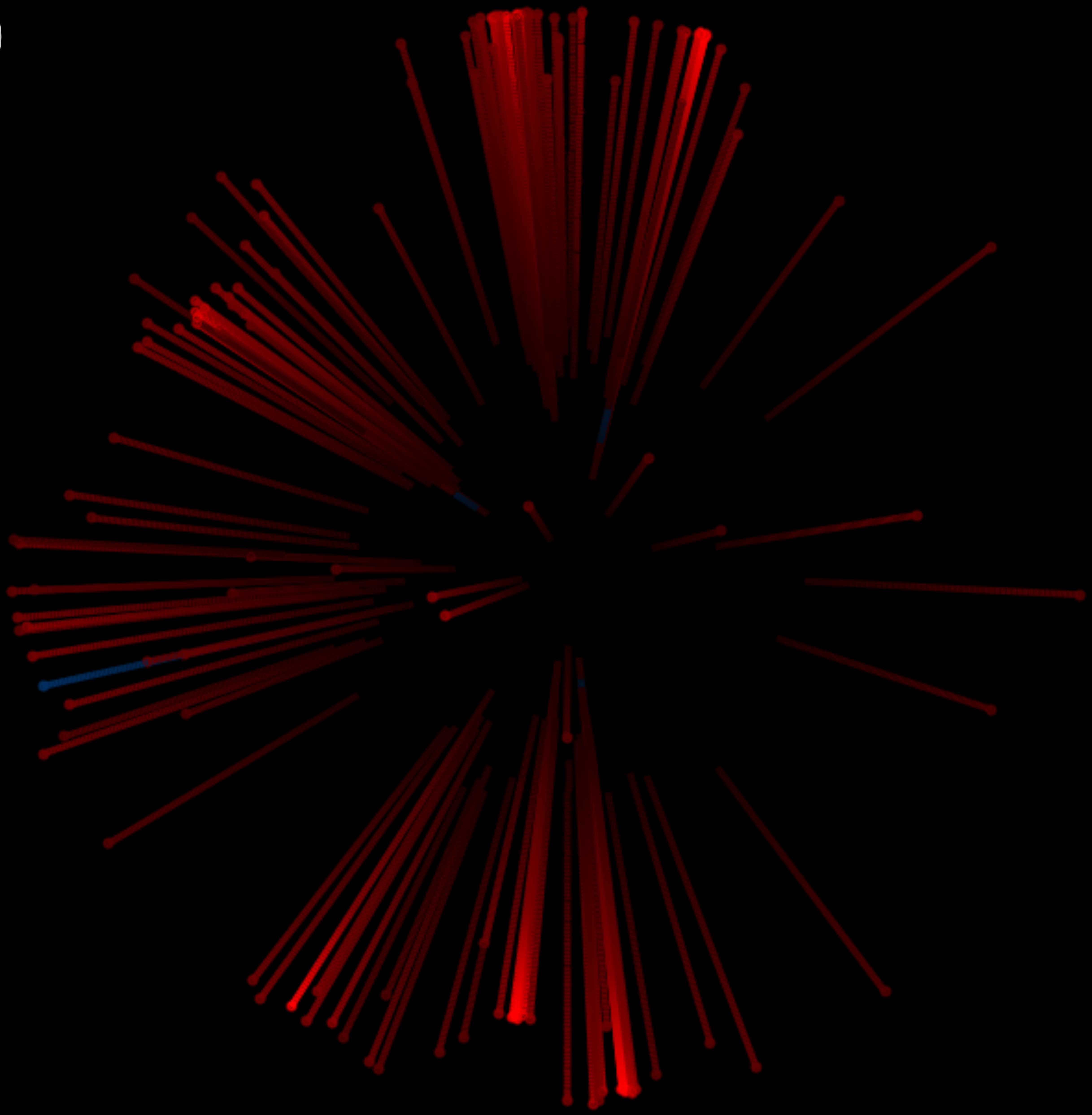
Jets through the LHC era
(a personal view)

5th KEK-PH, Jet Physics
via Zoom
30 November 2021



Gavin Salam
Rudolf Peierls Centre for
Theoretical Physics
& All Souls College, Oxford

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The context of this talk: LHC physics (colour-coded by directly-probed energy scales)

Standard-model physics (QCD & electroweak) — 100 MeV - 4 TeV	**top-quark physics** — 170 GeV - O(TeV)	**Higgs physics** — 125 GeV - 500 GeV
direct new-particle searches — 100 GeV - 8 TeV	**flavour physics (bottom & some charm)** — 1 - 5 GeV	**heavy-ion physics** — 100 MeV - 500 GeV

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Key high-energy physics goals (my view)

1. Establish the structure of the Higgs sector of the SM
2. Search for signs of physics beyond the SM, direct (incl. dark matter candidates, SUSY, etc.) and indirect
3. Measure SM parameters, proton structure (PDFs), establish theory-data comparison methods, etc.

The Lagrangian and Higgs interactions: two out of three qualitatively new!

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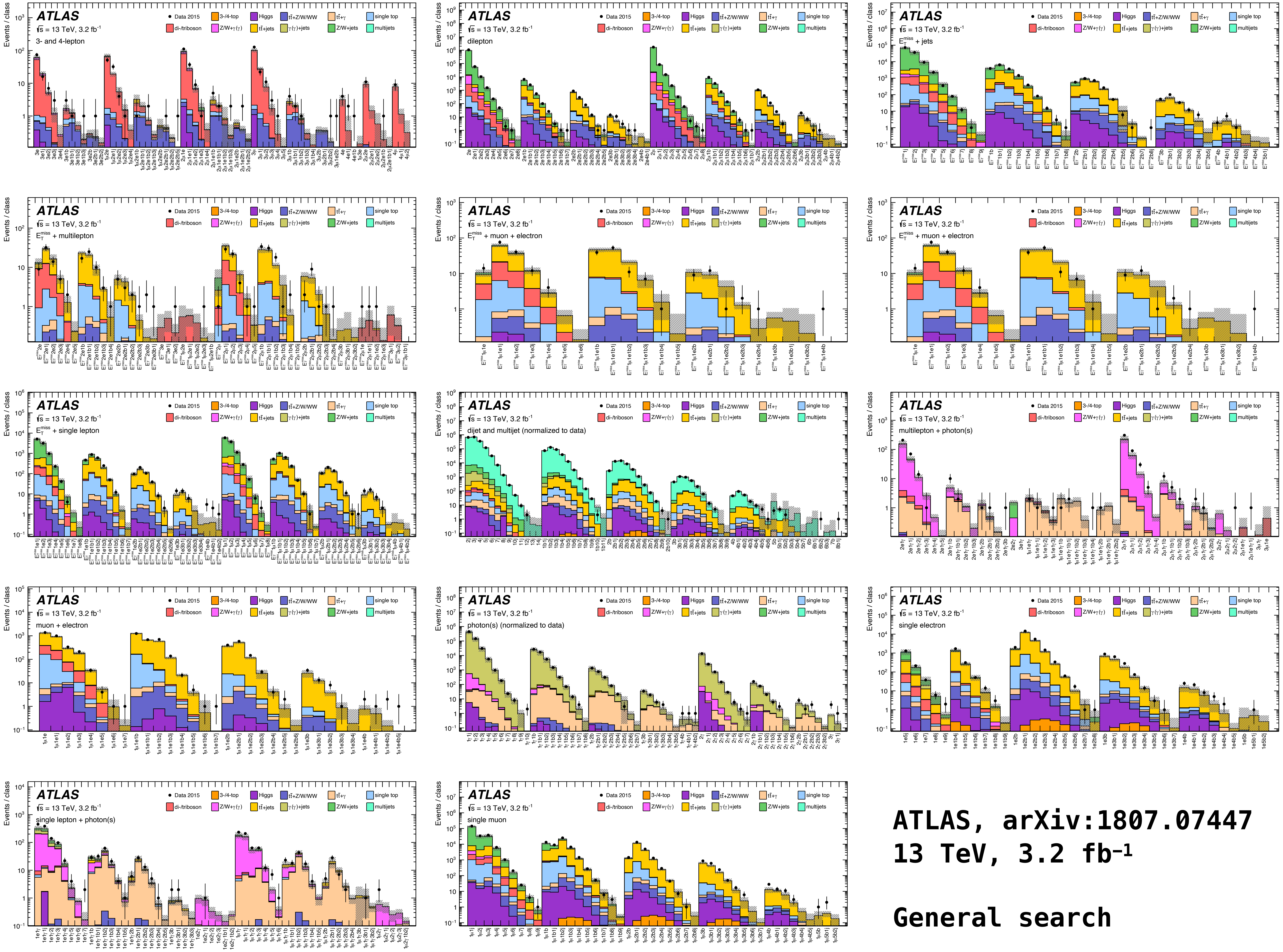
Higgs potential → self-interaction ("sixth?" force between scalars).

Holds the SM together.

Unobserved

Broadband searches (here an example with 704 event classes, >36000 bins)

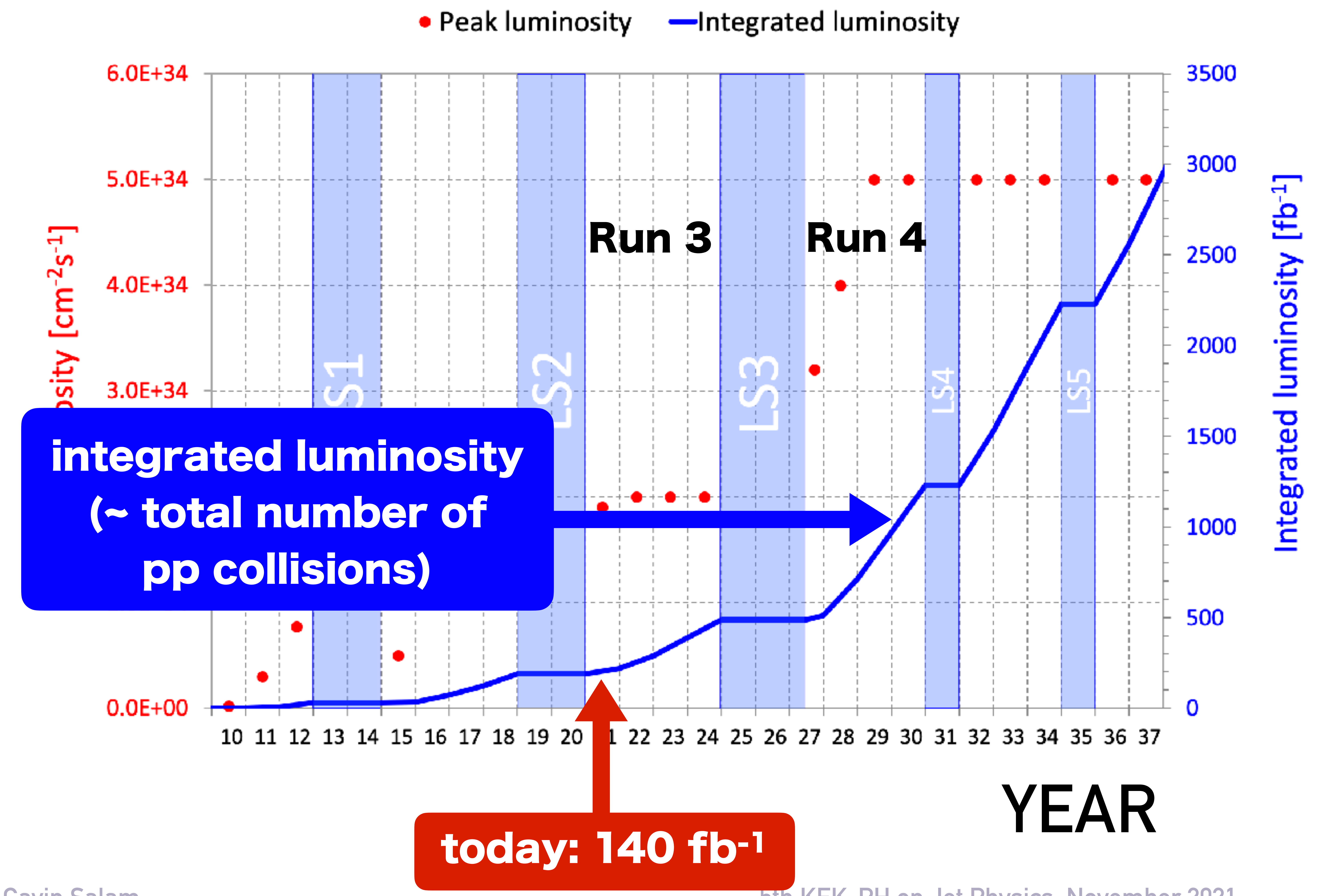


Just one illustration out of many searches at the LHC

ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb^{-1}

General search

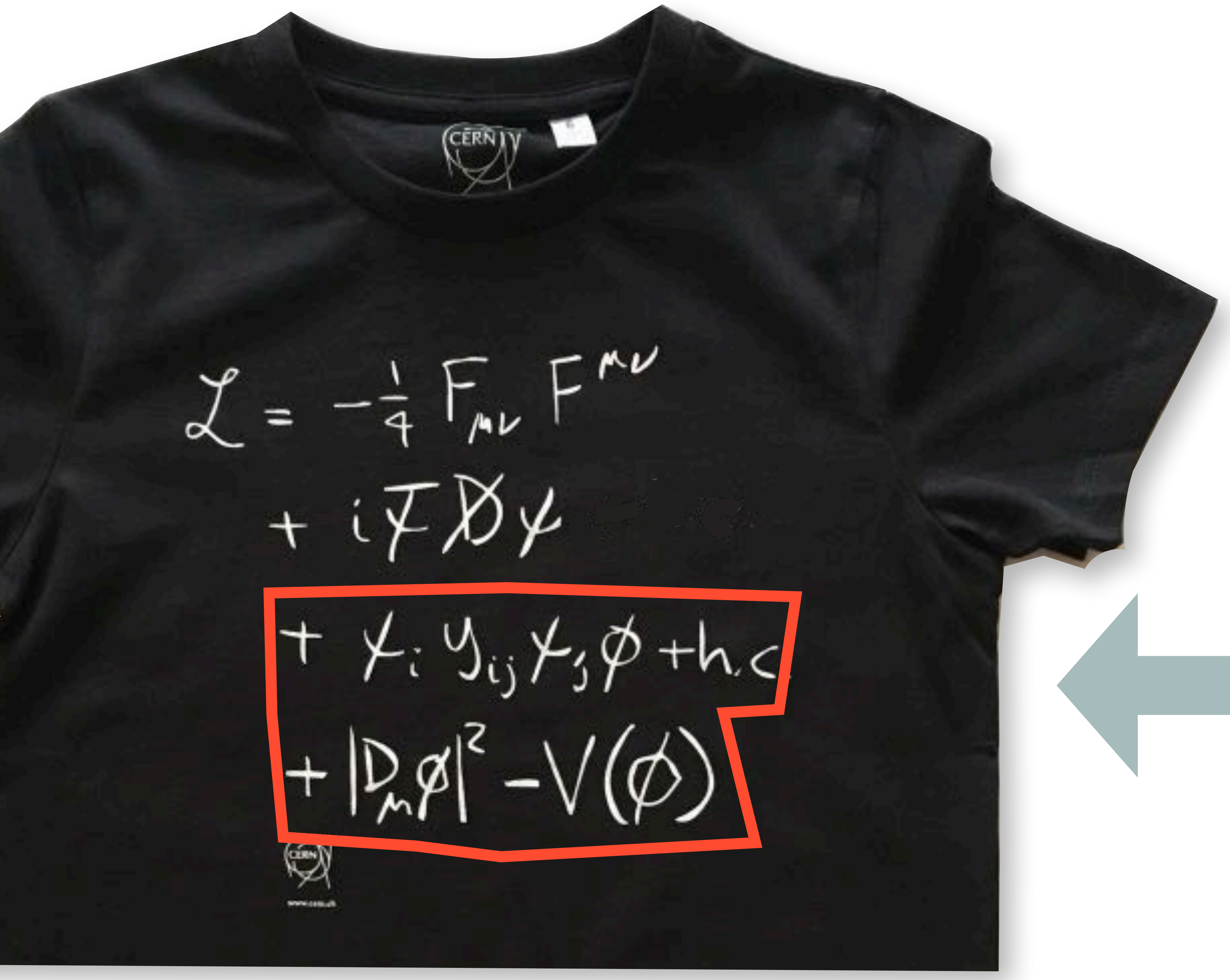
LHC luminosity v. time



year	lumi (fb^{-1})	
2020	140	
2025	450	(× 3)
2030	1200	(× 8)
2037	3000	(× 20)

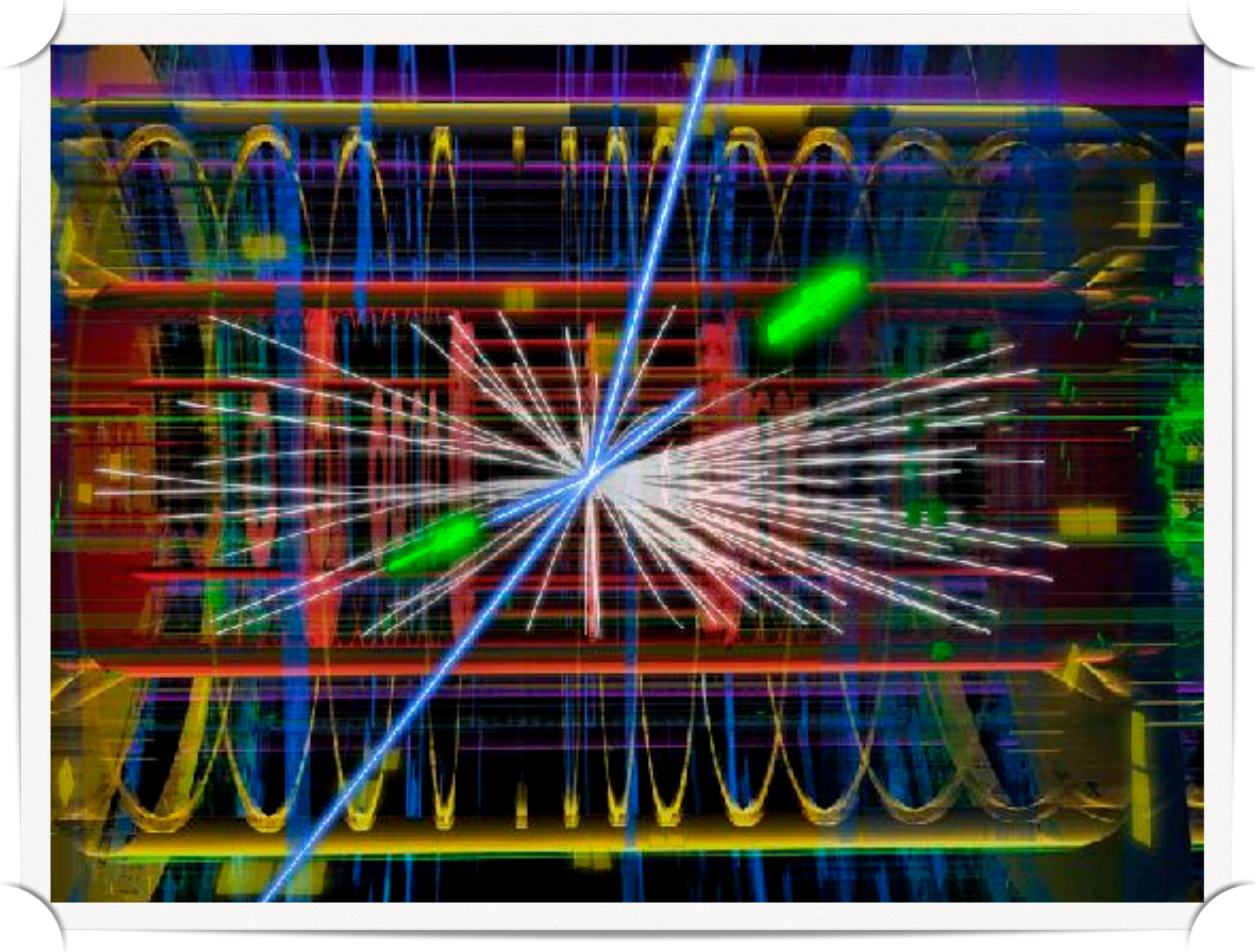
95% of collisions still to be delivered

UNDERLYING THEORY



how do you make quantitative connection?

EXPERIMENTAL DATA



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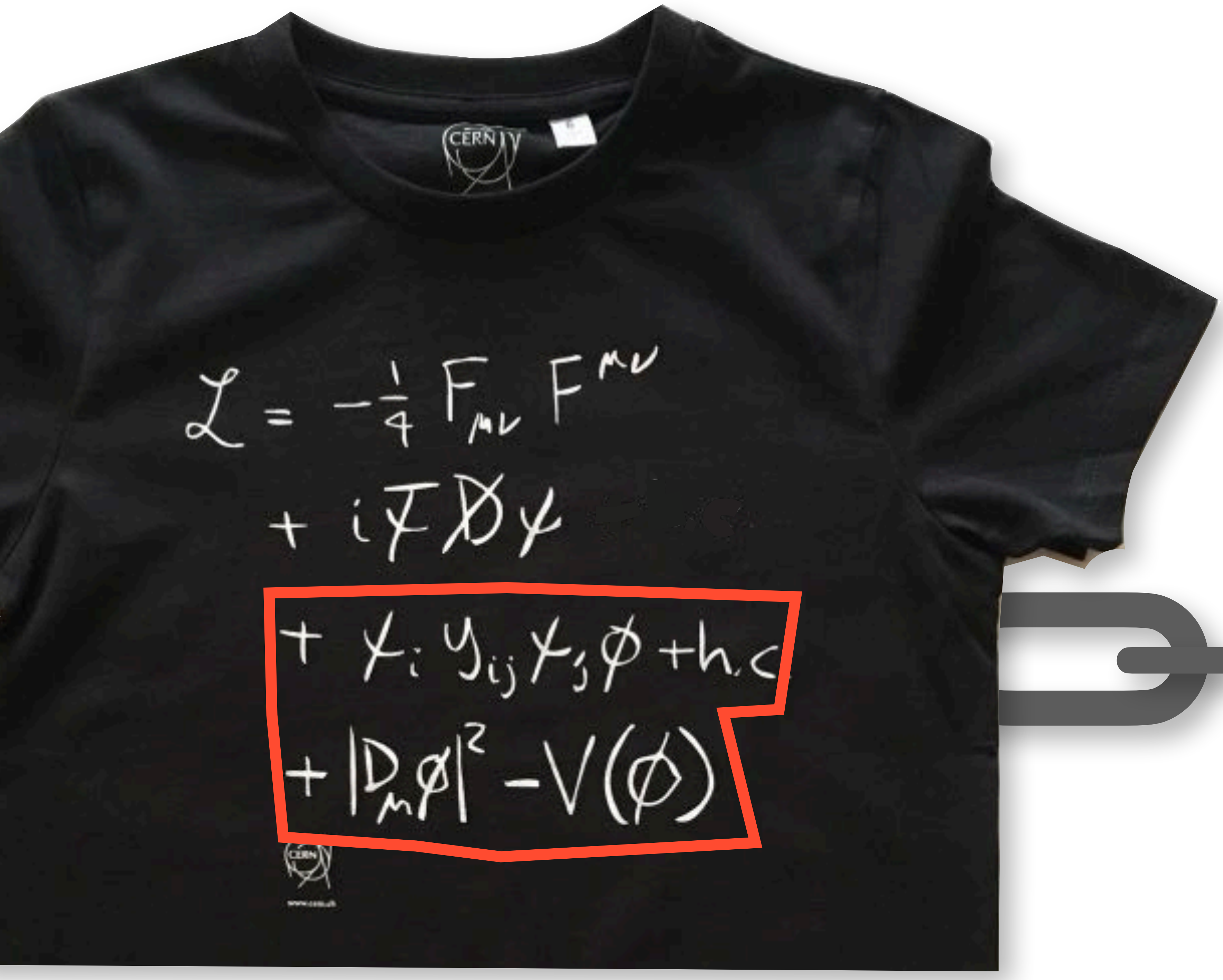

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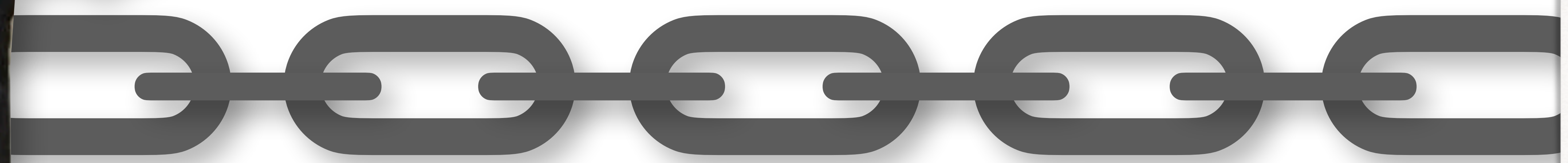
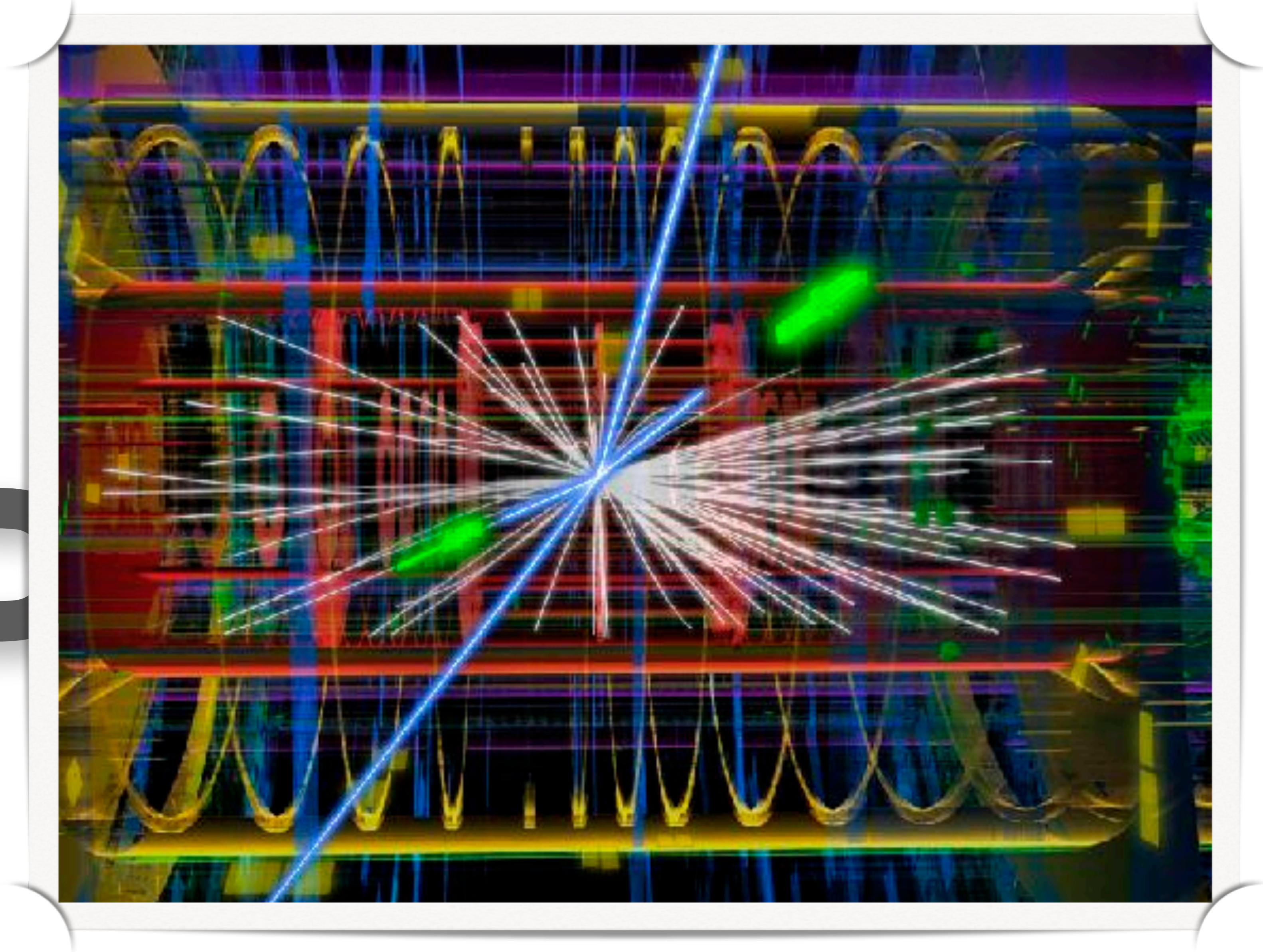
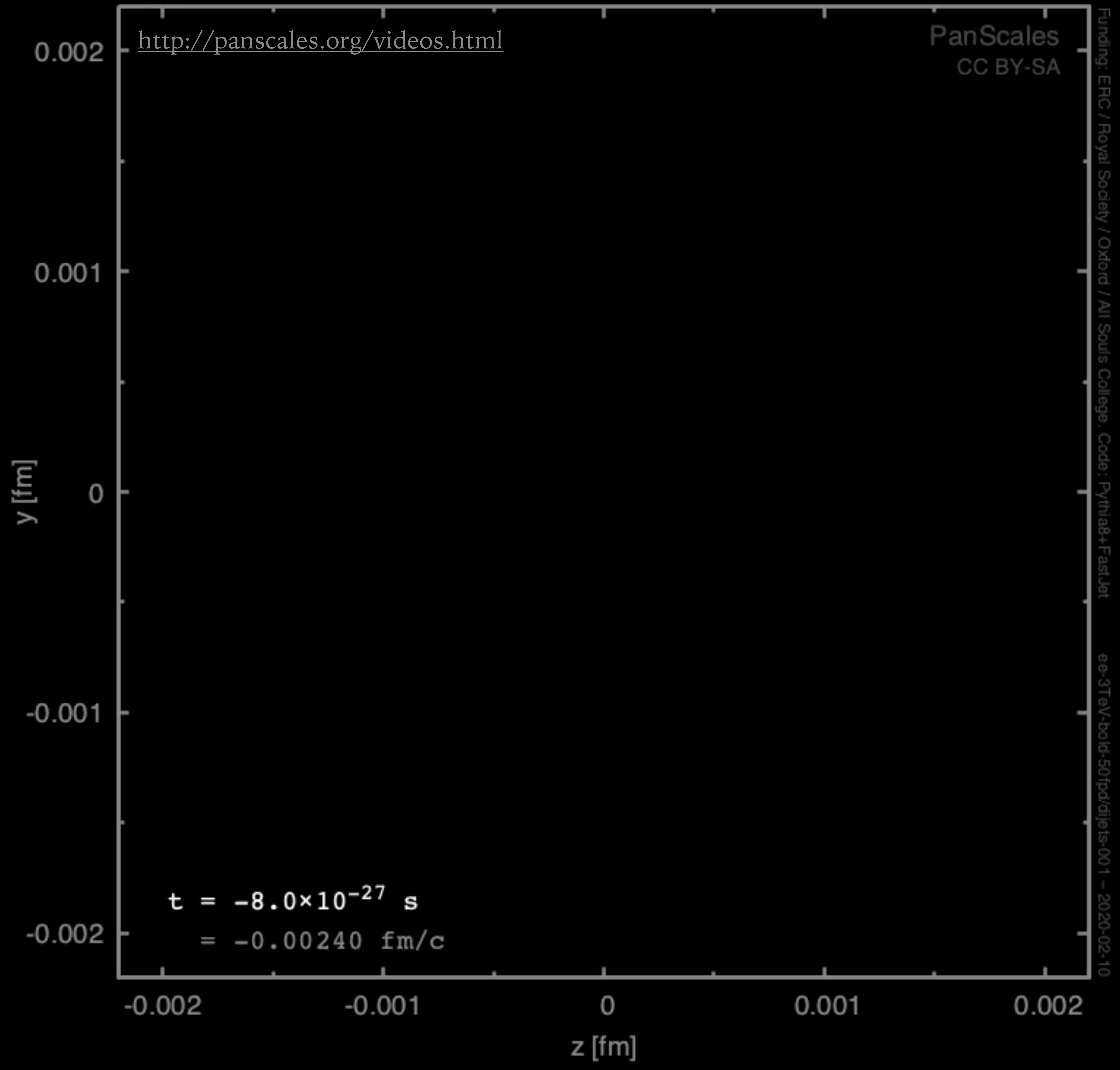




through a chain of experimental and theoretical links

[in particular Quantum Chromodynamics (QCD)]

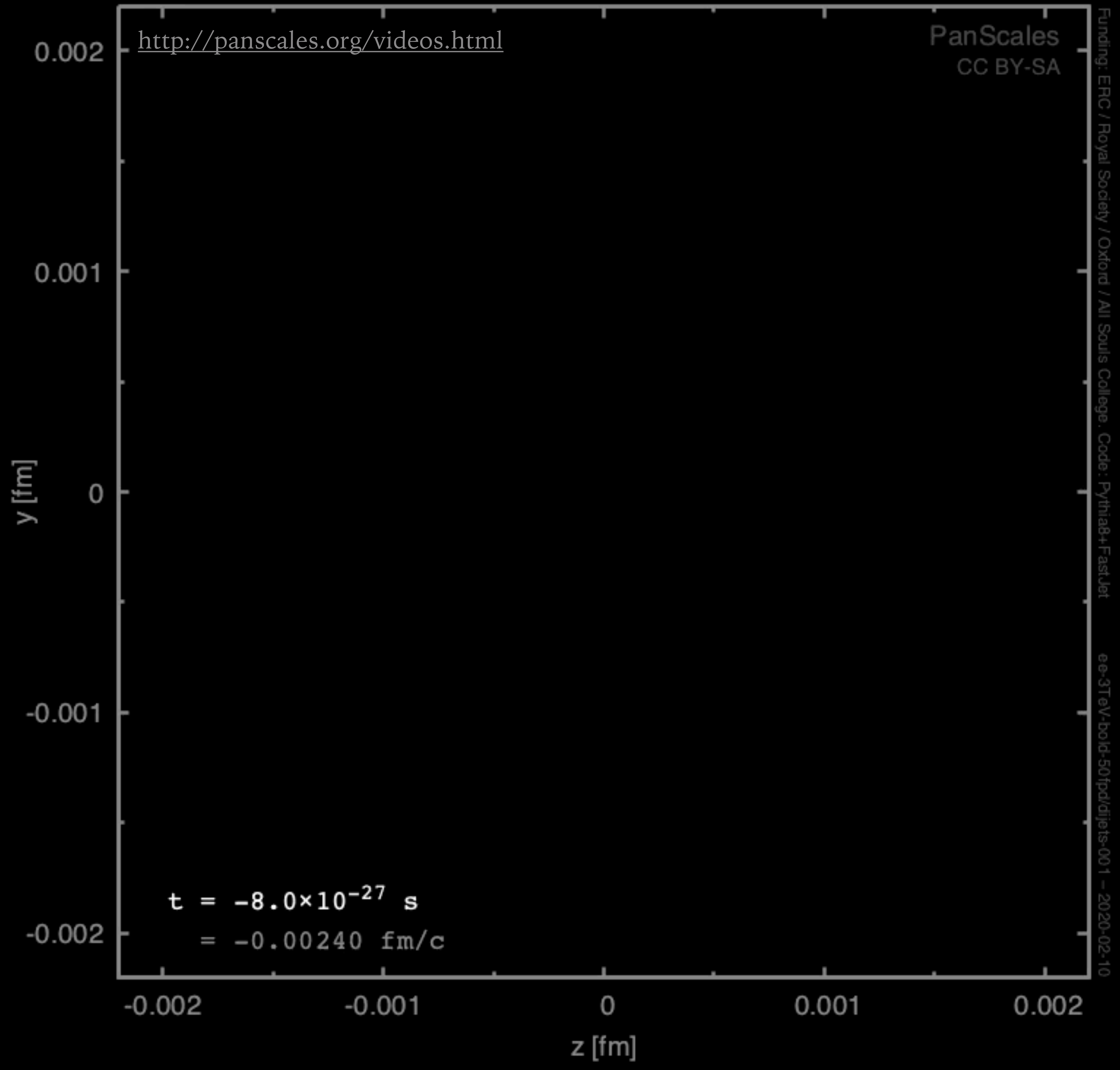


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



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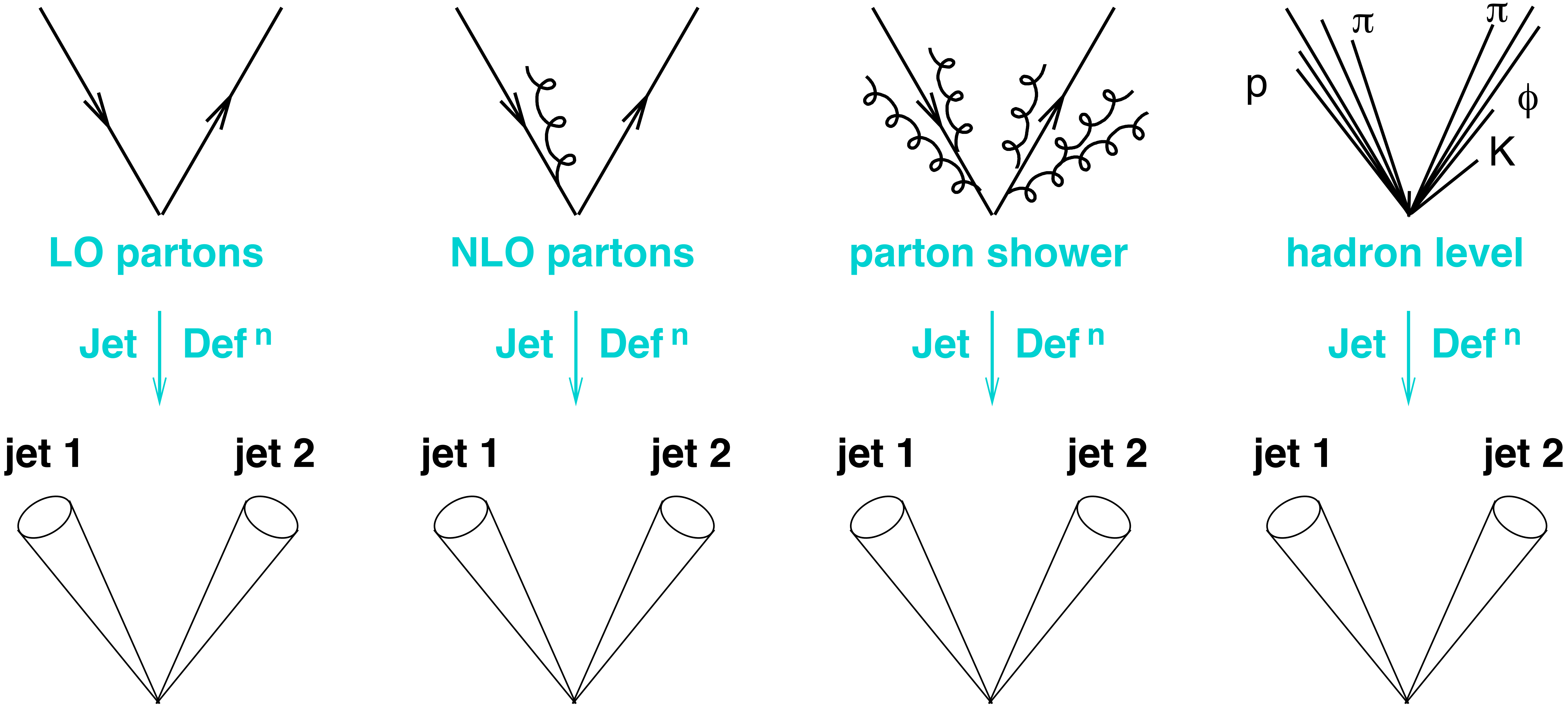
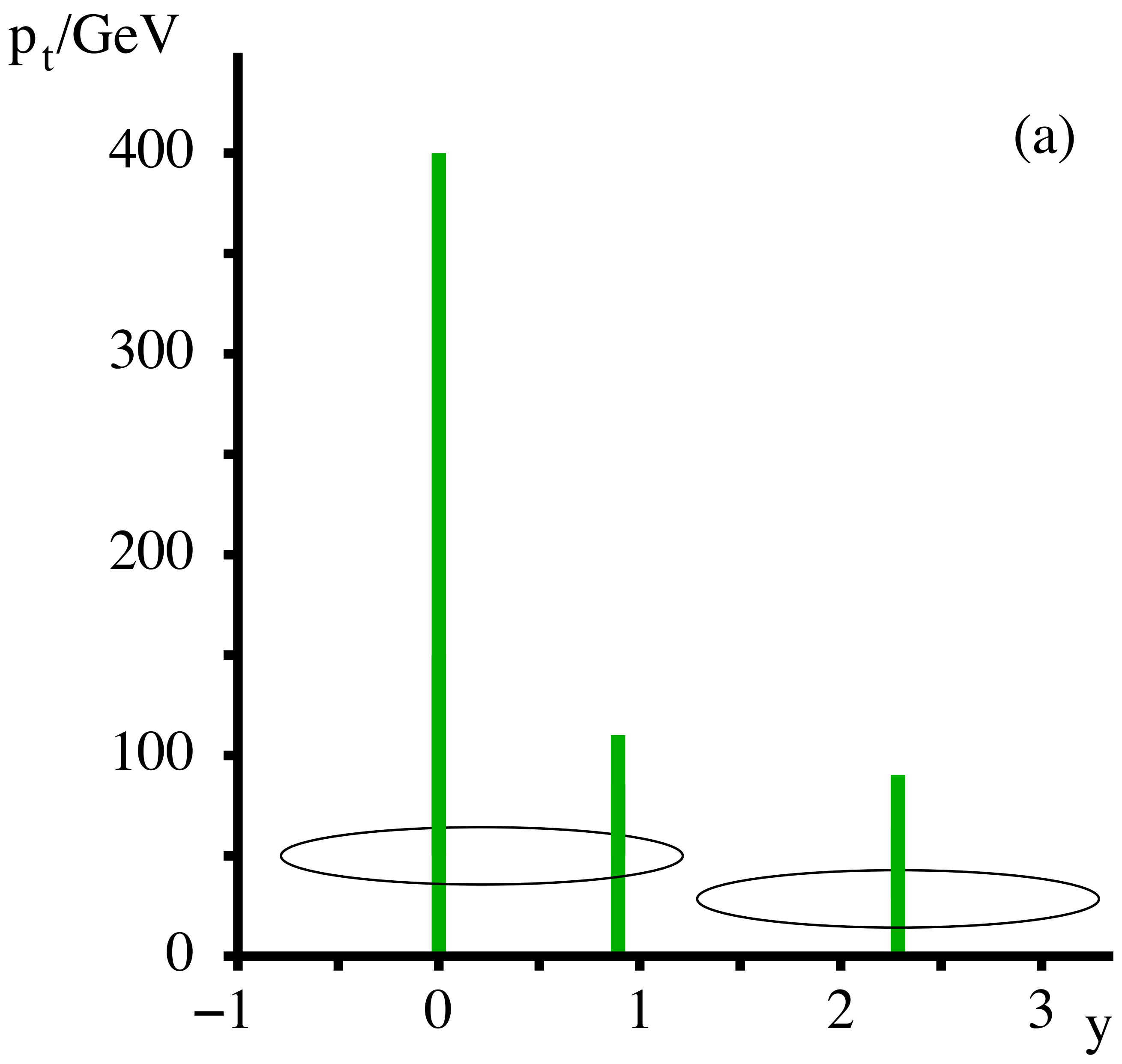
Jet finding projects high-dim info to low number of dimensions in a robust, reproducible way

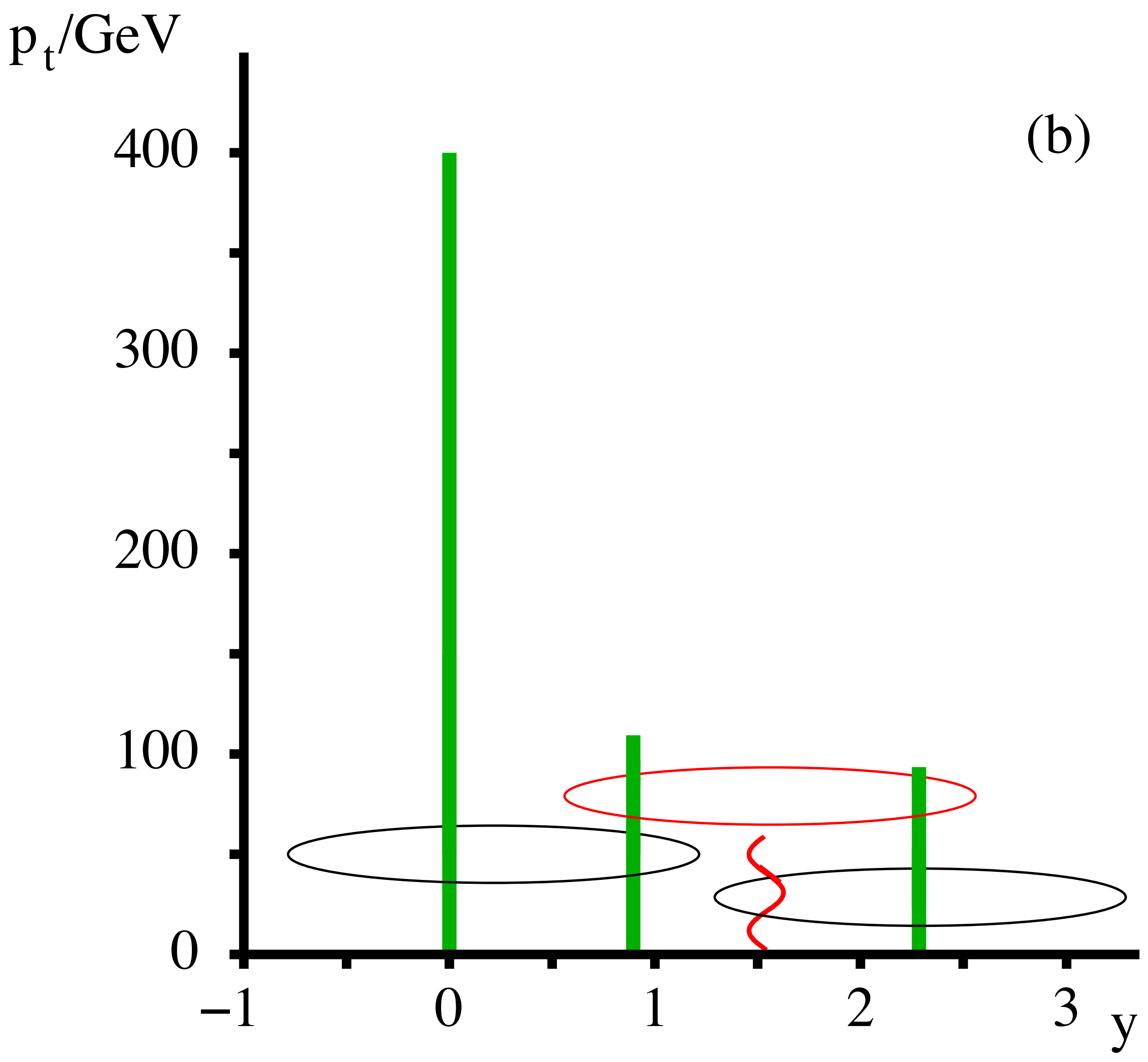


Projection to jets should be resilient to QCD effects

step back ~15 years

pre-LHC hadron-collider jet algorithms (cone algorithms) were infrared unsafe





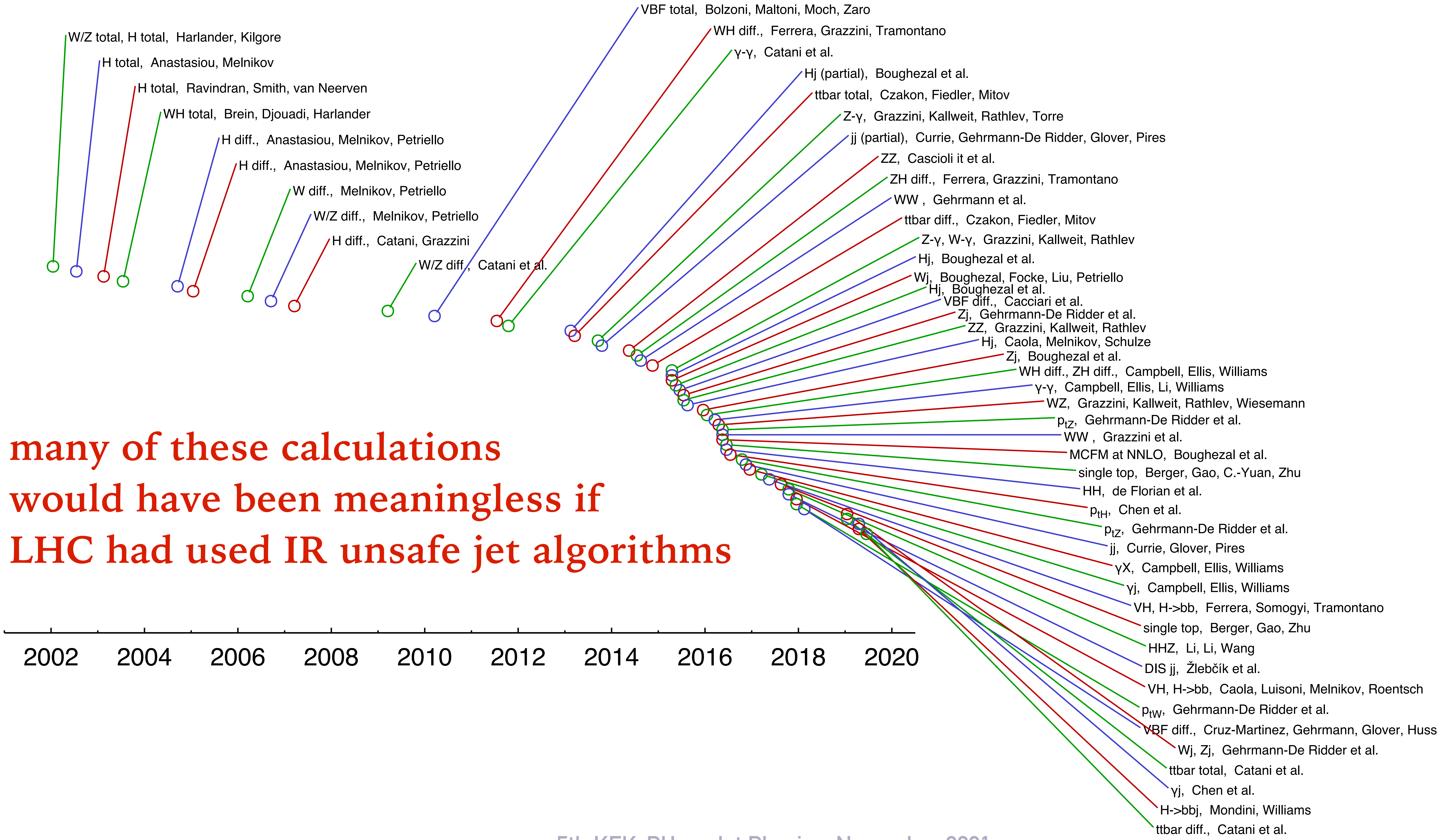
infrared unsafety = strong sensitivity to low-momentum perturbations of event structure

→ uncancelled ∞ in perturbative QCD calculations

Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
$W/Z/H$ + 1 jet cross section	NNLO	NLO
3 jet cross section	NLO	LO
$W/Z/H$ + 2 jet cross section	NLO	LO
jet masses in 3 jets, $W/Z/H + 2$ jets	LO	none

GPS & Soyez
arXiv:0704.0292

yet we were on the cusp of a revolution in precision QCD (NNLO) calculations



many of these calculations
would have been meaningless if
LHC had used IR unsafe jet algorithms

possible solution
"sequential recombination" k_t algorithm

Marunouchi, Tokyo (c. 2009)

Catani, Dokshitzer, Seymour & Webber '93
Ellis & Soper '93

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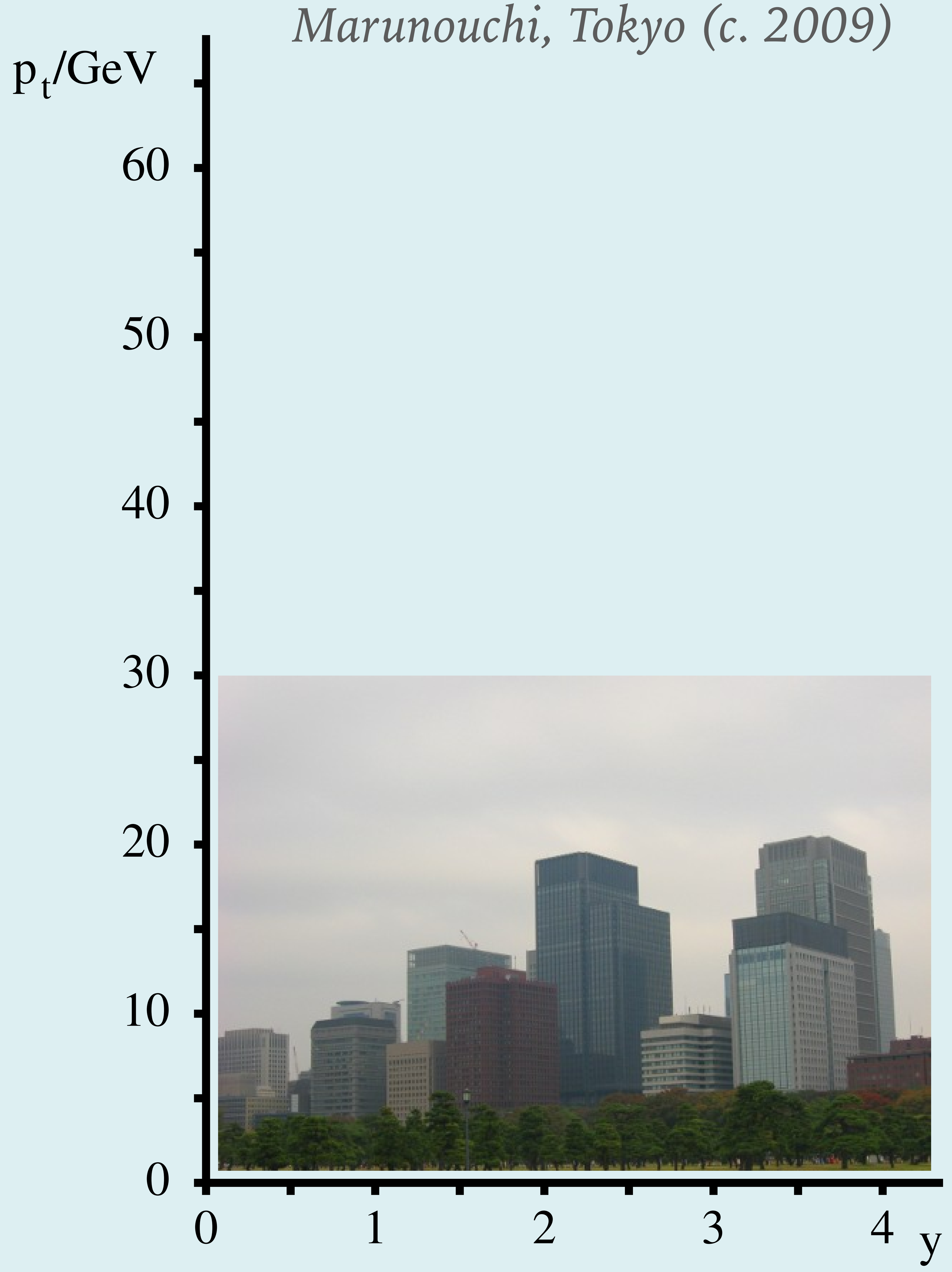

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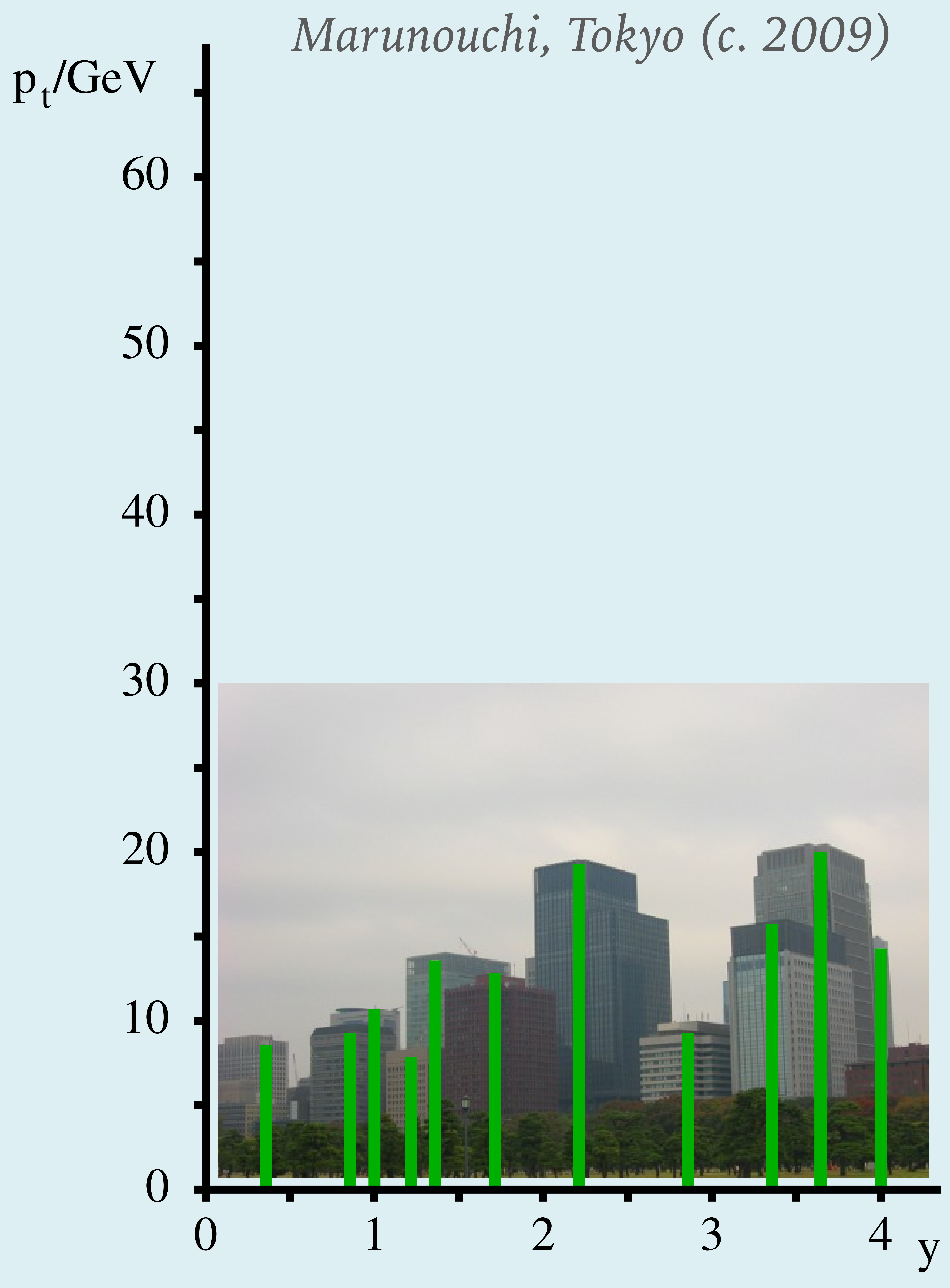

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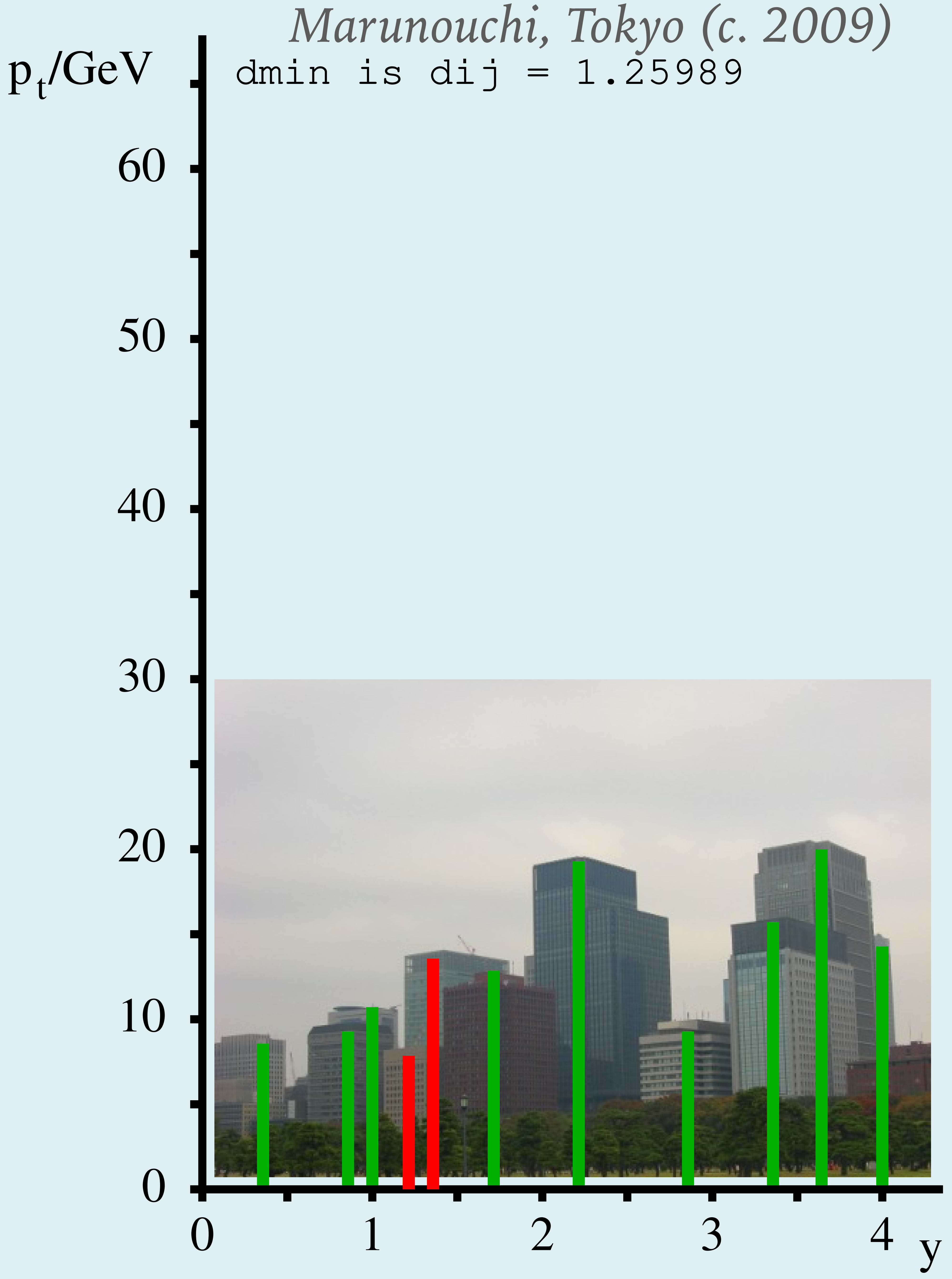

