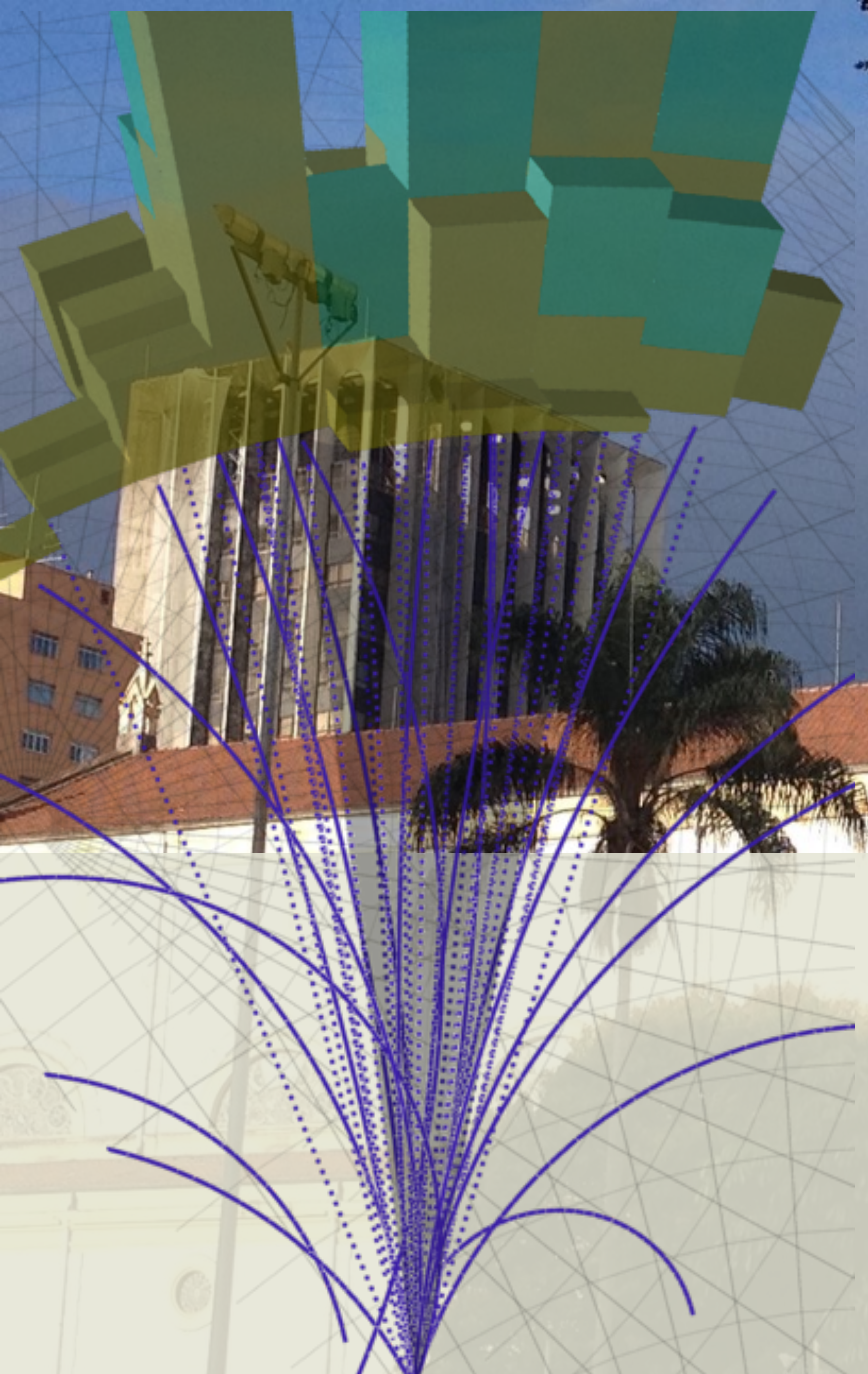
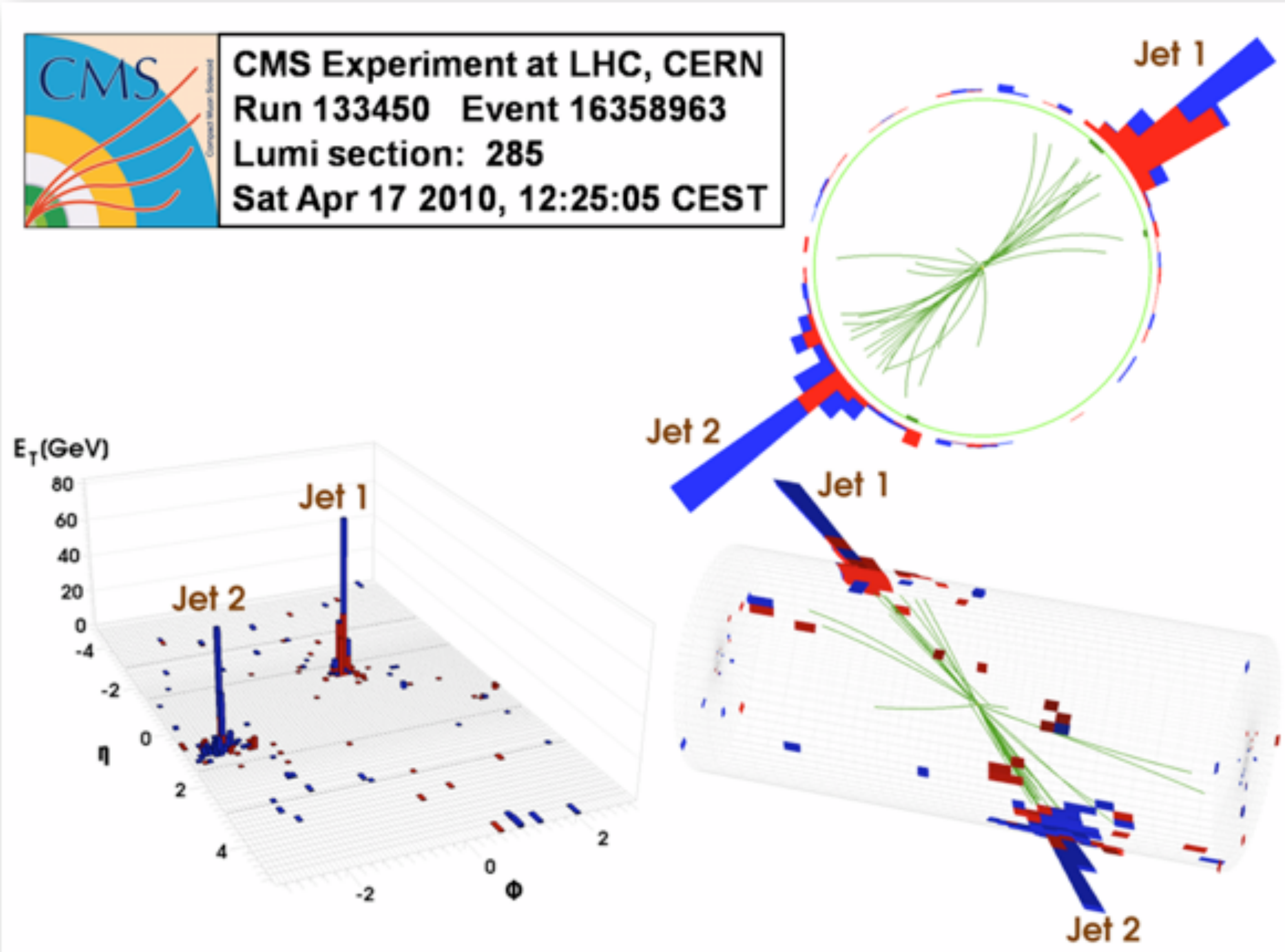
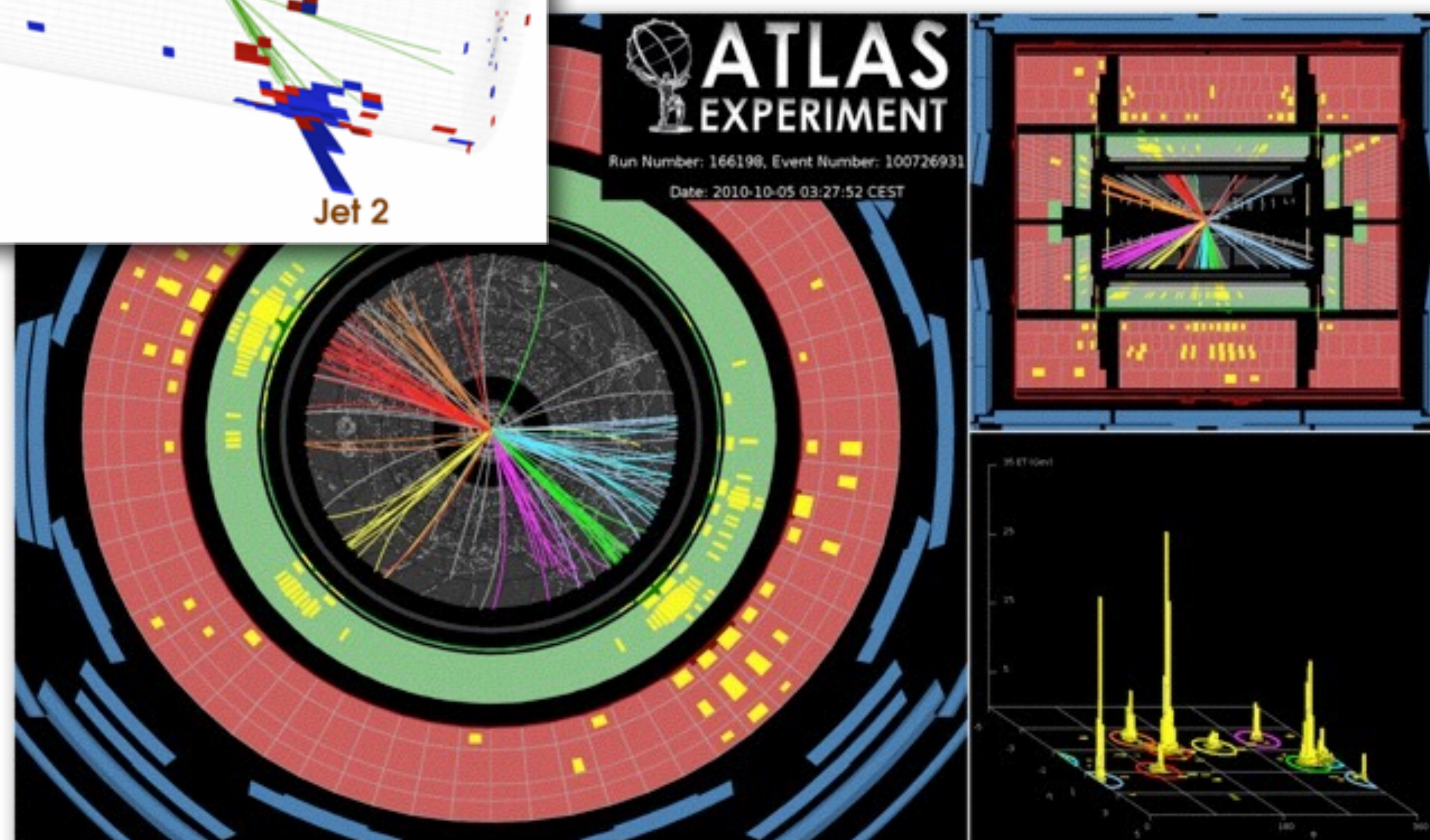


Basics of QCD: jets & jet substructure

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

ICTP–SAIFR school on QCD and LHC physics
July 2015, São Paulo, Brazil





JETS

Collimated, energetic bunches of particles

Find all papers by ATLAS and CMS

850 records found

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

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

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

Display results: 25 results | single list

No exact match found for *cern-ph-ep*, using *cern ph ep* instead...

HEP **850** records found 1 - 25 jump to record: 1 Search took 0.18 seconds.

1. **Z boson production in p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with the ATLAS detector**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Jul 22, 2015. 19 pp.
   CERN-PH-EP-2015-146
   e-Print: **arXiv:1507.06232 [hep-ex]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Search for an additional, heavy Higgs boson in the $H \to ZZ$ decay channel at $\sqrt{s}$ = 8 TeV in pp collision data with the ATLAS detector**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Jul 21, 2015. 46 pp.
   CERN-PH-EP-2015-154
   e-Print: **arXiv:1507.05930 [hep-ex]** | **PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

3. **Pseudorapidity distribution of charged hadrons in proton-proton collisions at sqrt(s) = 13 TeV**
   CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Jul 21, 2015.
   CMS-FSQ-15-001, CERN-PH-EP-2015-180

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

538 records found

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

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

> 60% of papers use jets!

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

Display results: 25 results | single list

No exact match found for *cern-ph-ep*, using *cern ph ep* instead...

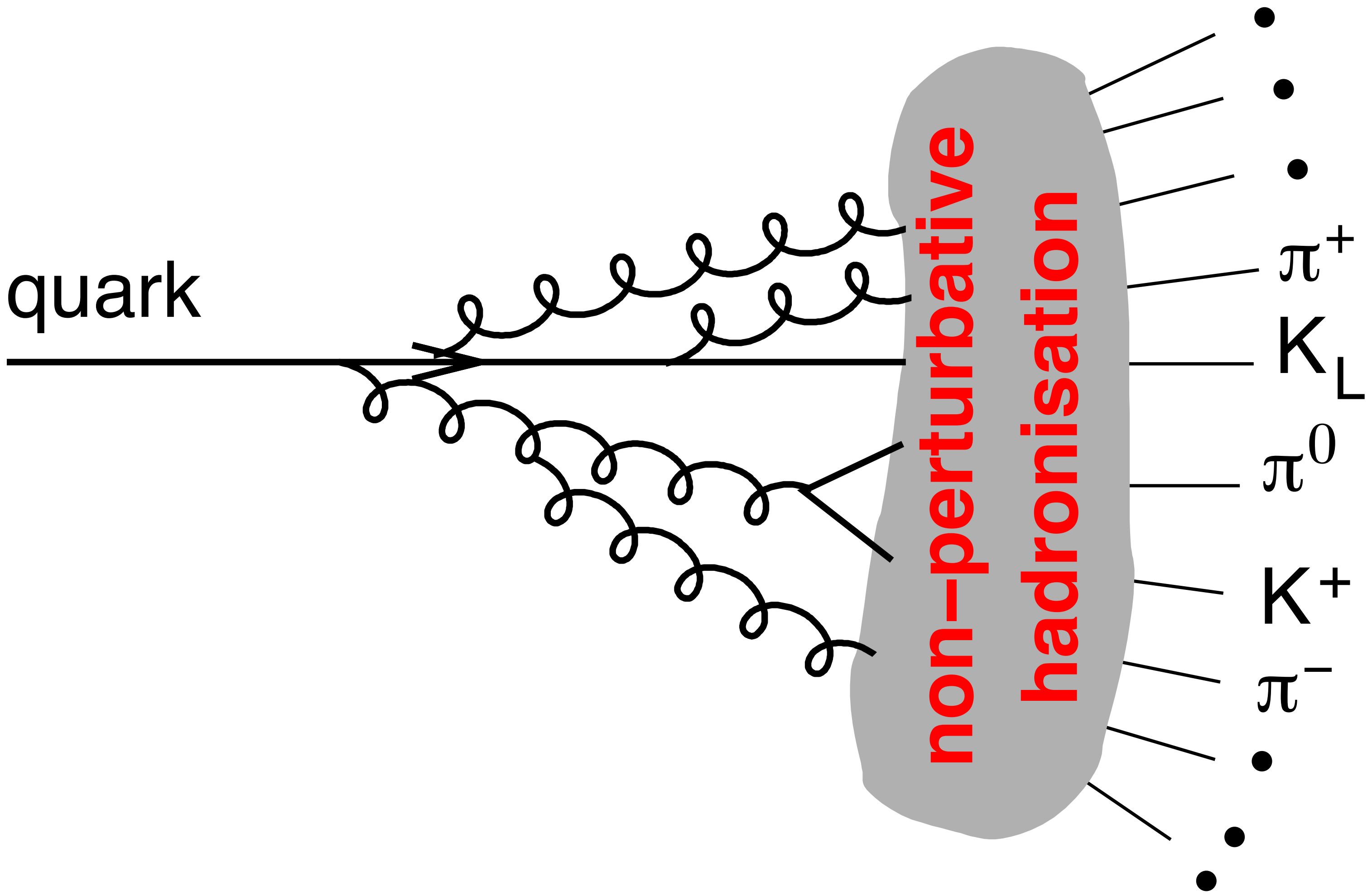
HEP **538** records found 1 - 25 jump to record: 1 Search took 0.18 seconds.

1. **Search for an additional, heavy Higgs boson in the $H \to ZZ$ decay channel at $\sqrt{s}$ = 8 TeV in pp collision data with the ATLAS detector**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Jul 21, 2015. 46 pp.
   CERN-PH-EP-2015-154
   e-Print: **arXiv:1507.05930 [hep-ex] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Summary of the searches for squarks and gluinos using $\sqrt{s}$ = 8 TeV pp collisions with the ATLAS experiment at the LHC**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Jul 20, 2015. 91 pp.
   CERN-PH-EP-2015-162
   e-Print: **arXiv:1507.05525 [hep-ex] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record - Cited by 1 record

3. **Search for photonic signatures of gauge-mediated supersymmetry in 8 TeV pp collisions with the ATLAS detector**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Jul 20, 2015. 43 pp.

Why do we see jets?



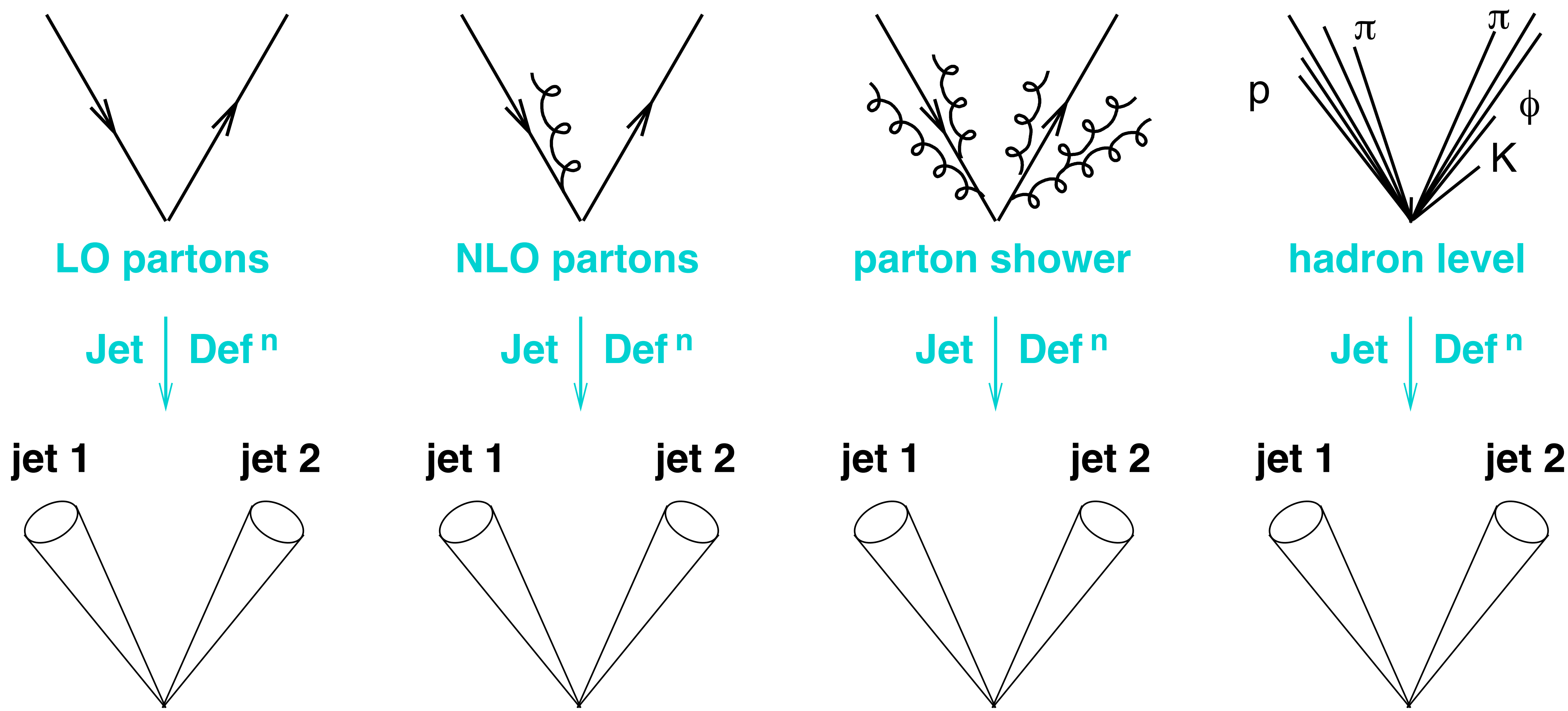
Gluon emission

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

Non-perturbative physics

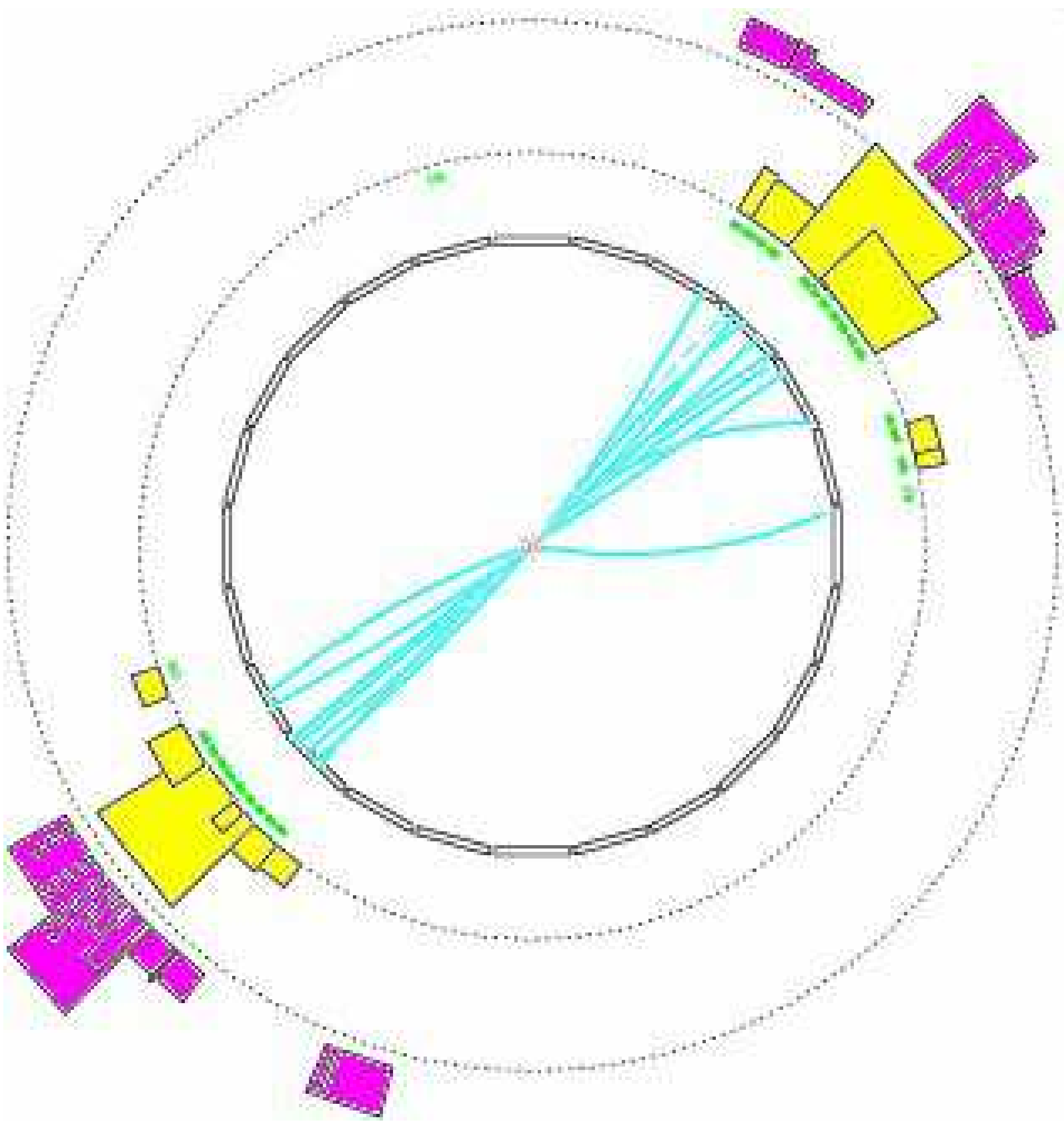
$$\alpha_s \sim 1$$

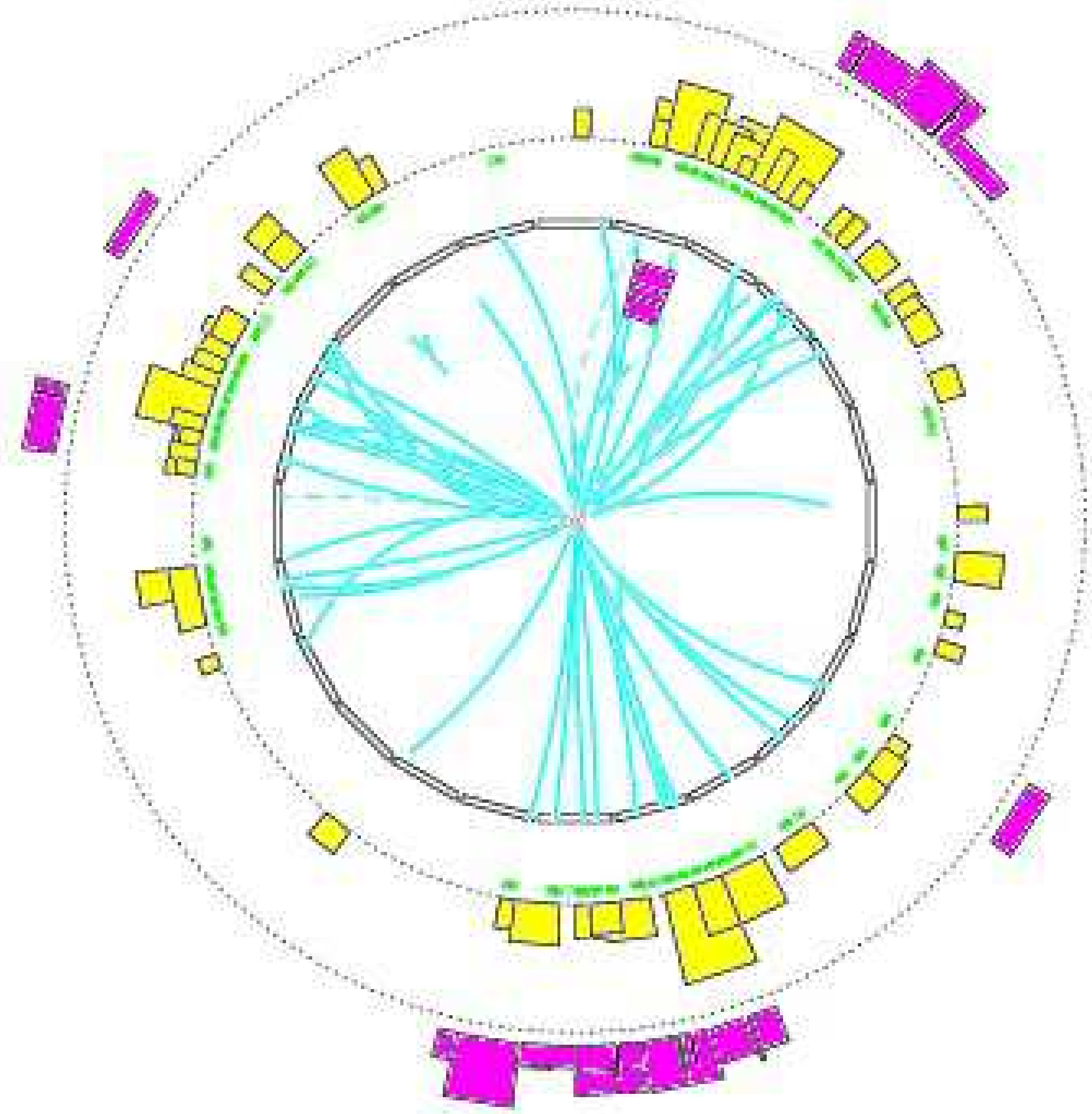
Jet finding as a form of projection



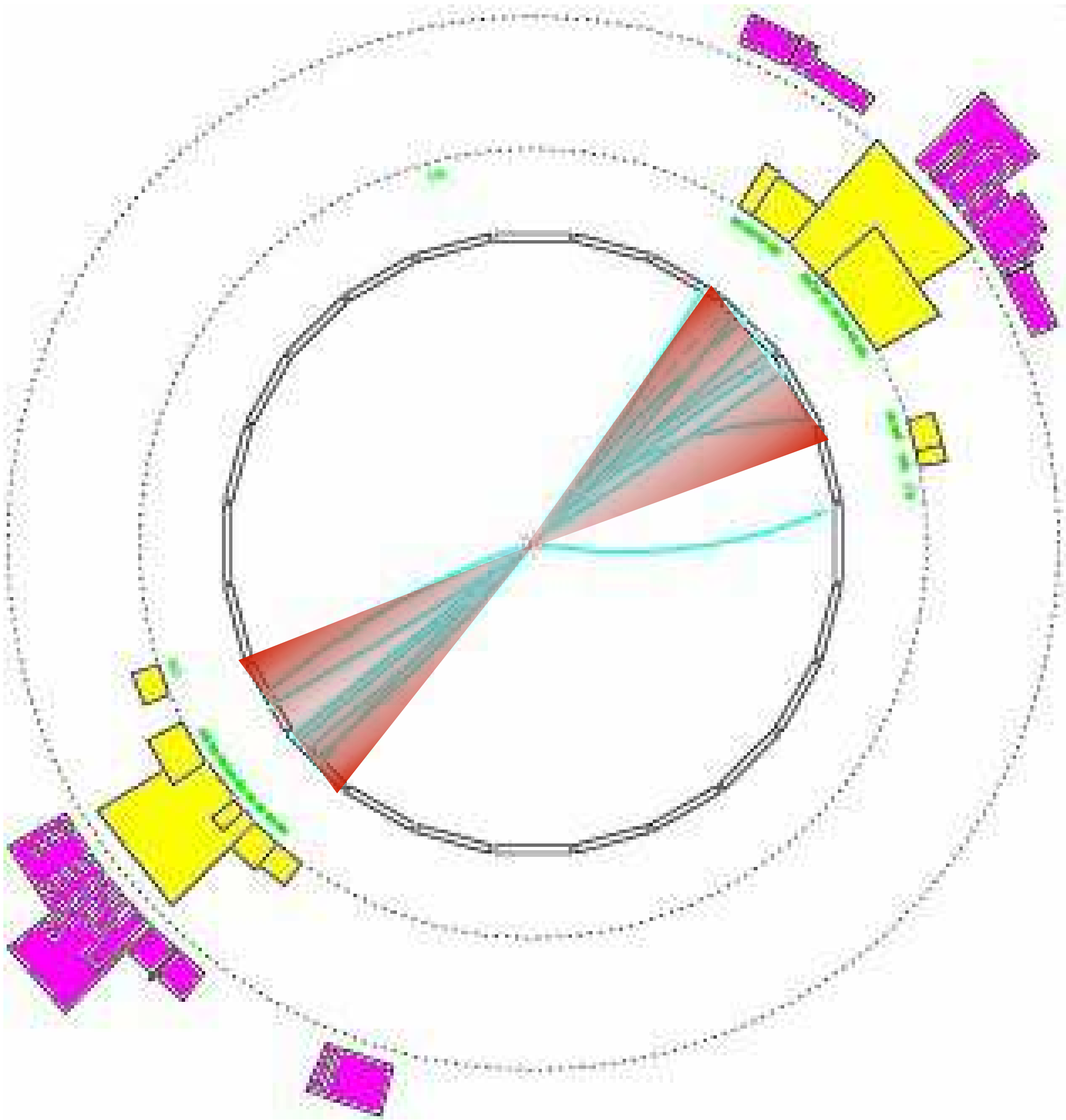
Projection to jets should be resilient to QCD effects

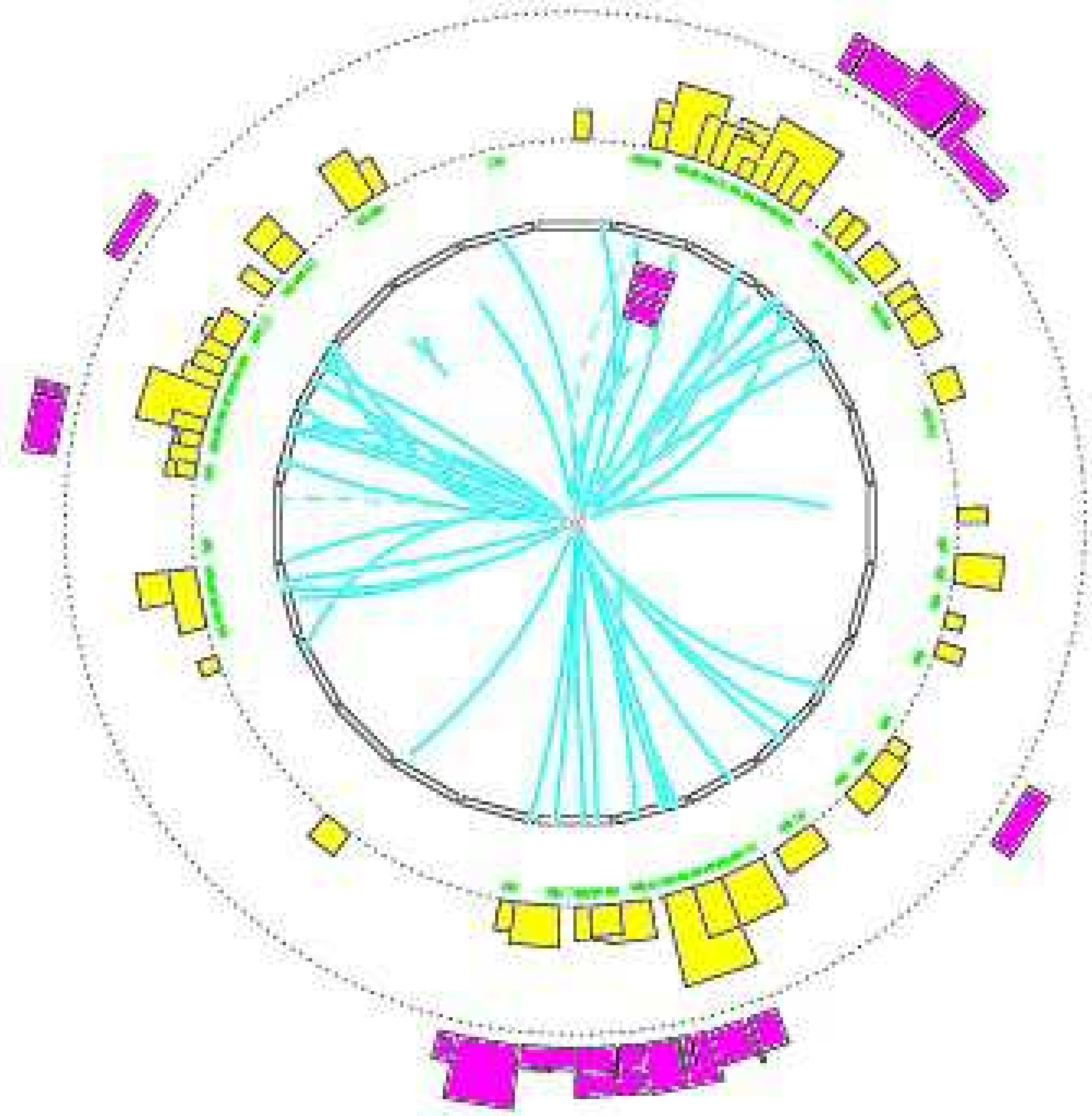
Reconstructing jets is an ambiguous task





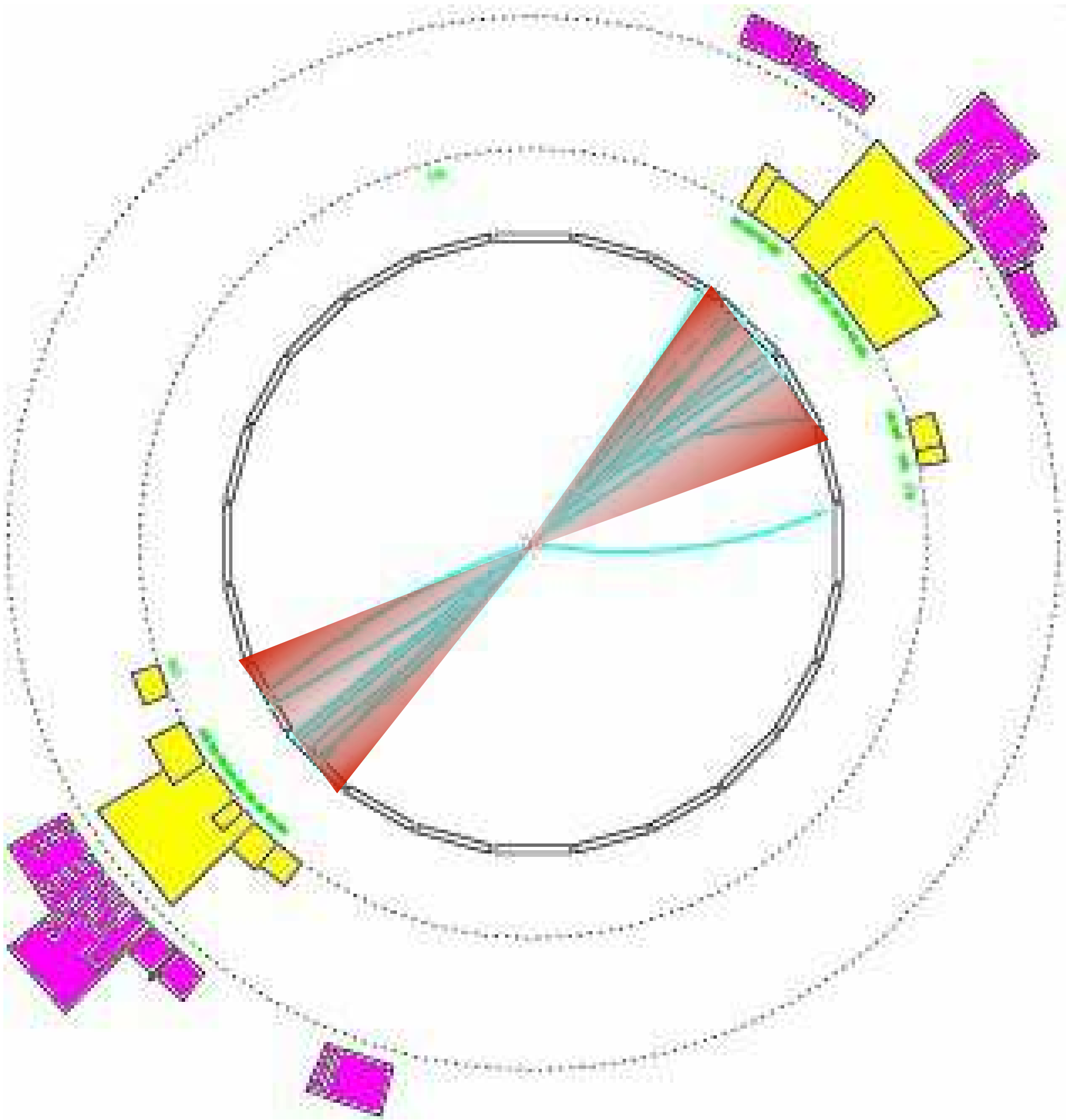
Reconstructing jets is an ambiguous task



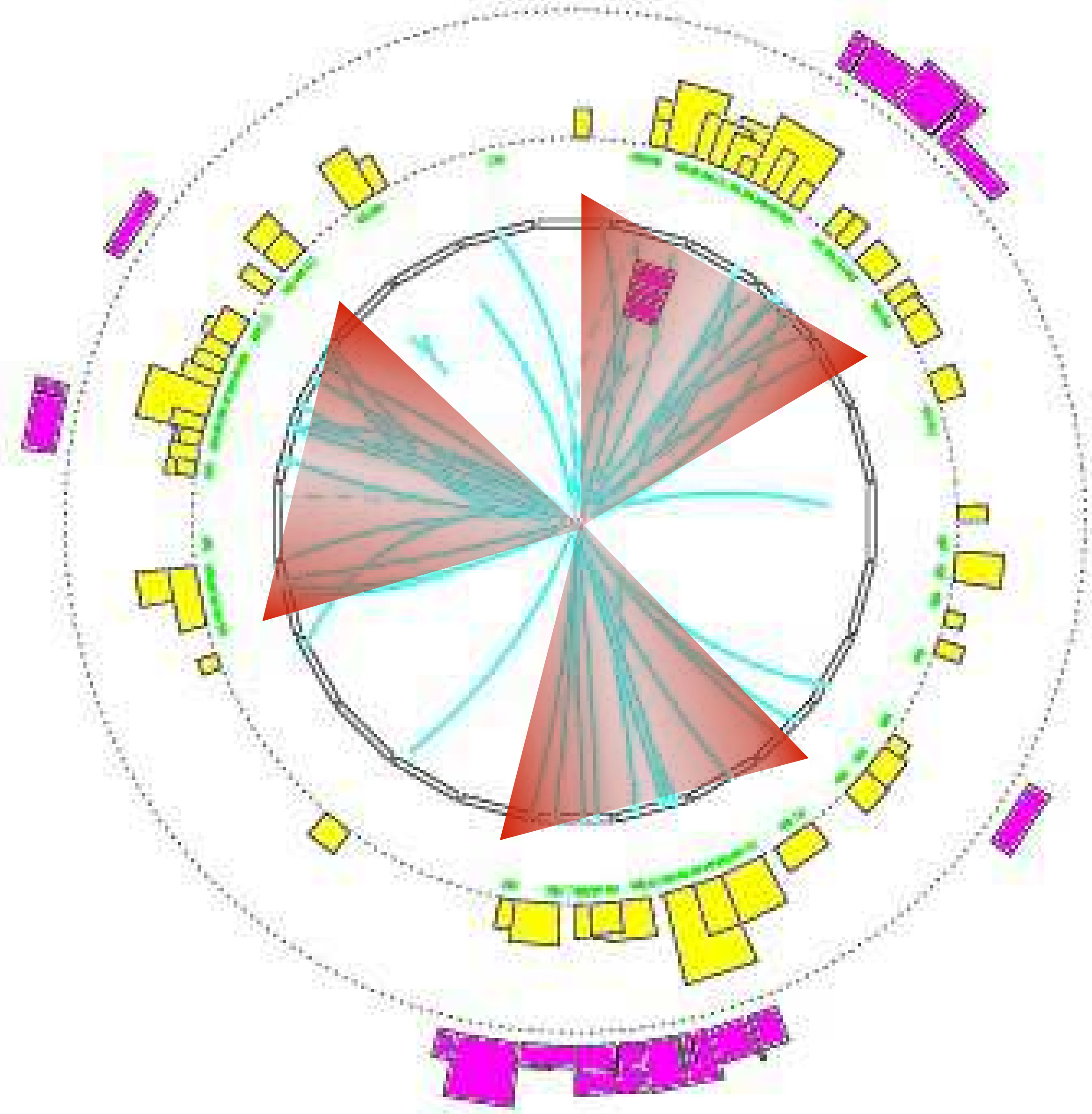


2 clear jets

Reconstructing jets is an ambiguous task

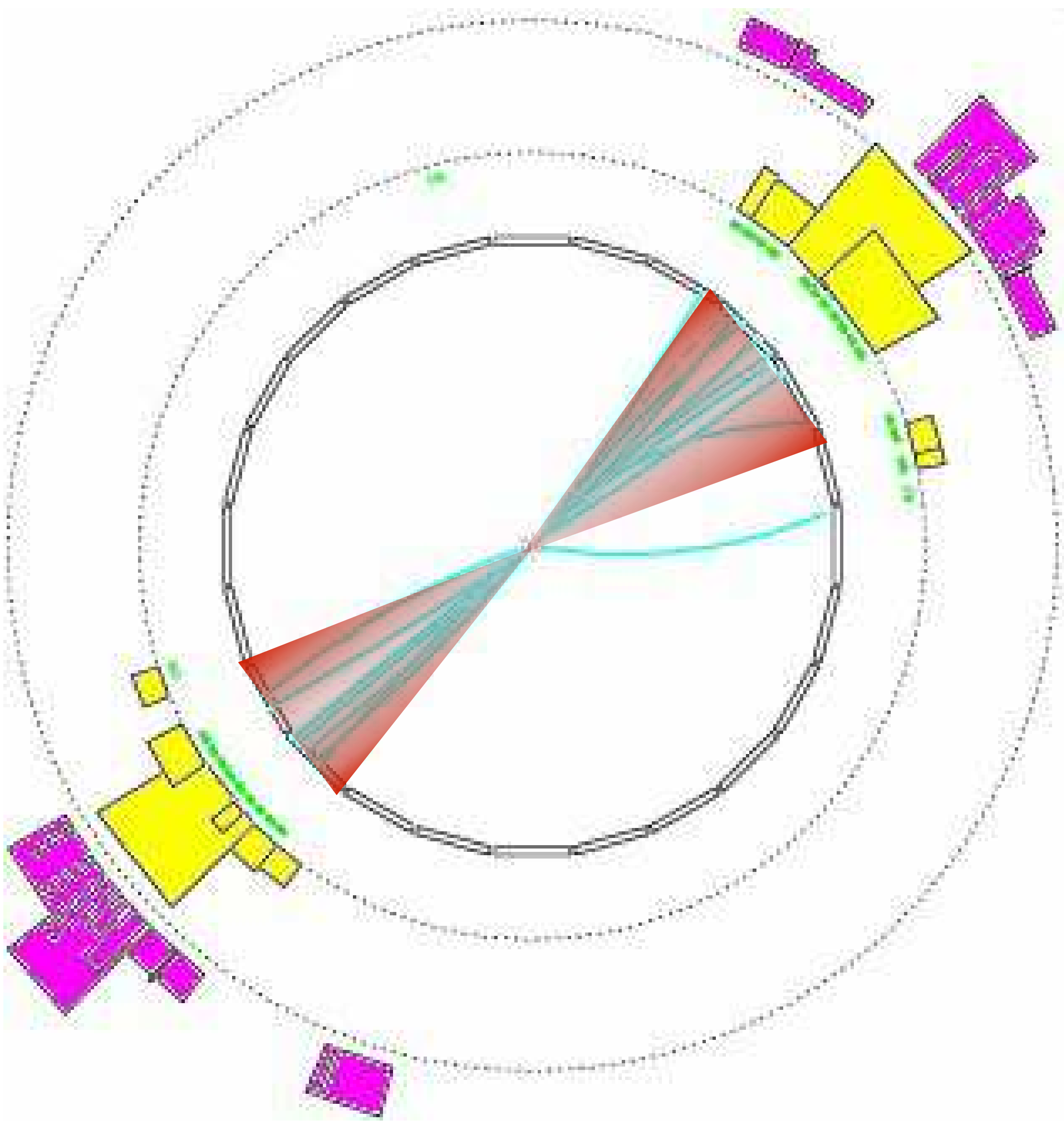


2 clear jets

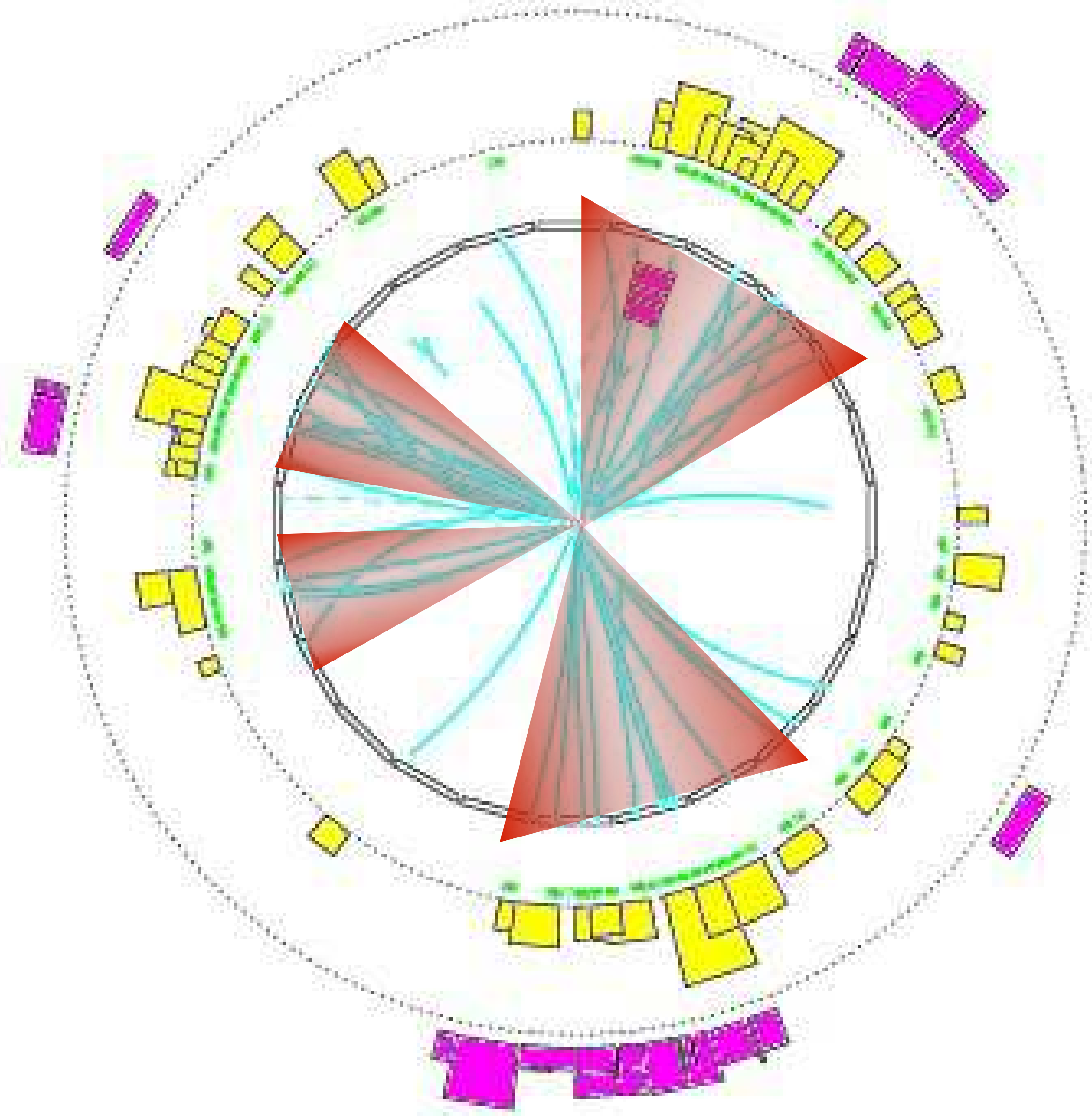


3 jets?

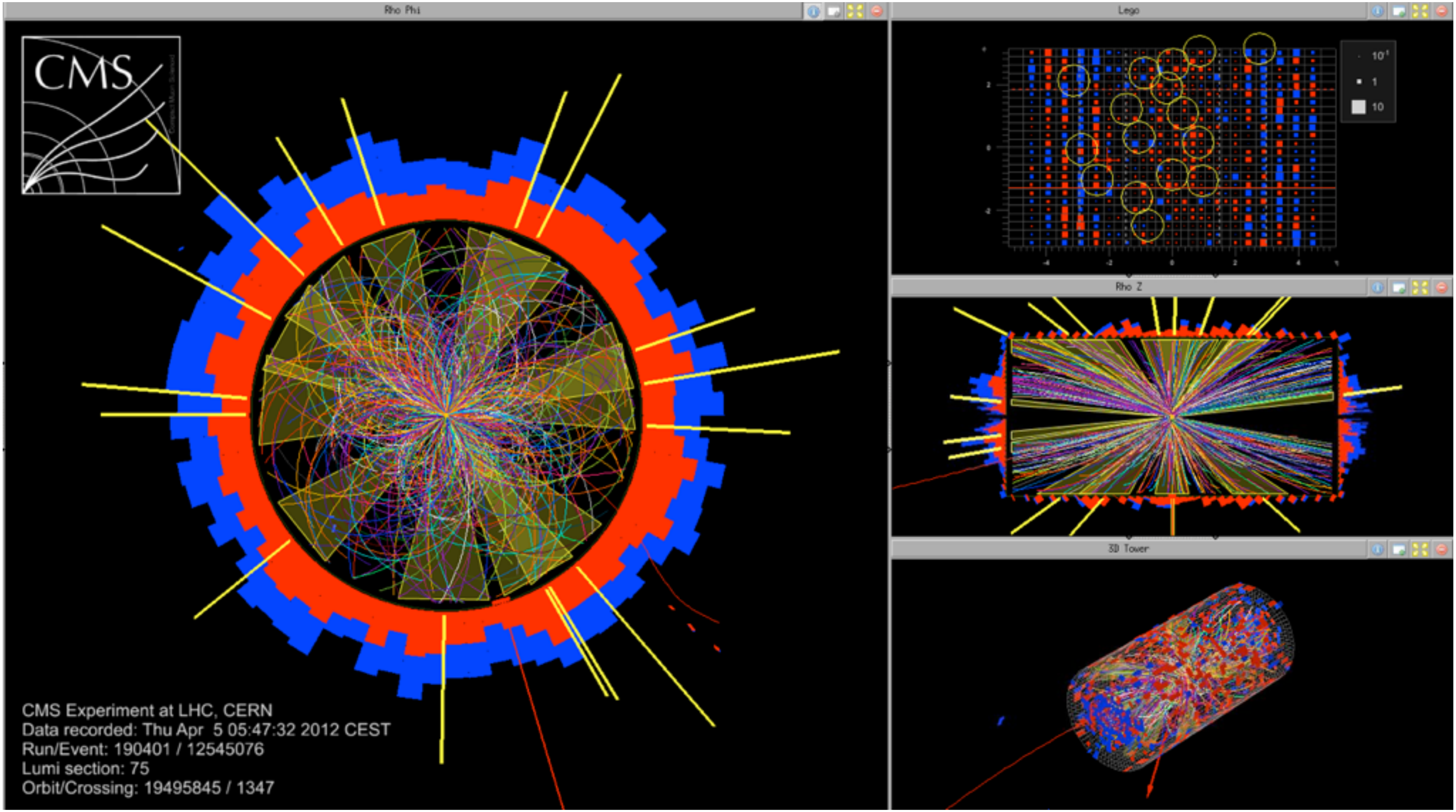
Reconstructing jets is an ambiguous task



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, ...

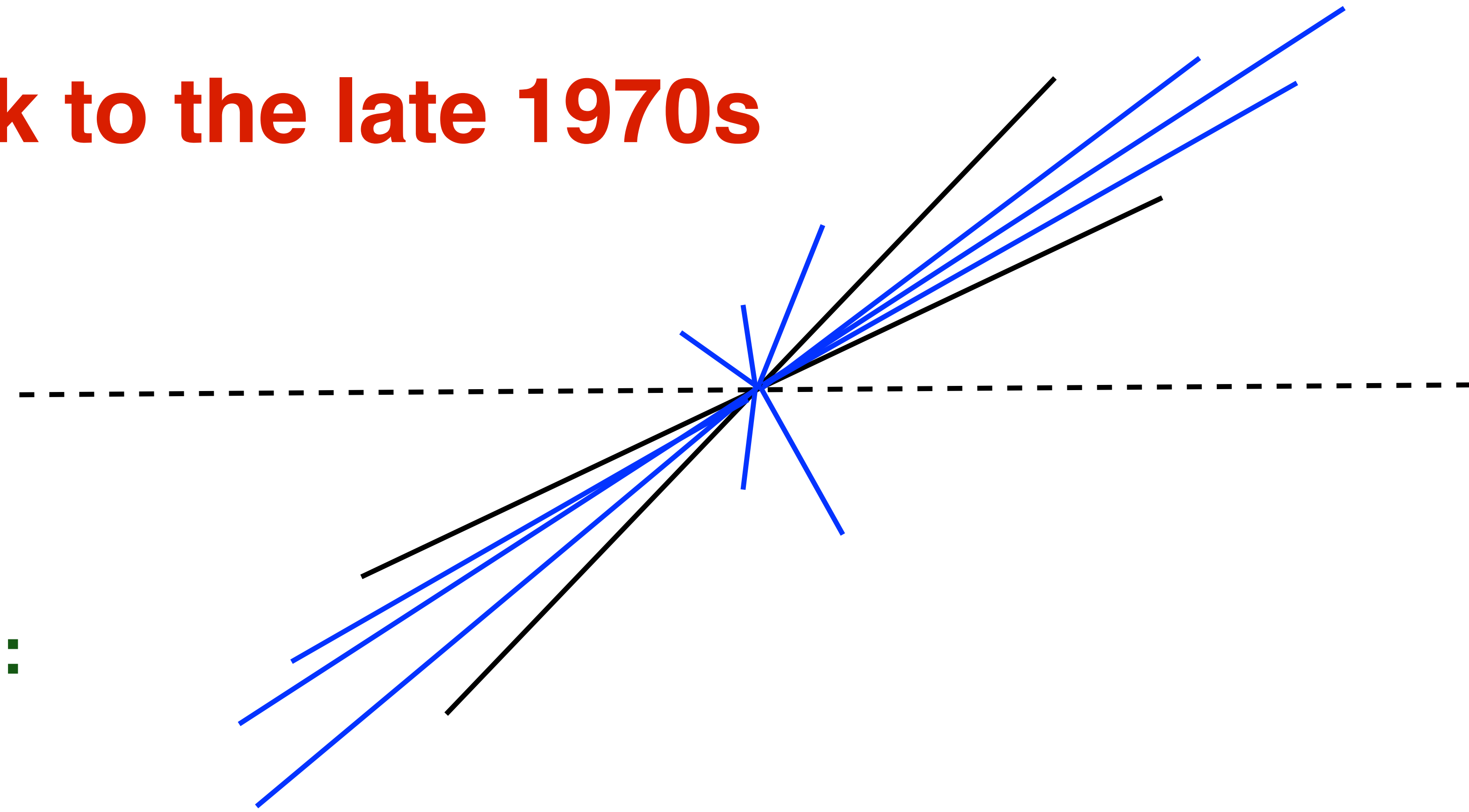
jets

- 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



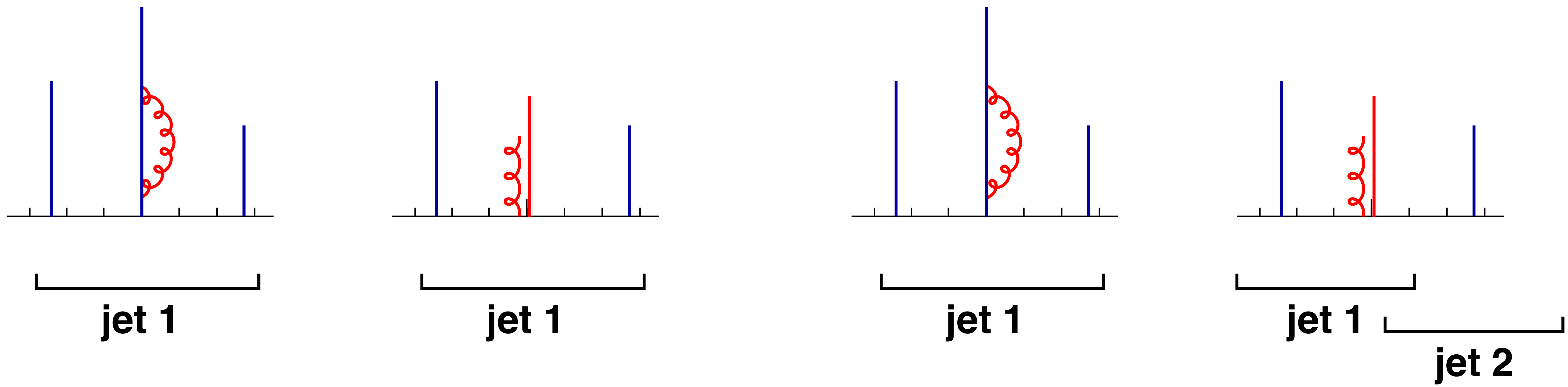
Sterman and Weinberg,
Phys. Rev. Lett. 39, 1436 (1977):

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 | **Collinear Unsafe**



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

Infinities cancel **Infinities do not cancel**

Invalidates perturbation theory

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

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

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

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

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

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

Clustering grows around hard cores

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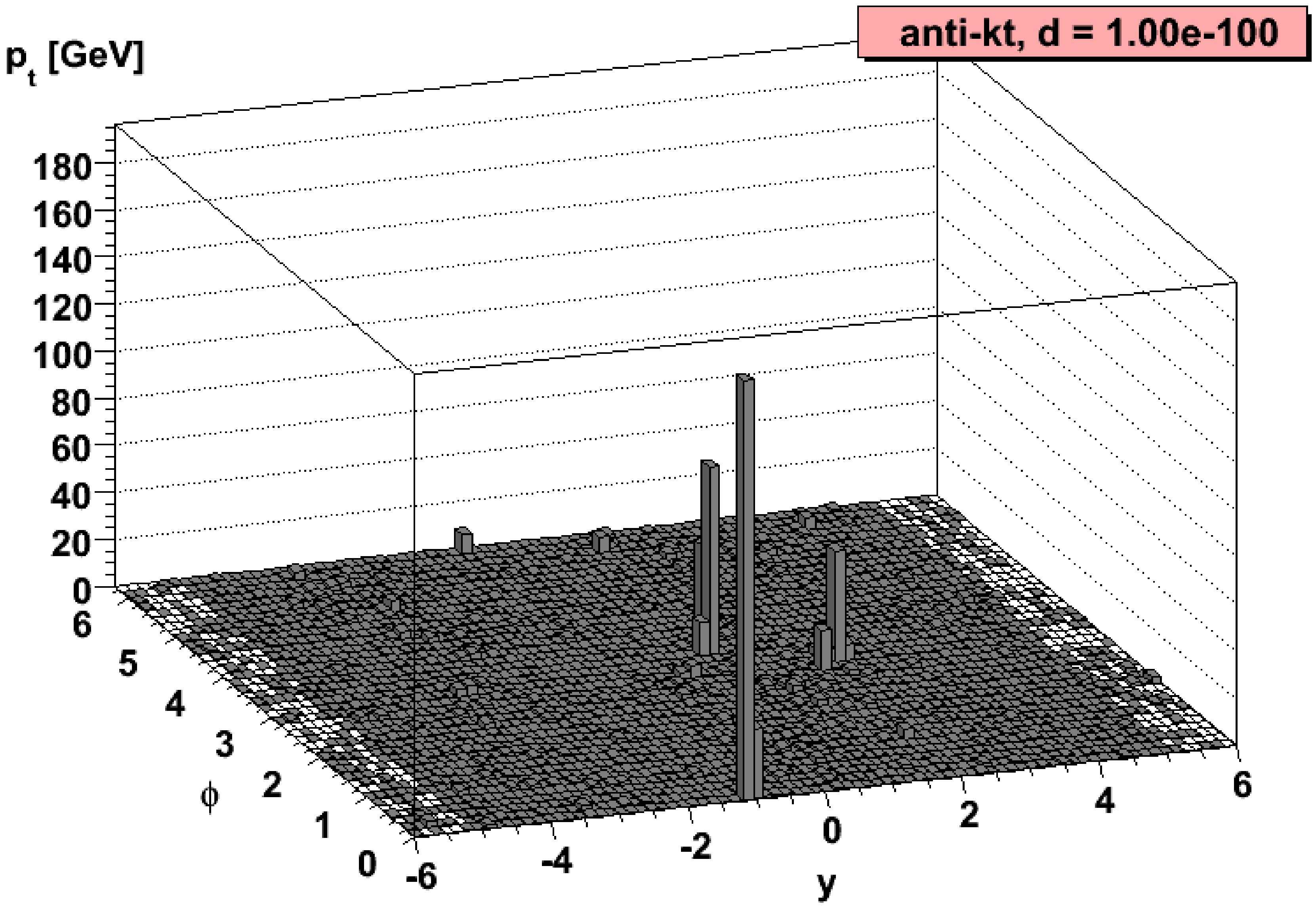
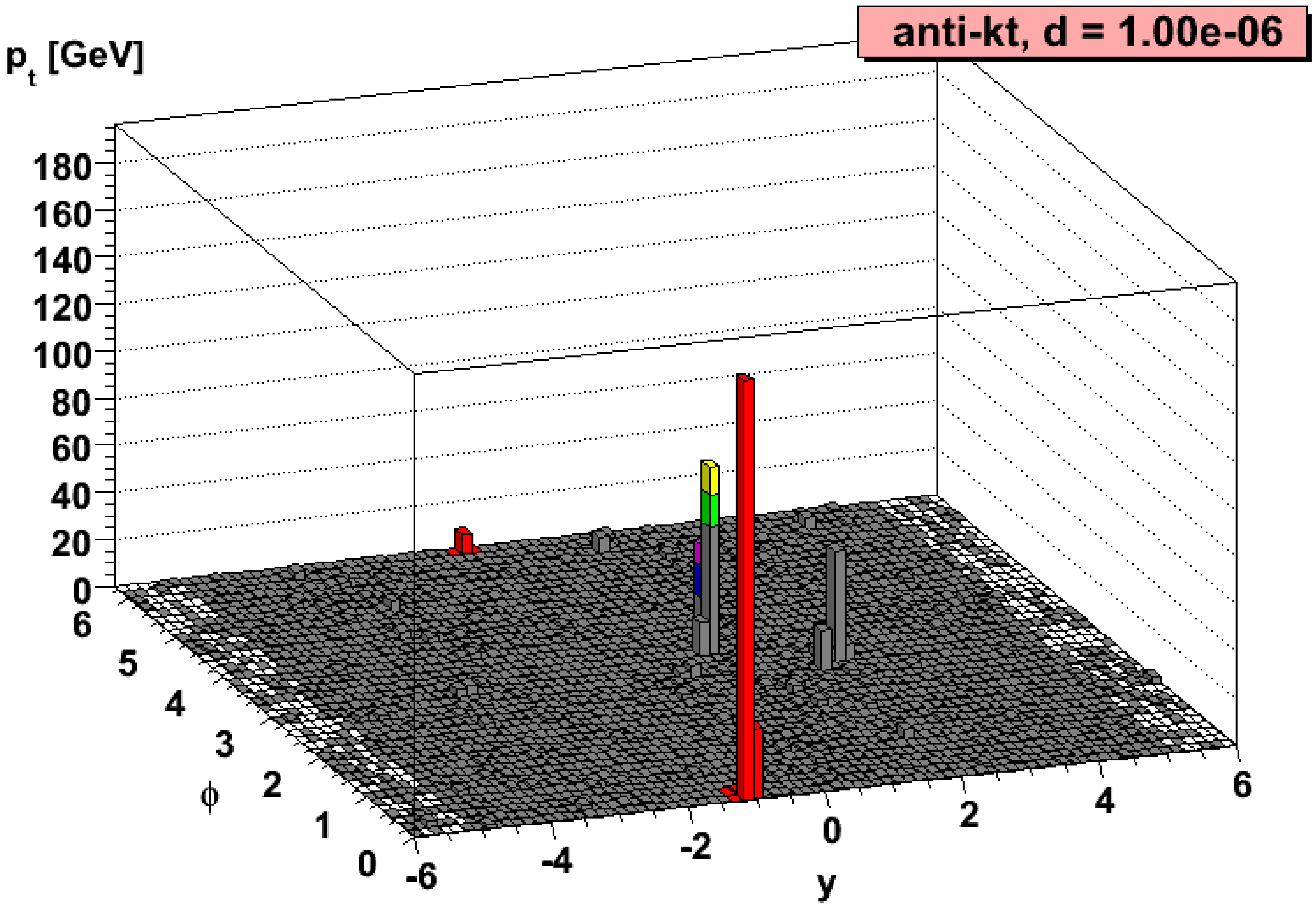


Anti-k_t in action

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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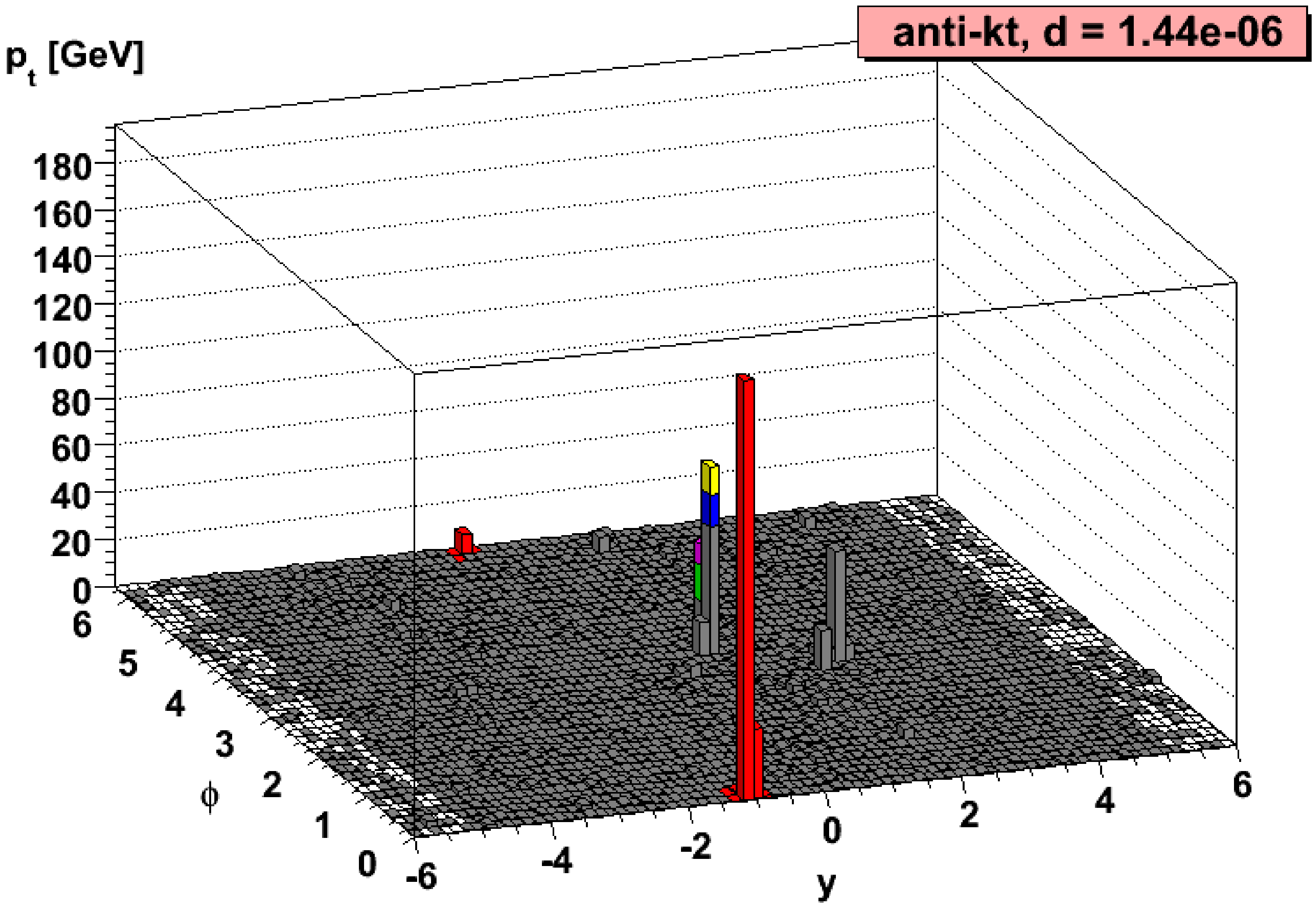

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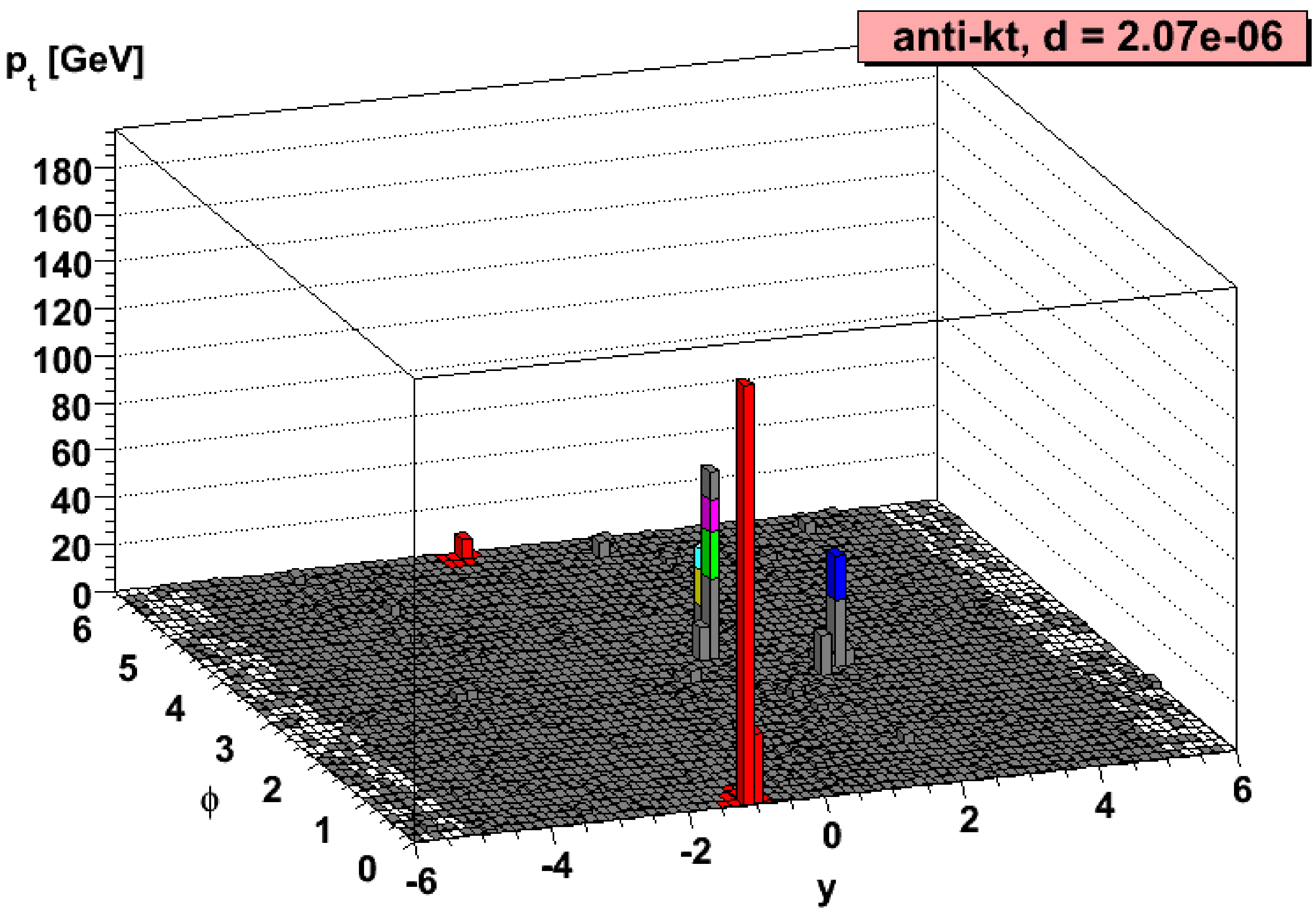

Clustering grows around hard cores

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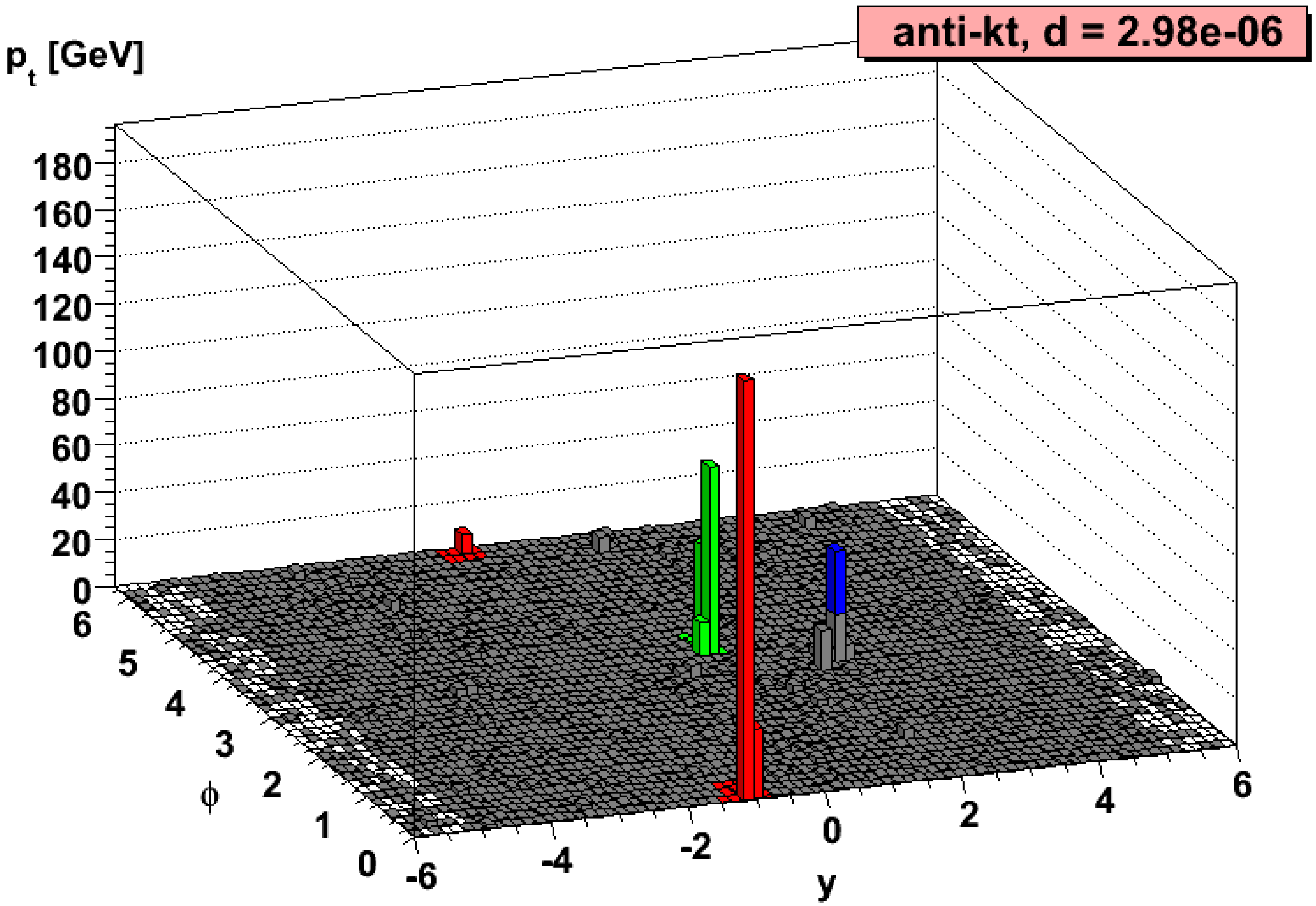

