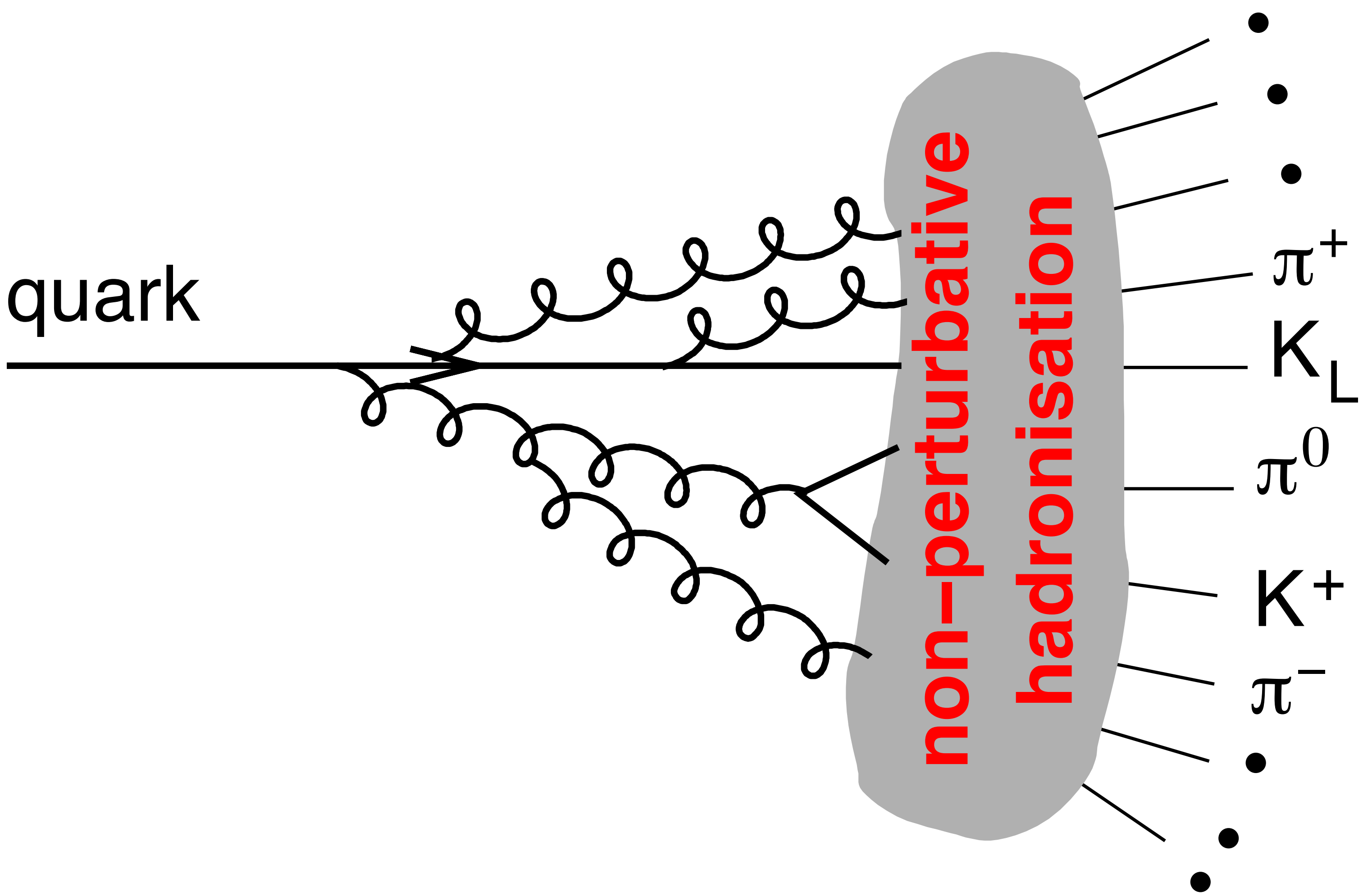
> 60% of papers use jets!

HEP 1,289 records found 1 - 25 jump to record: 1 Sear

1. **Measurement of the cross section for electroweak production of a Z boson, a photon and two jets in pr TeV and constraints on anomalous quartic couplings**
CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Feb 23, 2020.
CMS-SMP-18-007, CERN-EP-2020-007
e-Print: **arXiv:2002.09902** **[hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

2. **Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ Te**
ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Feb 18, 2020. 44 pp.
CERN-EP-2019-273
e-Print: **arXiv:2002.07546** **[hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to ATLAS News article
Detailed record

3. **Search for physics beyond the standard model in events with jets and two same-sign or at least three collisions at $\sqrt{s} = 13$ TeV**
CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Jan 27, 2020. 47 pp.
CMS-SUS-19-008, CERN-EP-2020-001
e-Print: **arXiv:2001.10086** **[hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server

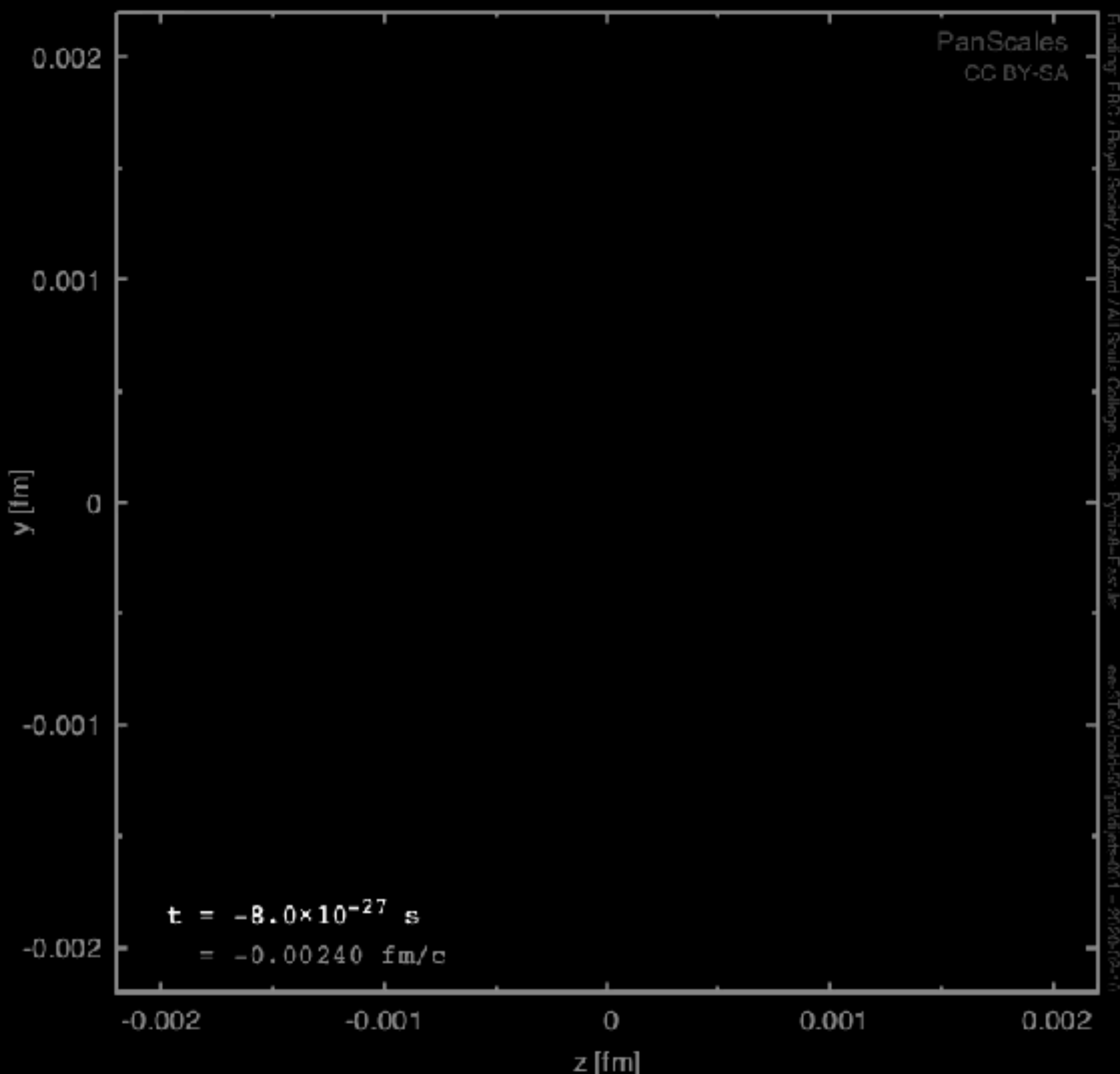


Gluon emission

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

Non-perturbative physics

$$\alpha_s \sim 1$$

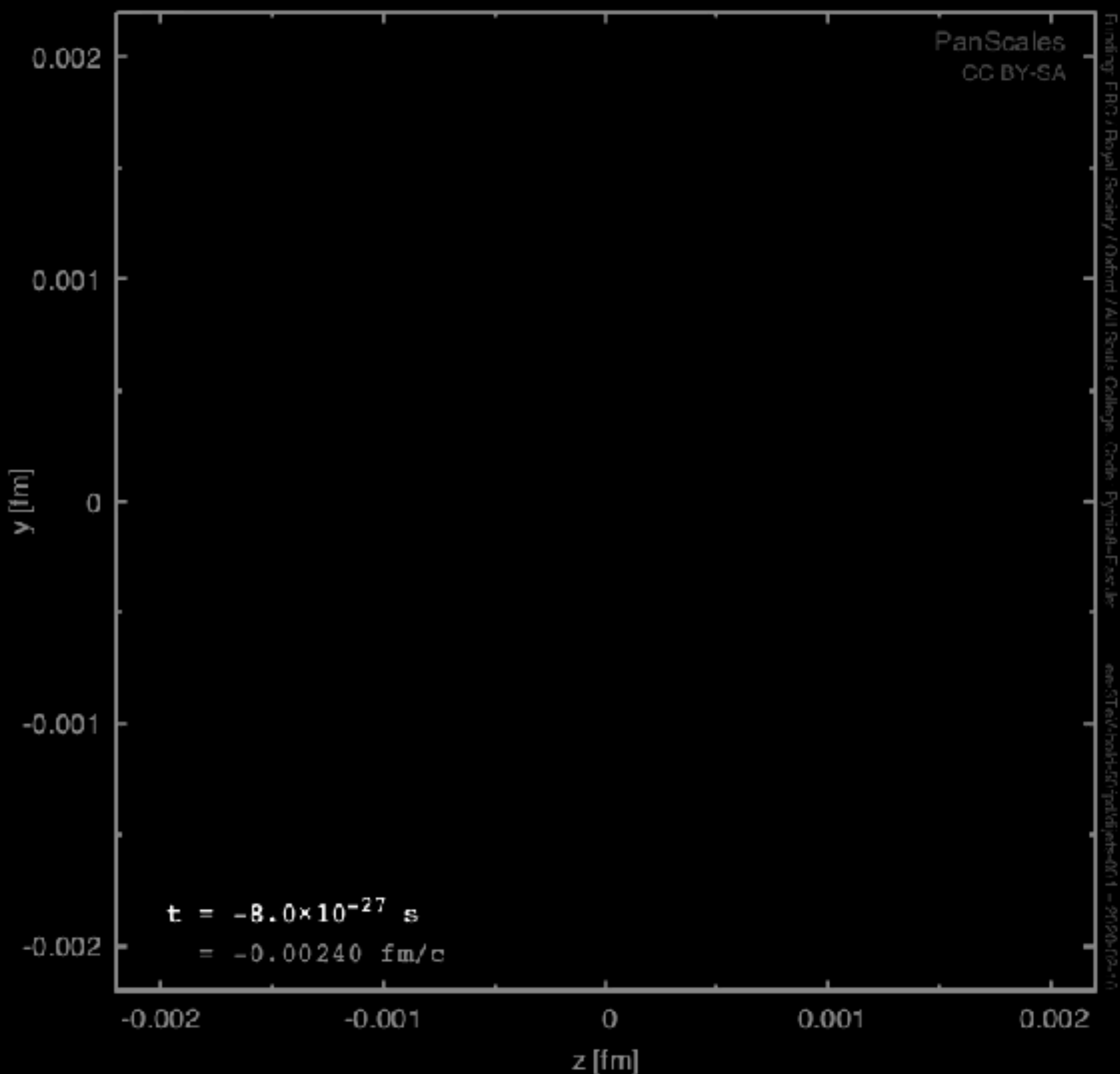


incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time



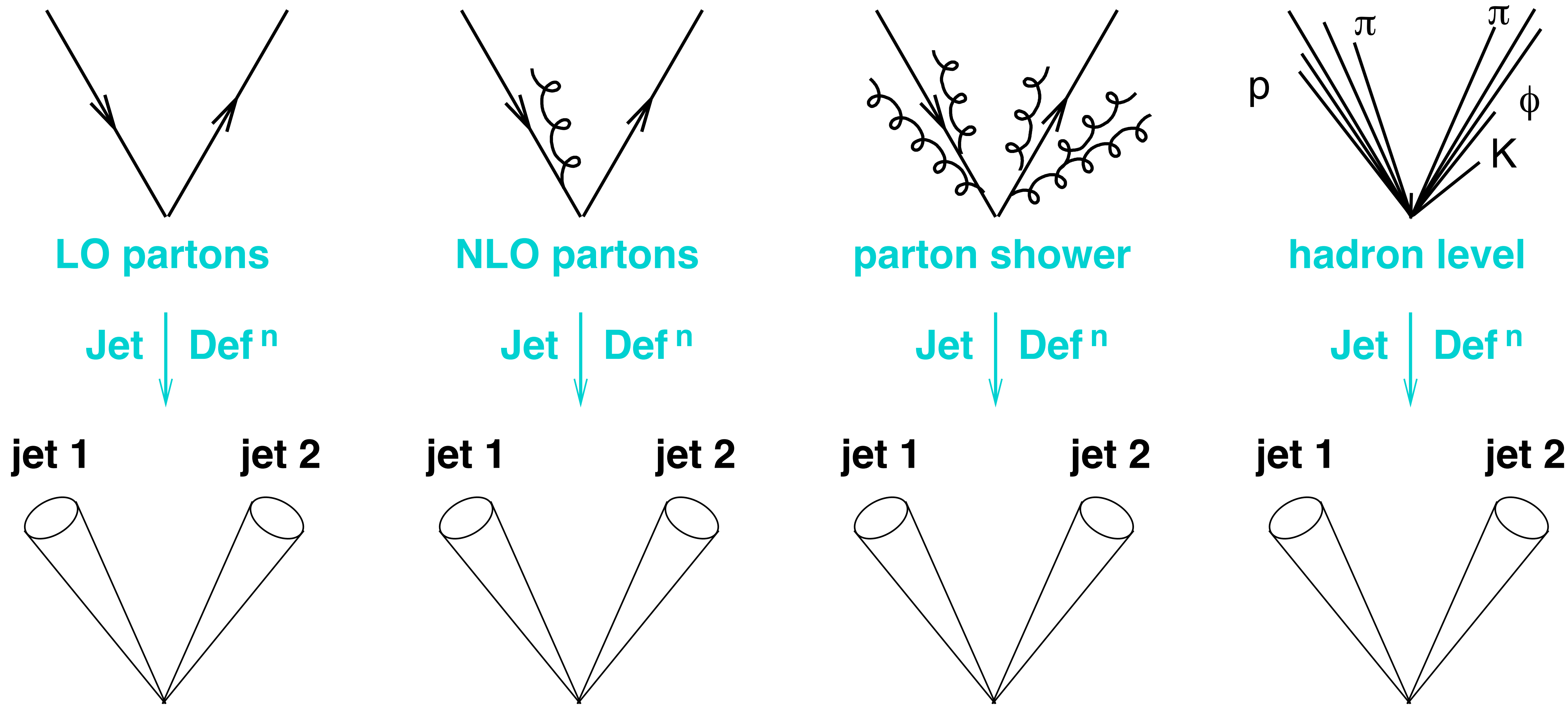
incoming beam particle

intermediate particle

final particle

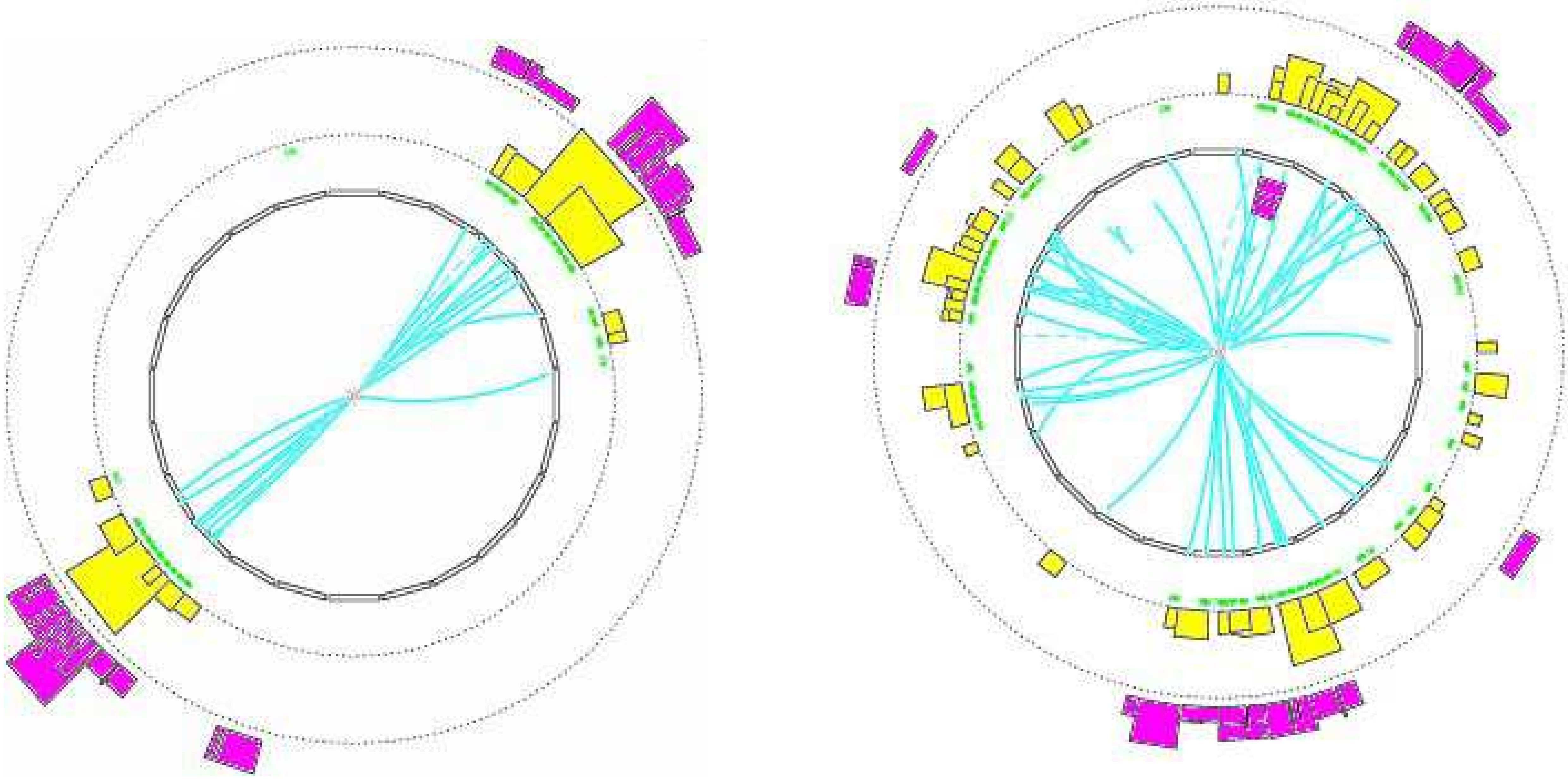
Event evolution spans 7 orders of magnitude in space-time

Jet finding as a form of projection

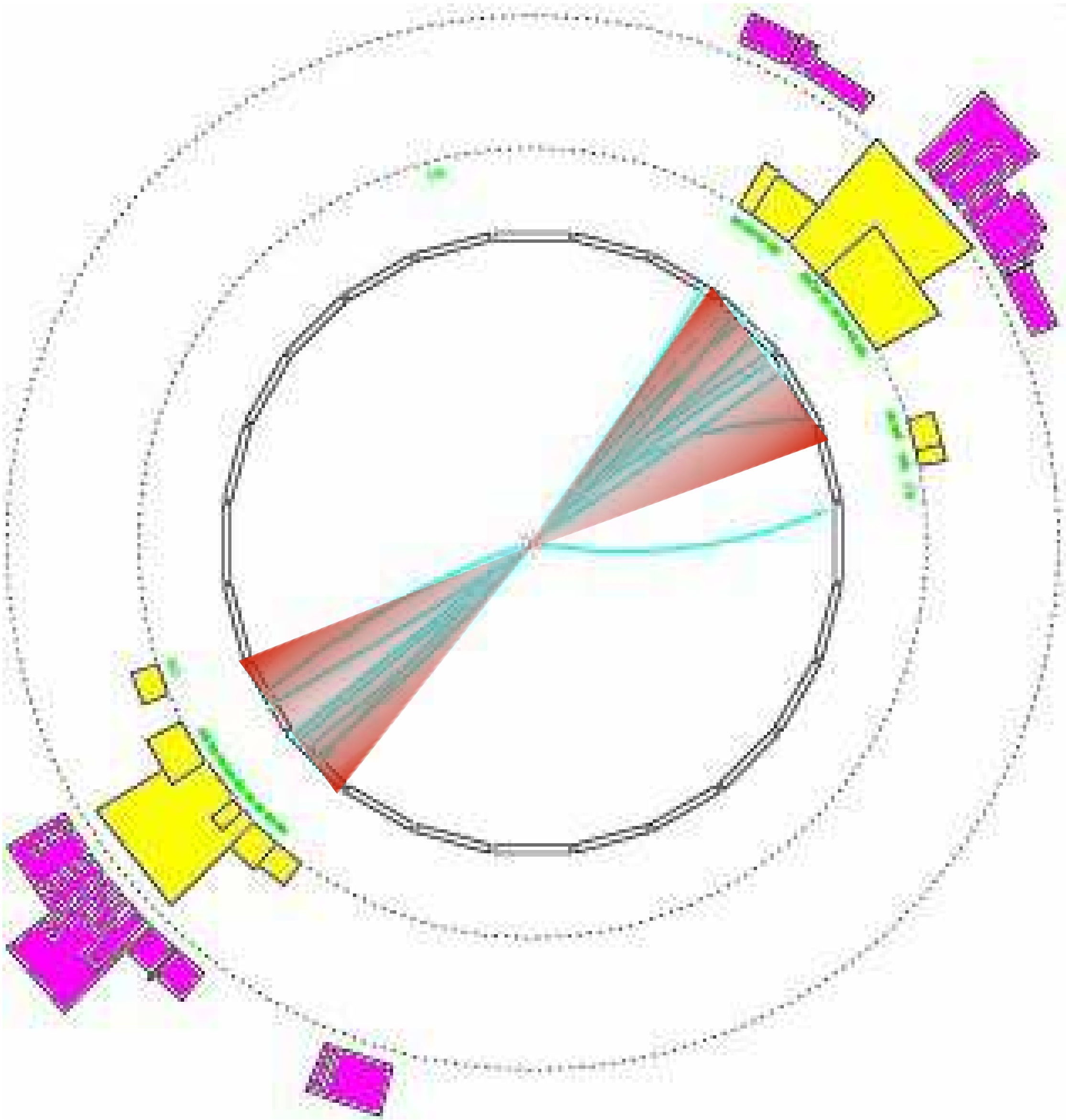


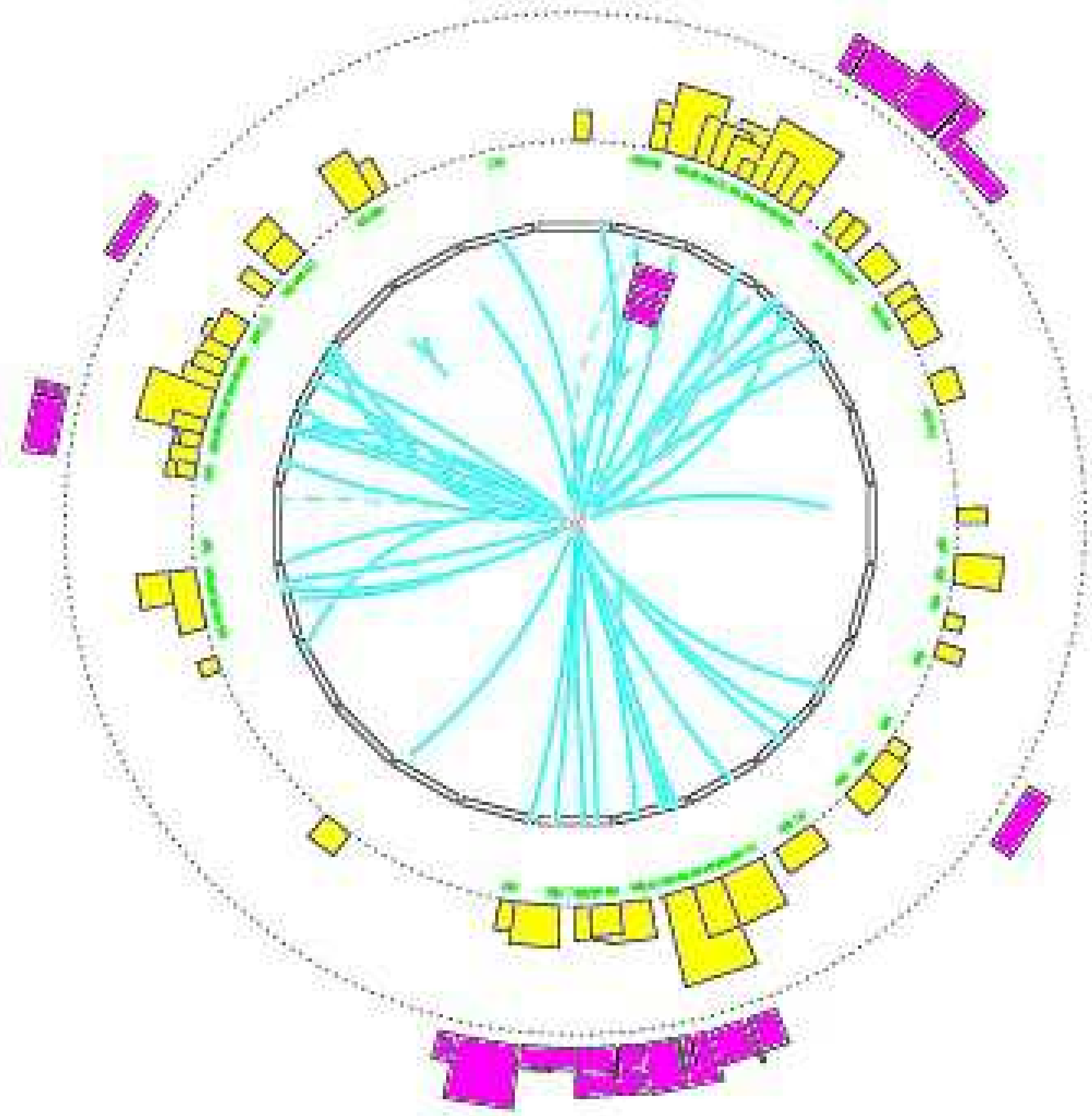
Projection to jets should be resilient to QCD effects

Reconstructing jets is an ambiguous task



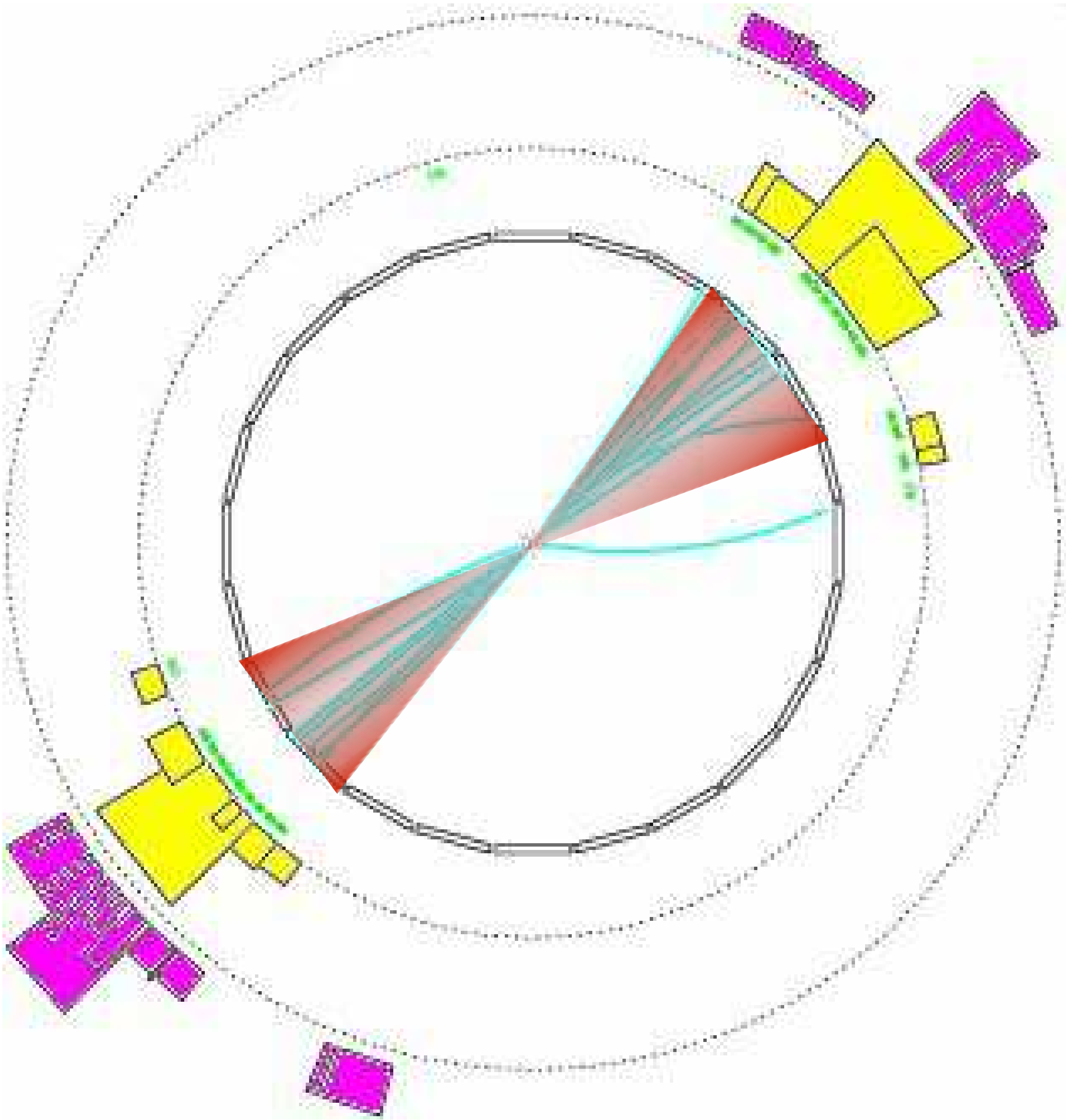
Reconstructing jets is an ambiguous task



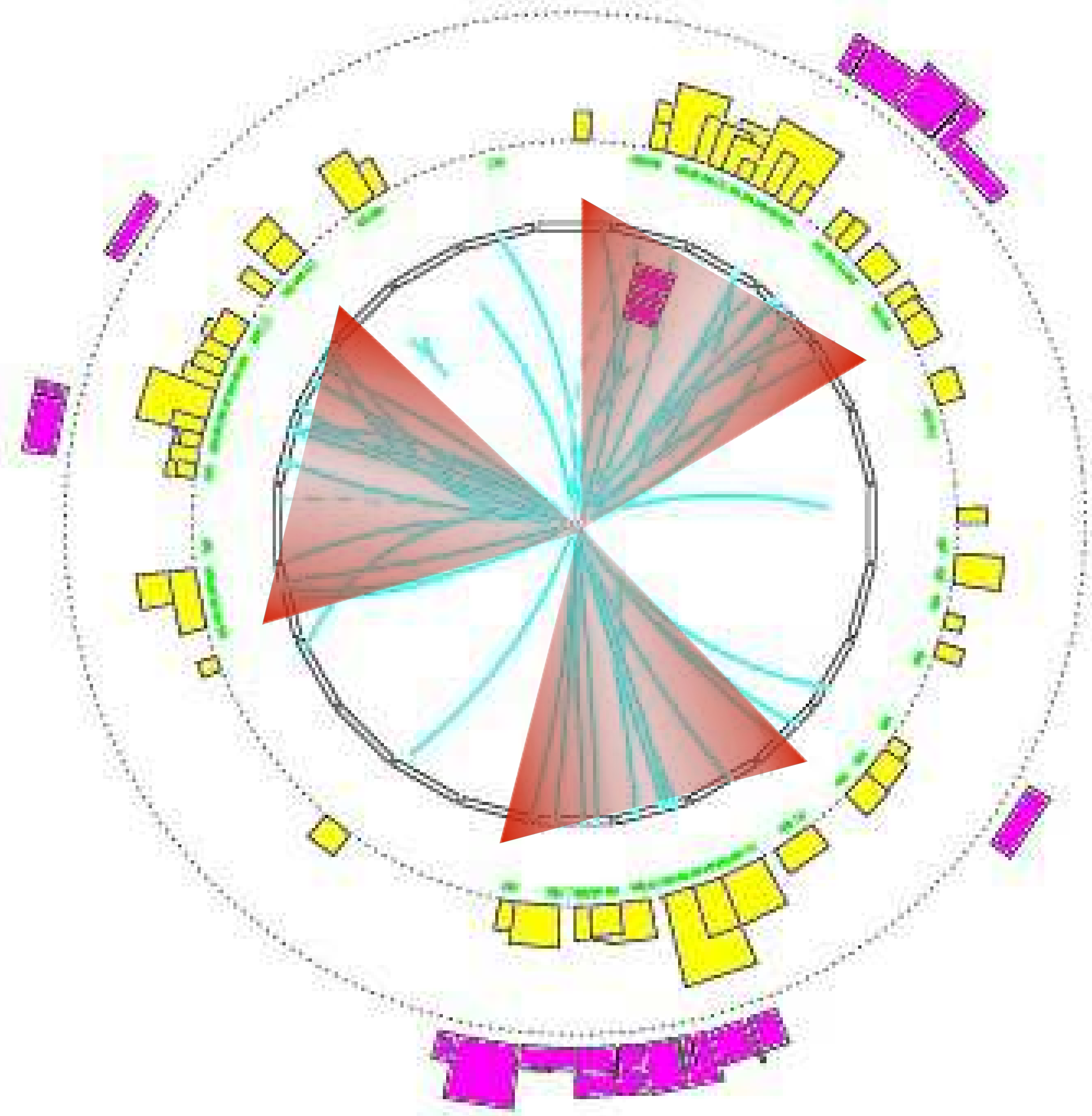


2 clear jets

Reconstructing jets is an ambiguous task

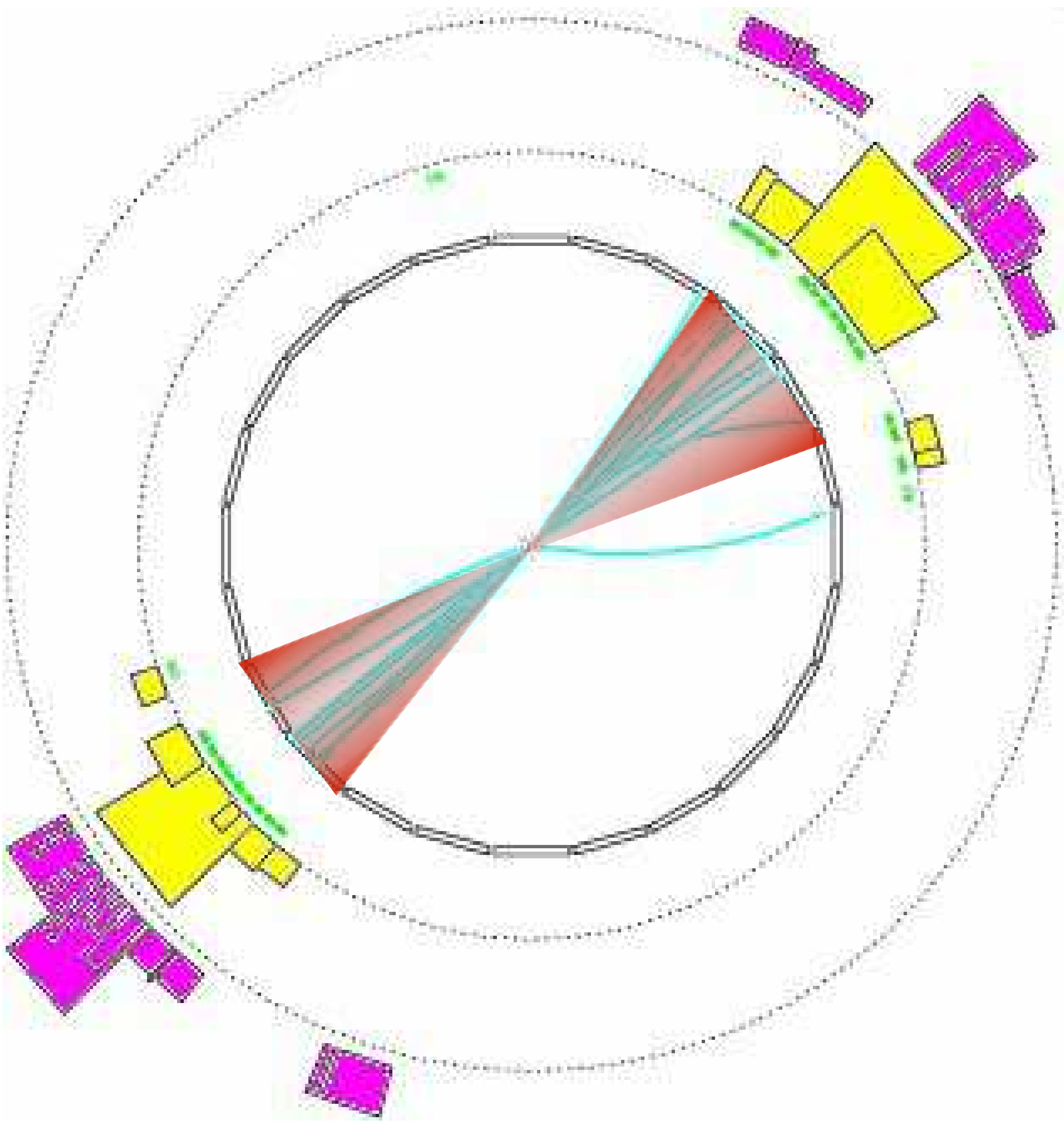


2 clear jets

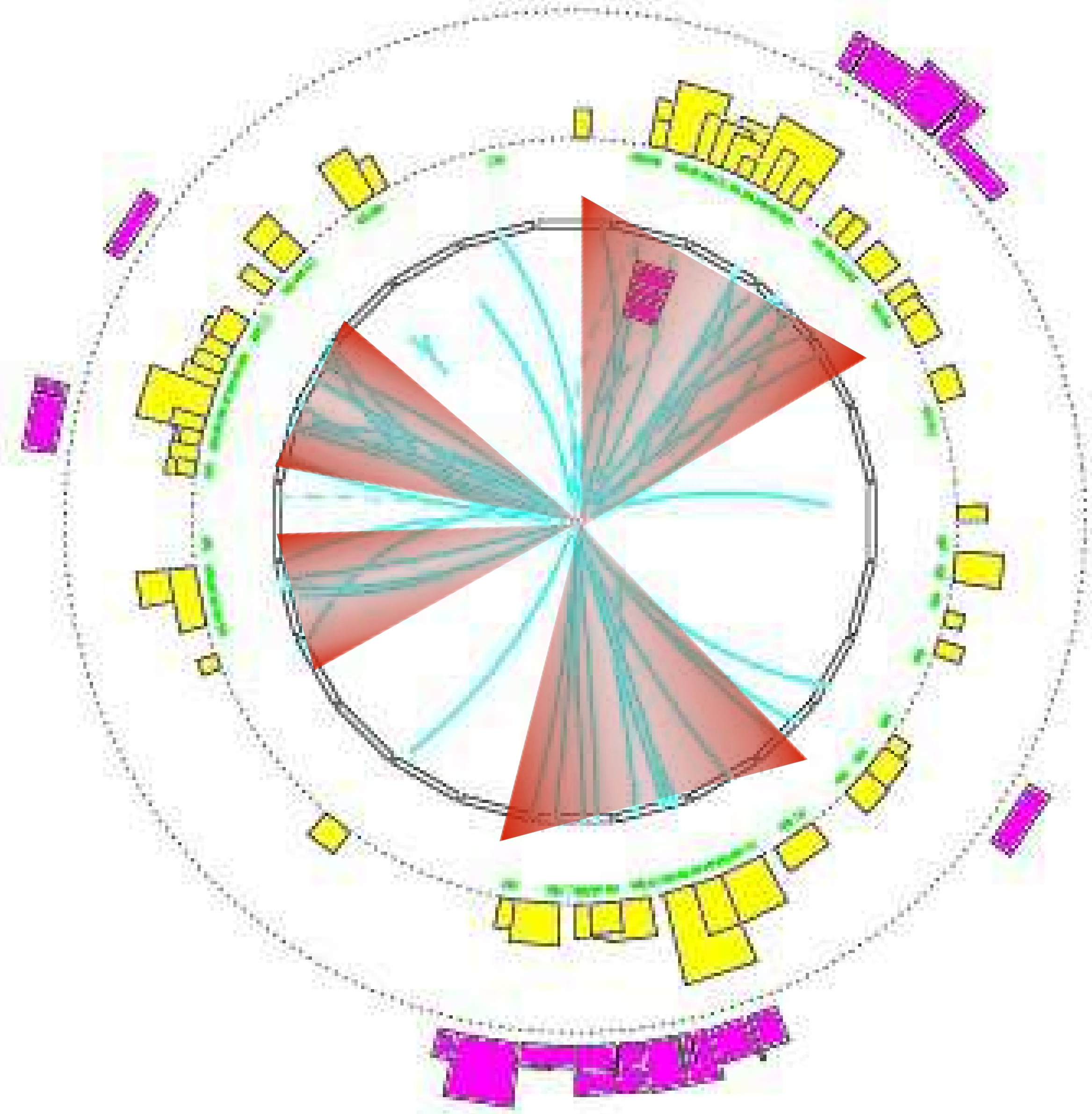


3 jets?

Reconstructing jets is an ambiguous task

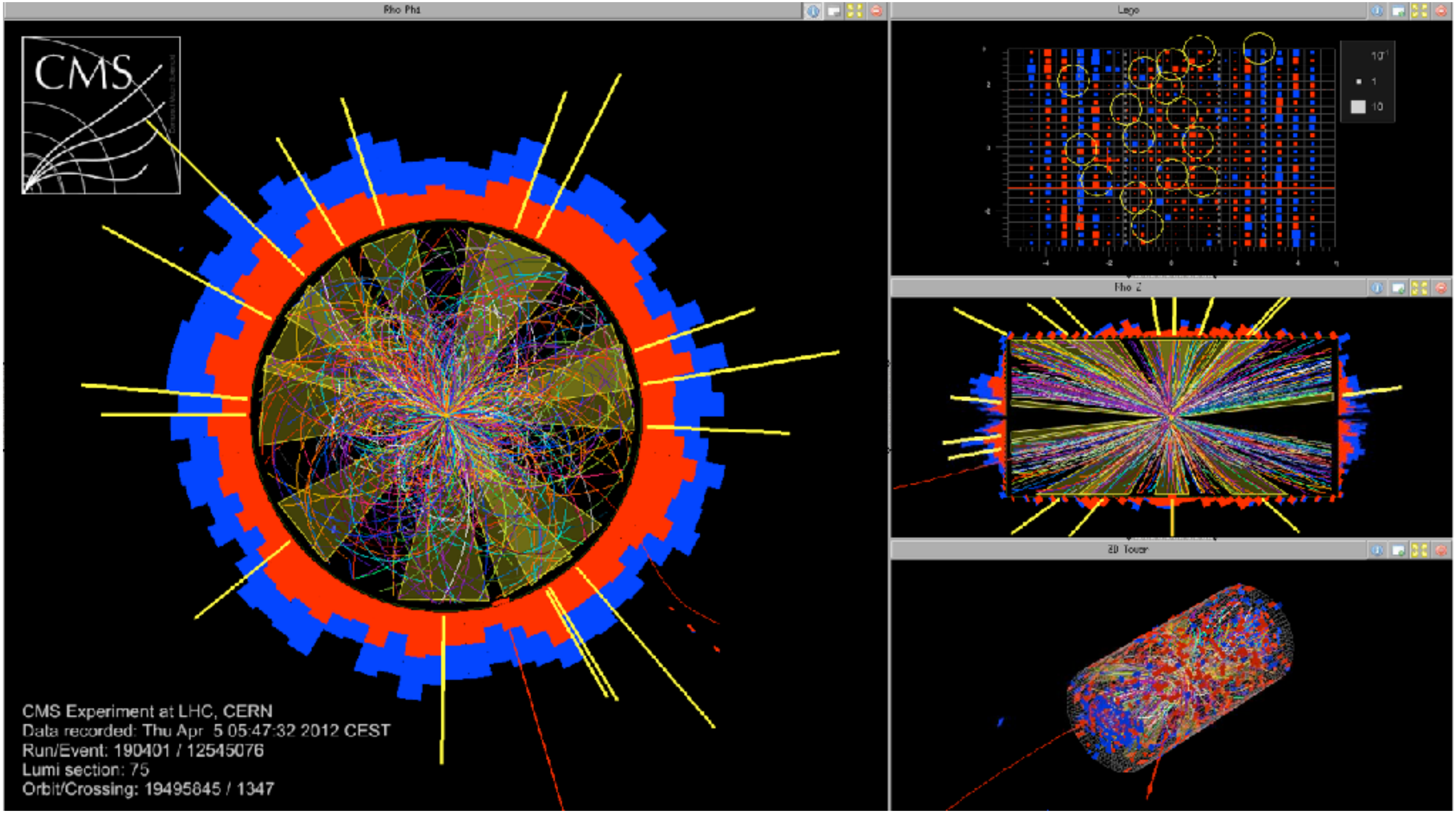


2 clear jets



3 jets?

or 4 jets?


Rho Phi
Lego
Rho Z
3D Tower
CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 5 05:47:32 2012 CEST
Run/Event: 190401 / 12545076
Lumi section: 75
Orbit/Crossing: 19495845 / 1347

Make a choice: specify a jet definition

$$\{p_i\} \xrightarrow{\text{jet definition}} \{j_k\}$$

particles,
4-momenta,
calorimeter towers, ...

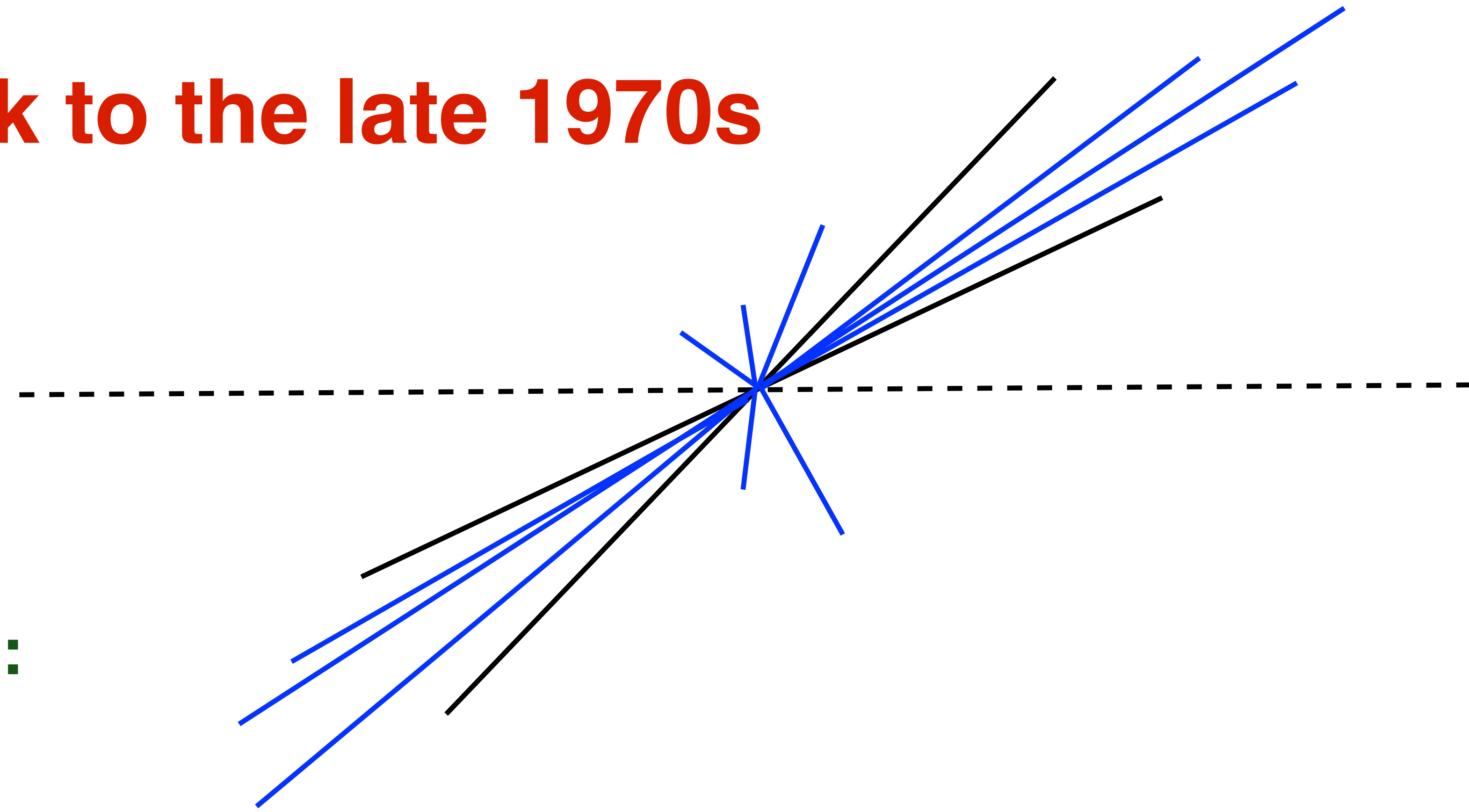
jets

- Which particles do you put together into a same jet?
- How do you recombine their momenta (4-momentum sum is the obvious choice, right?)

"Jet [definitions] are legal contracts between theorists and experimentalists"
-- MJ Tannenbaum

They're also a way of organising the information in an event
1000's of particles per events, up to 20.000,000 events per second

Jet definitions date back to the late 1970s



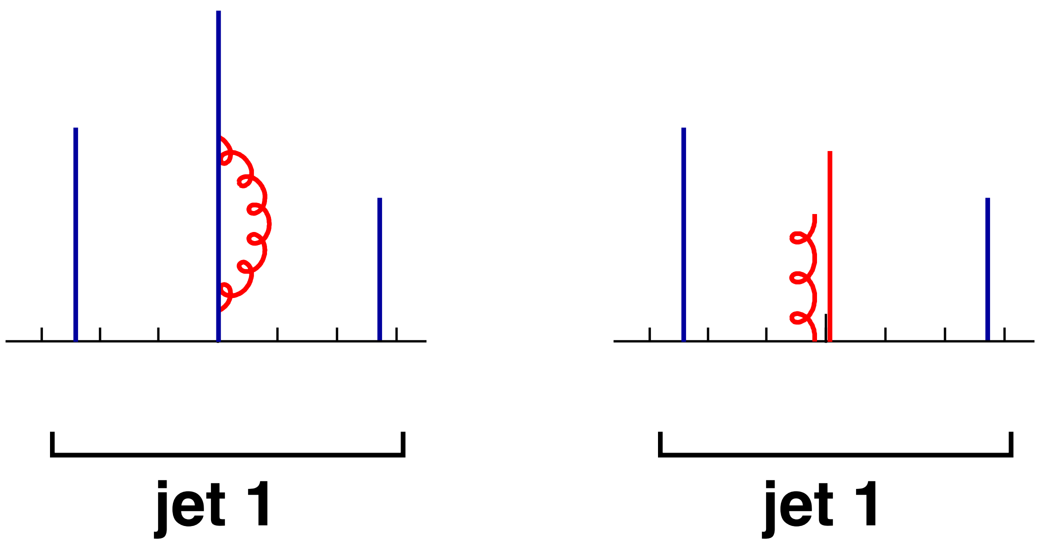
Sterman and Weinberg,
Phys. Rev. Lett. 39, 1436 (1977):

To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\varepsilon \ll 1$ 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-

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

Key requirement: infrared and collinear safety

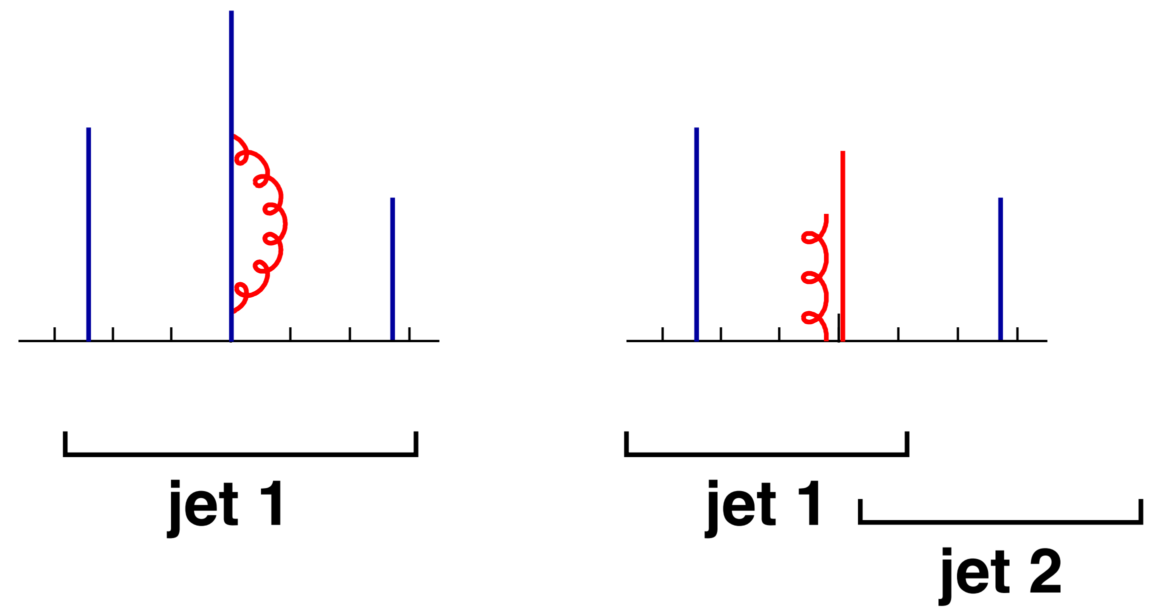
Collinear Safe



α_s^n x $(-\infty)$ $\qquad$ α_s^n x $(+\infty)$

Infinities cancel

Collinear Unsafe



α_s^n x $(-\infty)$ $\qquad$ α_s^n x $(+\infty)$

Infinities do not cancel

Invalidates perturbation theory

hadron-collider k_t algorithm

Two parameters, *R* and $p_{t,min}$

(These are the two parameters in essentially every widely used hadron-collider jet algorithm)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = p_{ti}^2, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Sequential recombination algorithm

1. Find smallest of d_{ij}, d_{iB}
2. If *ij*, recombine them
3. If *iB*, call i a jet and remove from list of particles
4. repeat from step 1 until no particles left

   Only use jets with $p_t > p_{t,min}$

Inclusive k_t algorithm

S.D. Ellis & Soper, 1993

Catani, Dokshitzer, Seymour & Webber, 1993

hadron-collider k_t algorithm

Two parameters, *R* and *$p_{t,min}$*
(These are the two parameters in essentially every widely used hadron-collider jet algorithm)

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Sequential recombination algorithm

1. Find smallest of d_{ij}, d_{iB}
2. If ij, recombine them
3. **If *iB*, call *i* a jet and remove from list of particles**

If a particle i has no neighbours j within a distance $\Delta R_{ij} \leq R$, then $d_{iB} <$ all d_{ij}, and i becomes a jet.

k_t in action

$\mathbf{k_t}$ alg.: Find smallest of

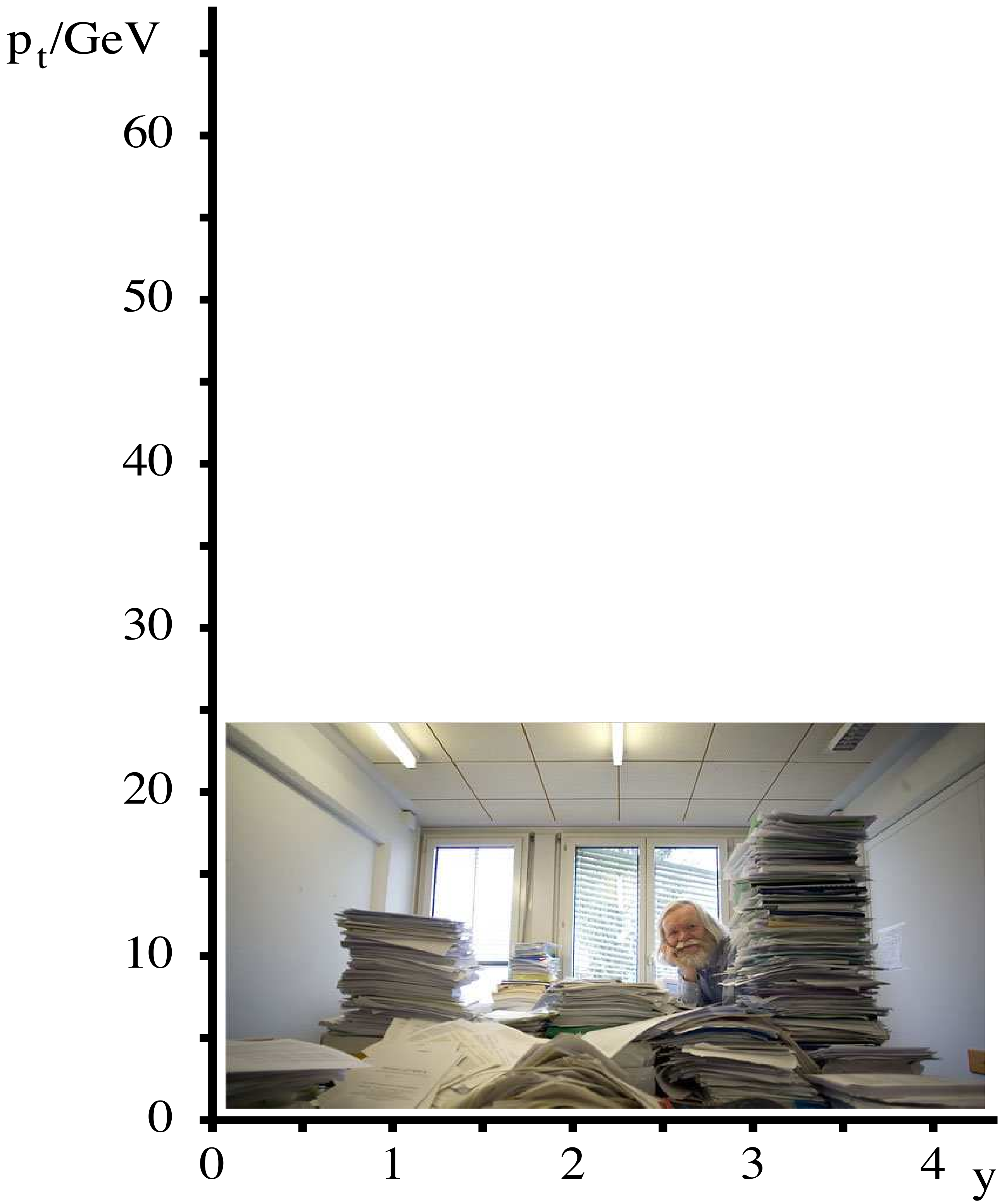
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = k_{ti}^2$$

- If d_{ij} recombine
- if d_{iB}, i is a jet

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

k_t in action



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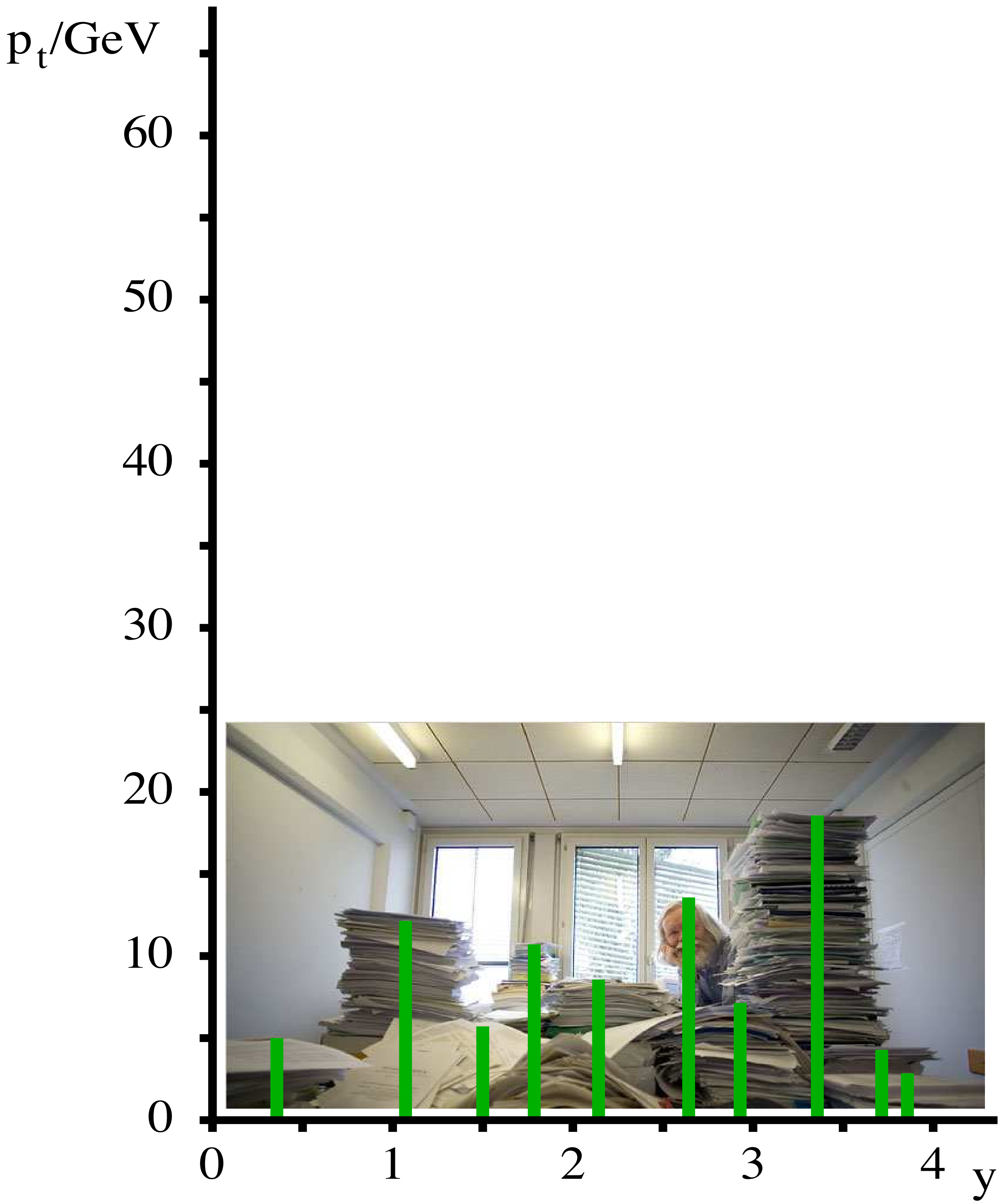

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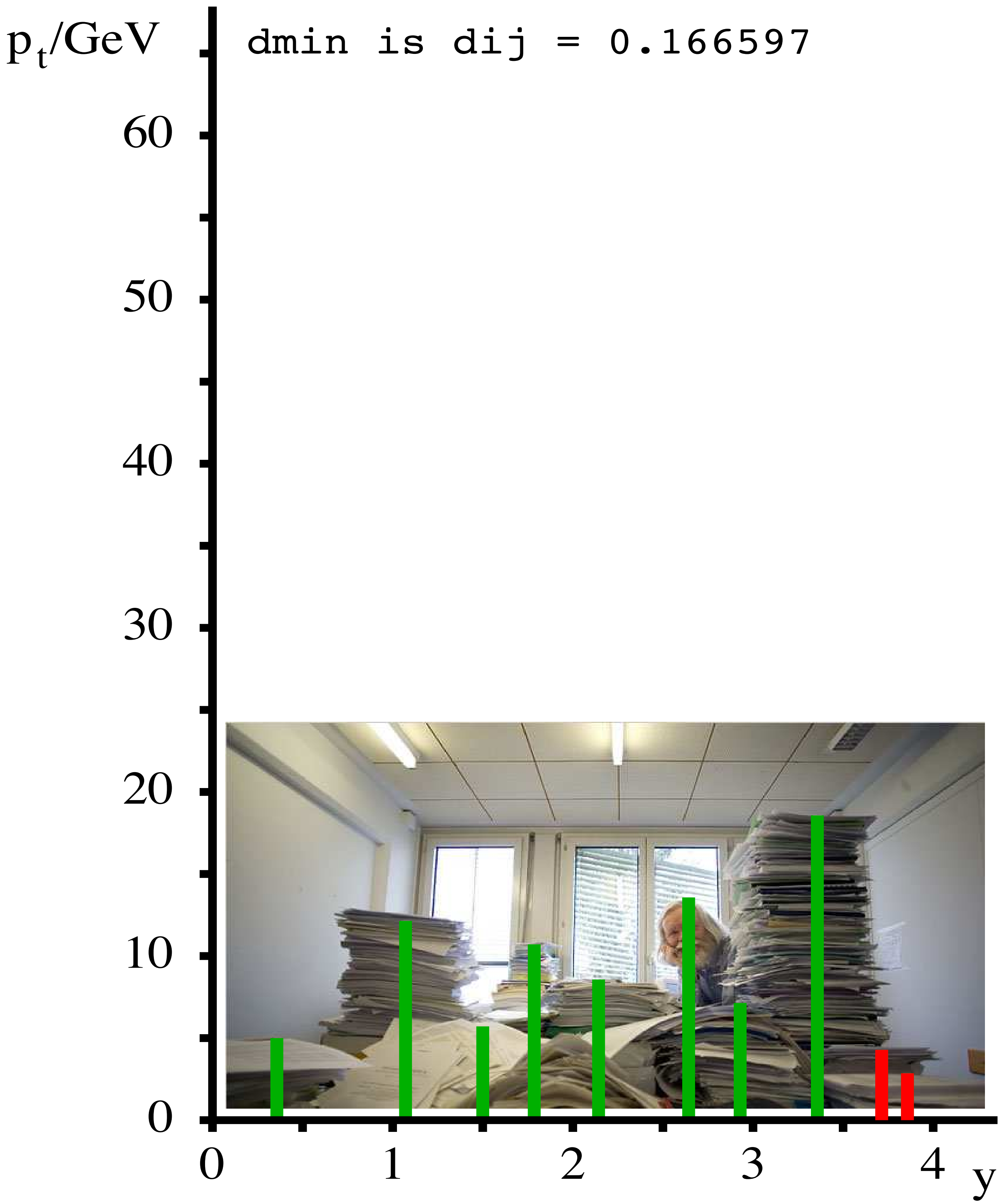

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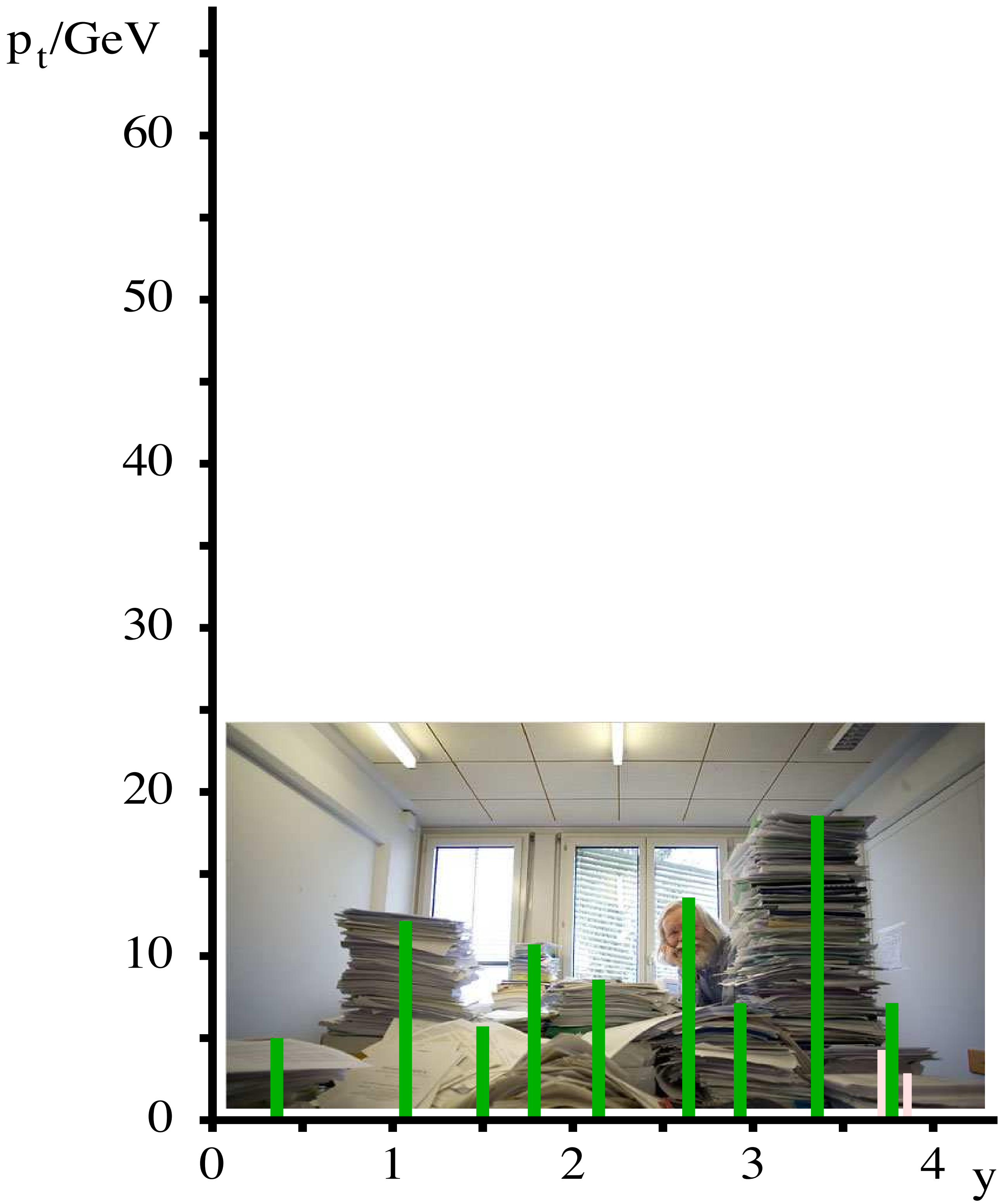

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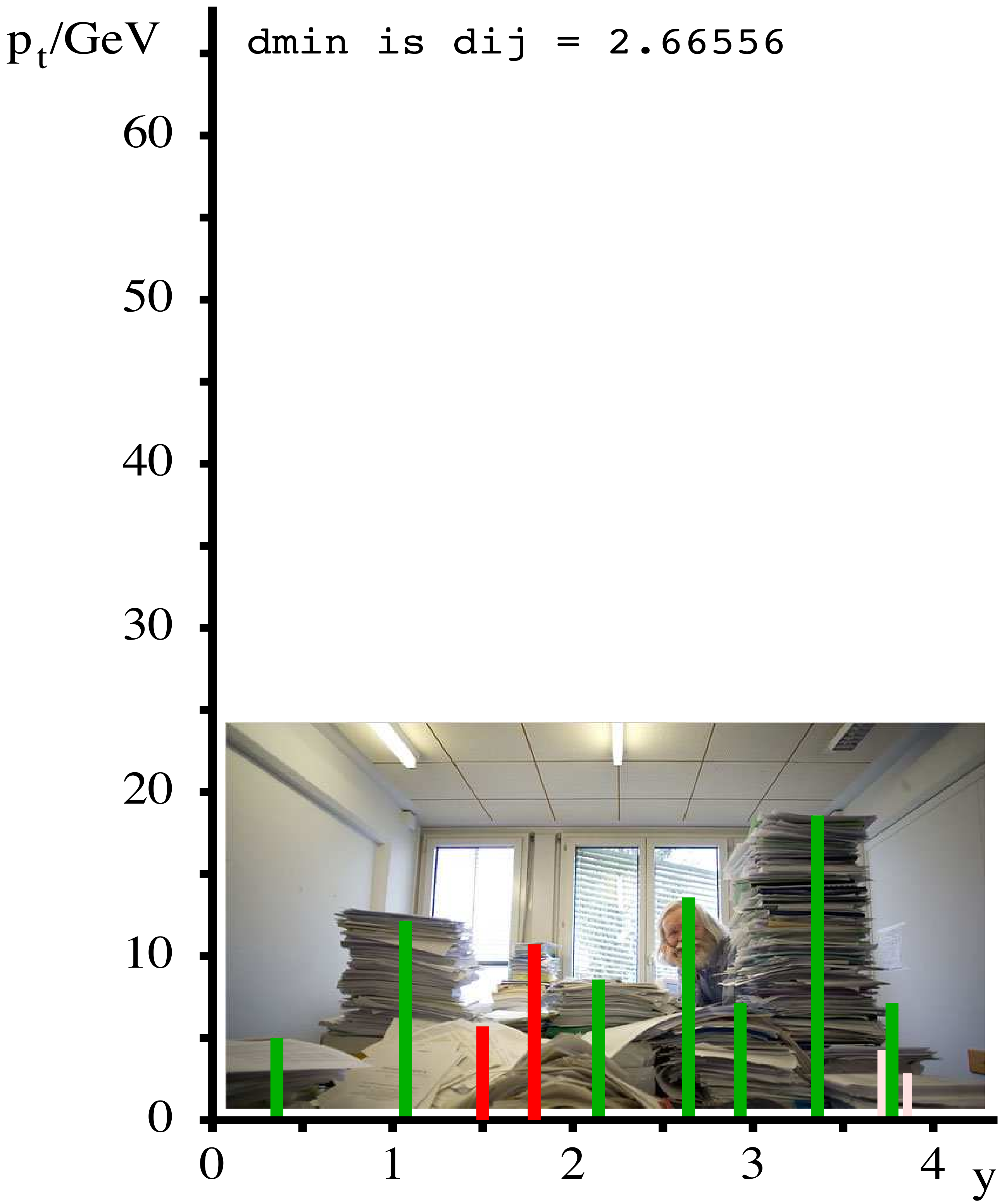

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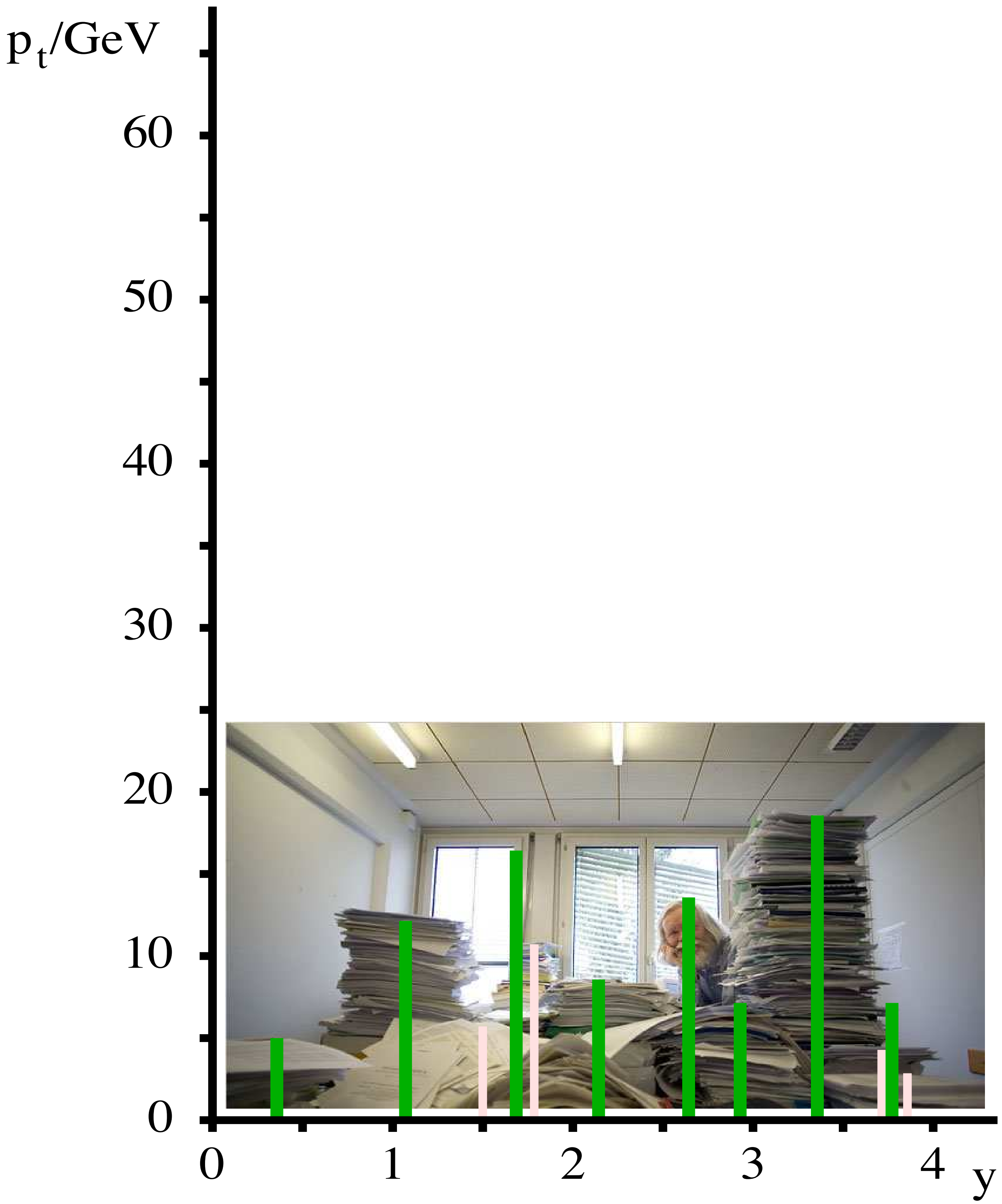