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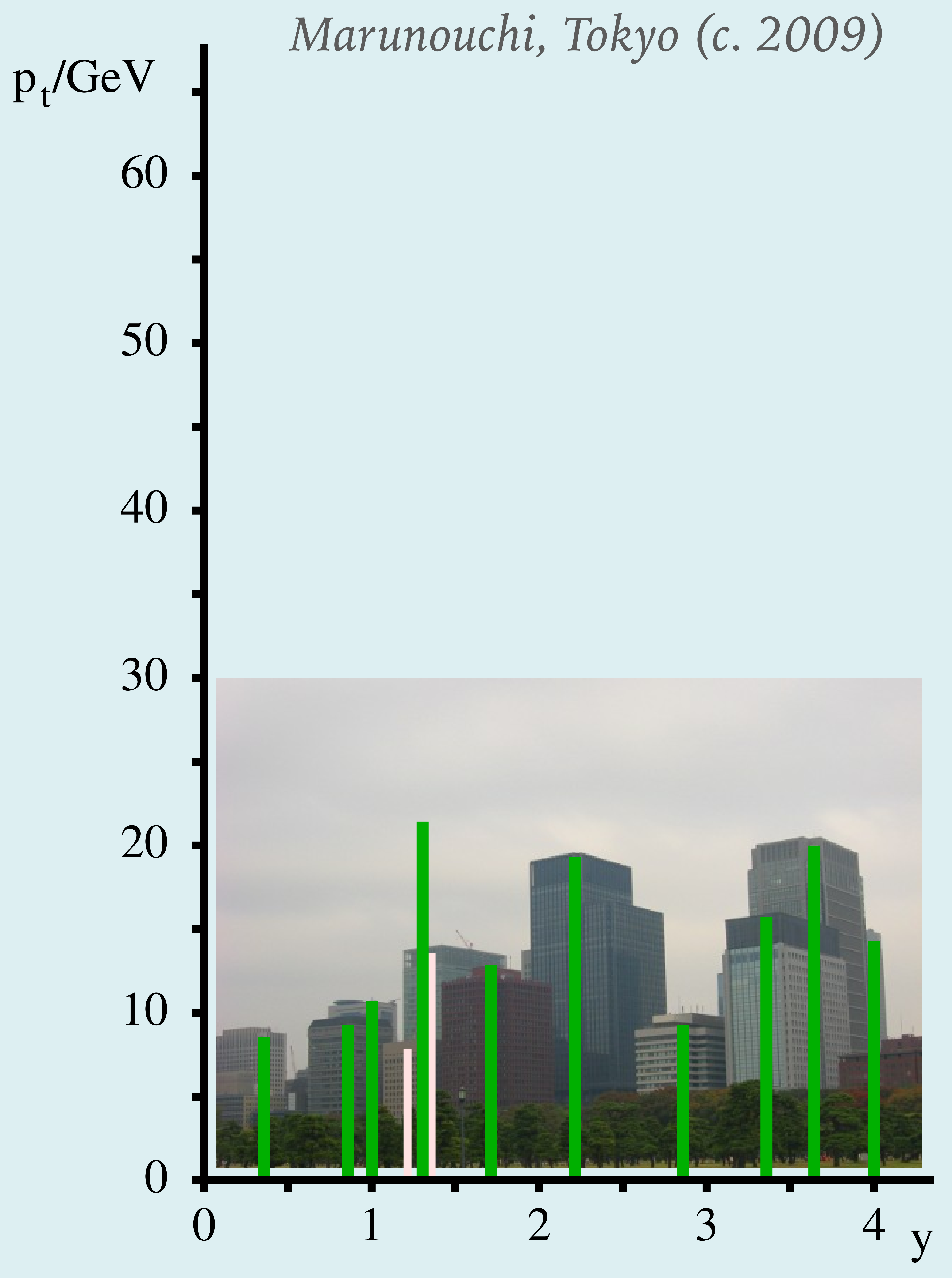

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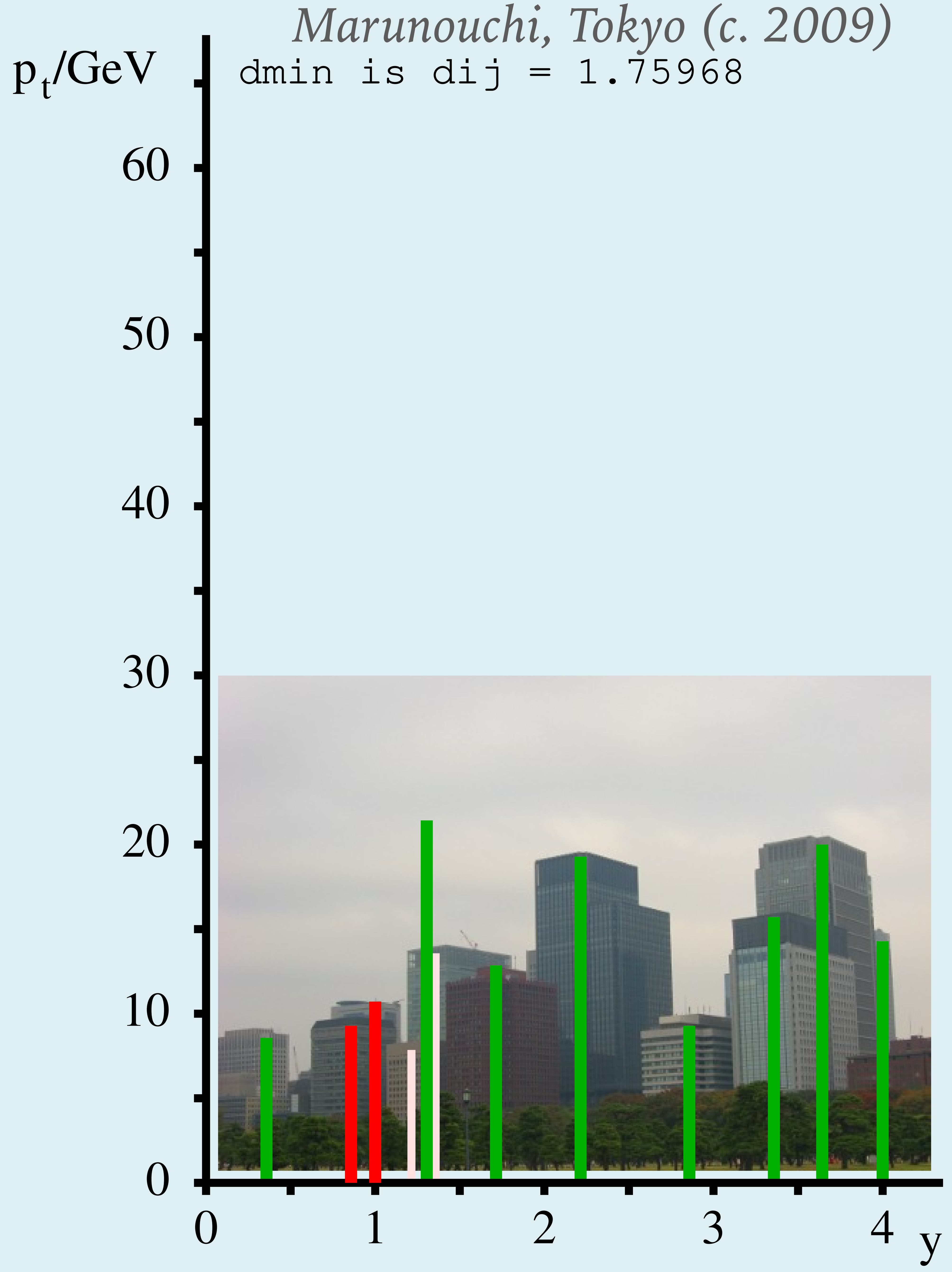

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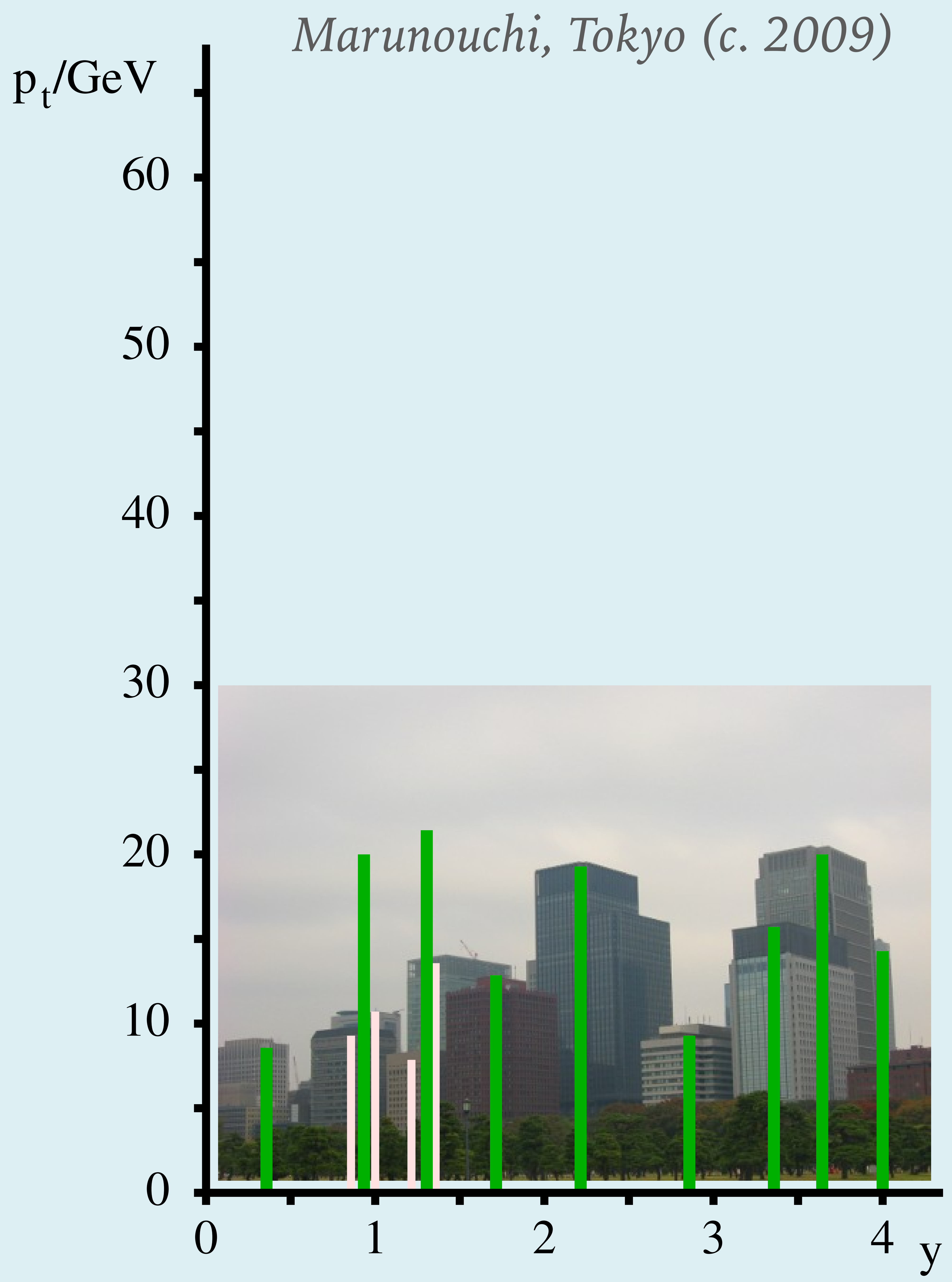

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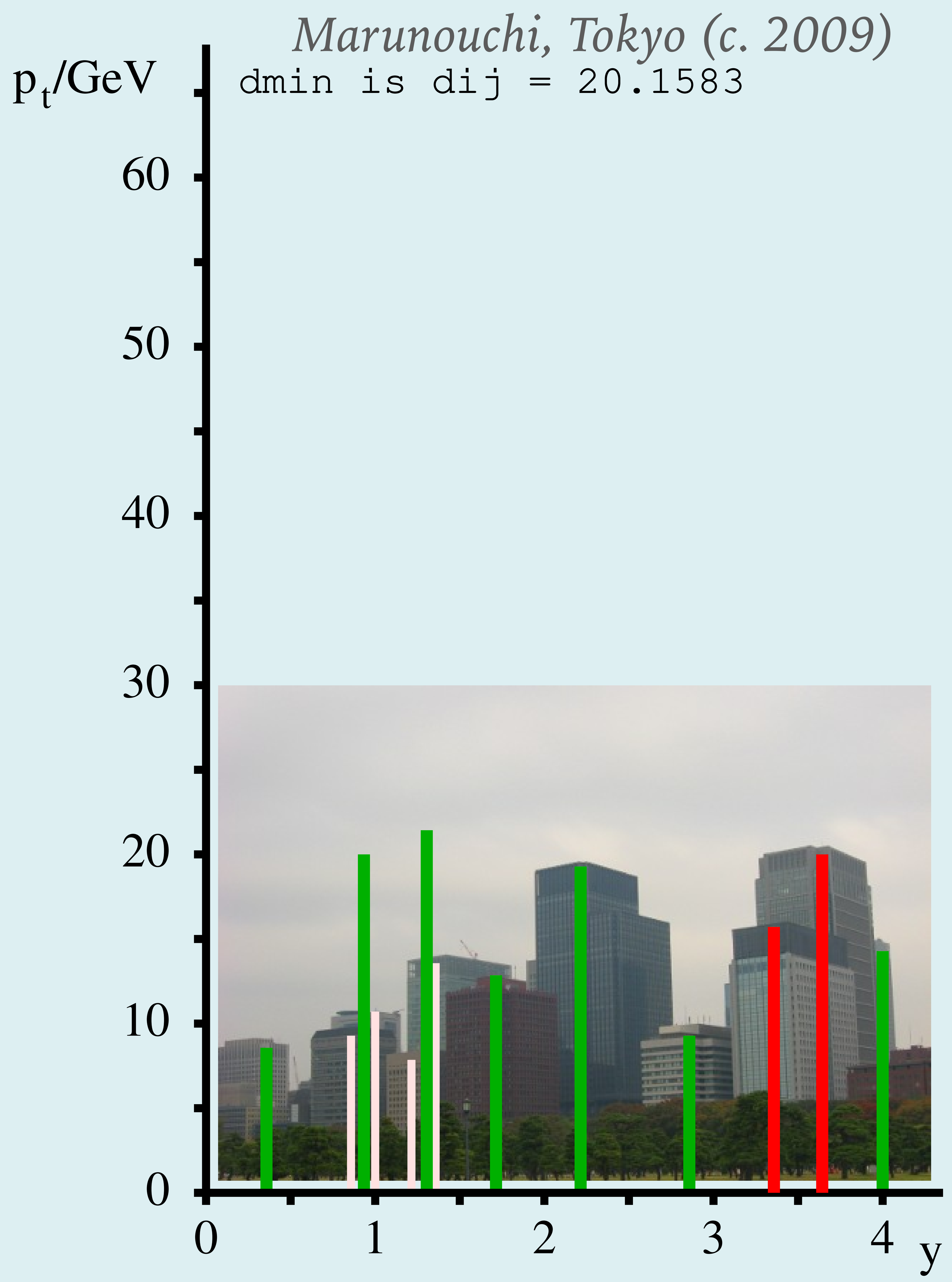

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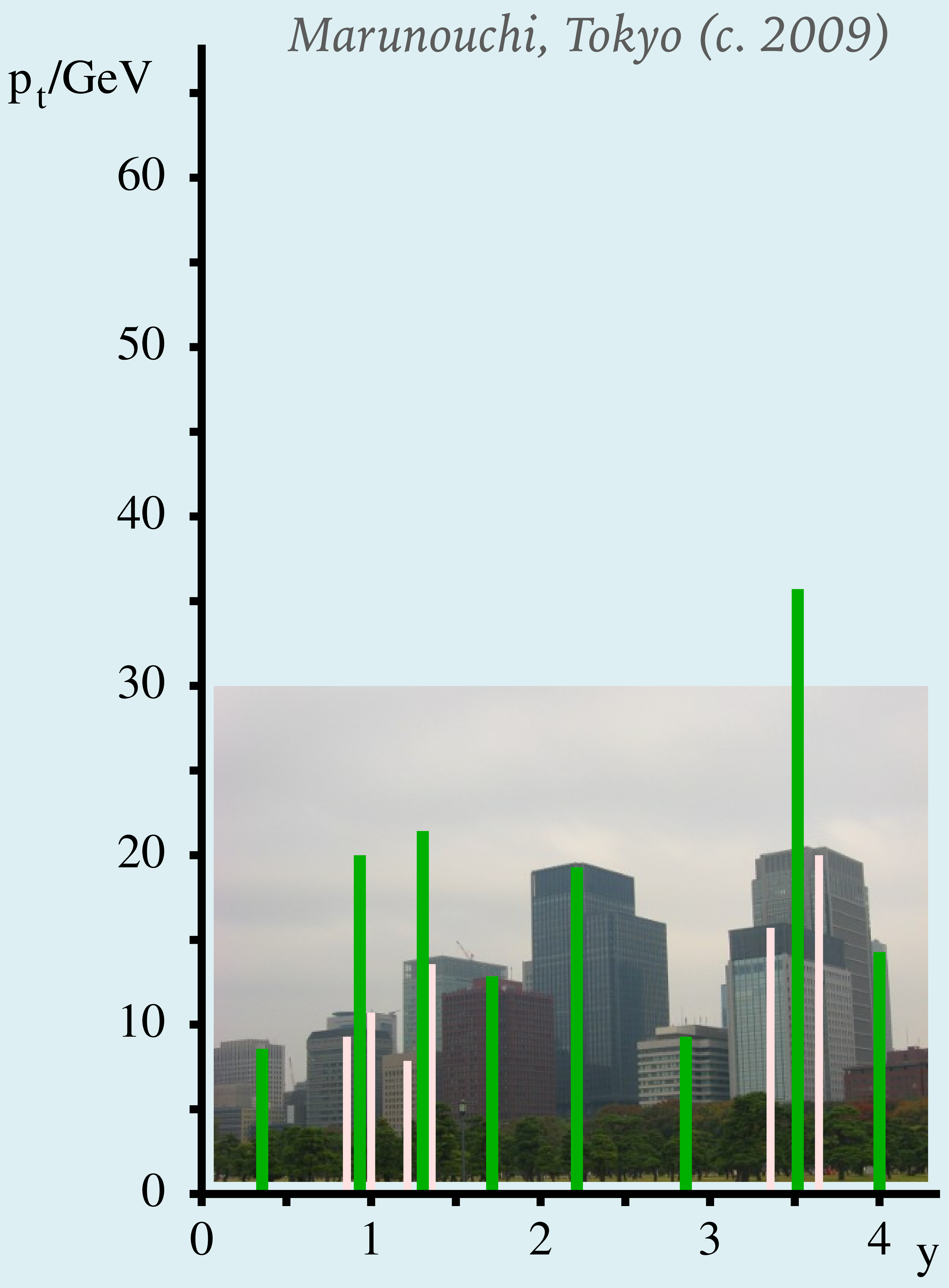

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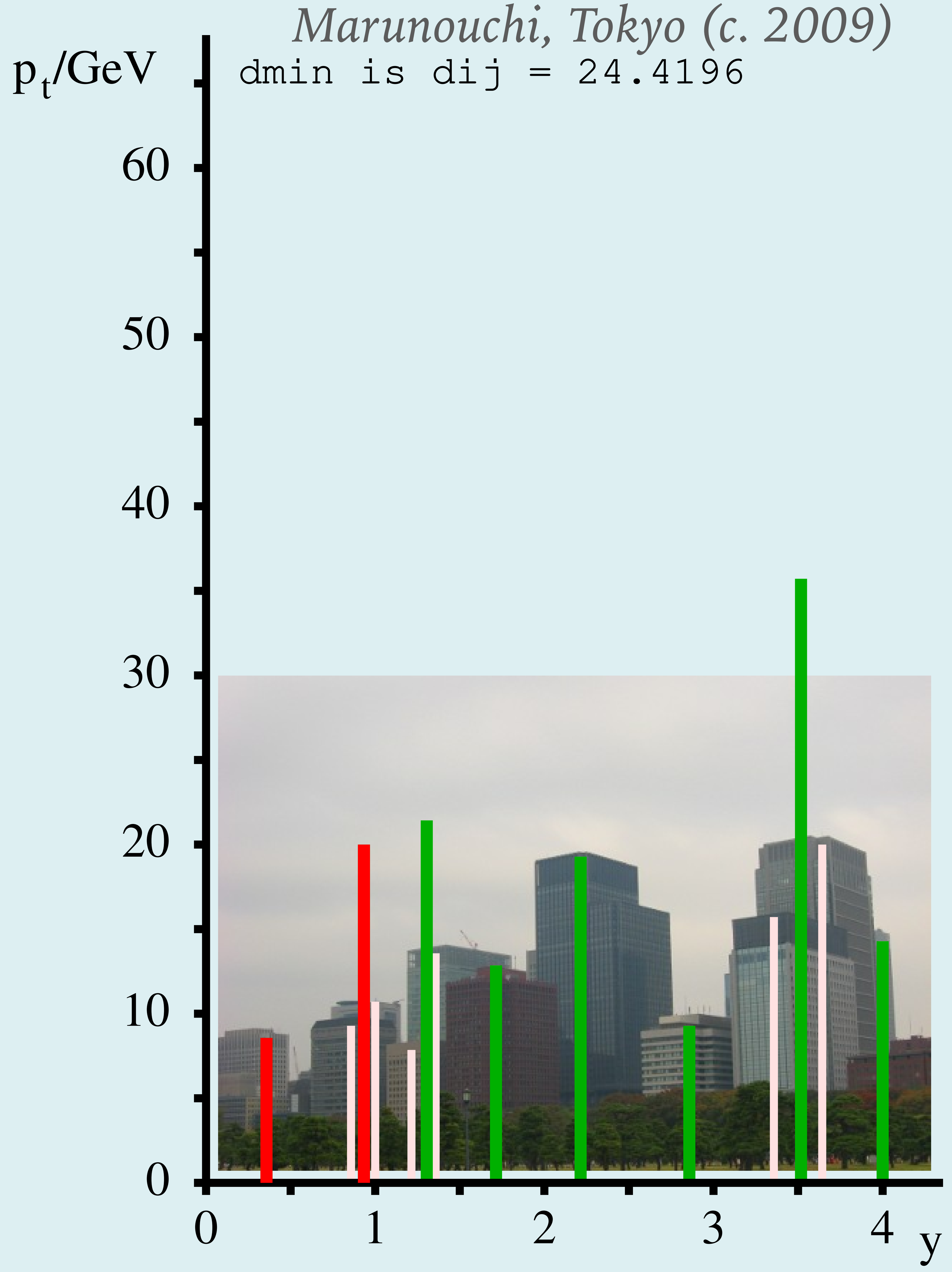

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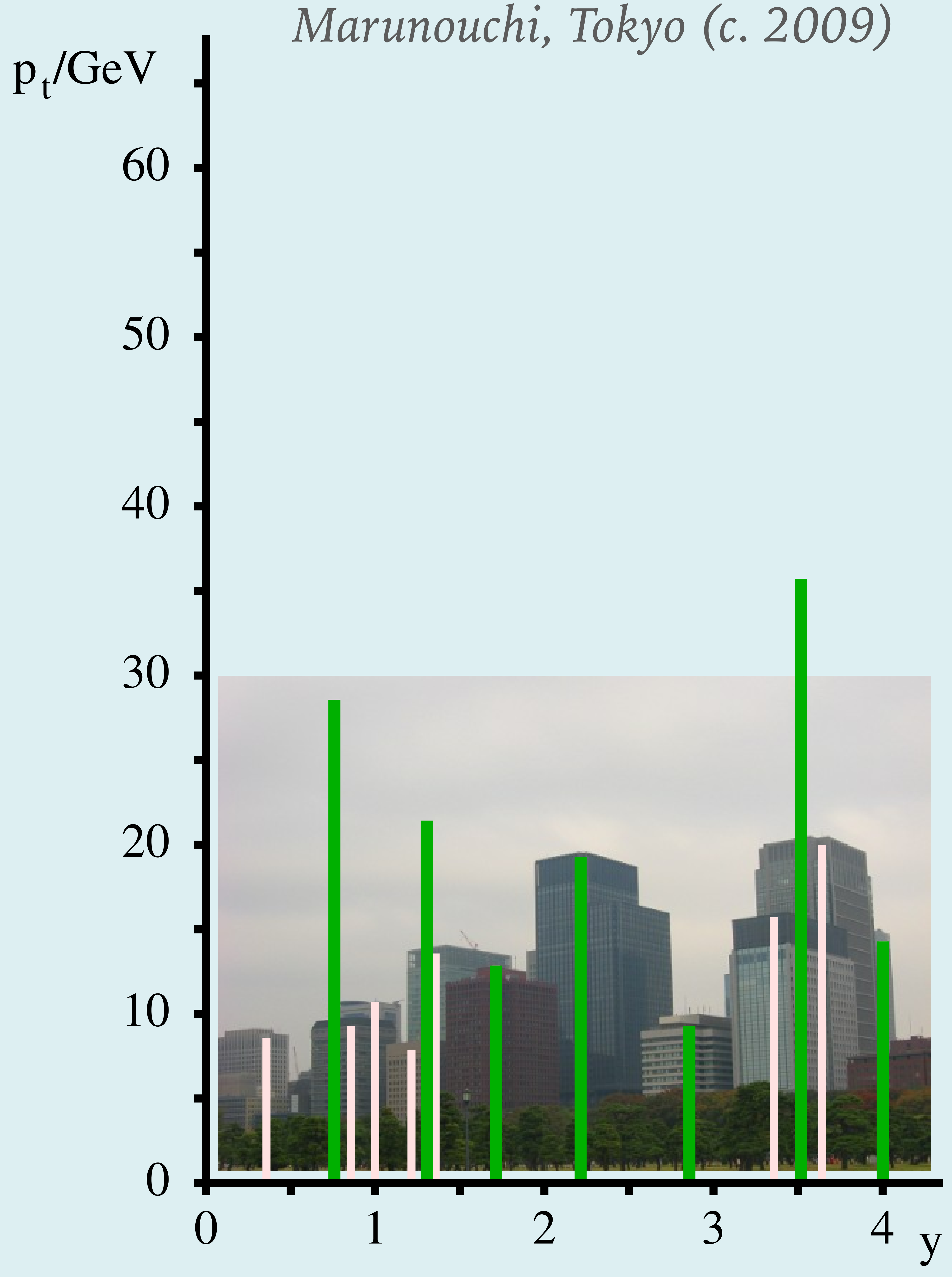

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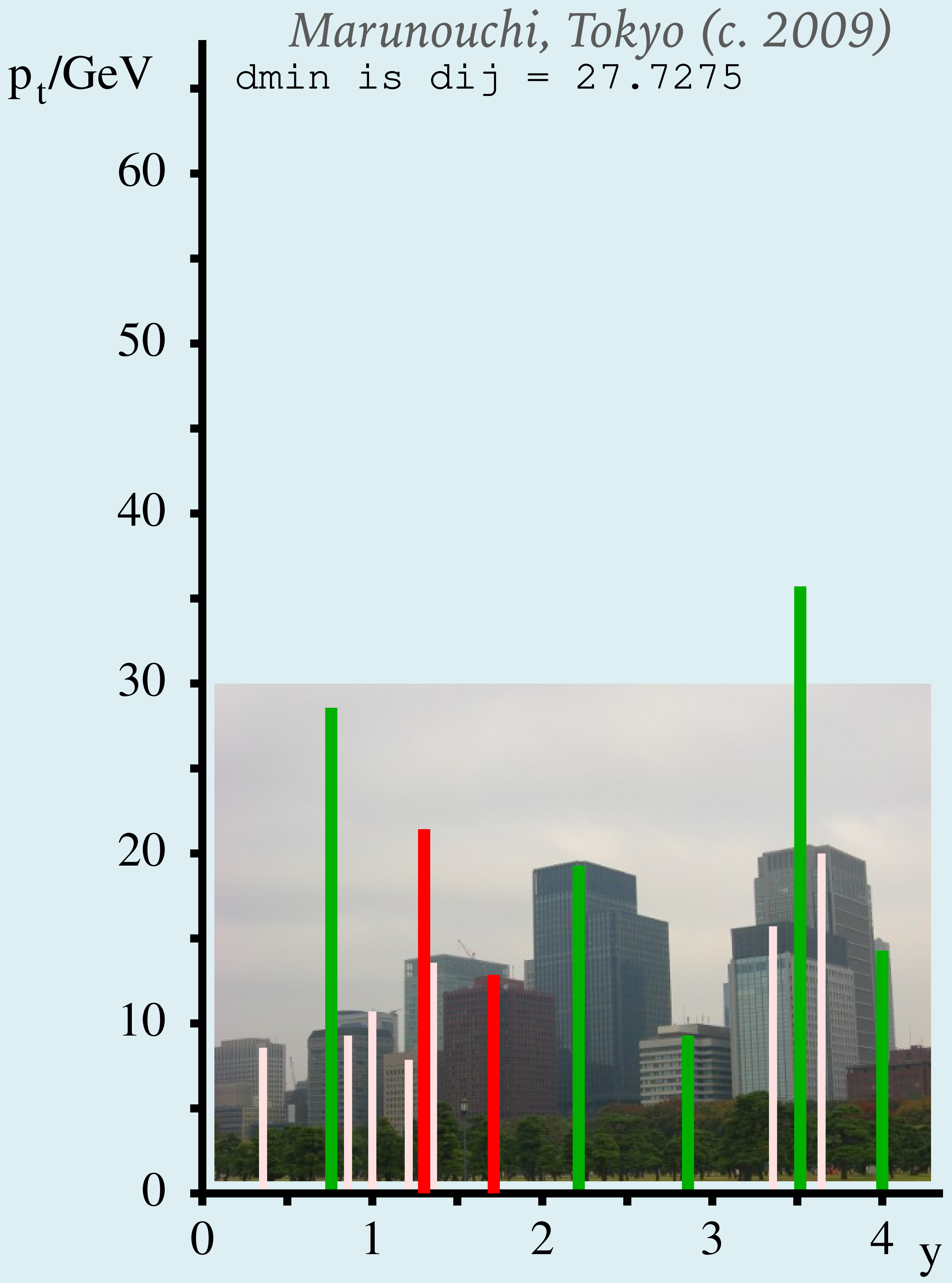

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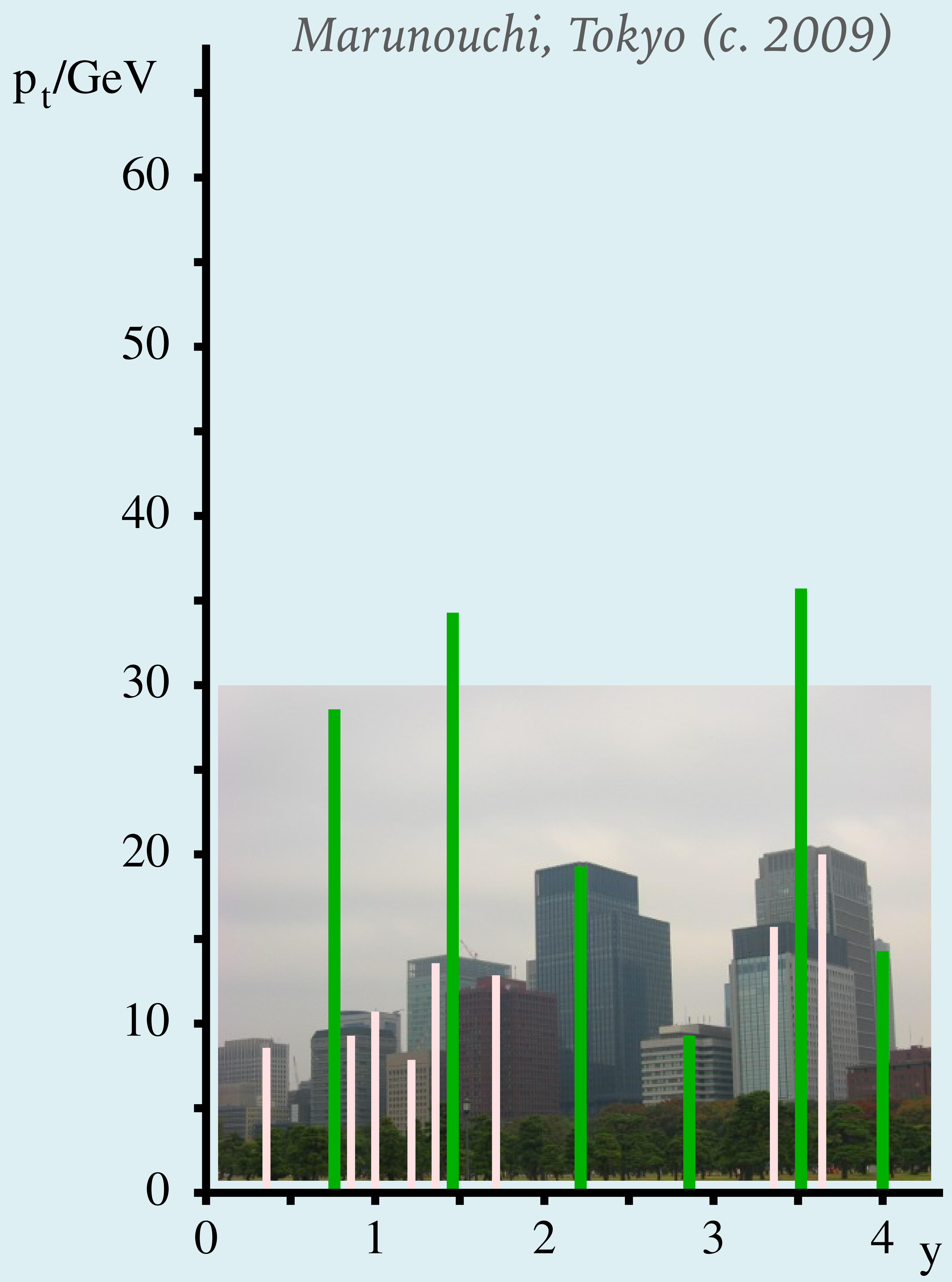

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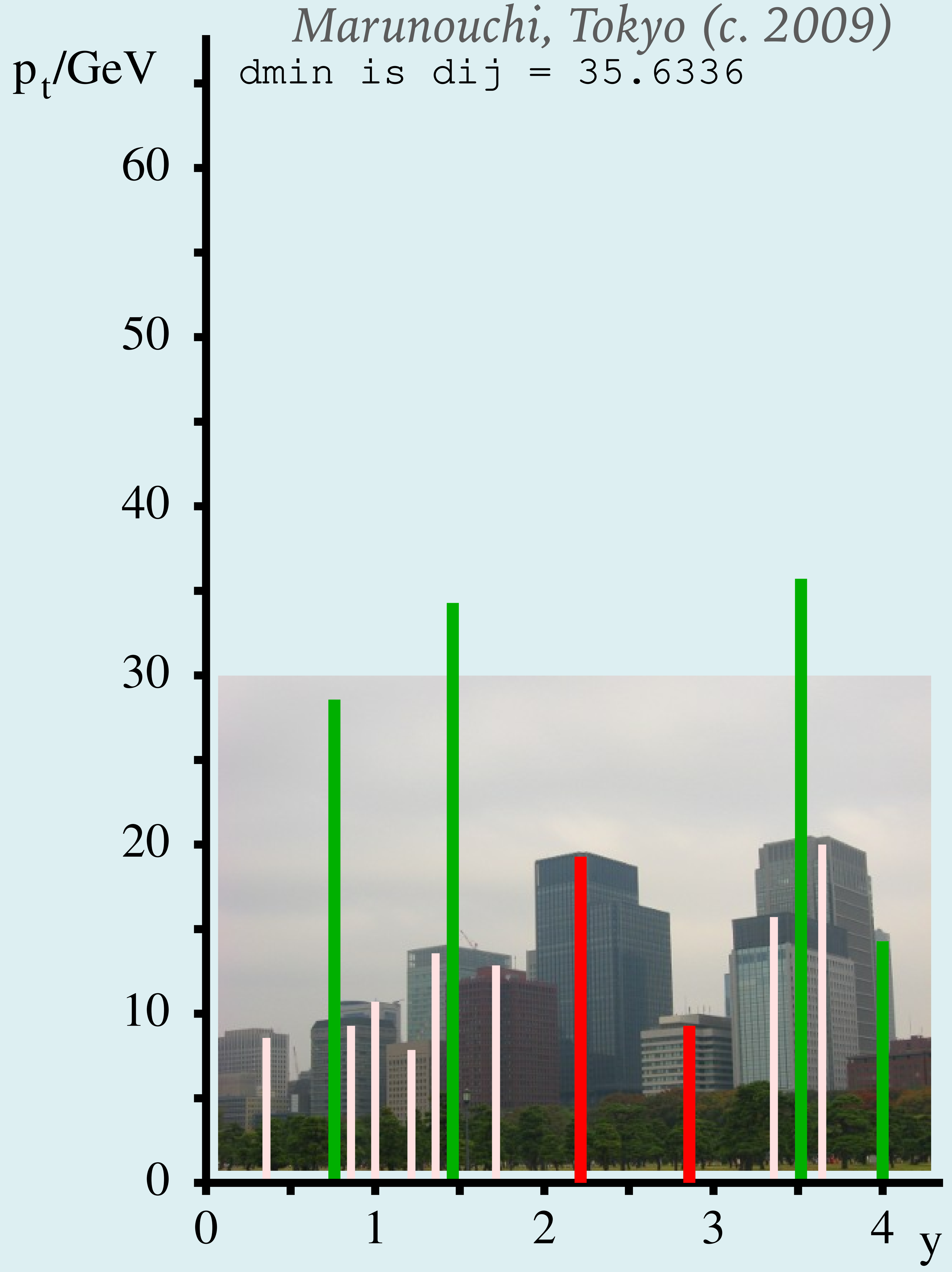

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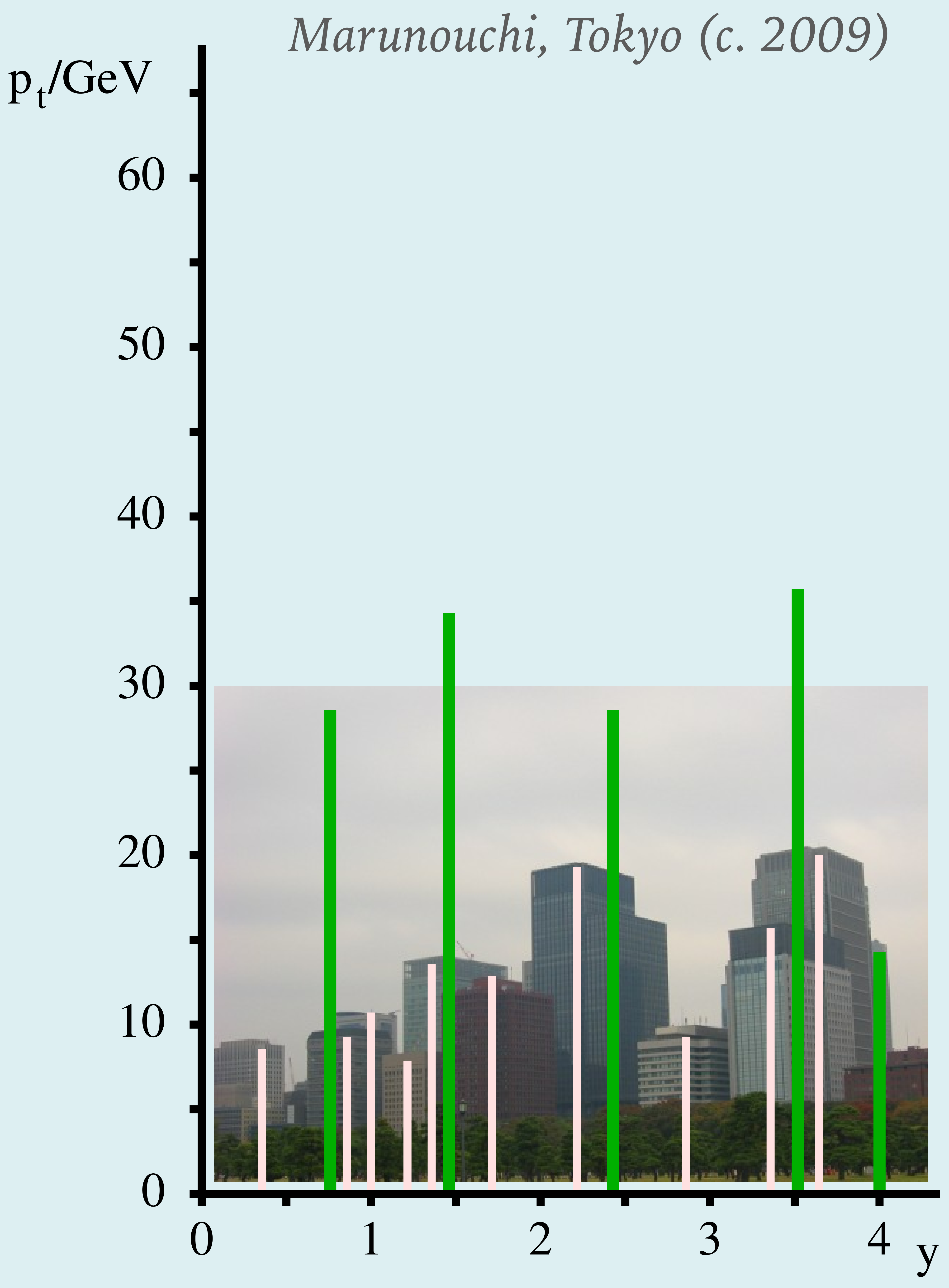

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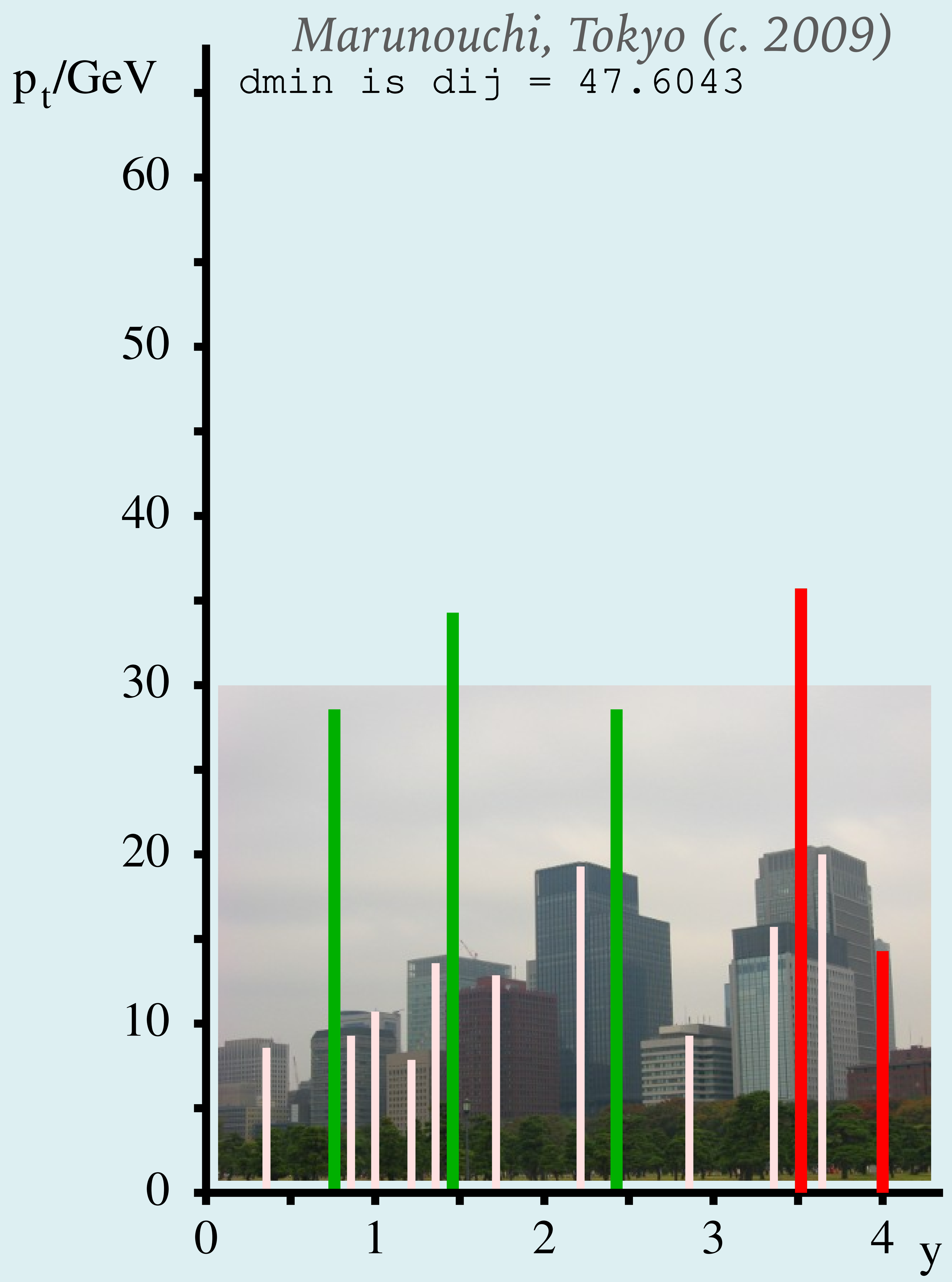

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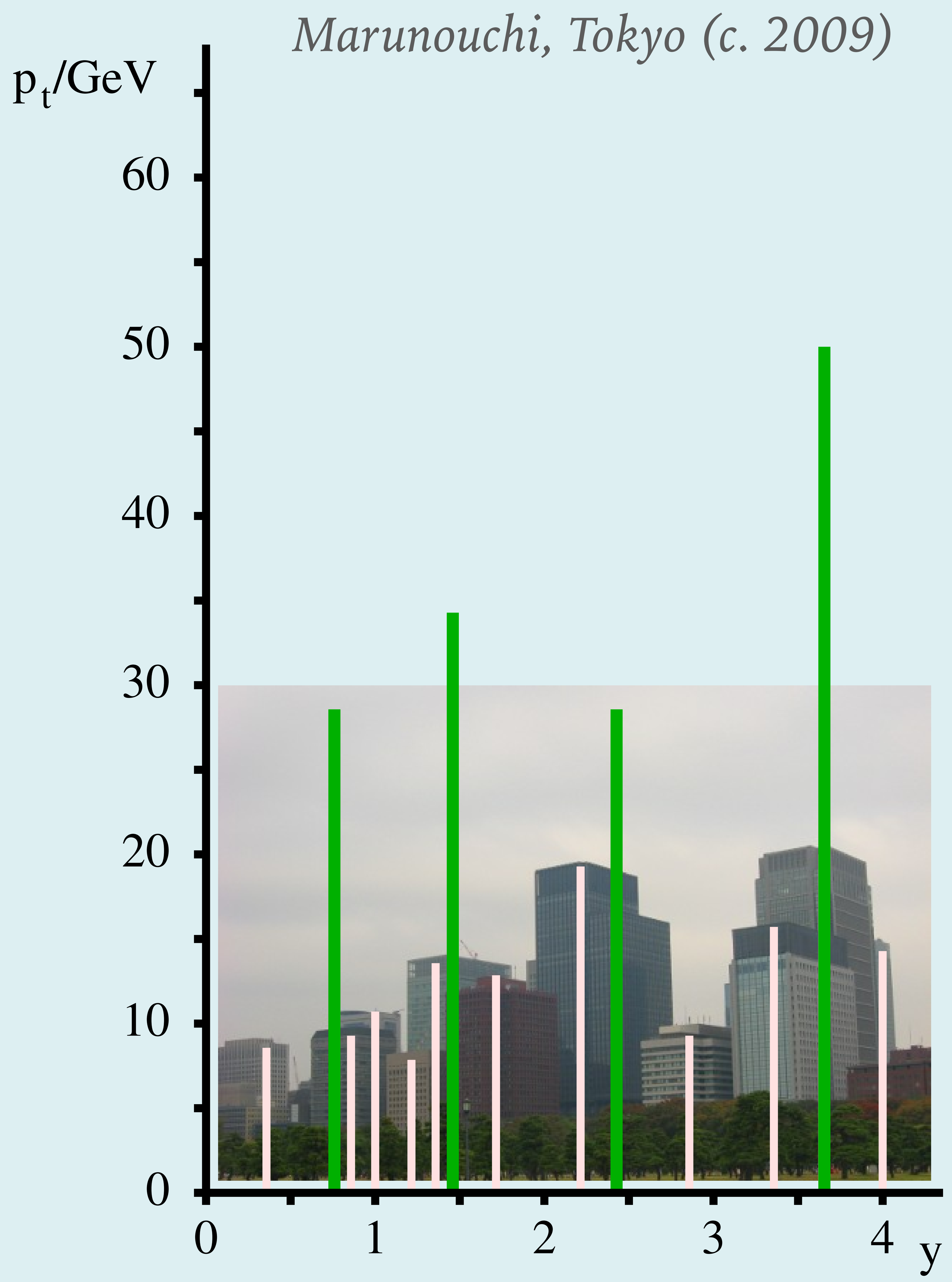

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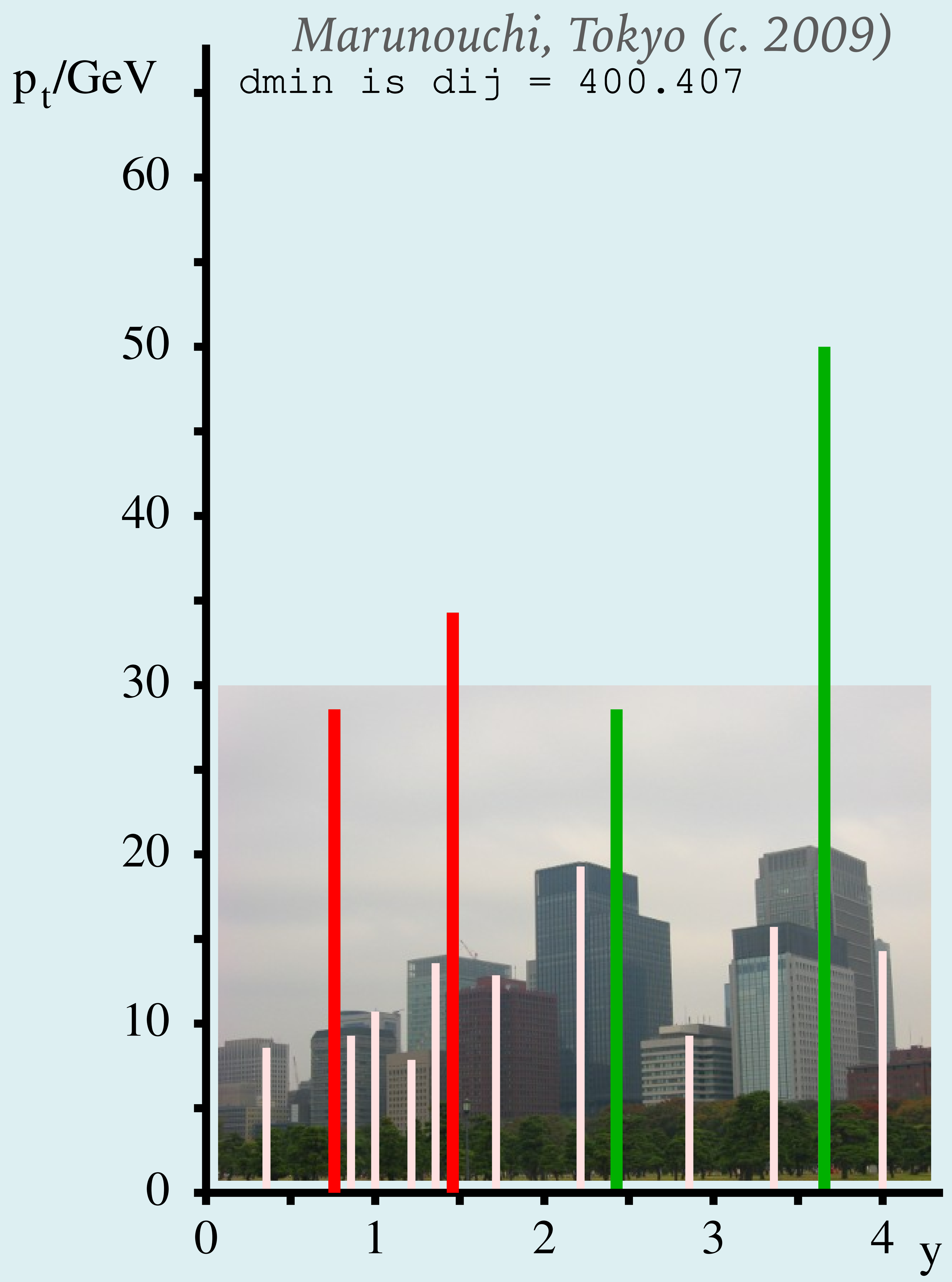

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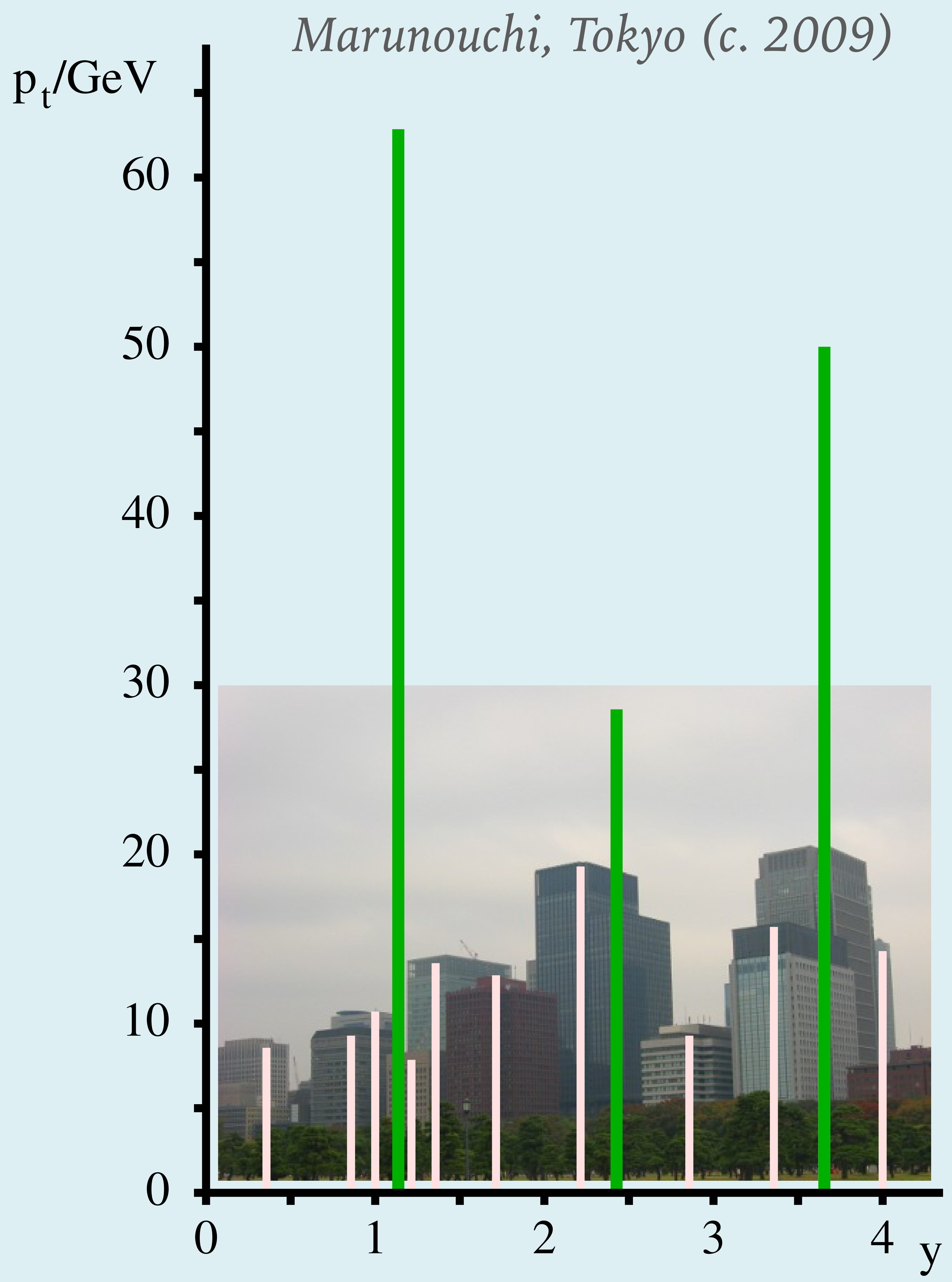

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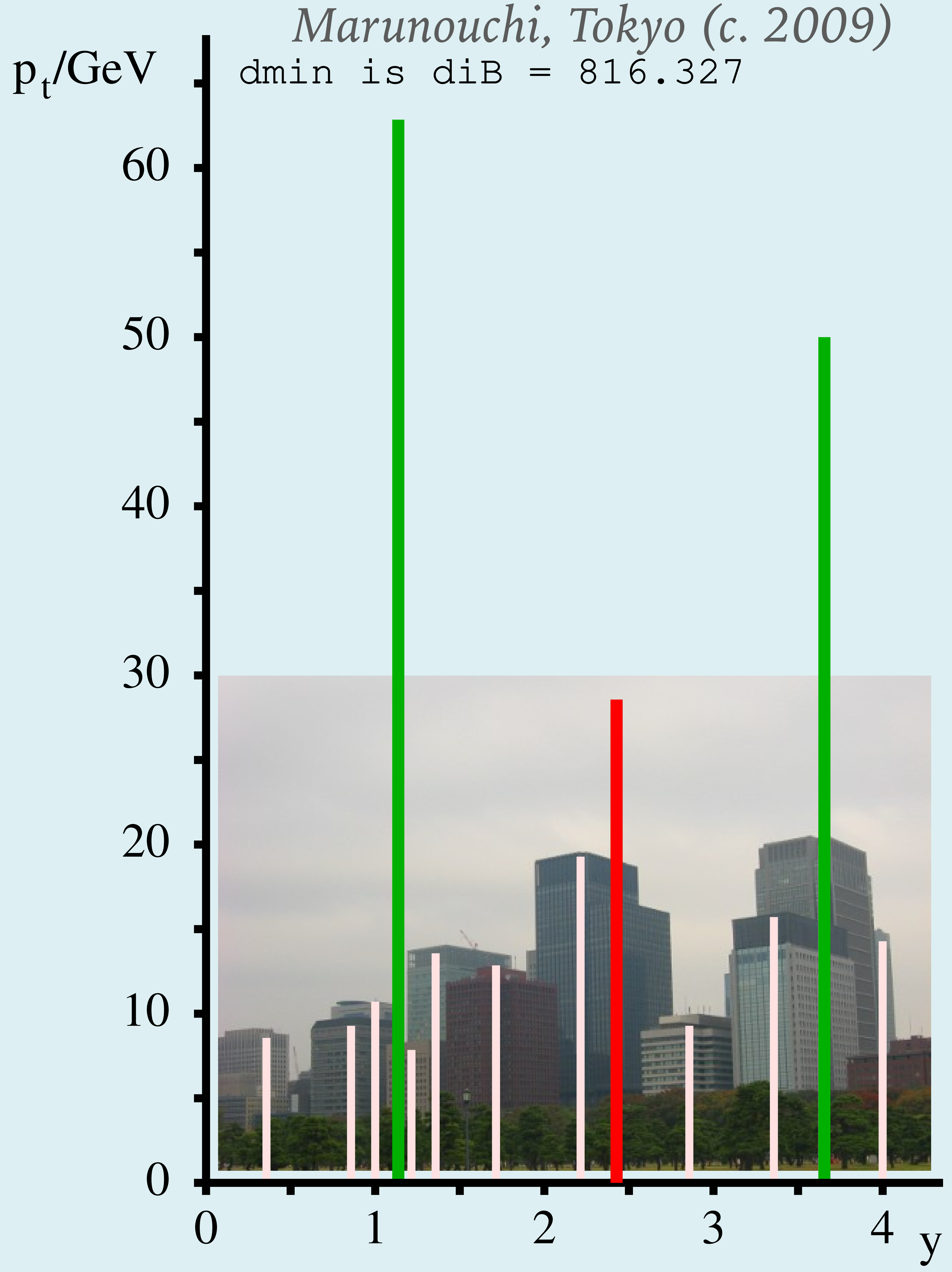

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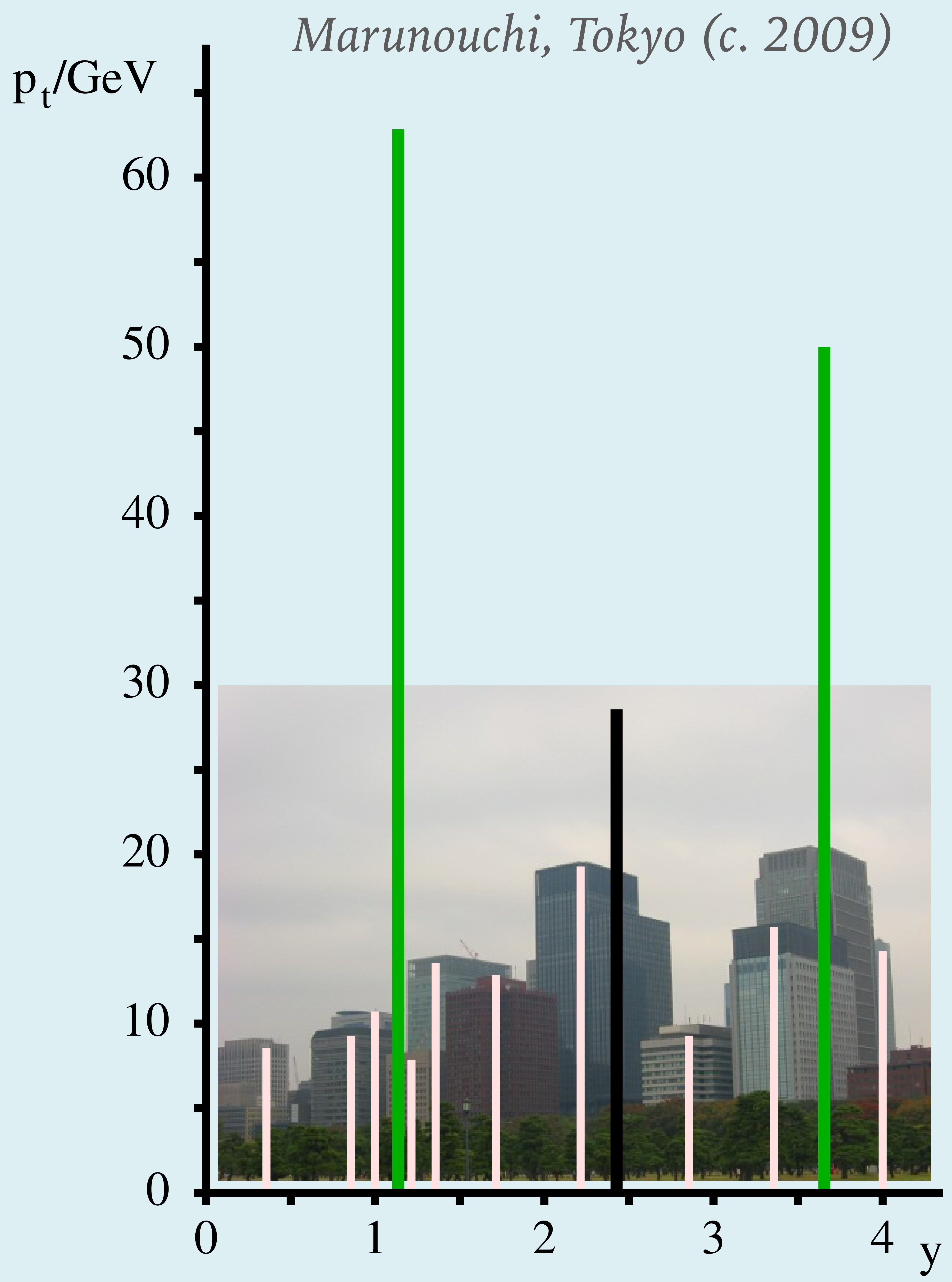

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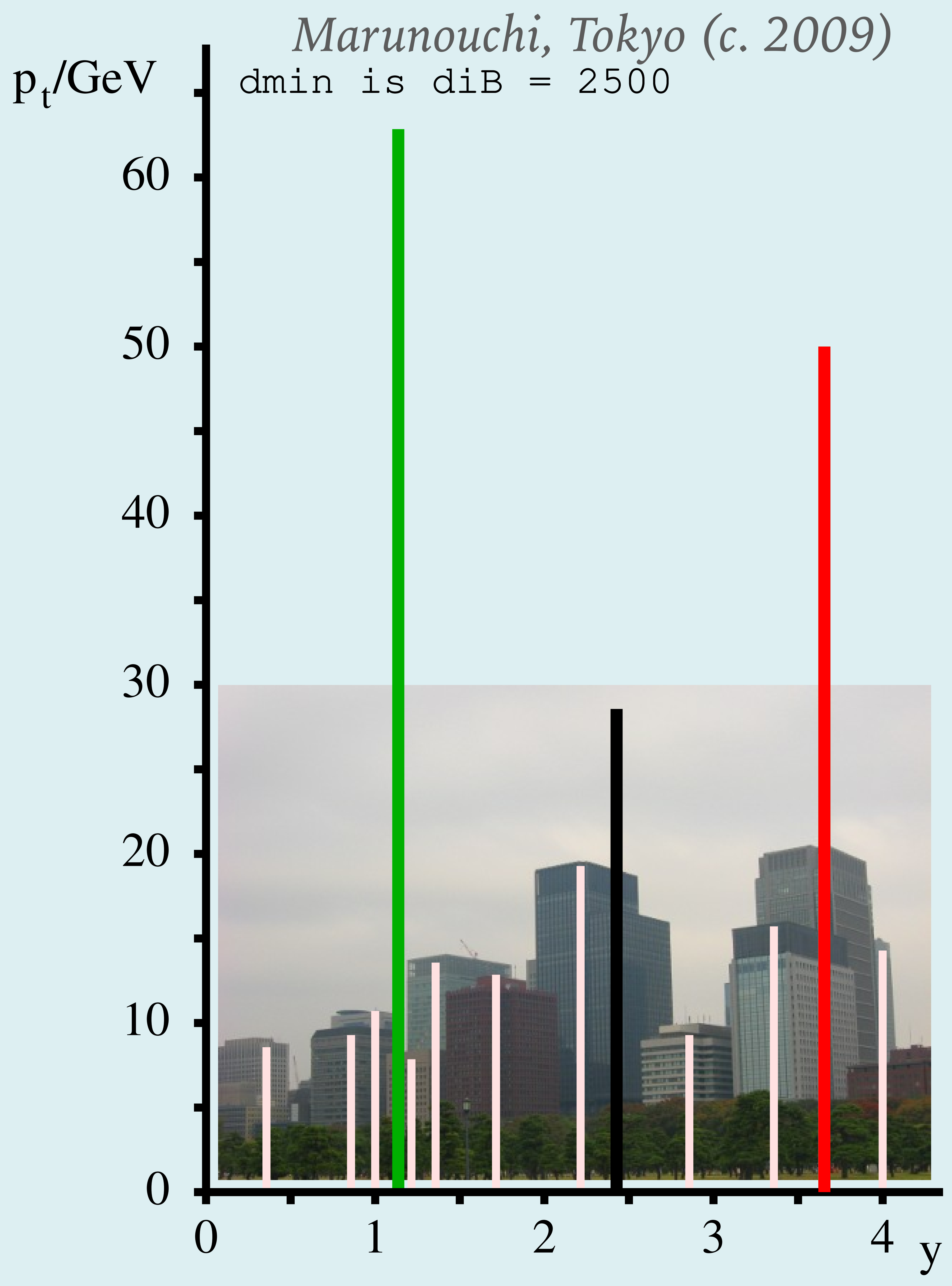
$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = p_{ti}^2$$