Anti-k_t in action

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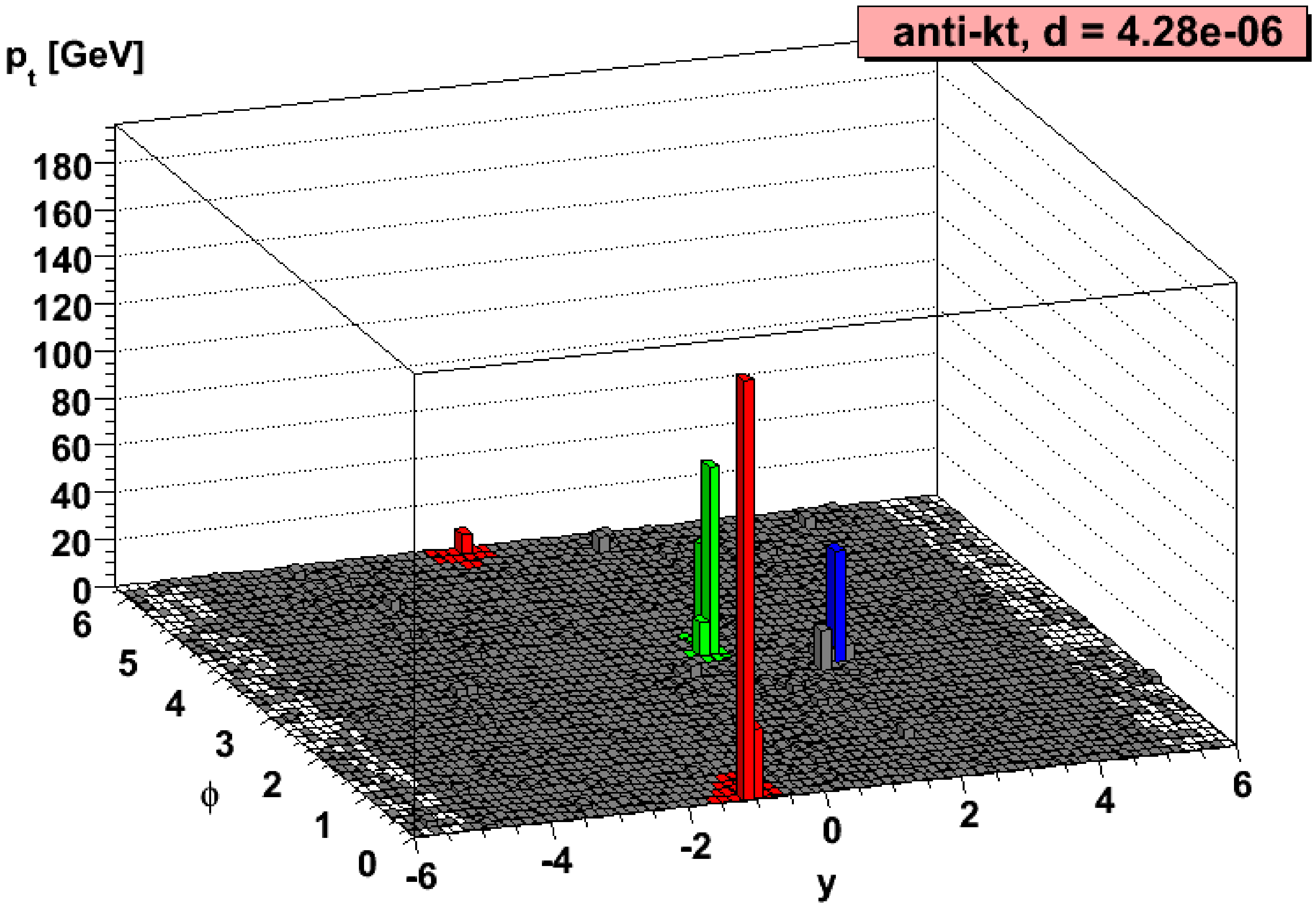

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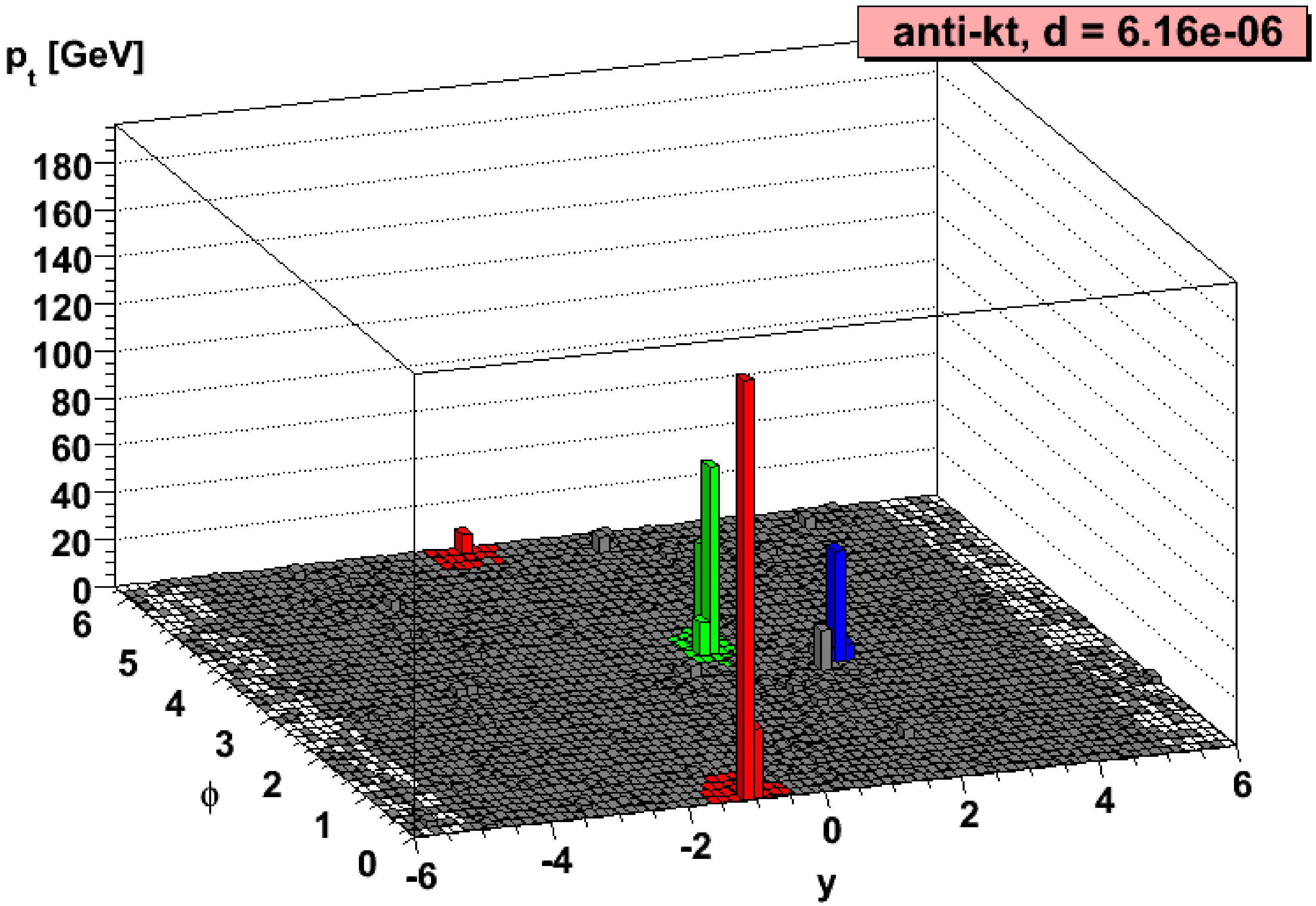

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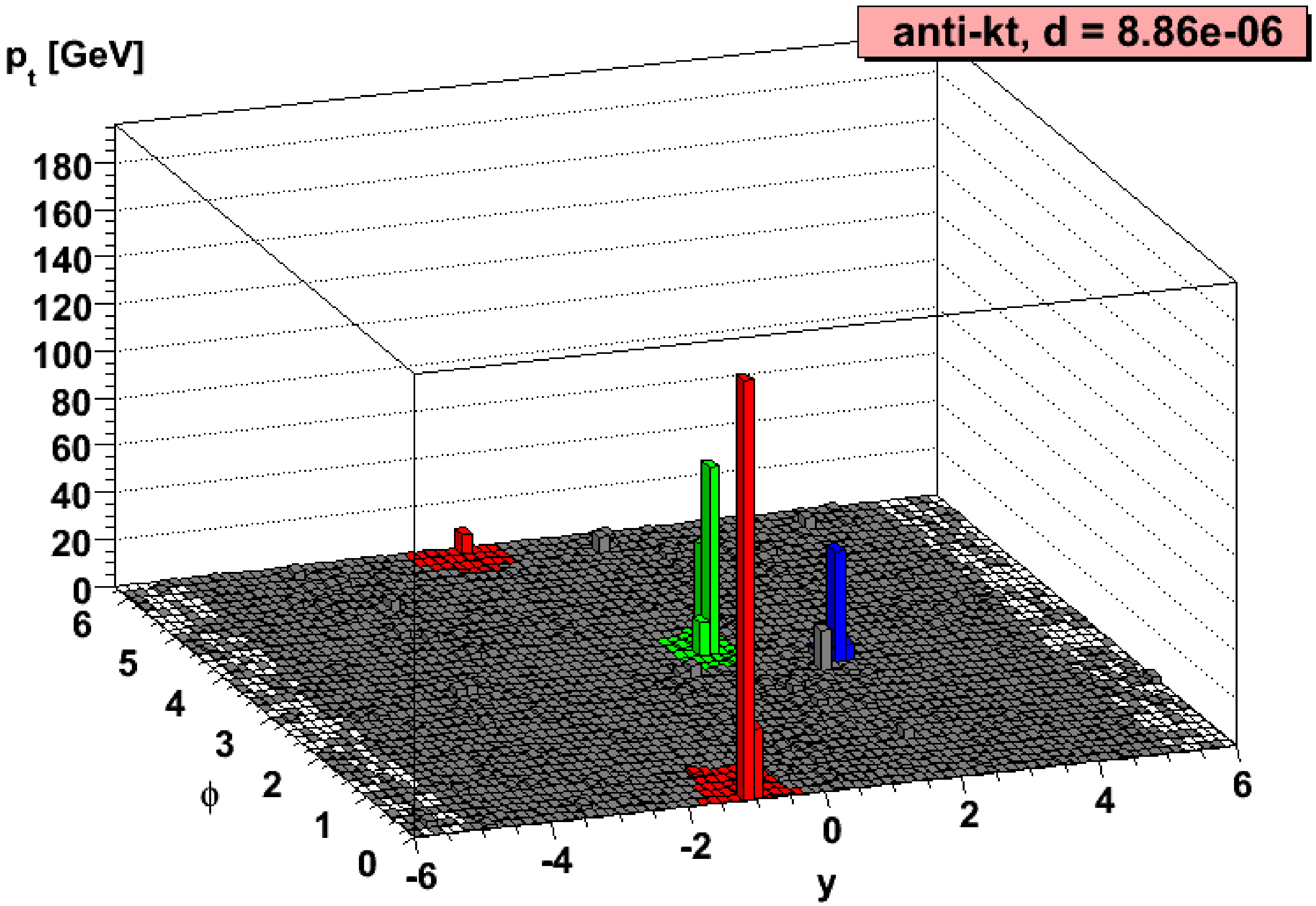

Clustering grows around hard cores

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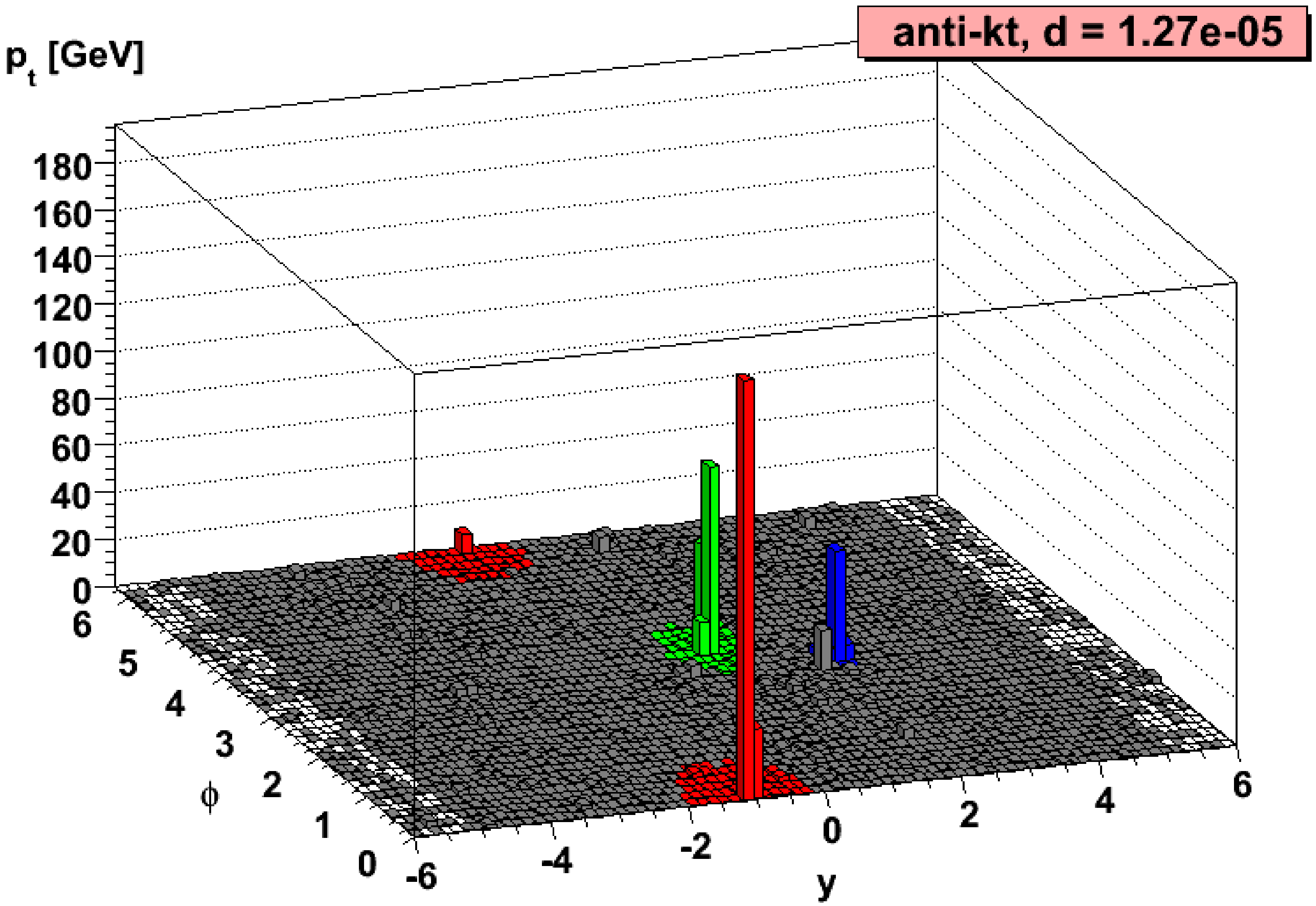

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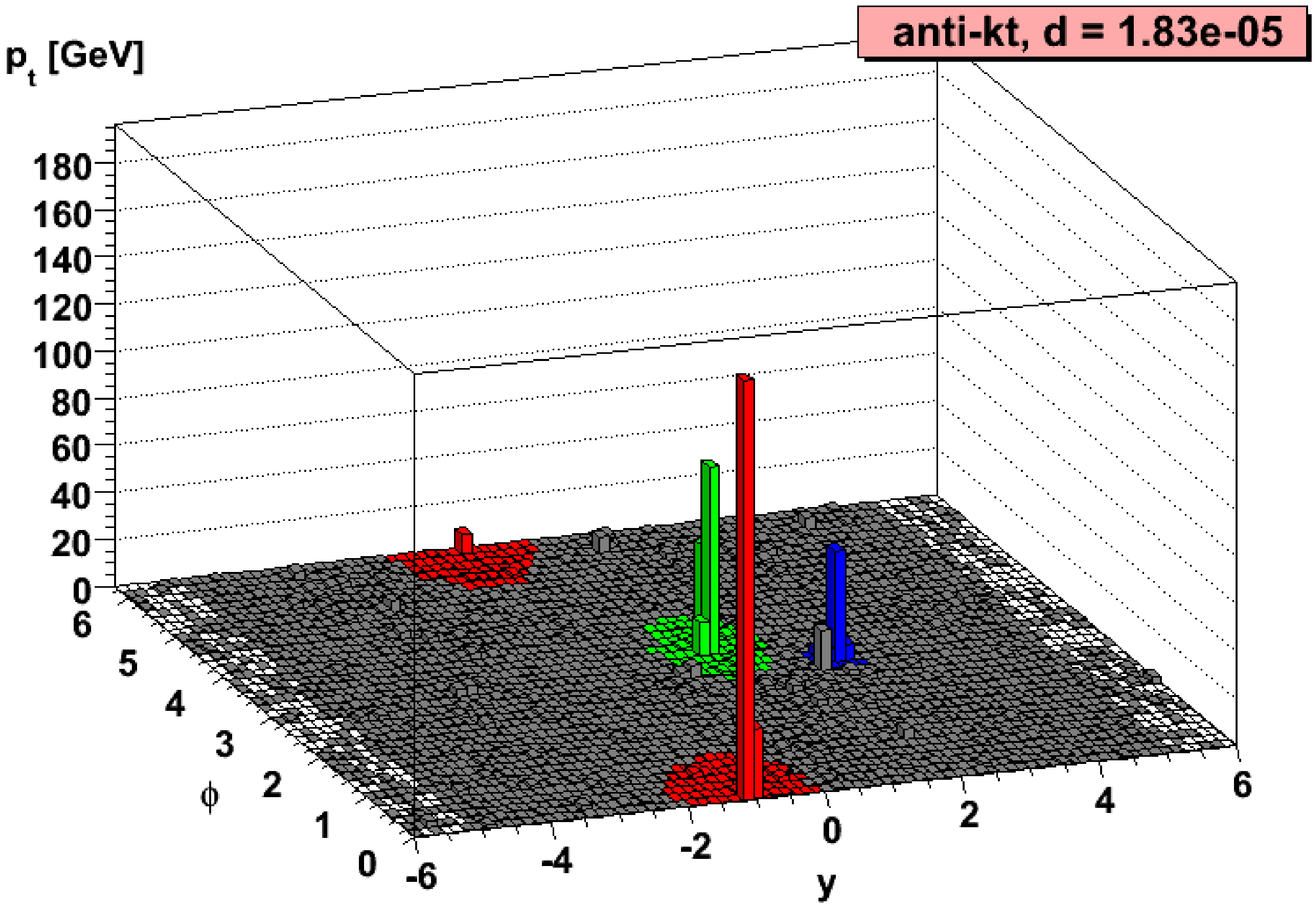

Clustering grows around hard cores

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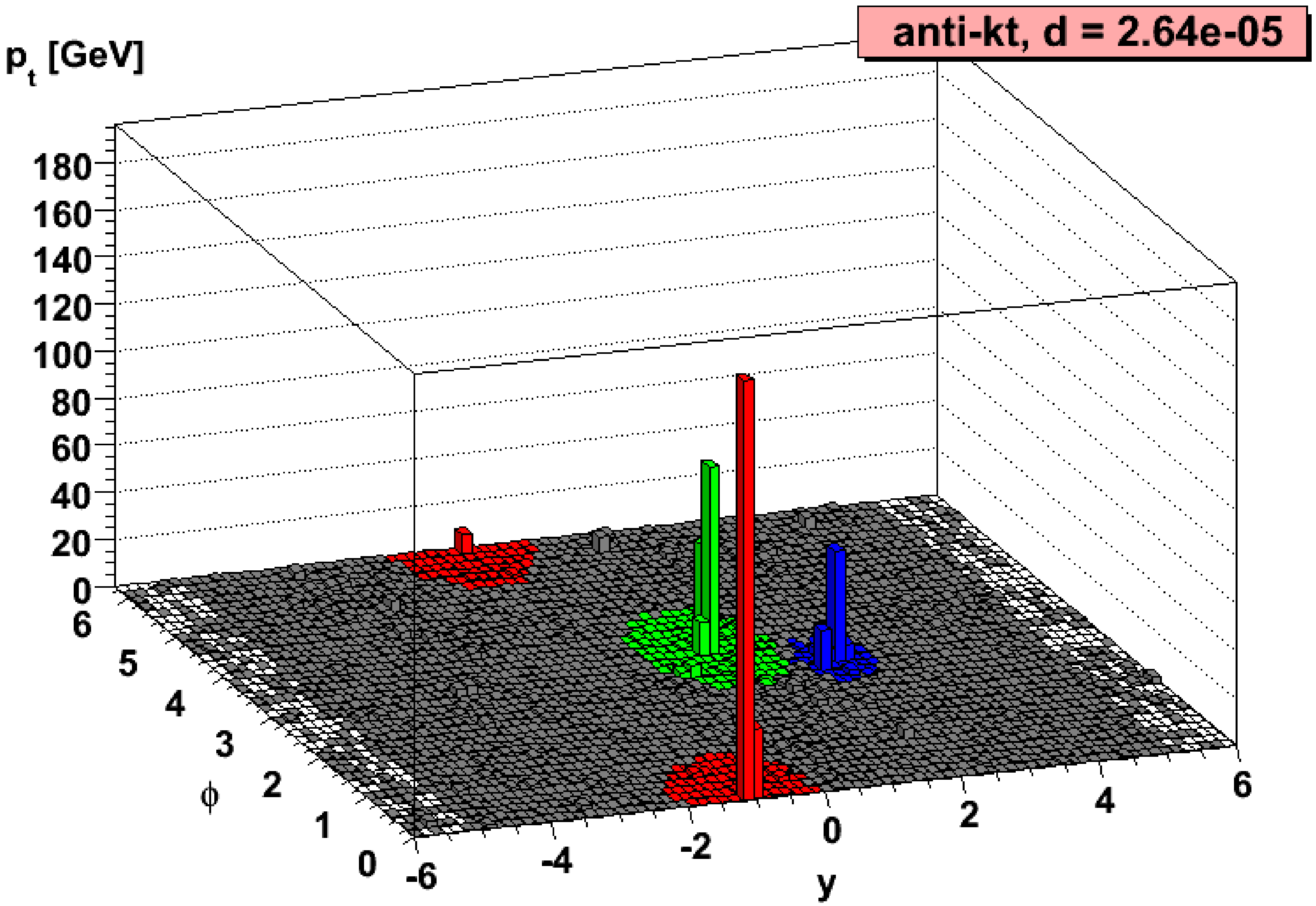

Anti-k_t in action

Clustering grows around hard cores

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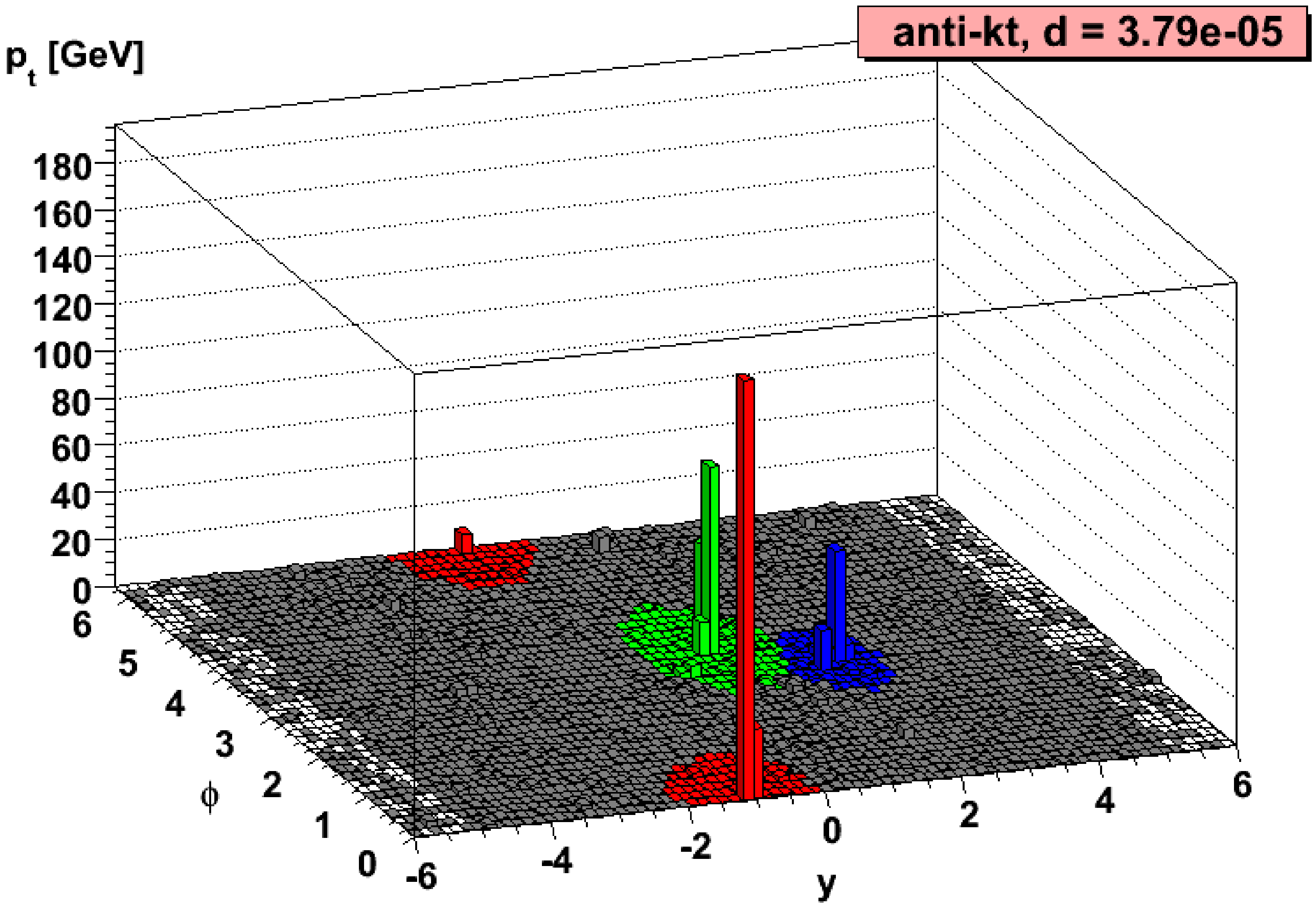

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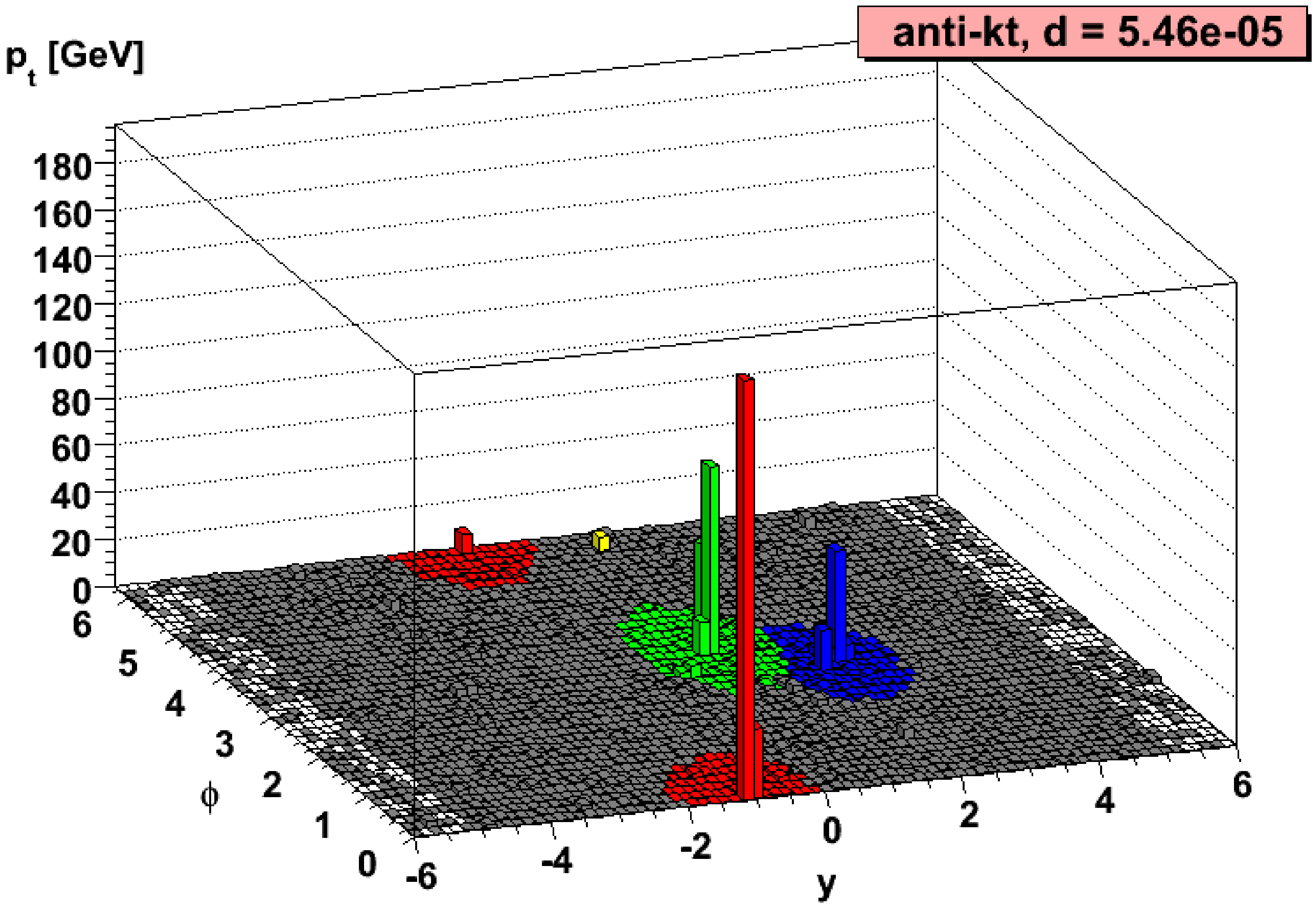

Anti-k_t in action

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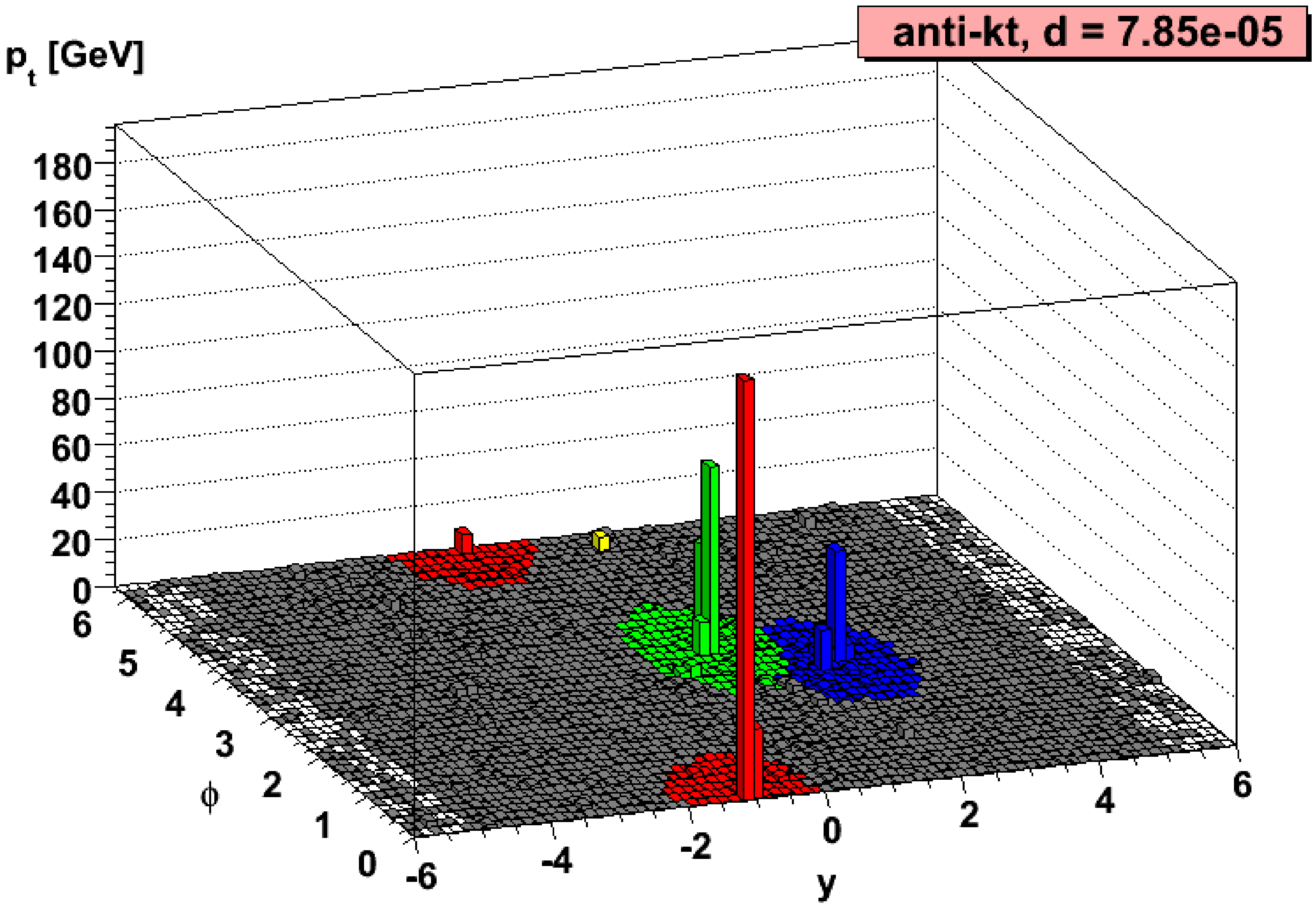

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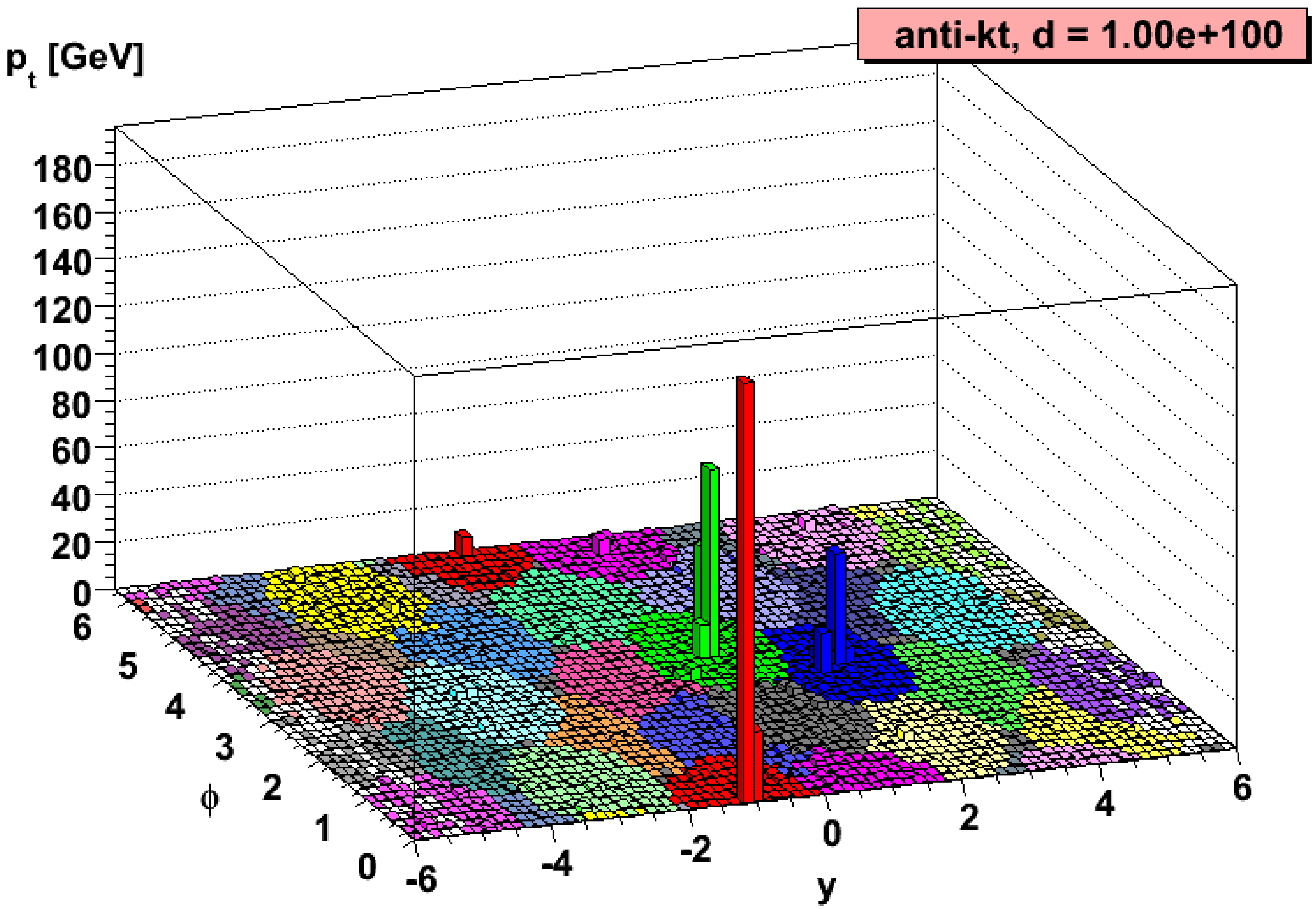
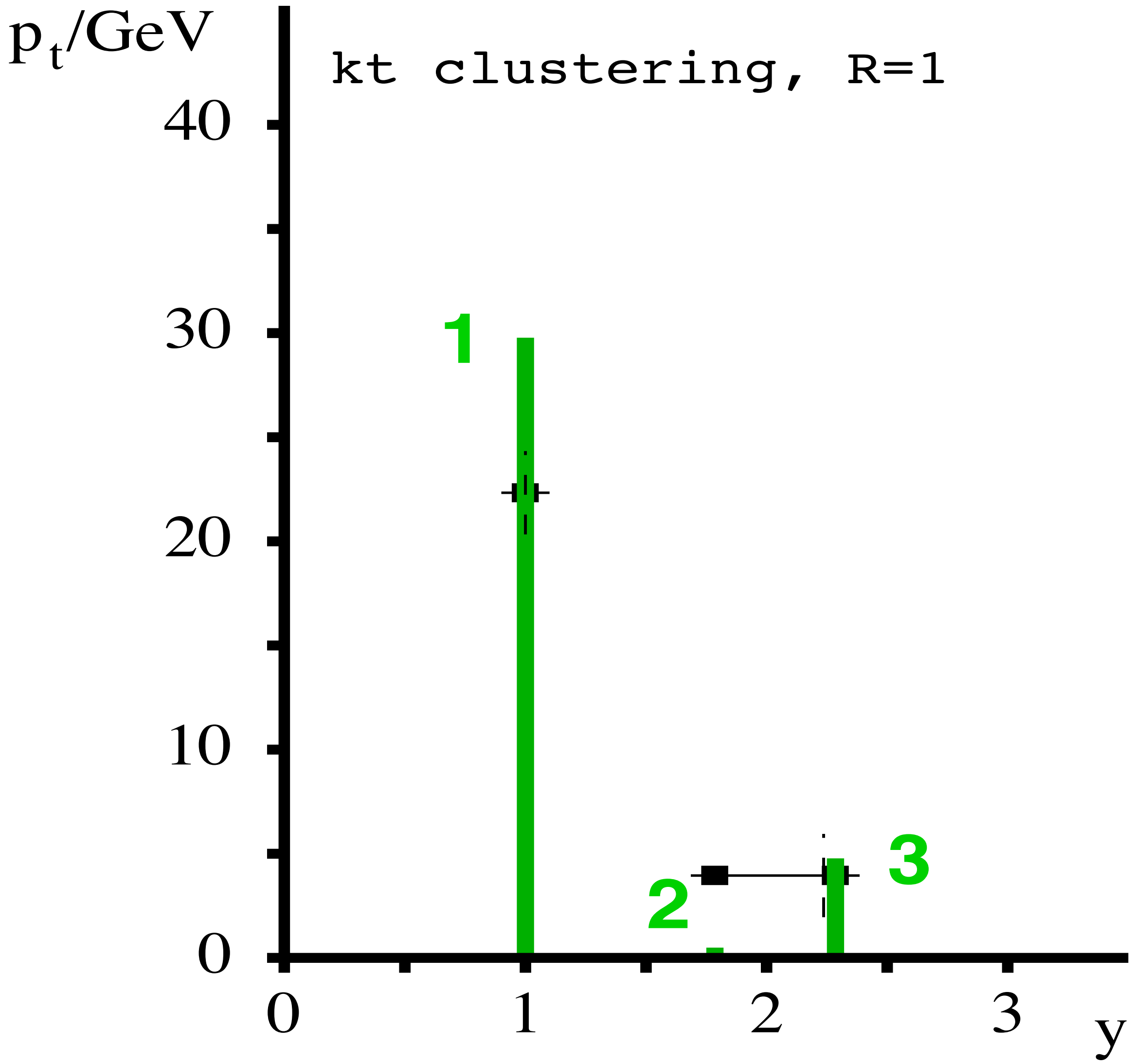
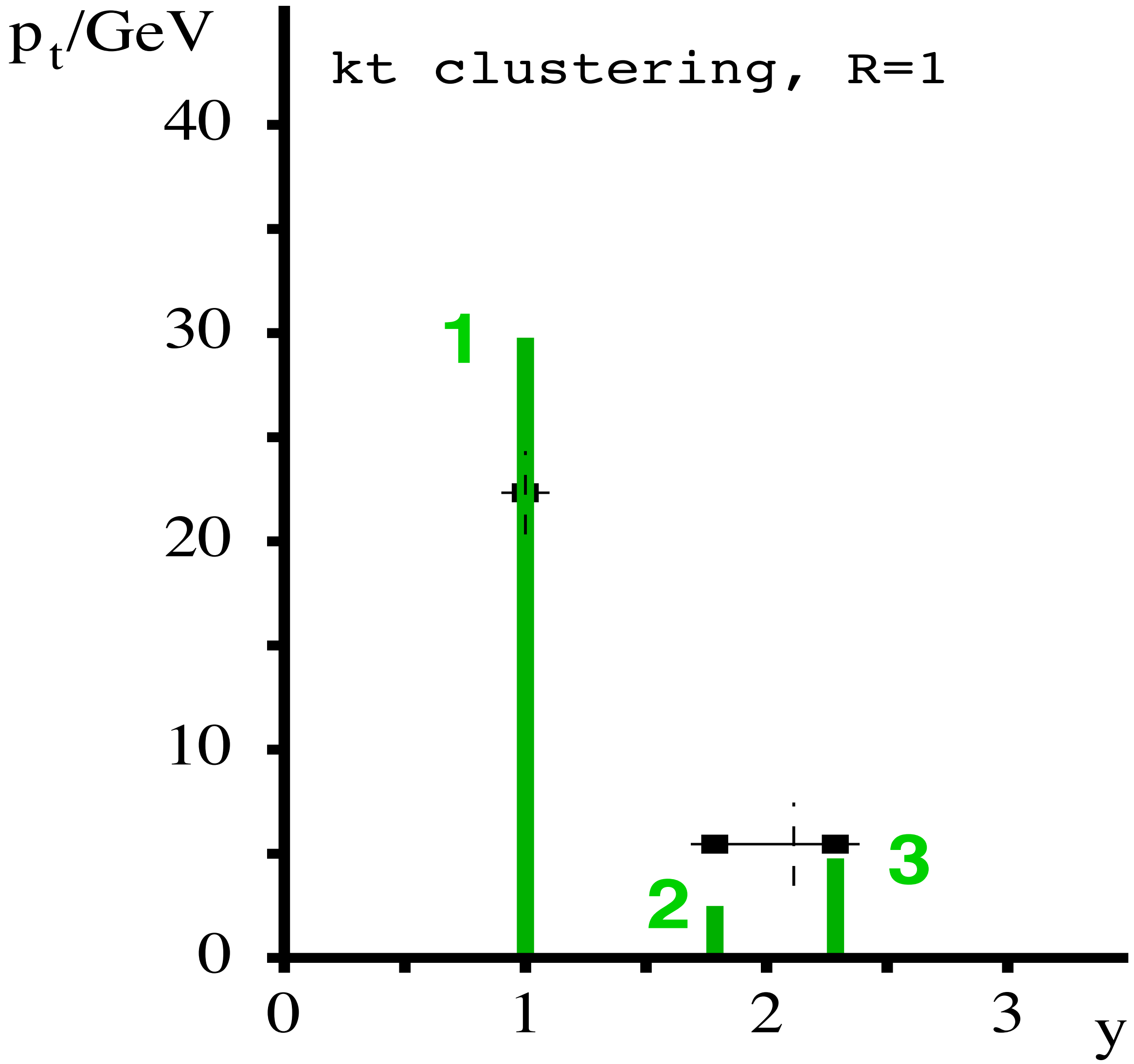


Anti-k_t gives circular jets ("cone-like") in a way that's infrared safe

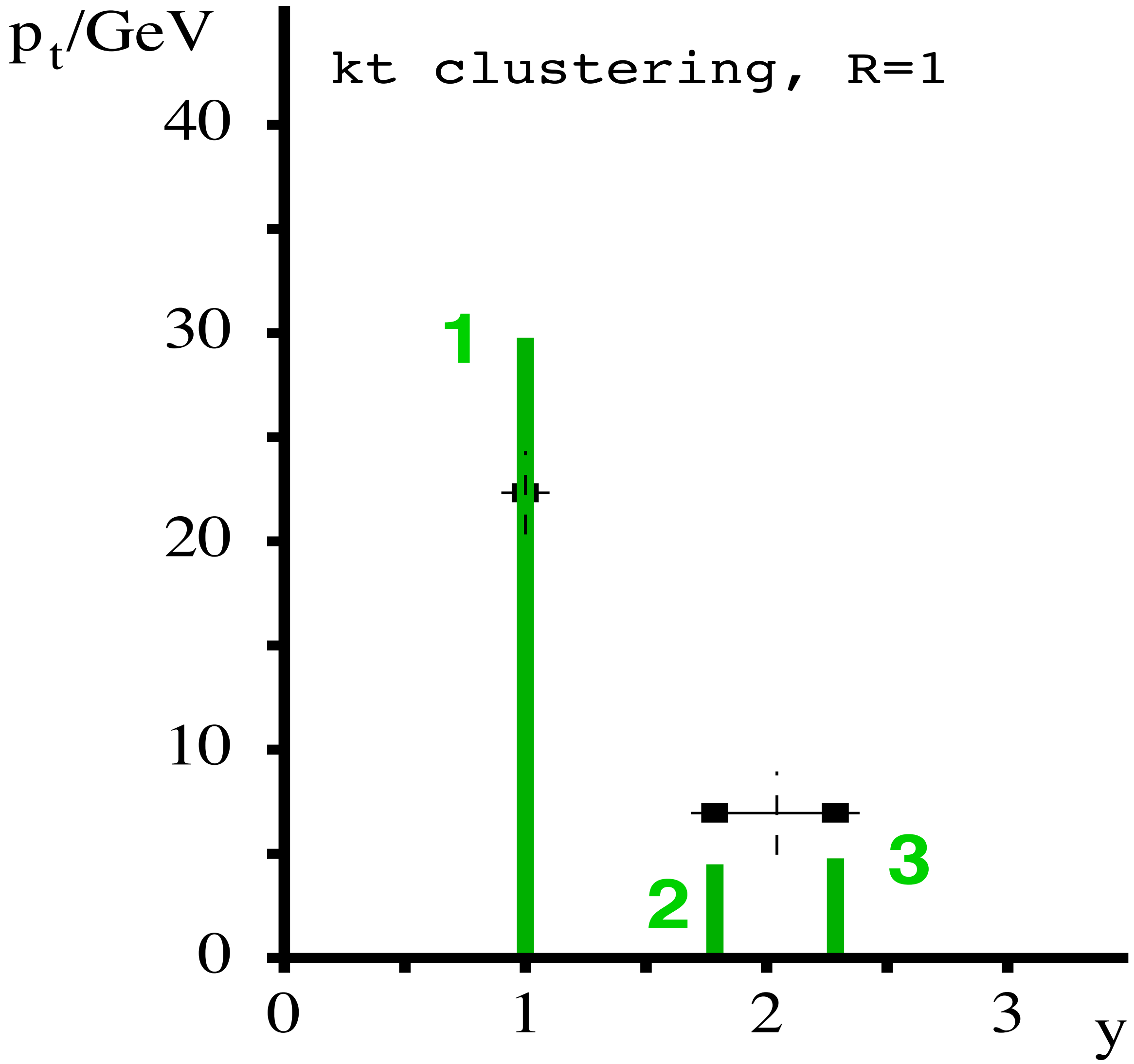
Linearity: k_t v. anti-k_t



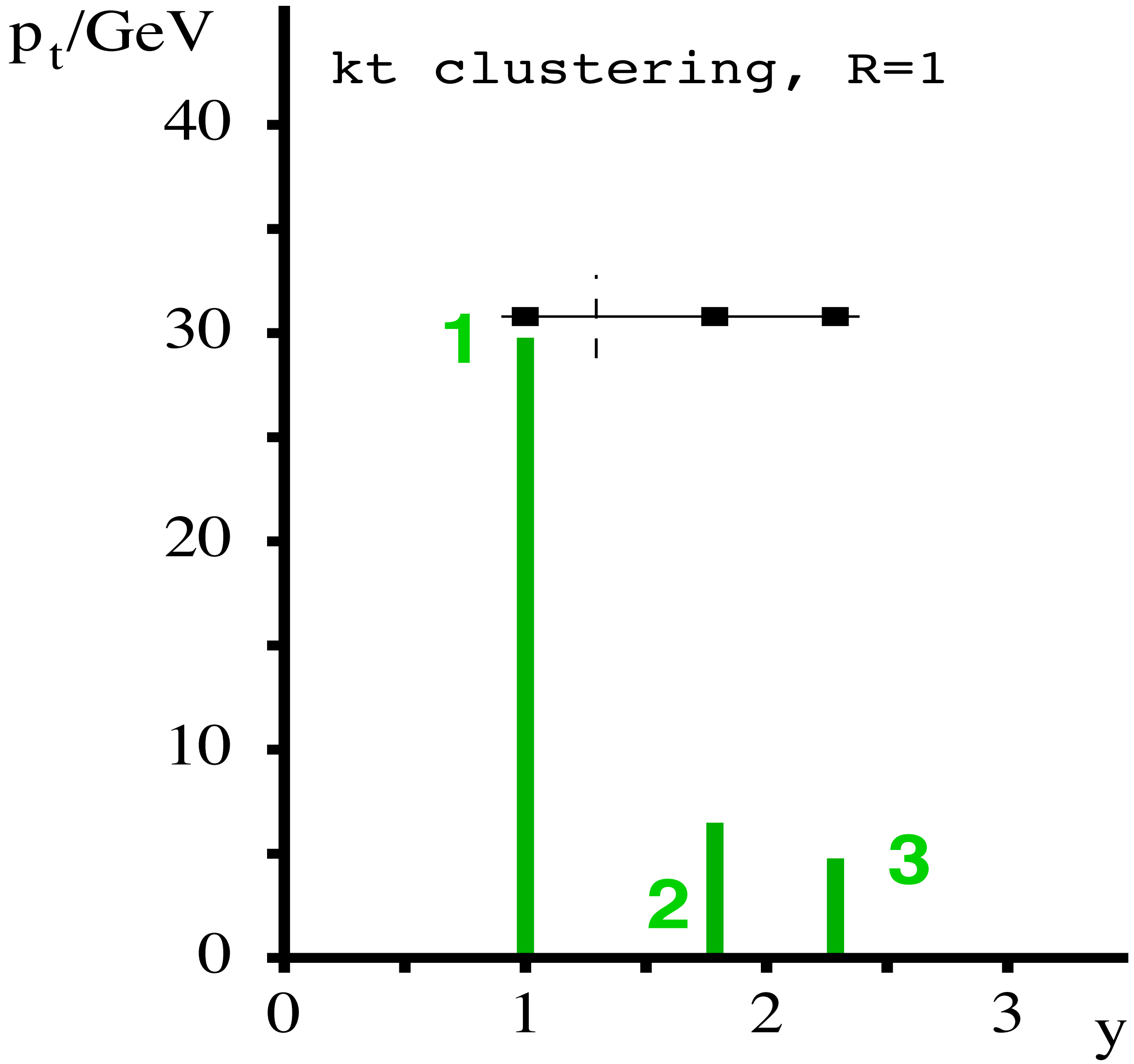
Linearity: k_t v. anti-k_t

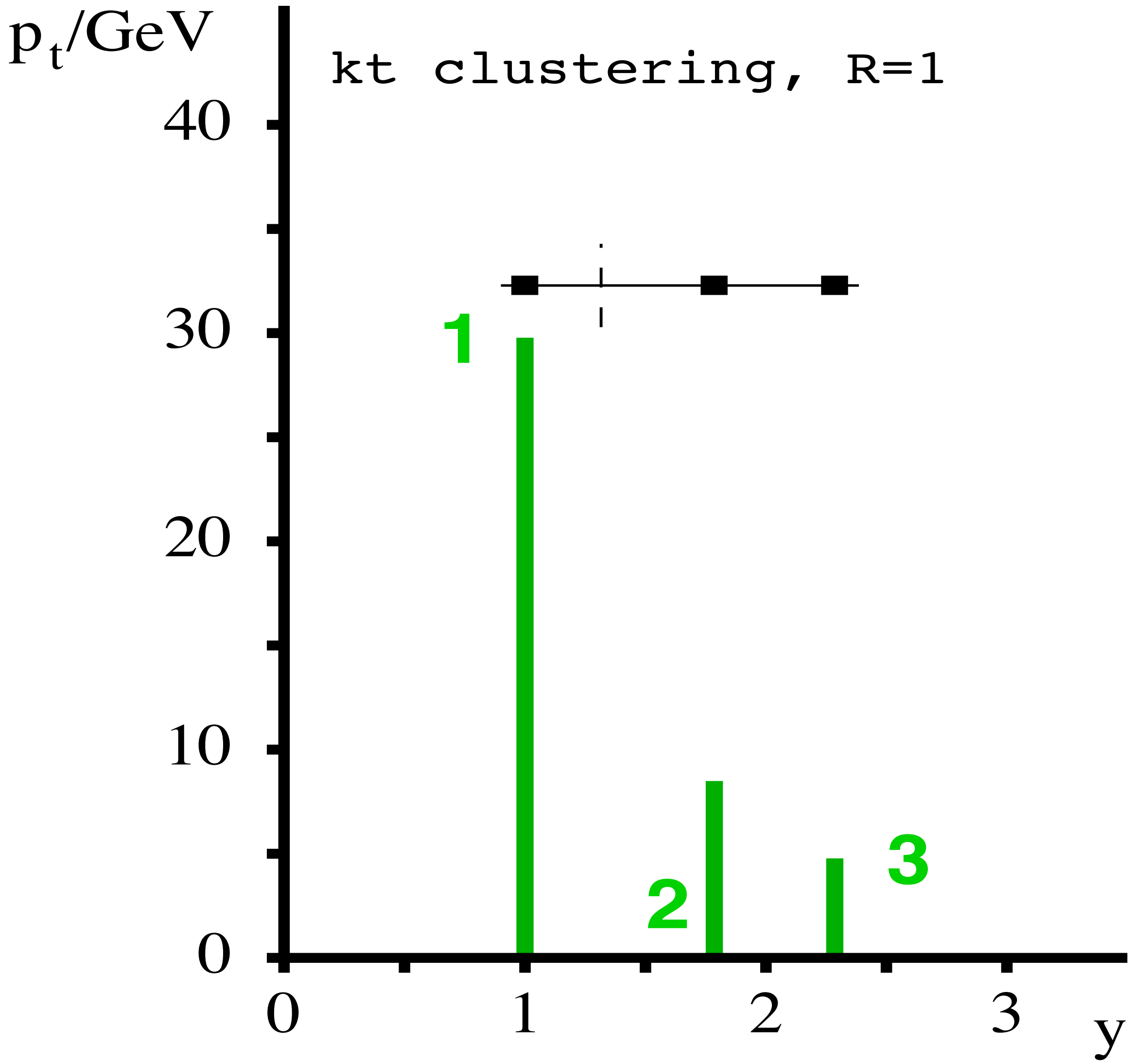


Linearity: k_t v. anti-k_t

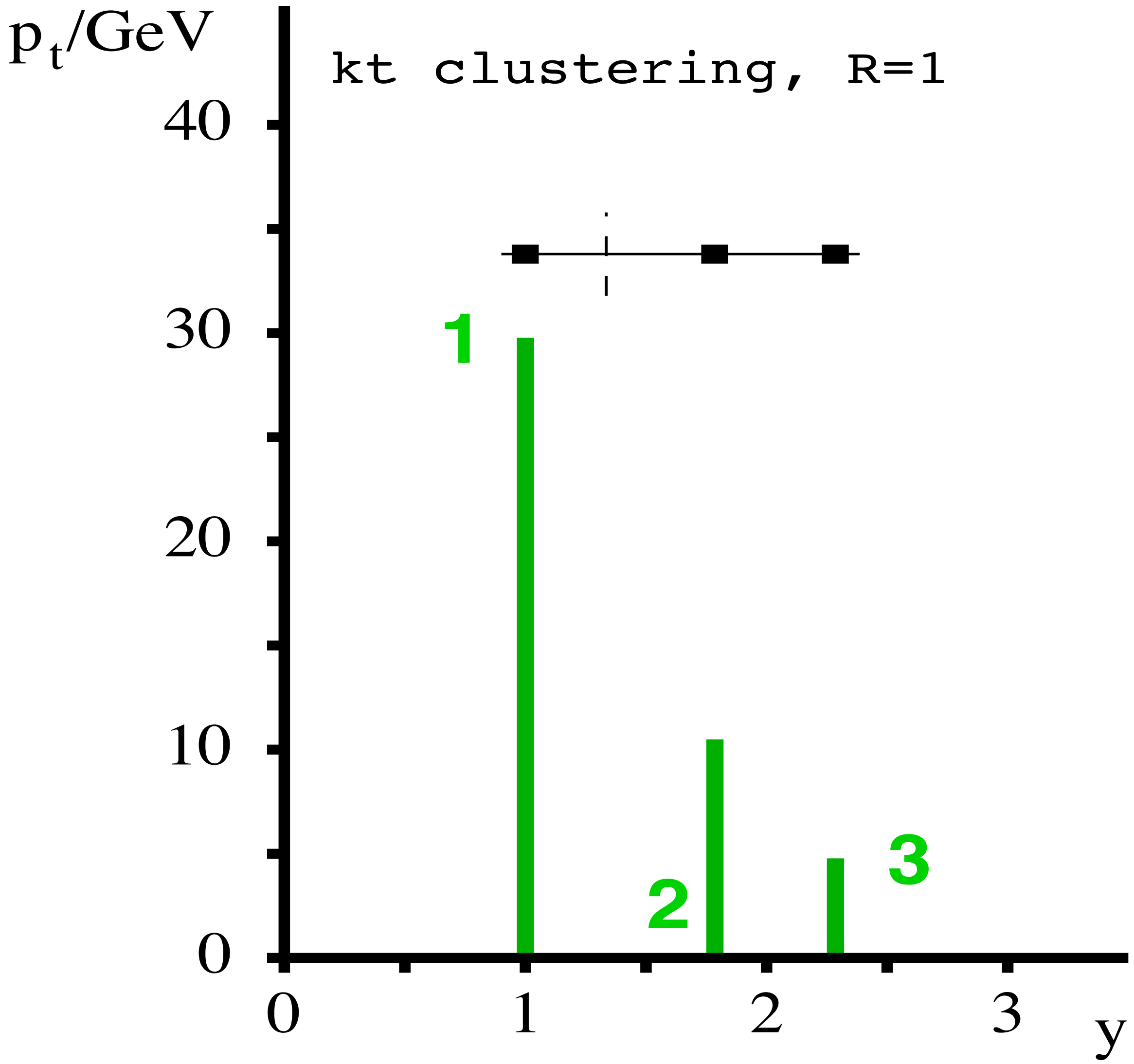


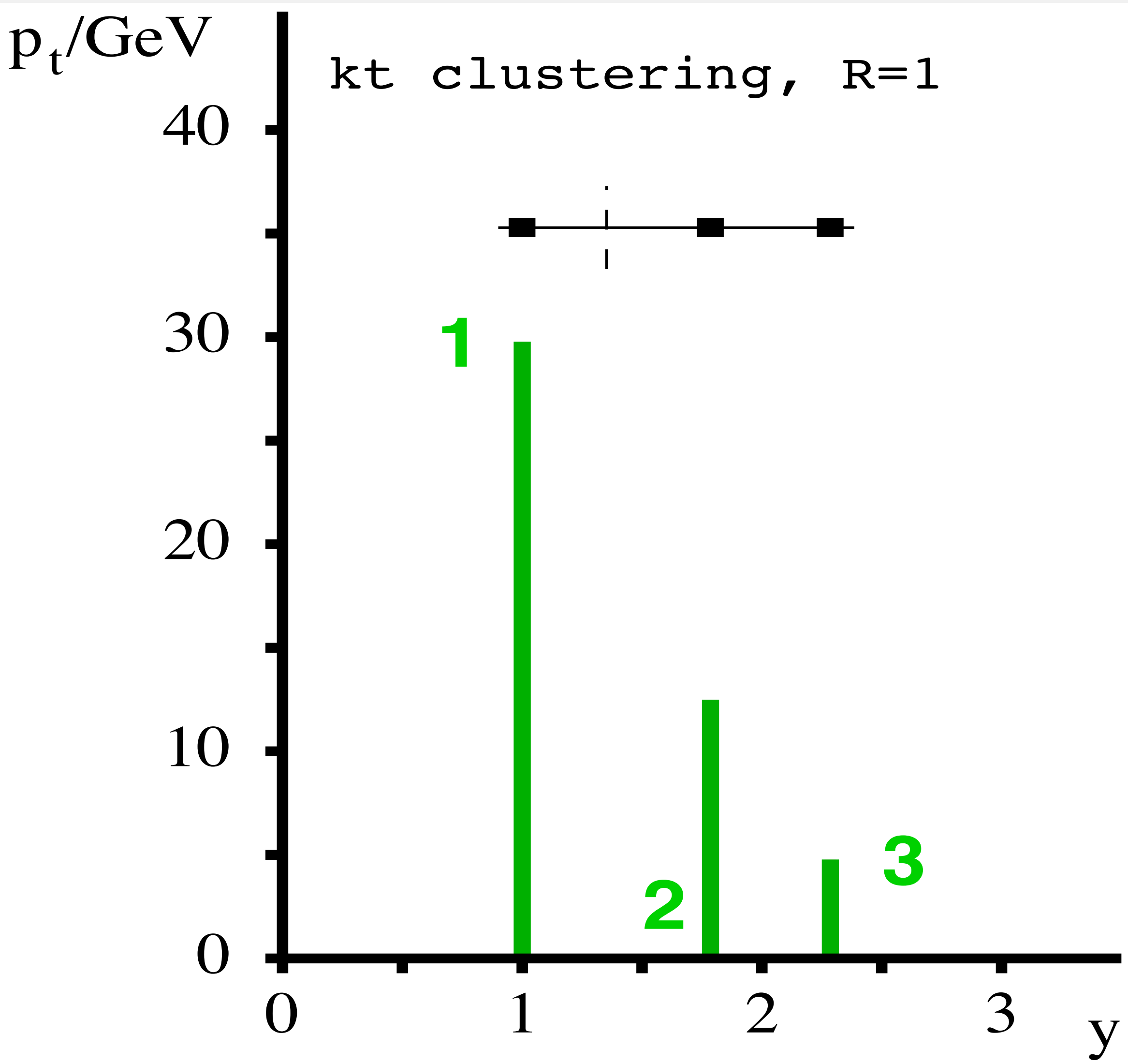
Linearity: k_t v. anti-k_t




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

Linearity: k_t v. anti-k_t




p_t/GeV
kt clustering, R=1
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30
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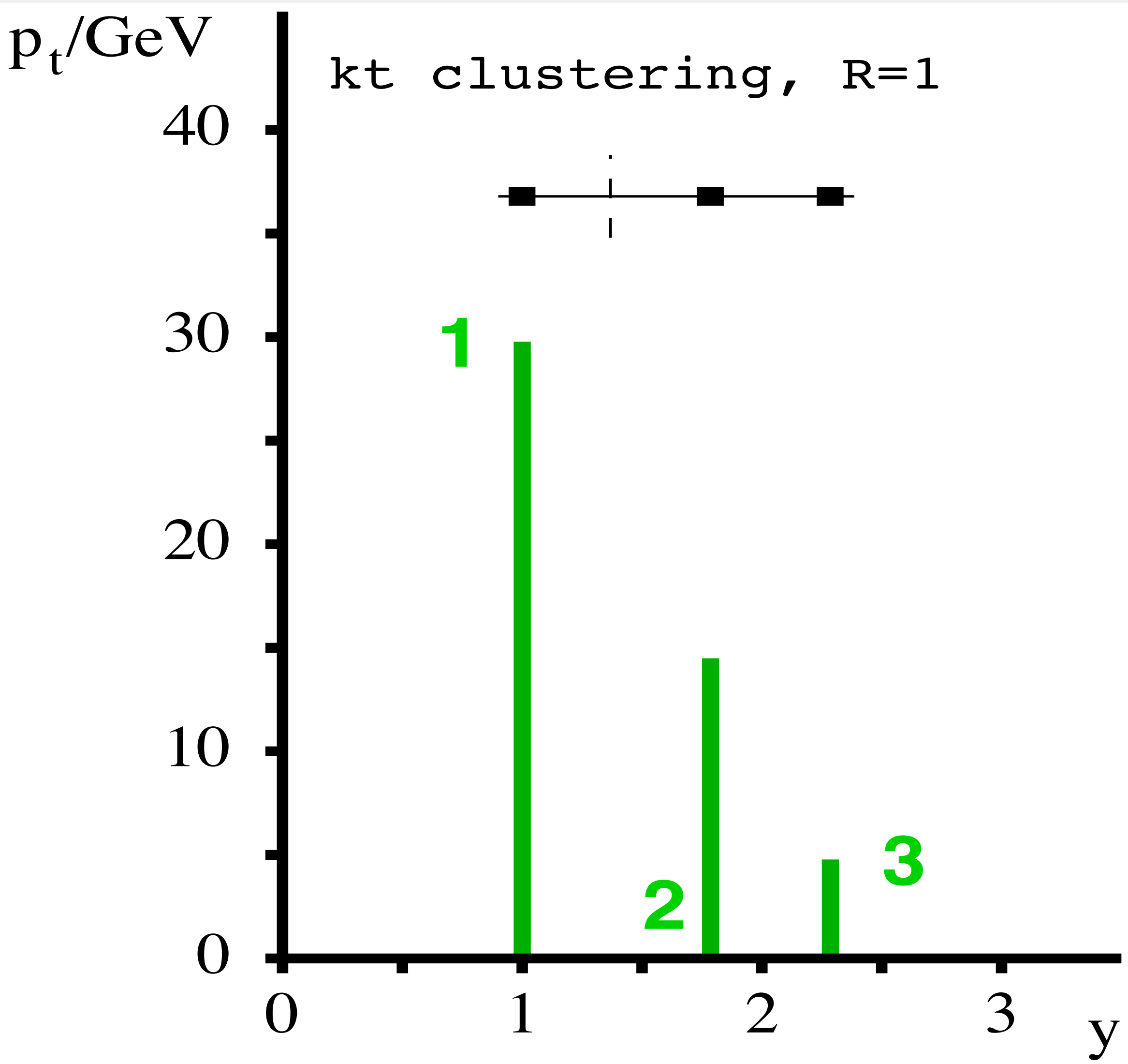

pt/GeV
kt clustering, R=1
40
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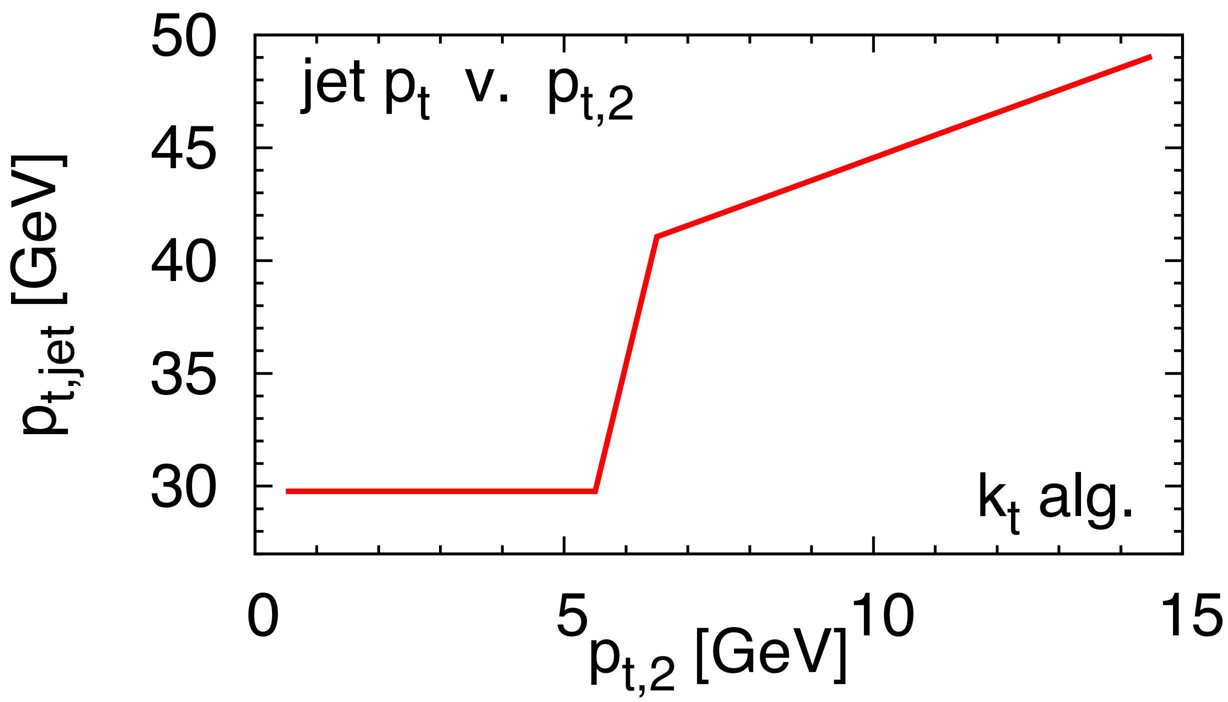
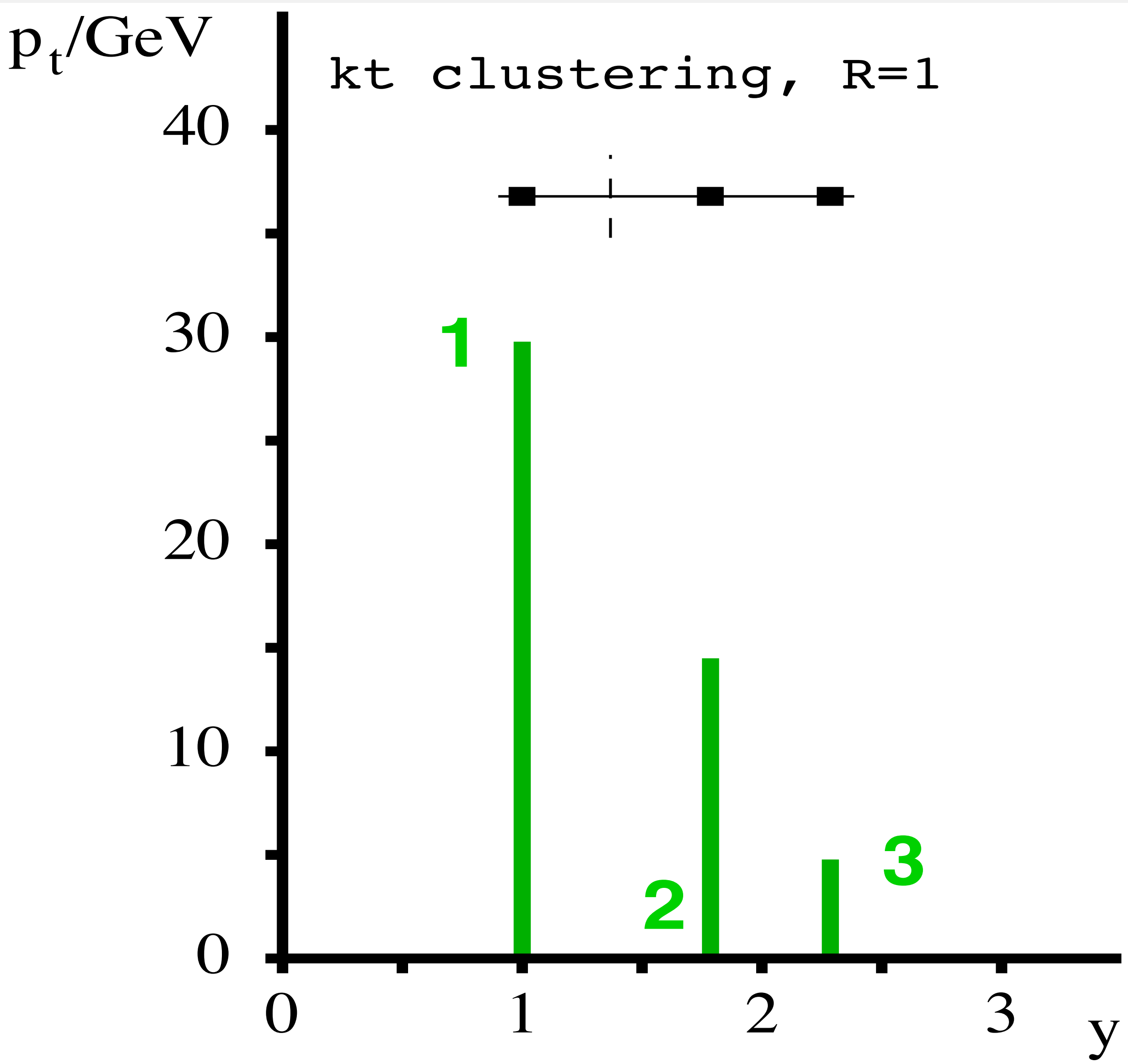
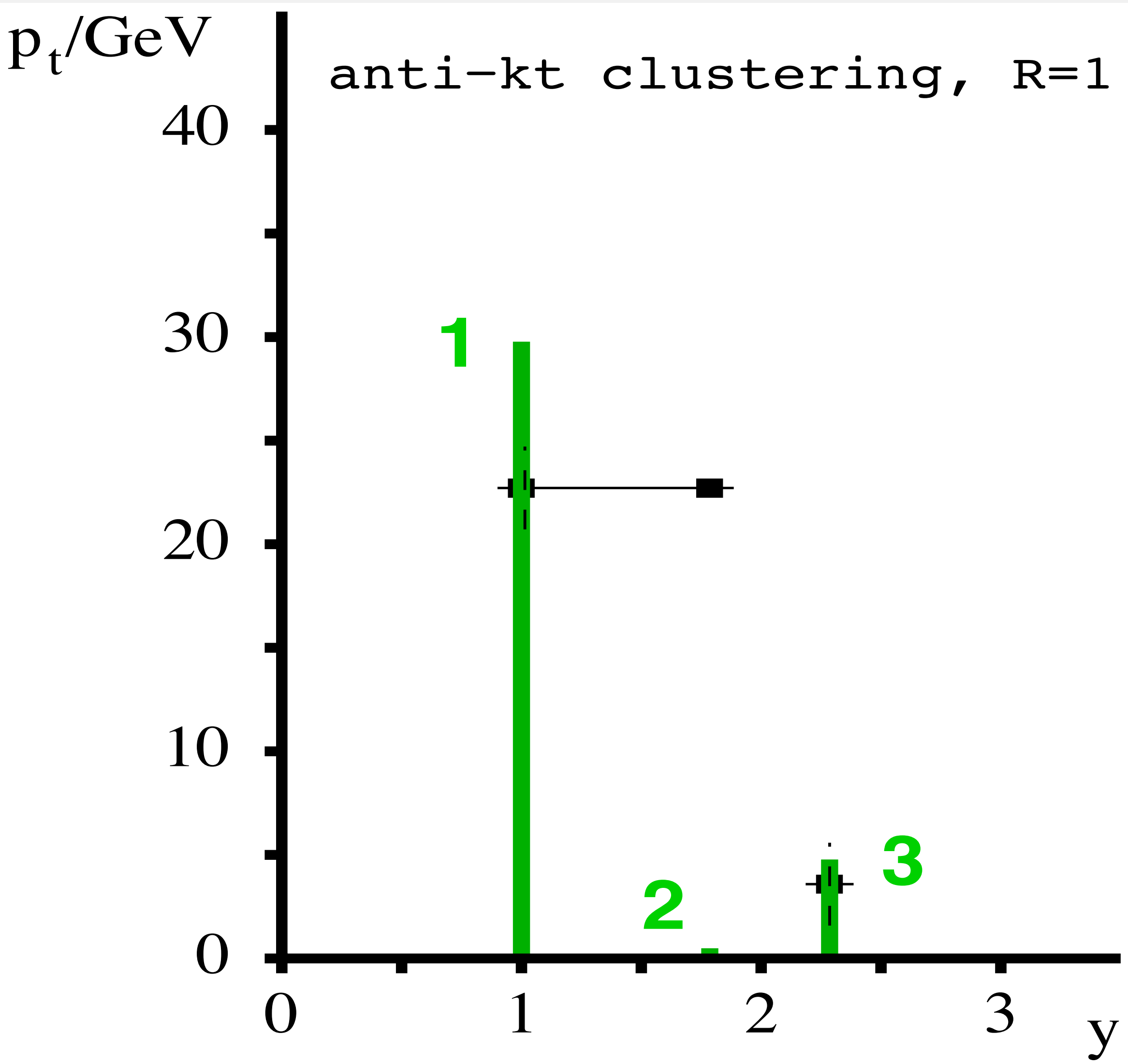
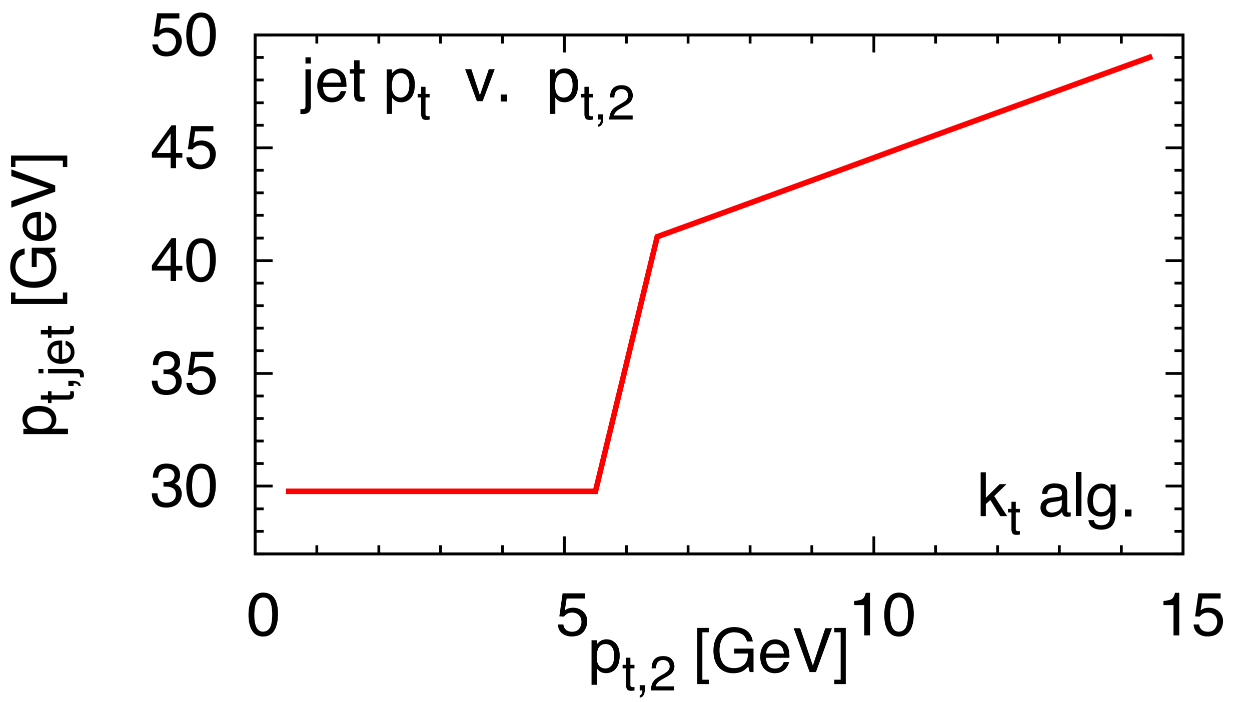