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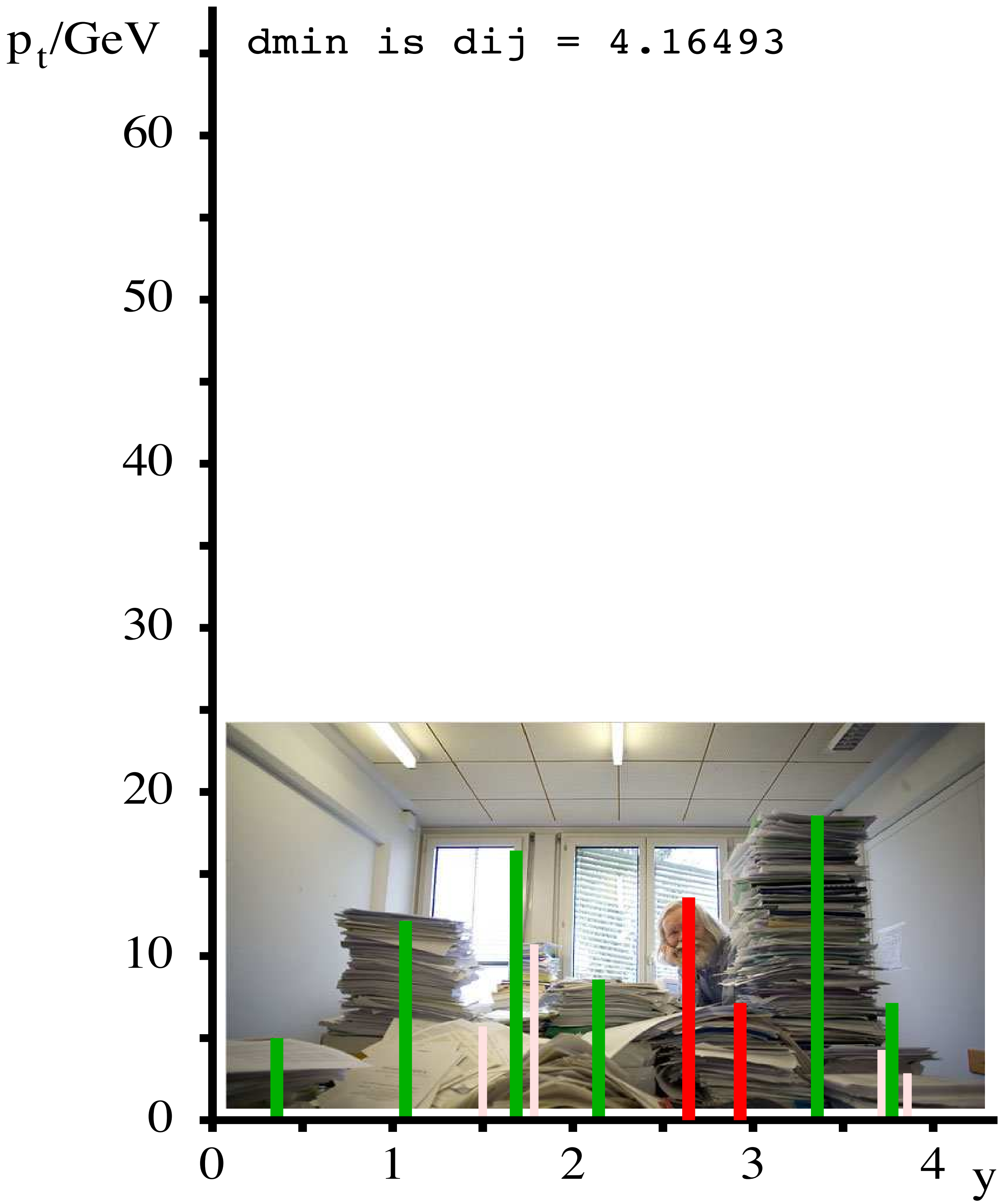
ϕ assumed 0 for all towers

k_t in action



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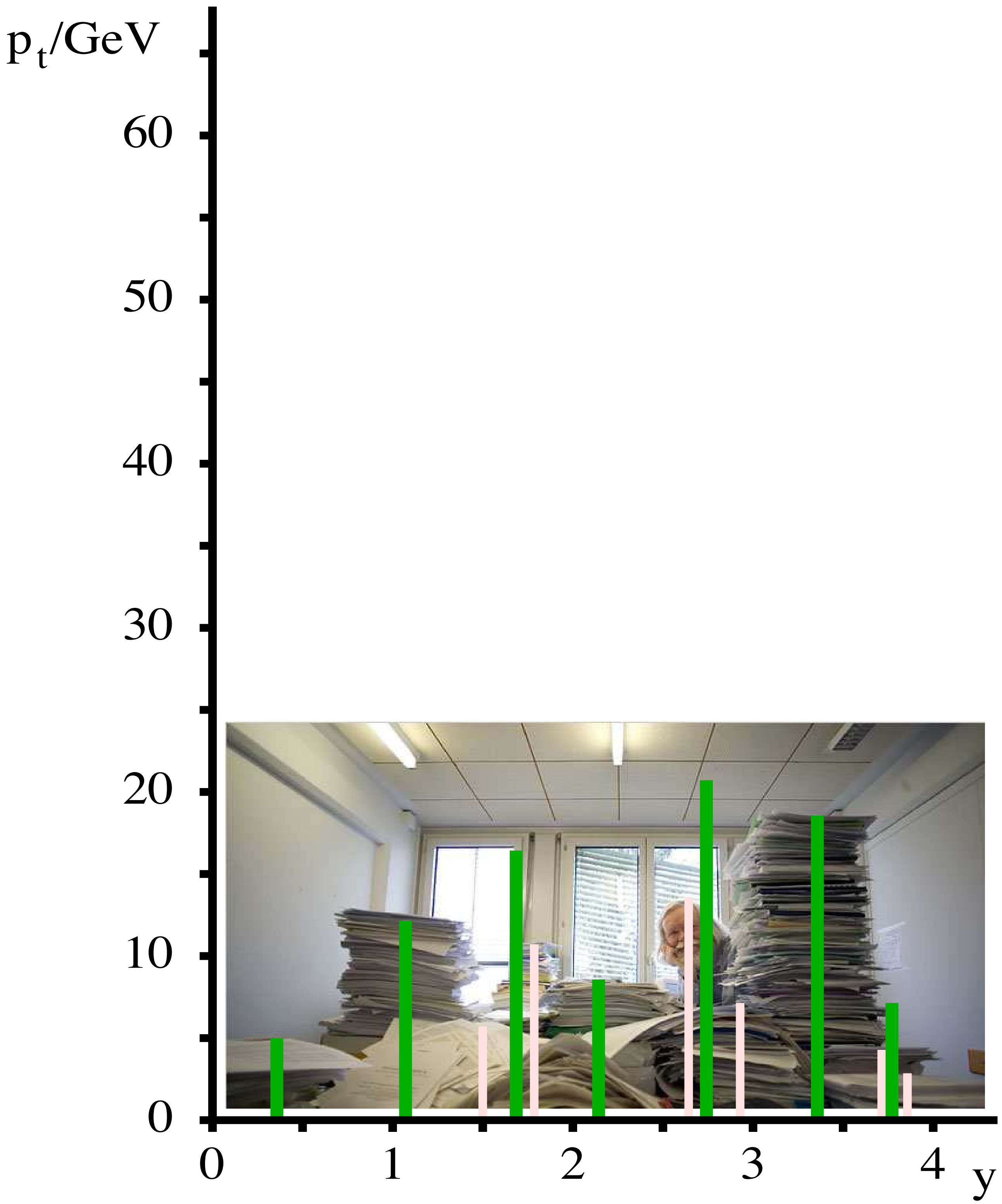
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

k_t in action



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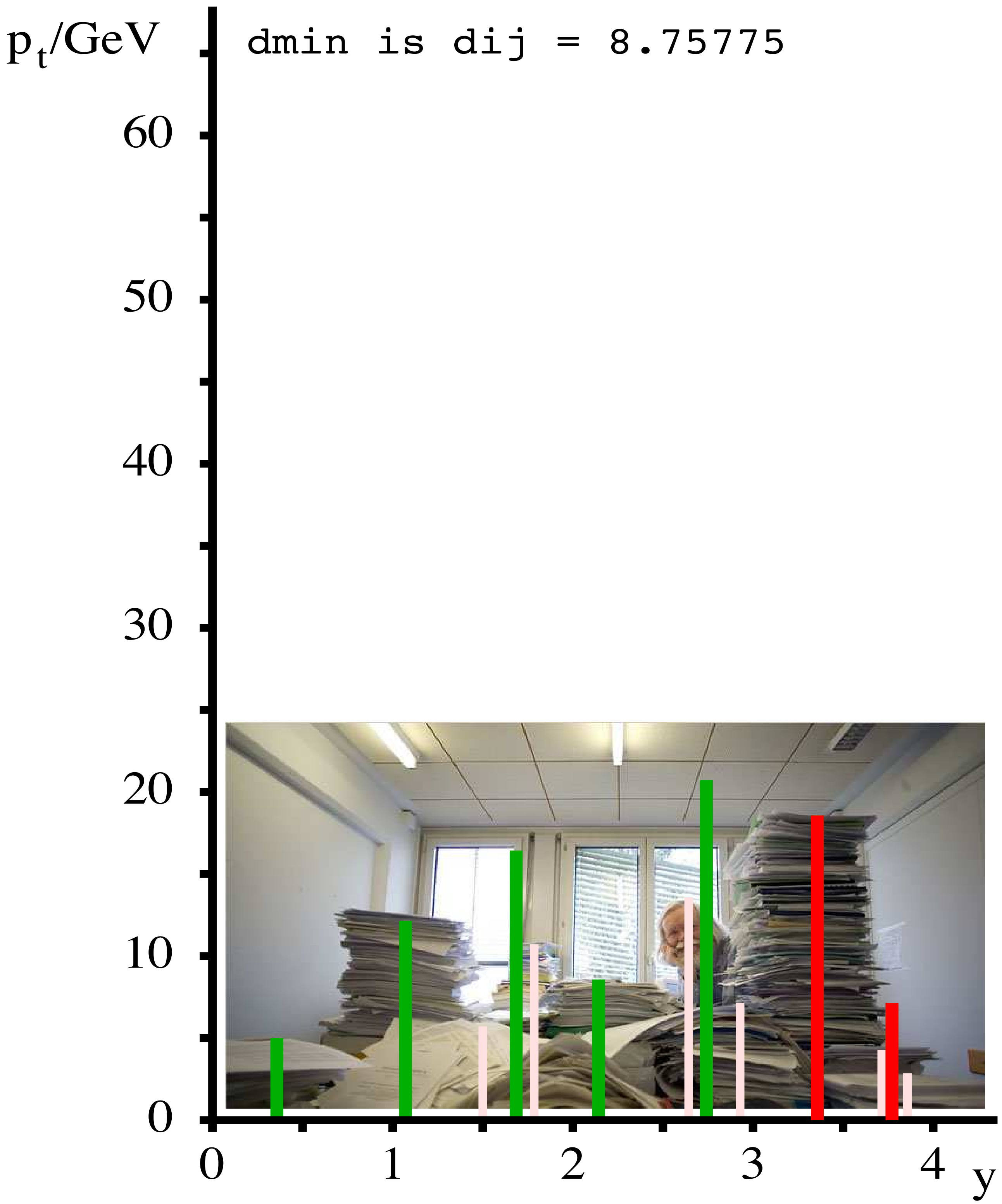

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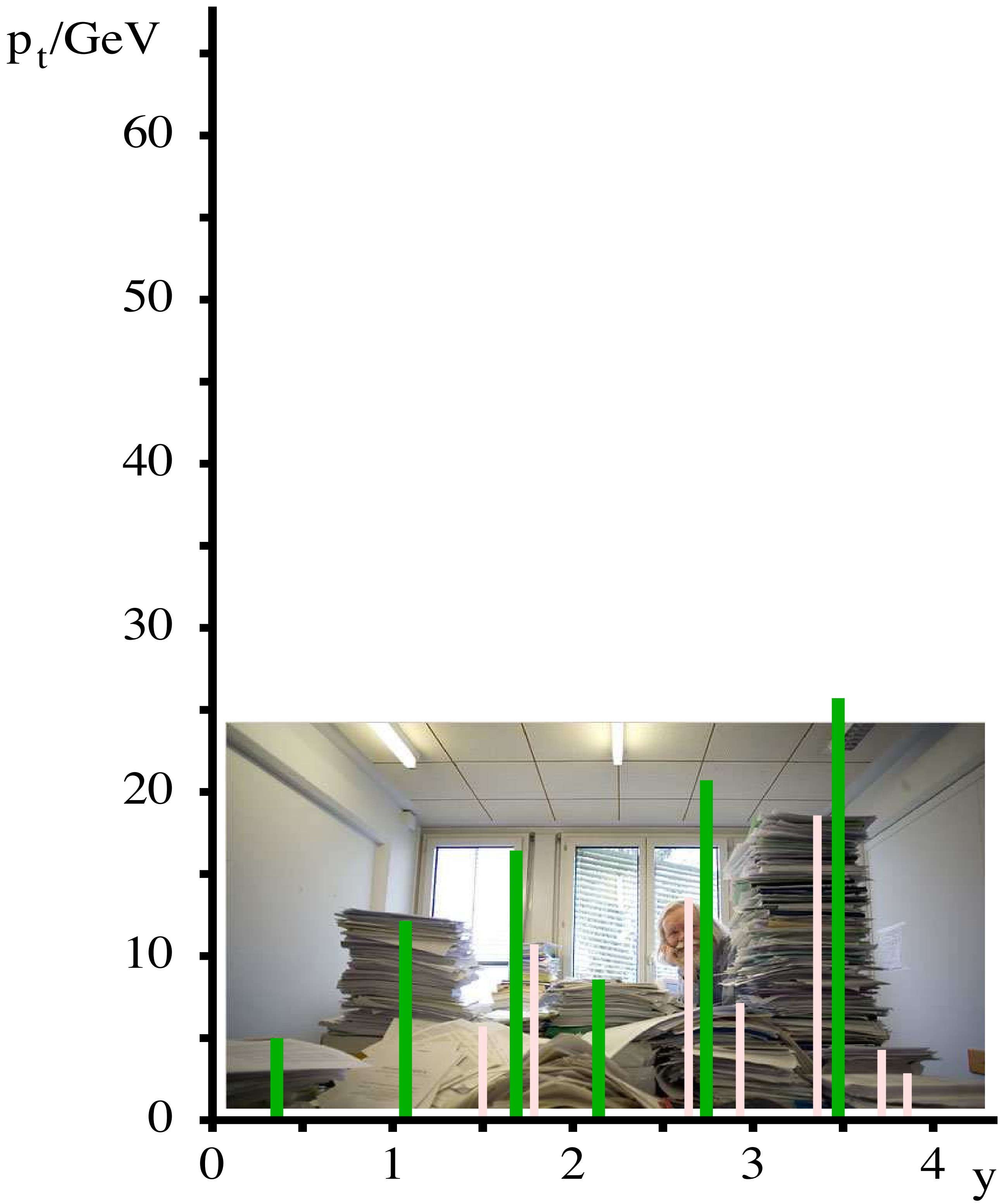

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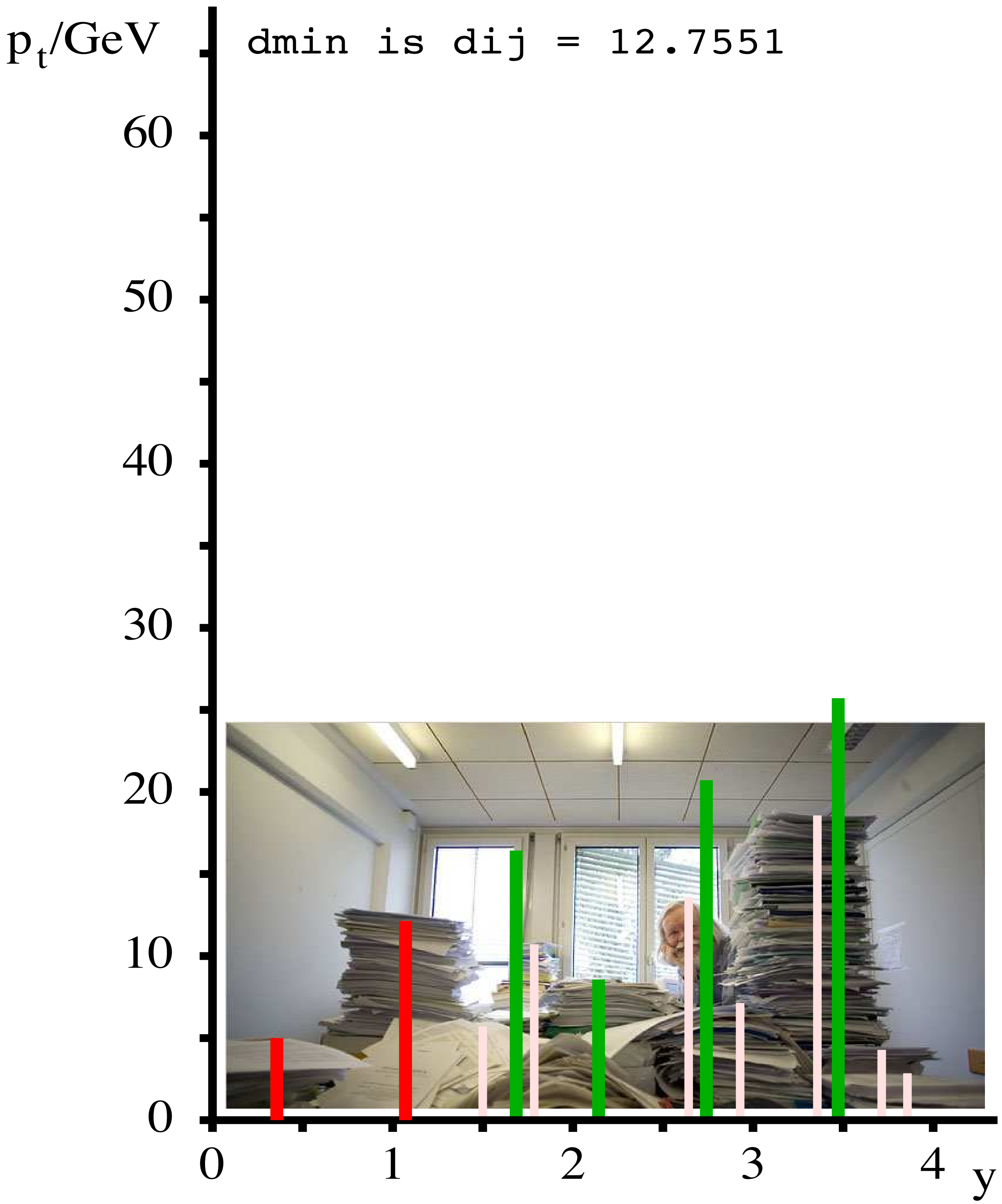

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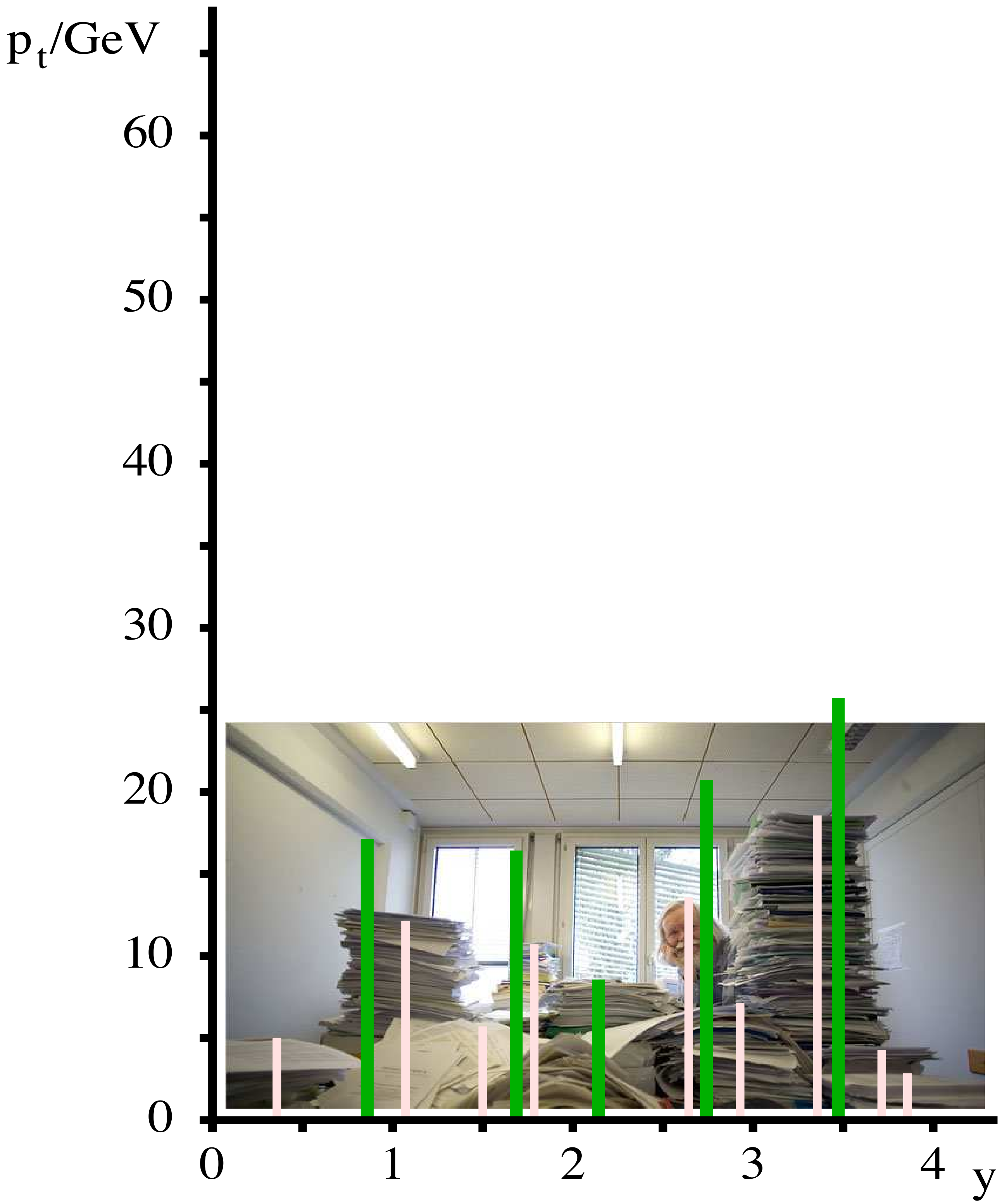

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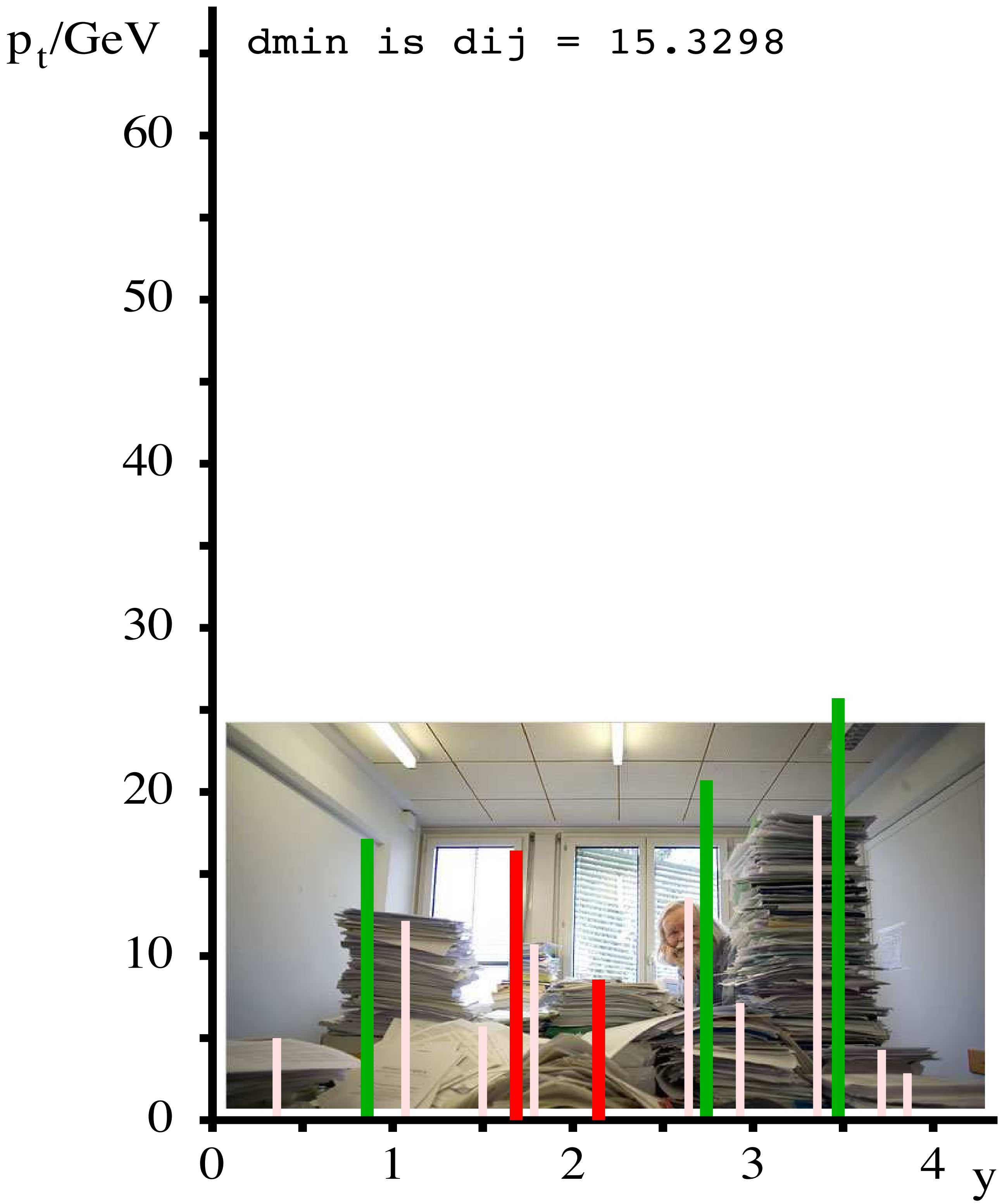

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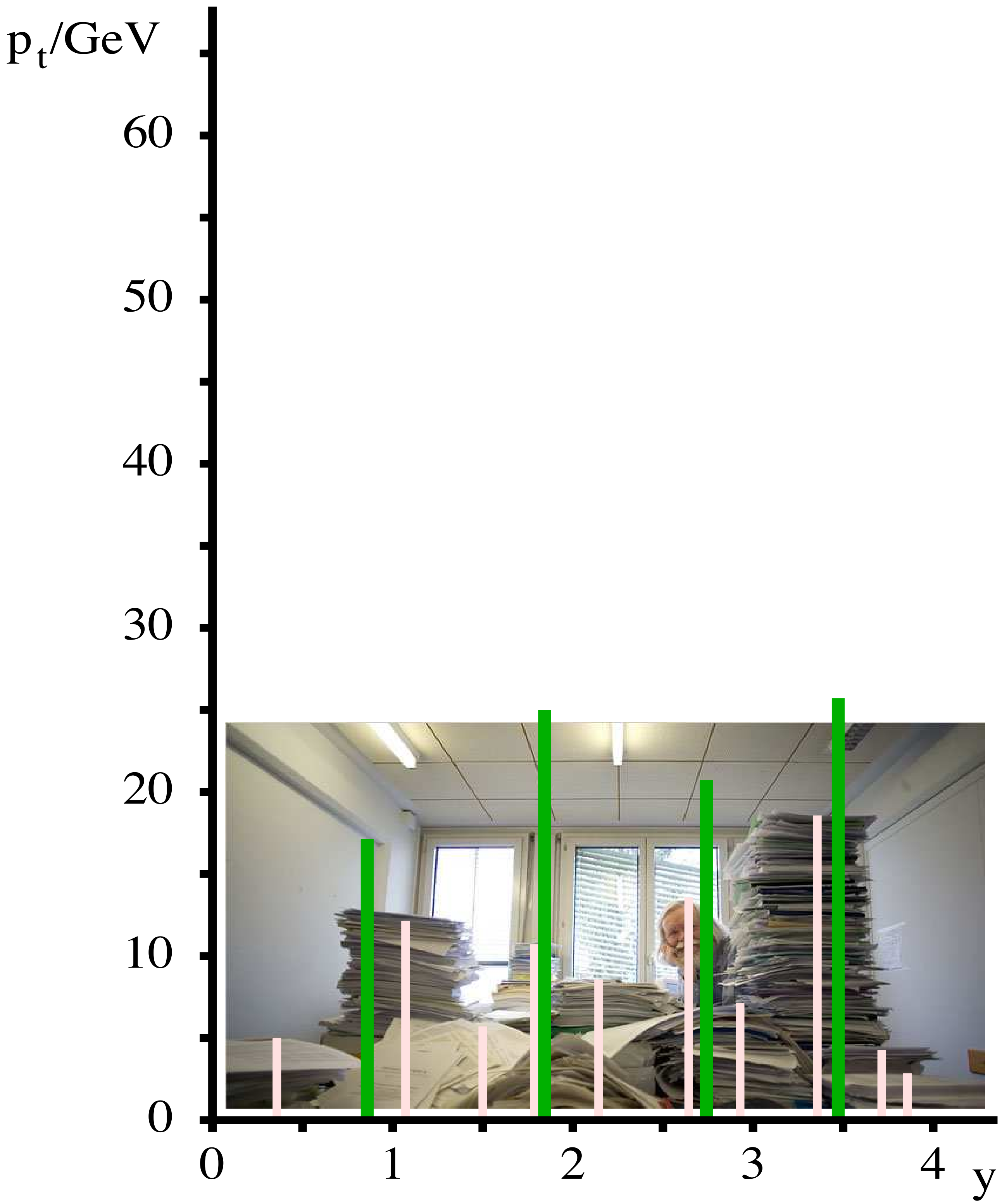

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ϕ assumed 0 for all towers

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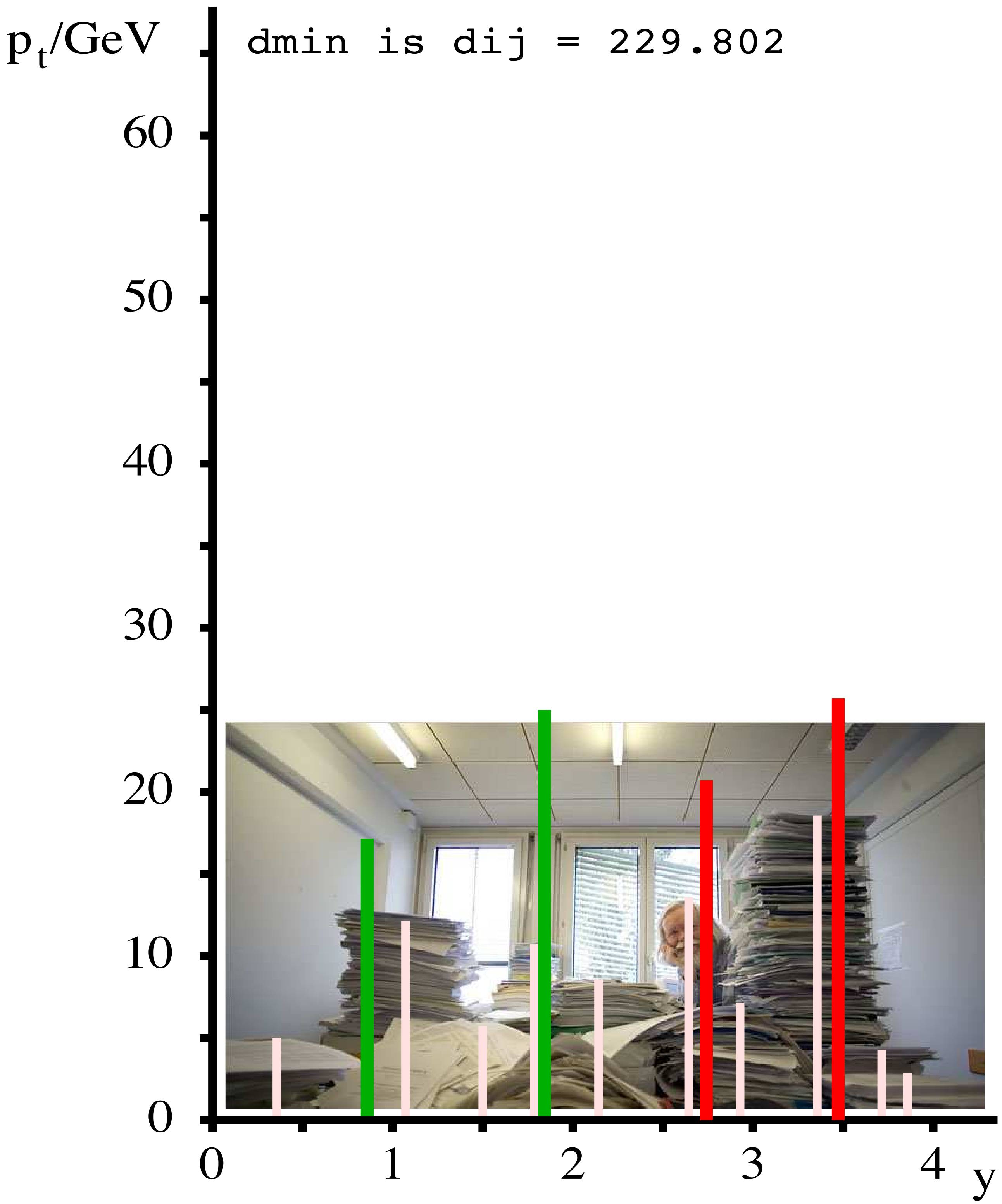

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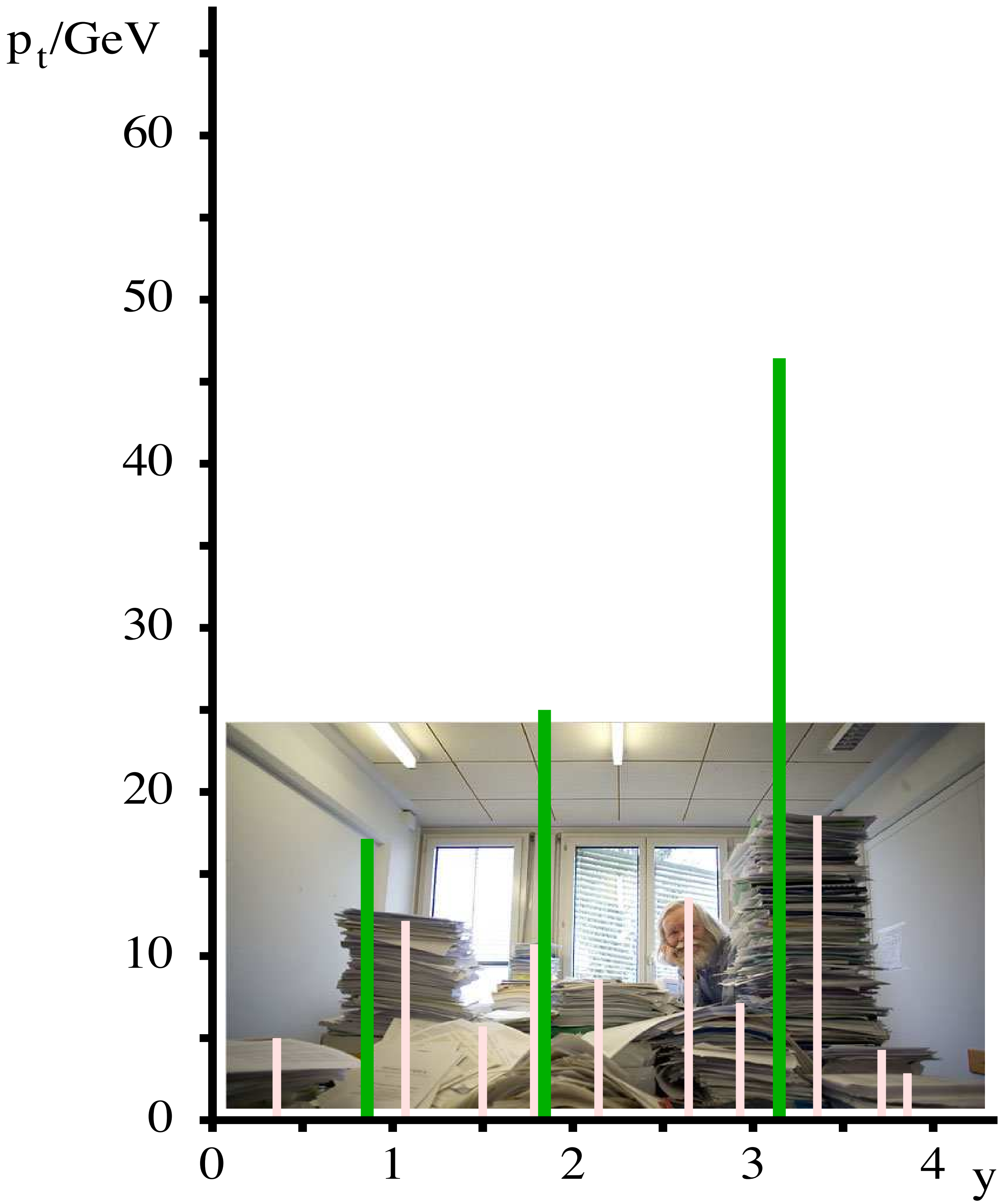

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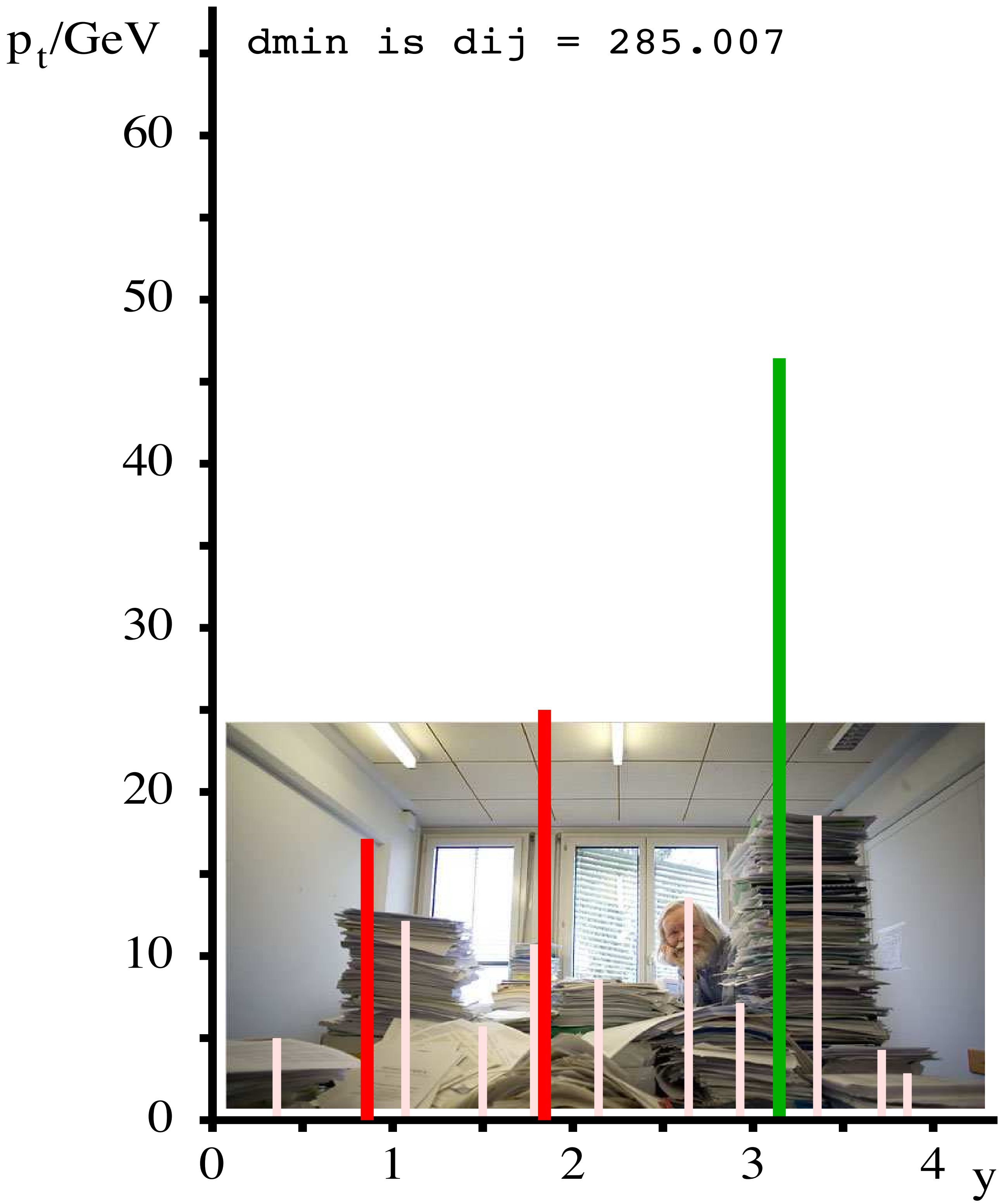


$\mathbf{k_t}$ alg.: Find smallest of

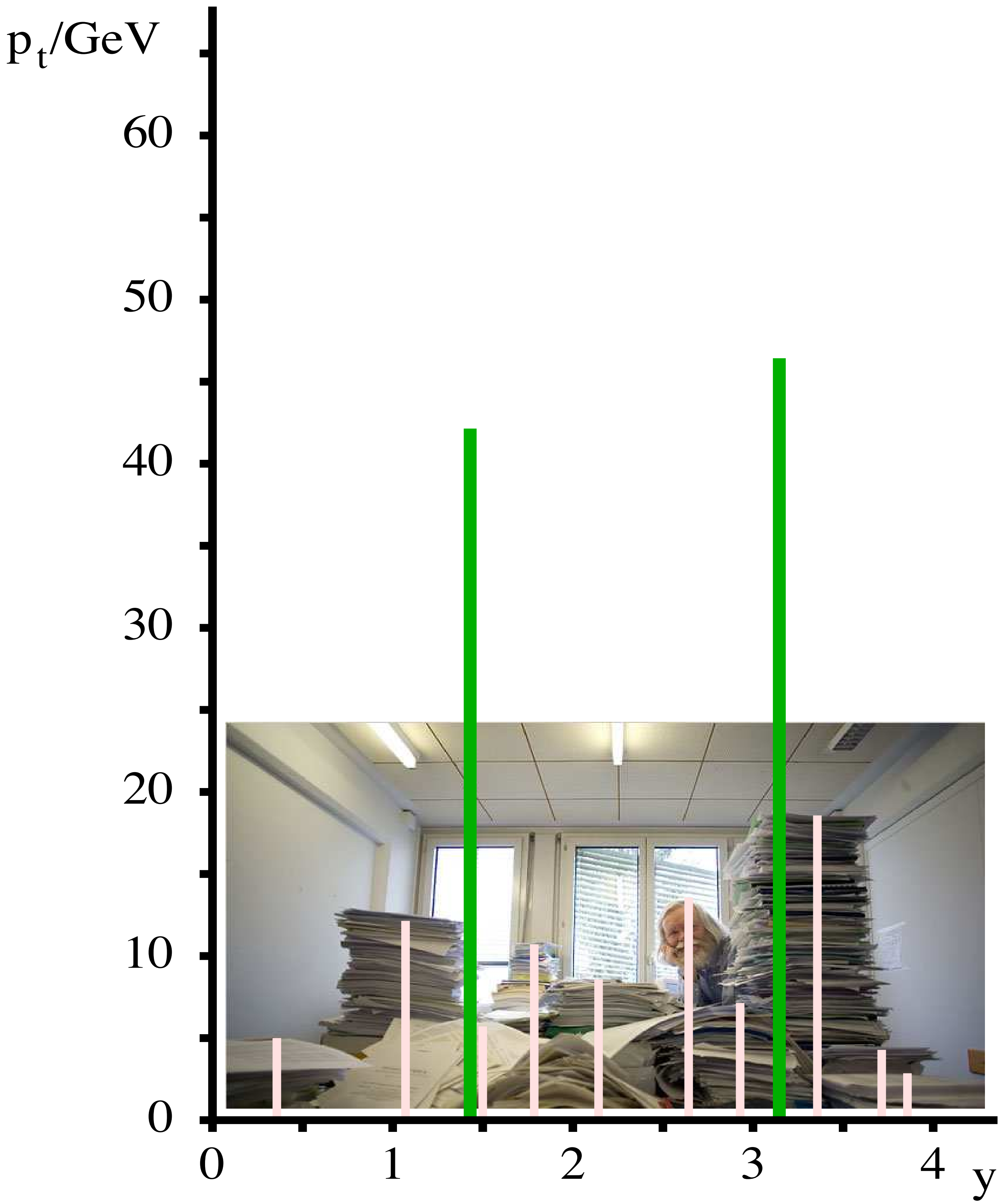
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = k_{ti}^2$$

- If d_{ij} recombine
- if d_{iB}, i is a jet

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

k_t in action



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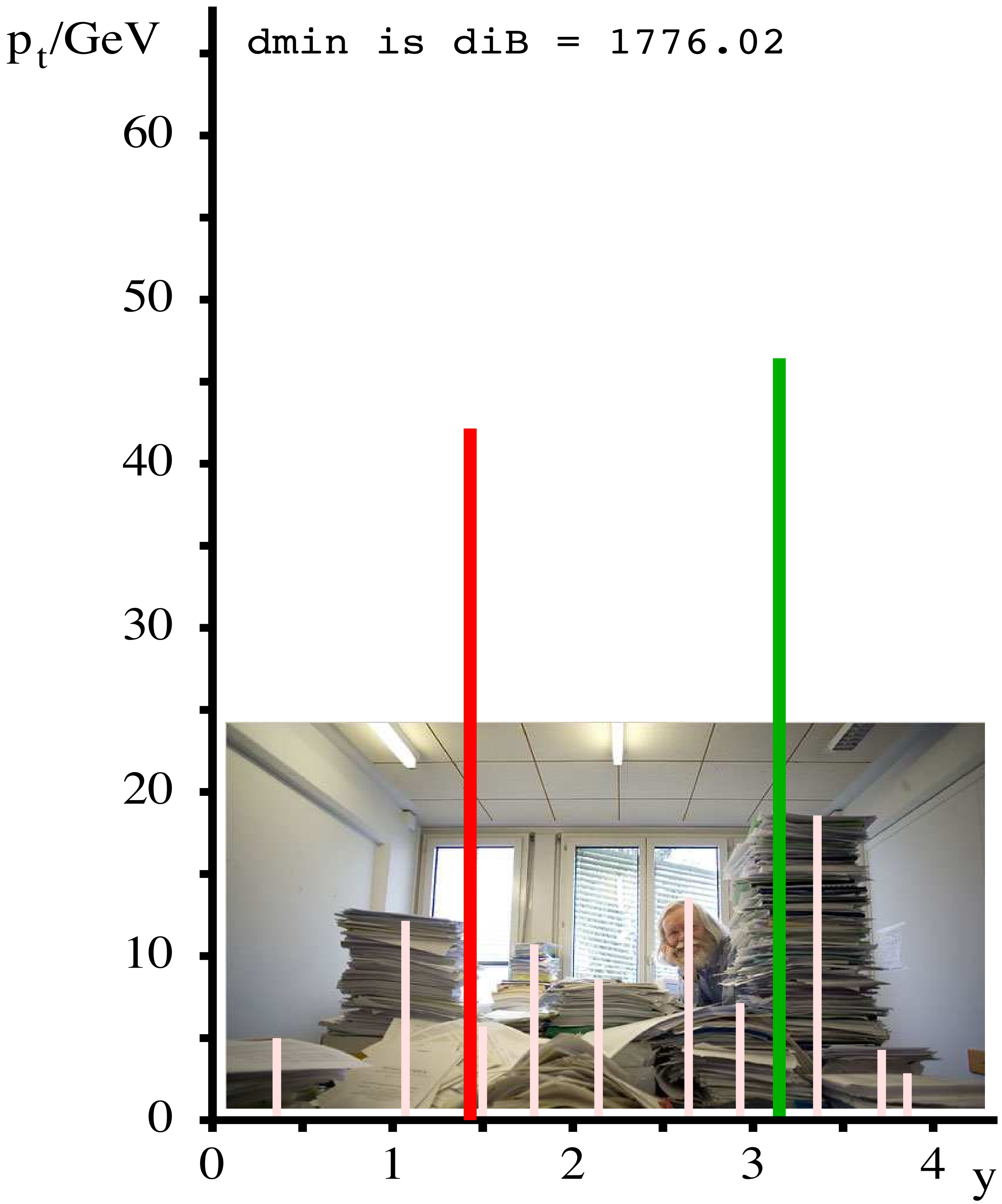

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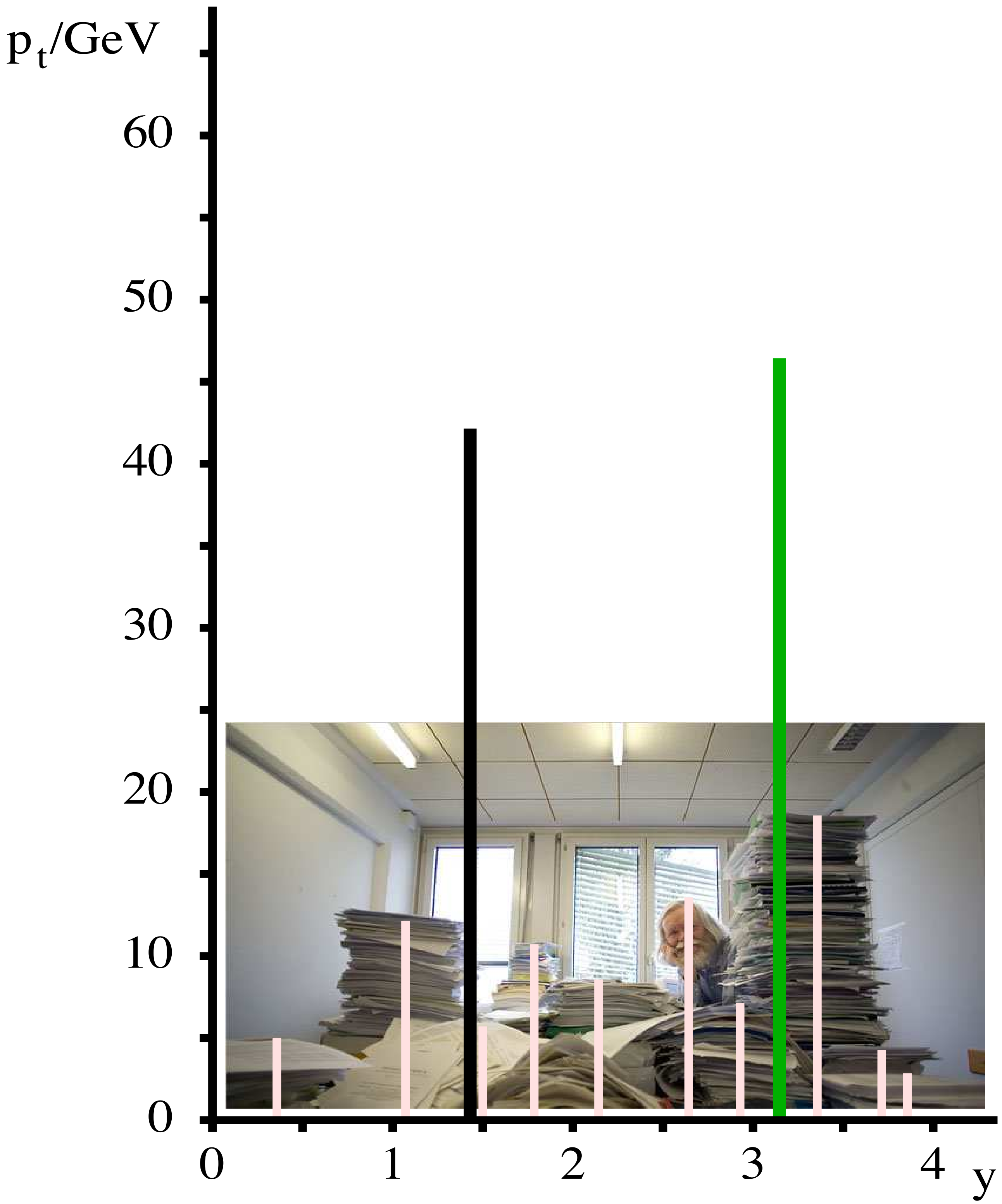

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Example clustering with k_t algorithm, $R = 1.0$

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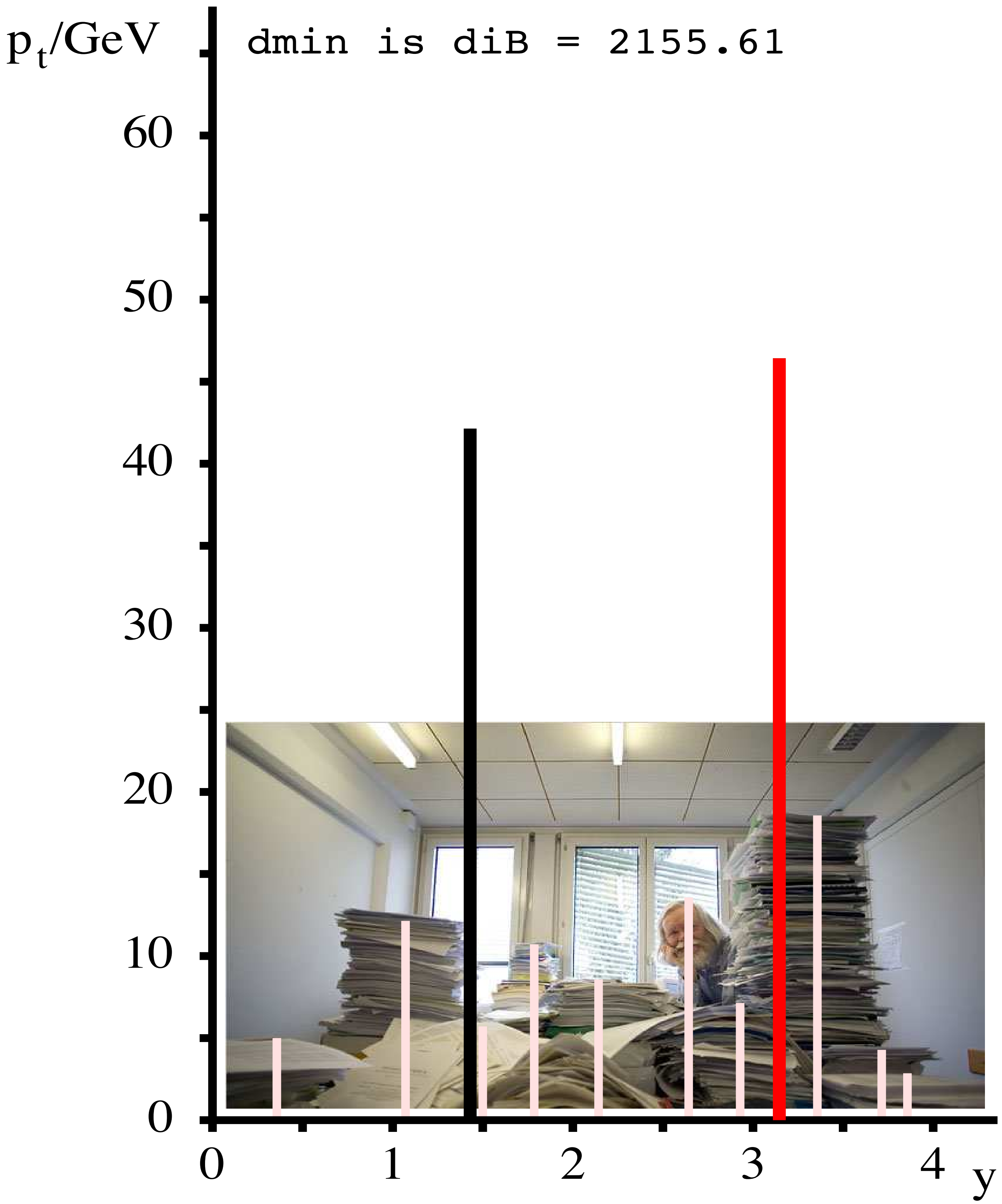

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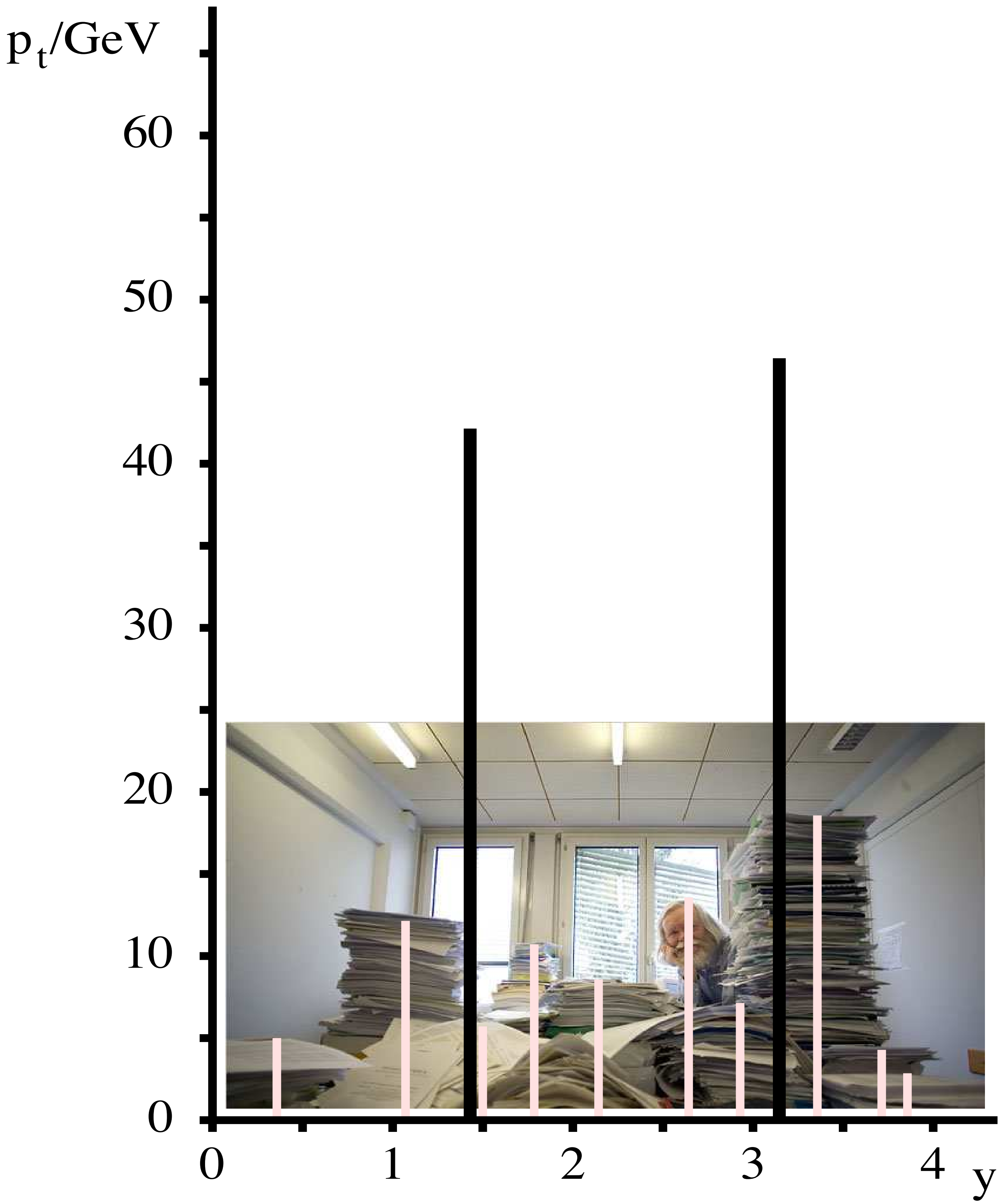

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- If d_{ij} recombine
- if d_{iB}, i is a jet

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination variants

Cambridge/Aachen: the simplest of hadron-collider algorithms

- Recombine pair of objects closest in ΔR_{ij}
- Repeat until all $\Delta R_{ij} > R$ — remaining objects are jets

Dokshitzer, Leder, Moretti, Webber '97 (Cambridge): more involved e+e− form
Wobisch & Wengler '99 (Aachen): simple inclusive hadron-collider form
One still applies a $p_{t,min}$ cut to the jets, as for inclusive k_t

C/A privileges the collinear divergence of QCD;
it 'ignores' the soft one

Anti-k_t: formulated similarly to inclusive k_t, but with

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{p_{ti}^2}$$

Cacciari, GPS & Soyez '08 [+Delsart unpublished]

Anti-k_t privileges the collinear divergence of QCD and disfavours clustering between pairs of soft particles

Most pairwise clusterings involve at least one hard particle

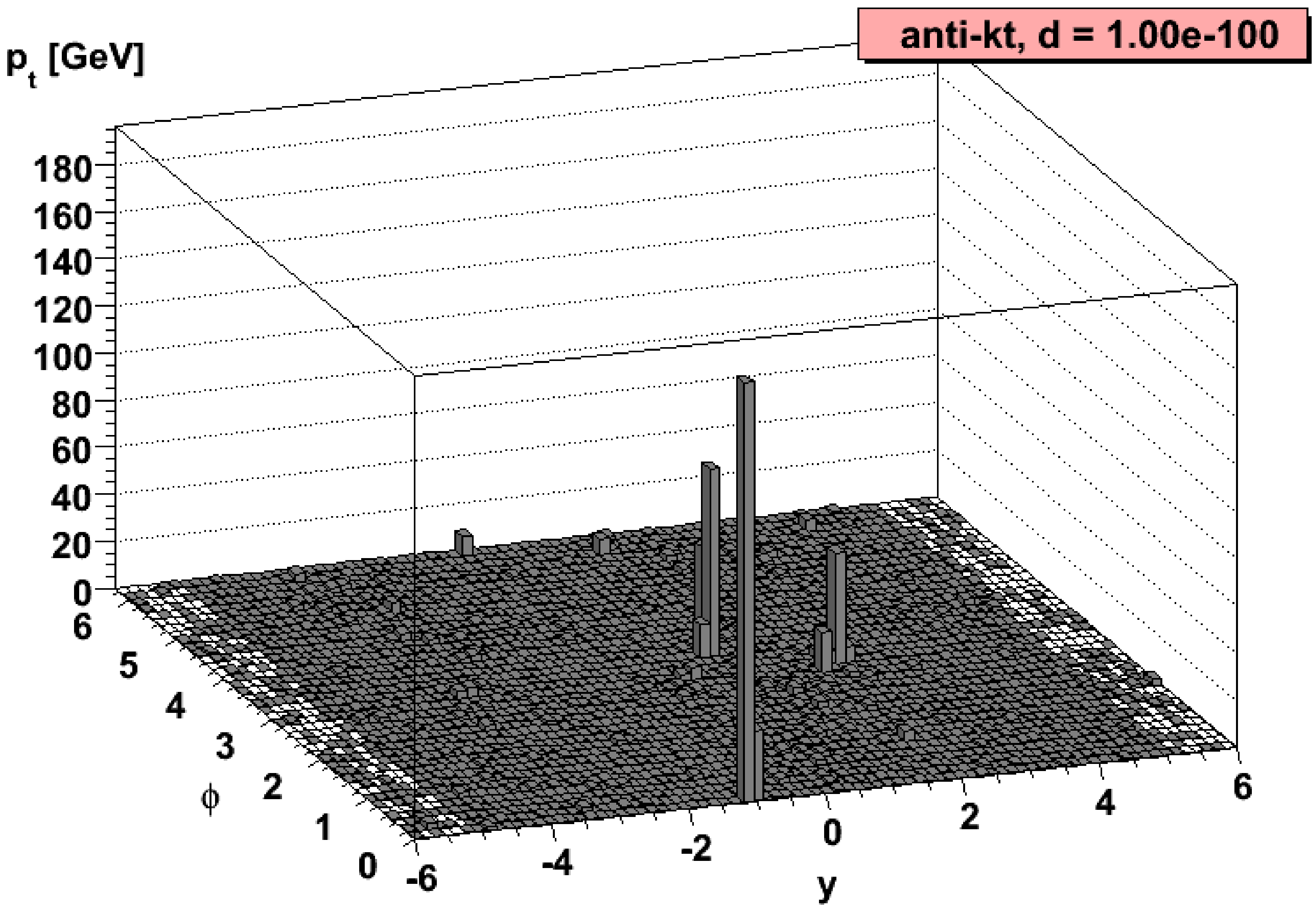
Clustering grows around hard cores

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{p_{ti}^2}$$

Anti-k$_t$ in action

Clustering grows around hard cores

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$$



Anti-k_t in action

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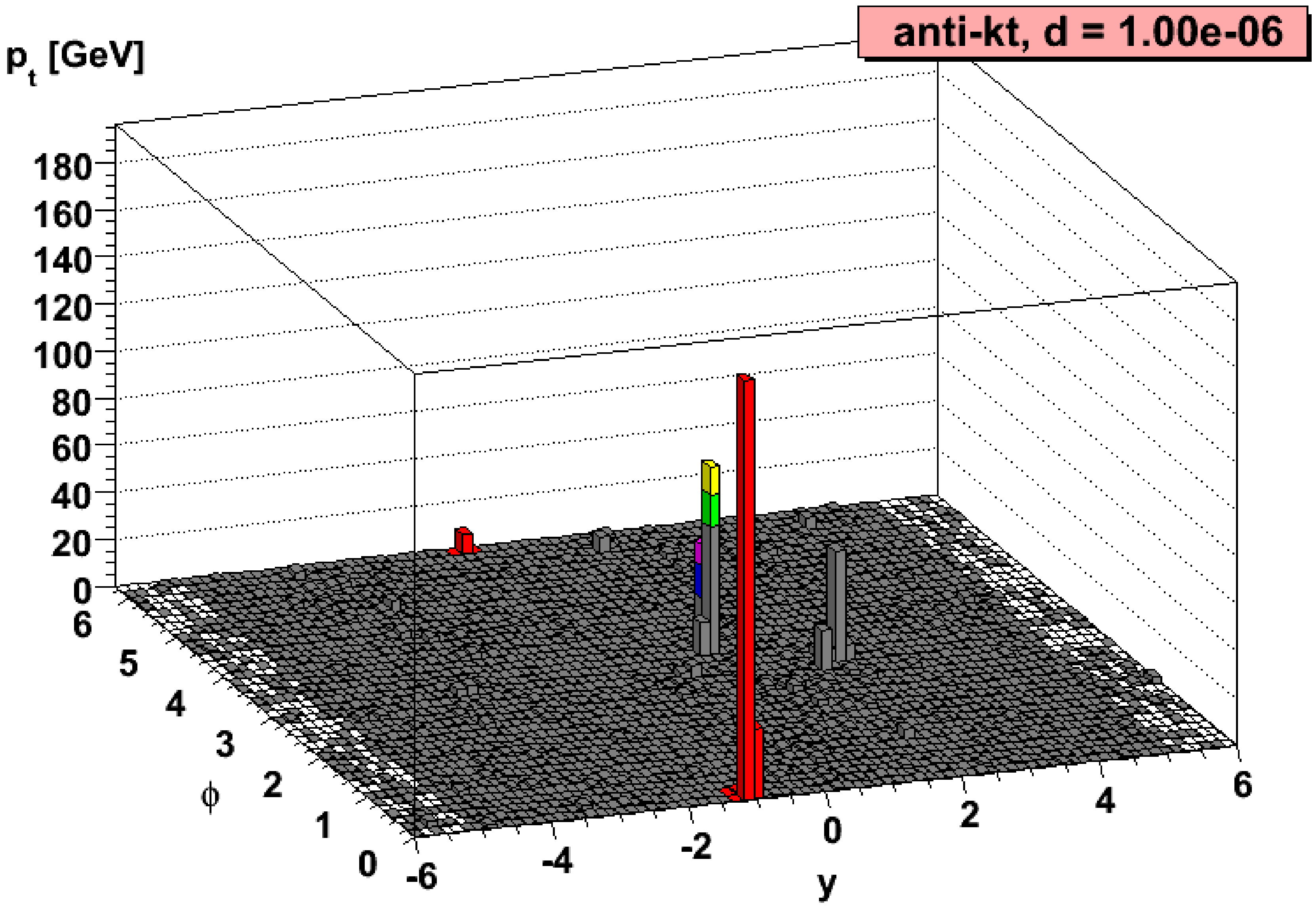

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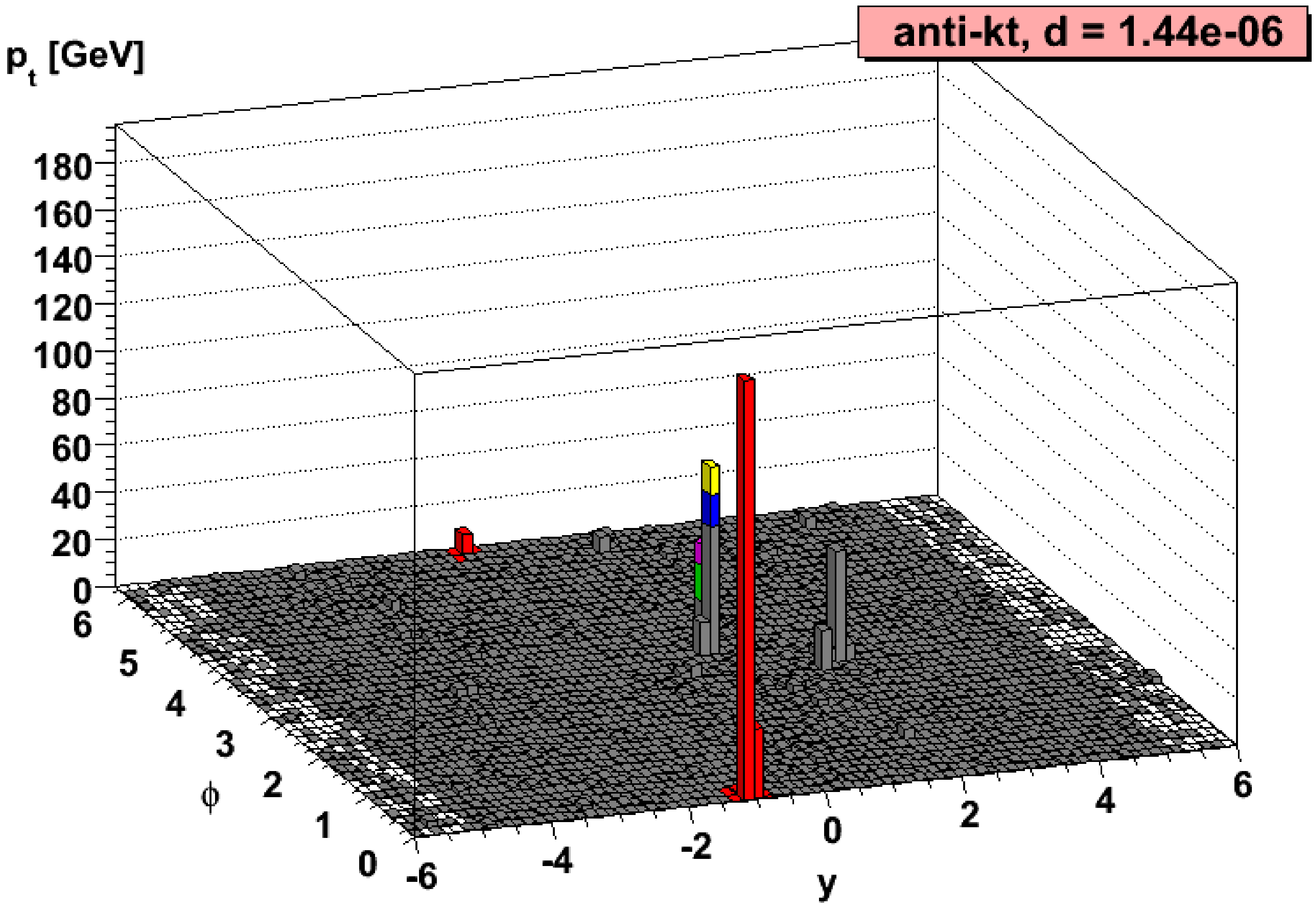

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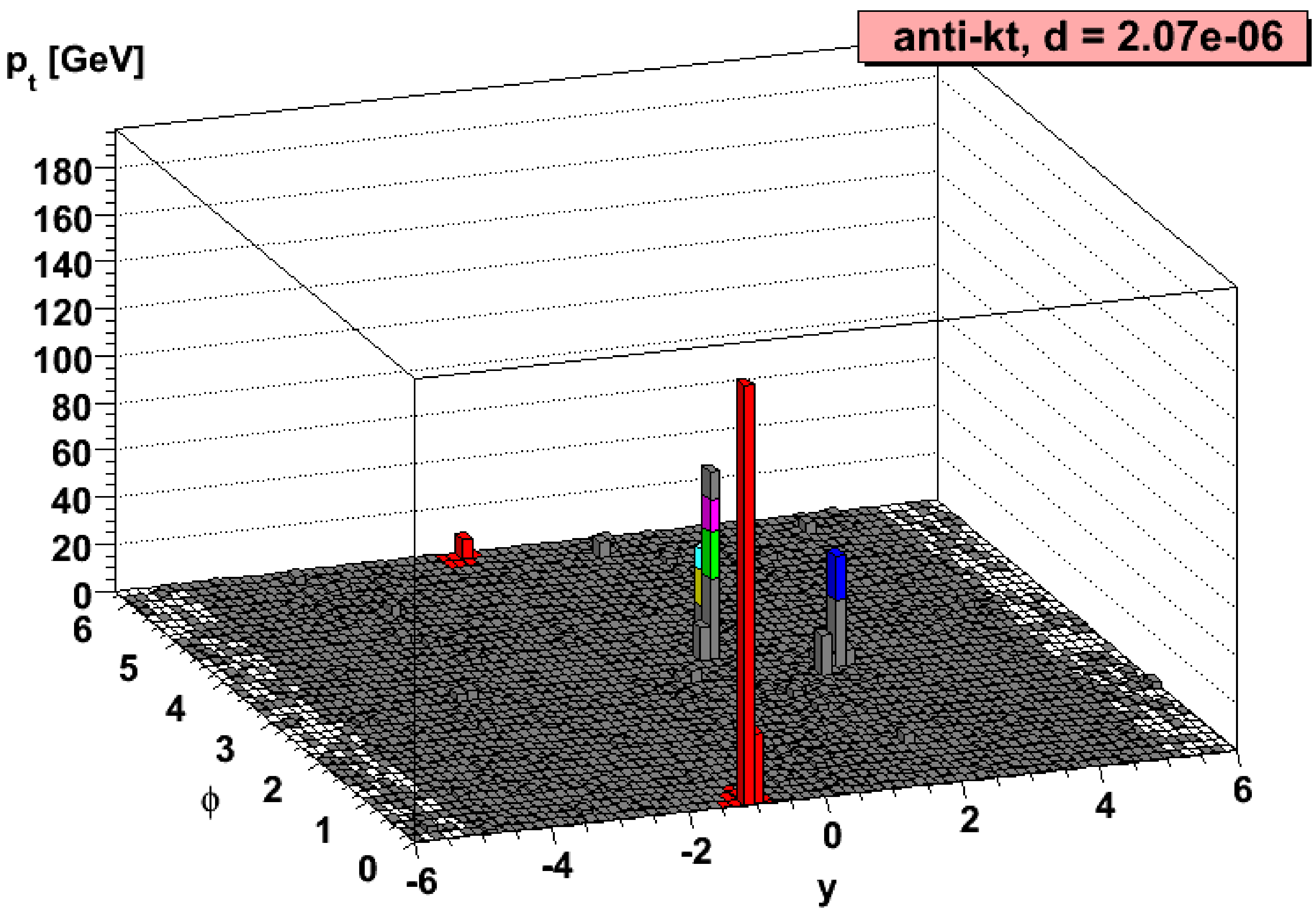