2. if d_{ij} recombine particles into one
3. if d_{iB} declare i to be a jet

Accept all jets above some some threshold transverse momentum



possible solution

"sequential recombination" k_t algorithm

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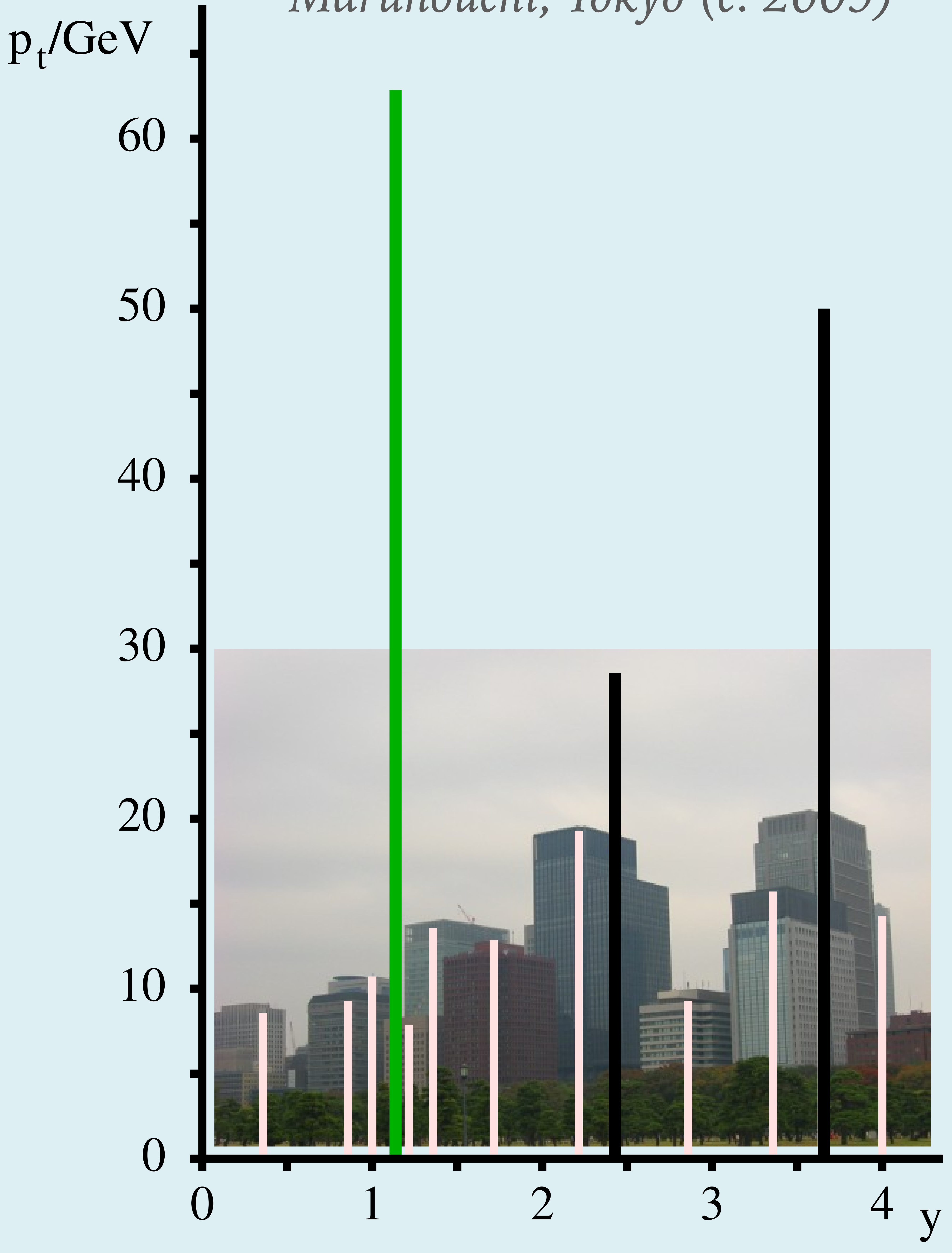
Marunouchi, Tokyo (c. 2009)



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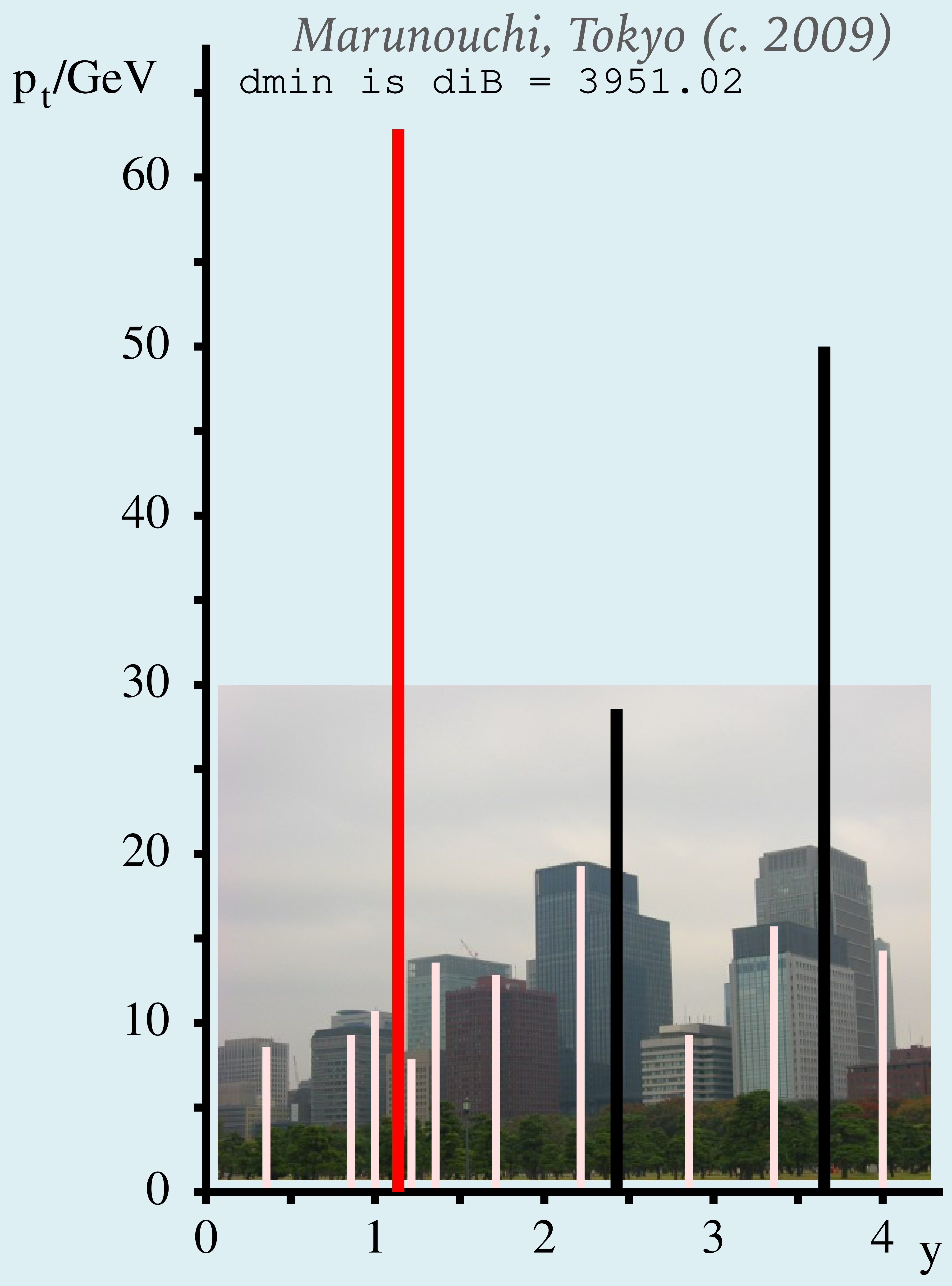

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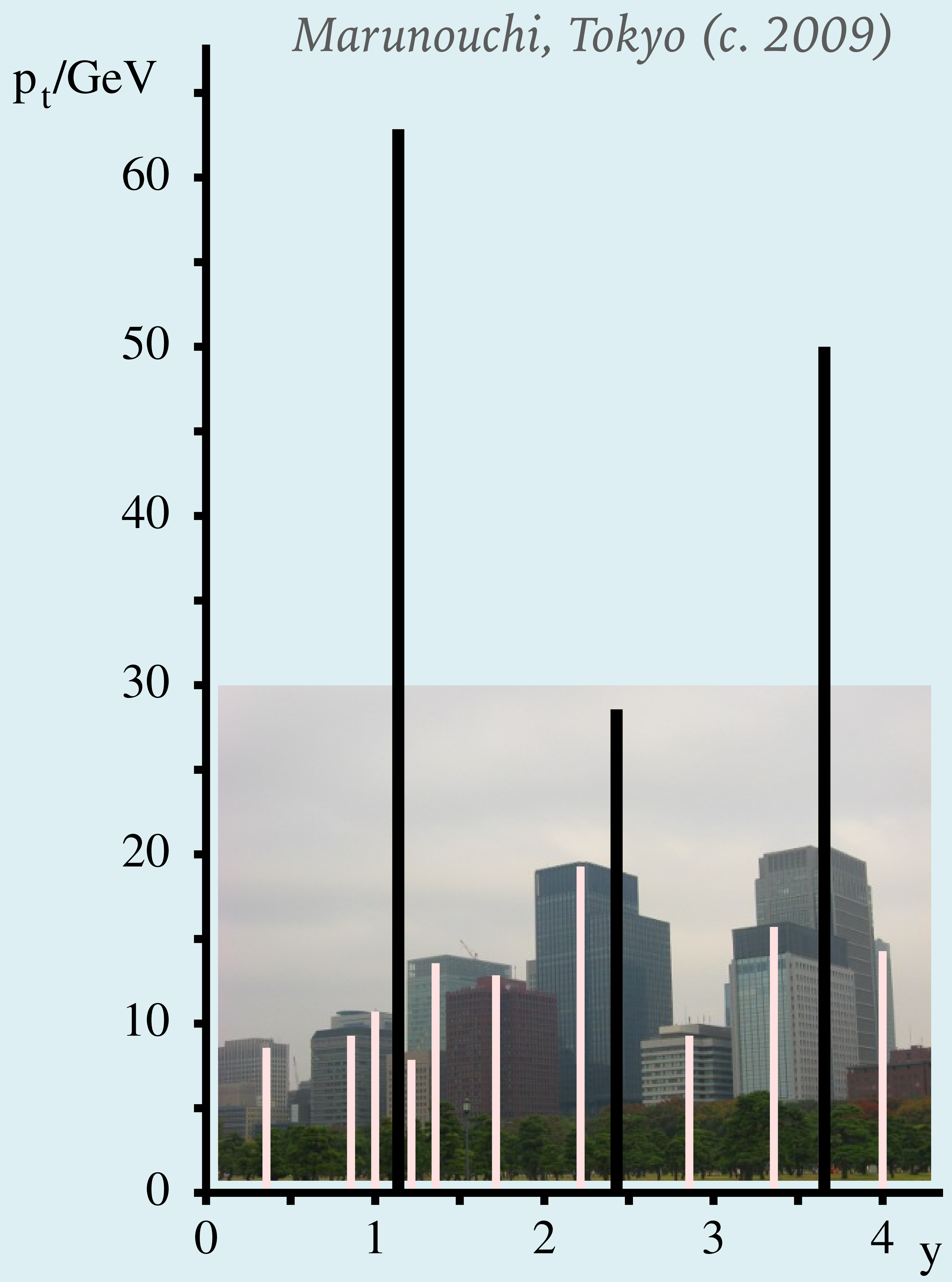
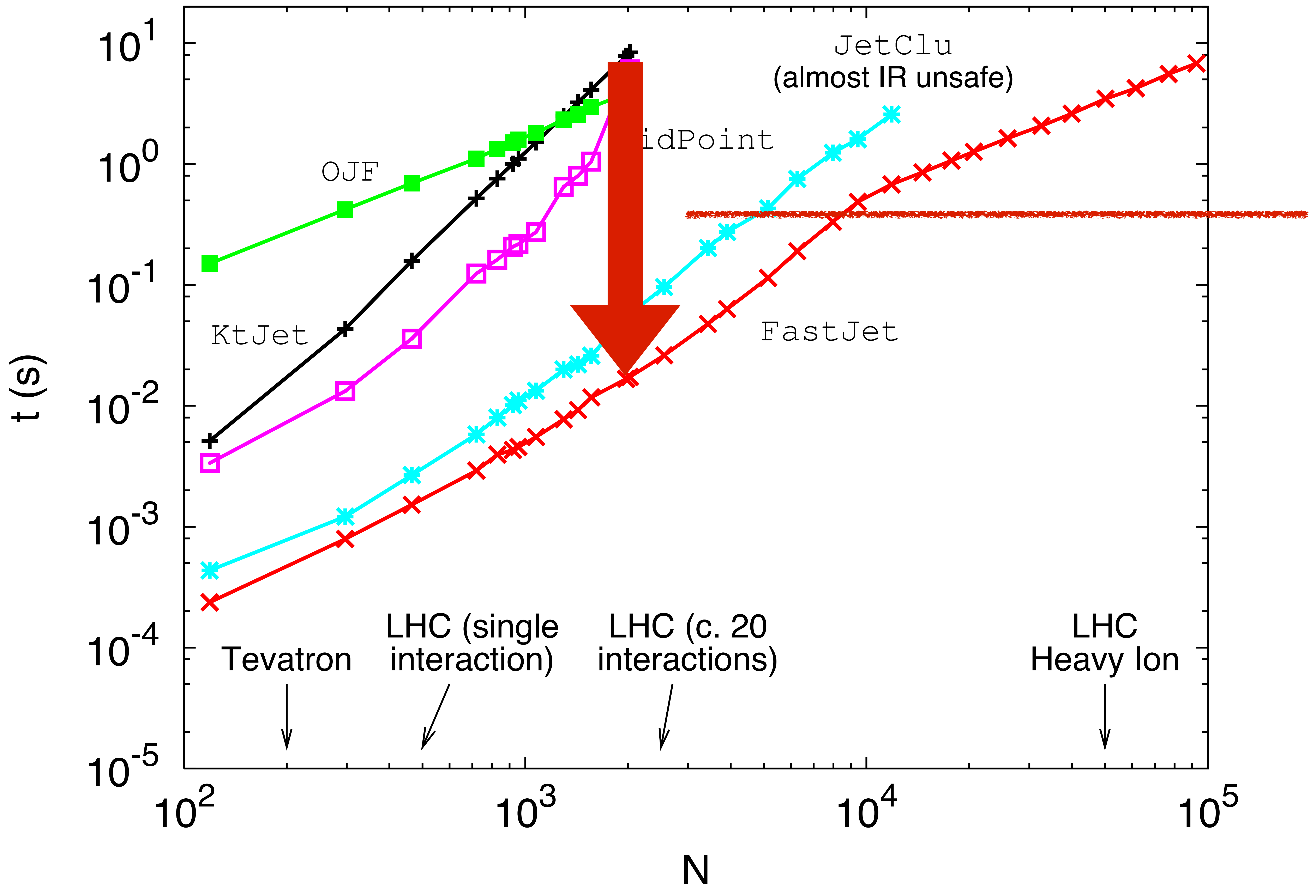



c. 2005
kt adapts to the jet structure
the cone is too rigid
cone has big hadronisation corrections
cone is infrared unsafe
many theorists
the cone gives nice conical jets
kt's a vacuum cleaner
kt's too irregular I can't correct for pileup
kt's too slow
many experimenters

advance #1: computational speed for IR safe "sequential recombination" jet algorithms

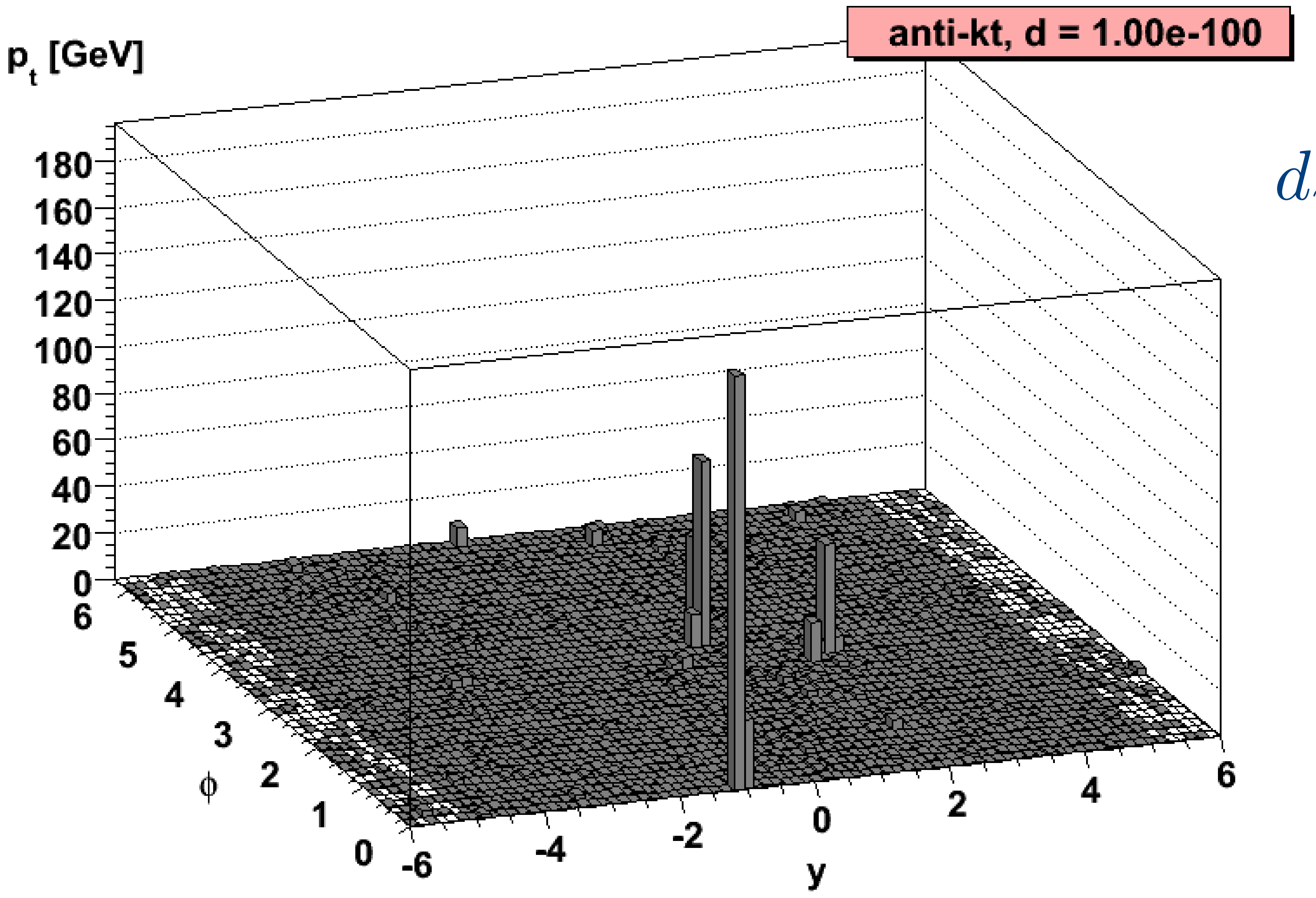


factor of ~1000 speedup, using the "FastJet lemma"

Exploits underlying geometric information to speed clustering from N^3 up to to $N \ln N$

Cacciari & GPS
hep-ph/0512210

advance #2: change clustering distances ($p_t \to 1/p_t$)



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Clustering grows around hard cores

Gives **circular jets**

Cacciari, GPS & Soyez
0802.1189

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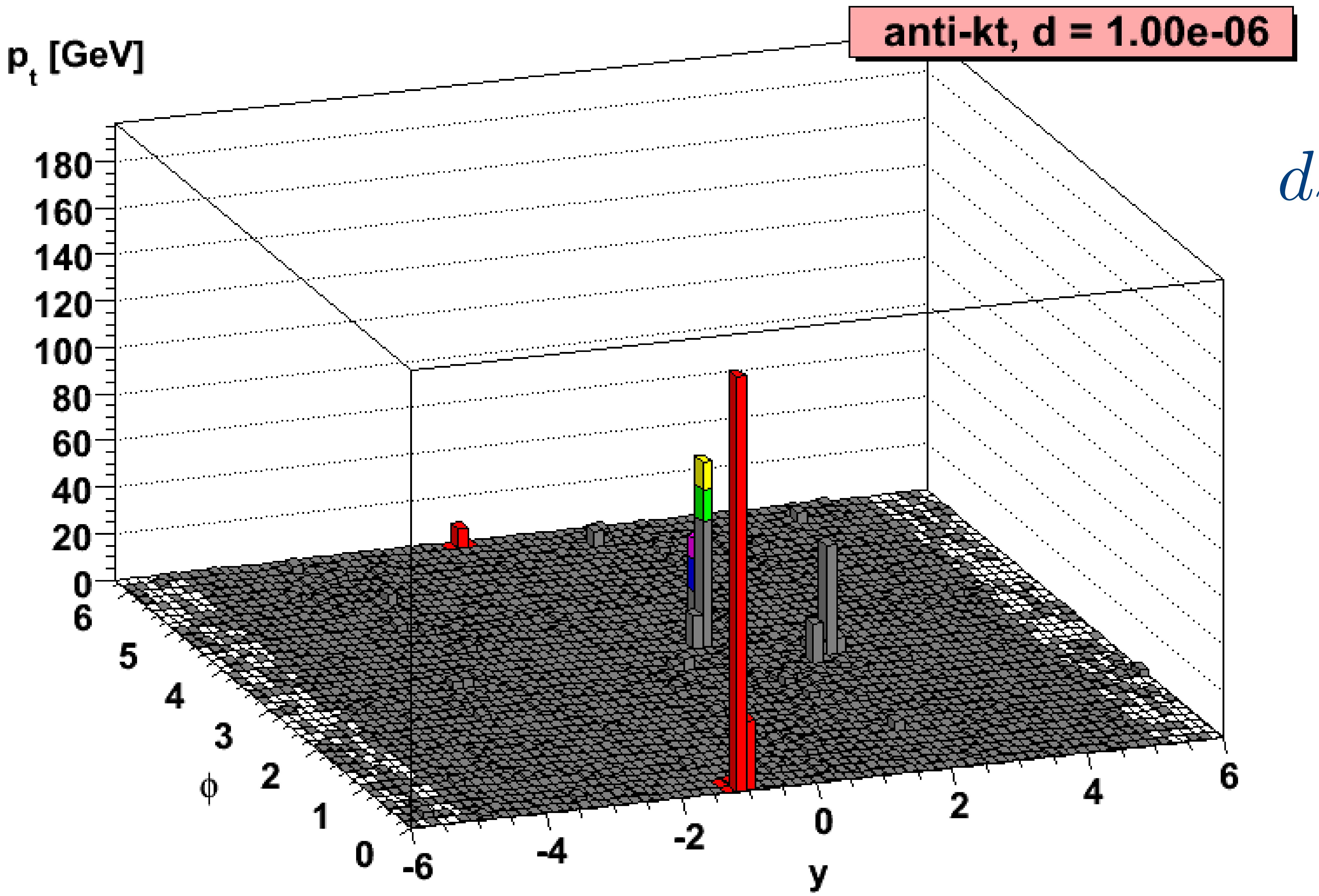

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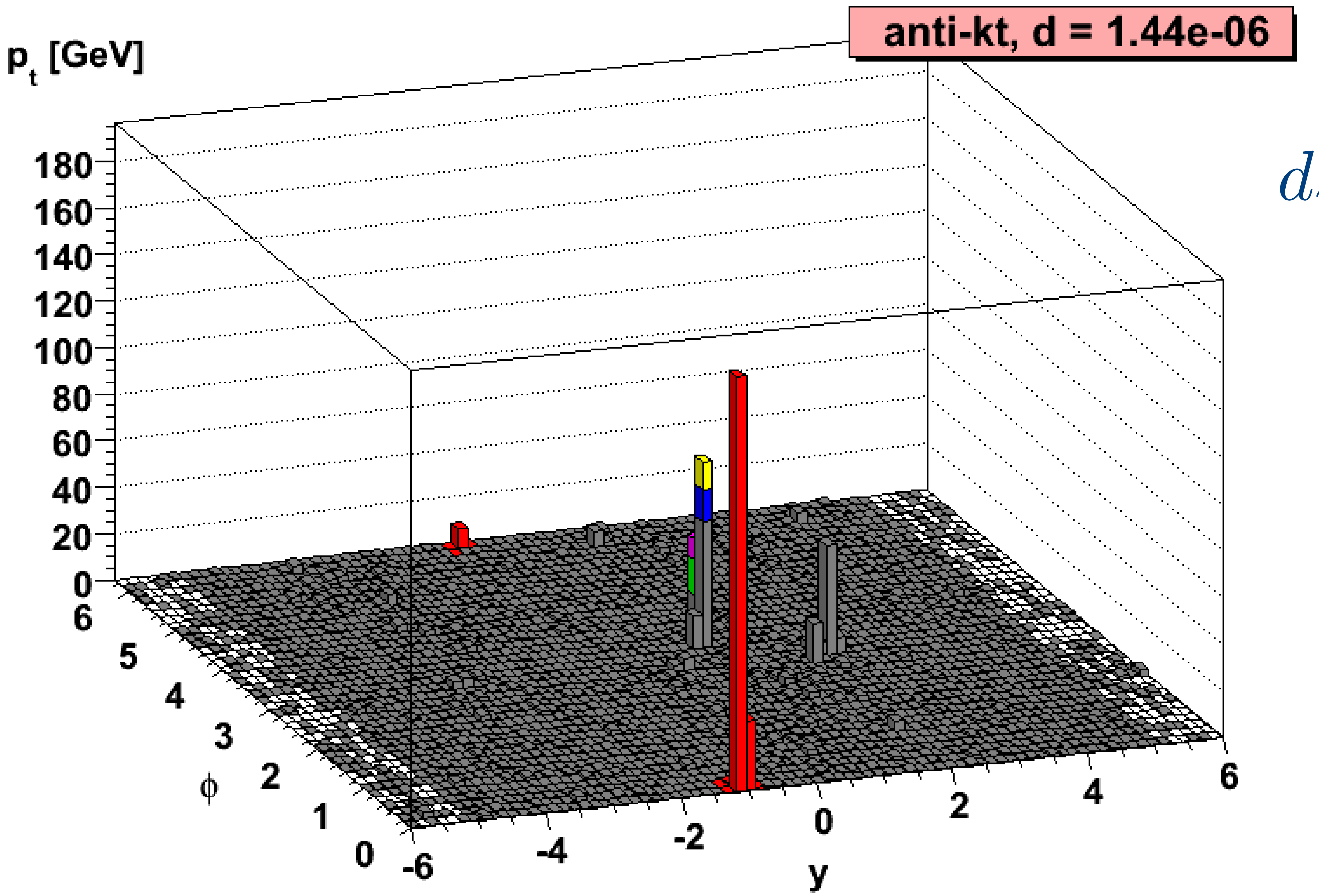

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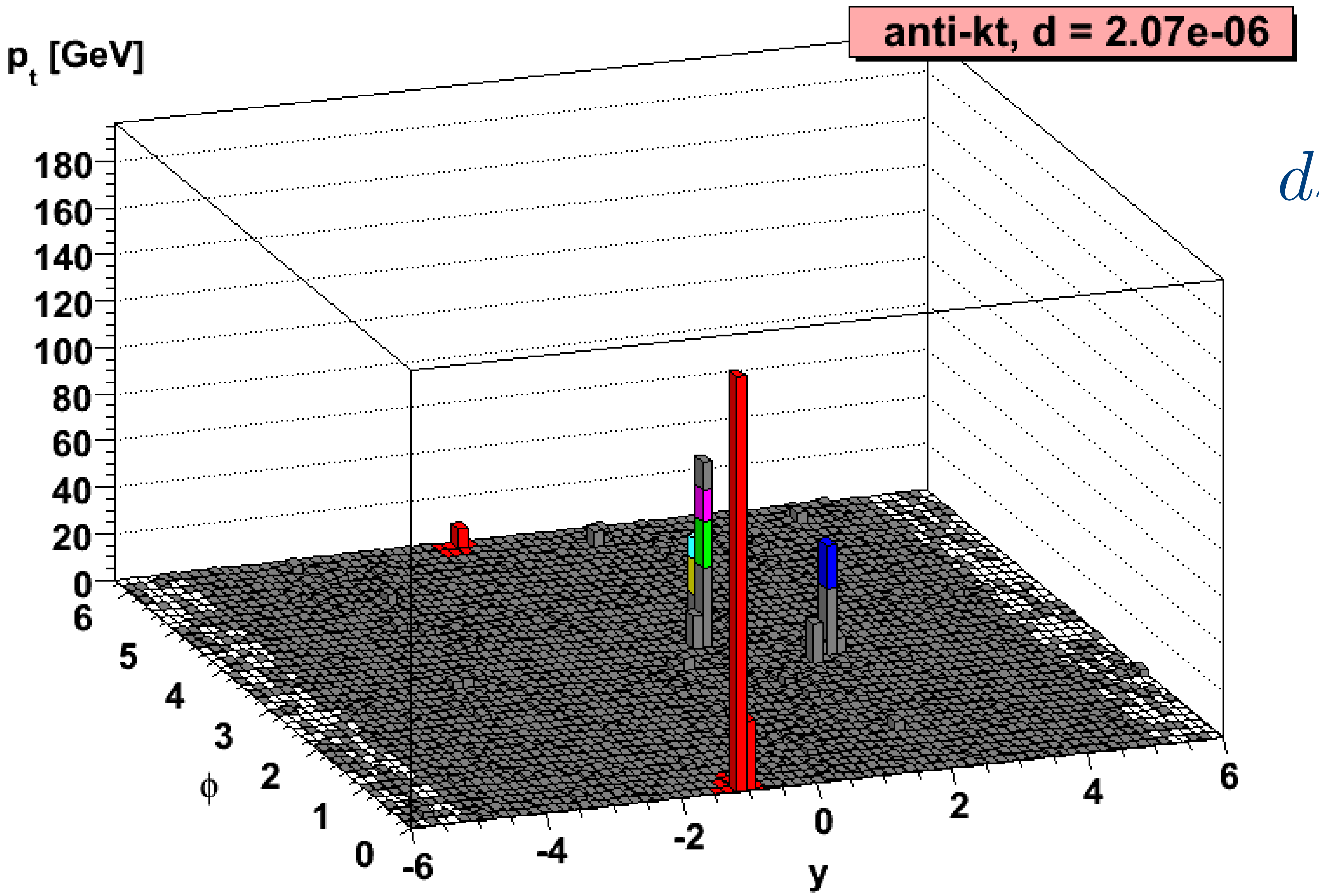

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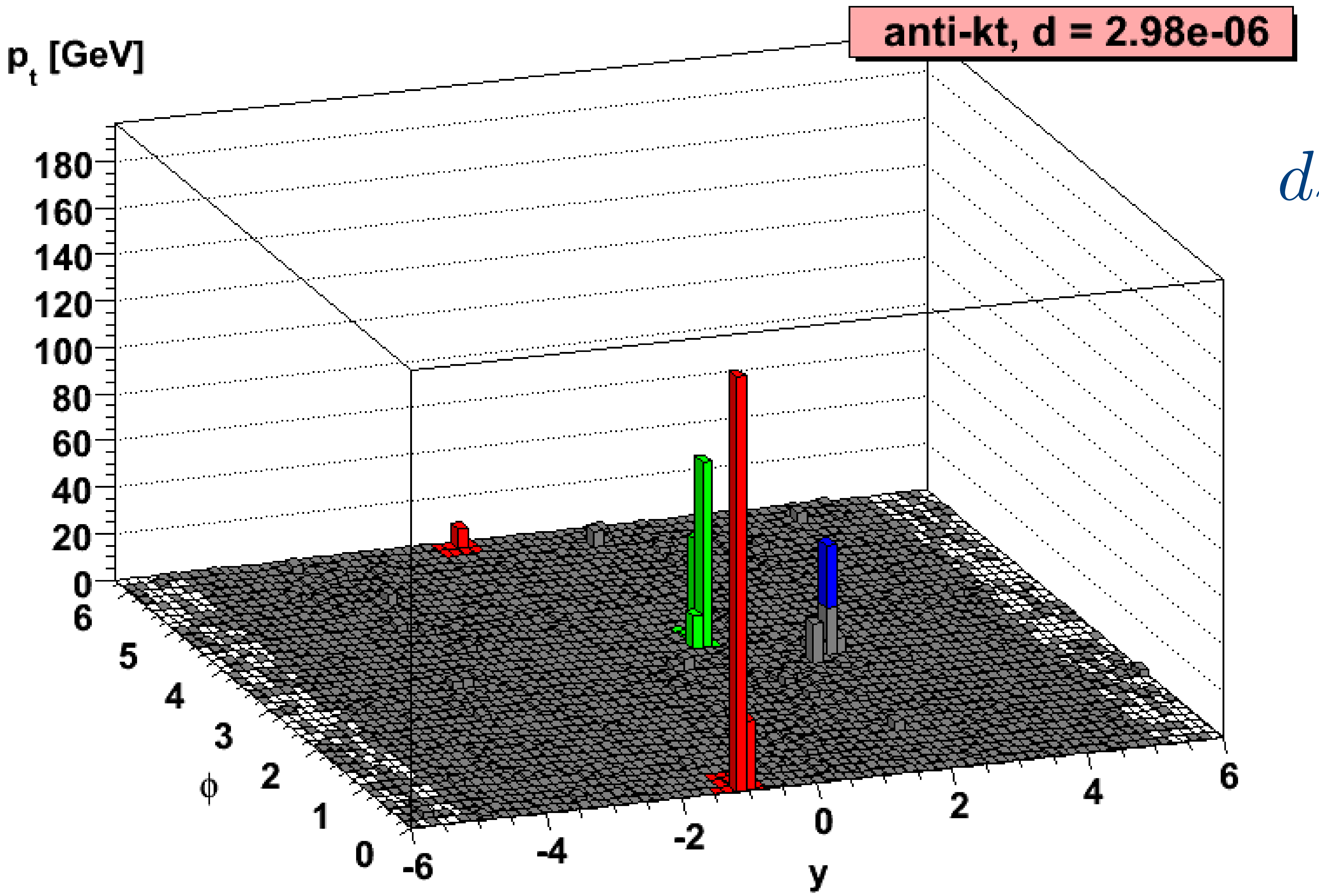

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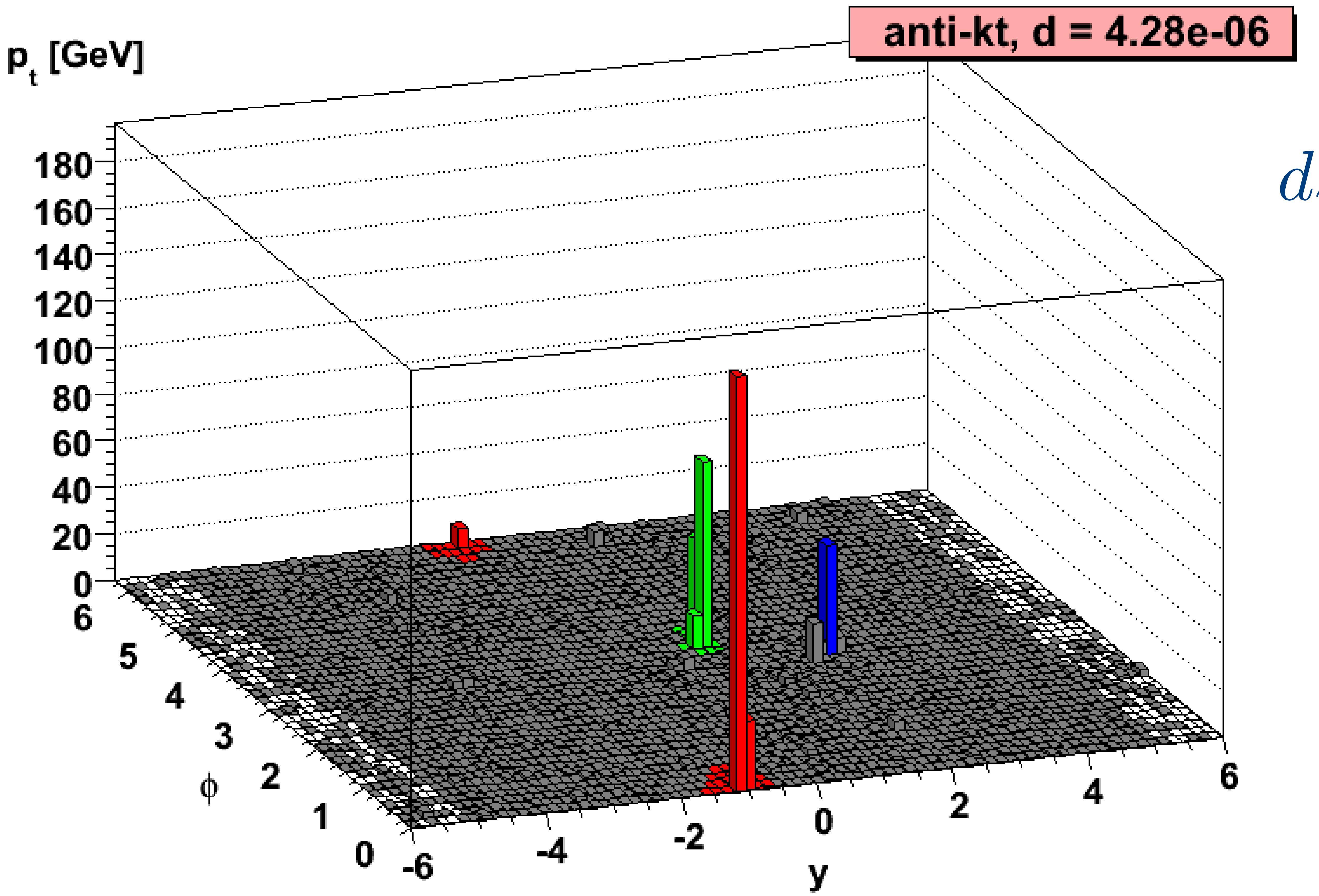

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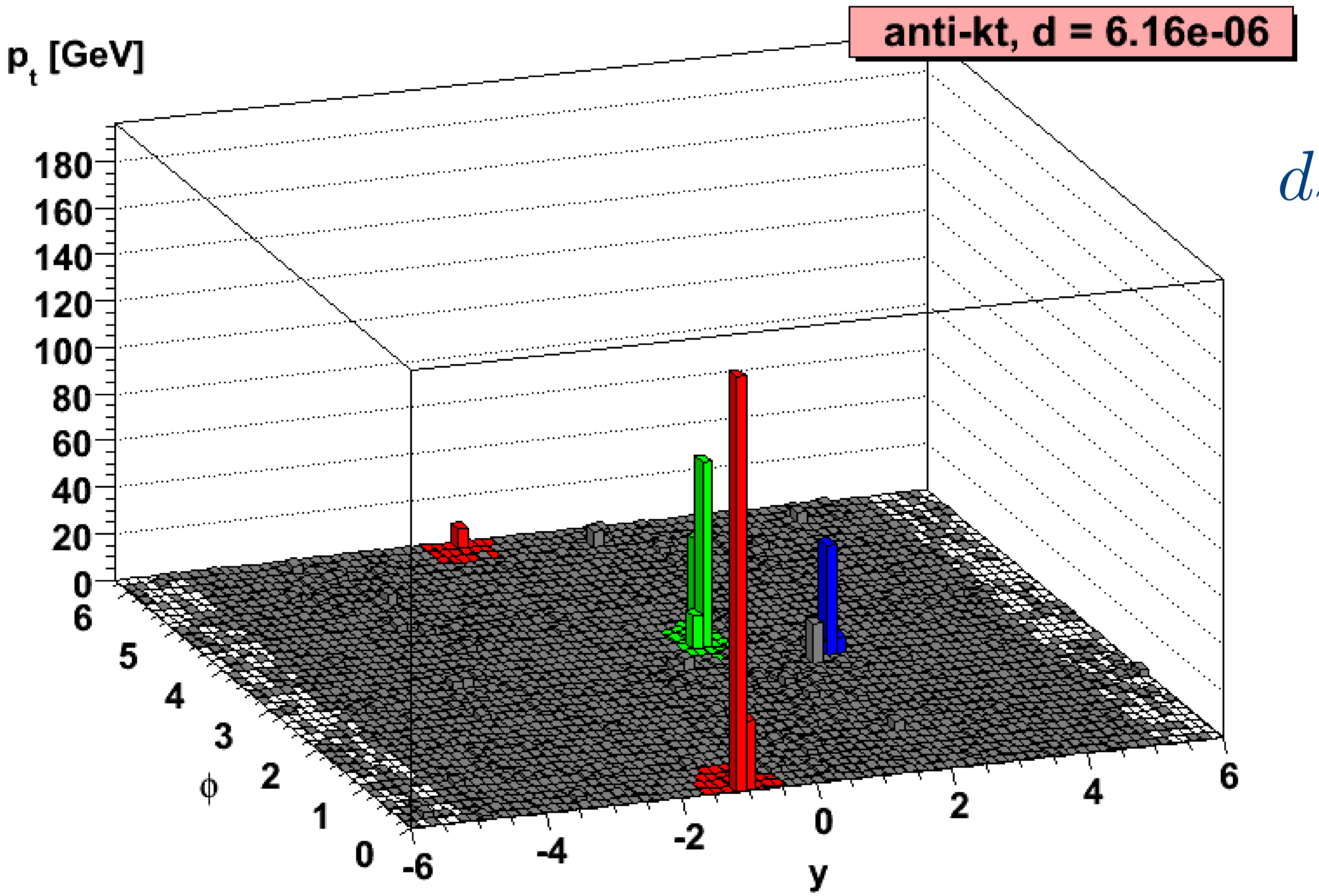

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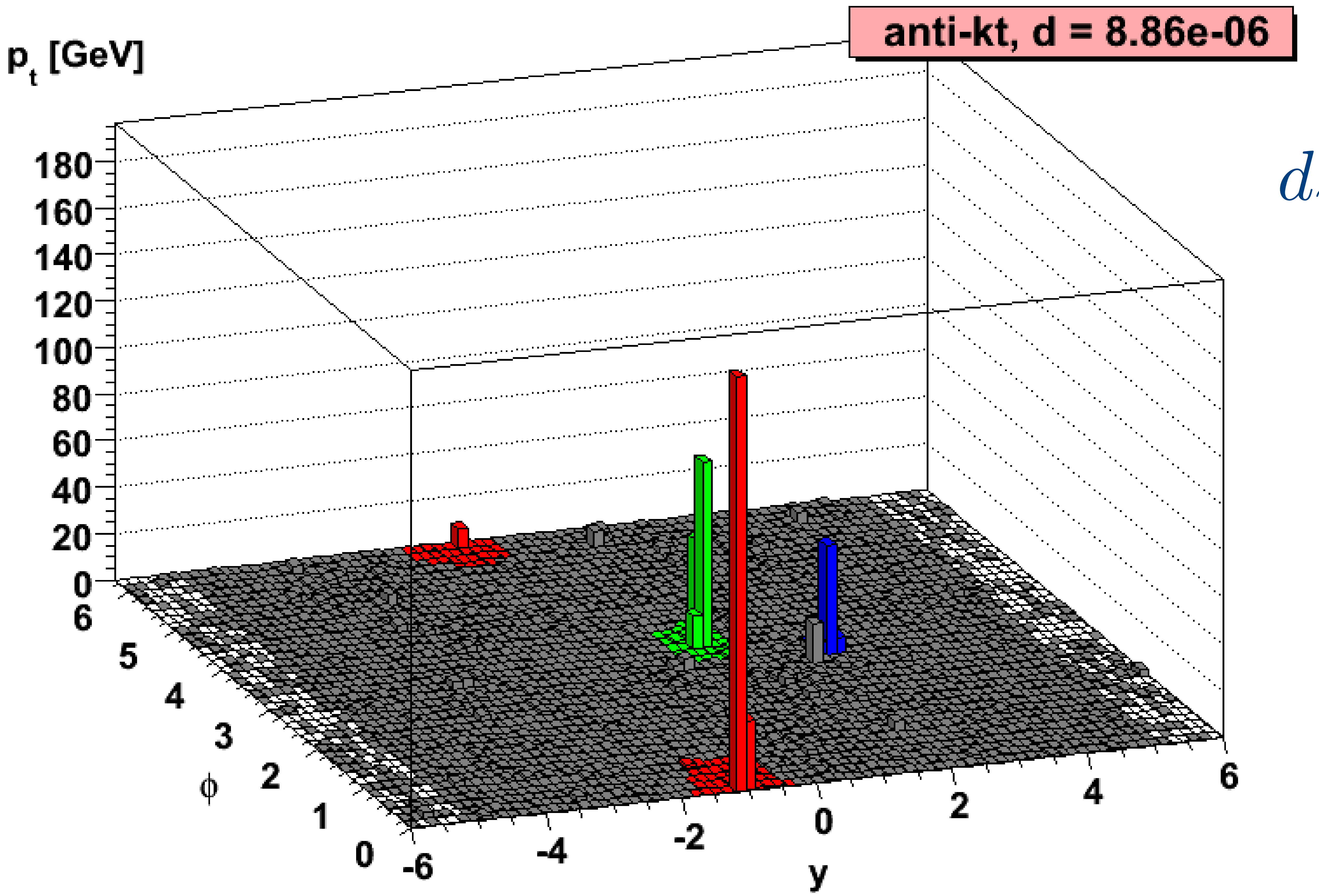

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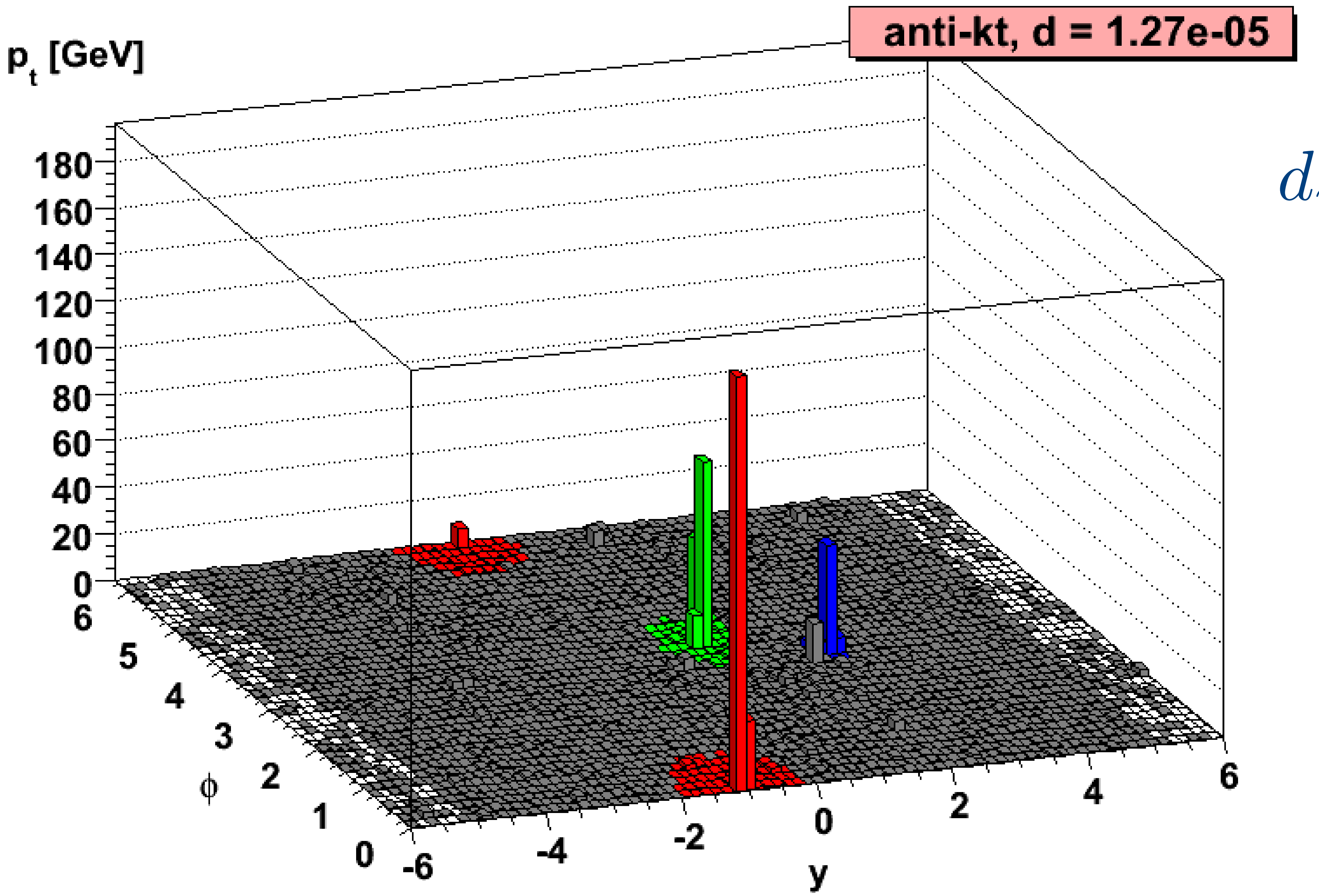

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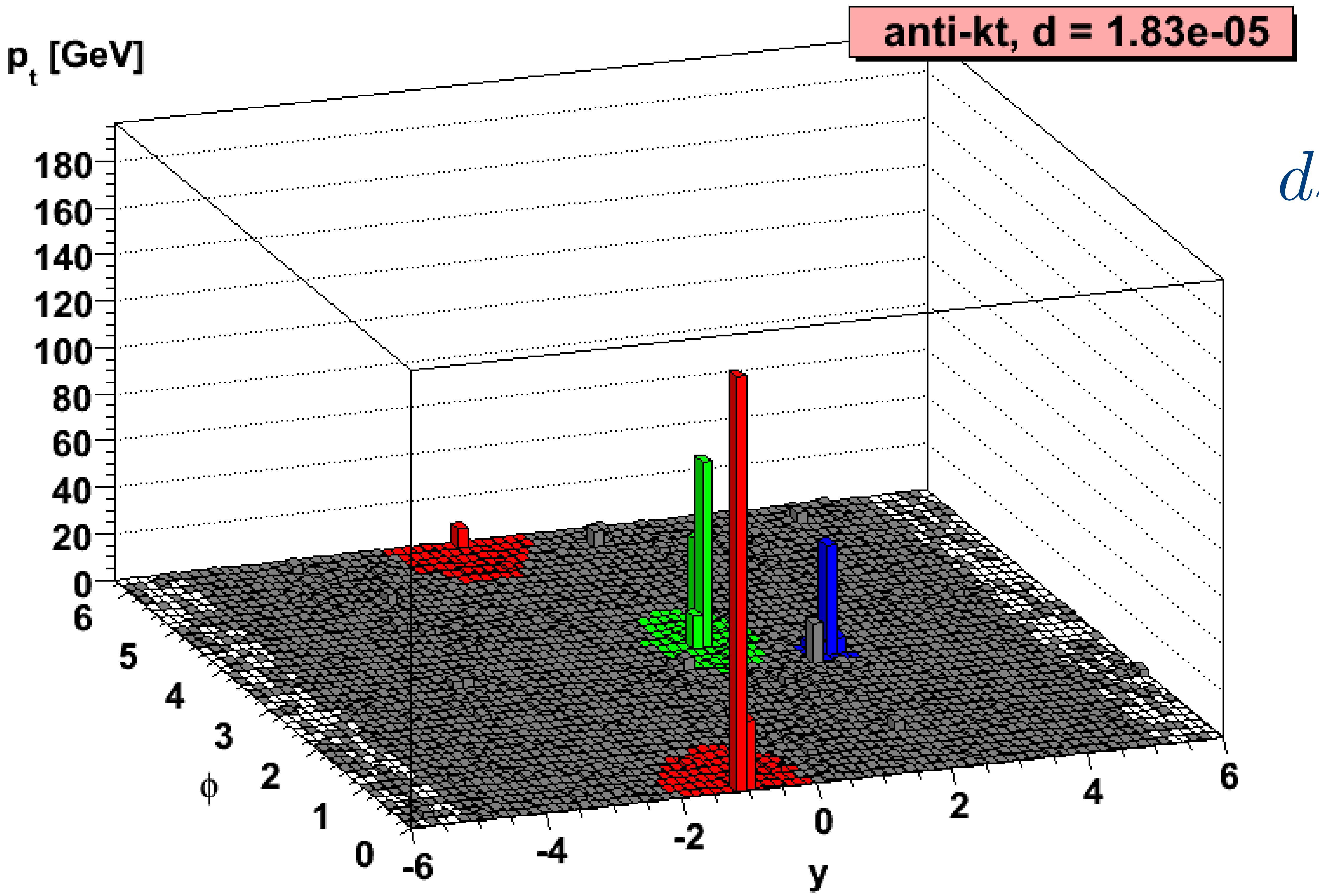

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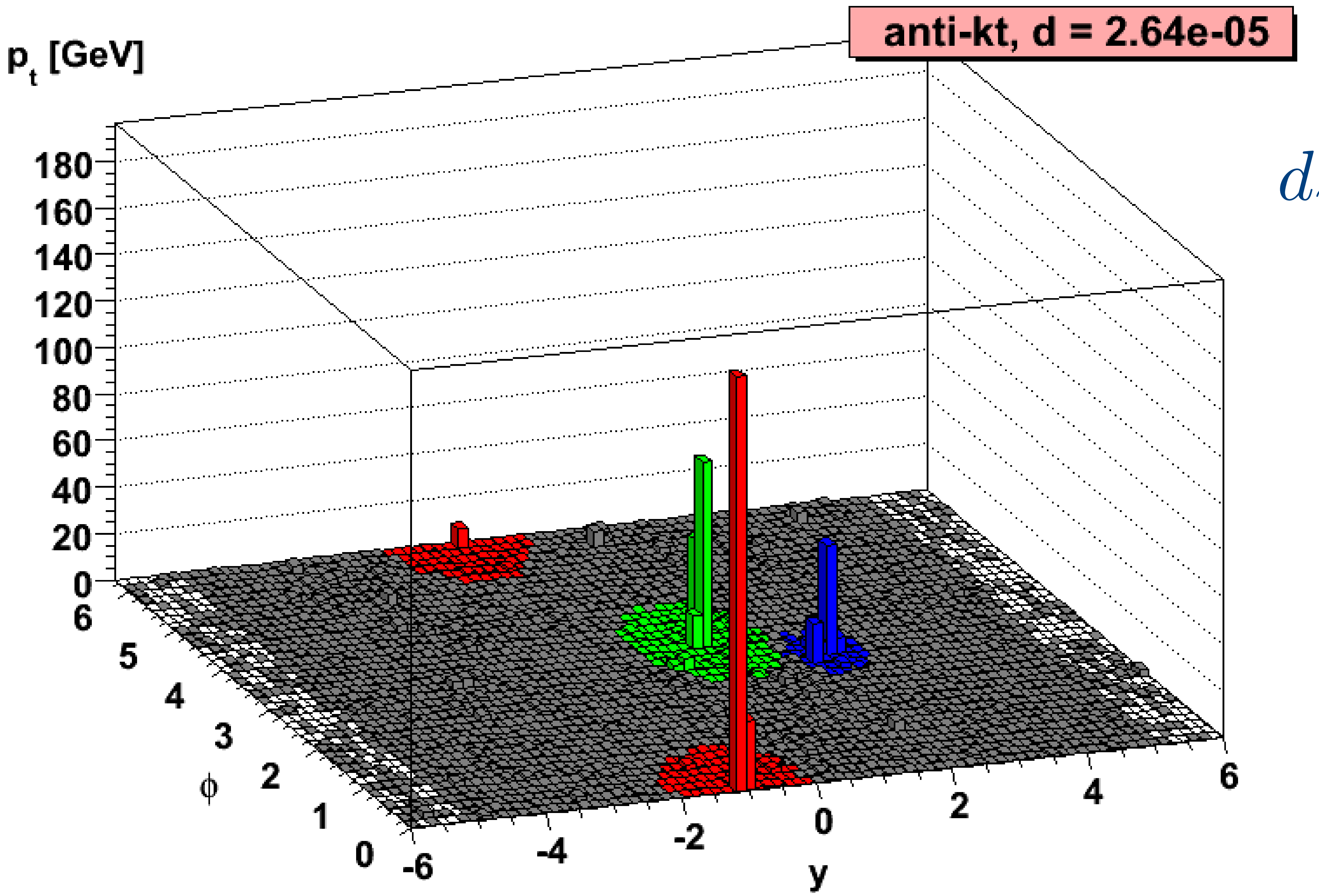

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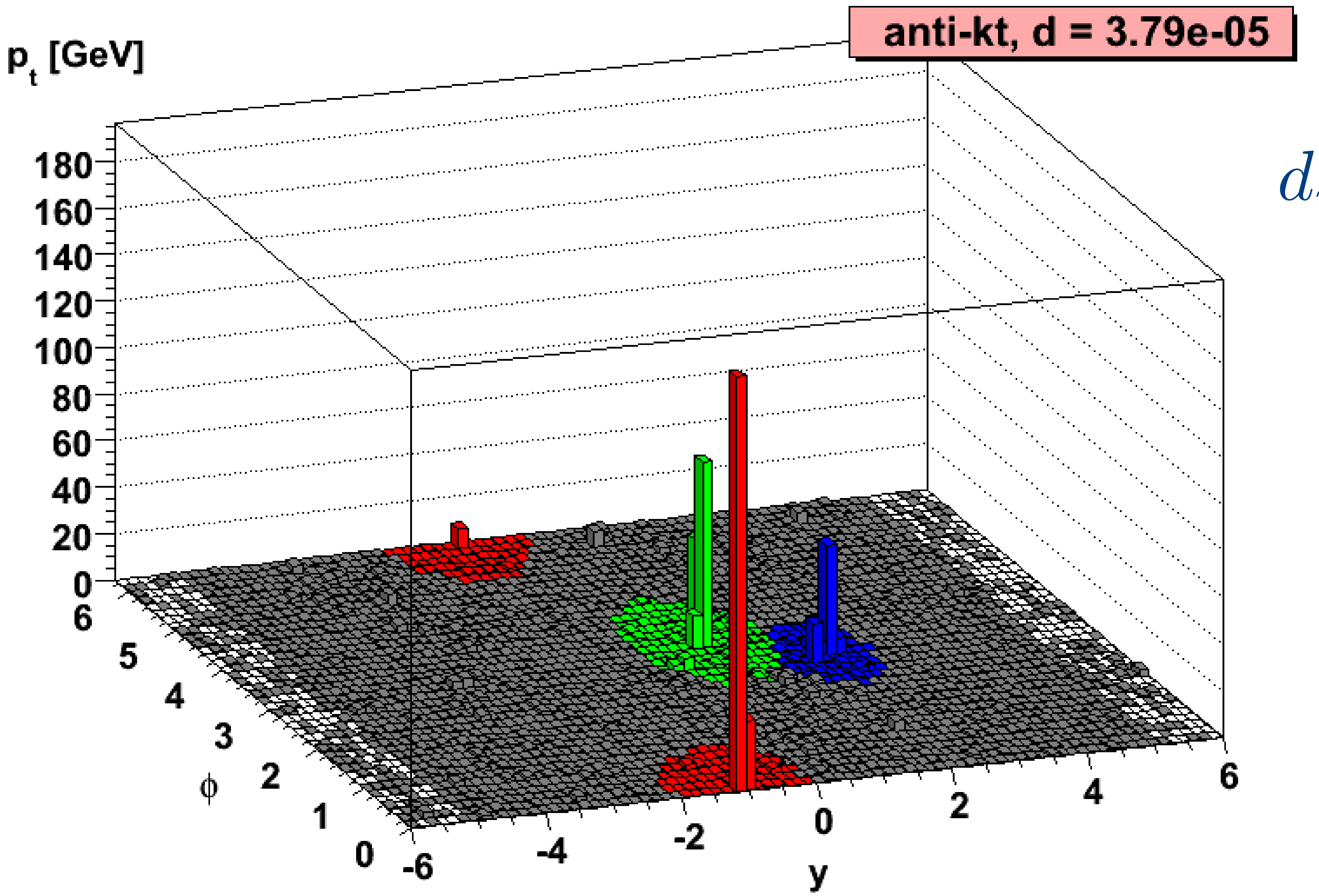

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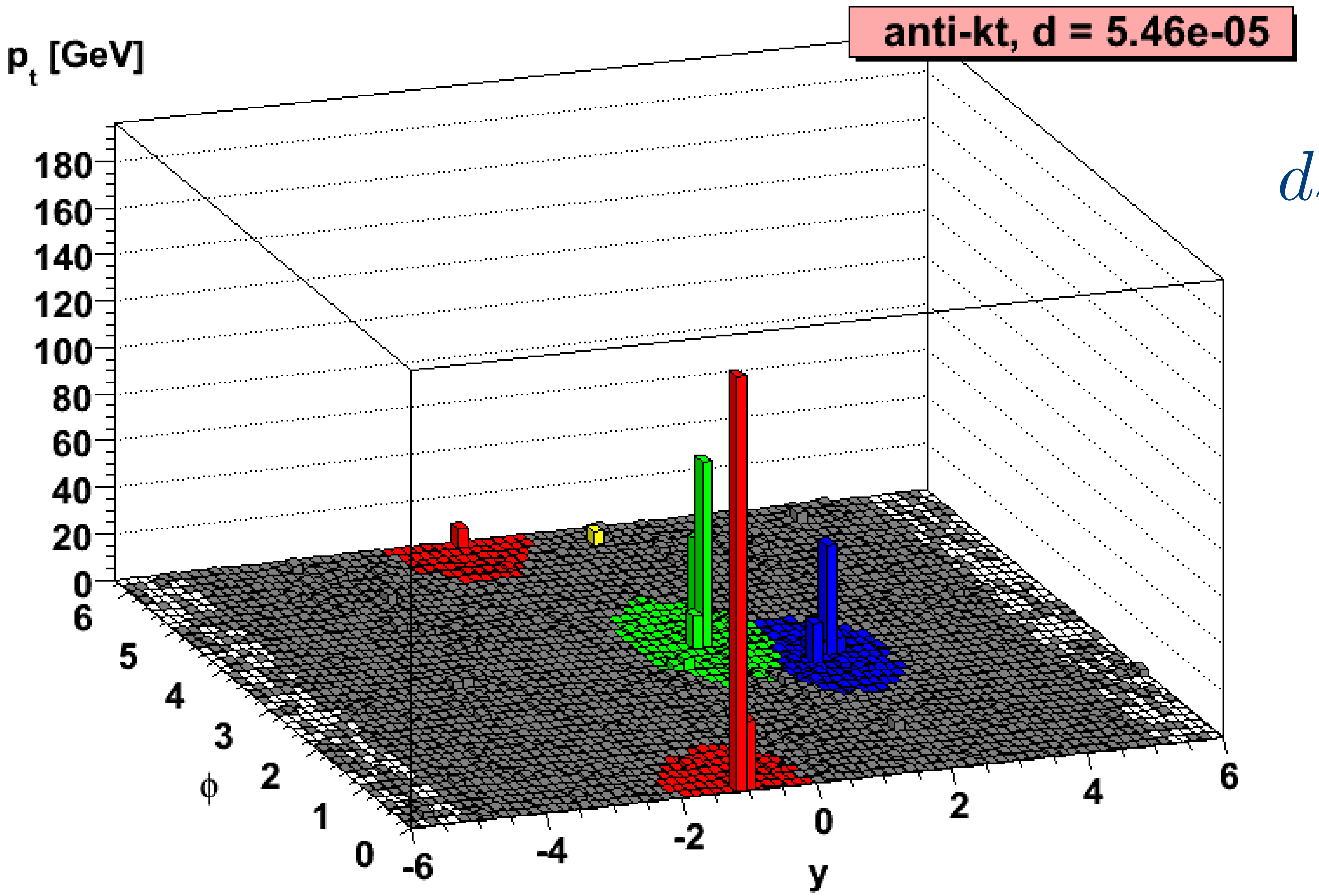