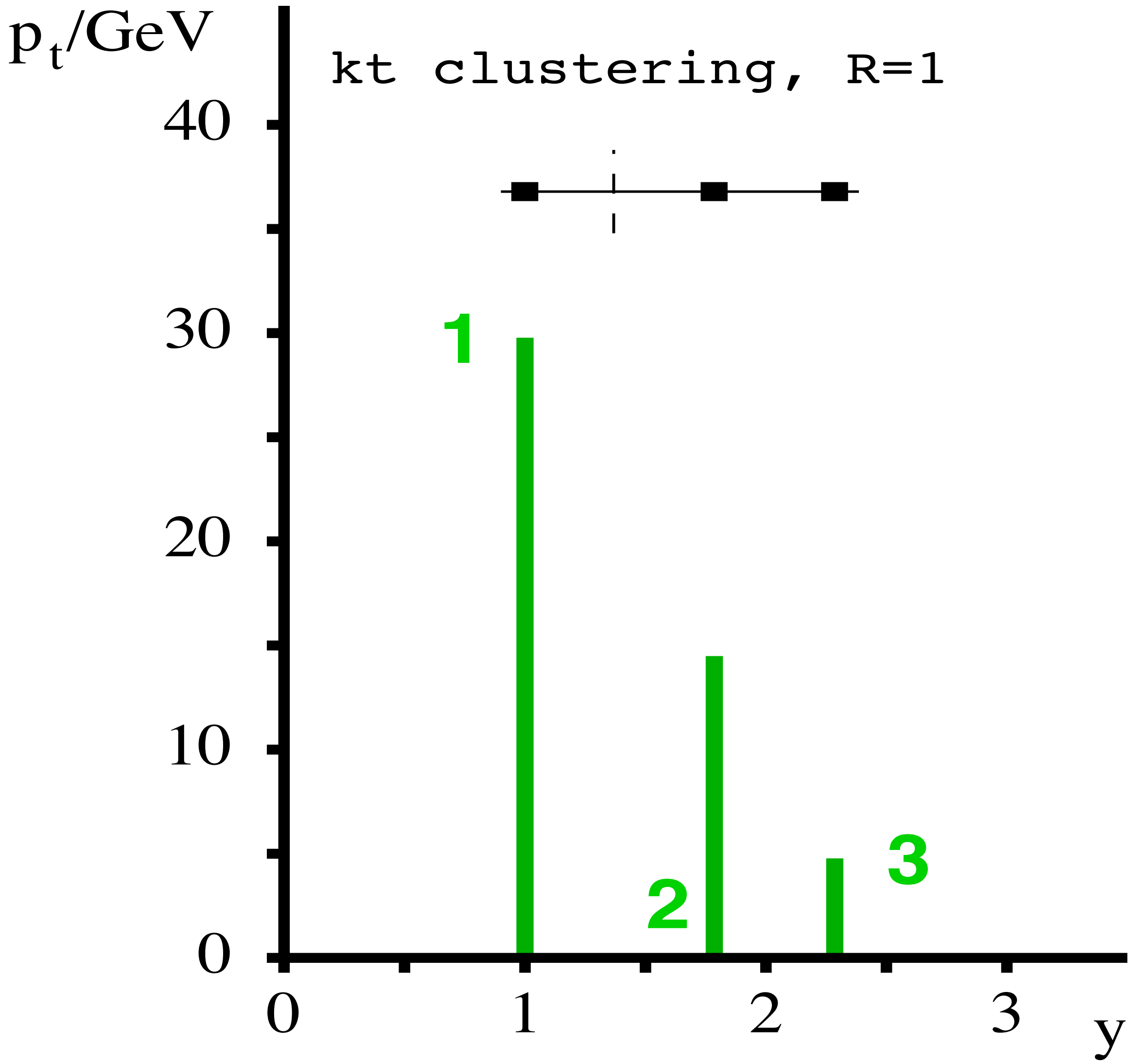
50
45
40
35
30
jet pt v. pt,2
pt,jet [GeV]
kt alg.
0
5
10
15
pt,2 [GeV]

Linearity: k_t v. anti-k_t

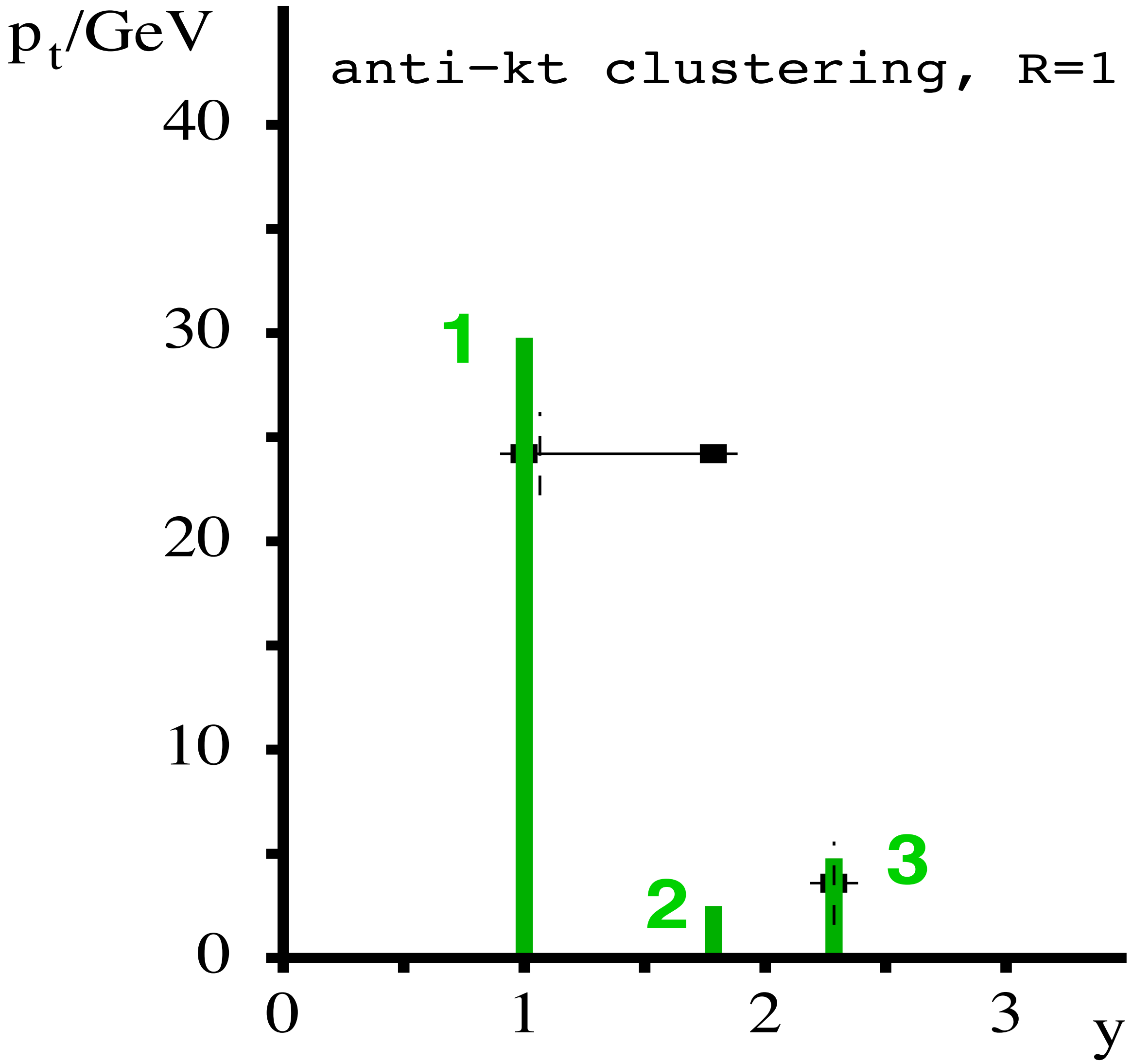




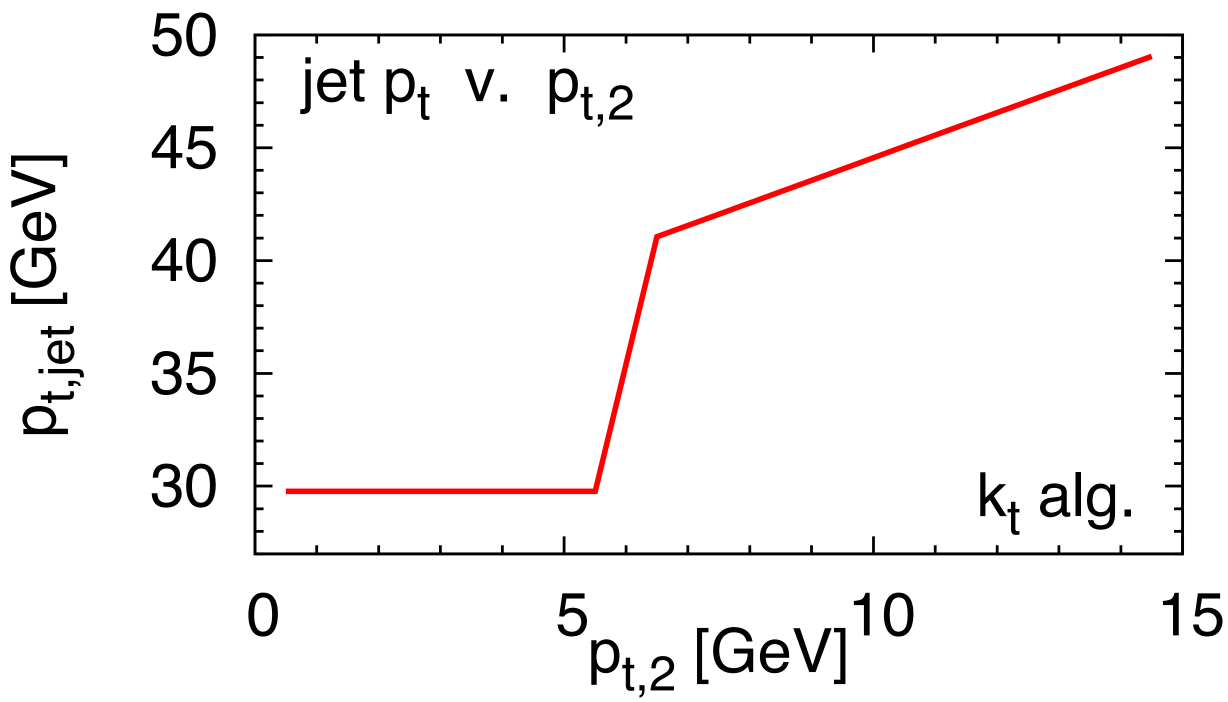




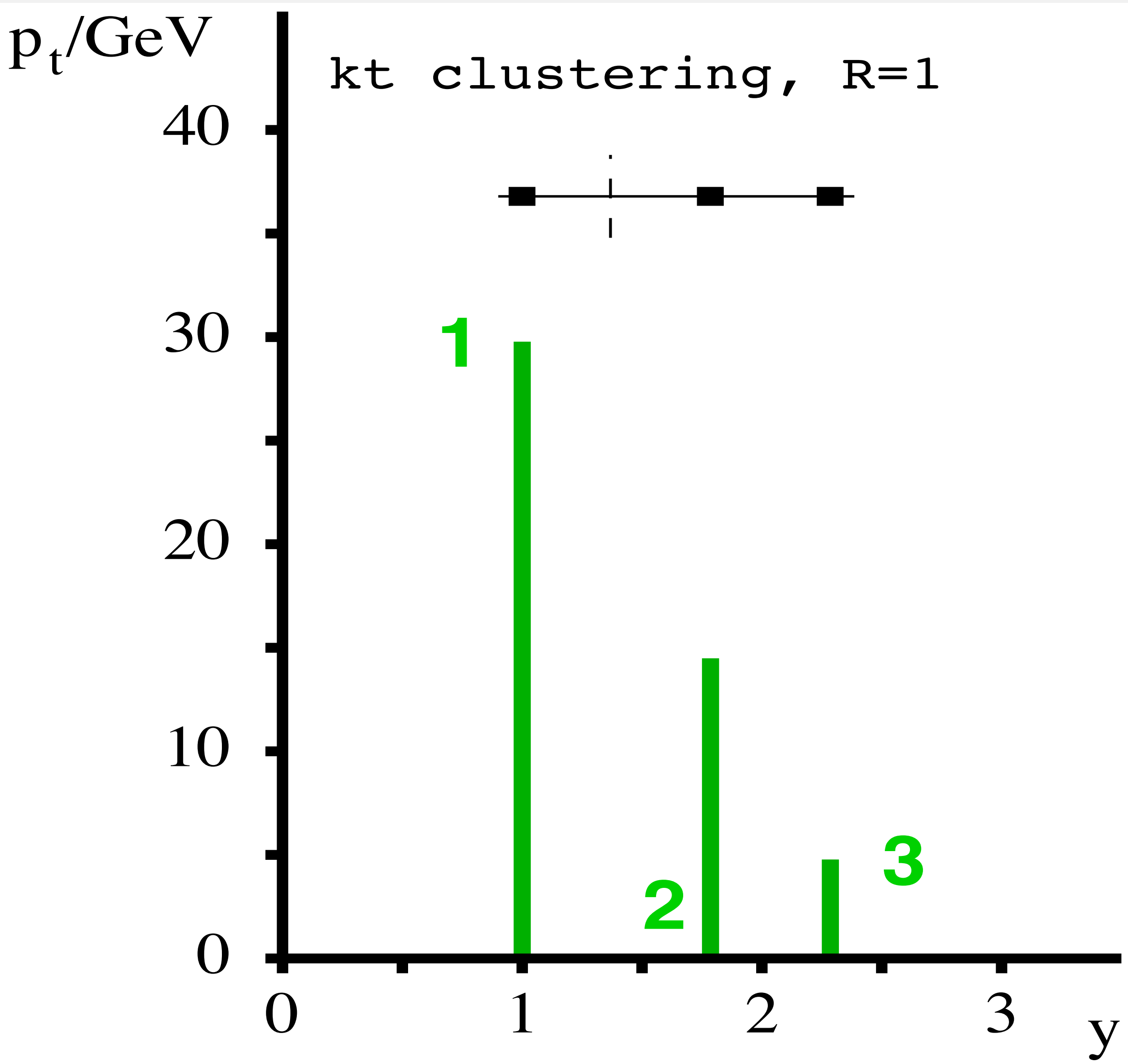
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



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



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


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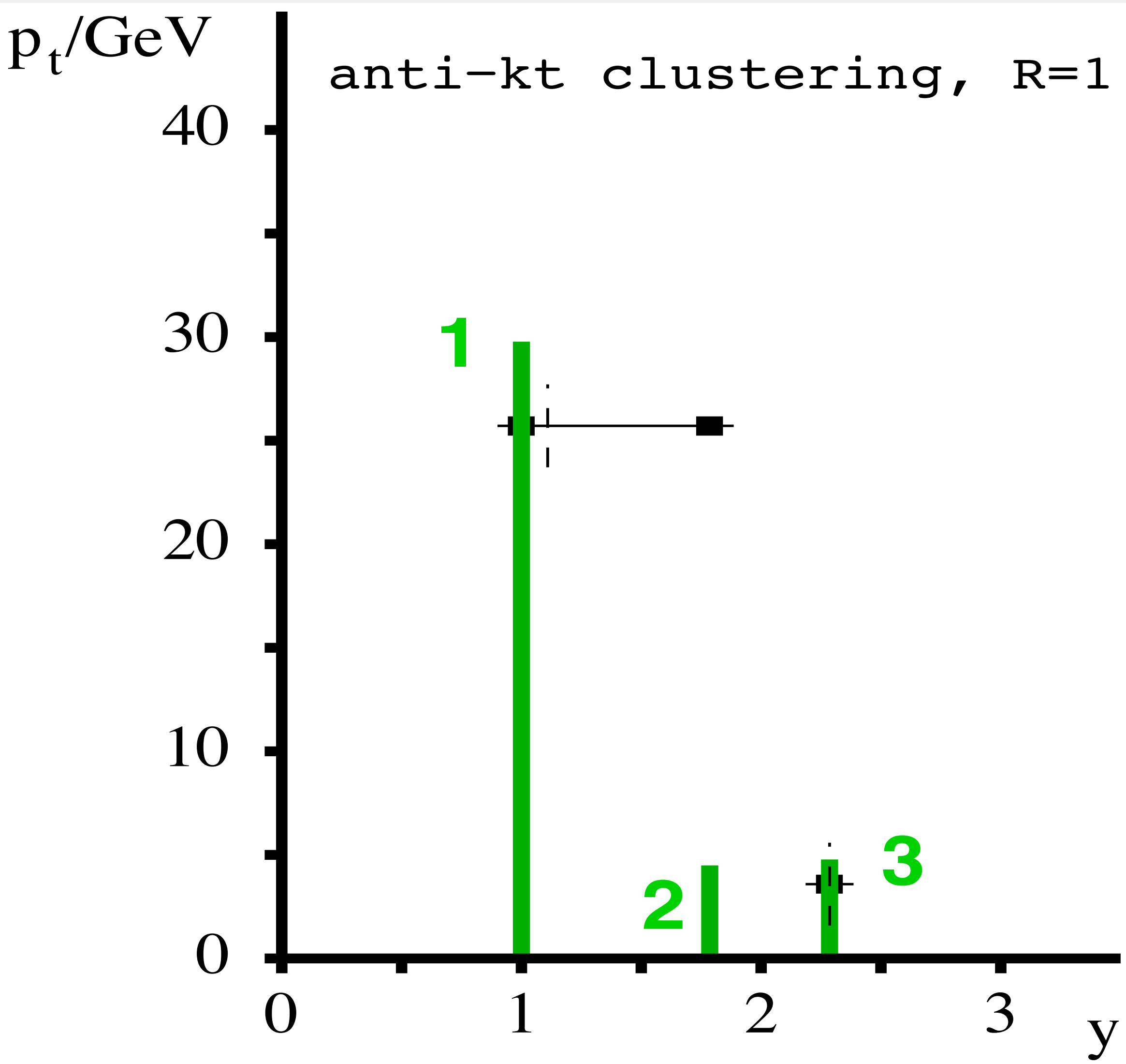
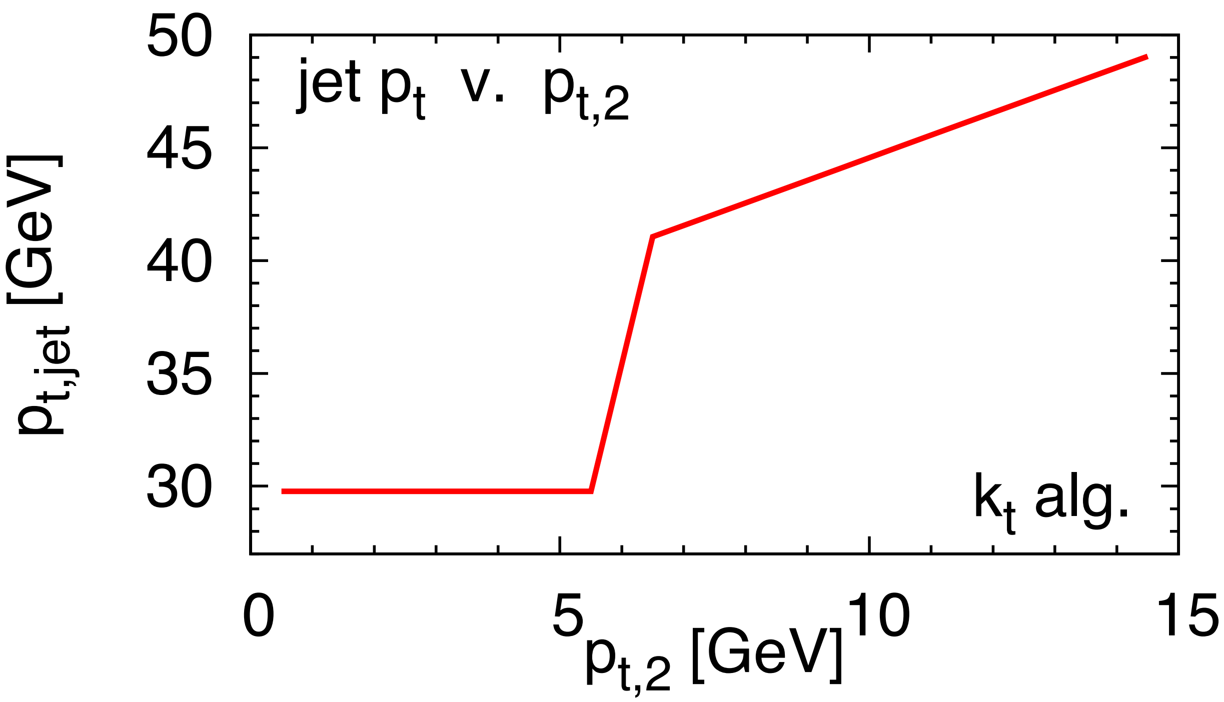

p_t/GeV
anti−kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y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k_t alg.
p_t,jet [GeV]
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30
0
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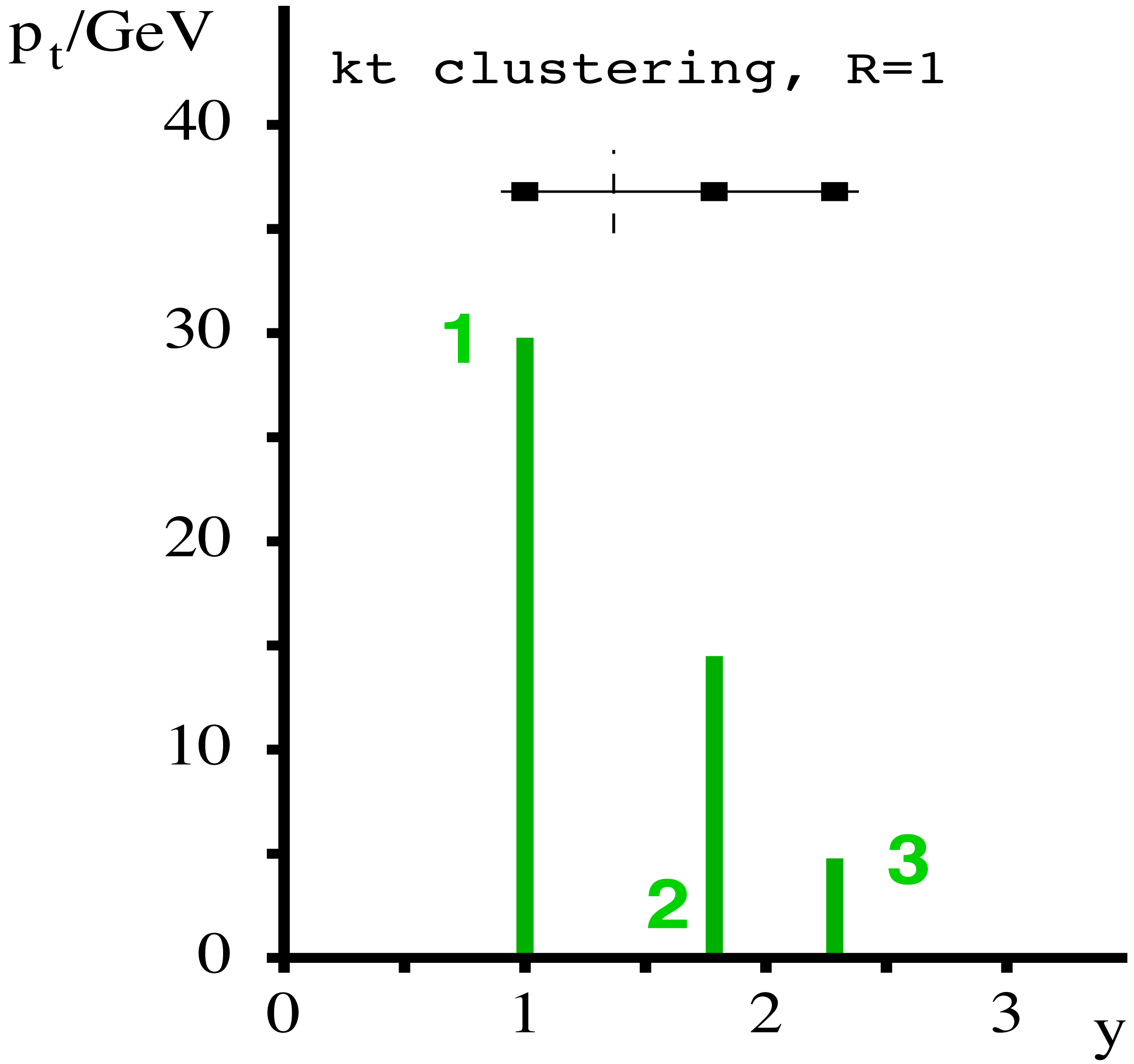
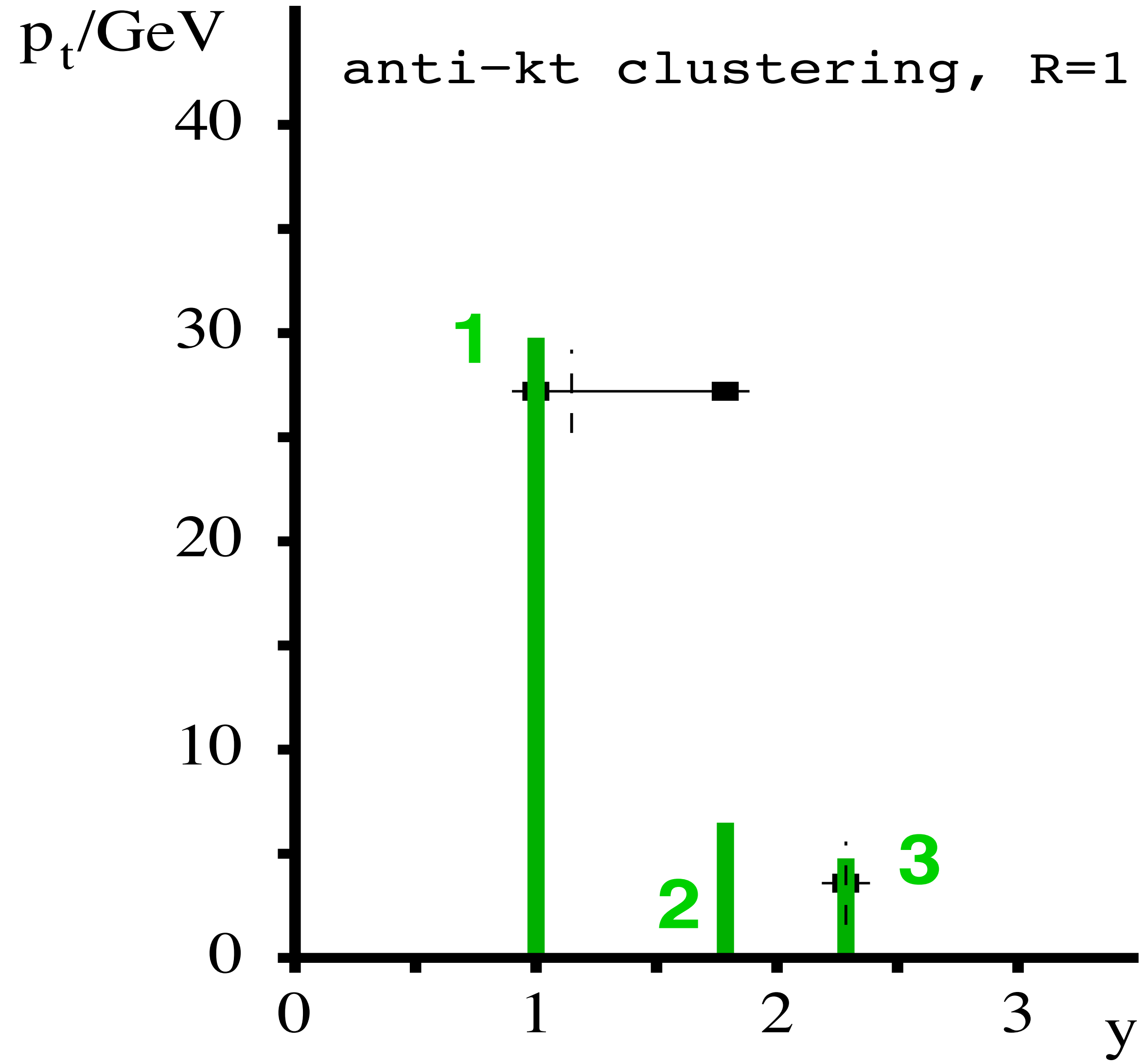
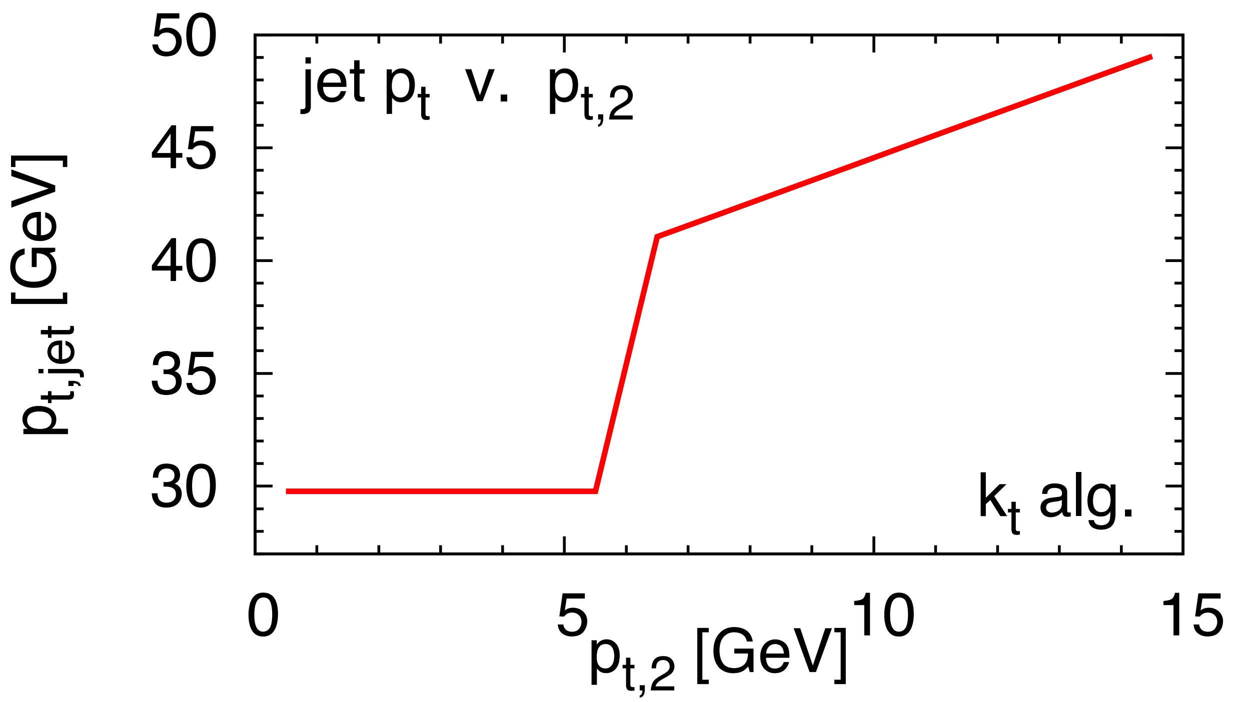
p_t,2 [GeV]

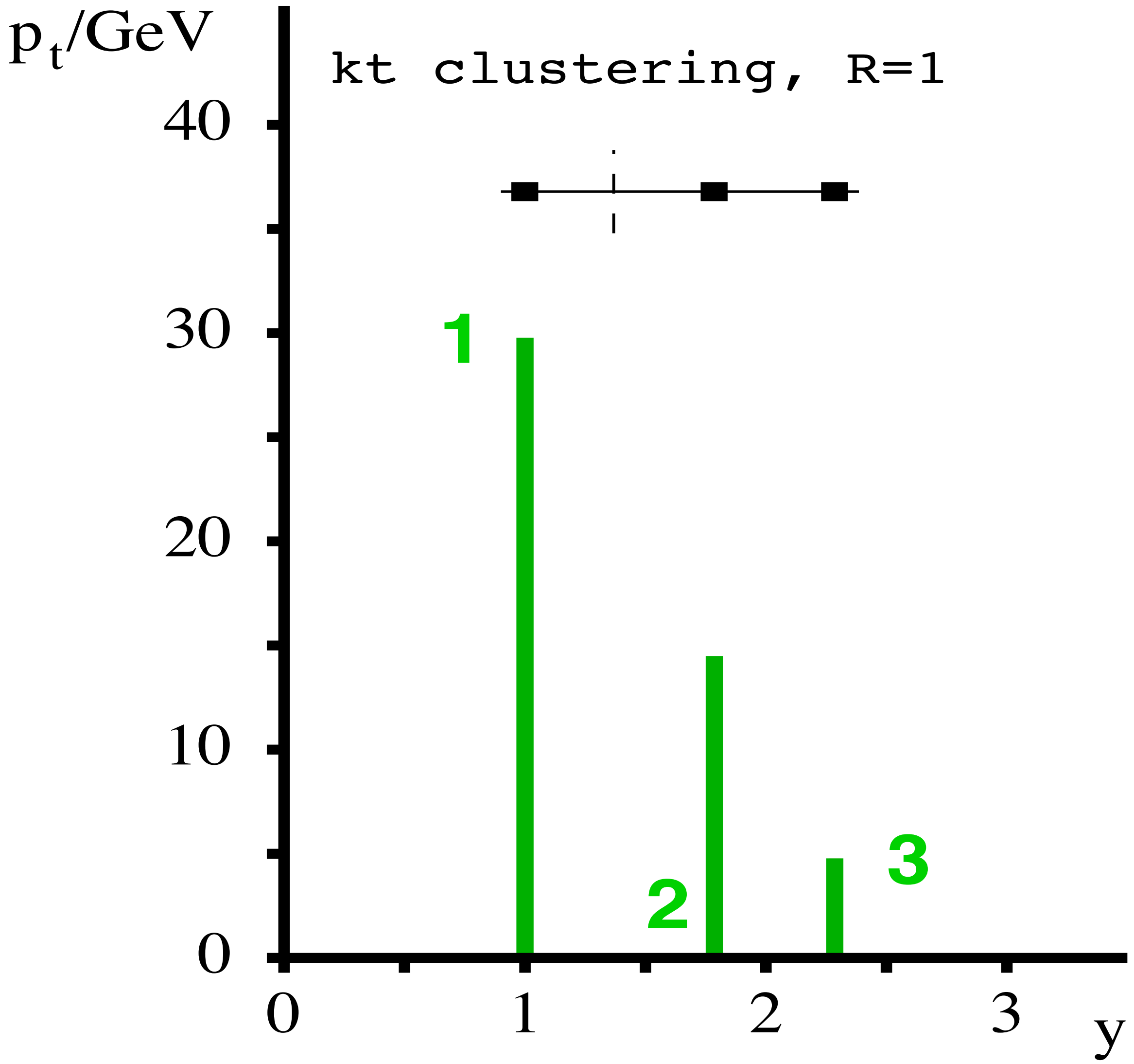
Linearity: k_t v. anti-k_t

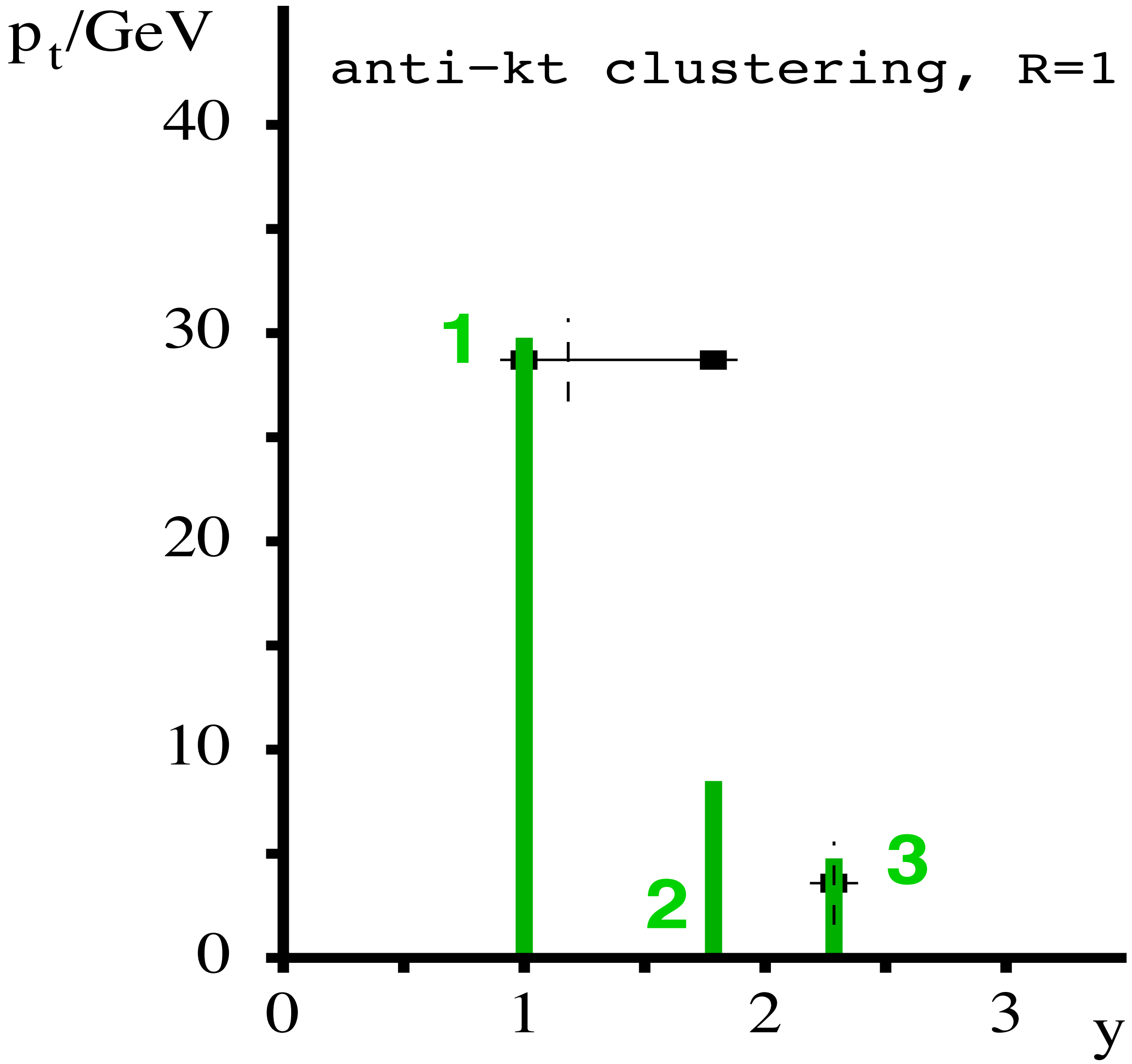


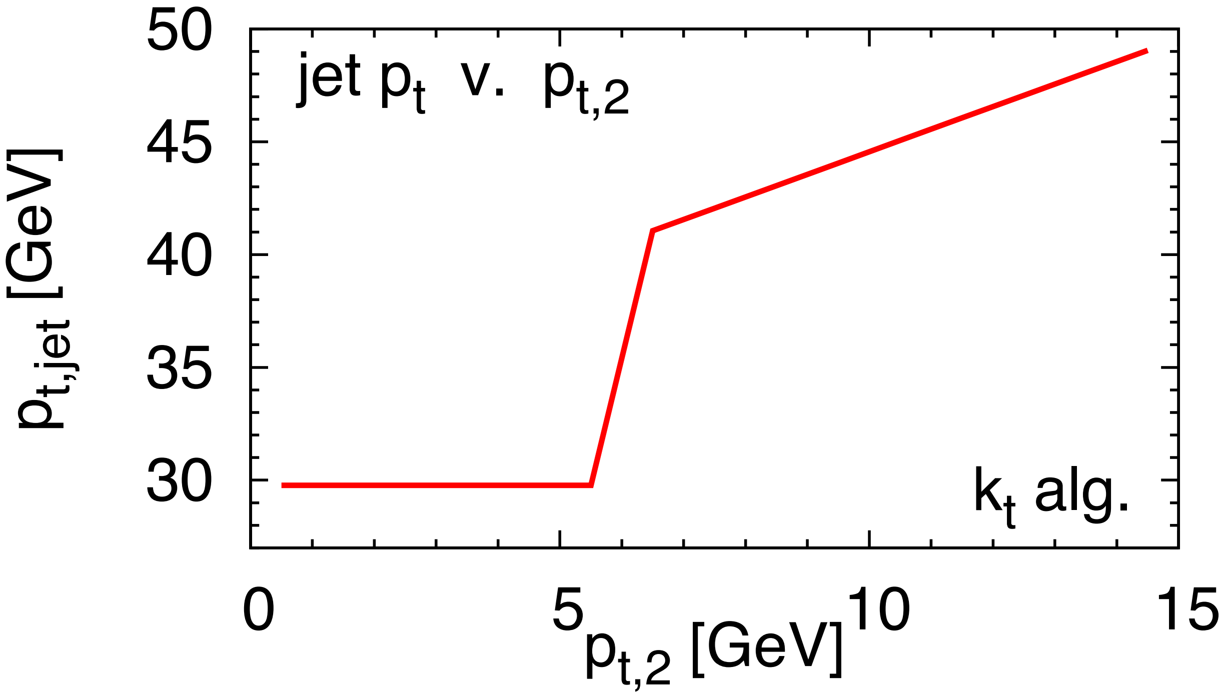


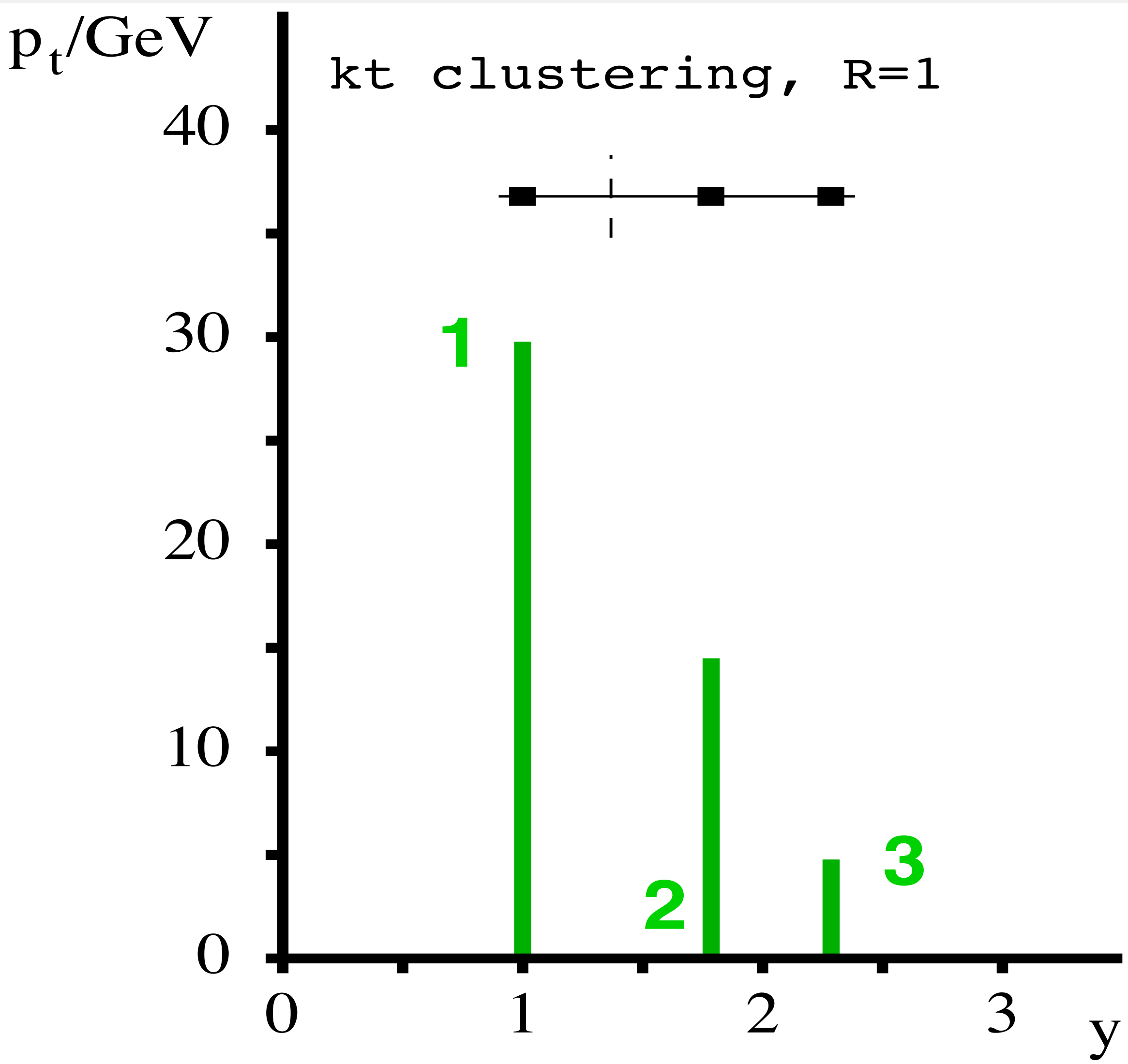


Linearity: k_t v. anti-k_t









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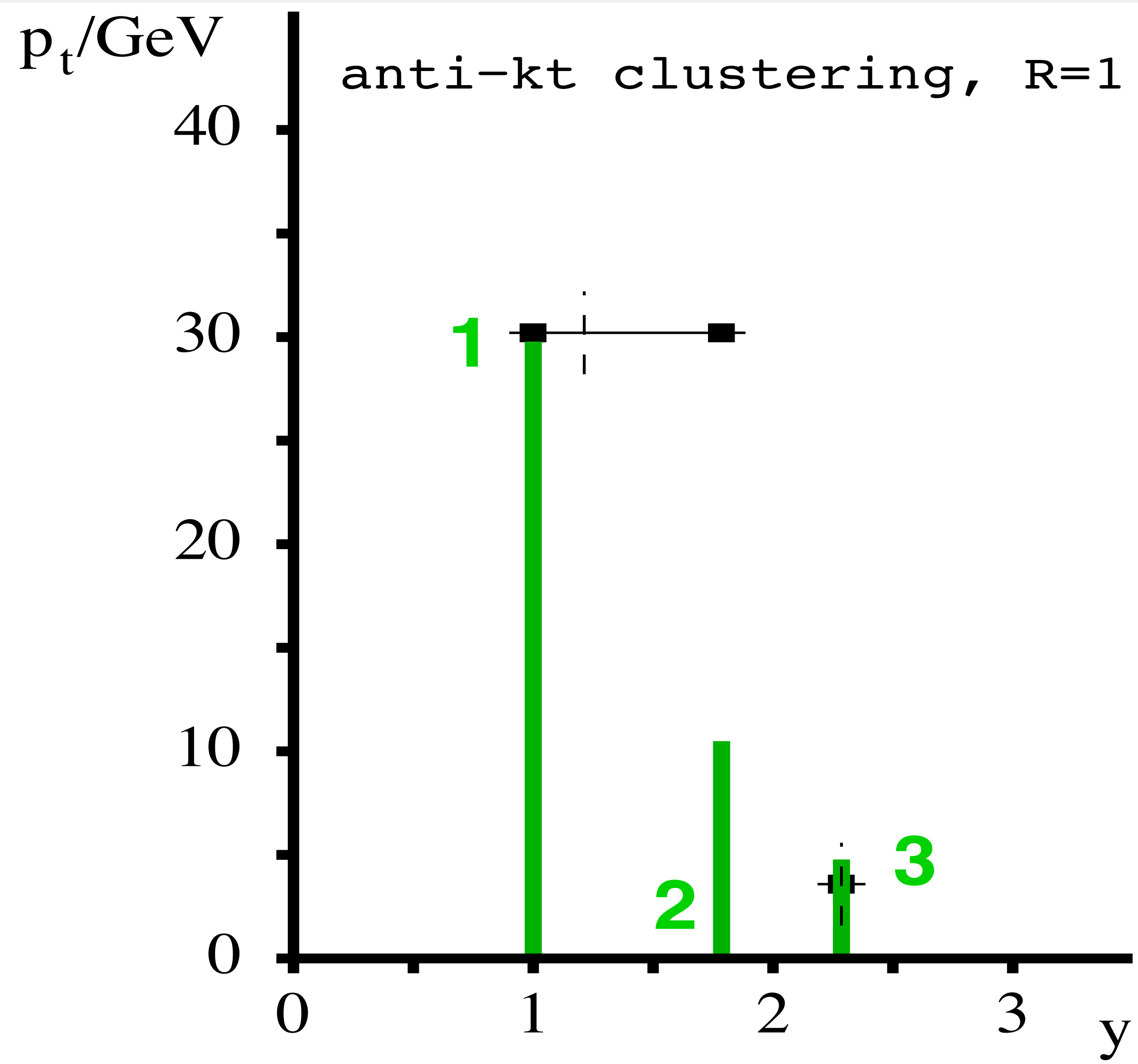
1
2
3
y



p_t/GeV
anti-kt clustering, R=1
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20
10
0
1
2
3
0
1
2
3
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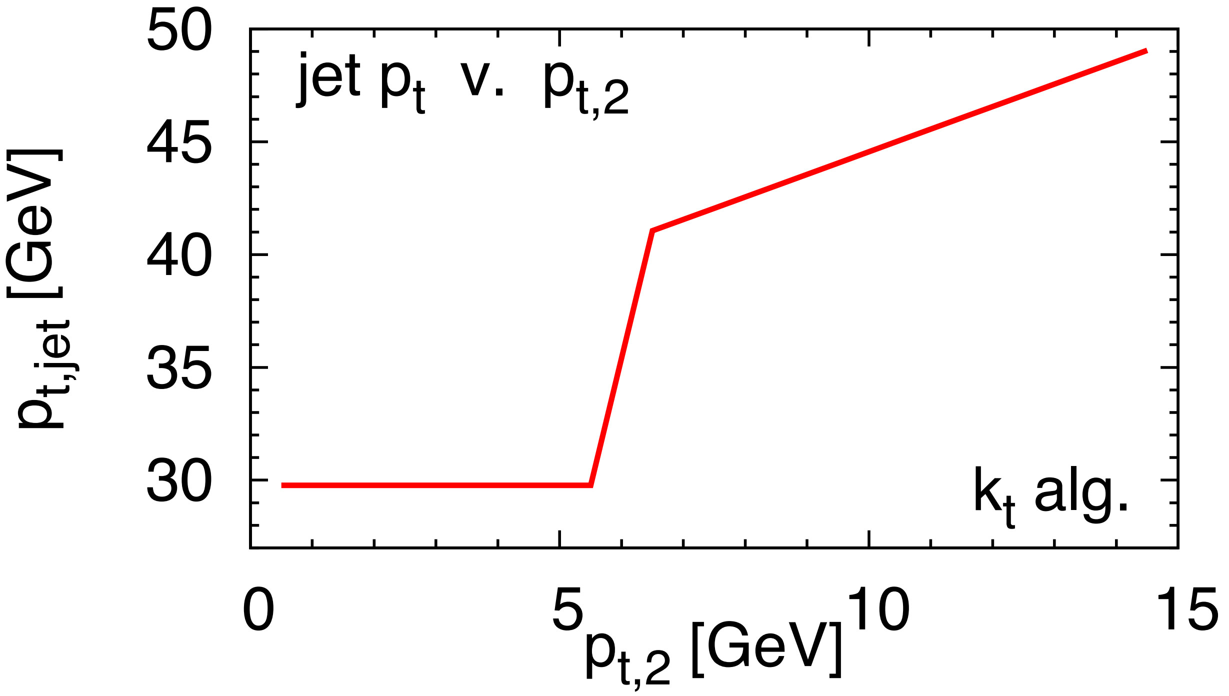

jet p_t v. p_t,2
k_t alg.
p_t,jet [GeV]
p_t,2 [GeV]
50
45
40
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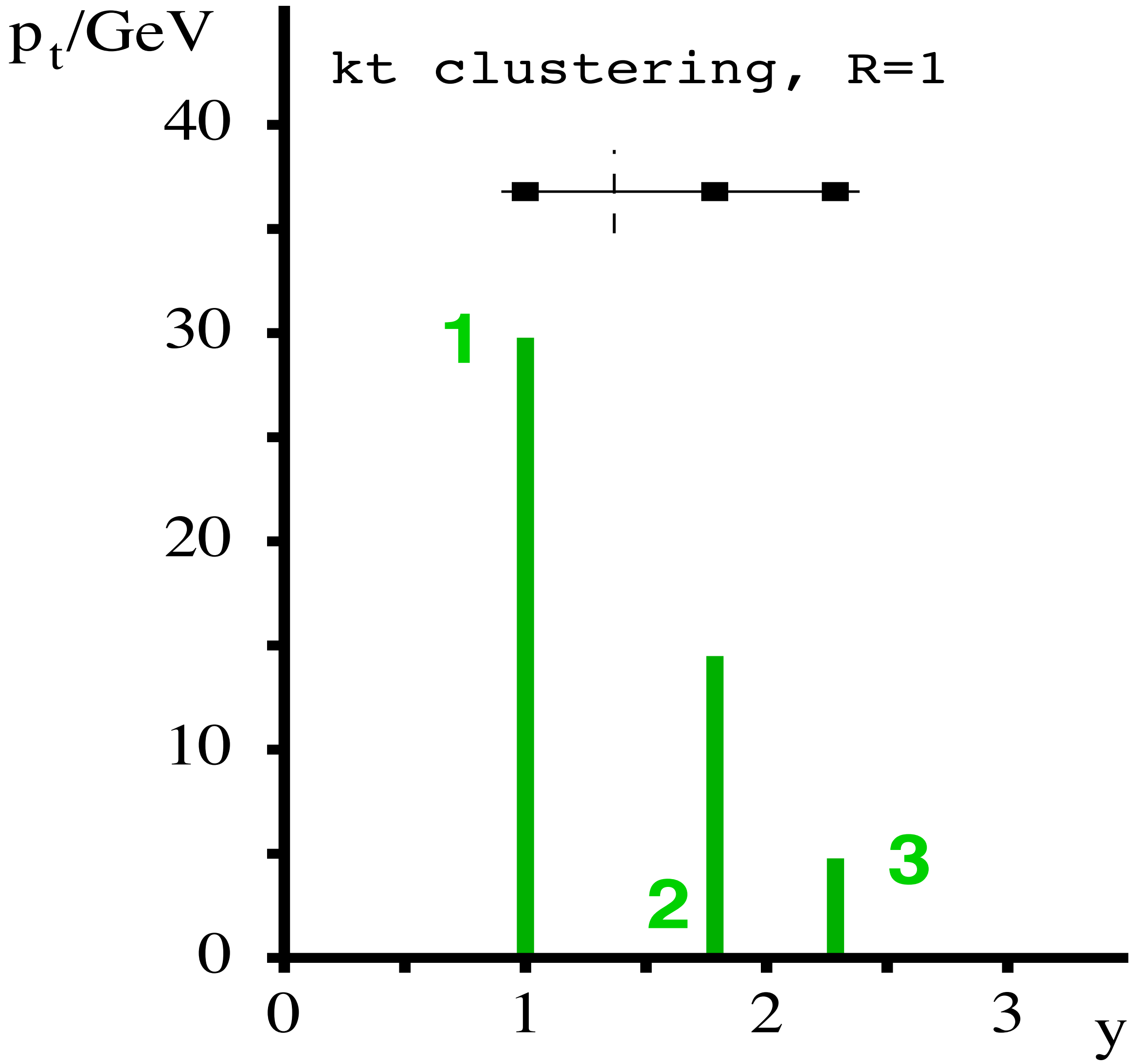

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
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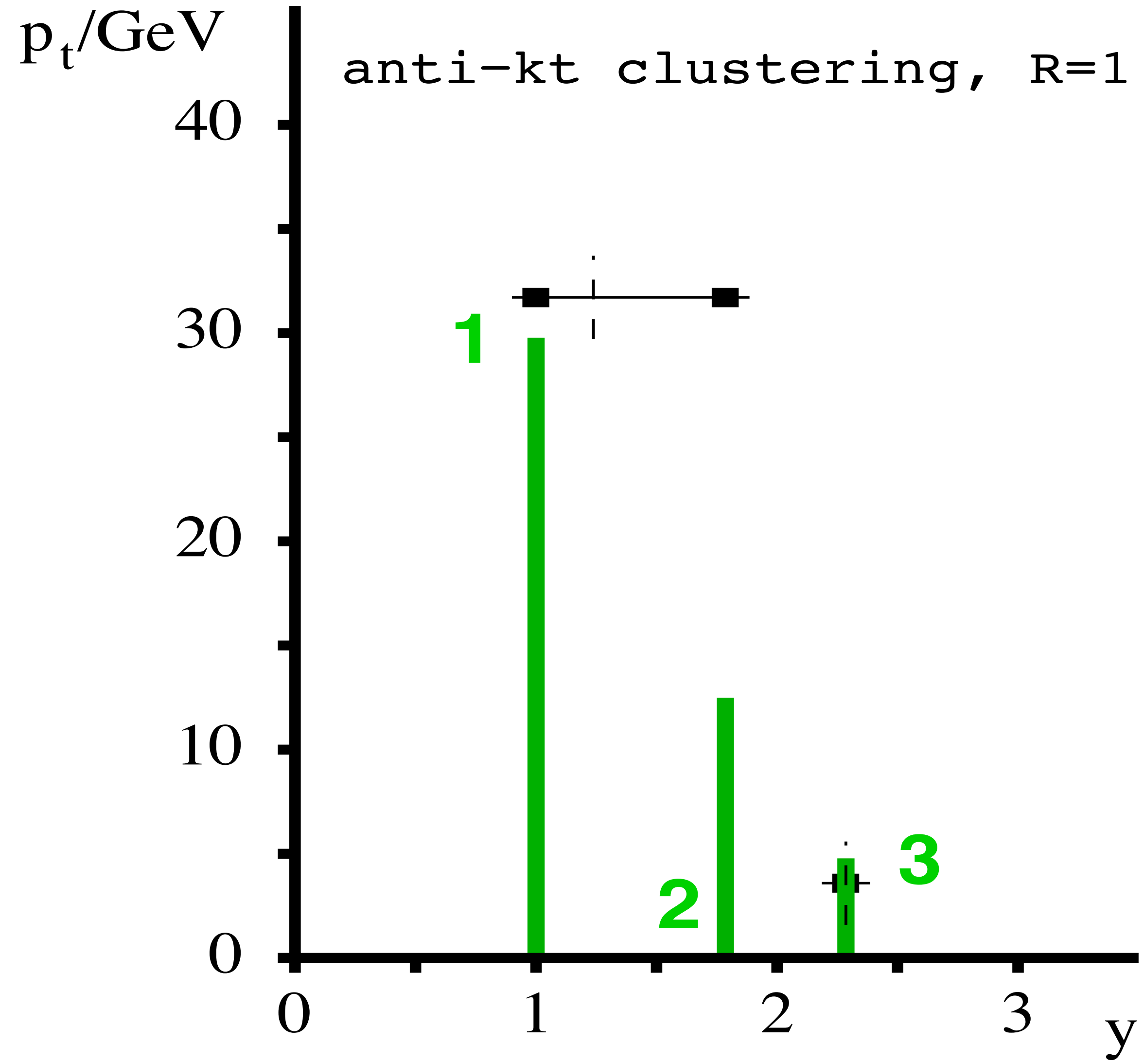
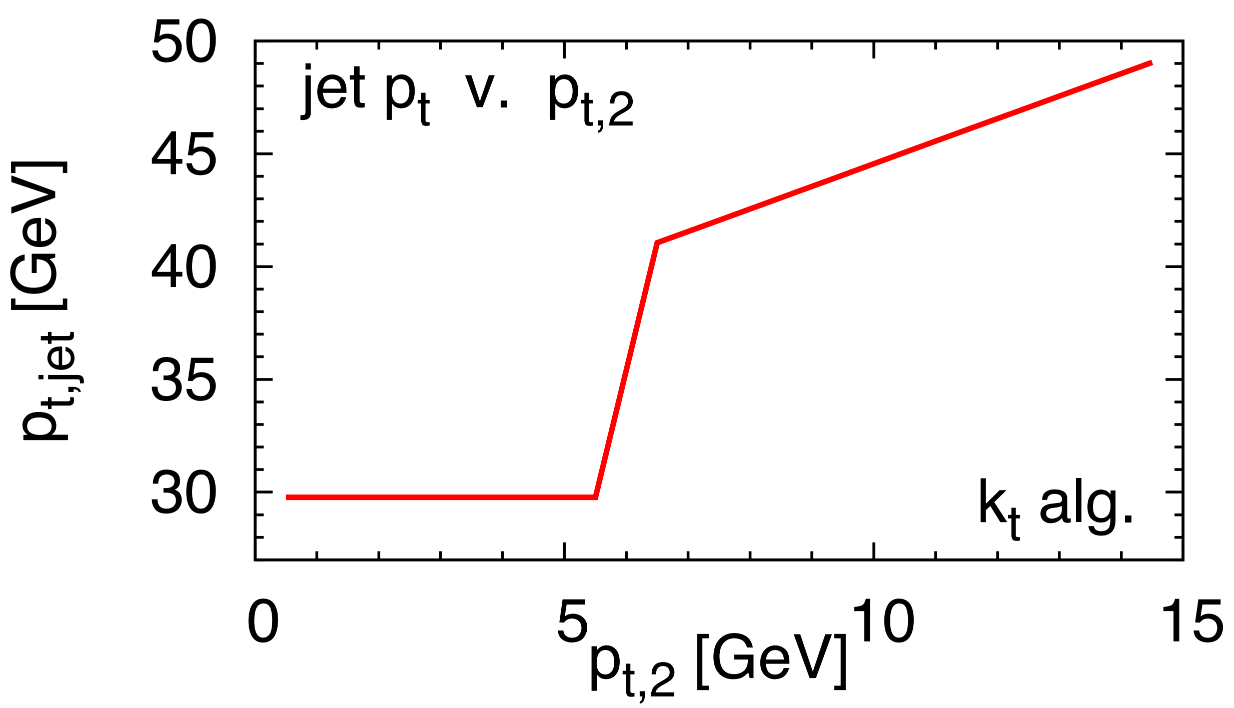
1
2
3
y

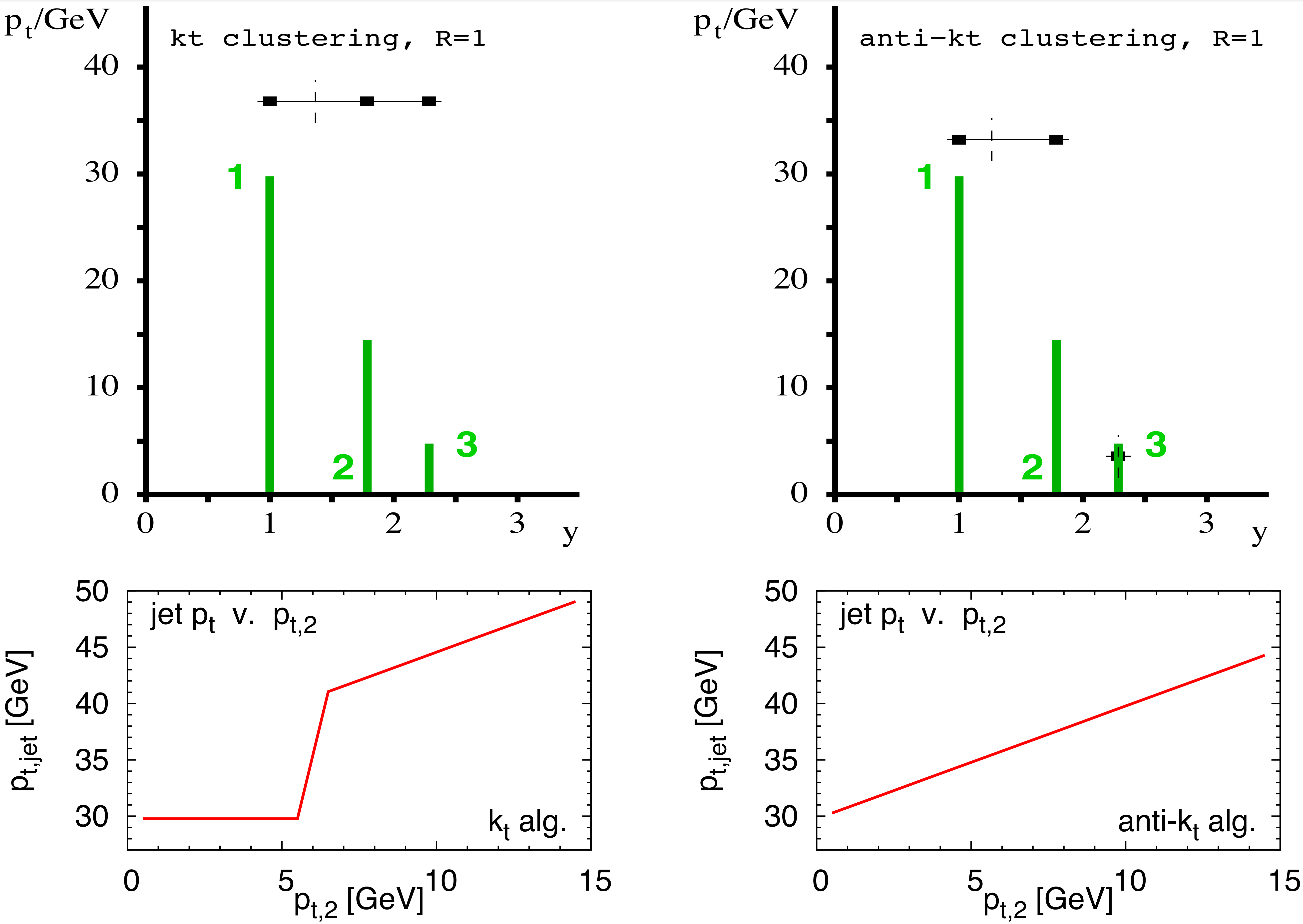


p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



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

Linearity: k_t v. anti-k_t



```
// 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 algorithms, or also most of the old IRC-unsafe ones, for legacy purposes

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

More this afternoon in the tutorial

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

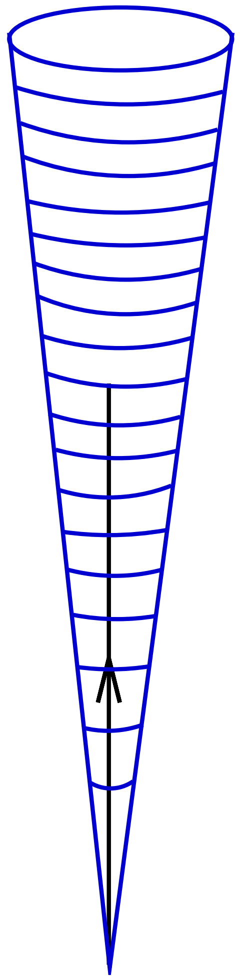
jet_algorithm can be any one of the four IRC safe algorithms, or also most of the old IRC-unsafe ones, for legacy purposes

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

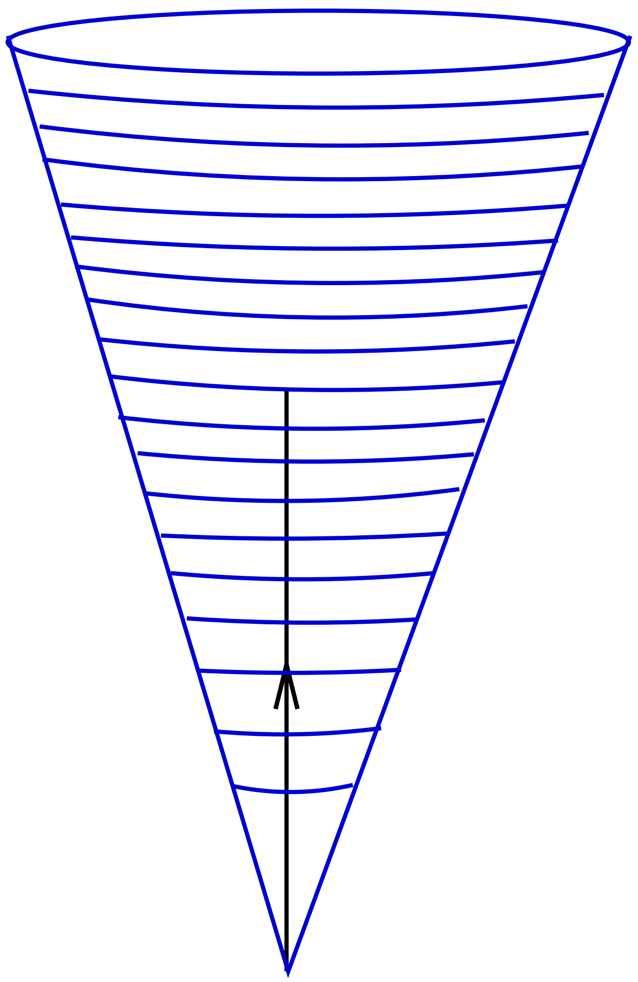
```
// extract the jets
vector<PseudoJet> jets = jet_def(input_particles);