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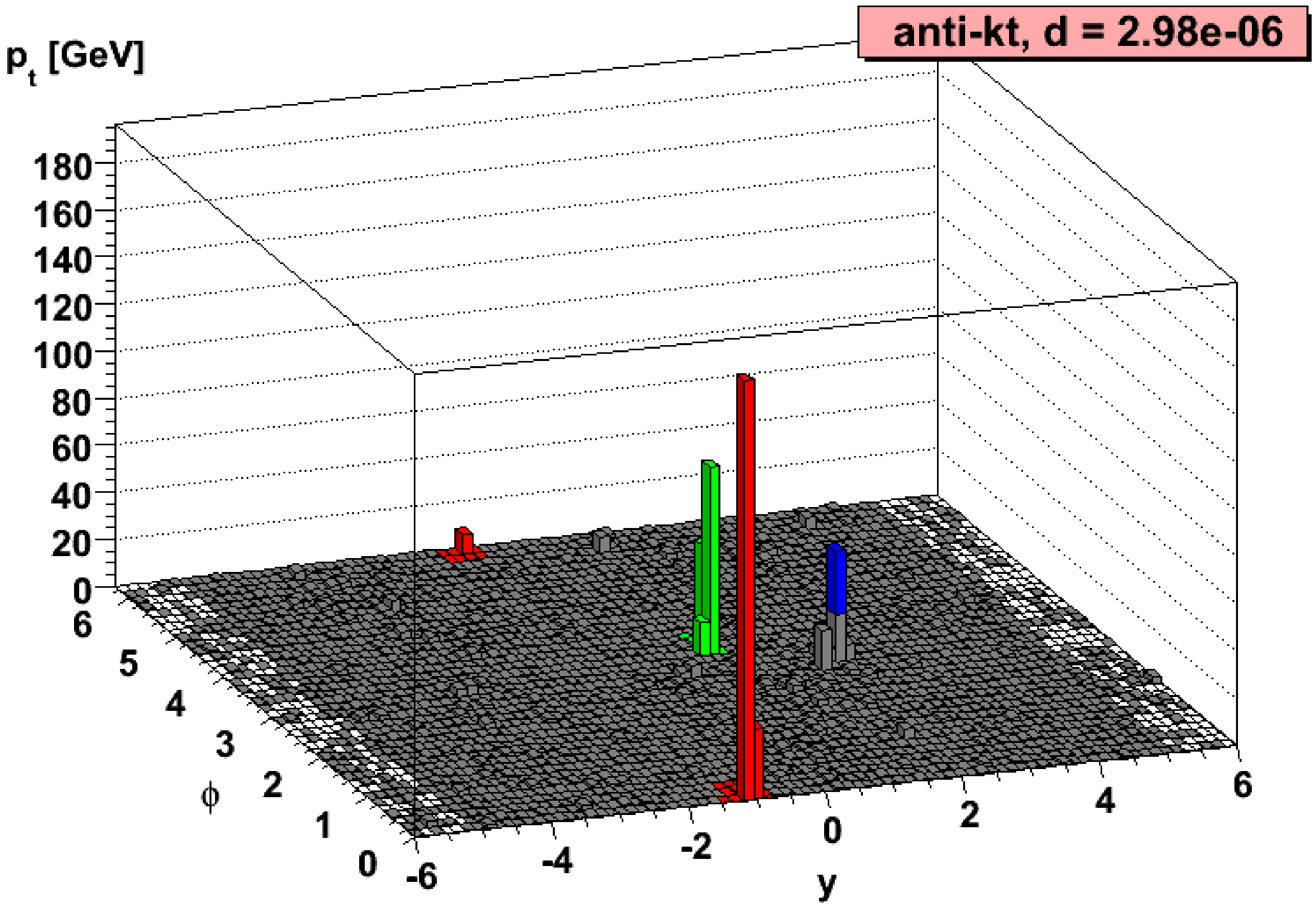

Anti-k_t in action

Clustering grows around hard cores

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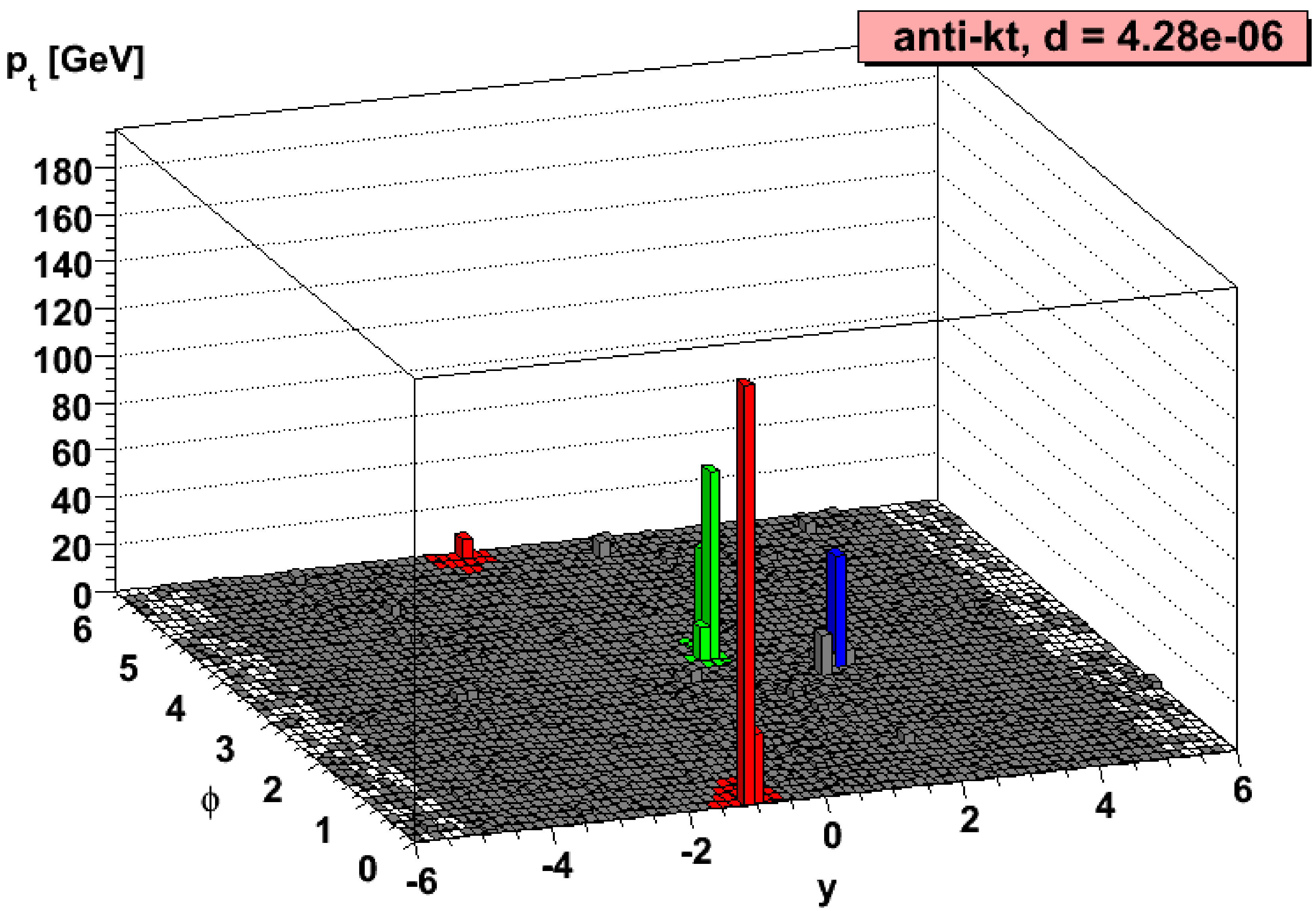

Anti-k_t in action

Clustering grows
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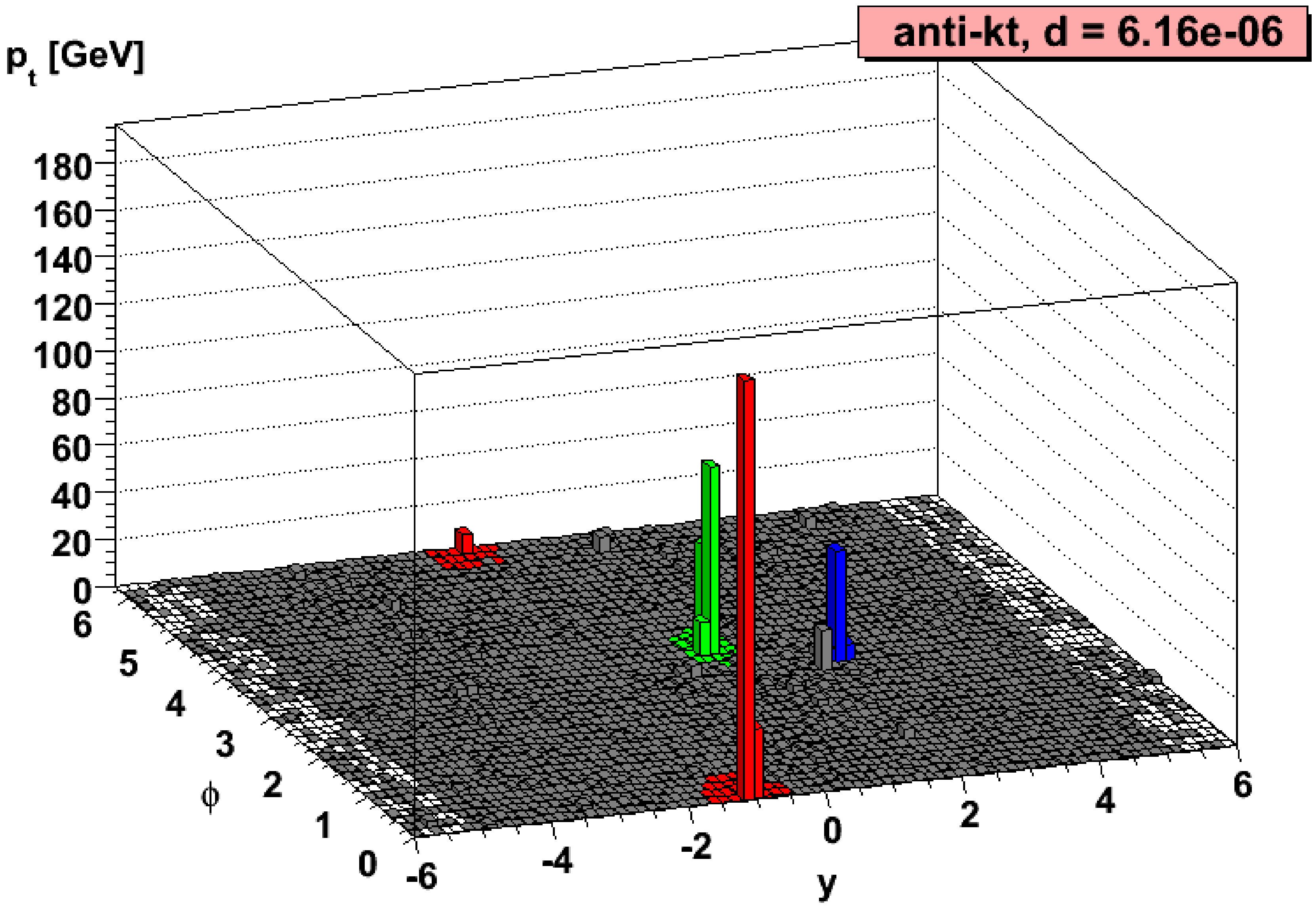
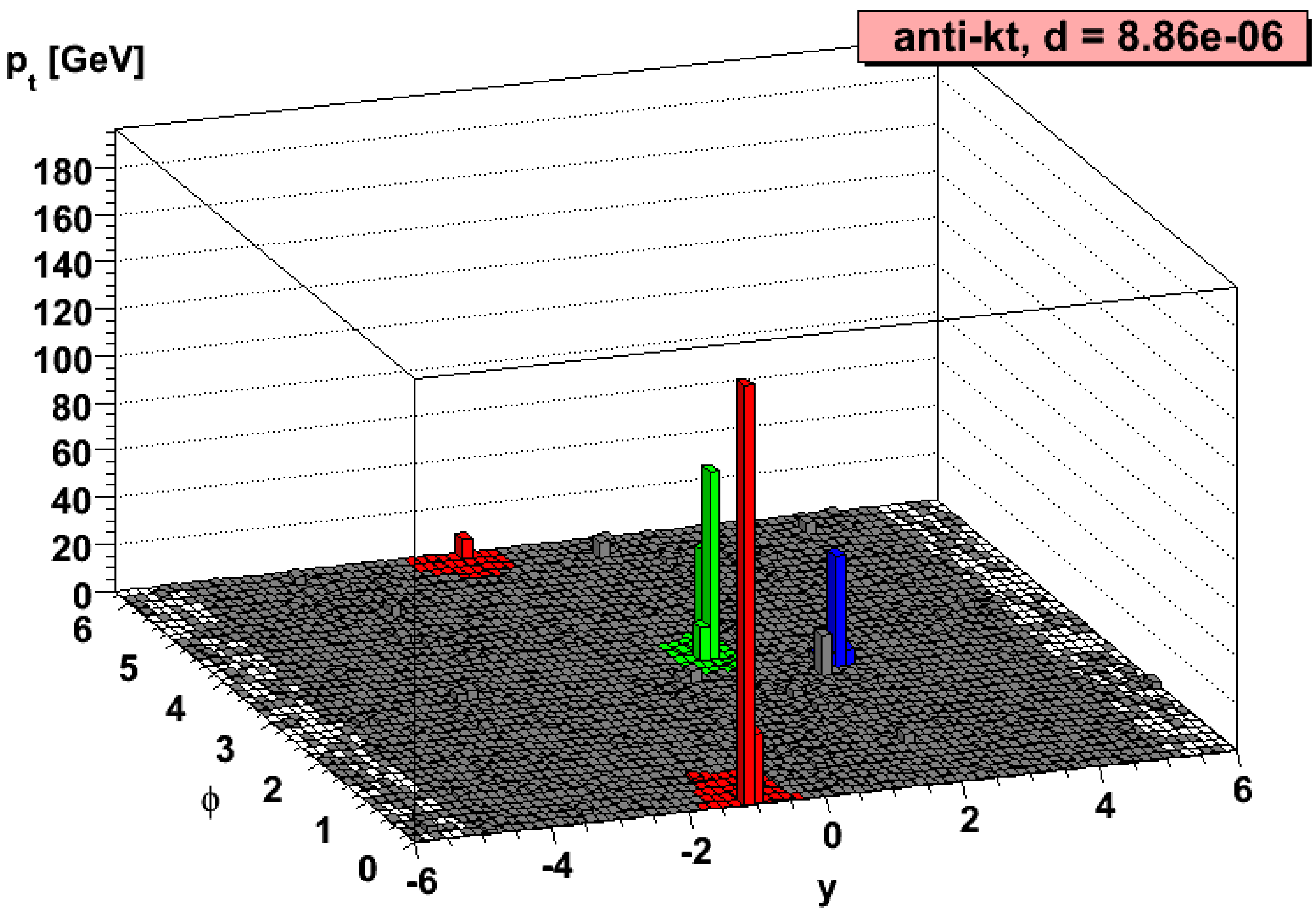


Anti-k$_t$ in action

Clustering grows around hard cores

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$$



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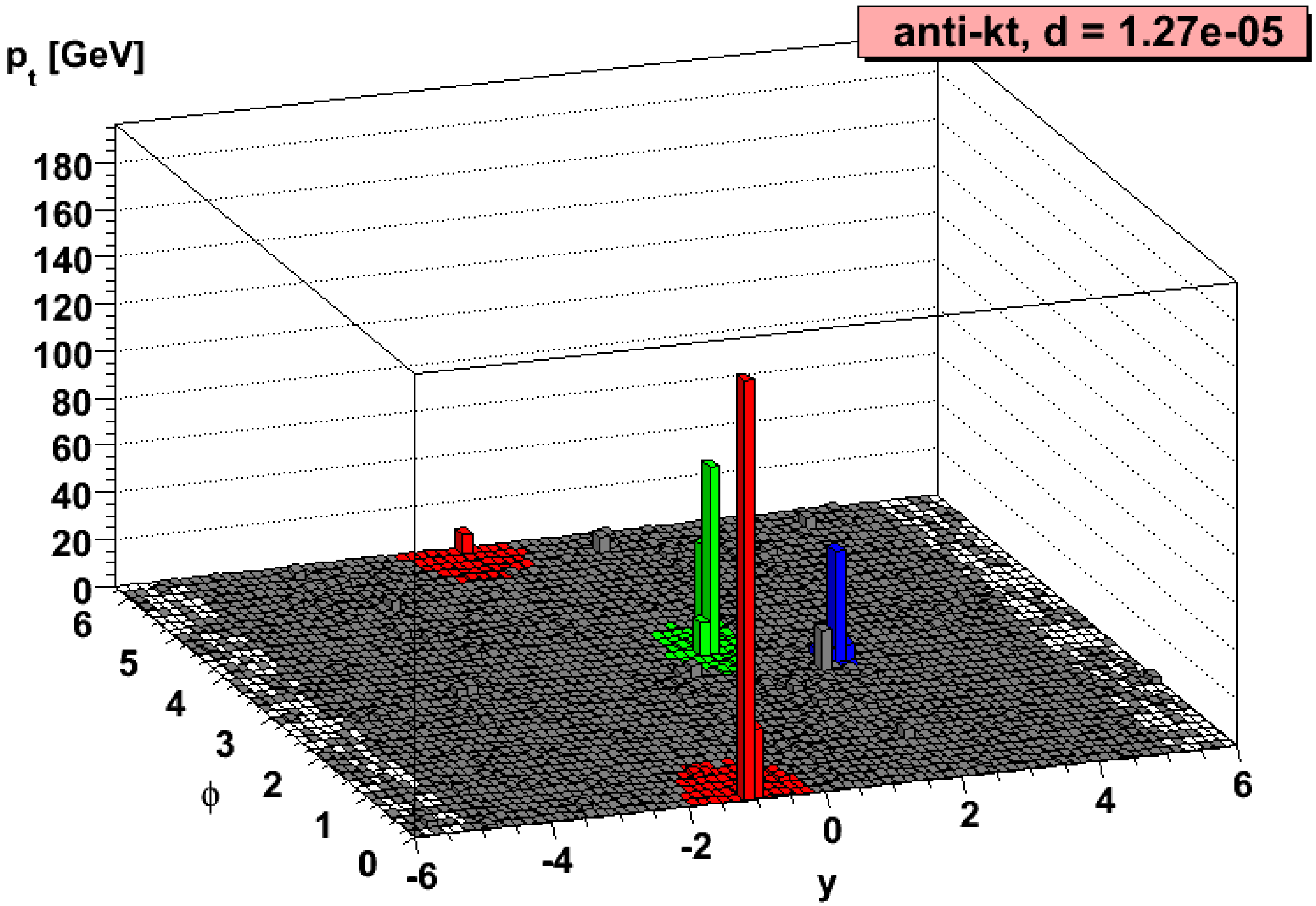

Anti-k_t in action

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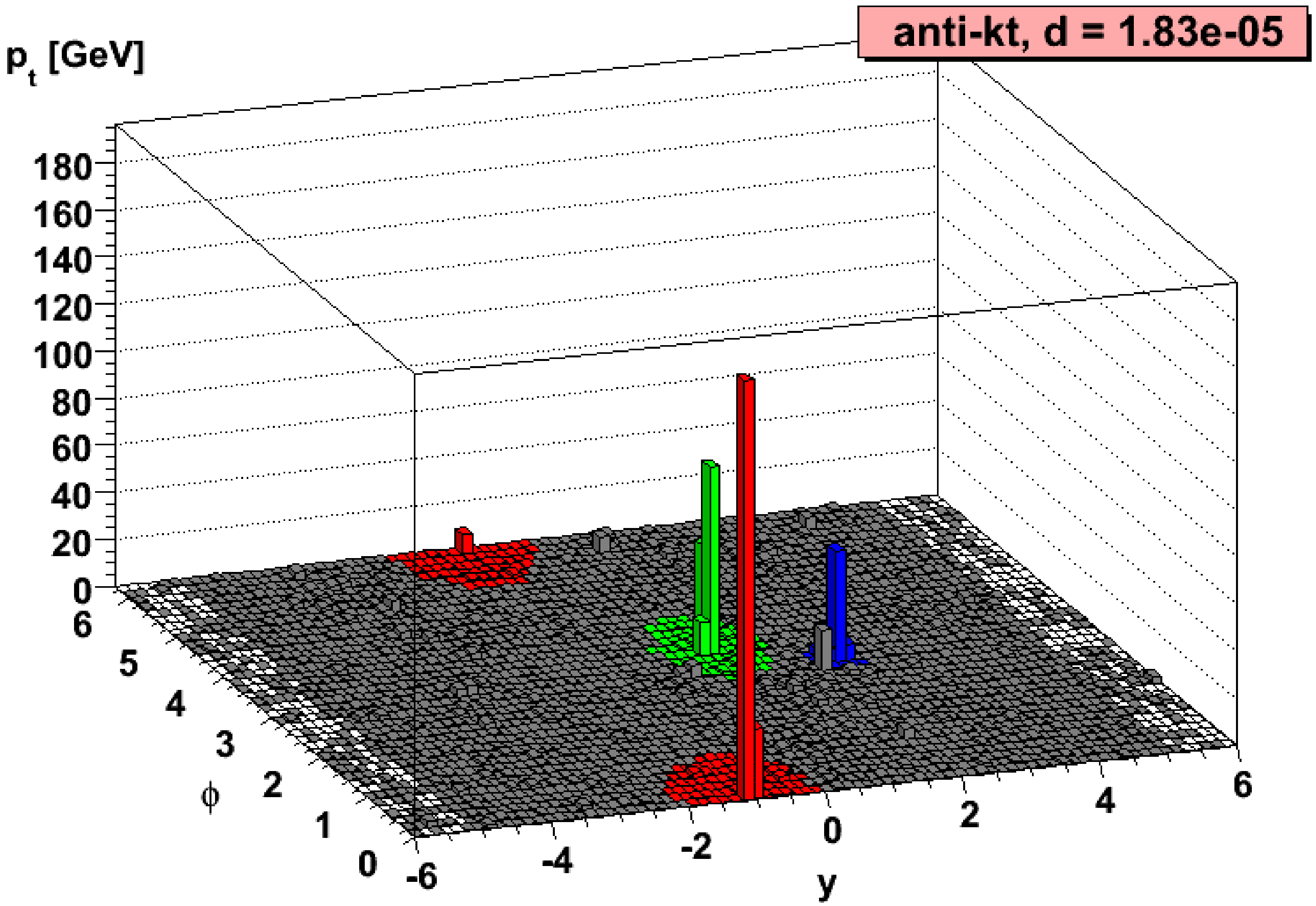

Anti-k_t in action

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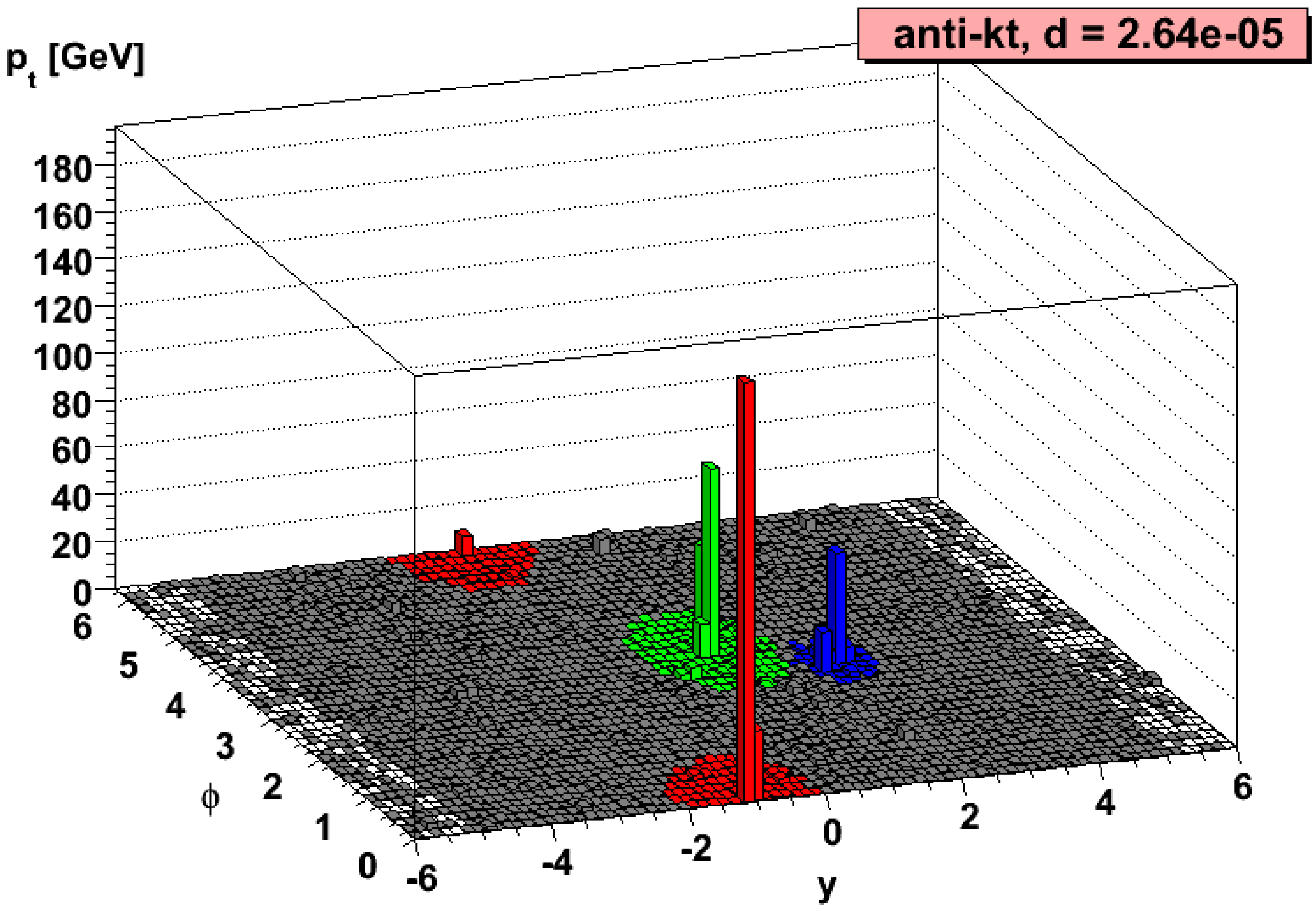

Anti-k$_t$ in action

Clustering grows around hard cores

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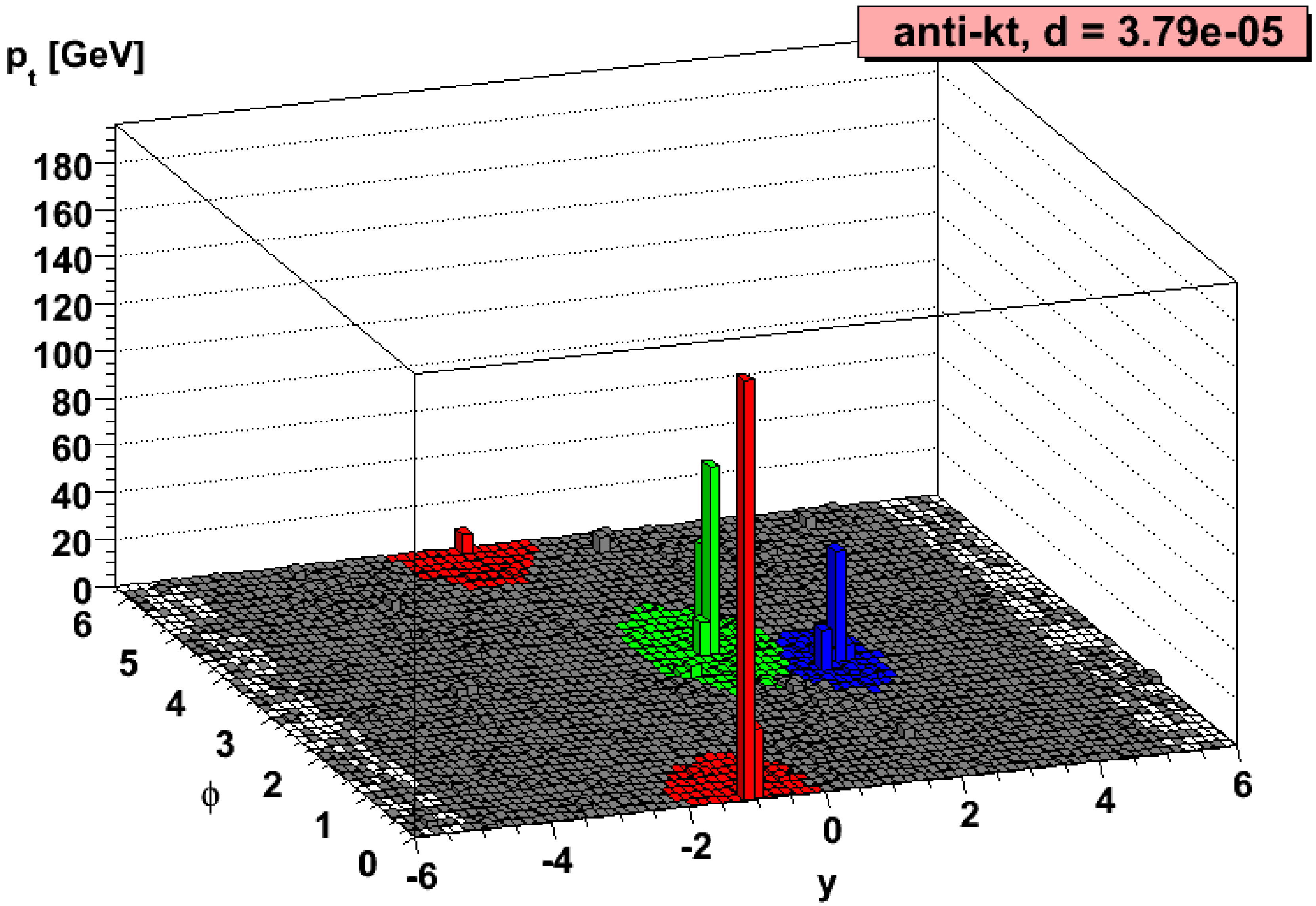

Anti-k_t in action

Clustering grows around hard cores

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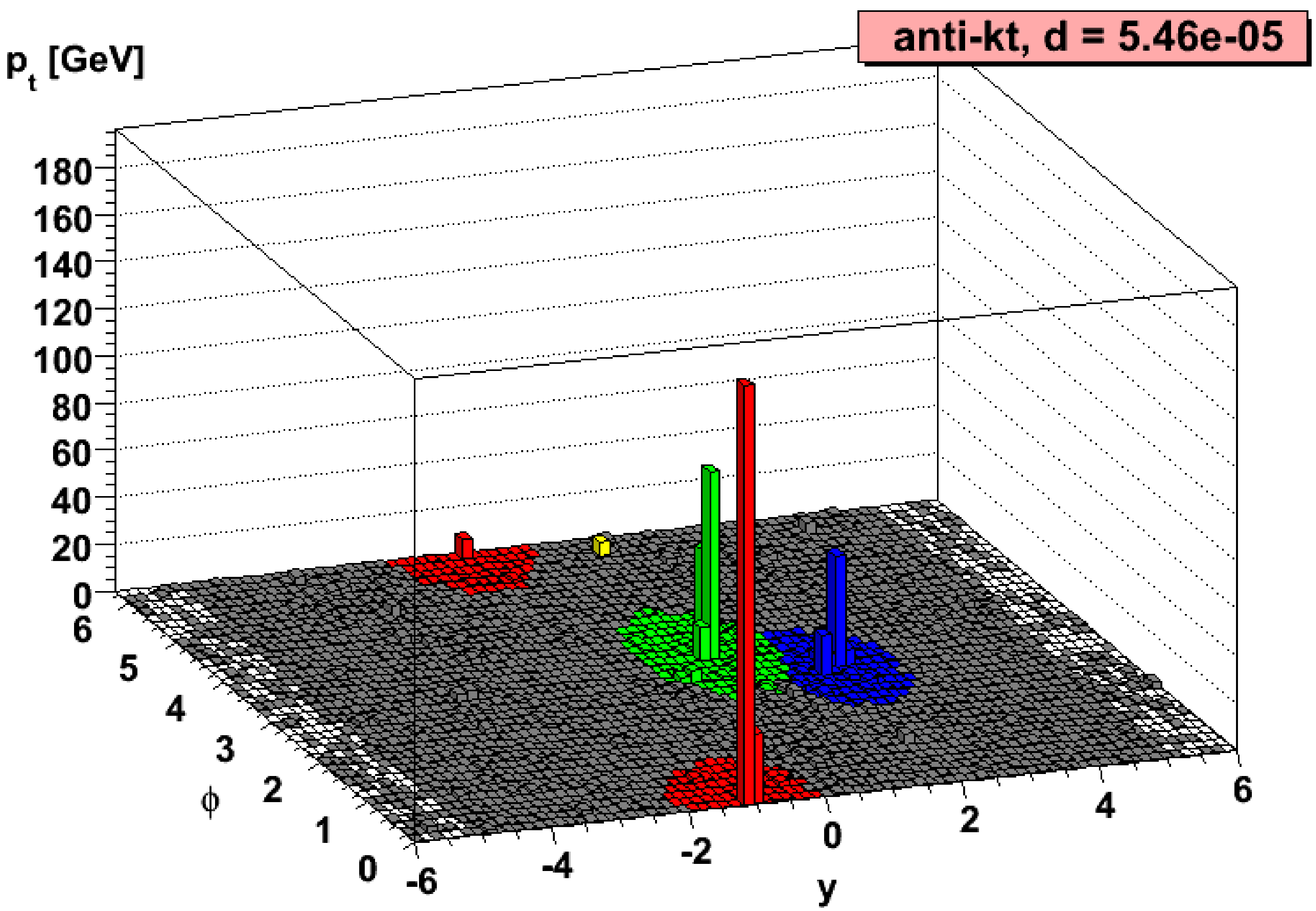

Anti-k_t in action

Clustering grows around hard cores

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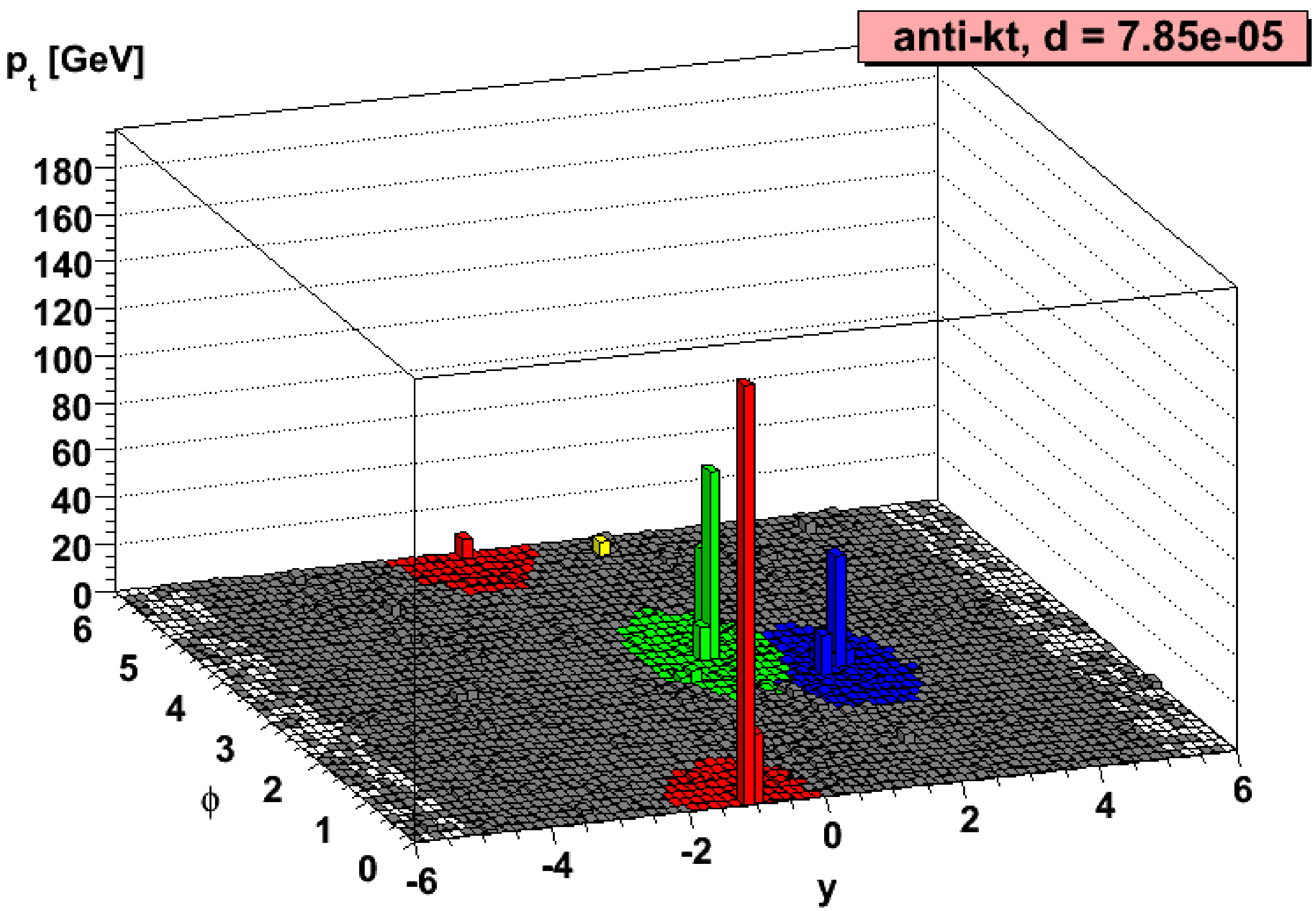

Clustering grows around hard cores

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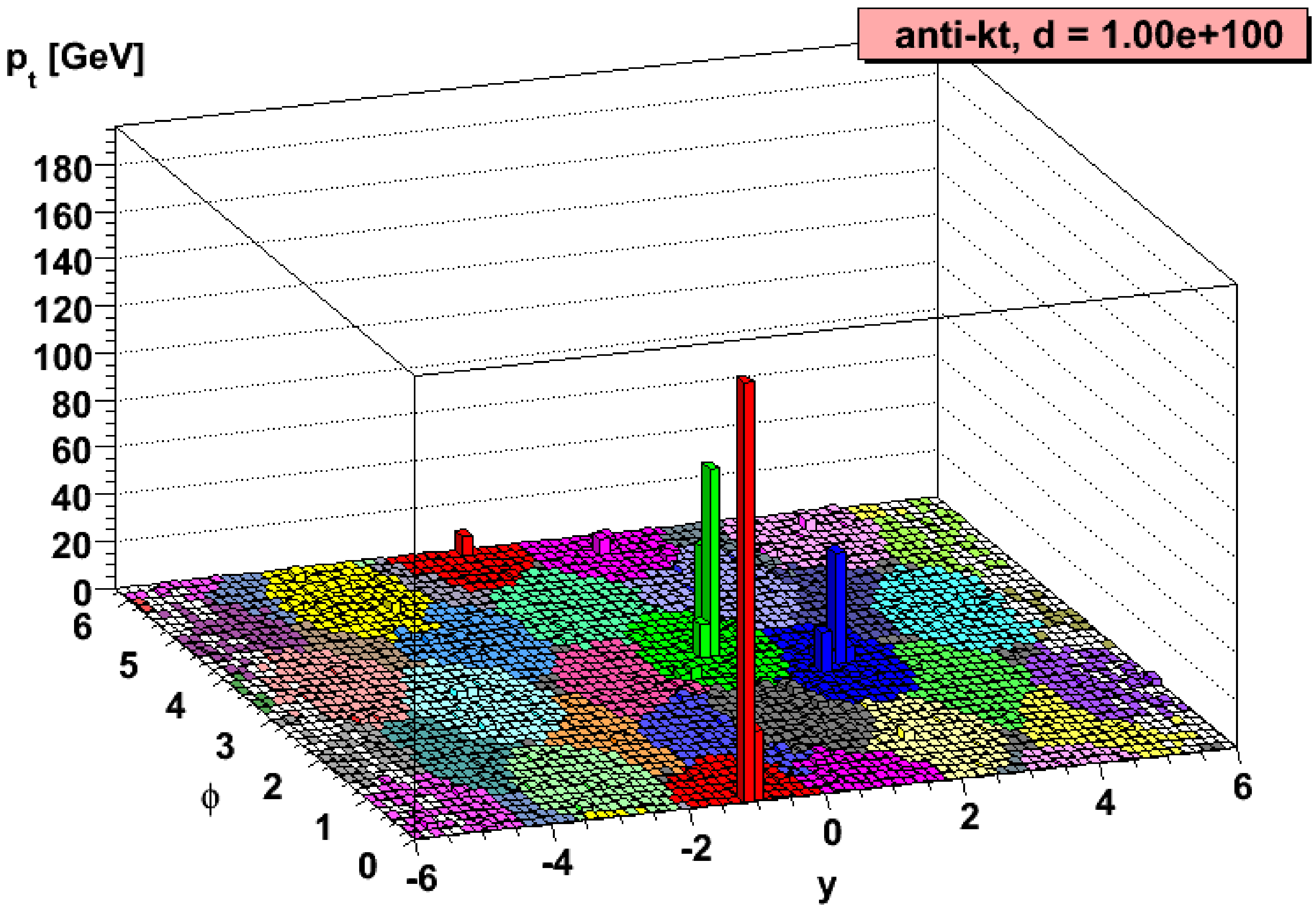
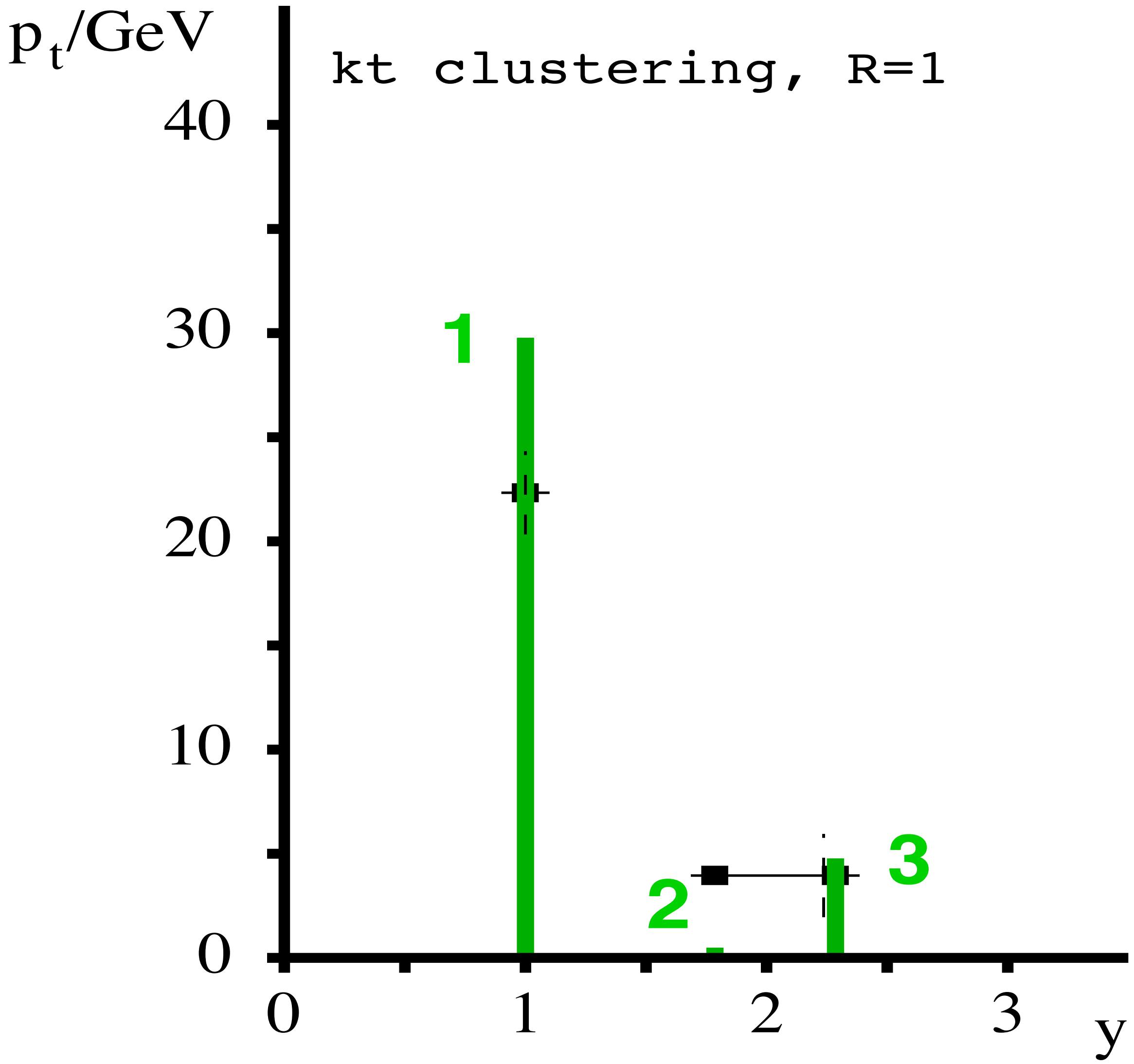
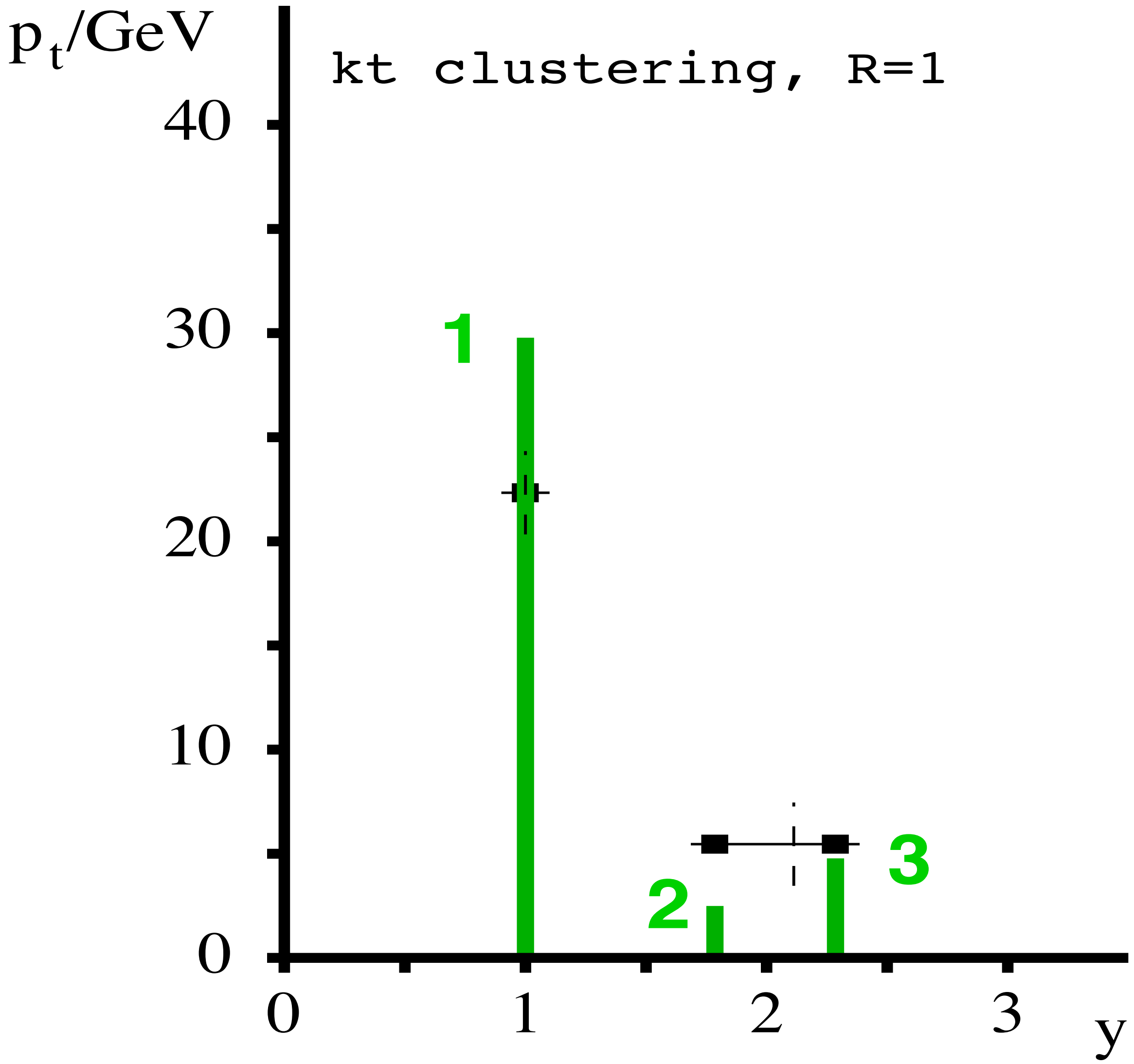


Anti-k_t gives circular jets ("cone-like") in a way that's infrared safe



p_t/GeV
kt clustering, R=1
40
30
20
10
0
0
1
2
3
y
1
2
3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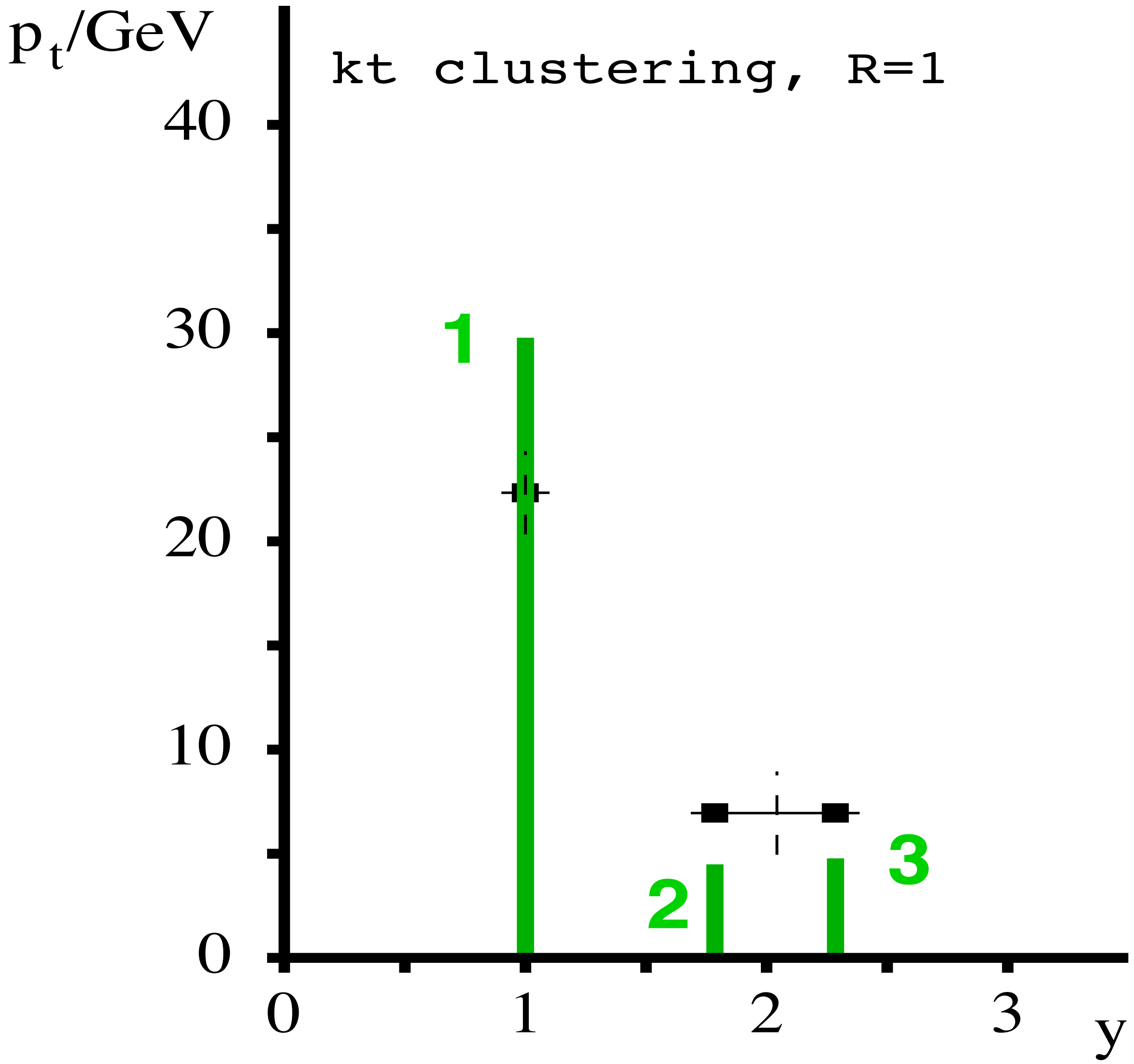
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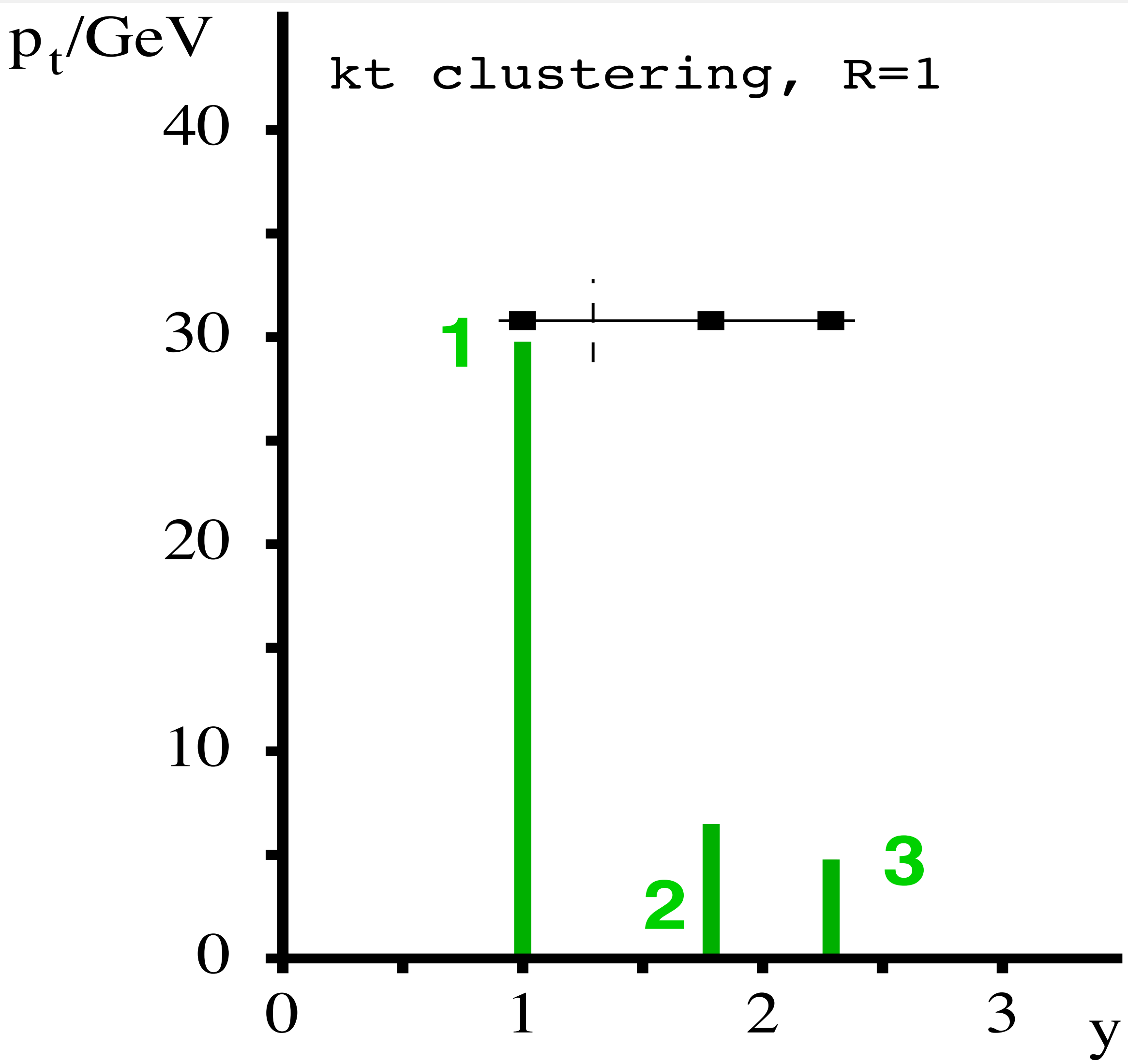

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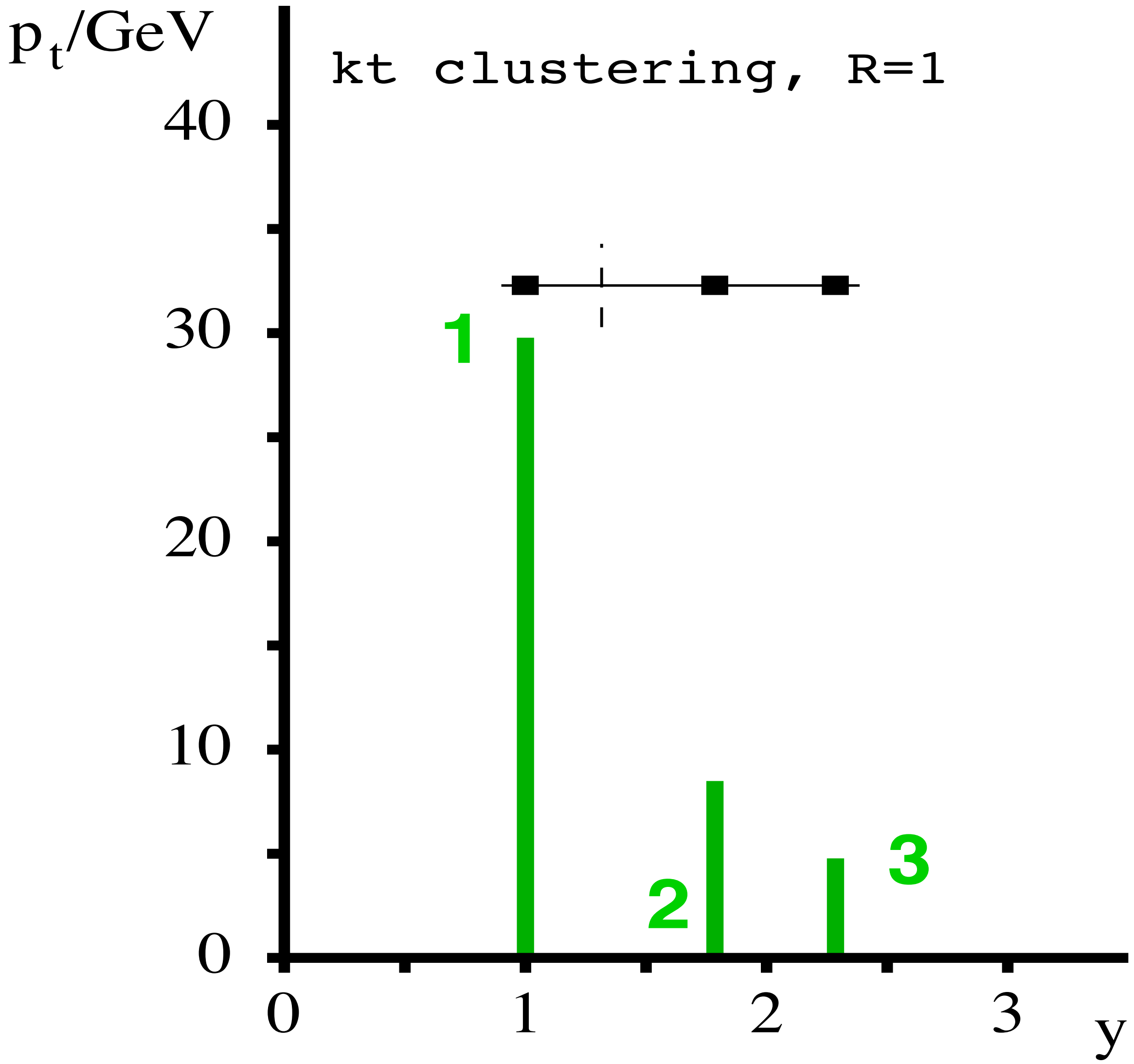

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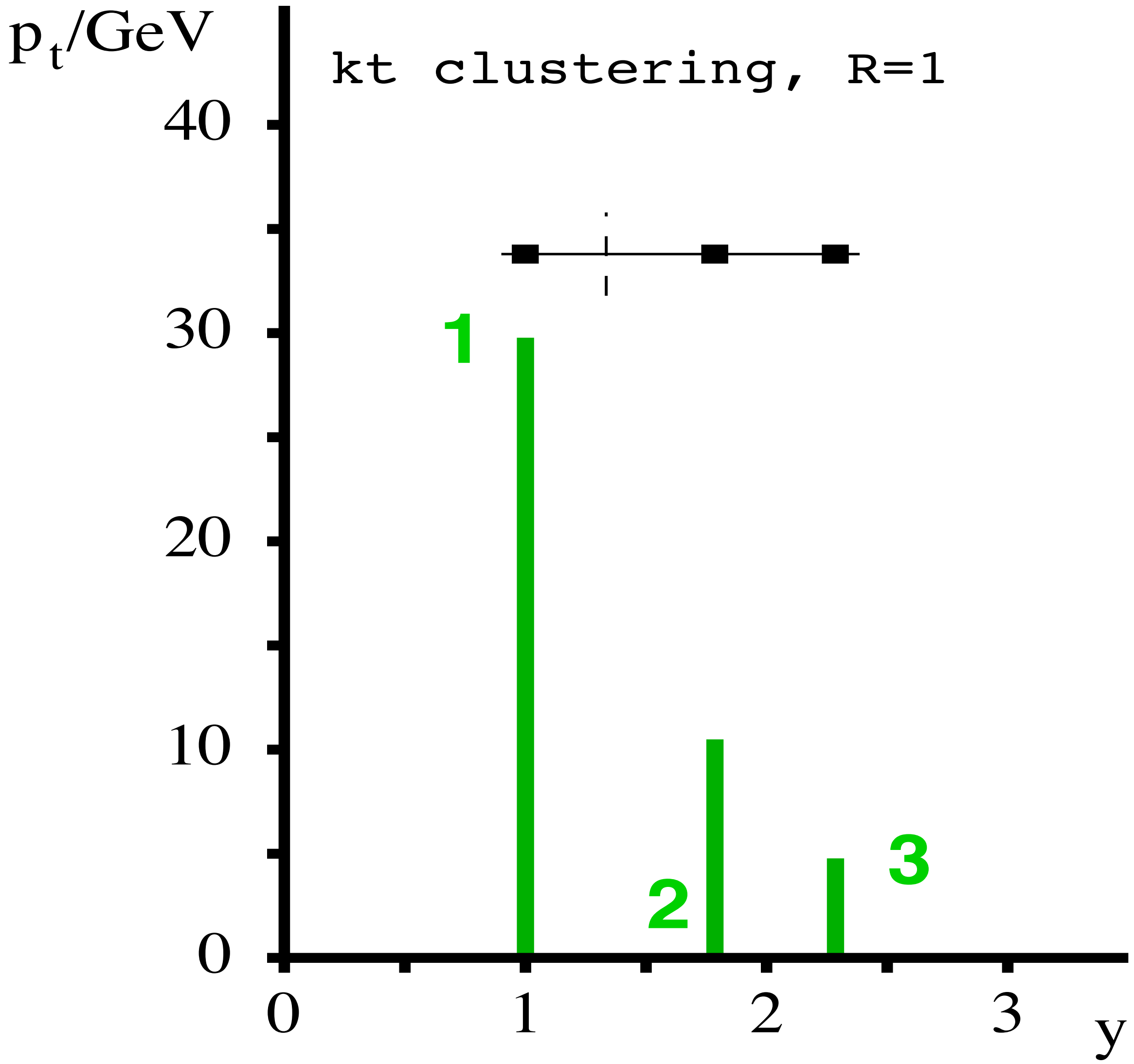
Linearity: k_t v. anti-k_t



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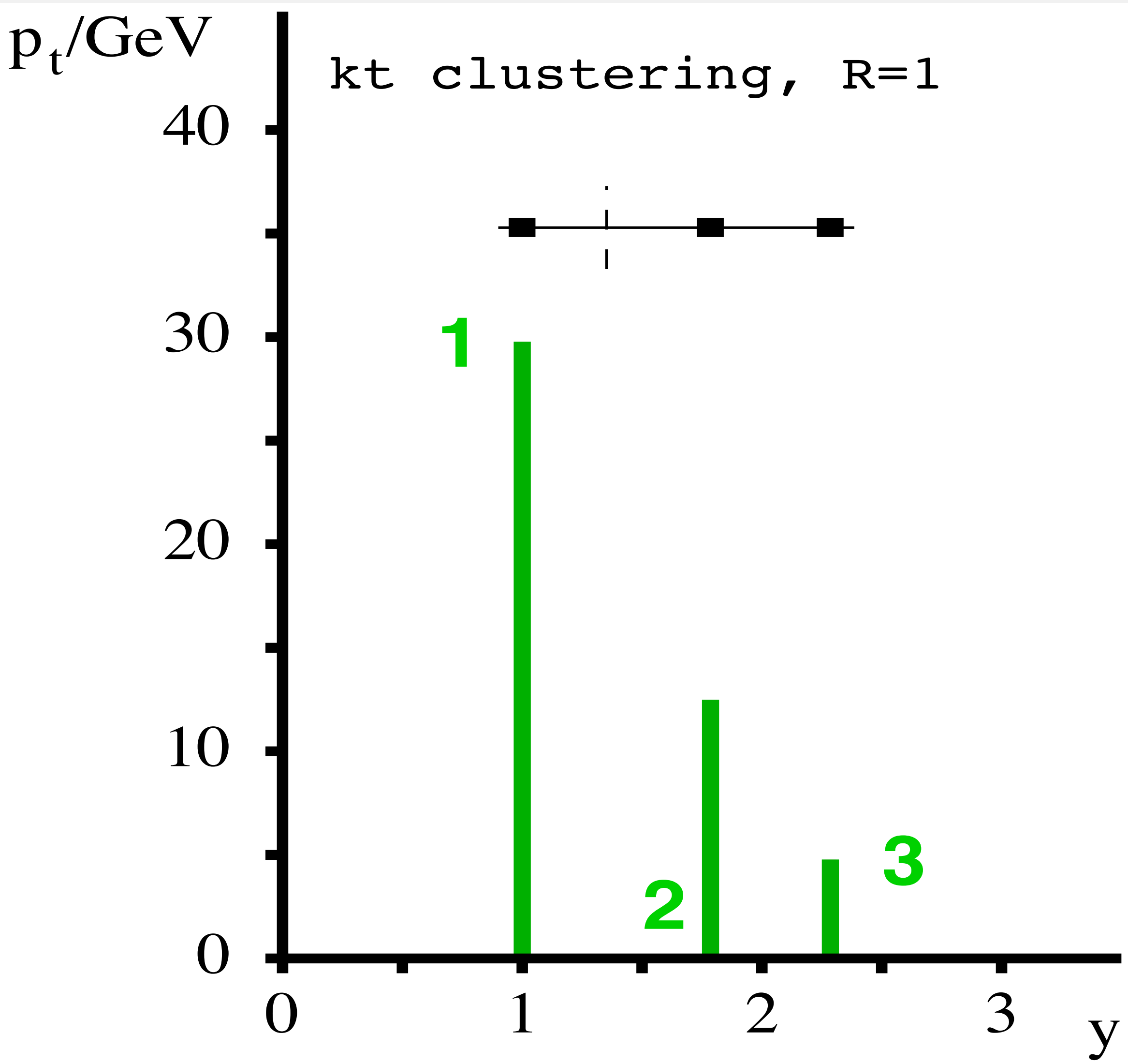

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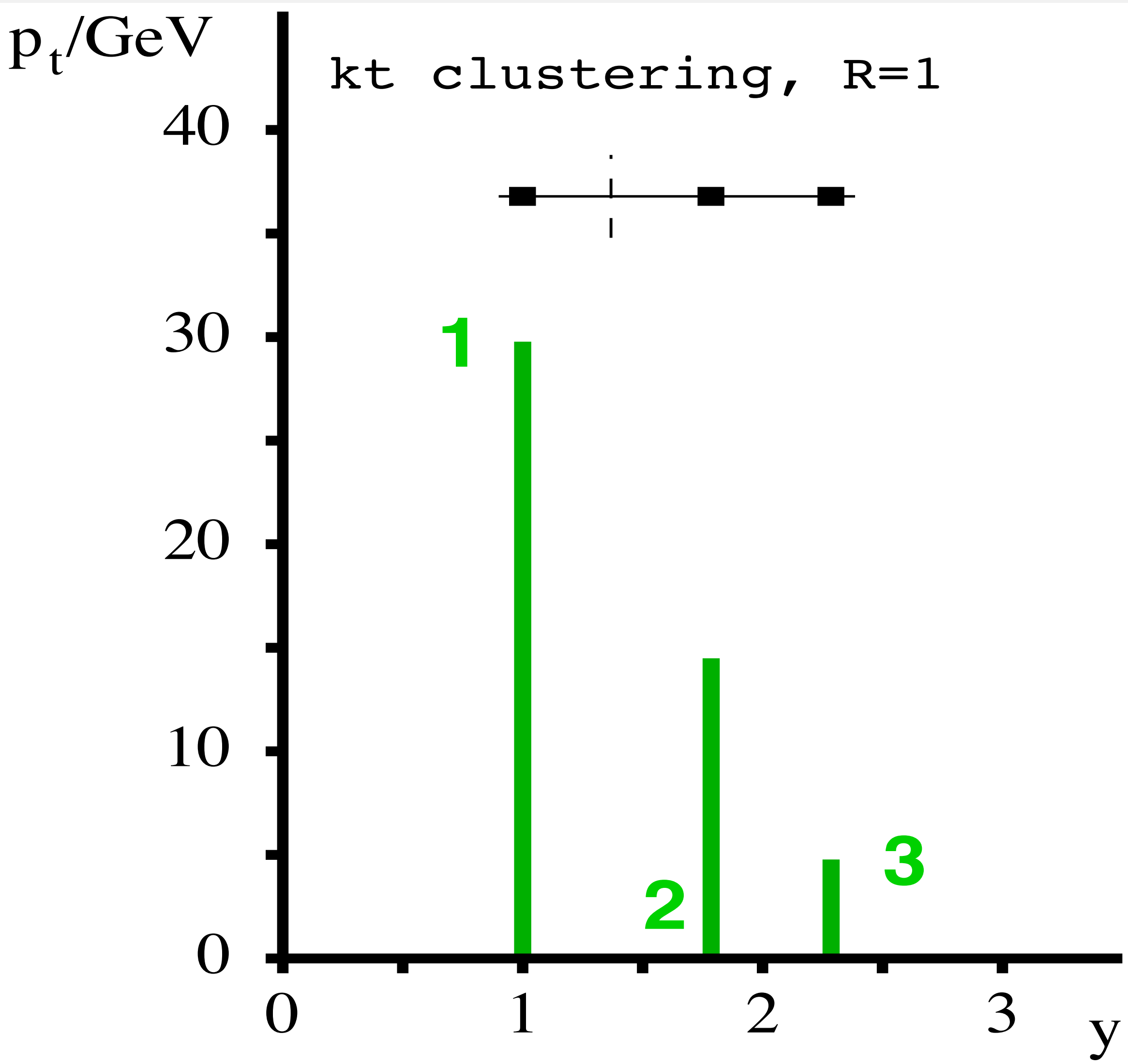