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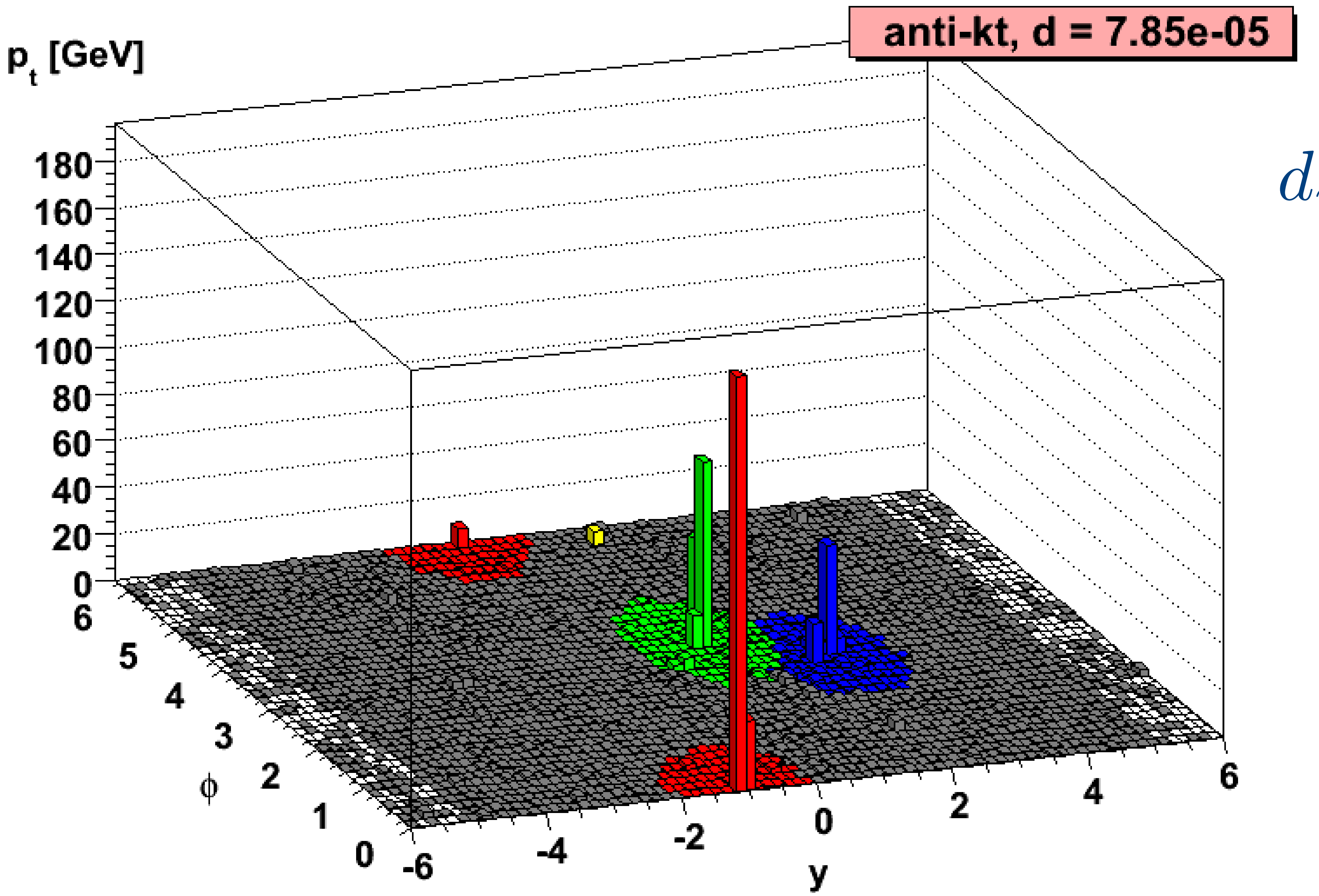

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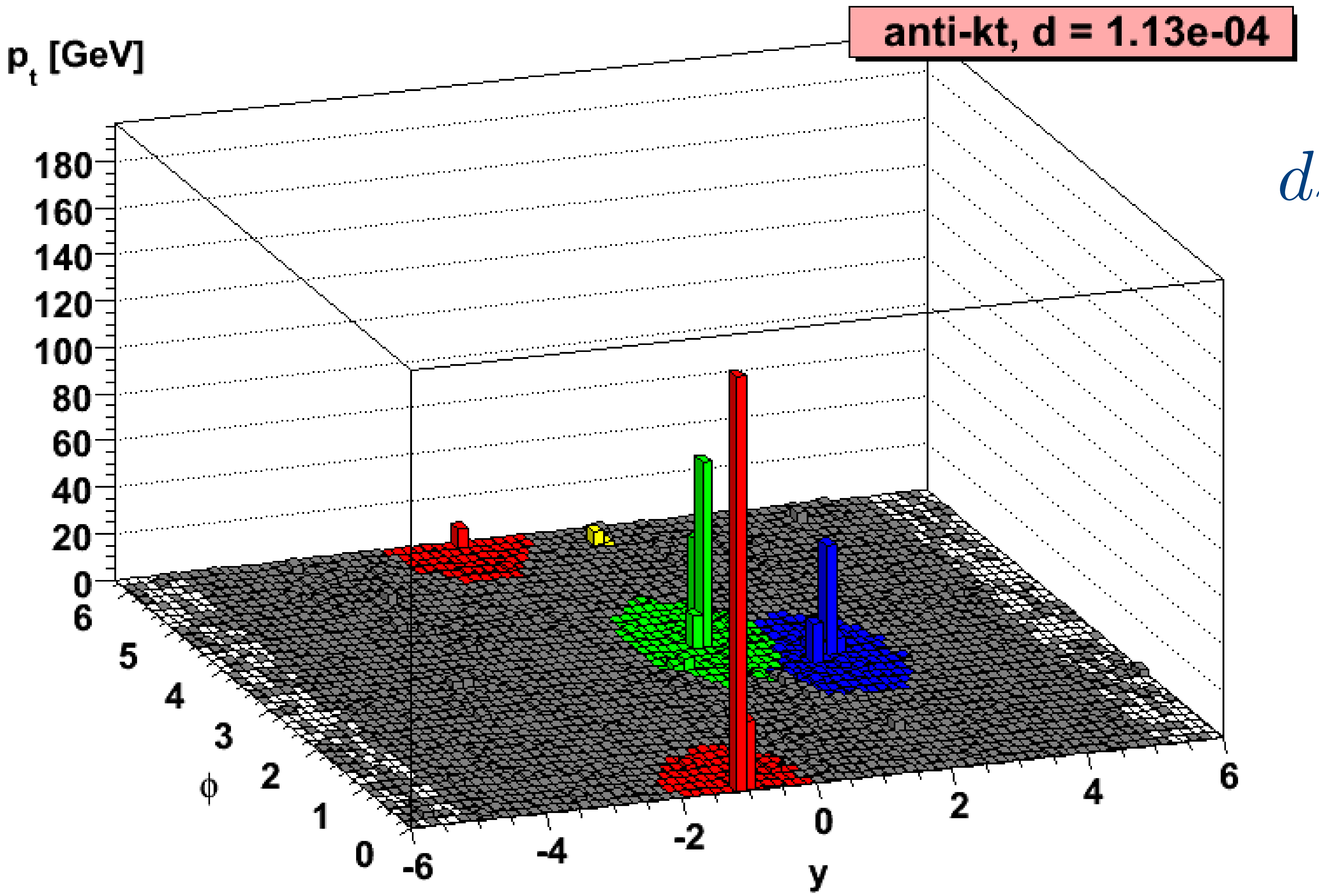

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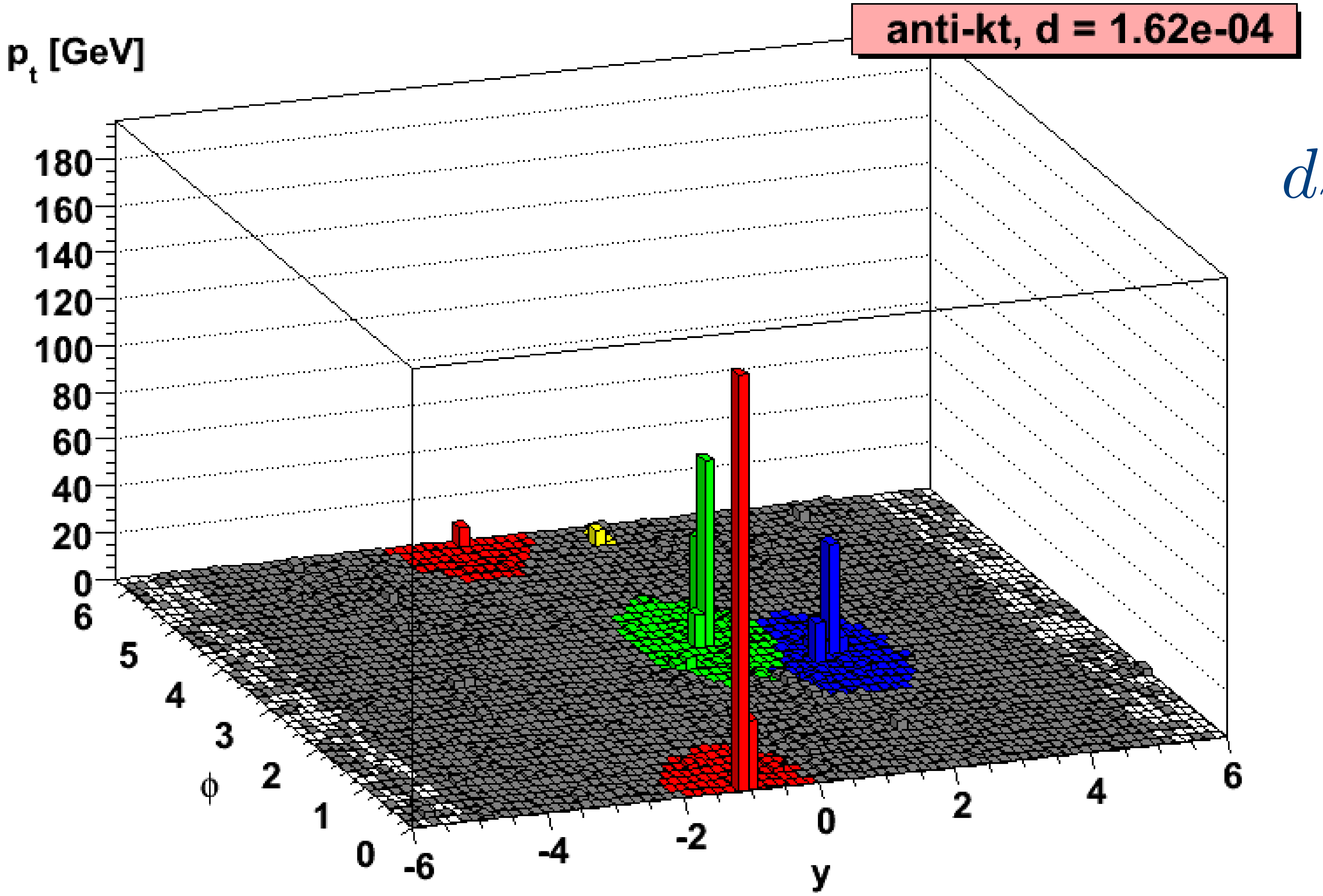

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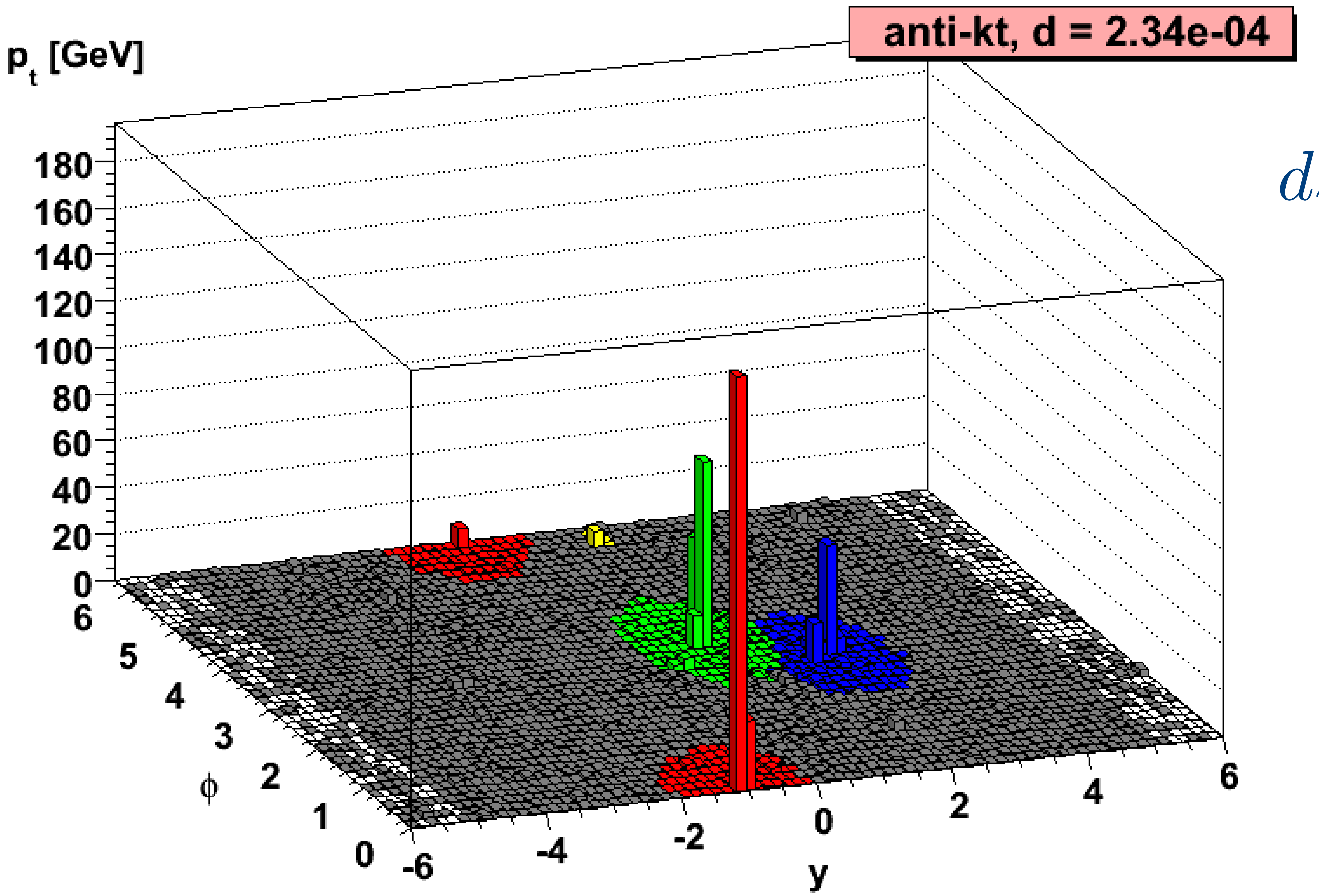

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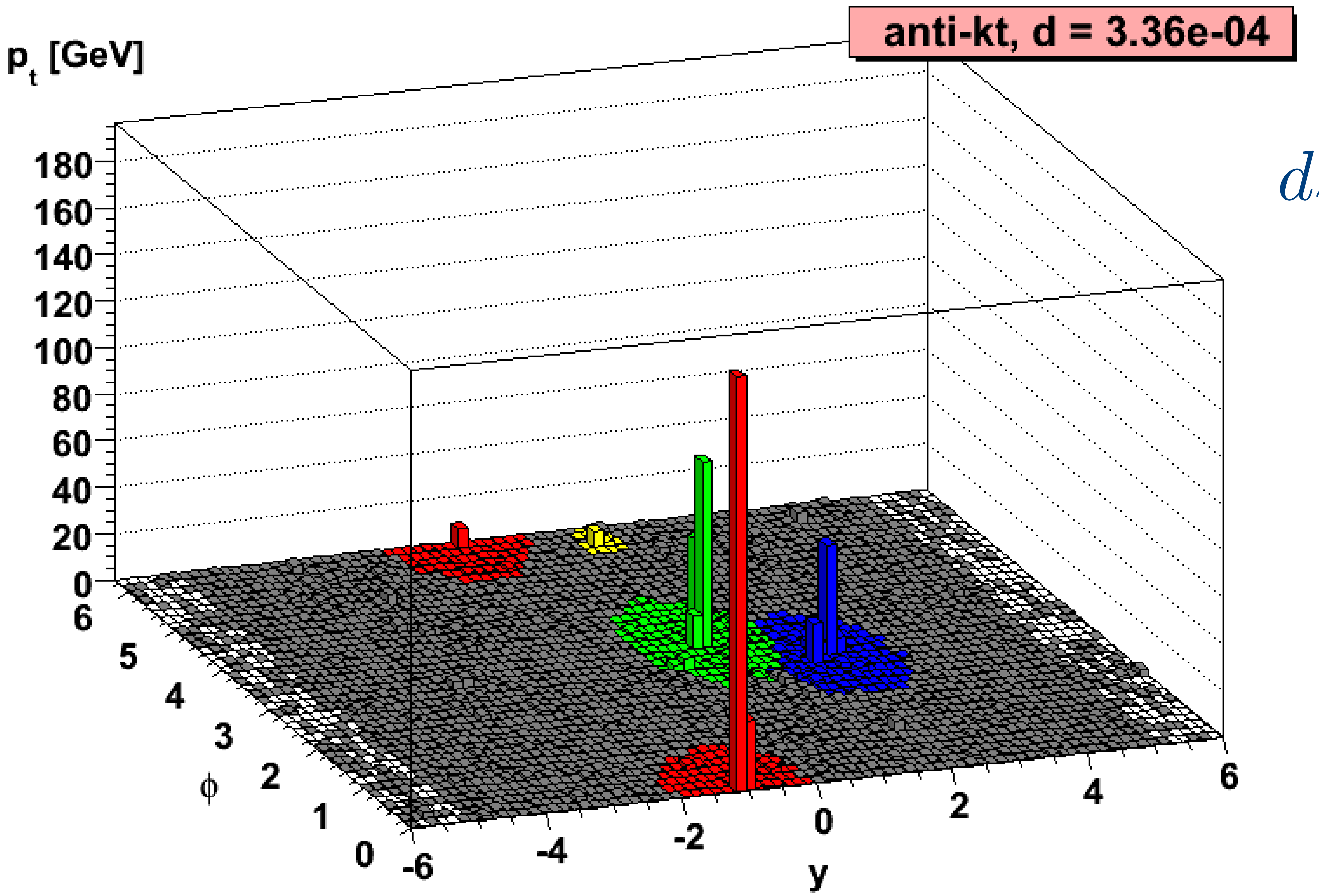

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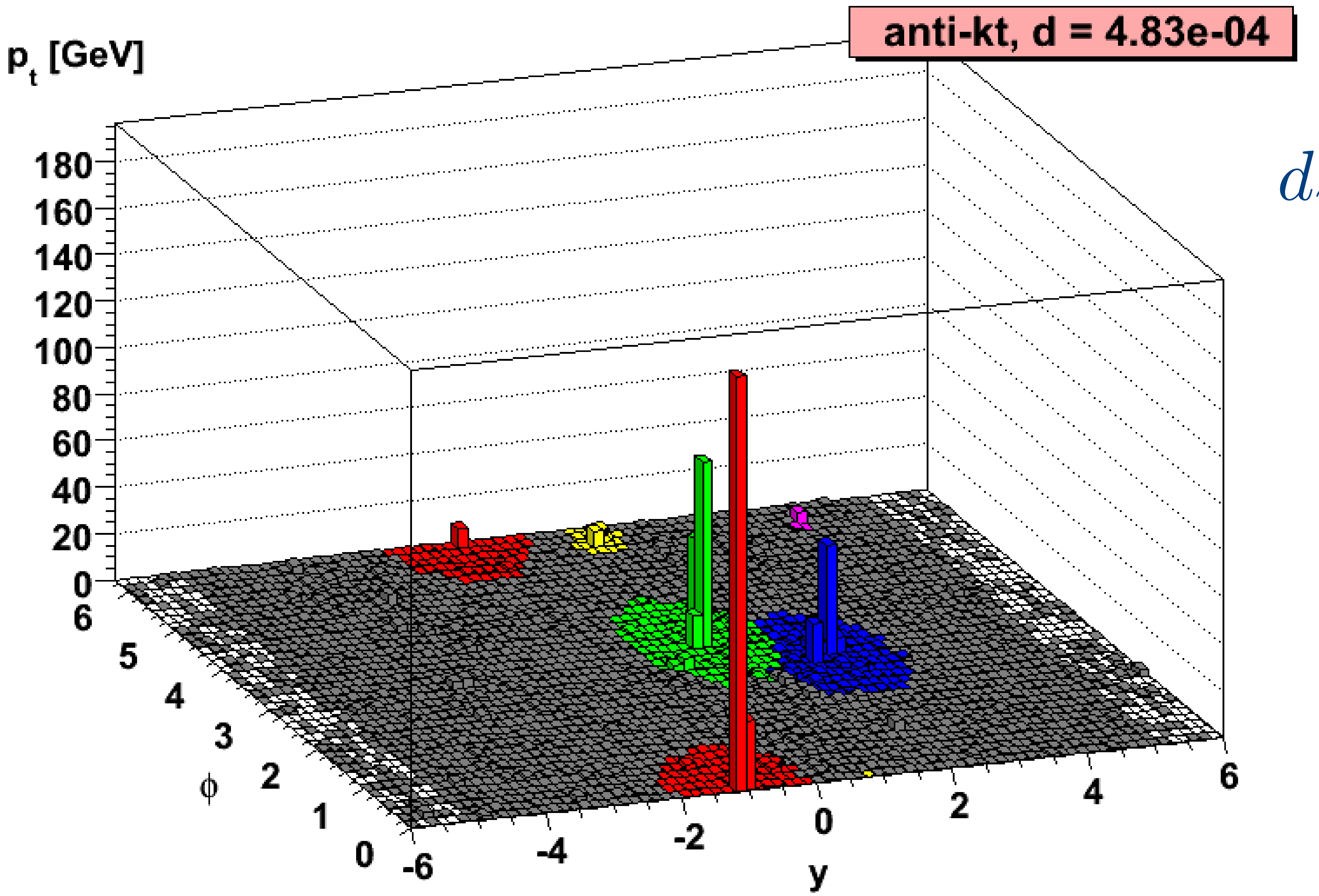

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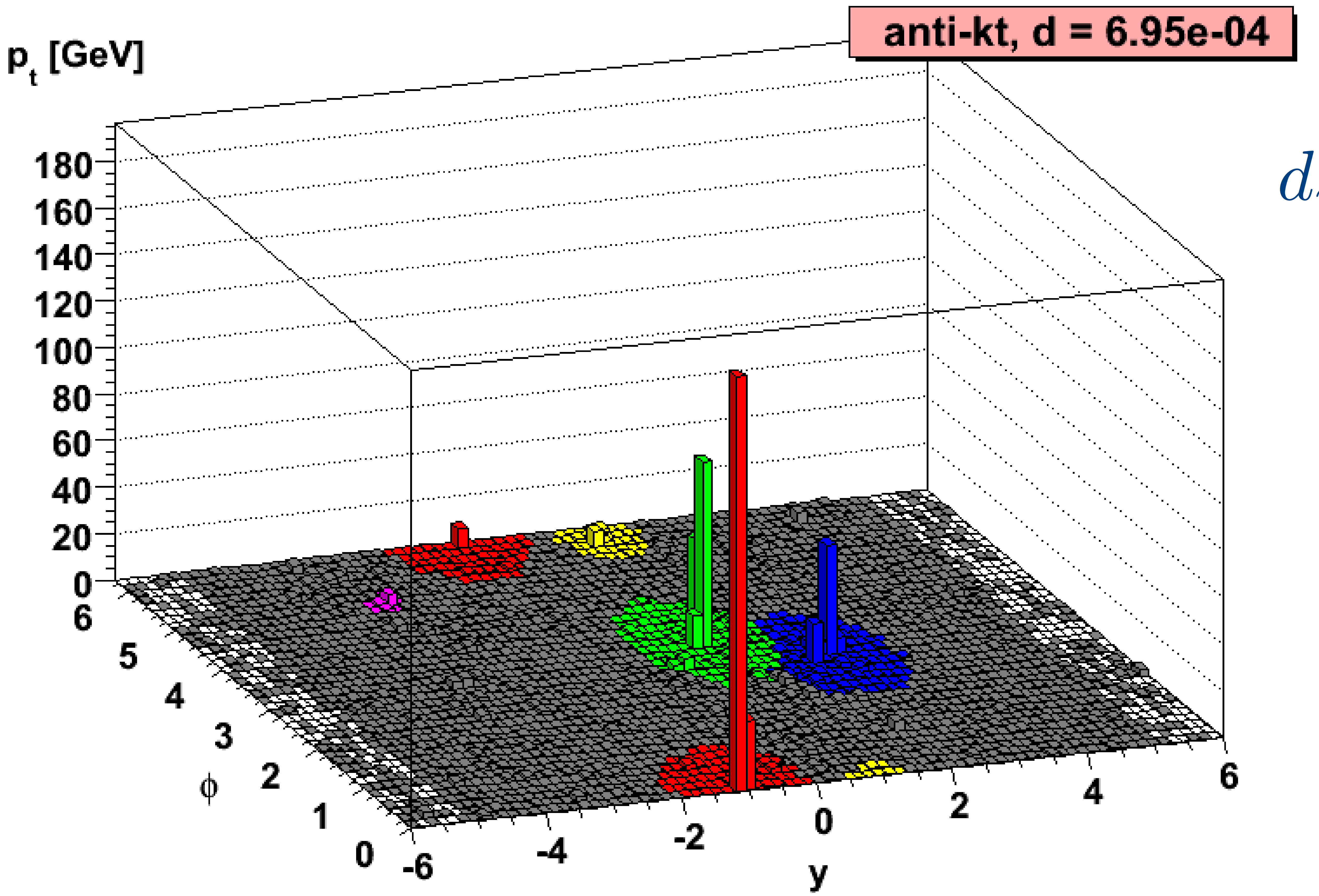

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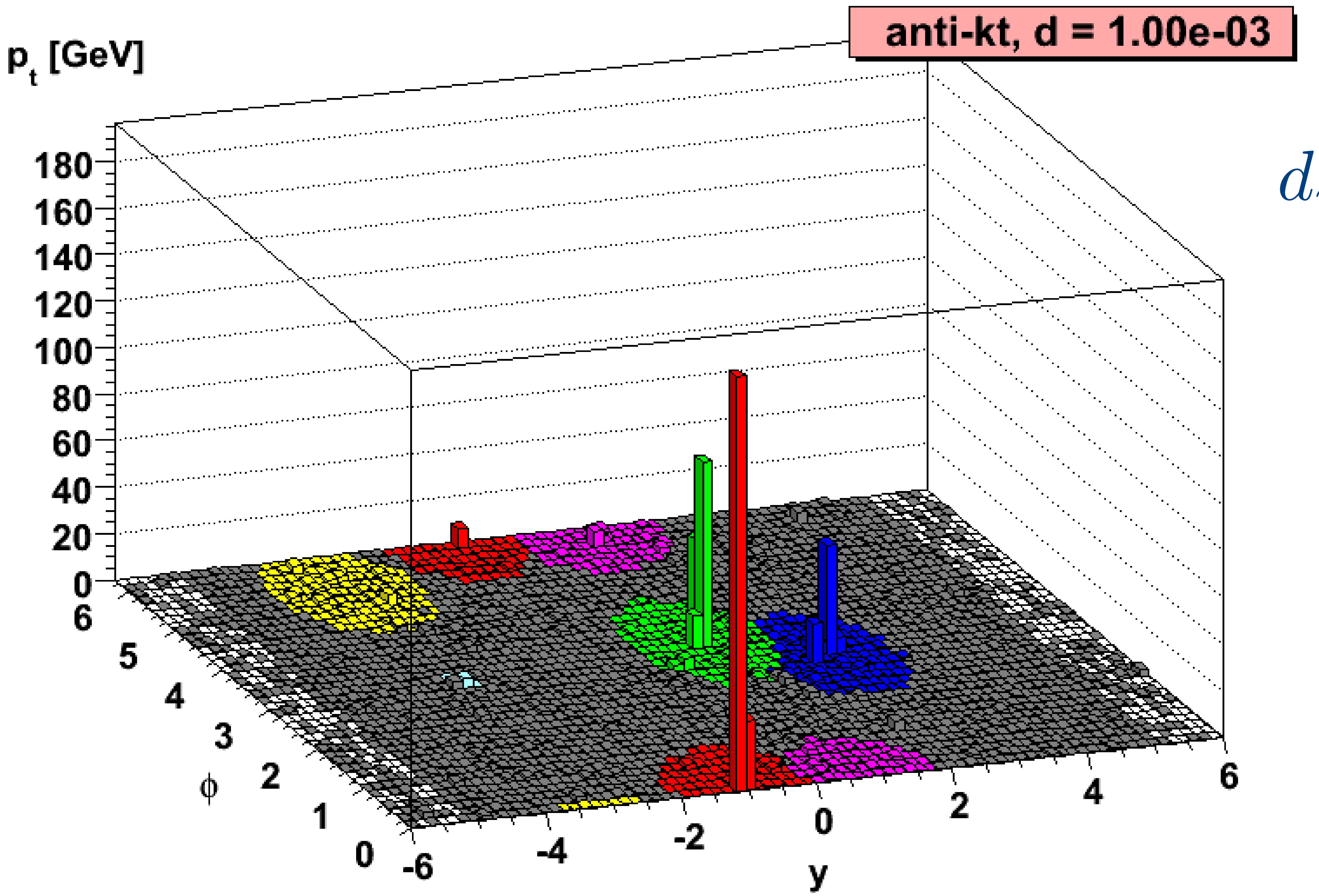

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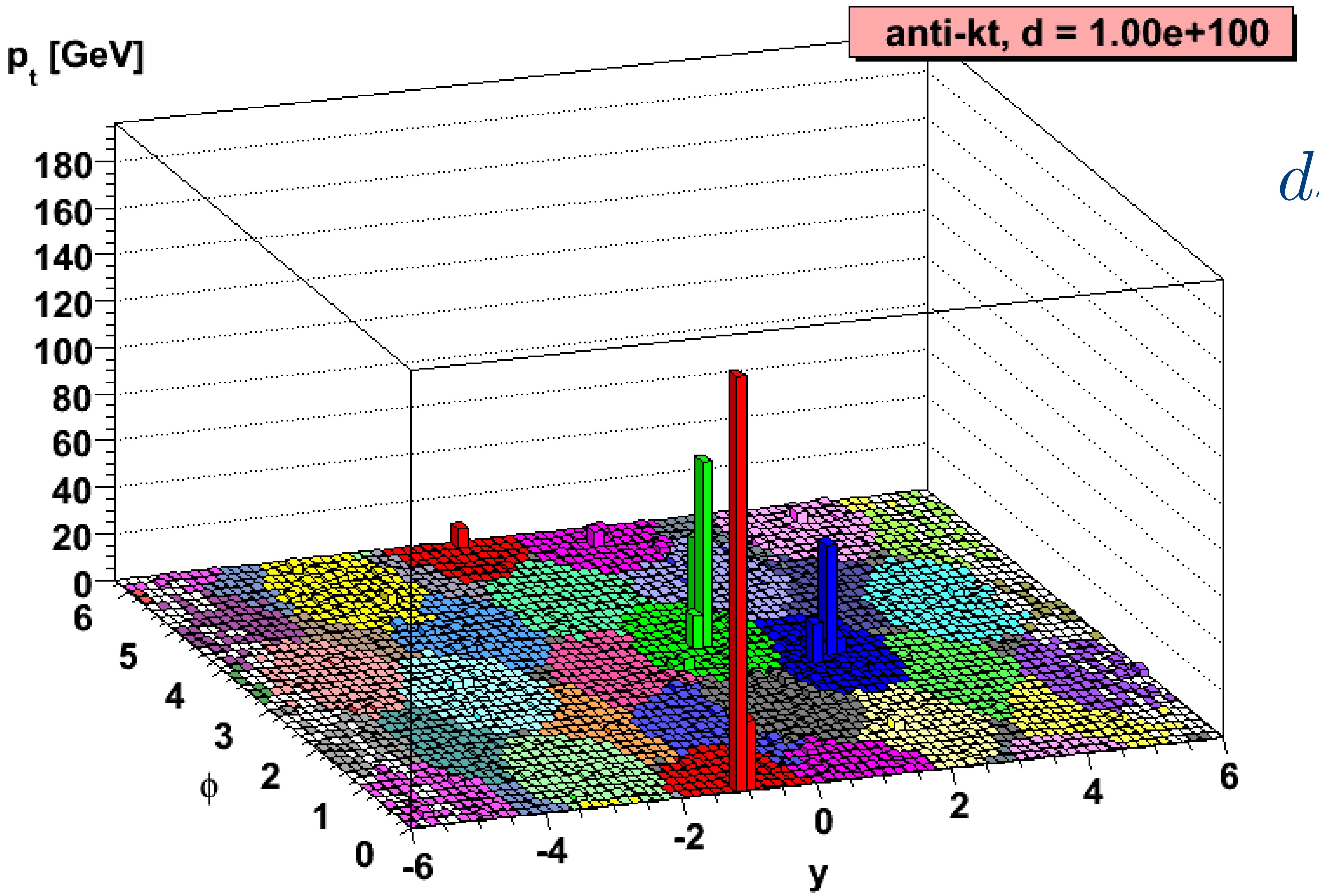

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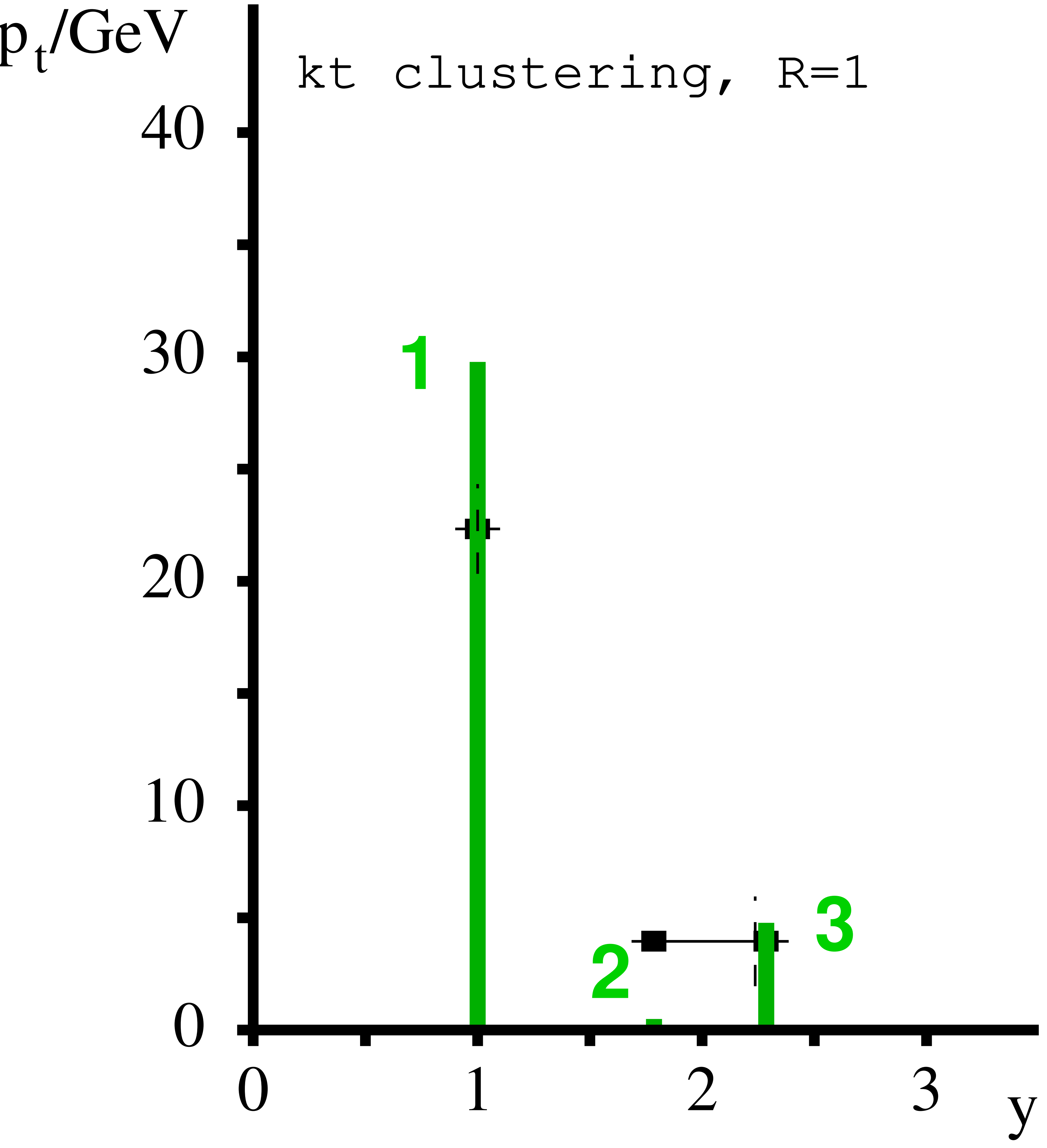
p_t/GeV
kt clustering, R=1
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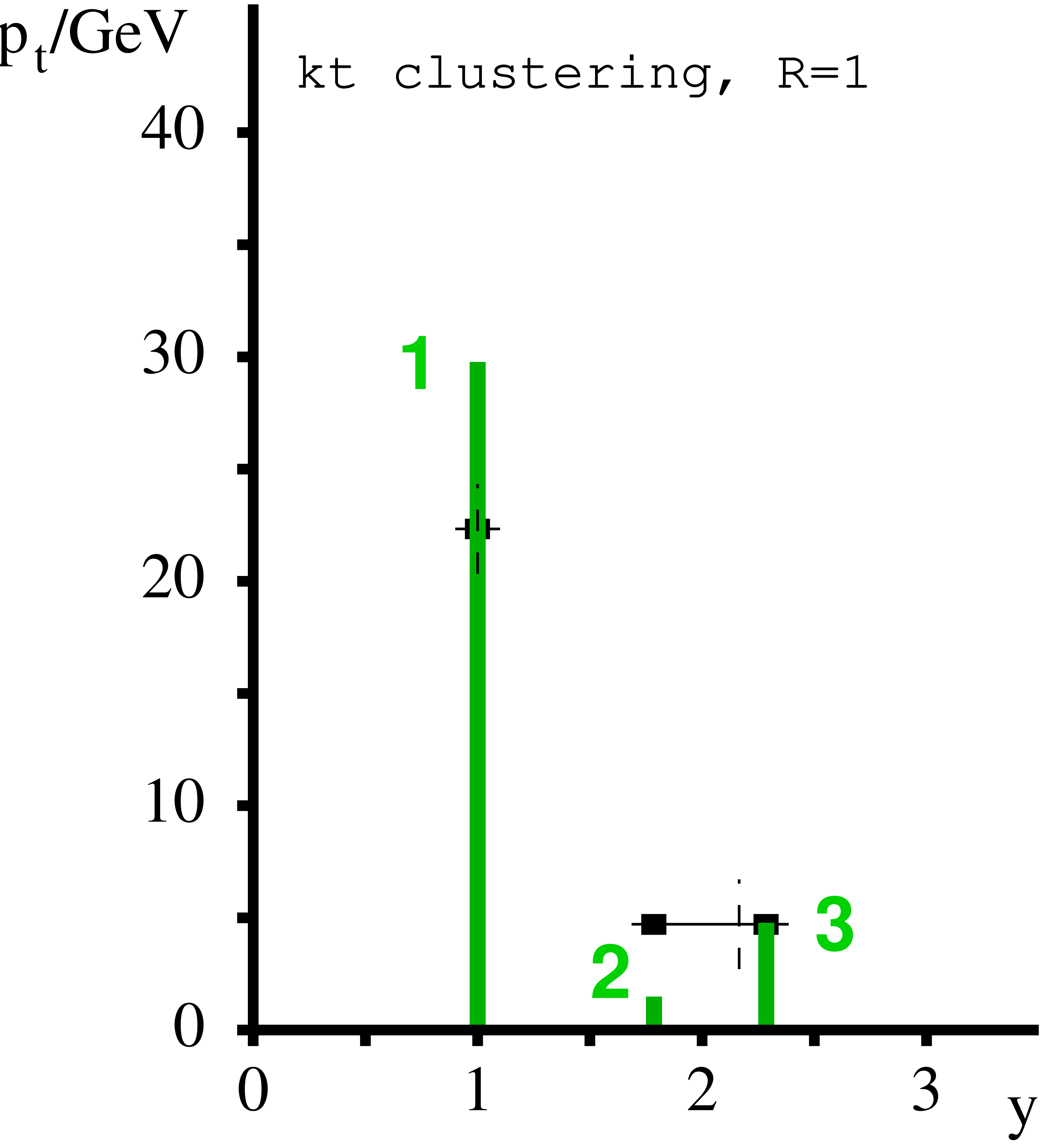

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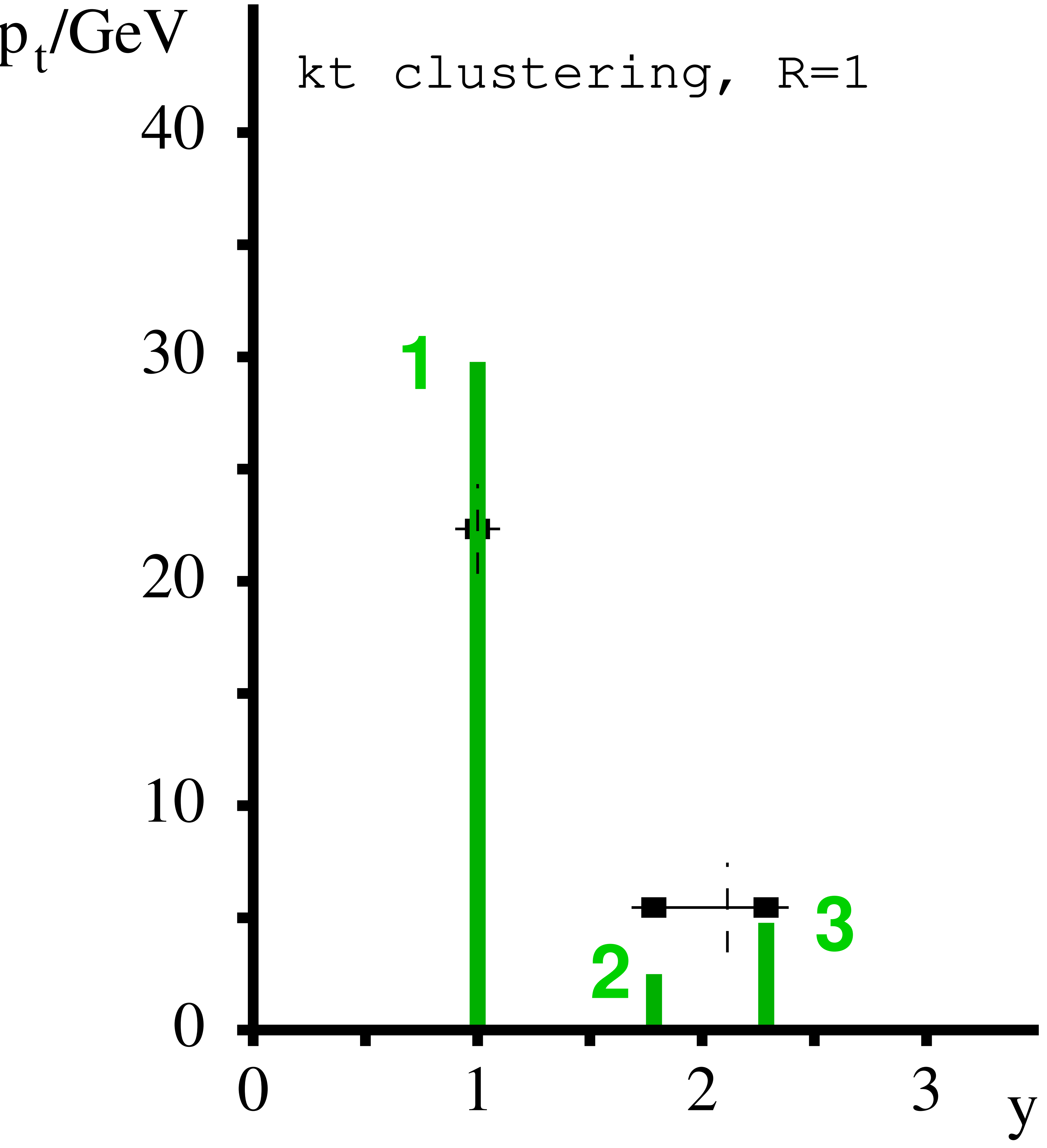

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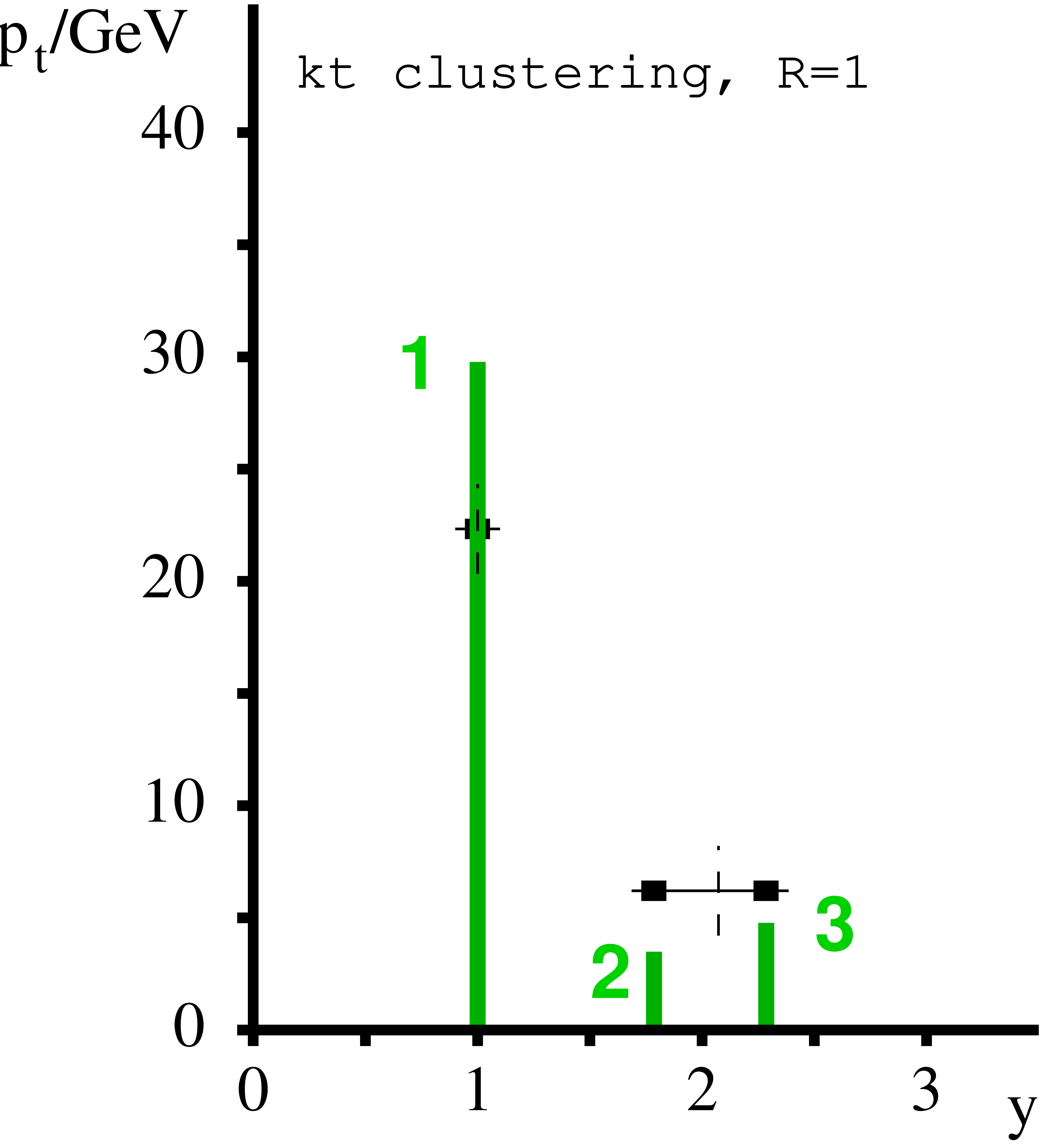

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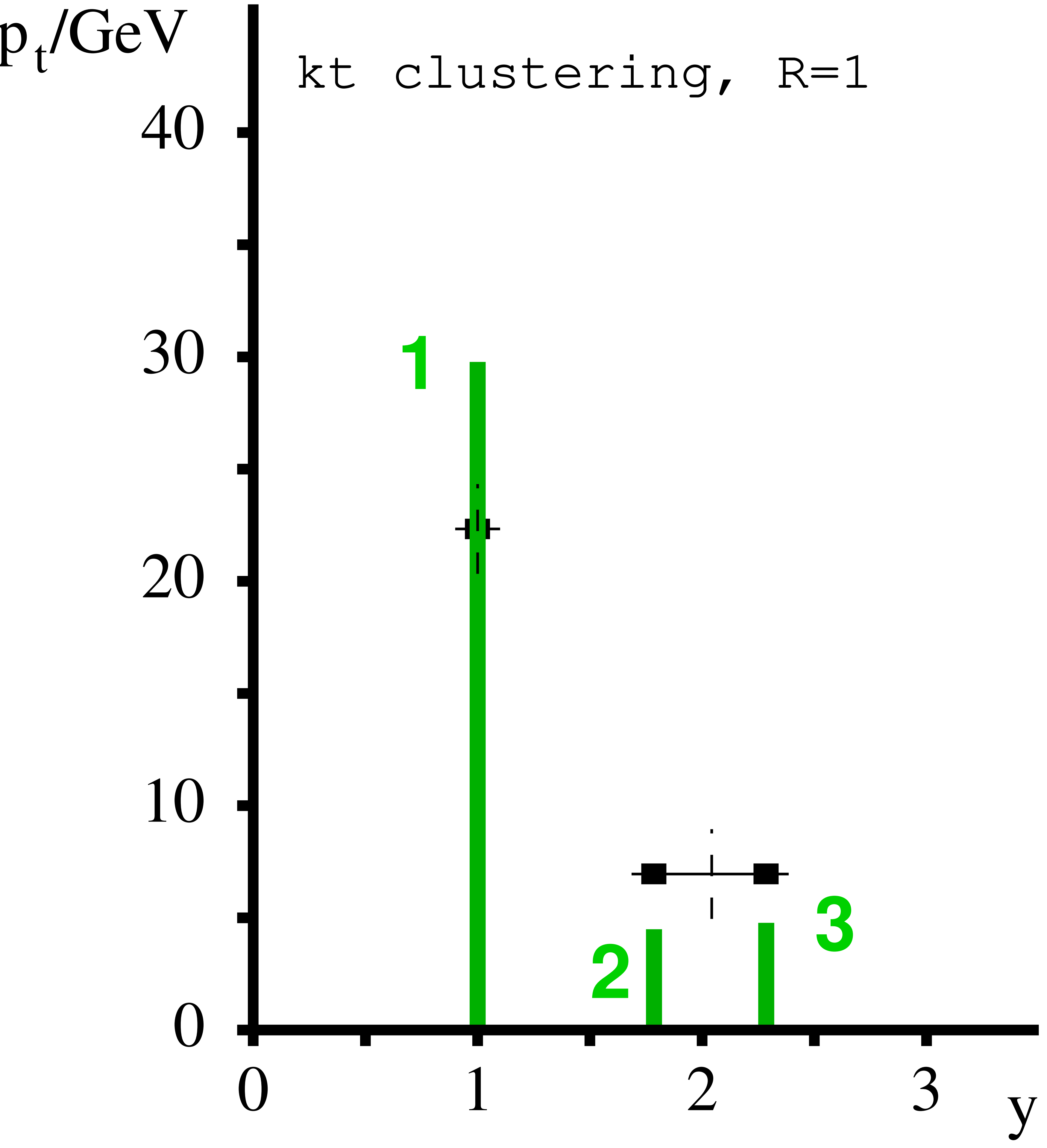

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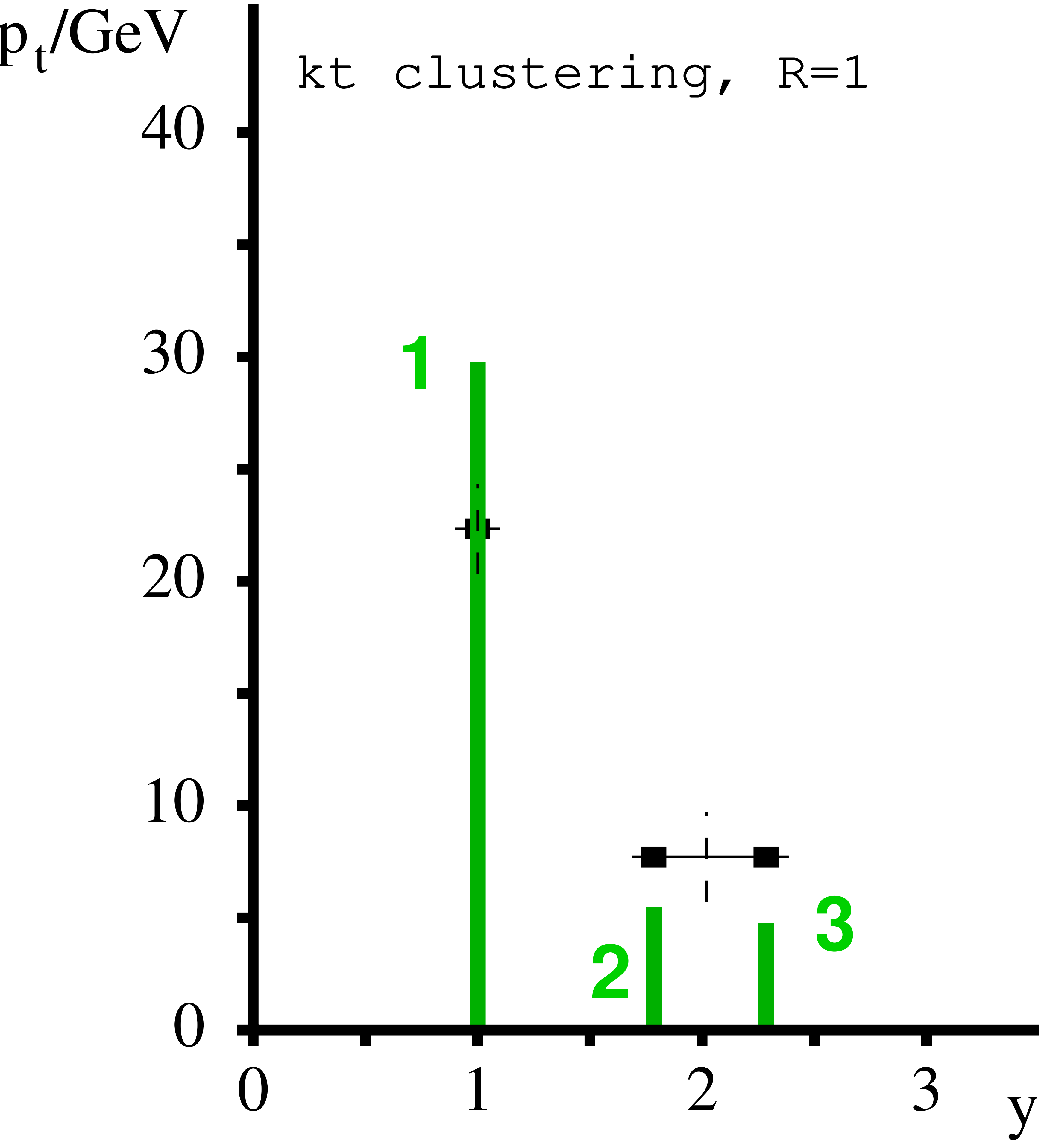

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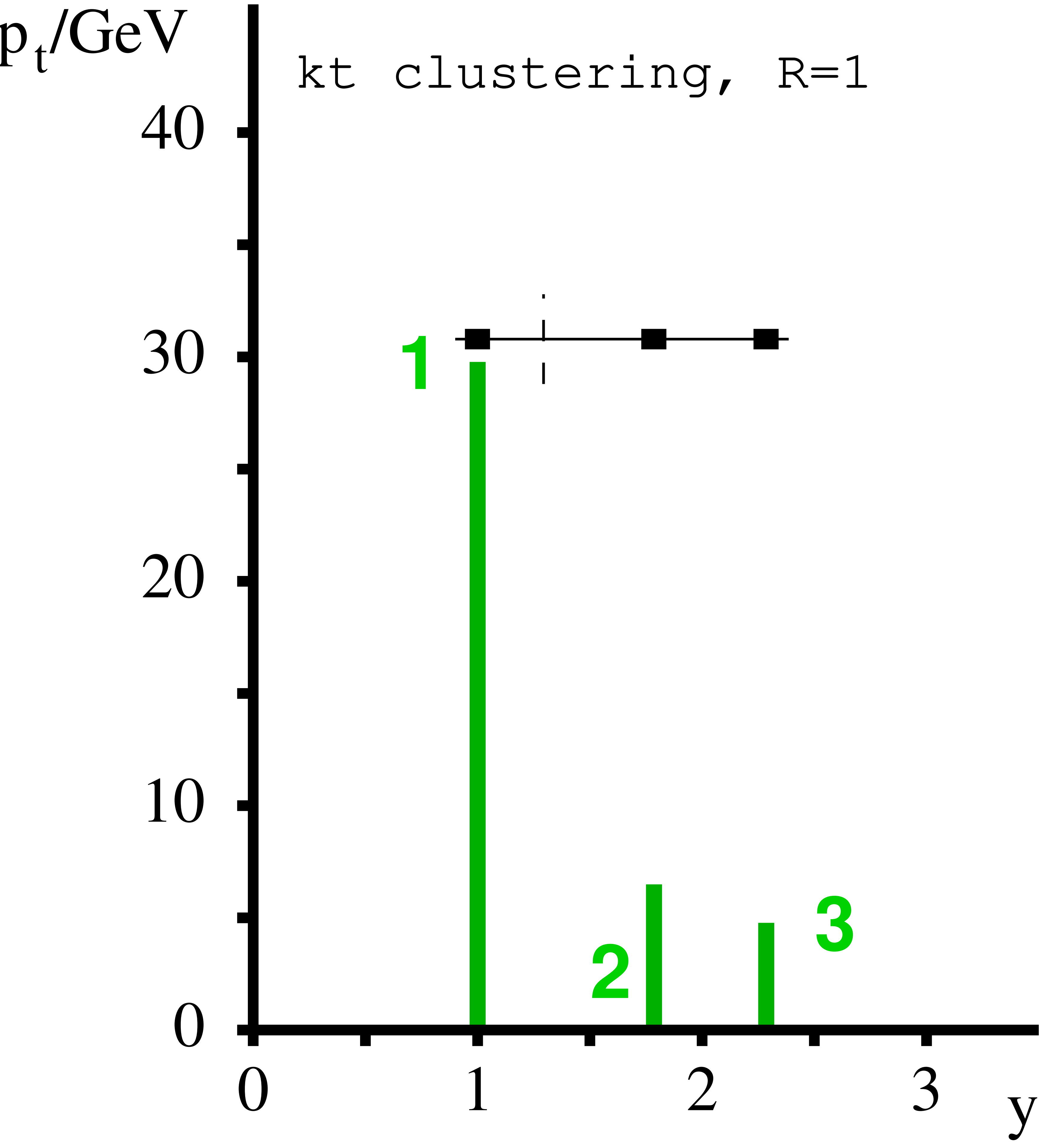

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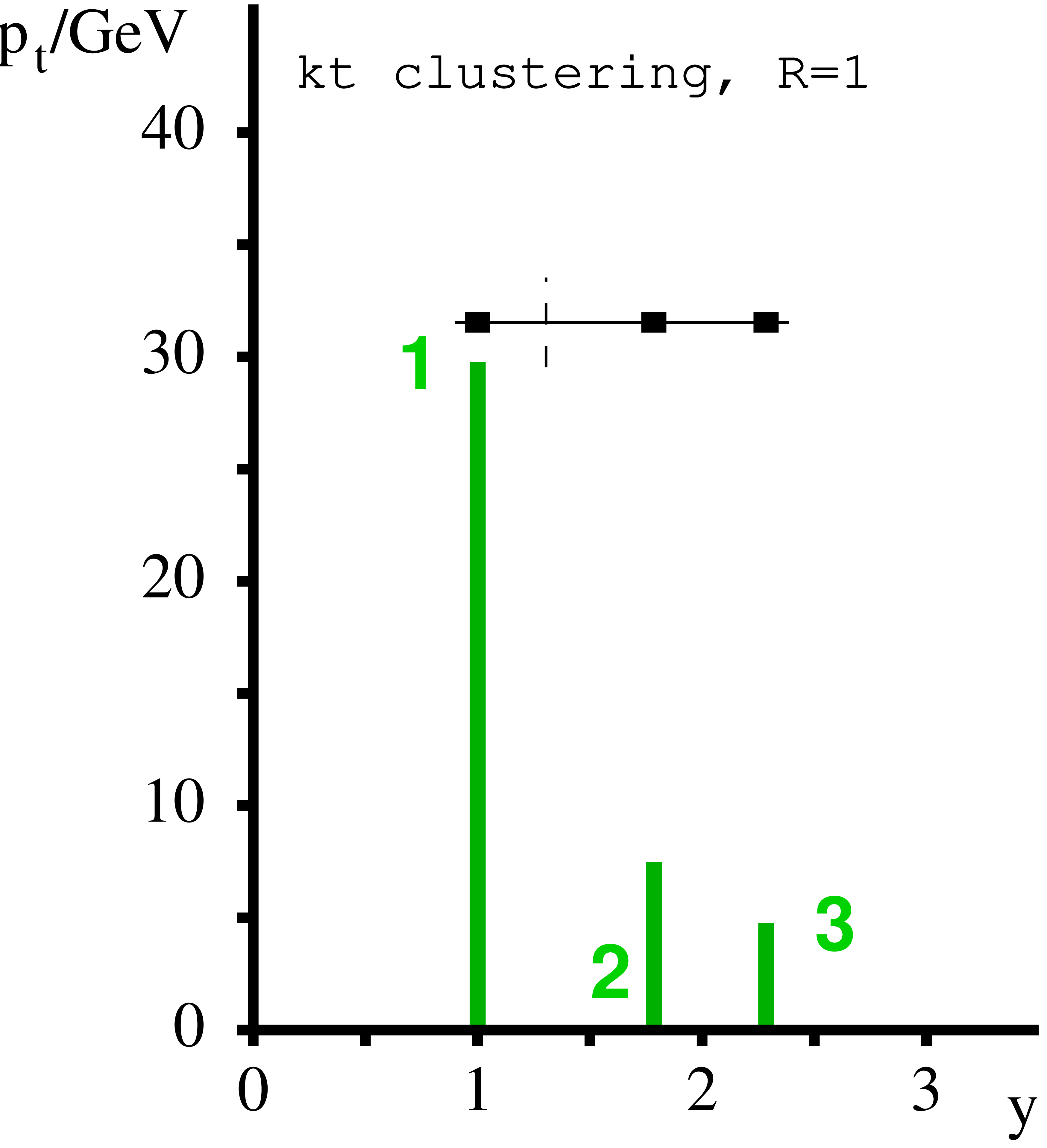