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

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

More this afternoon in the tutorial

Small jet radius

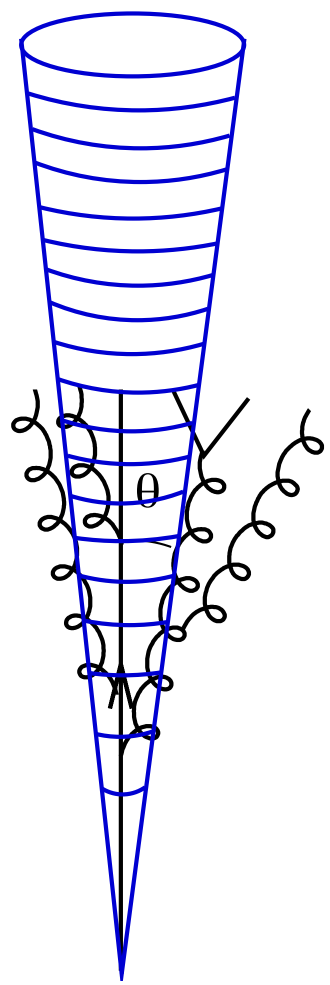


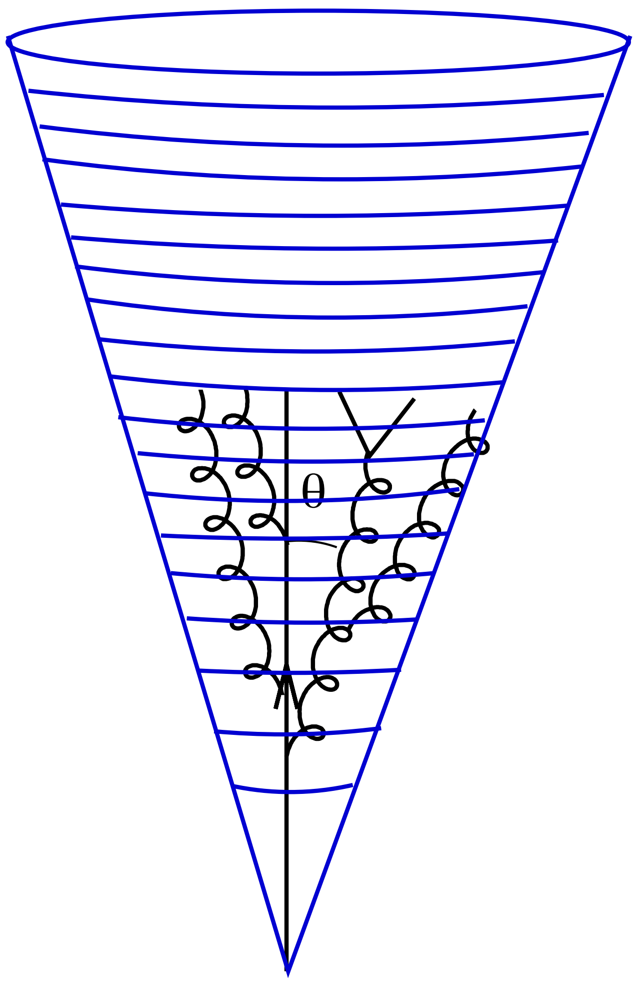
Large jet radius



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

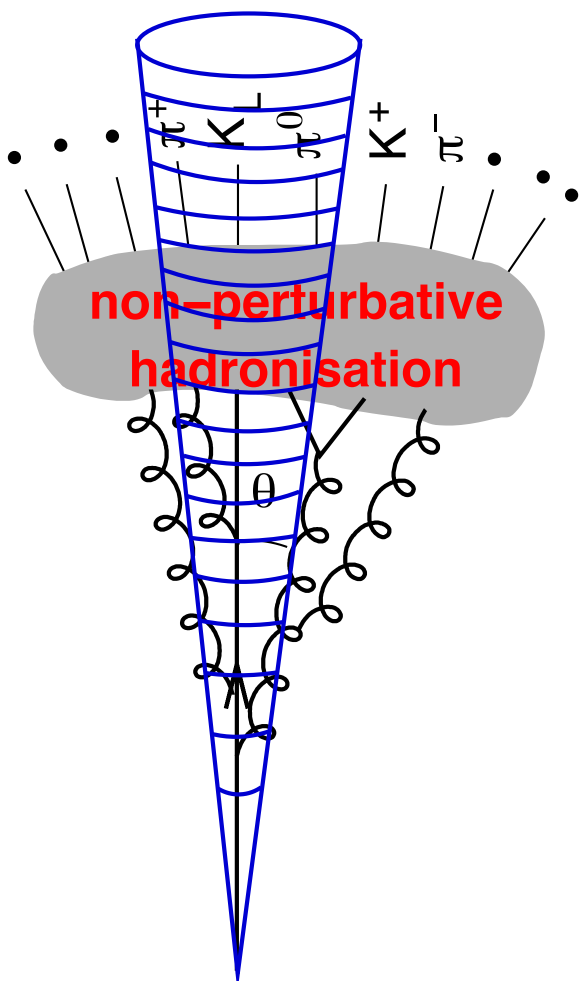
Small jet radius **Large jet radius**

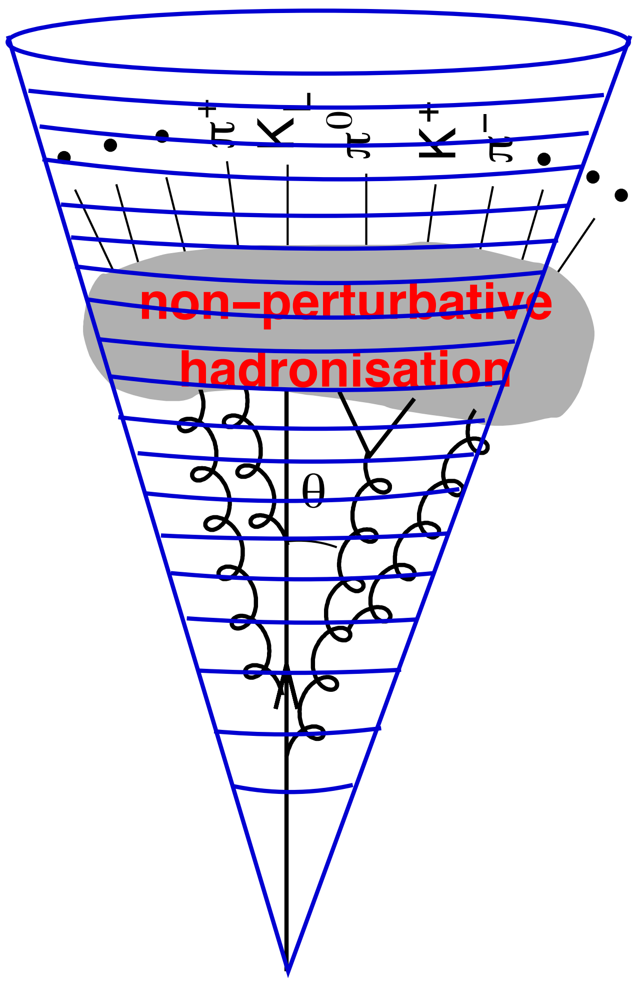




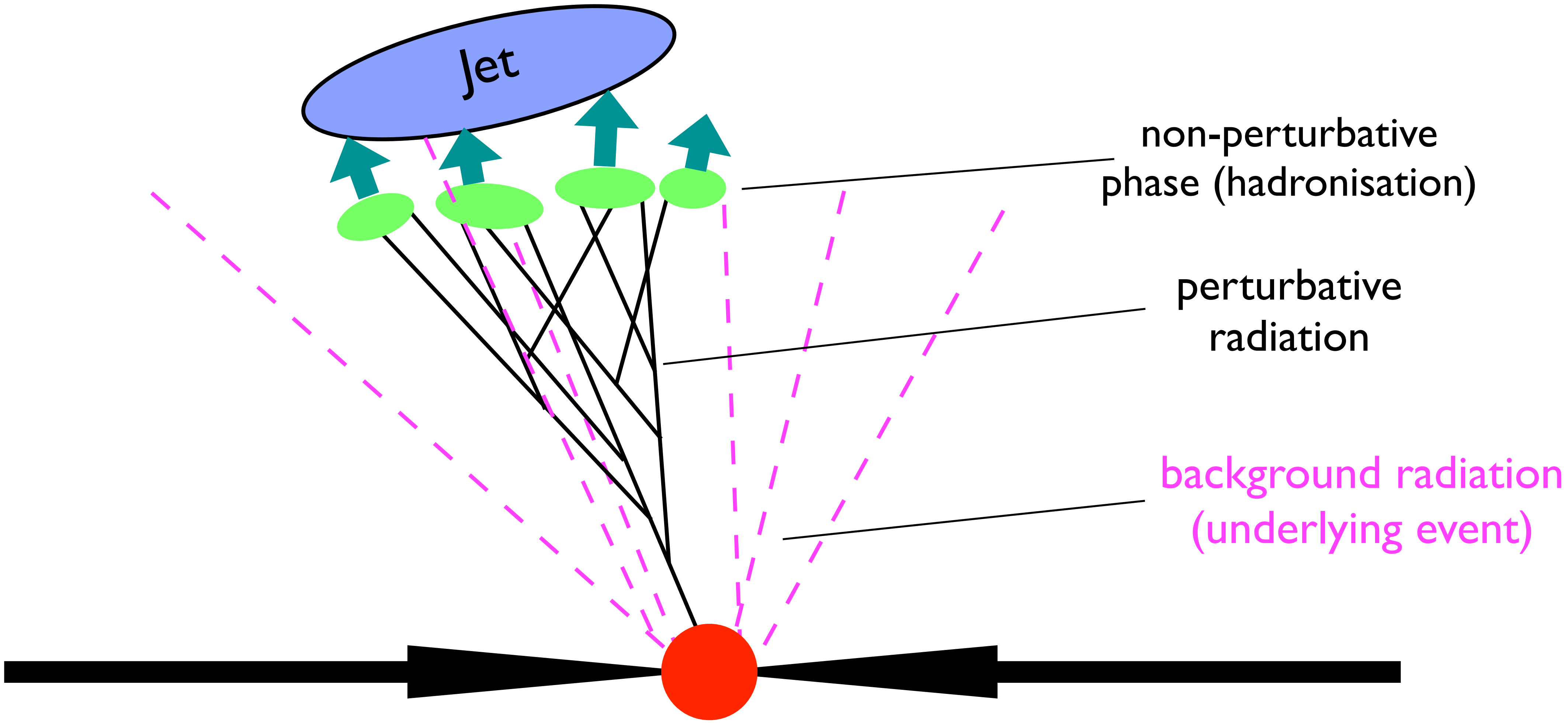
perturbative fragmentation: **large jet radius better**
(it captures more)

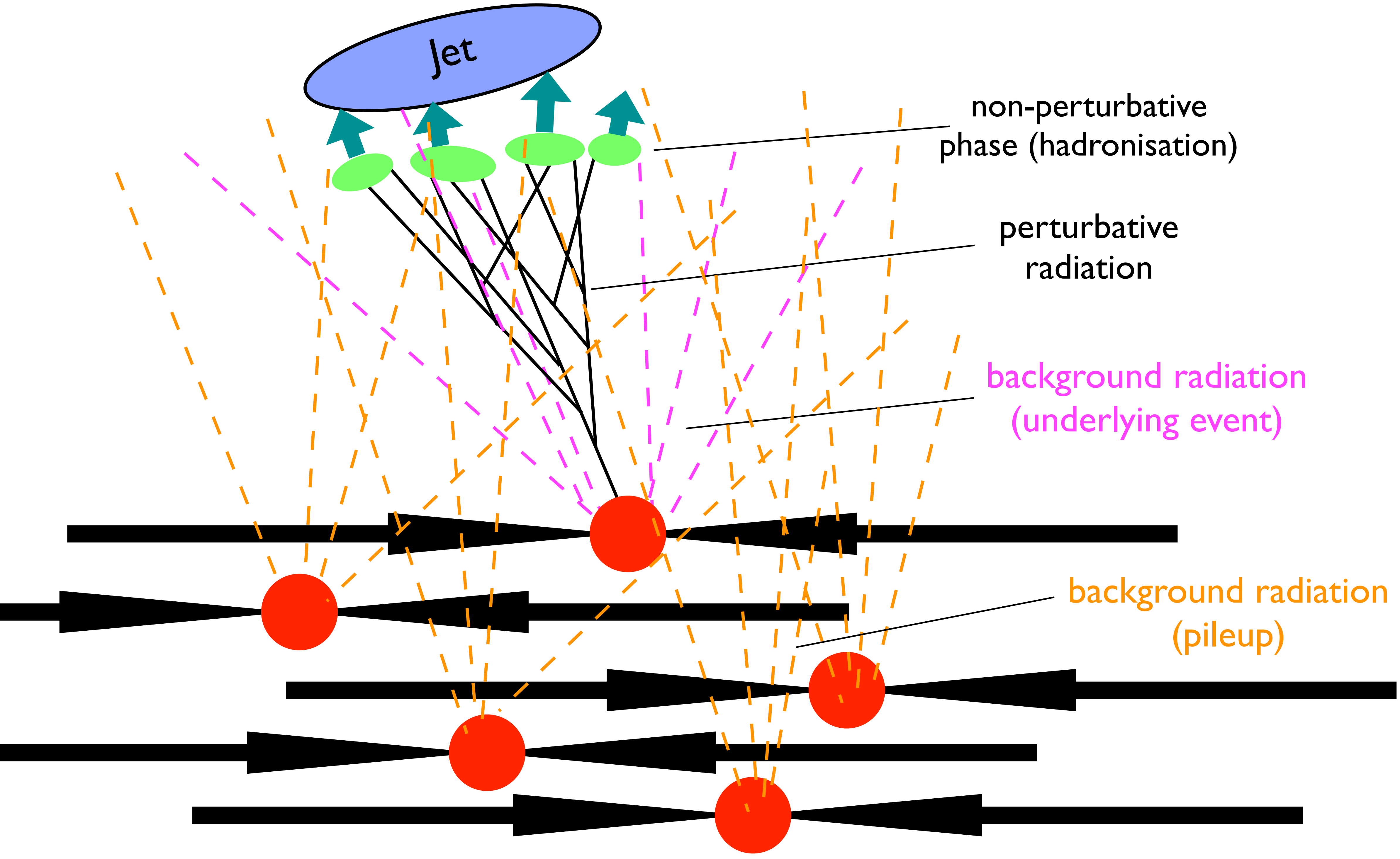
Small jet radius **Large jet radius**

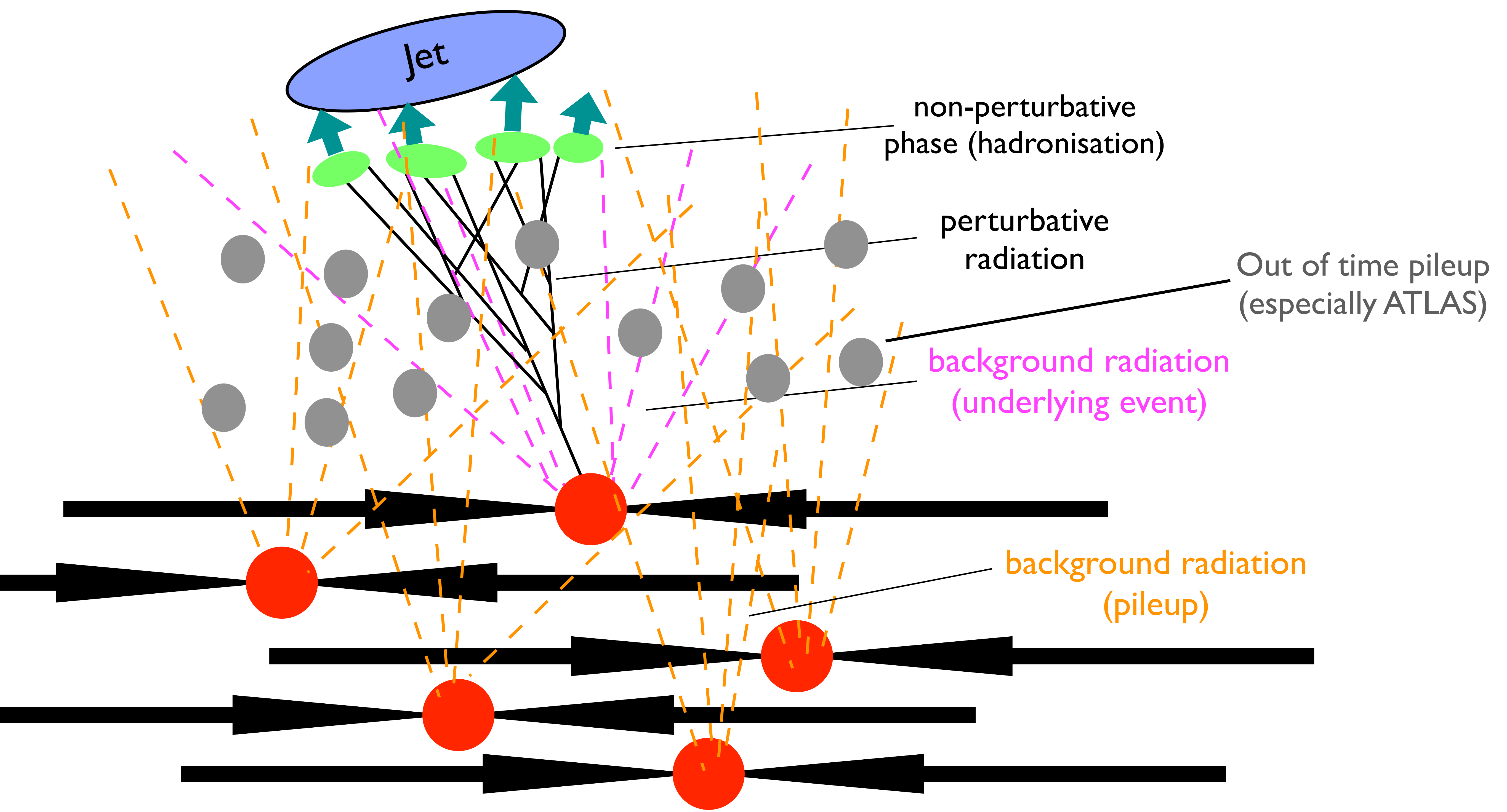




non-perturbative fragmentation: **large jet radius better**
(it captures more)

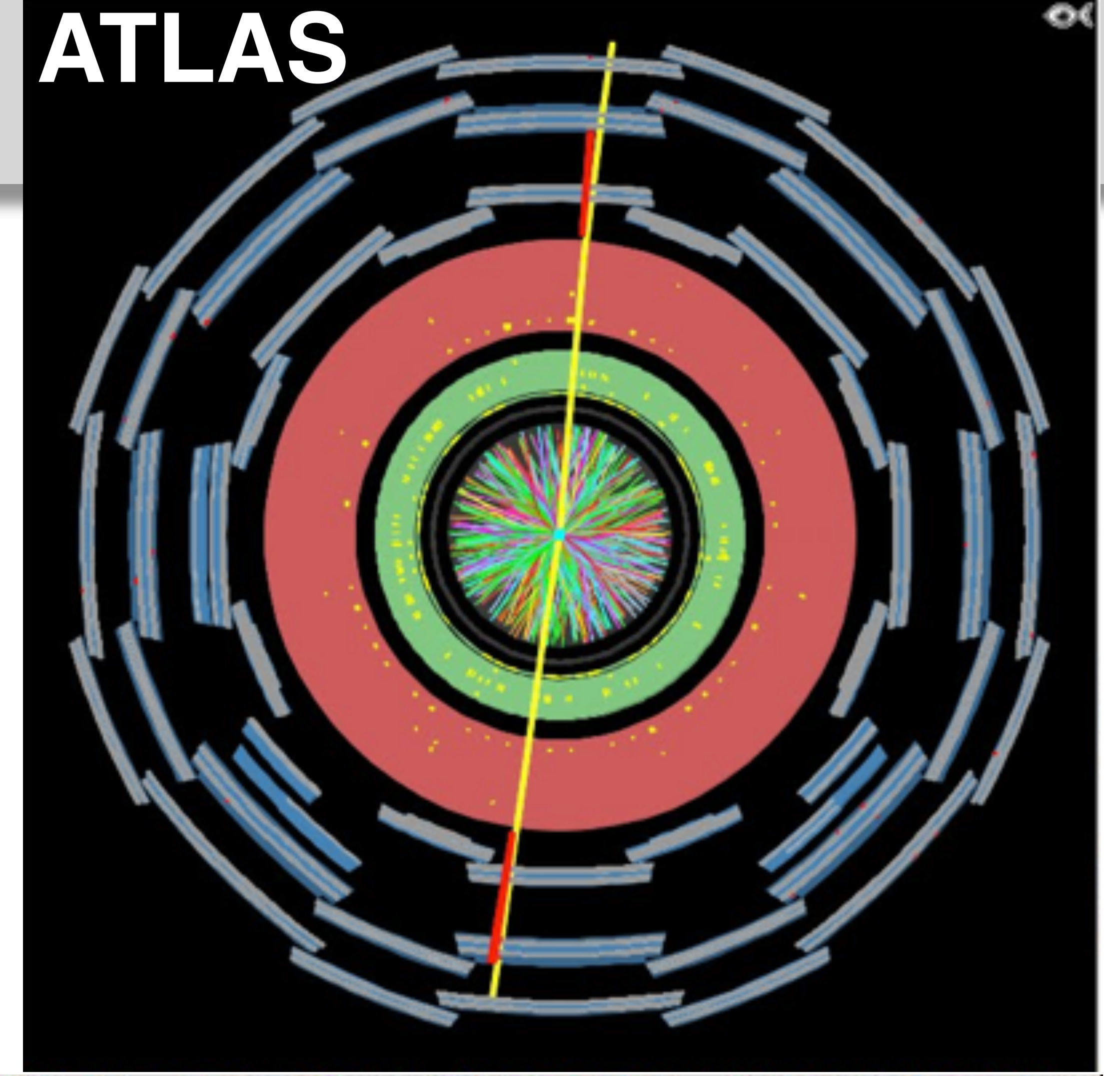

Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
background radiation
(underlying event)


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

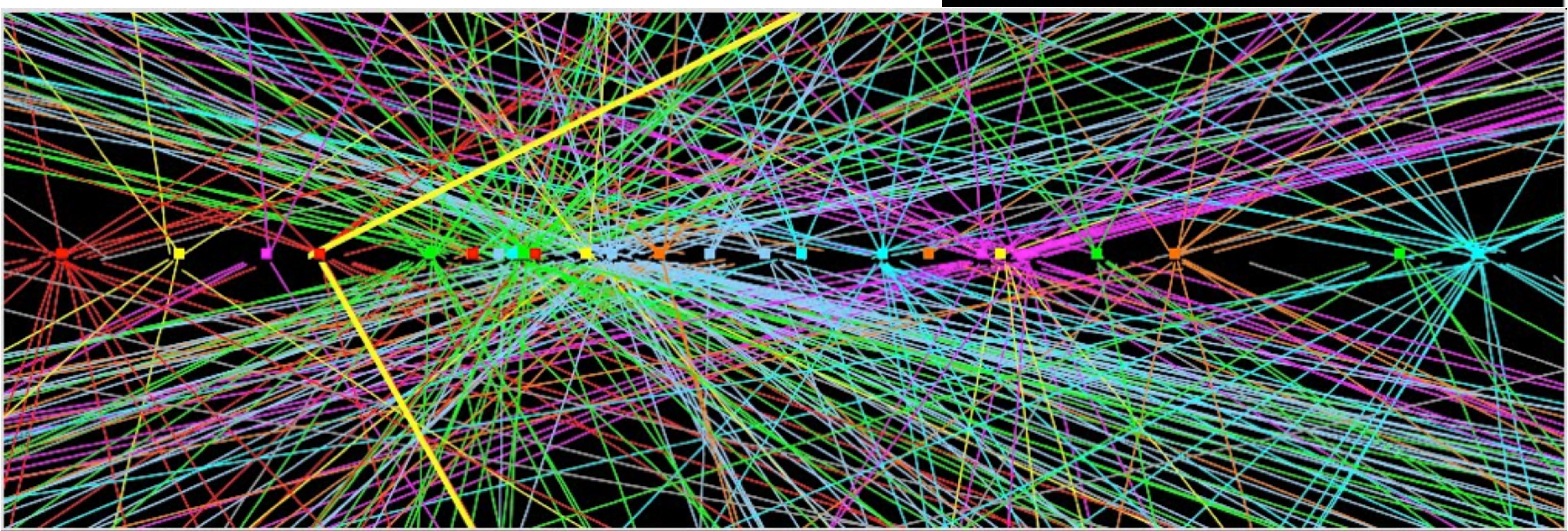

Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
Out of time pileup
(especially ATLAS)
background radiation
(underlying event)
background radiation
(pileup)

Pileup for real

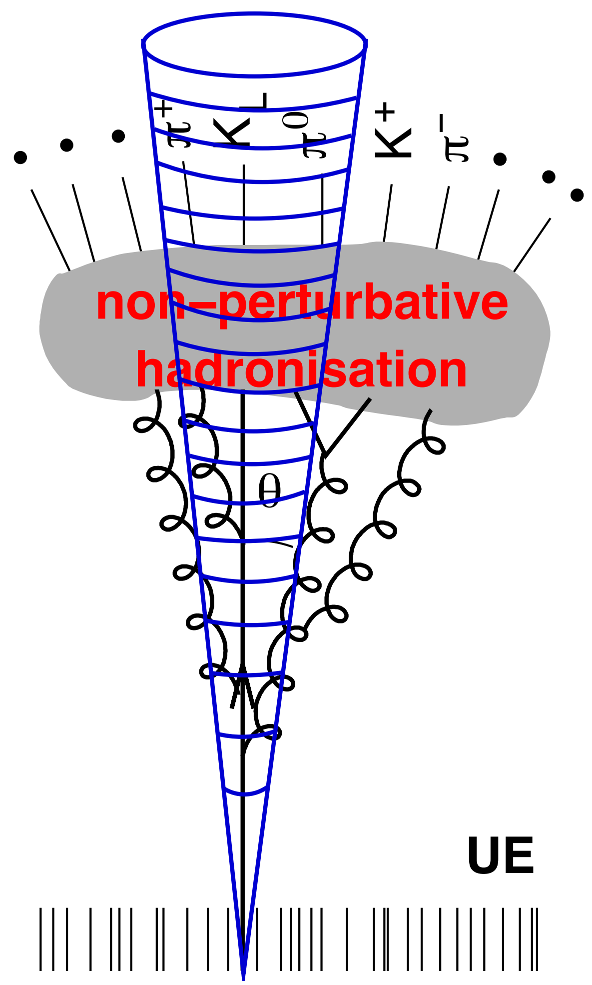
~ 20 m



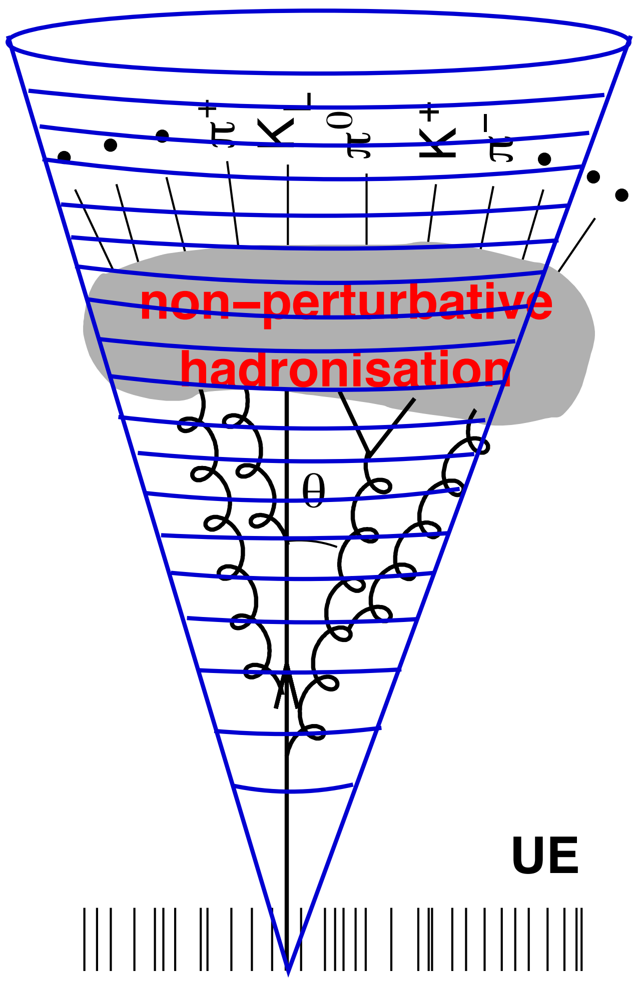
a few cm



Small jet radius

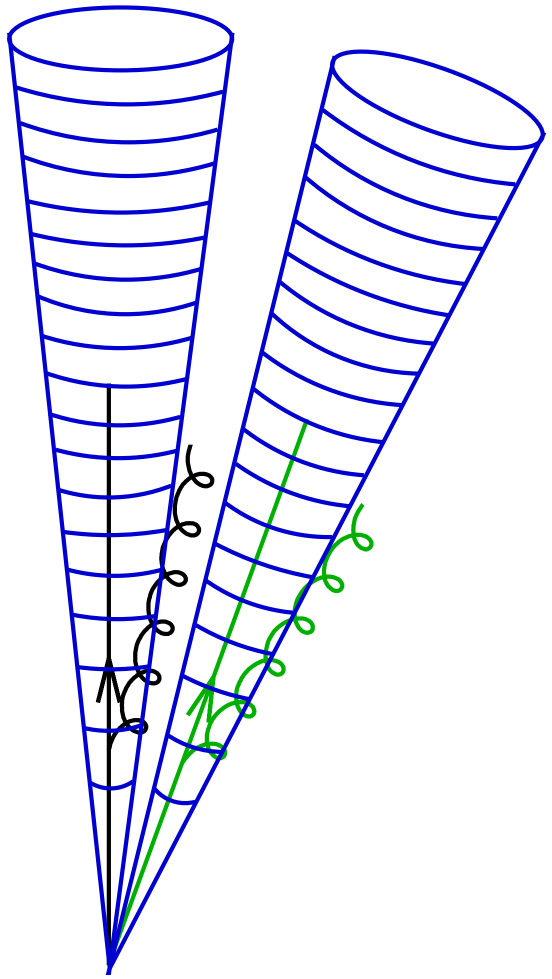


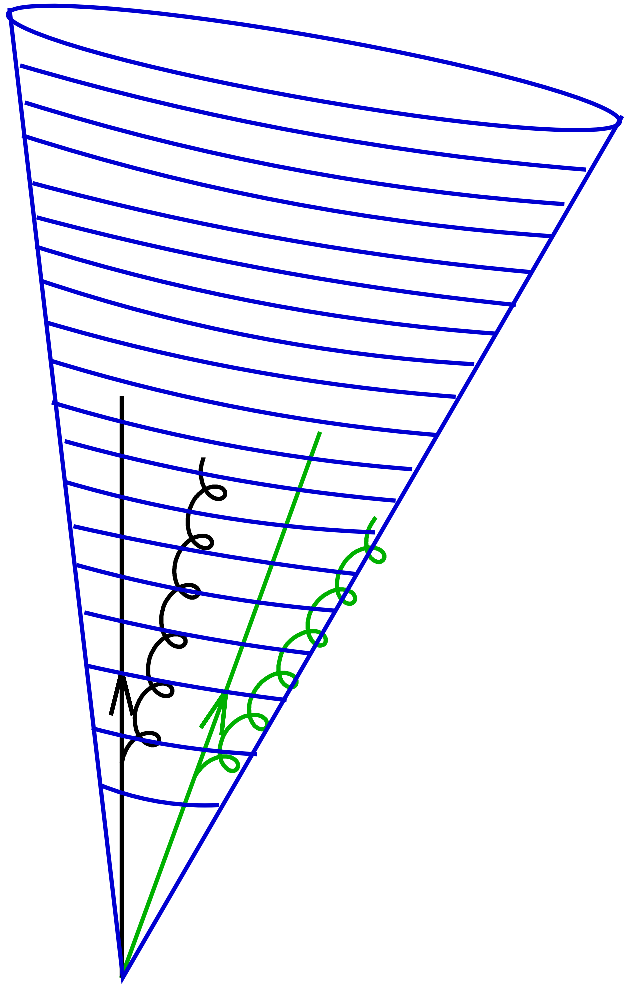
Large jet radius



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

Small jet radius **Large jet radius**





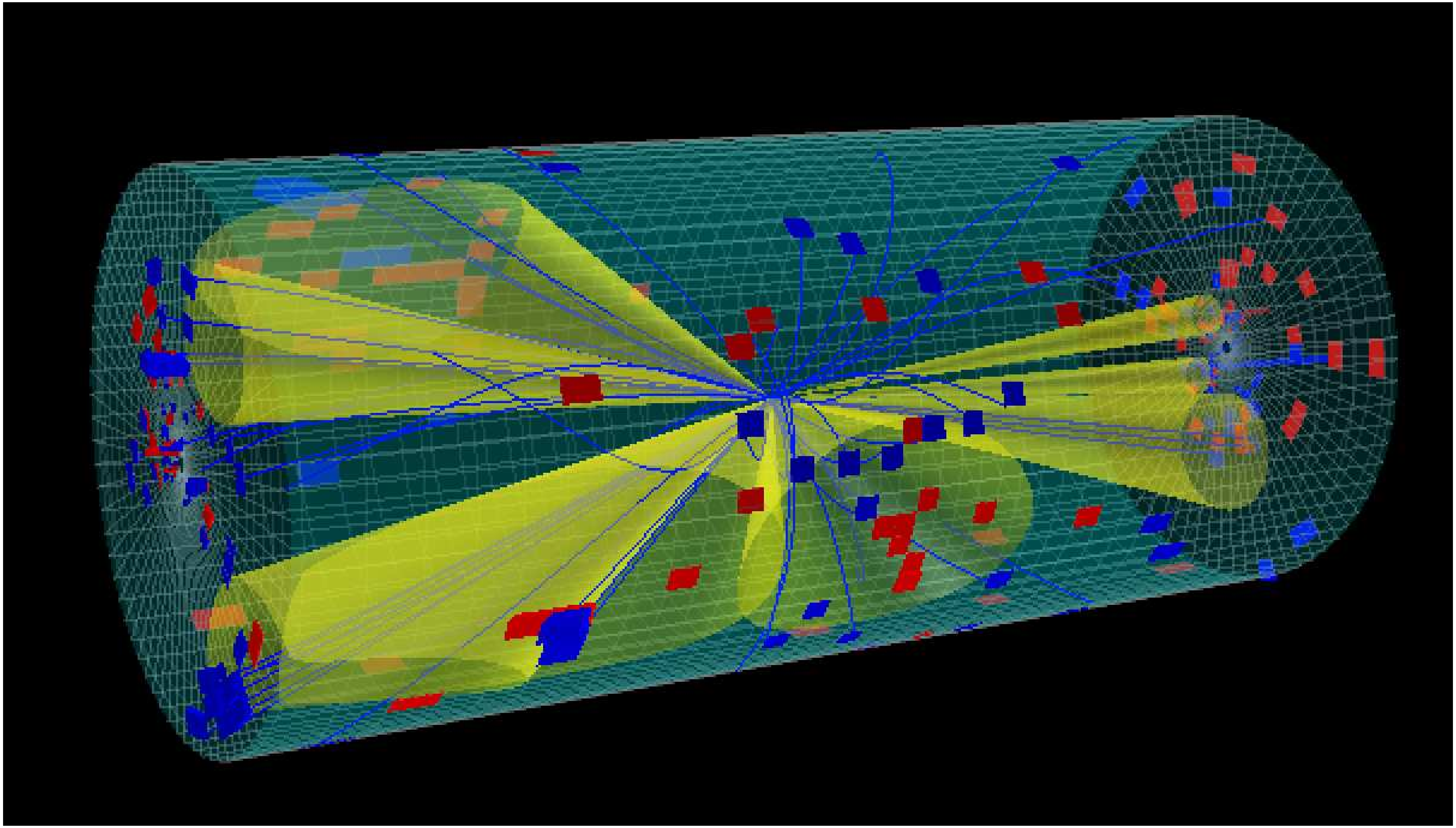
multi-hard-parton events: **small jet radius better**
(it resolves partons more effectively)

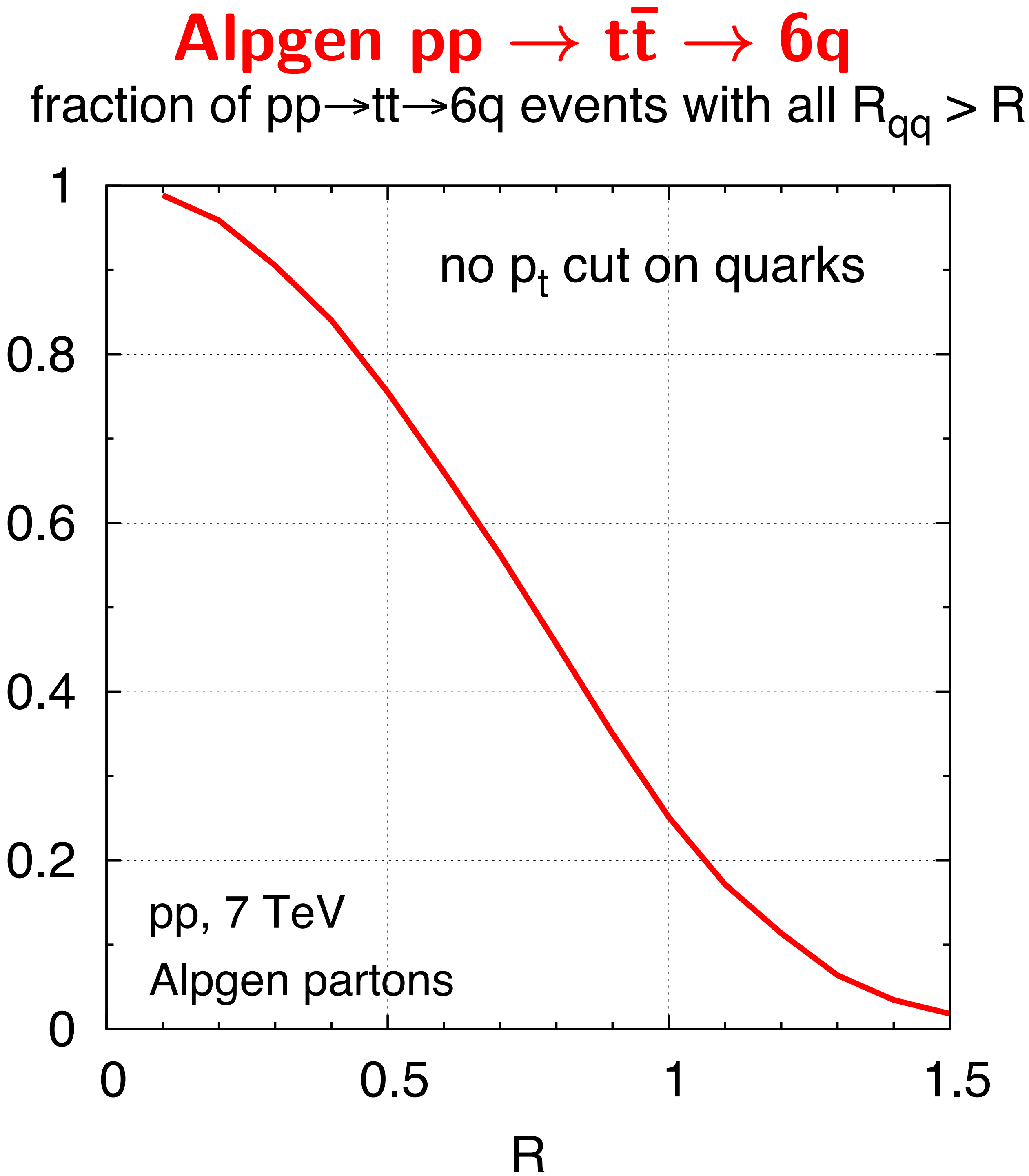
Can we capture all quarks and gluons?

Should we capture all quarks and gluons?

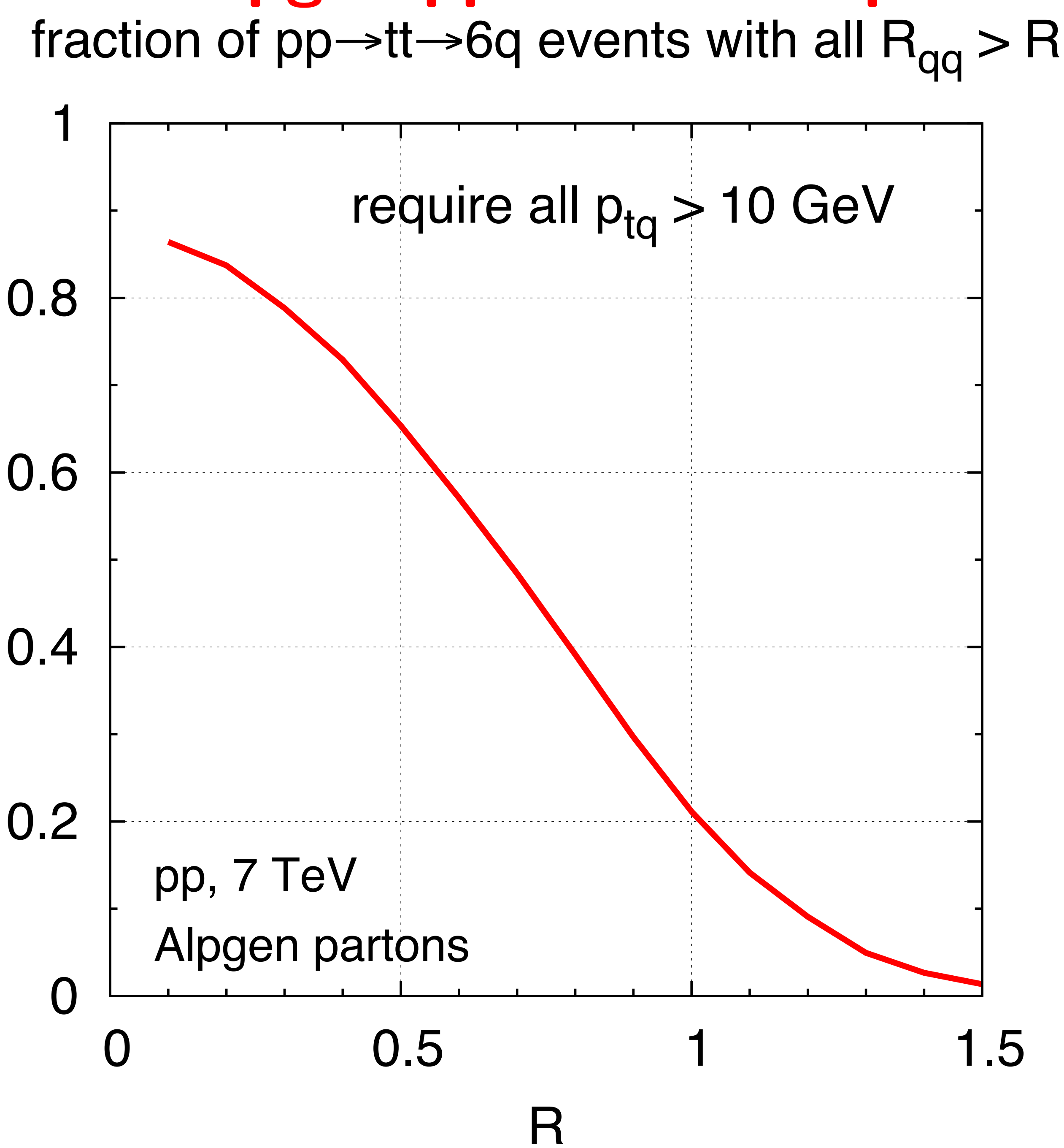
$pp \to t\bar{t}$

simulated with Pythia, displayed with Delphes

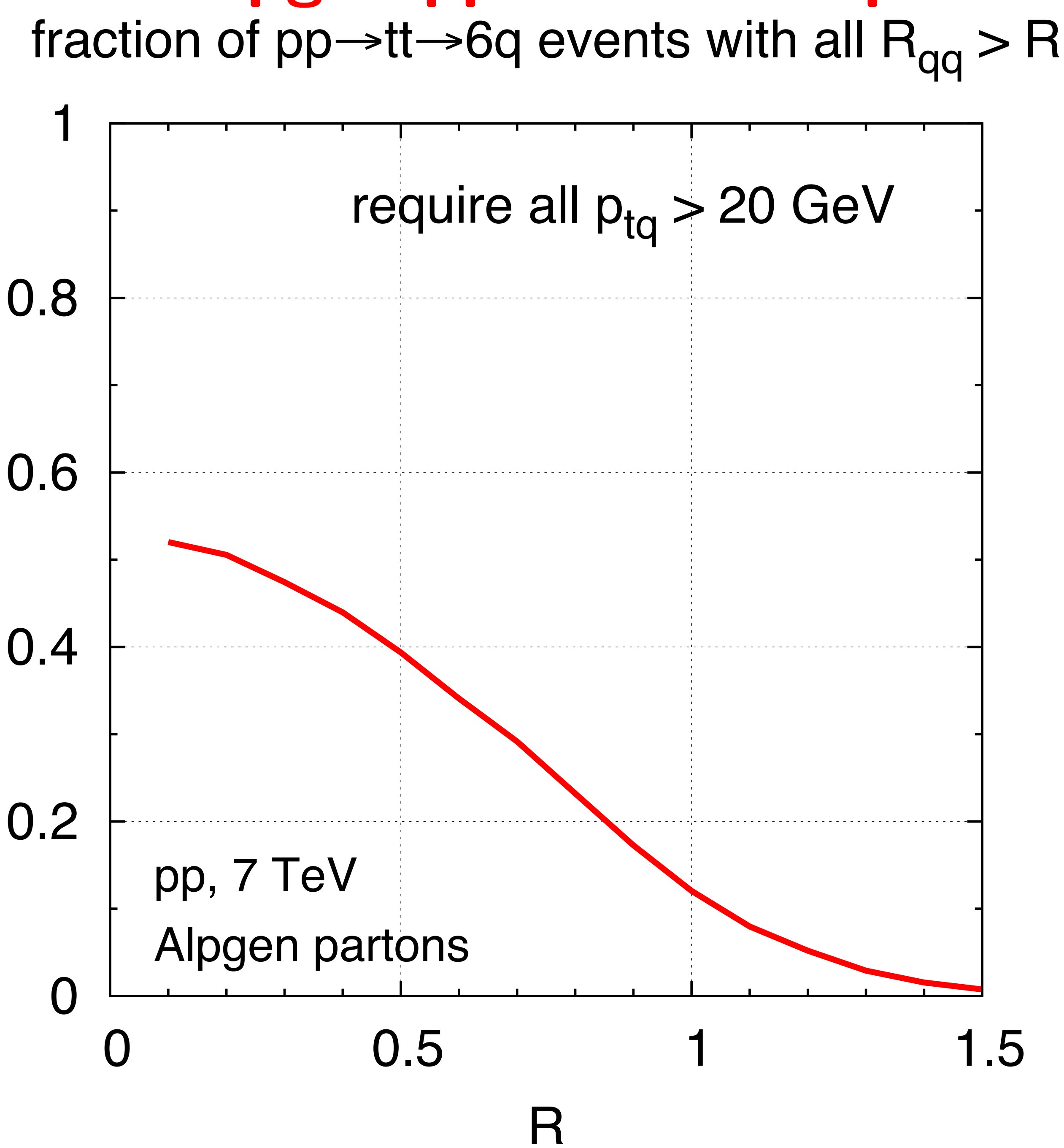



Alpgen pp → $t\bar{t}$ → 6q
fraction of pp→tt→6q events with all R_{qq} > R
no p_t cut on quarks
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

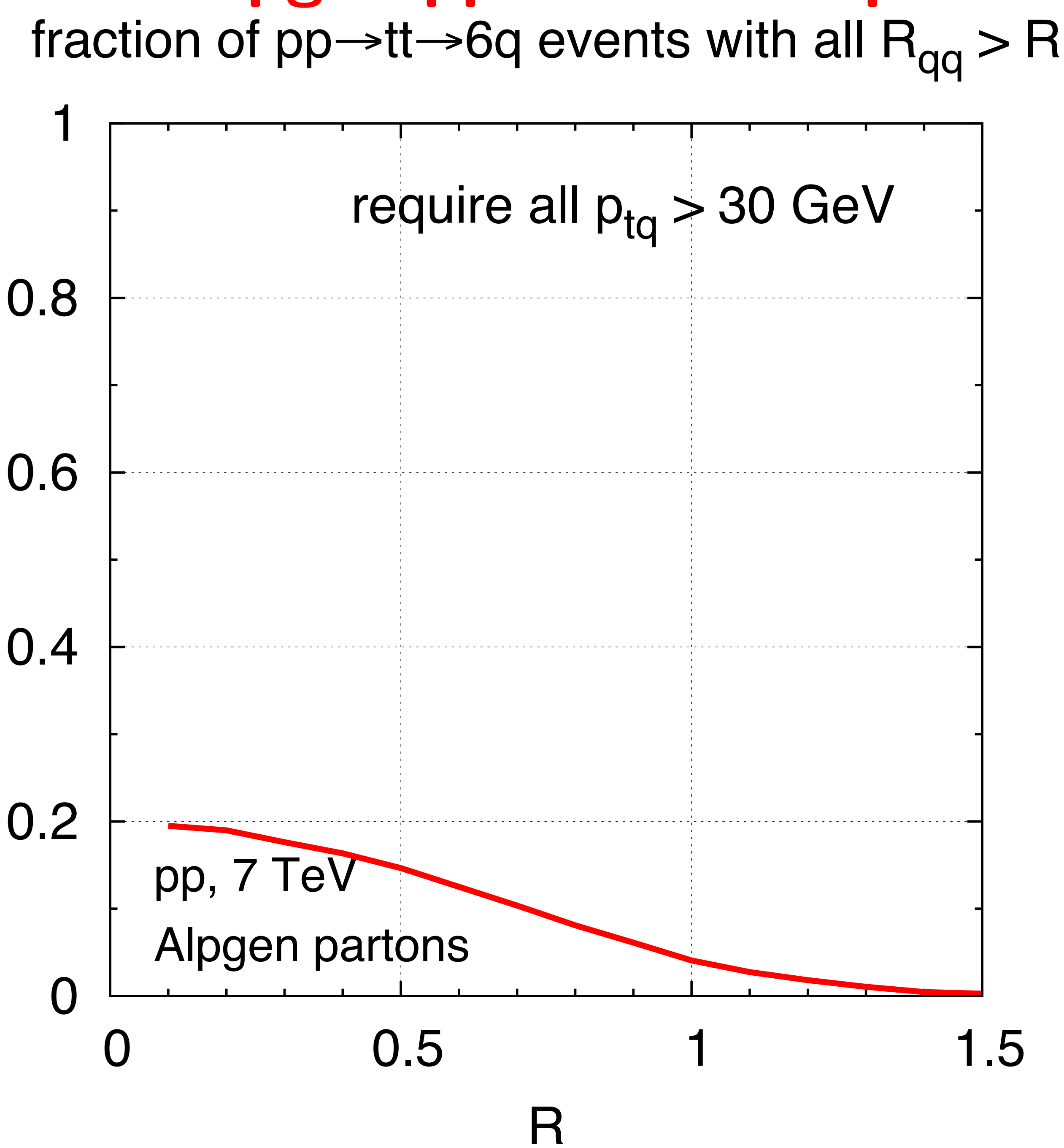
Alpgen $pp \to t\bar{t} \to 6q$



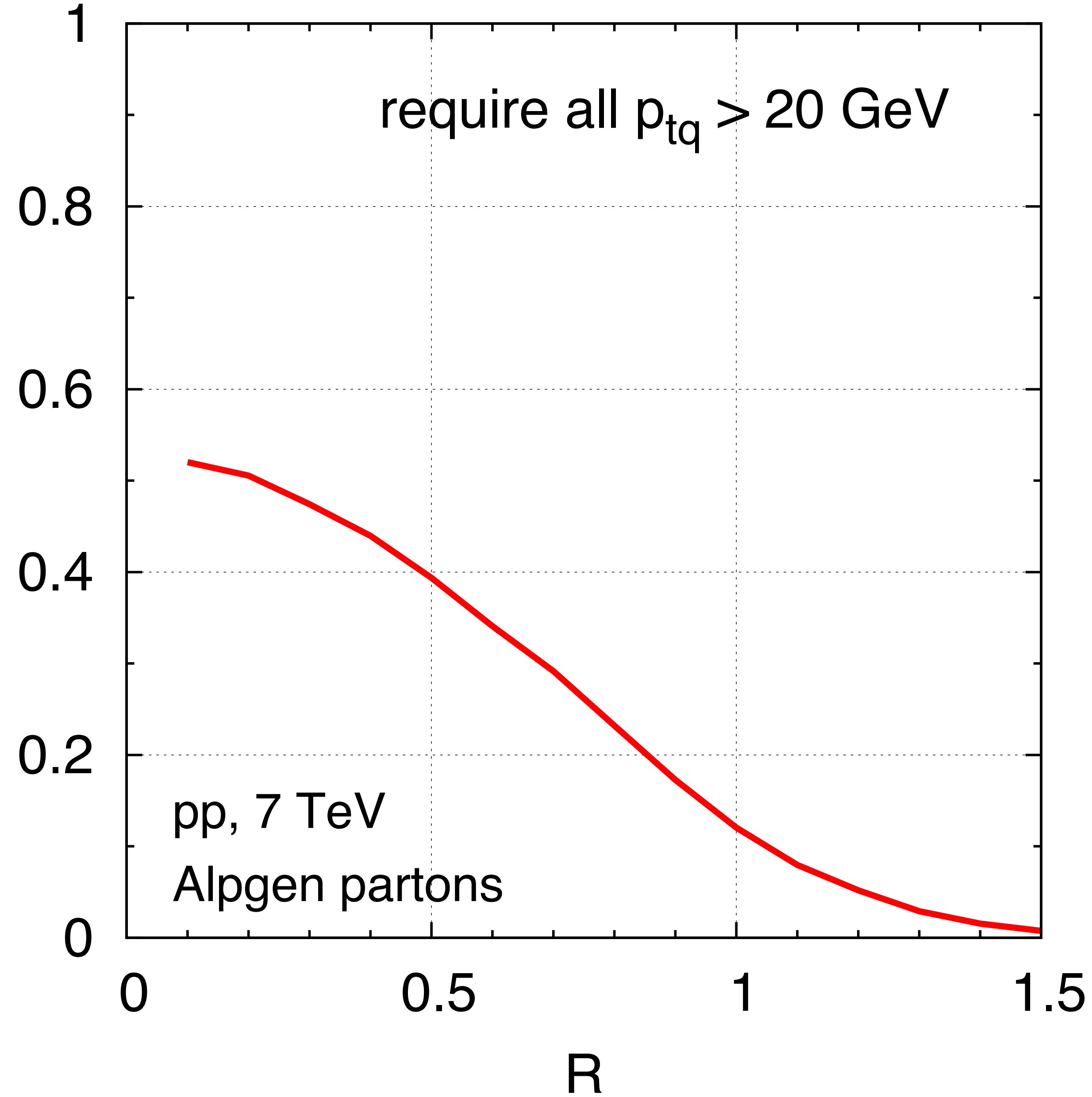
Alpgen $pp \to t\bar{t} \to 6q$



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

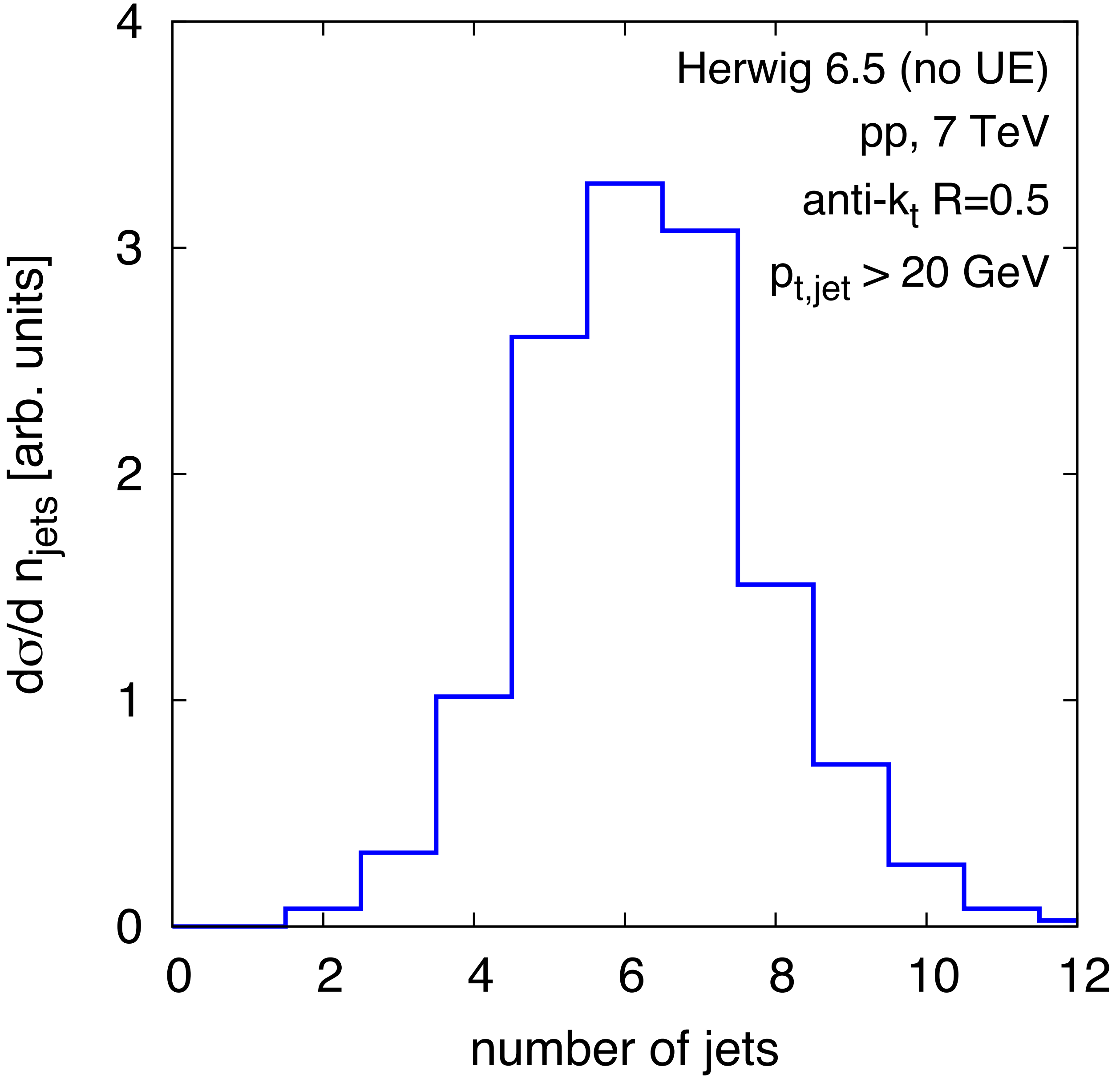


Alpgen $pp \to t\bar{t} \to 6q$



Herwig $pp \to t\bar{t} \to$ hadrons

Distribution of number of jets



Two things that make jets@LHC special

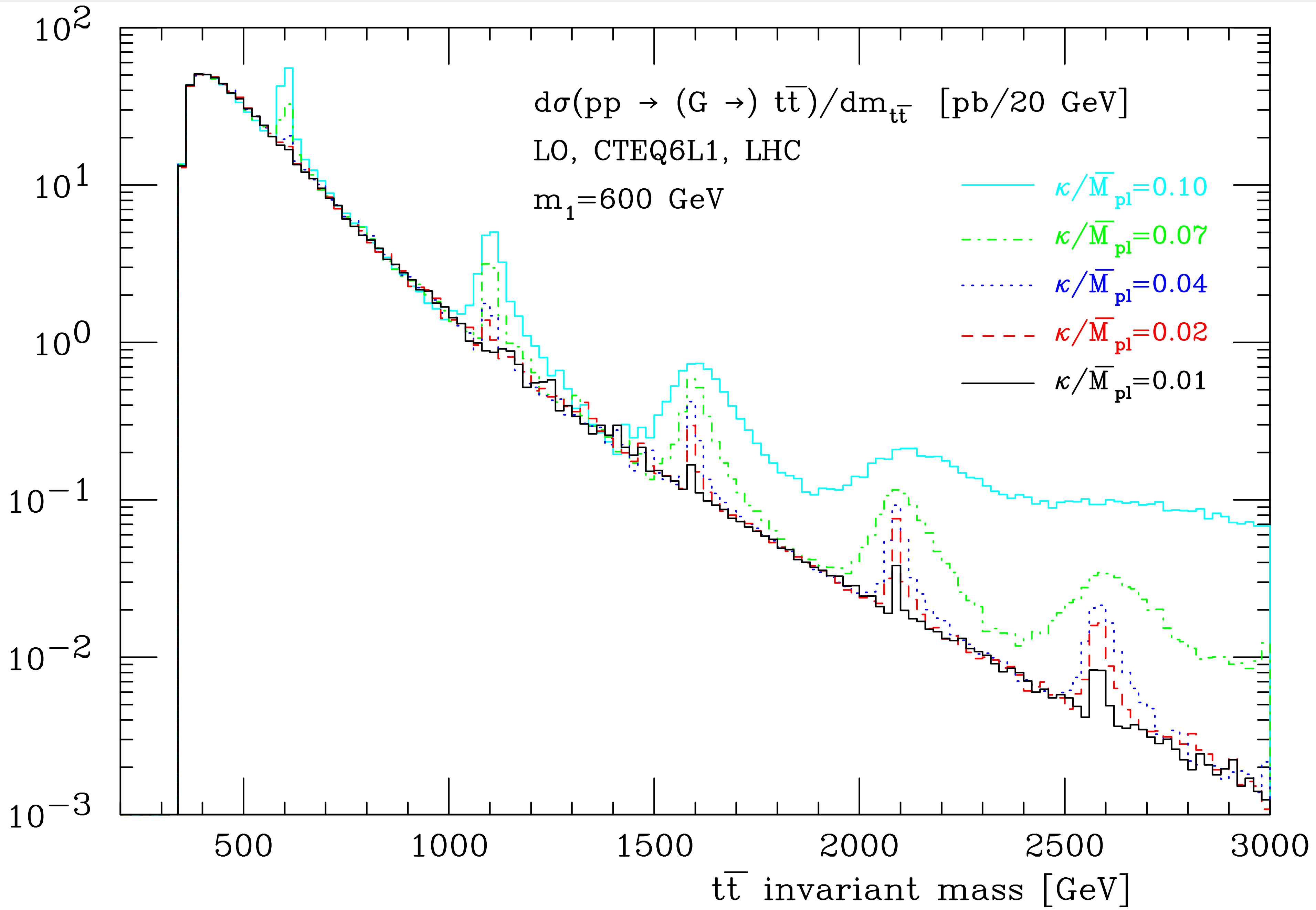
The large hierarchy of scales

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

The huge pileup

$$n_{\text{pileup}} \sim 20 - 40$$

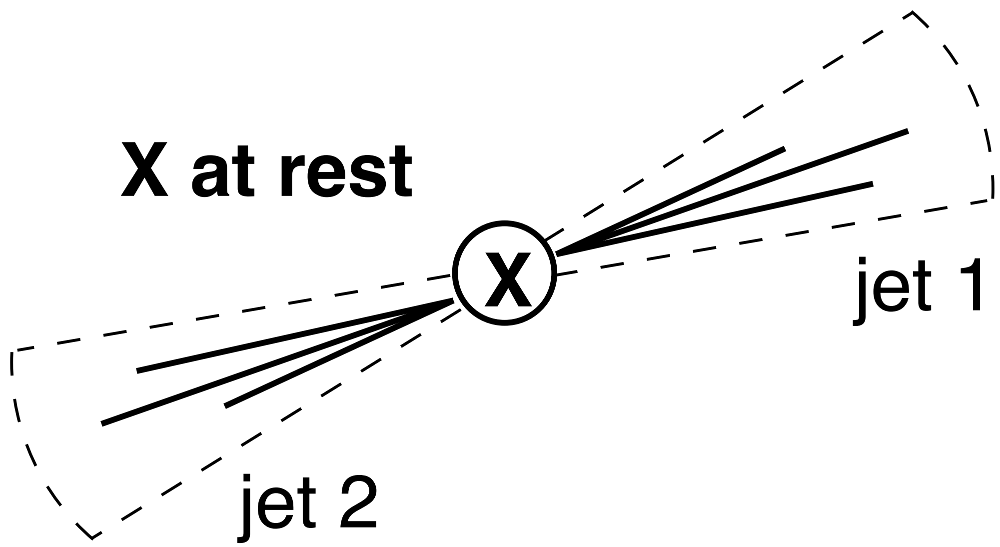
[These involve two opposite extremes: low p_t and high p_t, which nevertheless talk to each other]



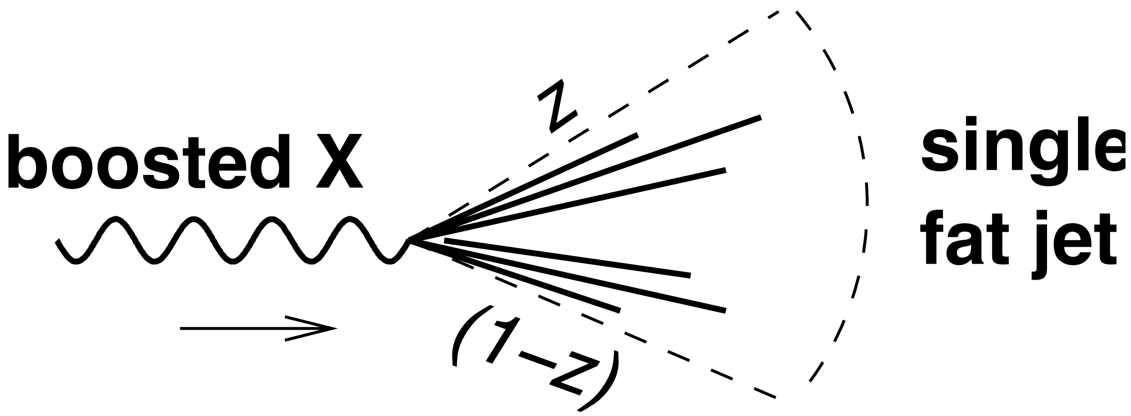
RS KK resonances $\to t\bar{t}$, from Frederix & Maltoni, 0712.2355

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

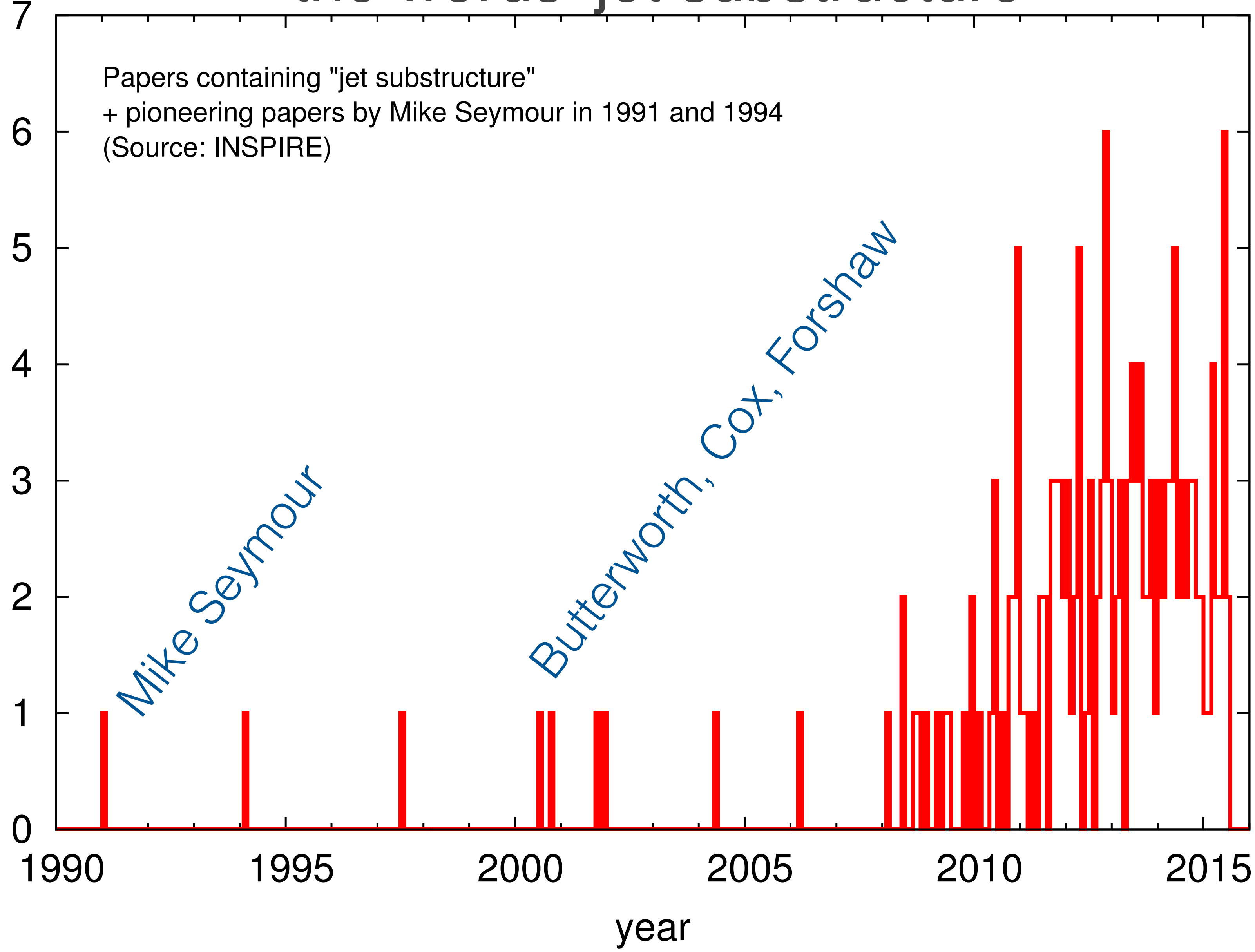


Happens for $p_t \gtrsim 2m/R$

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

Papers on jet substructure

Number of papers containing the words ‘jet substructure’



More than 150 papers since 2008
(+ some background noise)

Pioneered by M. Seymour in the early ‘90s

Exploded around 2008

Tagging & Grooming

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

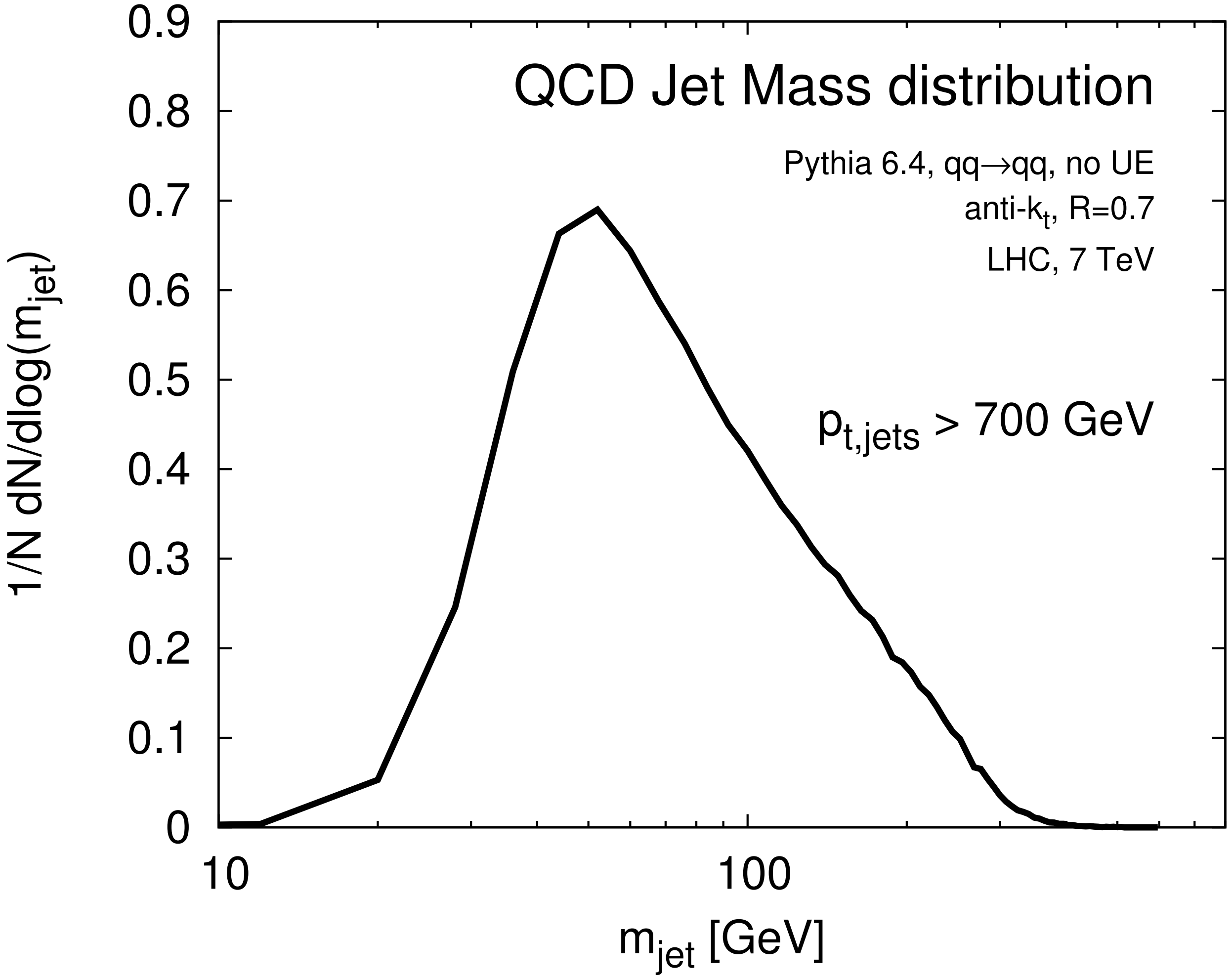
Tagging

- reduces the background, leaves much of signal

Grooming

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

One core idea for tagging

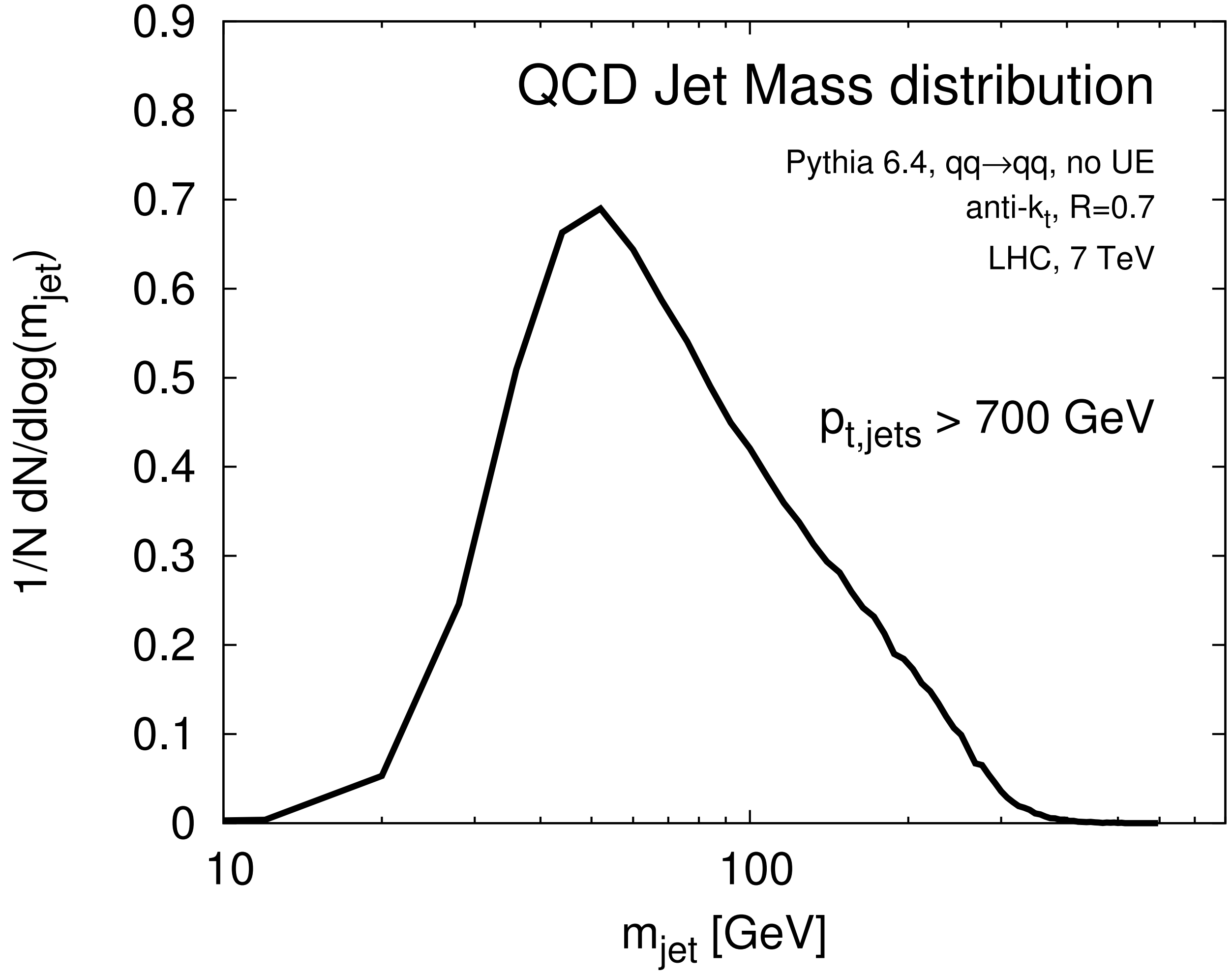


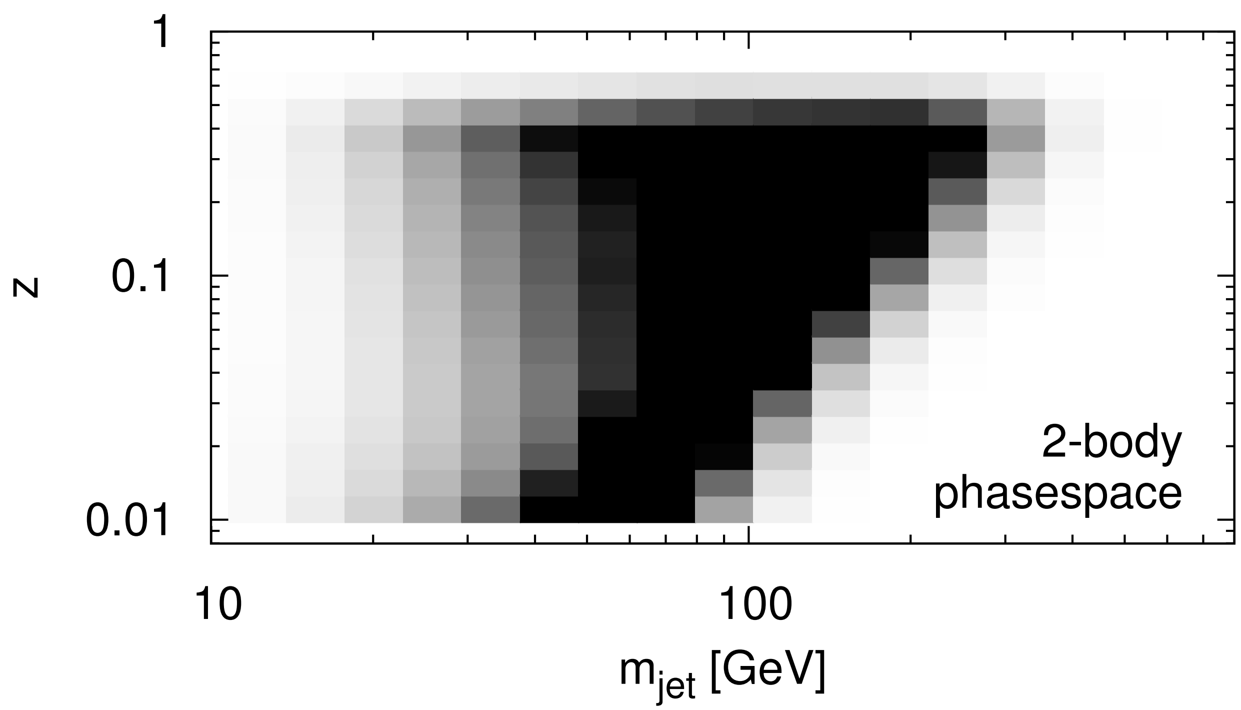
QCD jet mass distribution has the approximate

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

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

Inside the jet mass





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Work from '80s and '90s
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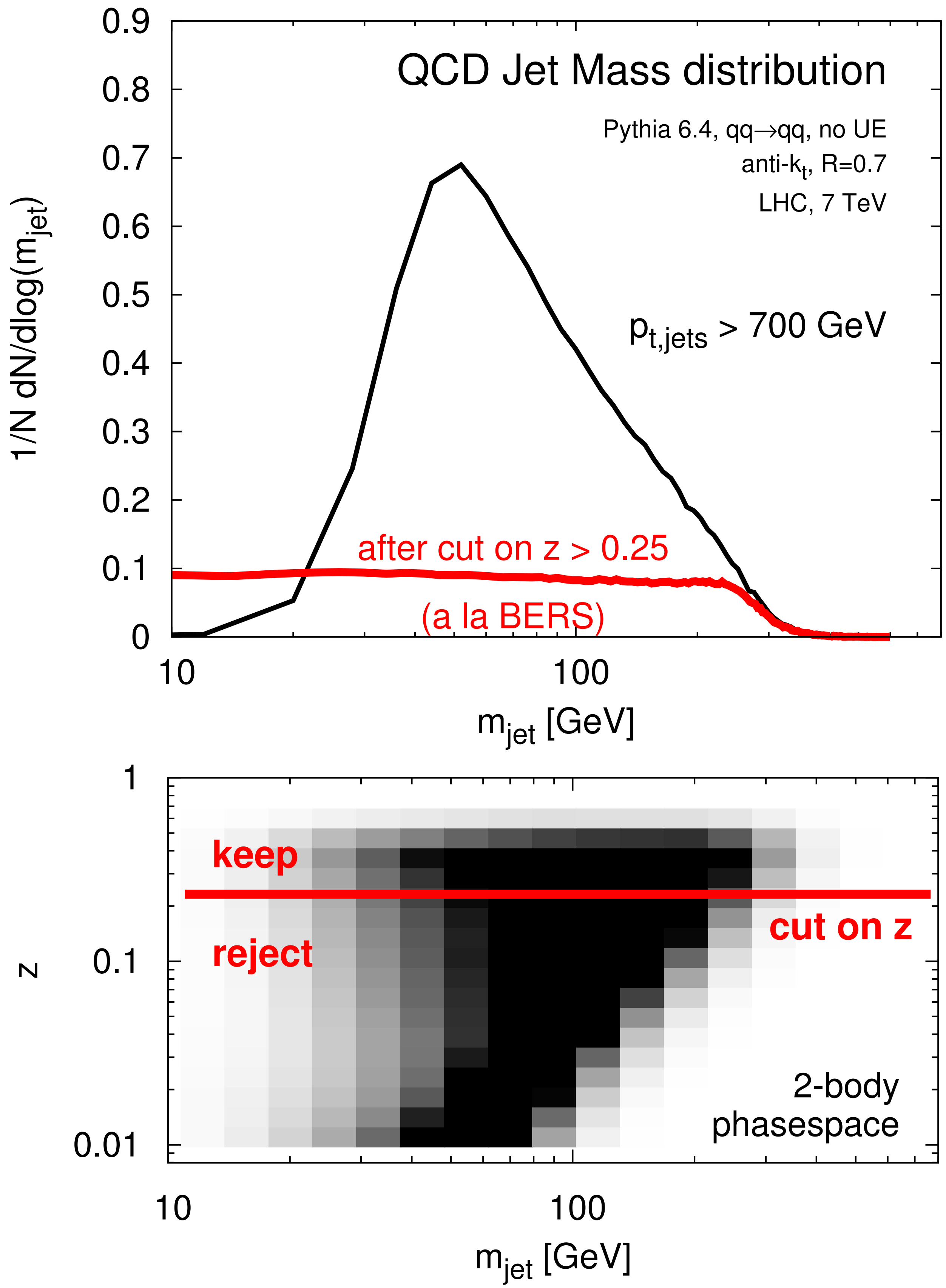
The logarithm comes from integral over soft divergence of QCD:

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



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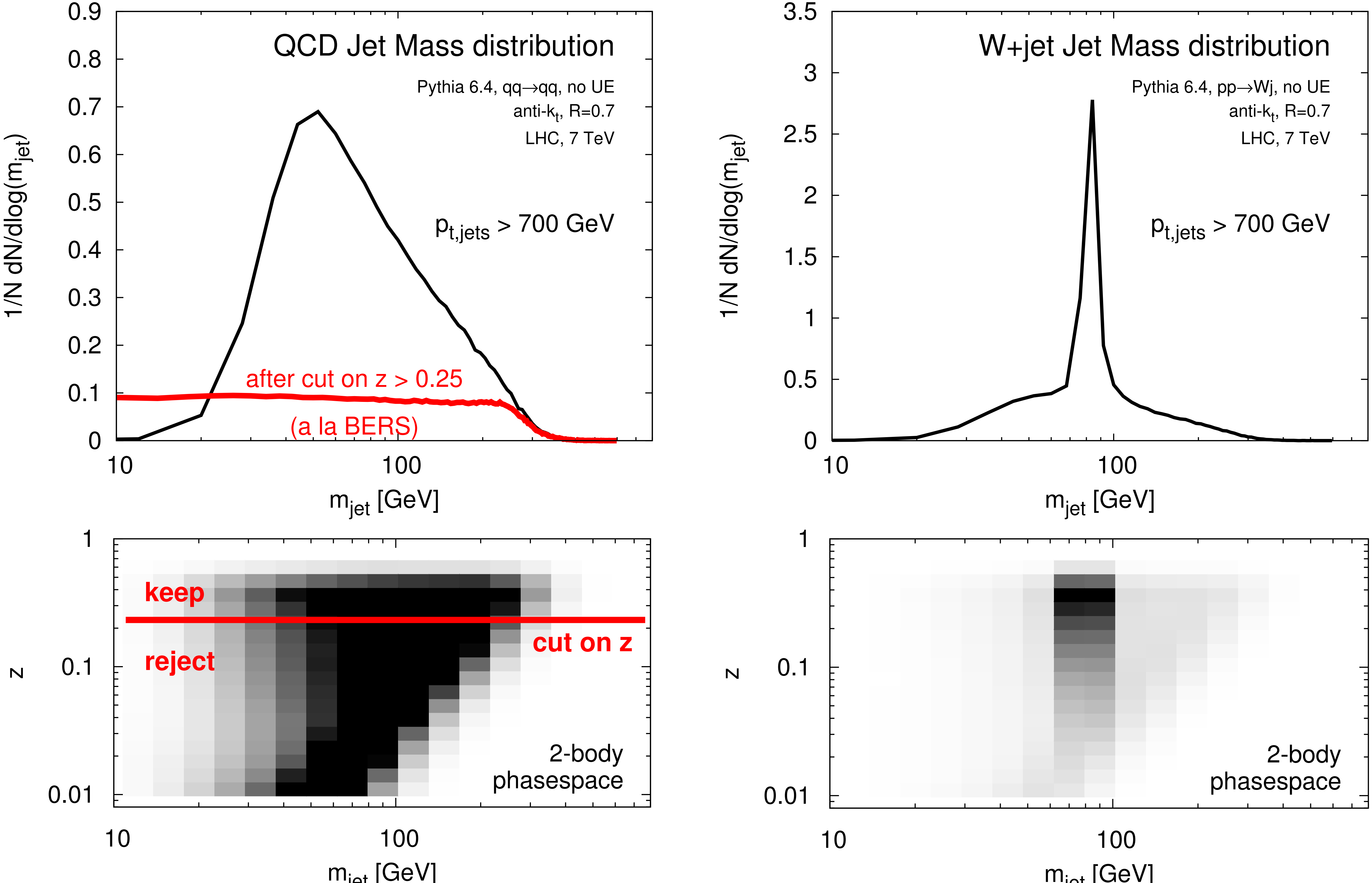
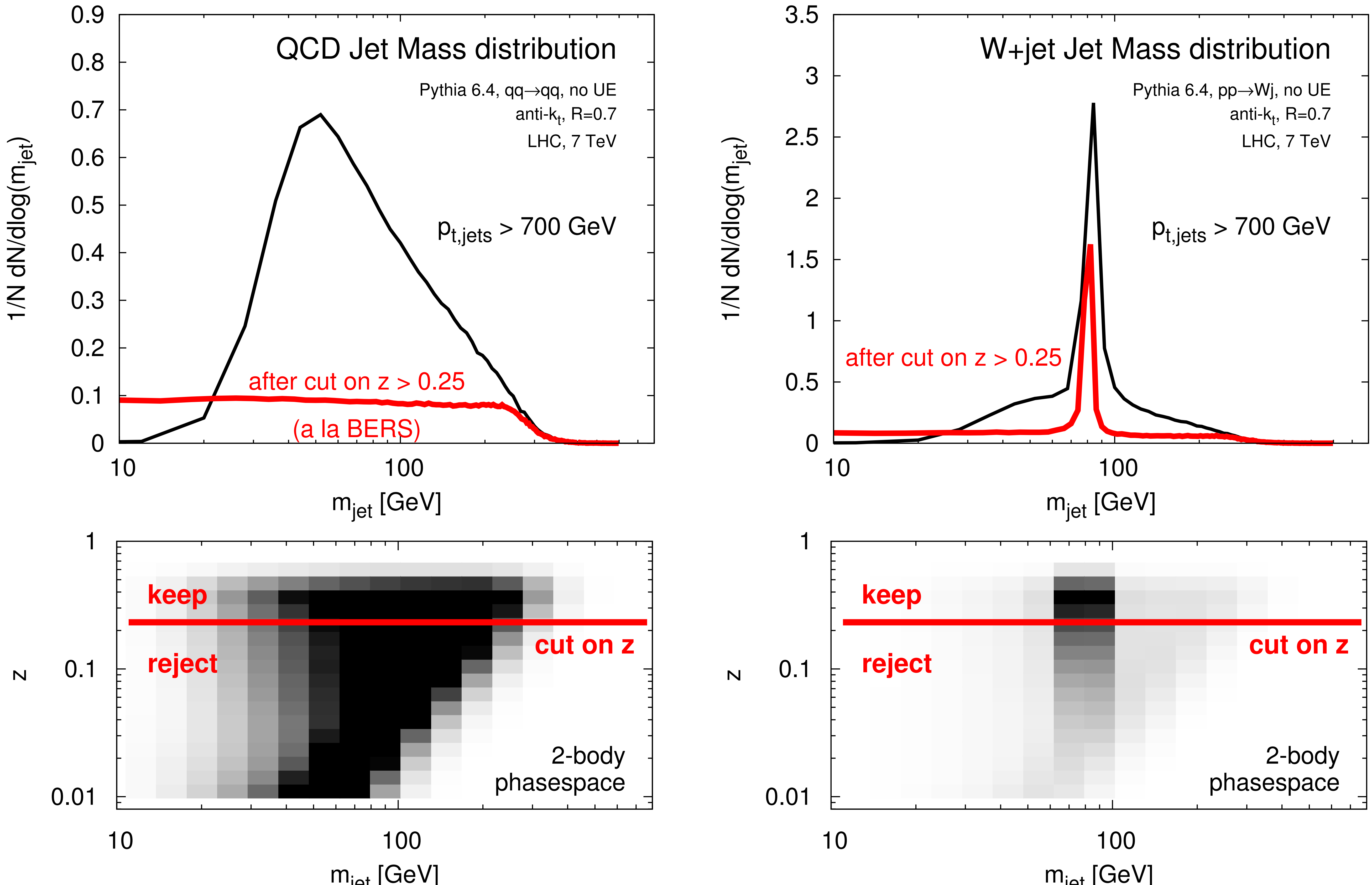
The logarithm comes from integral over soft divergence of QCD:

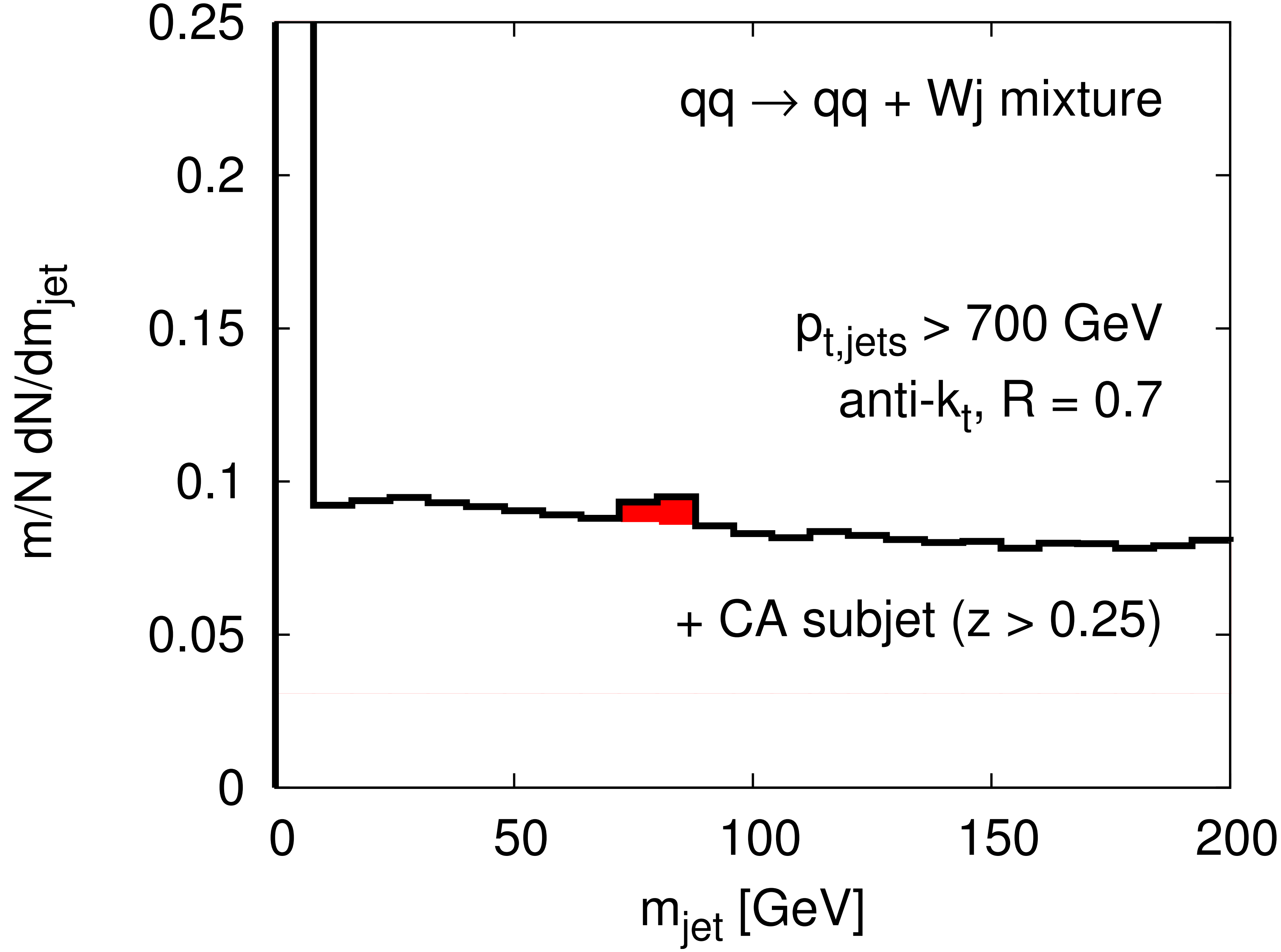
$$\int_{\frac{m^2}{p_t^2 R^2}}^{\frac{1}{2}} \frac{dz}{z}$$

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


QCD Jet Mass distribution
Pythia 6.4, qq→qq, no UE
anti-k_t, R=0.7
LHC, 7 TeV
$p_{t,jets}$ > 700 GeV
after cut on z > 0.25
(a la BERS)
1/N dN/dlog(m_{jet})
m_{jet} [GeV]
W+jet Jet Mass distribution
Pythia 6.4, pp→Wj, no UE
anti-k_t, R=0.7
LHC, 7 TeV
$p_{t,jets}$ > 700 GeV
1/N dN/dlog(m_{jet})
m_{jet} [GeV]
keep
reject
cut on z
2-body phasespace
z
m_{jet} [GeV]
2-body phasespace
z
m_{jet} [GeV]

Inside the jet mass

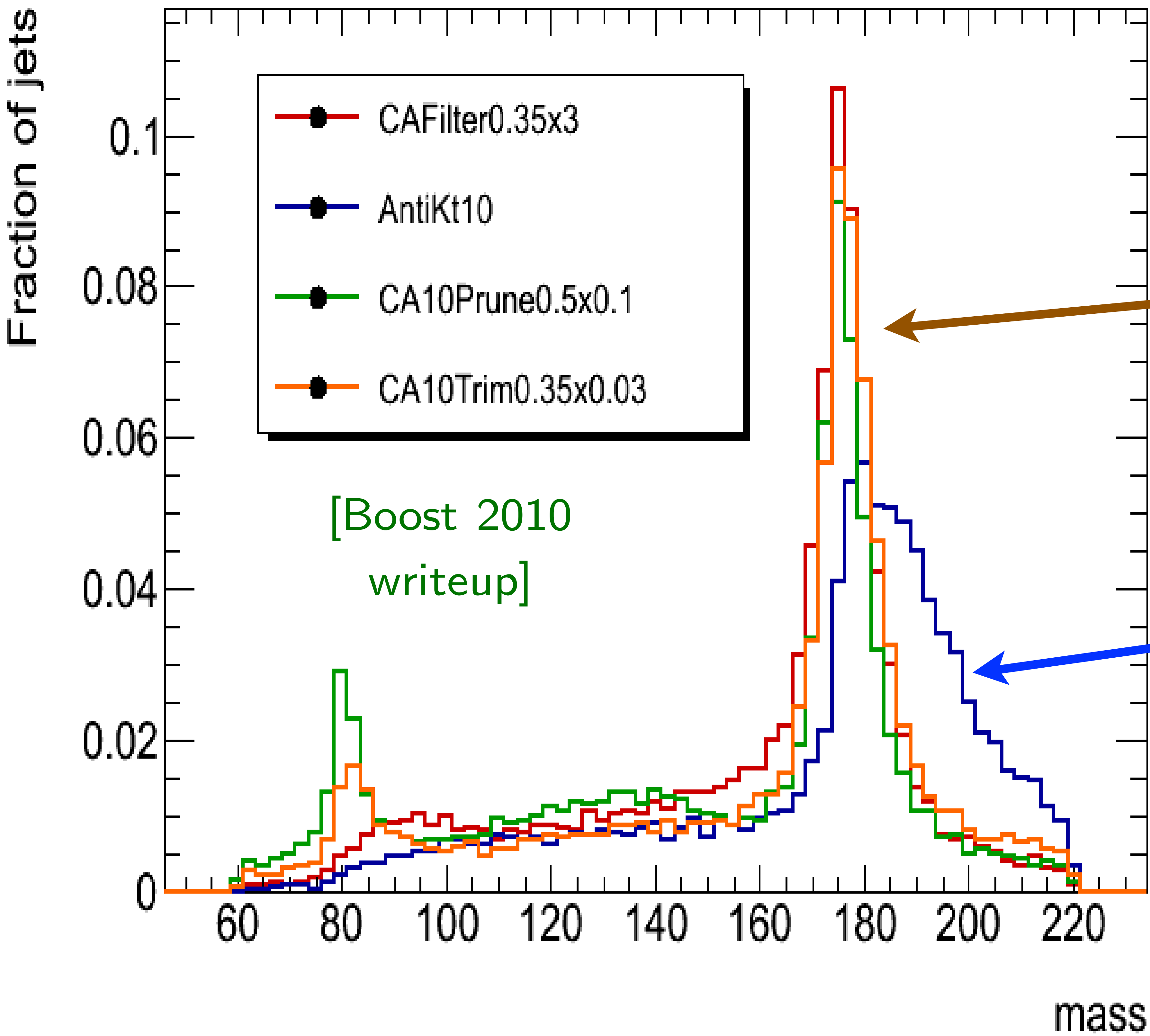




Signal + bkgd after cut on z

One core idea for grooming

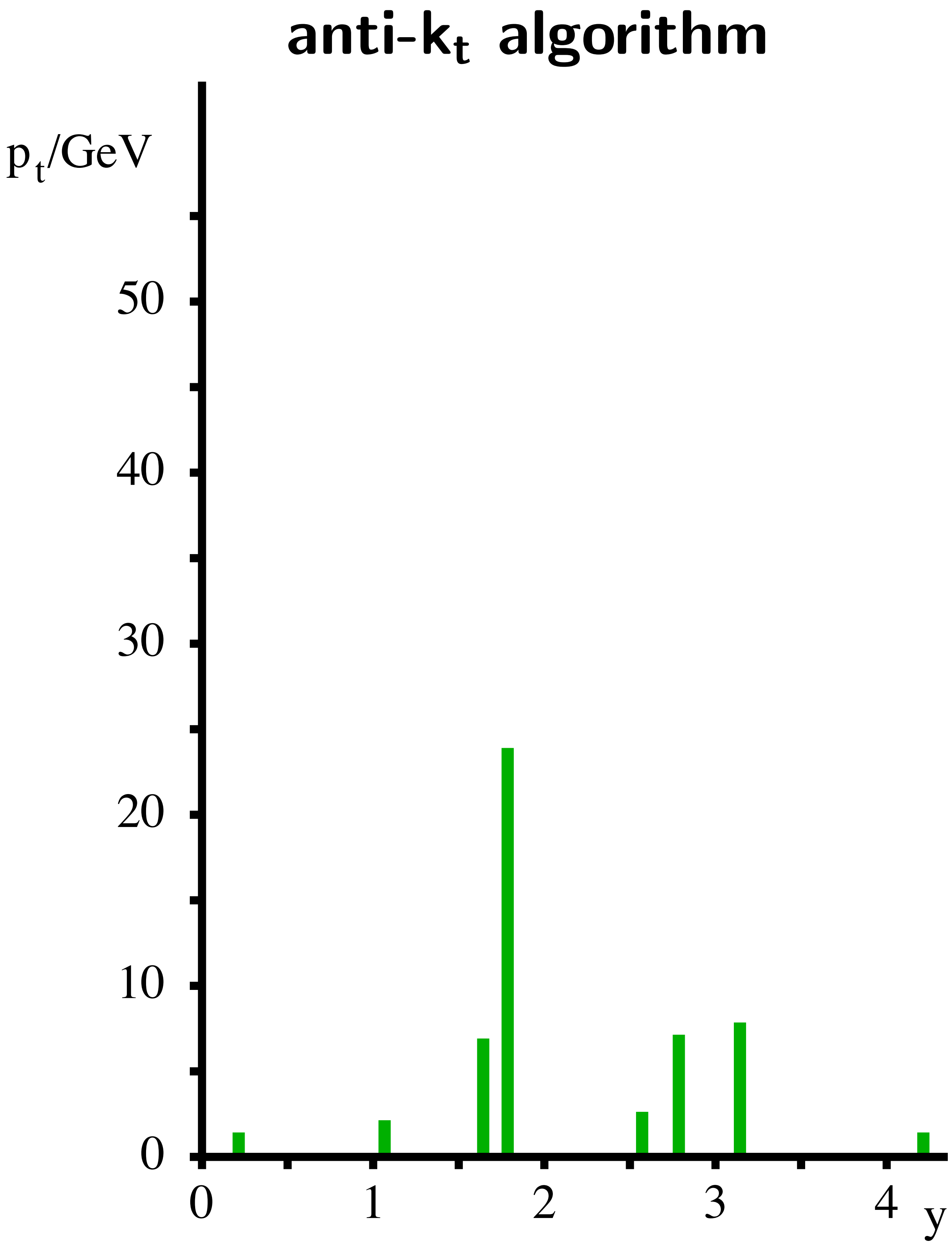
[see blackboard]



Groomed jet masses

Plain jet mass (anti-k_t)

How do the tools work in practice?



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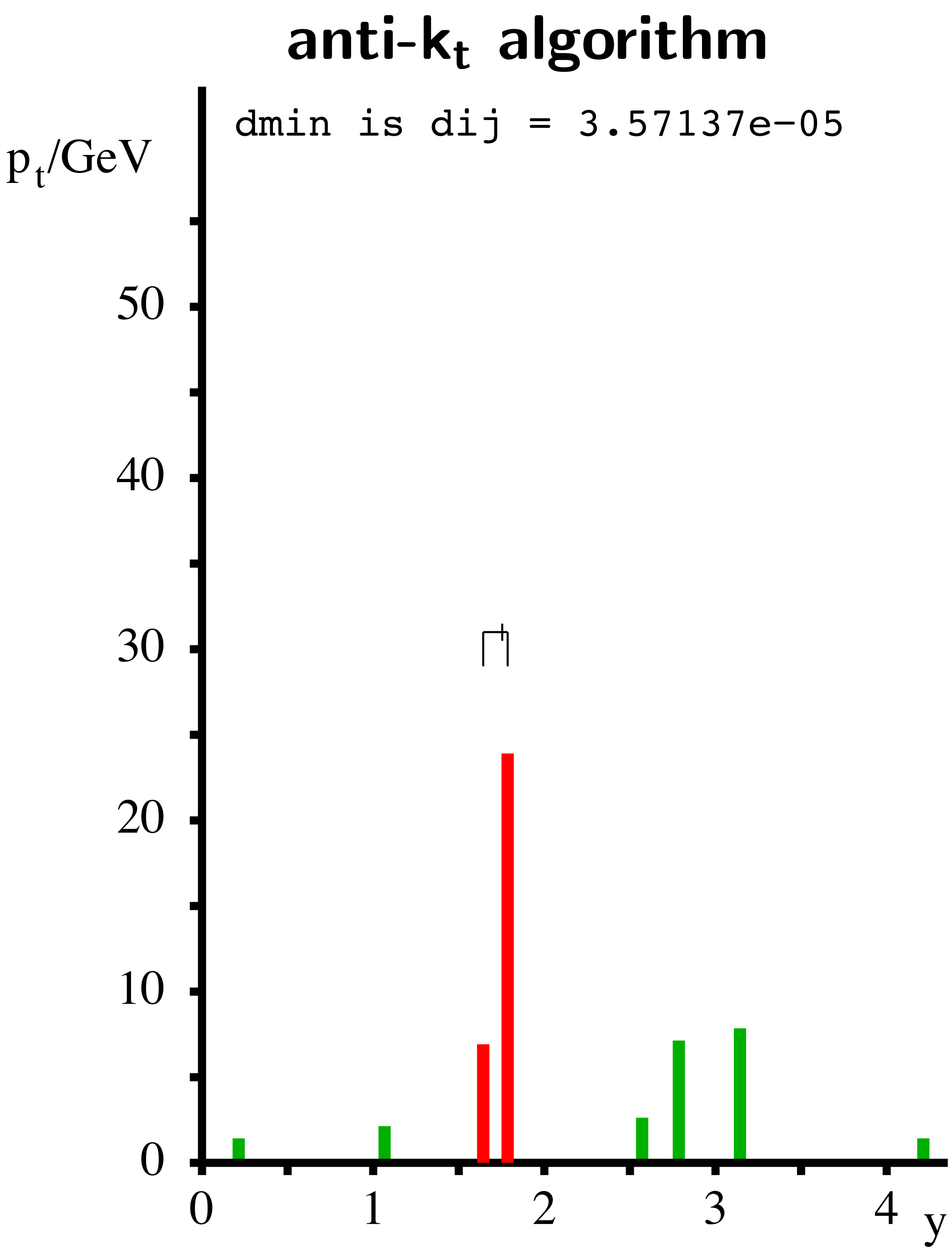
This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).

Identifying jet substructure: try out anti-k_t



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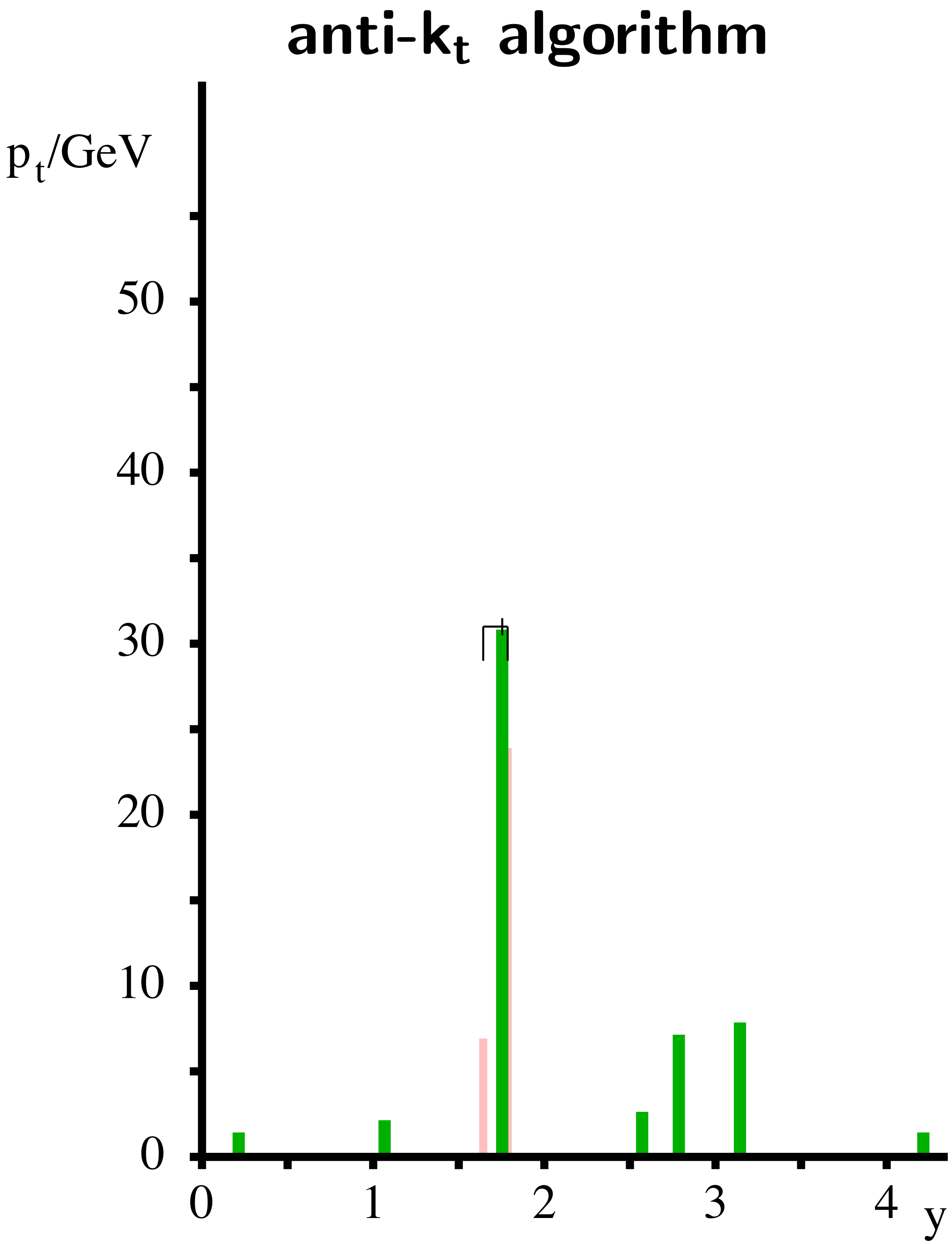

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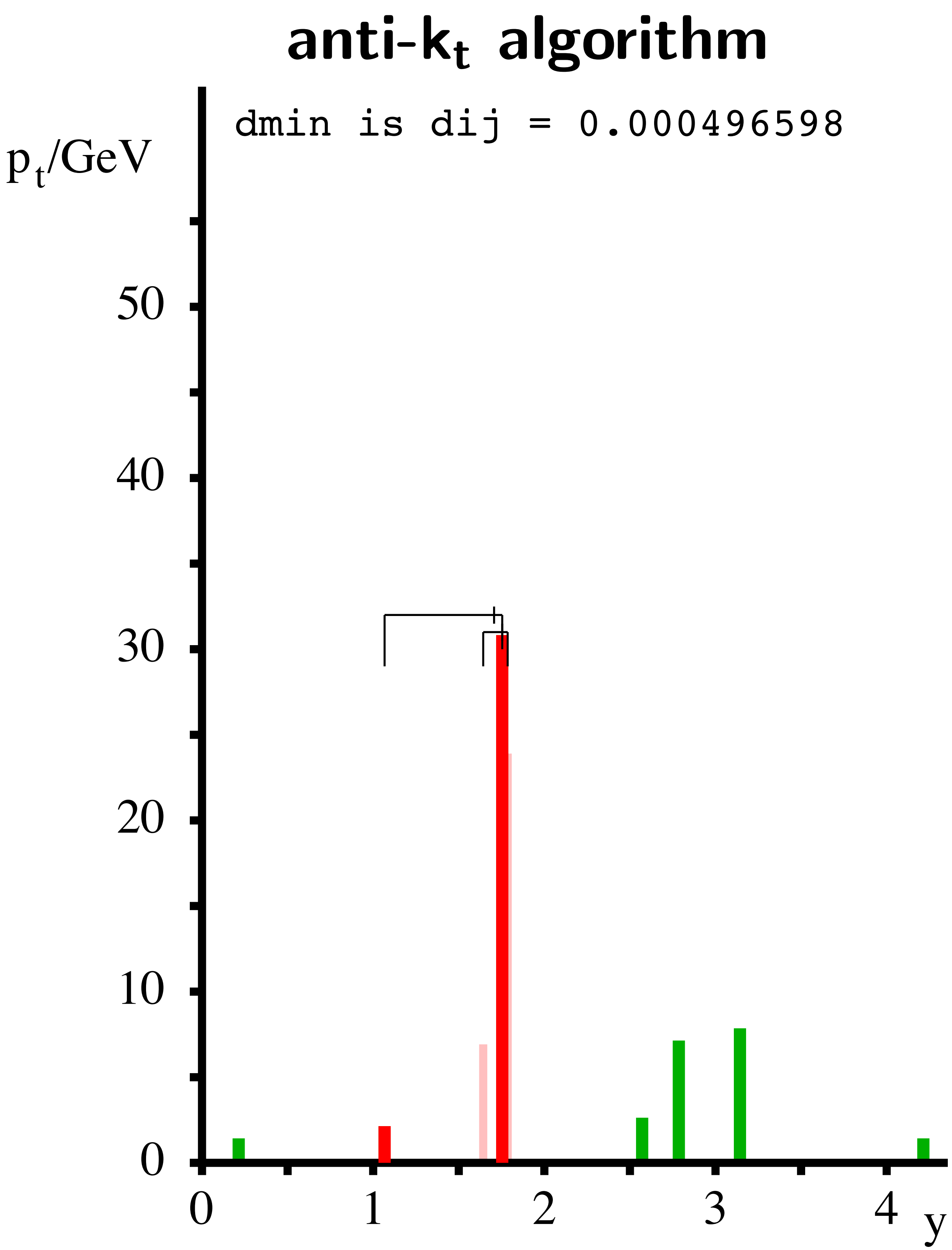

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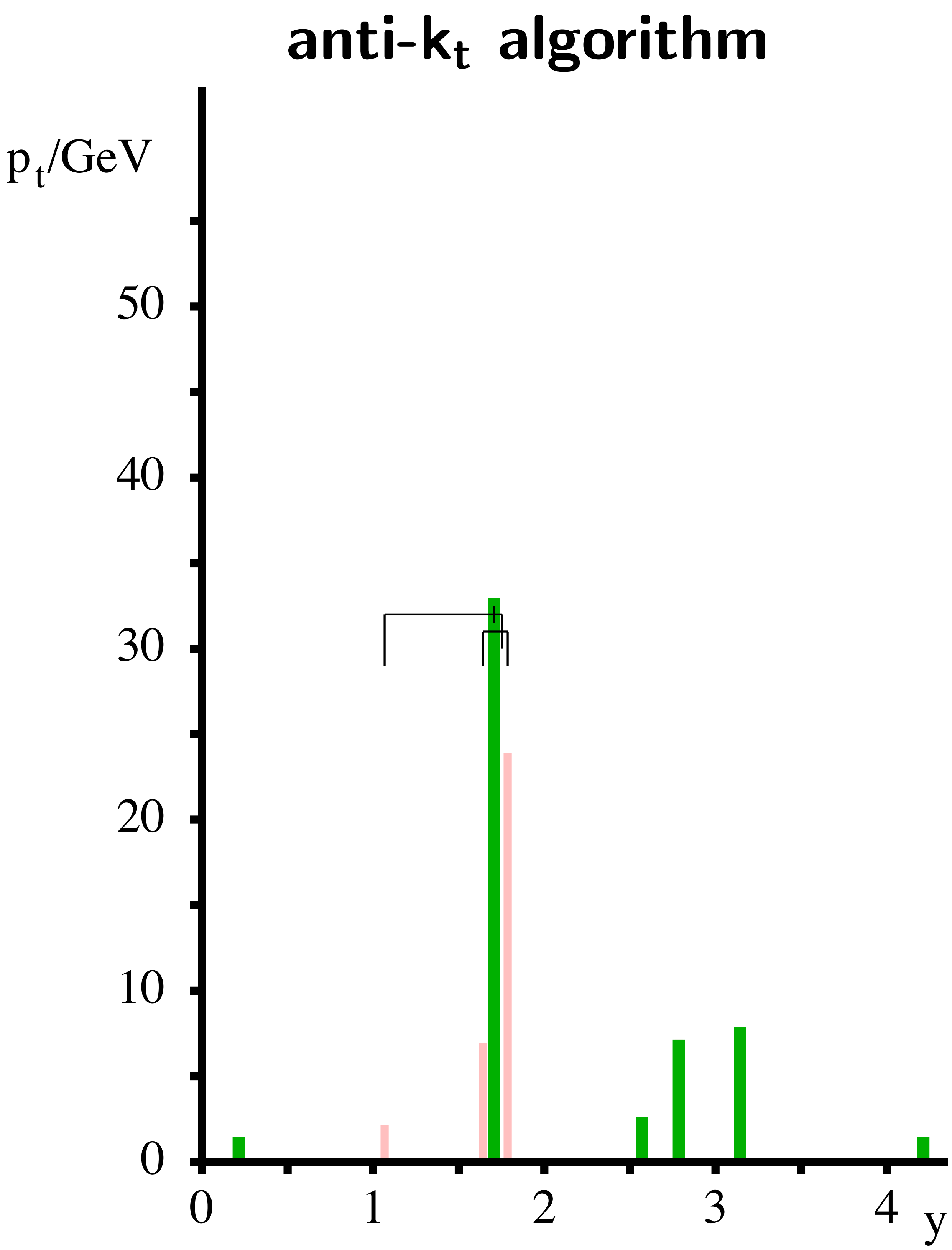

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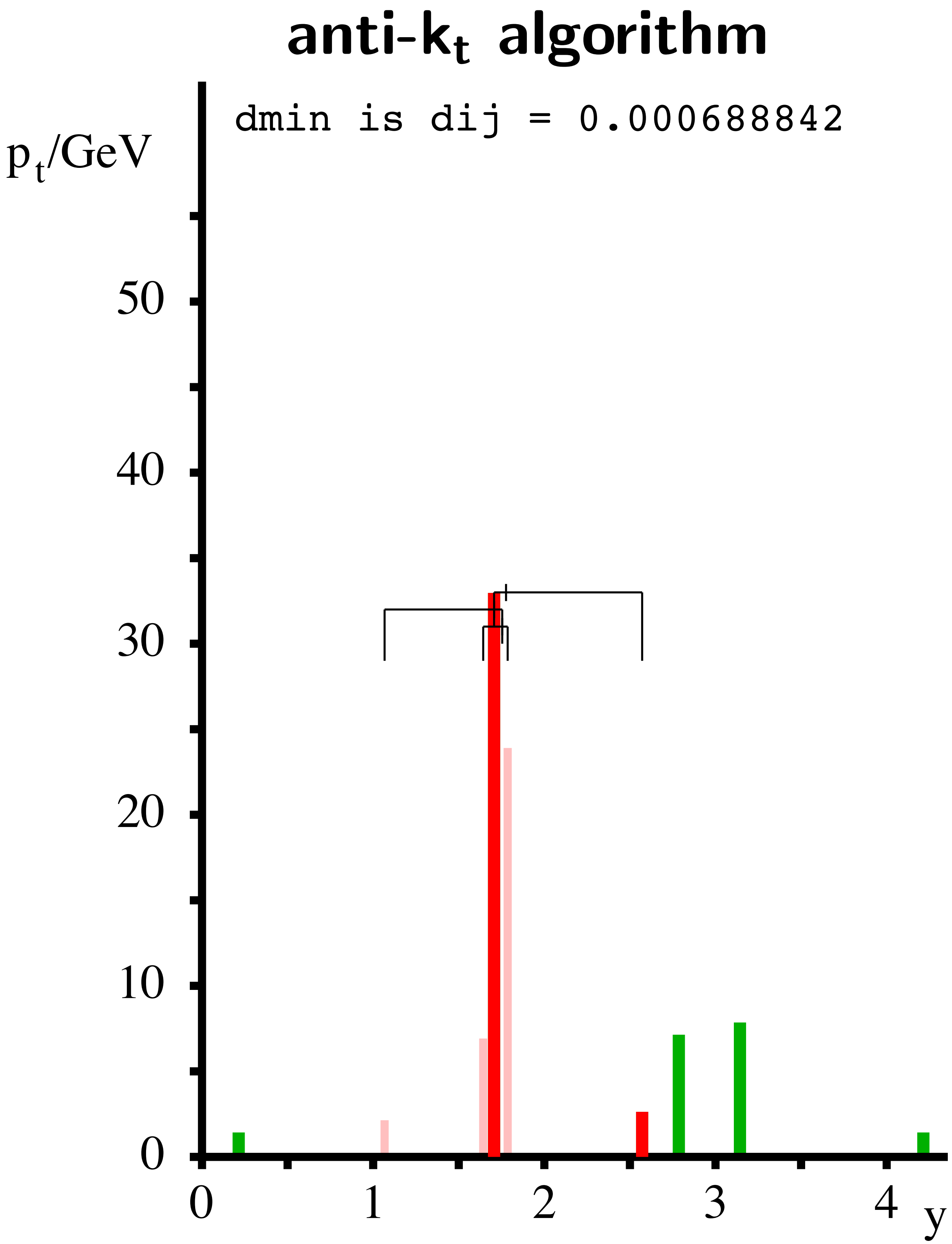

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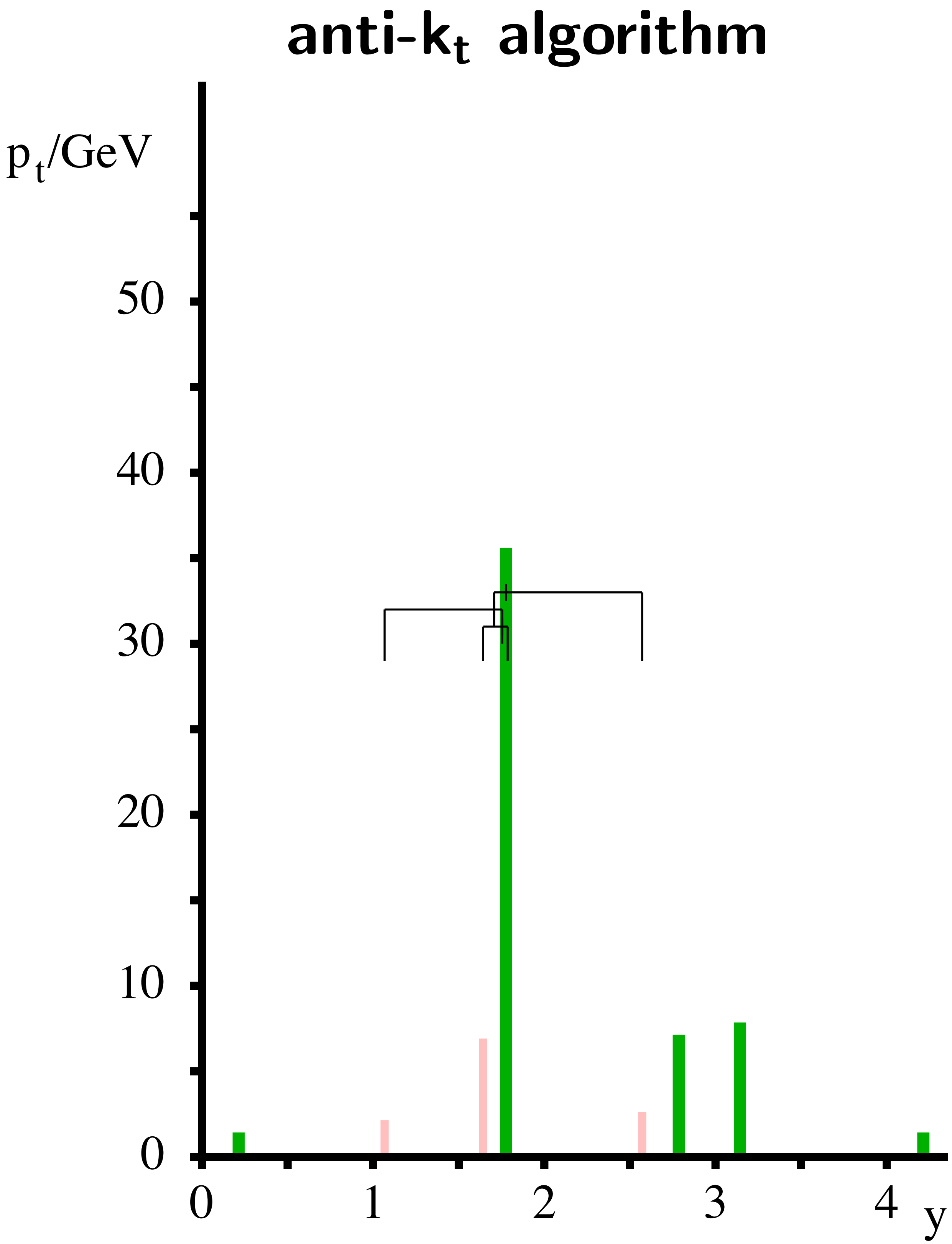

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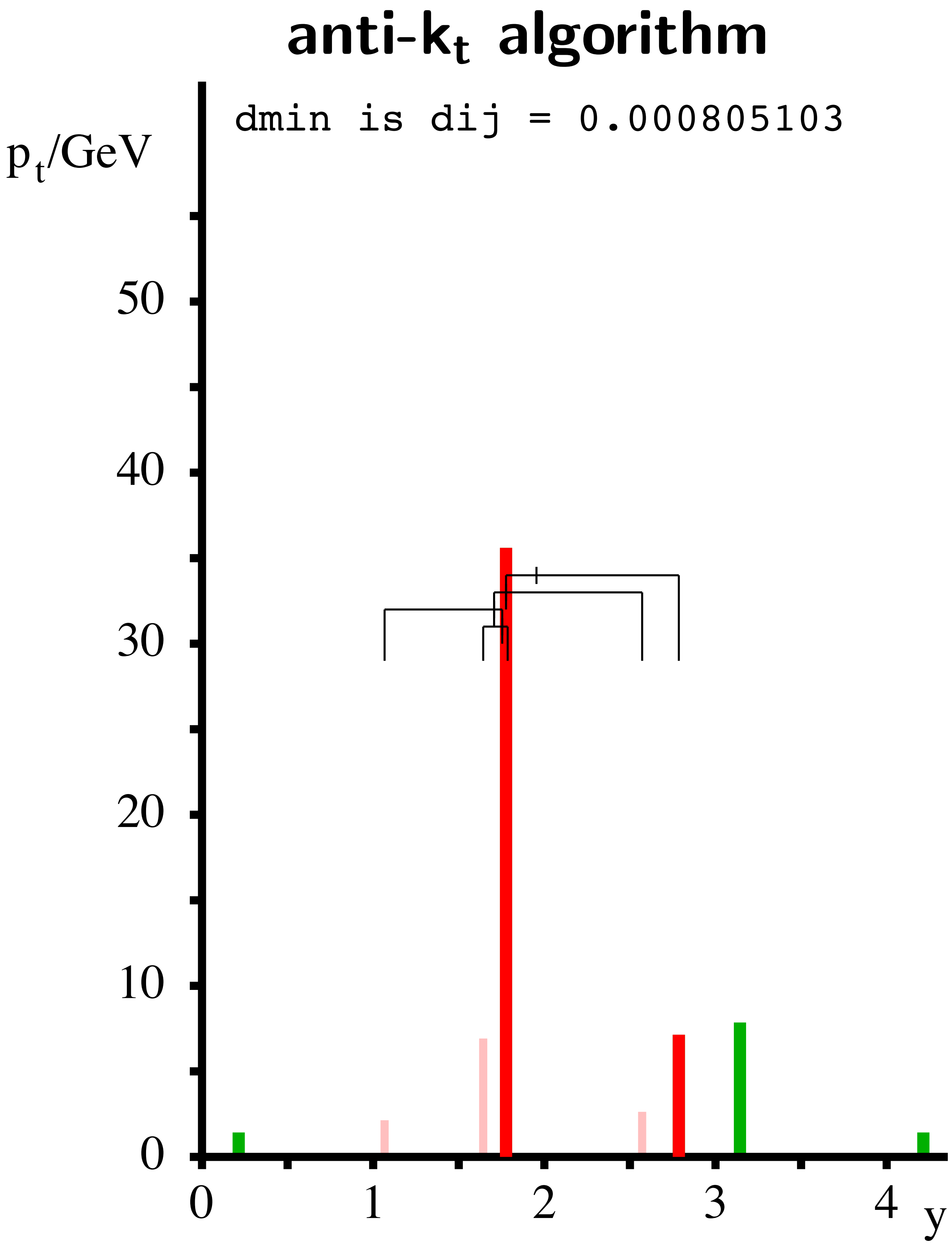

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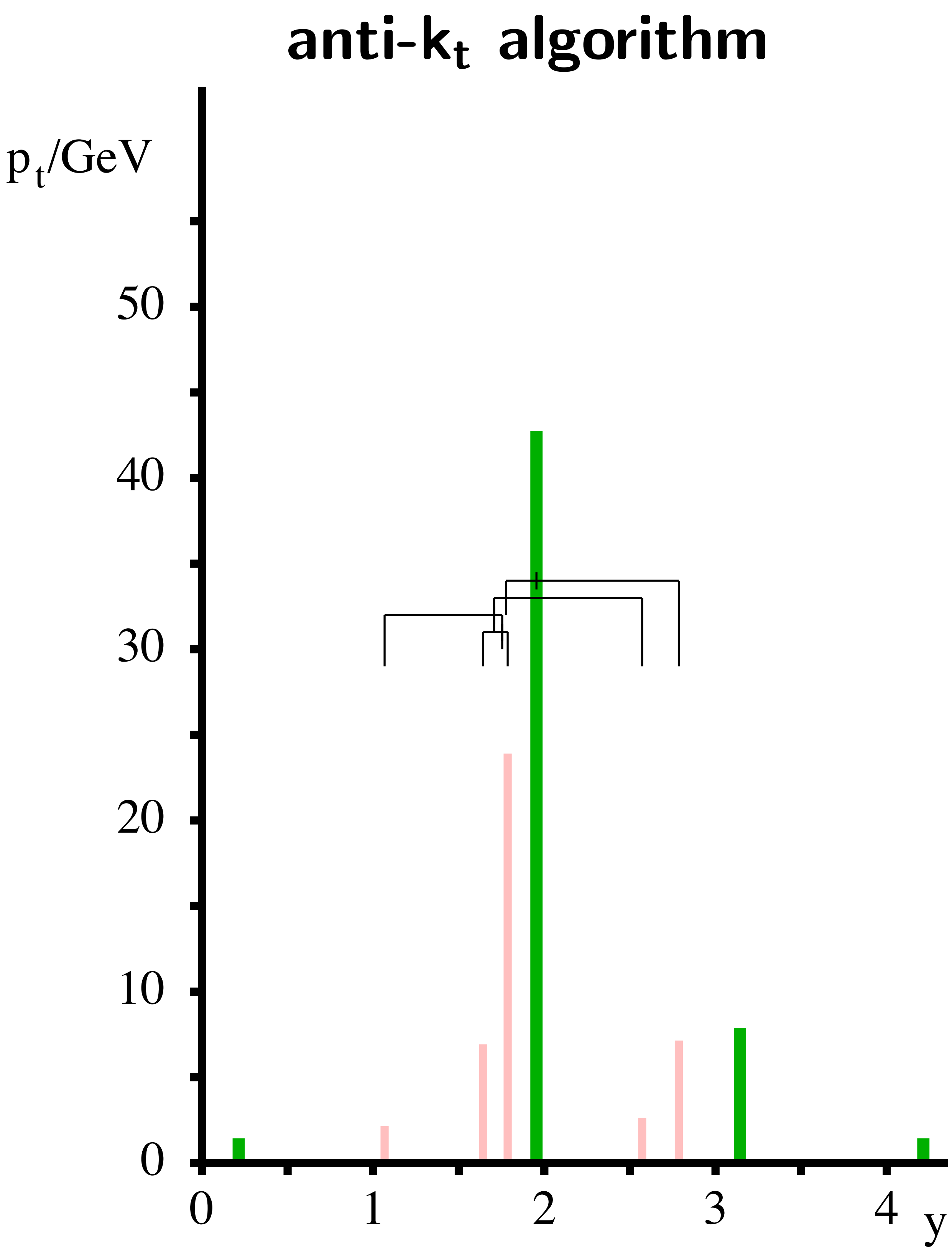

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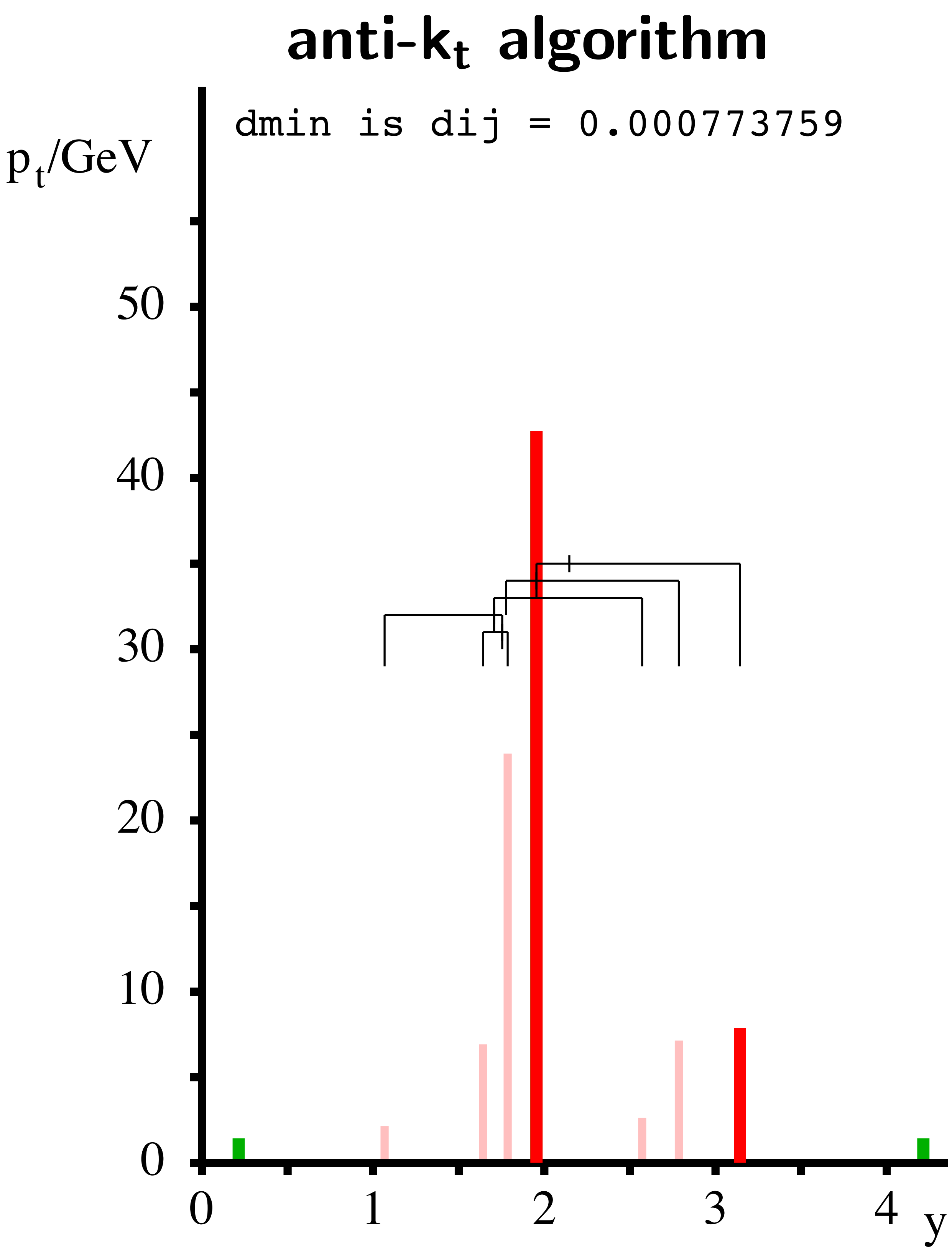

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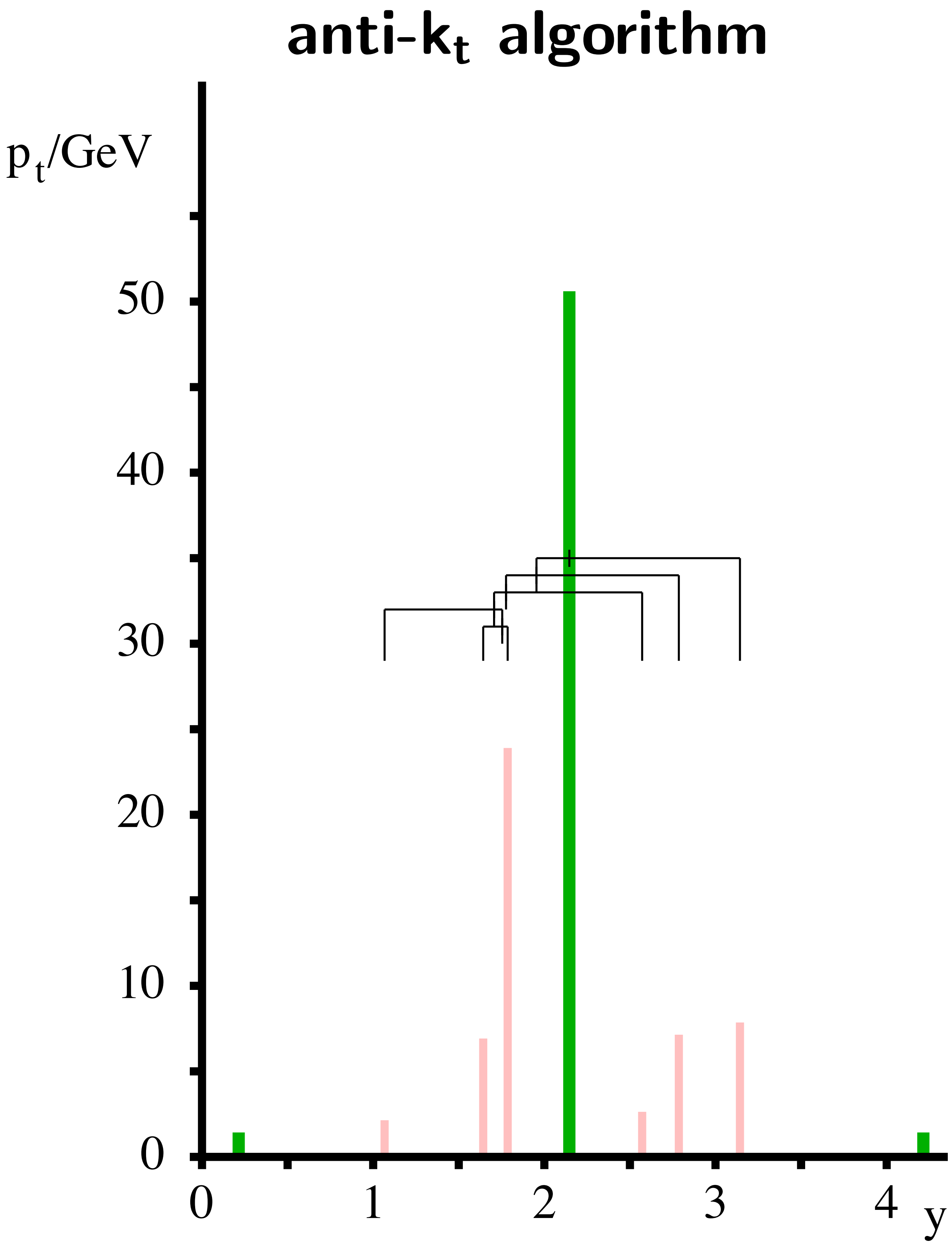

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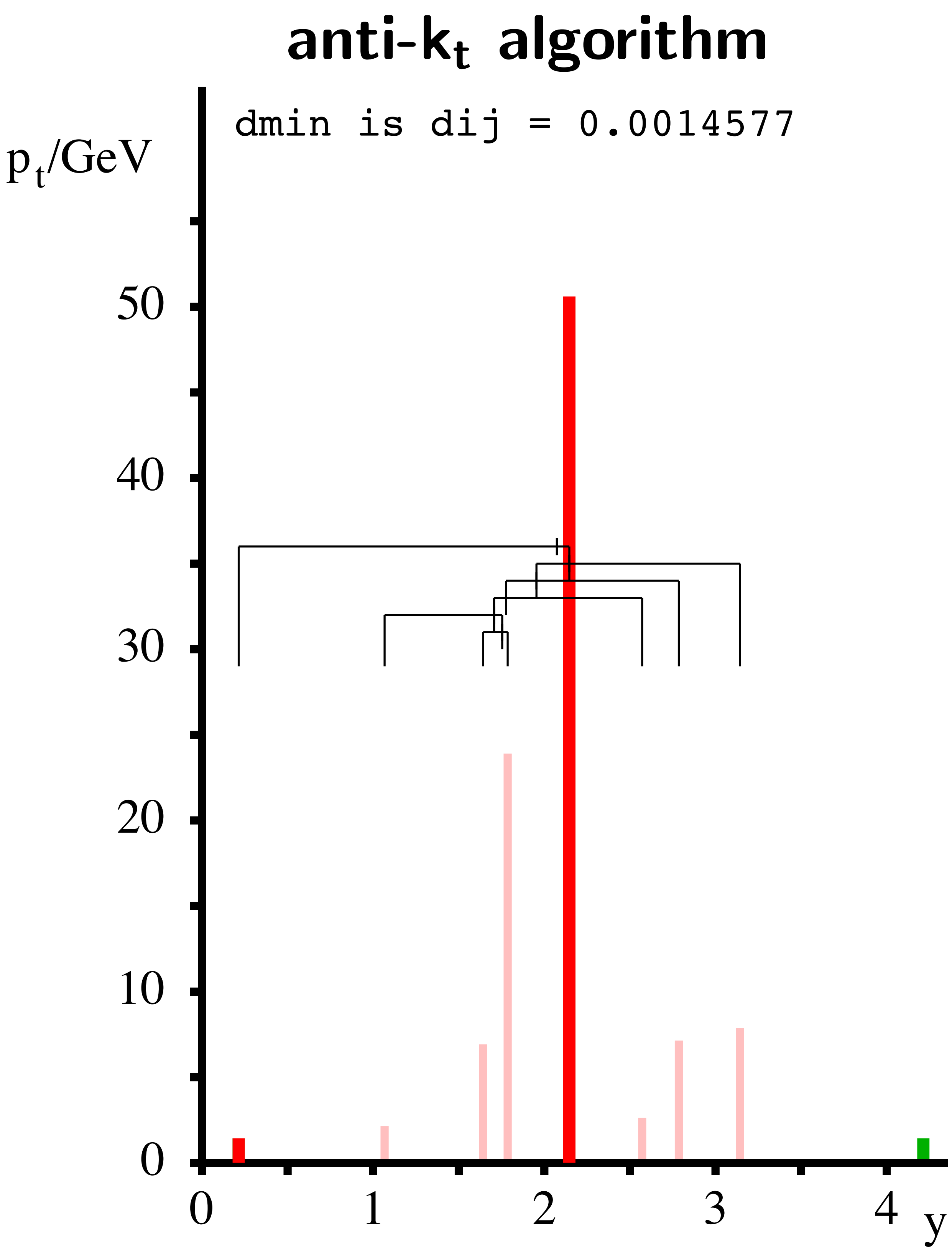

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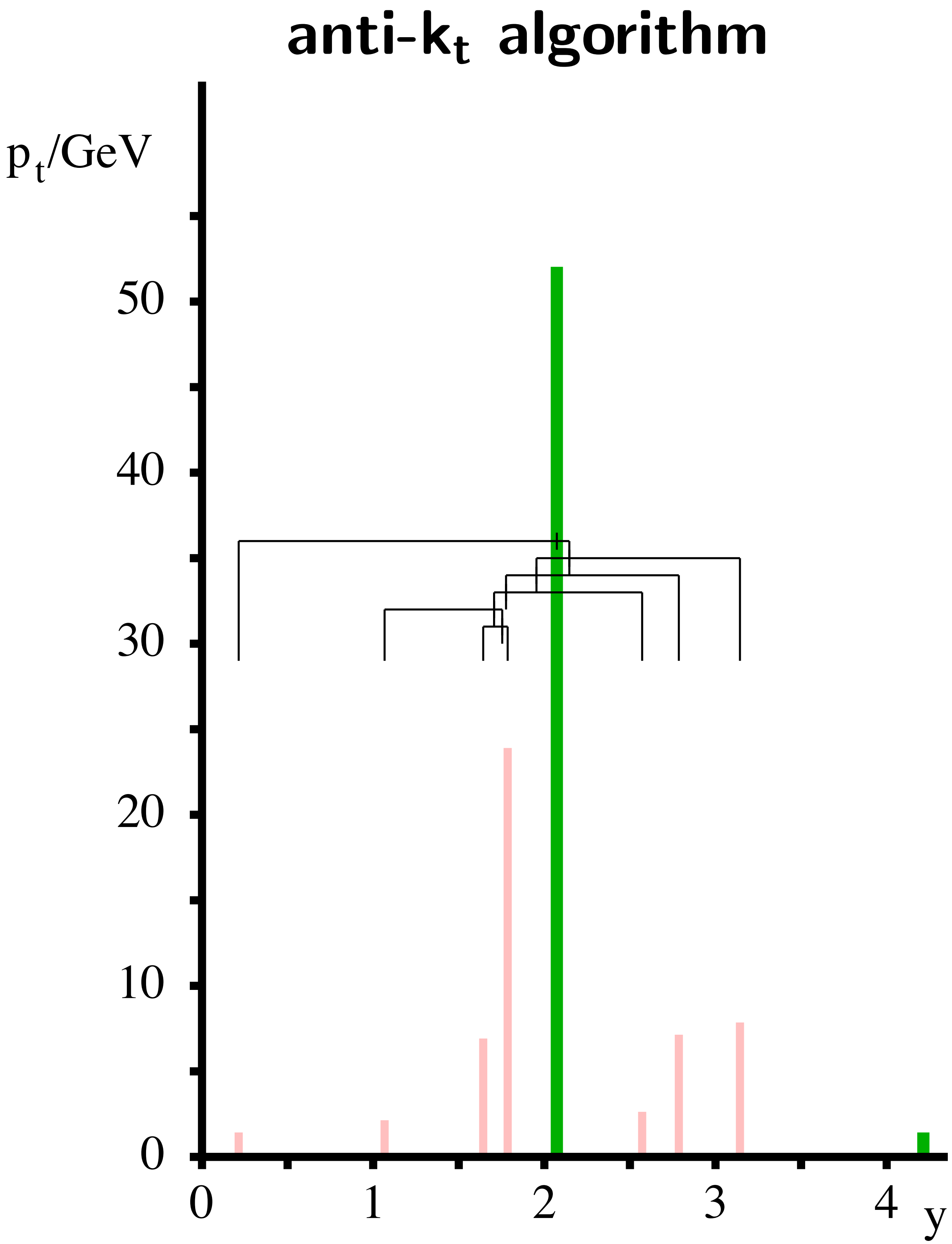

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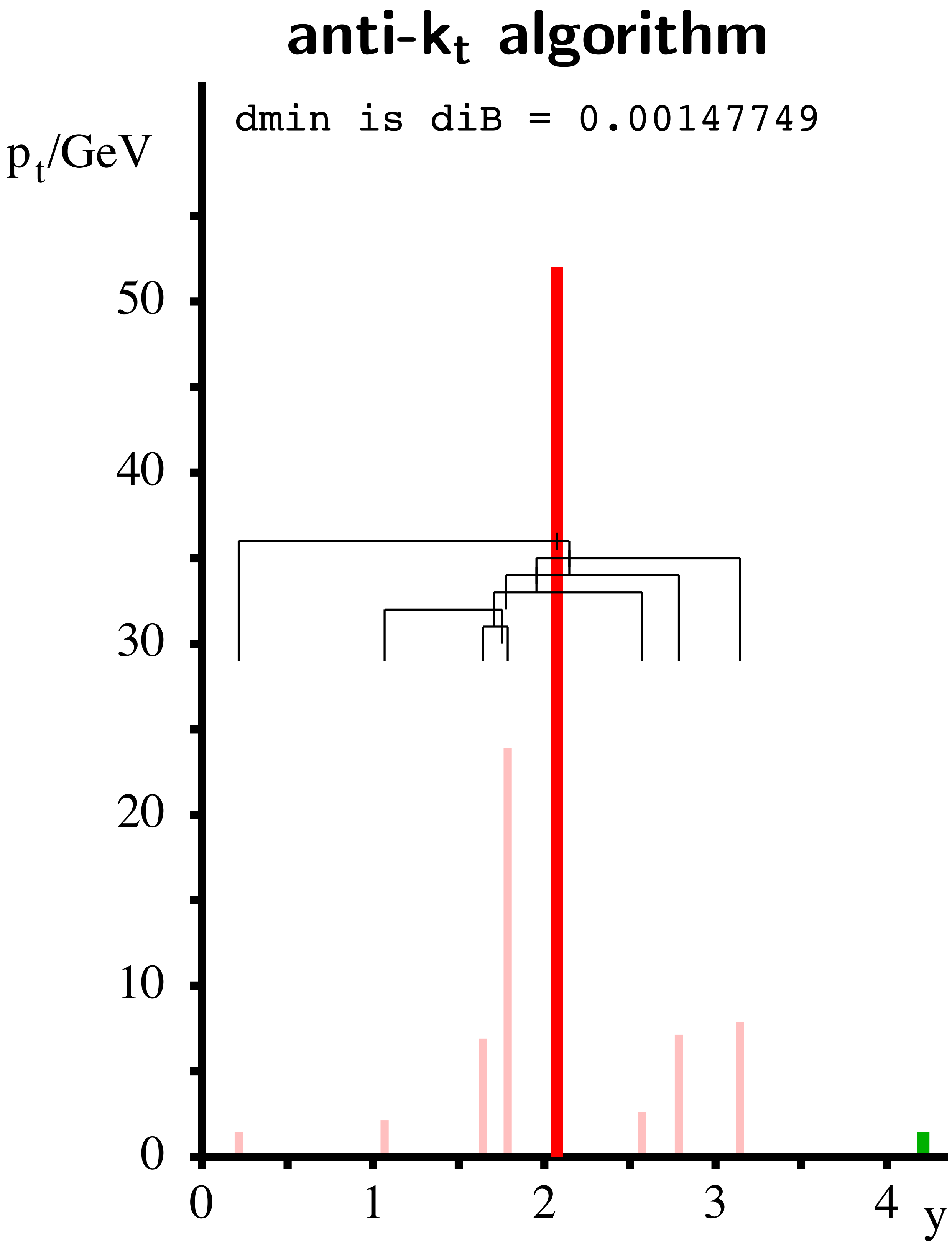

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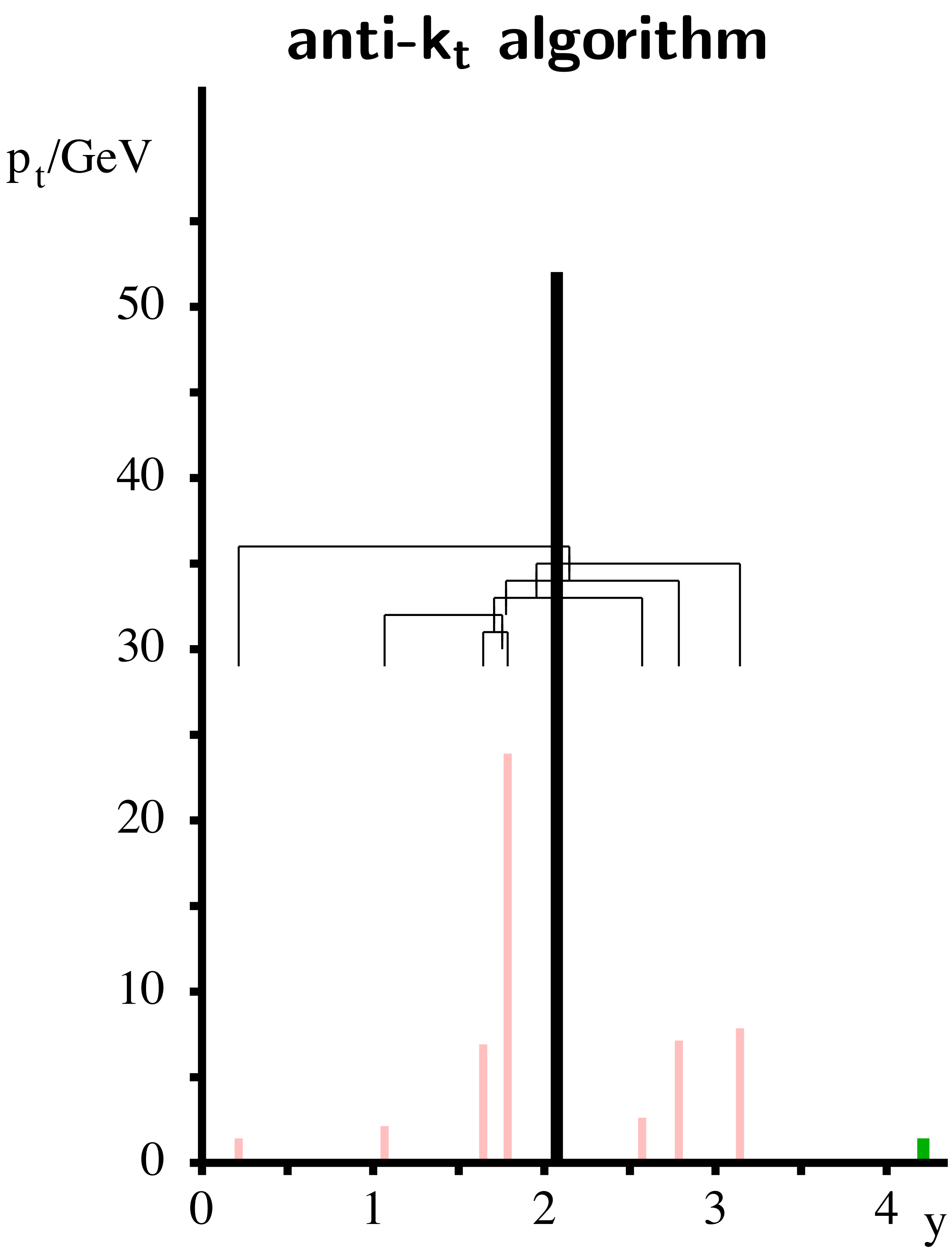

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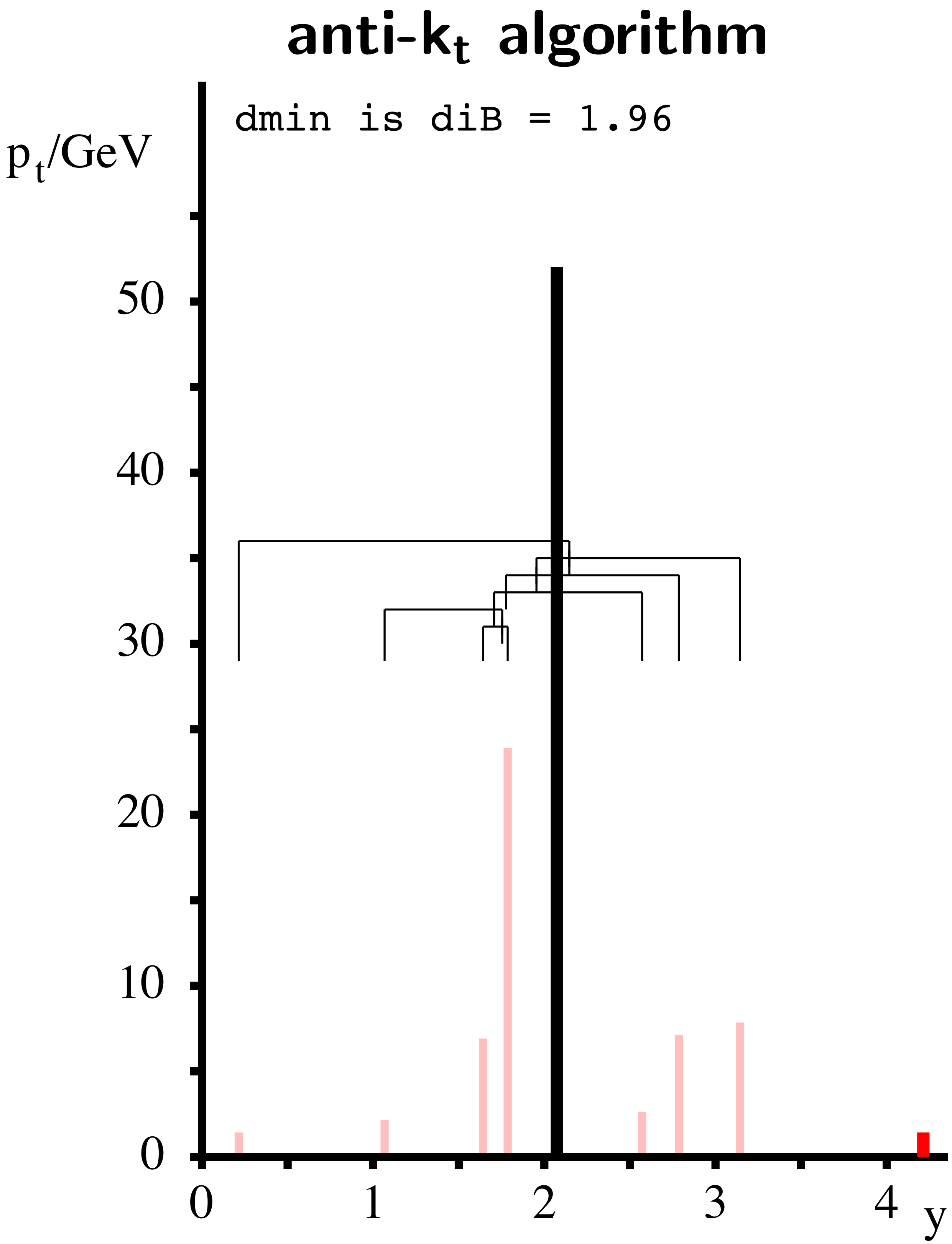