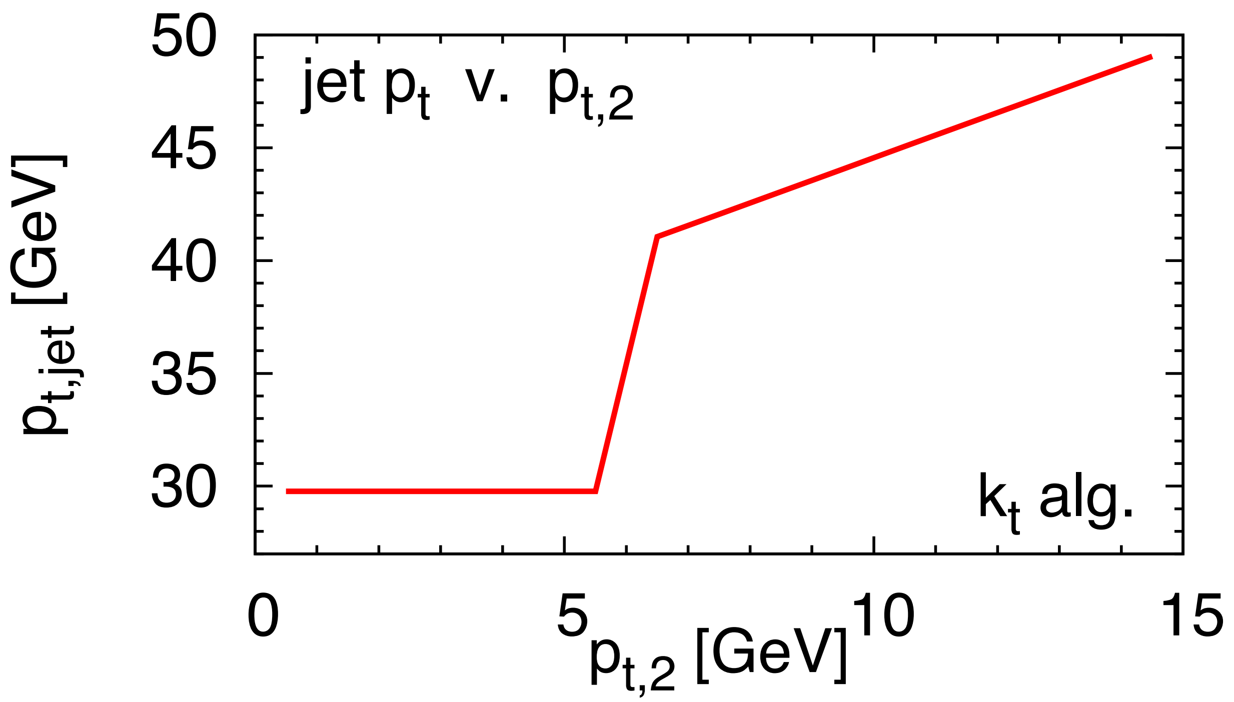

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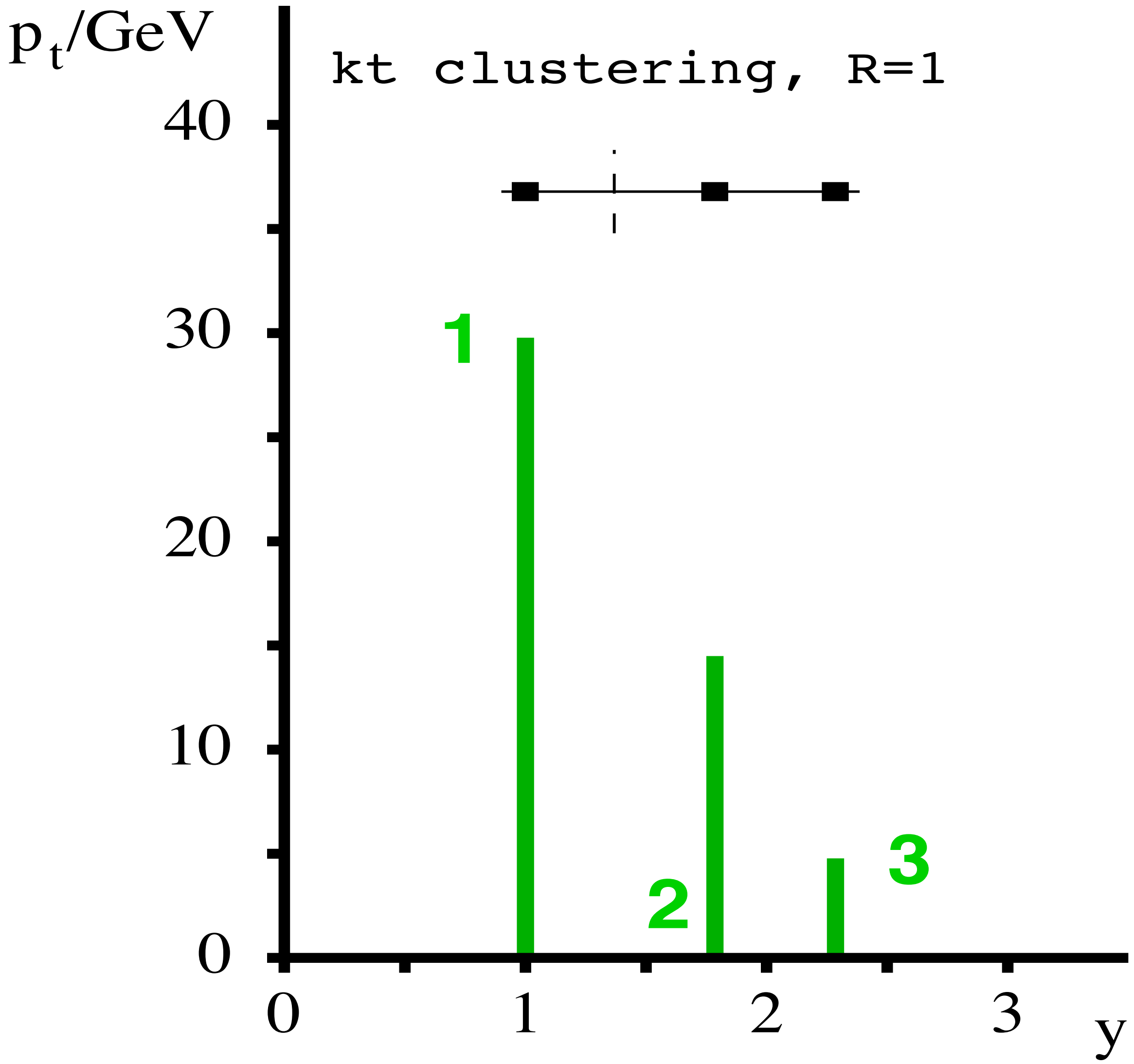
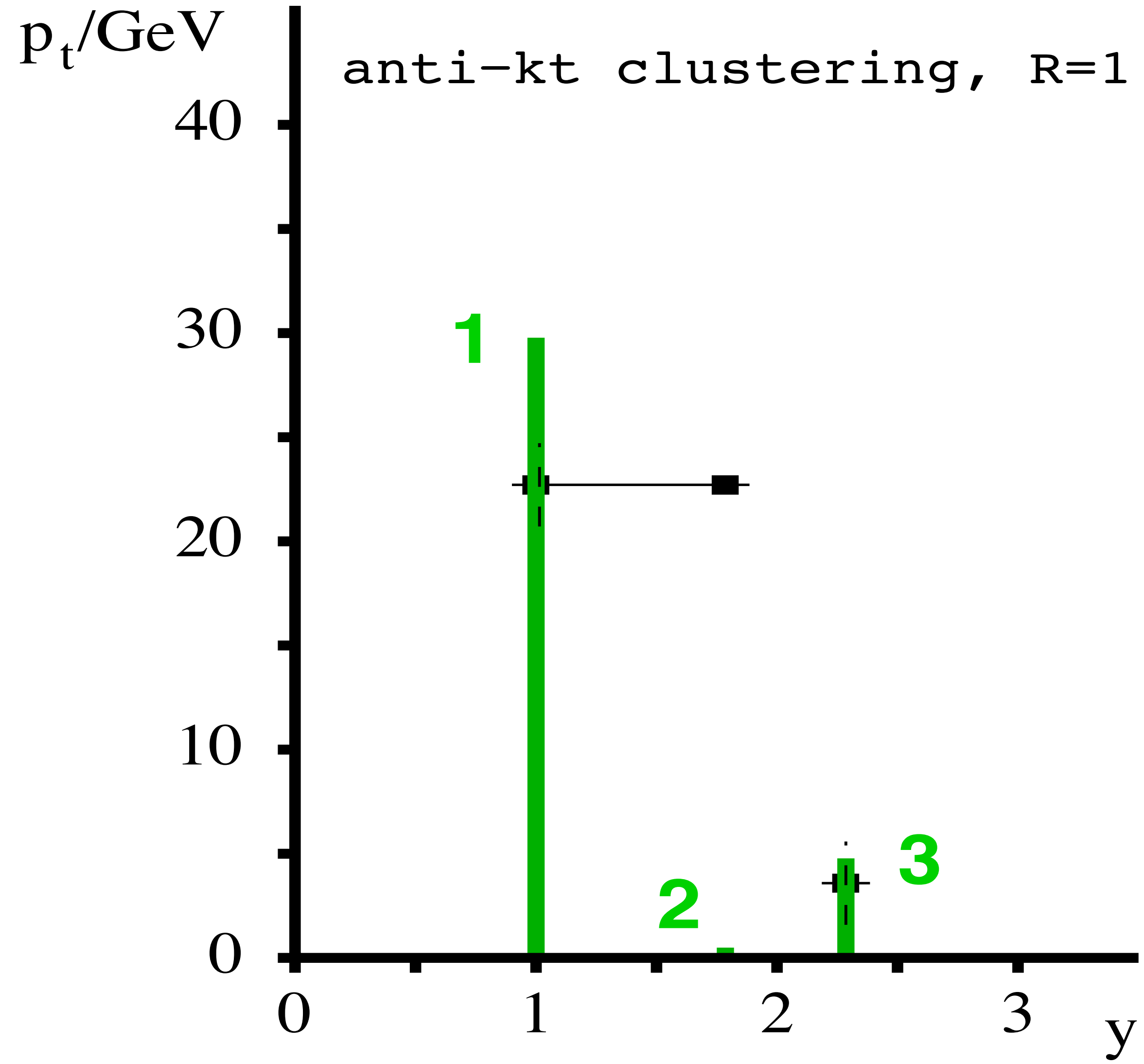
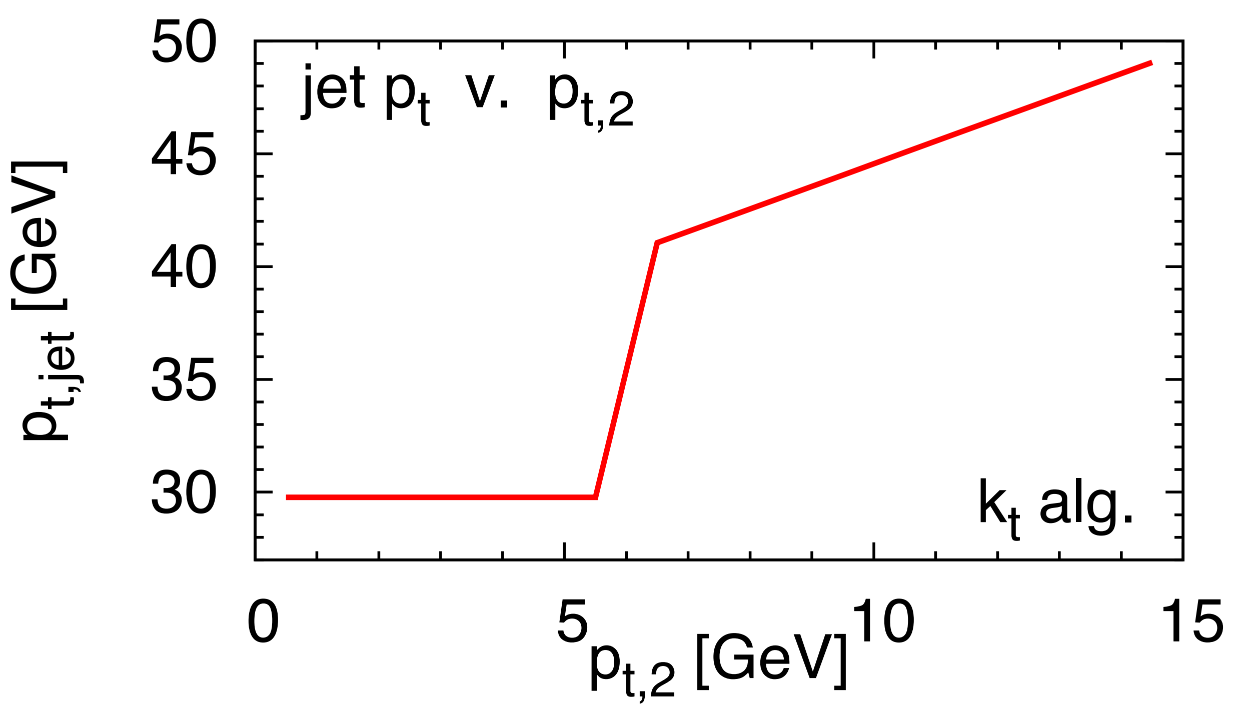
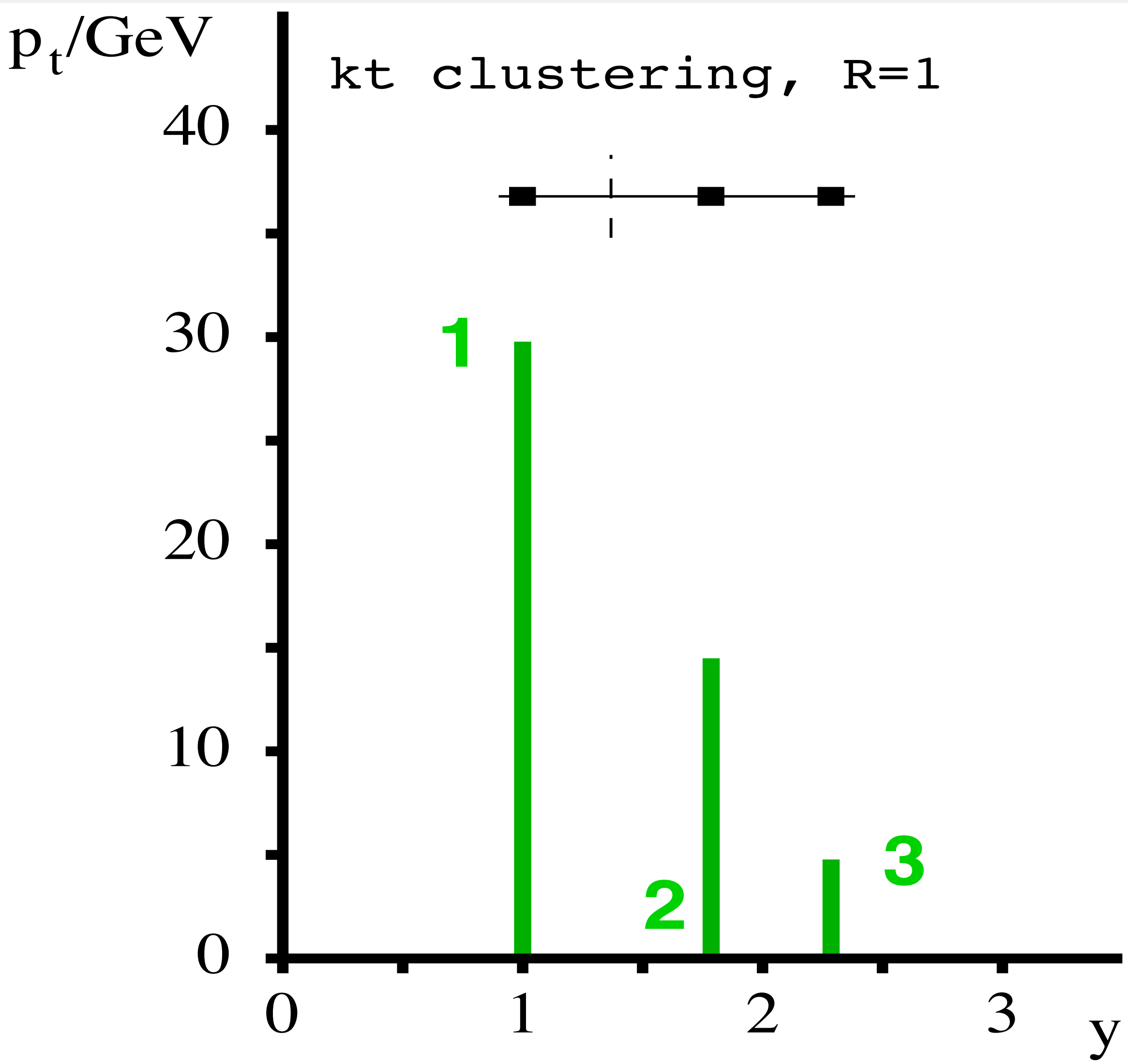
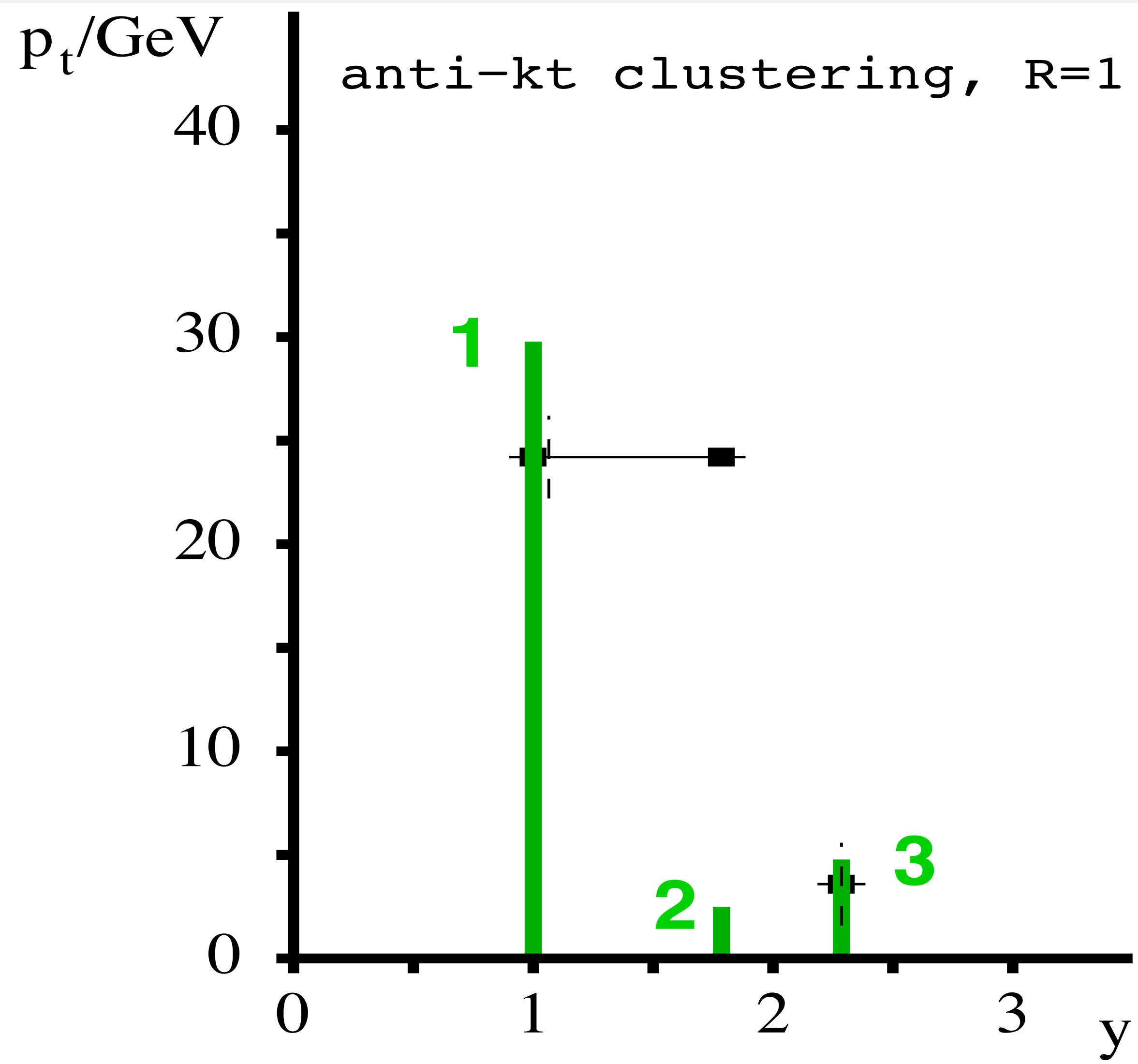


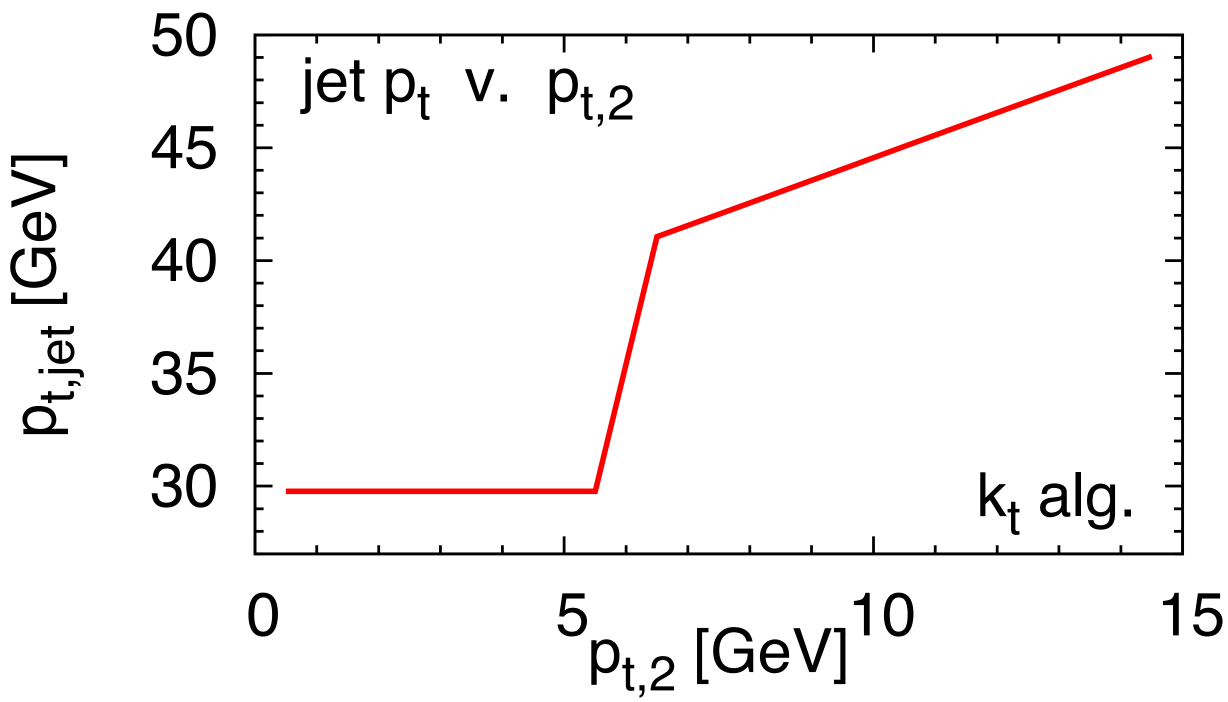


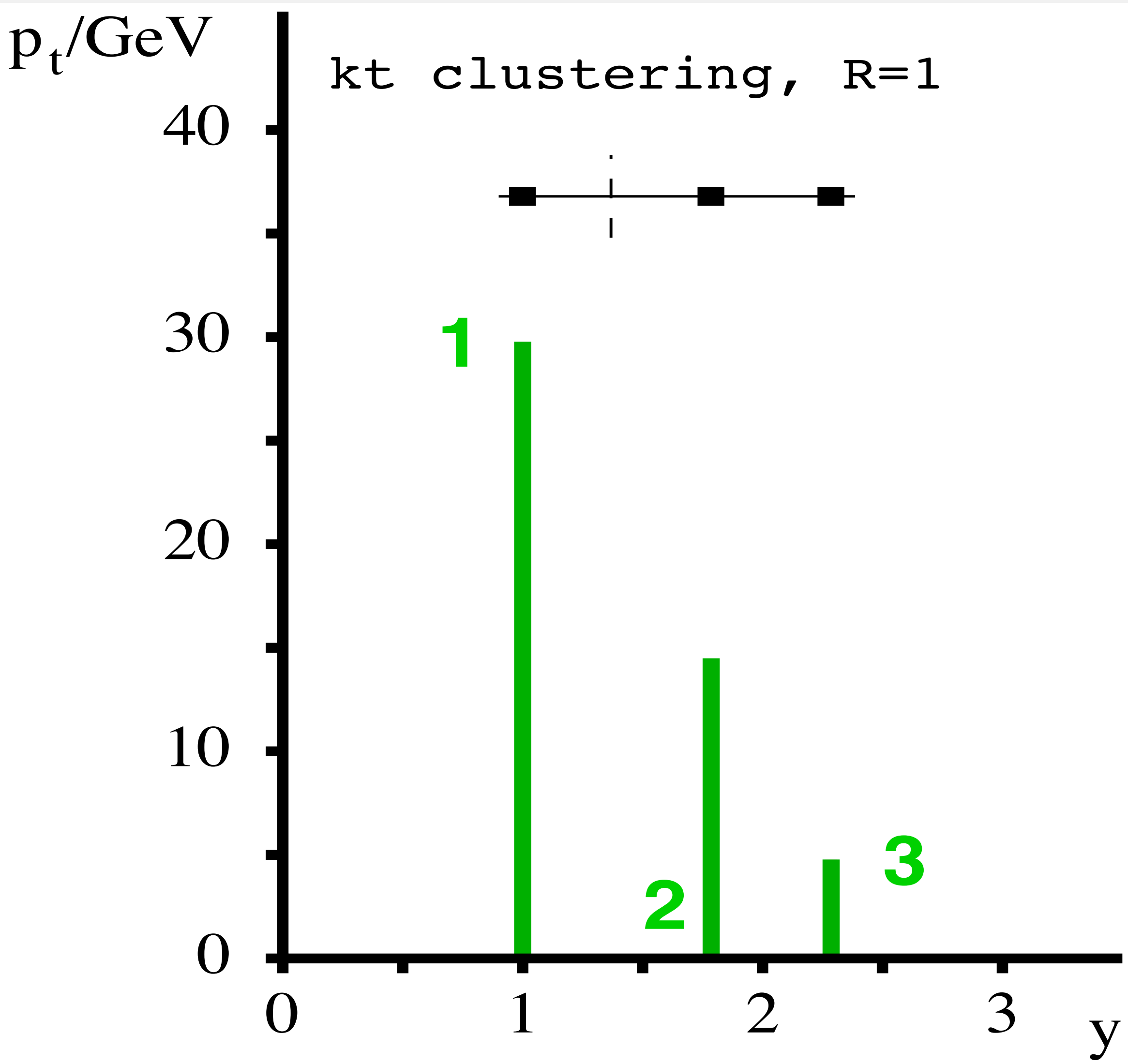


Linearity: k_t v. anti-k_t








pt/GeV
kt clustering, R=1
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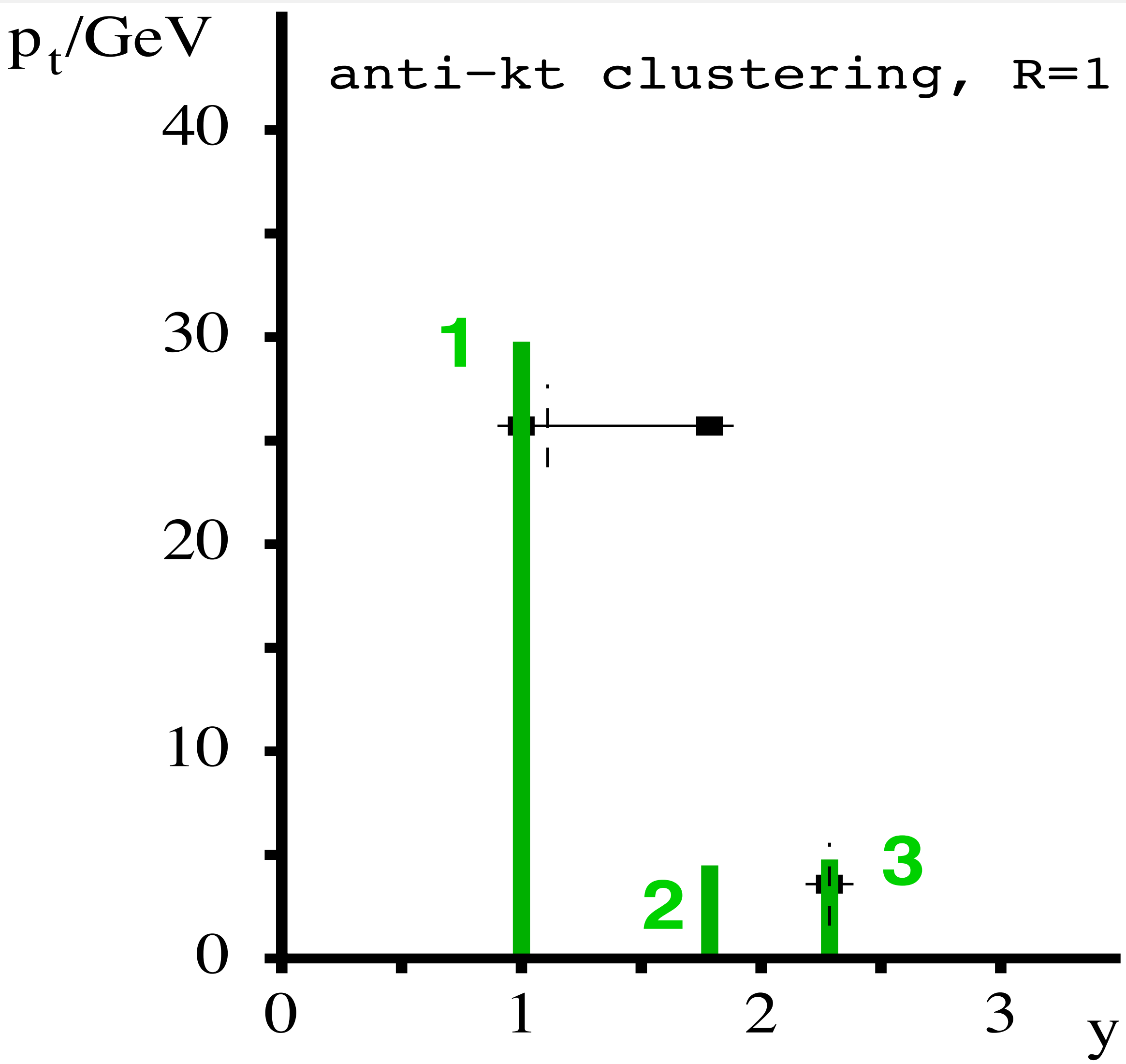
y


pt/GeV
anti−kt clustering, R=1
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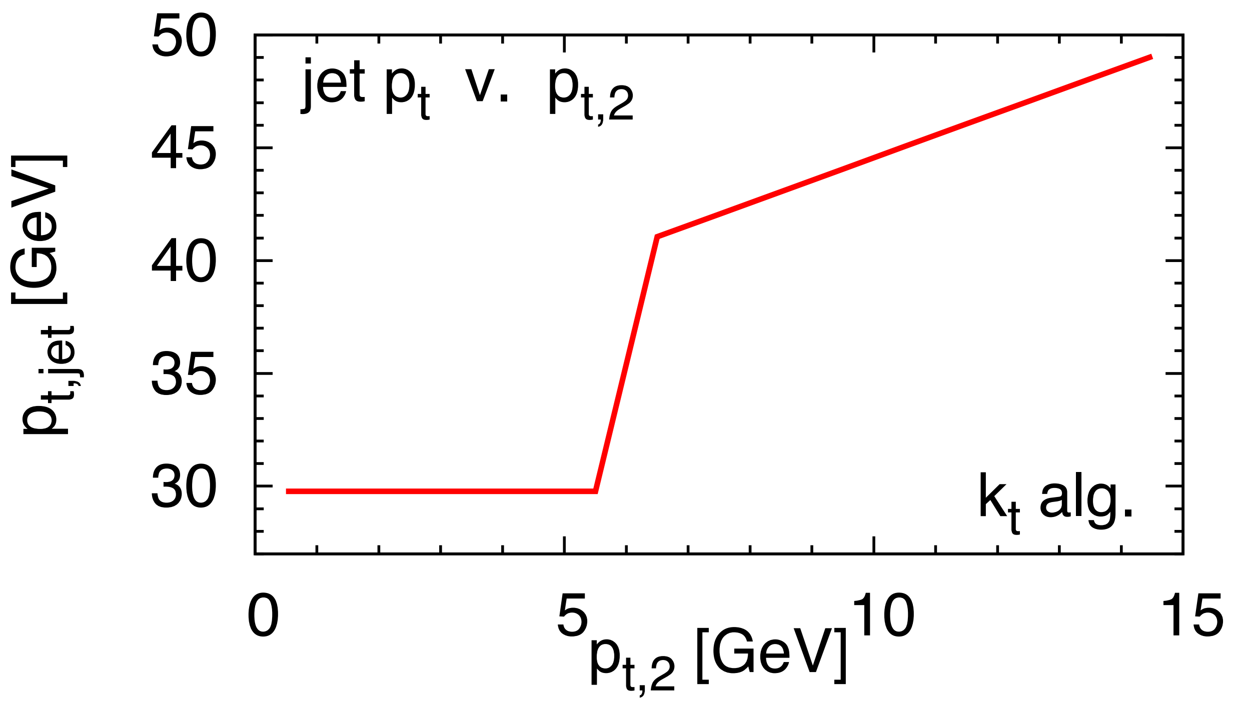
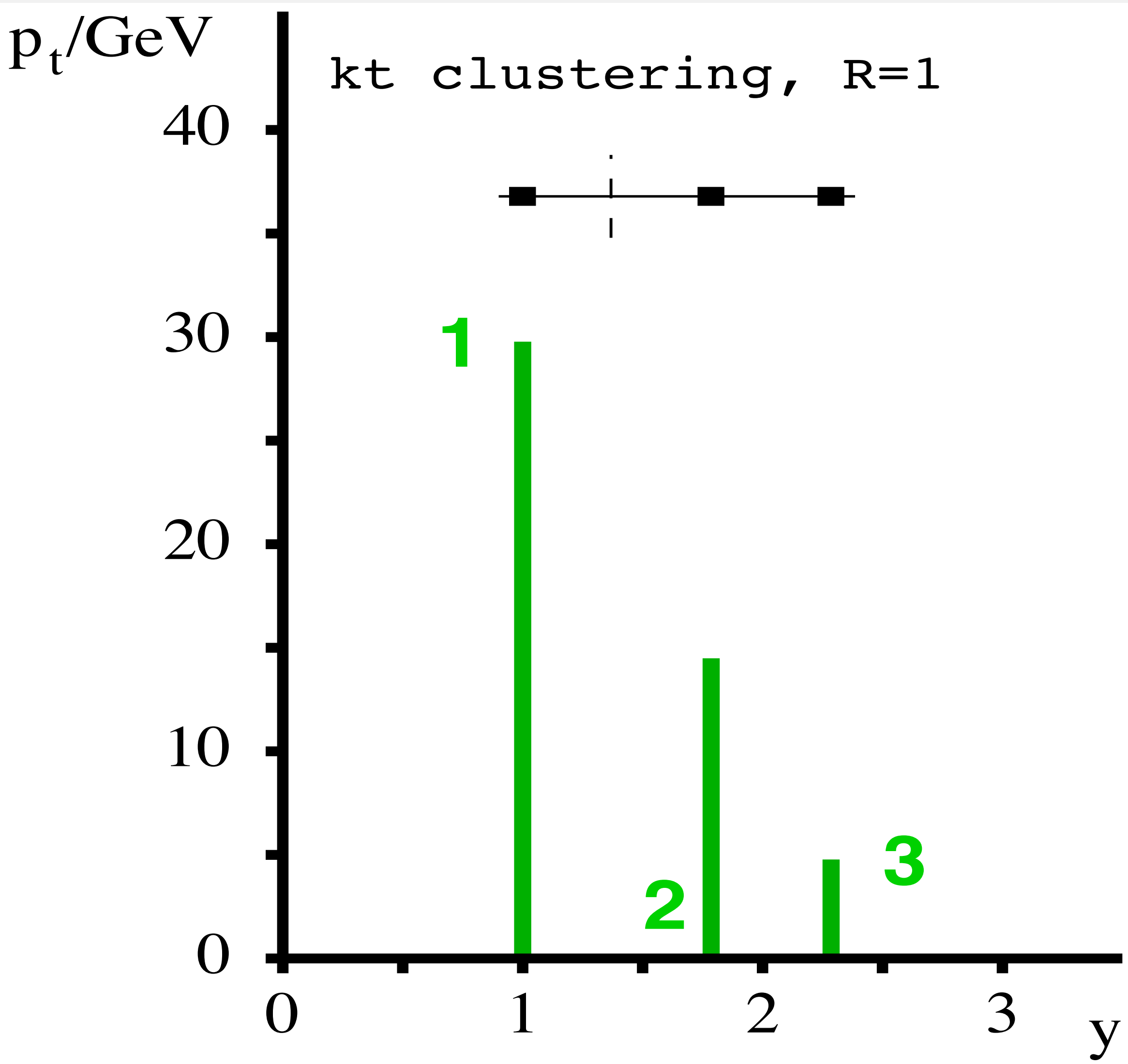
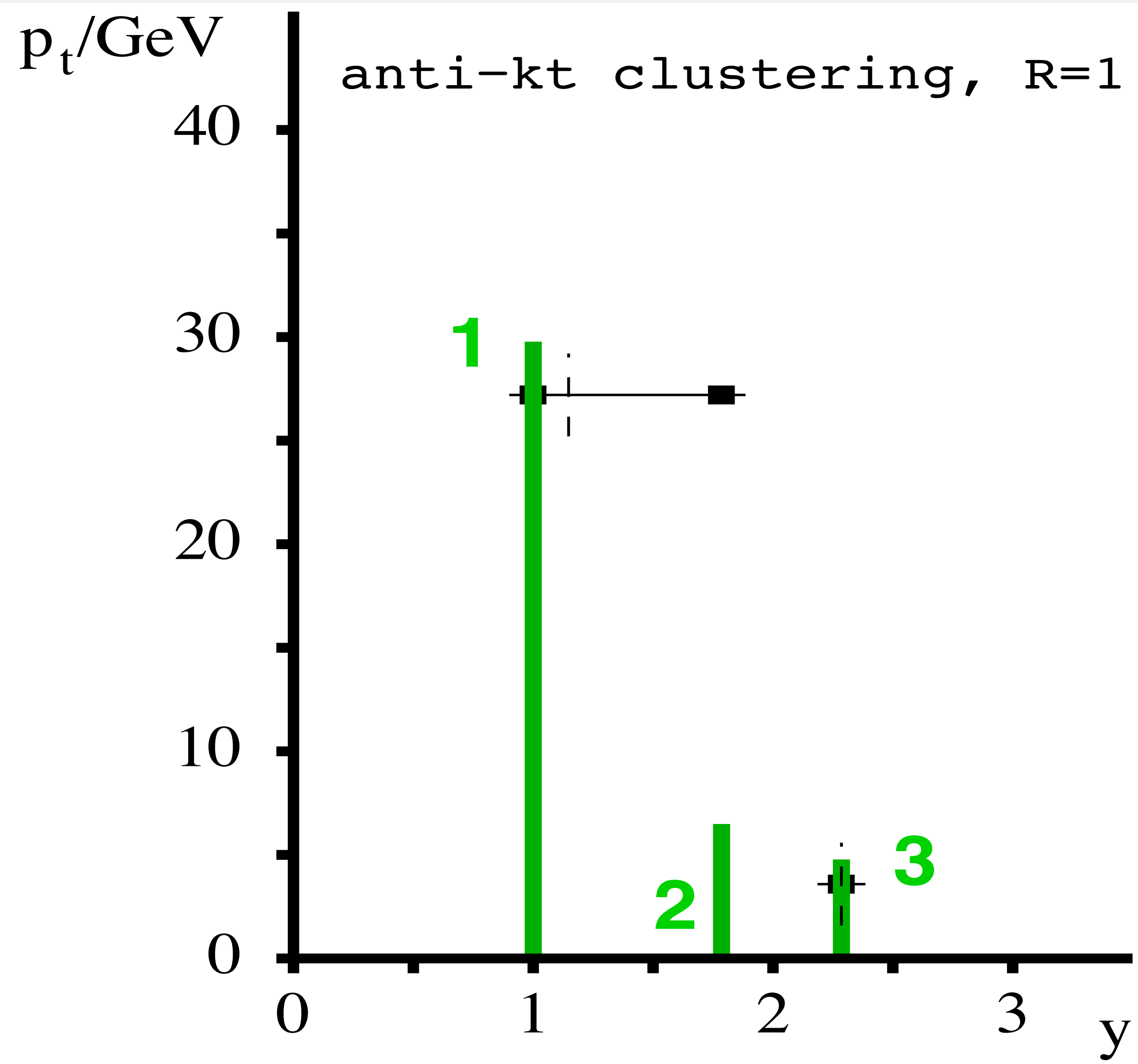
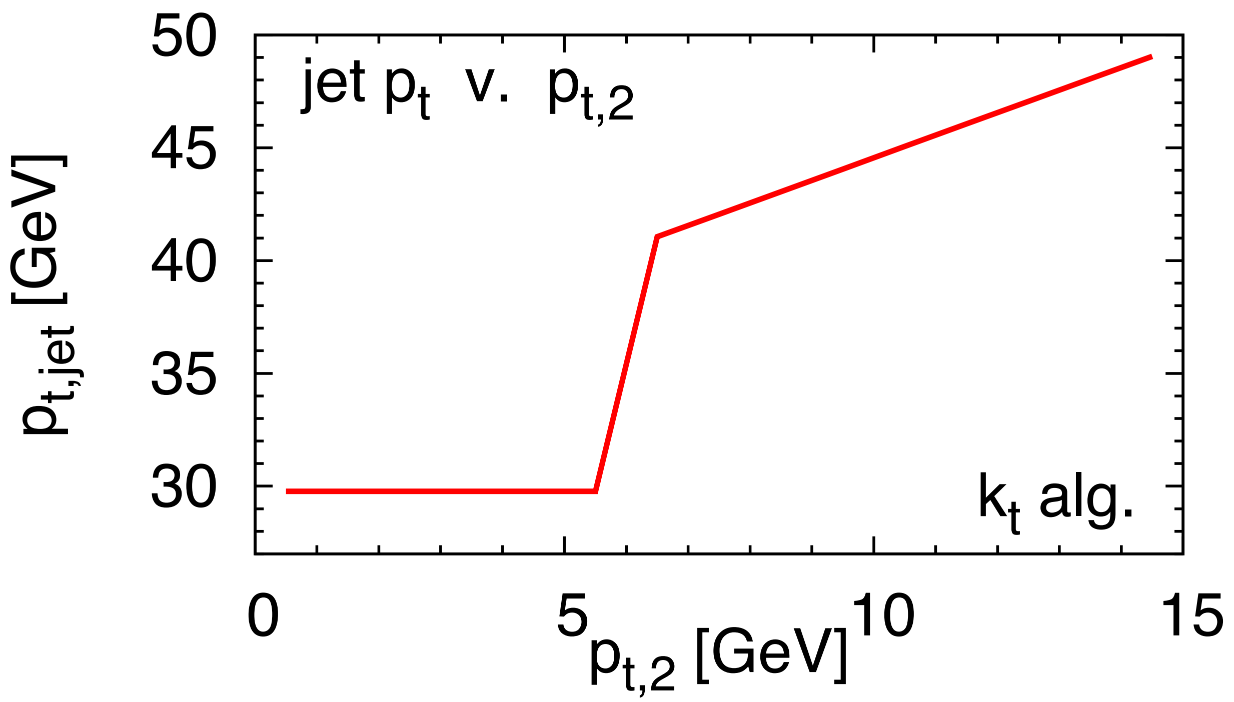
y


jet pt v. pt,2
kt alg.
pt,jet [GeV]
pt,2 [GeV]
50
45
40
35
30
0
5
10
15

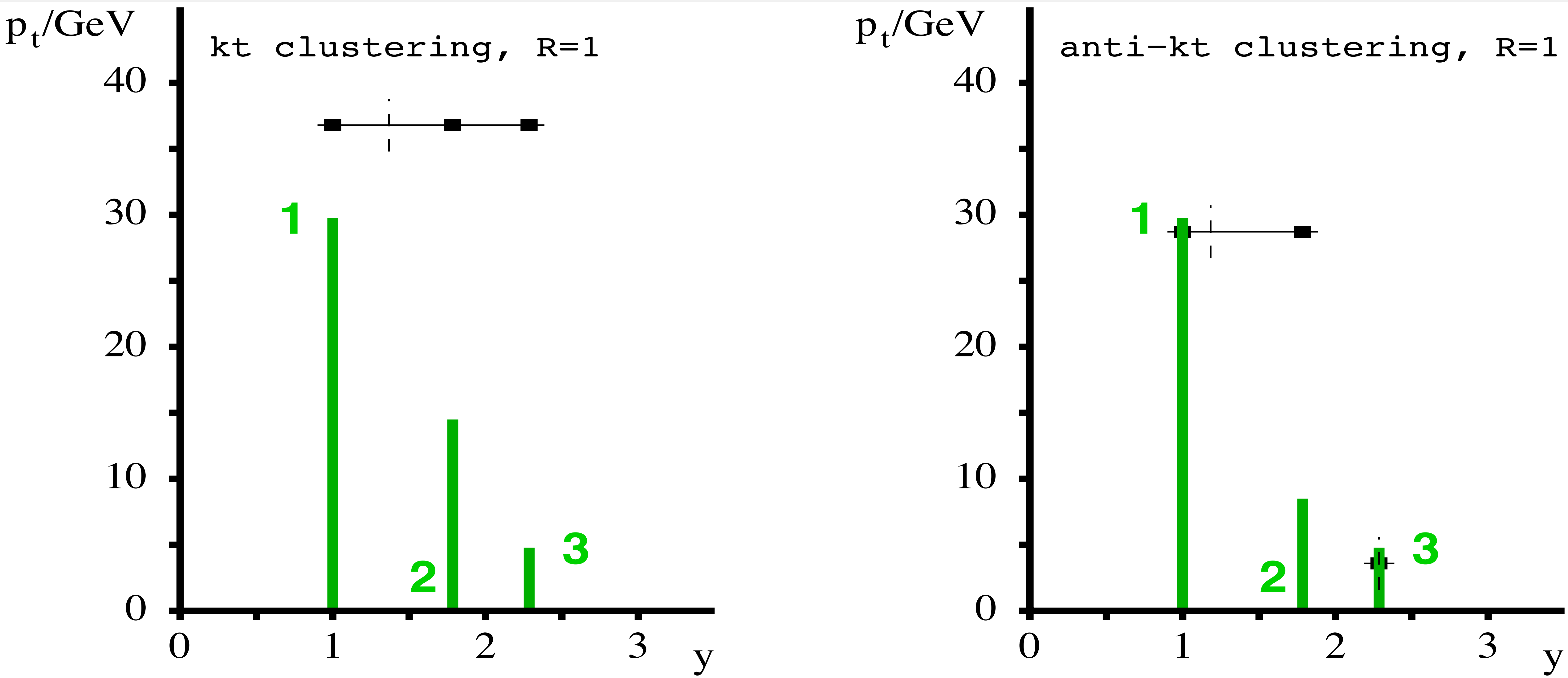
Linearity: k_t v. anti-k_t

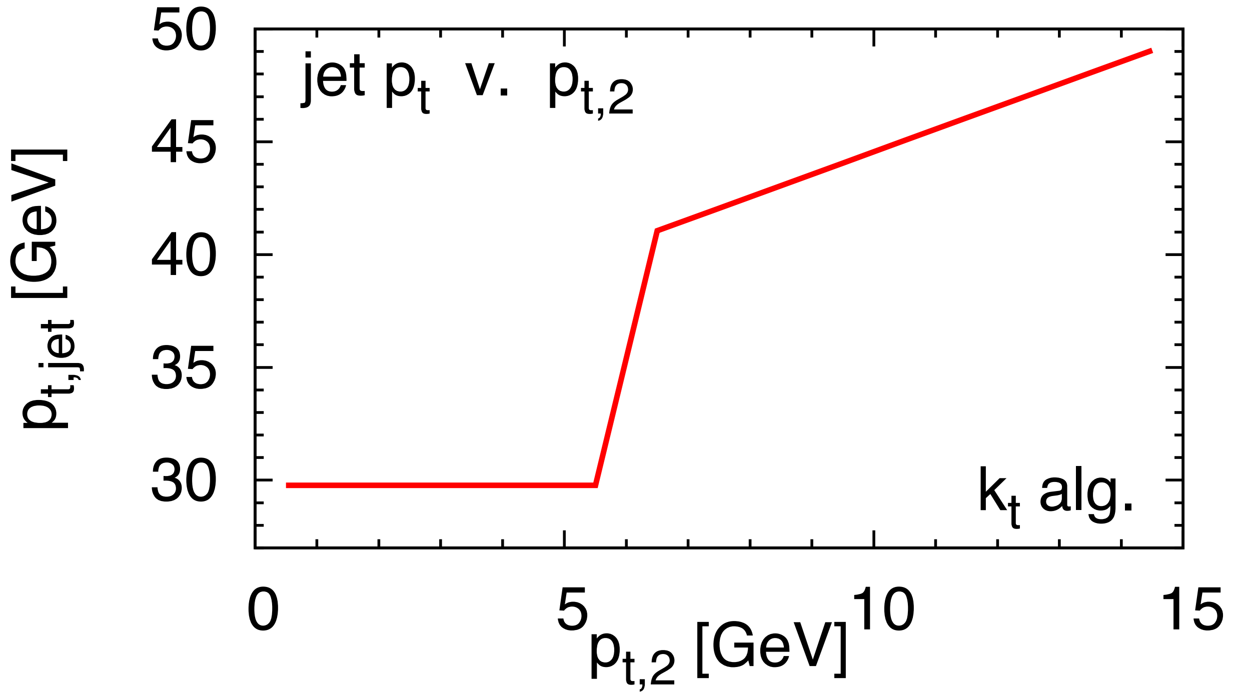




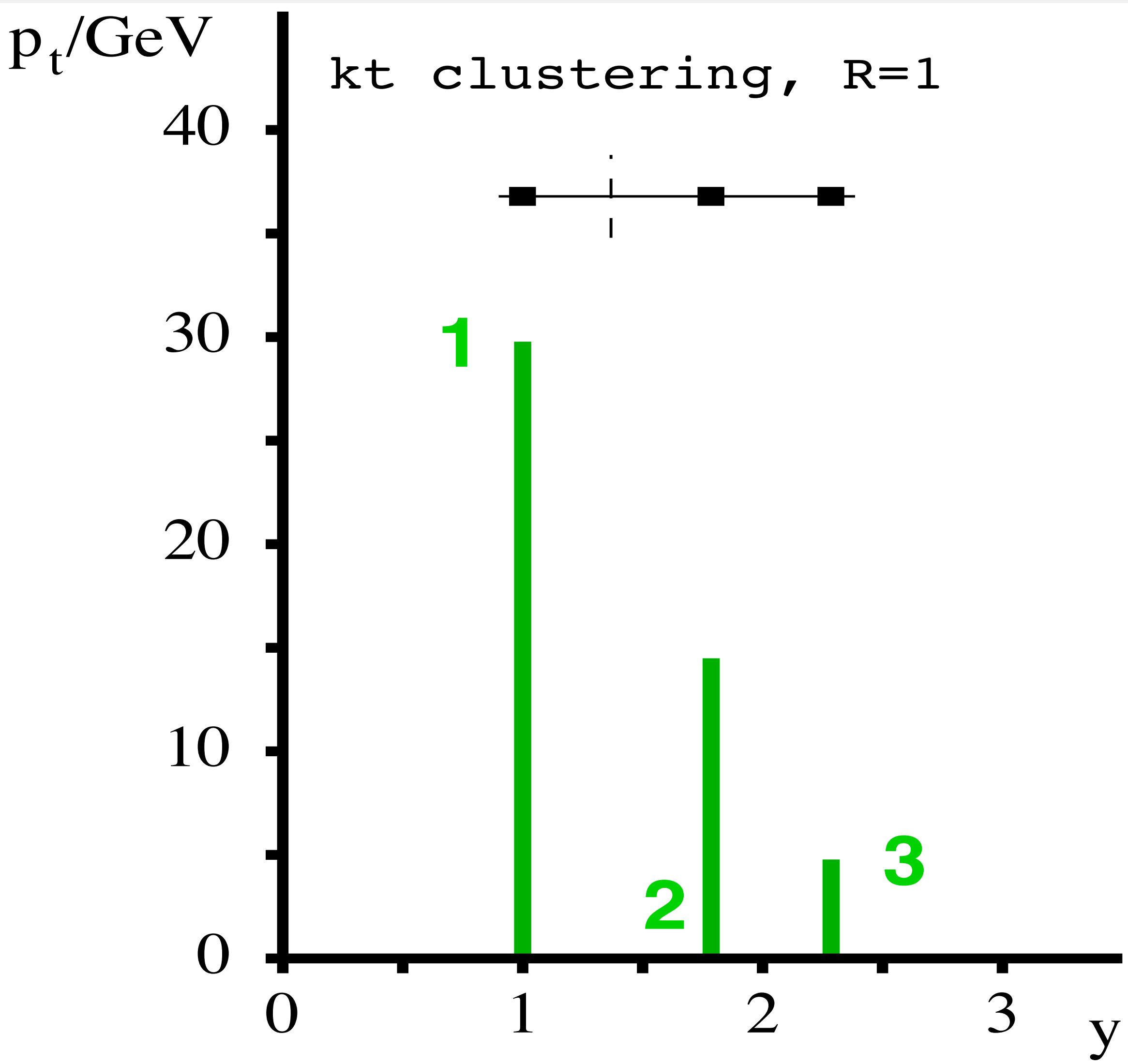


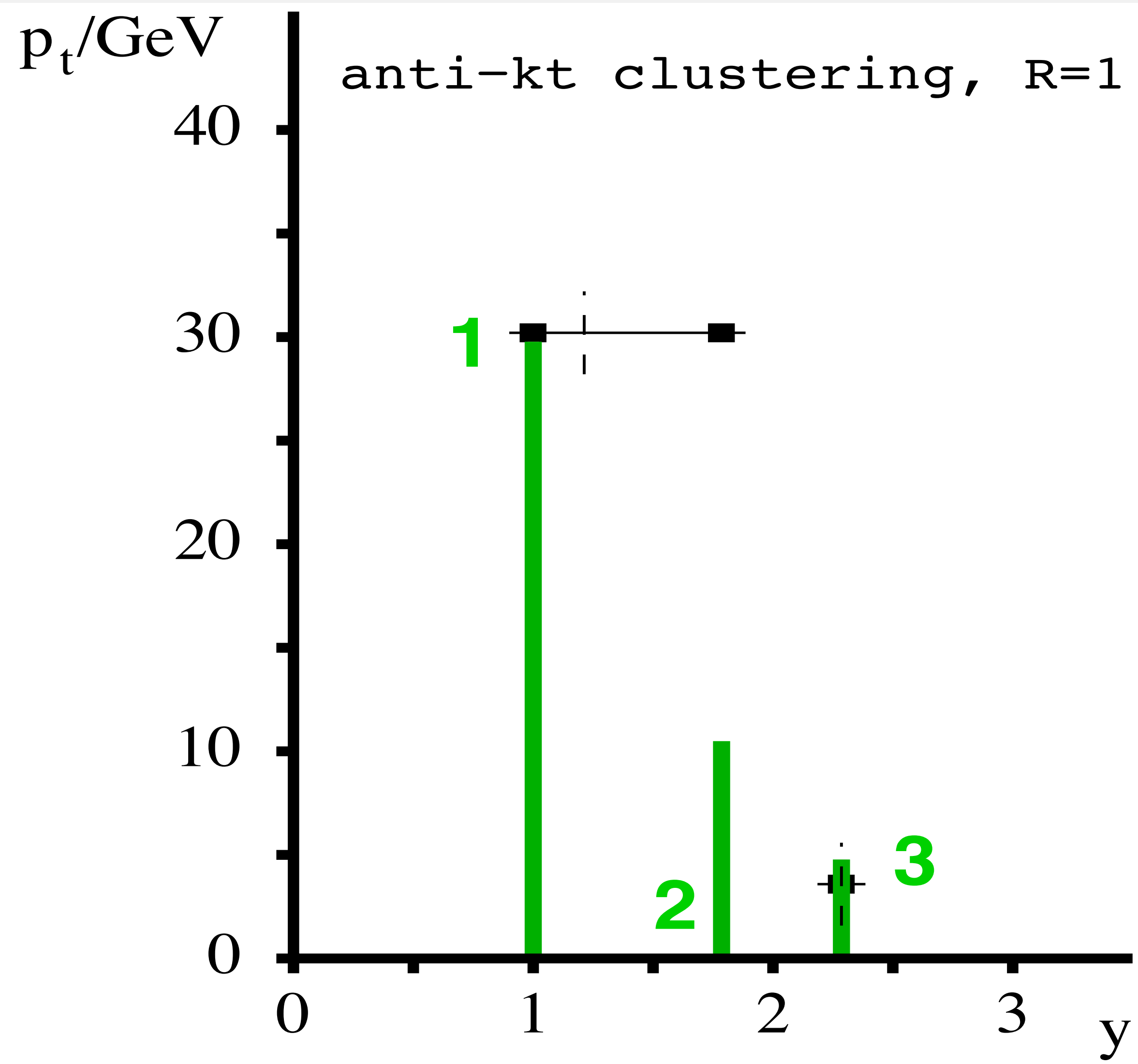
Linearity: k_t v. anti-k_t

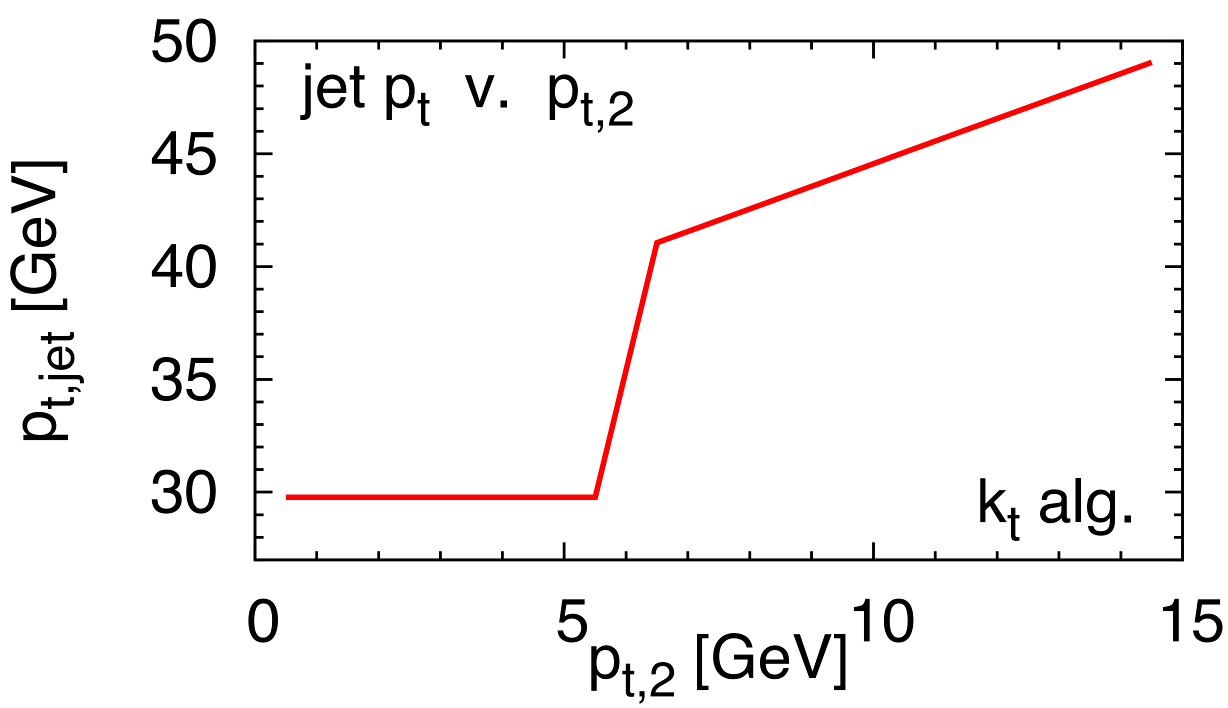




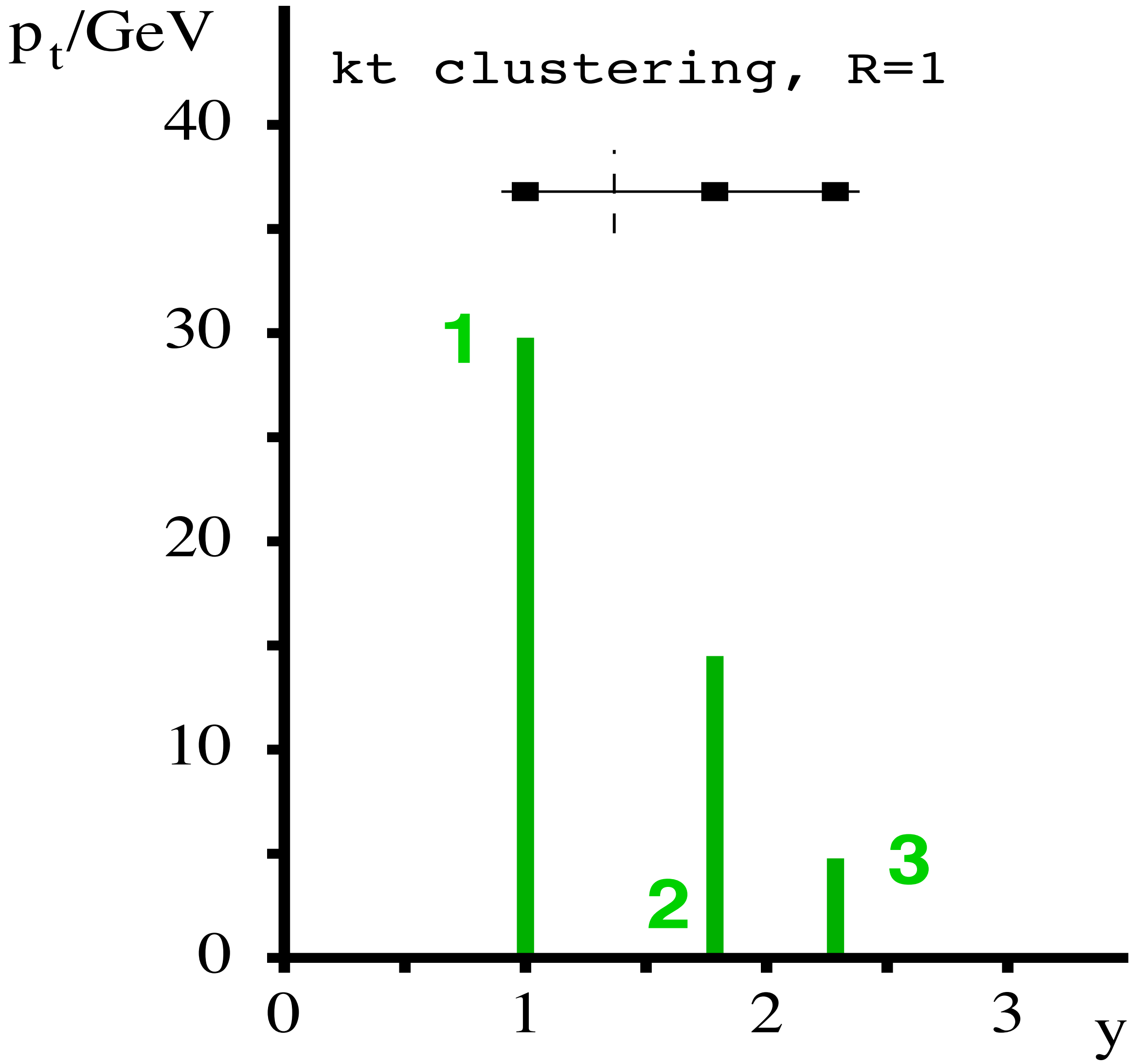
Linearity: k_t v. anti-k_t

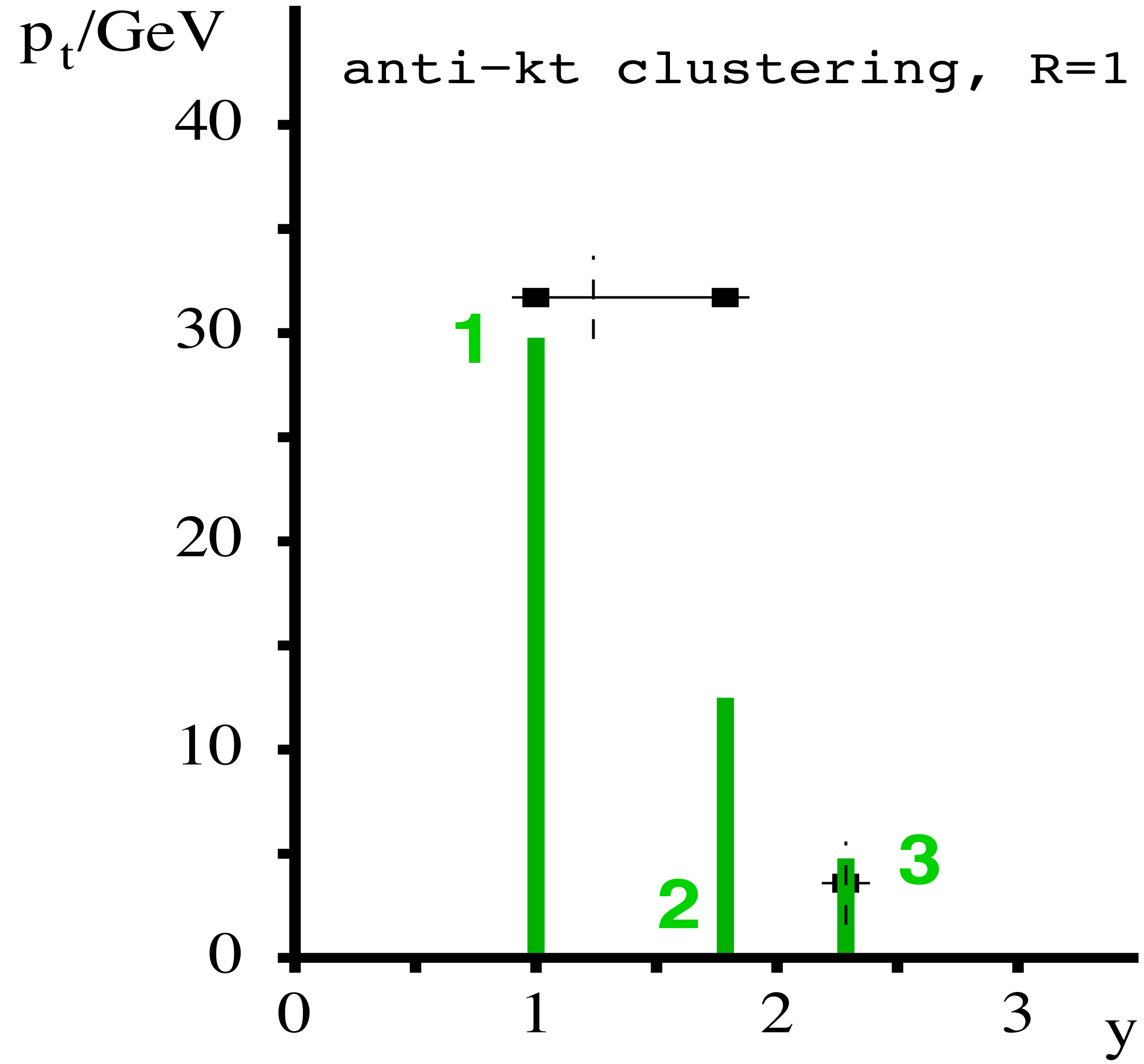


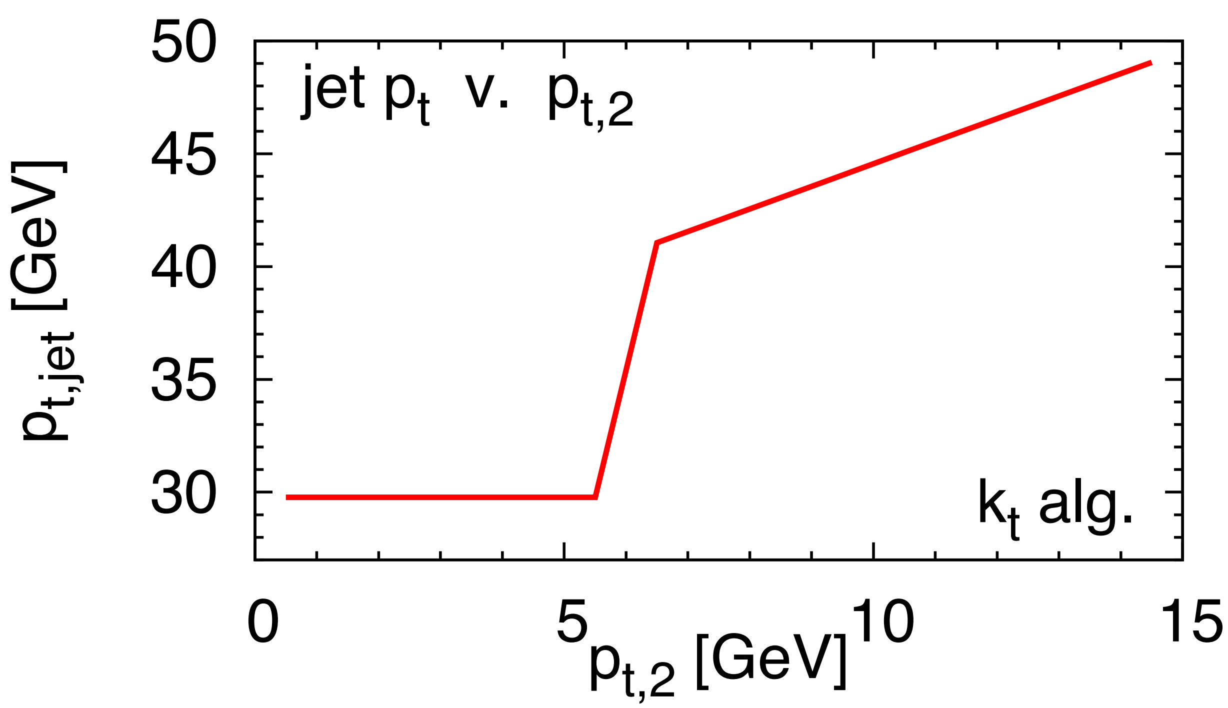




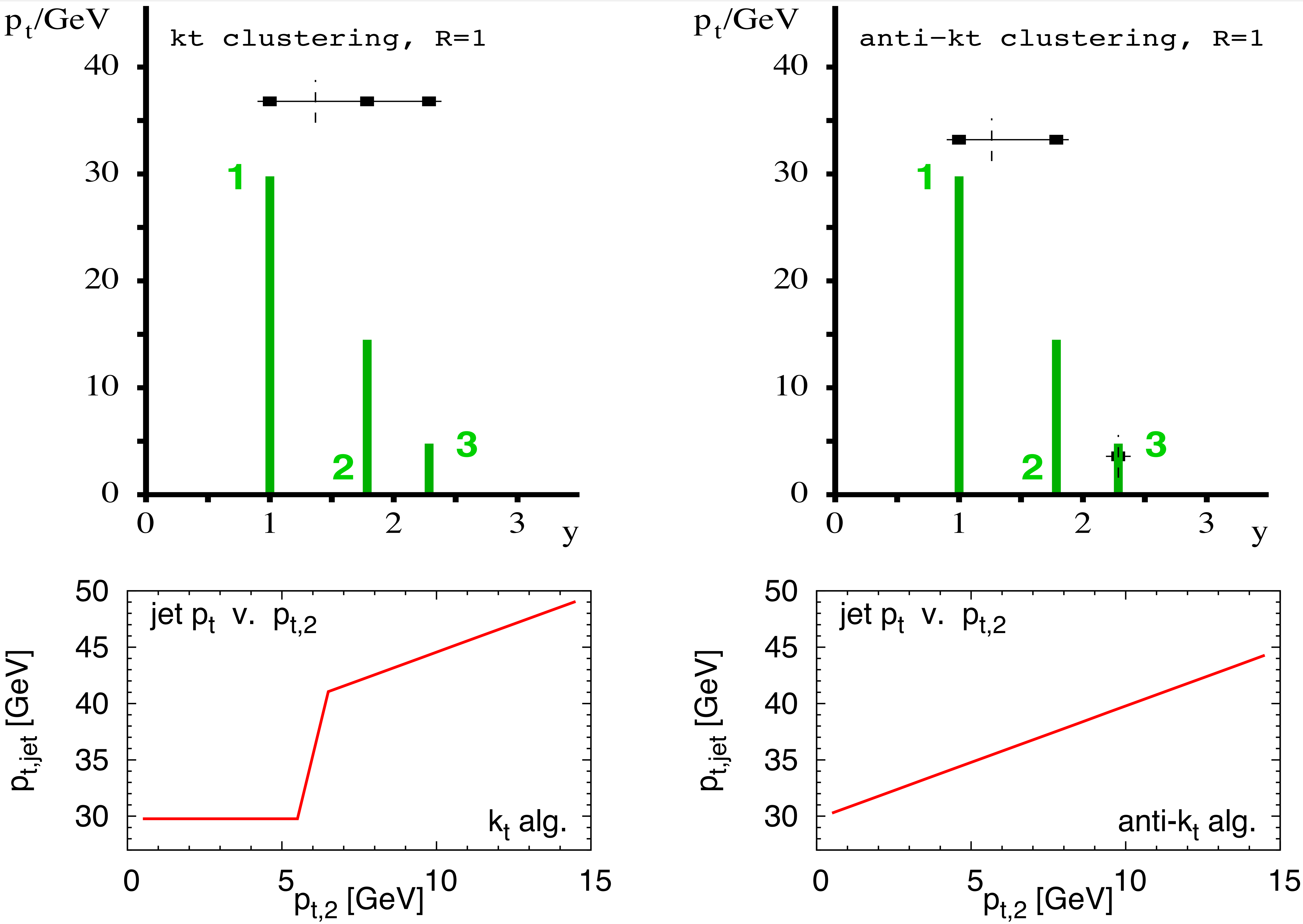
Linearity: k_t v. anti-k_t



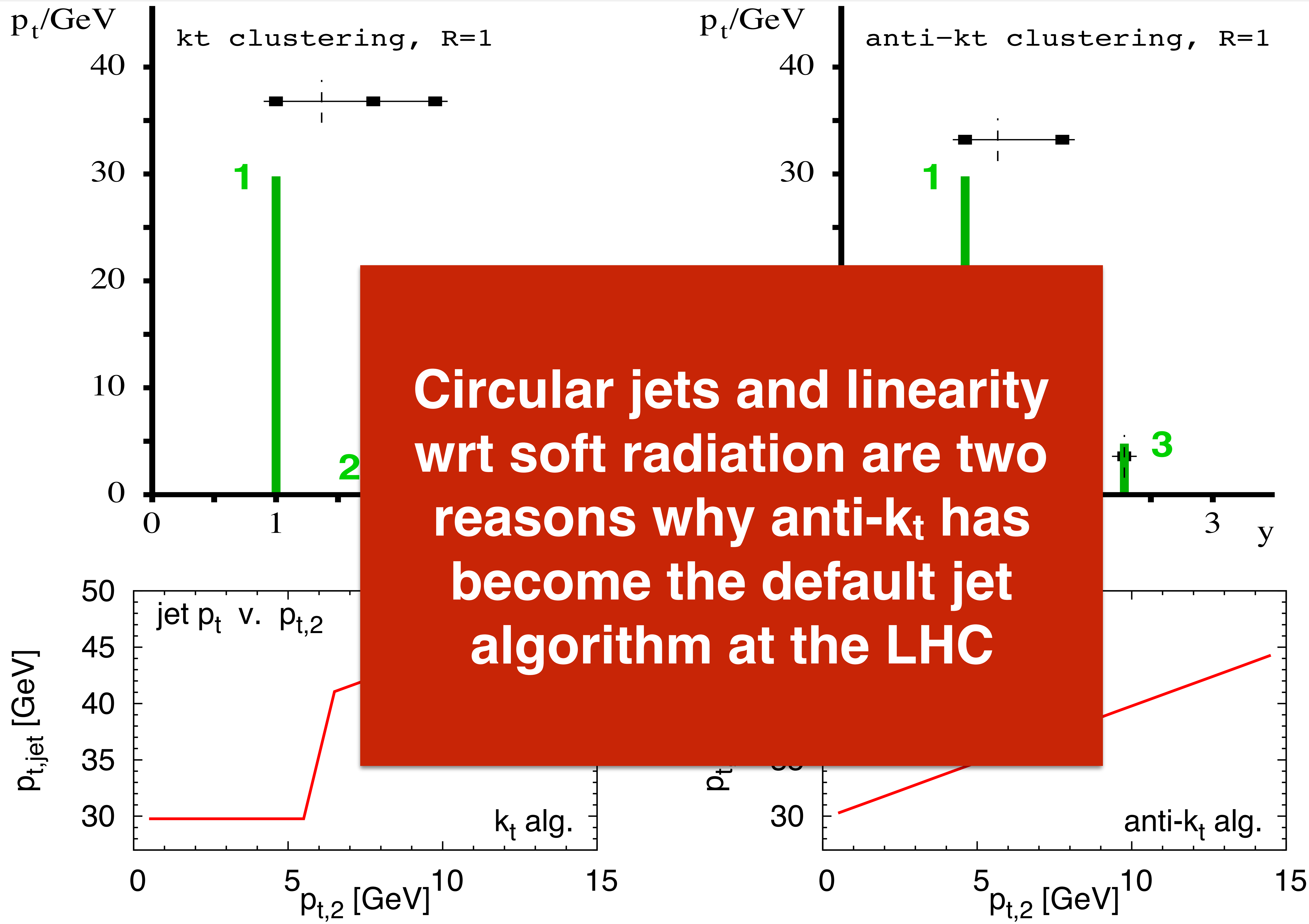




Linearity: k_t v. anti-k_t



Linearity: k_t v. anti-k_t



Circular jets and linearity wrt soft radiation are two reasons why anti-k_t has become the default jet algorithm at the LHC

```
// specify a jet definition
double R = 0.4
JetDefinition jet_def(antikt_algorithm, R);
```

jet_algorithm can be any one of the four IRC safe pp-collider algorithms, or also a variety of e^+e^- algorithms, both native and plugins

```
// specify the input particles
vector<PseudoJet> input_particles = . . .;
```

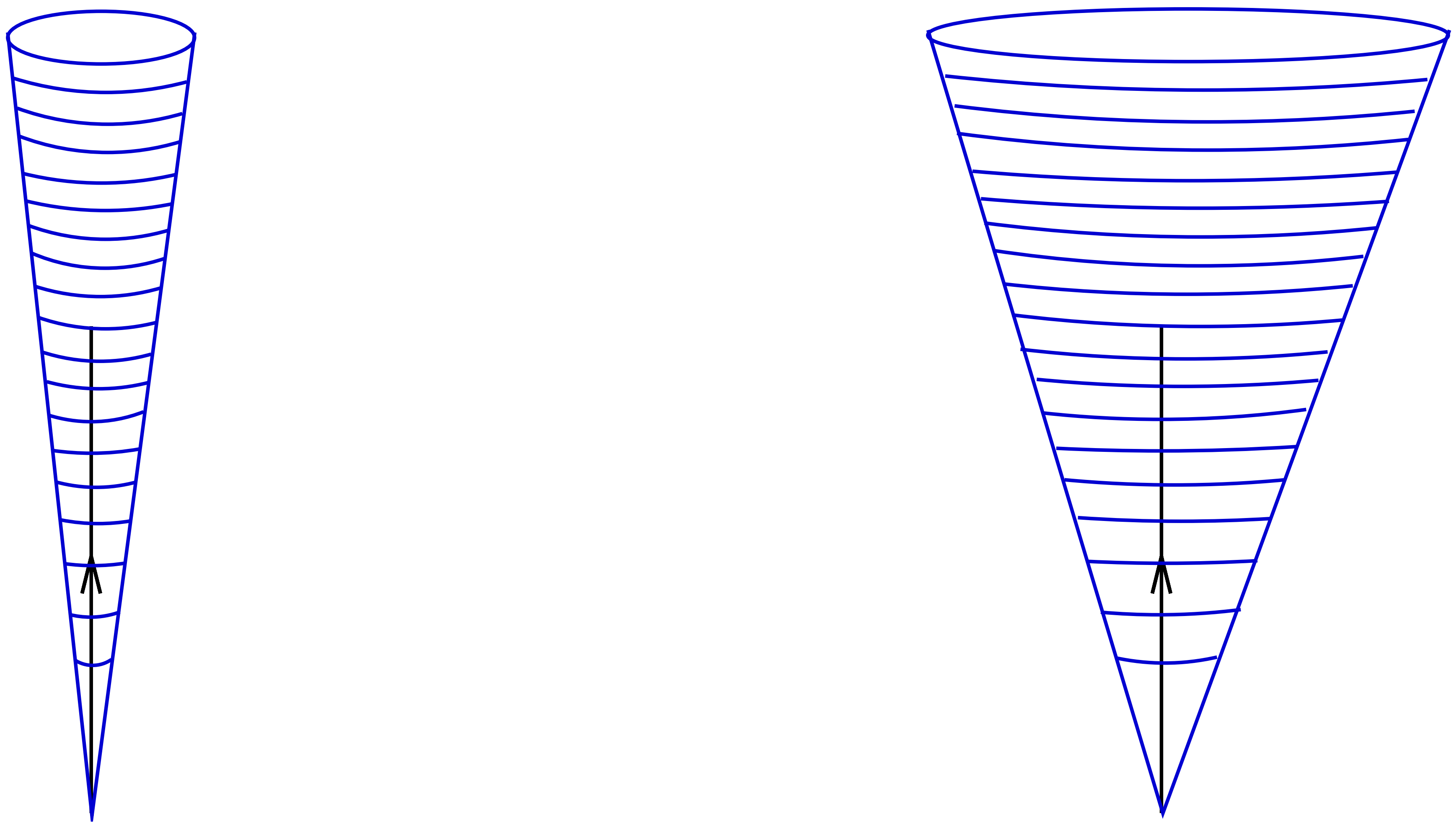
```
// specify a jet definition
double R = 0.4
JetDefinition jet_def(antikt_algorithm, R);
```

jet_algorithm can be any one of the four IRC safe pp-collider algorithms, or also a variety of e^+e^- algorithms, both native and plugins

```
// specify the input particles
vector<PseudoJet> input_particles = . . .;
```

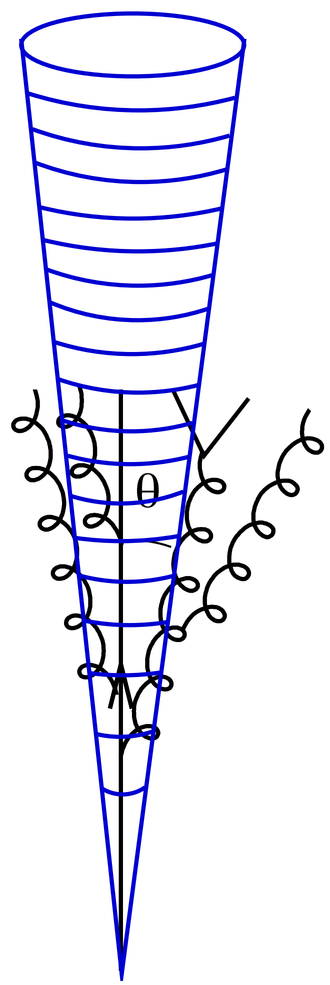
```
// extract the jets
vector<PseudoJet> jets = jet_def(input_particles);

// pt of hardest jet
double pt_hardest = jets[0].pt();

// constituents of hardest jet
vector<PseudoJet> constituents = jets[0].constituents();
```