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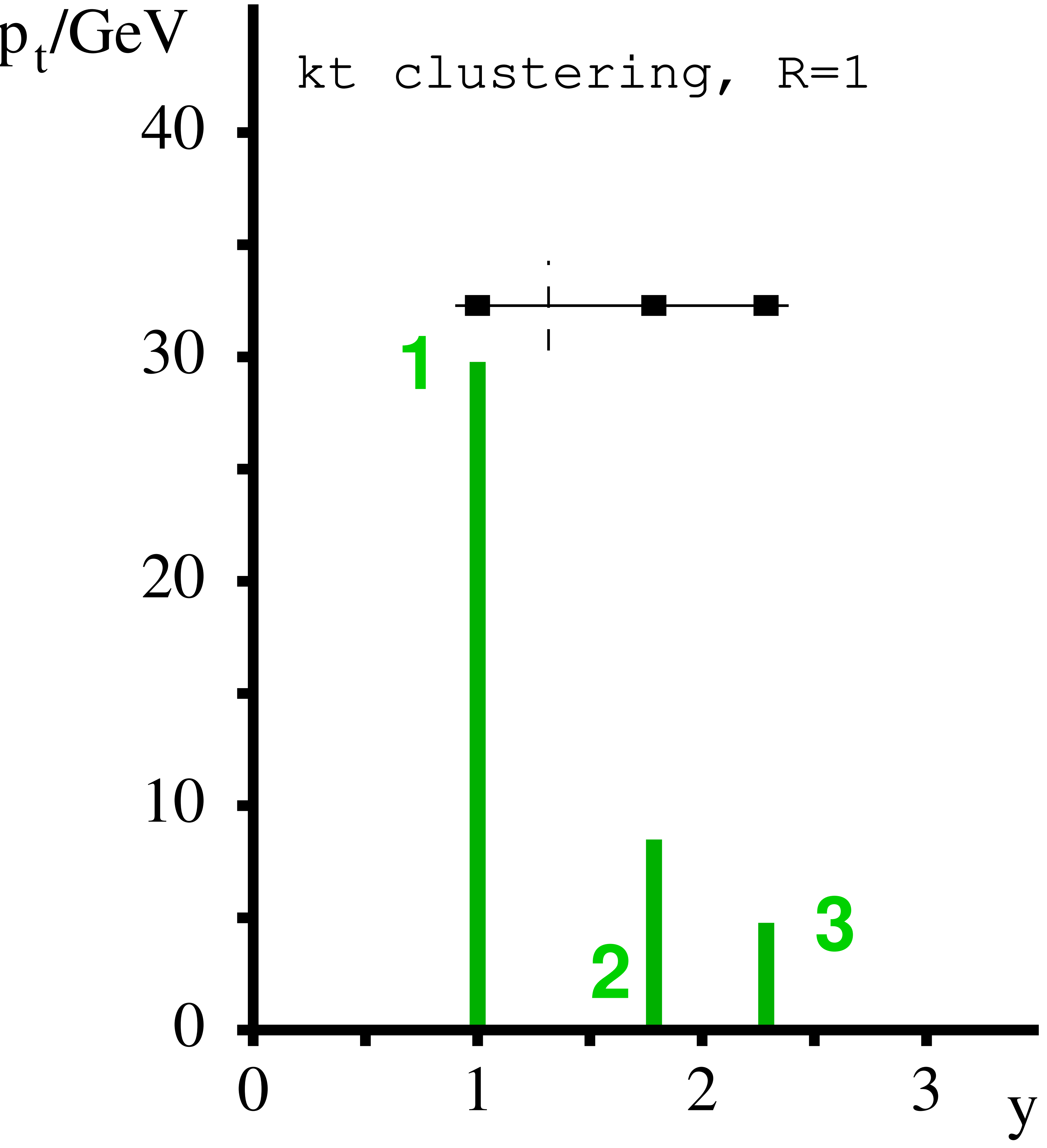

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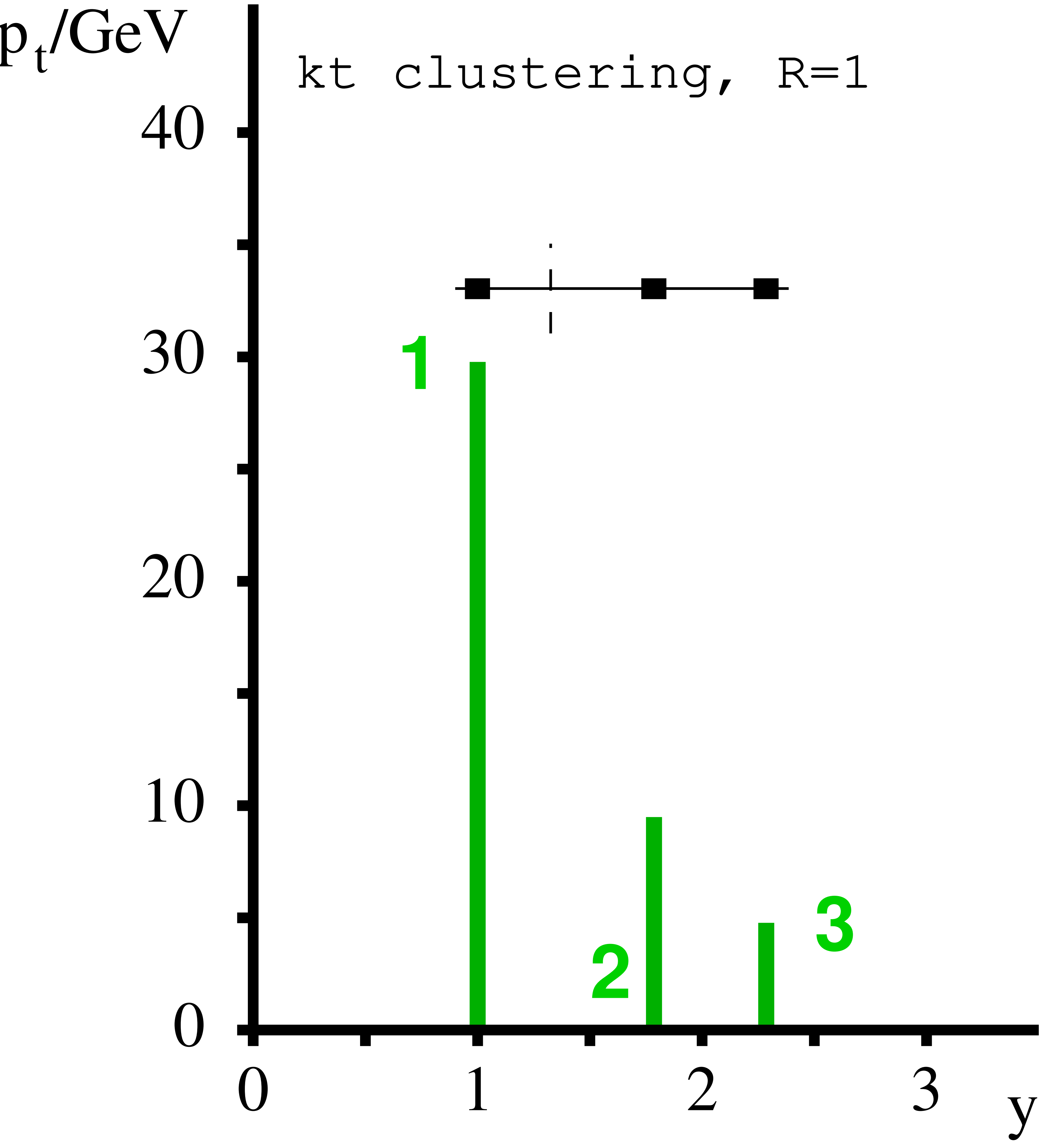

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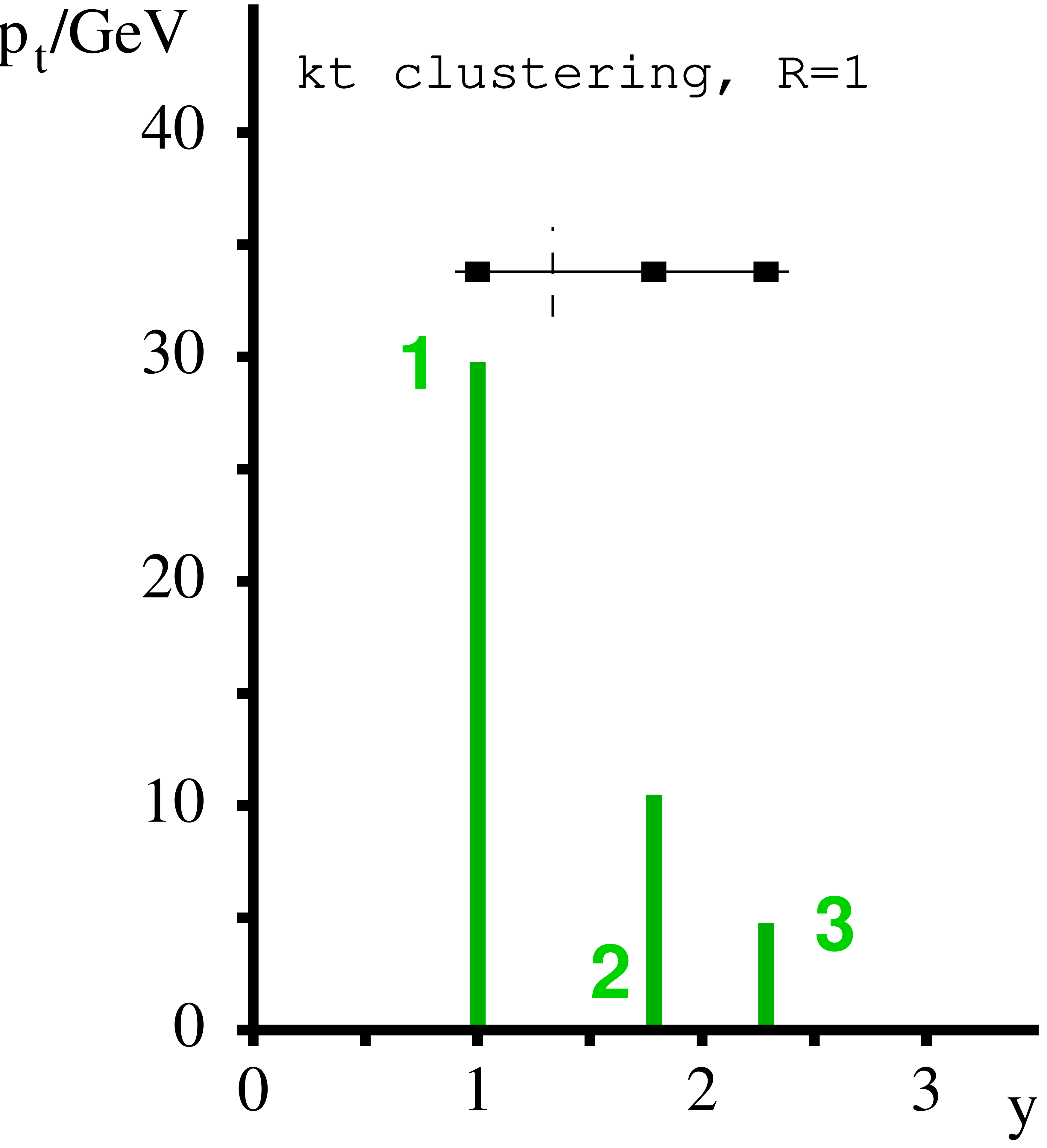

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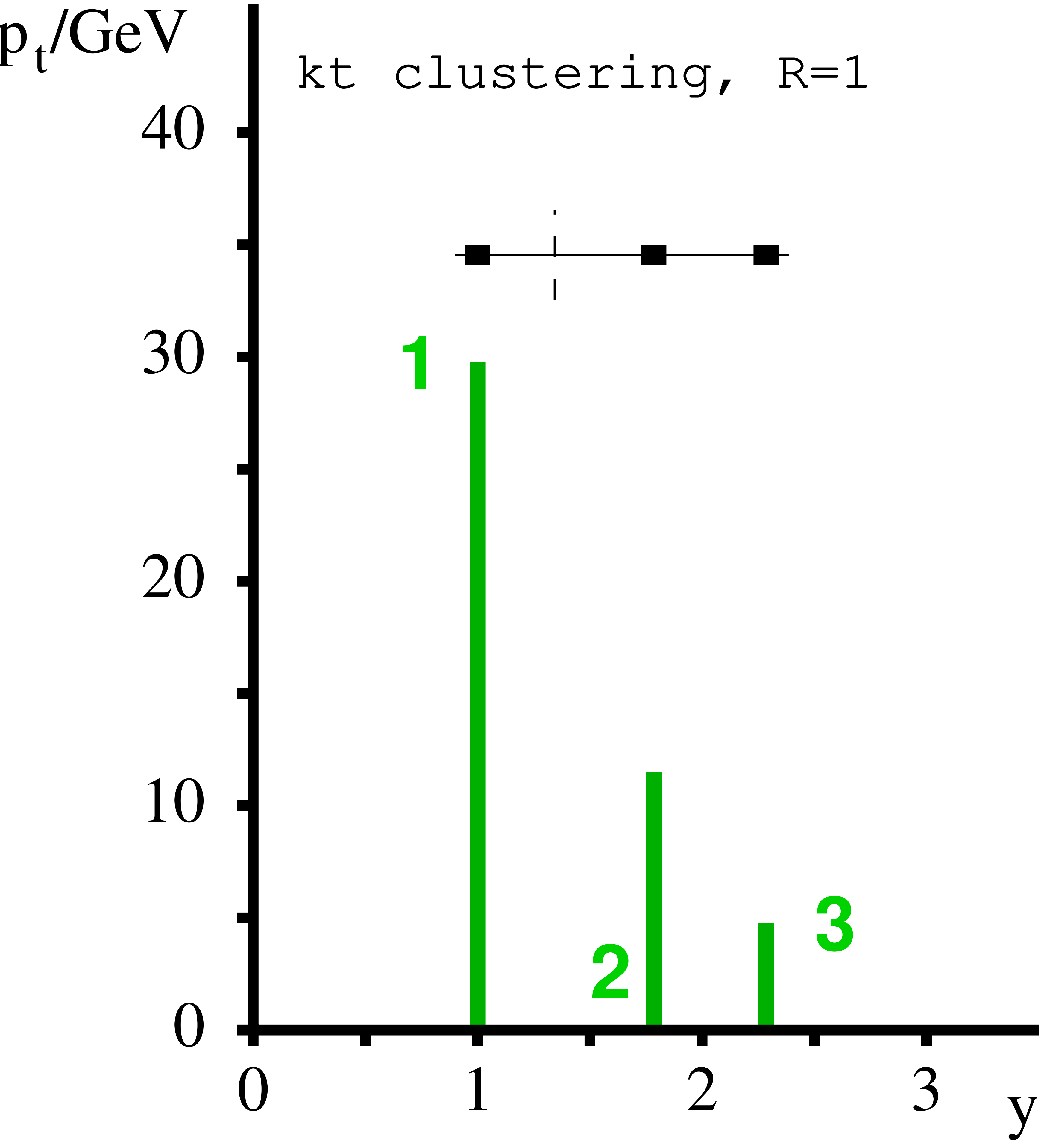

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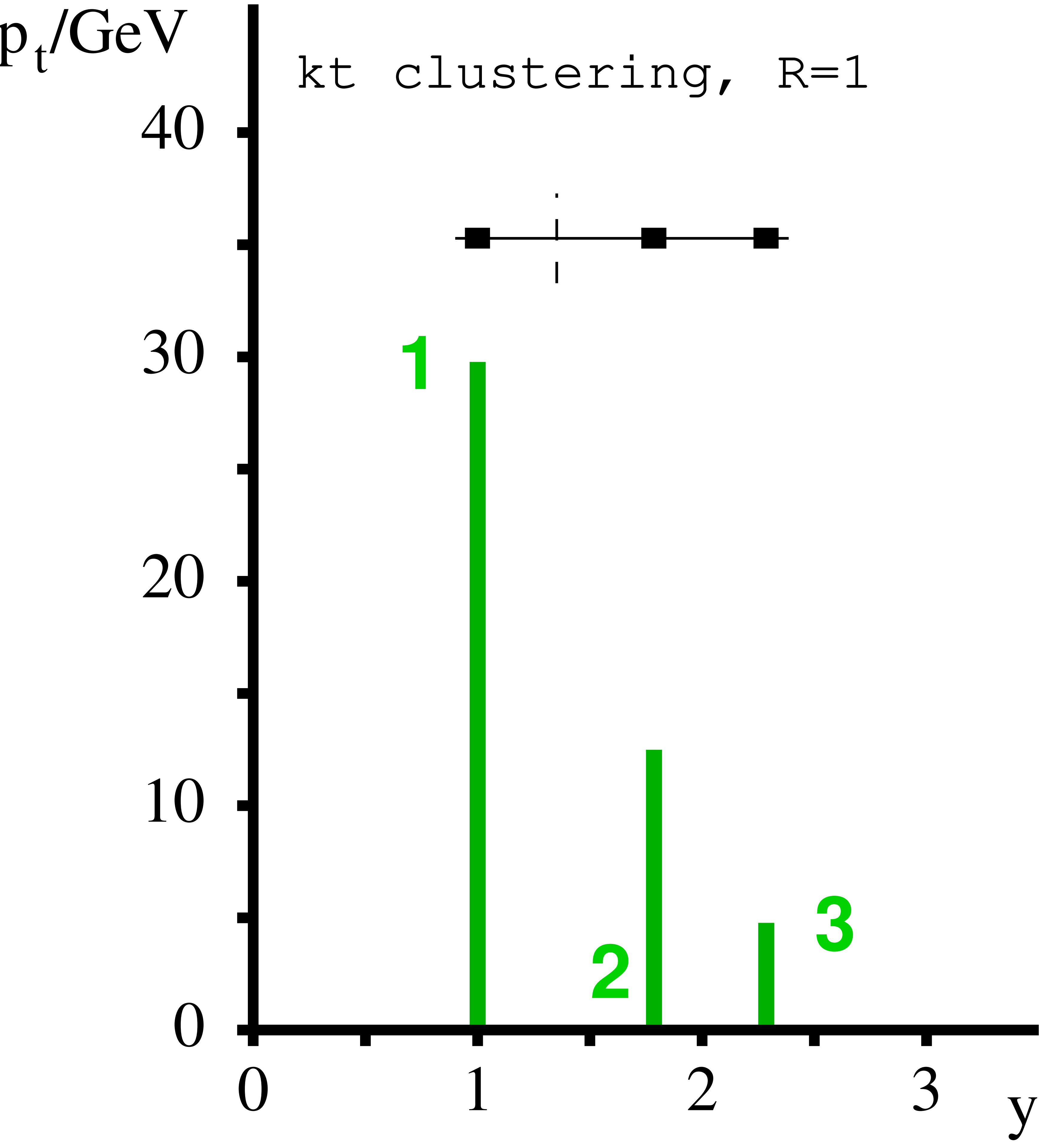
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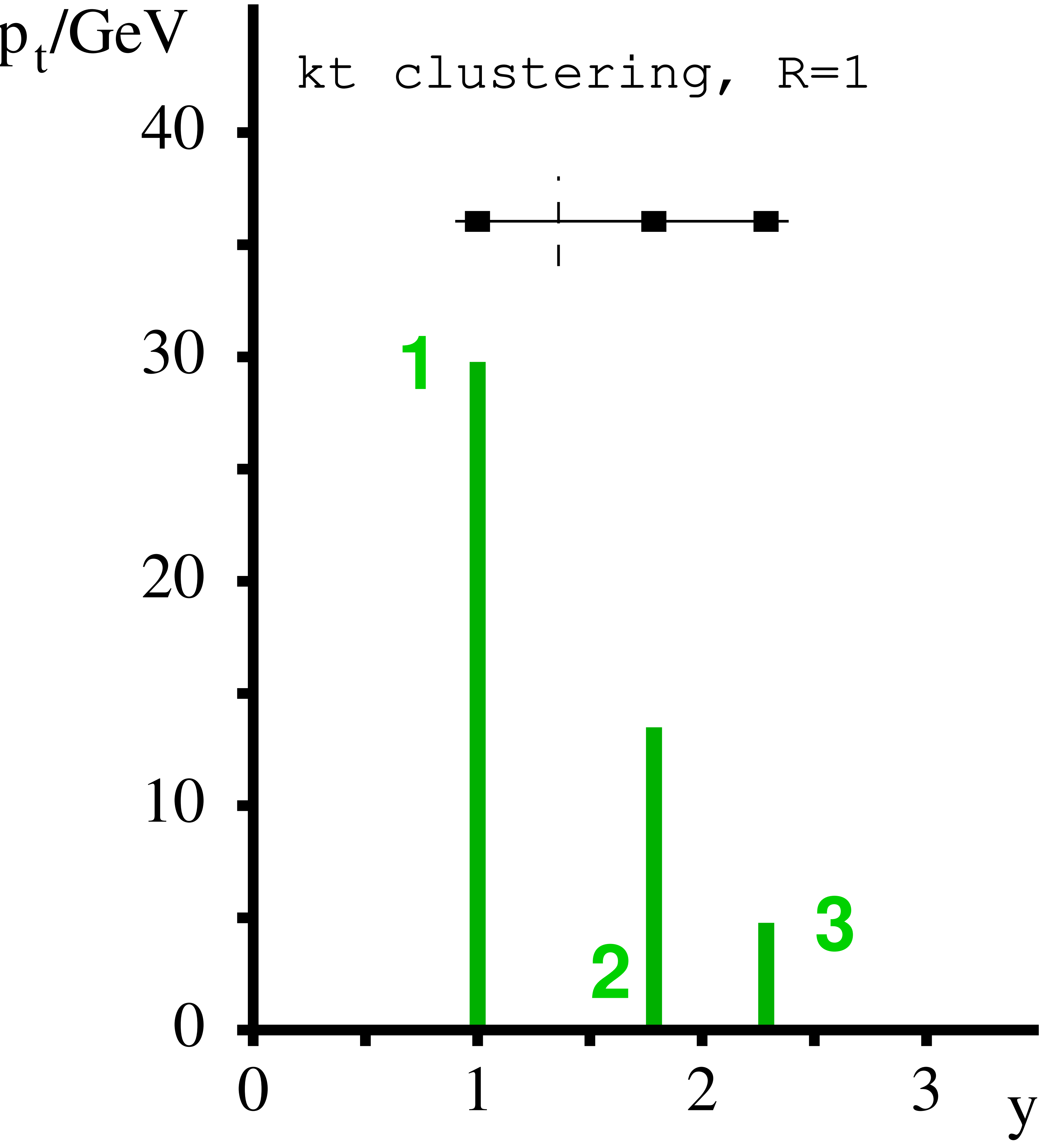
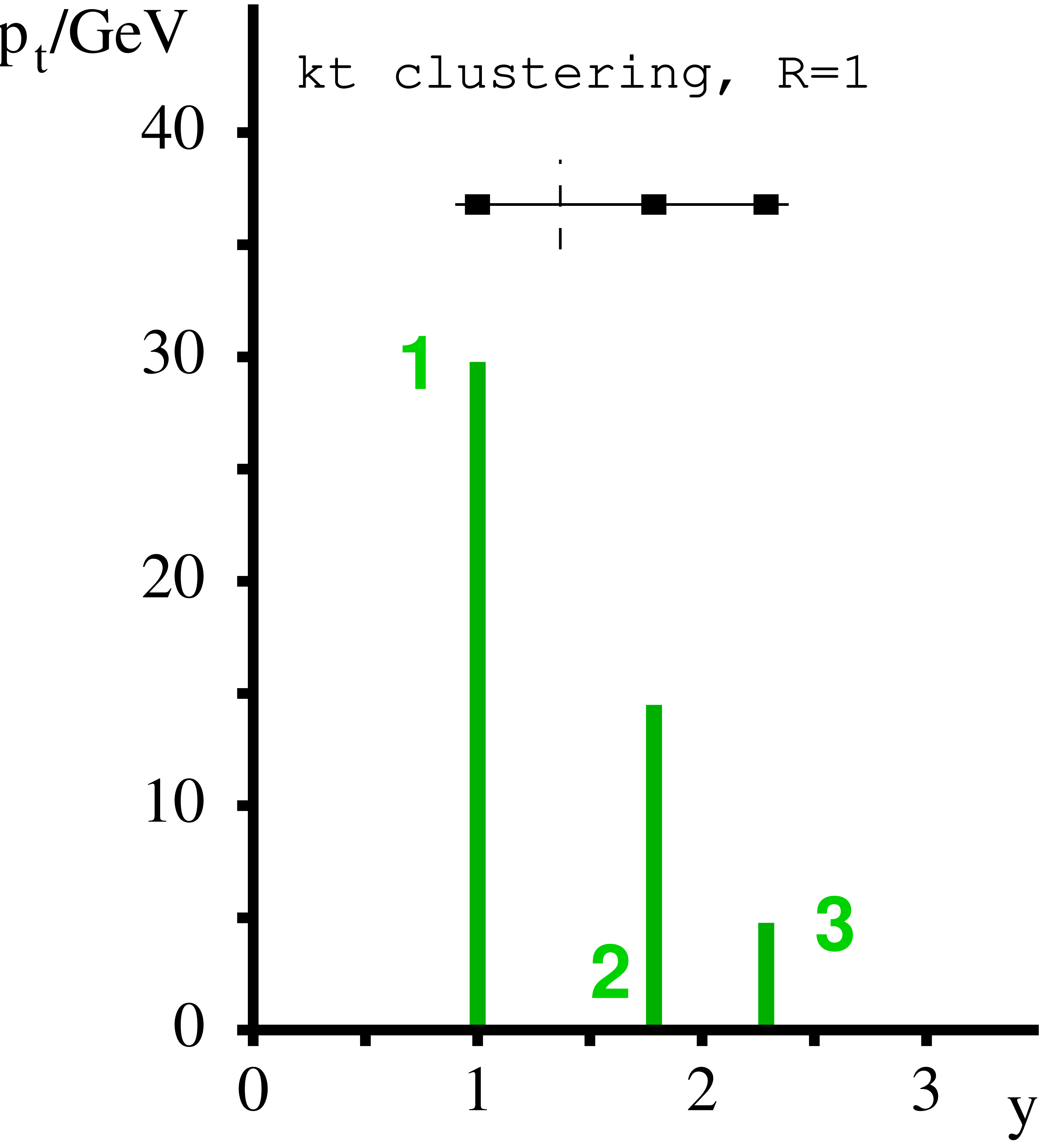
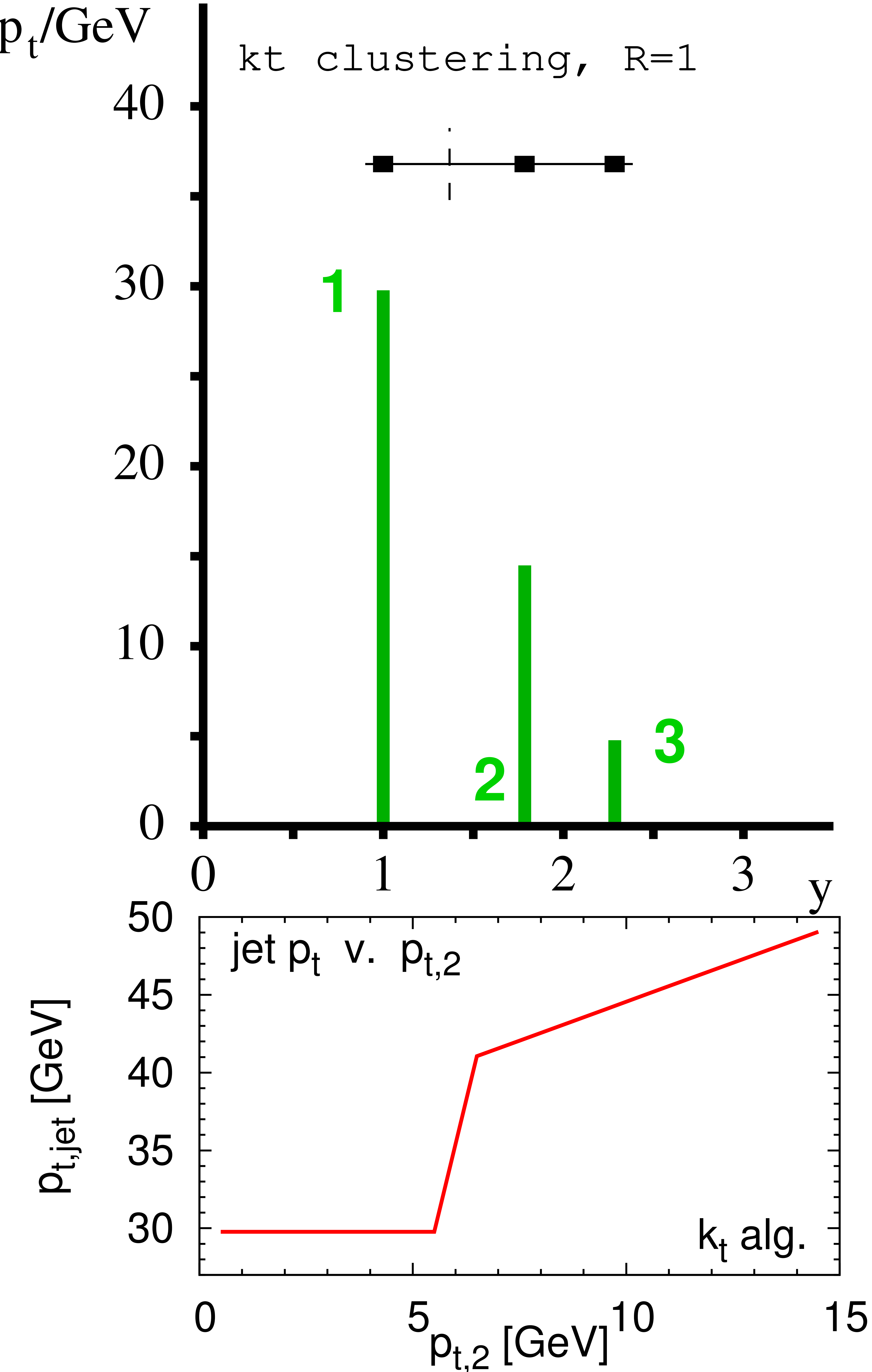
y



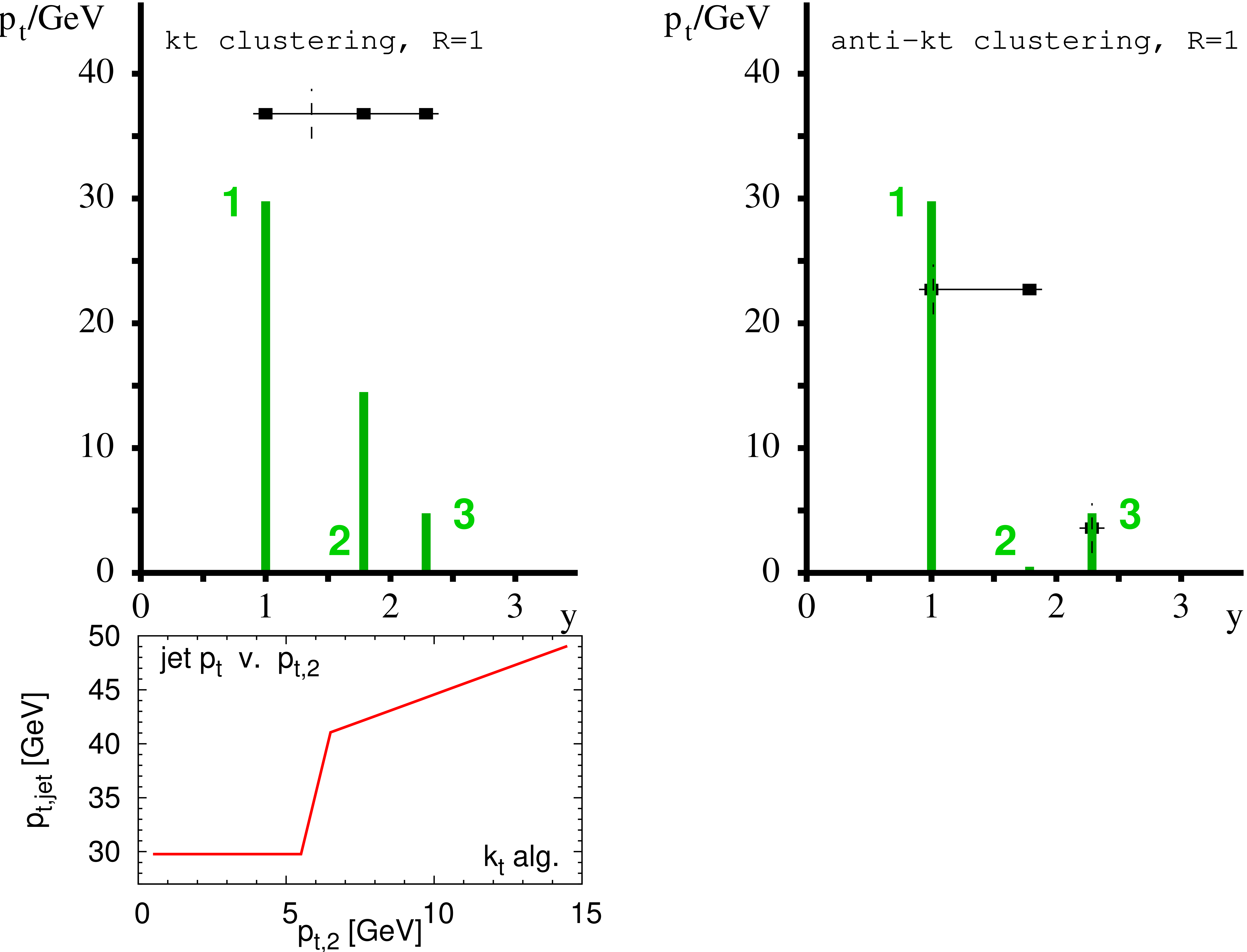
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

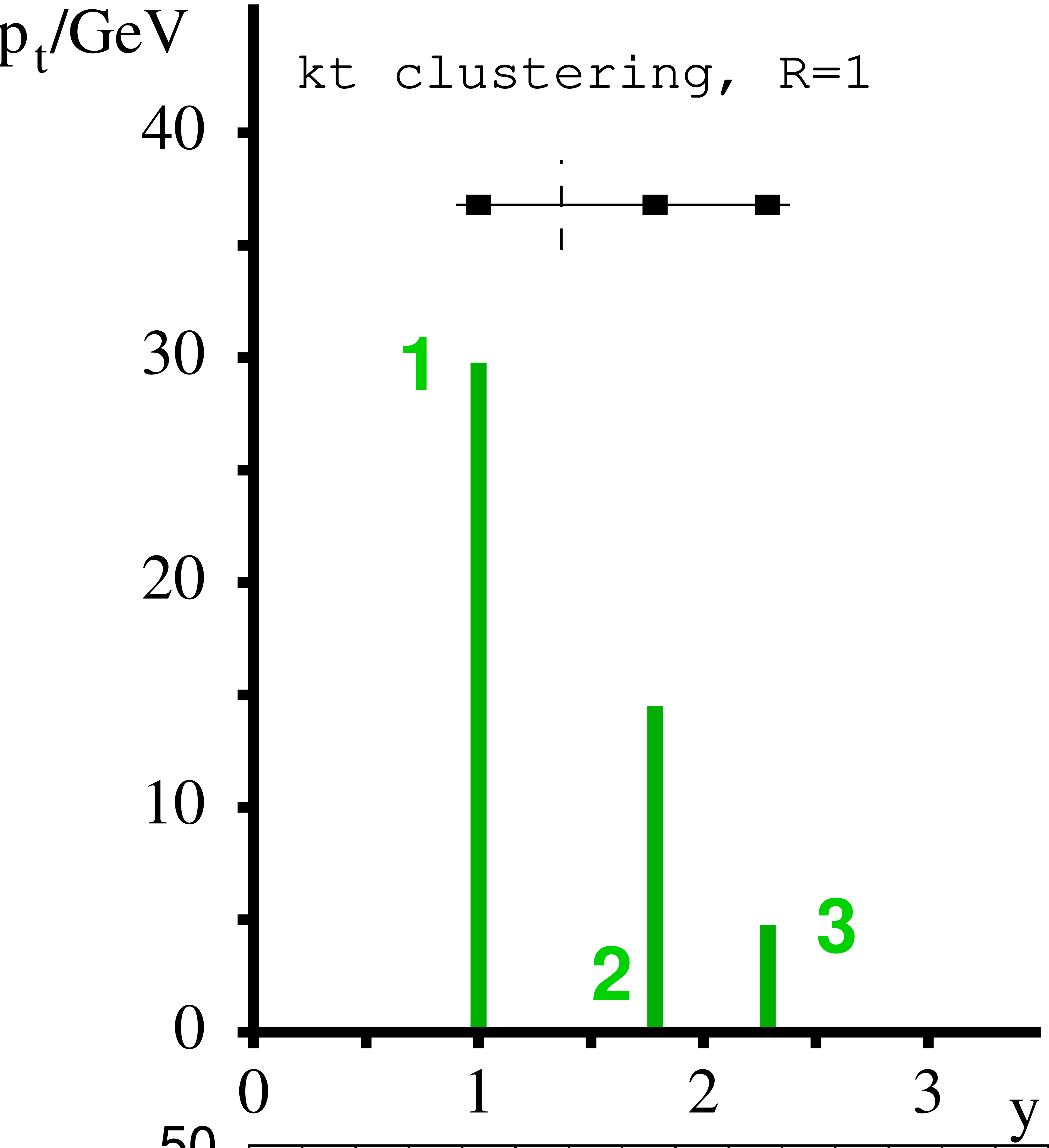


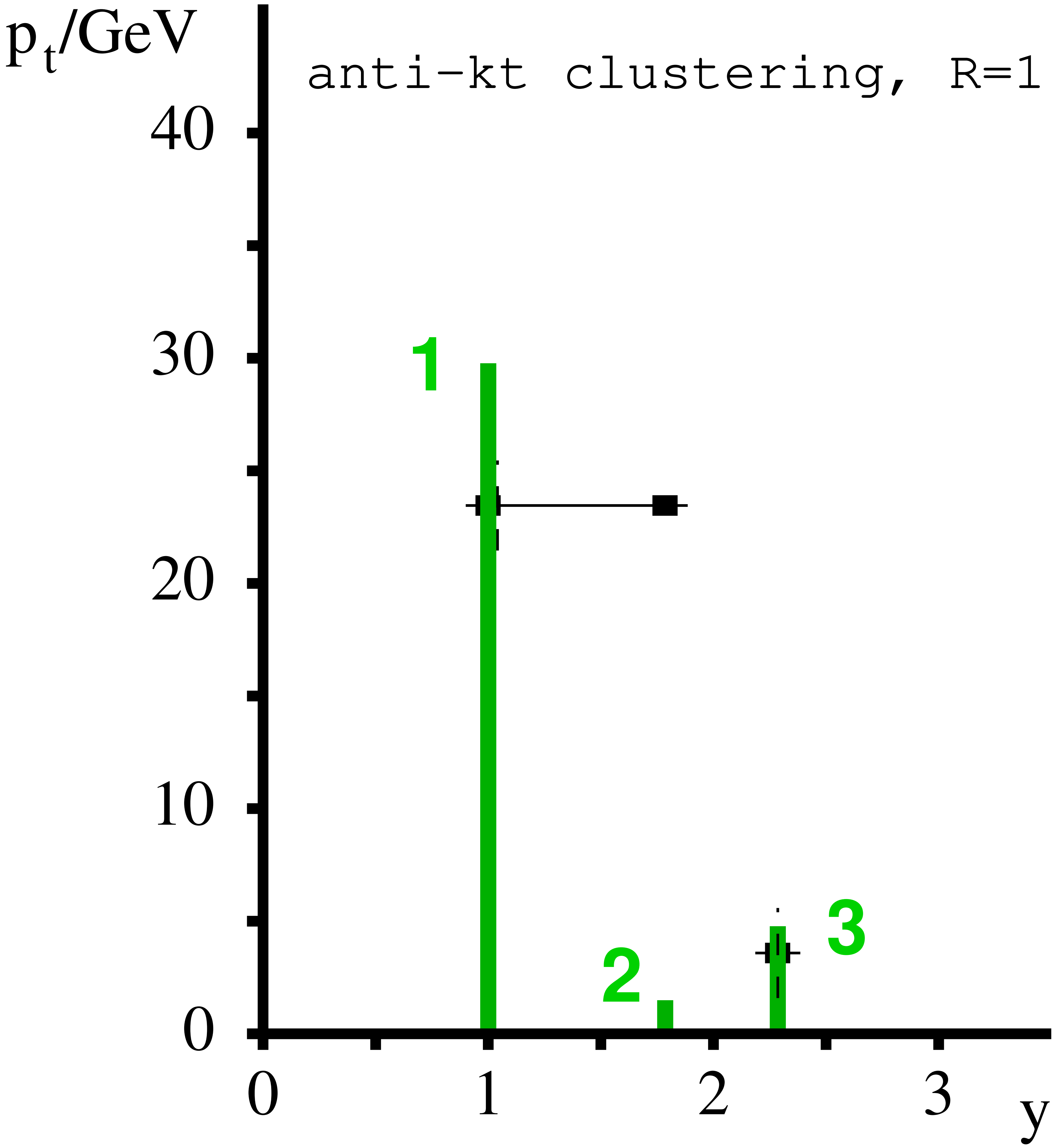
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

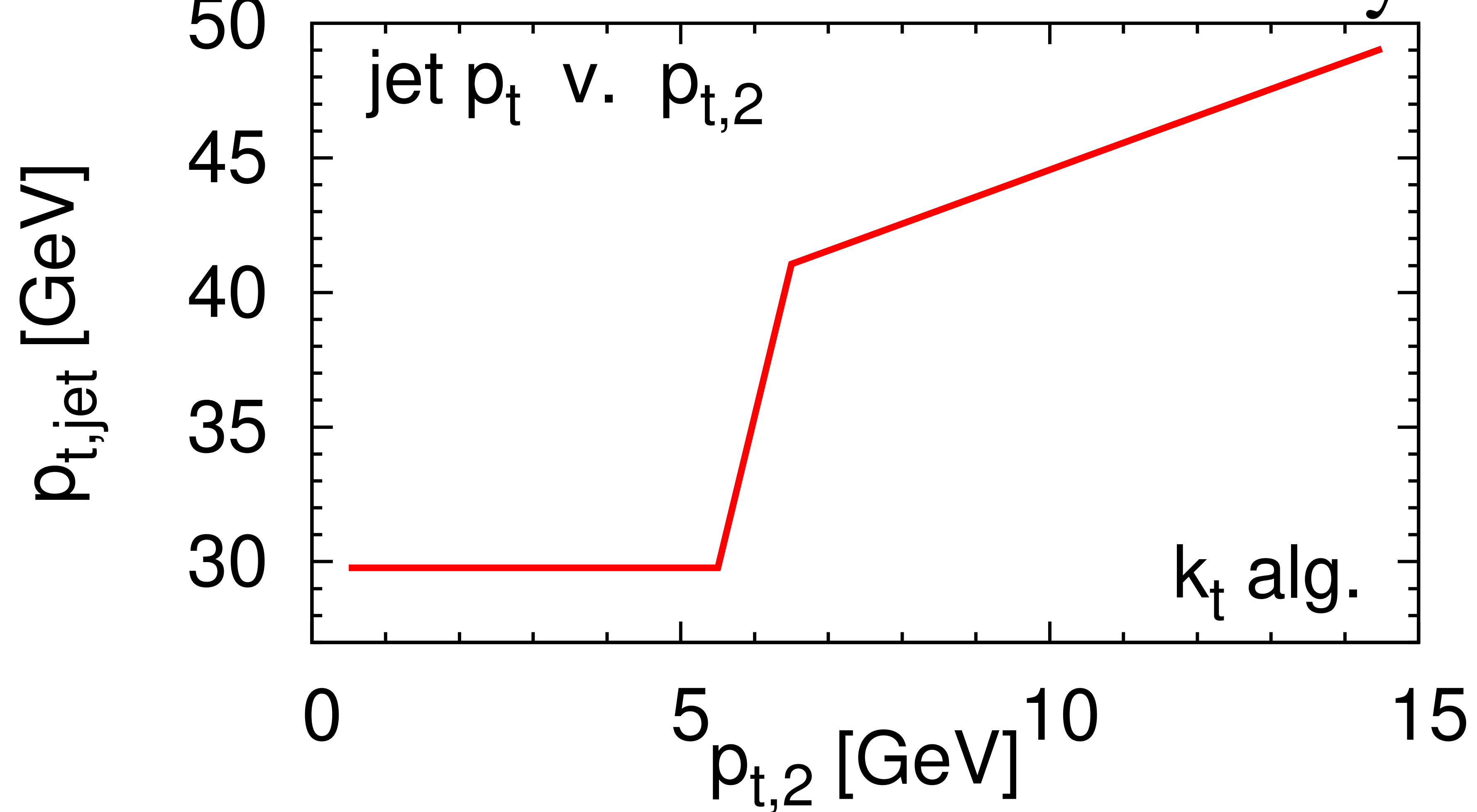


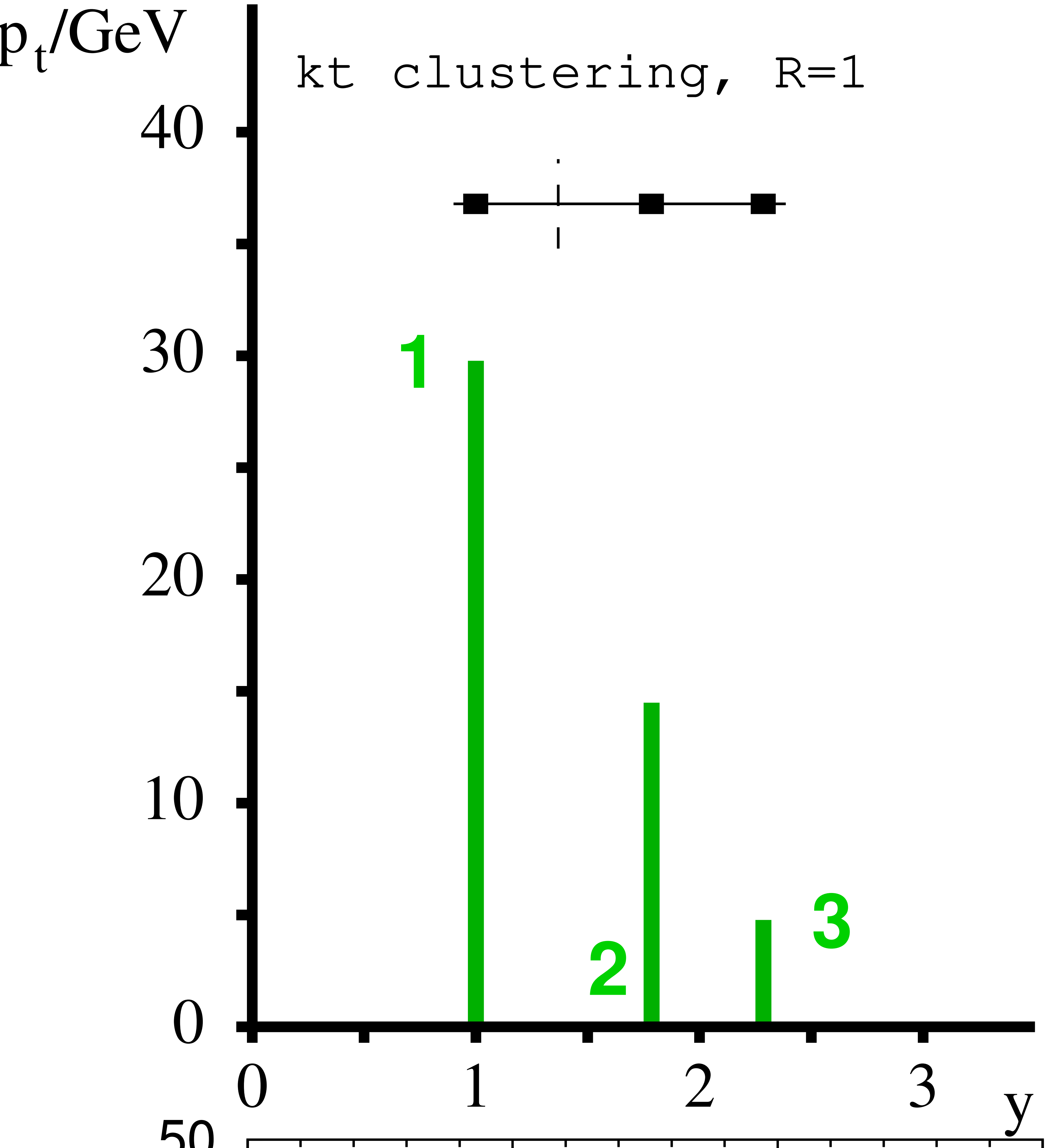
kt clustering, R=1
p_t/GeV
1
2
3
y
jet p_t v. $p_{t,2}$
k_t alg.
$p_{t,jet}$ [GeV]
$p_{t,2}$ [GeV]


kt clustering, R=1
anti-kt clustering, R=1
p_t/GeV
y
1
2
3
jet p_t v. p_t,2
p_t,jet [GeV]
p_t,2 [GeV]
k_t alg.

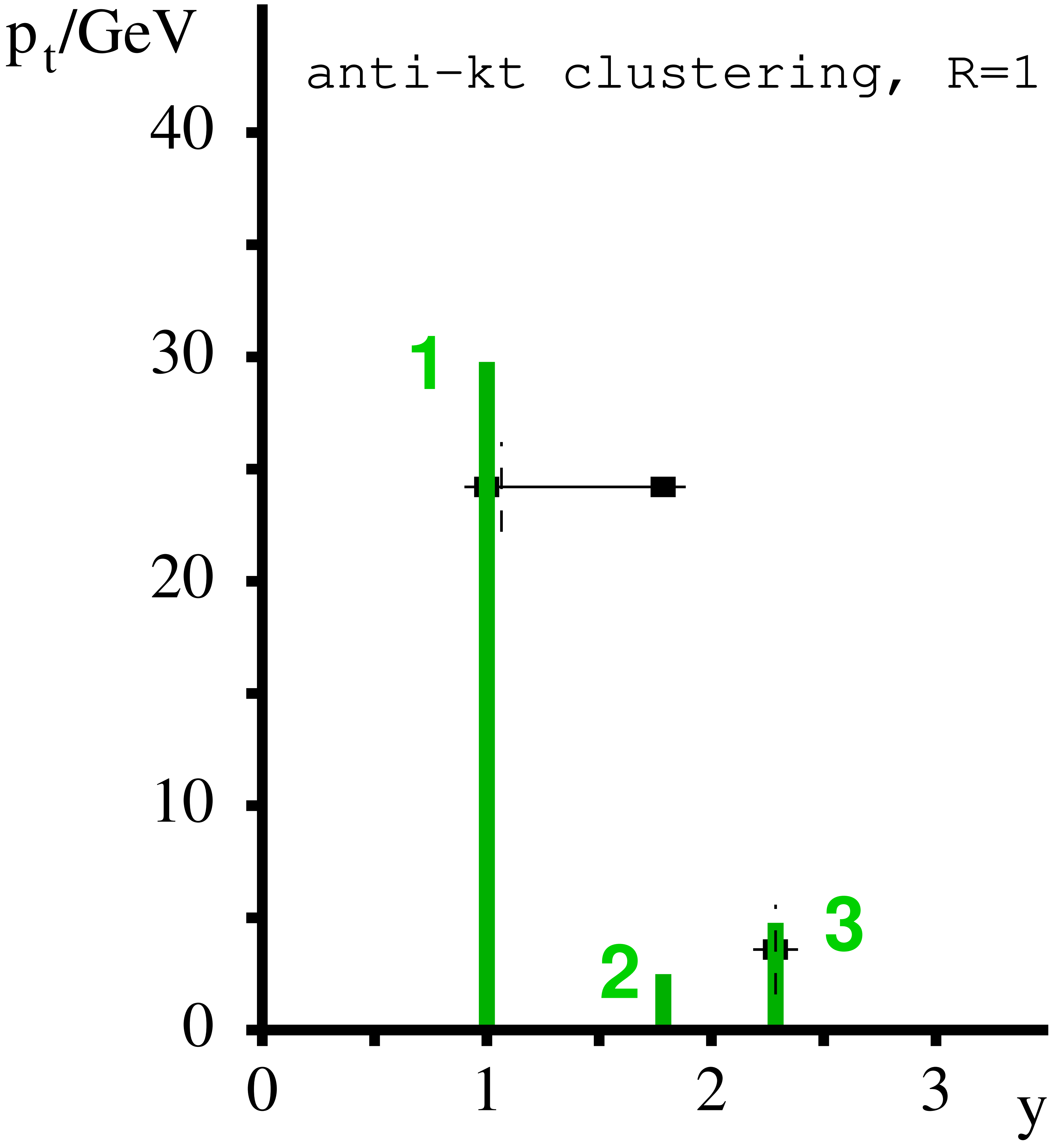

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y


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

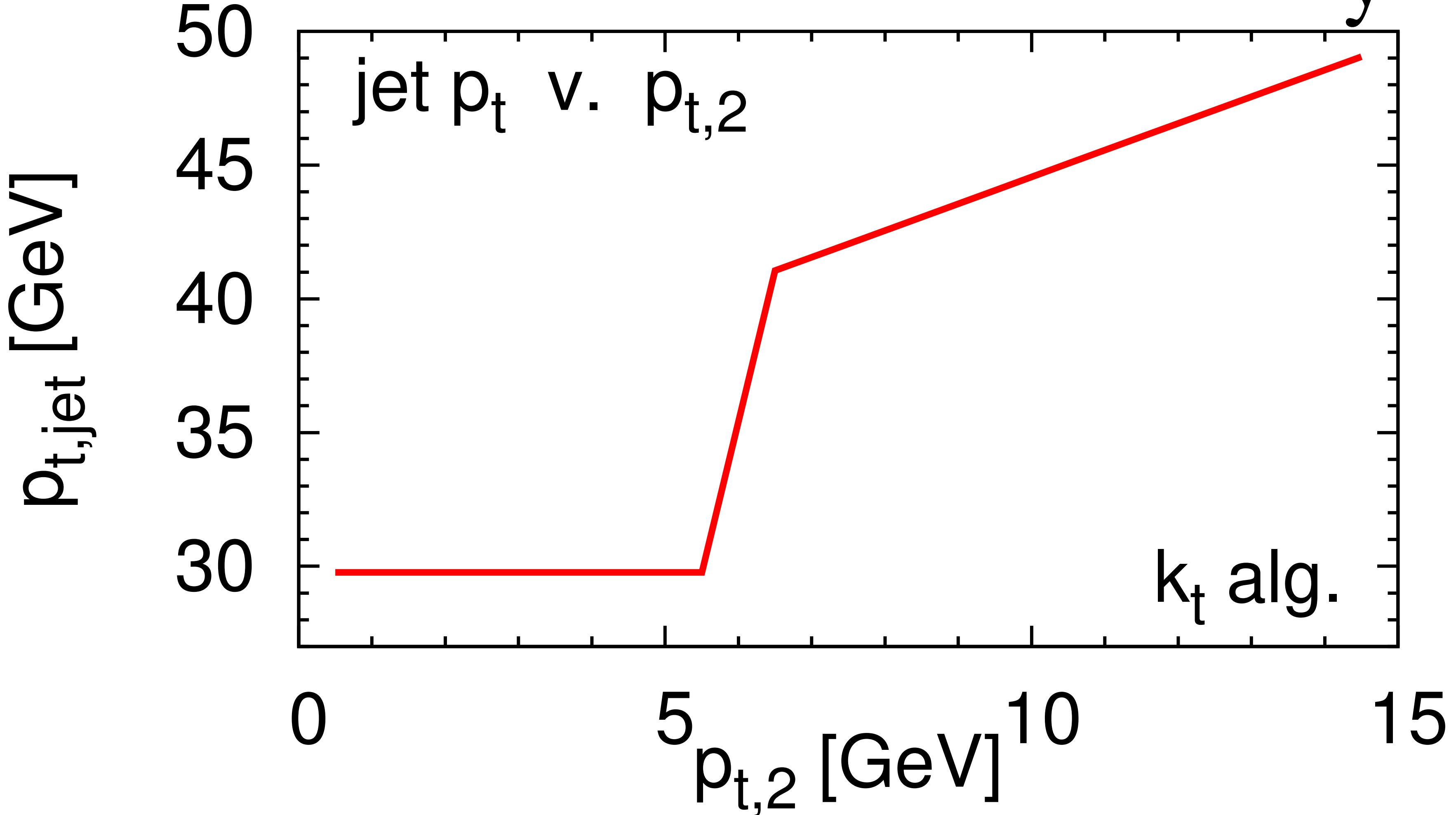

jet p_t v. p_t,2
k_t alg.
p_t,jet [GeV]
50
45
40
35
30
0
5
10
15
p_t,2 [GeV]



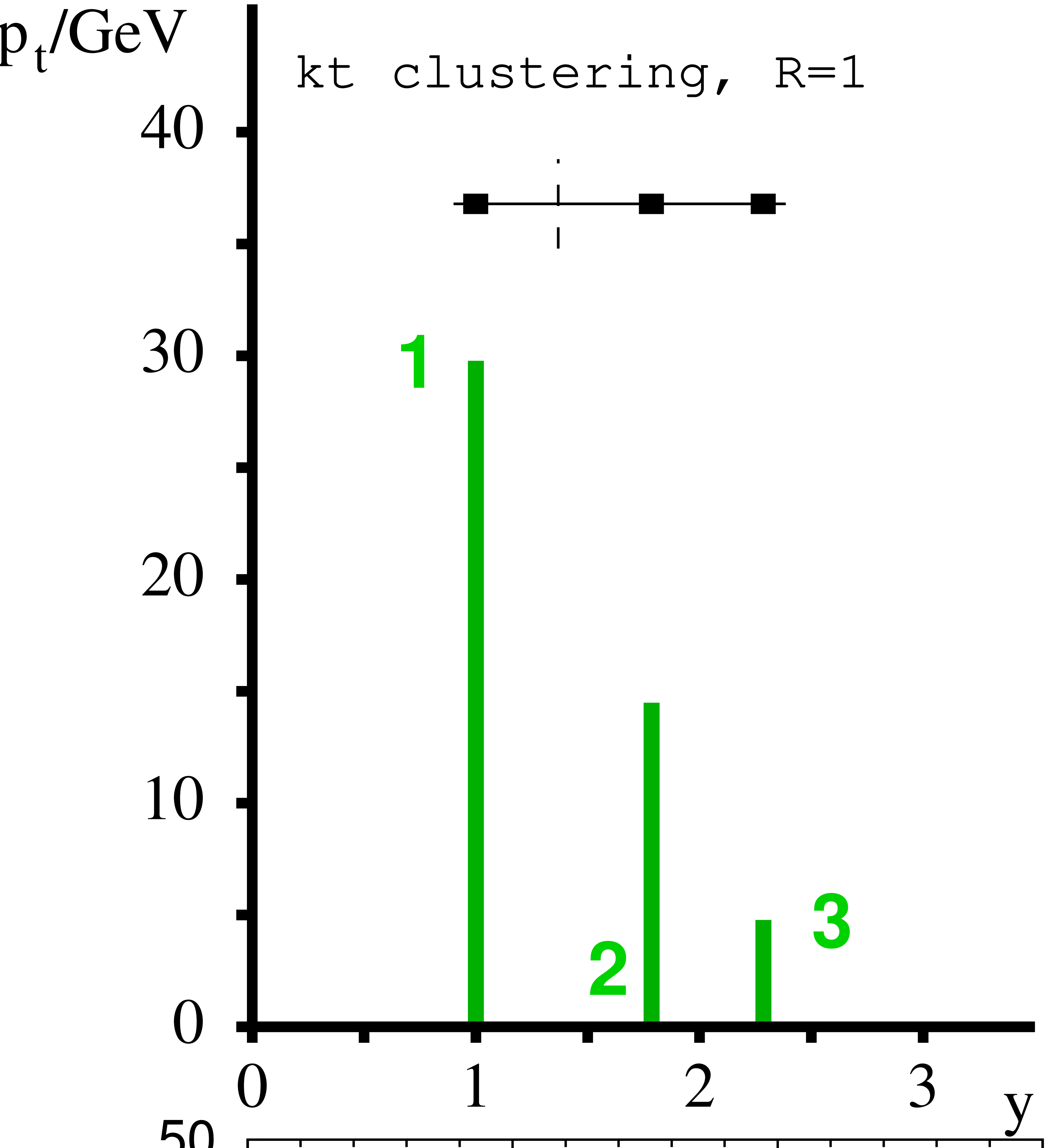
kt clustering, R=1
p_t/GeV
y
1
2
3



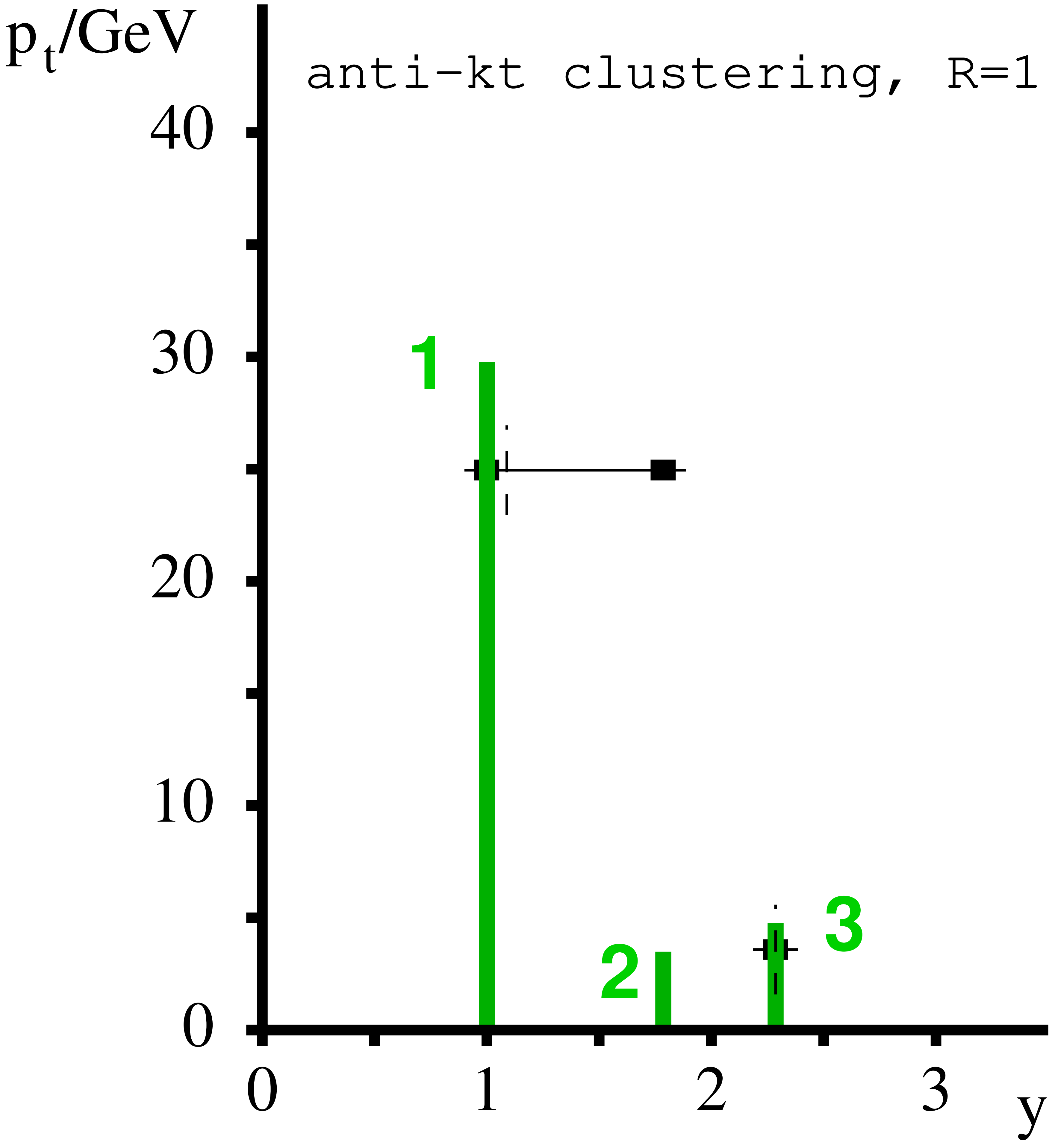
anti-kt clustering, R=1
p_t/GeV
y
1
2
3



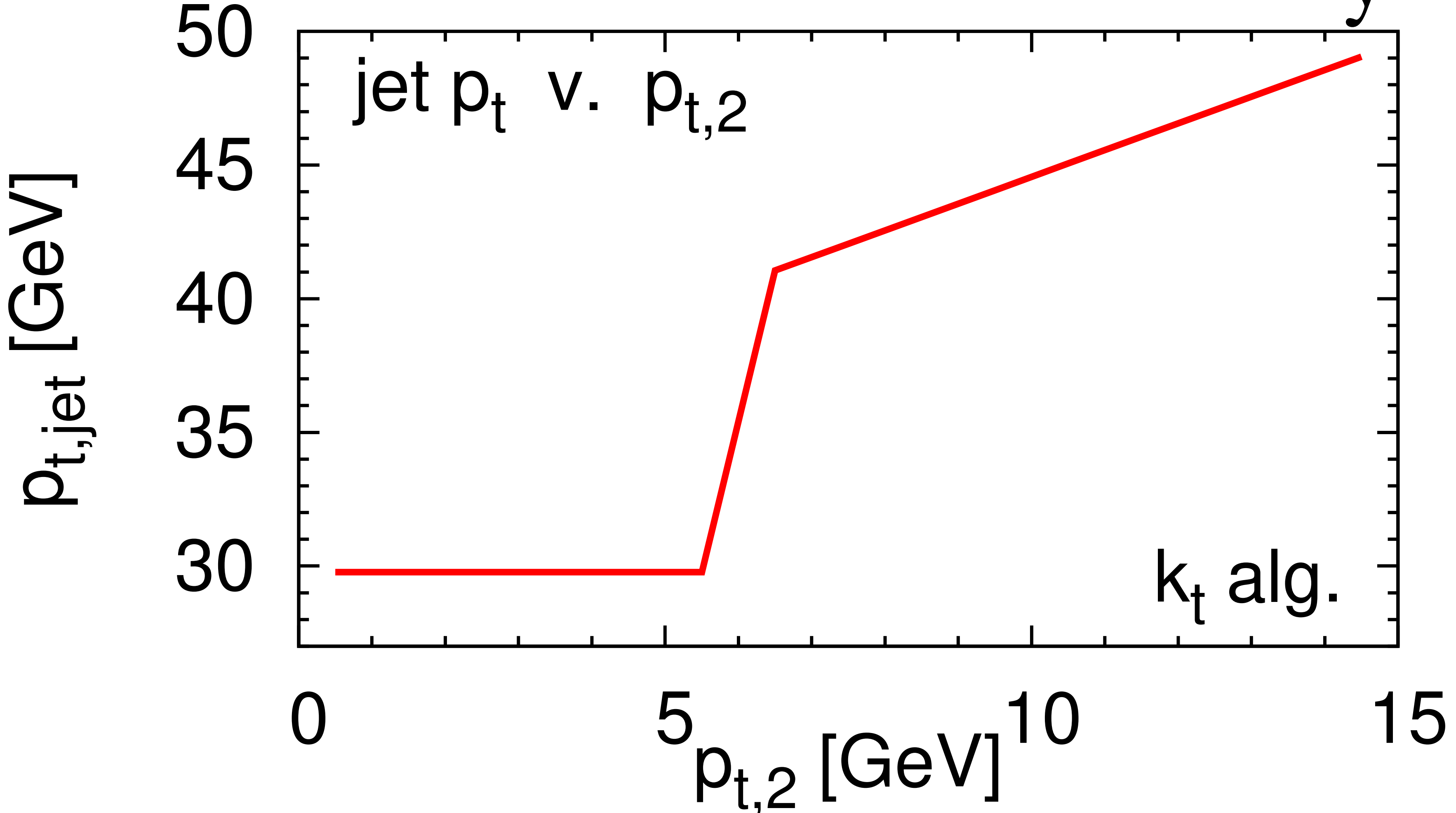
jet p_t v. p_t,2
p_t,jet [GeV]
p_t,2 [GeV]
k_t alg.