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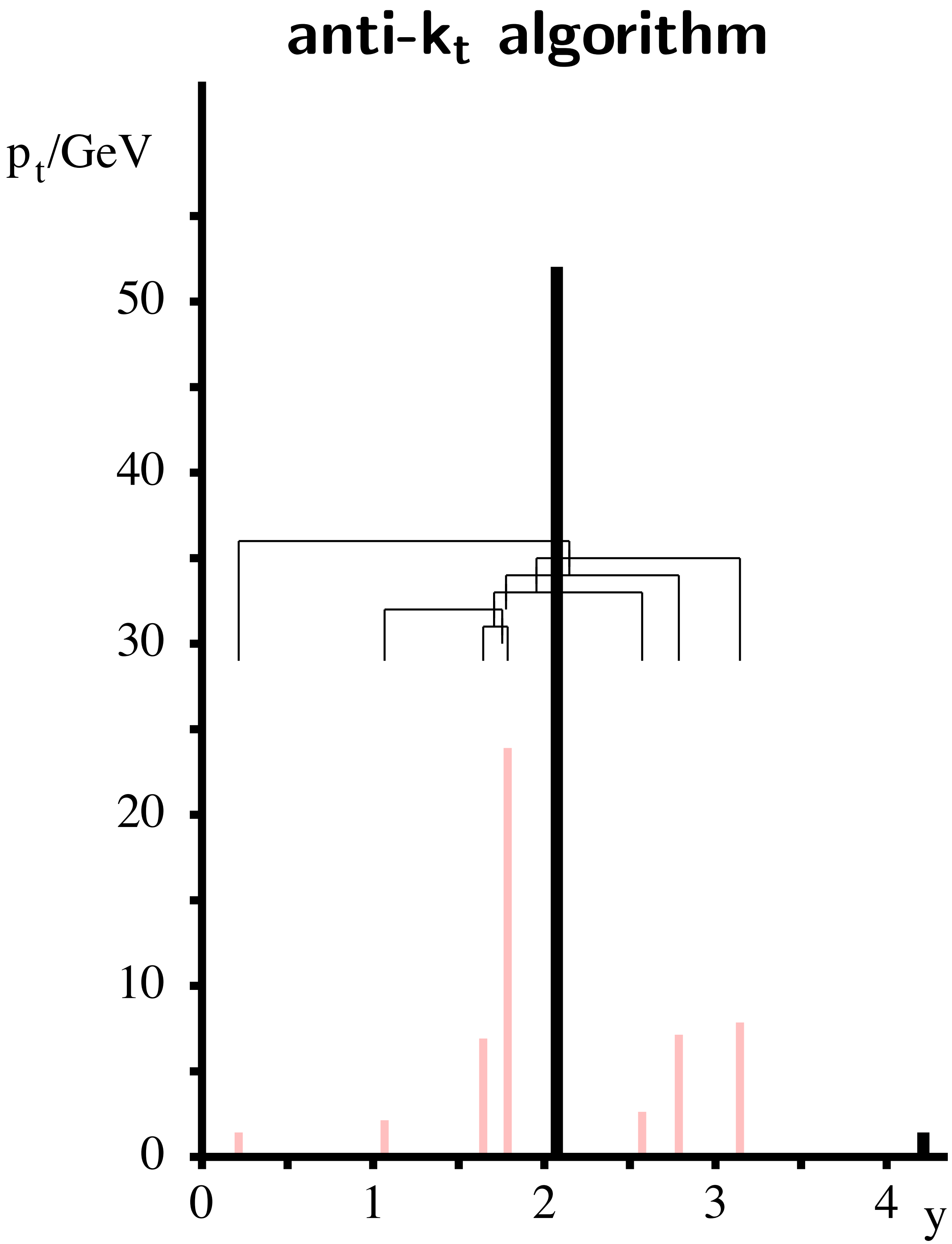

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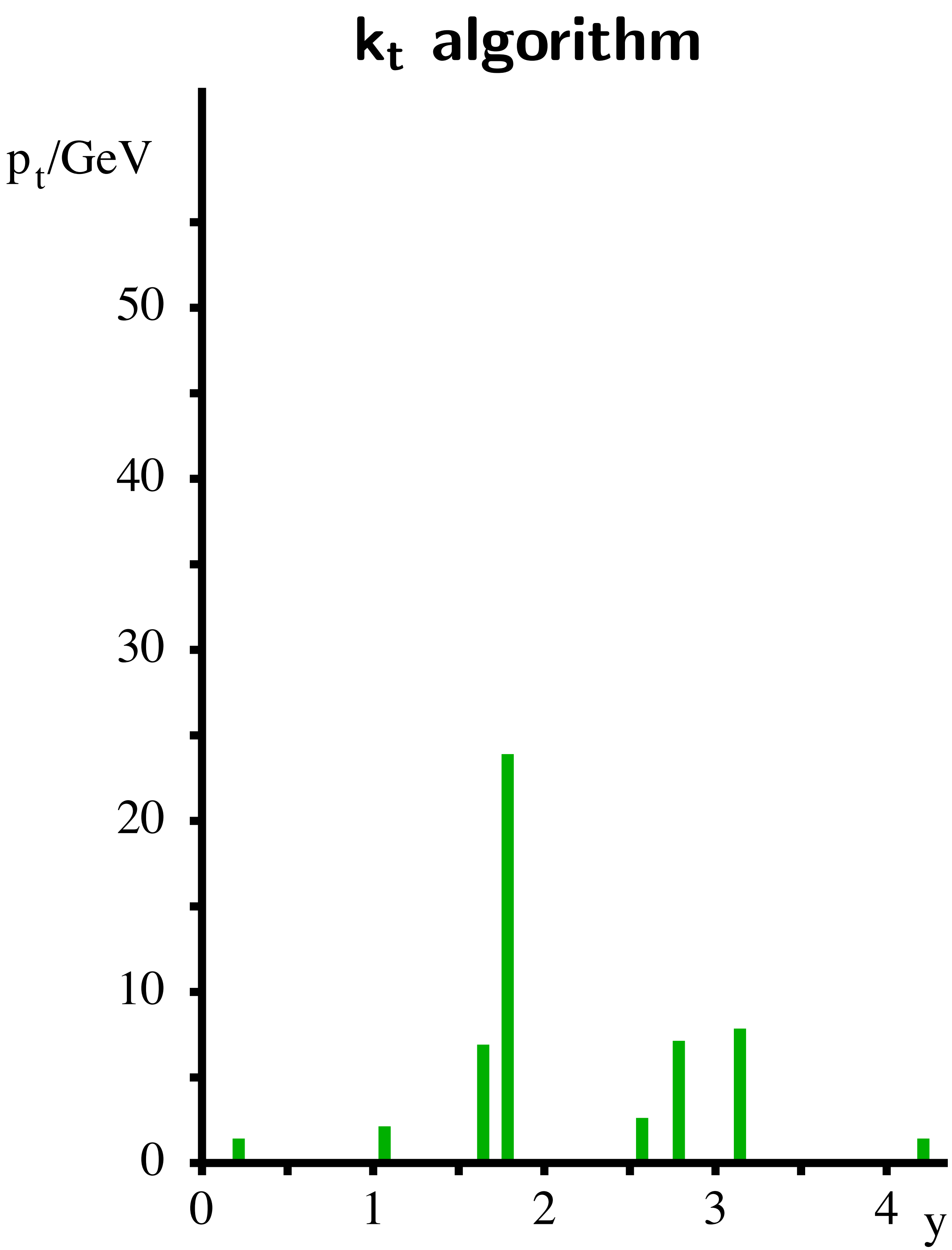

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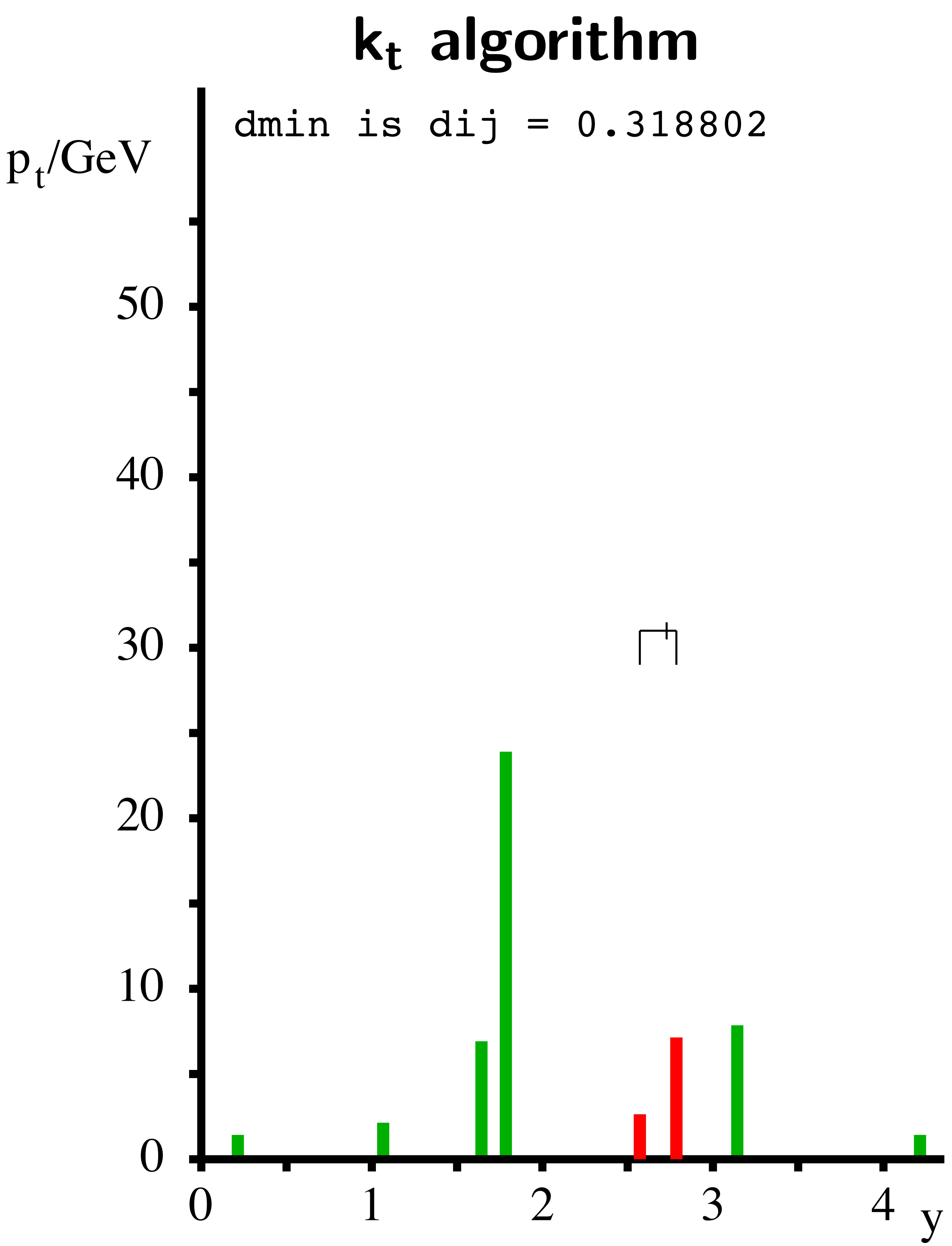

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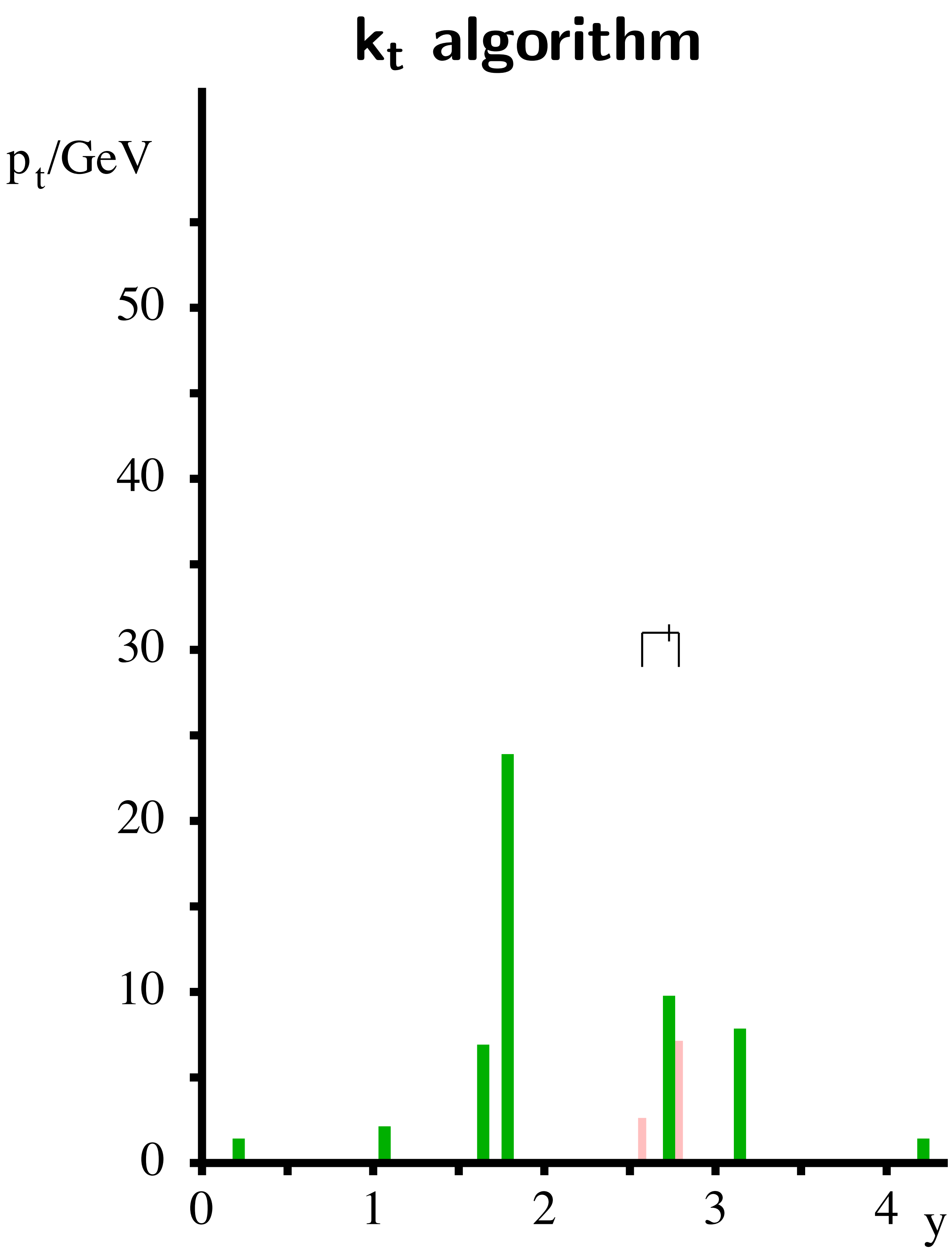

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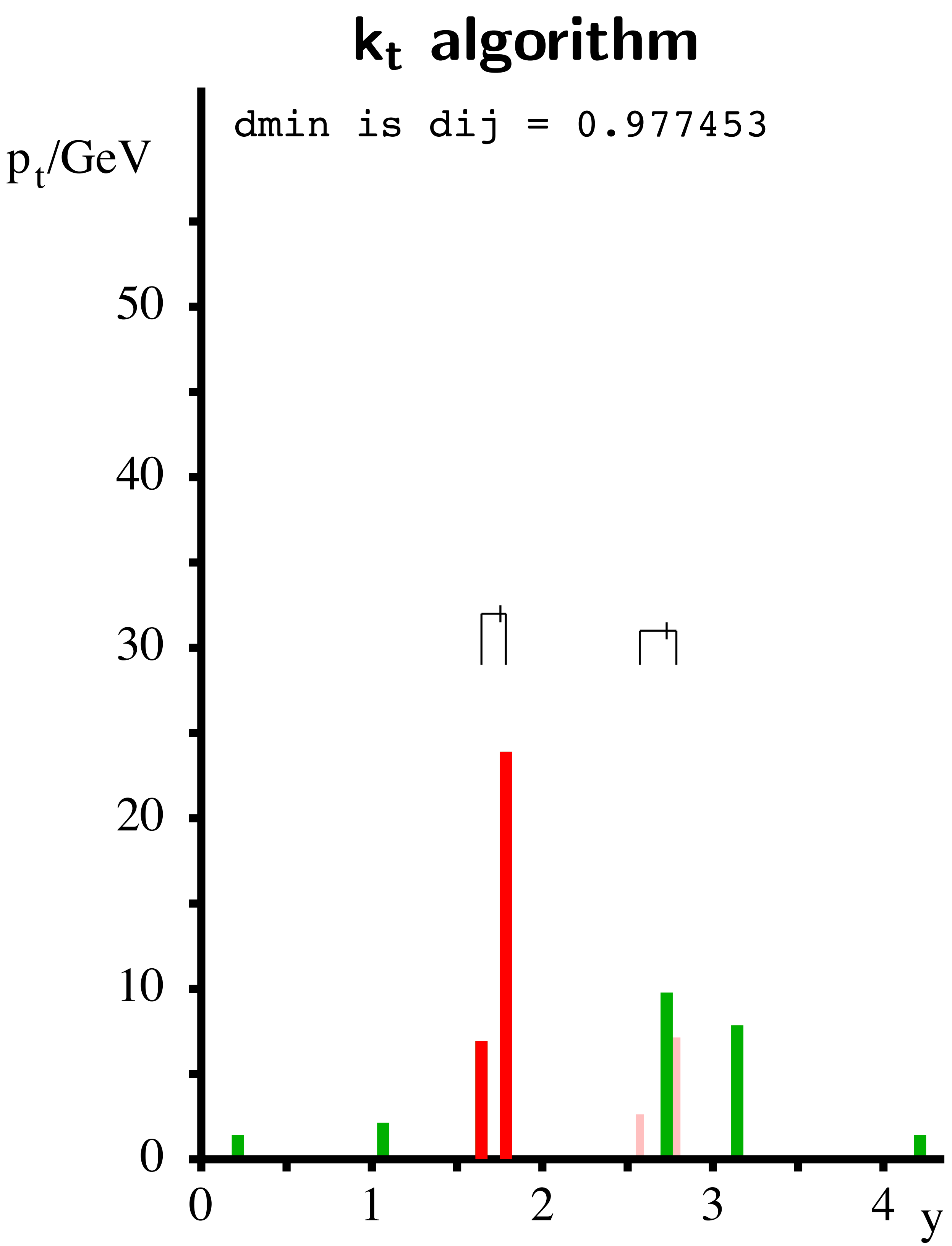

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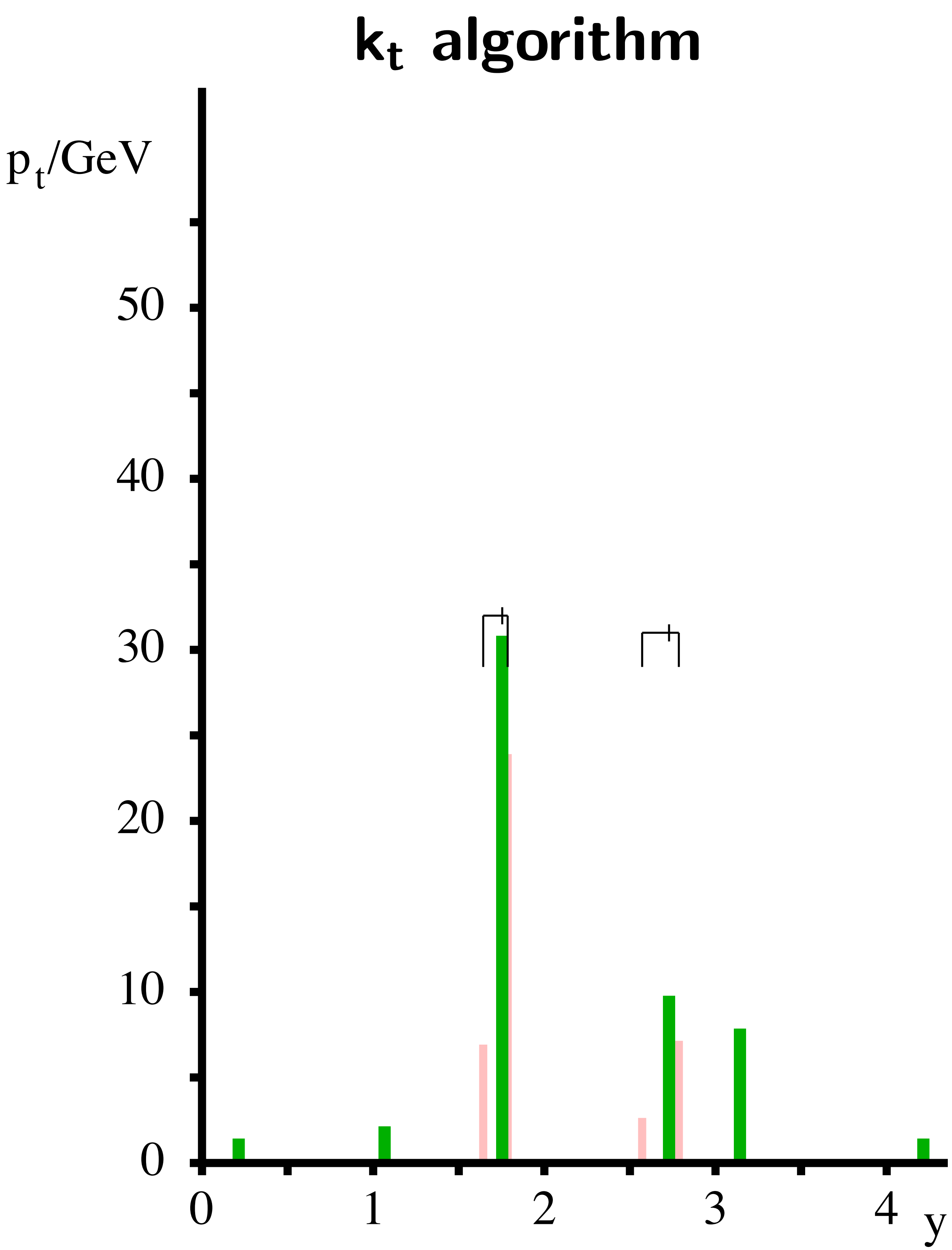

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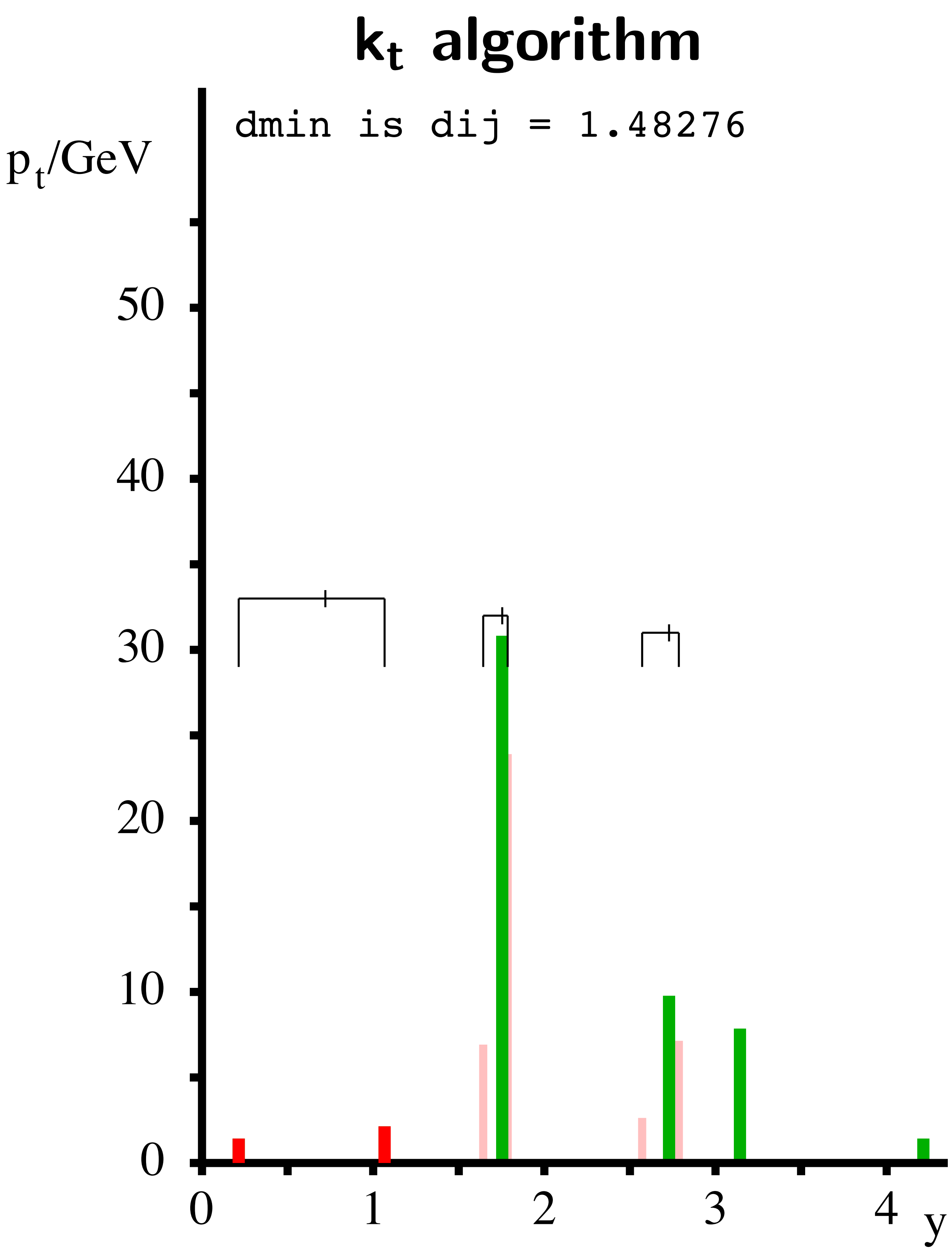

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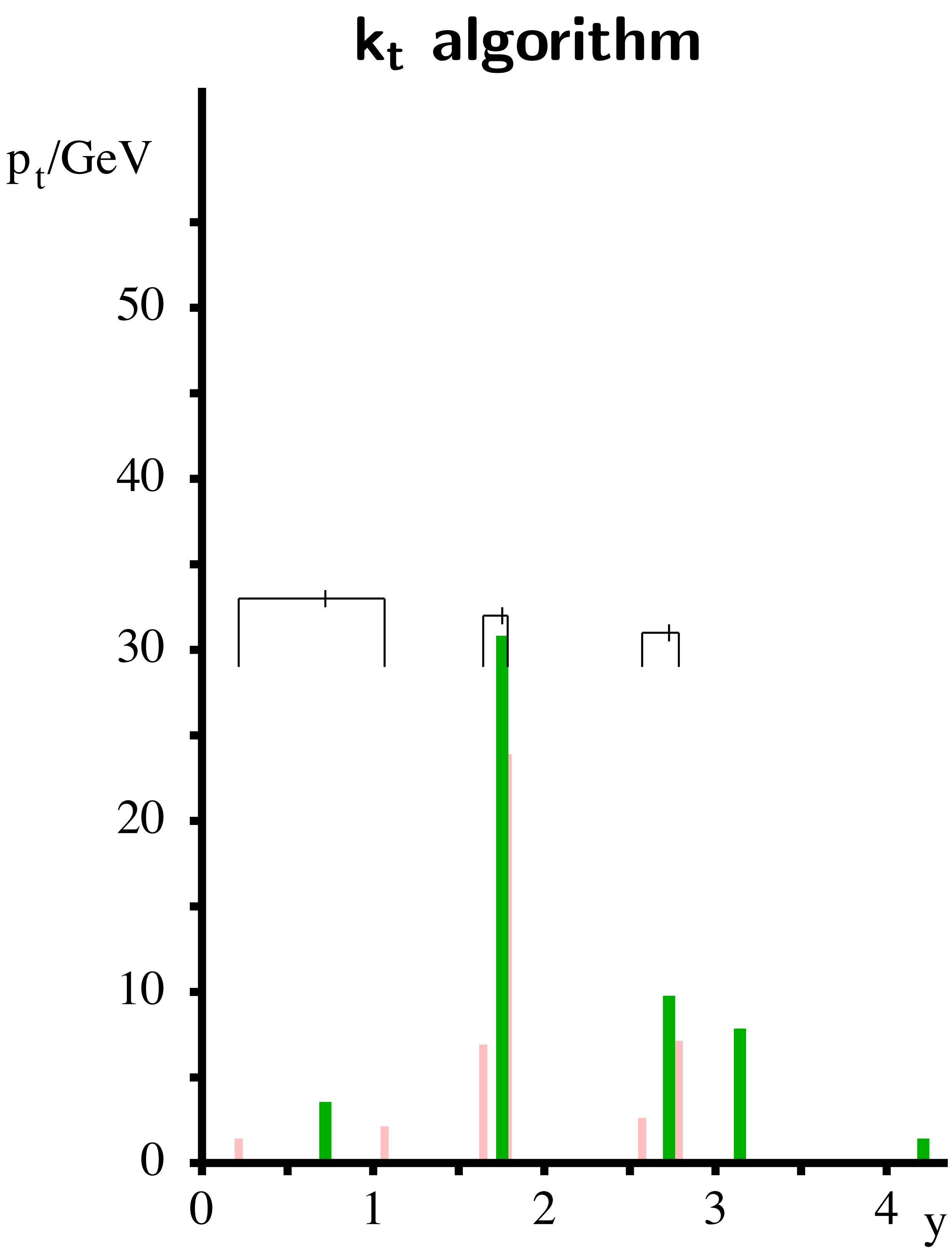

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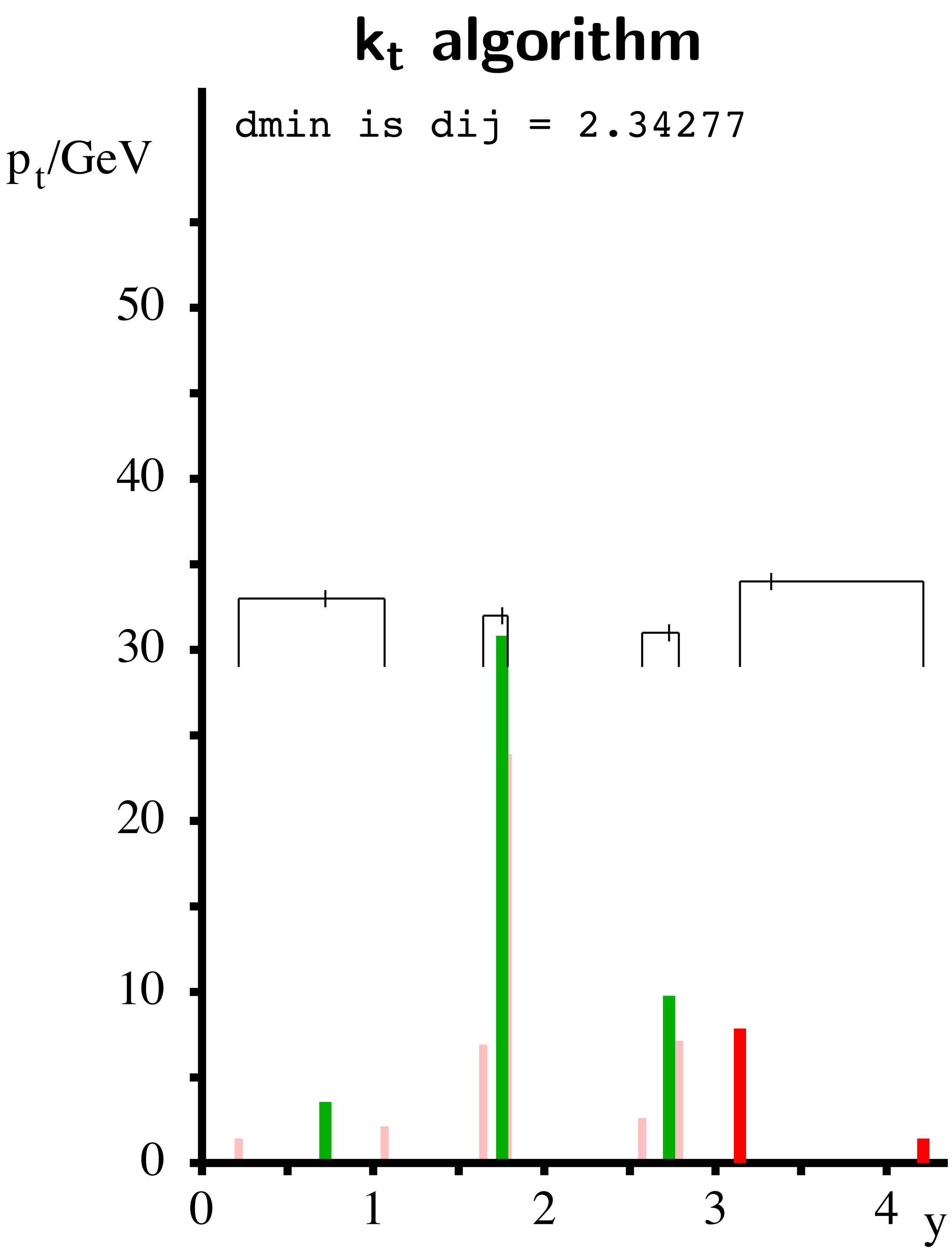

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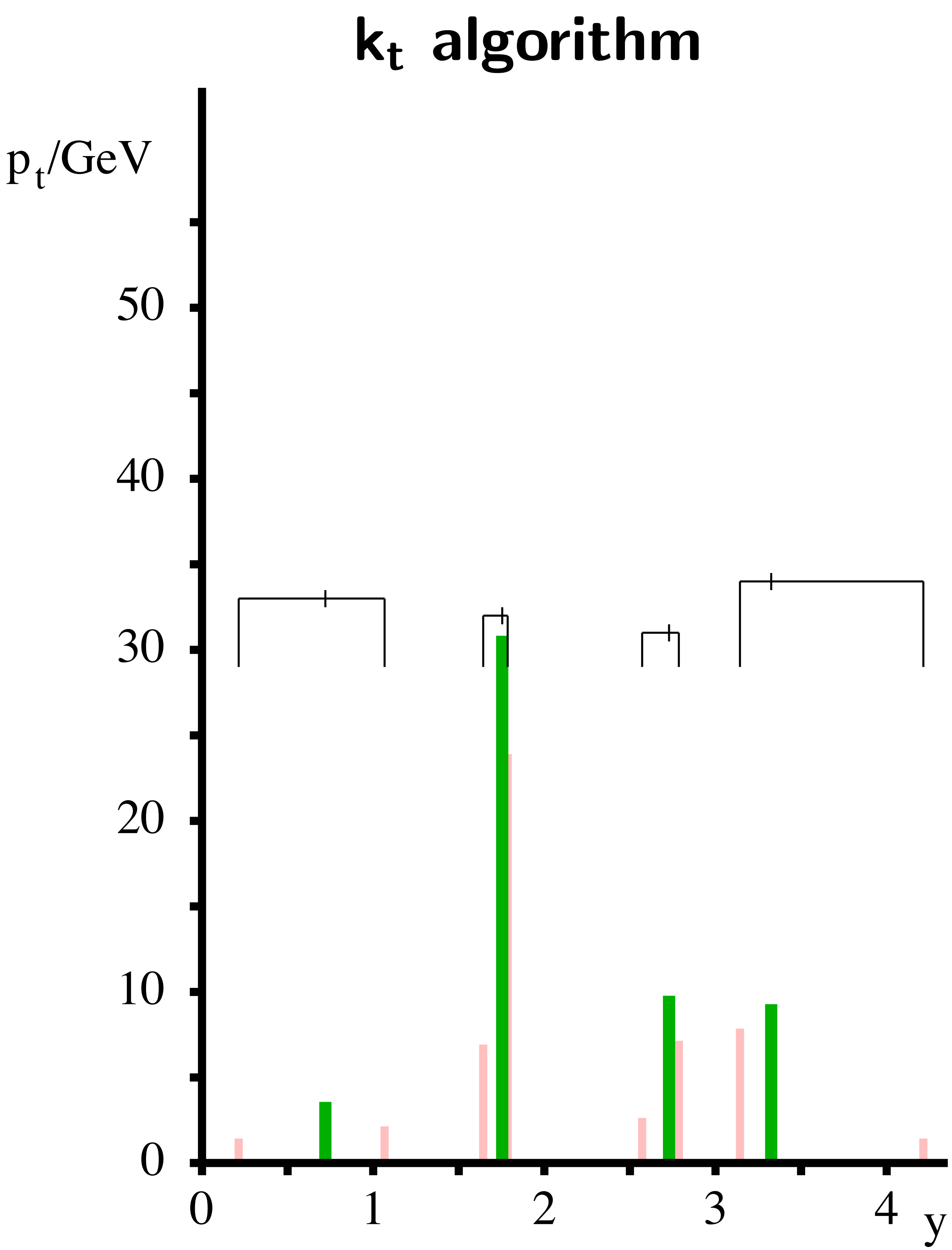

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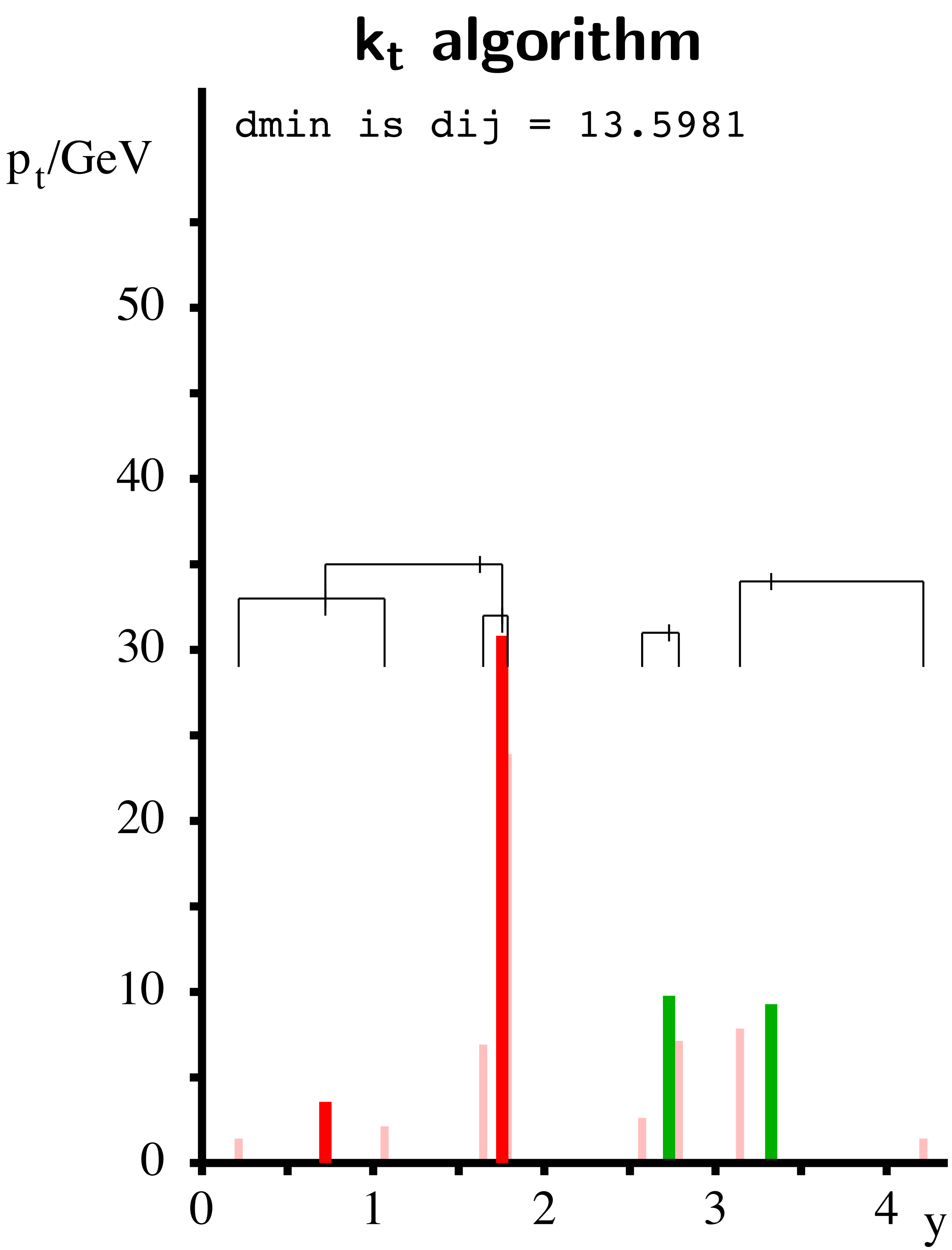

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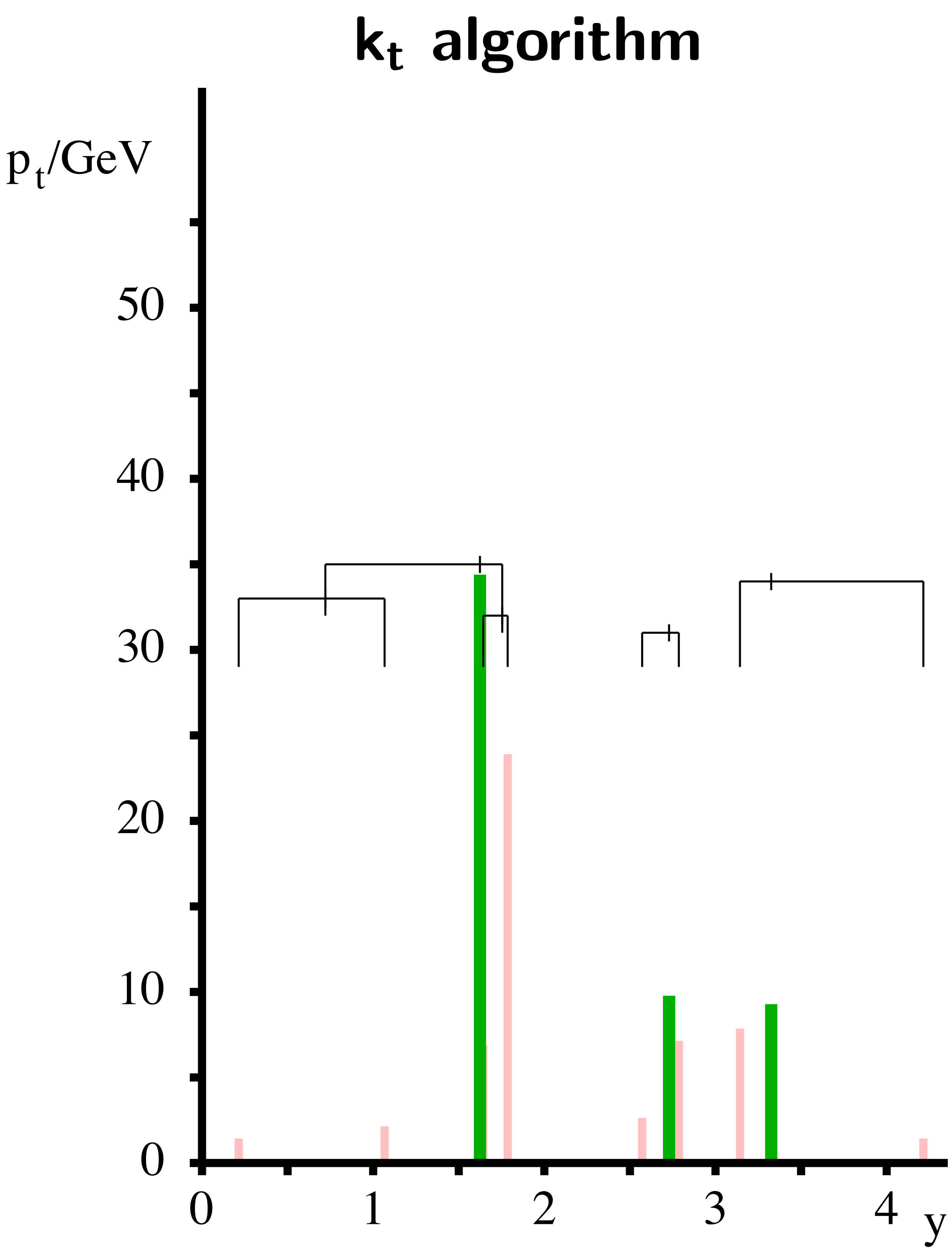

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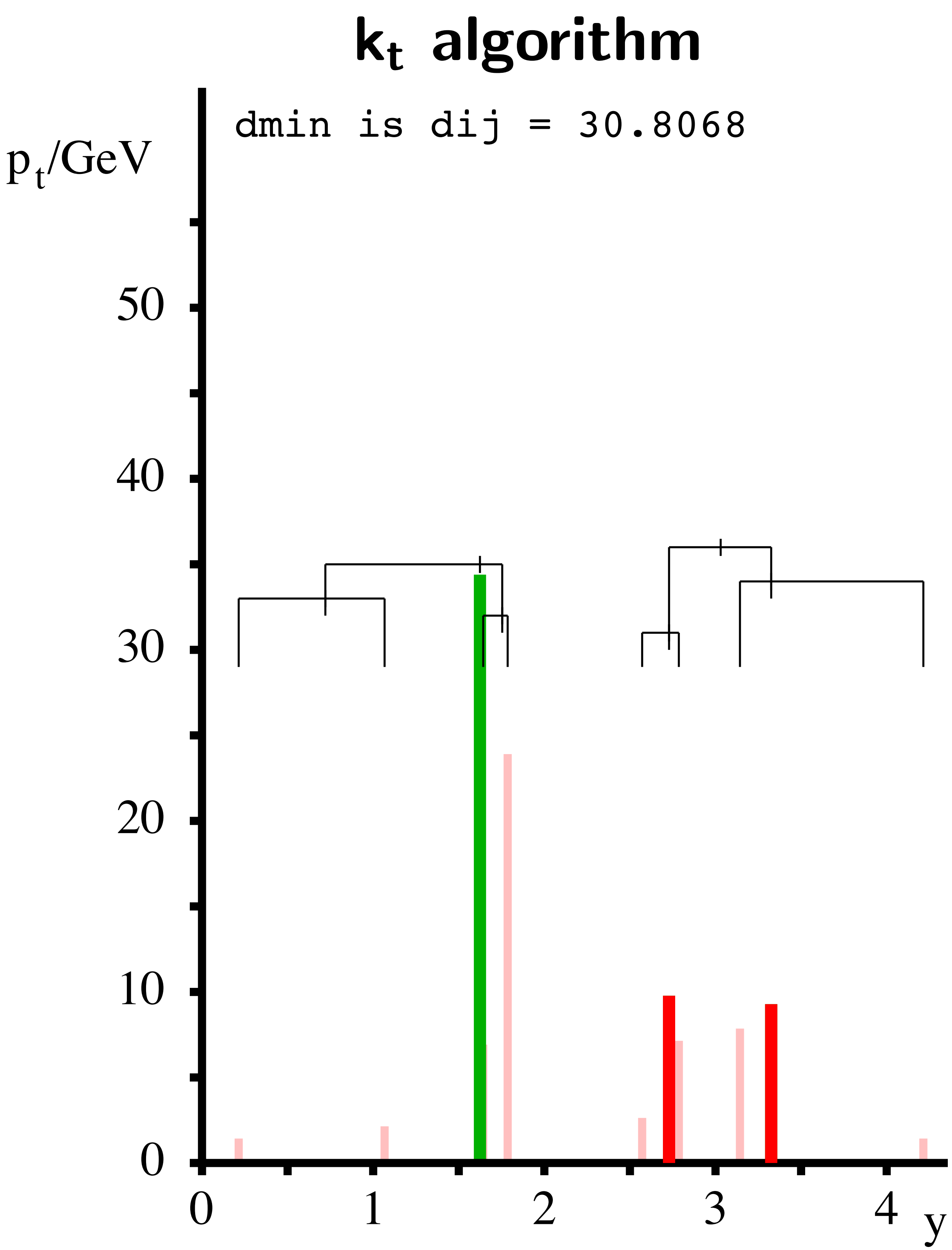

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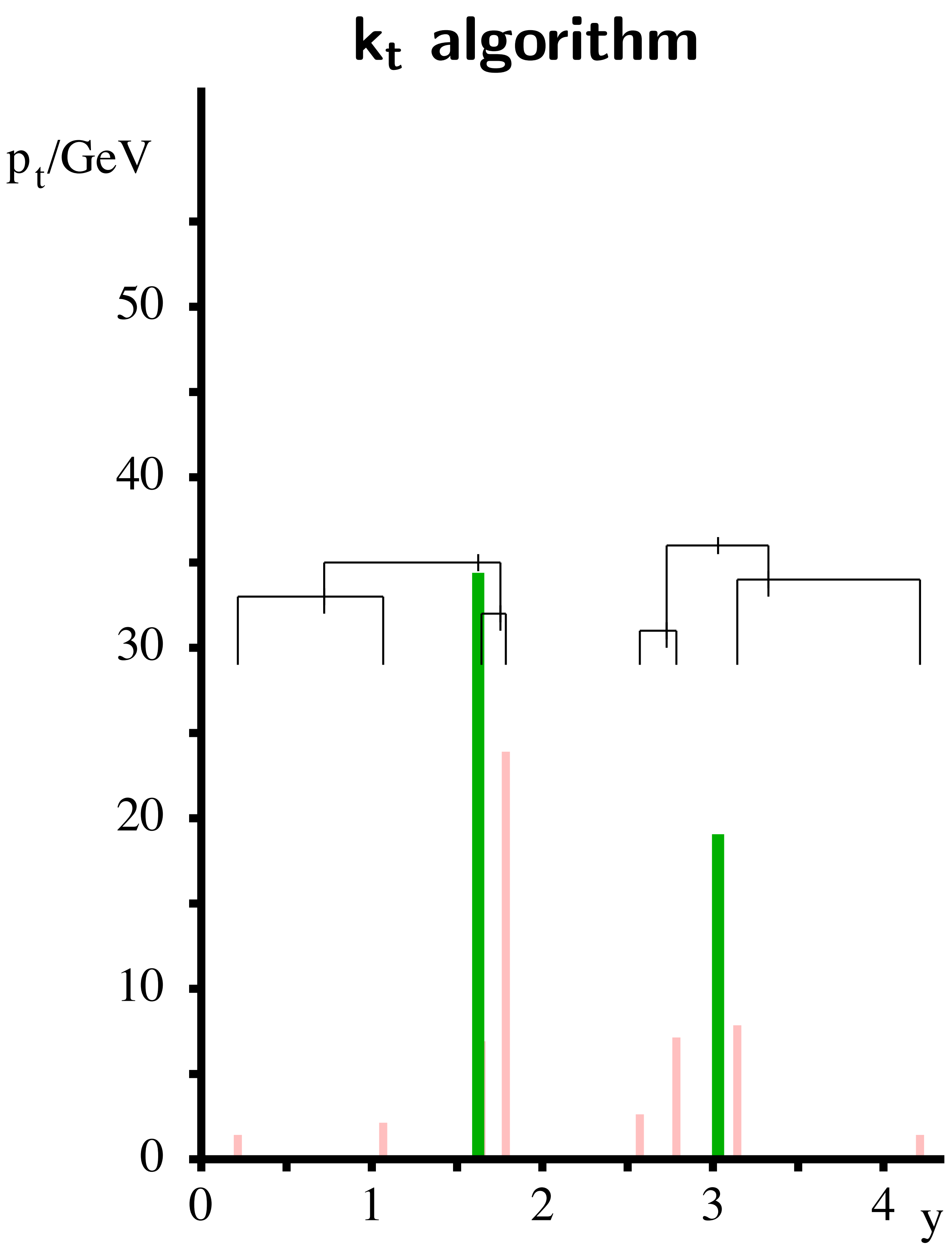

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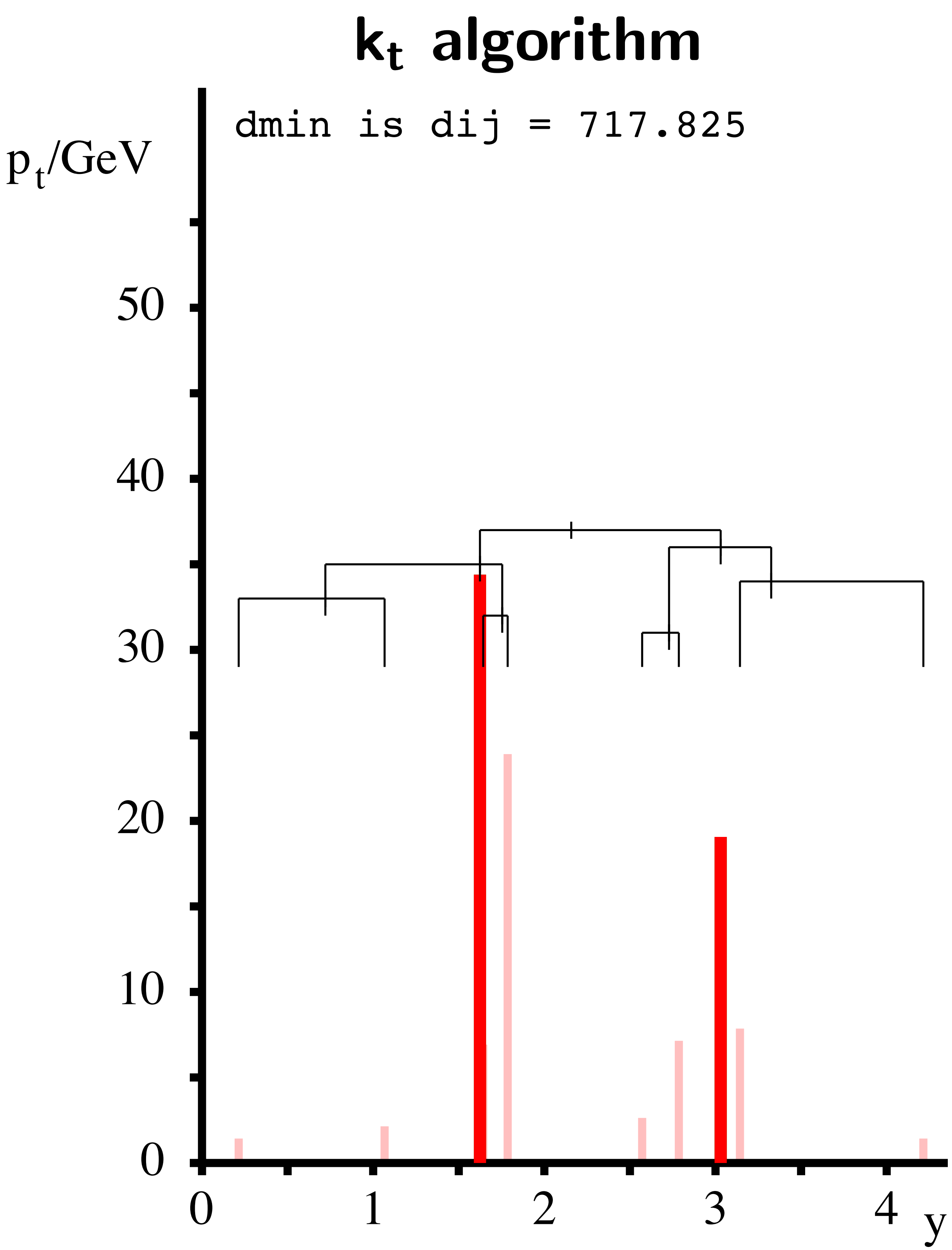

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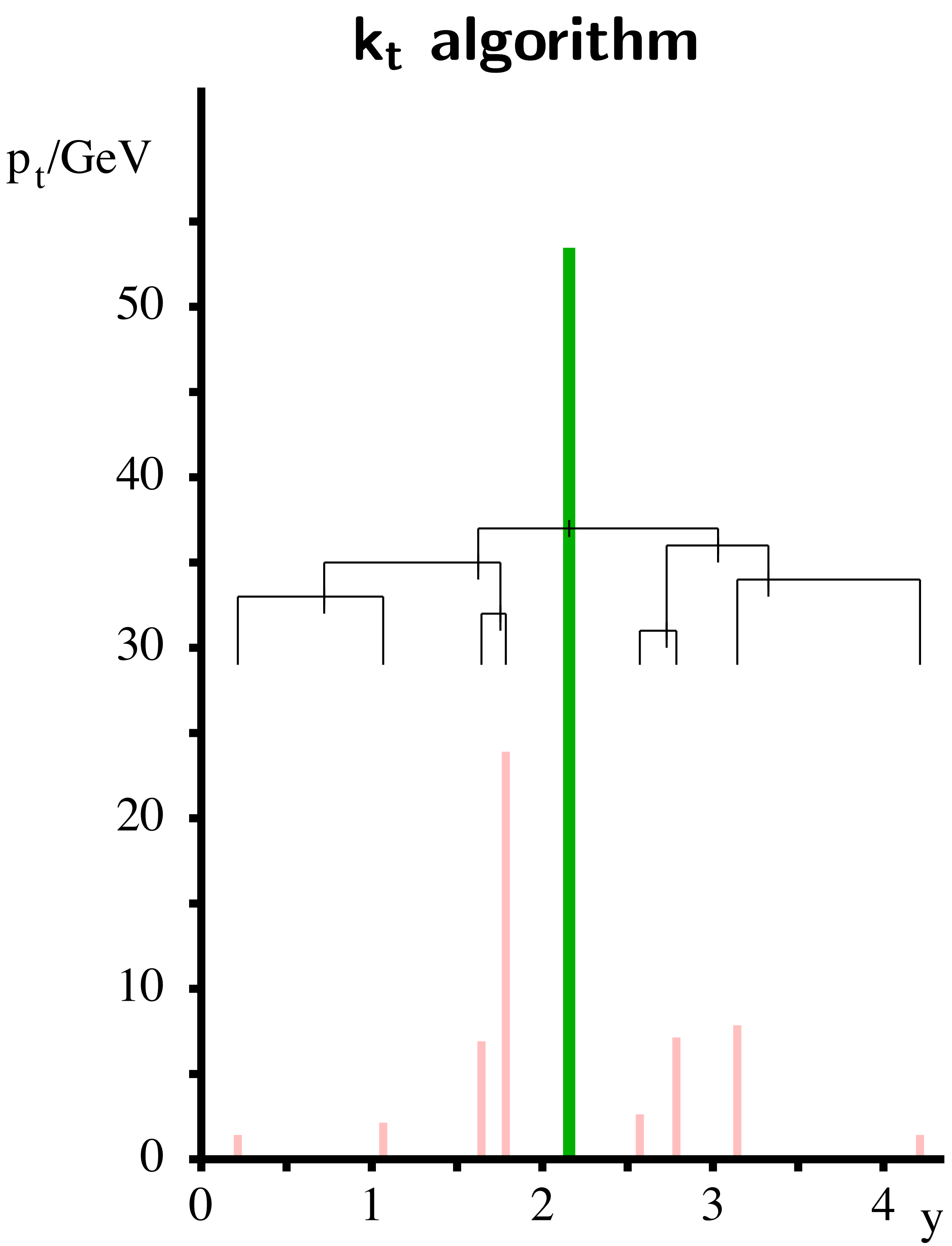
Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics



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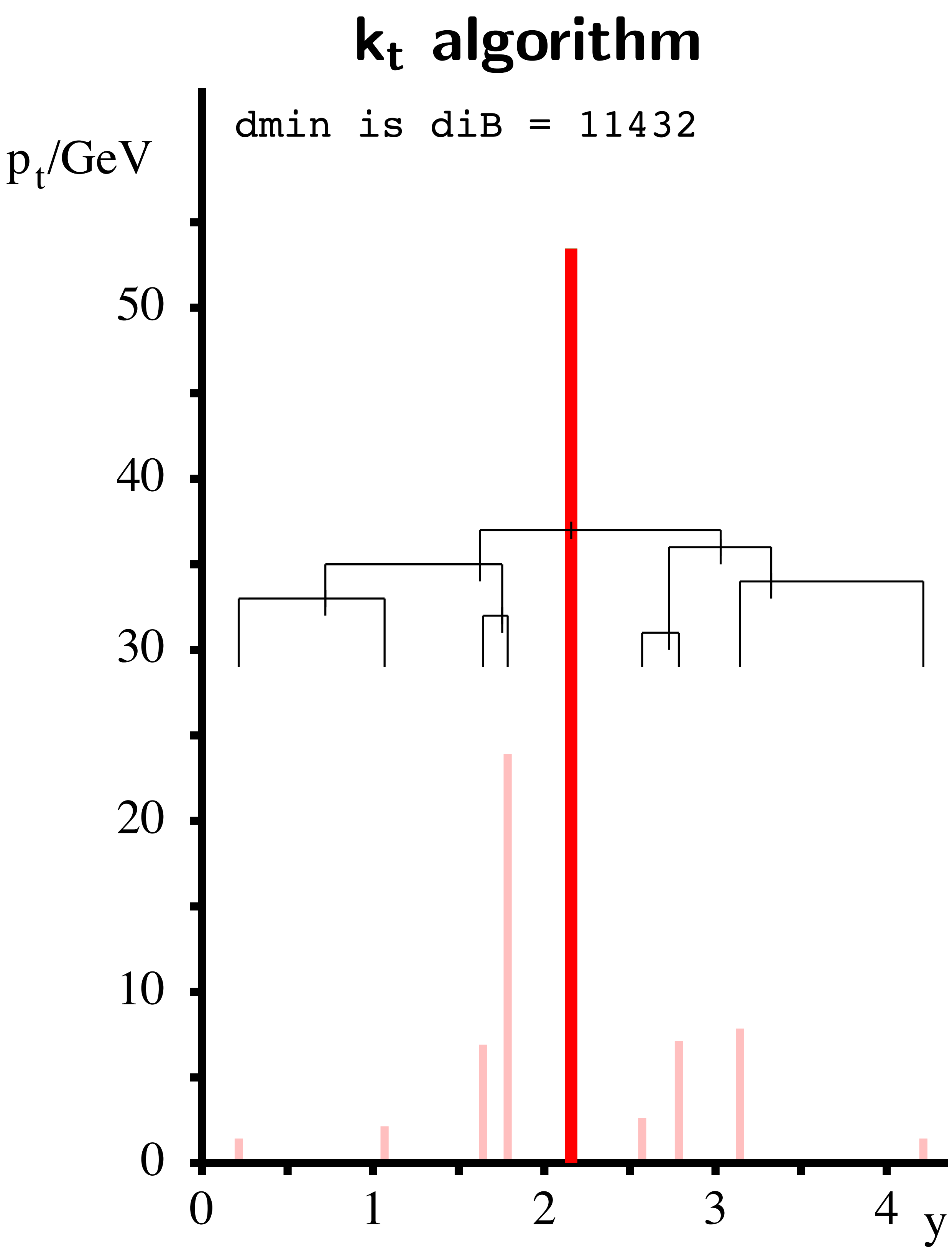

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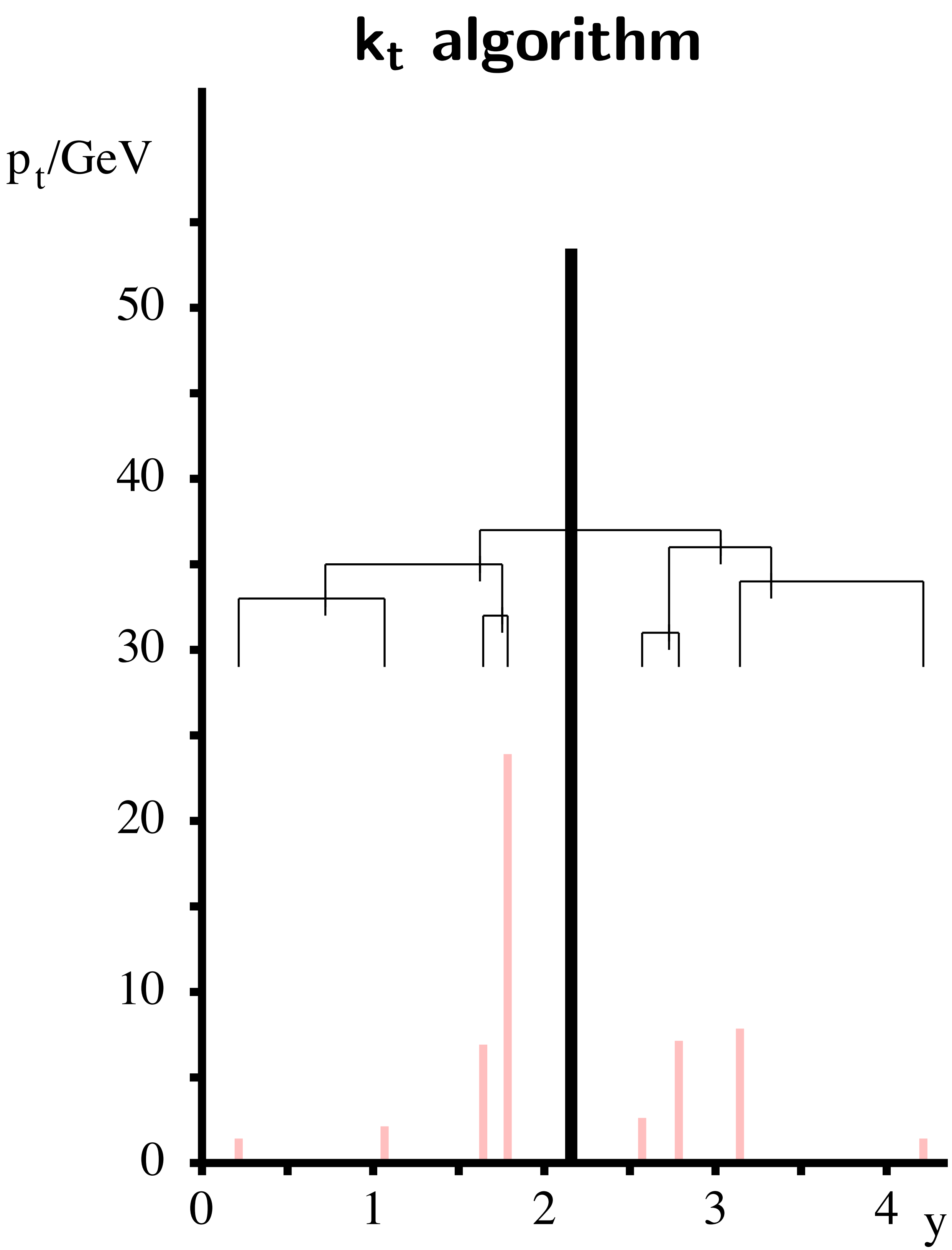

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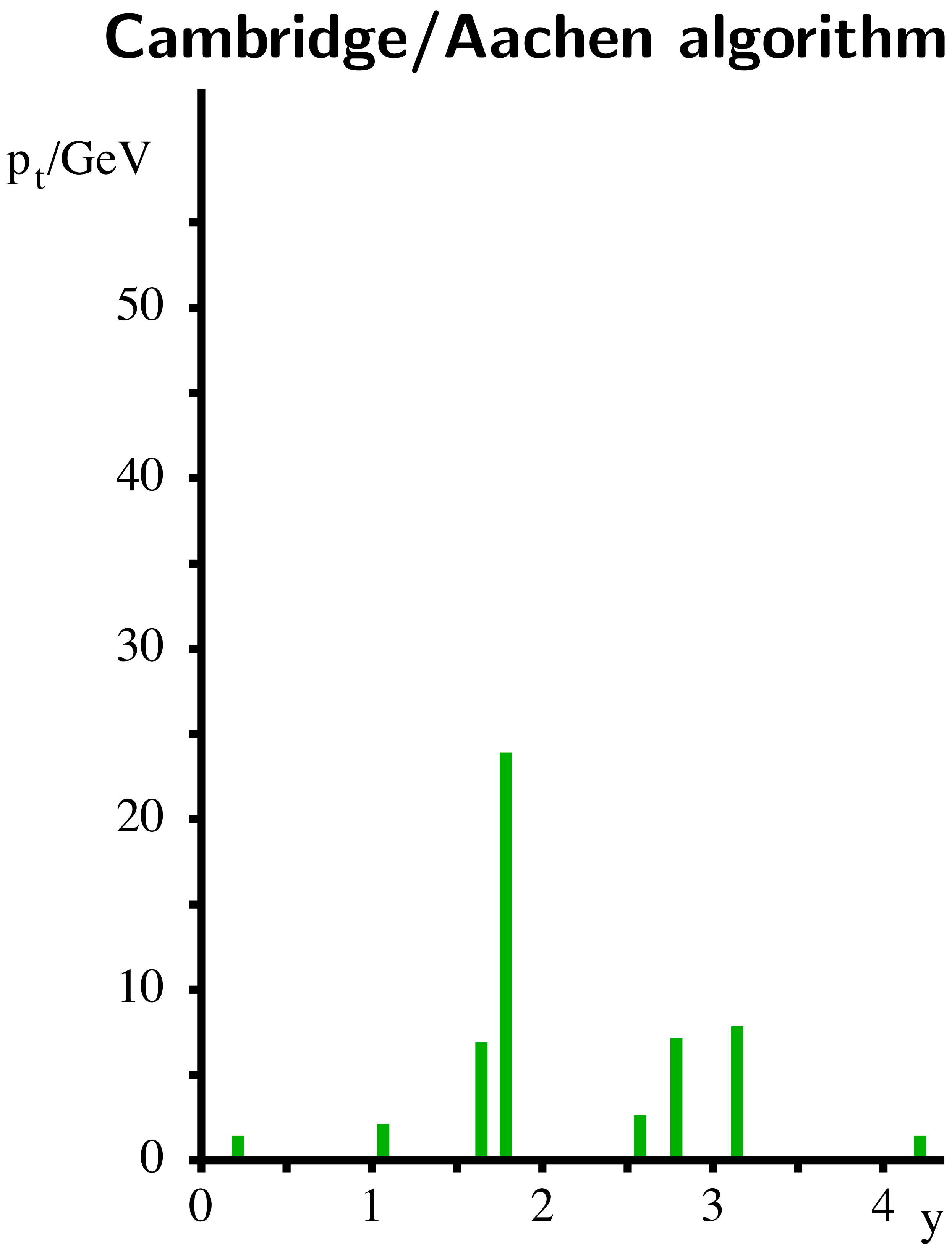
This meant it was the first algorithm to be used for jet substructure.