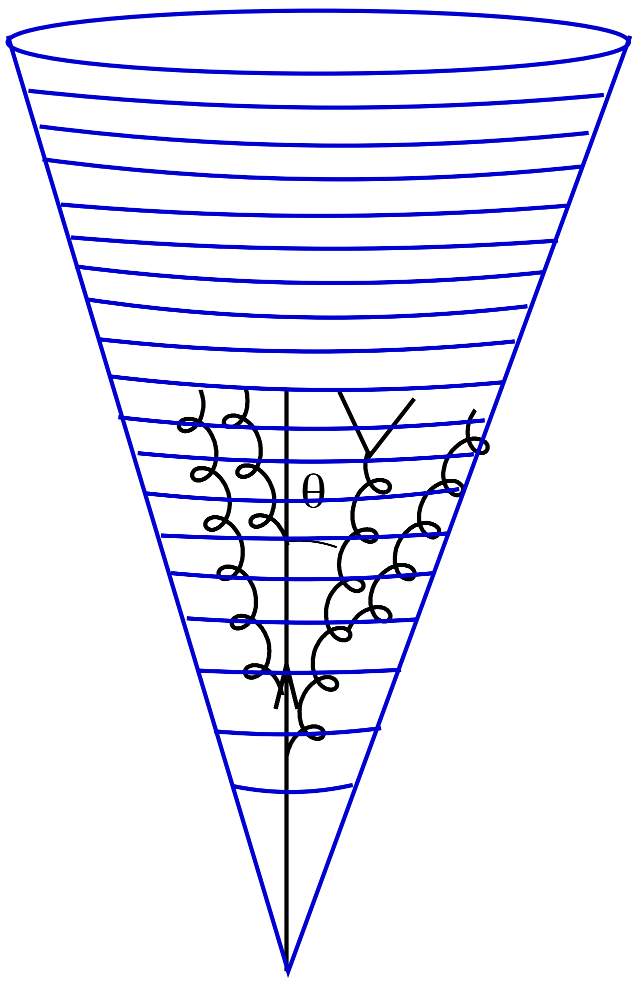
Small jet radius **Large jet radius**



single parton @ LO: **jet radius irrelevant**

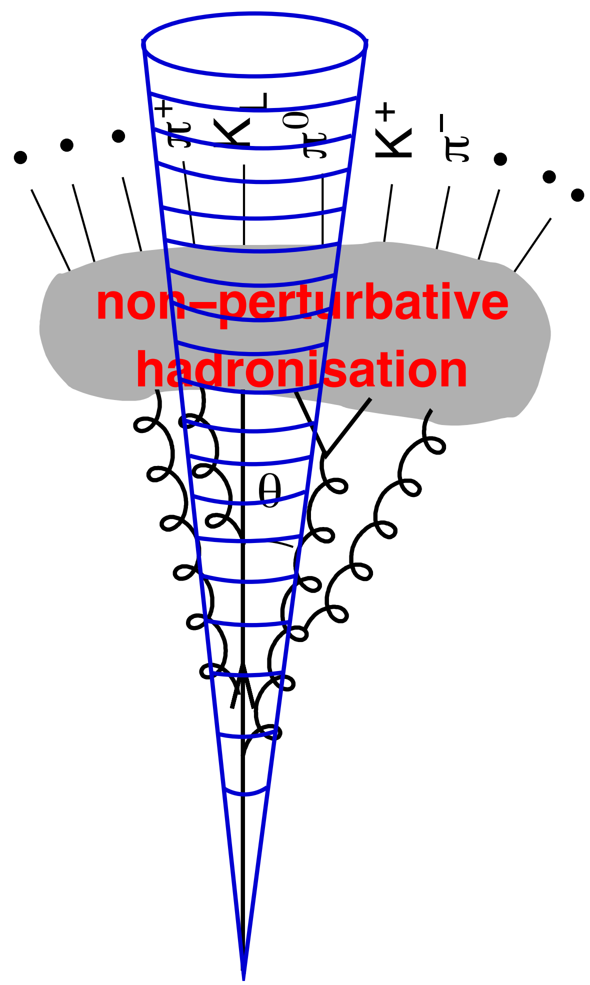
Small jet radius **Large jet radius**

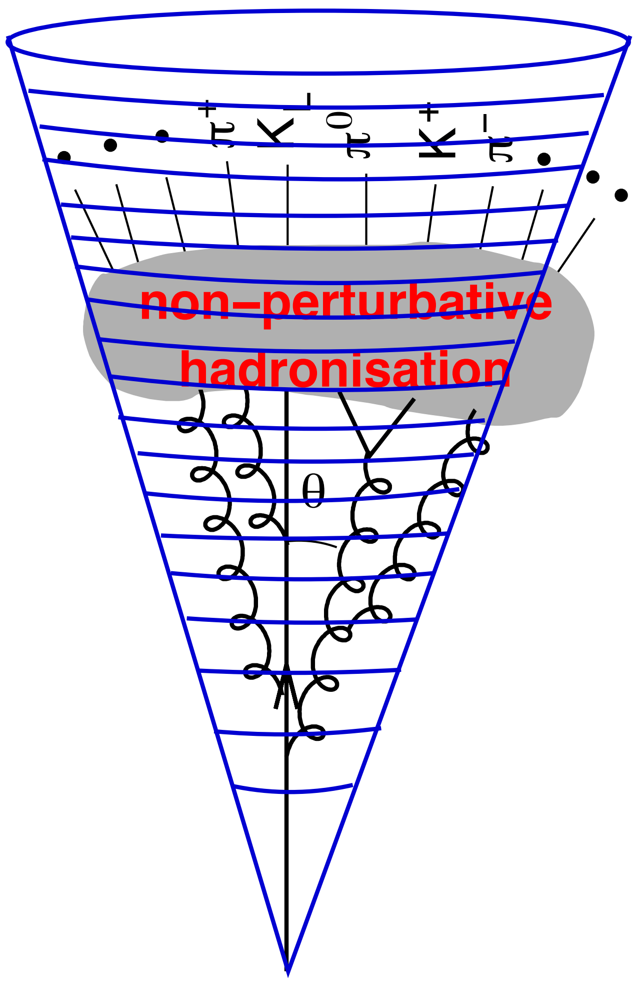




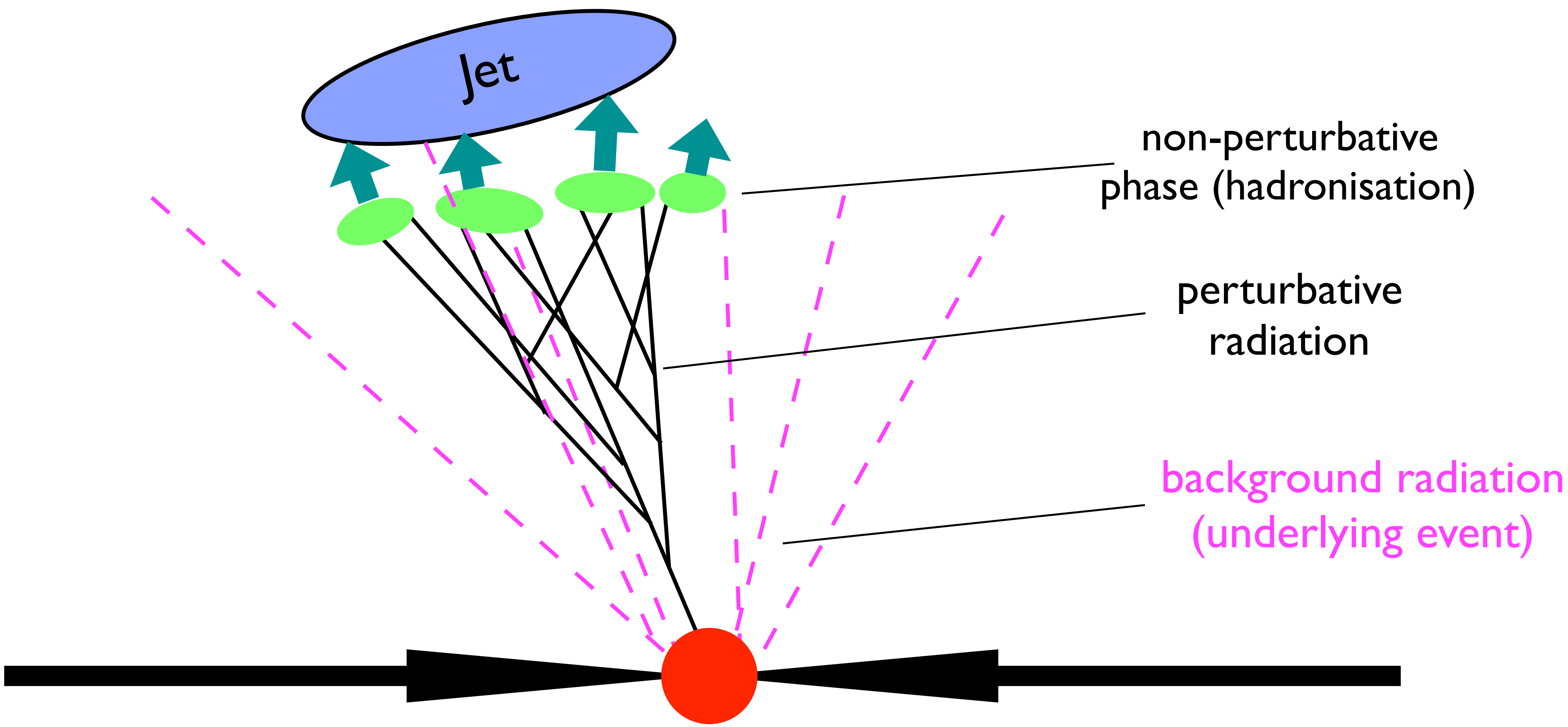
perturbative fragmentation: **large jet radius better**
(it captures more)

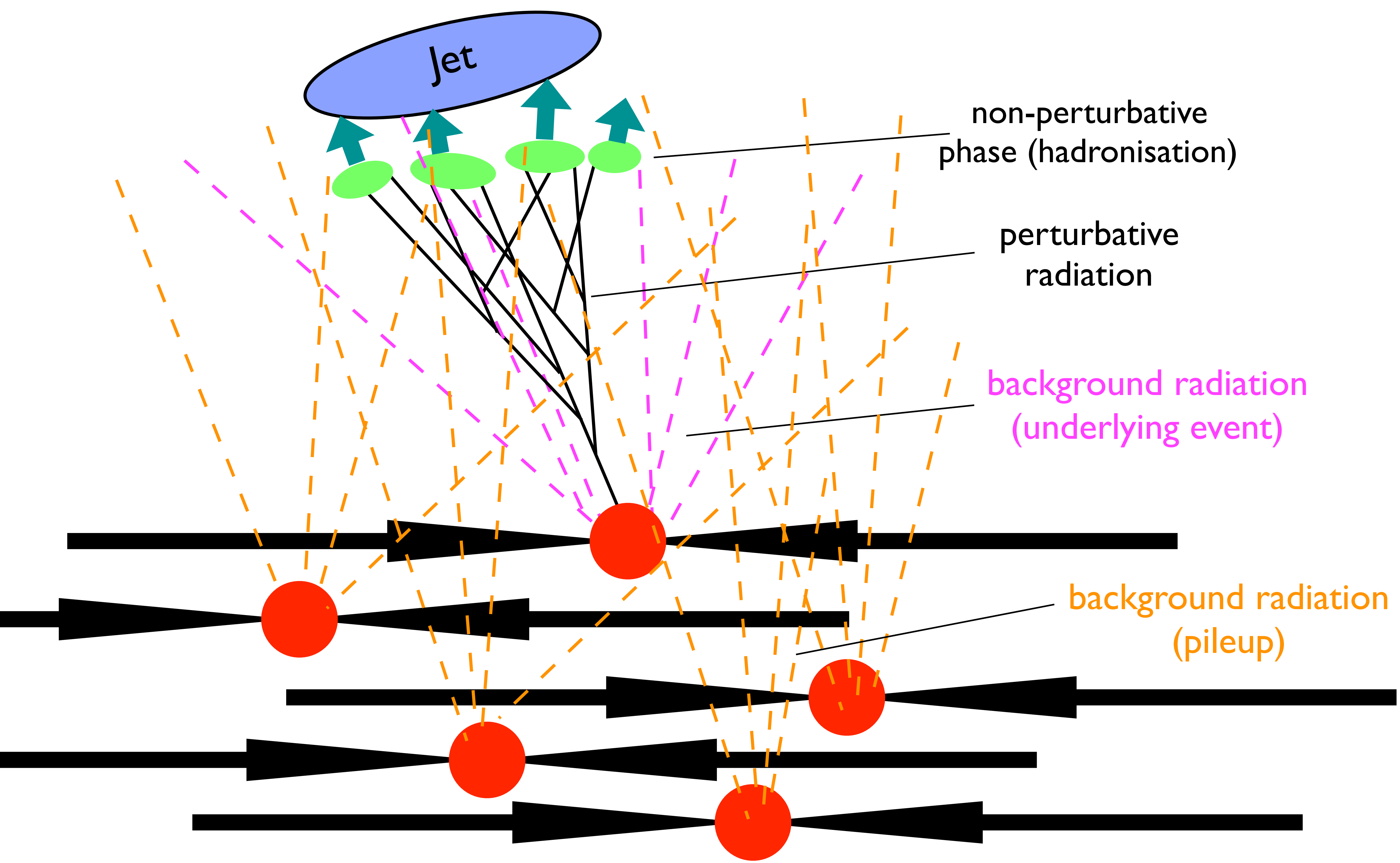
Small jet radius | **Large jet radius**



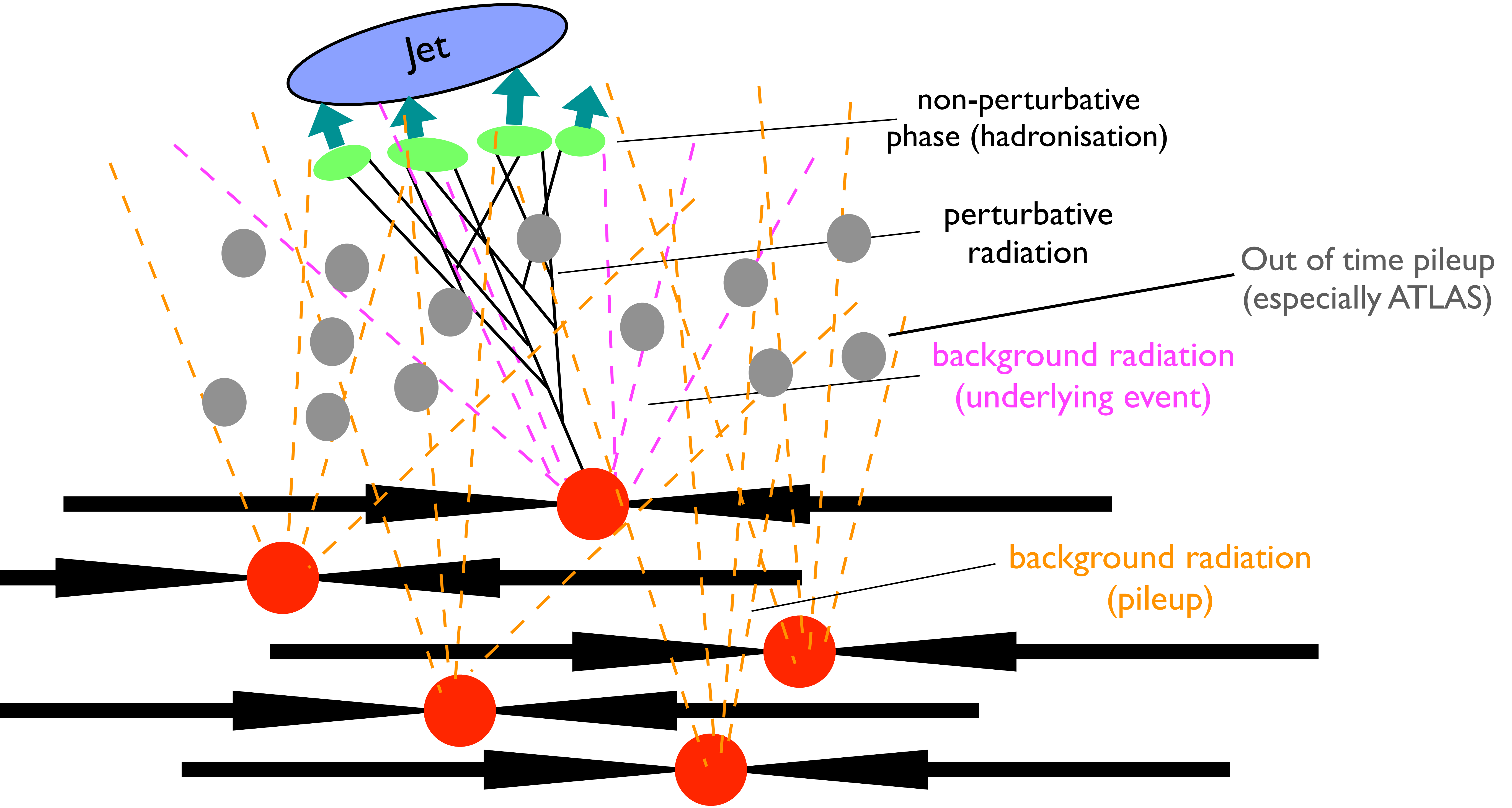


non-perturbative fragmentation: **large jet radius better**
(it captures more)


Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
background radiation
(underlying event)


Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
background radiation
(underlying event)
background radiation
(pileup)

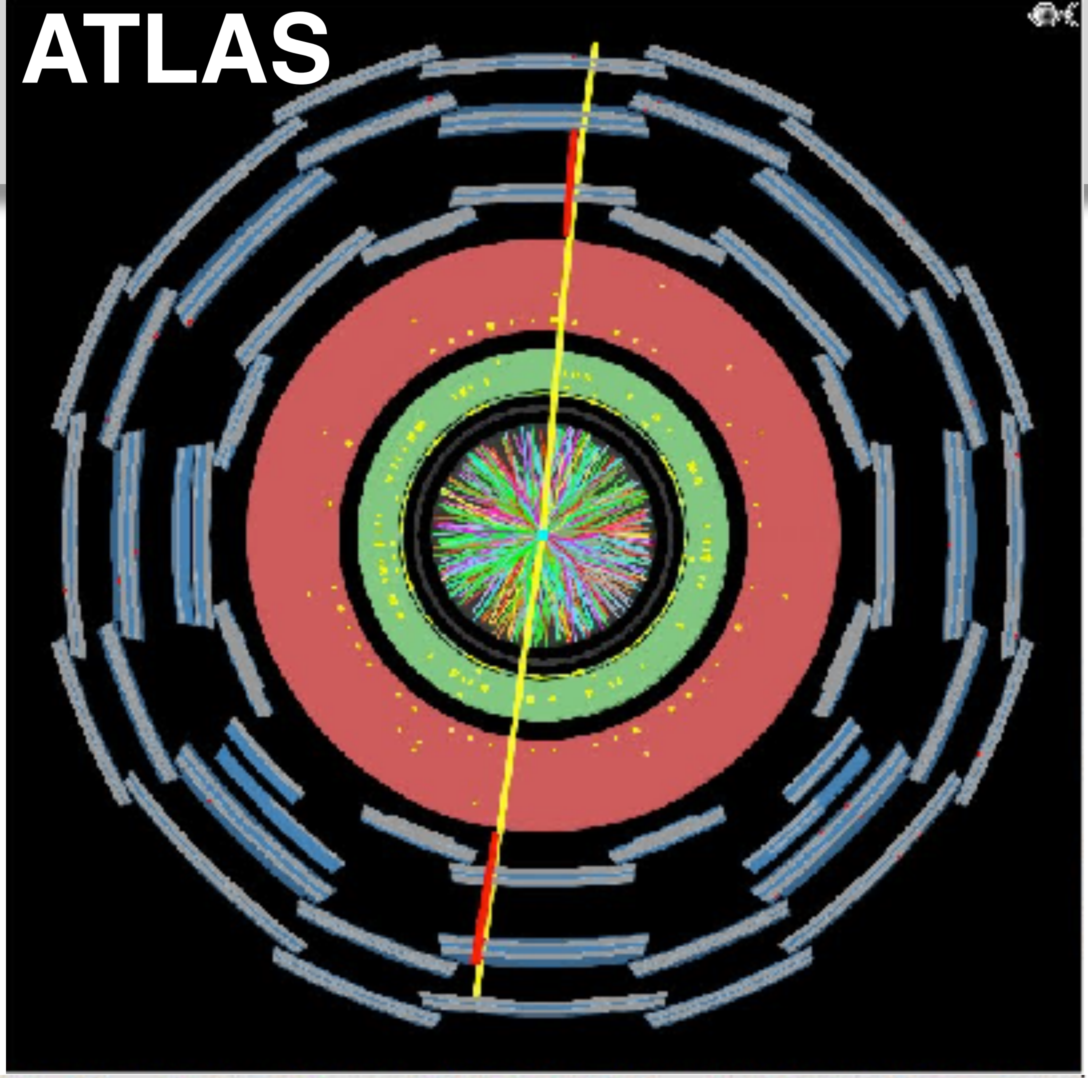
Pileup



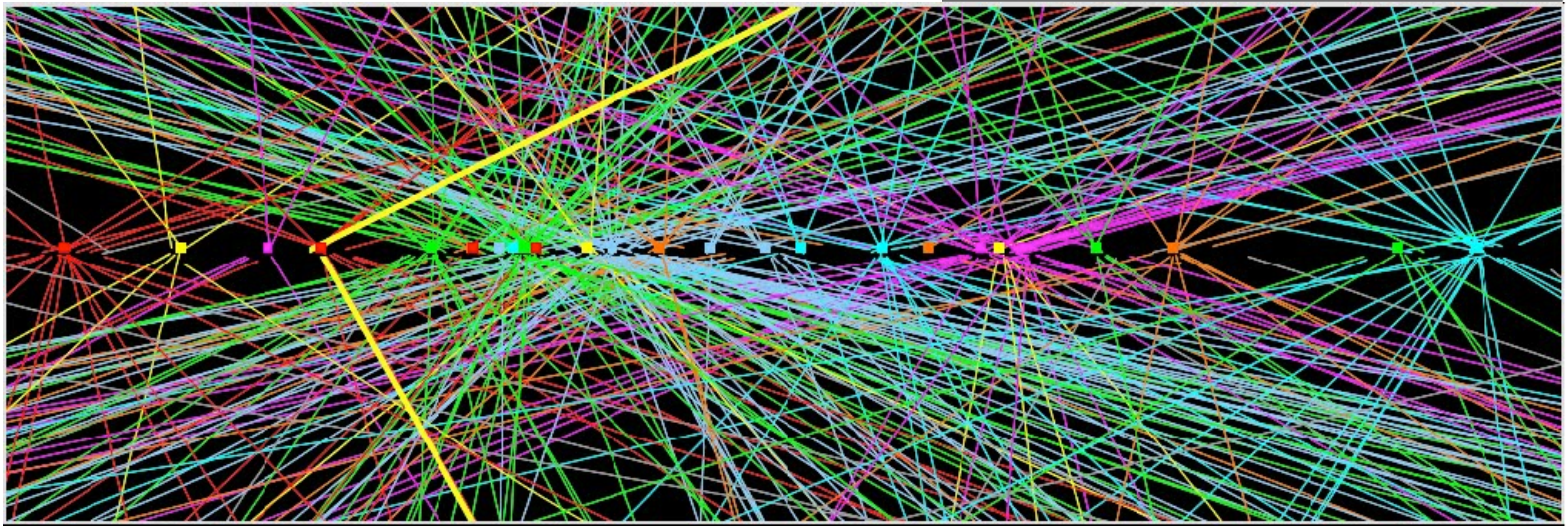
Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
Out of time pileup
(especially ATLAS)
background radiation
(underlying event)
background radiation
(pileup)

Pileup for real

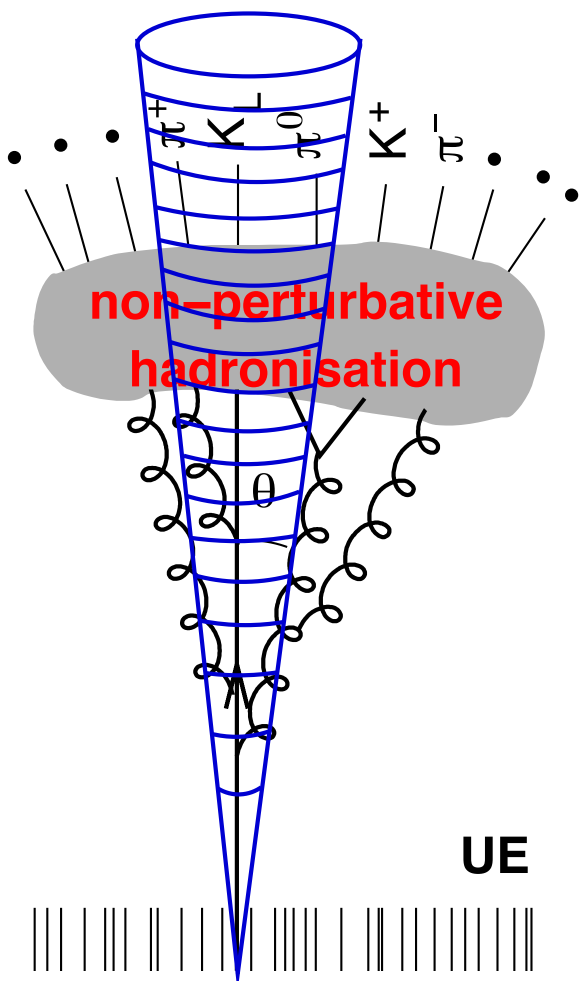
~ 20 m

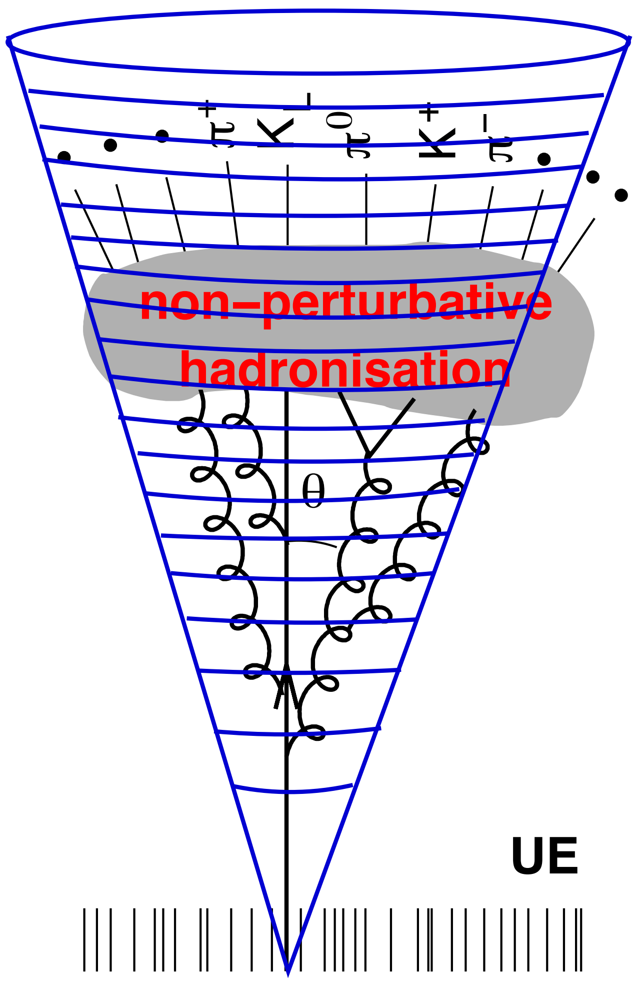


a few cm



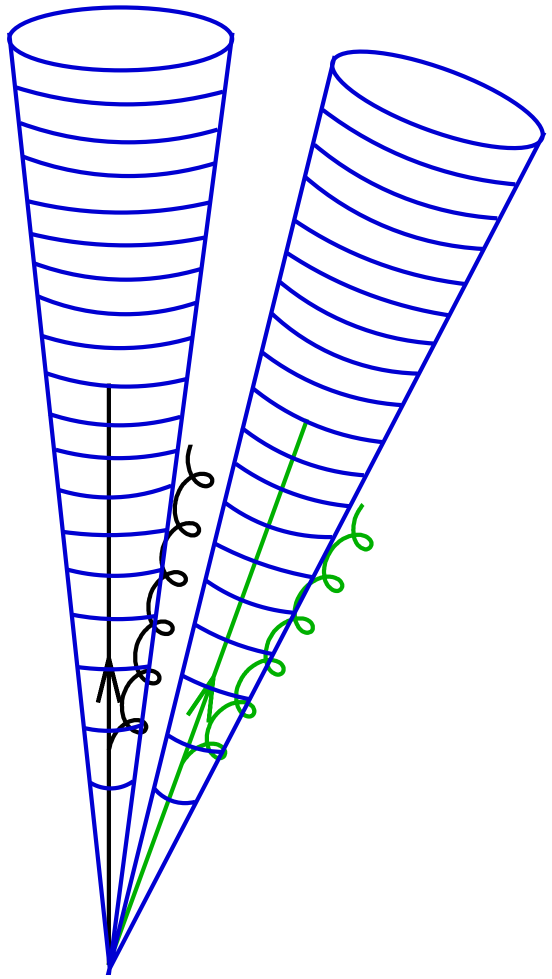
Small jet radius | **Large jet radius**

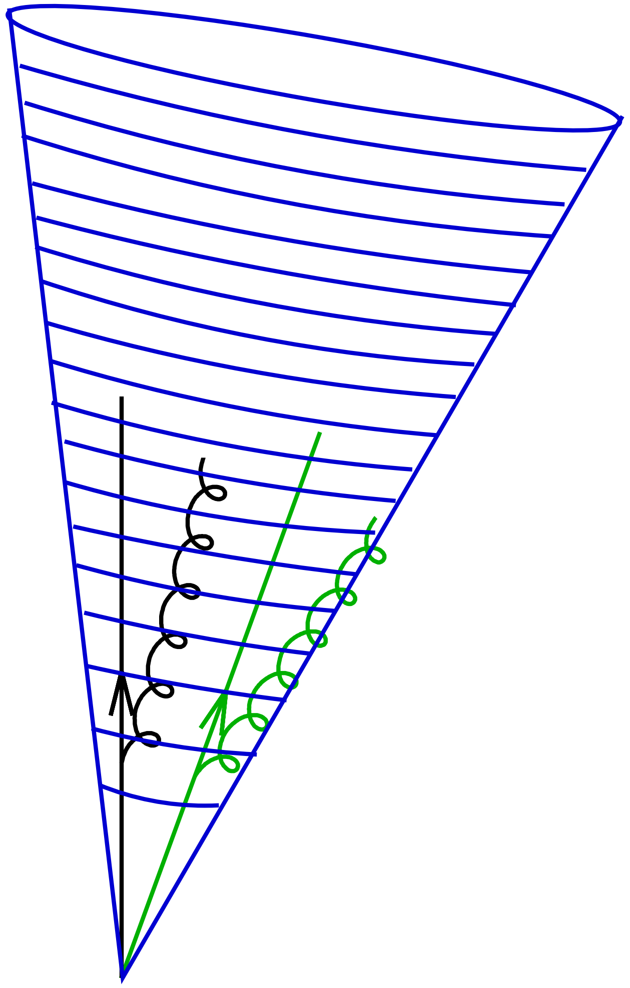




underlying ev. & pileup “noise”: **small jet radius better**
(it captures less)

Small jet radius **Large jet radius**





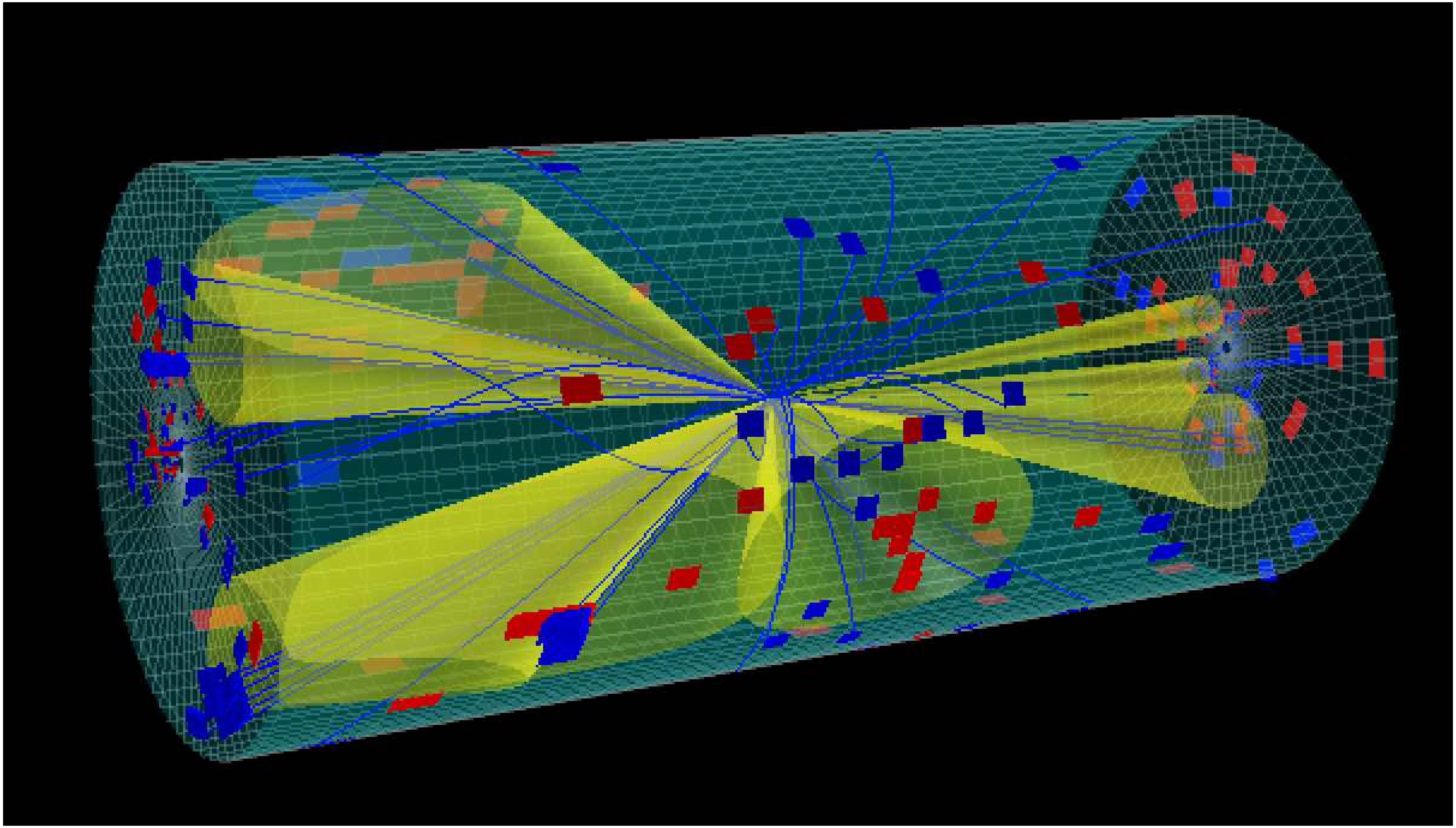
multi-hard-parton events: **small jet radius better**
(it resolves partons more effectively)

Can we capture all quarks and gluons?

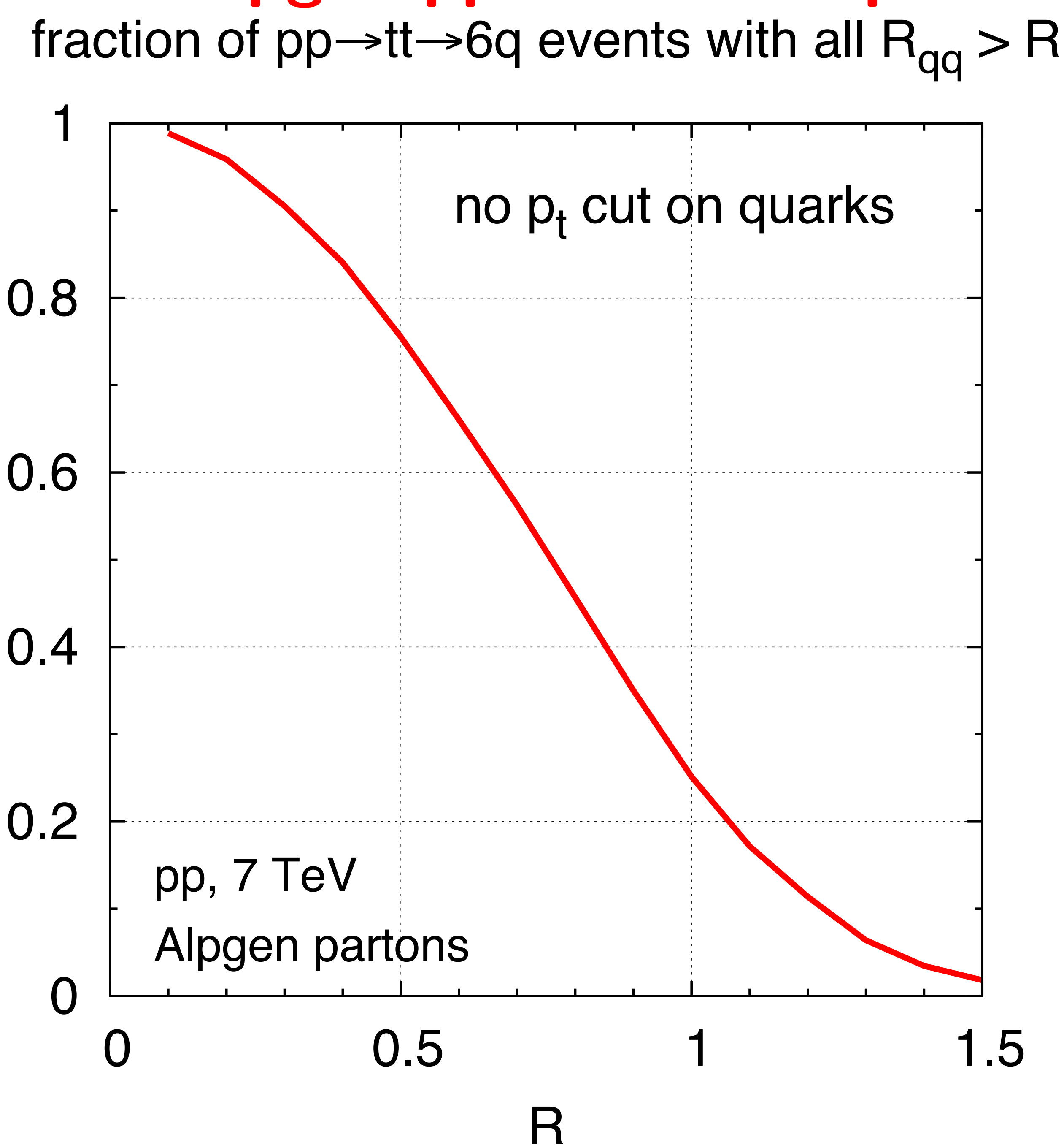
Should we capture all quarks and gluons?

$pp \to t\bar{t}$

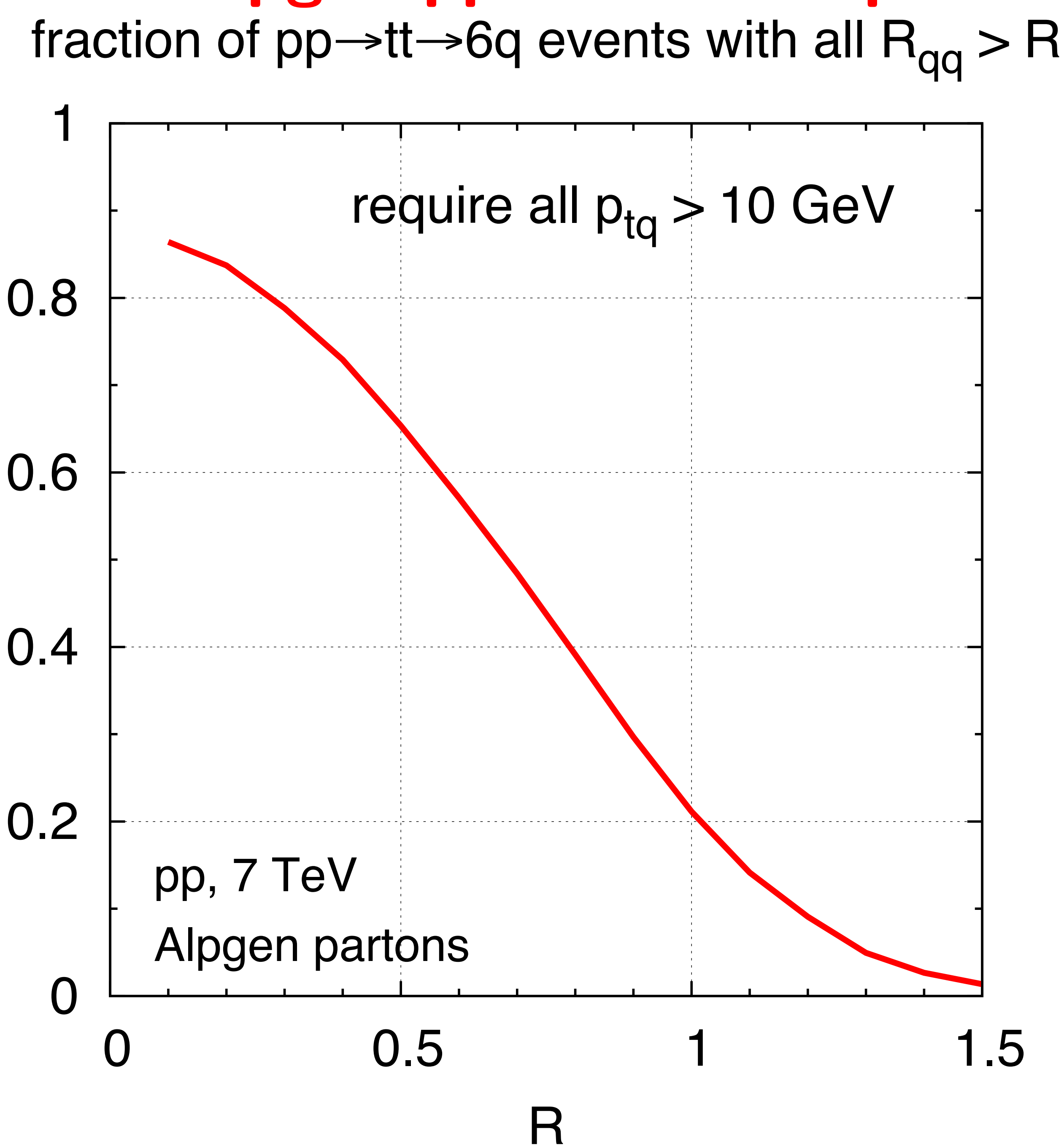
simulated with Pythia, displayed with Delphes



Alpgen $pp \to t\bar{t} \to 6q$



Alpgen $pp \to t\bar{t} \to 6q$



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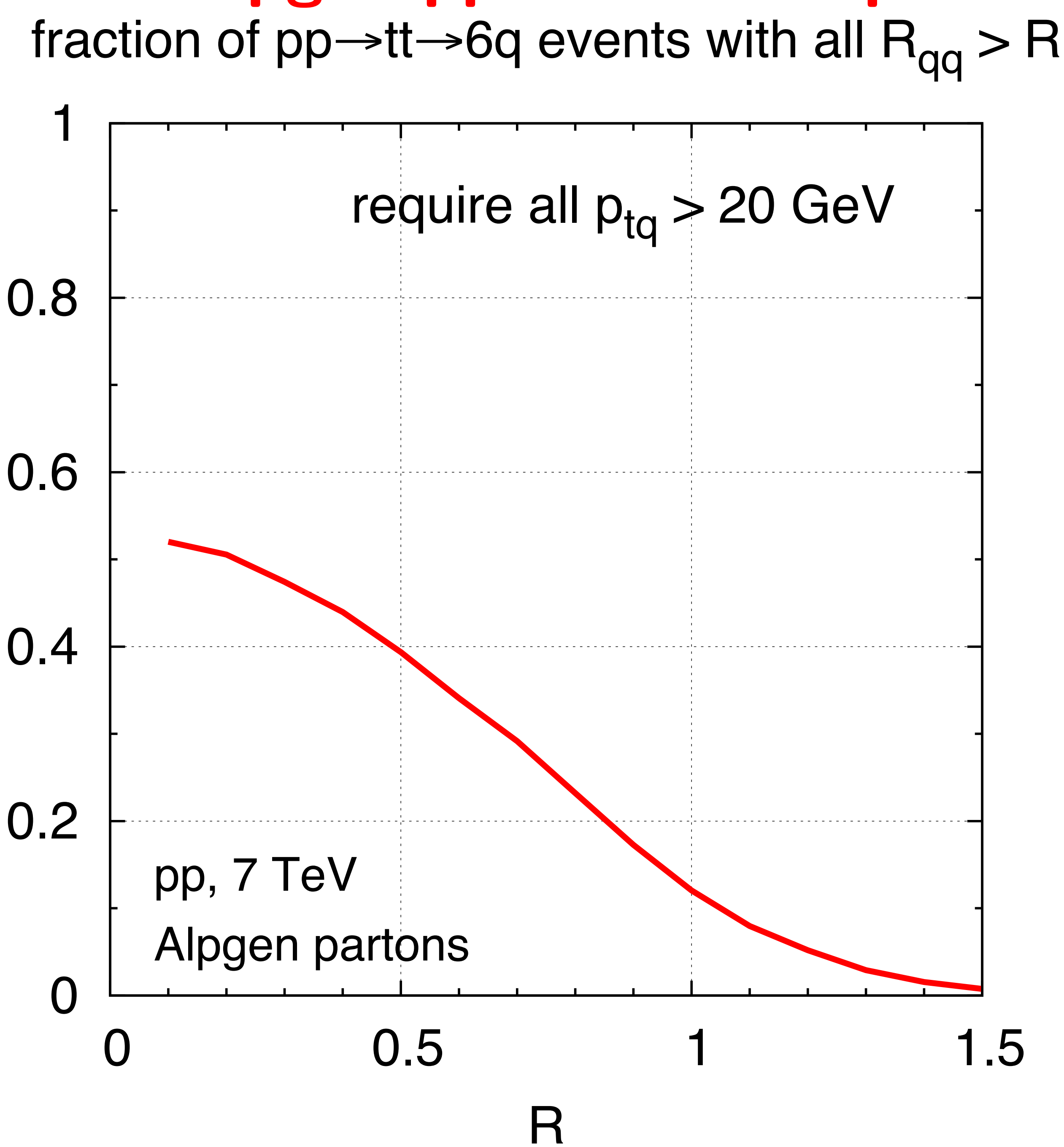
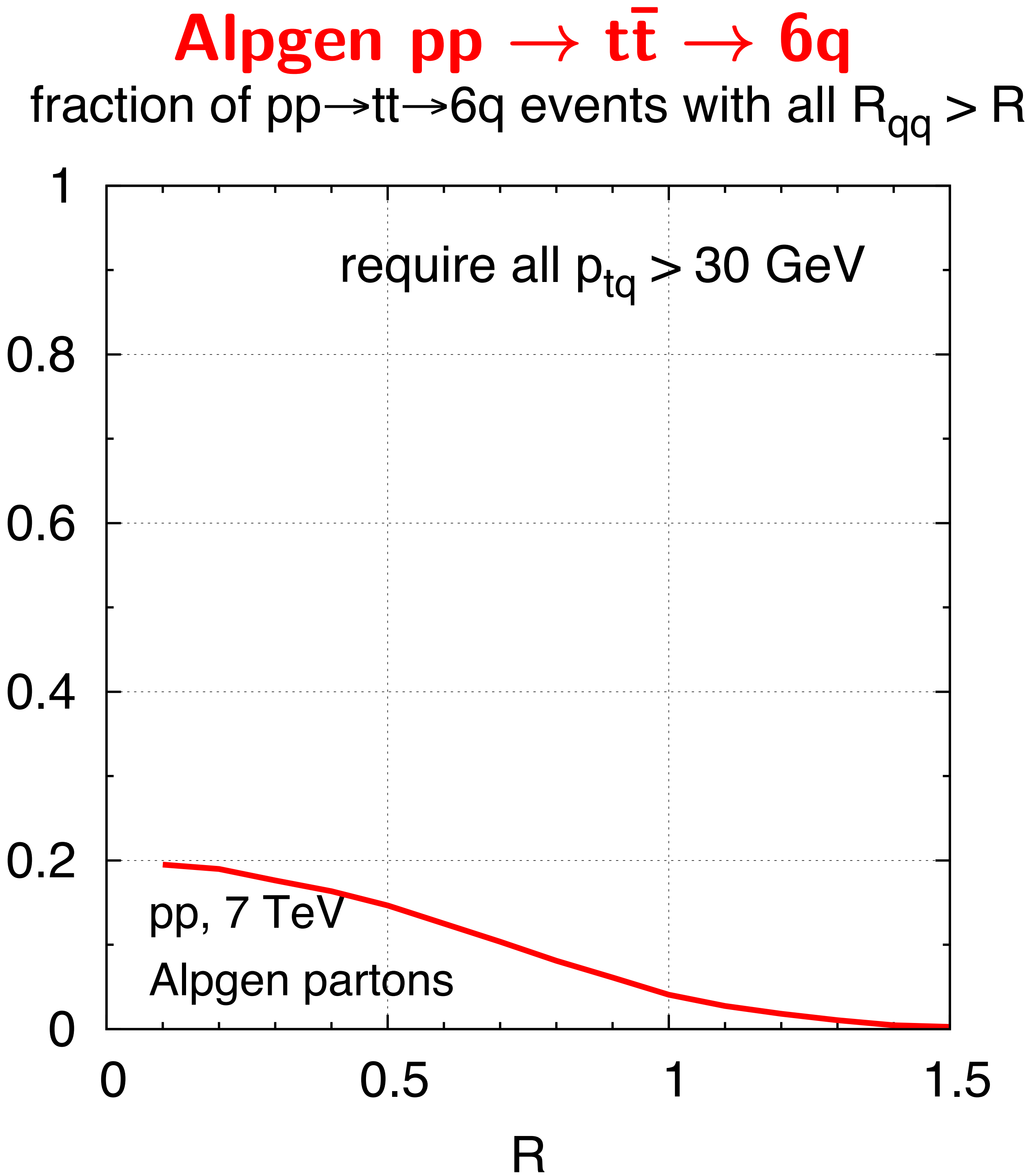
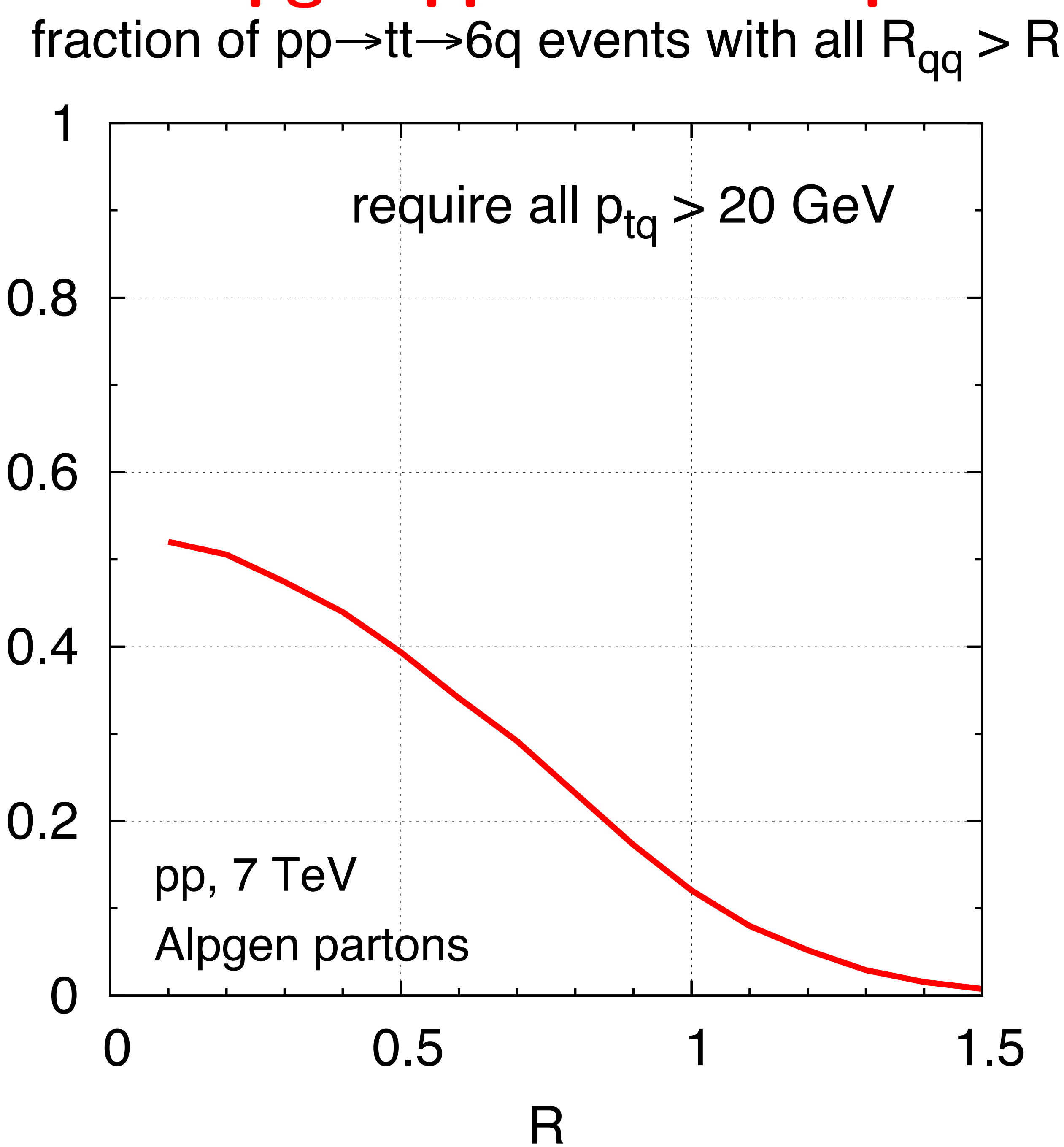


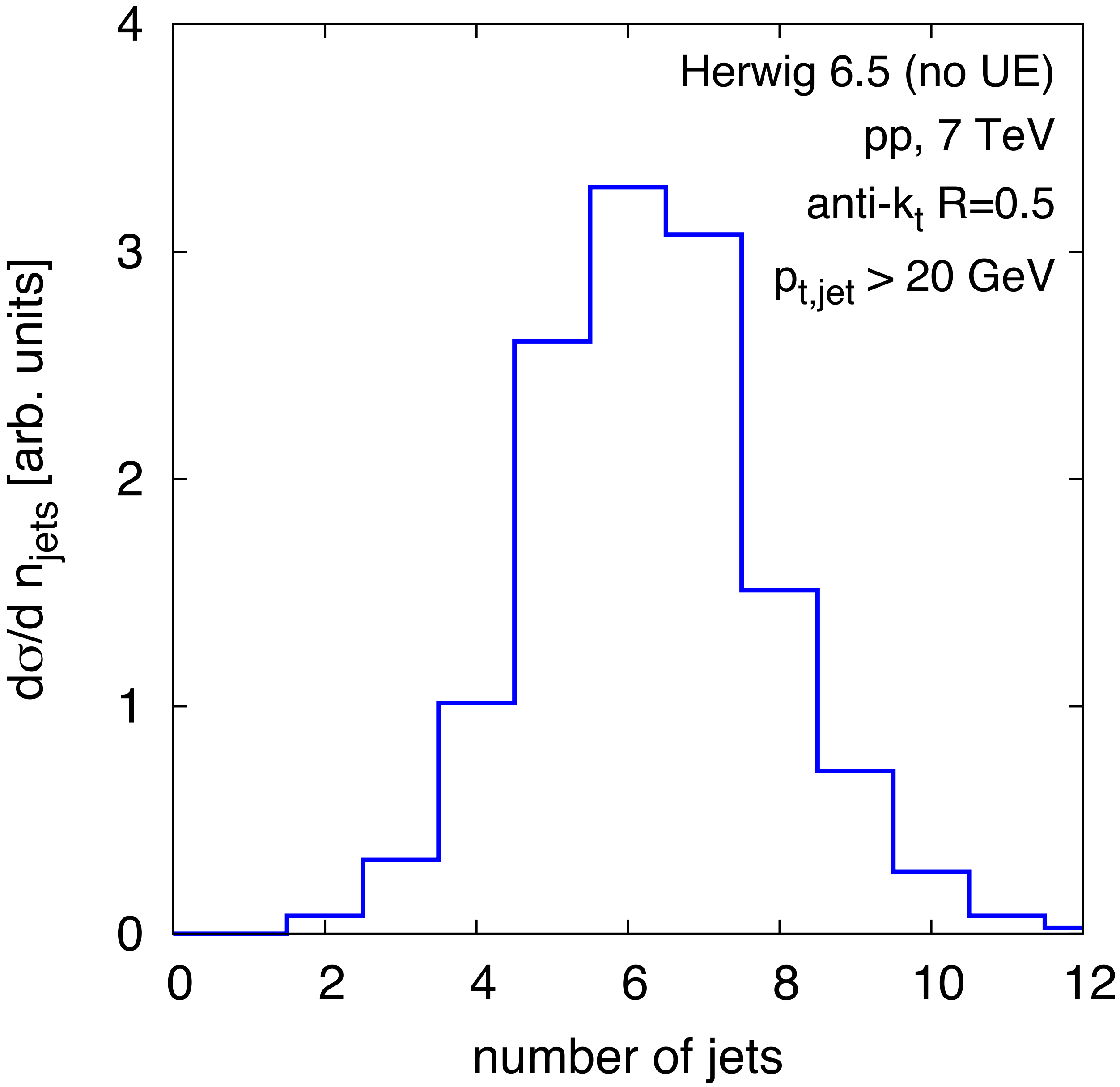

Alpgen pp → $t\bar{t}$ → 6q
fraction of pp→tt→6q events with all R_{qq} > R
require all p_{tq} > 30 GeV
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

Alpgen pp → $t\bar{t}$ → 6q



Herwig pp → $t\bar{t}$ → hadrons

Distribution of number of jets



Two things that make jets@LHC special

The large hierarchy of scales

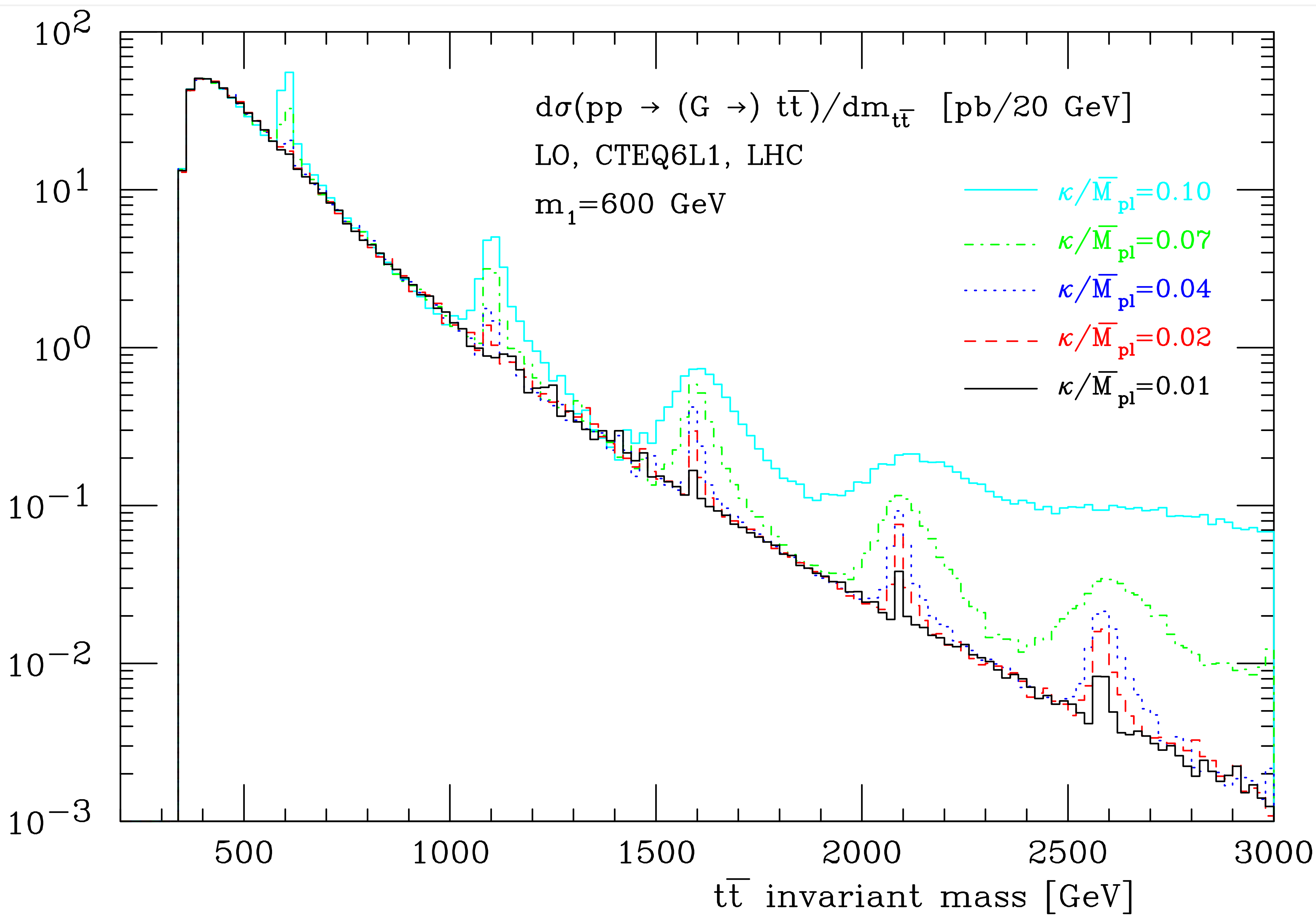
$$\sqrt{s} \gg M_{EW}$$

The huge pileup

$$n_{pileup} \sim 20 - 40 \; (\rightarrow 140 \text{ at HL-LHC})$$

[These involve two opposite extremes: low p_t and high p_t, which nevertheless talk to each other]

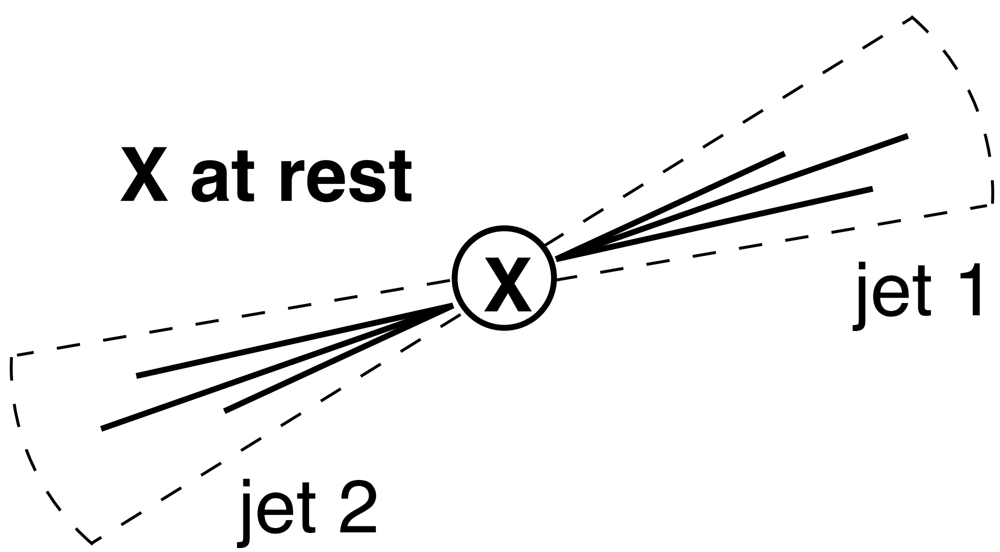
e.g. ttbar resonances



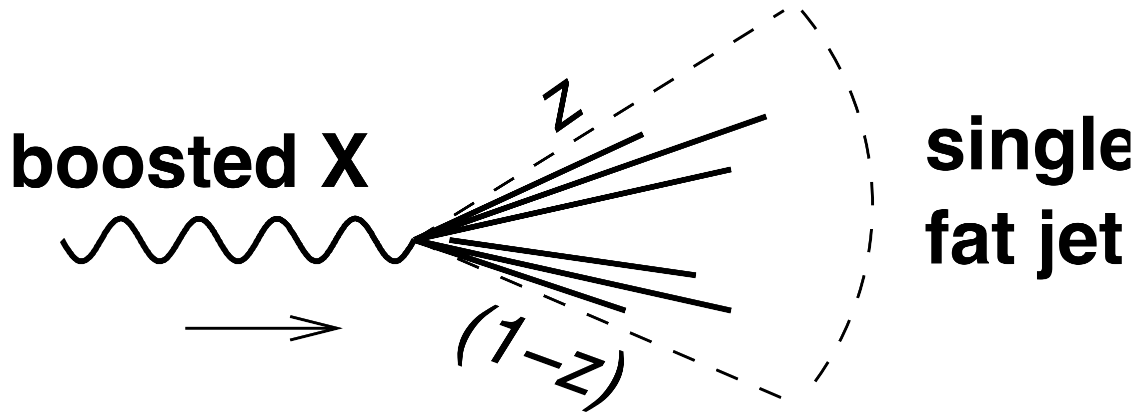
RS KK resonances $\to t\bar{t}$, from Frederix & Maltoni, 0712.2355

NB: QCD dijet spectrum is $\sim 10^3$ times $t\bar{t}$

Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

Two widely used terms
though there's not a
consensus about
what they mean

Tagging

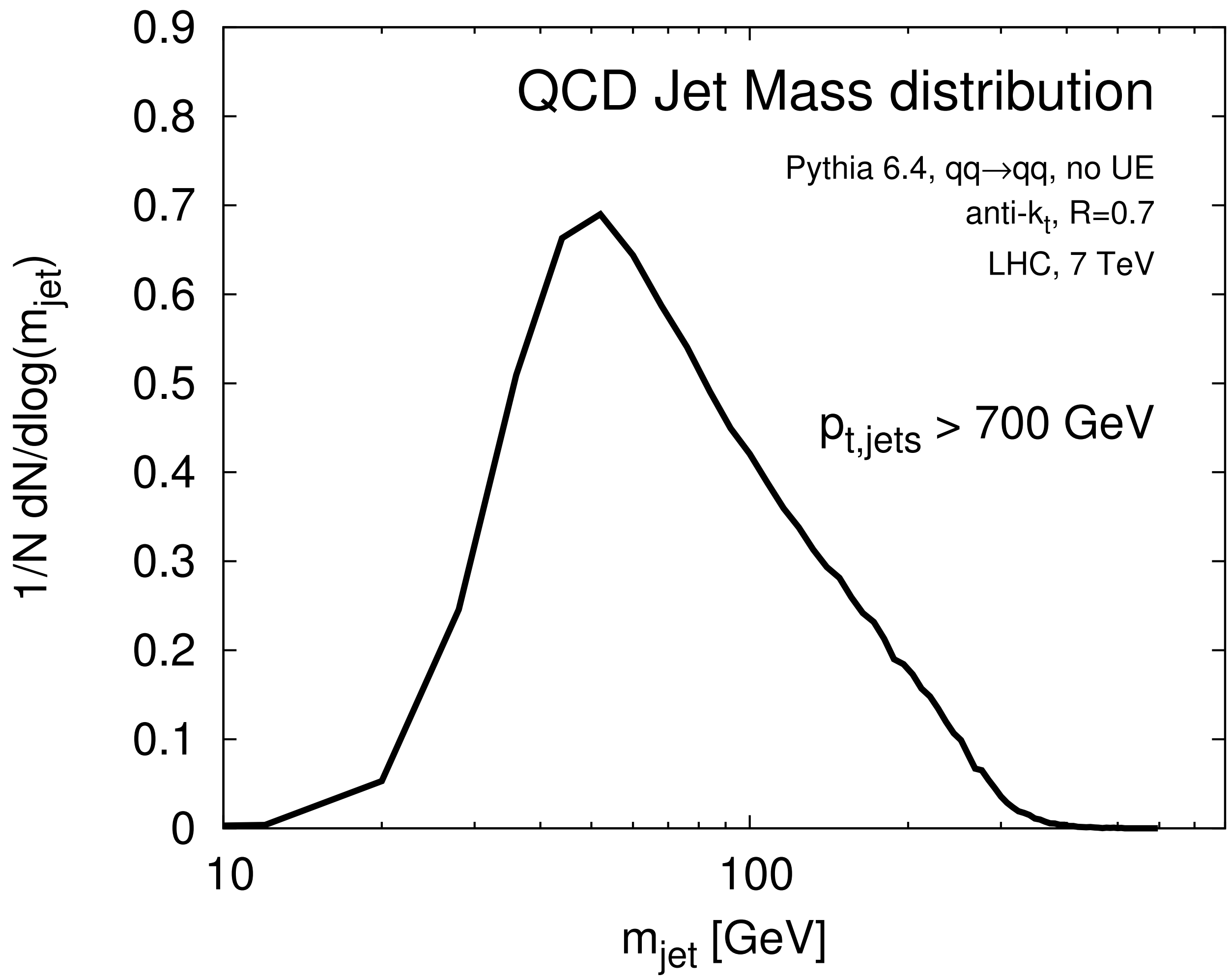
- reduces the background, leaves much of signal
- you can tag with underlying hard n-prong structure and based on radiation pattern

Grooming

- improves signal mass resolution (removing pileup, etc.), without significantly changing background & signal event numbers

One core idea for tagging

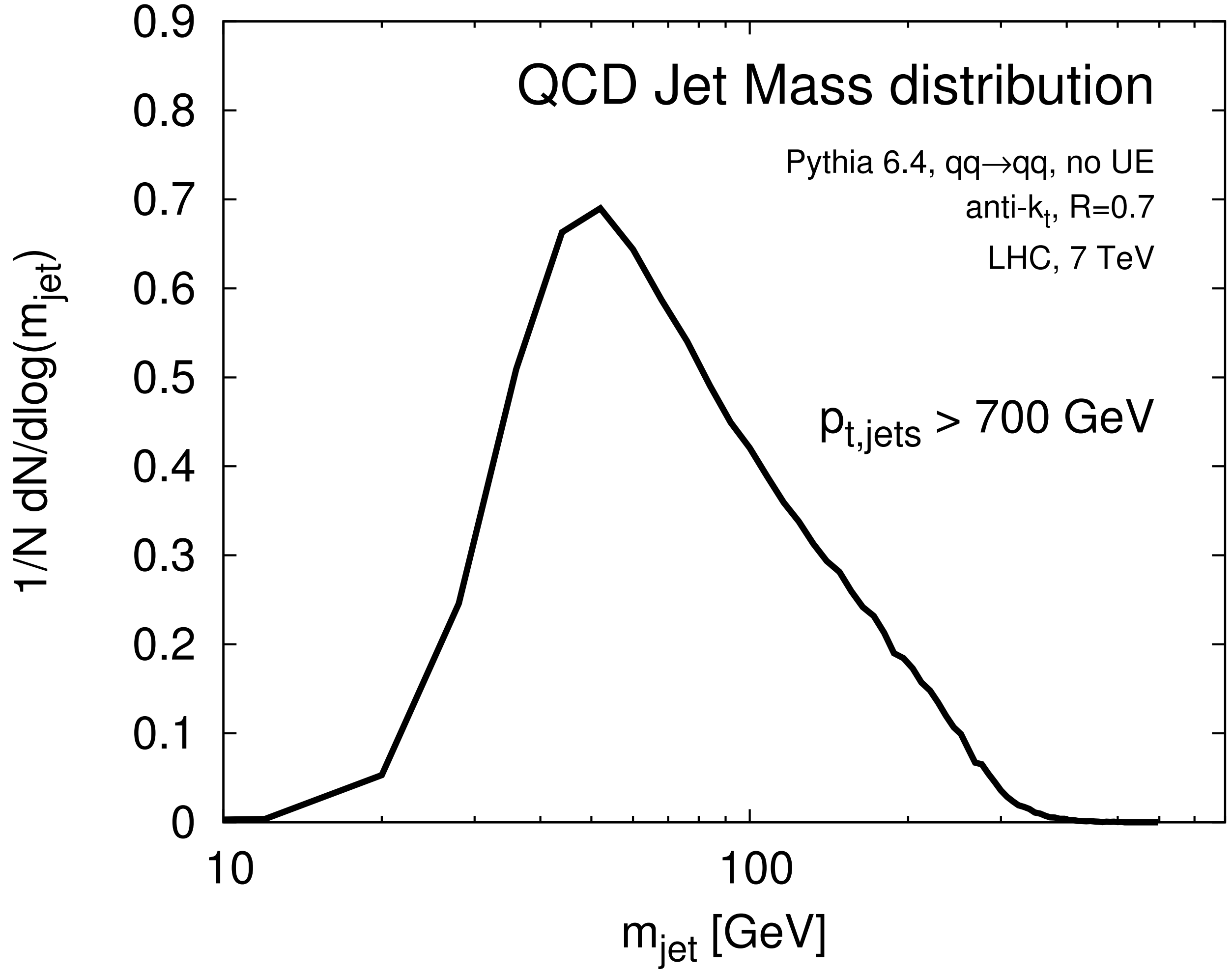
Inside the jet mass

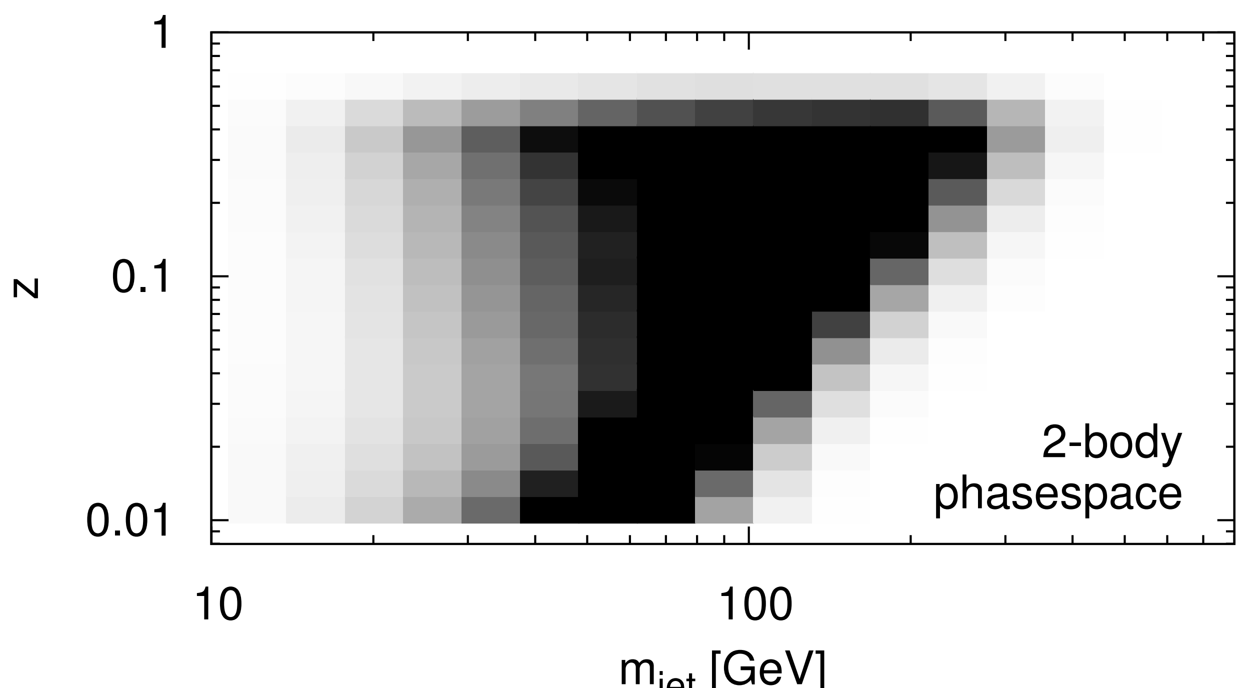


QCD jet mass distribution has the approximate

$$\frac{dN}{d\ln m} \sim \alpha_s \ln \frac{p_t R}{m} \times \text{Sudakov}$$

Work from '80s and '90s
+ Almeida et al '08





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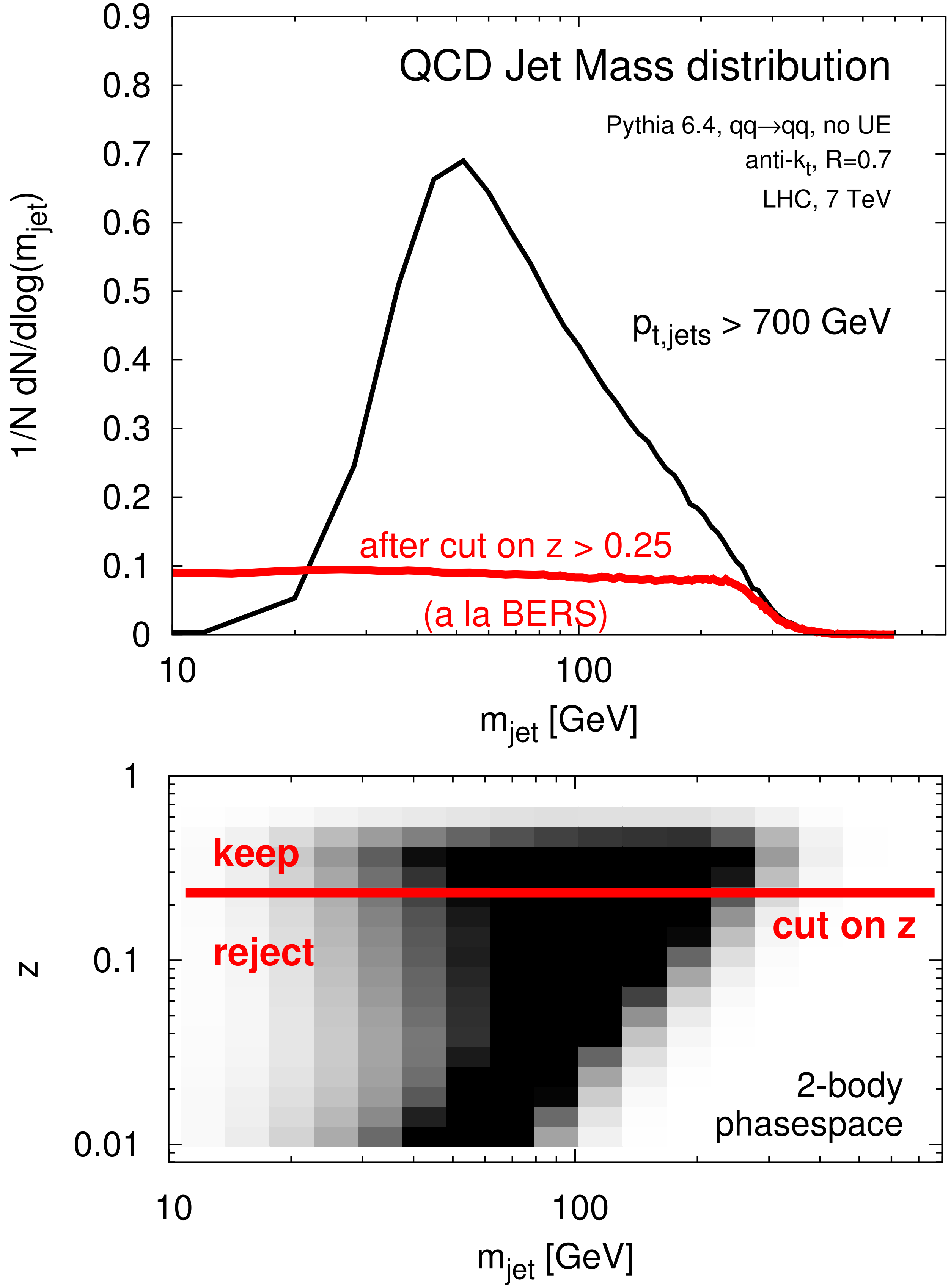
The logarithm comes from integral over soft divergence of QCD:

$$\int_{\frac{m^2}{p_t^2 R^2}}^{\frac{1}{2}} \frac{dz}{z}$$



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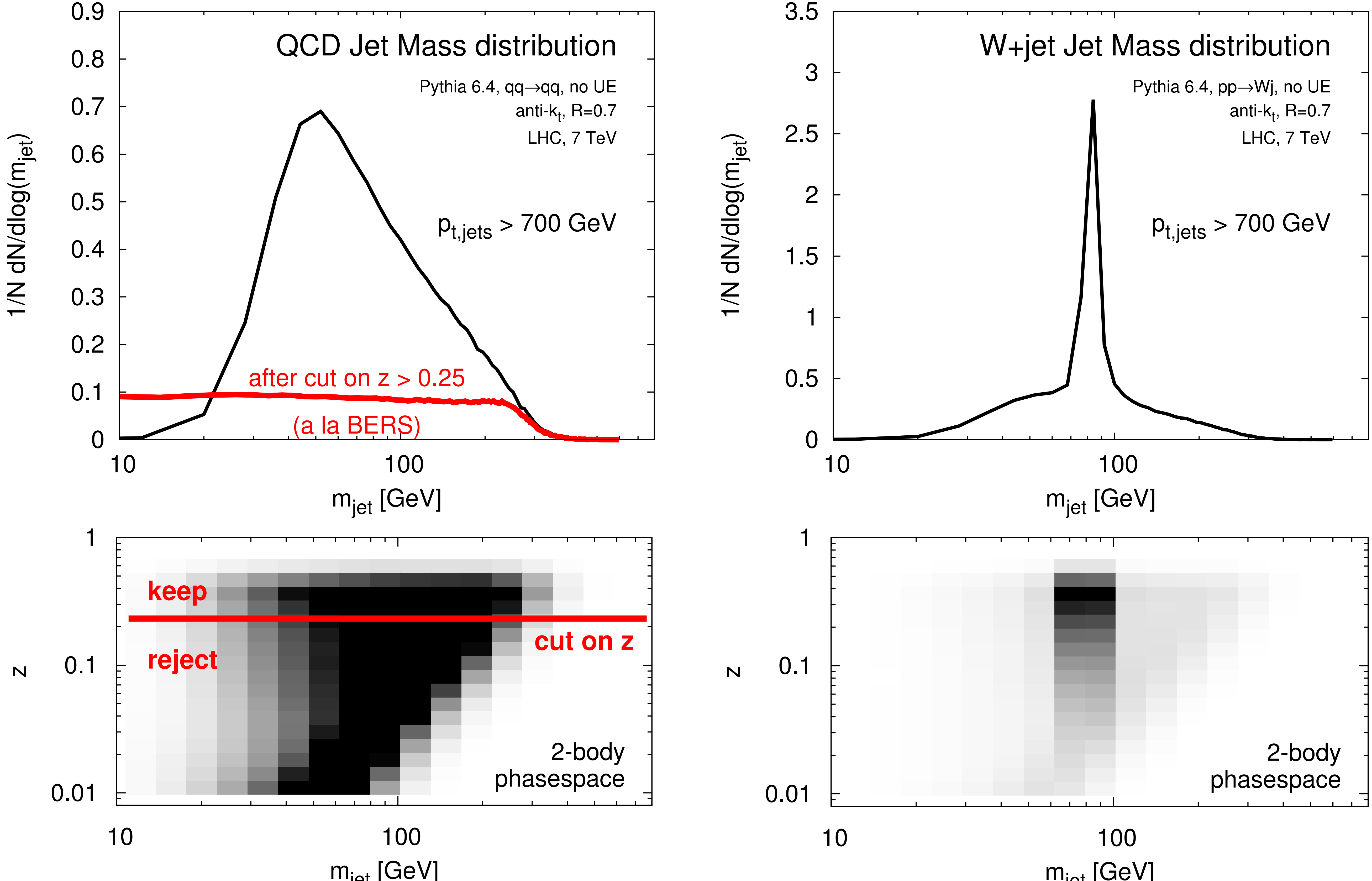
The logarithm comes from integral over soft divergence of QCD:

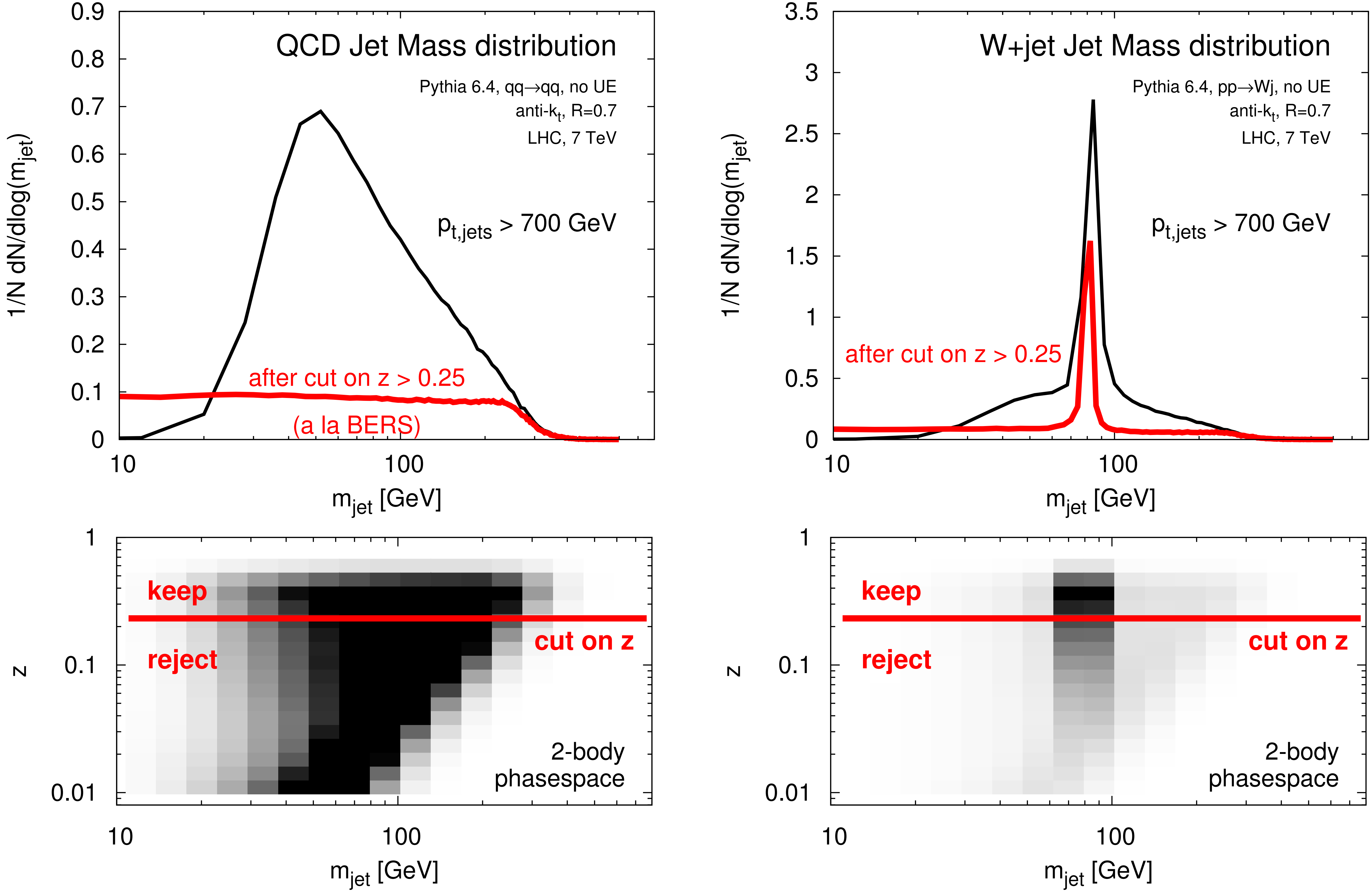
$$\int_{\frac{m^2}{p_t^2 R^2}}^{\frac{1}{2}} \frac{dz}{z}$$

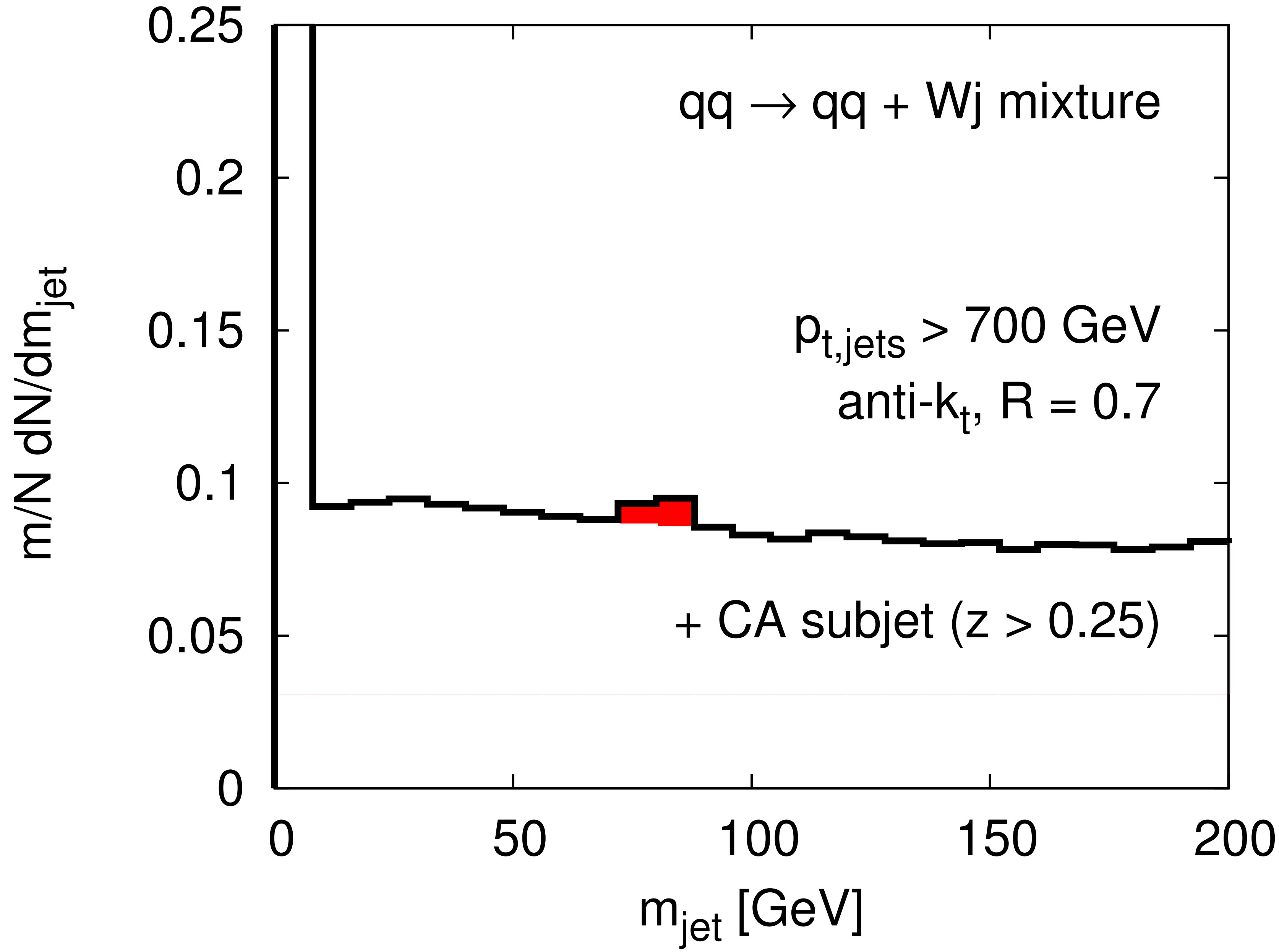
A hard cut on z reduces QCD background & simplifies its shape

Inside the jet mass



Inside the jet mass

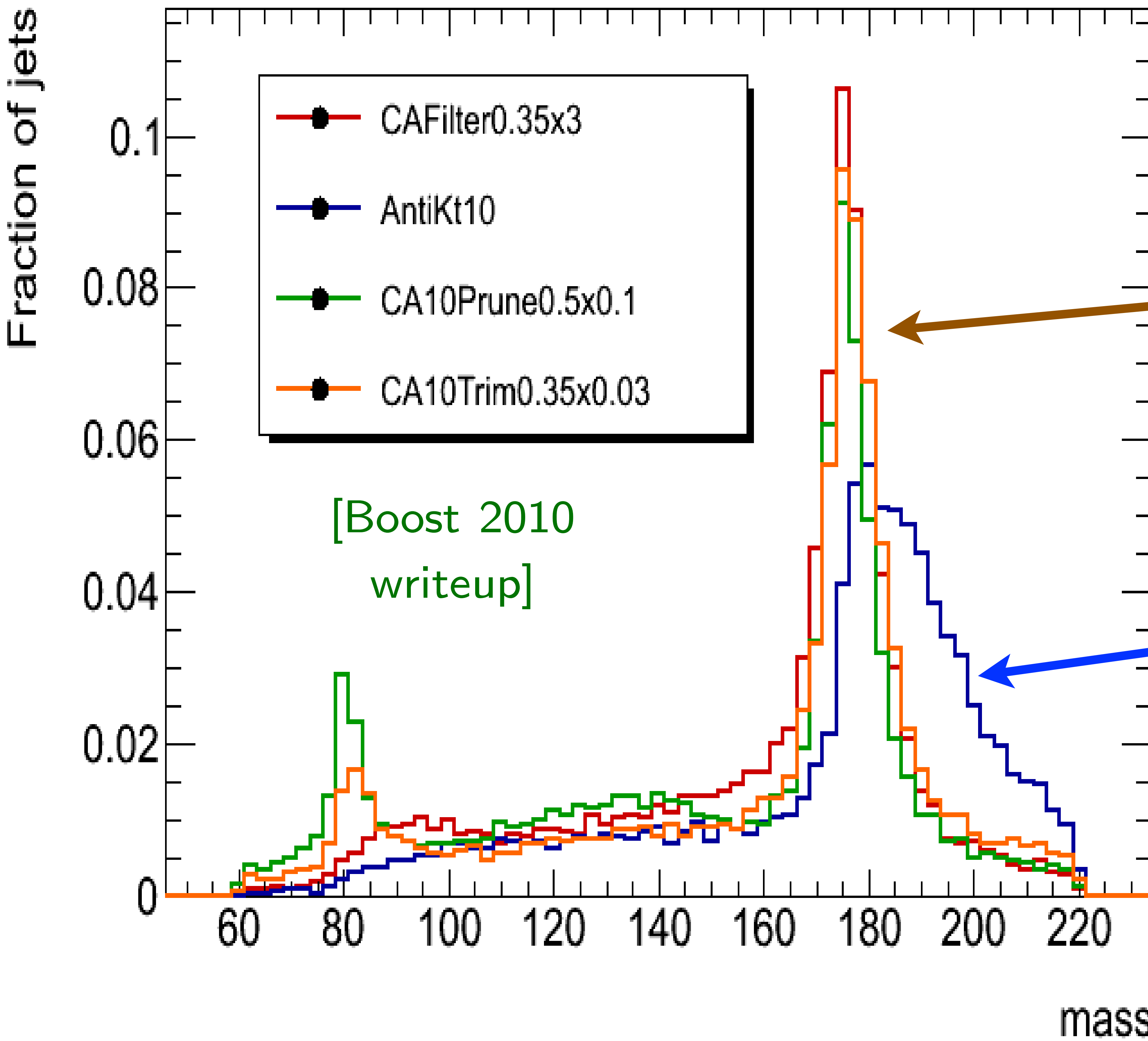




Signal + bkgd
after cut on z

One core idea for grooming

[see blackboard]

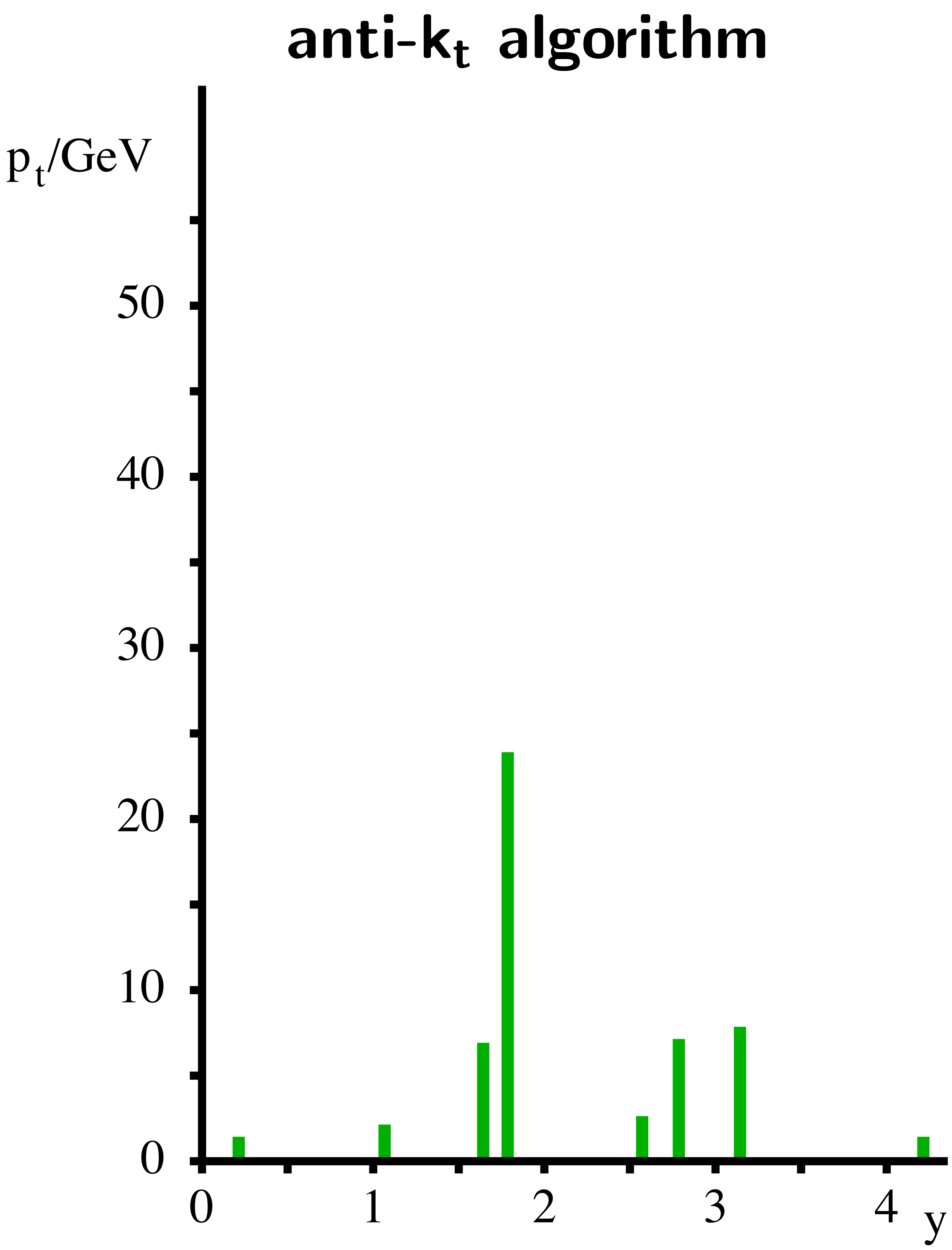


Groomed jet masses

Plain jet mass (anti-k_t)

How do the tools work in practice?

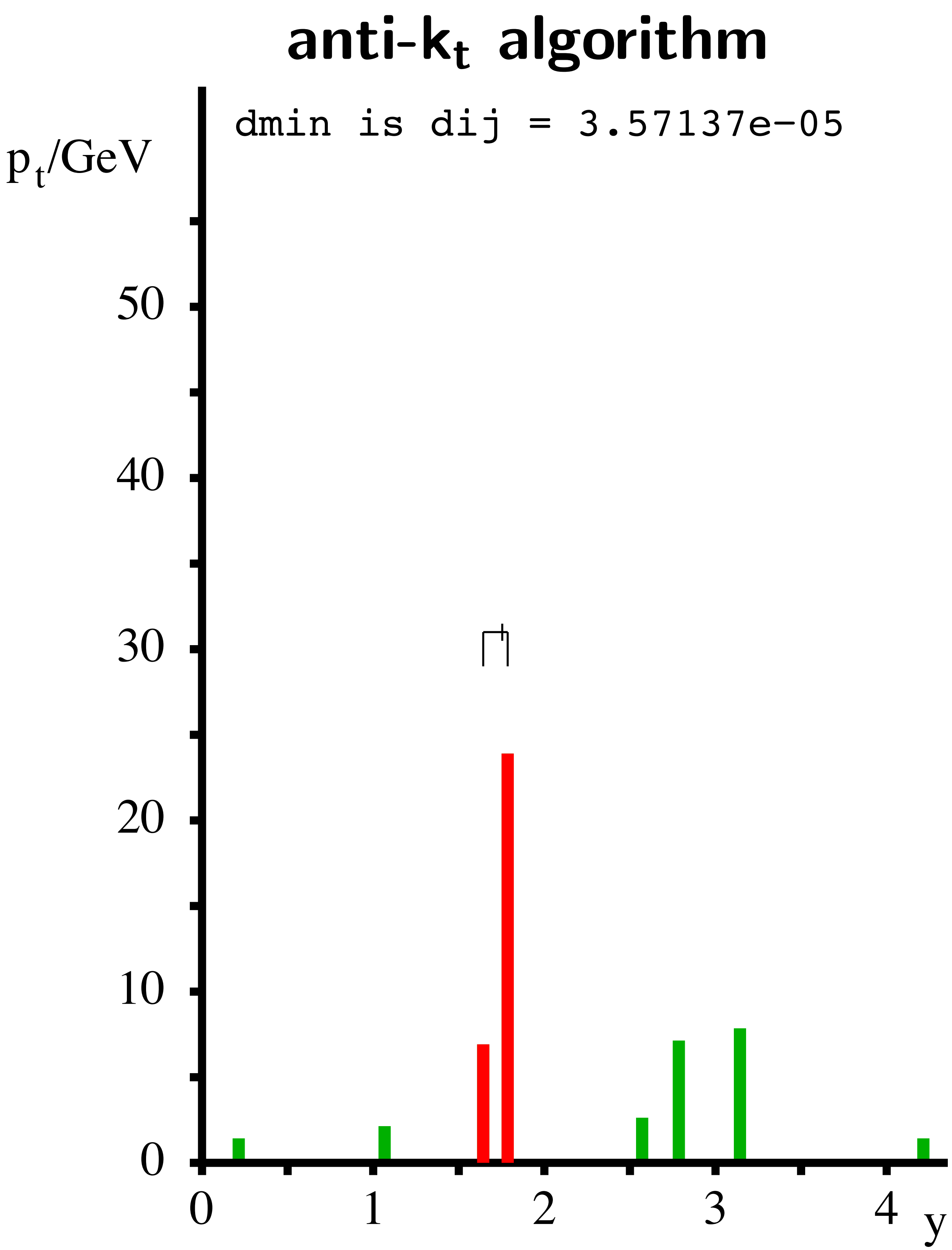
Identifying jet substructure: try out anti-k_t



How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).

Identifying jet substructure: try out anti-k_t



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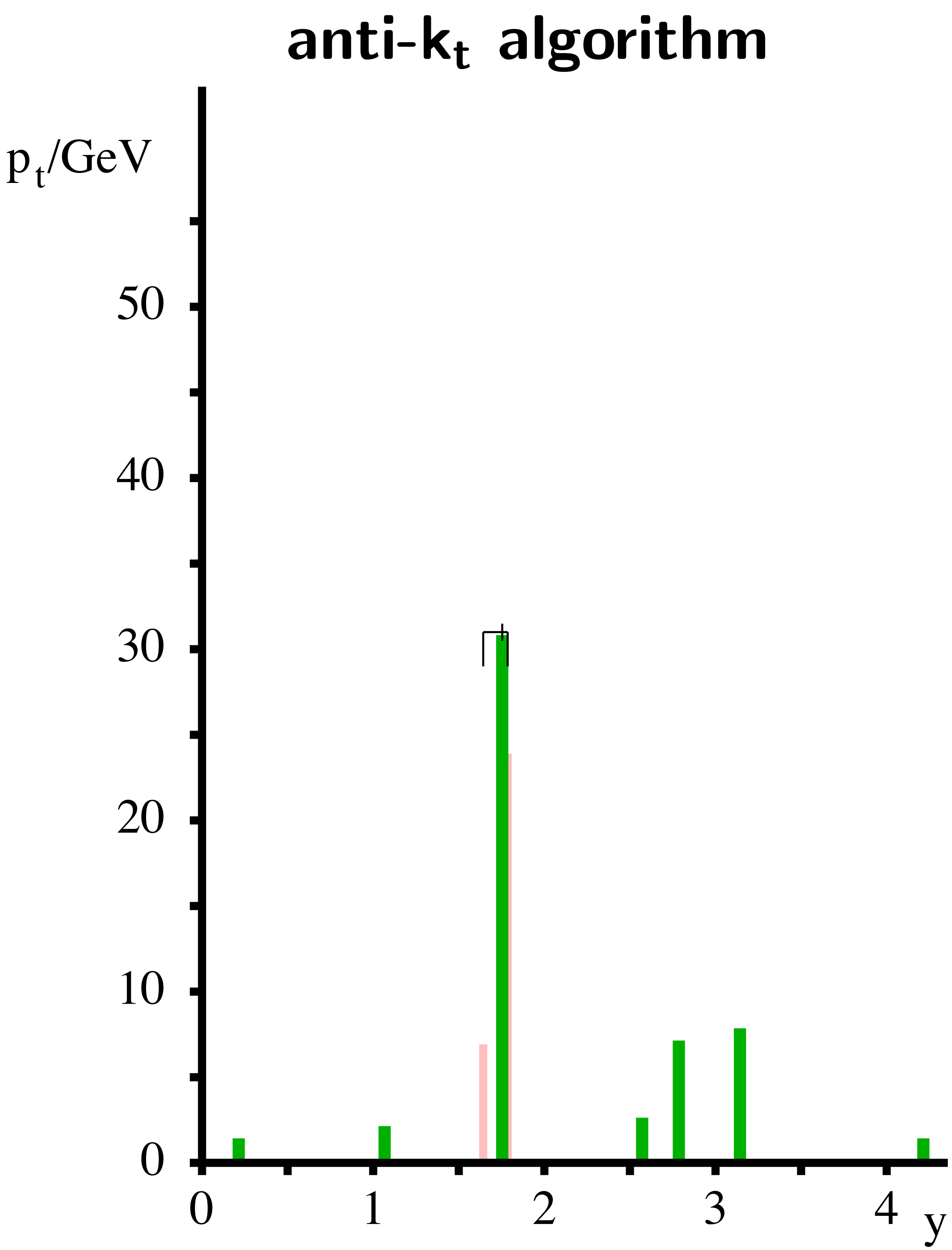

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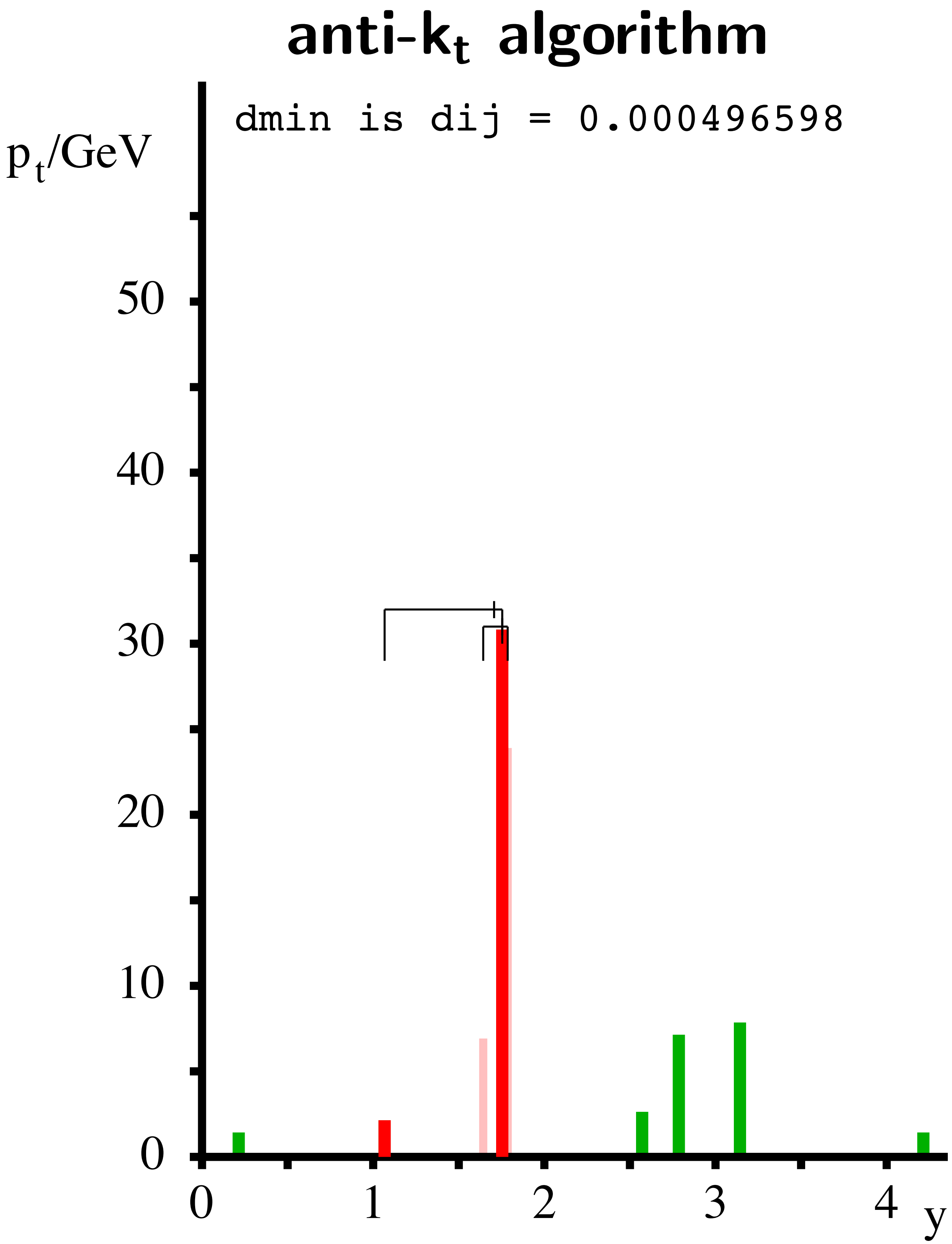

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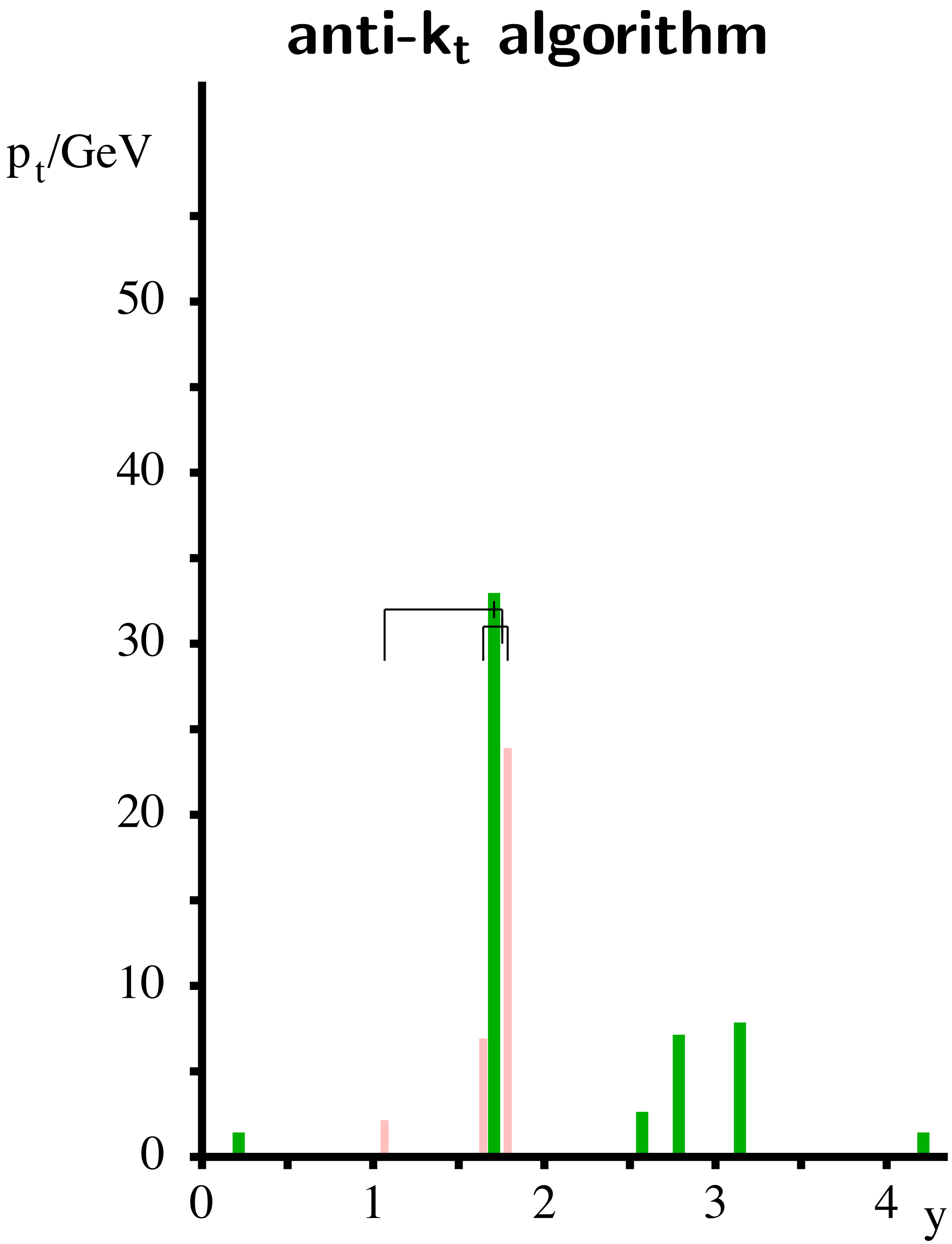

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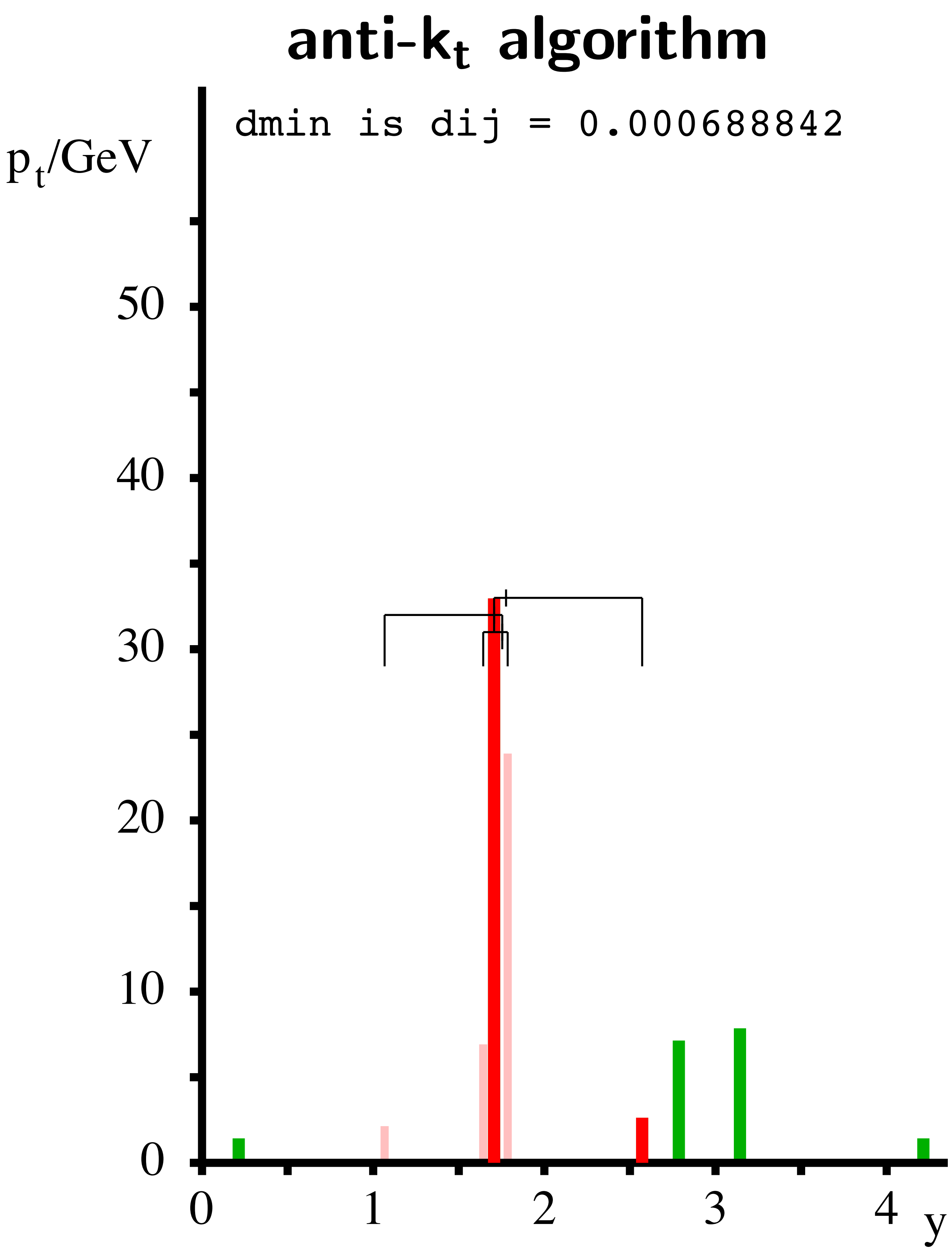

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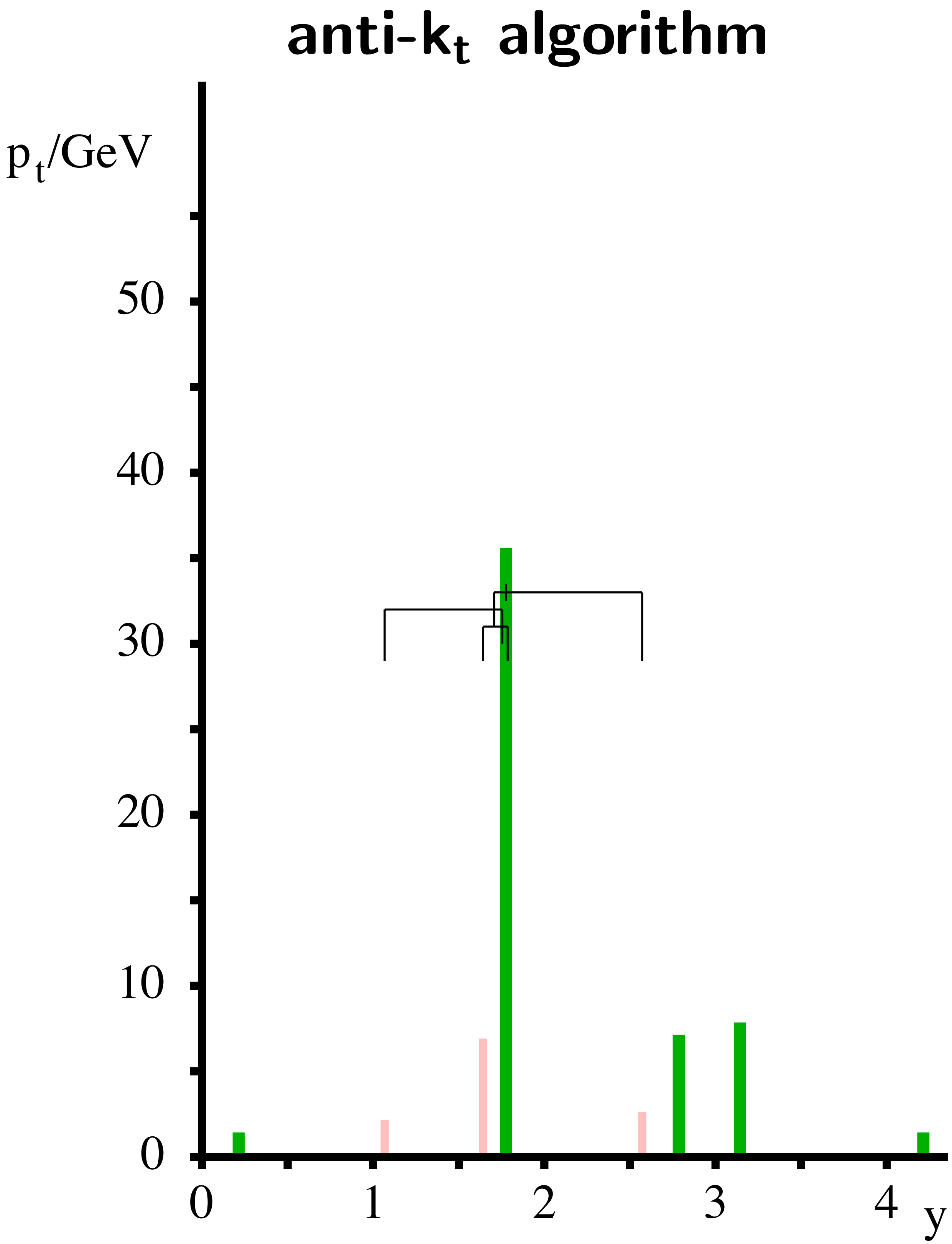

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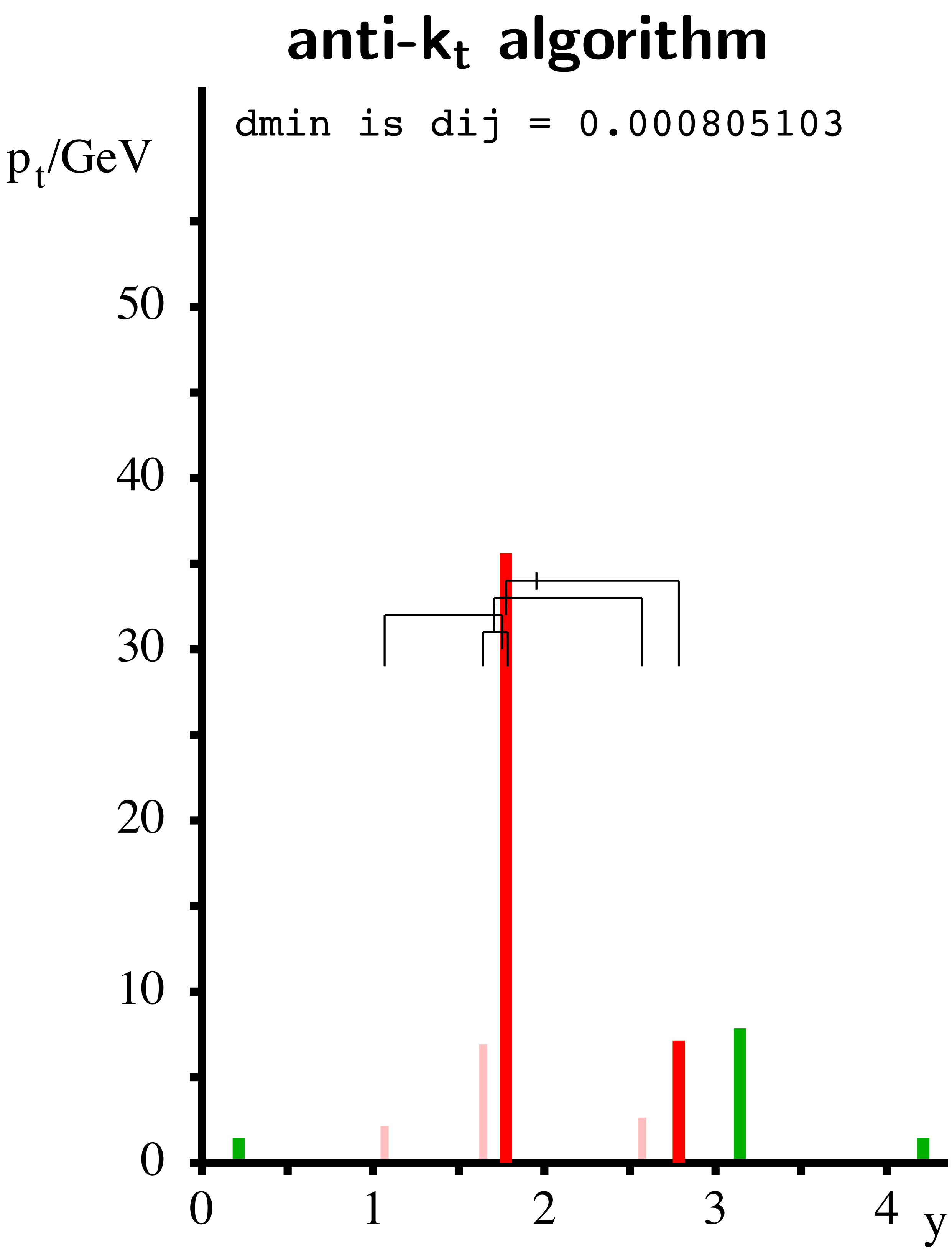

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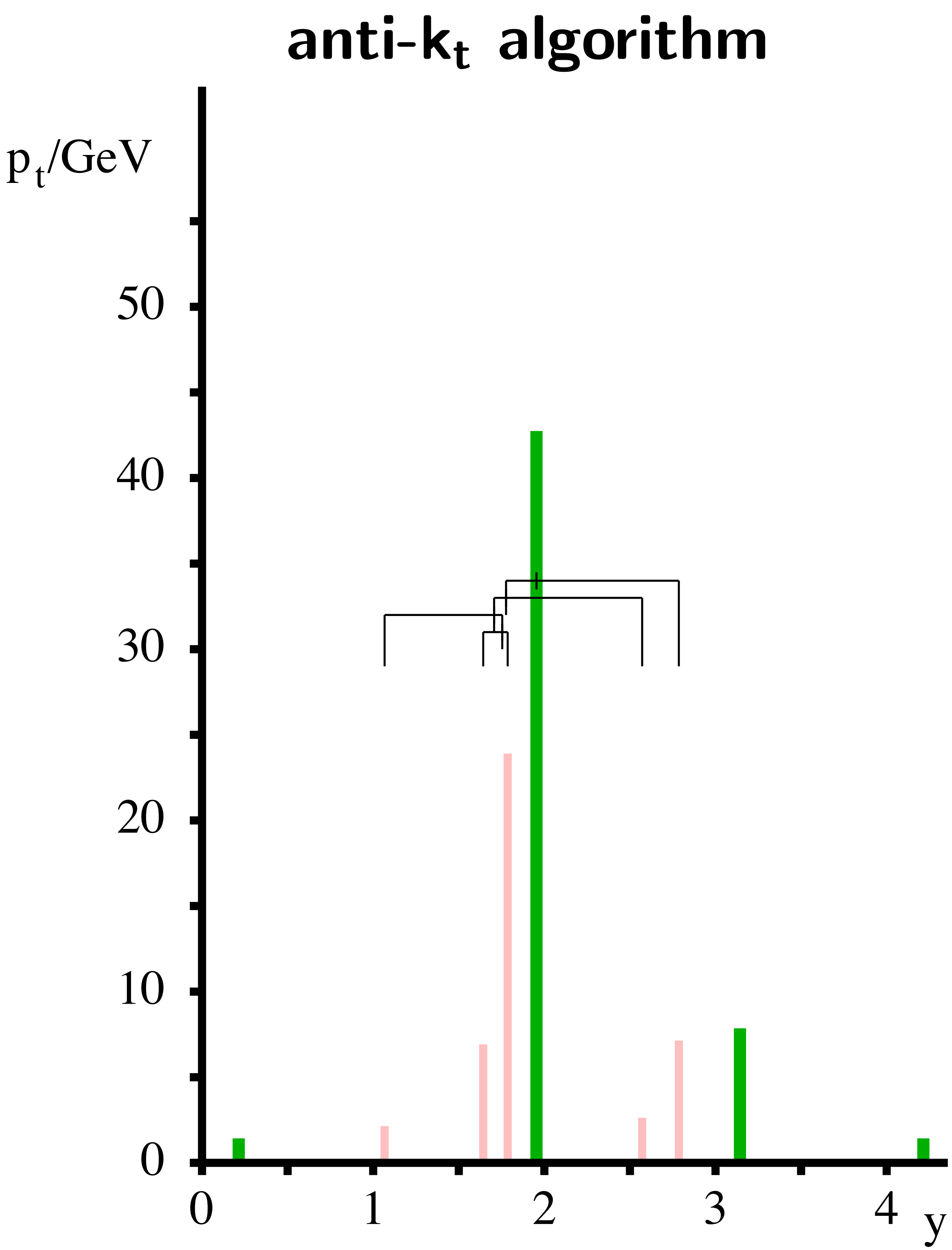
Anti-k_t gradually makes its way through the secondary blob → no clear identification of substructure associated with 2nd parton.



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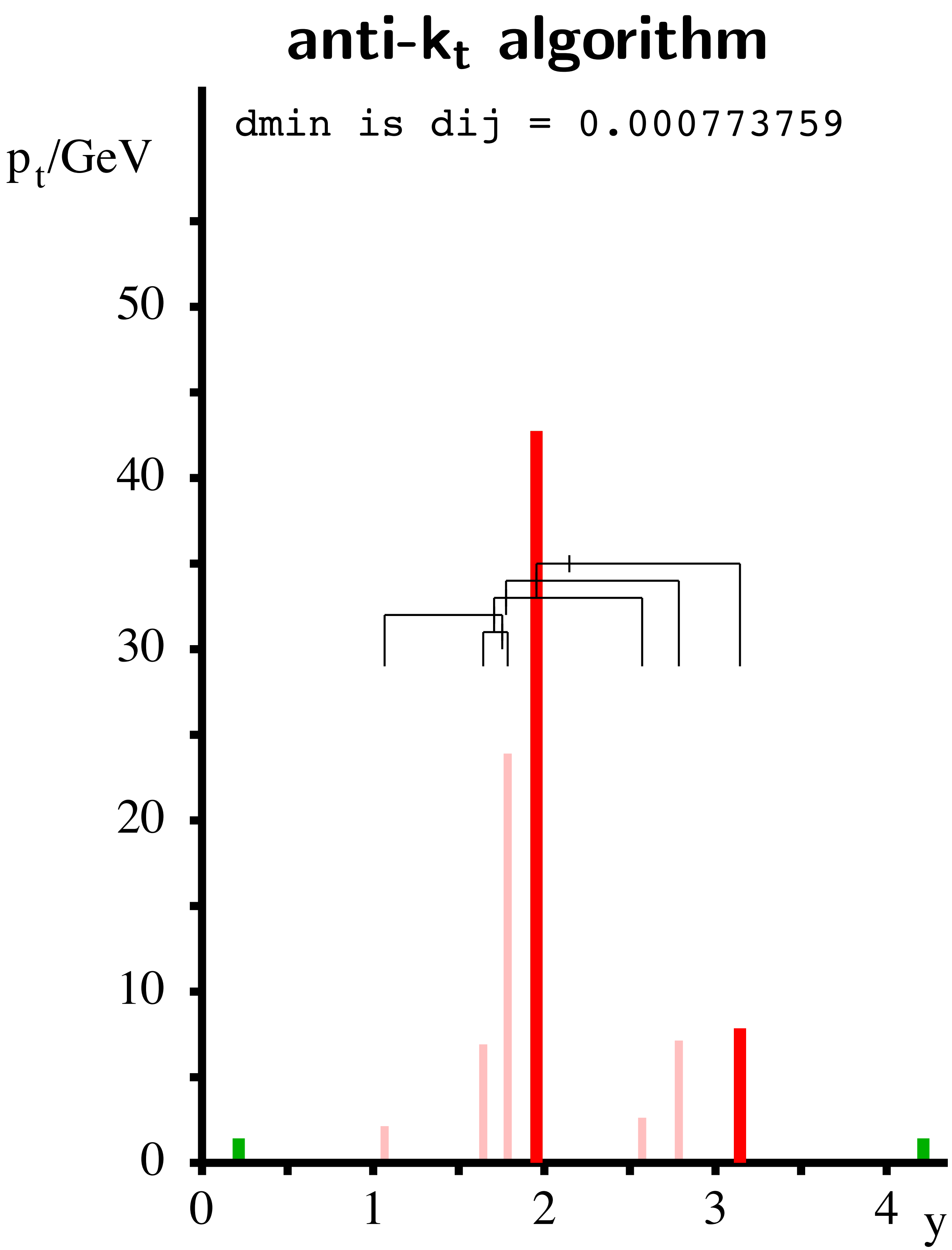

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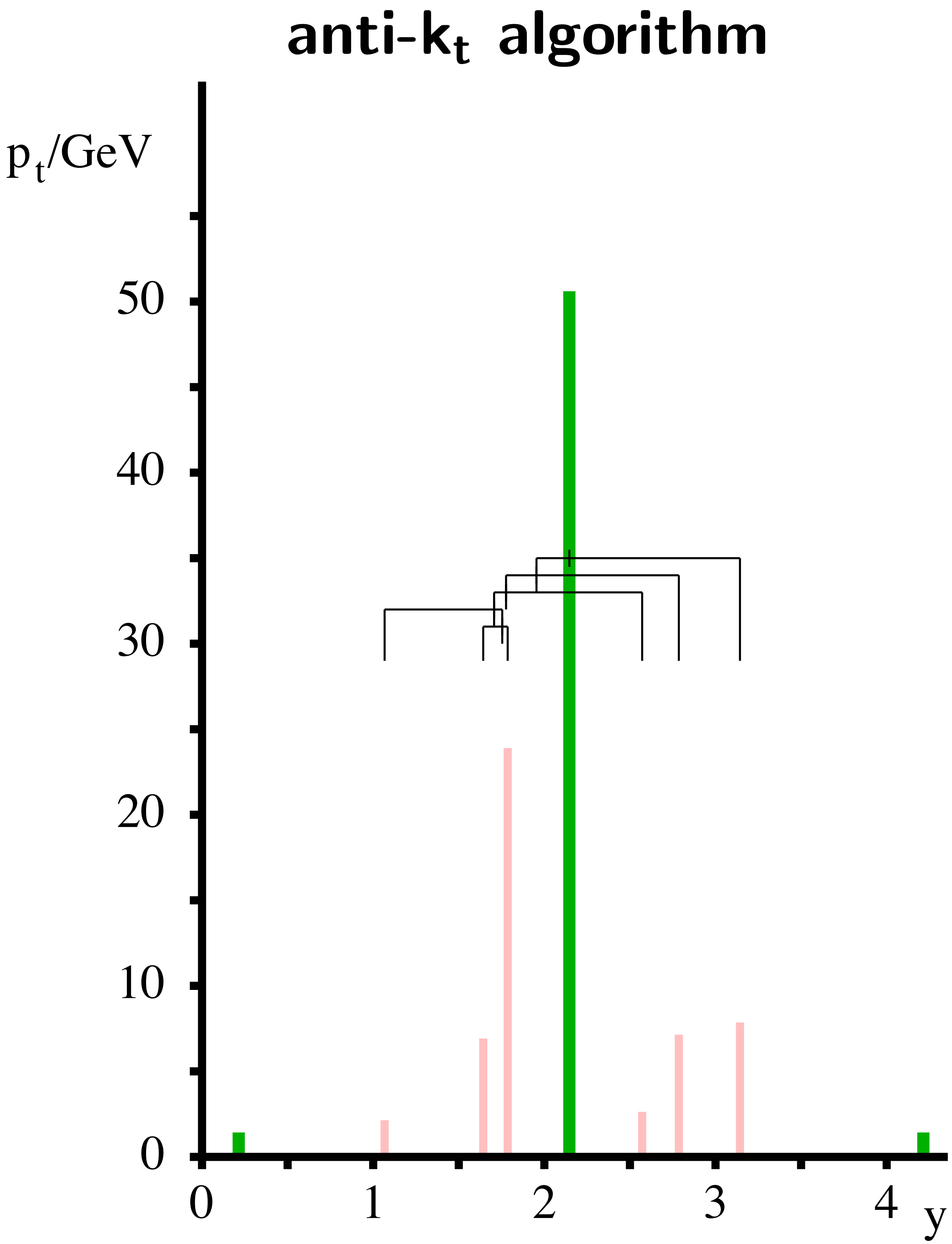

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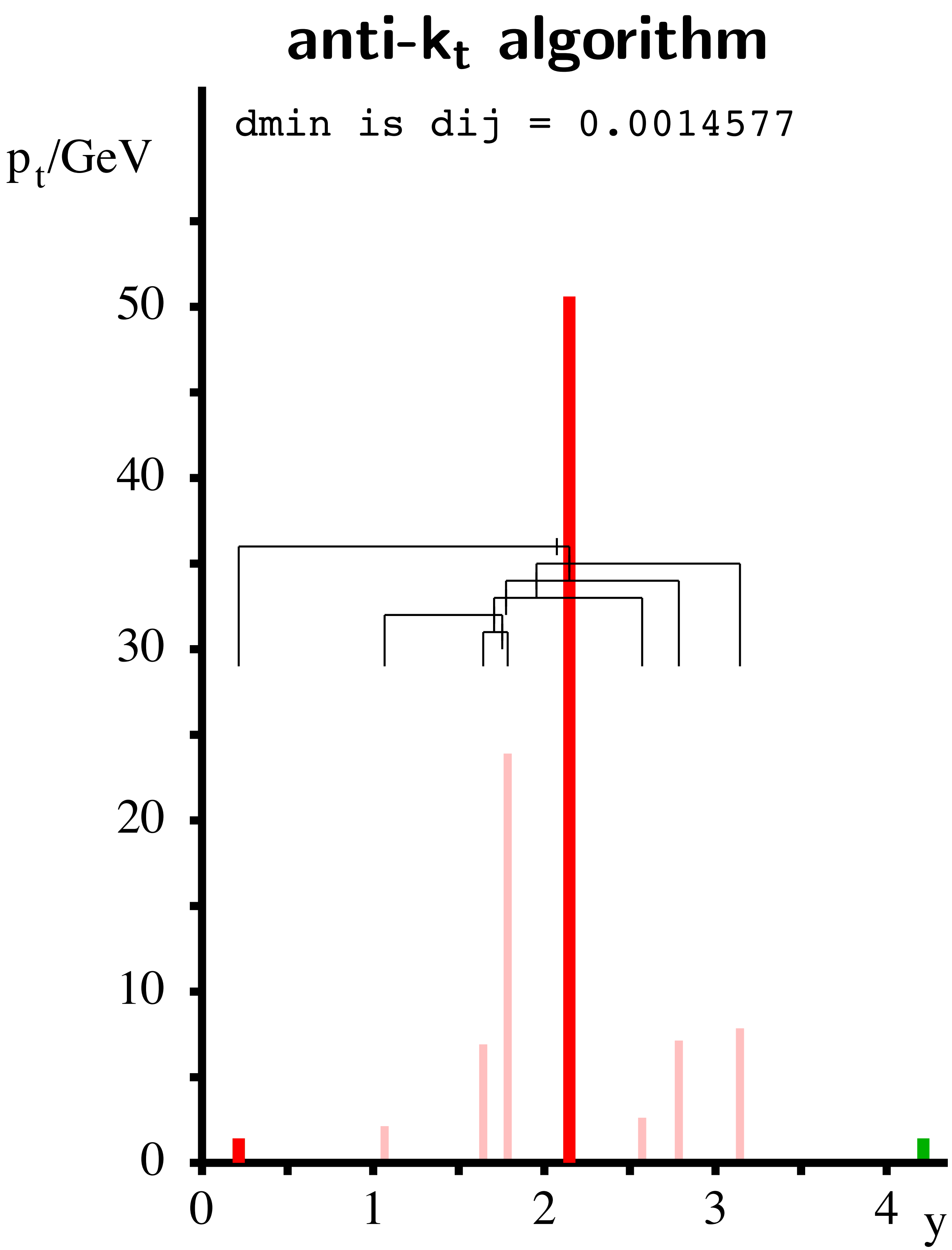

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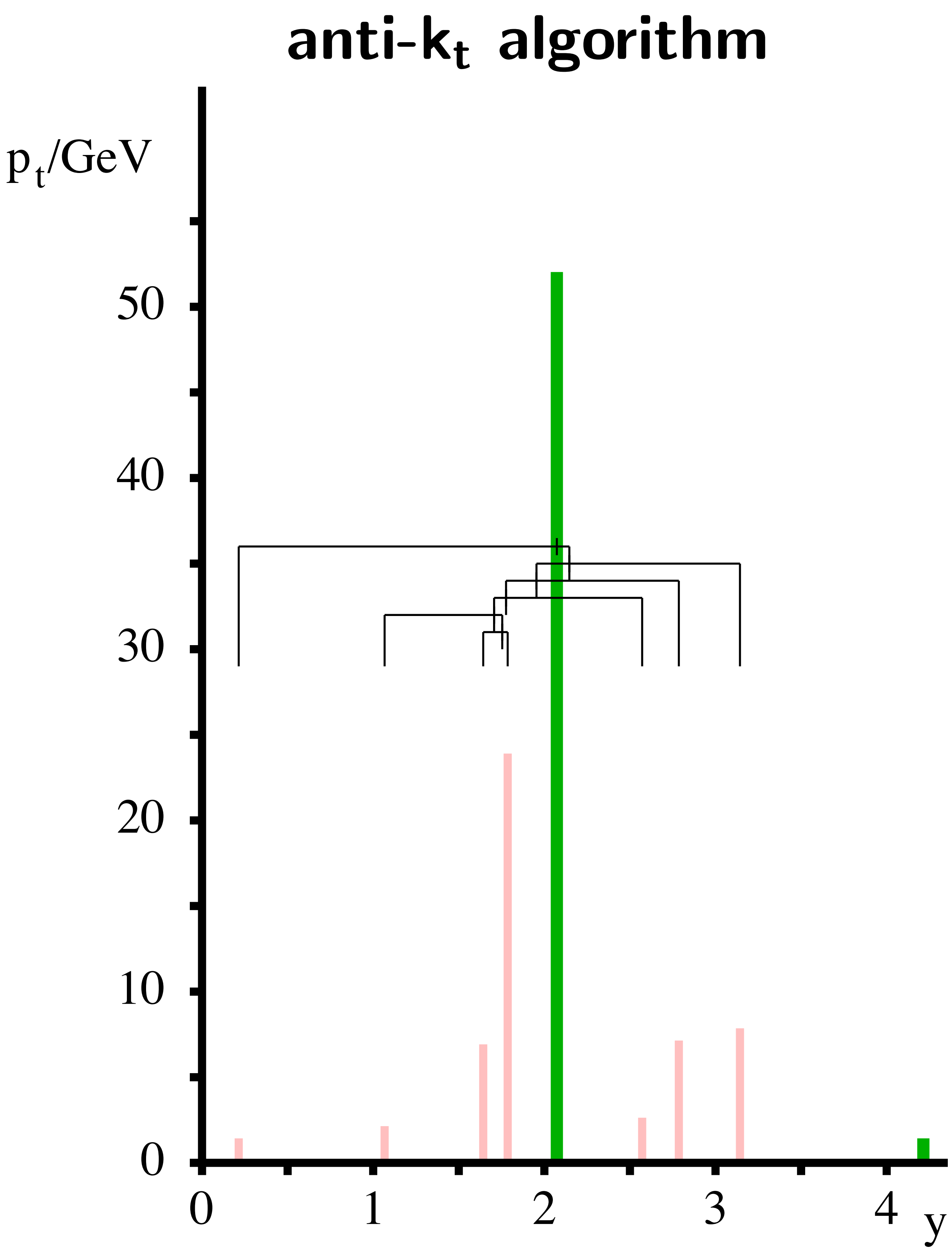

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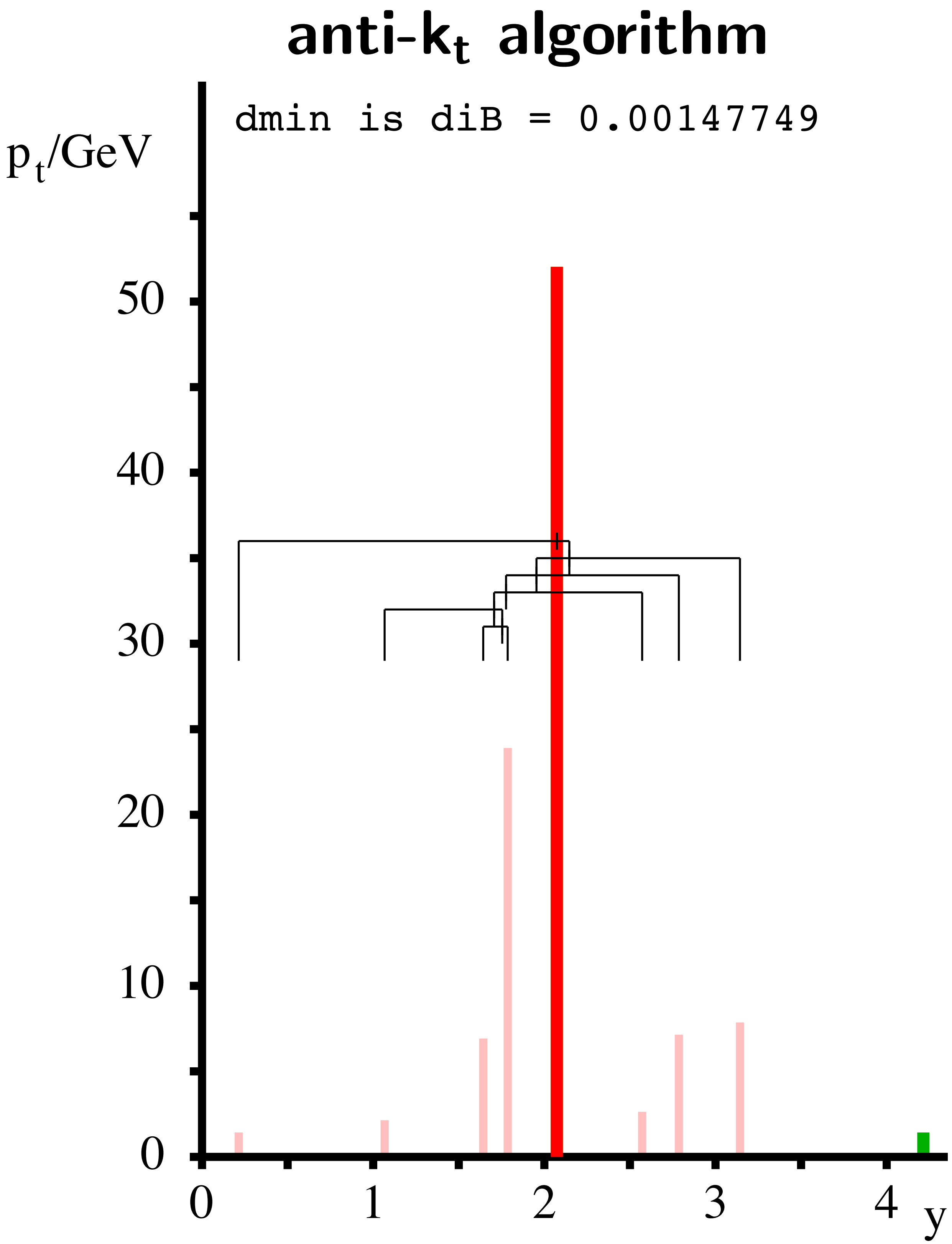

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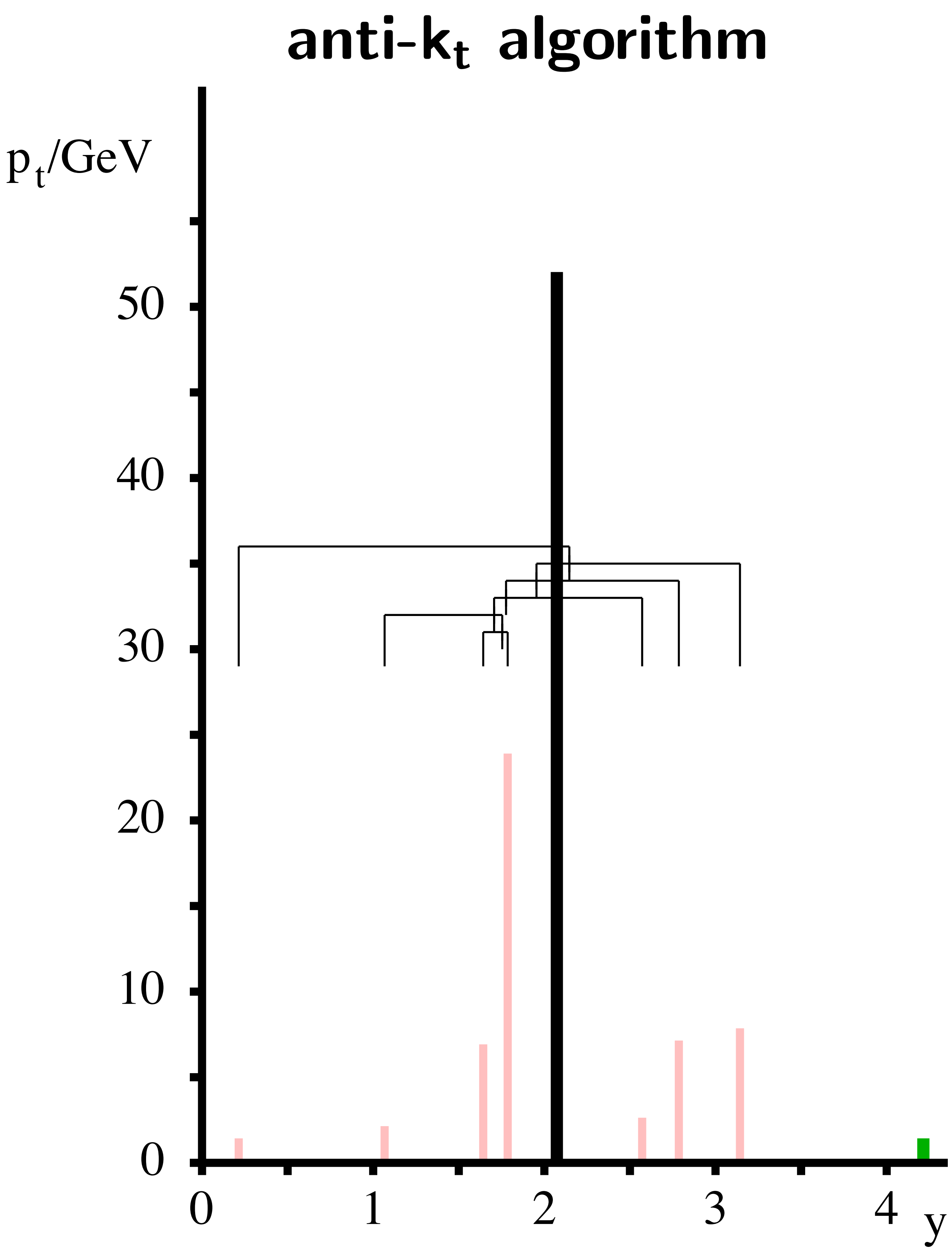

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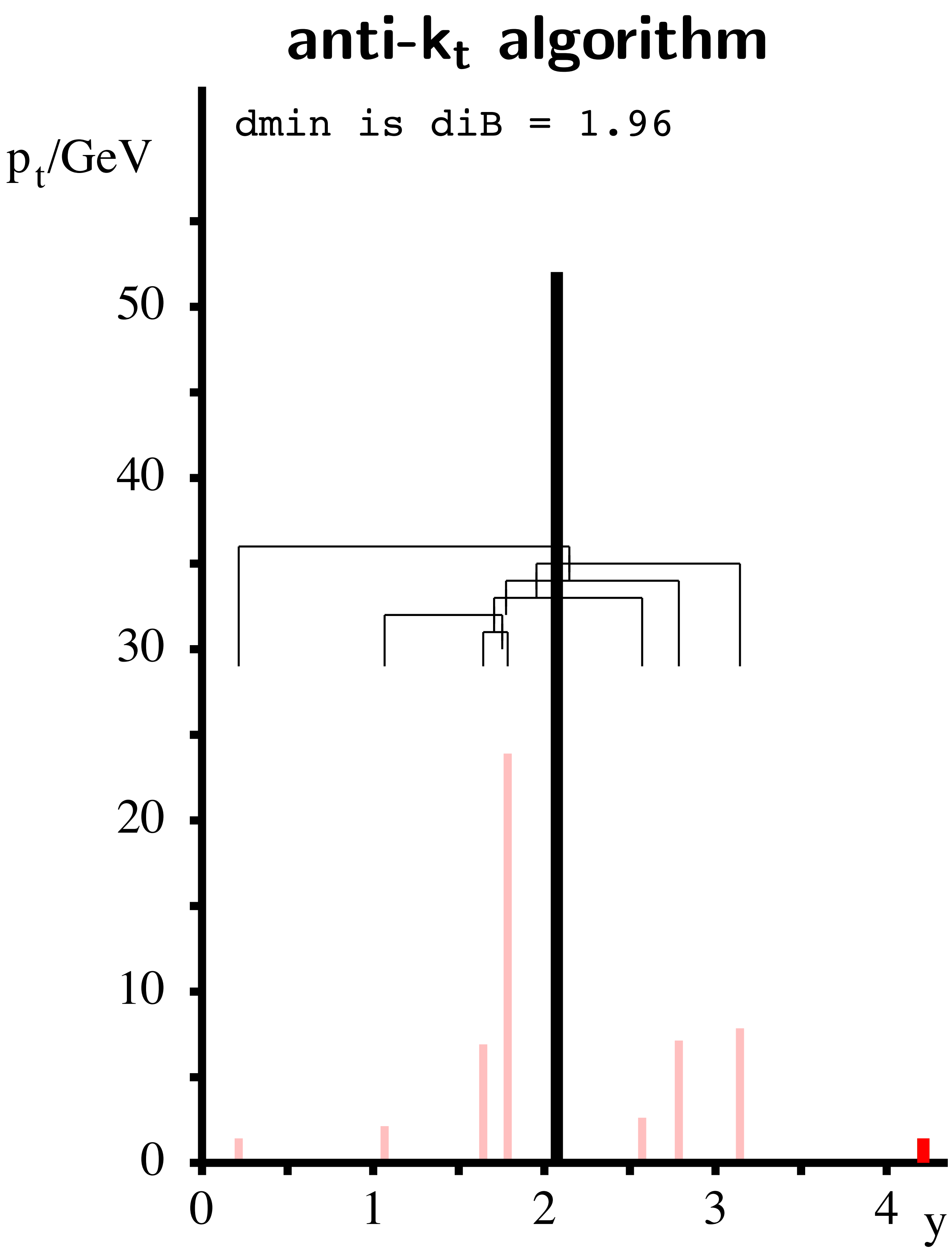