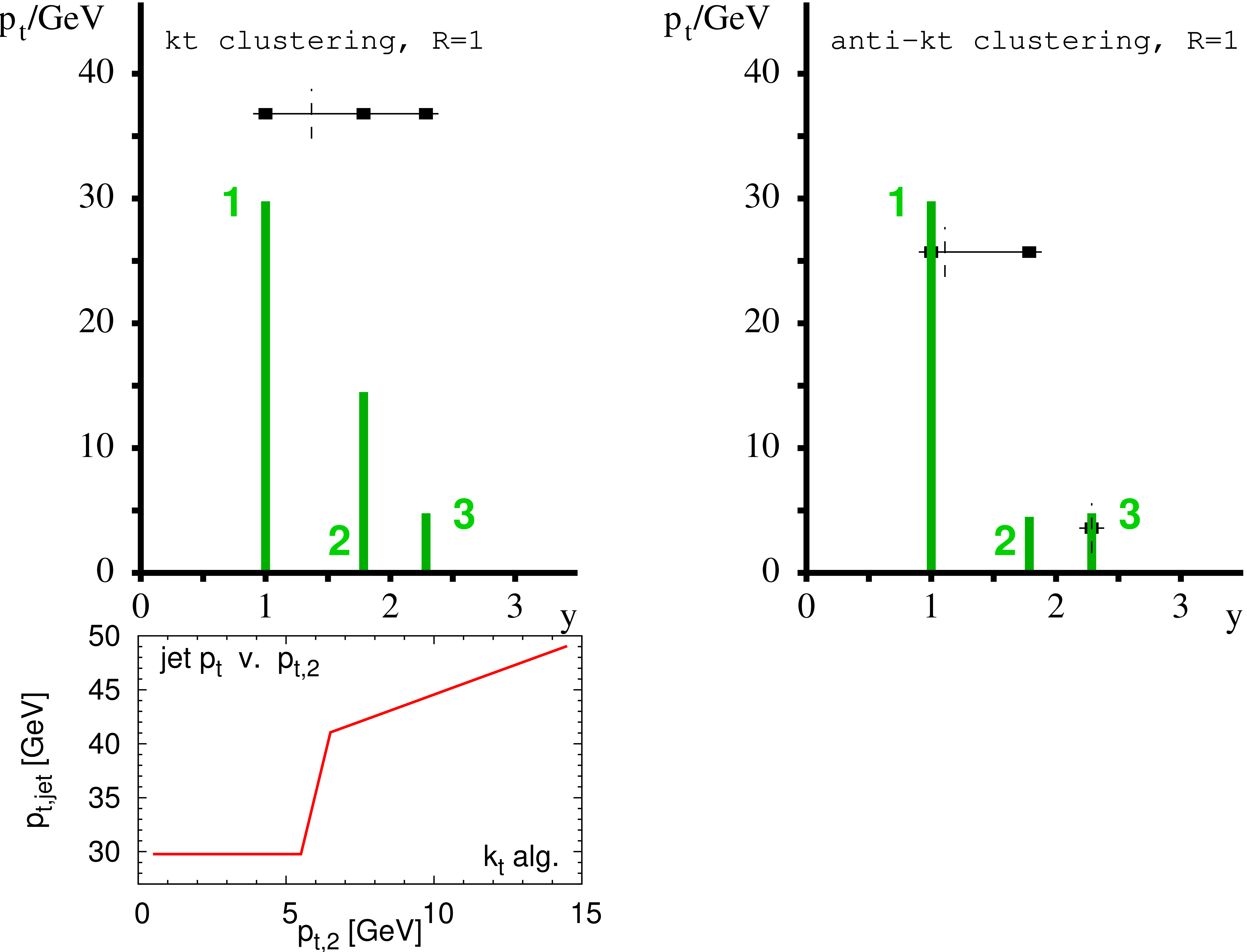
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



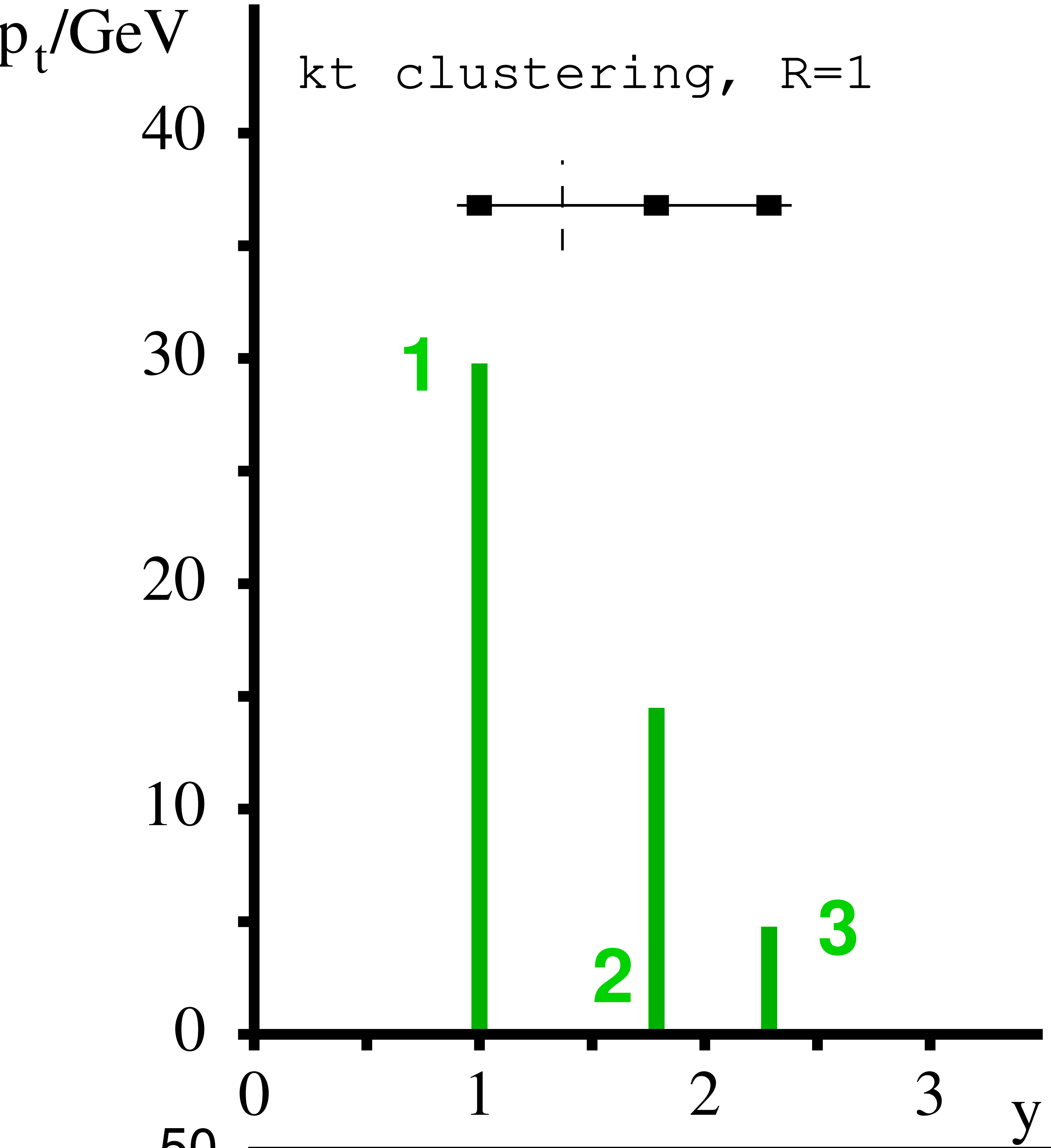
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



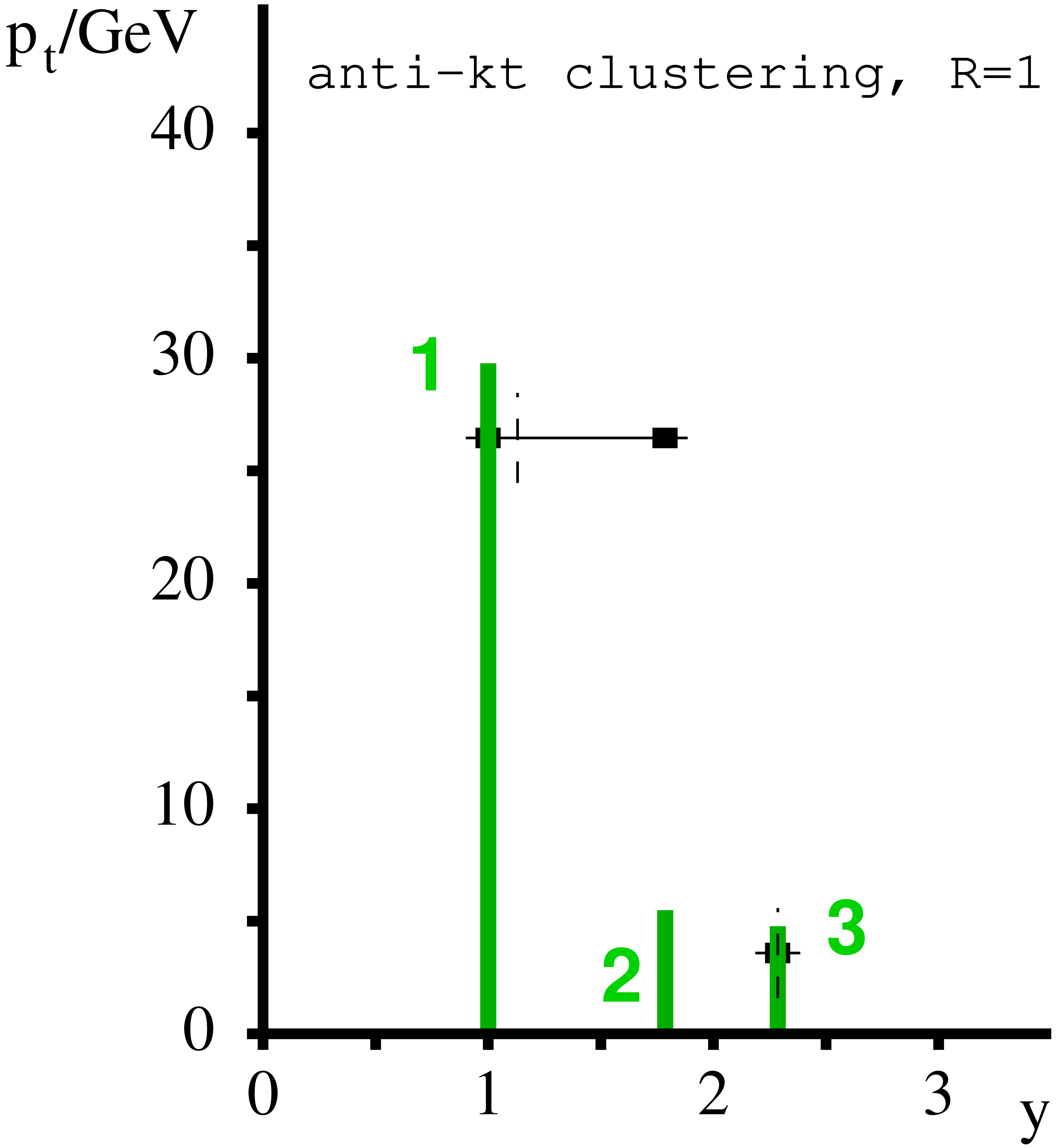
jet p_t v. p_t,2
p_t,jet [GeV]
50
45
40
35
30
k_t alg.
0
5
10
15
p_t,2 [GeV]



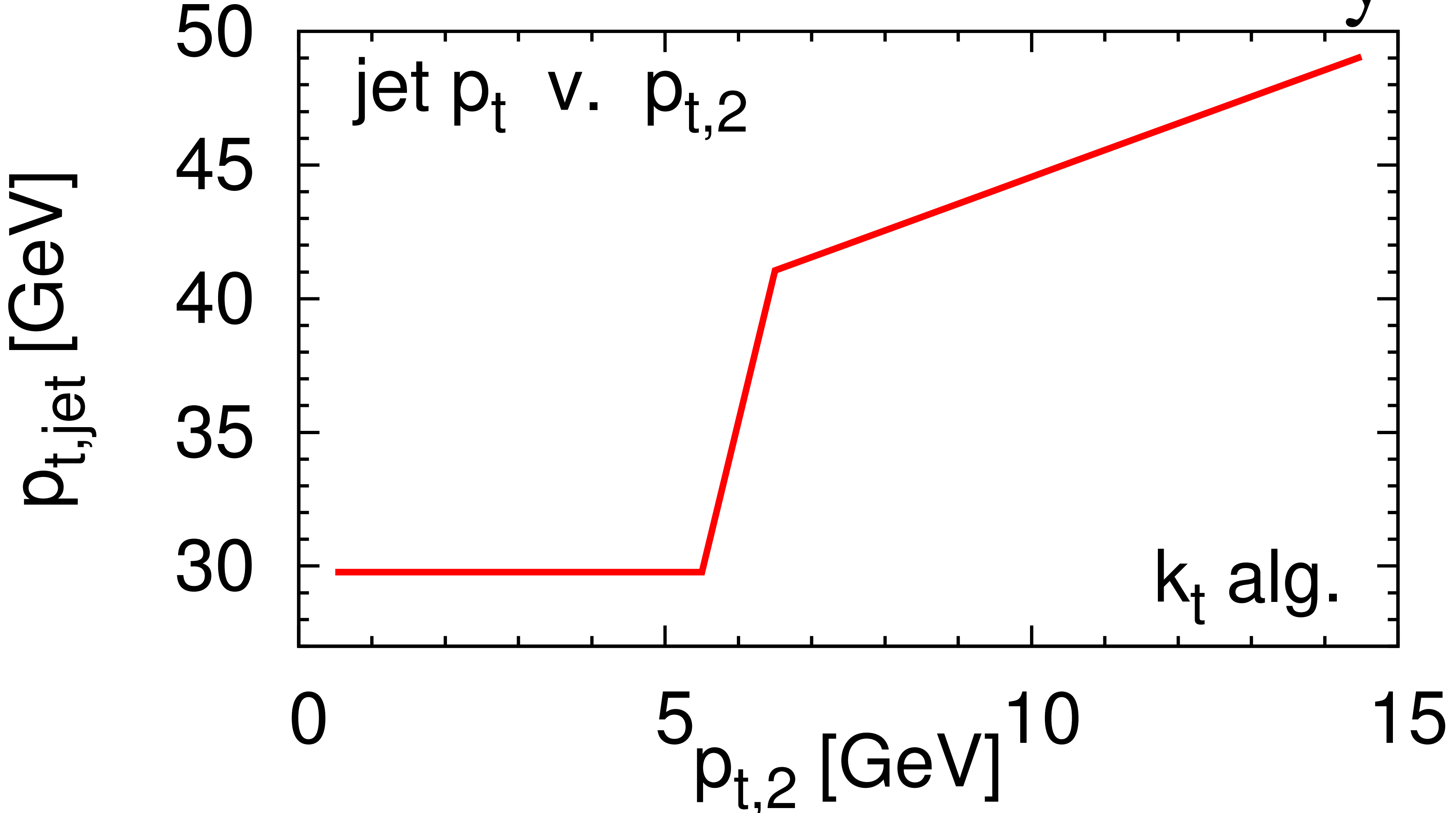
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
jet p_t v. p_t,2
p_t,jet [GeV]
50
45
40
35
30
k_t alg.
0
5
10
15
p_t,2 [GeV]



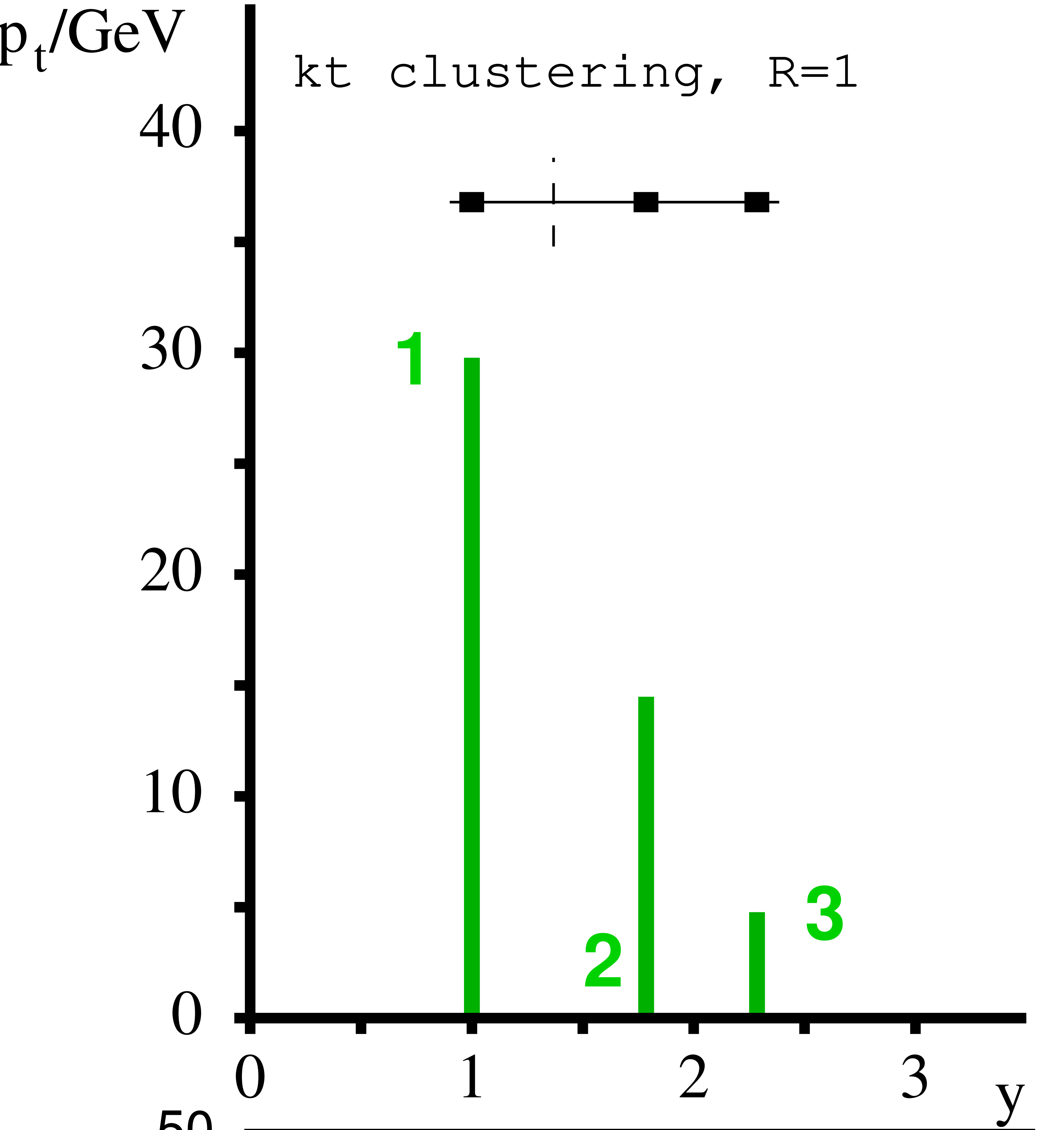
p_t/GeV
kt clustering, R=1
40
30
20
10
0
0
1
2
3
y
1
2
3

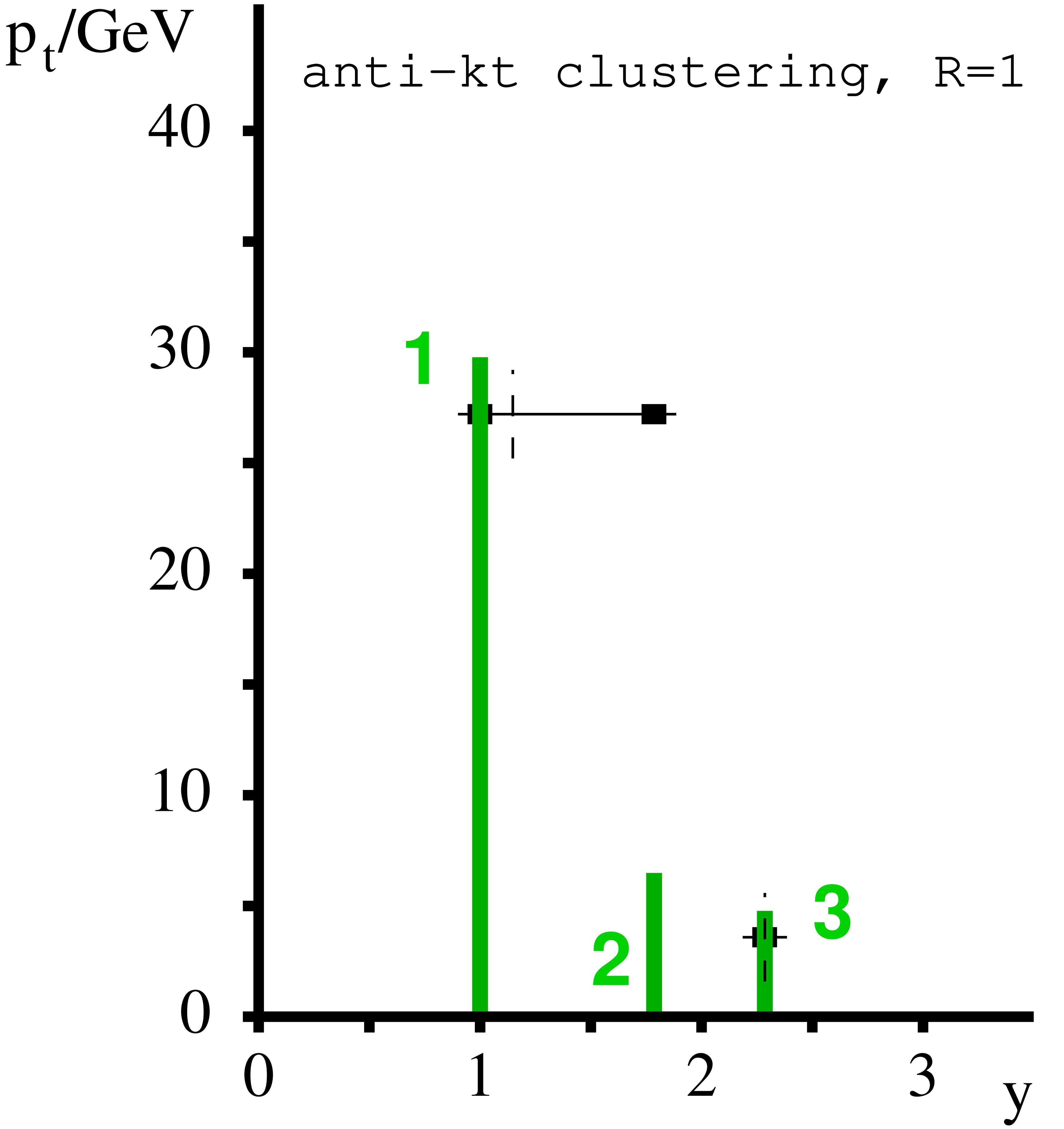


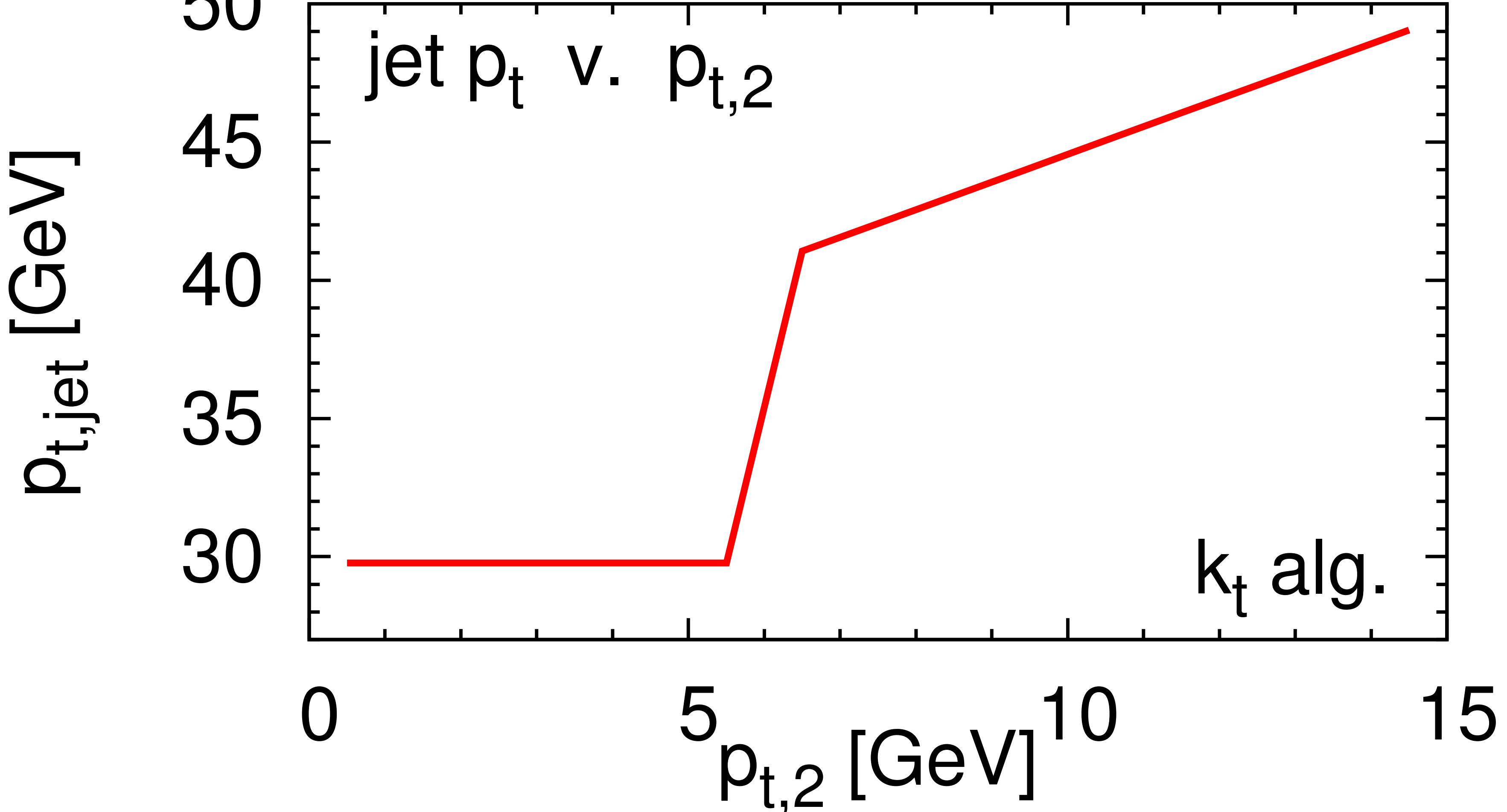
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
0
1
2
3
y
1
2
3

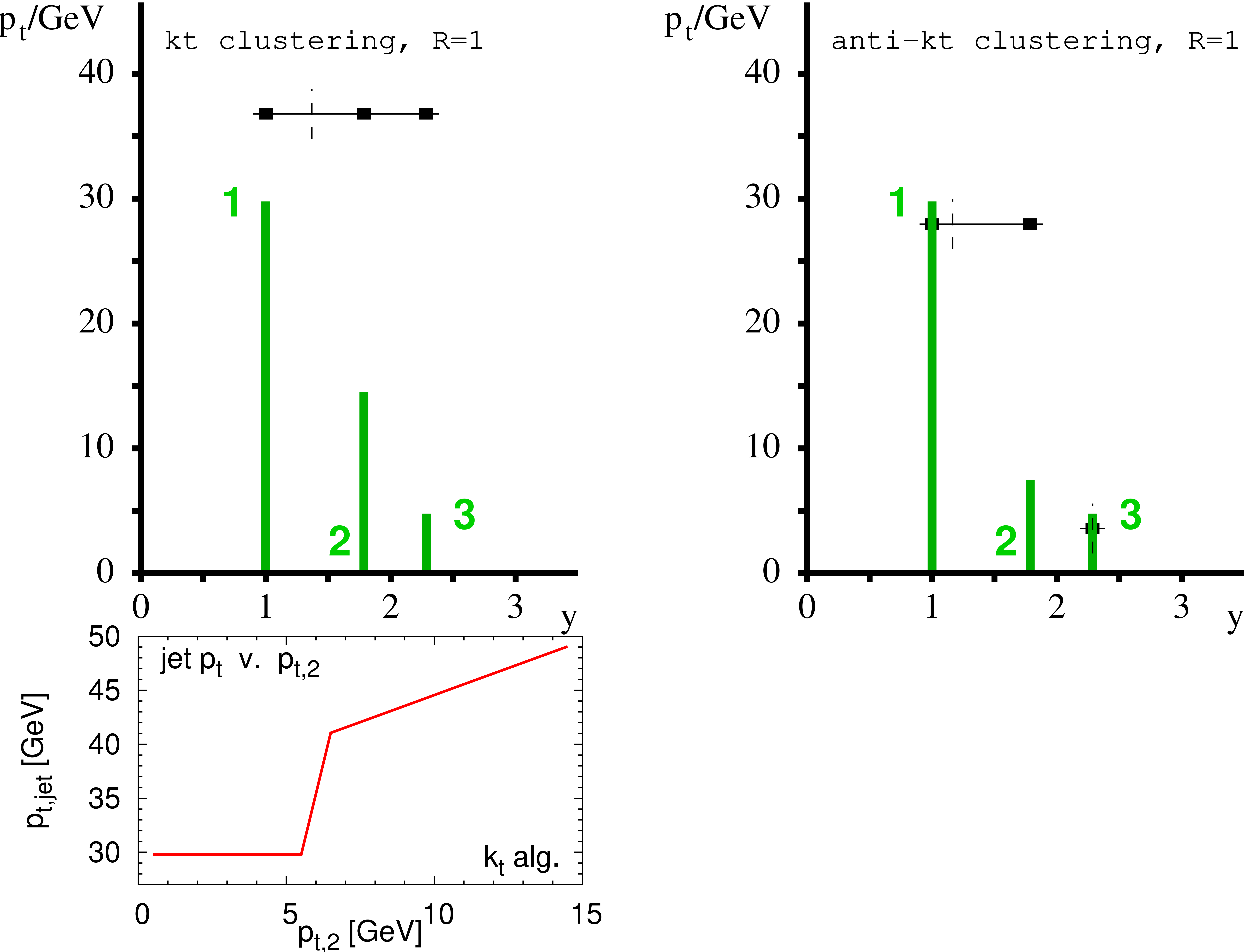


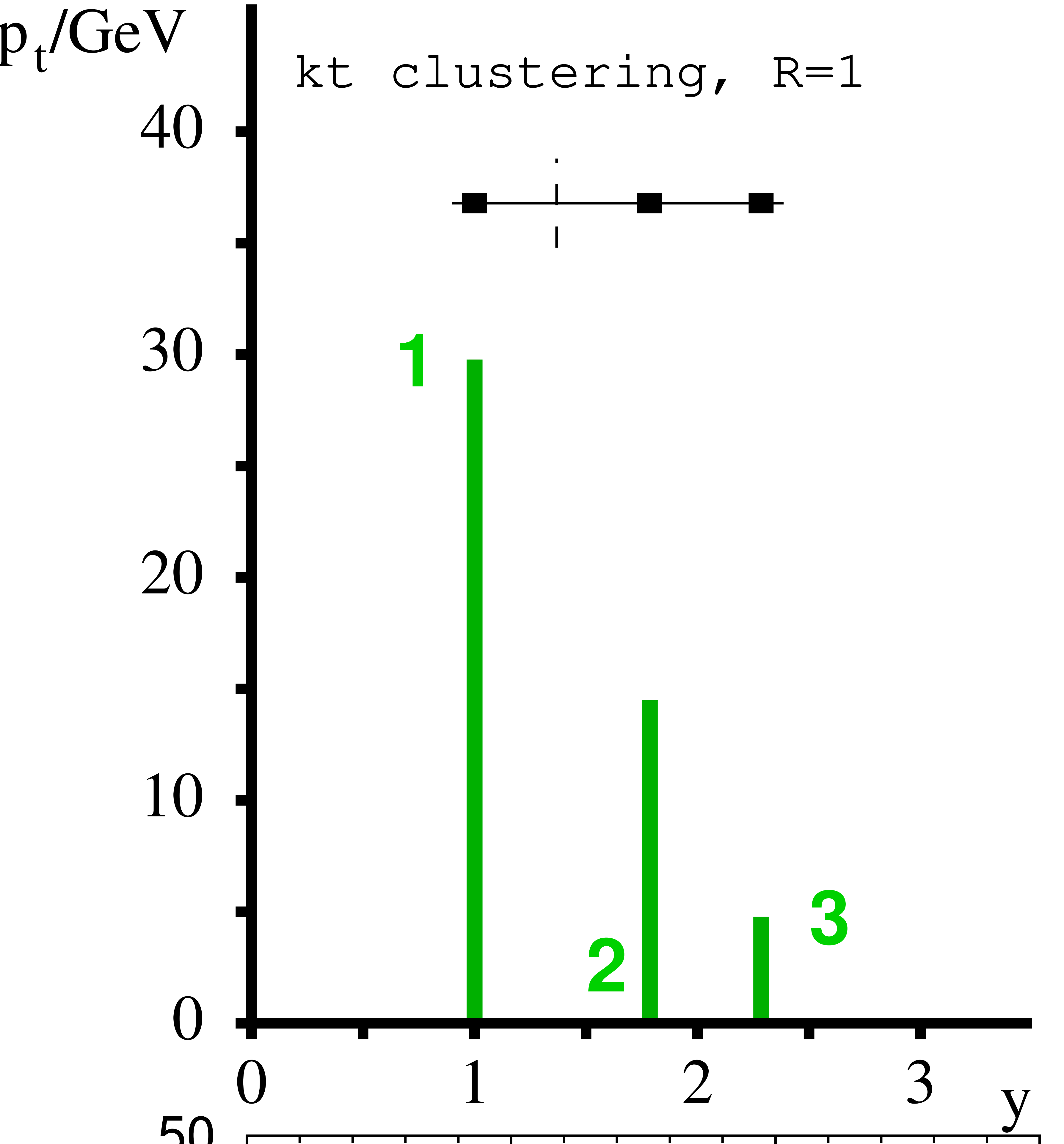
jet p_t v. p_t,2
p_t,jet [GeV]
50
45
40
35
30
k_t alg.
0
5
10
15
p_t,2 [GeV]


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

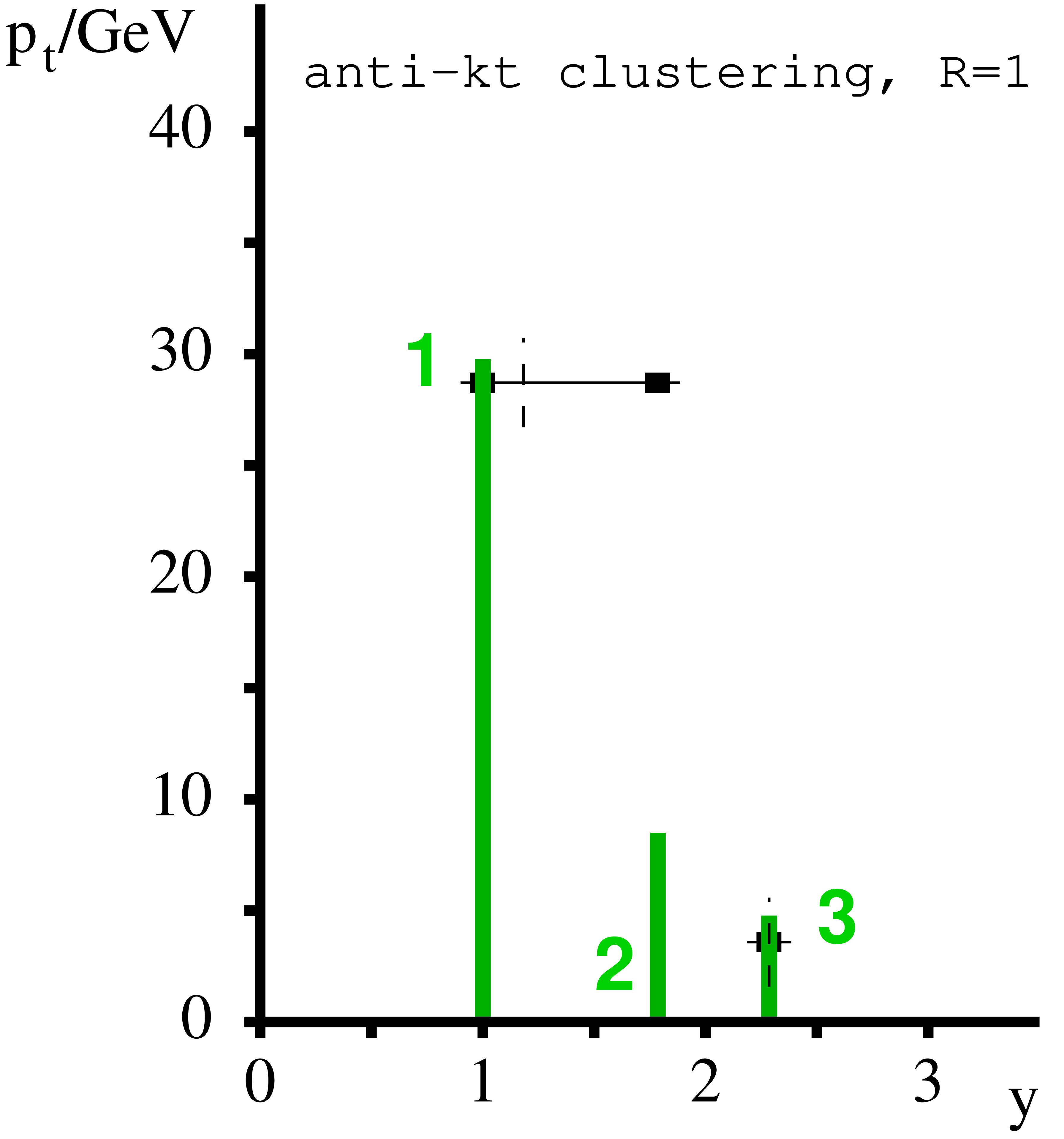

p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y


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

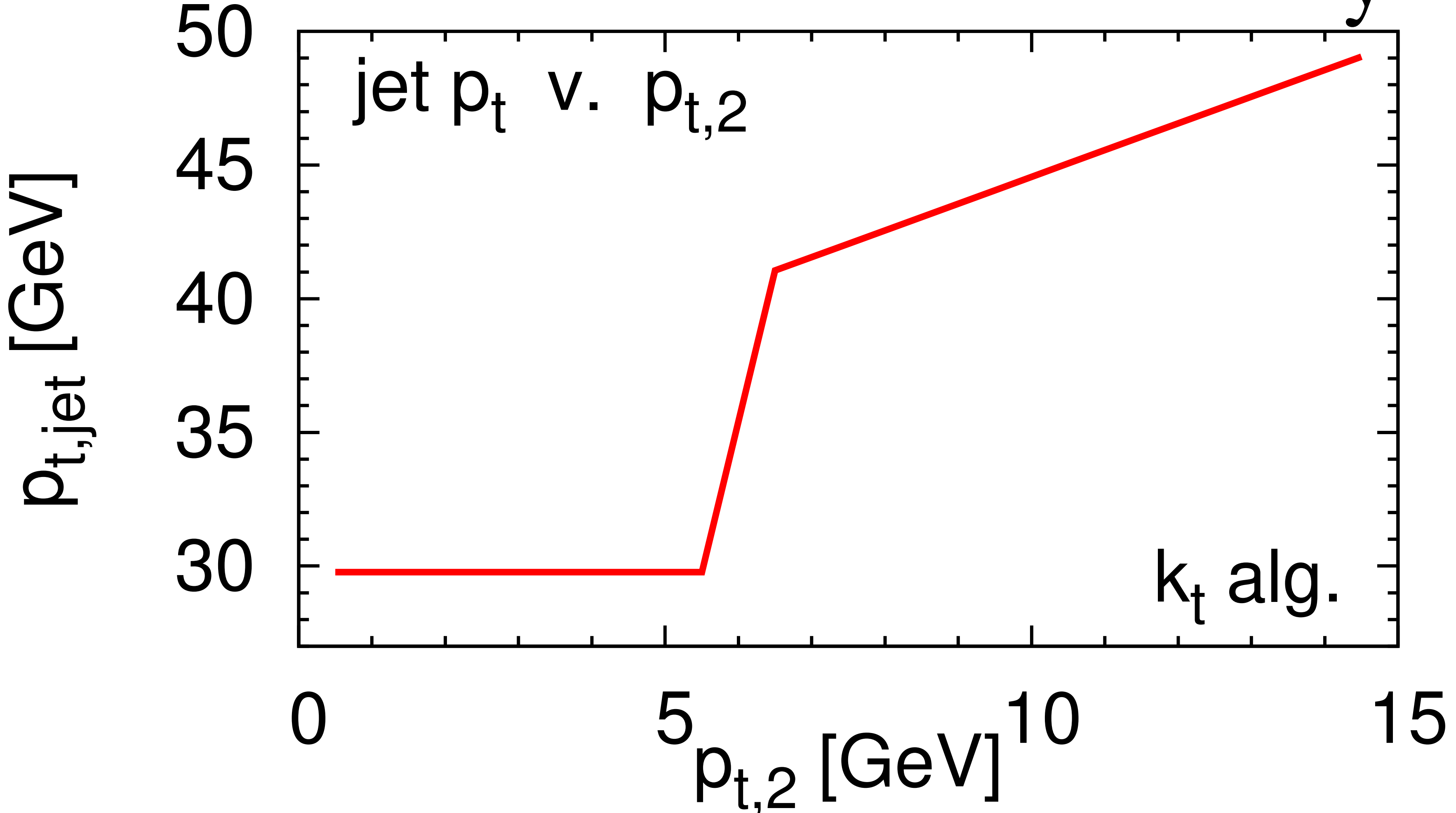

kt clustering, R=1
anti-kt clustering, R=1
pt/GeV
y
1
2
3
jet pt v. pt,2
pt,jet [GeV]
pt,2 [GeV]
kt alg.



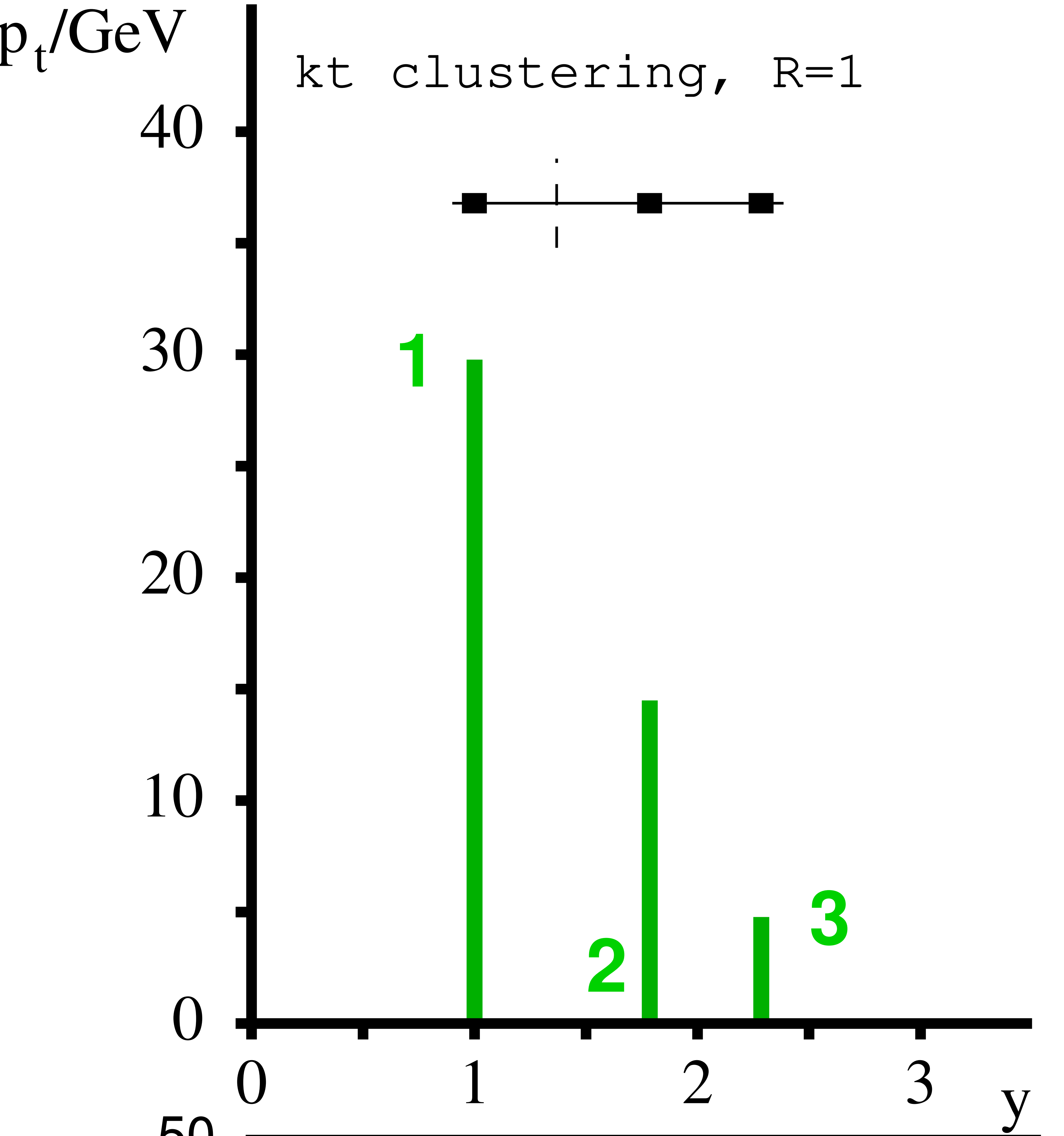
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

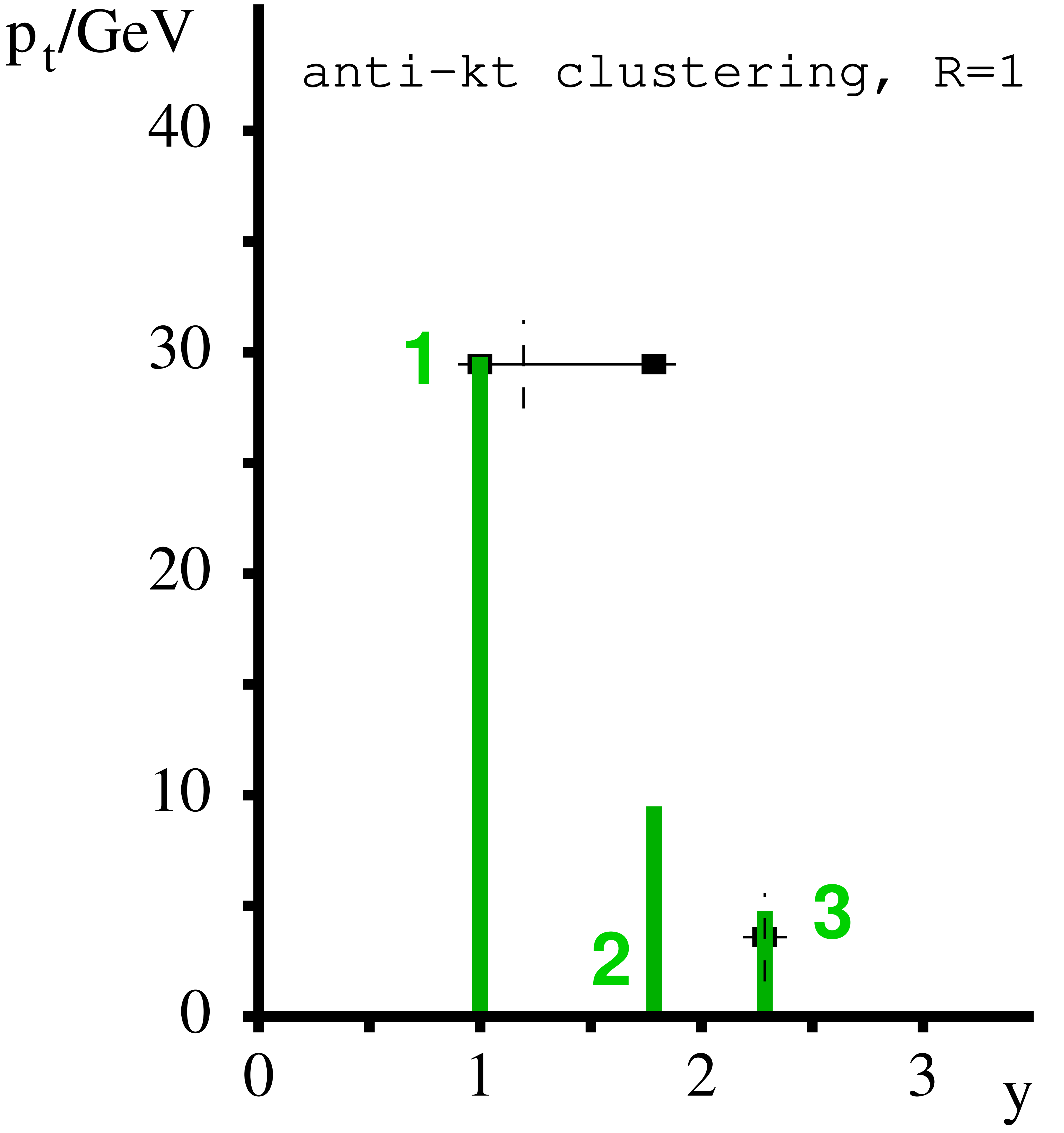


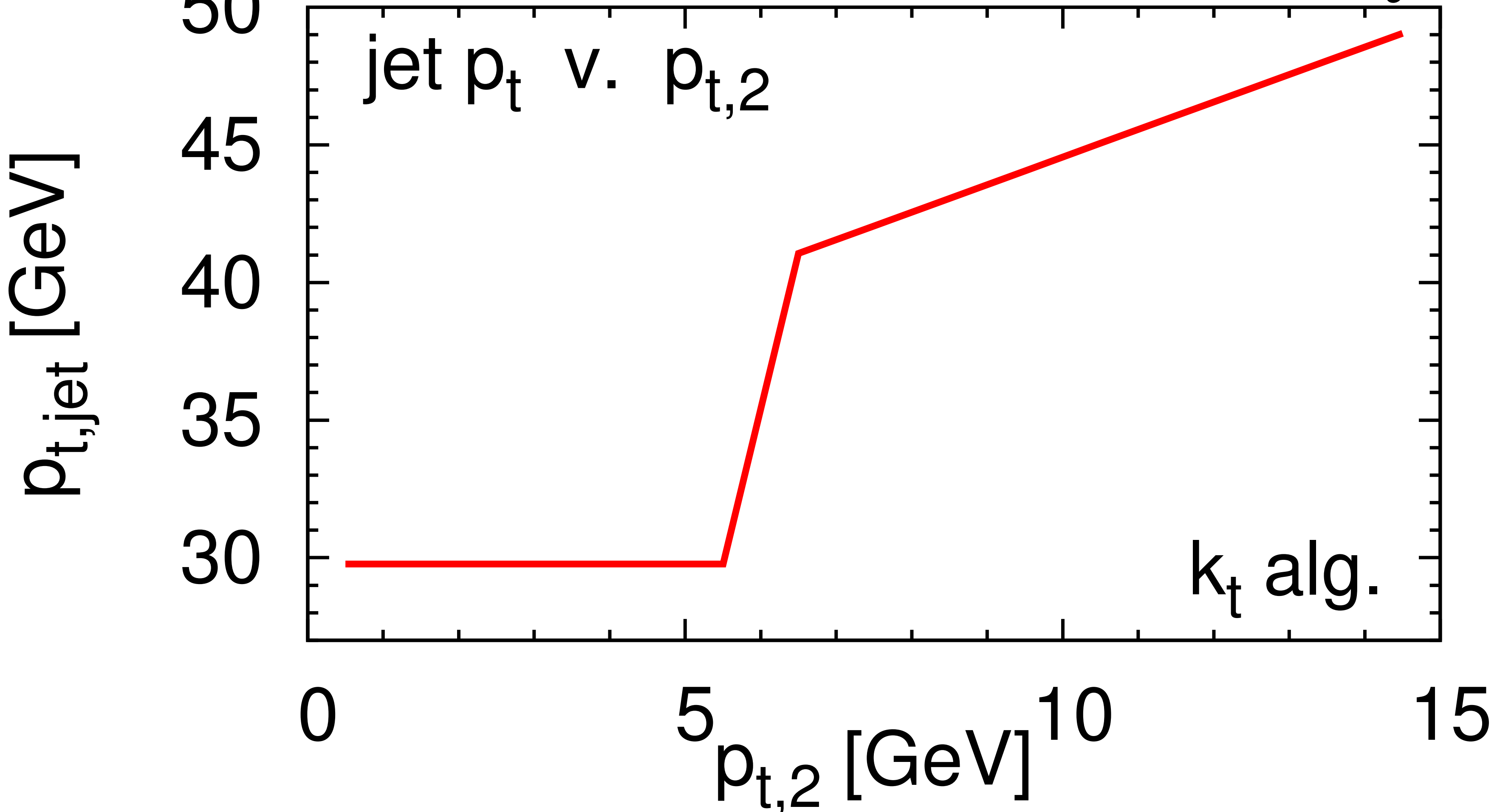
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

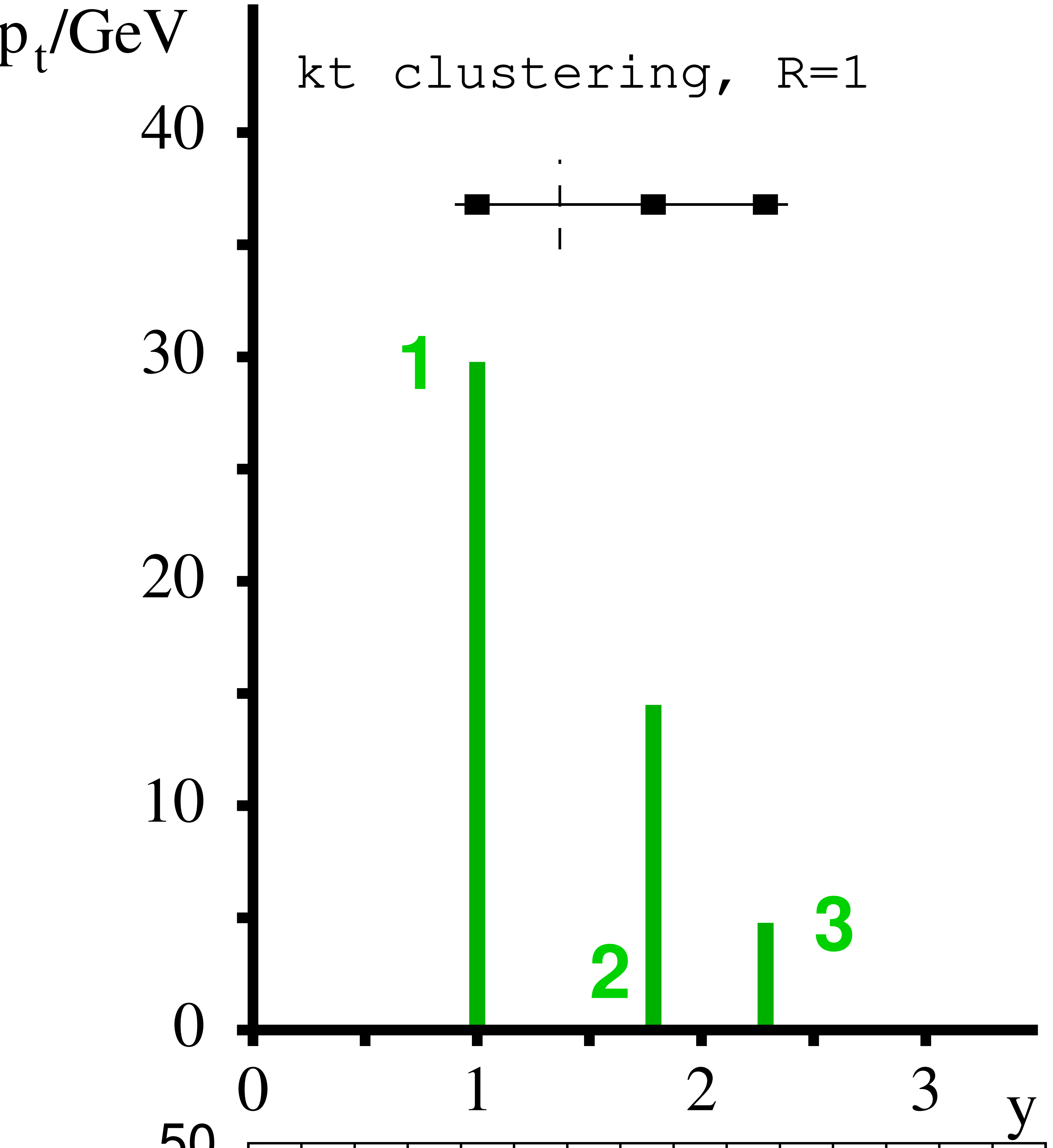


jet p_t v. p_t,2
p_t,jet [GeV]
k_t alg.
50
45
40
35
30
0
5
10
15
p_t,2 [GeV]

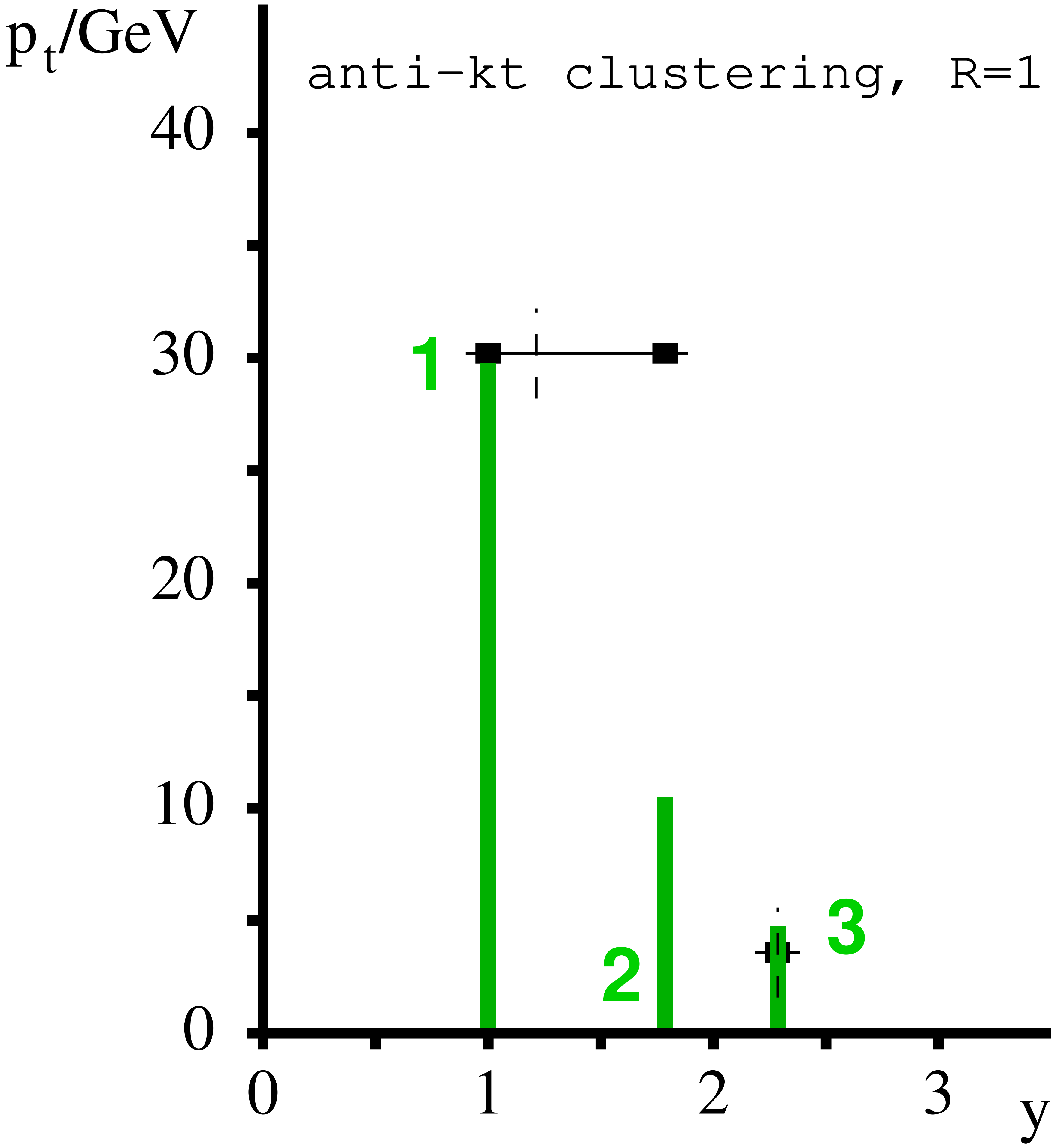

pt/GeV
kt clustering, R=1
1
2
3
y


pt/GeV
anti-kt clustering, R=1
1
2
3
y

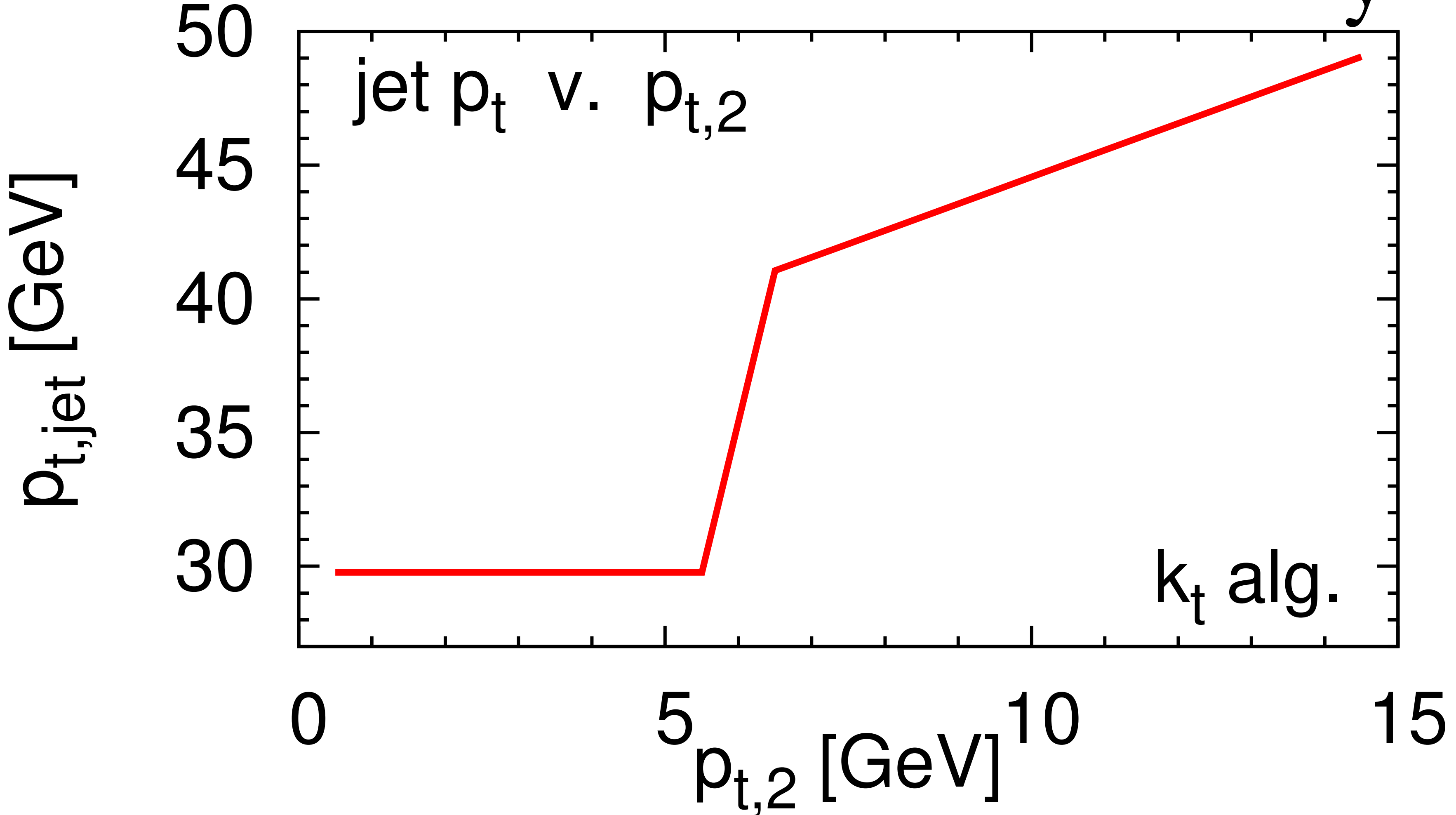

jet pt v. pt,2
pt,jet [GeV]
kt alg.
pt,2 [GeV]