Seymour '93

Butterworth, Cox & Forshaw '02



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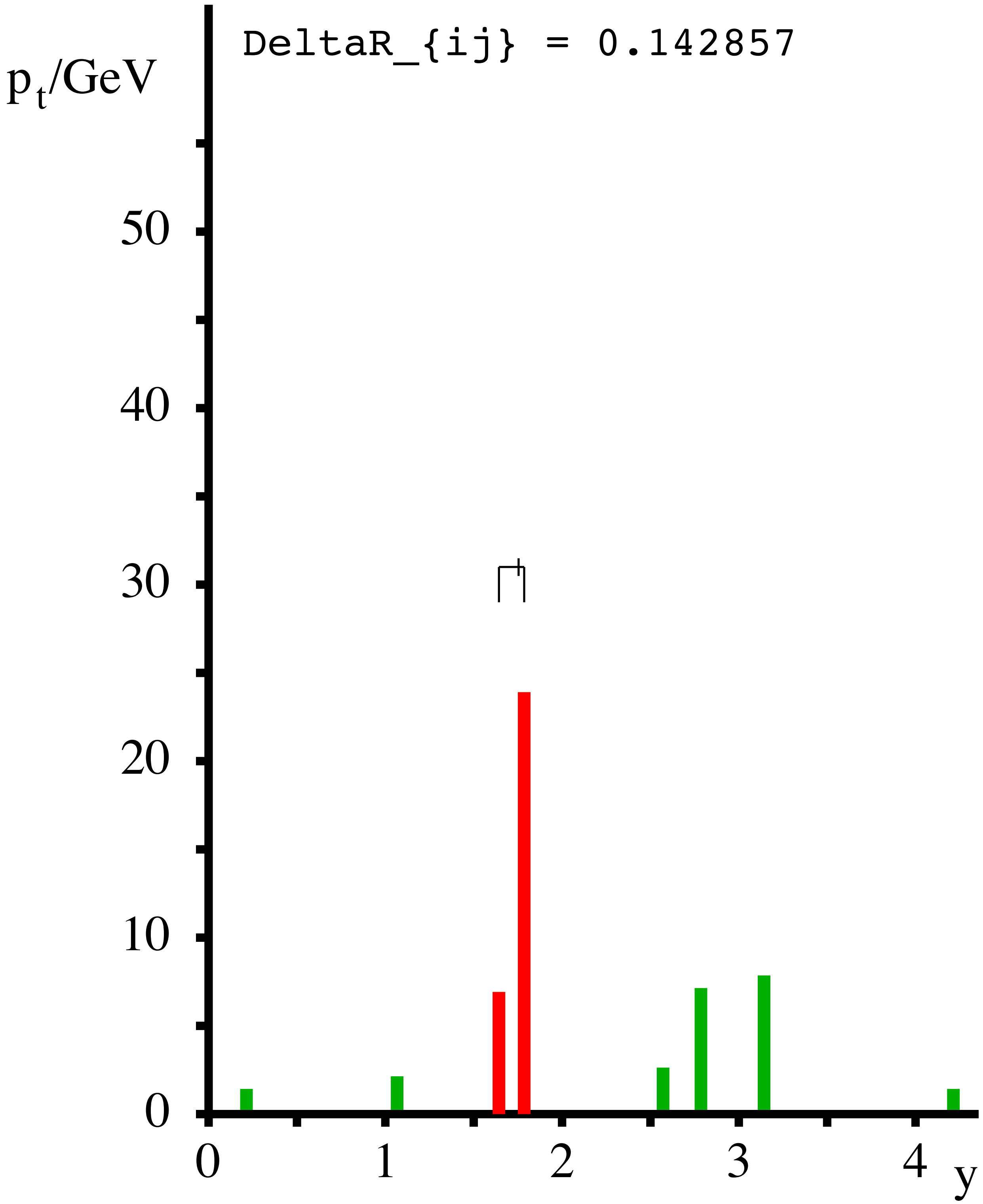

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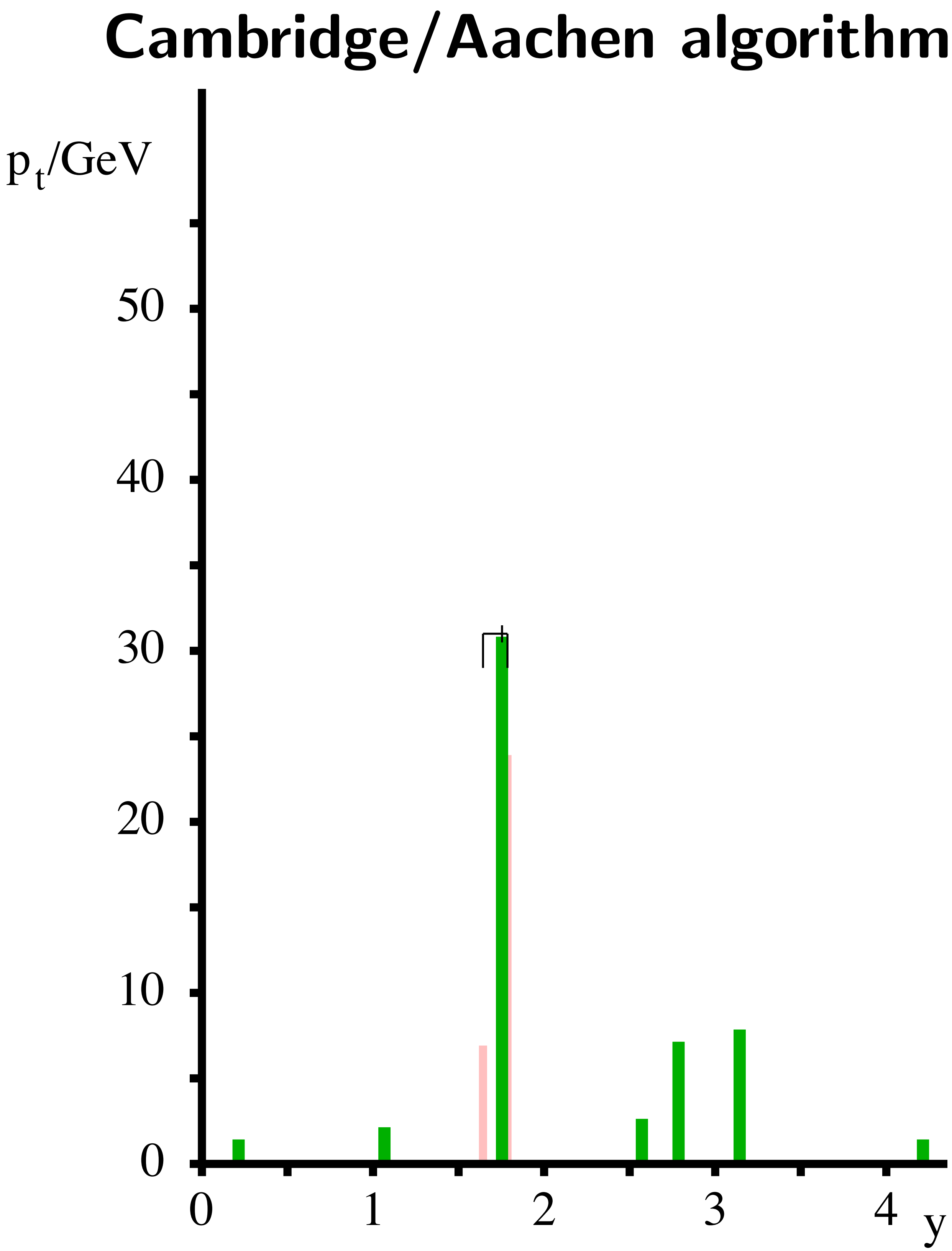

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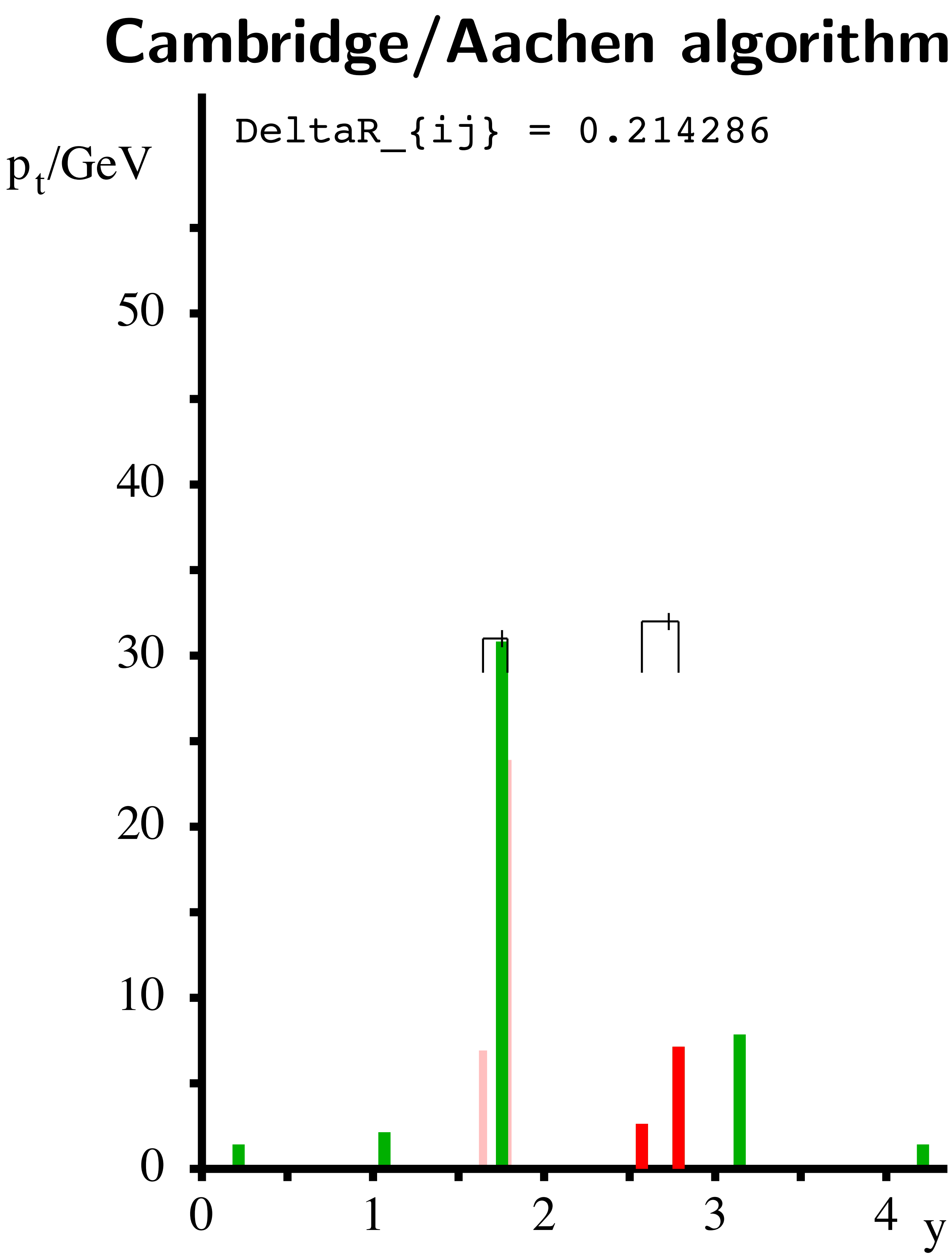

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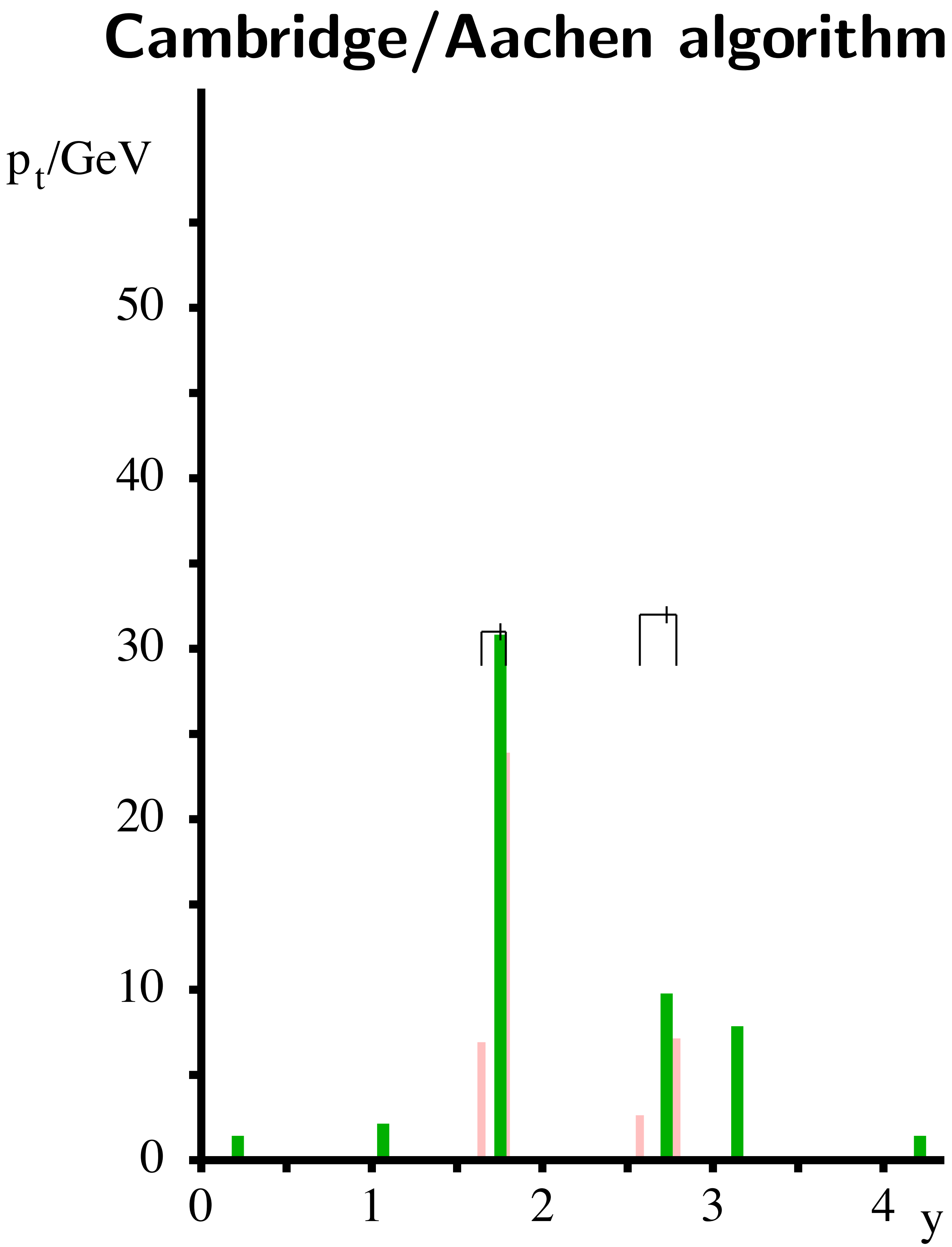

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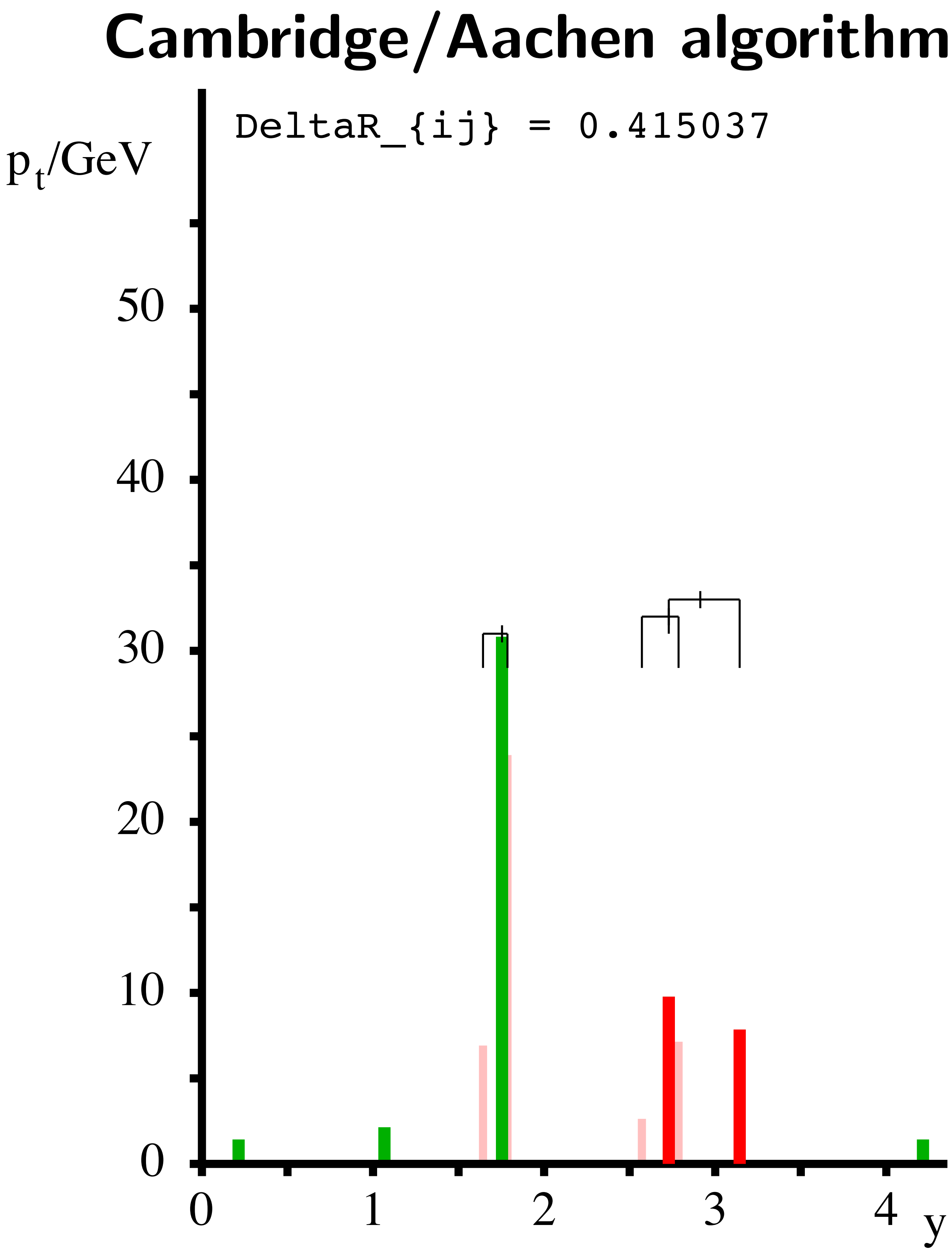

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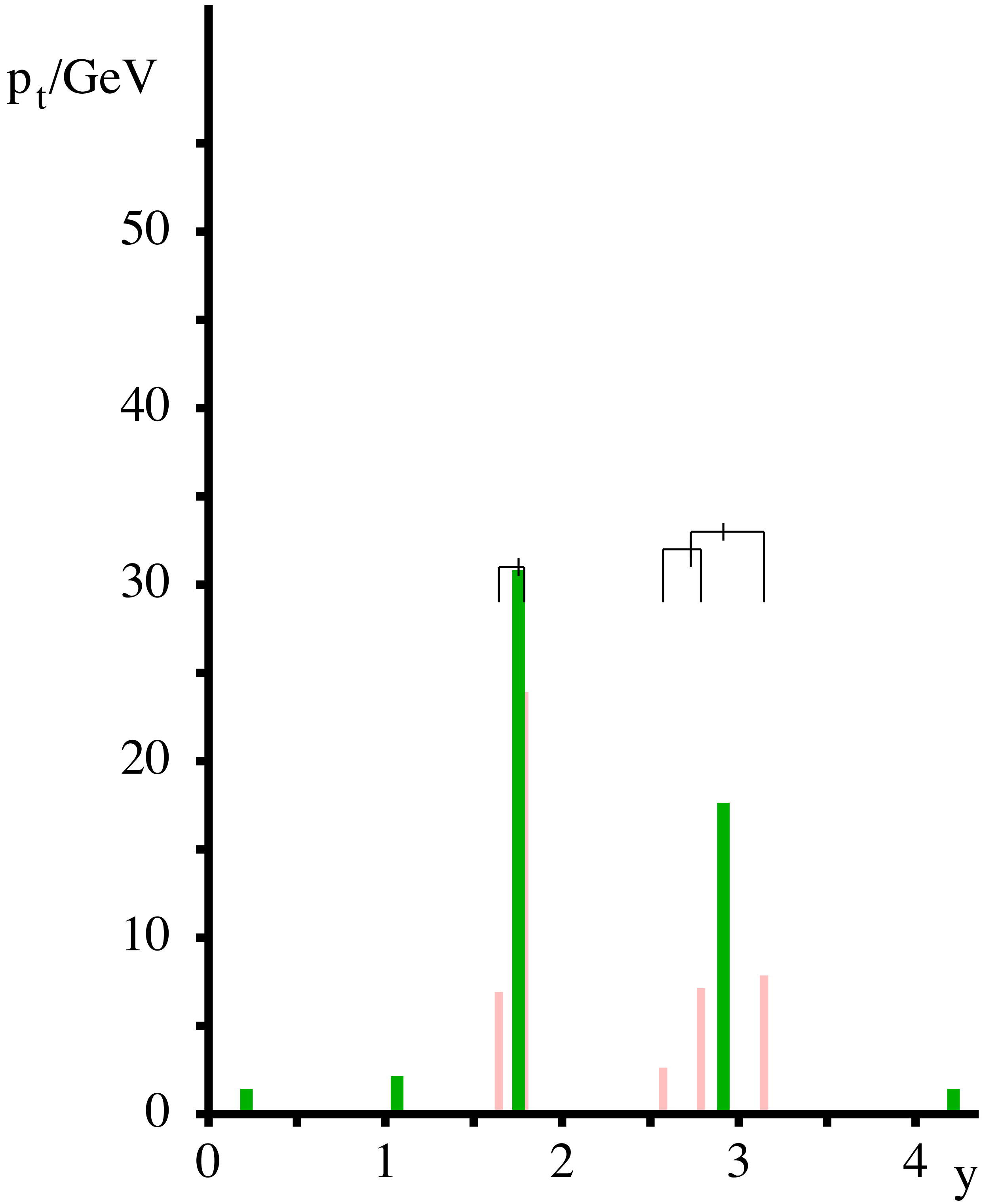

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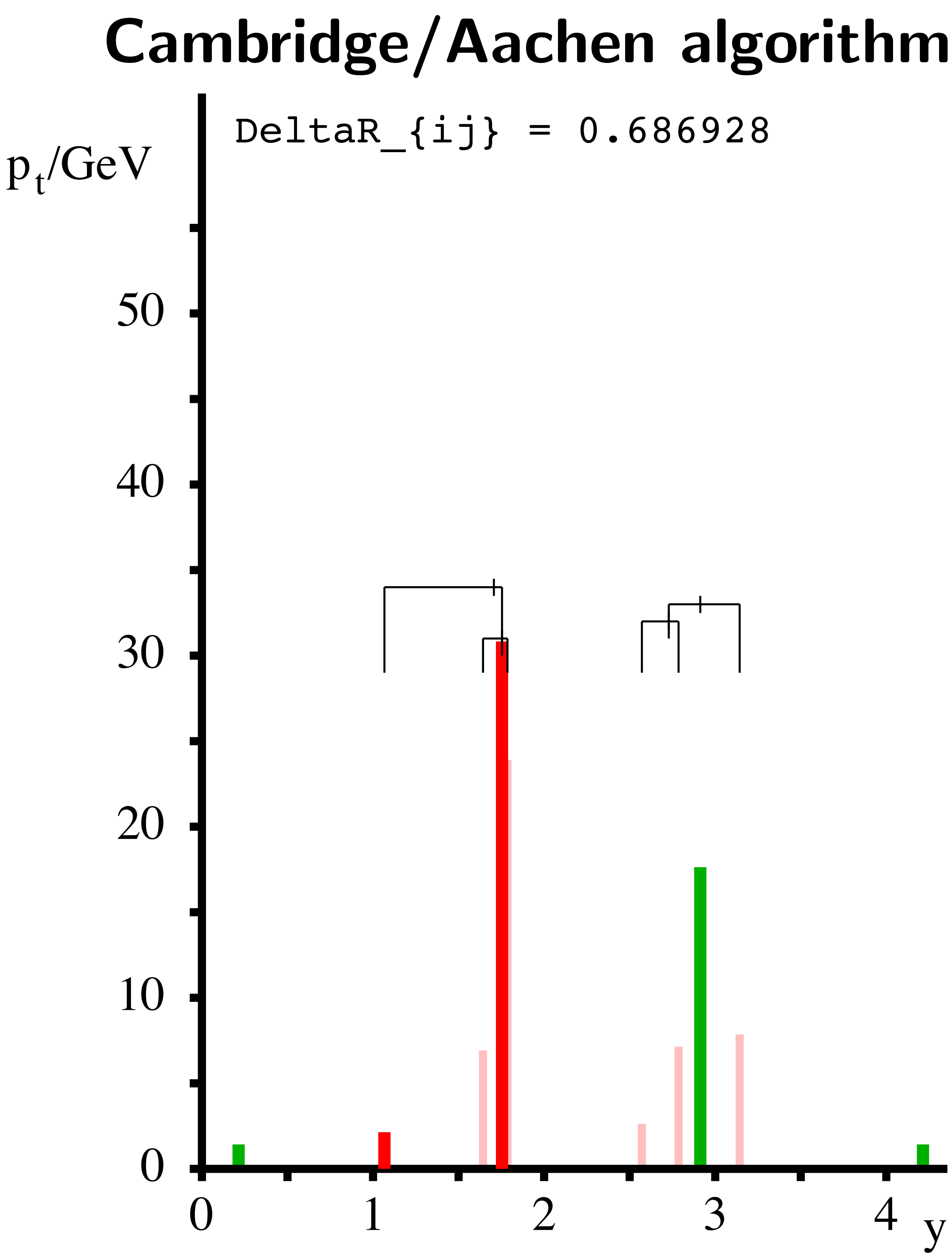

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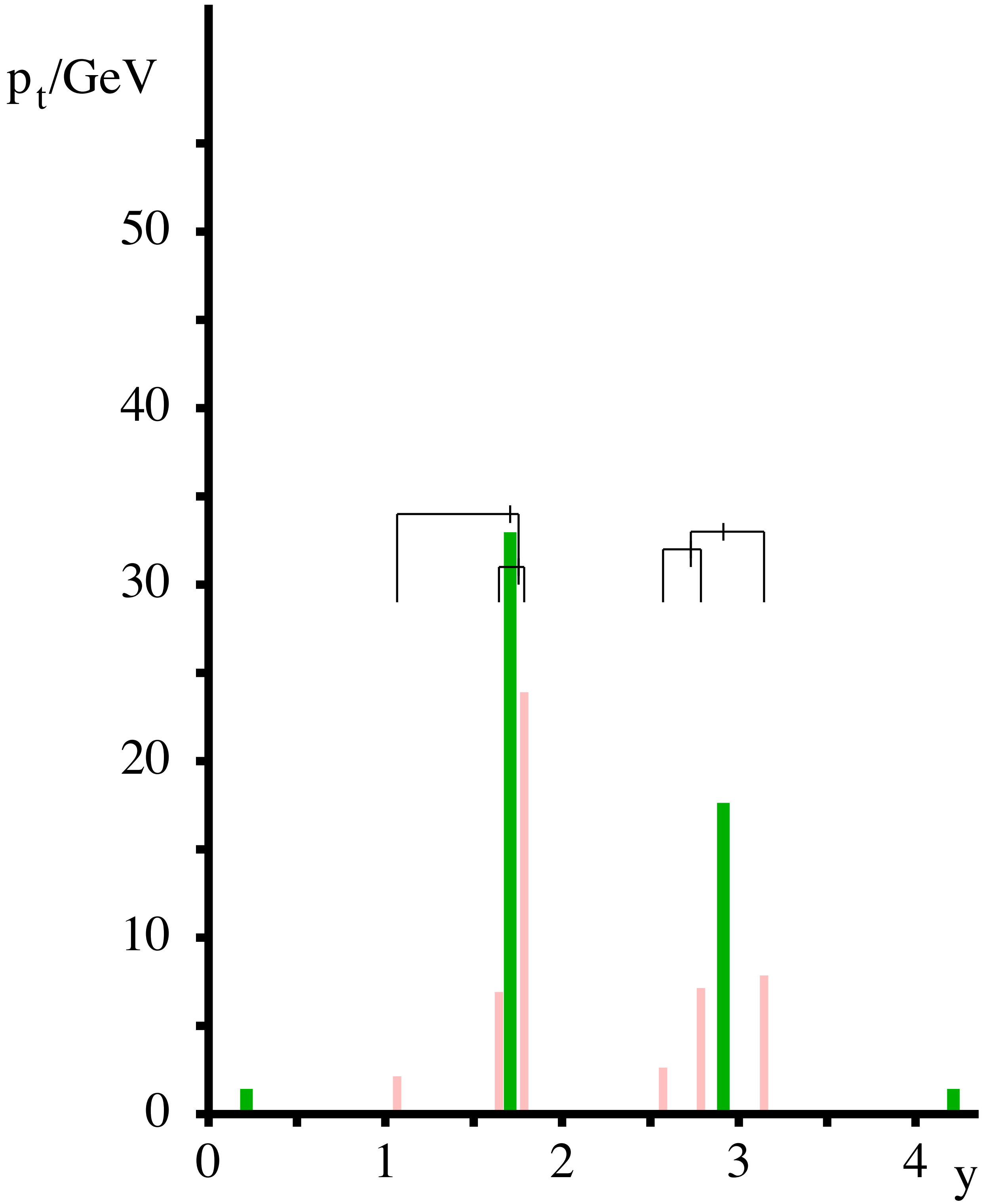

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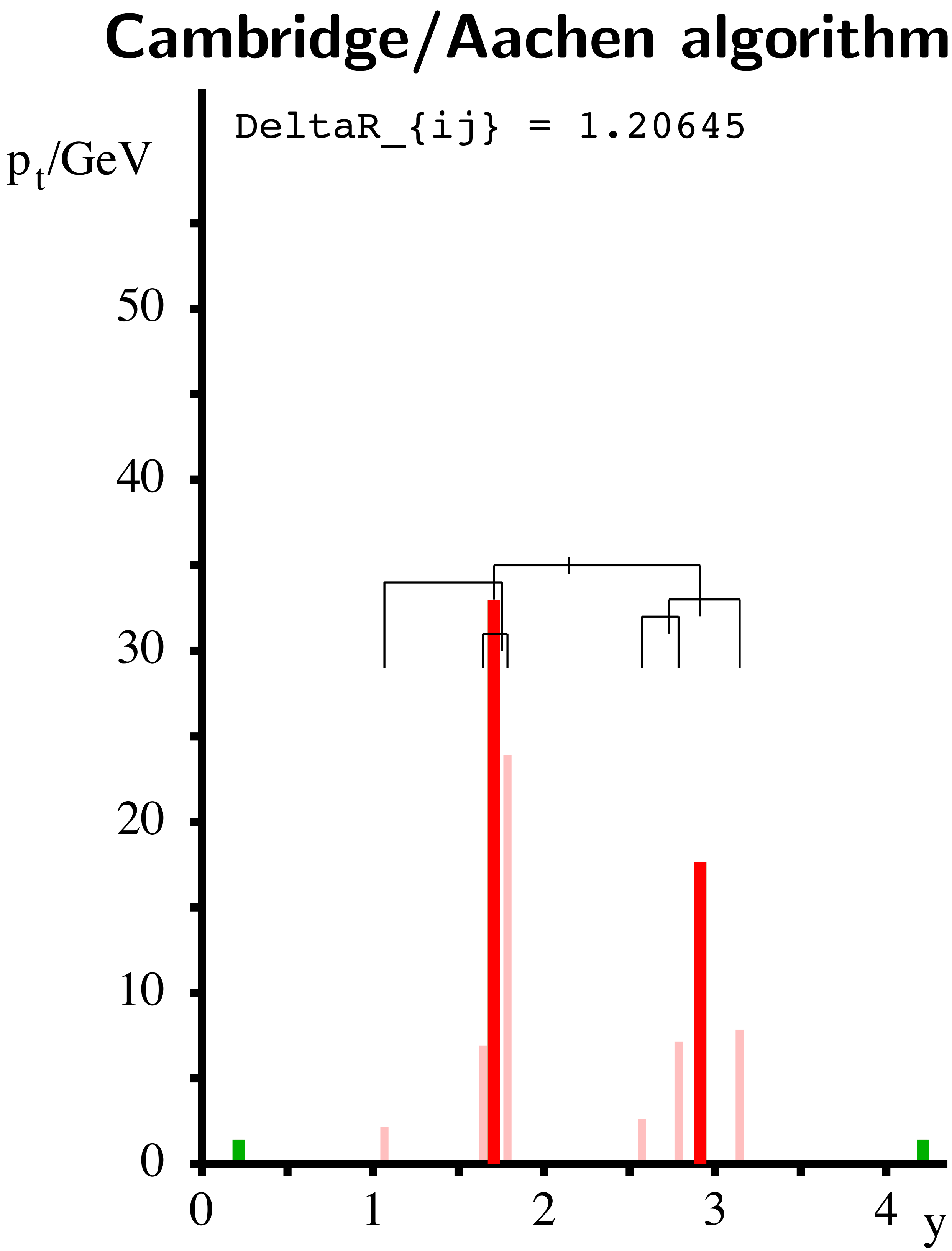
C/A identifies two hard blobs with limited soft contamination



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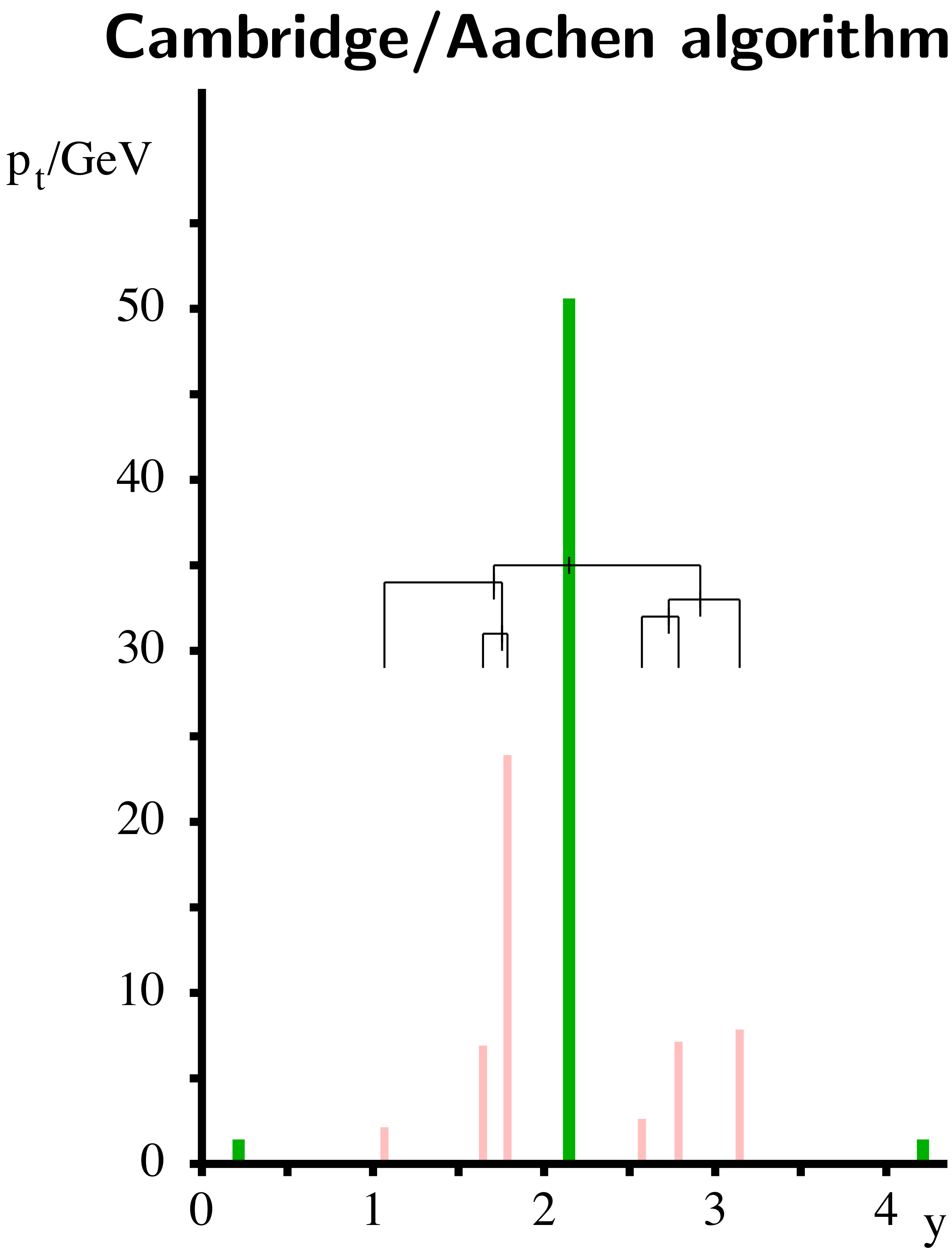

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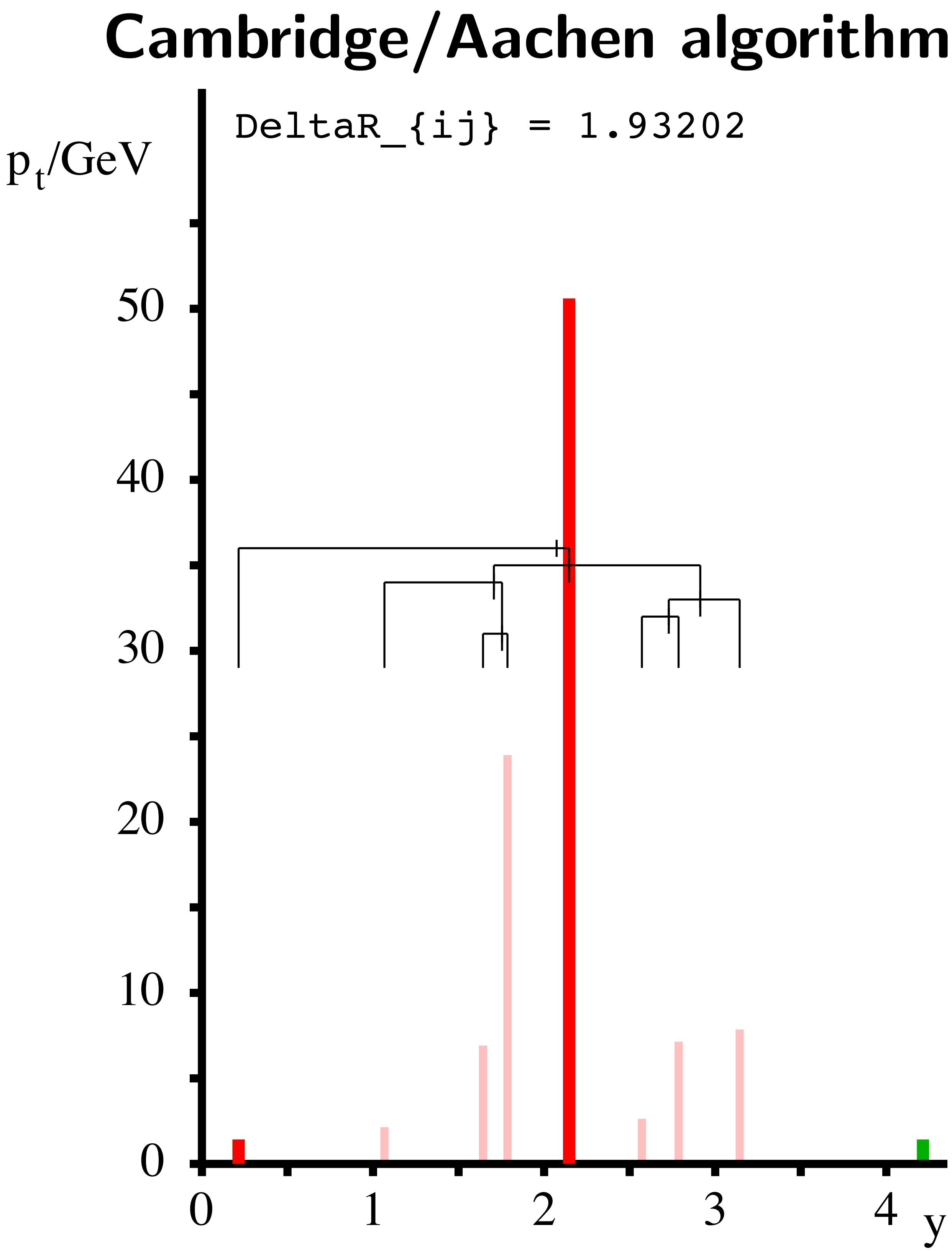

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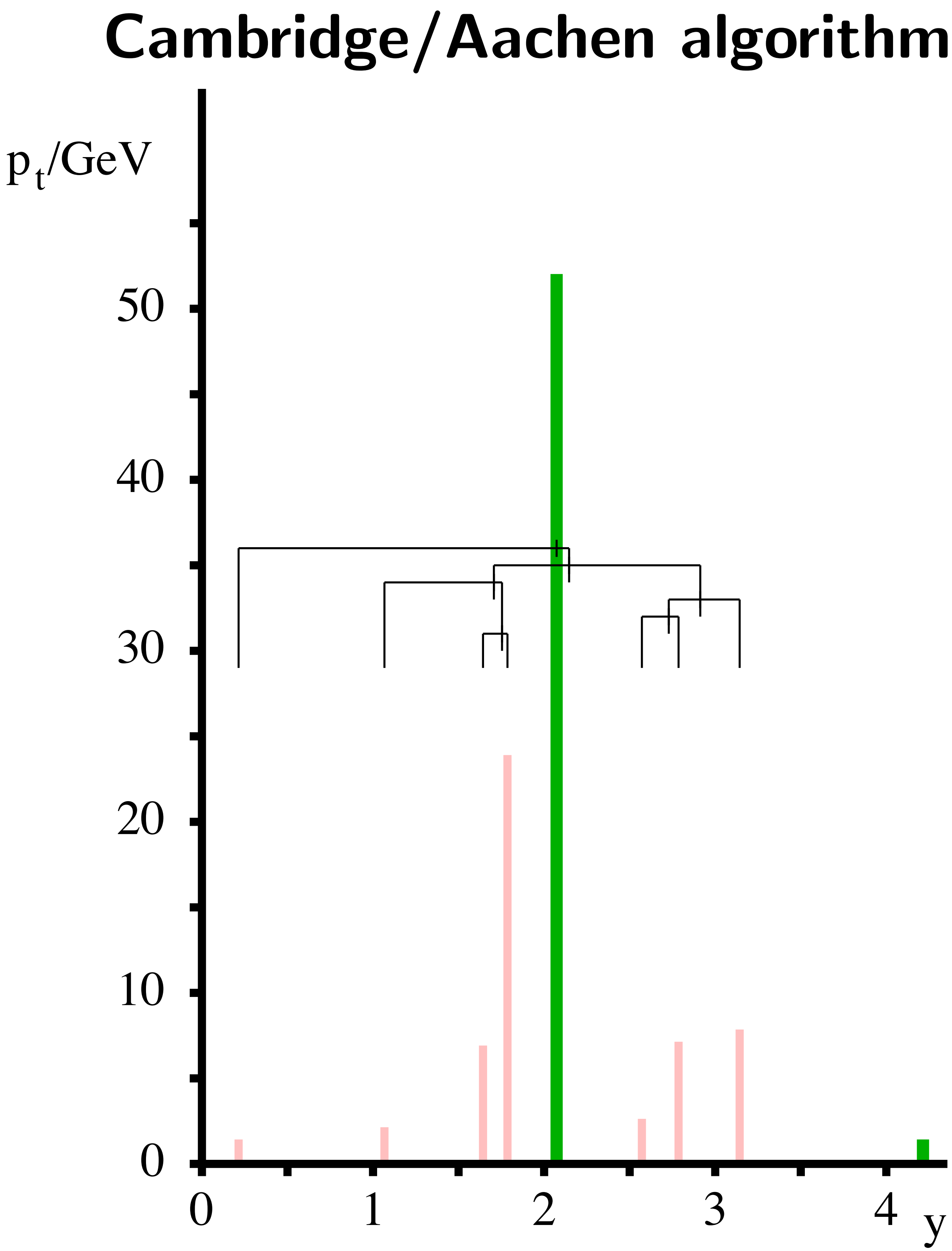

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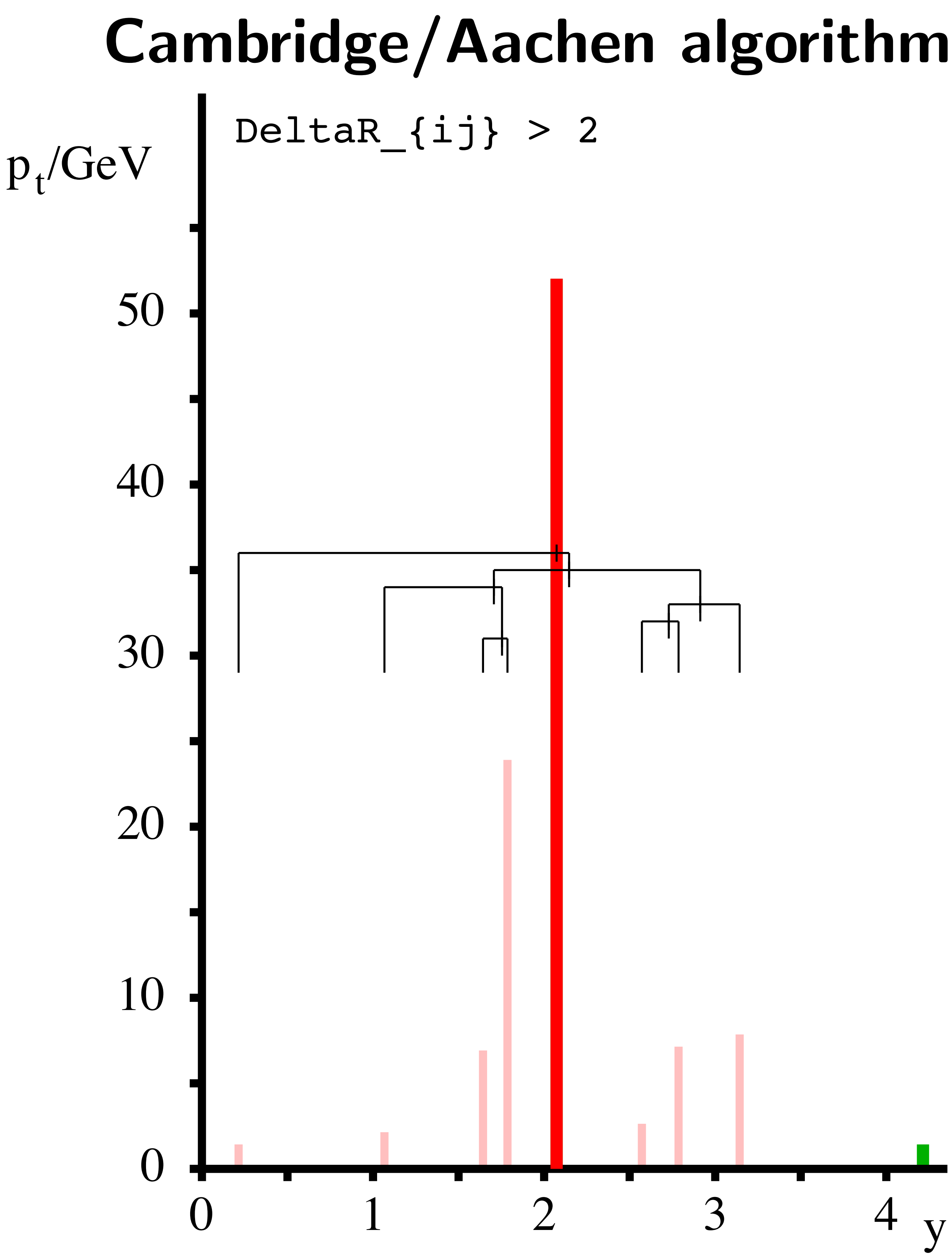

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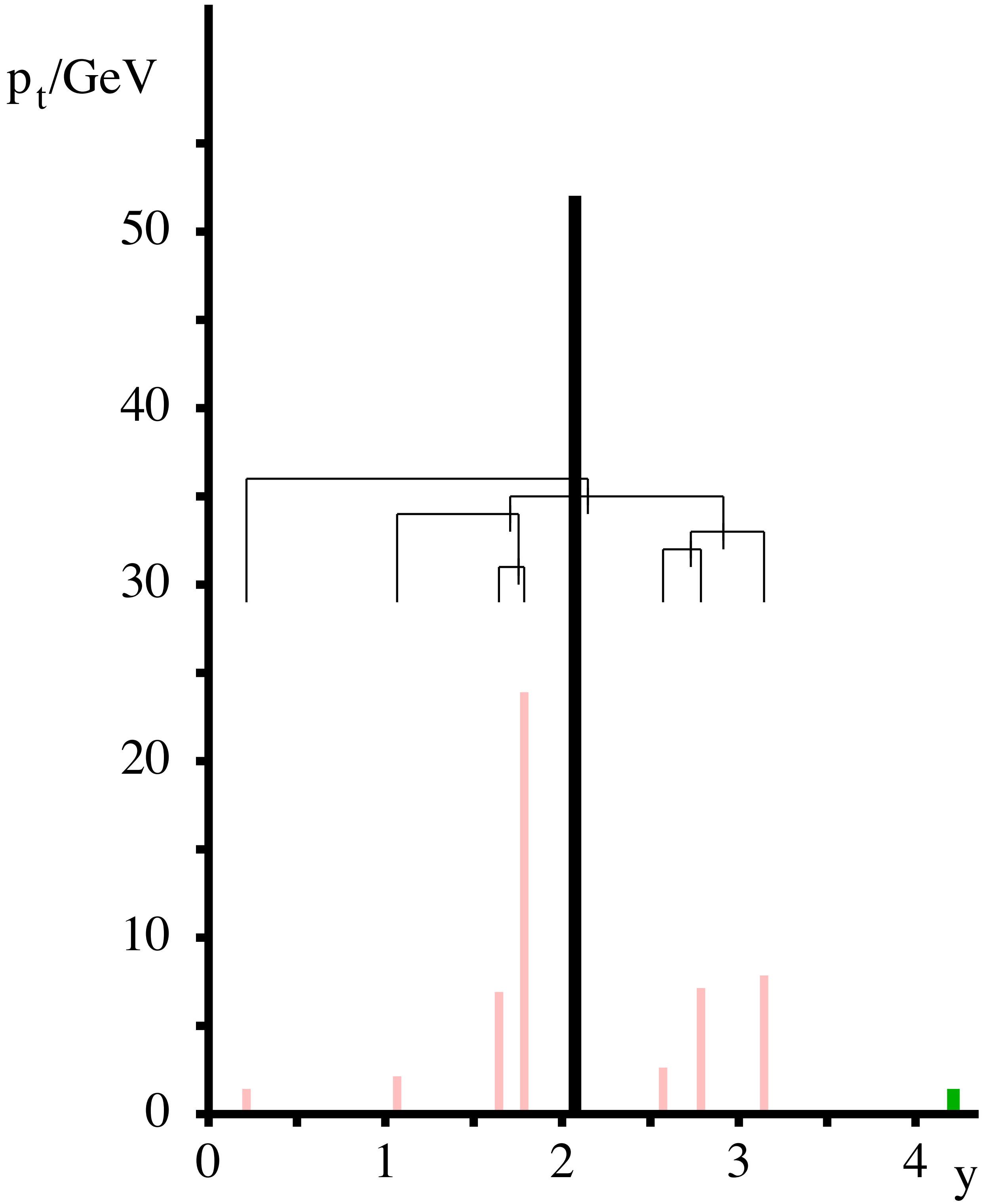
Cambridge/Aachen algorithm



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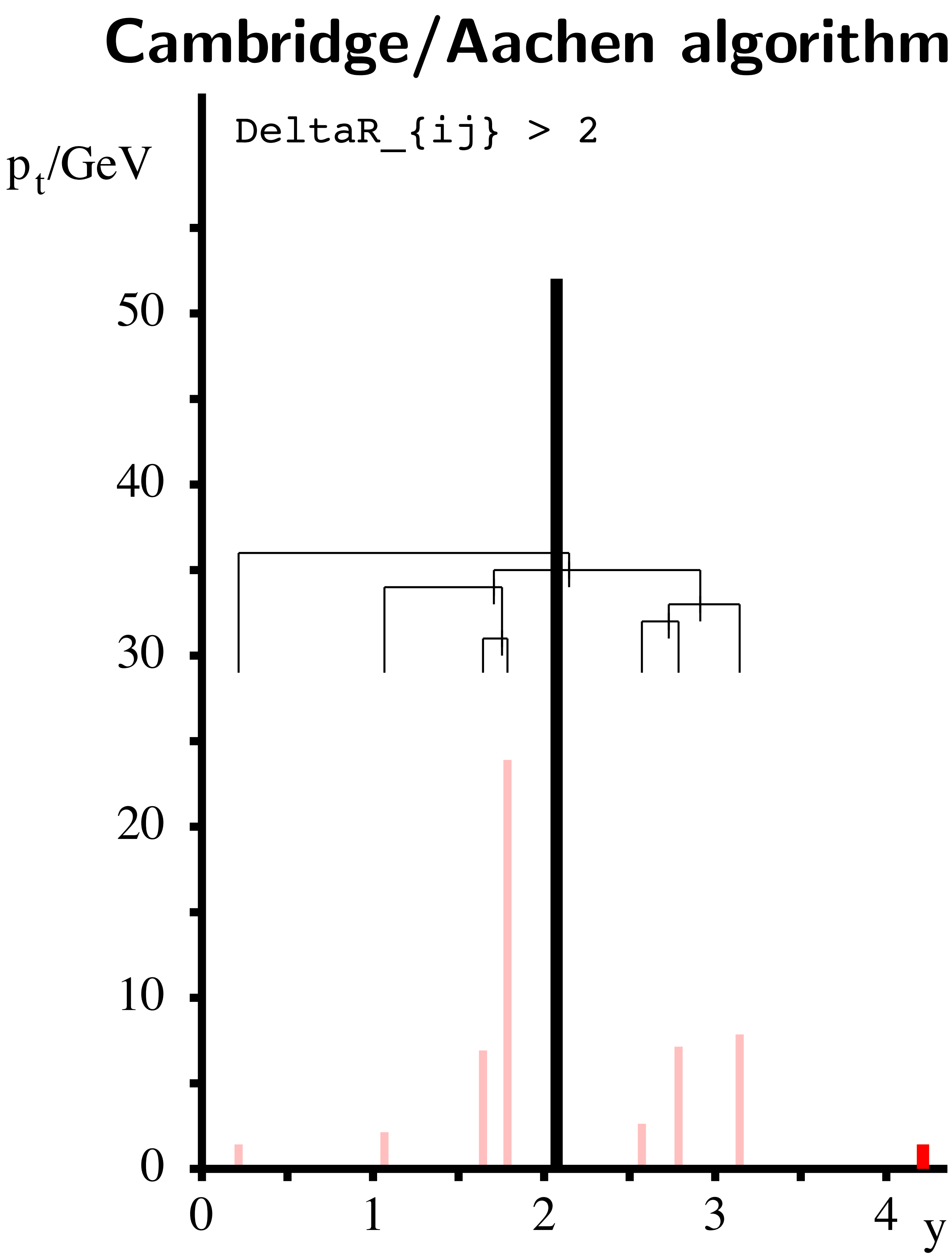

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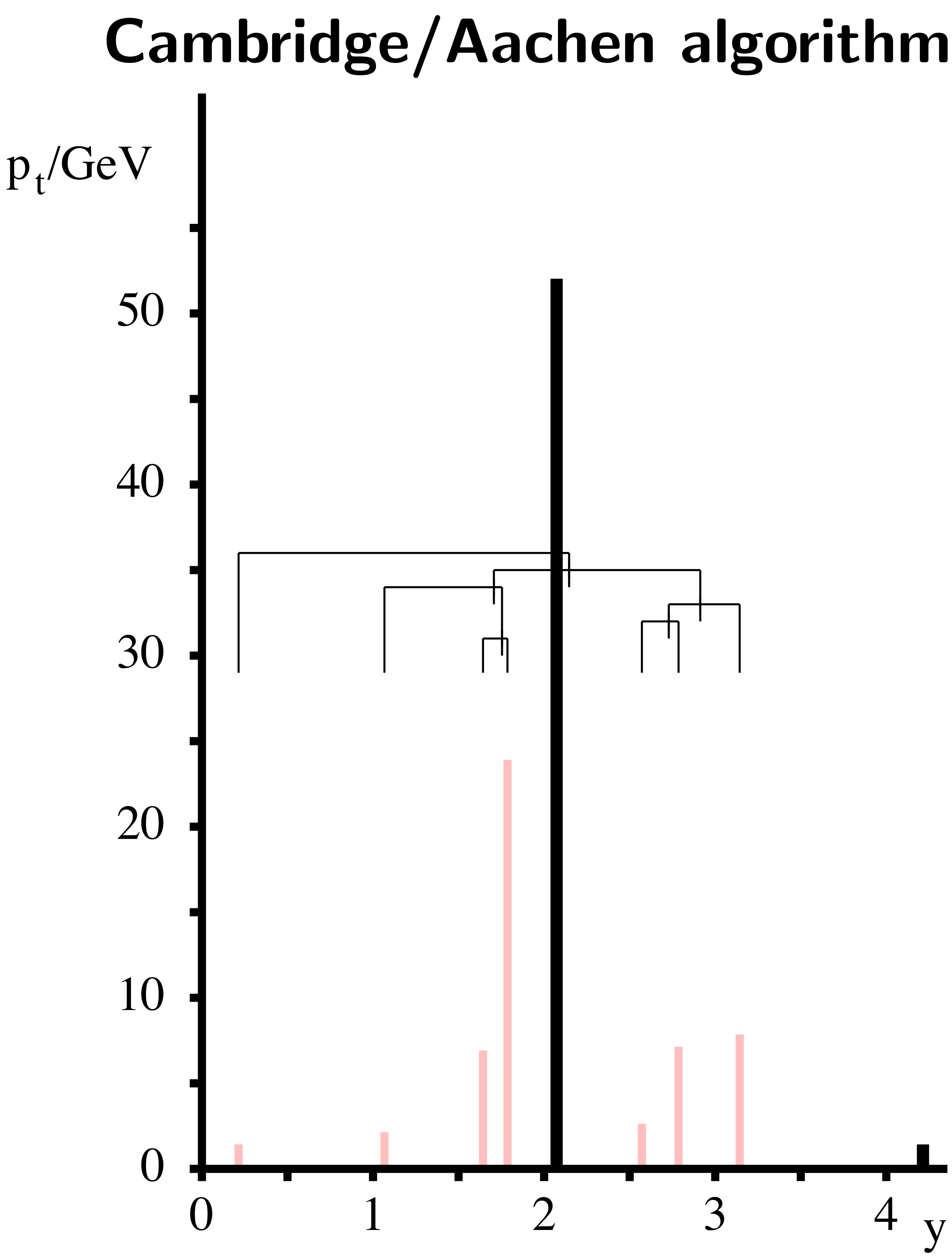


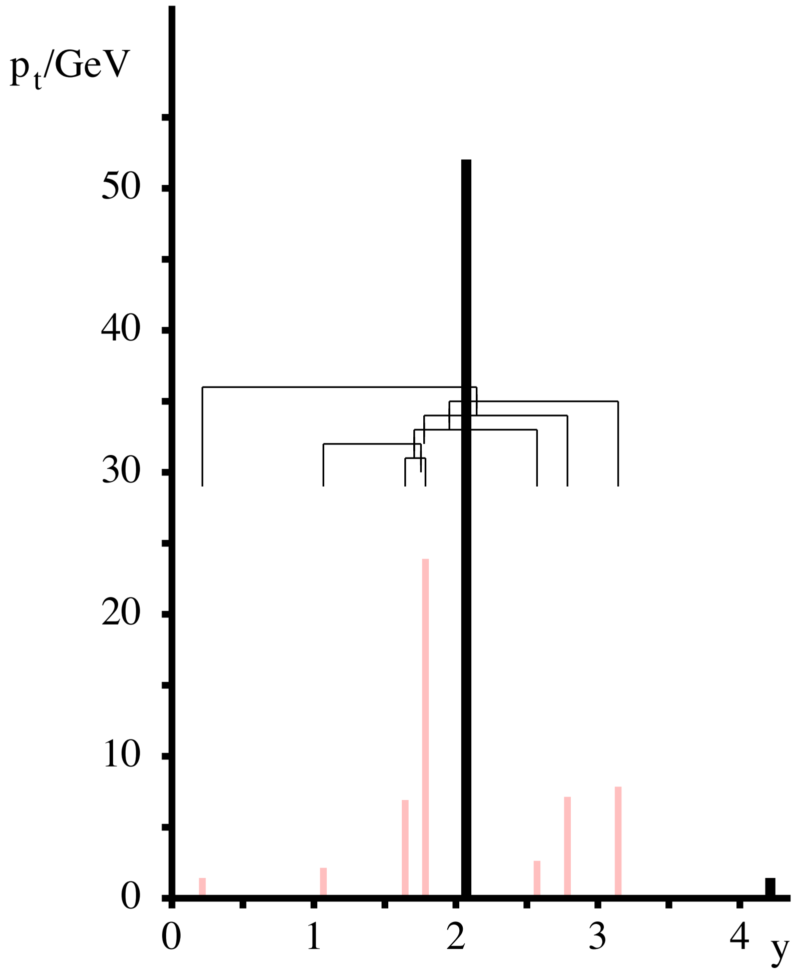
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

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

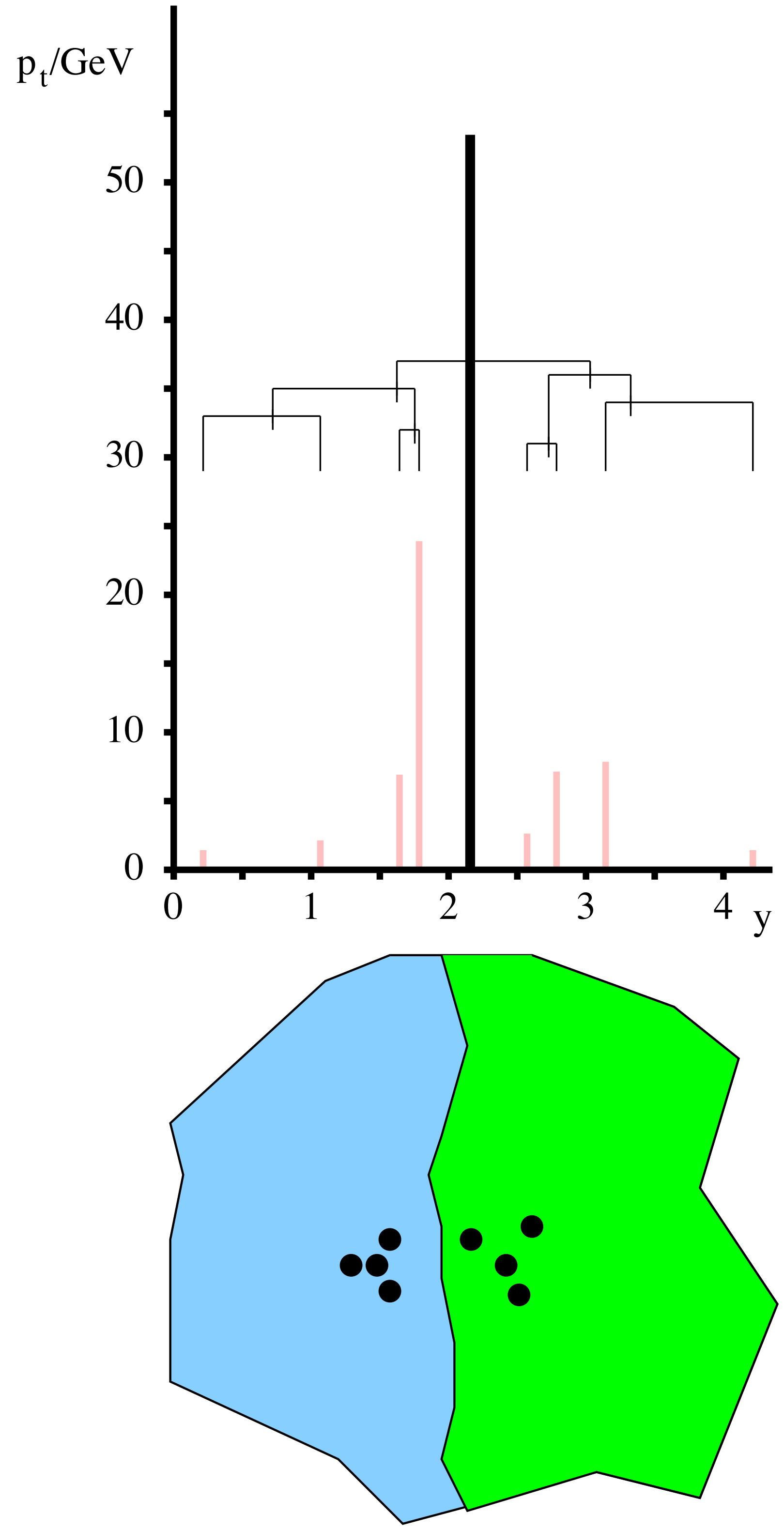
The interesting substructure is buried inside the clustering sequence — it's less contaminated by soft junk, but needs to be pulled out with special techniques

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

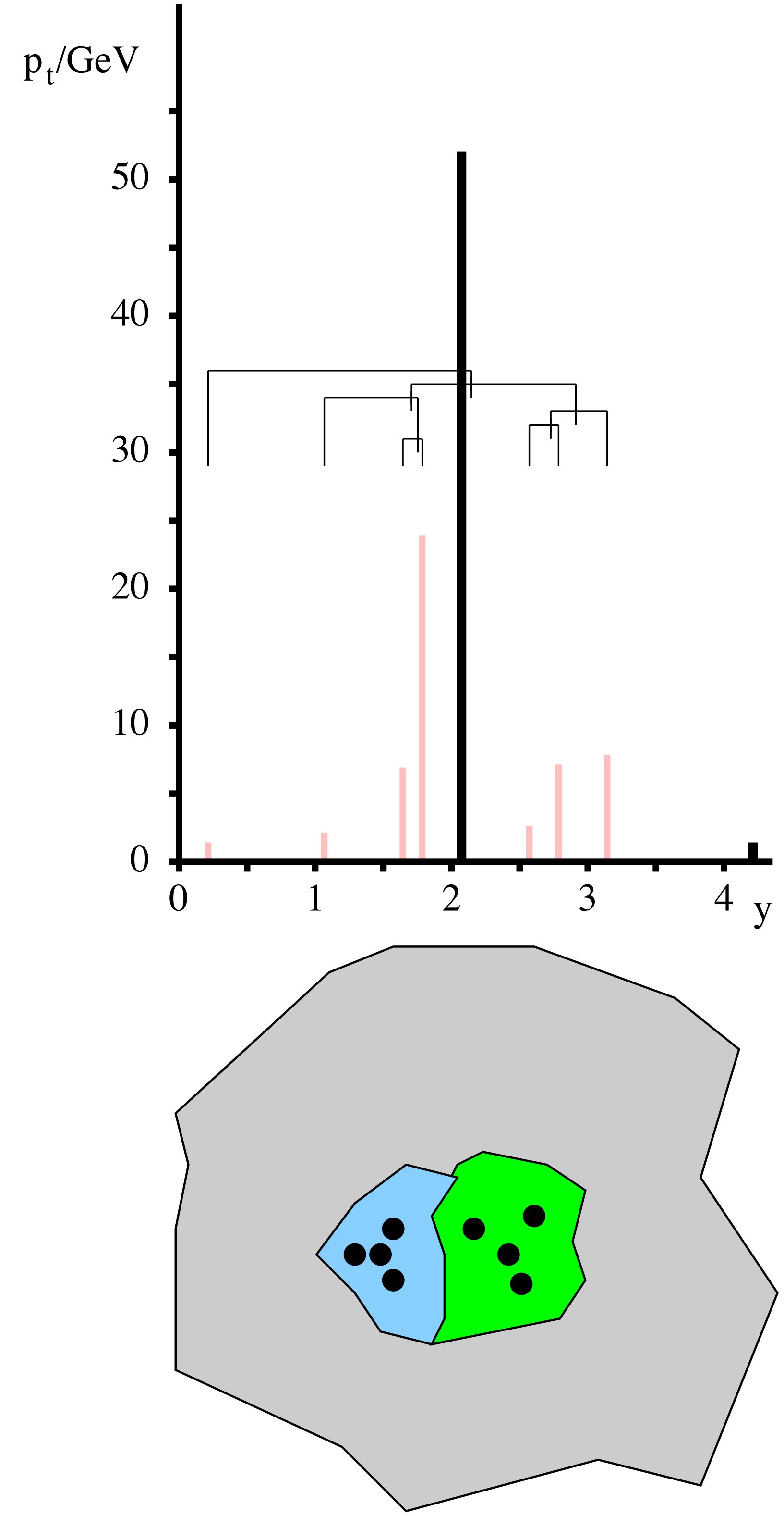
anti-k_t algorithm



k_t algorithm



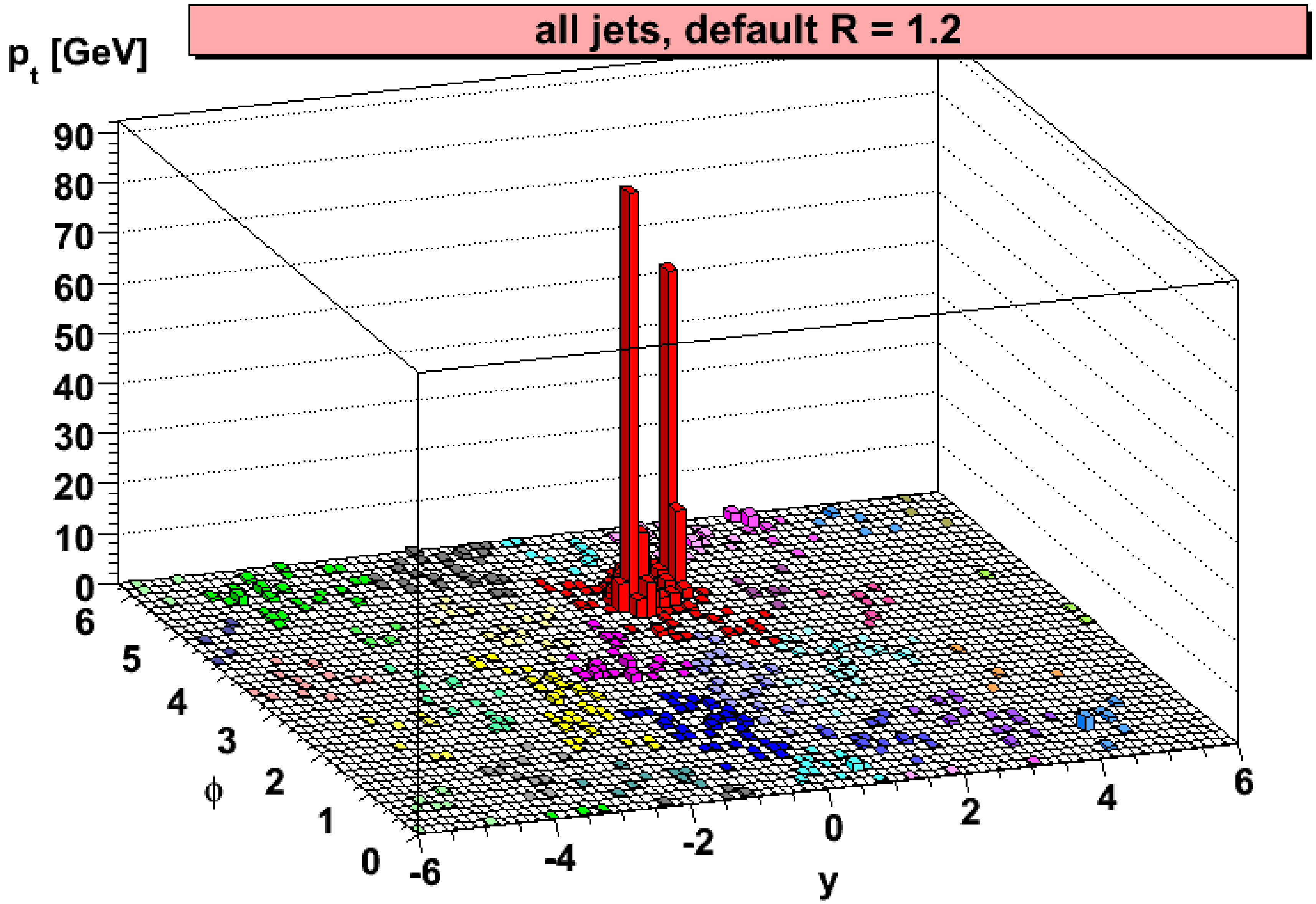
Cambridge/Aachen



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

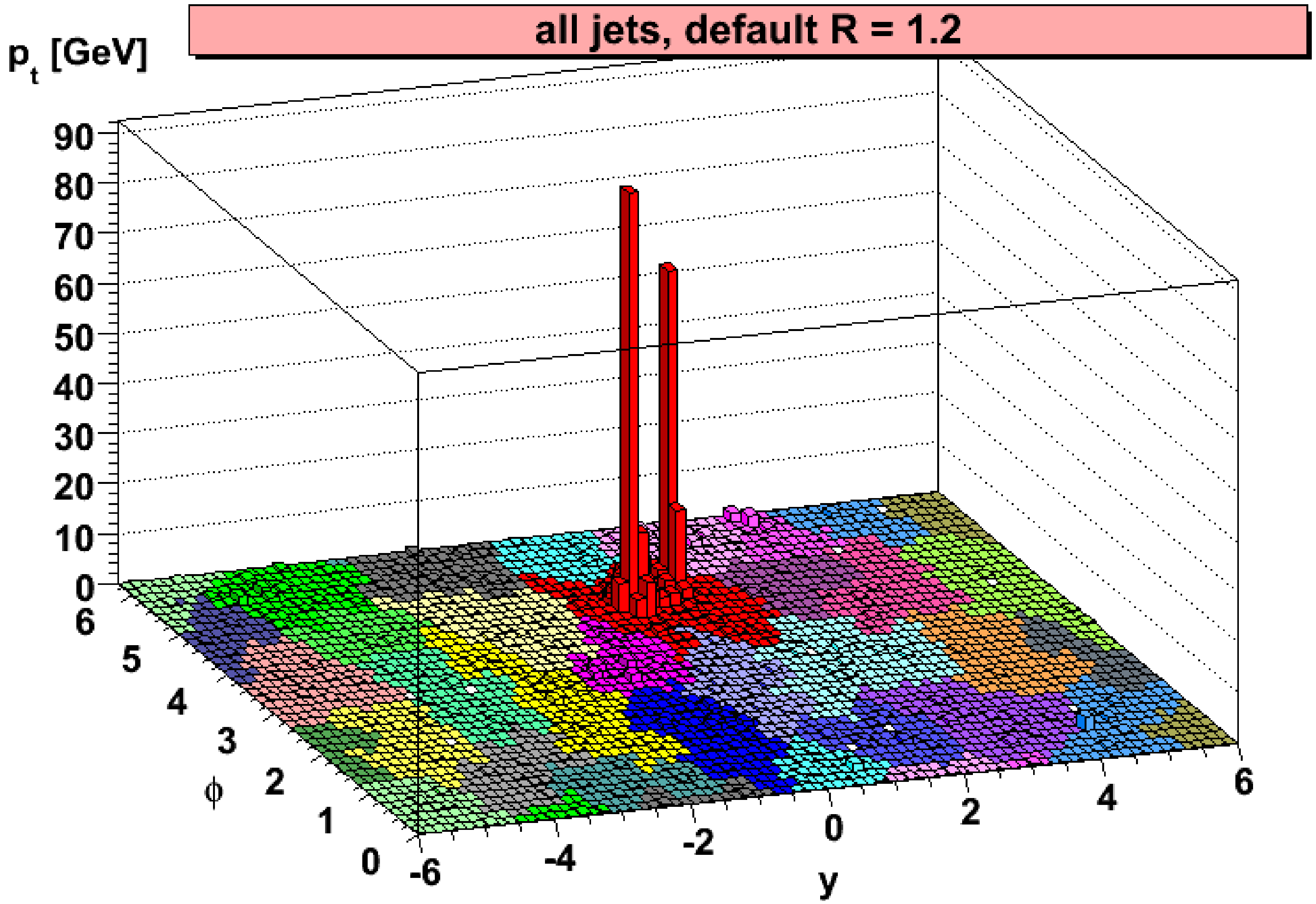
Butterworth, Davison, Rubin & GPS '08

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

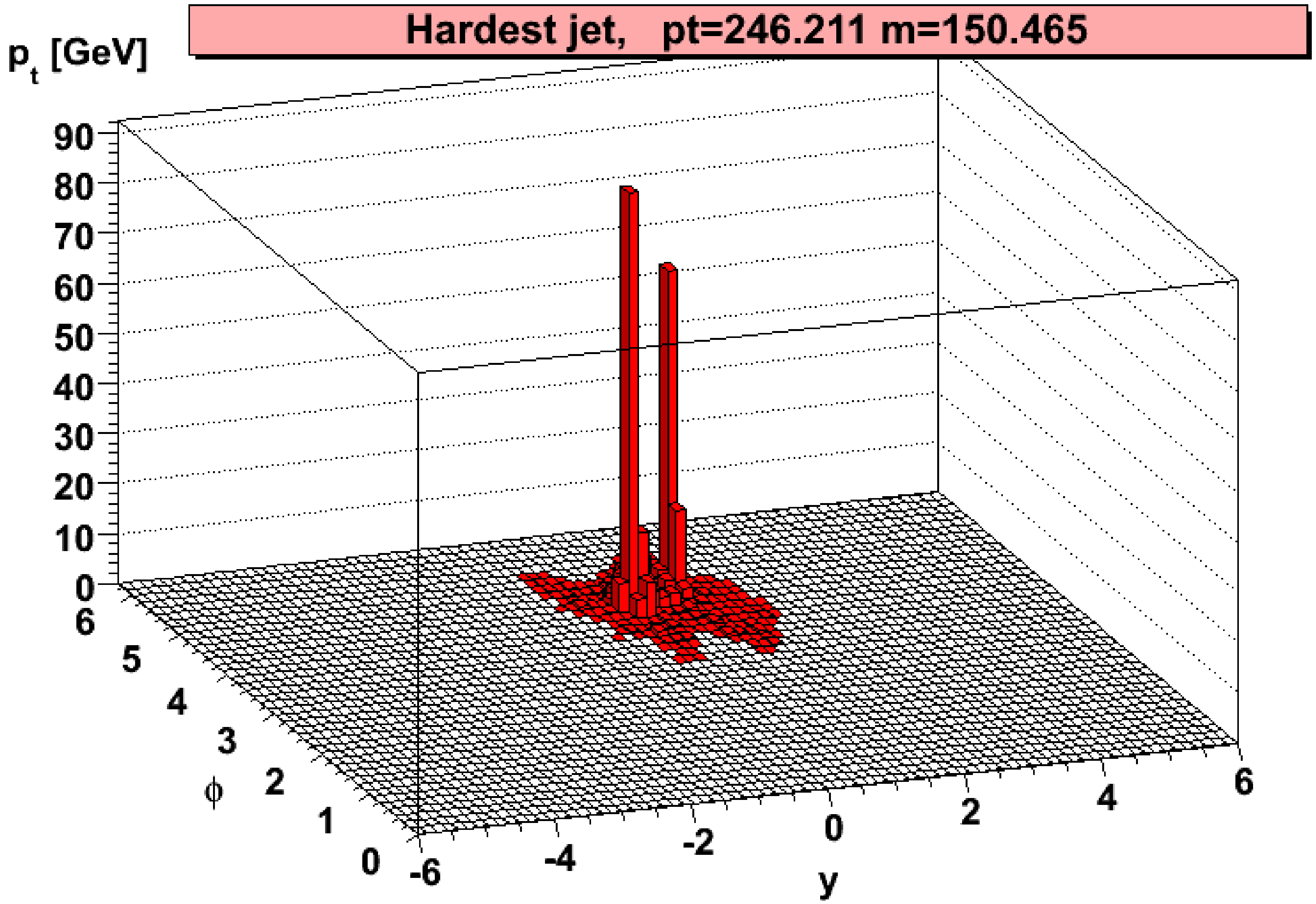
Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

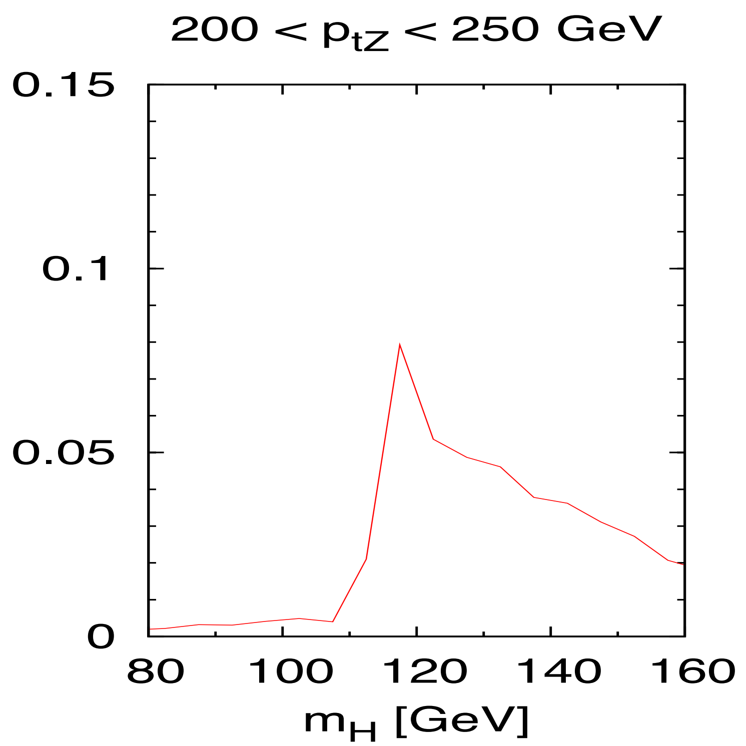
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



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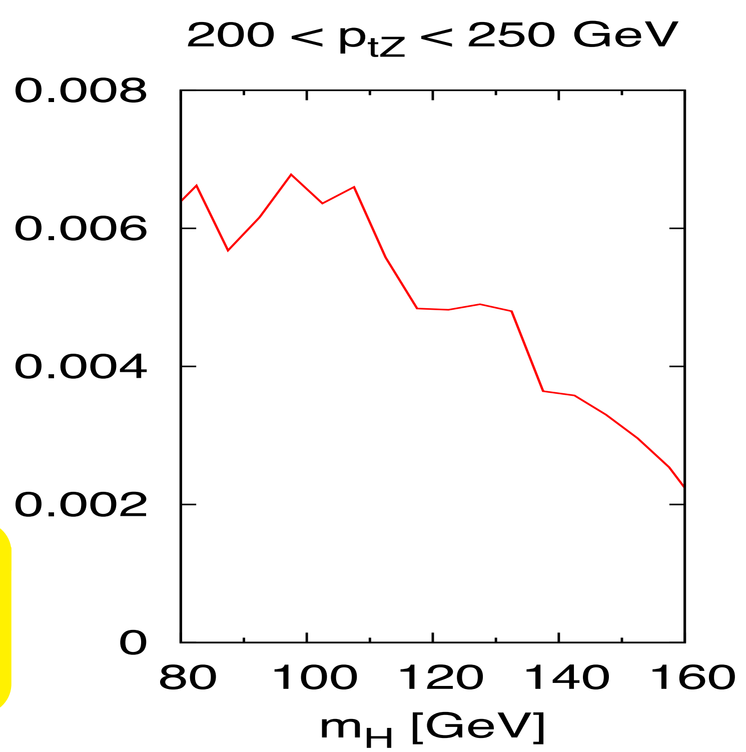

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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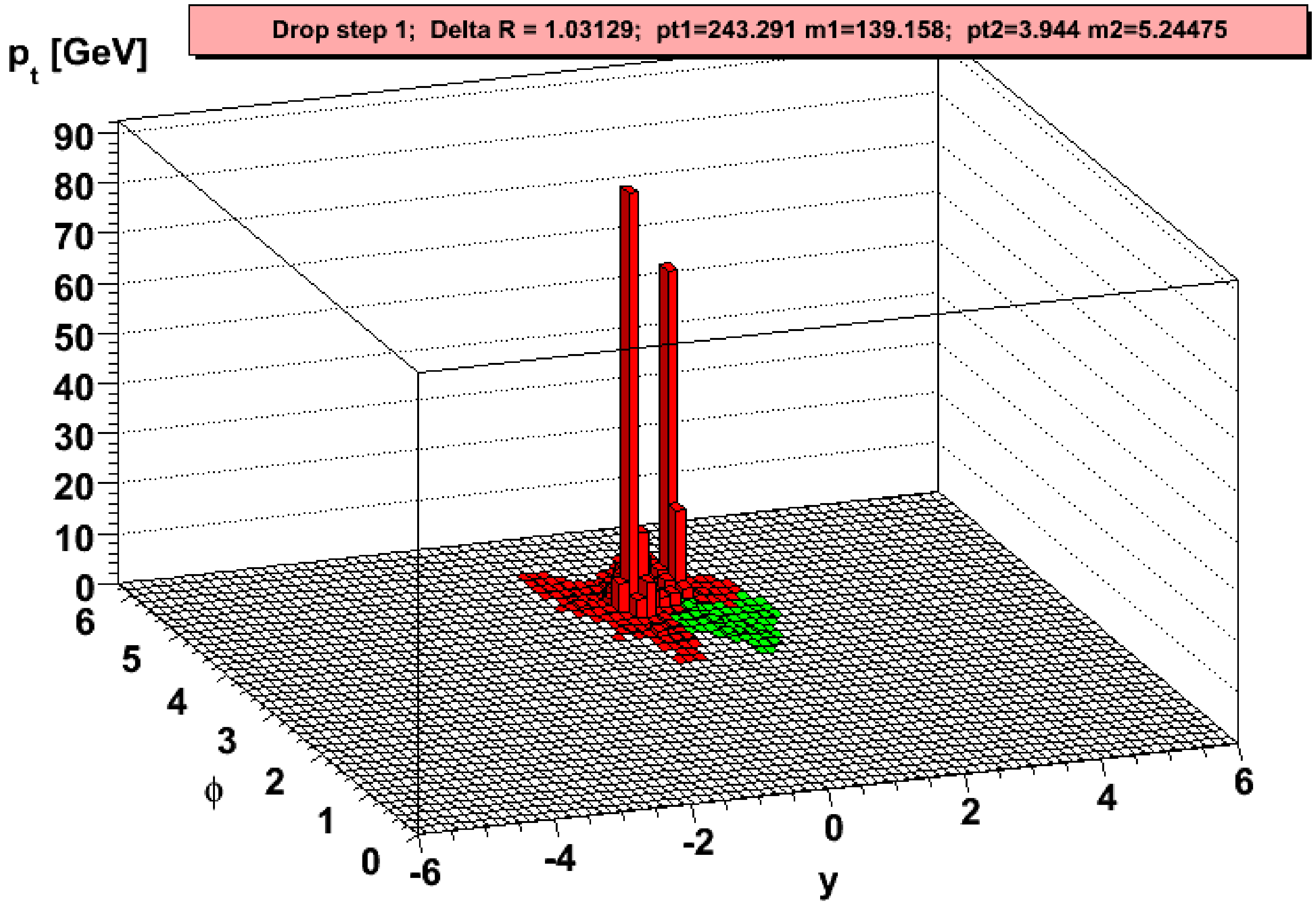
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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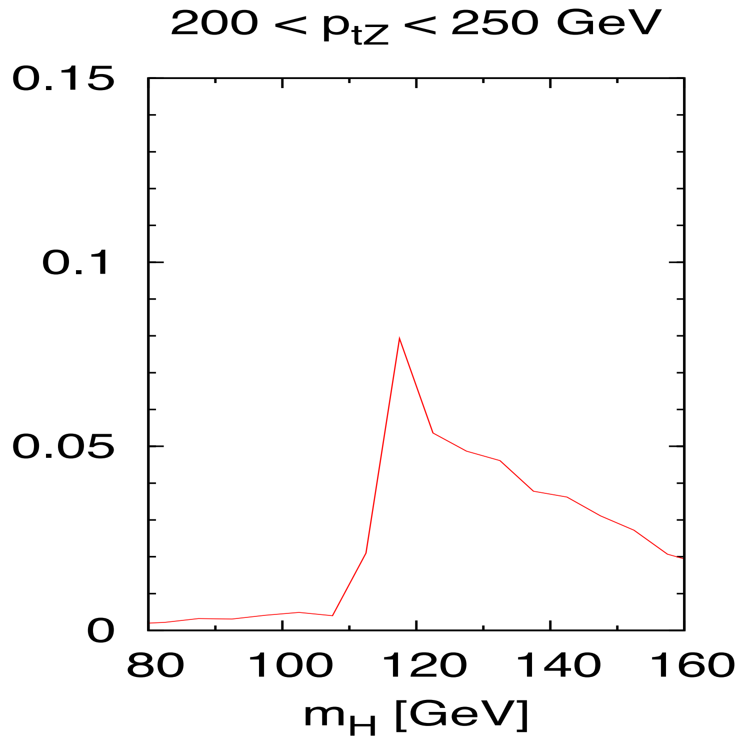