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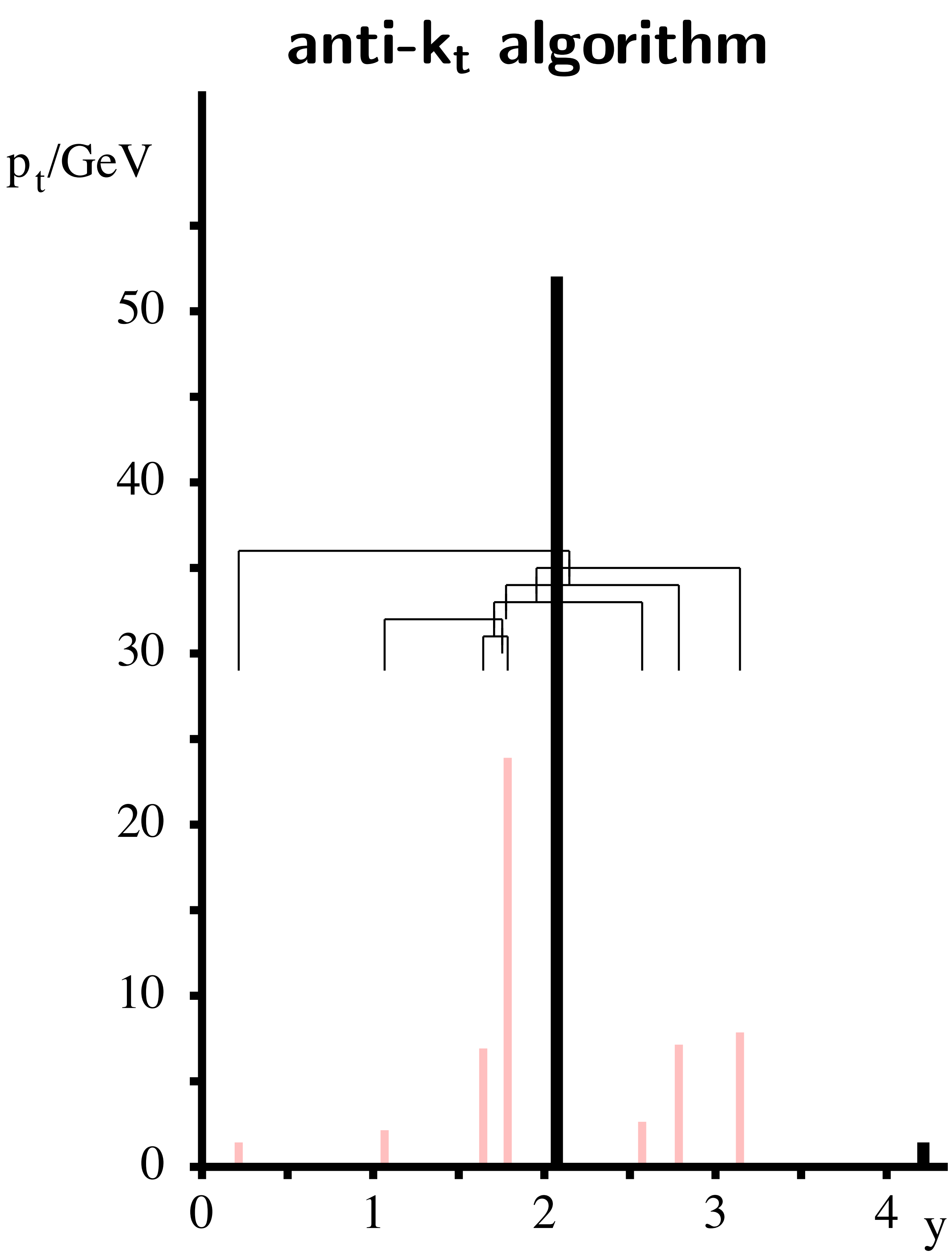

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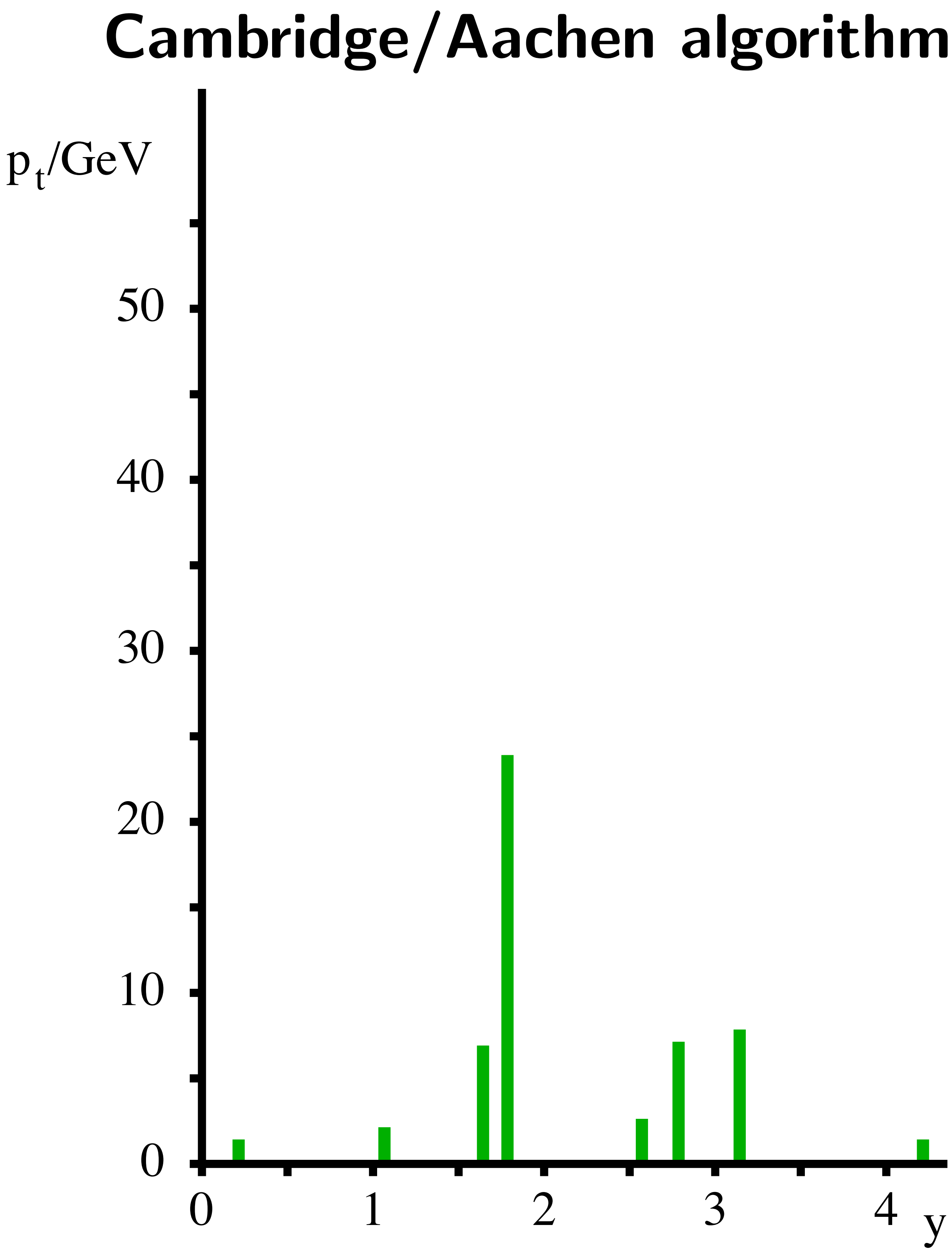

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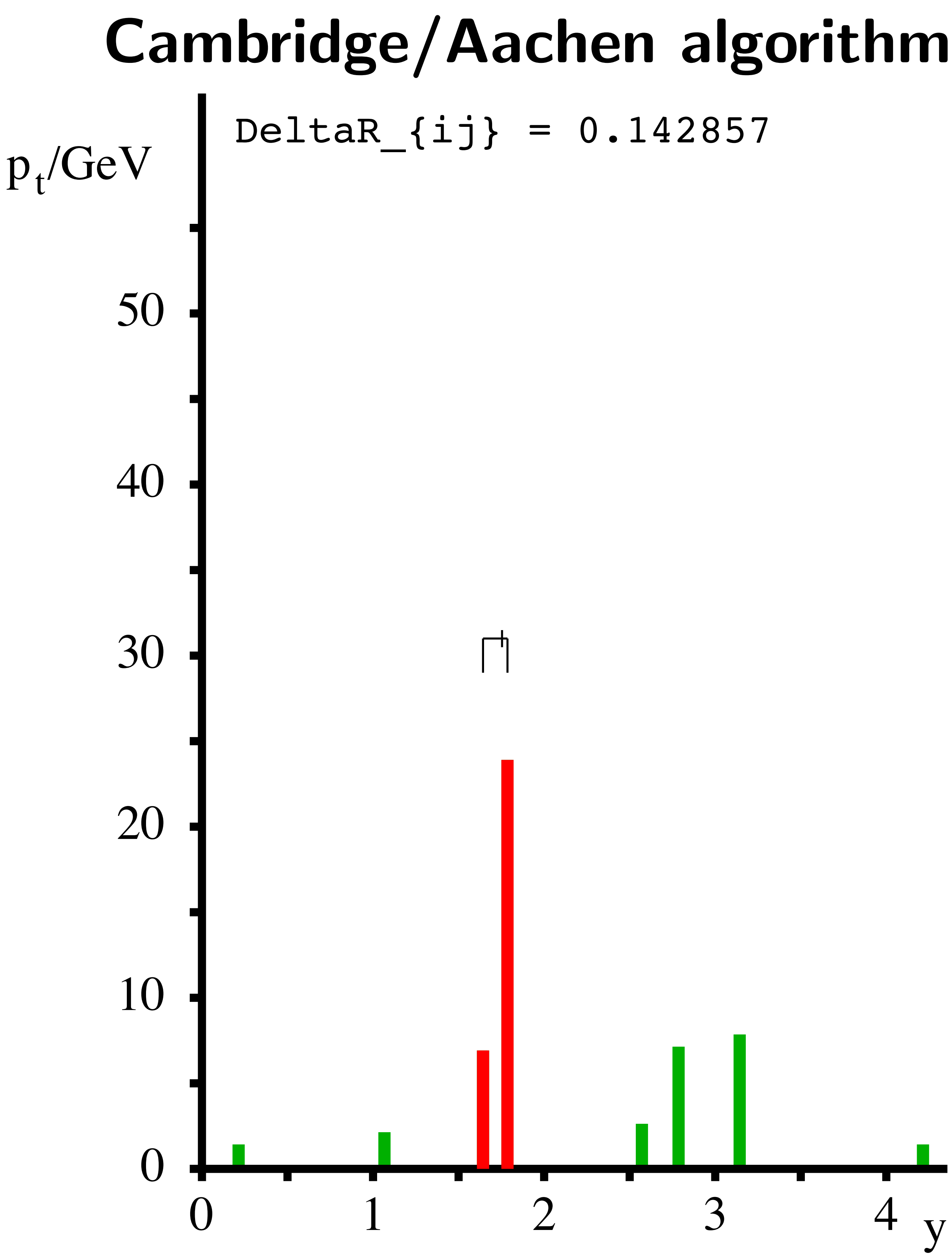

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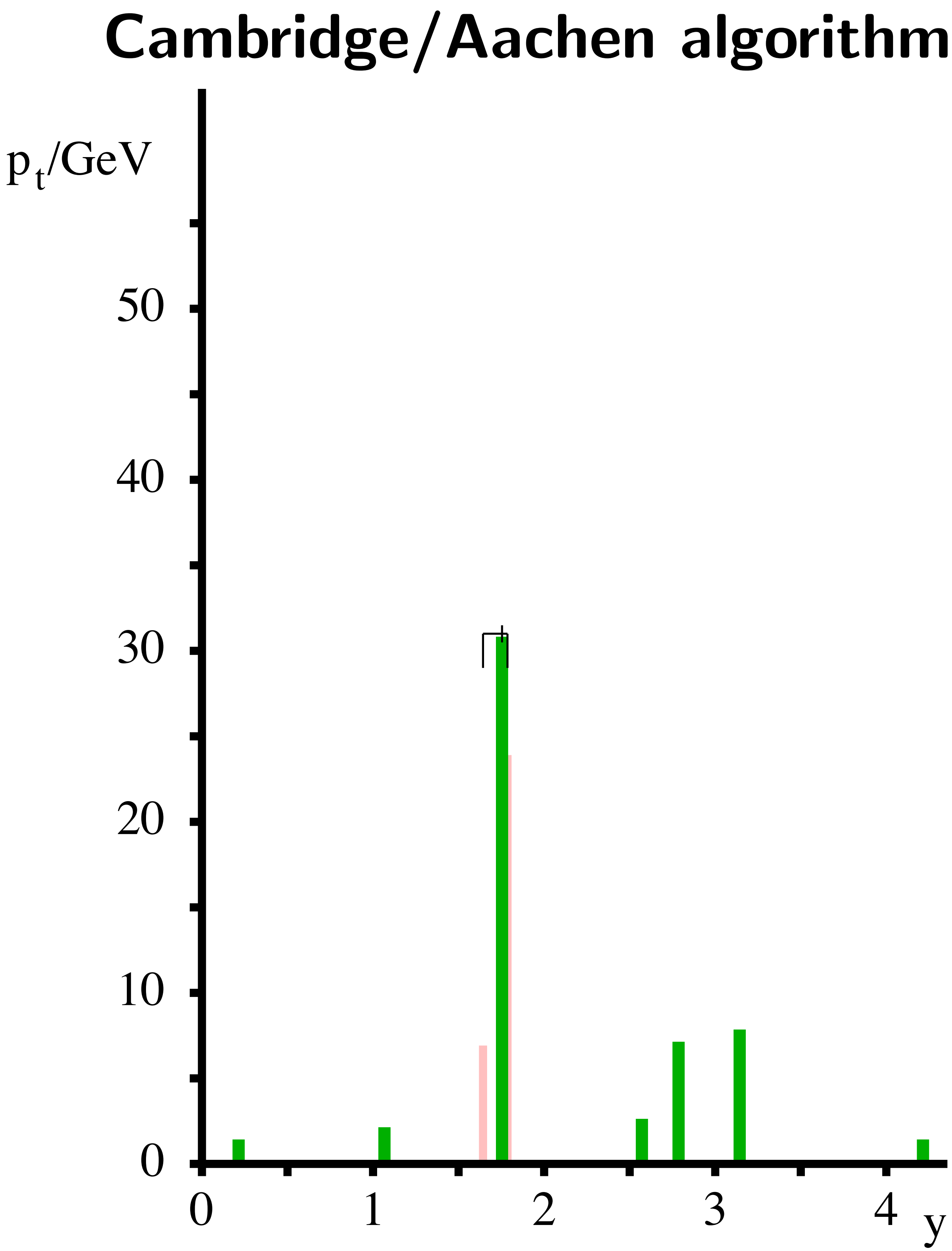

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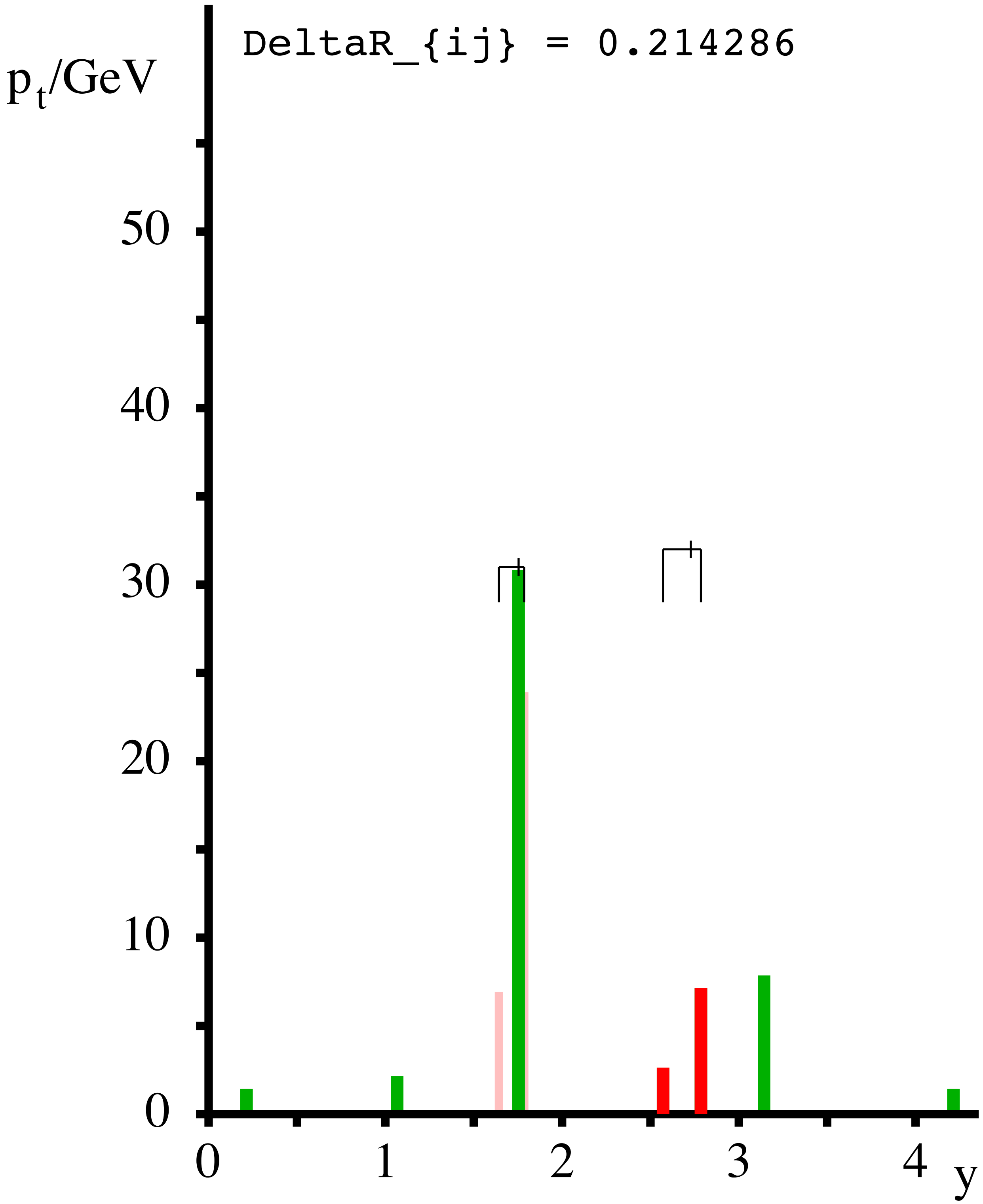
Cambridge/Aachen algorithm



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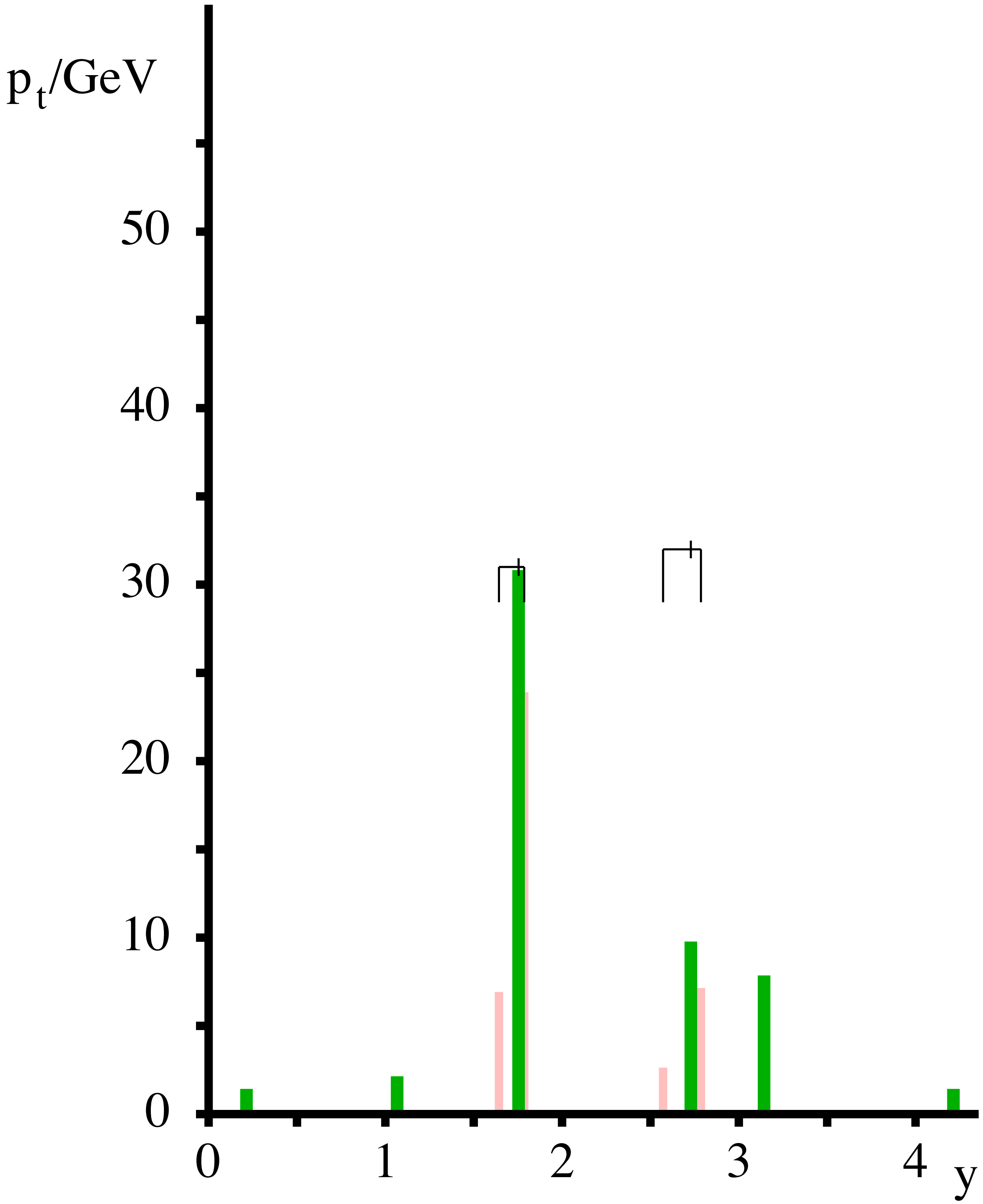

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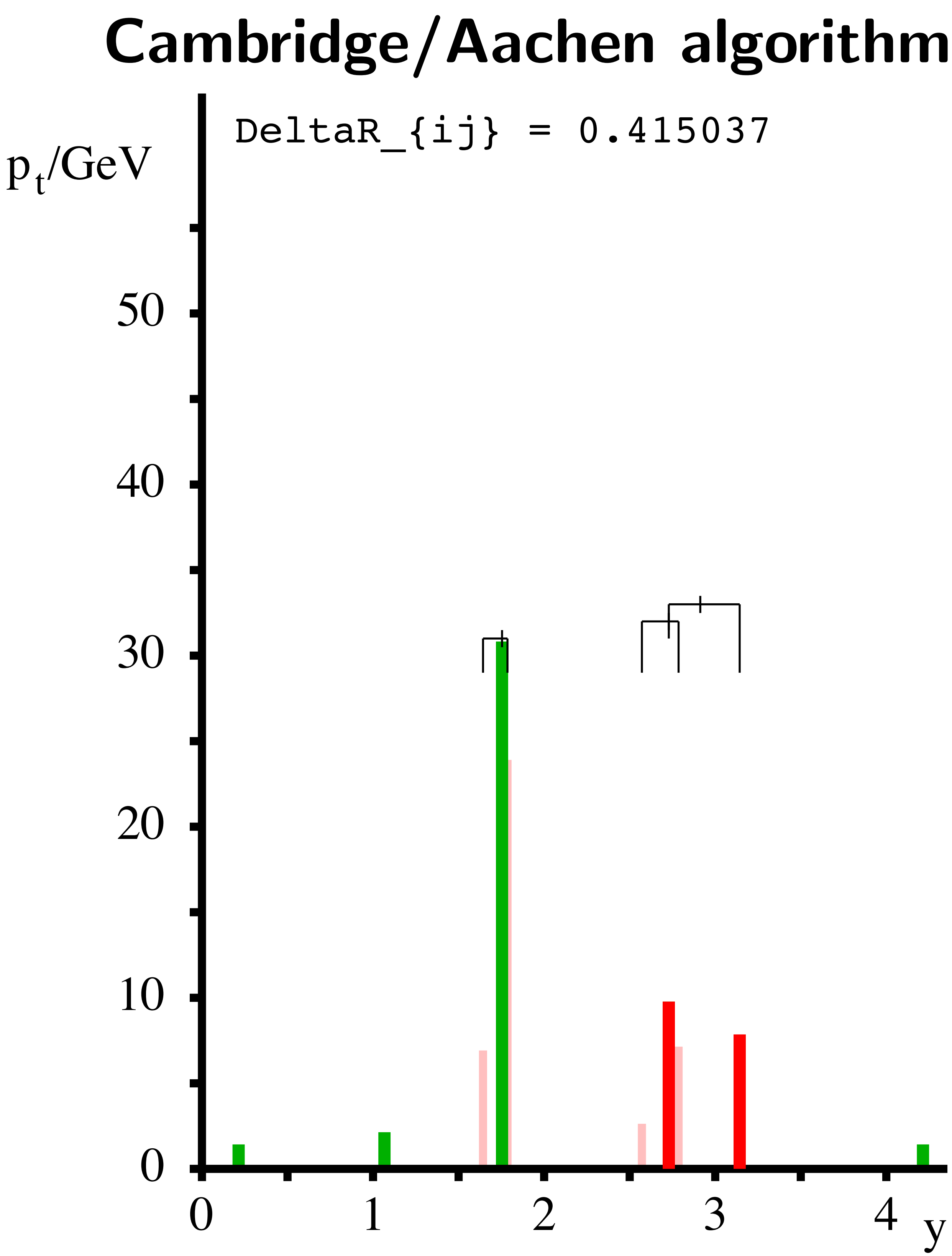

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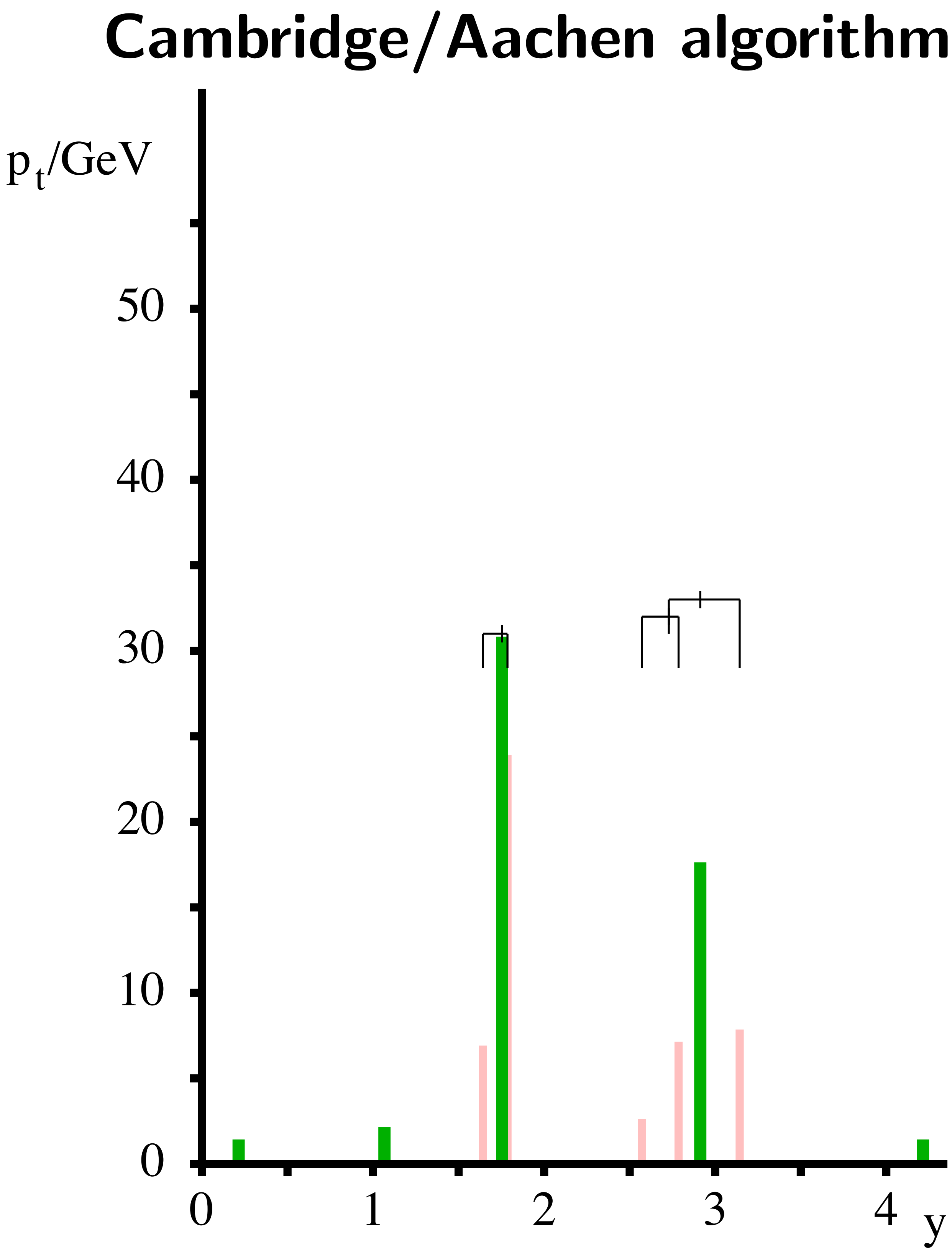

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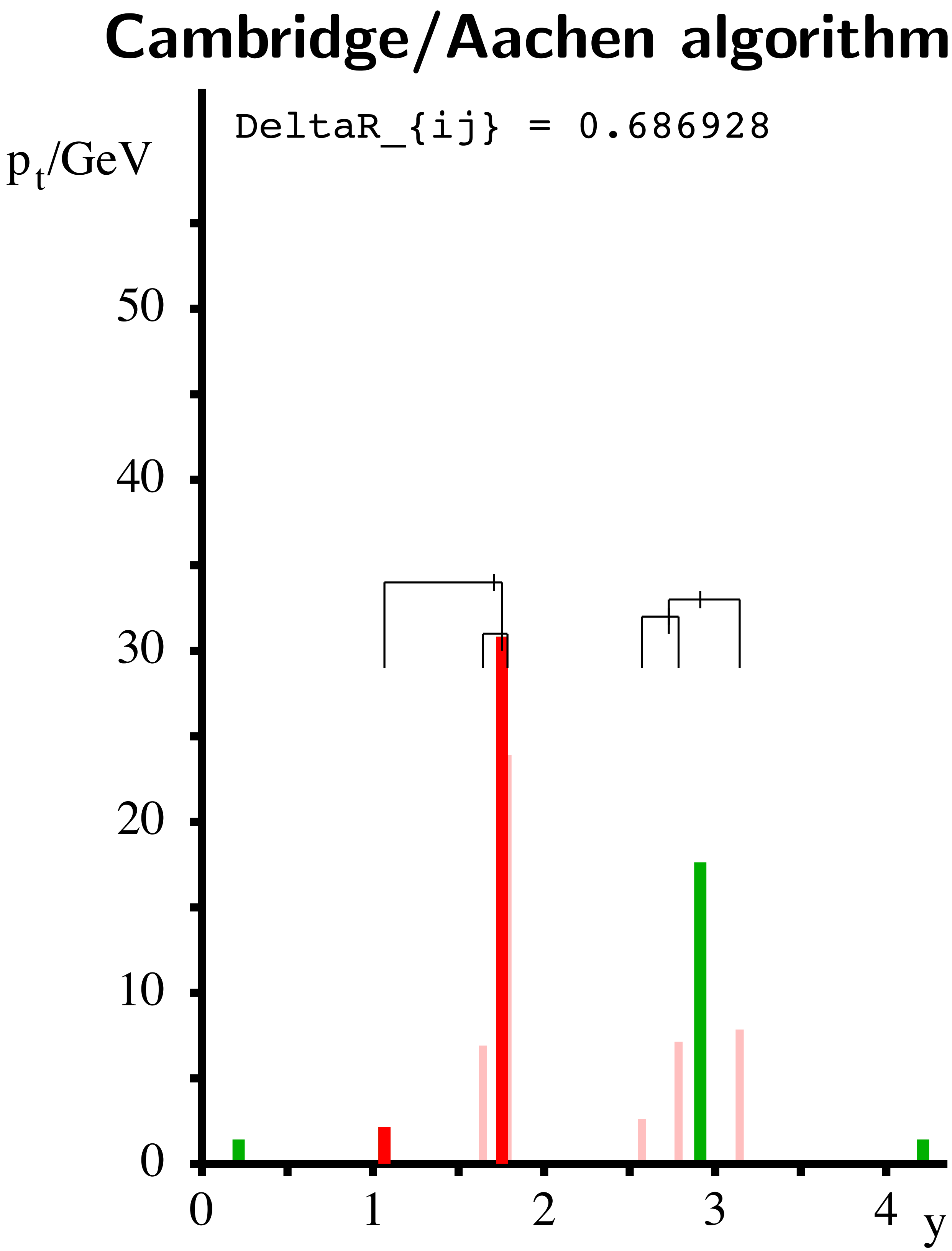

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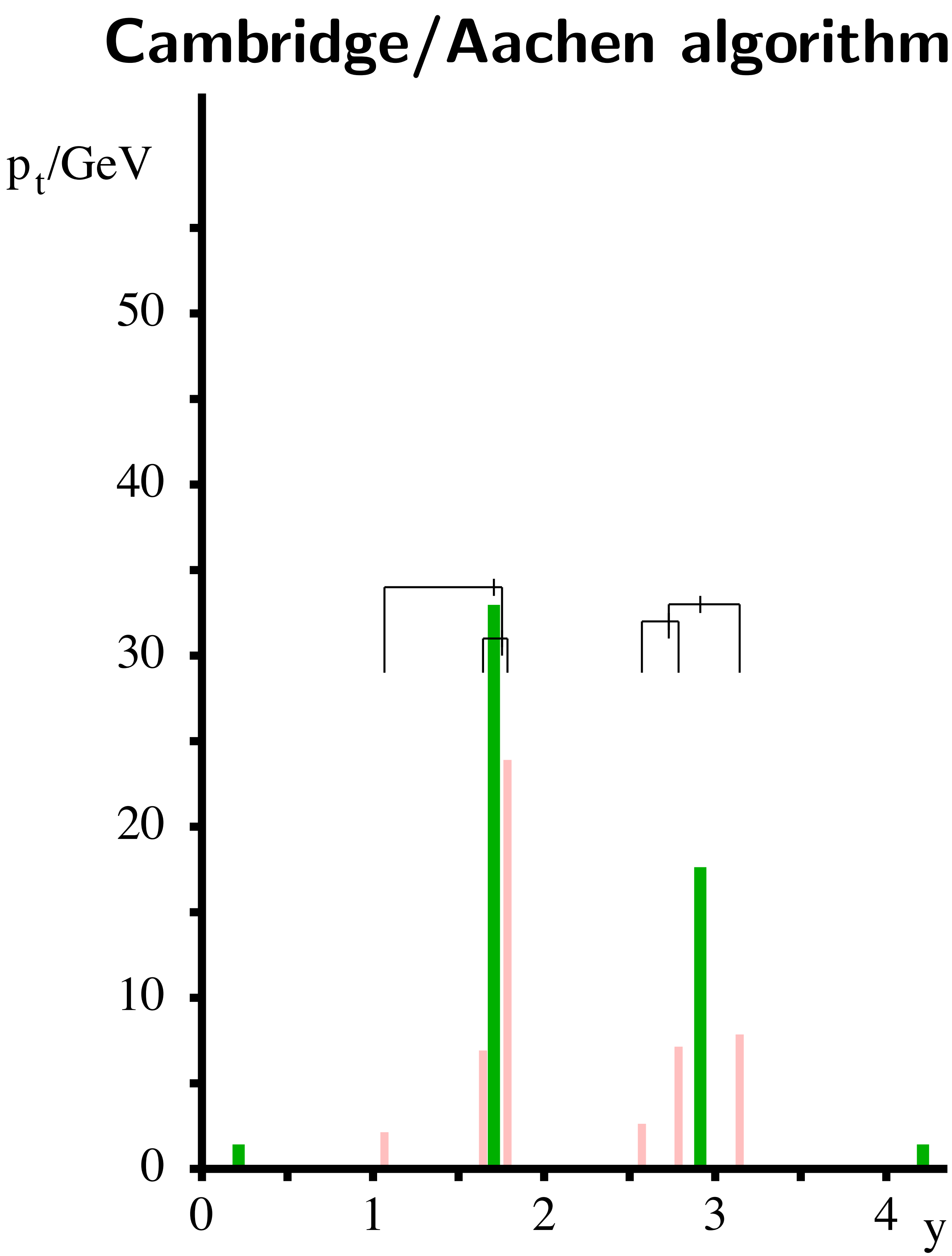
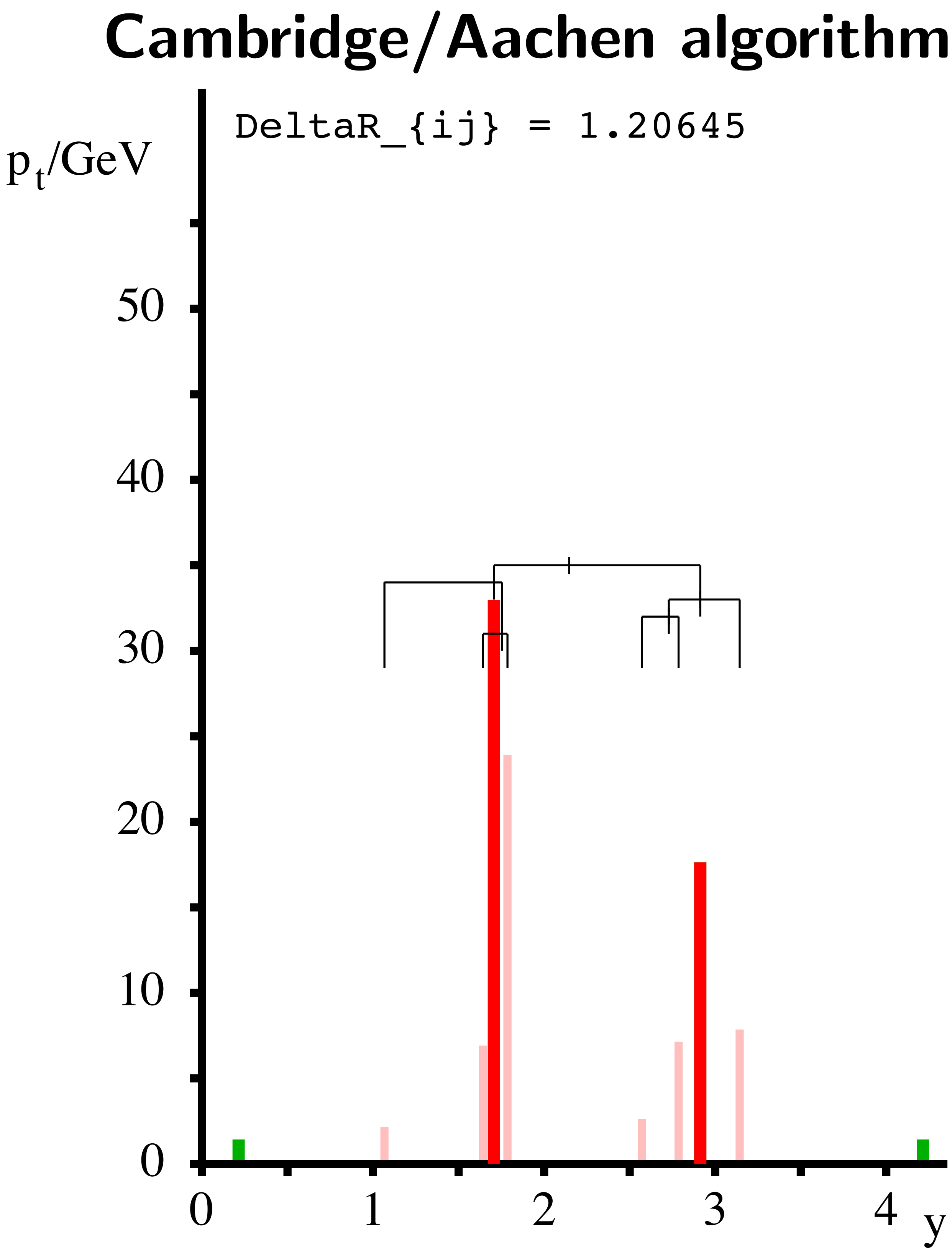


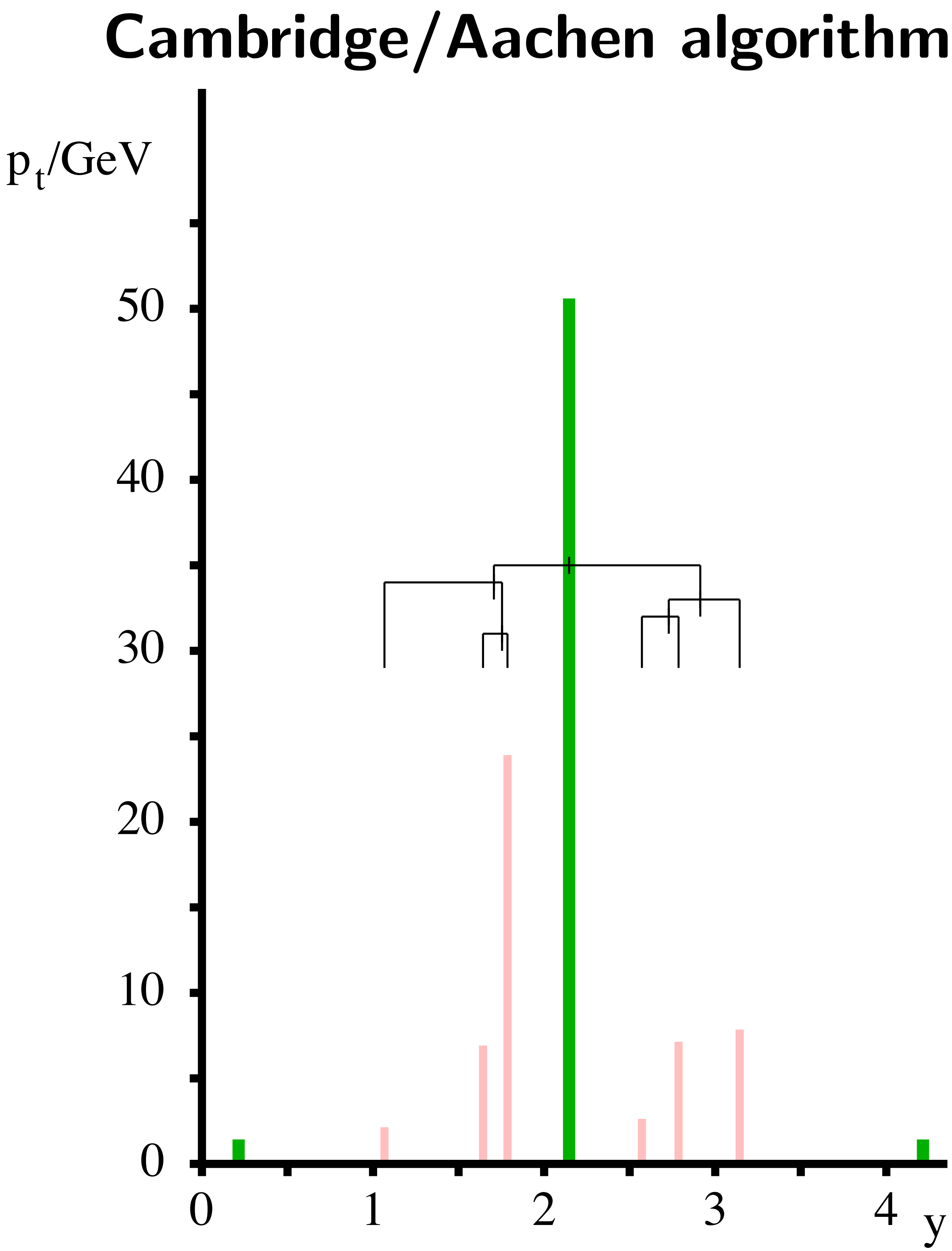
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination



How well can an algorithm identify the “blobs” of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them



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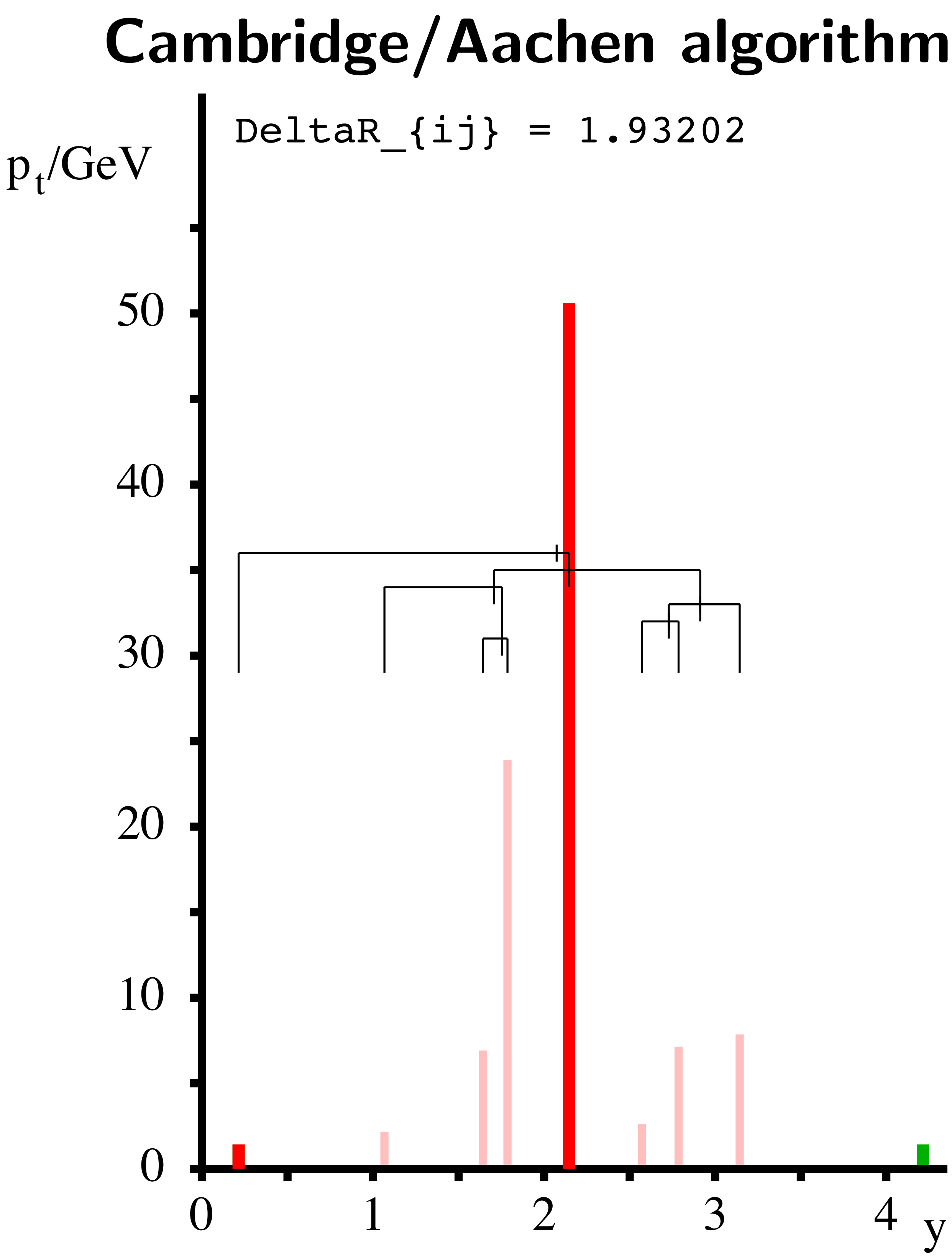
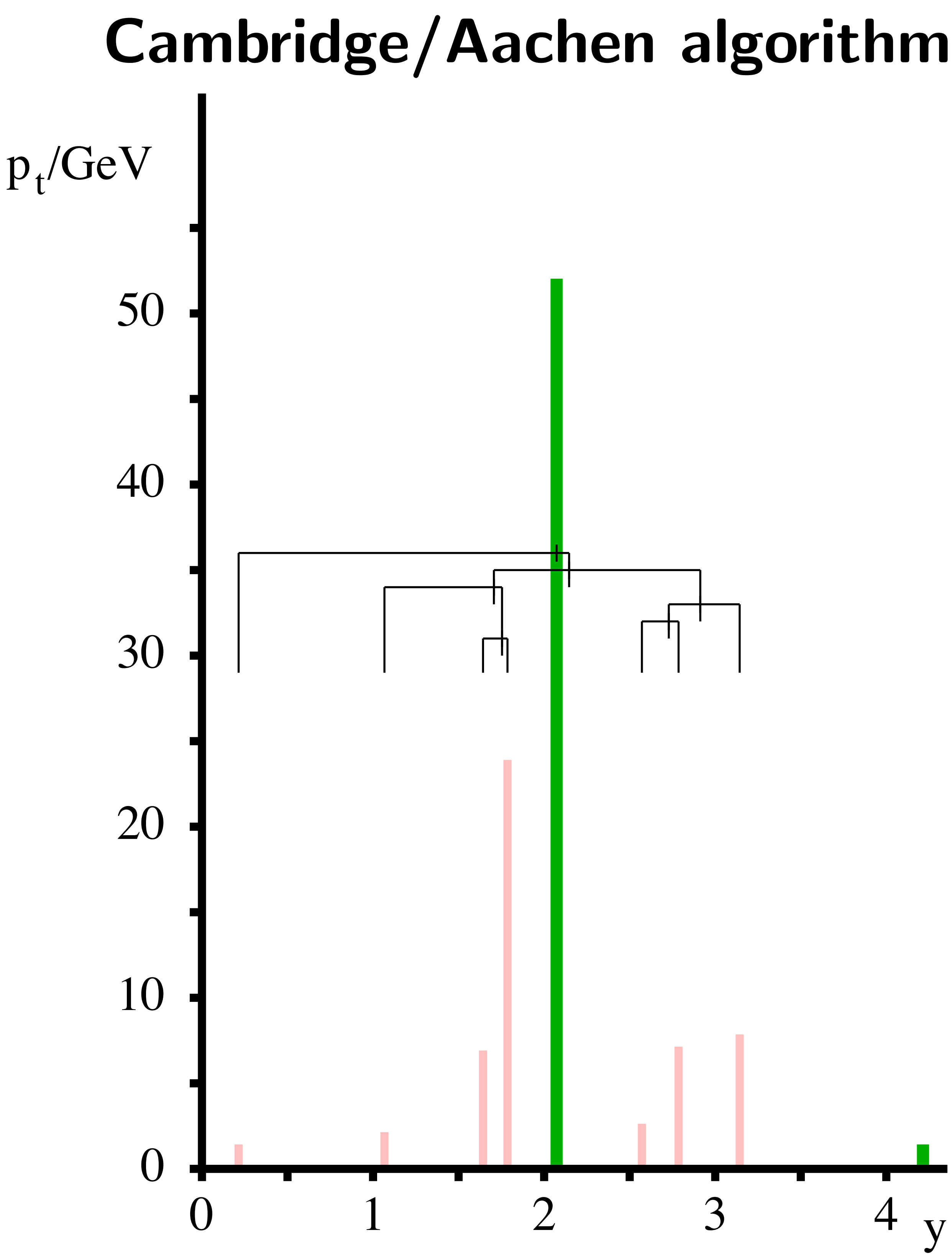


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk



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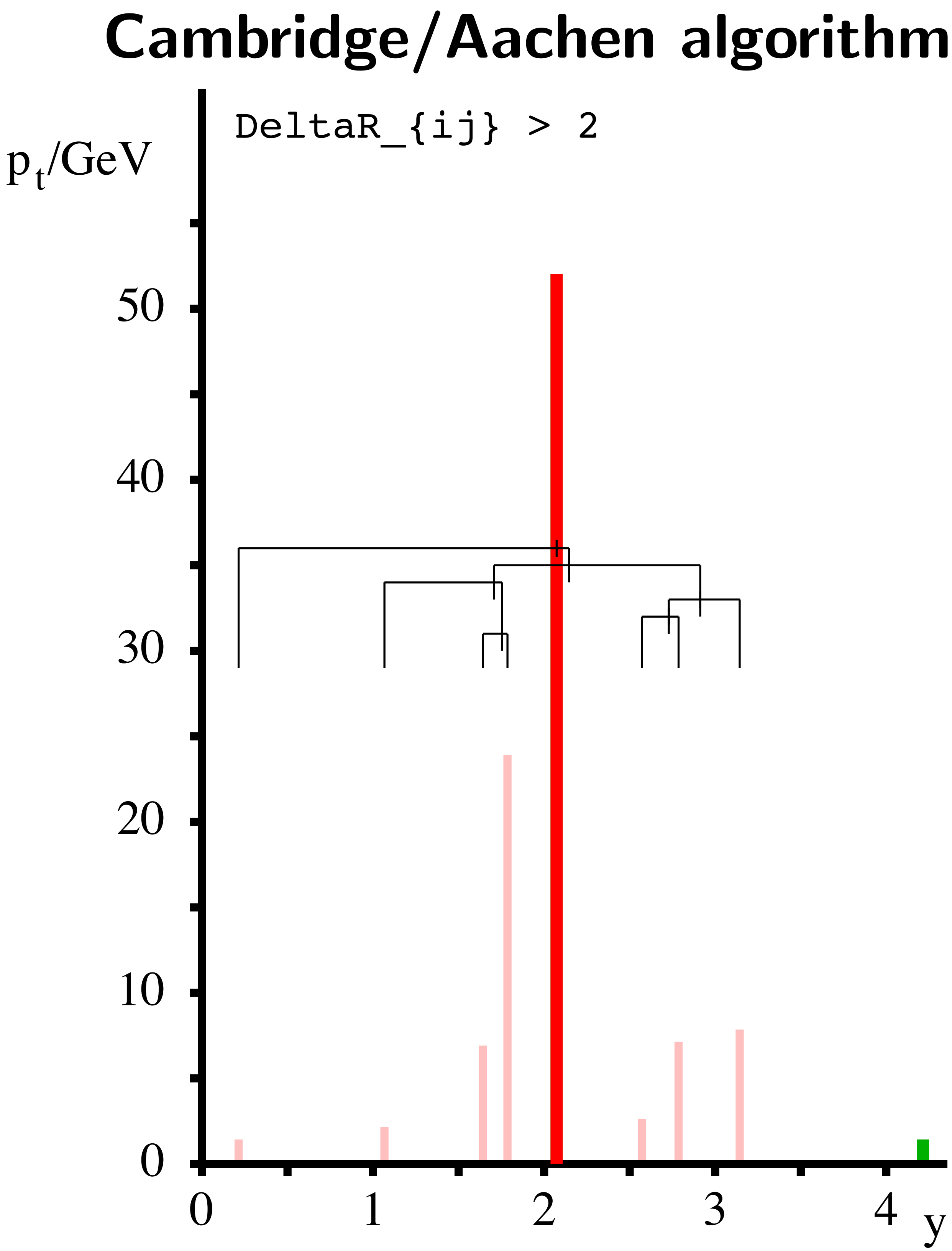

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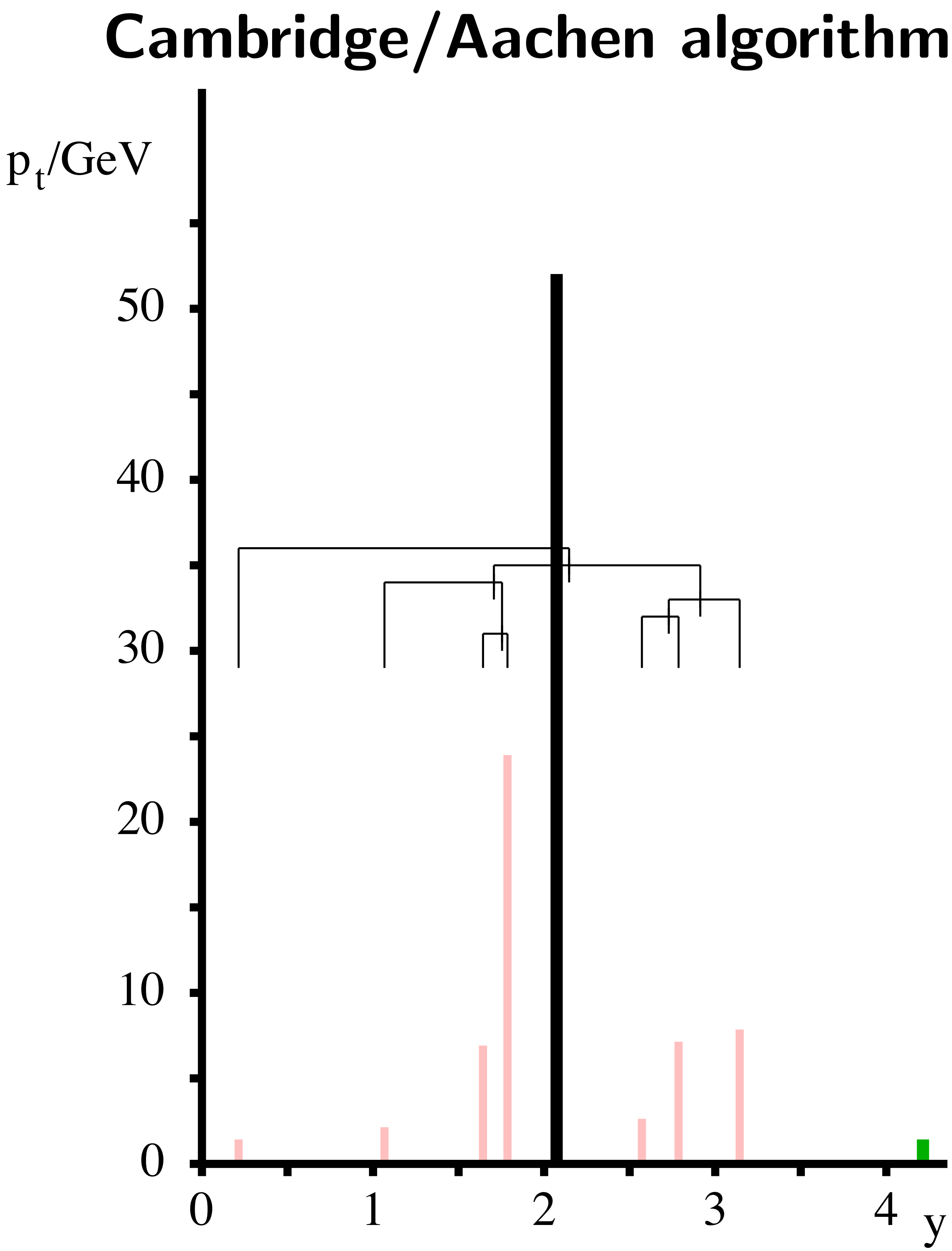

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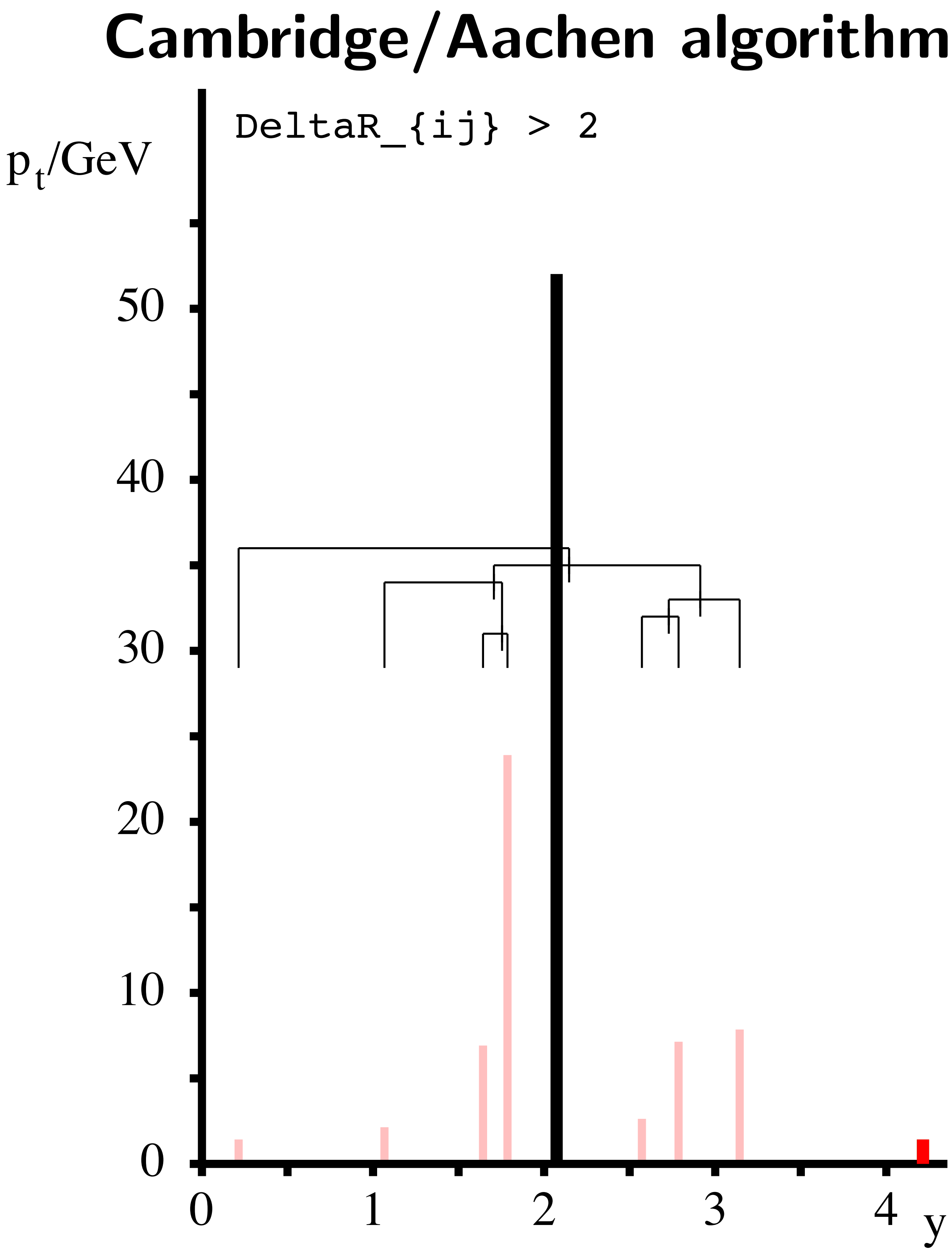

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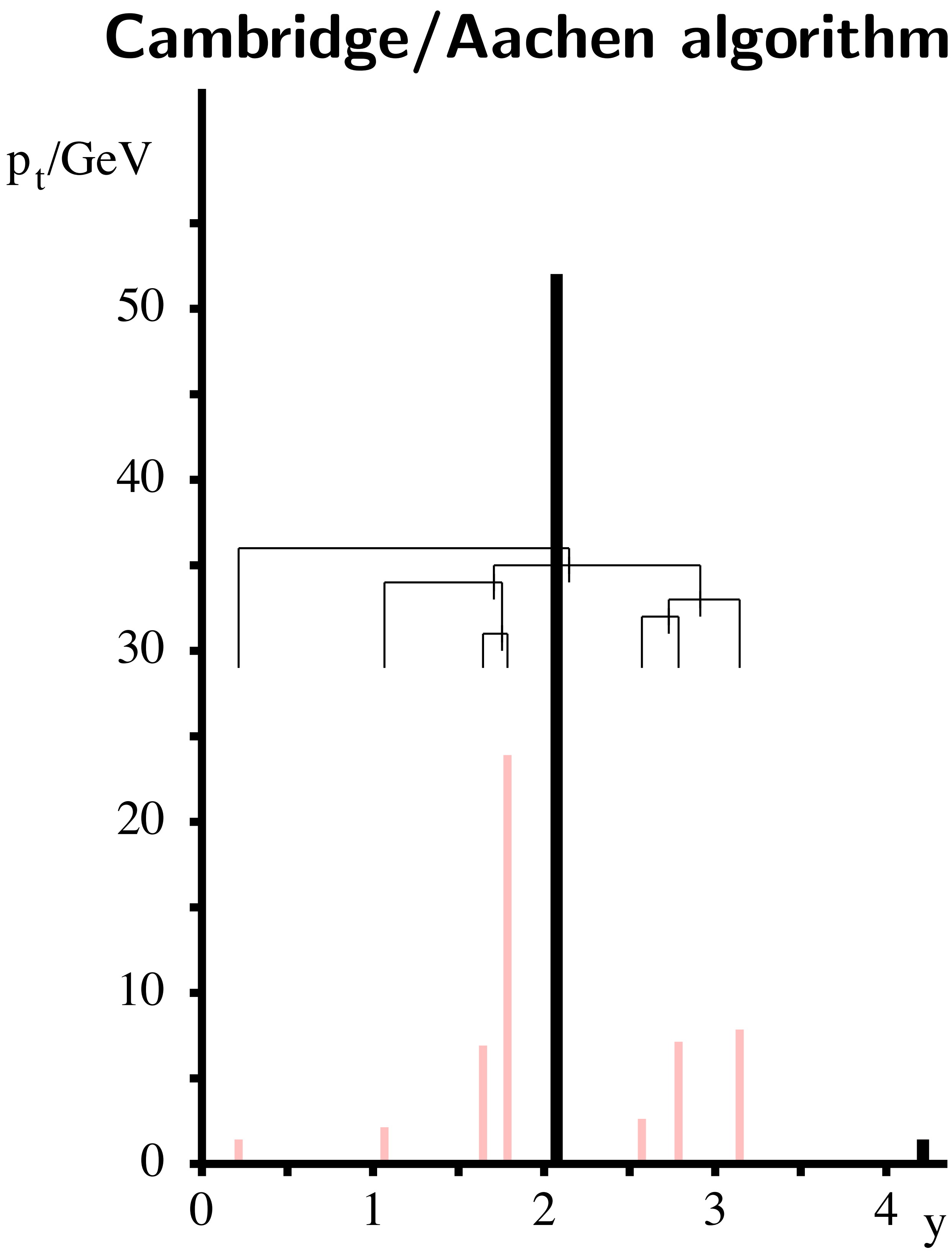
Identifying jet substructure: Cam/Aachen



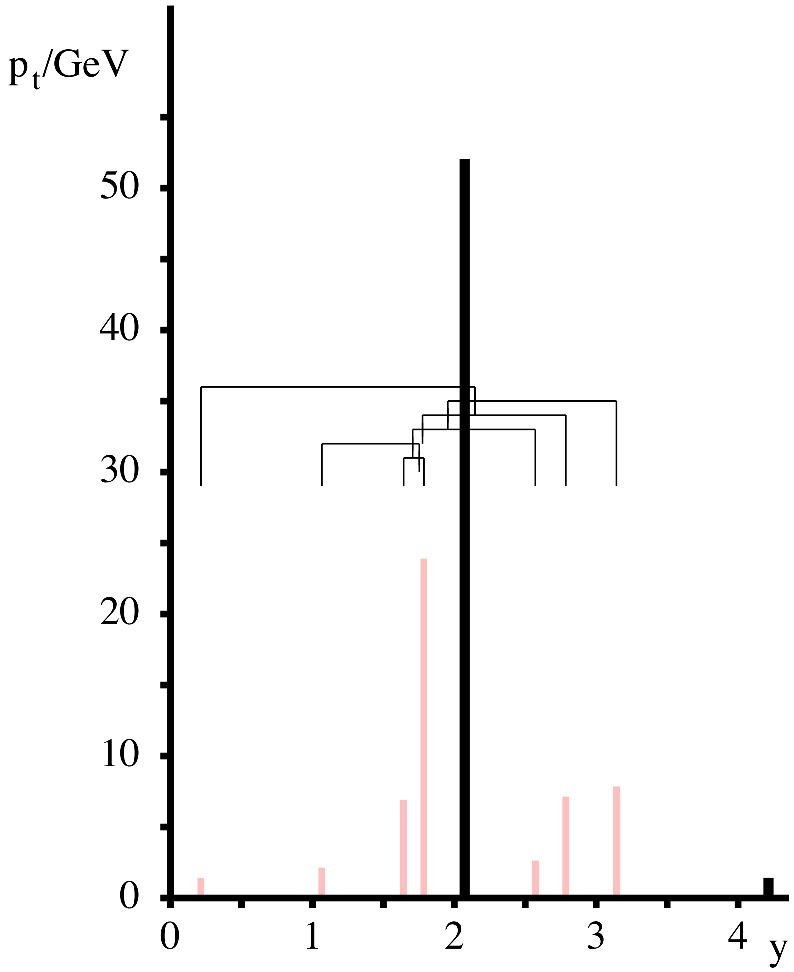
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination, joins them, and then adds in remaining soft junk

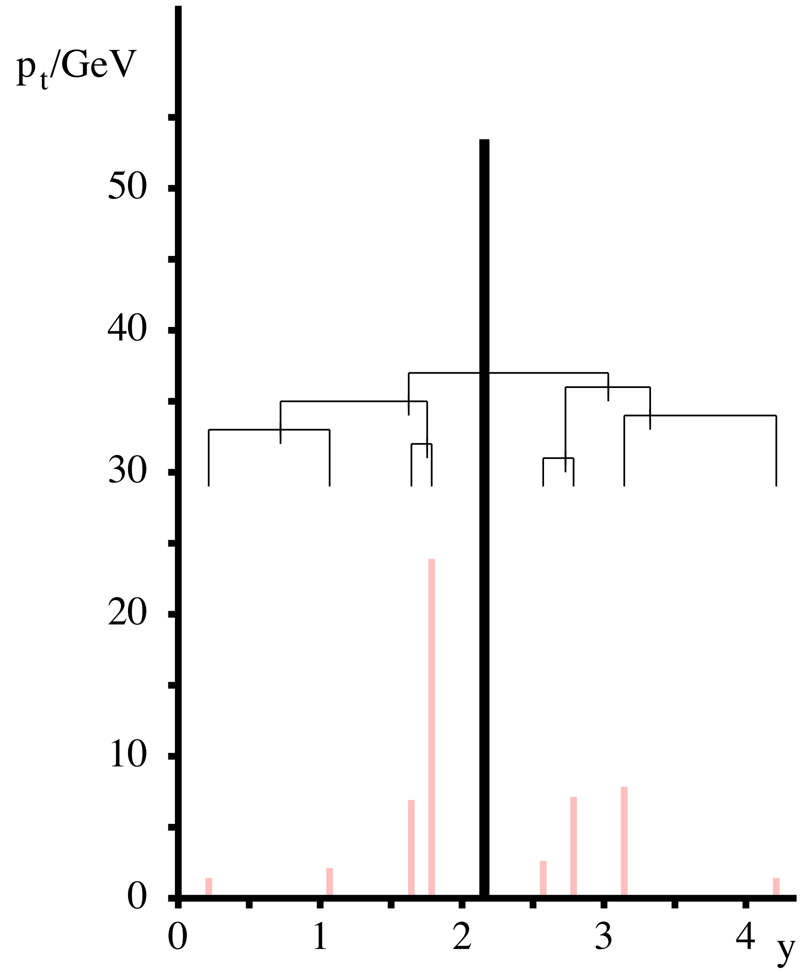
The interesting substructure is buried inside the clustering sequence — it's less contaminated by soft junk, but needs to be pulled out with special techniques