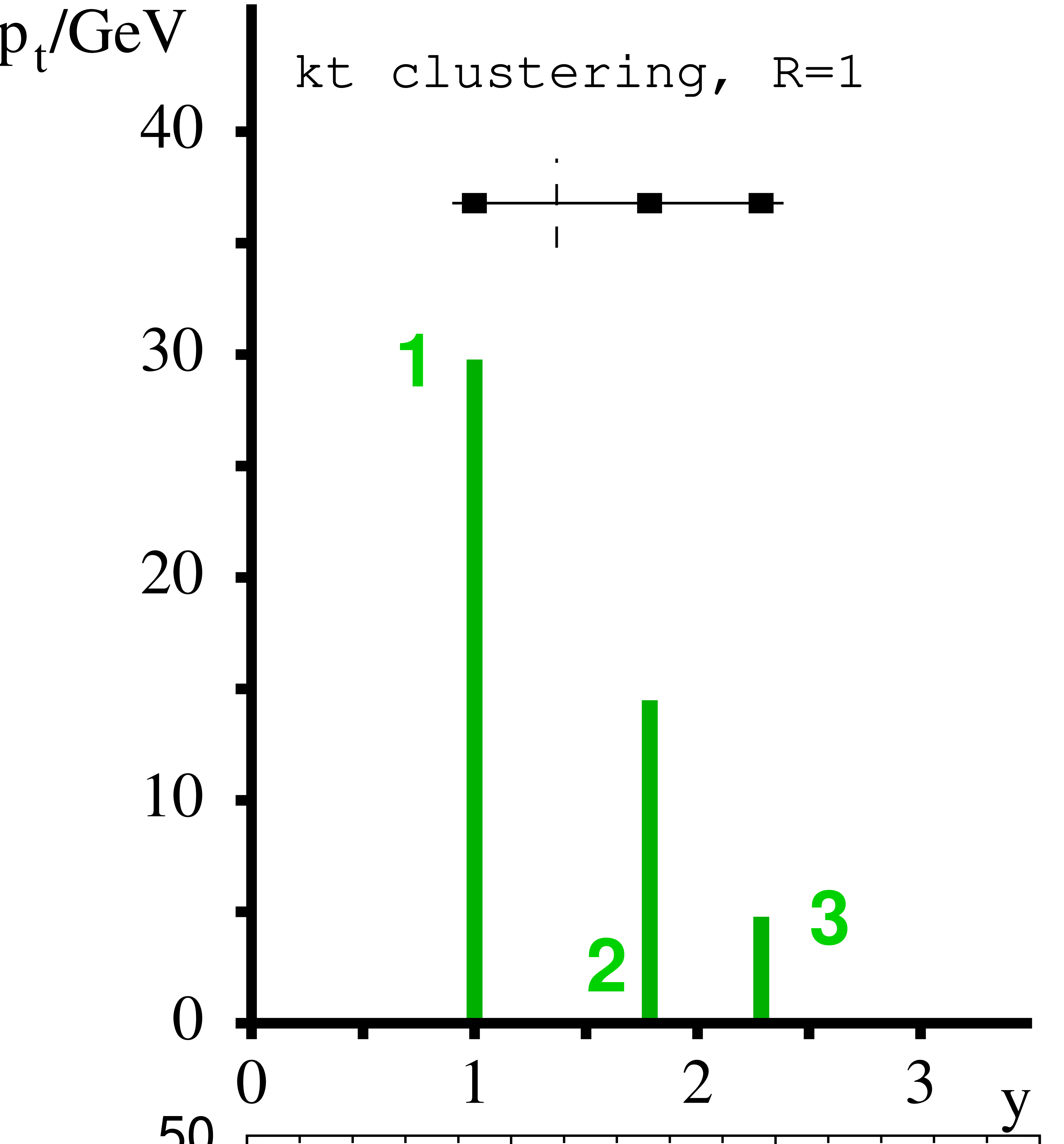
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



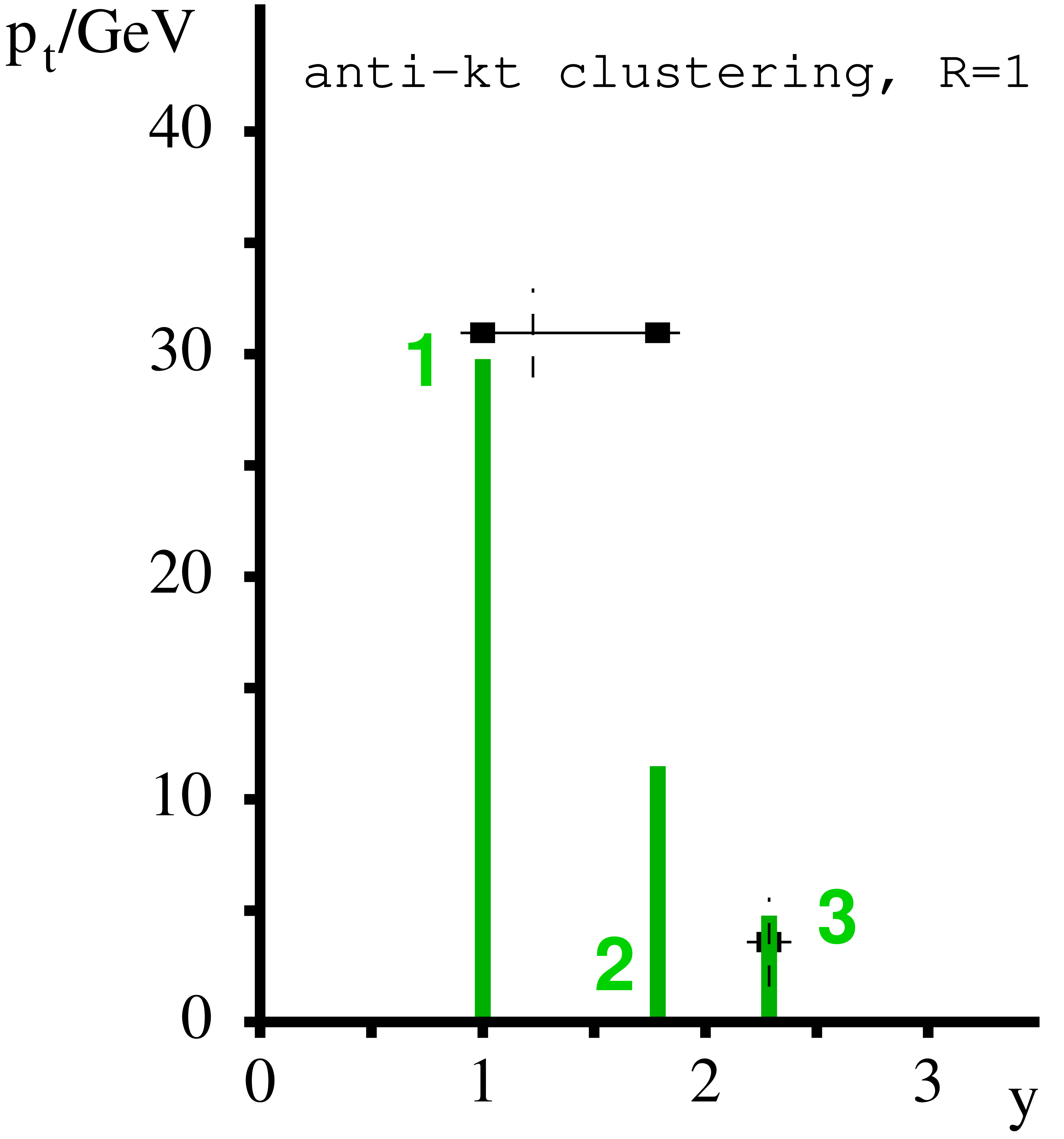
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



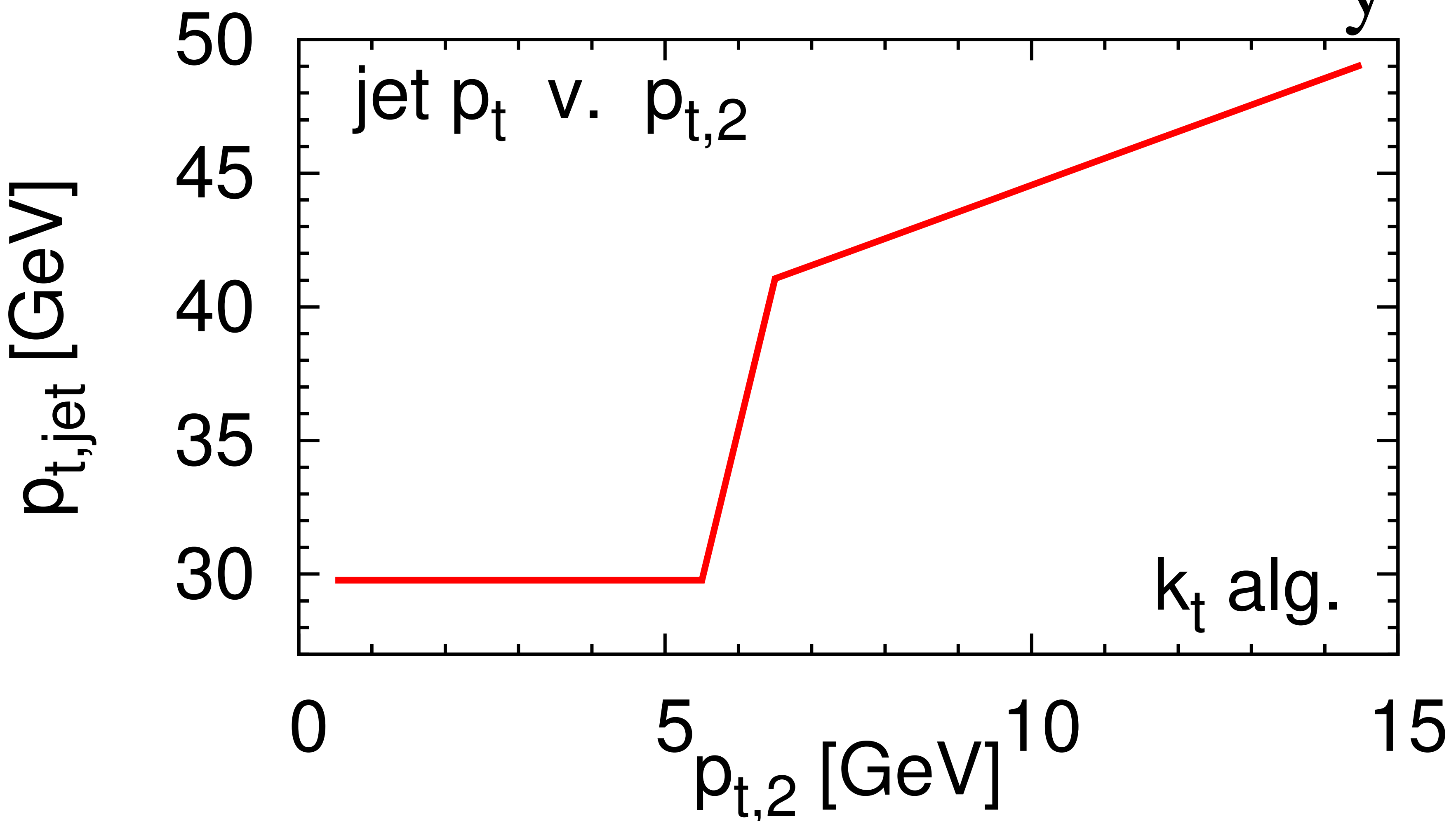
jet p_t v. $p_{t,2}$
k_t alg.
$p_{t,jet}$ [GeV]
50
45
40
35
30
0
5
10
15
$p_{t,2}$ [GeV]



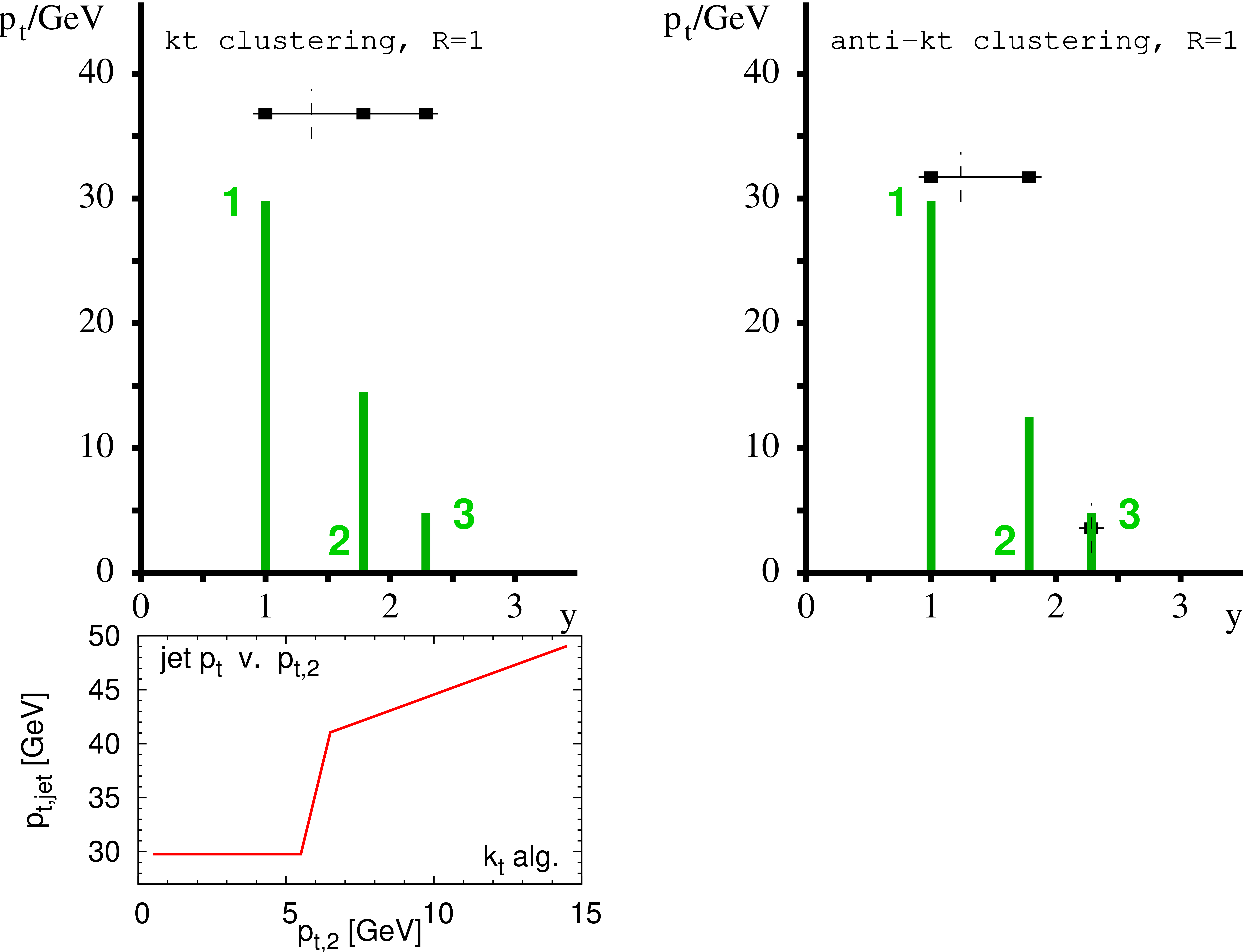
p_t/GeV
kt clustering, R=1
1
2
3
y

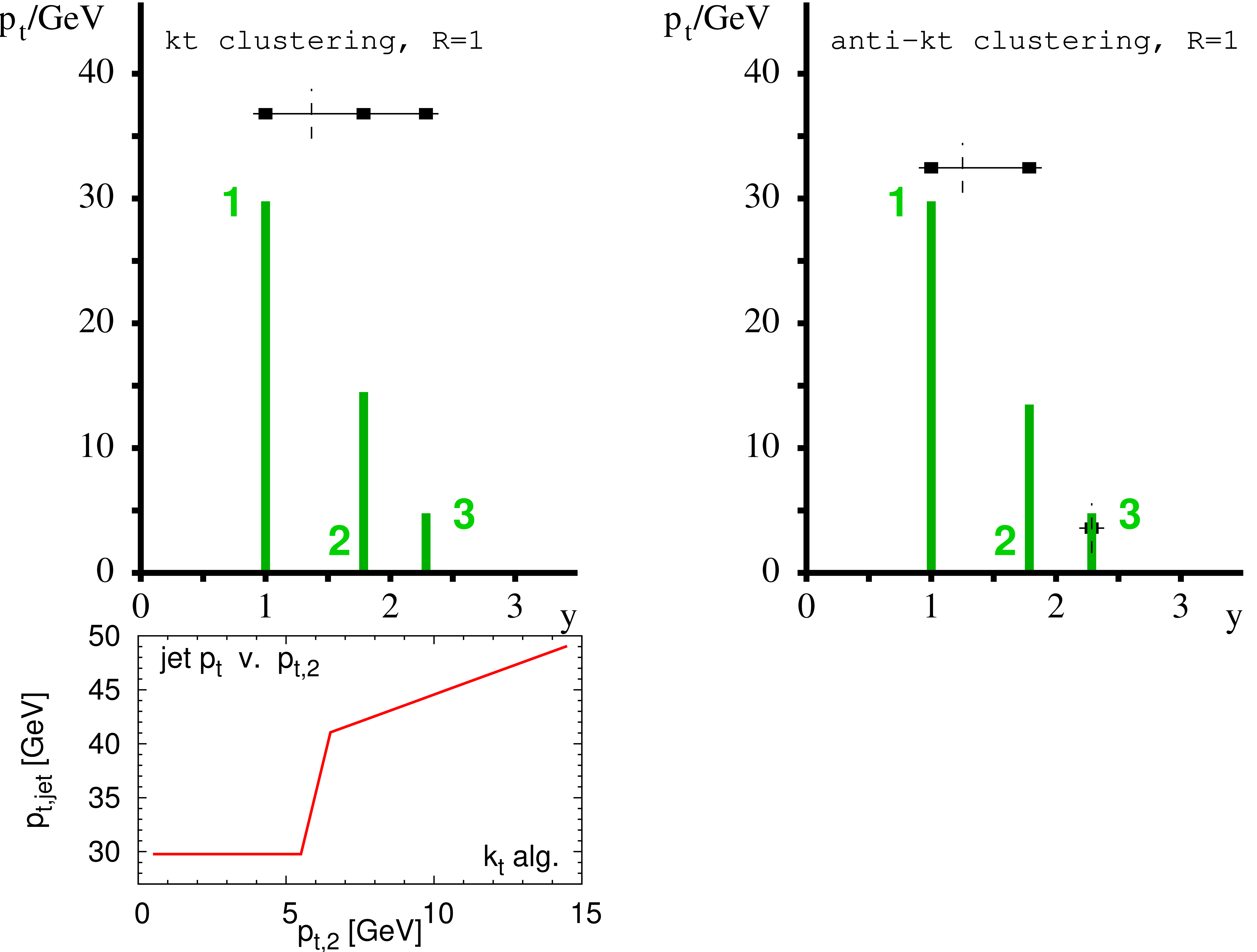


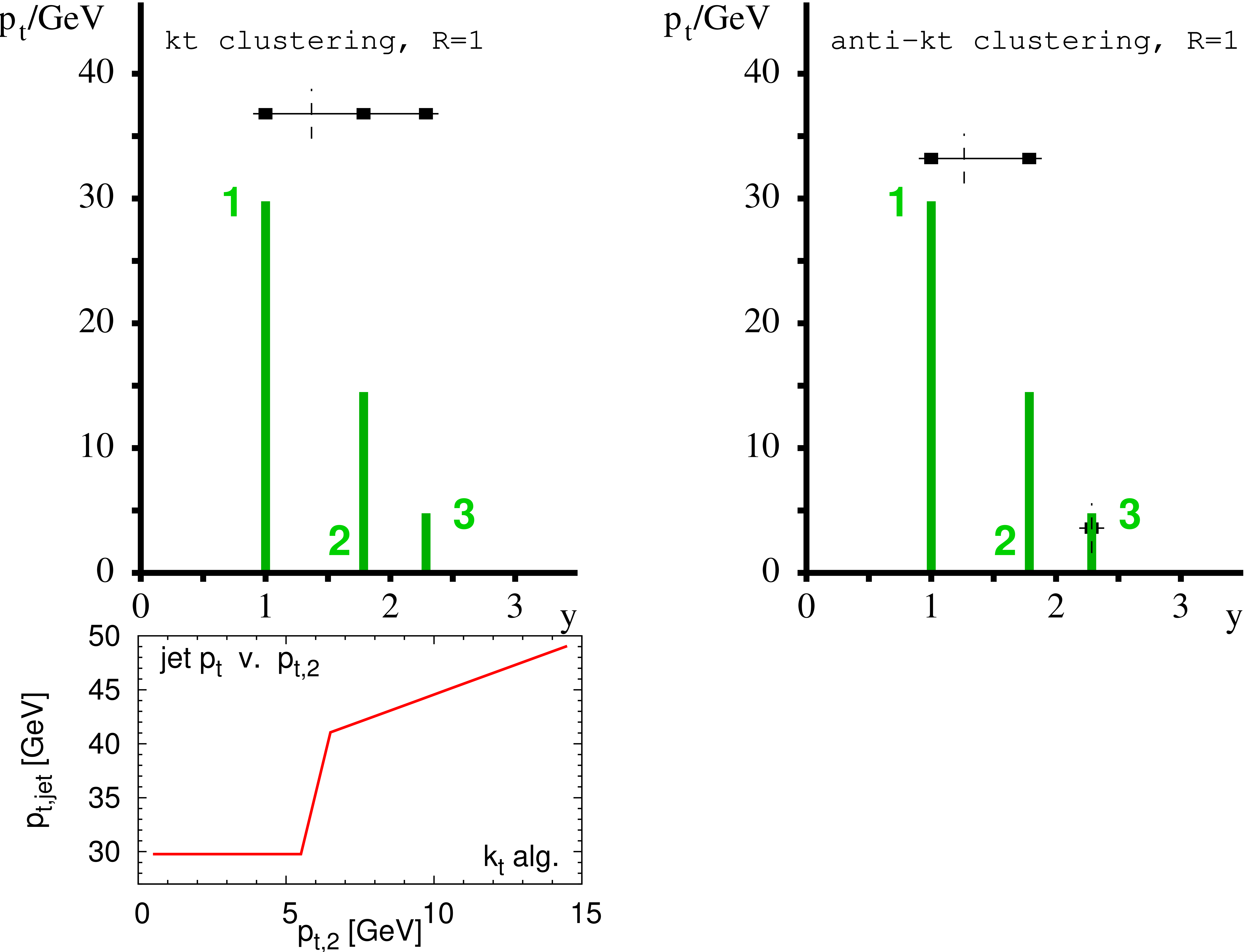
p_t/GeV
anti-kt clustering, R=1
1
2
3
y



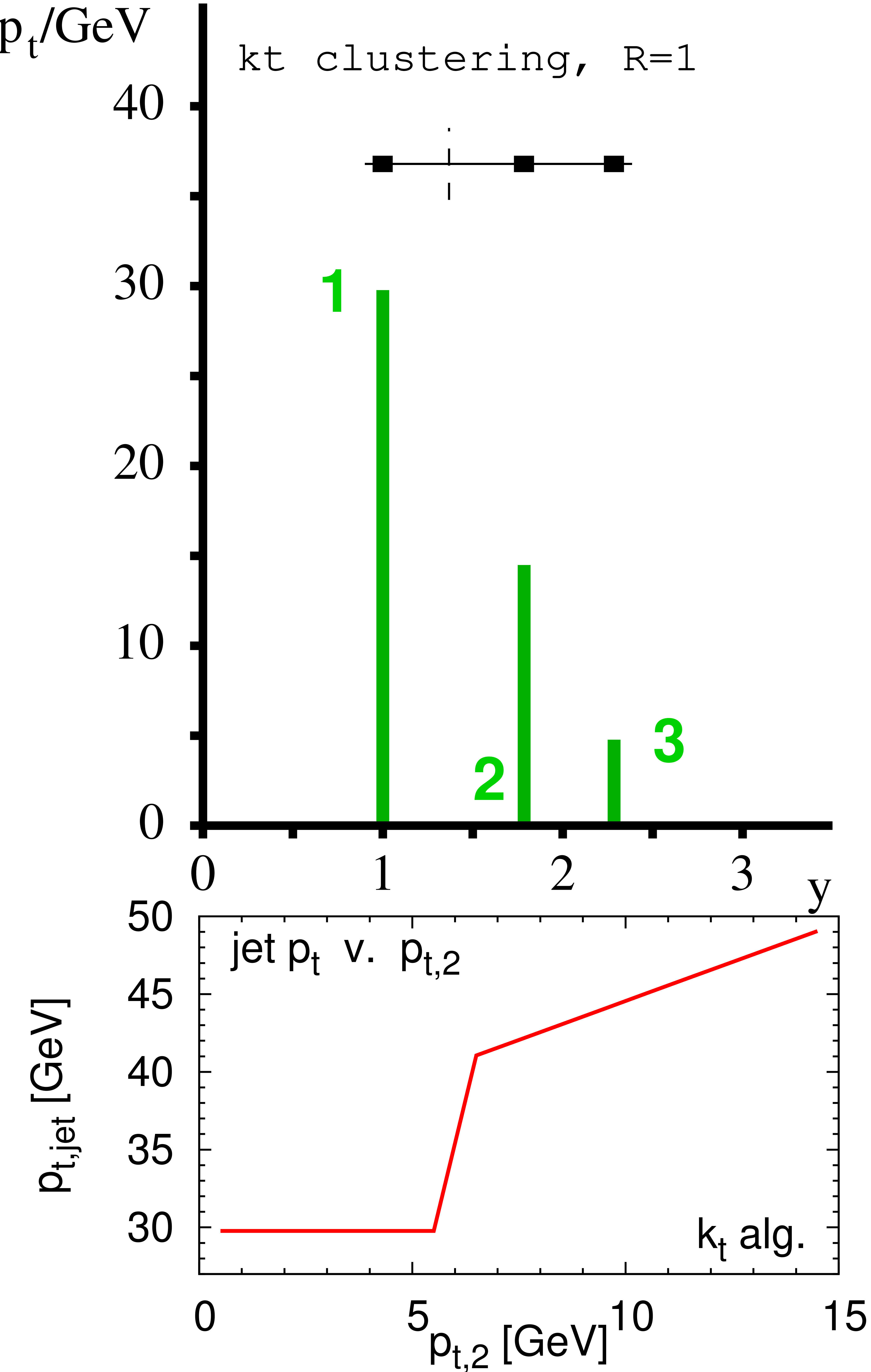
jet p_t v. p_t,2
p_t,jet [GeV]
k_t alg.
p_t,2 [GeV]

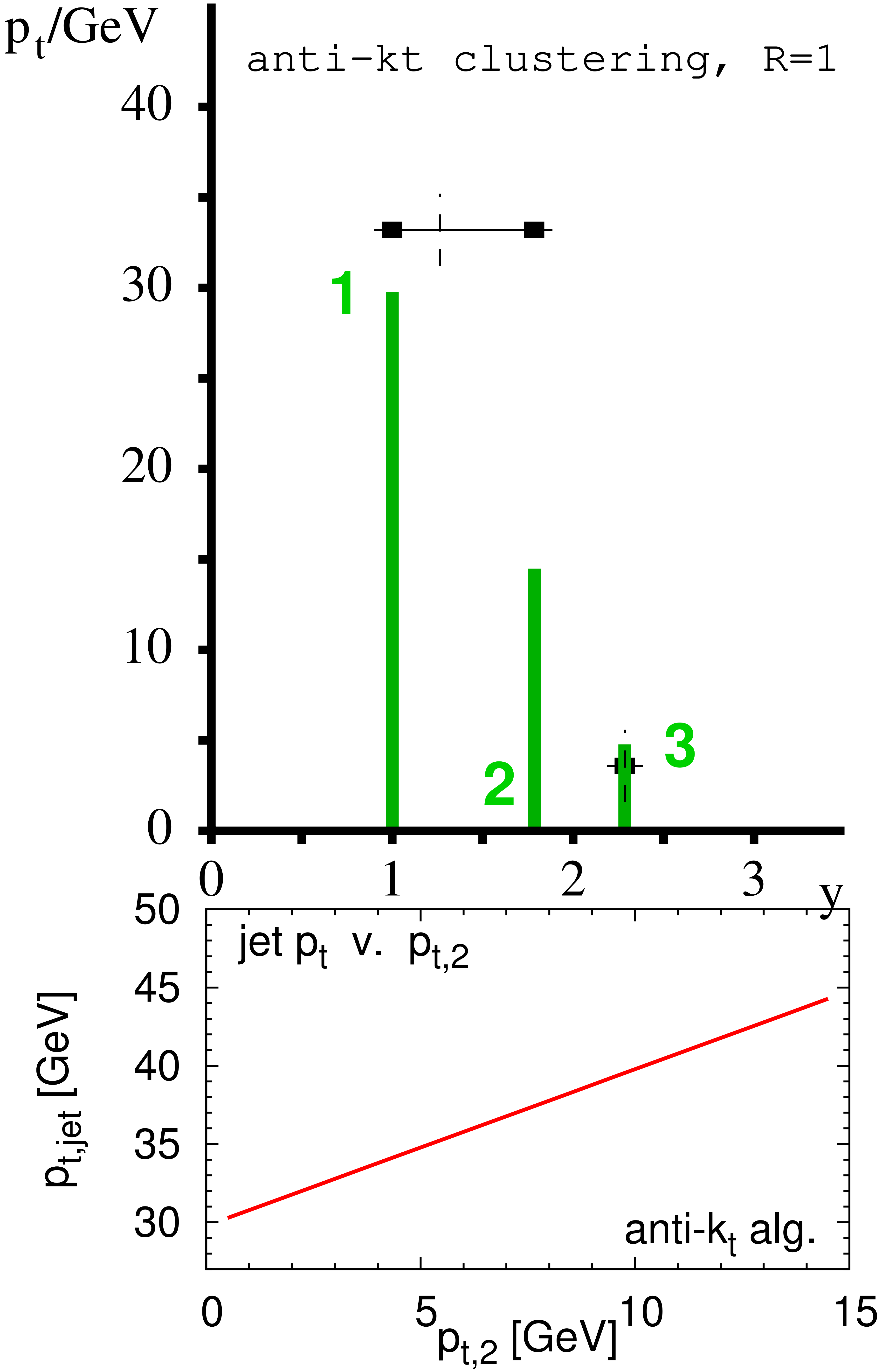

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
jet p_t v. p_t,2
p_t,jet [GeV]
50
45
40
35
30
k_t alg.
0
5
10
15
p_t,2 [GeV]

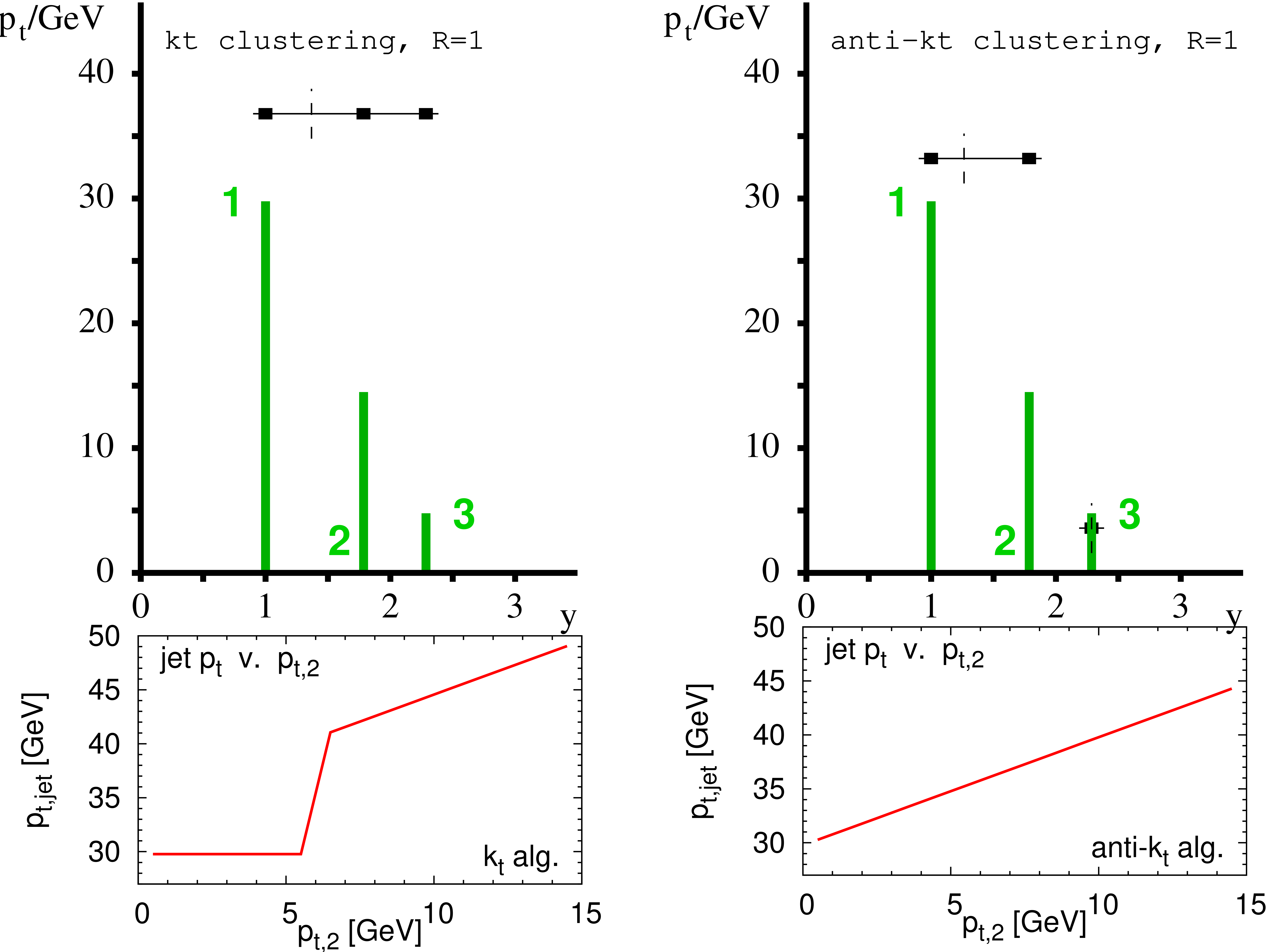

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
jet p_t v. p_t,2
p_t,jet [GeV]
50
45
40
35
30
k_t alg.
0
5
10
15
p_t,2 [GeV]



kt clustering, R=1
anti-kt clustering, R=1
p_t/GeV
y
1
2
3
jet p_t v. $p_{t,2}$
k_t alg.
$p_{t,jet}$ [GeV]
$p_{t,2}$ [GeV]

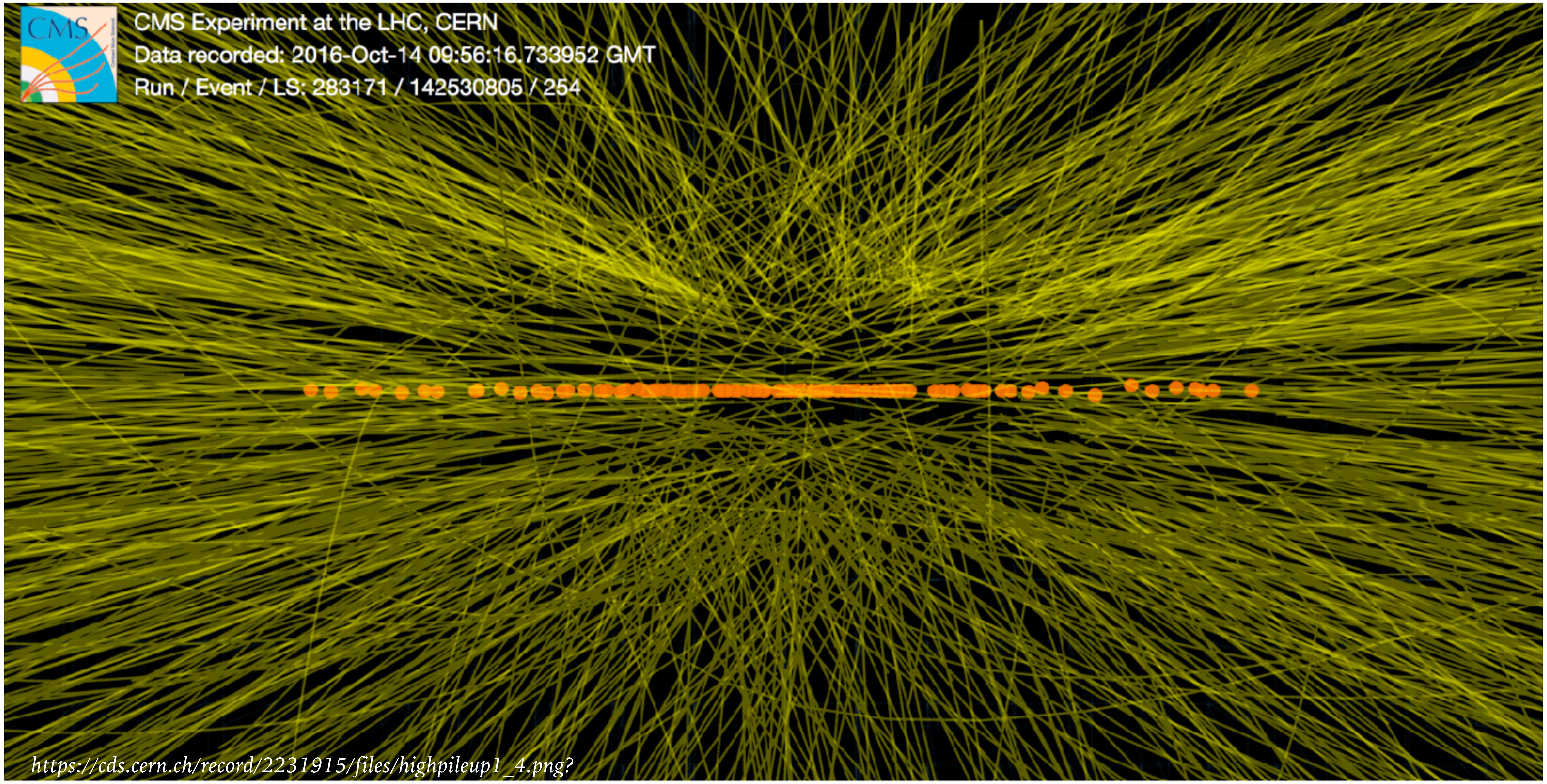

p_t/GeV
kt clustering, R=1
1
2
3
y
jet p_t v. p_t,2
p_t,jet [GeV]
k_t alg.
p_t,2 [GeV]


p_t/GeV
anti-kt clustering, R=1
1
2
3
y
jet p_t v. p_t,2
p_t,jet [GeV]
anti-k_t alg.
p_t,2 [GeV]



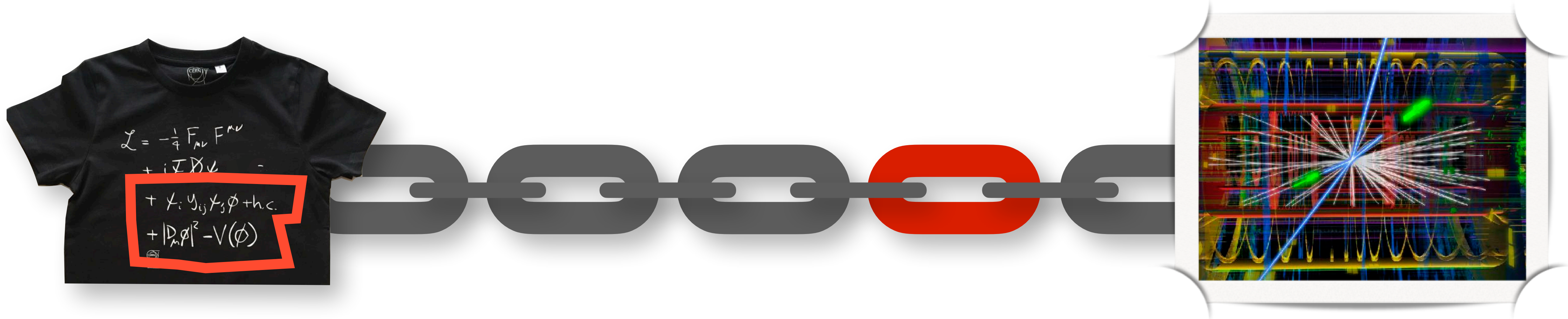
anti-k_t jet algorithm gives jet momentum with better linearity than k_t algorithm (or many other jet algorithms)

advance #3: removal of pileup (many simultaneous pp collisions)

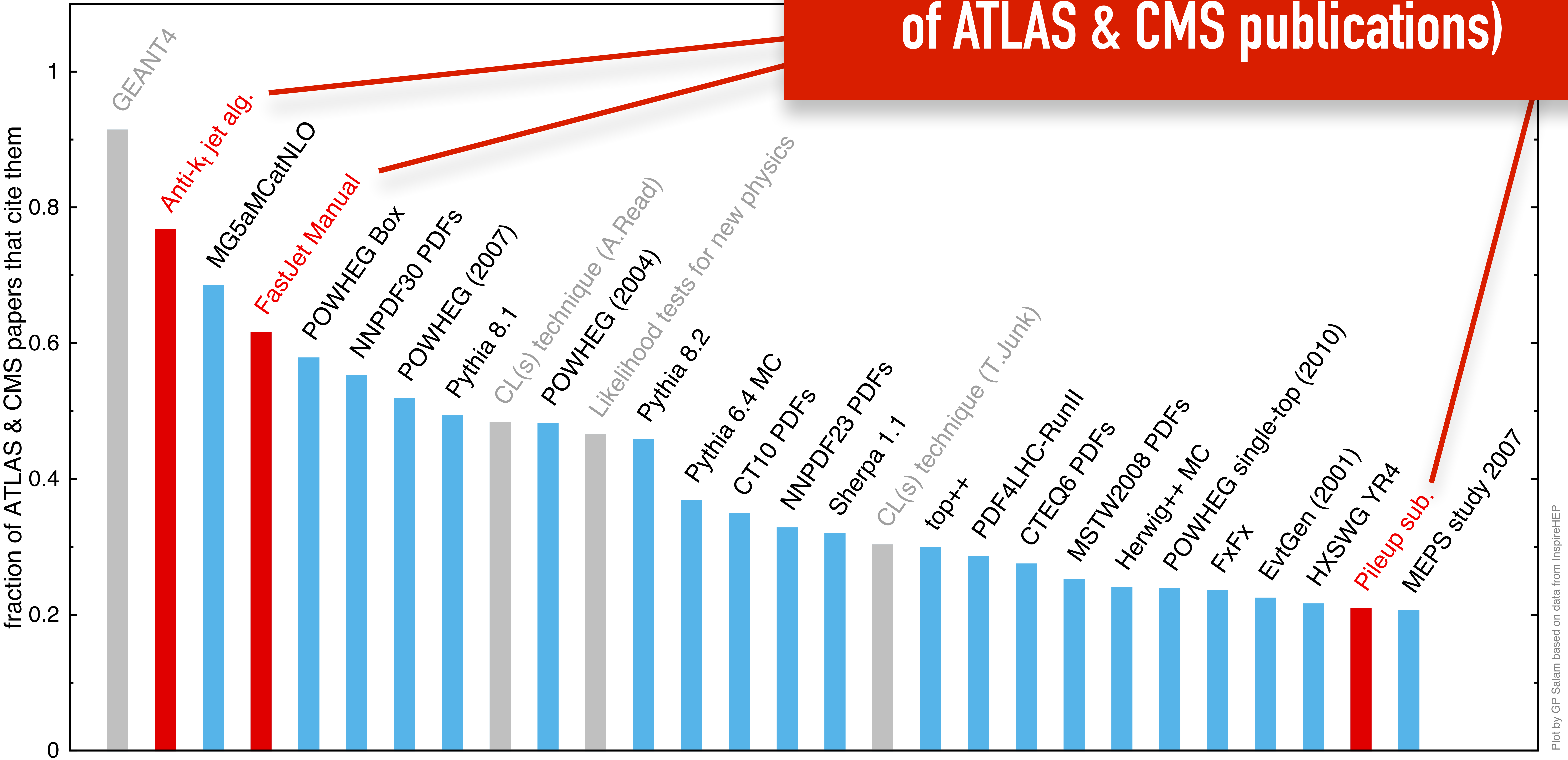


Nowadays many methods used (area-subtraction, particle/unified flow objects, PUPPI, soft-killer, …) and machine-learning likely to play increasing role

Beyond scope of today’s talk



those 3 advances are central to LHC physics today (e.g. anti-k_t used in >70% of ATLAS & CMS publications)



looking inside jets — basics

most jet finding based on correspondence

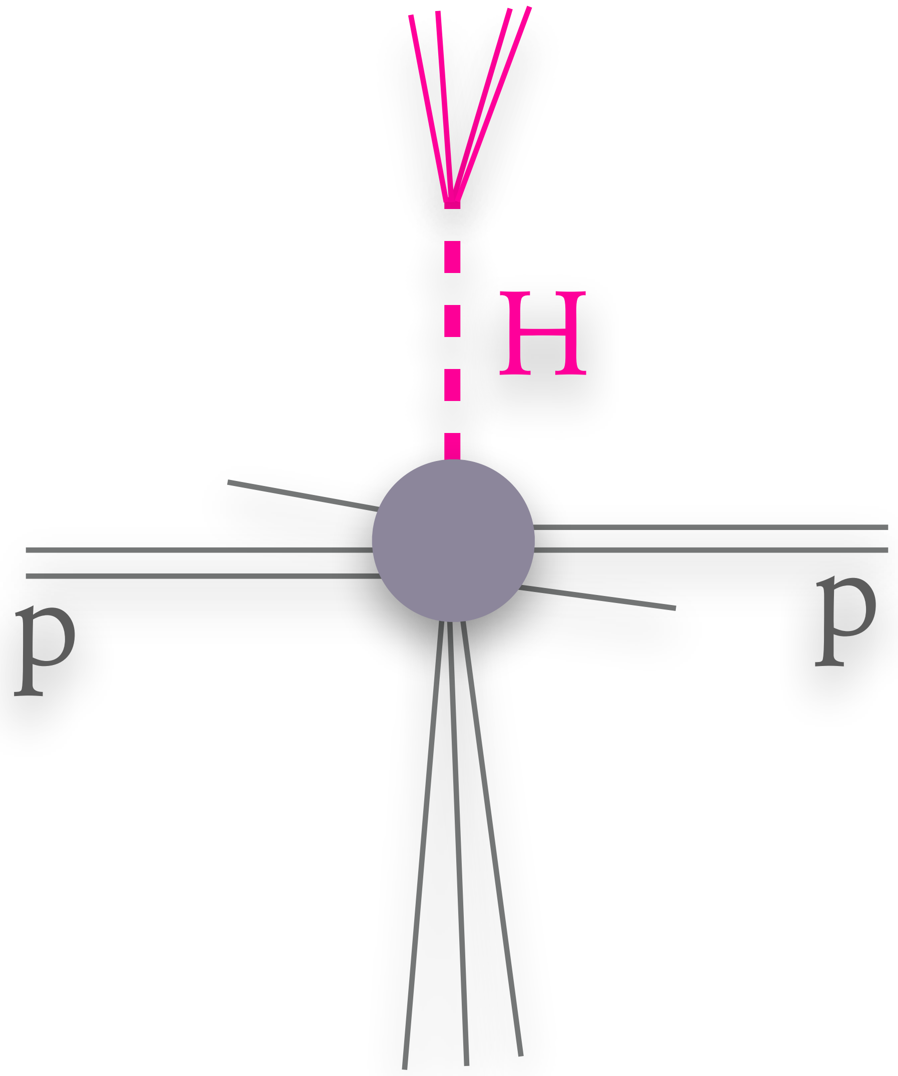
1 jet = 1 hard QCD parton (quark or gluon)

LHC forces us to go beyond that regime

high p_T Higgs & [SD] jet mass

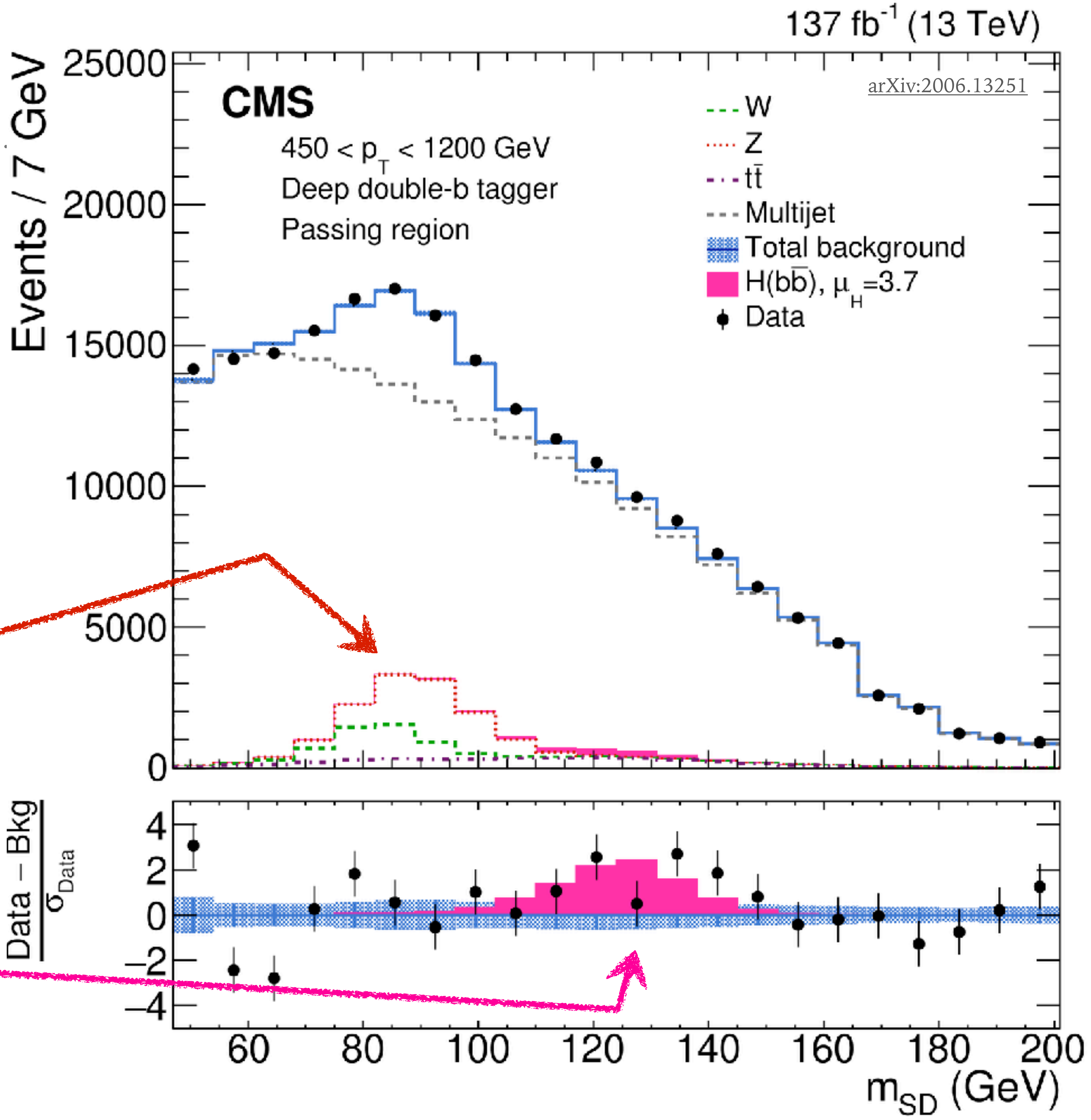
We wouldn't trust electromagnetism if we'd only tested it at one length/momentum scale.

New Higgs interactions need testing at both low and (here) **high momenta.**



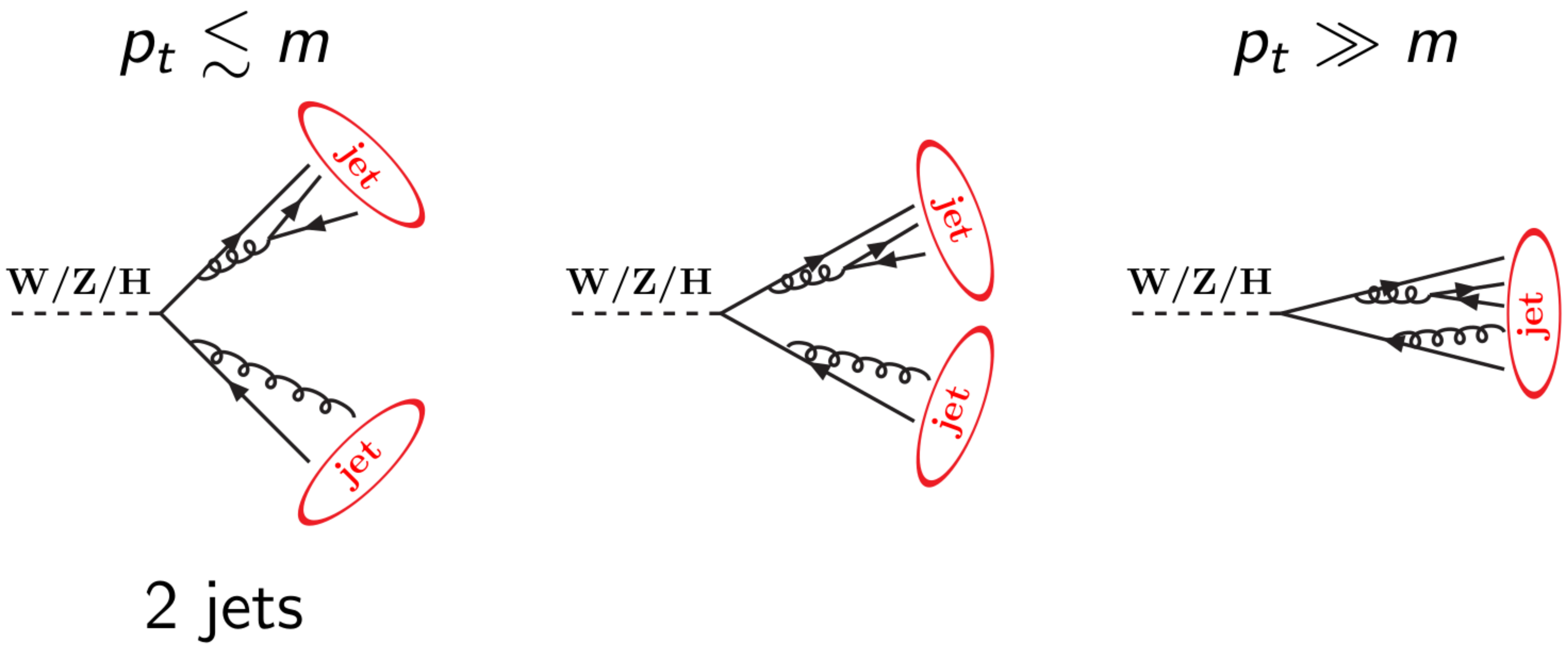
high-p_T
$Z \to bb$

high-p_T
$H \to bb$
(2.5 σ)?

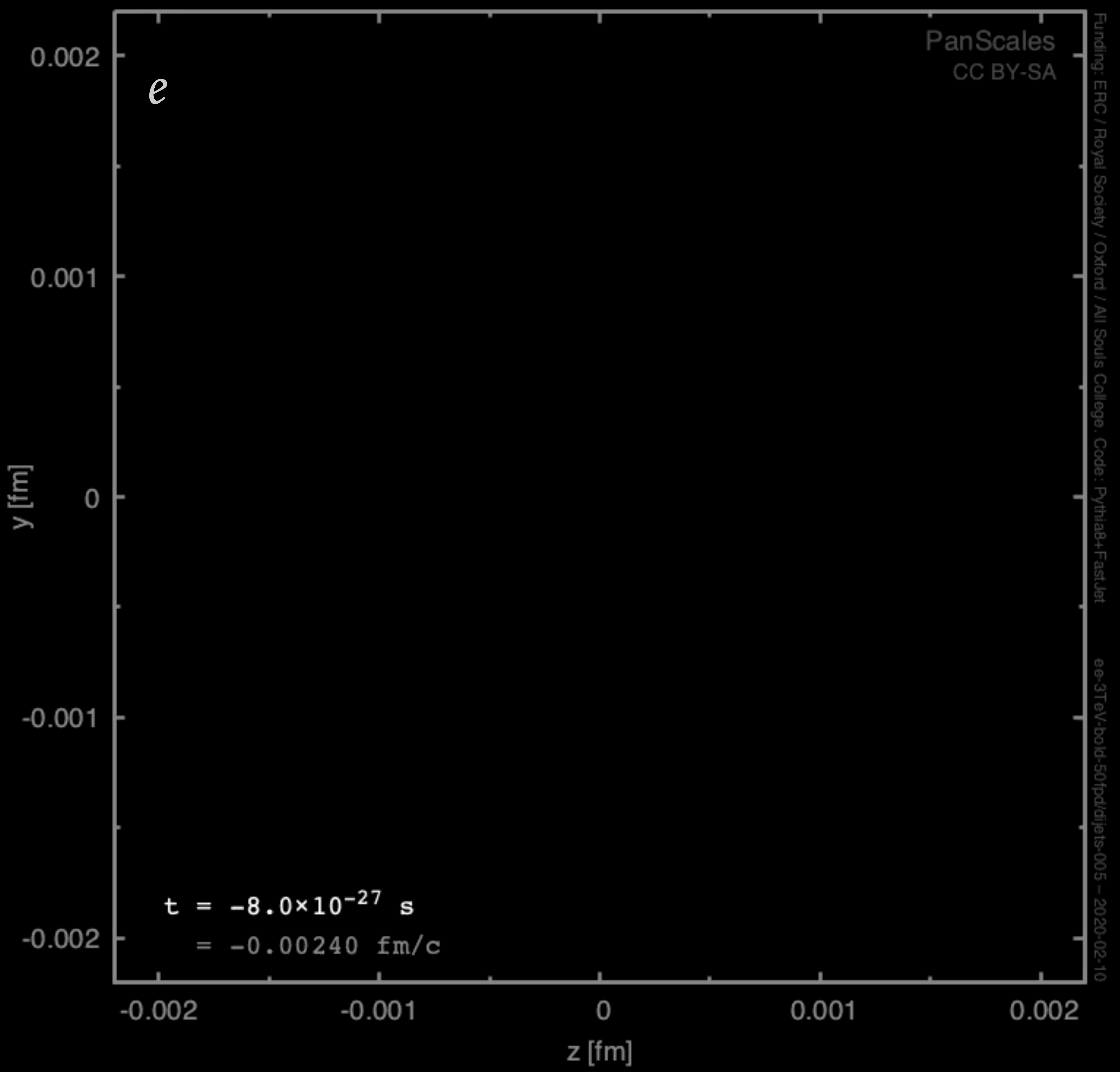


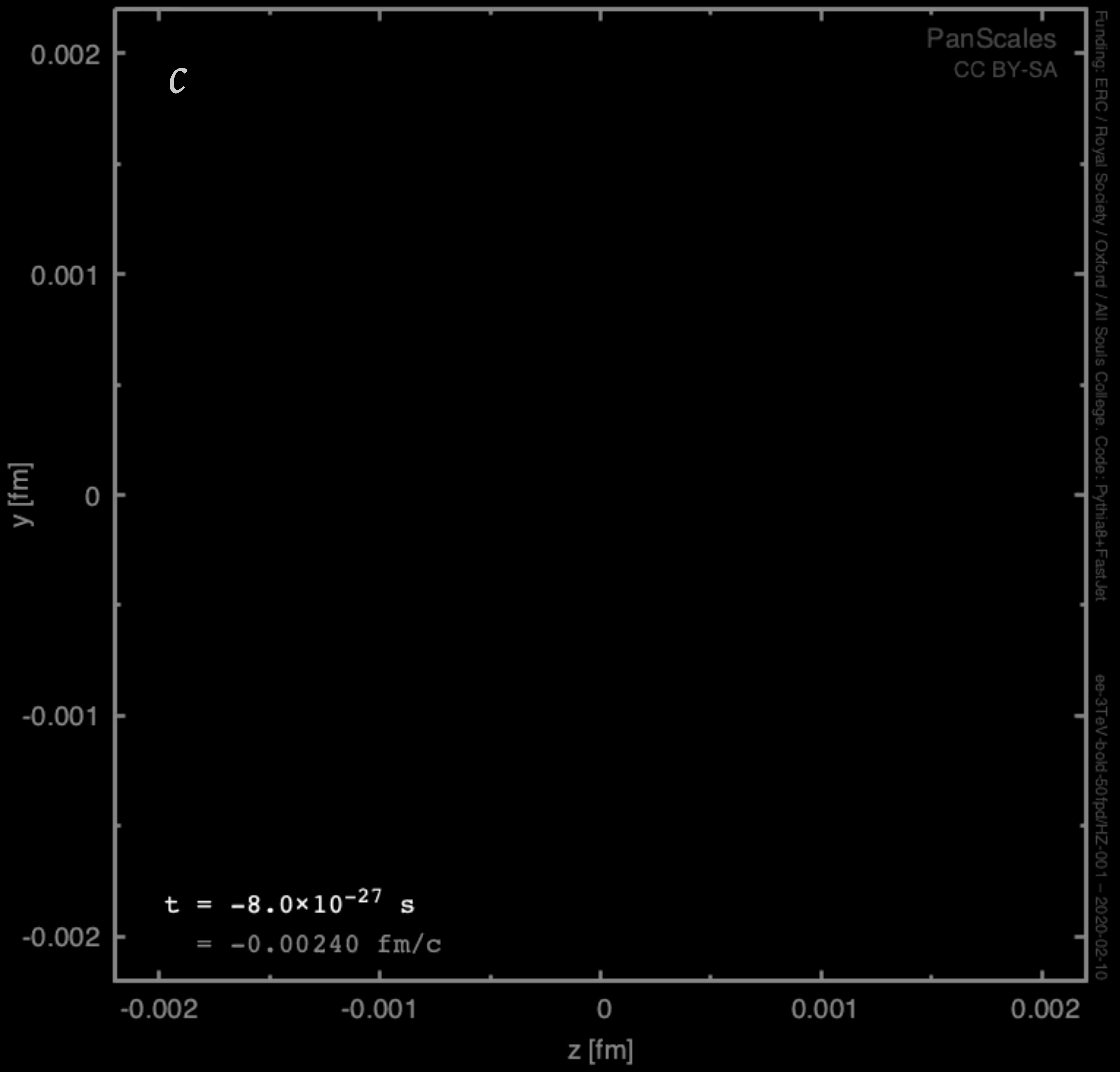
Jet substructure for boosted hadronc W/Z/H/t etc. decays

- At LHC energies, EW-scale particles (W/Z/t...) are often produced with $p_t \gg m$, leading to collimated decays.
- Hadronic decay products are thus often reconstructed into single jets.