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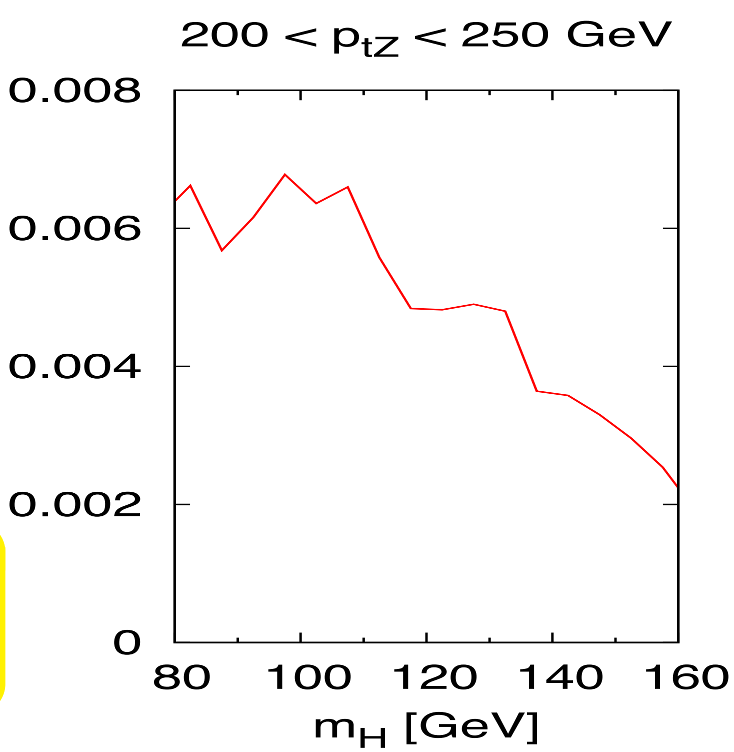


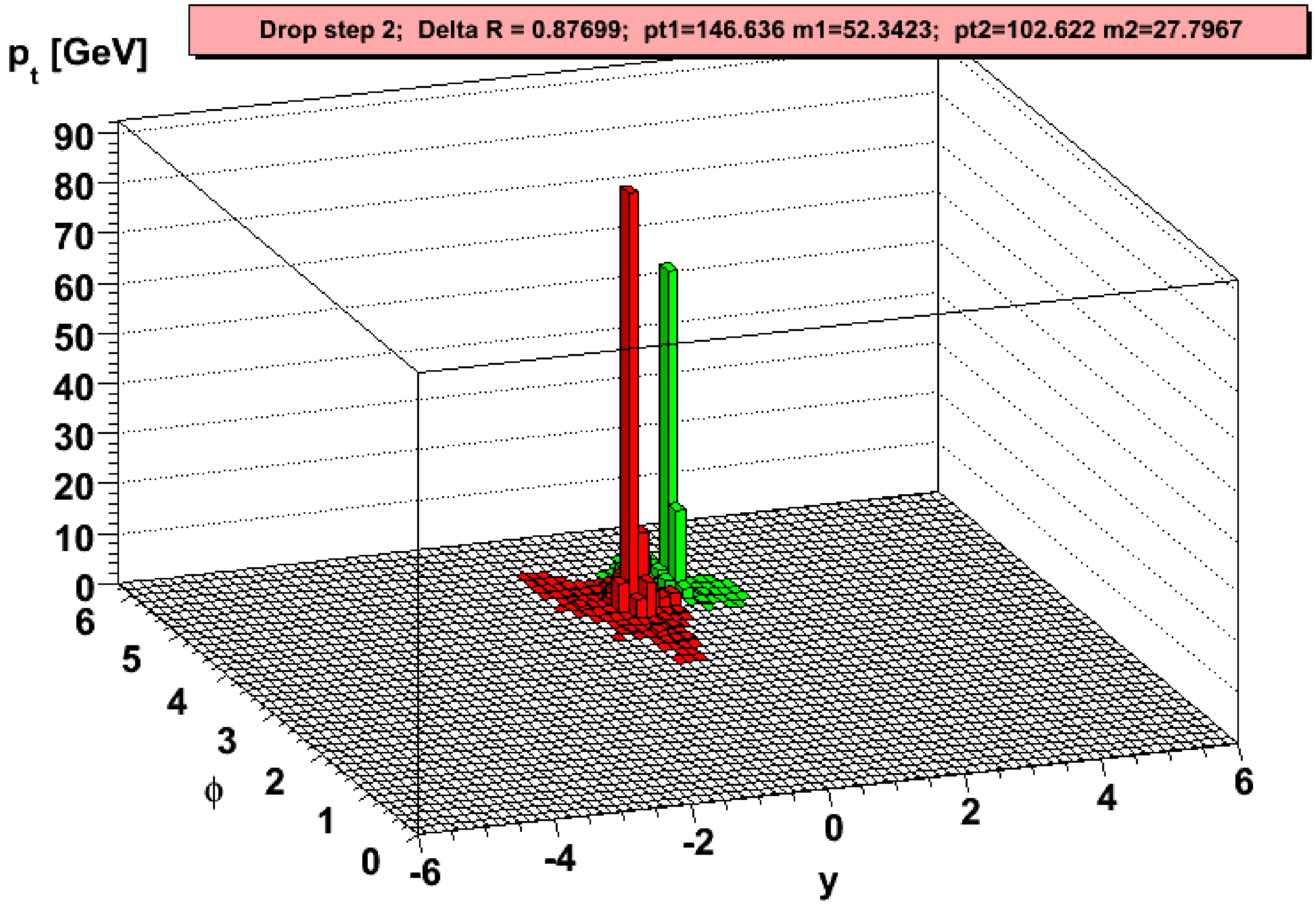
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

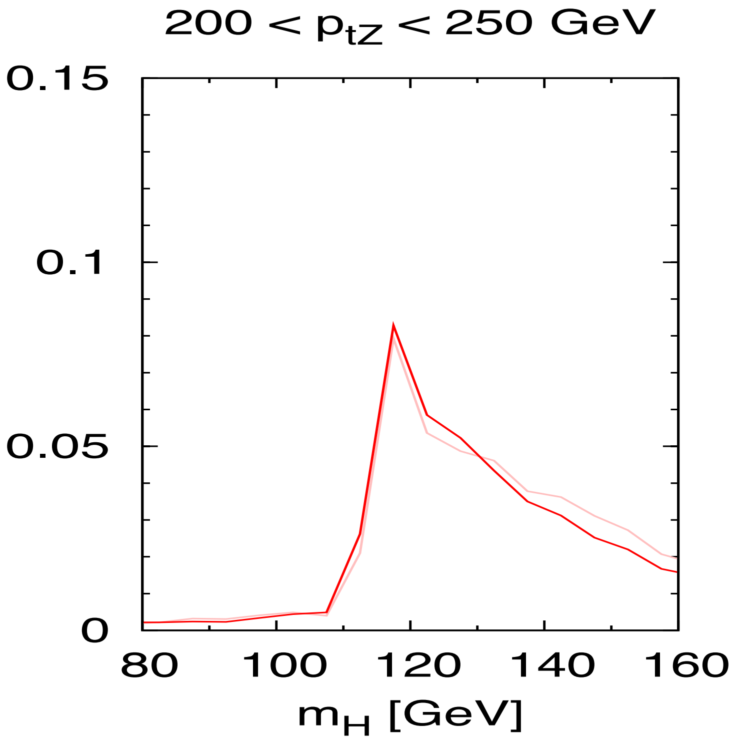
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



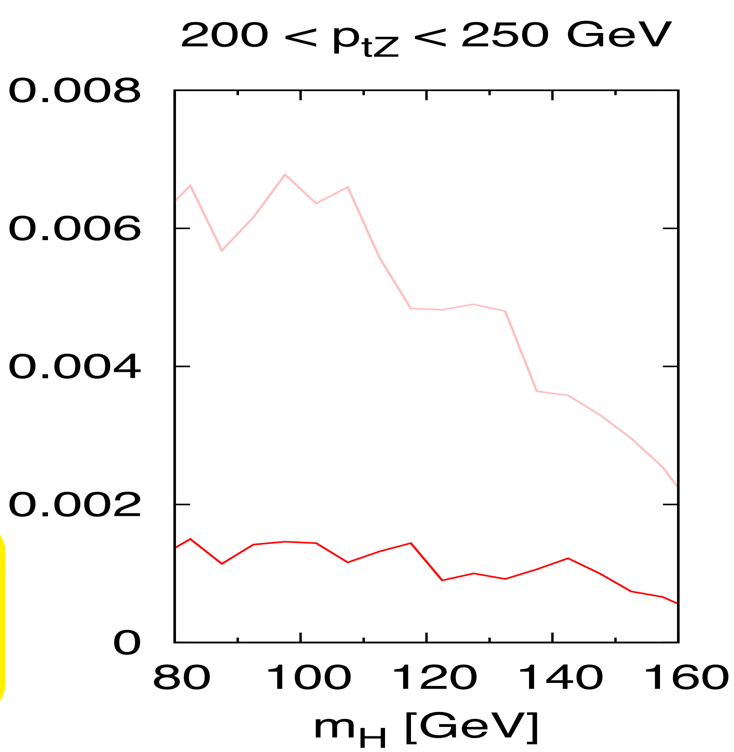
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

SIGNAL



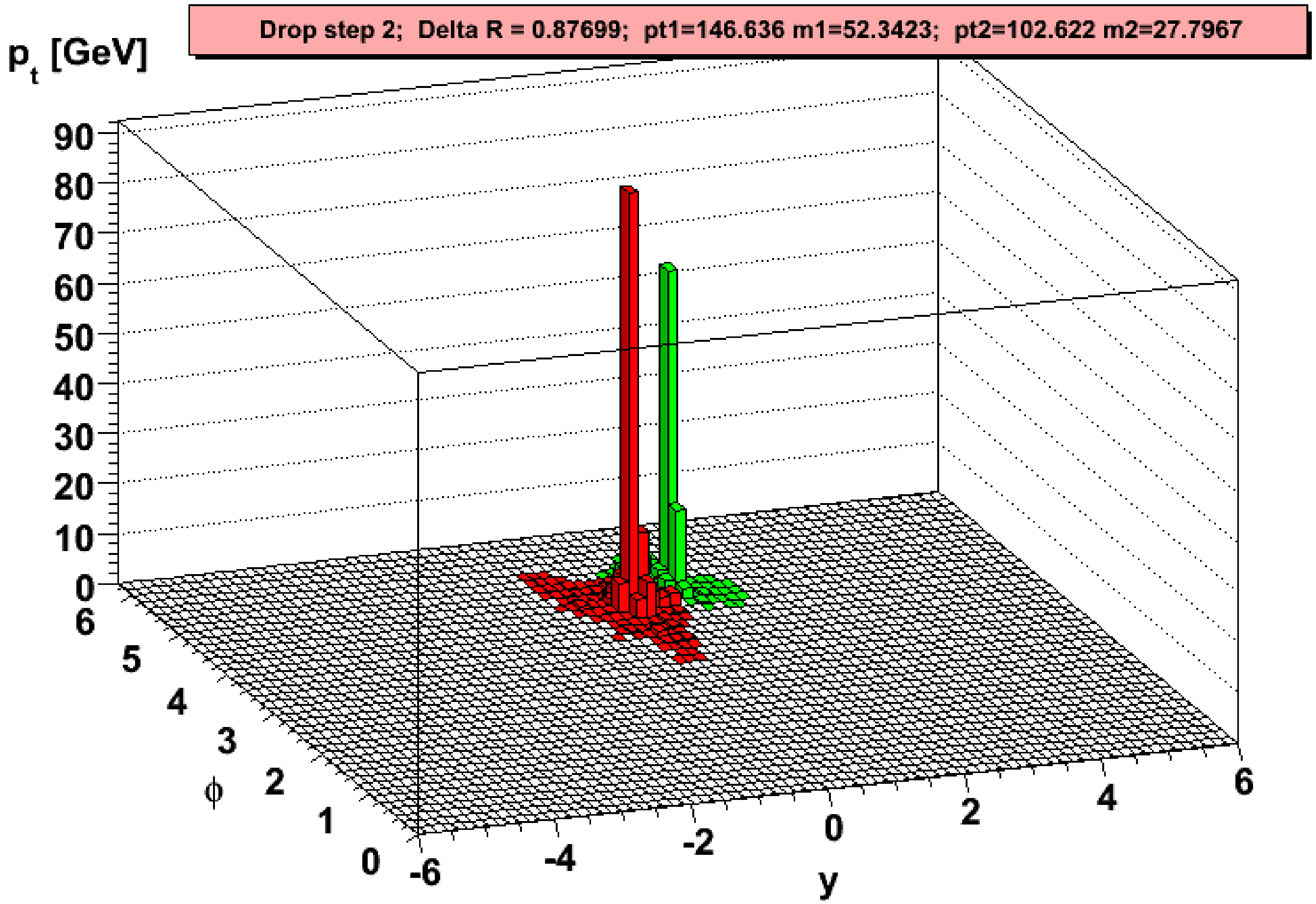
Zbb BACKGROUND

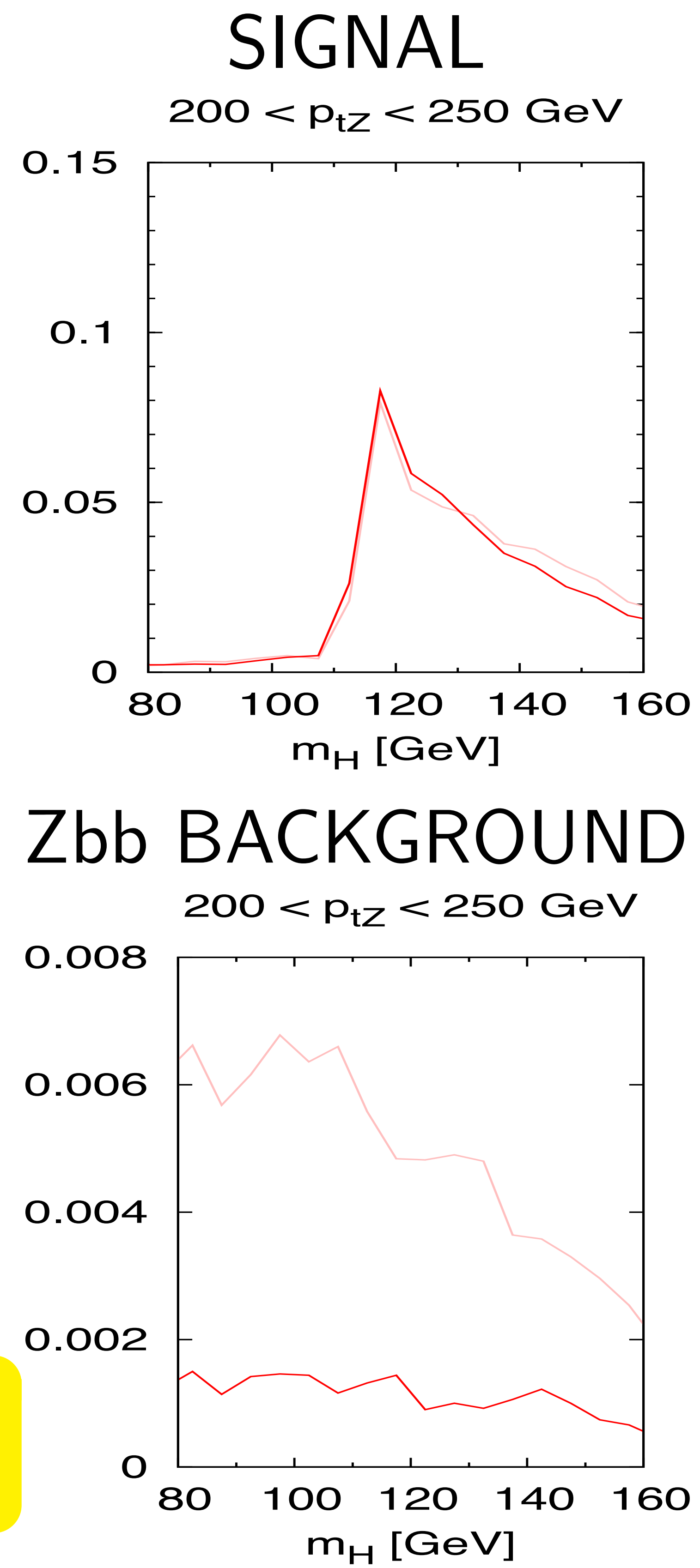


arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3





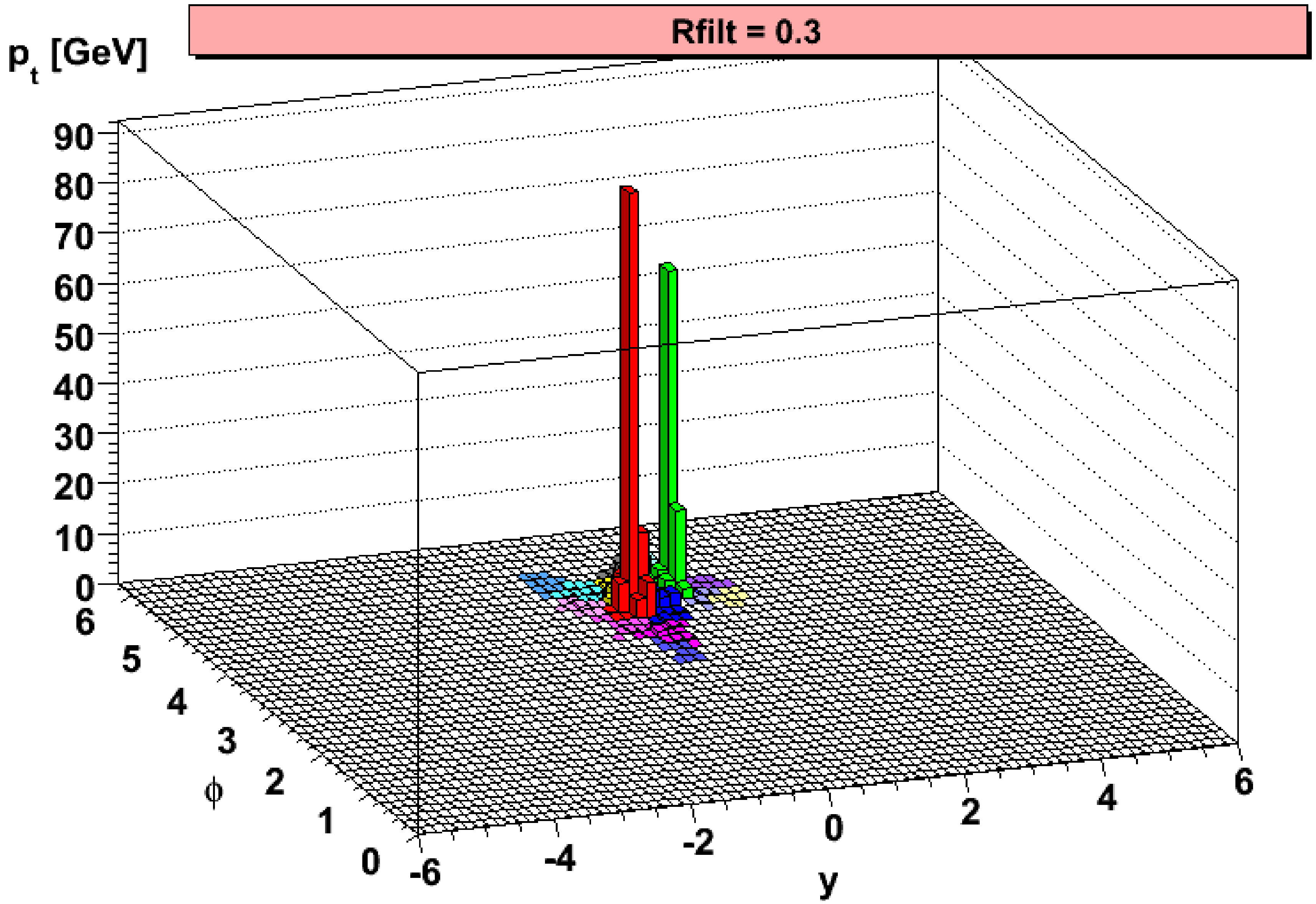
check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

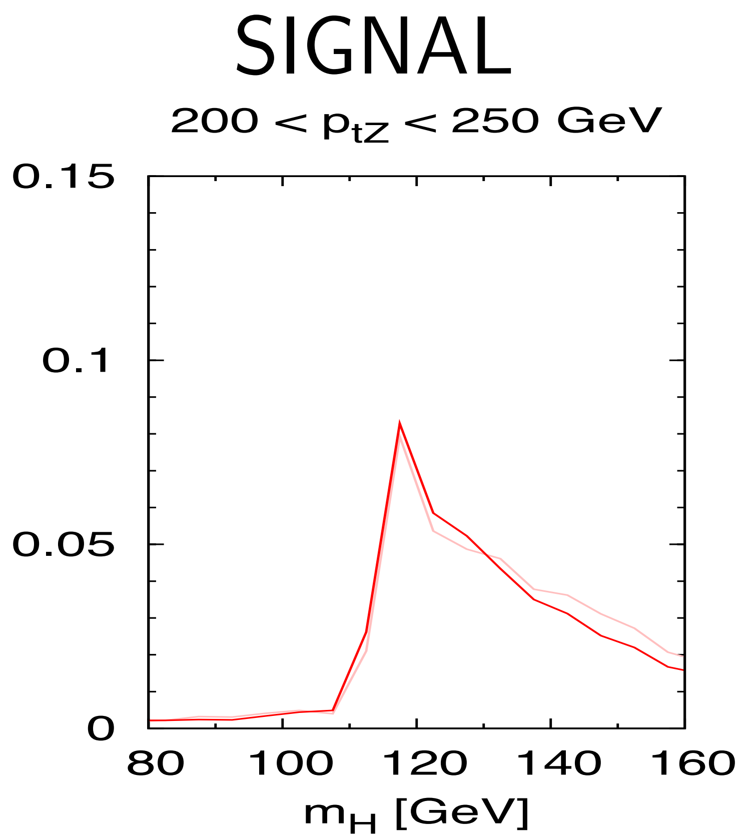
Butterworth, Davison, Rubin & GPS '08

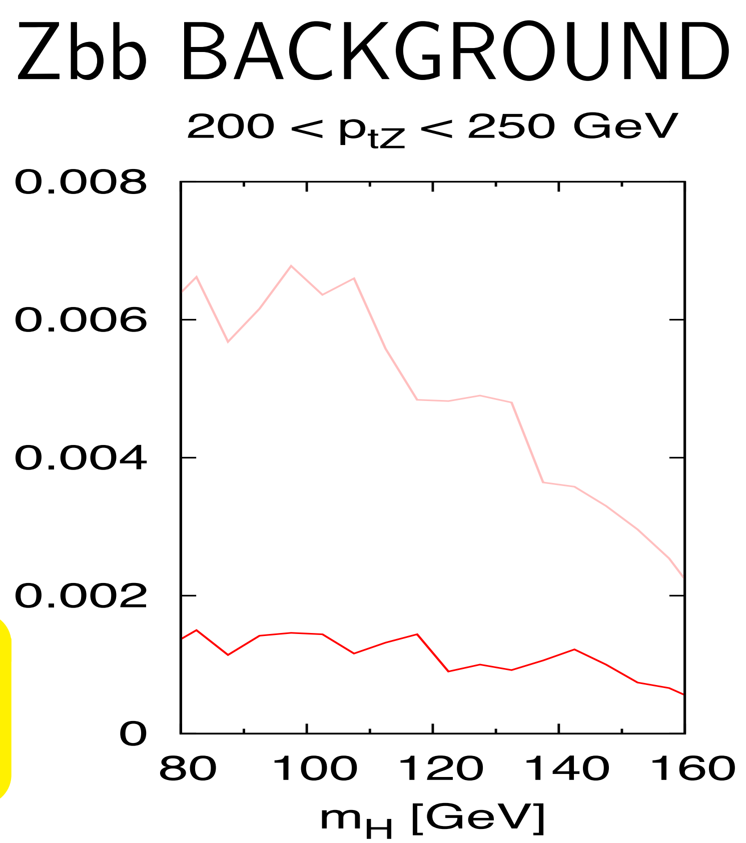
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







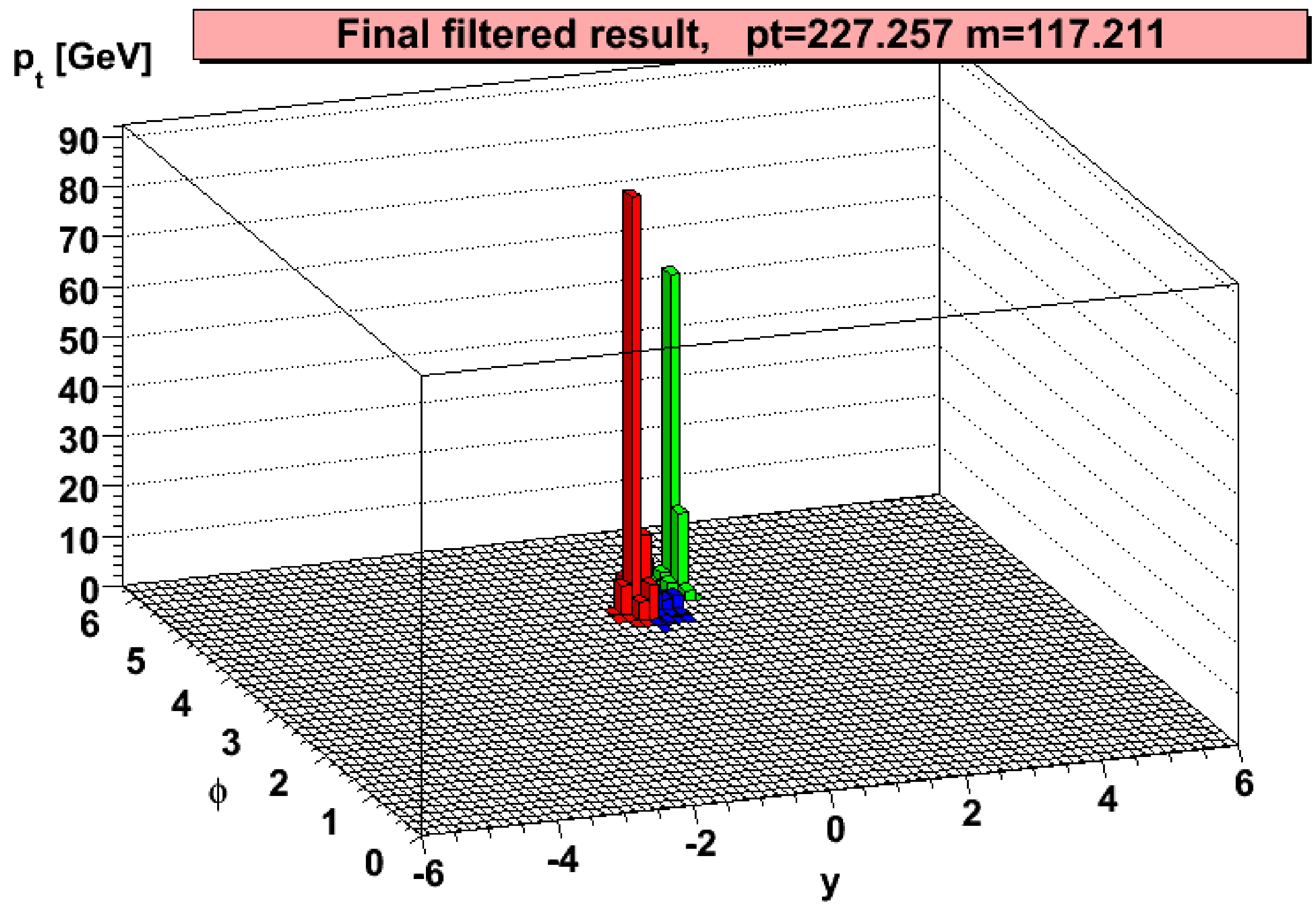
$R_{filt} = 0.3$

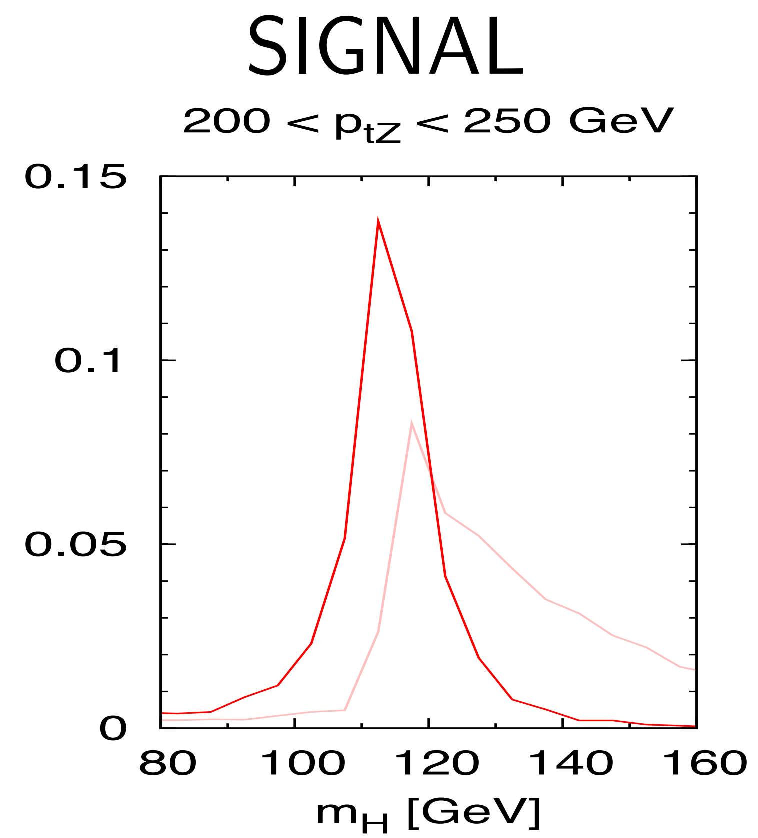
Butterworth, Davison, Rubin & GPS '08

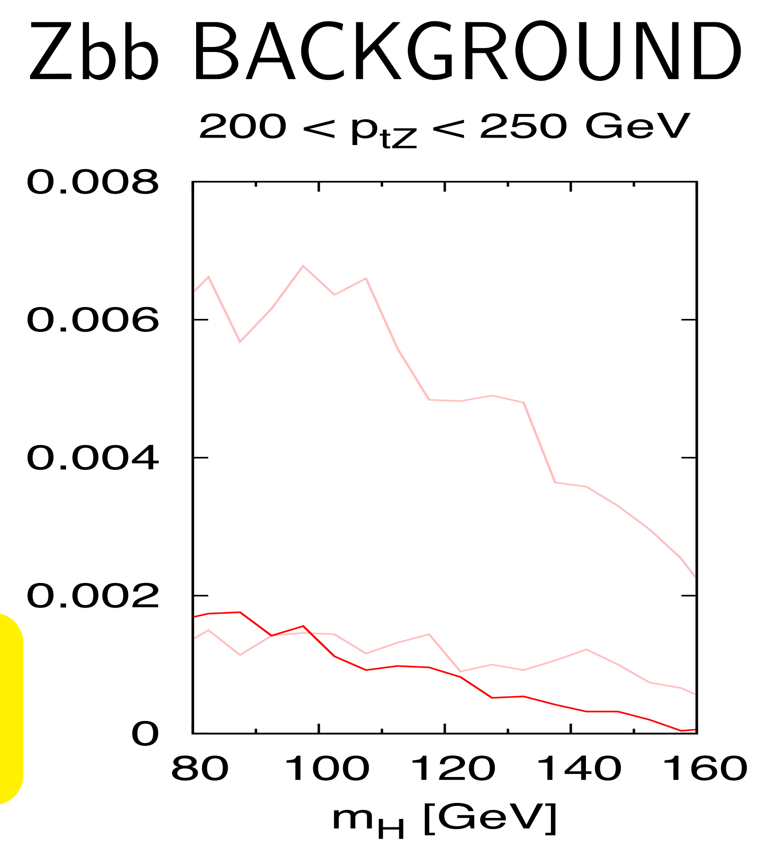
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







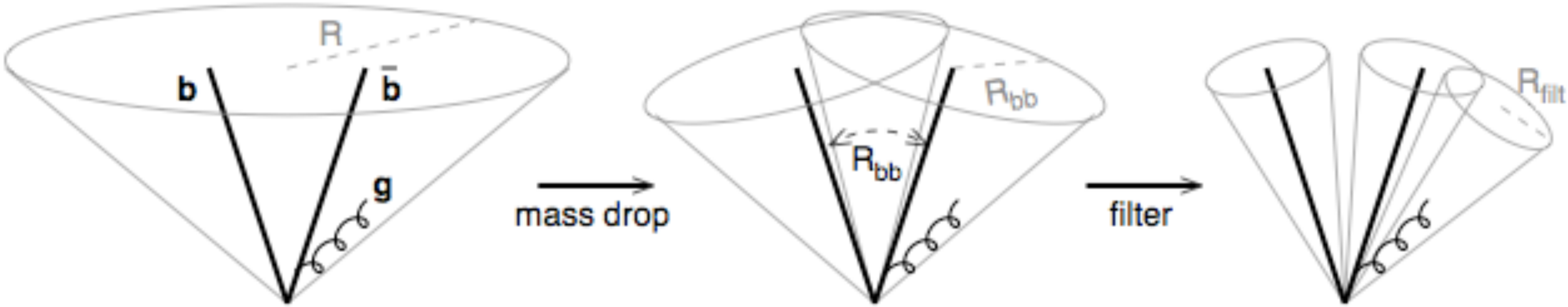
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

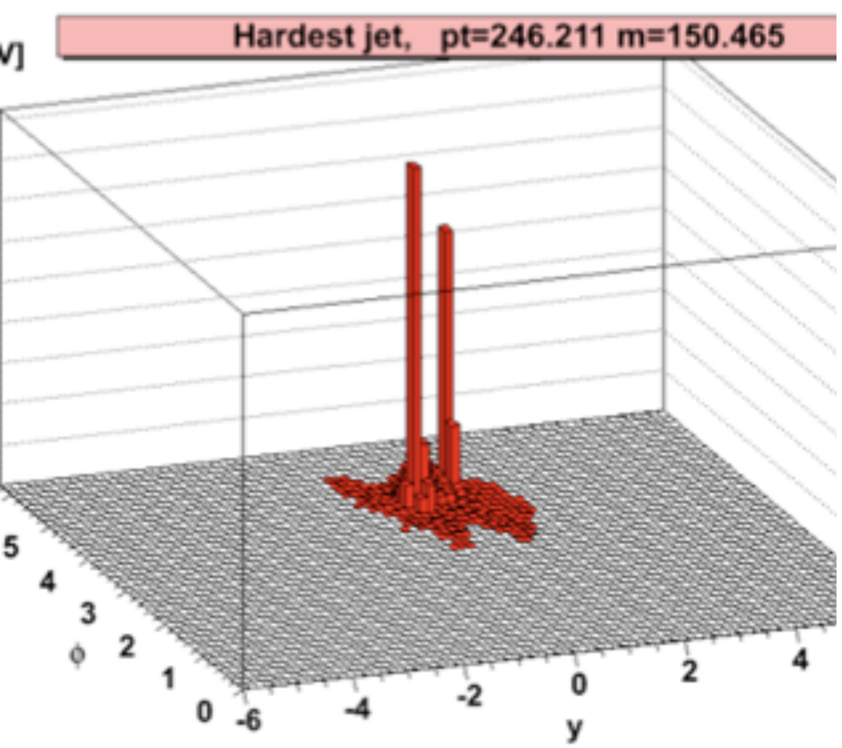
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

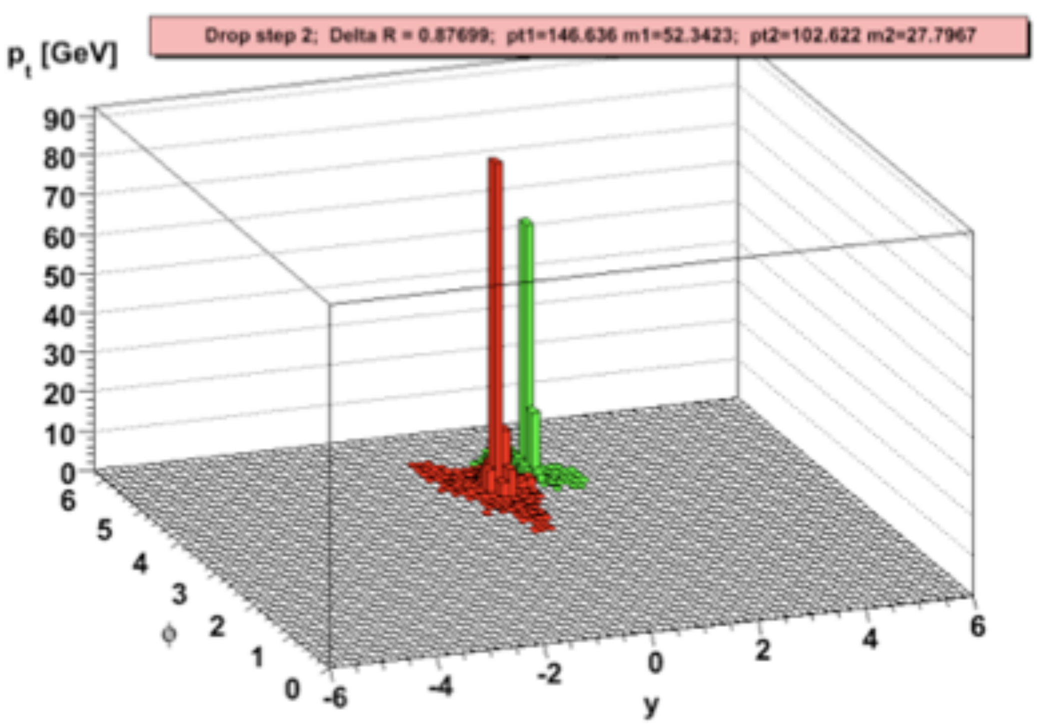
Boosted Higgs analysis

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

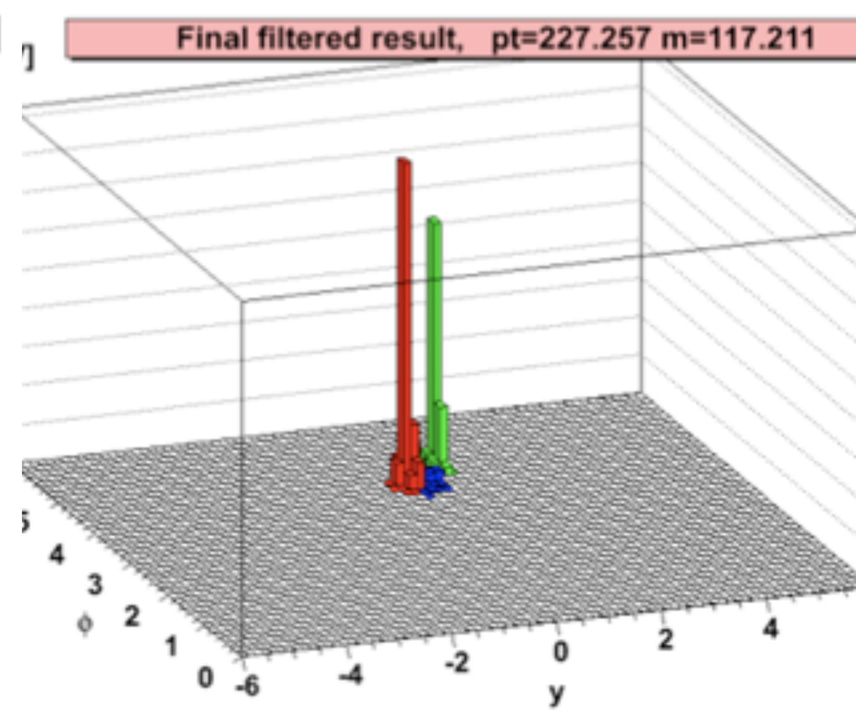




Cluster with a large R



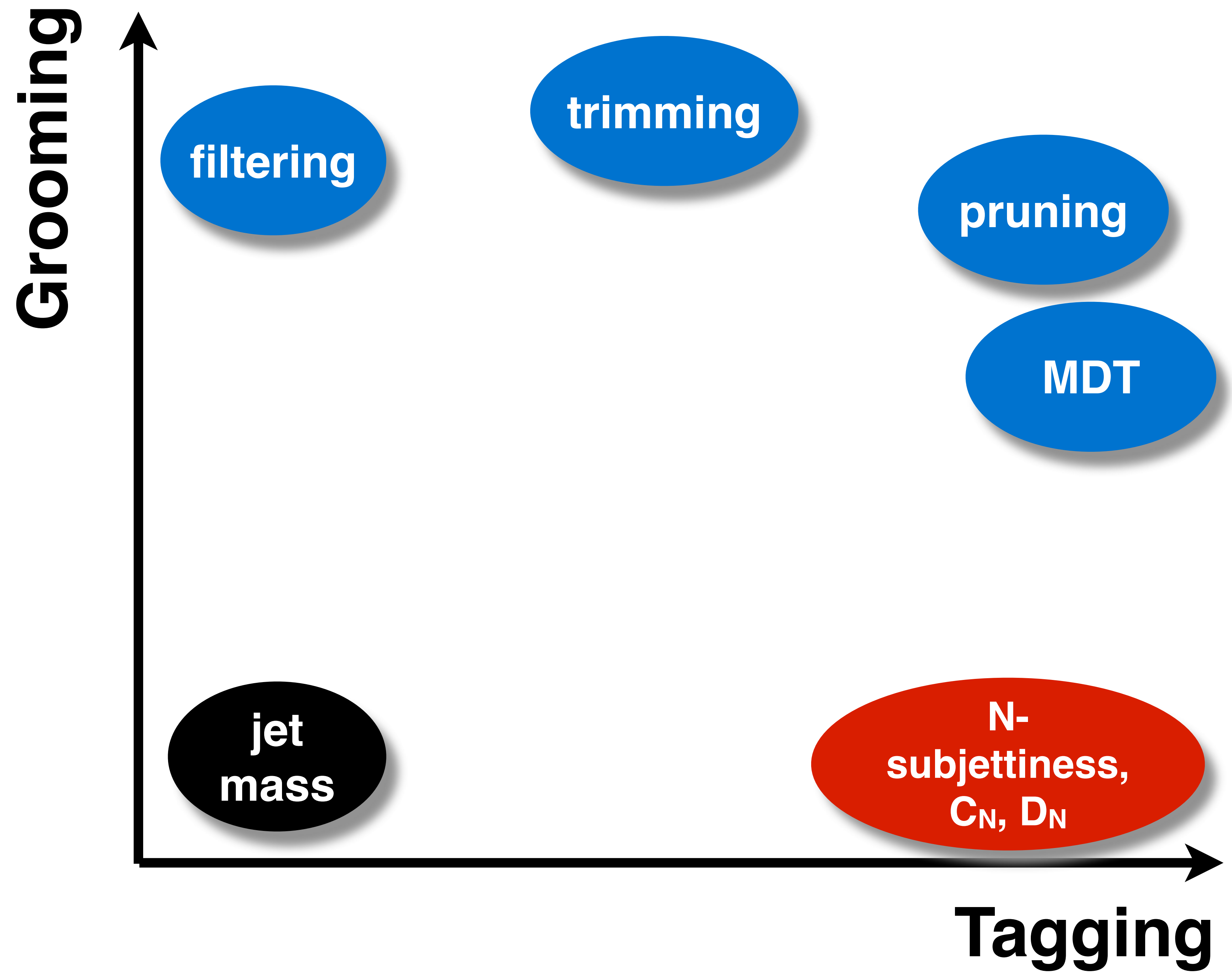
Undo the clustering into subjets, until a large mass drop is observed



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

different (2-body) substructure tools

Detailed relative positions depend on physics context
(and are possibly contentious!)



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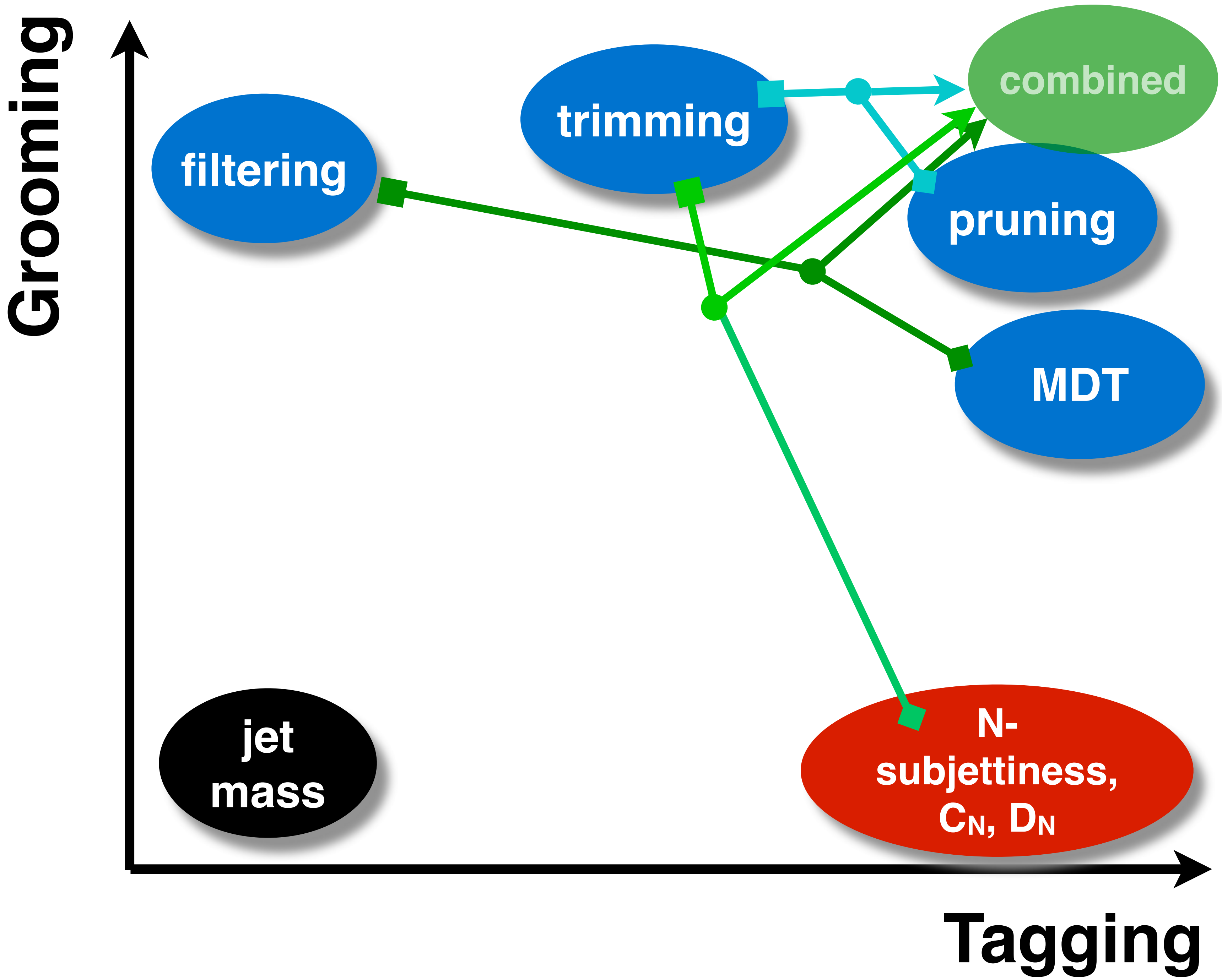

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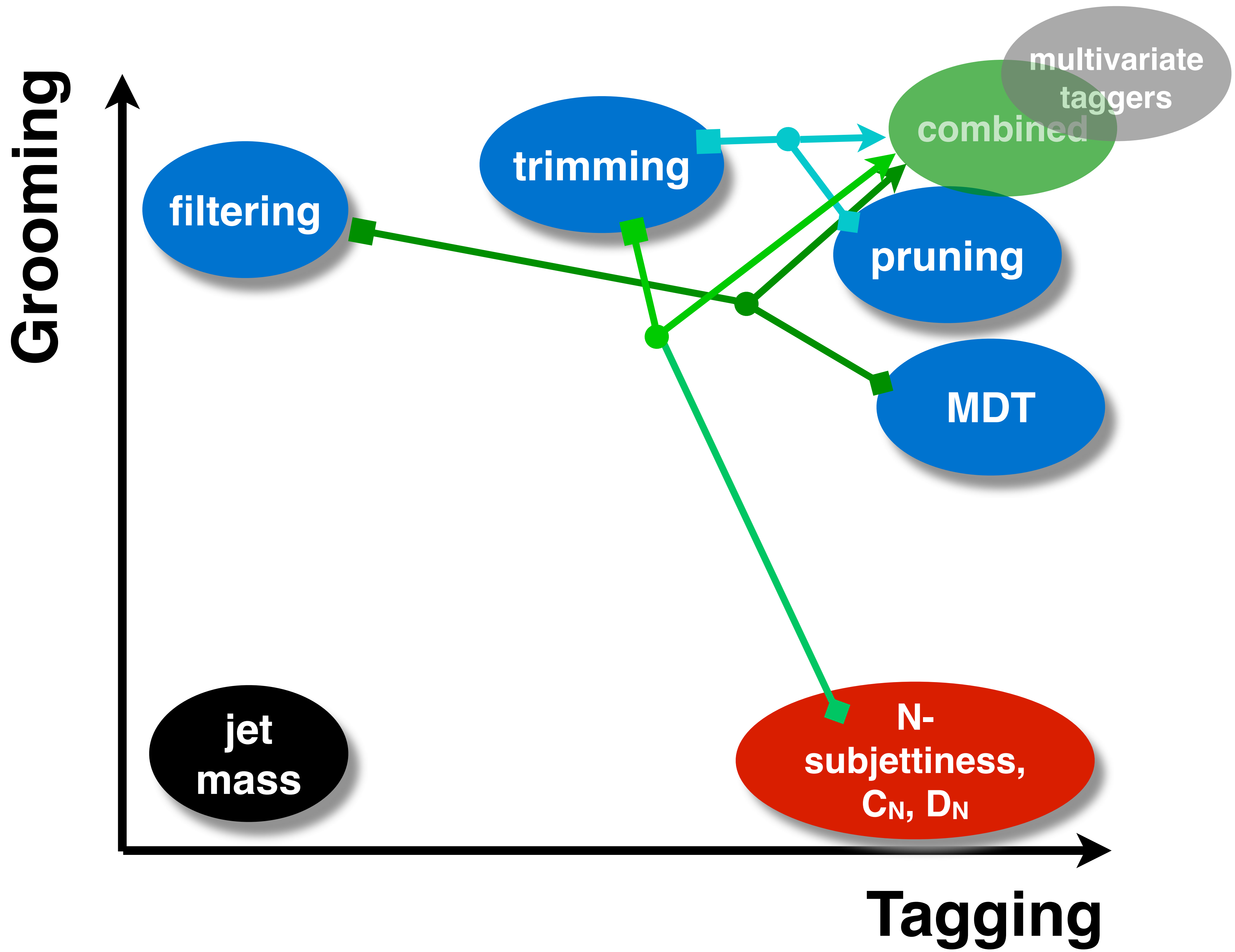

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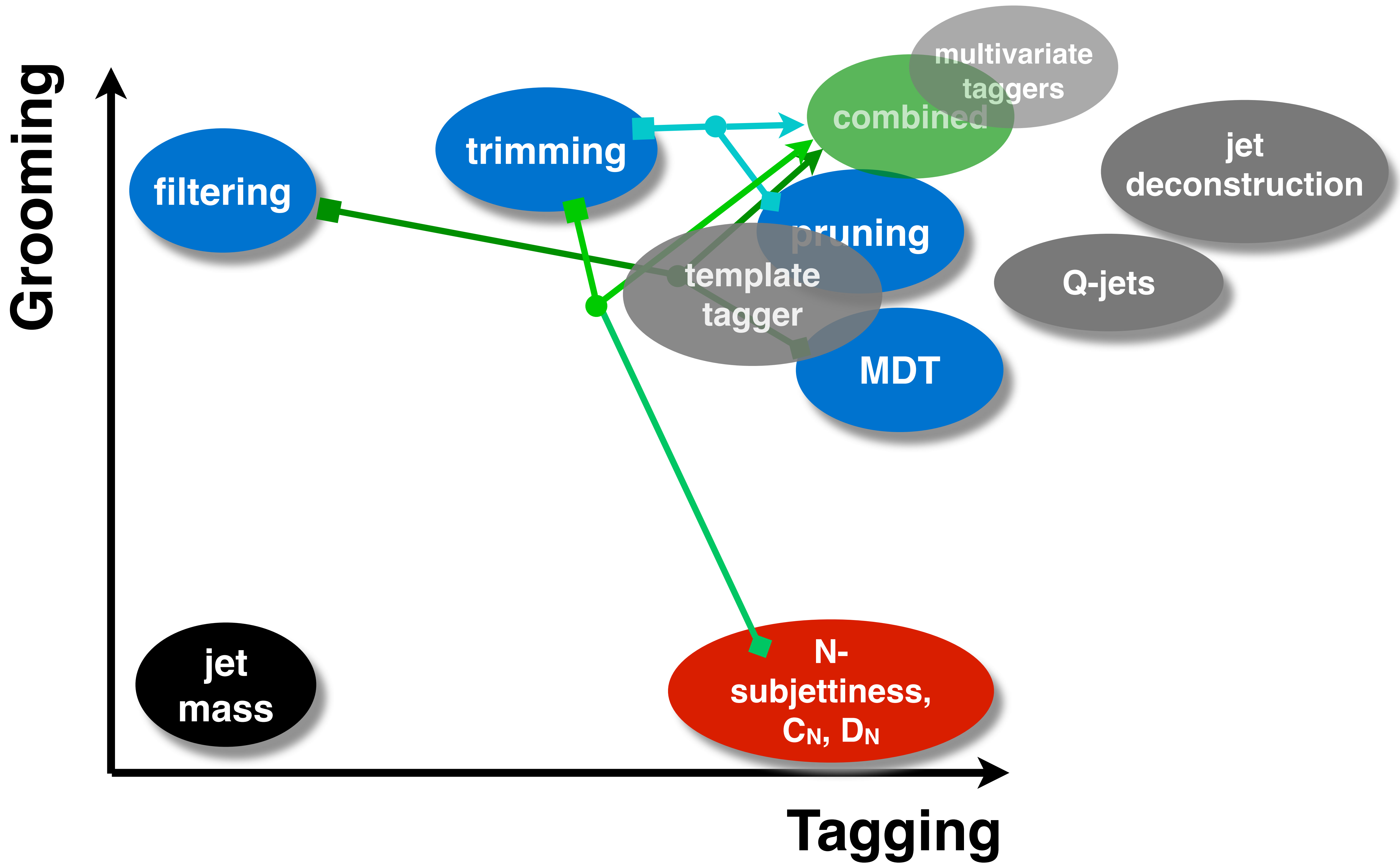
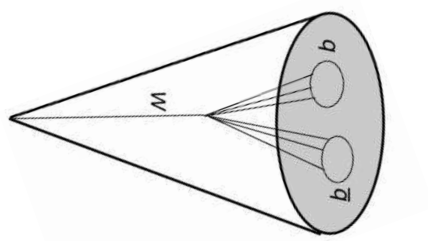
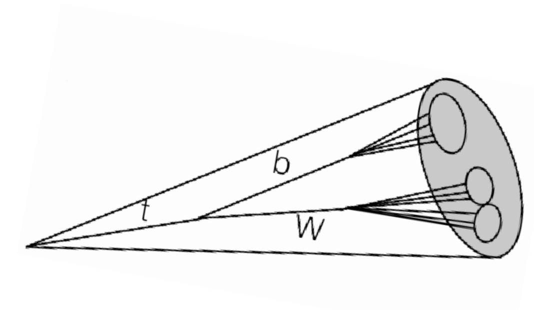


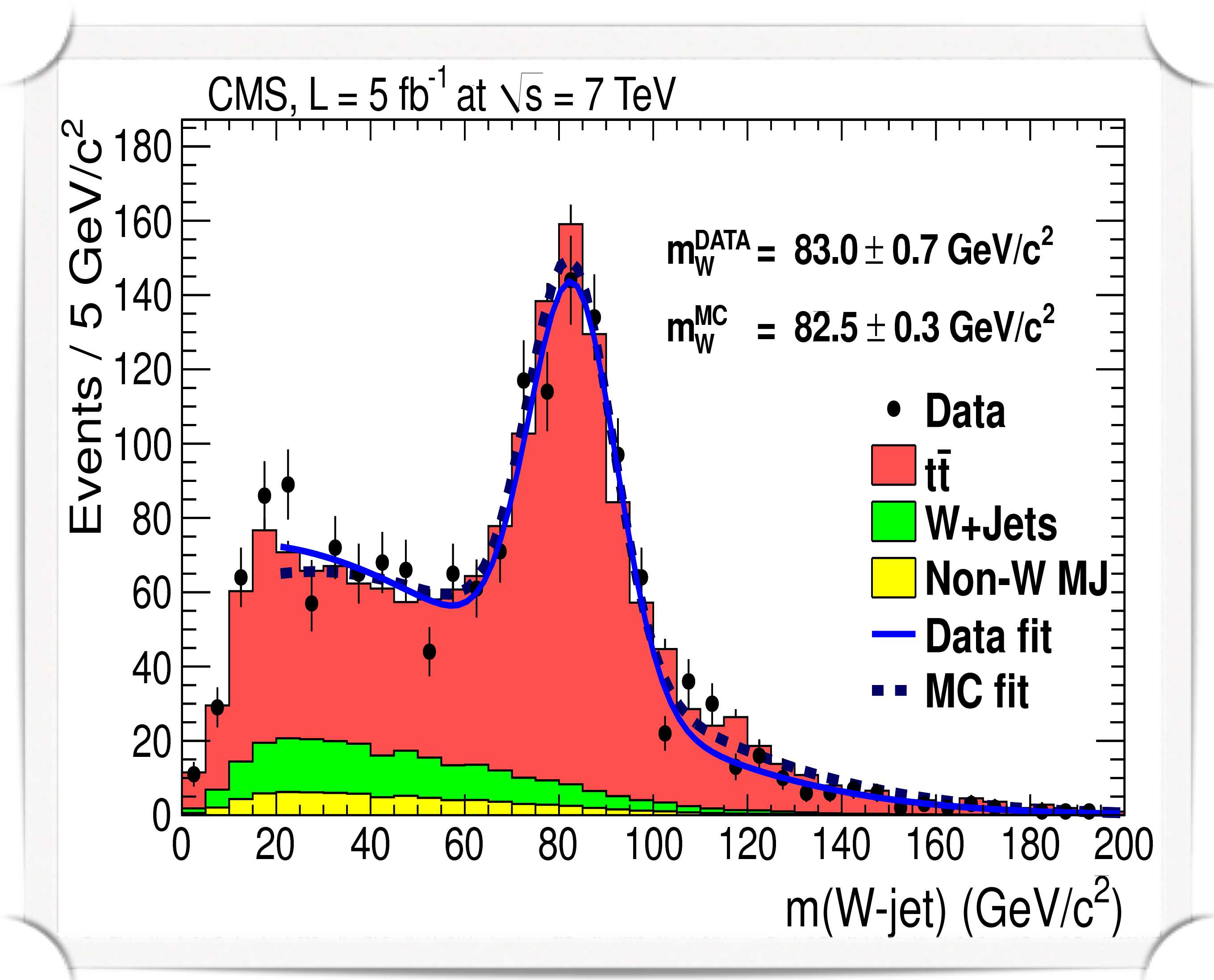
Seeing W's and tops in a single jet

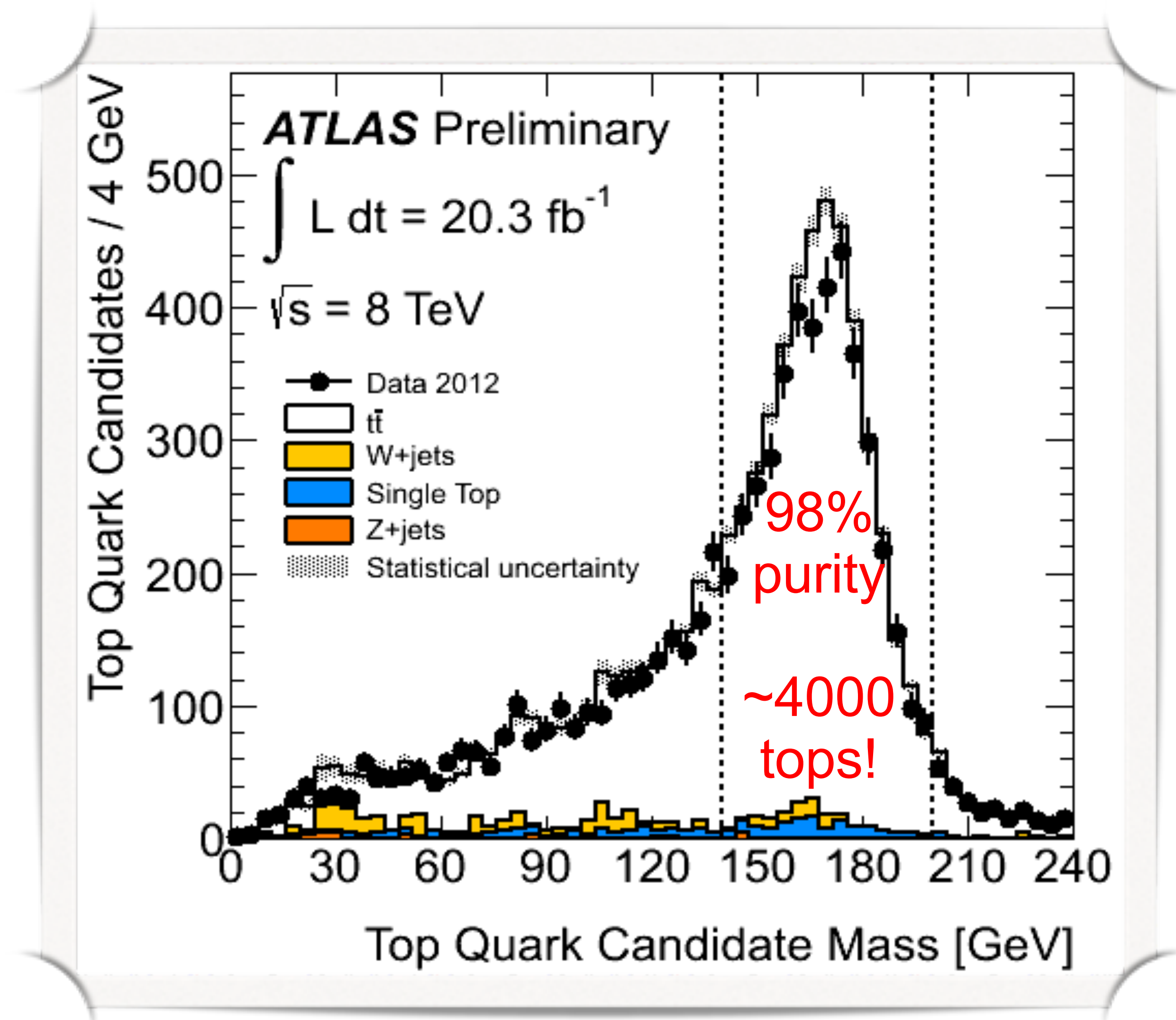
W's in a single jet



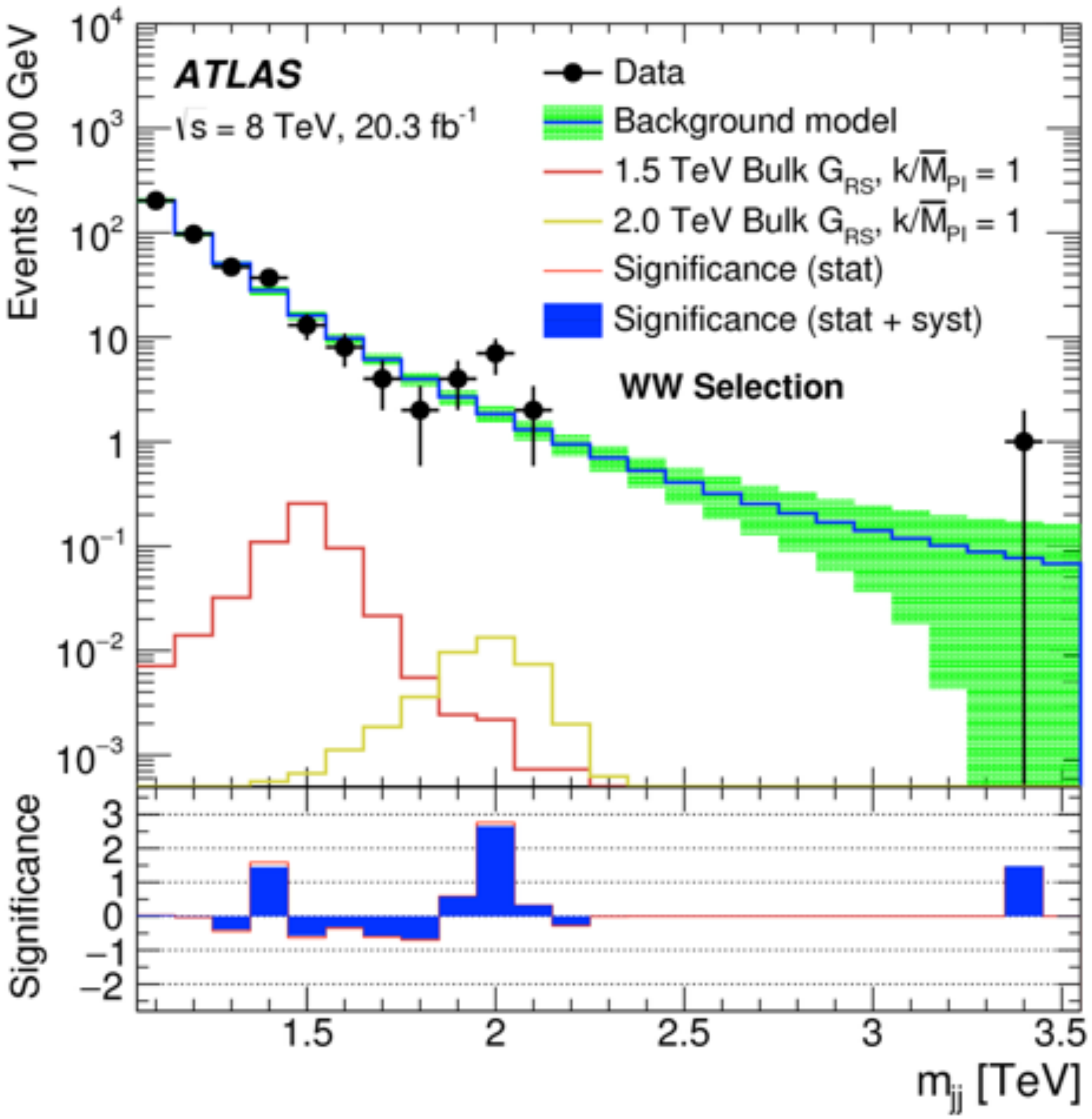
tops in a single jet

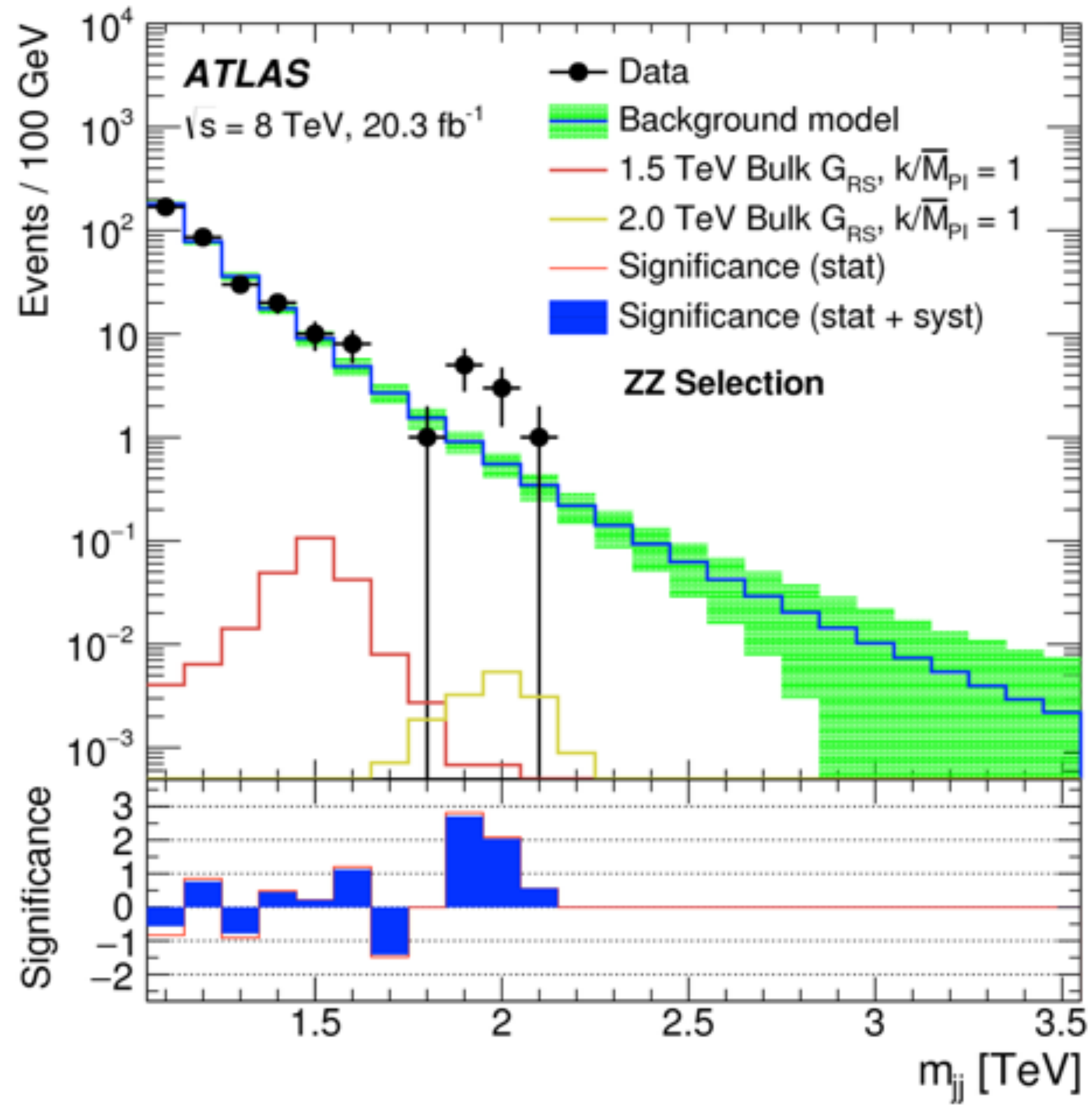






ATLAS di-boson excess





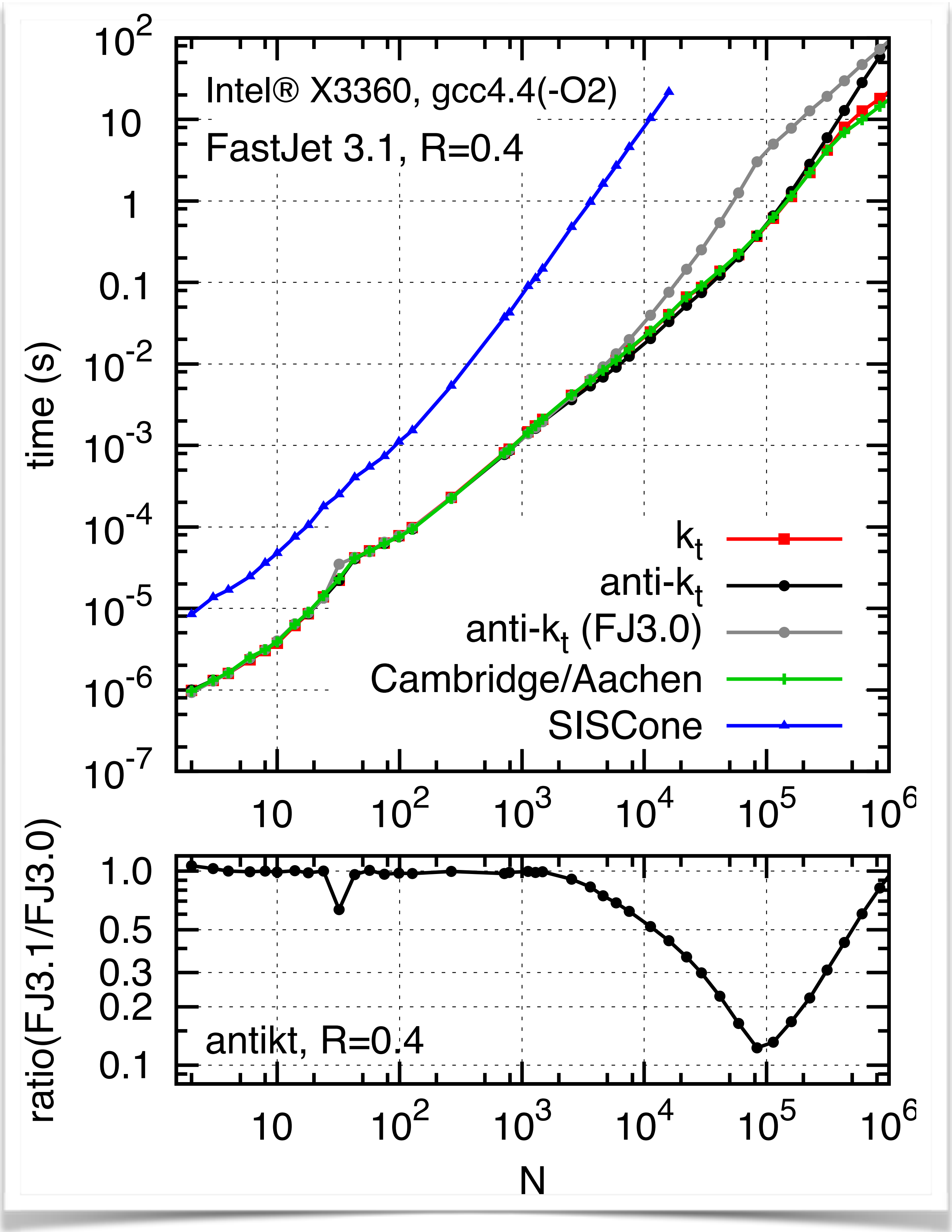
About 30 interpretations on arXiv so far!

Points to remember from these lectures

- Major difference relative to QED: quarks and gluons both emit gluons
- Non-perturbative physics lurks in many places; limiting its impact (jets), factorising unavoidable non-perturbative parts (PDFs), are both key to our successful use of perturbative QCD
- Tightly connected with infrared and collinear divergences, which are ubiquitous in QCD

EXTRAS

Time to cluster N particles in FastJet



Time to cluster N particles

Improvement wrt FJ 3.0.x, **factor of 2 for 10k**

Version 1.017 of FastJet Contrib is distributed with the following packages

Package	Version	Information
ClusteringVetoPlugin	1.0.0	README NEWS
ConstituentSubtractor	1.0.0	README NEWS
EnergyCorrelator	1.1.0	README NEWS
GenericSubtractor	1.2.0	README NEWS
JetCleanser	1.0.1	README NEWS
JetFFMoments	1.0.0	README NEWS
JetsWithoutJets	1.0.0	README NEWS
Nsubjettiness	2.1.0	README NEWS
RecursiveTools	1.0.0	README NEWS
ScJet	1.1.0	README NEWS
SoftKiller	1.0.0	README NEWS
SubjetCounting	1.0.1	README NEWS
ValenciaPlugin	2.0.0	README NEWS
VariableR	1.1.1	README NEWS