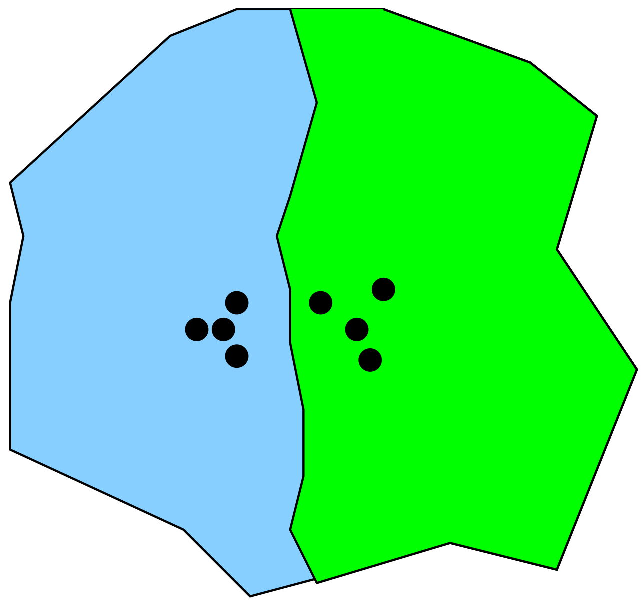
Butterworth, Davison, Rubin & GPS '08
Kaplan, Schwartz, Reherman & Tweedie '08
Butterworth, Ellis, Rubin & GPS '09
Ellis, Vermilion & Walsh '09

anti-k_t algorithm

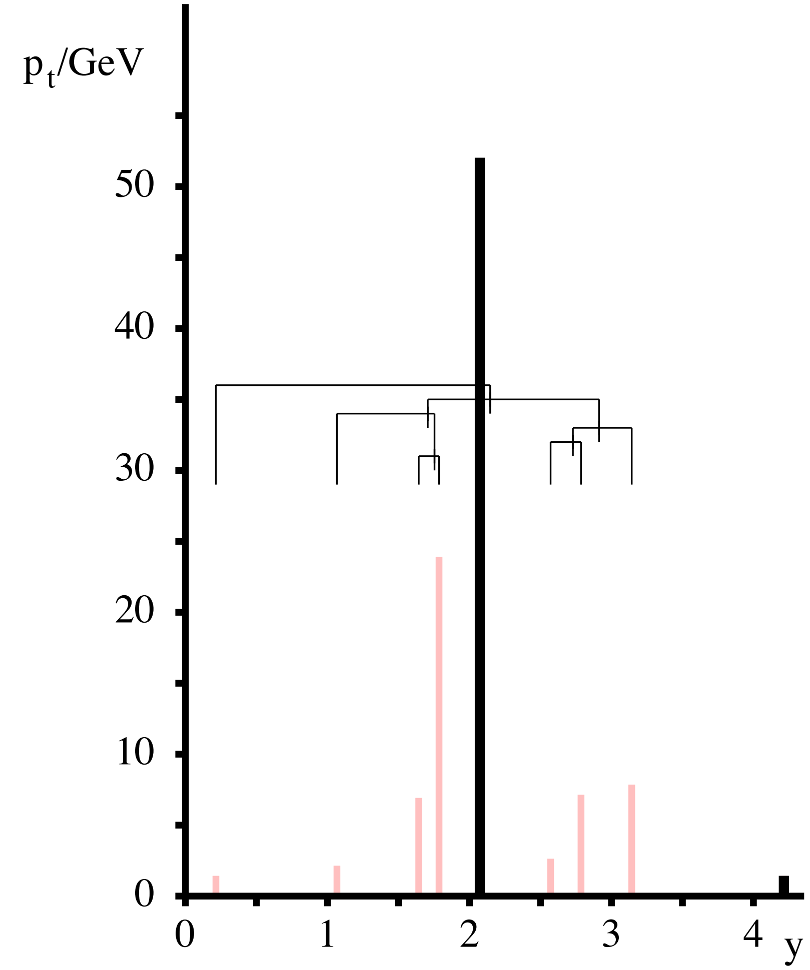


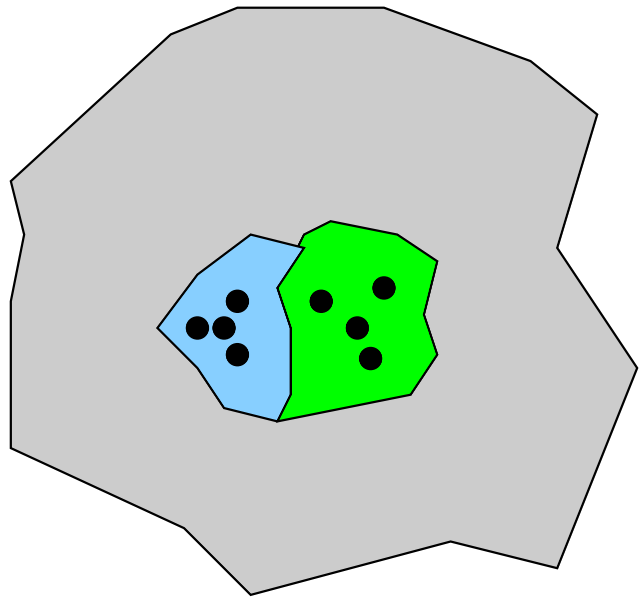
k_t algorithm





Cambridge/Aachen

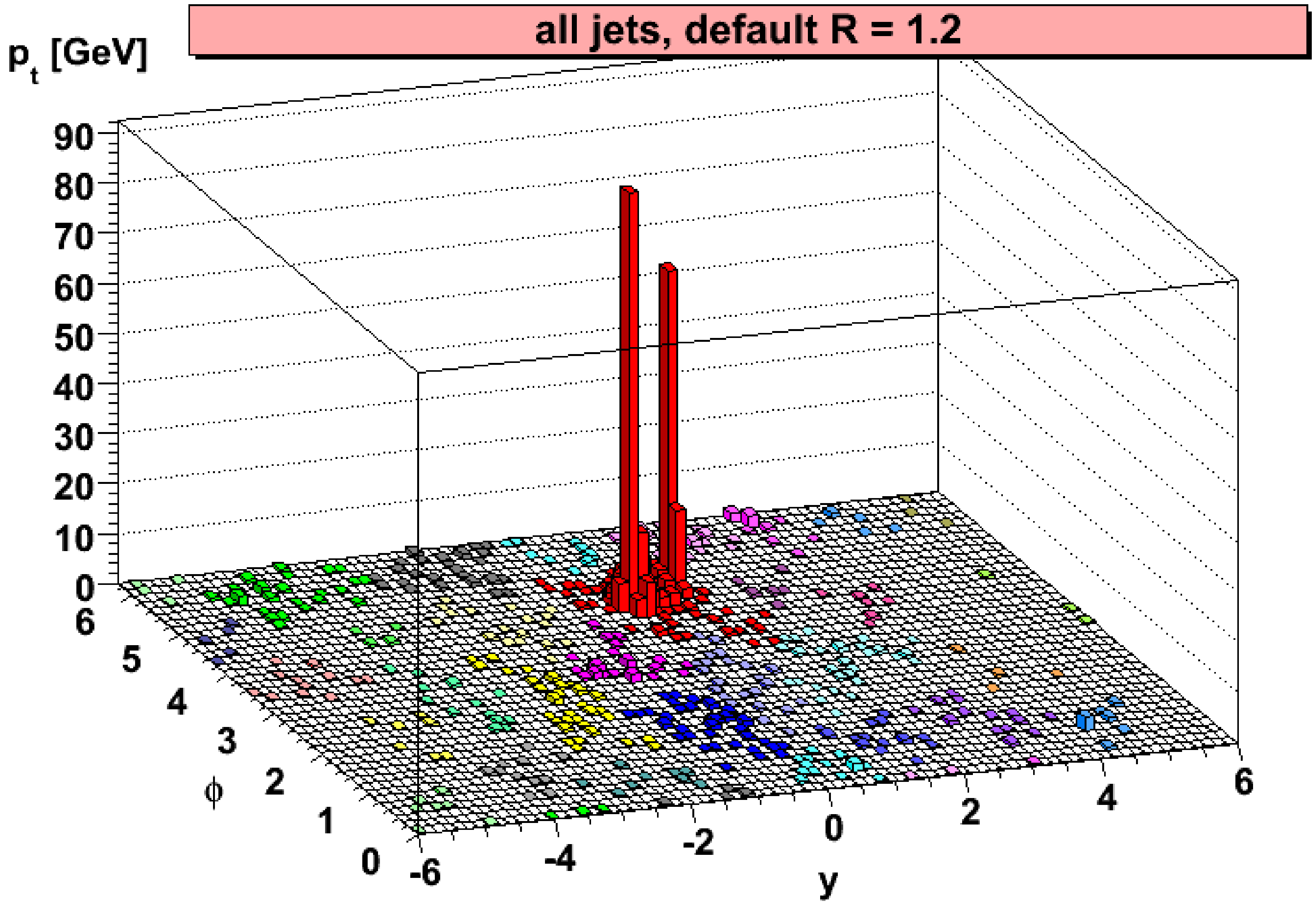




$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

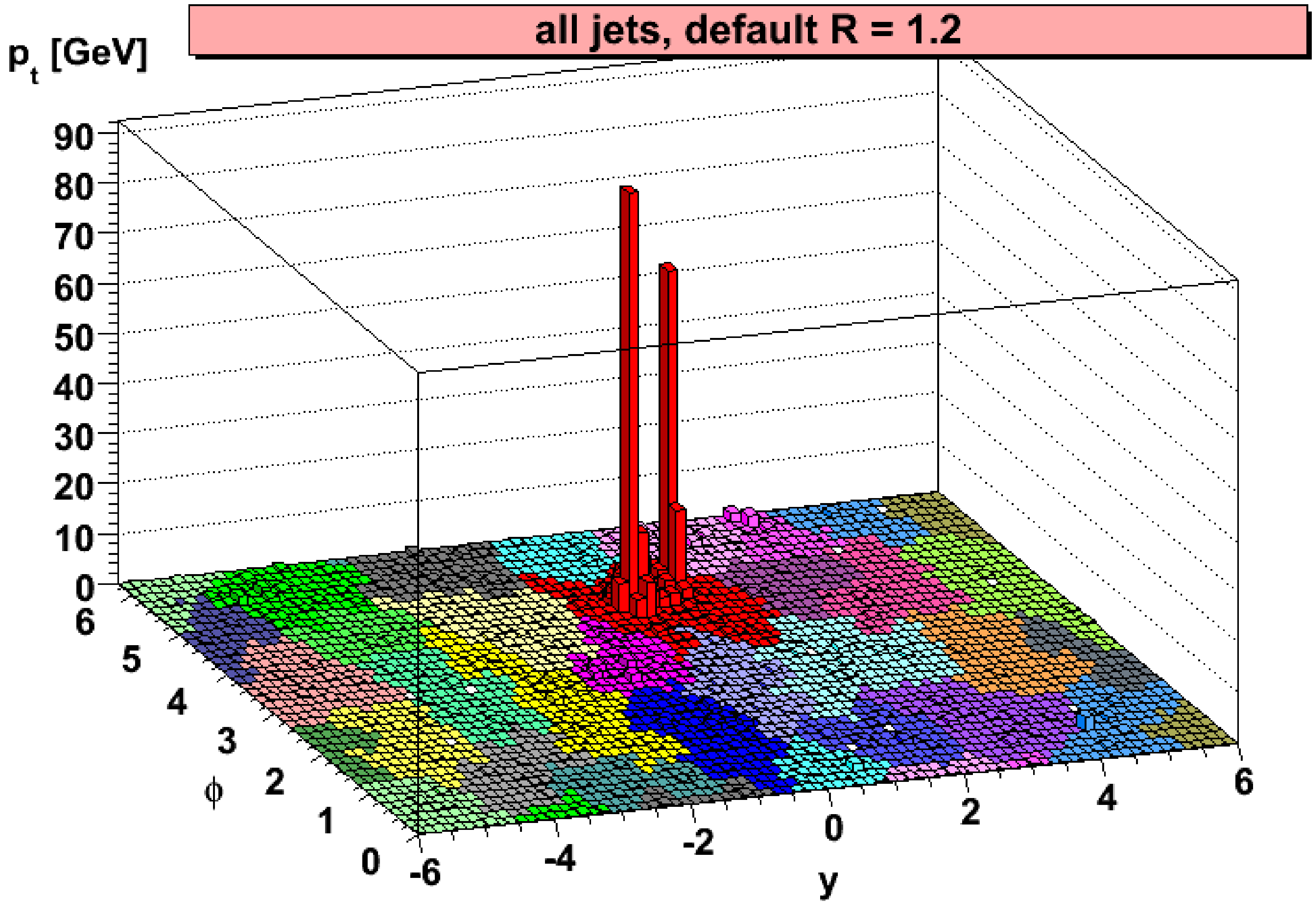
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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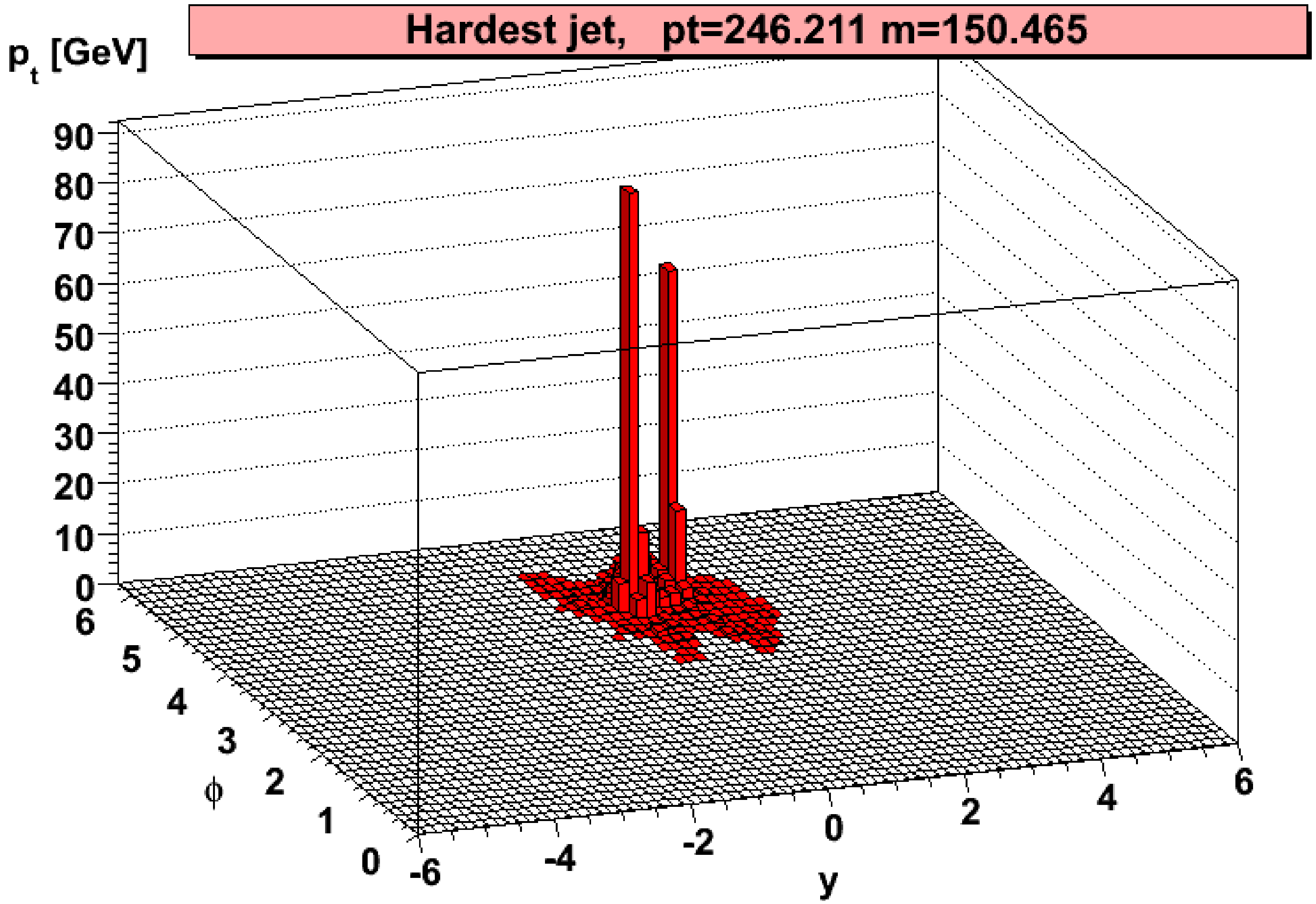
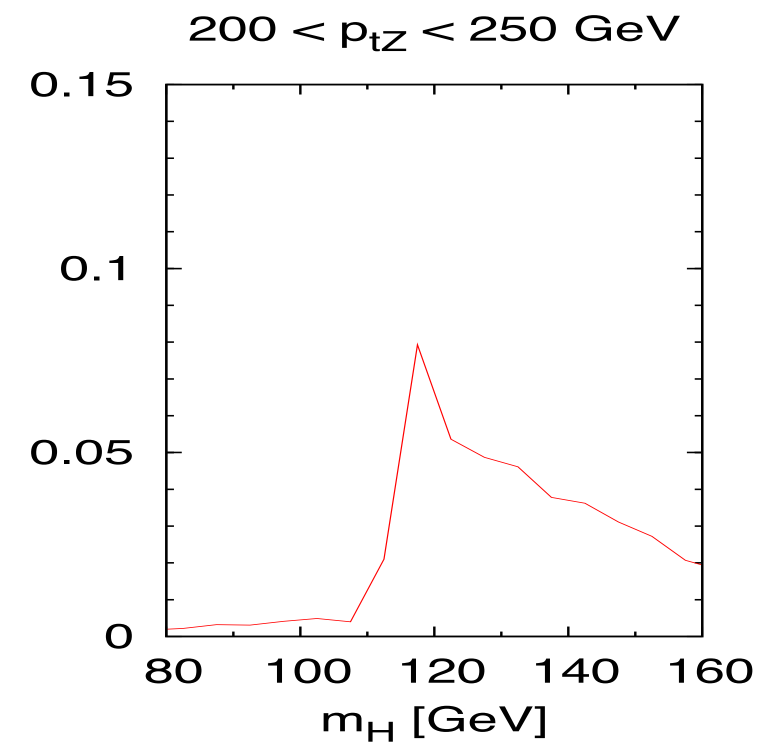


Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

SIGNAL



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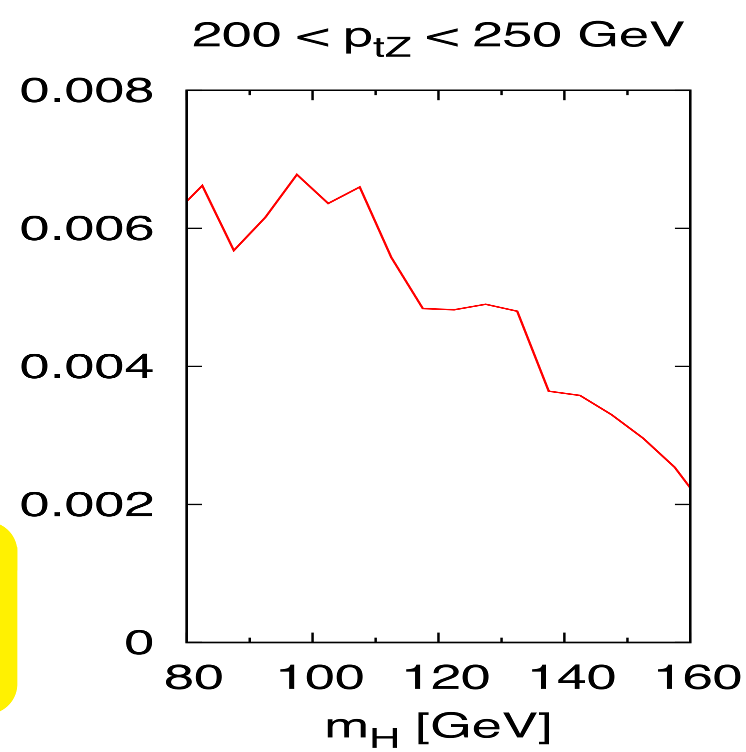

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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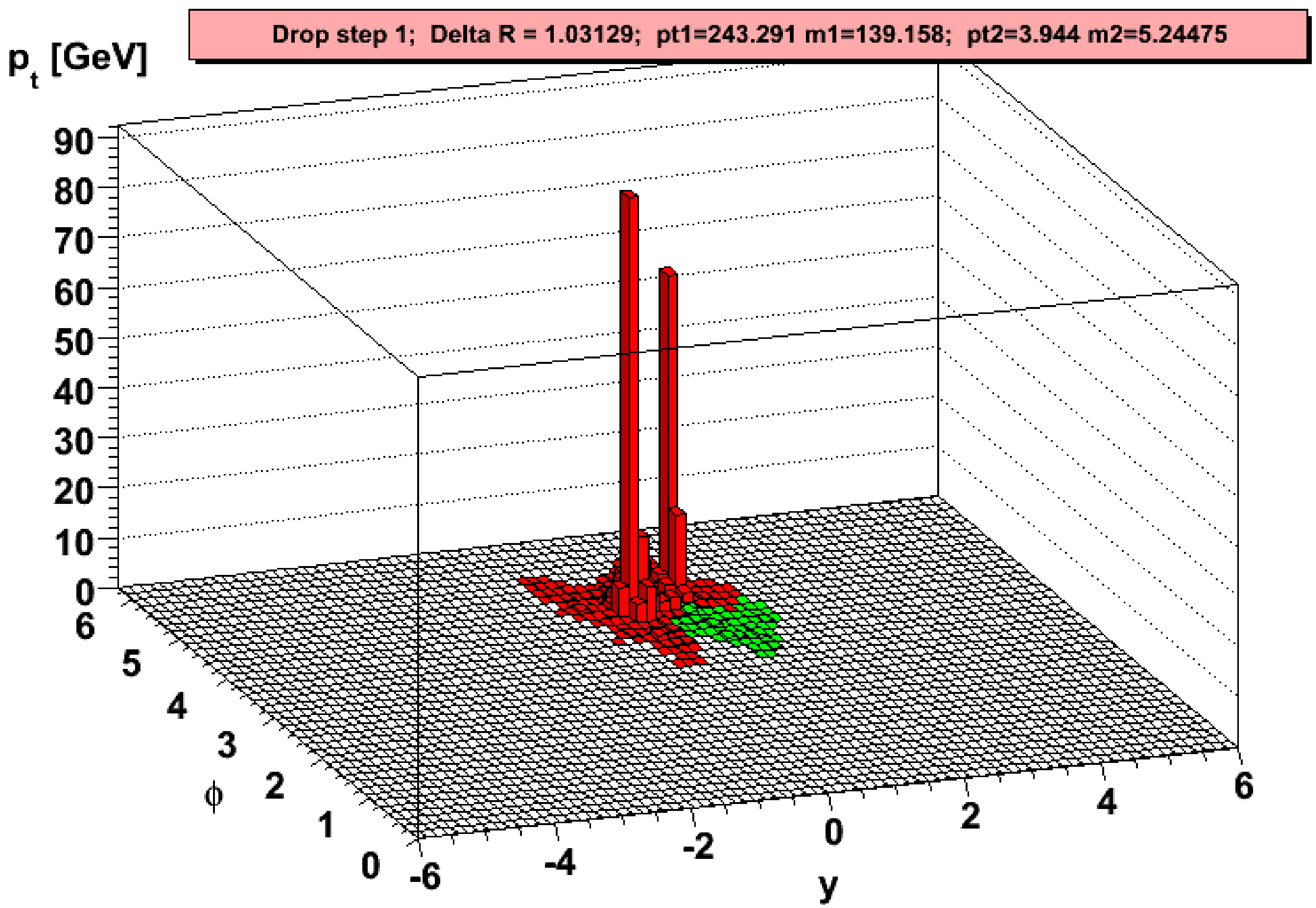
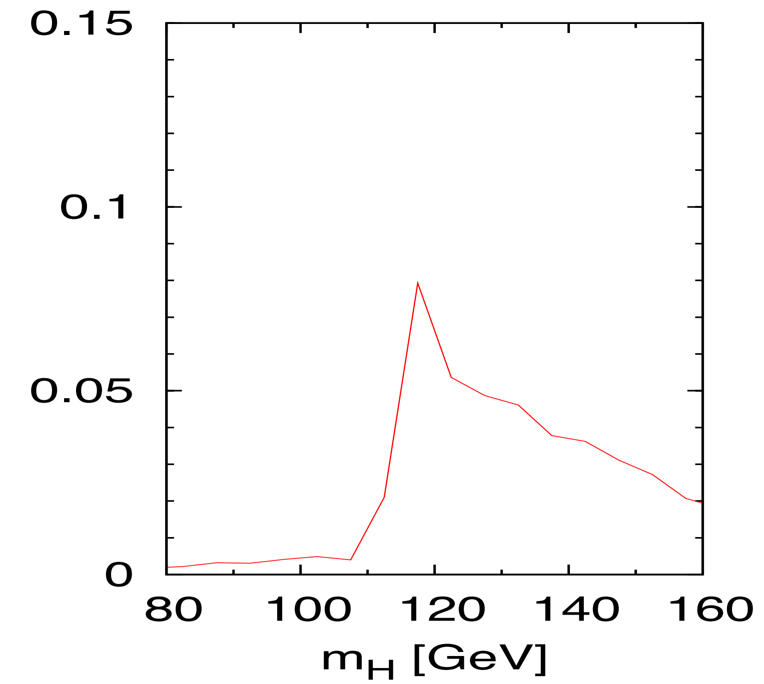


SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

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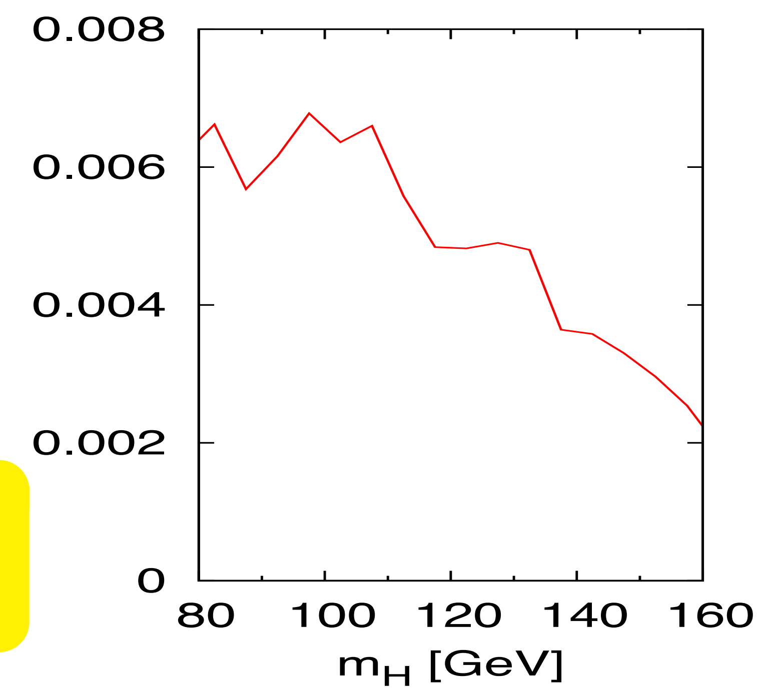


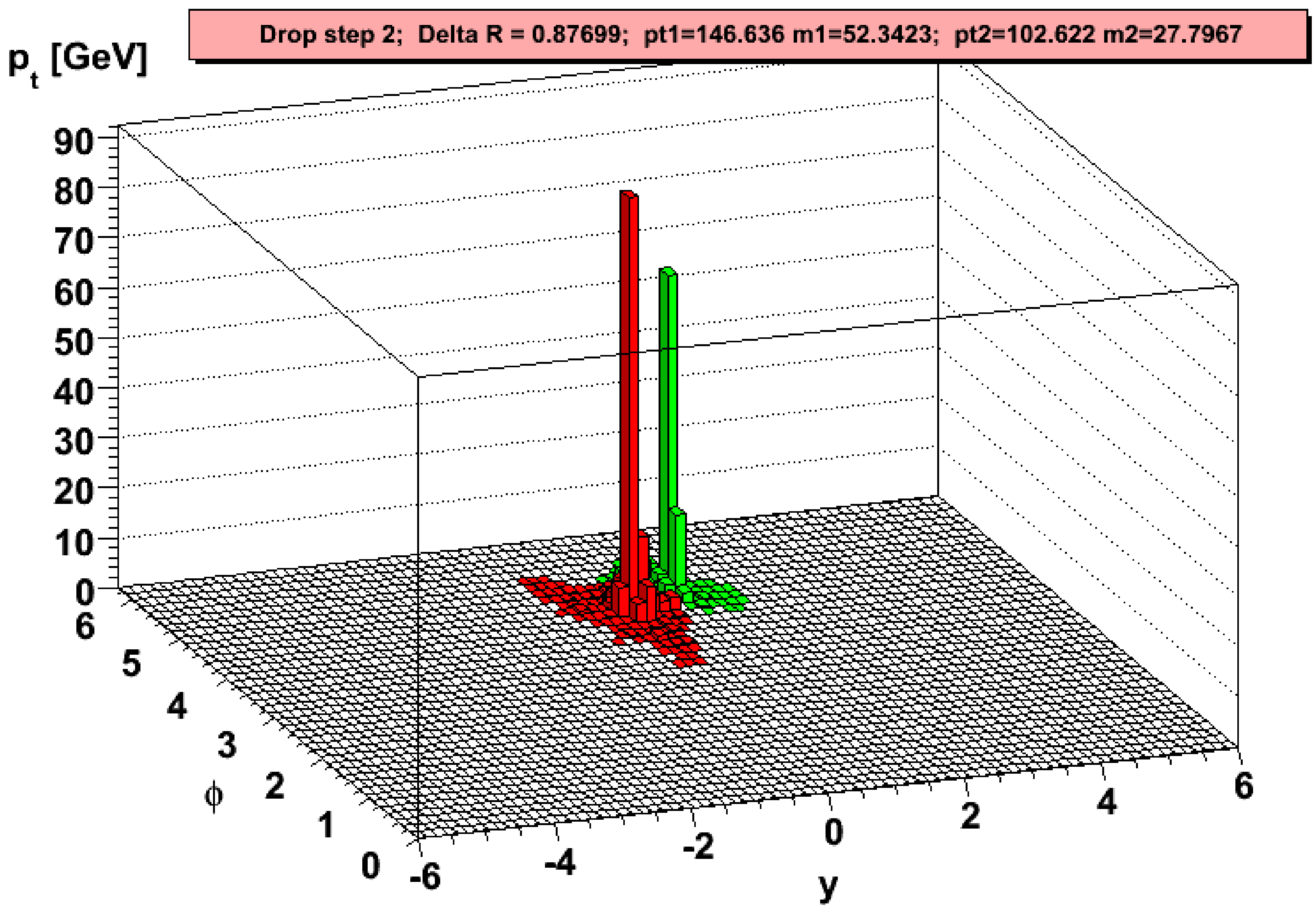
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

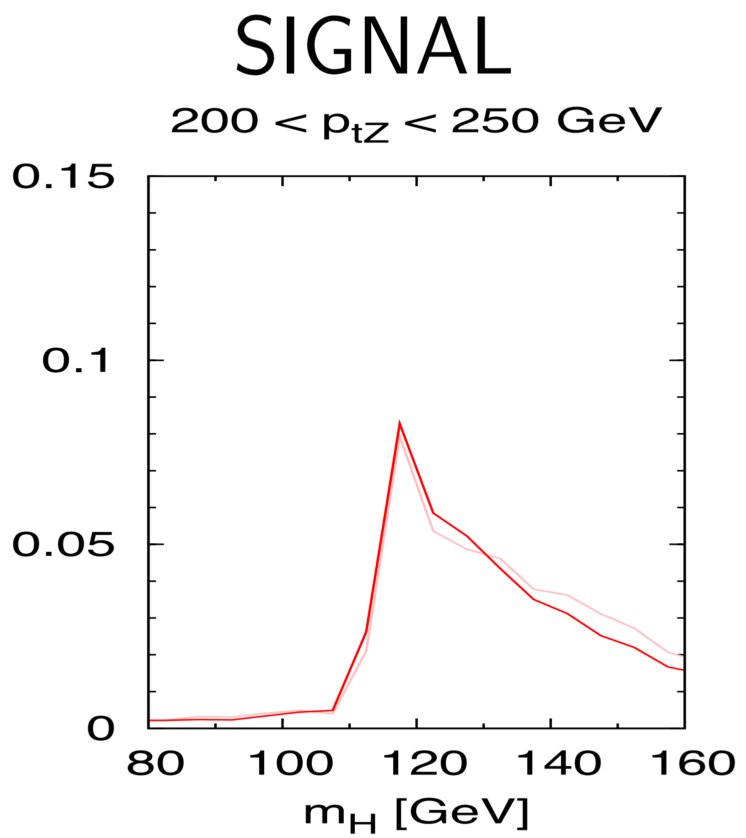
Butterworth, Davison, Rubin & GPS '08

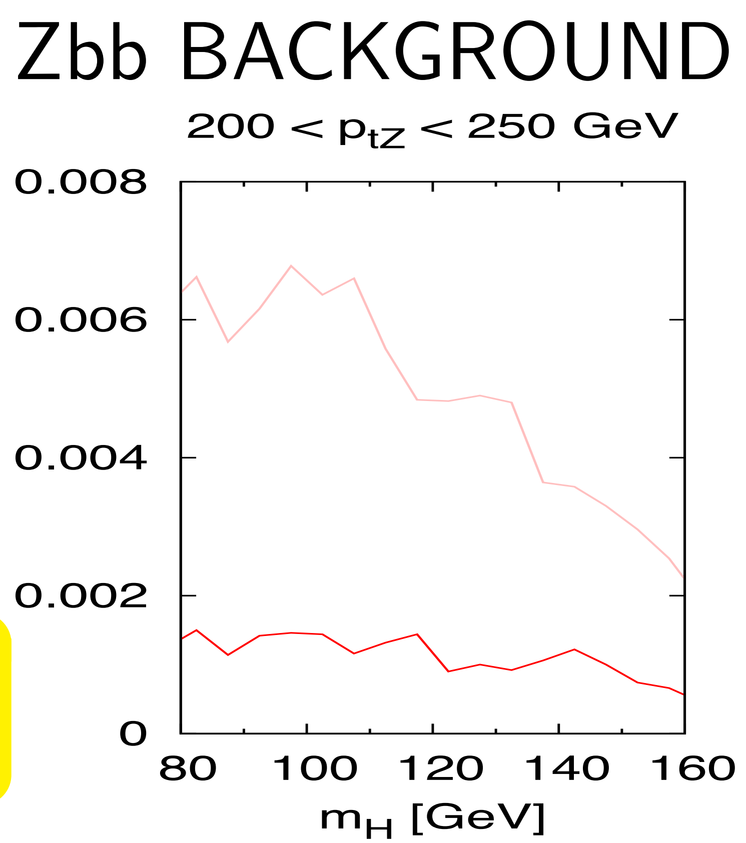
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







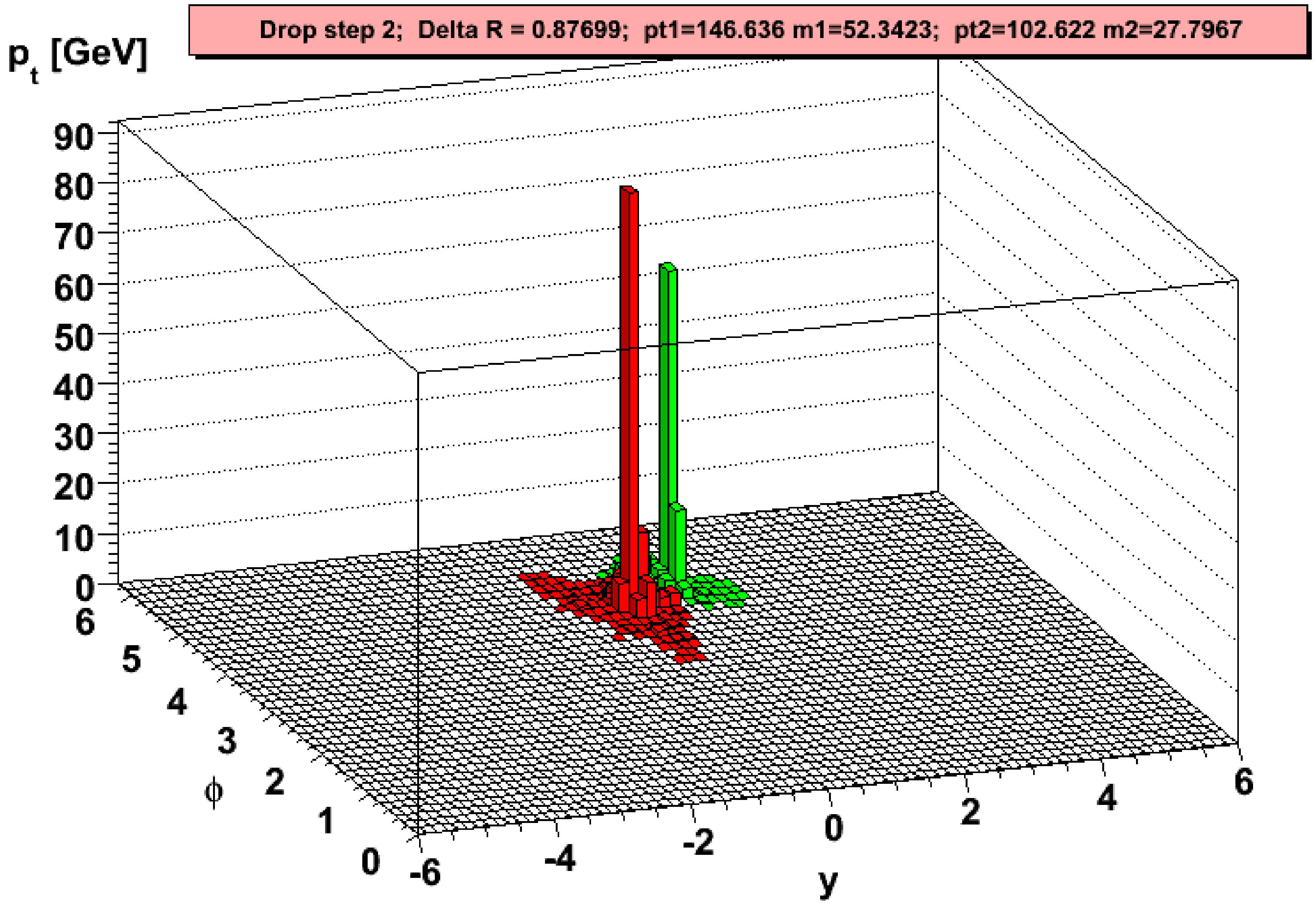
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

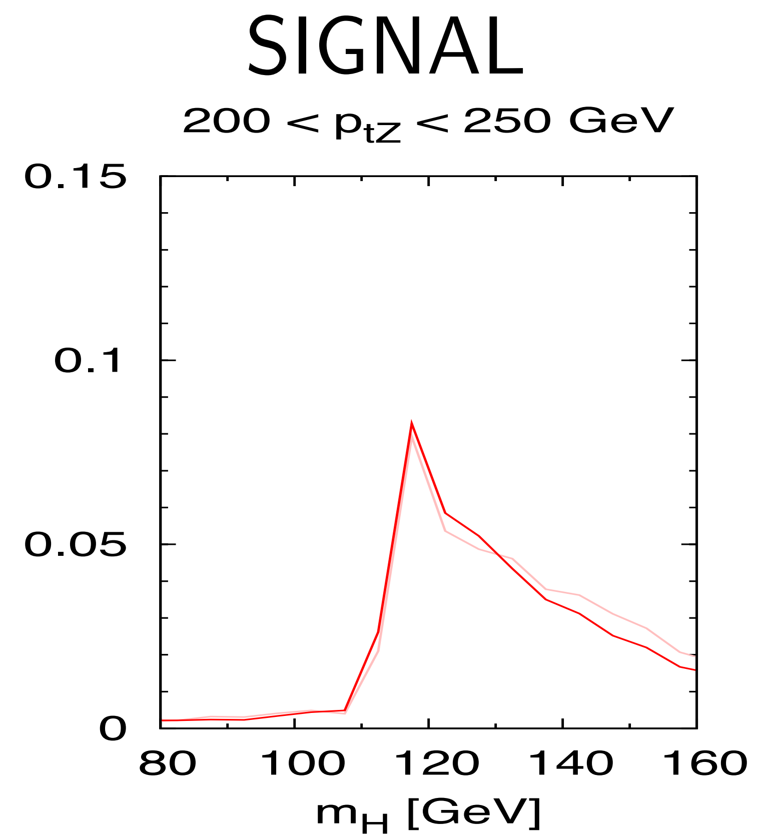
Butterworth, Davison, Rubin & GPS '08

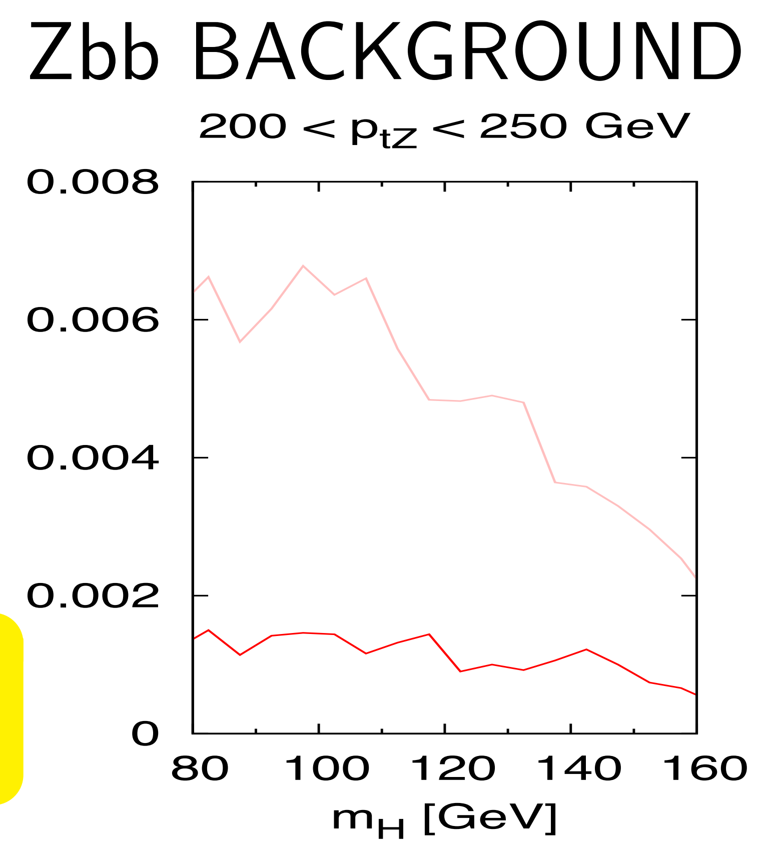
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







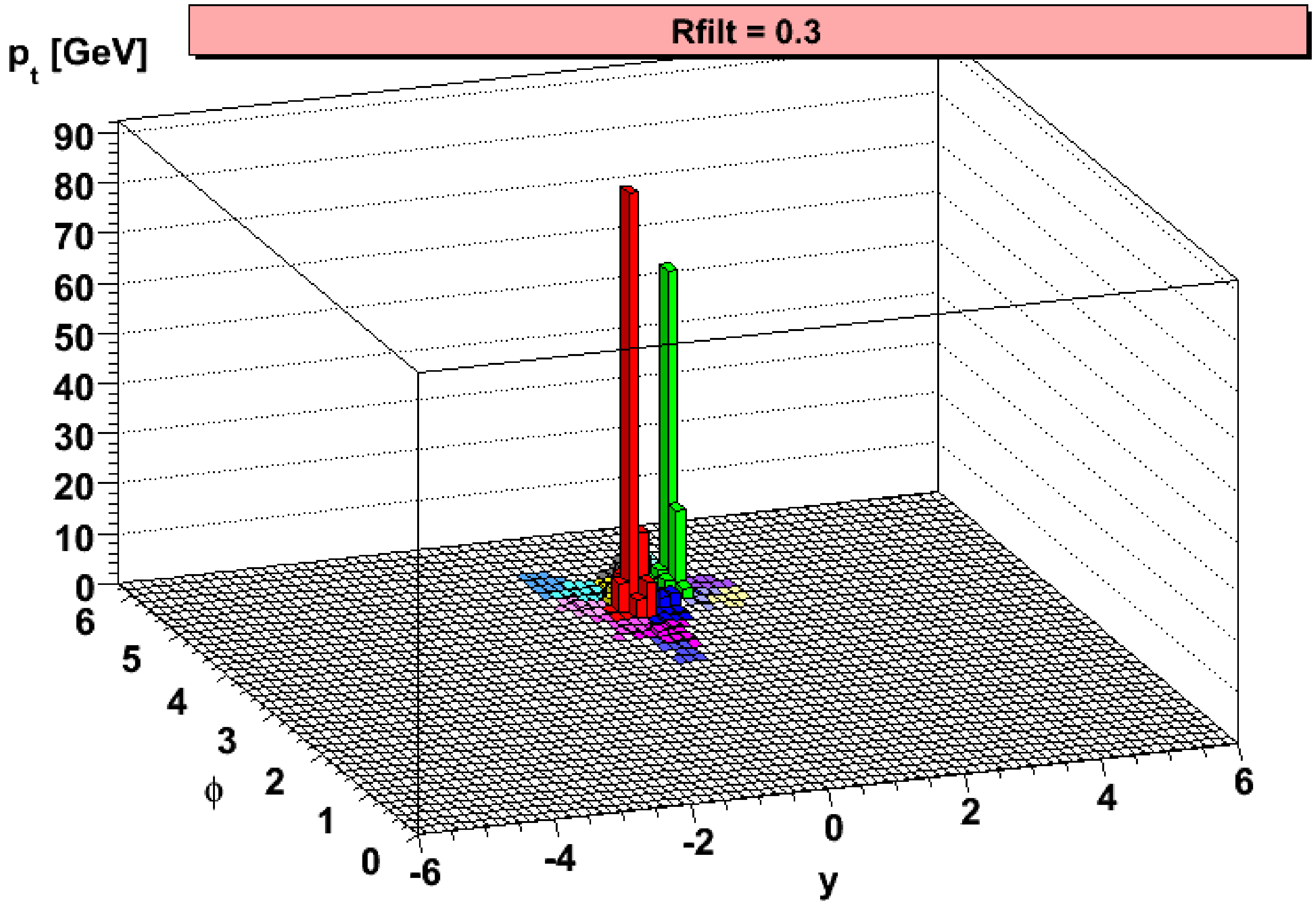
check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

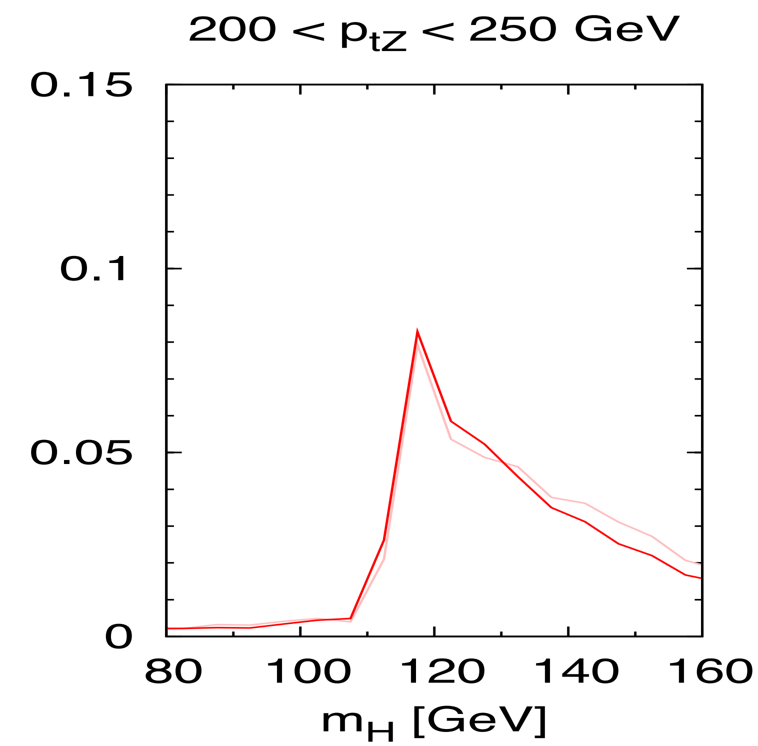
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

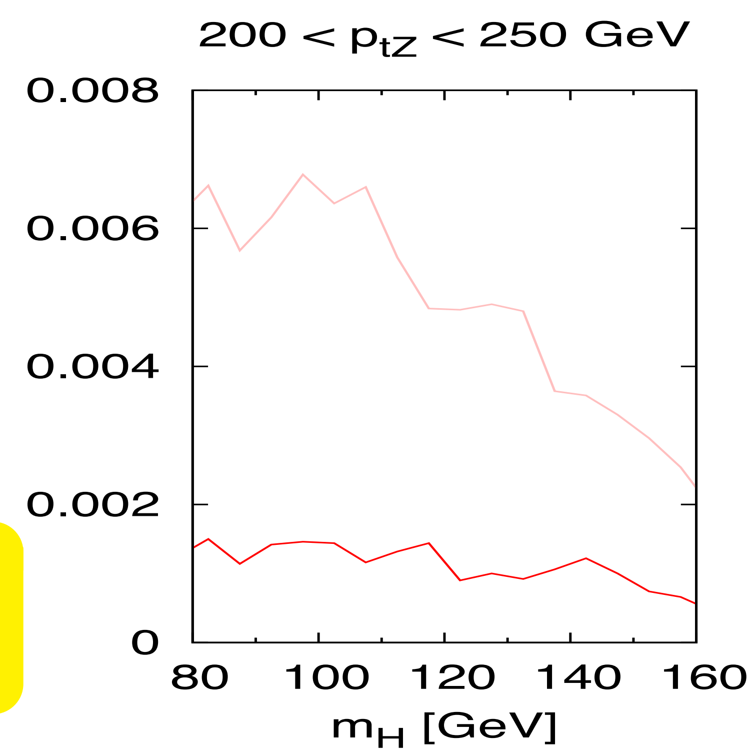


$R_{filt} = 0.3$

SIGNAL



Zbb BACKGROUND



Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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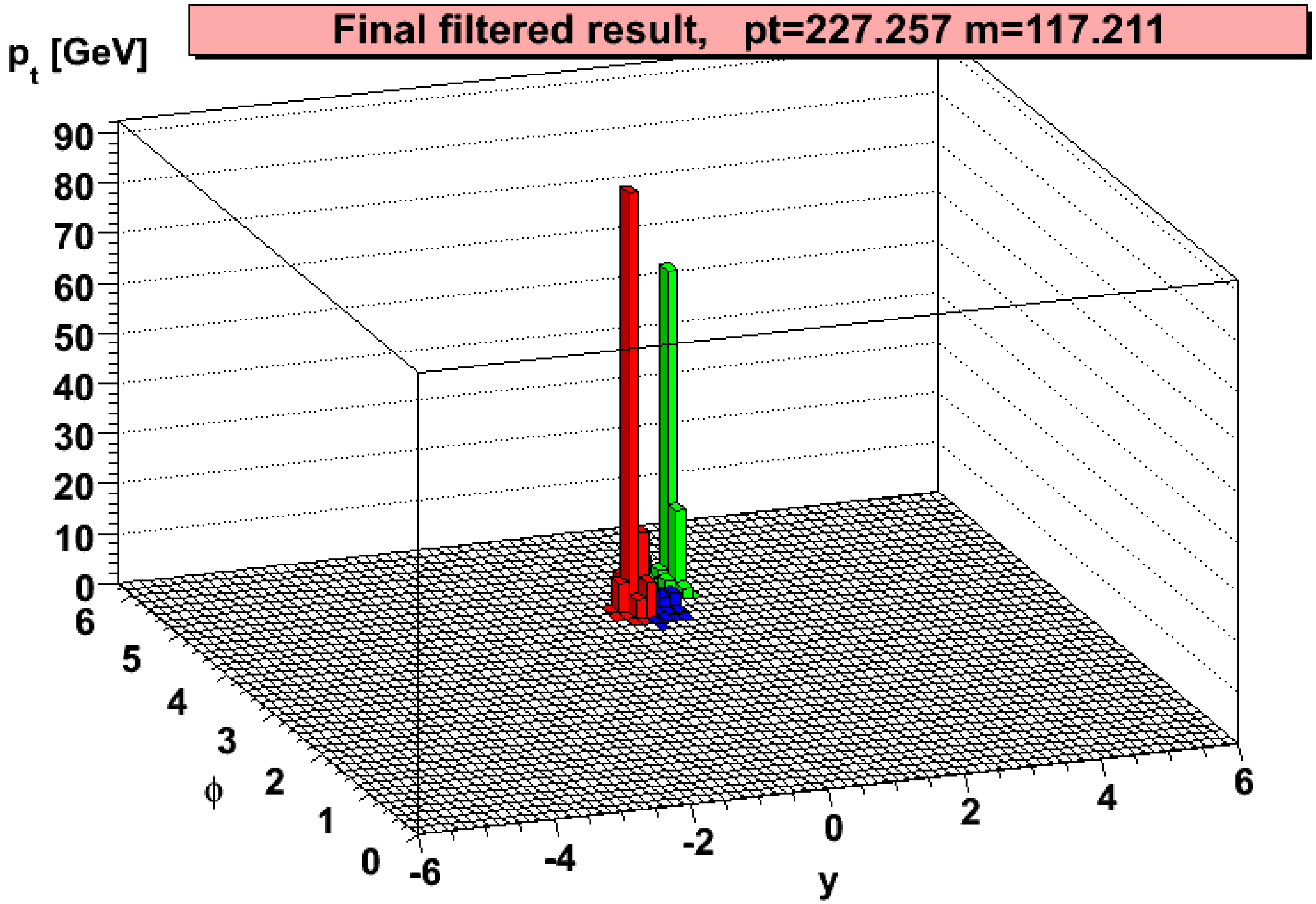
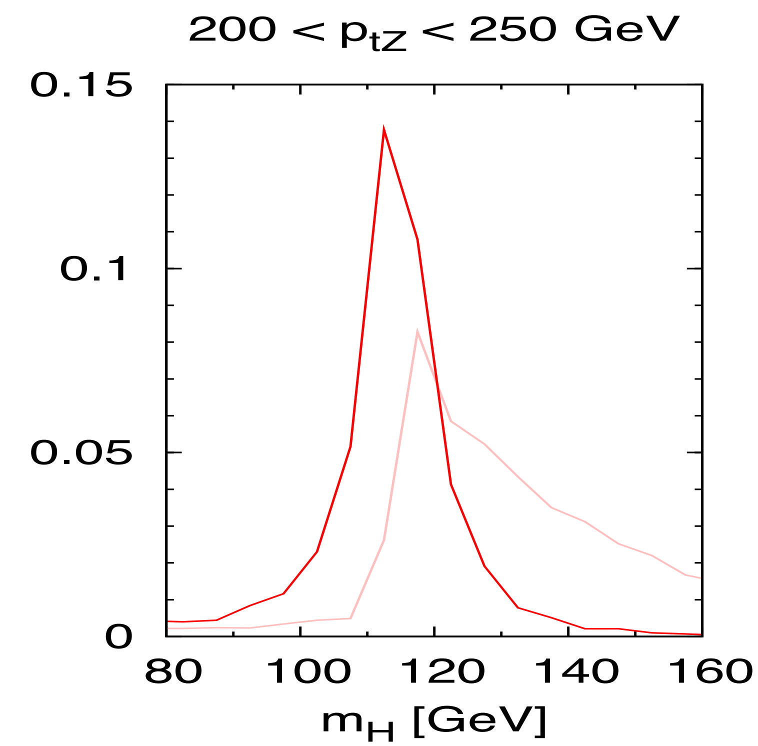


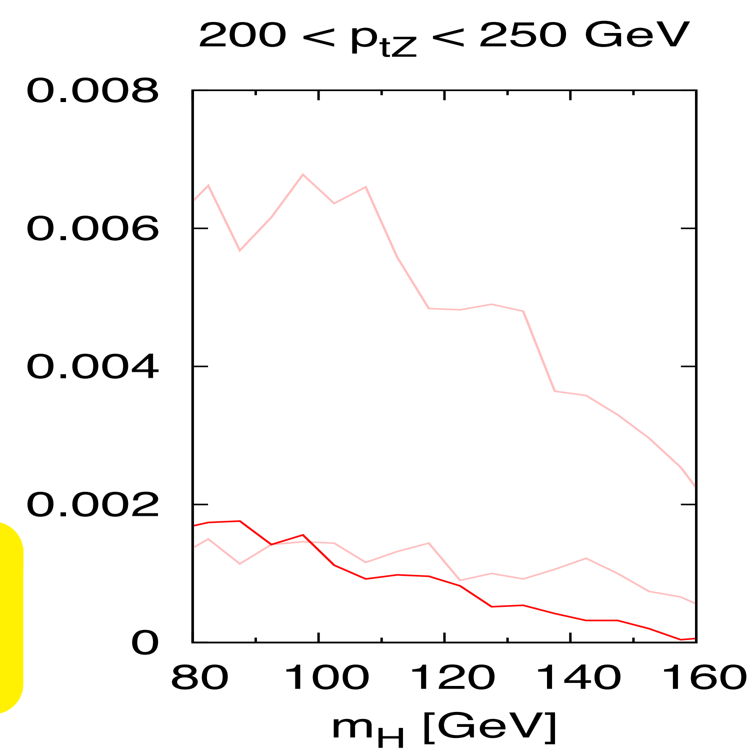
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

Butterworth, Davison, Rubin & GPS '08

SIGNAL



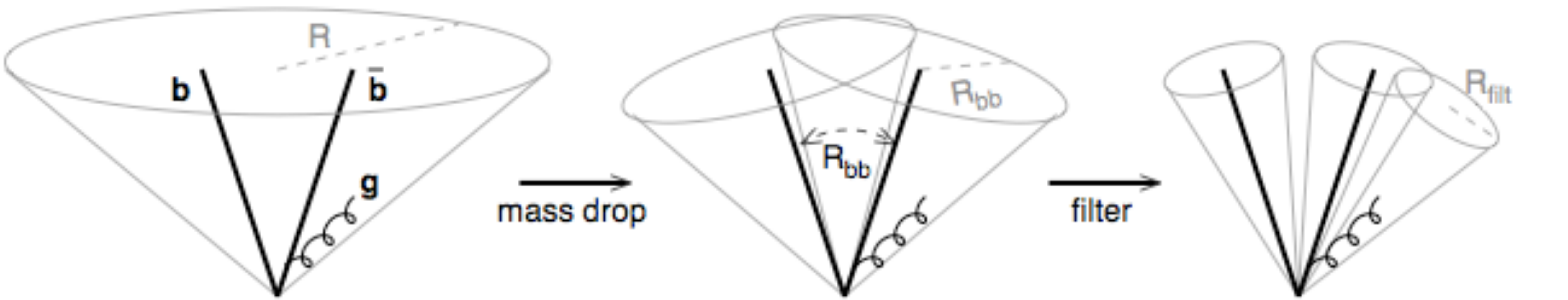
Zbb BACKGROUND

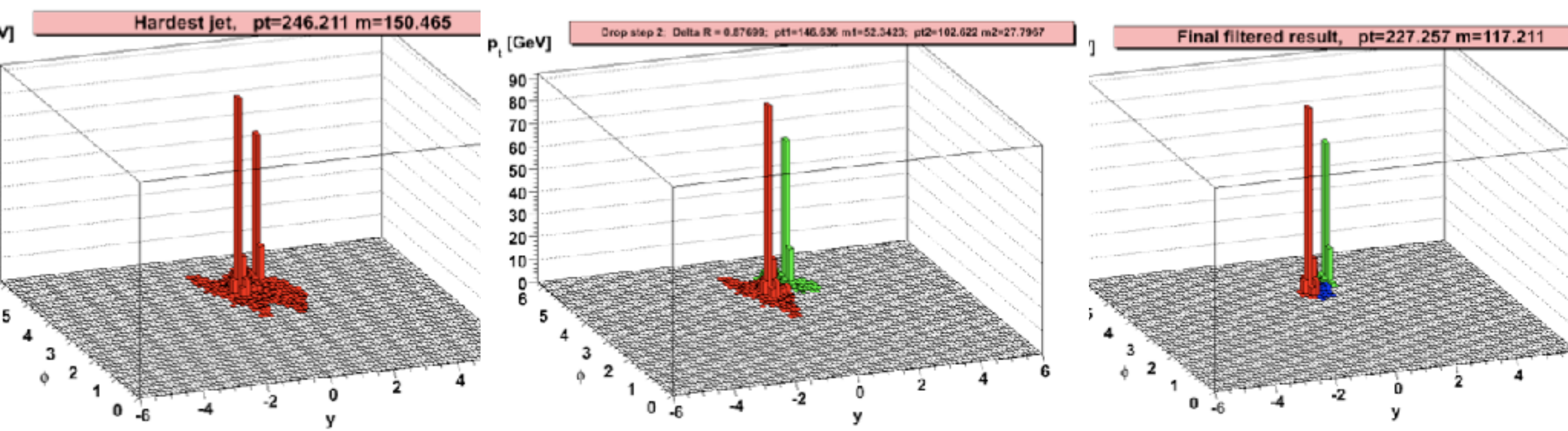


arbitrary norm.

Boosted Higgs analysis

$pp \to ZH \to \nu\nu b\bar{b}$





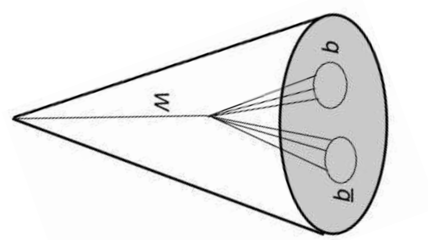
Cluster with a large R

Undo the clustering into subjets, until a large mass drop is observed

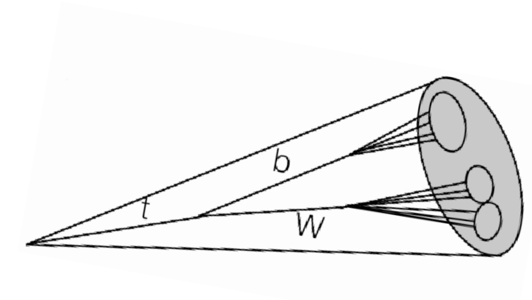
Re-cluster with smaller R, and keep only 3 hardest jets

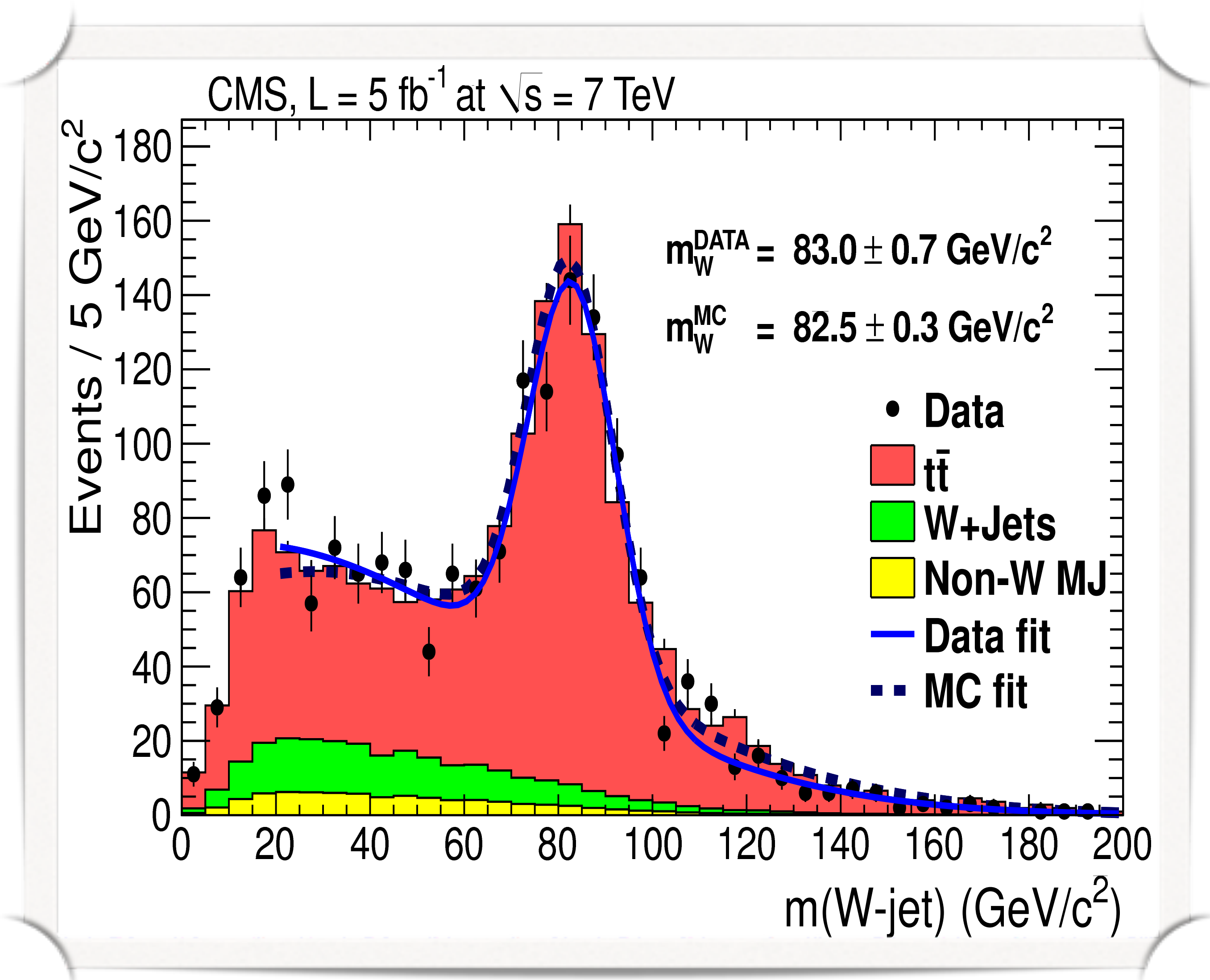
Seeing W's and tops in a single jet

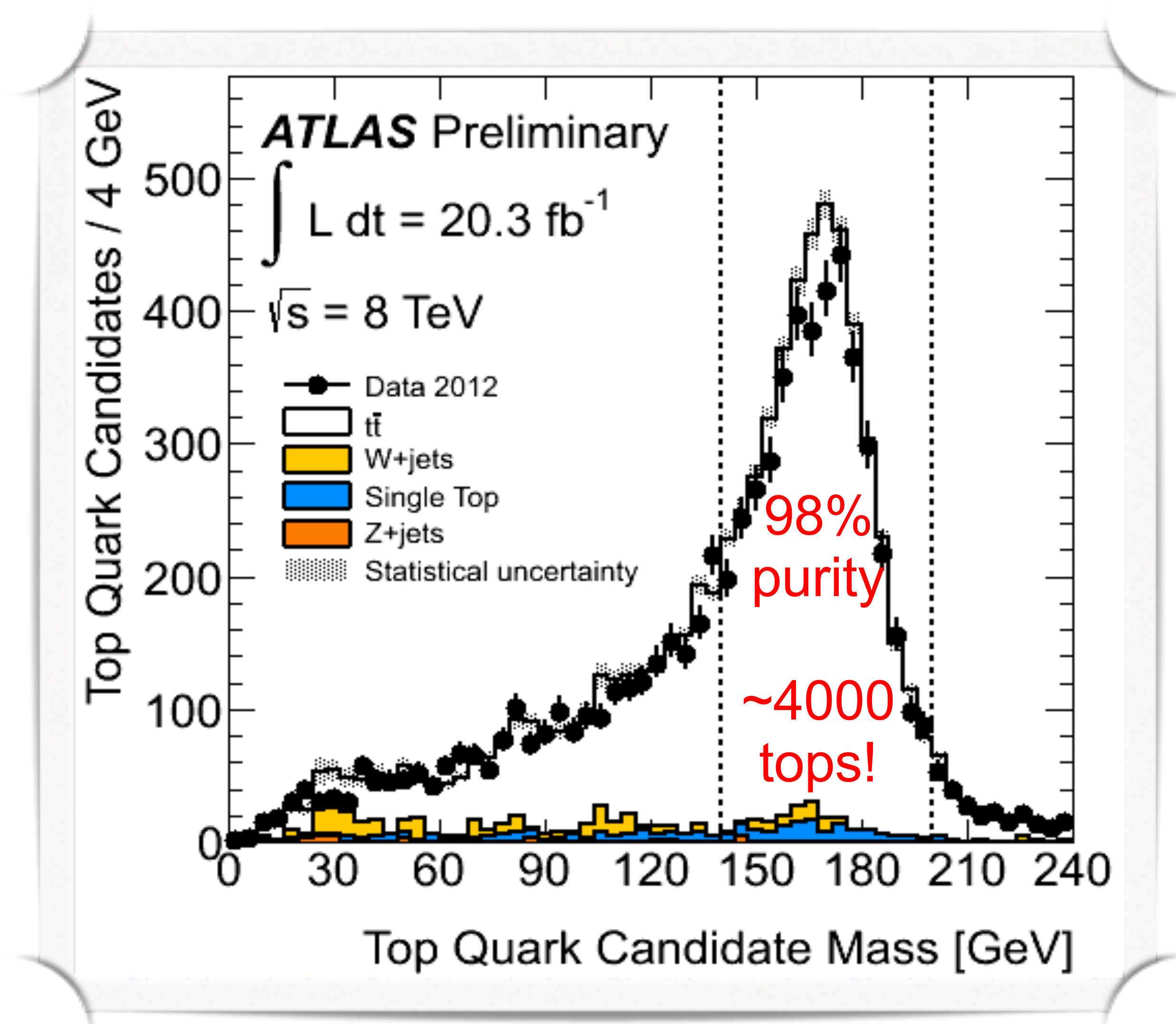
W's in a single jet



tops in a single jet



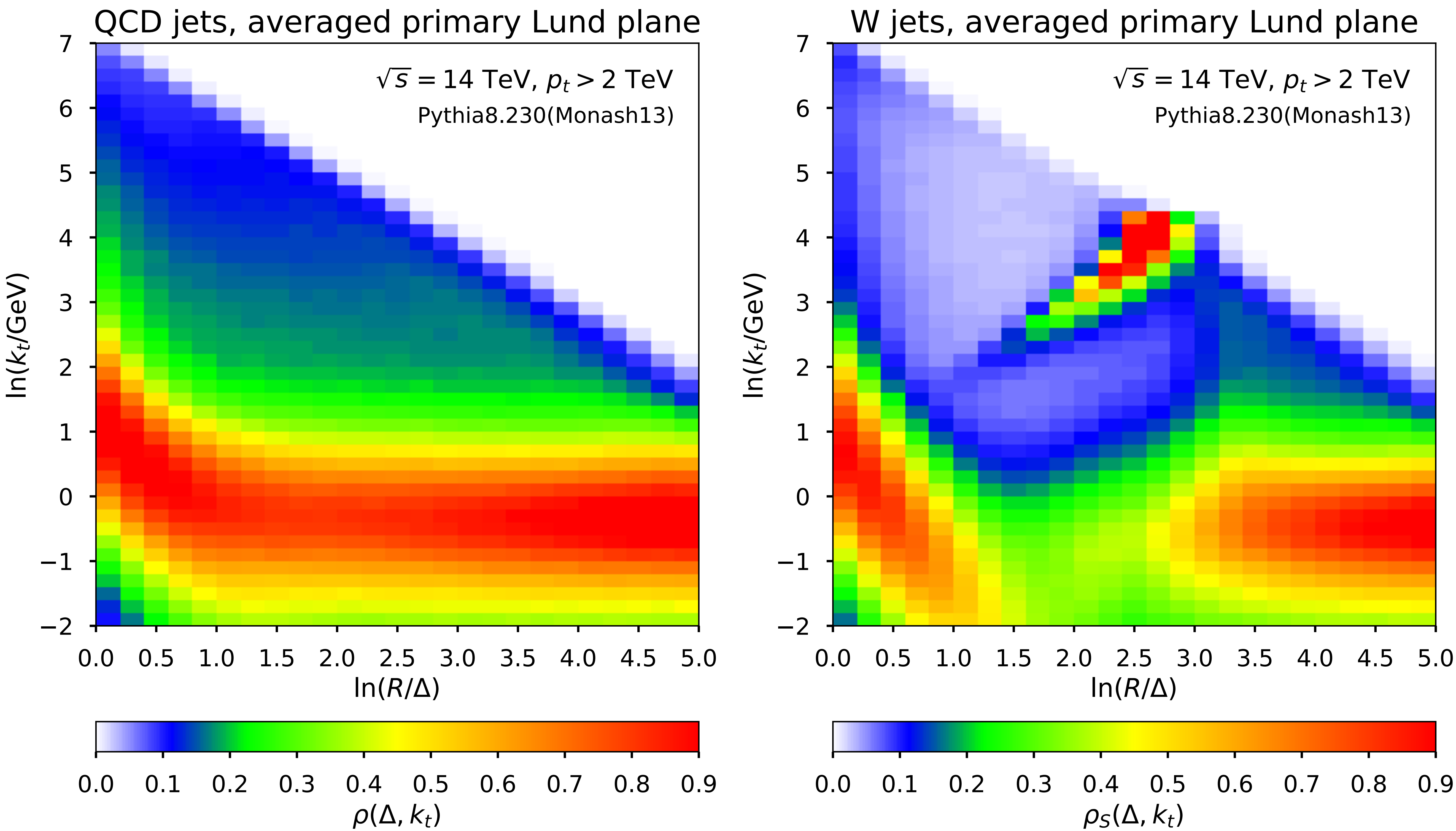




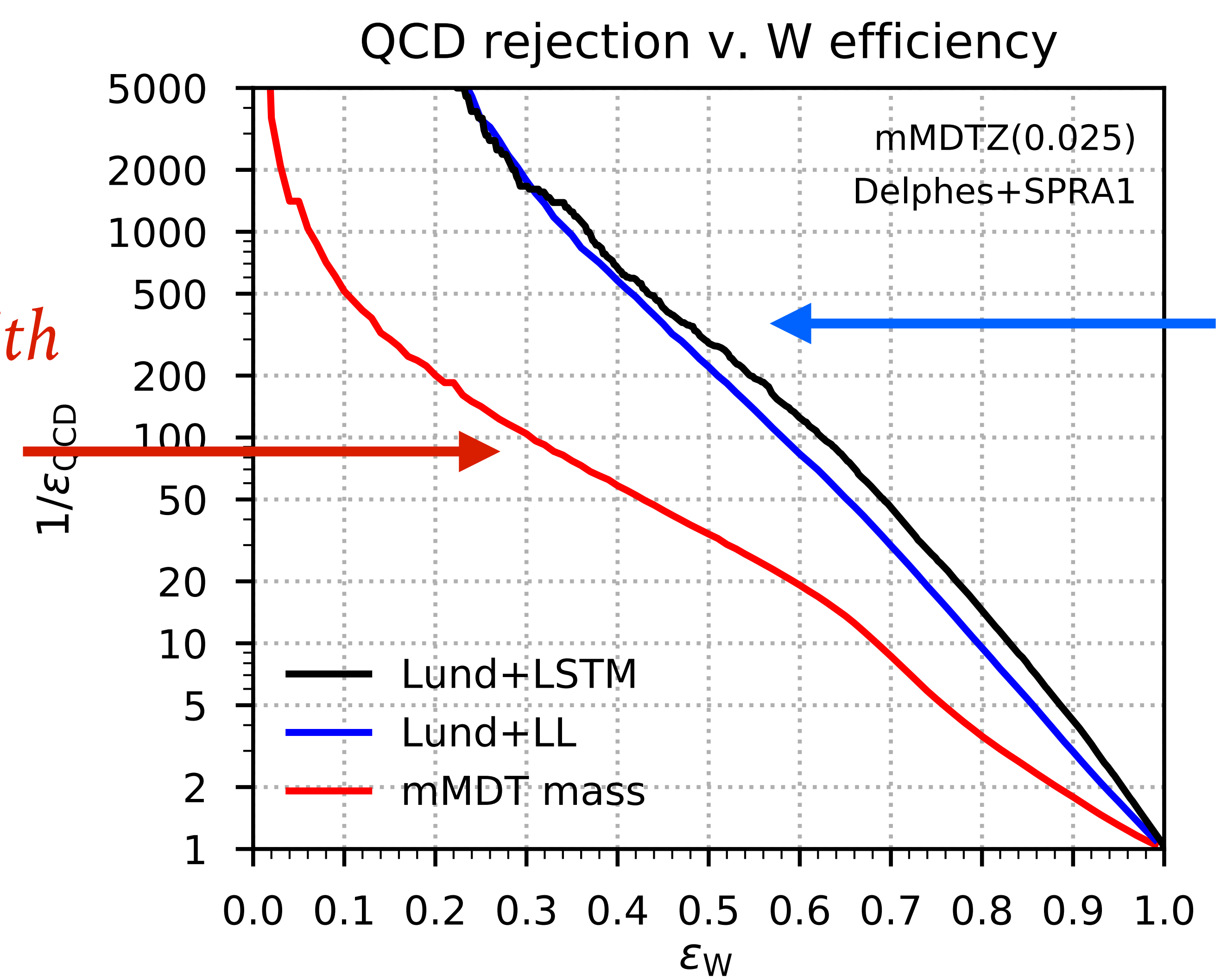
today’s jet substructure tools

- **SoftDrop:** uses the same key ideas of C/A declustering, but with better theoretical properties and more flexibility in phasespace
- **Subjettiness / energy-energy-correlations / energy-flow polynomials / Lund Plane structure:** all try to measure the energy flow around the core n-prong structure of a jet (e.g. 2-prong for Higgs decay)
- **Machine learning:** jet substructure is one of the most dynamic playgrounds for ML, with large gains to be had in pulling out all info from jets

intrajet energy flow for QCD jets & W jets



QCD rejection with just jet mass (SD/mMDT)



QCD rejection with use energy-flow within the jet (beyond just hard prongs)

5–10x better (and newer ML can do even better)

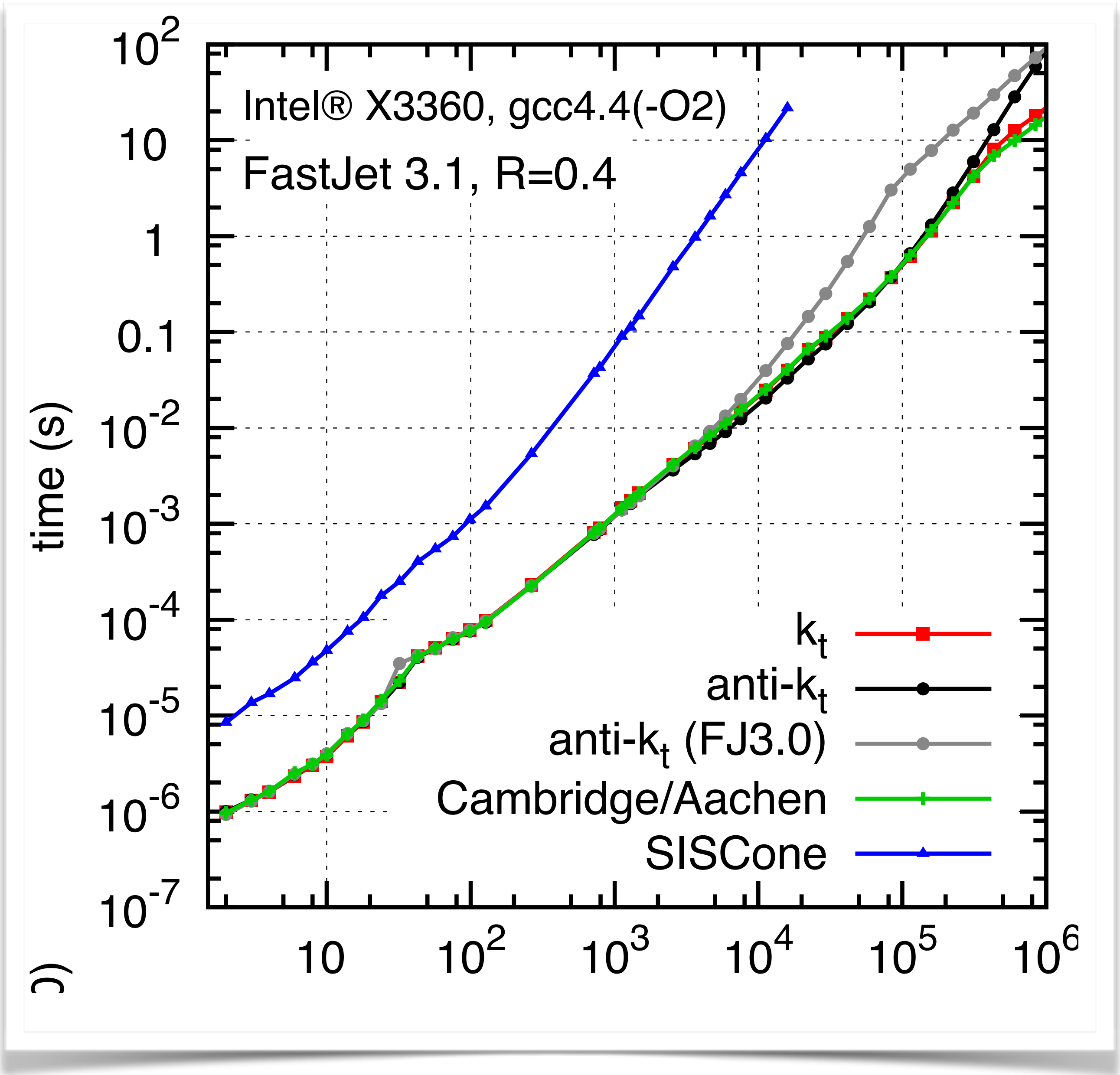
Dreyer, GPS & Soyez, arXiv:1807.04758

Take-home messages

- There are myriad approaches to jet finding
- For applications with a single moderately hard scale (e.g. ttbar), anti-kt, R=0.4, with a p_t cut of a few tens of GeV is often a good default
- For problems with multiple hard scales (e.g. highly boosted top / W / H / etc.) one needs to look at events on multiple angular scales: jet substructure

EXTRAS

Time to cluster N particles in FastJet



Time to cluster N particles

FJContrib packages

Version 1.043 of FastJet Contrib is distributed with the following packages

Package	Version	Release date	Information
ClusteringVetoPlugin	1.0.0	2015-05-04	README NEWS
ConstituentSubtractor	1.4.5	2020-02-23	README NEWS
EnergyCorrelator	1.3.1	2018-02-10	README NEWS
FlavorCone	1.0.0	2017-09-07	README NEWS
GenericSubtractor	1.3.1	2016-03-30	README NEWS
JetCleanser	1.0.1	2014-08-16	README NEWS
JetFFMoments	1.0.0	2013-02-07	README NEWS
JetsWithoutJets	1.0.0	2014-02-22	README NEWS
LundPlane	1.0.3	2020-02-23	README NEWS
Nsubjettiness	2.2.5	2018-06-06	README NEWS
QCDAwarePlugin	1.0.0	2015-10-08	README NEWS
RecursiveTools	2.0.0-beta2	2018-05-29	README NEWS
ScJet	1.1.0	2013-06-03	README NEWS
SoftKiller	1.0.0	2014-08-17	README NEWS
SubjetCounting	1.0.1	2013-09-03	README NEWS
ValenciaPlugin	2.0.2	2018-12-22	README NEWS
VariableR	1.2.1	2016-06-01	README NEWS