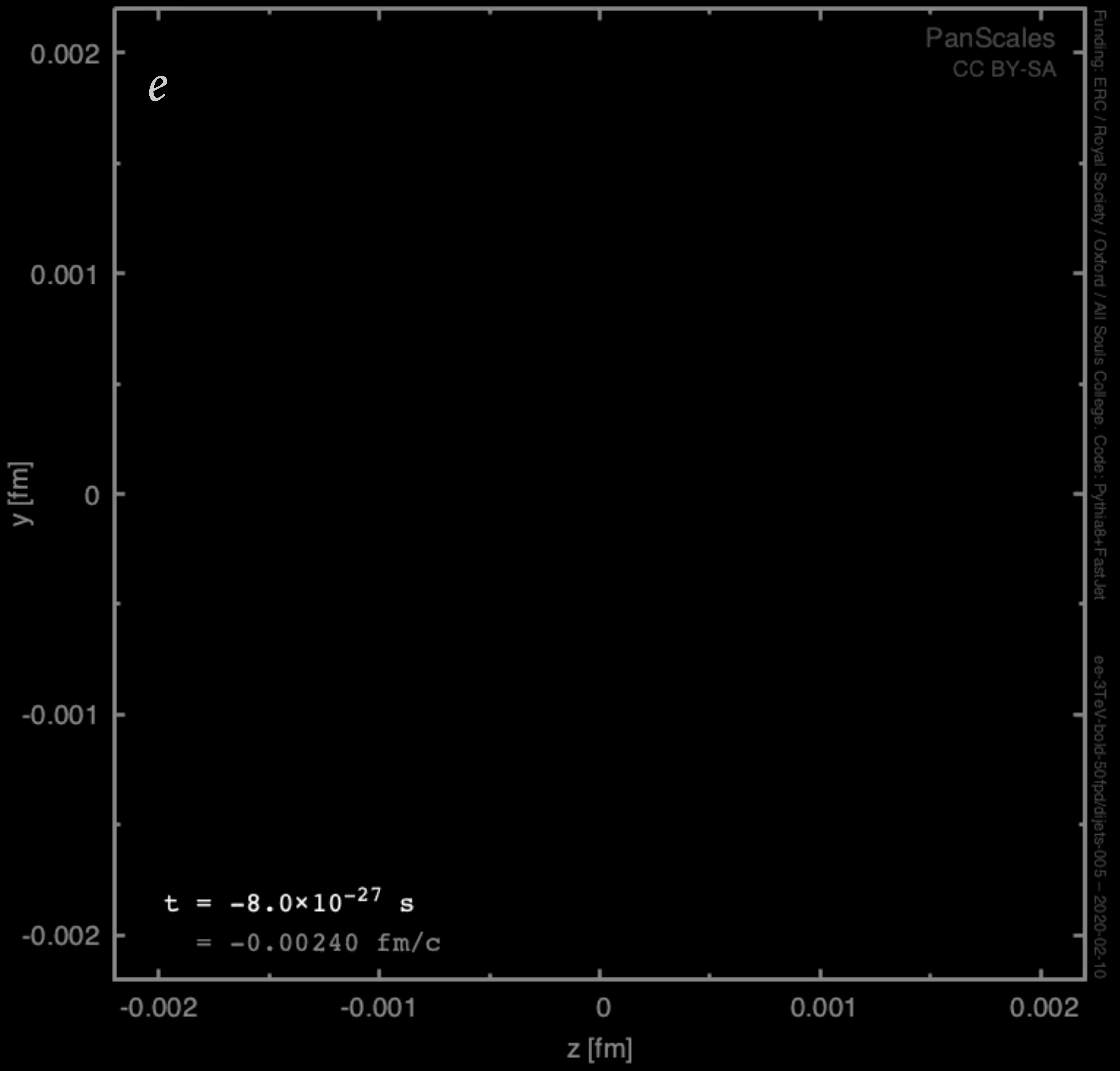


[Figure by G. Soyez]

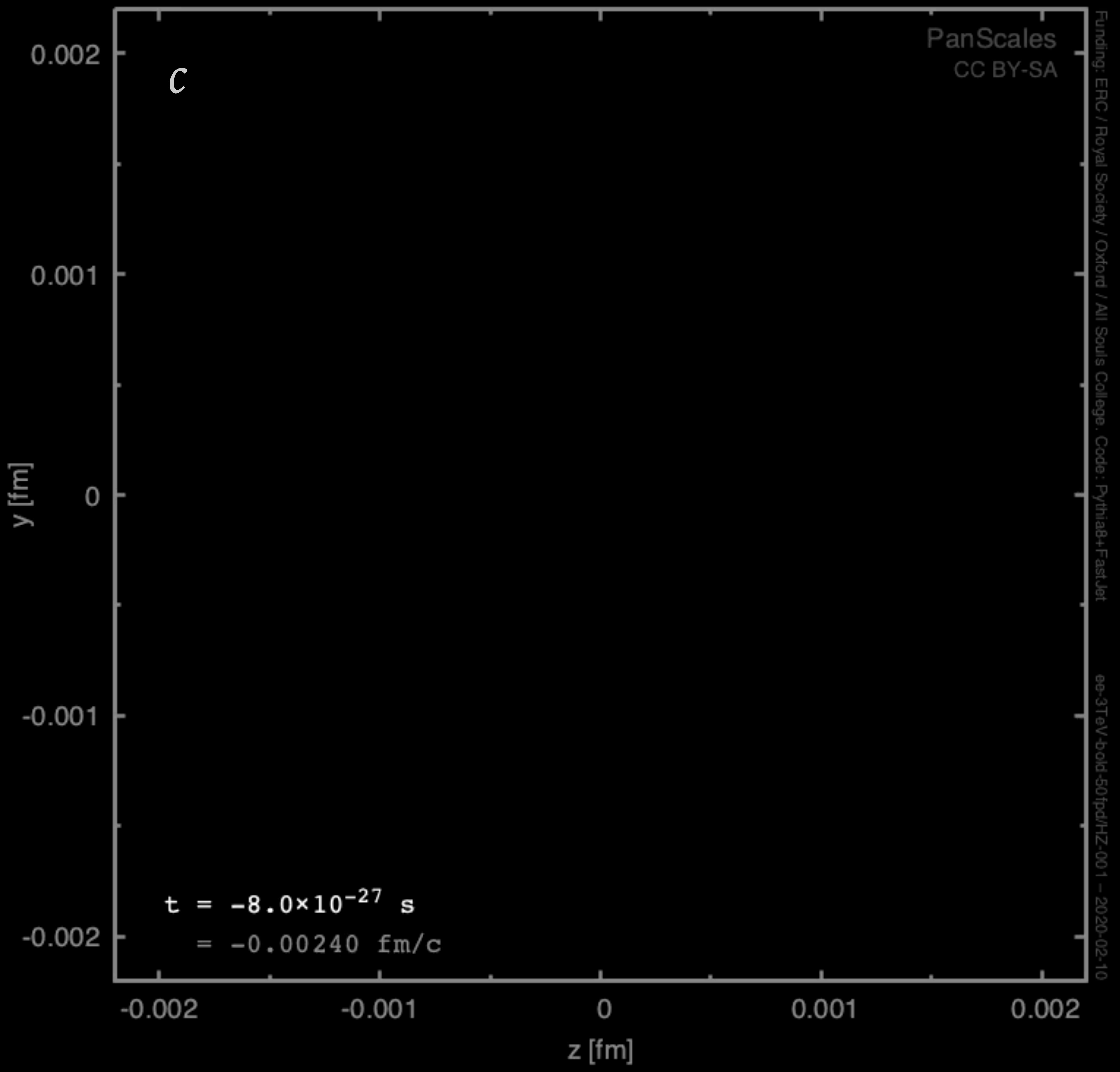

e
PanScales
CC BY-SA
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-bold-50fpd/dijets-005 – 2020-02-10
0.002
0.001
0
-0.001
-0.002
y [fm]
-0.002
-0.001
0
0.001
0.002
z [fm]
t = -8.0×10^{-27} s
= -0.00240 fm/c


c
PanScales
CC BY-SA
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-bold-50fpd/HZ-001 – 2020-02-10
0.002
0.001
0
-0.001
-0.002
y [fm]
-0.002
-0.001
0
0.001
0.002
z [fm]
t = -8.0×10^{-27} s
= -0.00240 fm/c

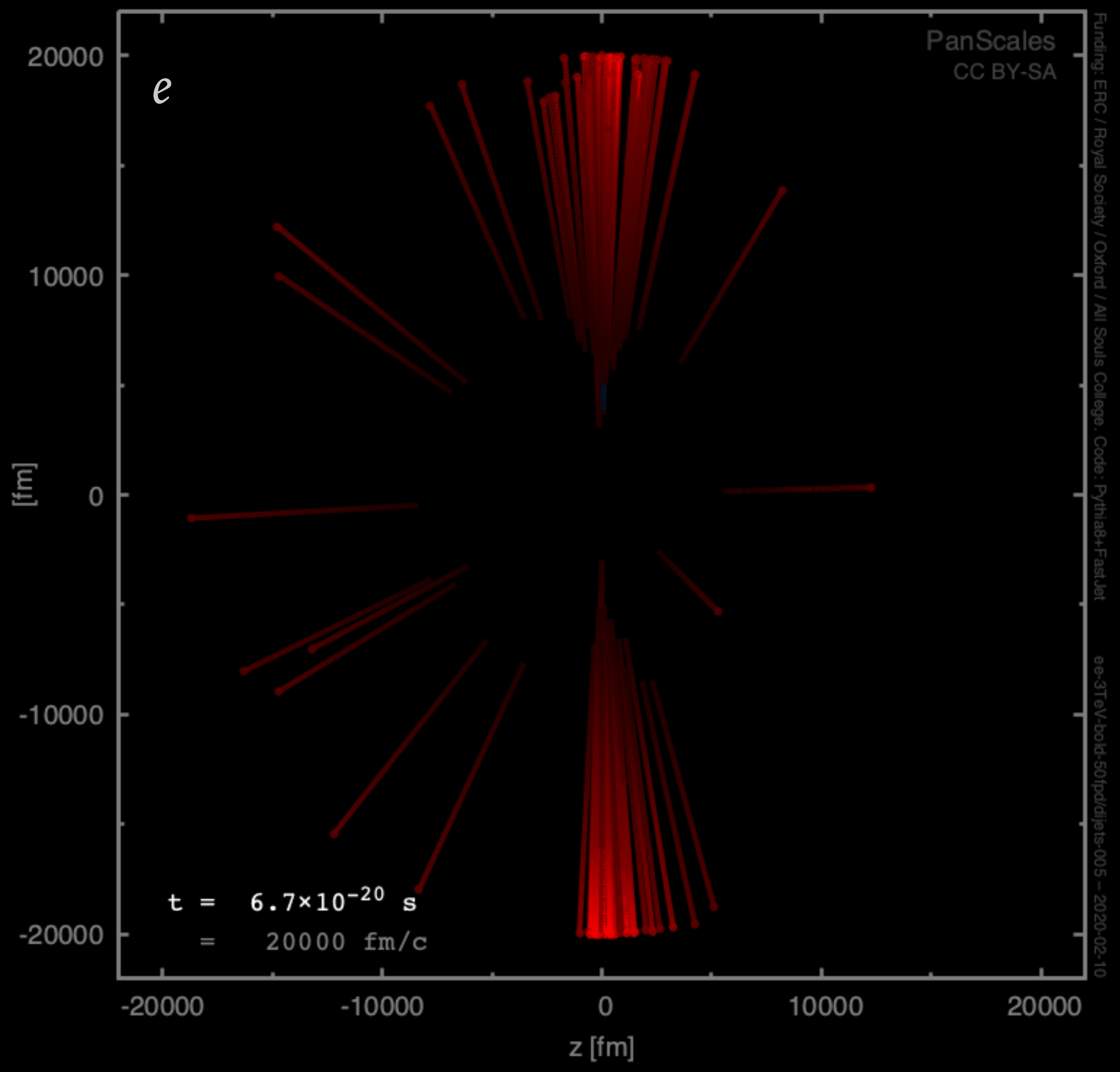
pure QCD event



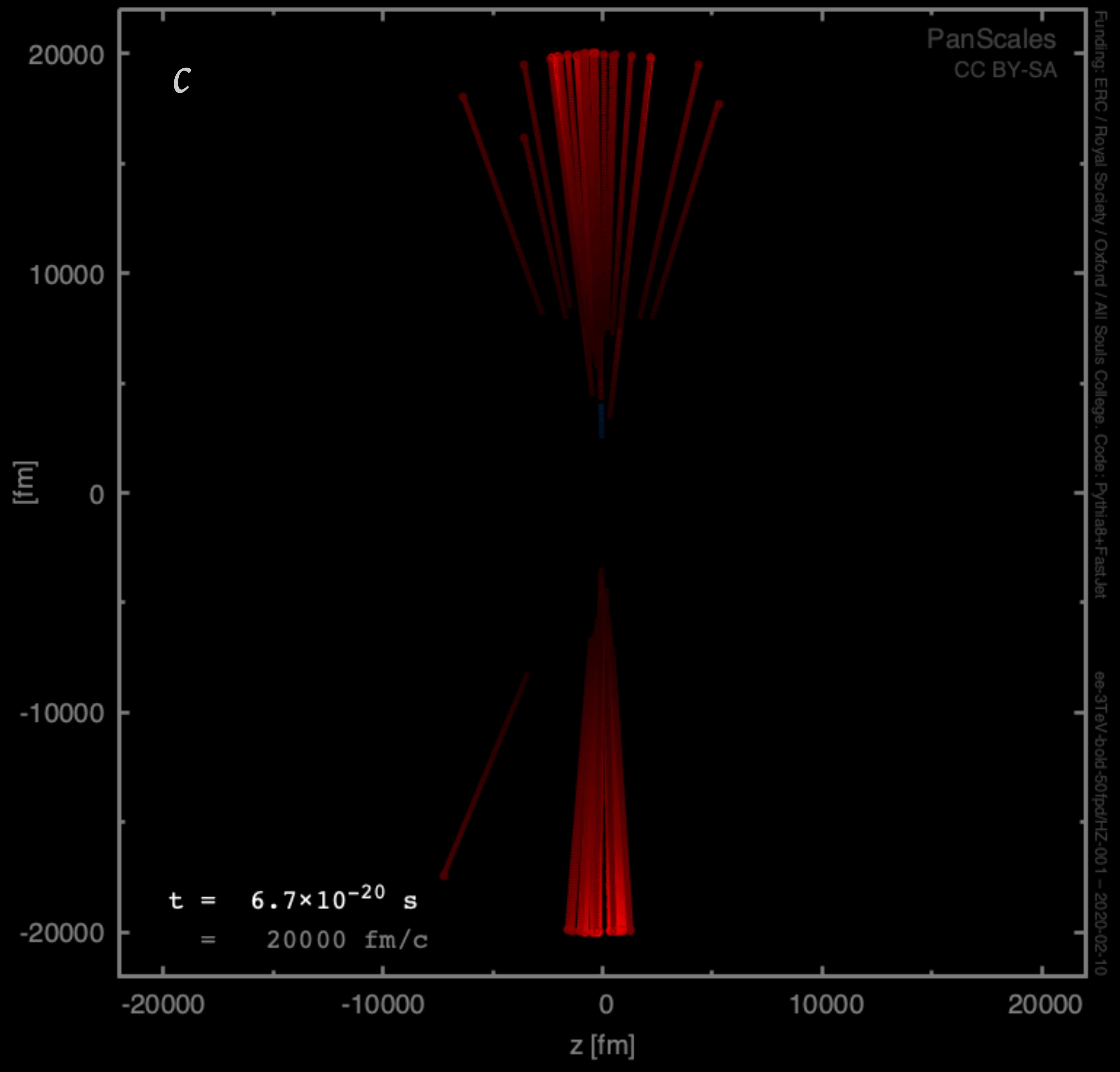
event with Higgs & Z boson decays



pure QCD event



event with Higgs & Z boson decays



1993

Searches for new particles using cone and cluster jet algorithms: A Comparative study
Michael H. Seymour (Lund U.). Jun 1993. 23 pp.
Published in **Z.Phys. C62 (1994) 127-138**
LU-TP-93-8
DOI: 10.1007/BF01559532

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document

Detailed record - Cited by 179 records 100+

"As a simple example (in fact the only way in which we use sub-jets in this paper), one could cluster the event until there is exactly one jet remaining-this is then the hardest jet. Then one could recluster only those particles that ended up in the hardest jet until there are exactly two jets-these are then the sub-jets corresponding to the hardest emission within the hardest jet."

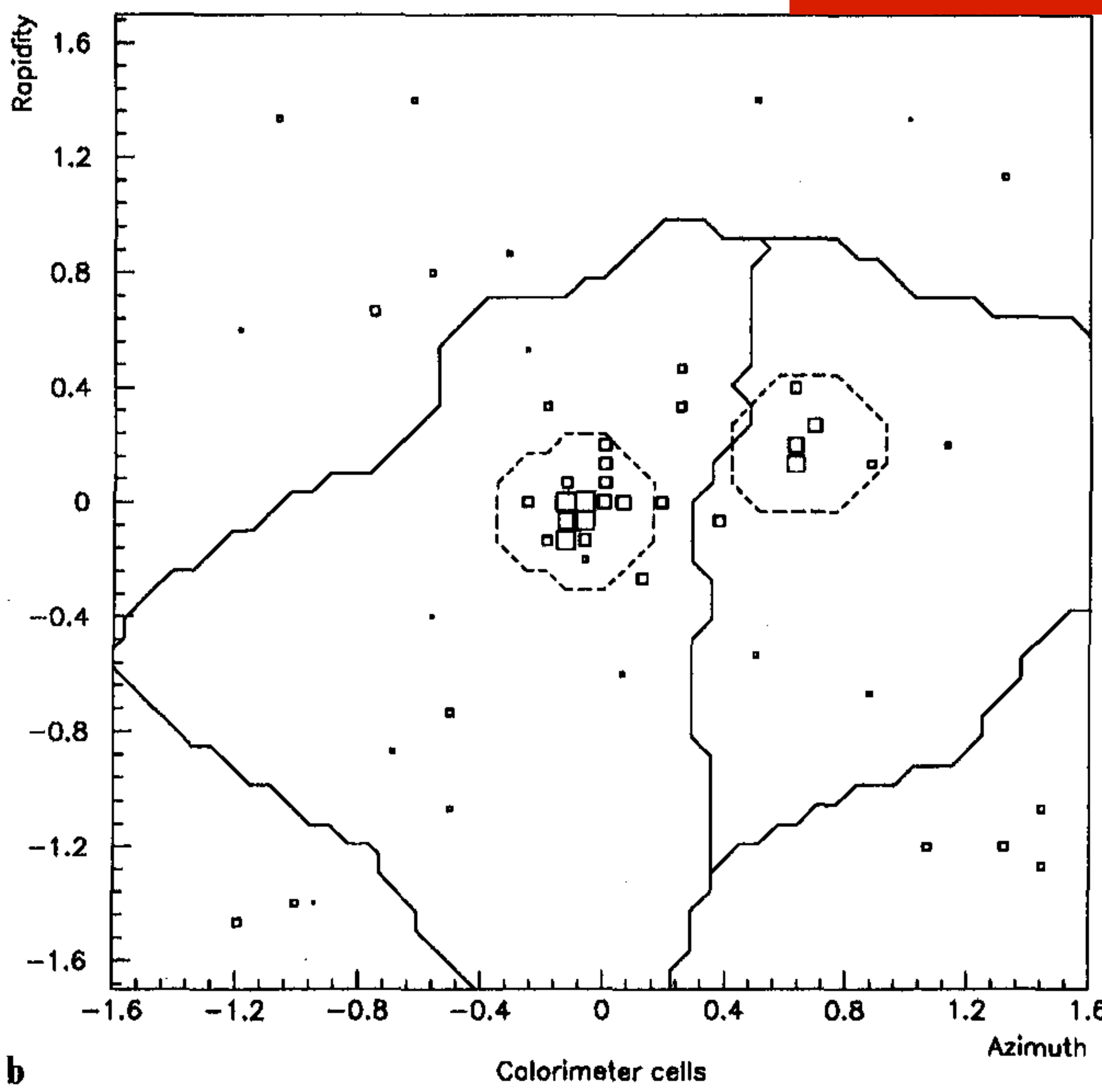


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

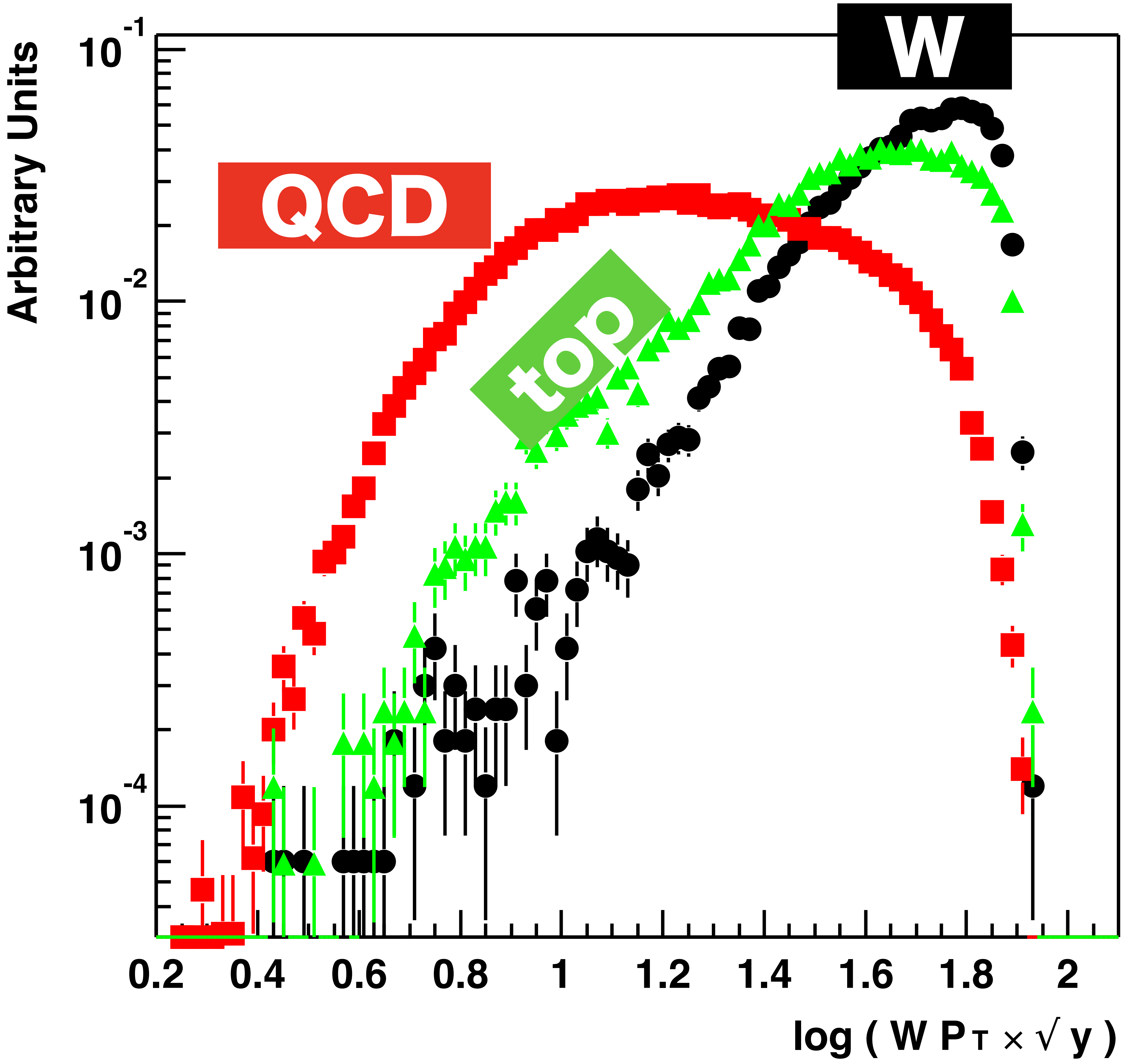
"Then we recluster only those particles that ended up in the hardest jet, using a radius $R=\alpha R_{jj}$,"

2002

WW scattering at the CERN LHC

J.M. Butterworth (University Coll. London), B.E. Cox, Jeffrey R. Forshaw (Manchester U.). Jan 2002. 29 pp.

Published in **Phys.Rev. D65 (2002) 096014**
MC-TH-01-13, MAN-HEP-01-05, UCL-HEP-2001-06
DOI: 10.1103/PhysRevD.65.096014
e-Print: hep-ph/0201098 | PDF



this analysis we develop a new technique. The extra pieces of information gained from the subjet decomposition are the y cut at which the subjets are defined and the four-vectors of the subjets. For a genuine W decay the expectation is that the scale at which the jet is resolved into subjets (i.e. yp_T^2) will be $\mathcal{O}(M_W^2)$. The distribution of $\log(p_T\sqrt{y})$ is shown in Figure 12(d). The scale of the splitting is indeed high in the signal and softer in the $W+$ jets background, where the hadronic W is in general a QCD jet rather than a genuine second W. A cut is applied at $1.6 < \log(p_T\sqrt{y}) < 2.0$. The effect of this cut is

$= \frac{1}{2}\log(d_{12})$

1997/8

Cambridge/Aachen algorithm

Better jet clustering algorithms
Yuri L. Dokshitzer (Milan U.), G.D. Leder, S. Moretti, B.R. Webber (Cambridge U.). Jul 1997. 33 pp.
Published in **JHEP 9708 (1997) 001**
CAVENDISH-HEP-97-06
DOI: 10.1088/1126-6708/1997/08/001
e-Print: **hep-ph/9707323** | **PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 890 records 500+

Hadronization corrections to jet cross-sections in deep inelastic scattering
M. Wobisch (Aachen, Tech. Hochsch.), T. Wengler (Heidelberg U.). Apr 1998. 10 pp.
Published in **In *Hamburg 1998/1999, Monte Carlo generators for HERA physics* 270-279**
PITHA-99-16
To be published in the proceedings of Conference: C98-04-27, p.270-279
Proceedings
e-Print: **hep-ph/9907280** | **PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 477 records 250+

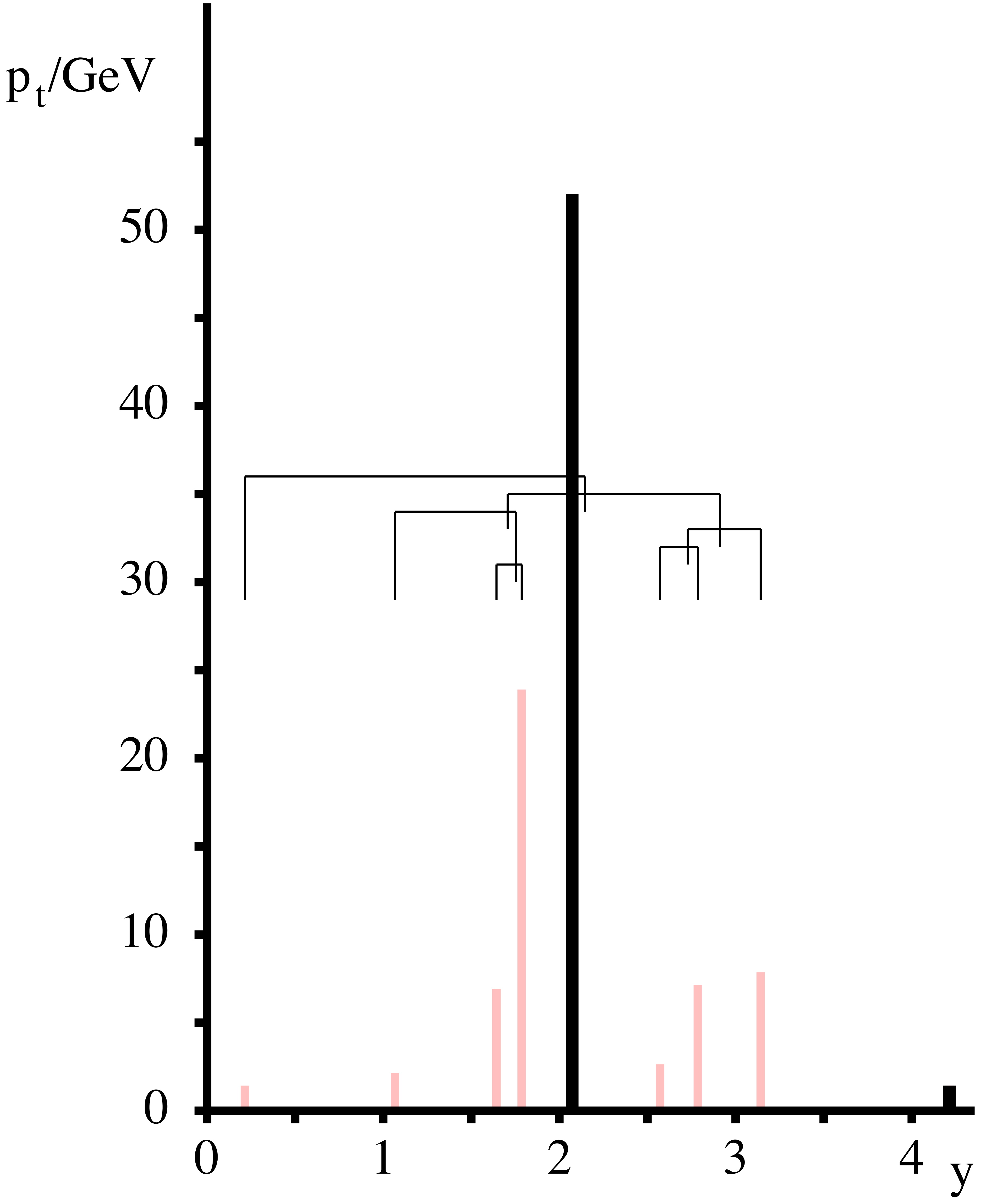
Abstract: We investigate modifications to the $k_\perp$-clustering jet algorithm which preserve the advantages of the original Durham algorithm while reducing non-perturbative corrections and providing better resolution of jet substructure. We find that a simple change in the sequence of clustering (combining smaller-angle pairs first), together with the 'freezing' of soft resolved jets, has beneficial effects.

the Cambridge / Aachen (C/A) jet algorithm

1. Identify pair of particles, i & j, with smallest ΔR_{ij}
2. If $\Delta R_{ij} < R$ (jet radius parameter)
   A. recombine i & j into a single particle
   B. loop back to step 1
3. Otherwise, stop the clustering

Dokshitzer, Leder, Moretti & Webber '97
Wobisch & Wengler '98

Cambridge/Aachen



A sequence of jet substructure tools taggers

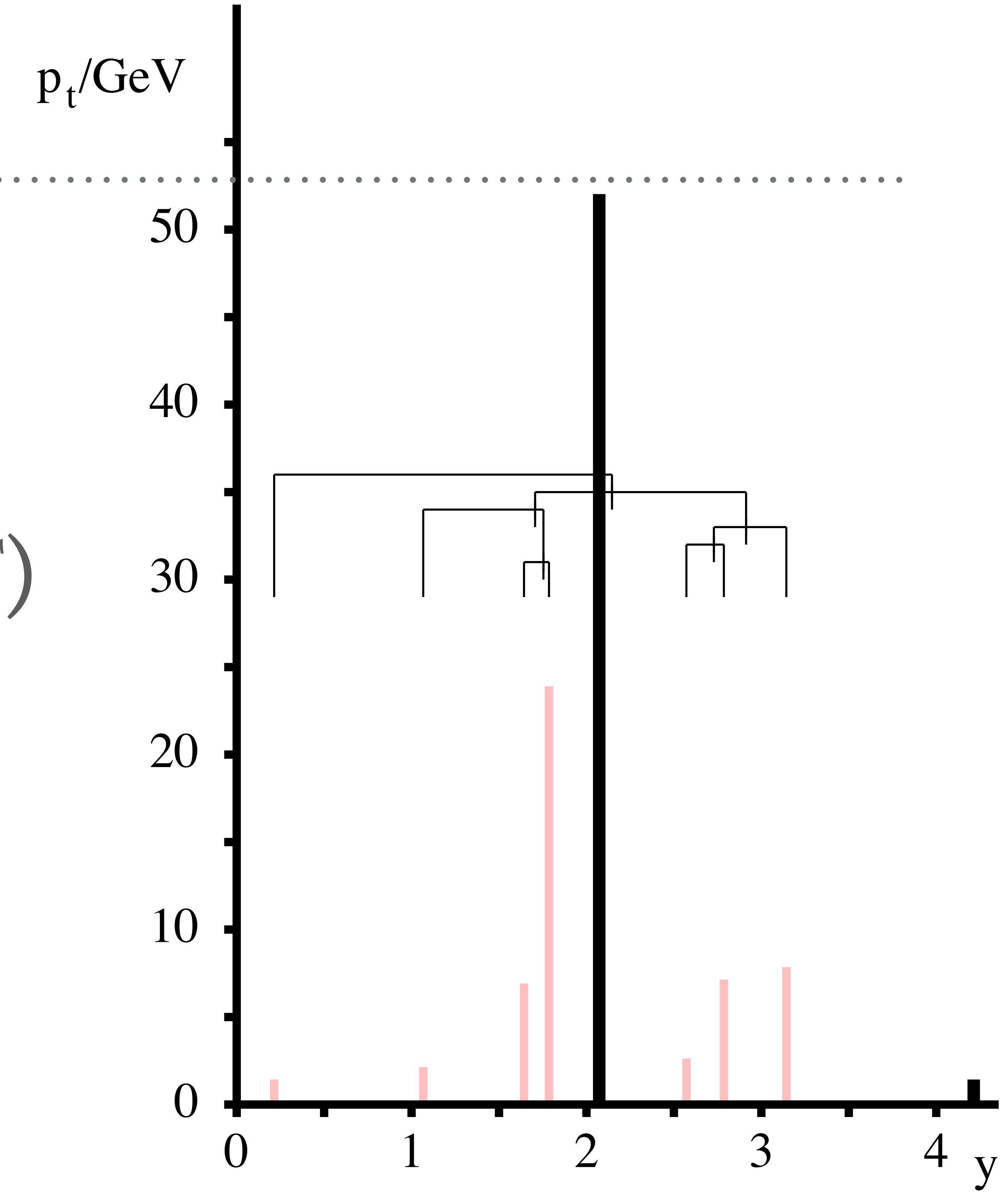
➤ **2008**: Mass-Drop Tagger (C/A declustering with a k_t/m cut)
[Butterworth, Davison, Rubin, GPS, arXiv:0802.2470]

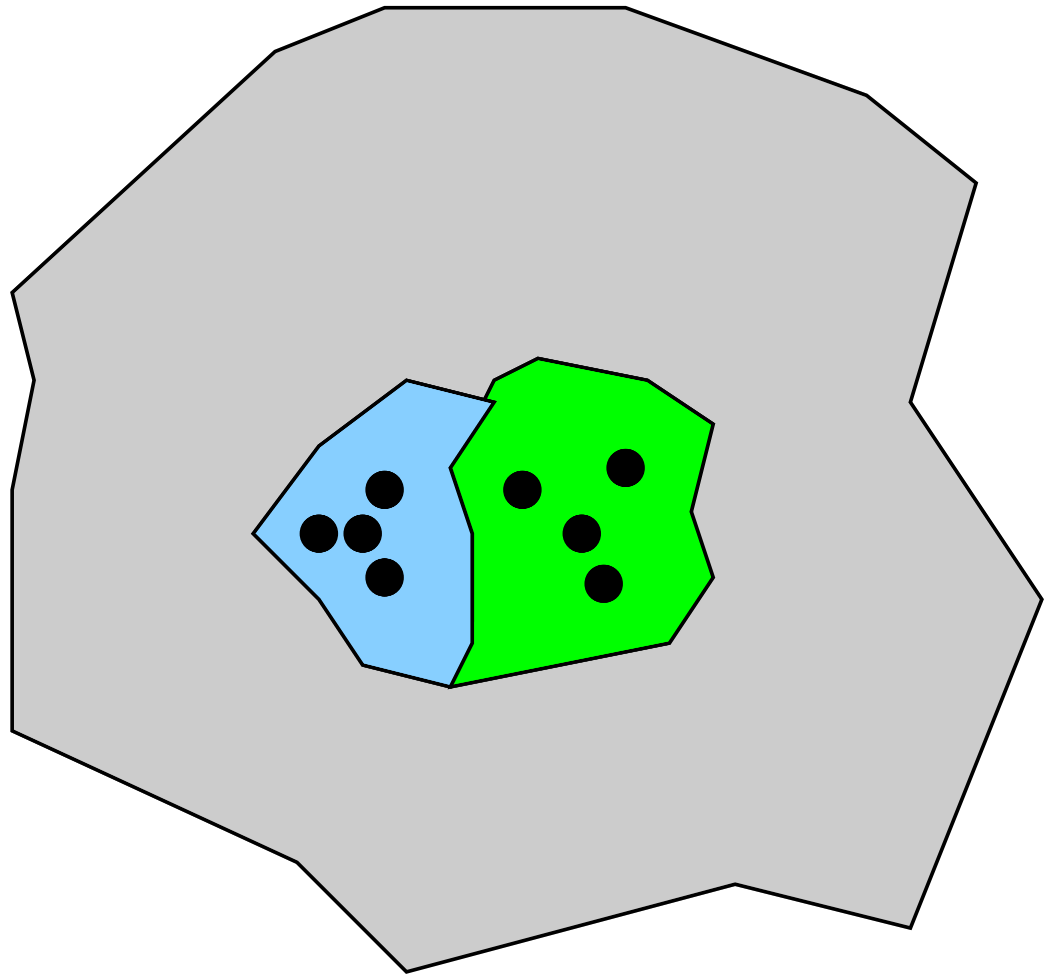
➤ **2013**: Soft Drop, β=0, aka modified mass-drop tagger (mMDT)
[Dasgupta, Fregoso, Marzani, GPS, arXiv:1307.0007]

➤ **2014**: Soft Drop, β≠0
[Larkoski, Marzani, Soyez, Thaler, arXiv:1402.2657]

1. Undo last clustering of C/A jet into subjets 1, 2
2. Stop if $z = \frac{\min(p_{t1}, p_{t2})}{p_{t1} + p_{t2}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta} > z_{\text{cut}}$
3. Else discard softer branch, repeat step 1 with harder branch

Cambridge/Aachen

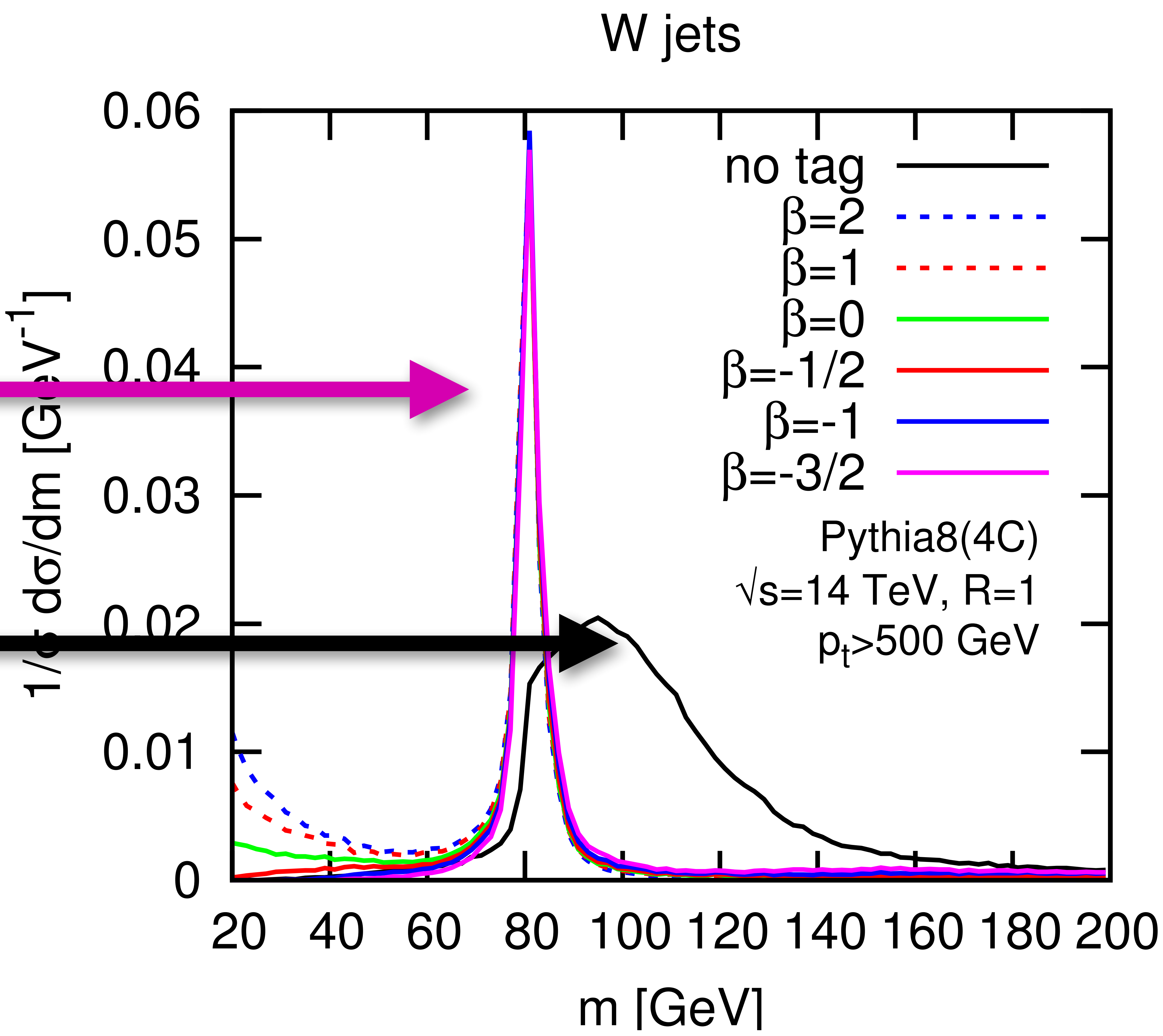




SoftDrop: action on signal (e.g. W/H/Z)

Soft Drop signal jet mass

raw signal (plain jet mass)



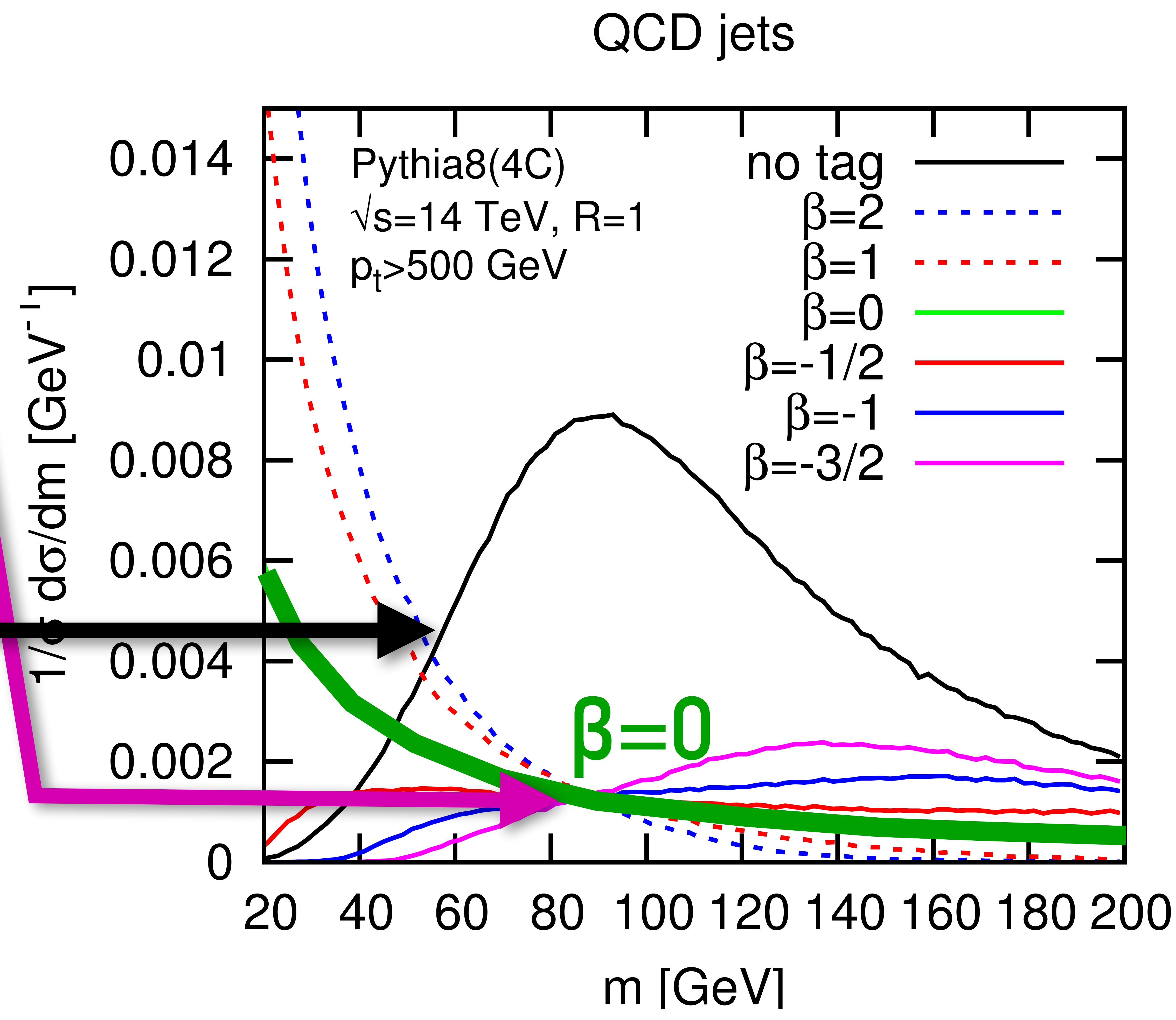
NB: z_{cut} chosen to keep signal efficiency fixed at 35% for all β

Plots from Larkoski, Marzani, Soyez & Thaler arXiv:1402.2657

SoftDrop: action on background (quark/gluon-induced jets)

Soft Drop background jet mass

raw background (plain jet mass)

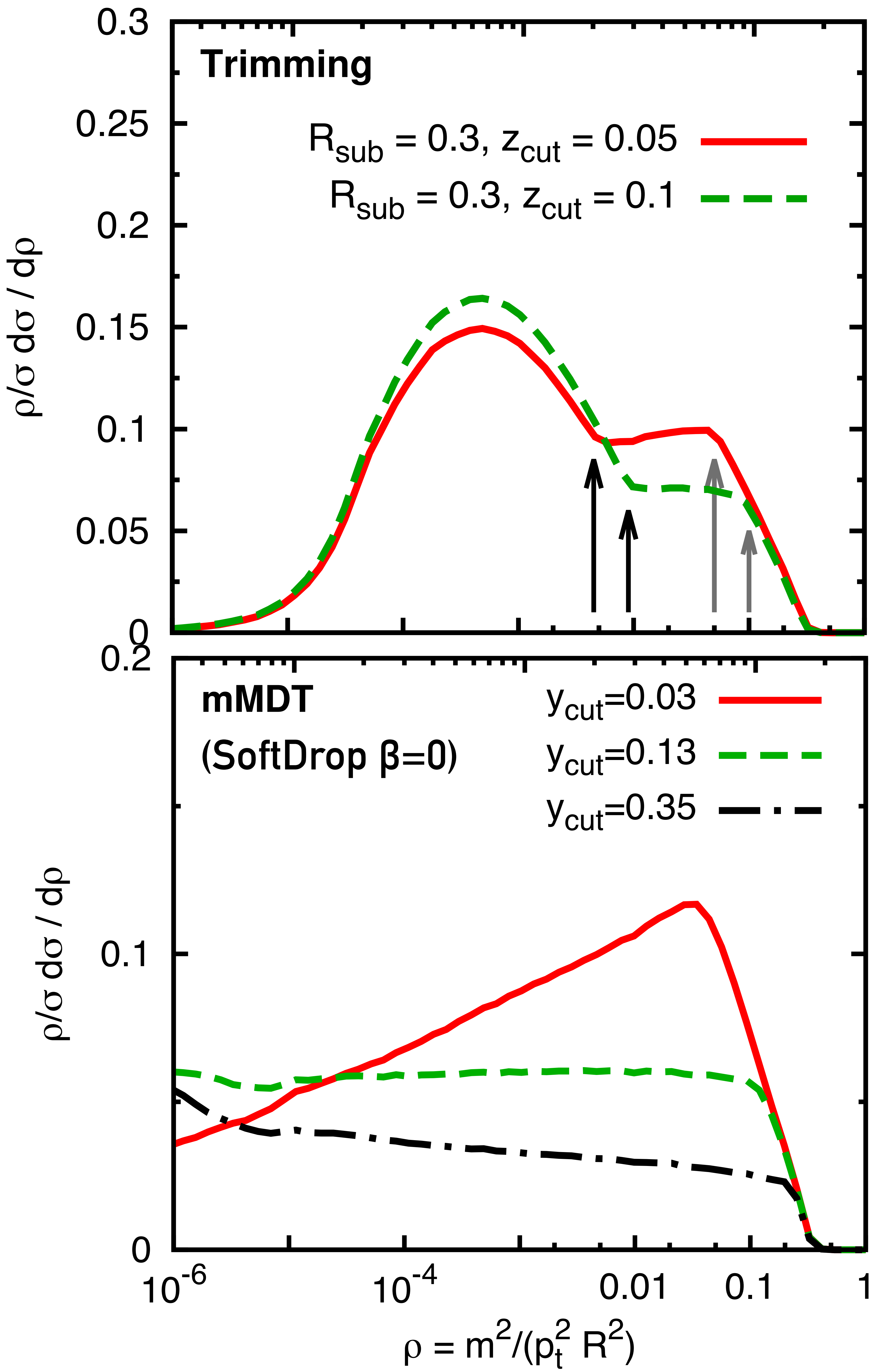


NB: z_{cut} chosen to keep signal efficiency fixed at 35% for all β

Plots from Larkoski, Marzani, Soyez & Thaler arXiv:1402.2657

For comparison: trimming sculpts background much more

- Trimming has three structures, induced by
  - z_{cut}
  - R_{sub}
  - Sudakov peak
- In comparison: just one structure in mMDT/SoftDrop (z_{cut})



SoftDrop β=0 (≡mMDT) has particularly simple QCD structure

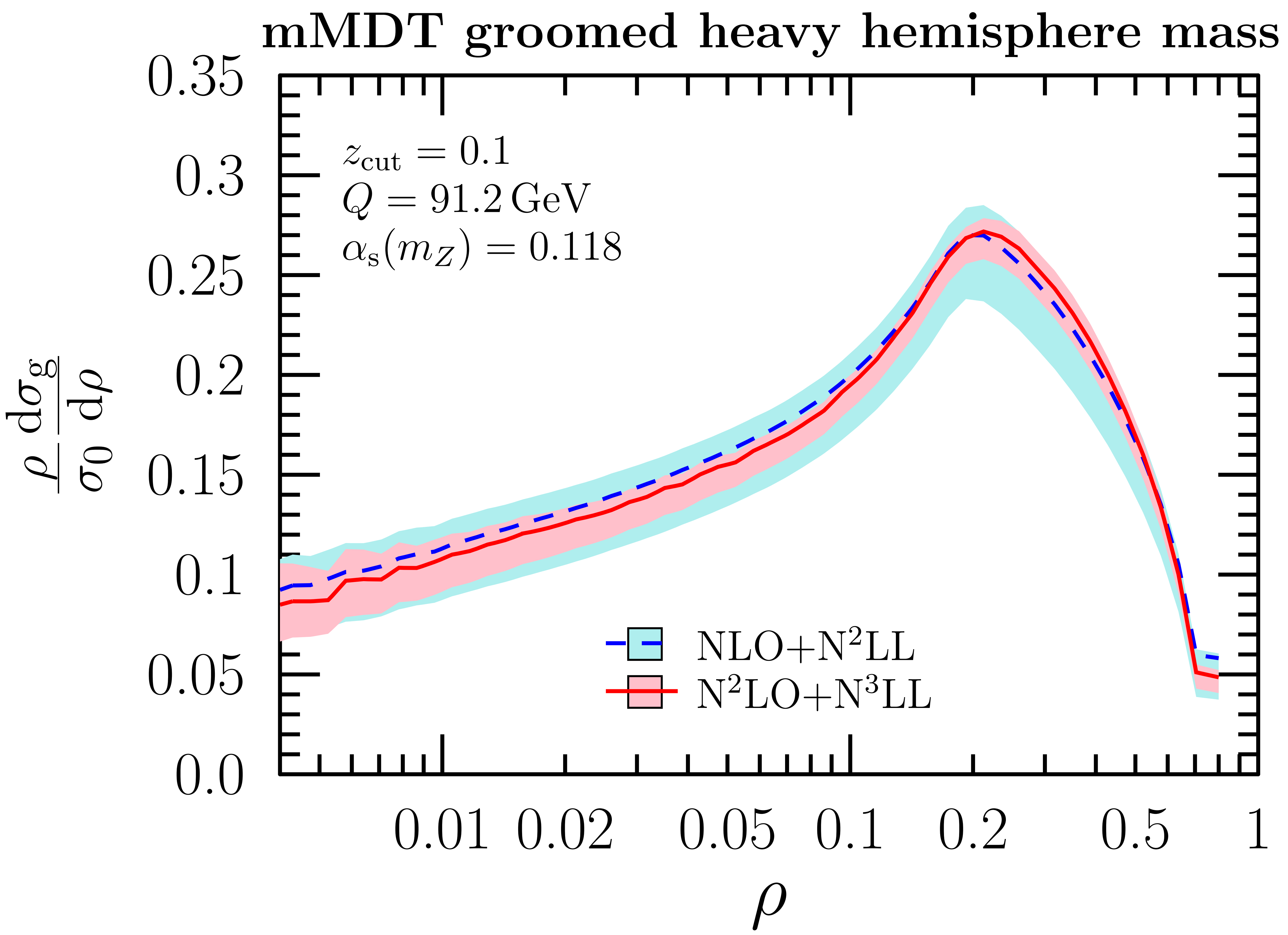
- most jet mass definitions involve **double-logarithmic** terms

$$(\alpha_s \ln^2 p_t/m)^n$$

- mMDT/SoftDrop($\beta = 0$) has only **single logarithms**

$$(\alpha_s \ln p_t/m)^n$$

- simplicity → most accurately calculated single-jet substructure observable



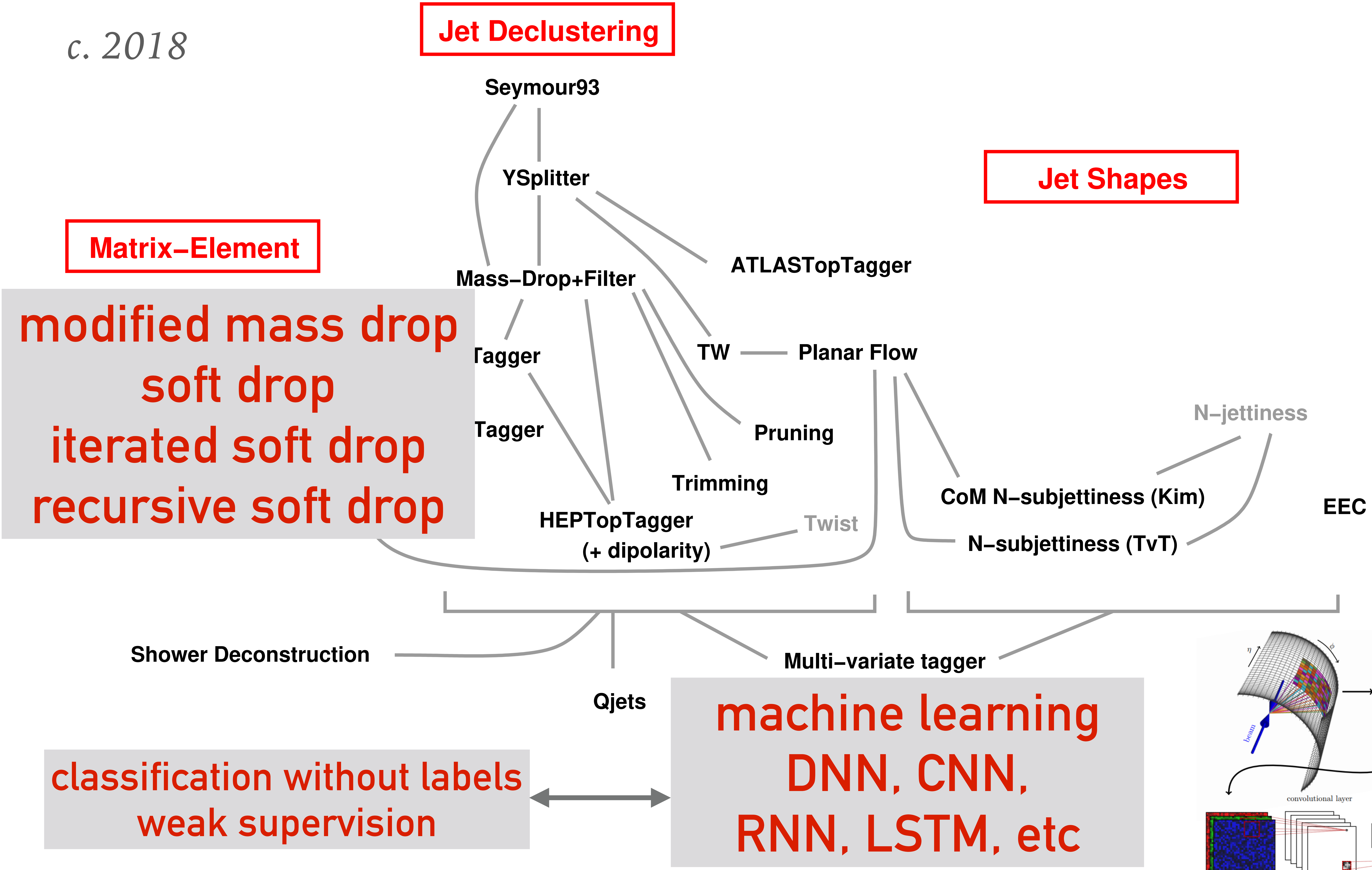
Kardos, Larkoski, Trocsanyi, arXiv:2002.00942 (small $z_{\rm cut}$)
other calc. approaches, see: Anderle et al, arXiv:2007.10355

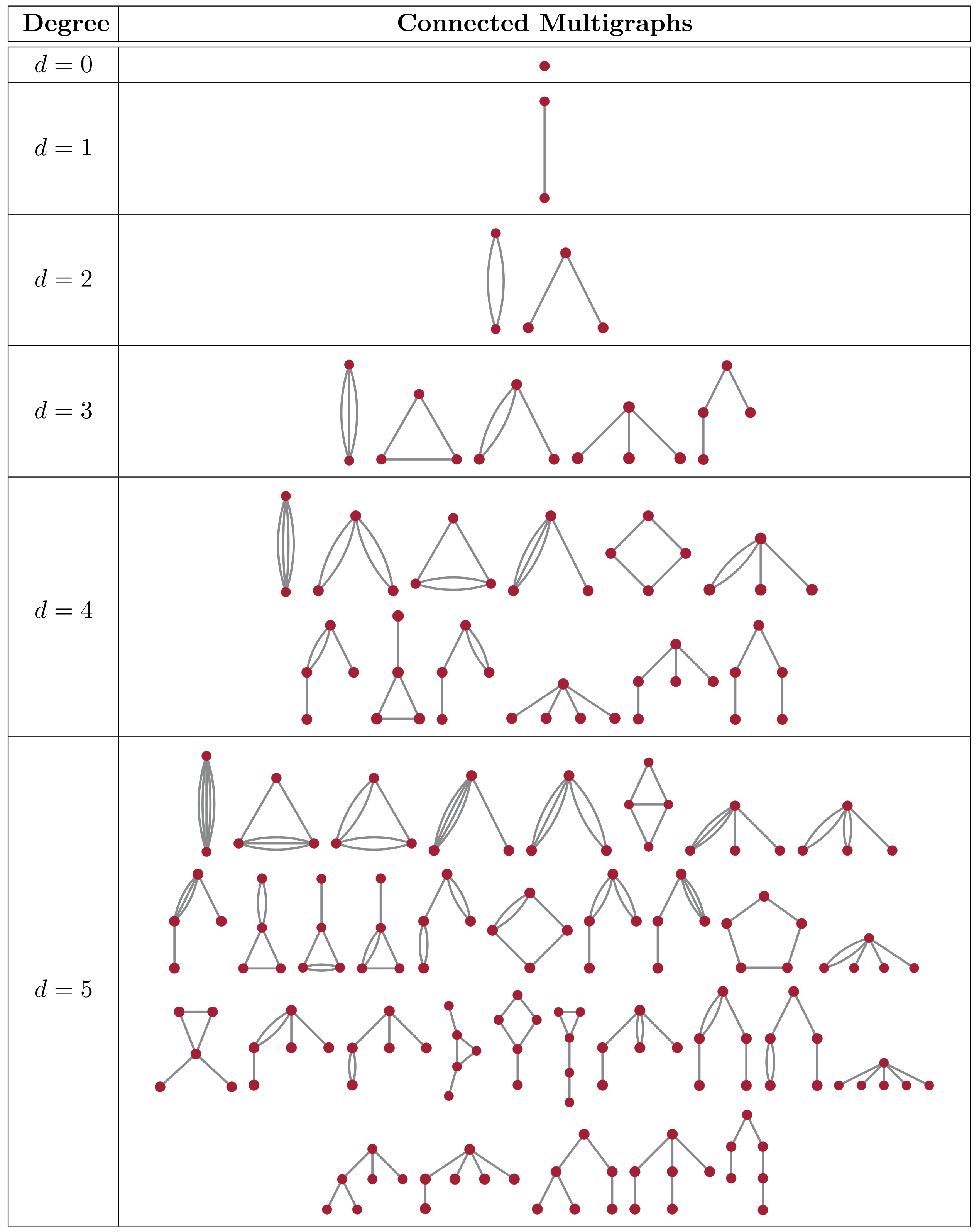
how much **more** info is there inside jets?

so far we examined use of hard 2-prong structure

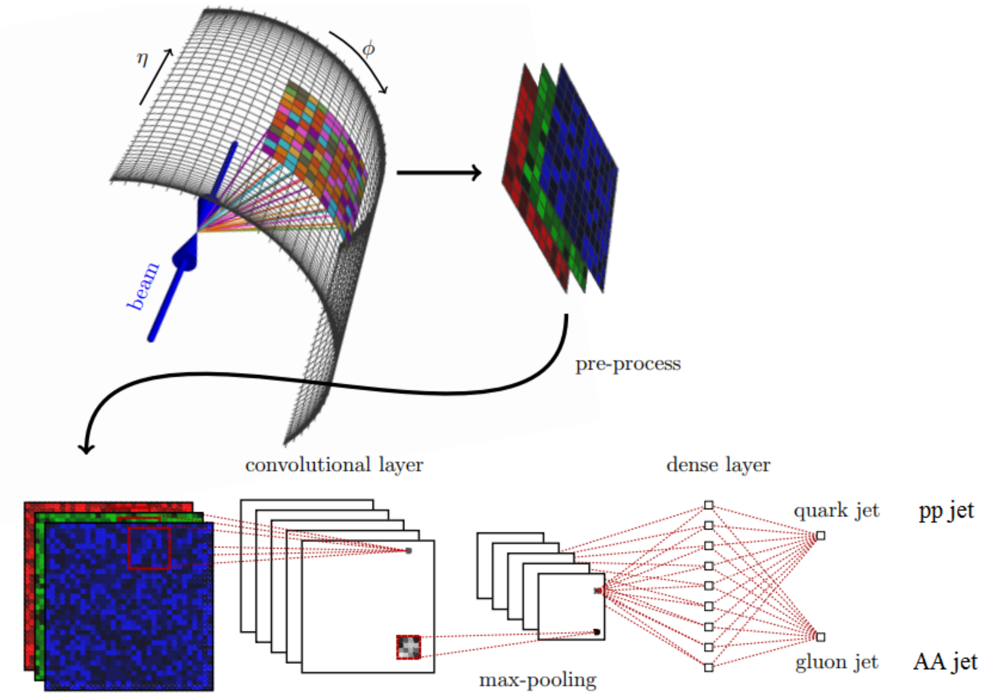
pp jet substructure field is full of activity

c. 2018



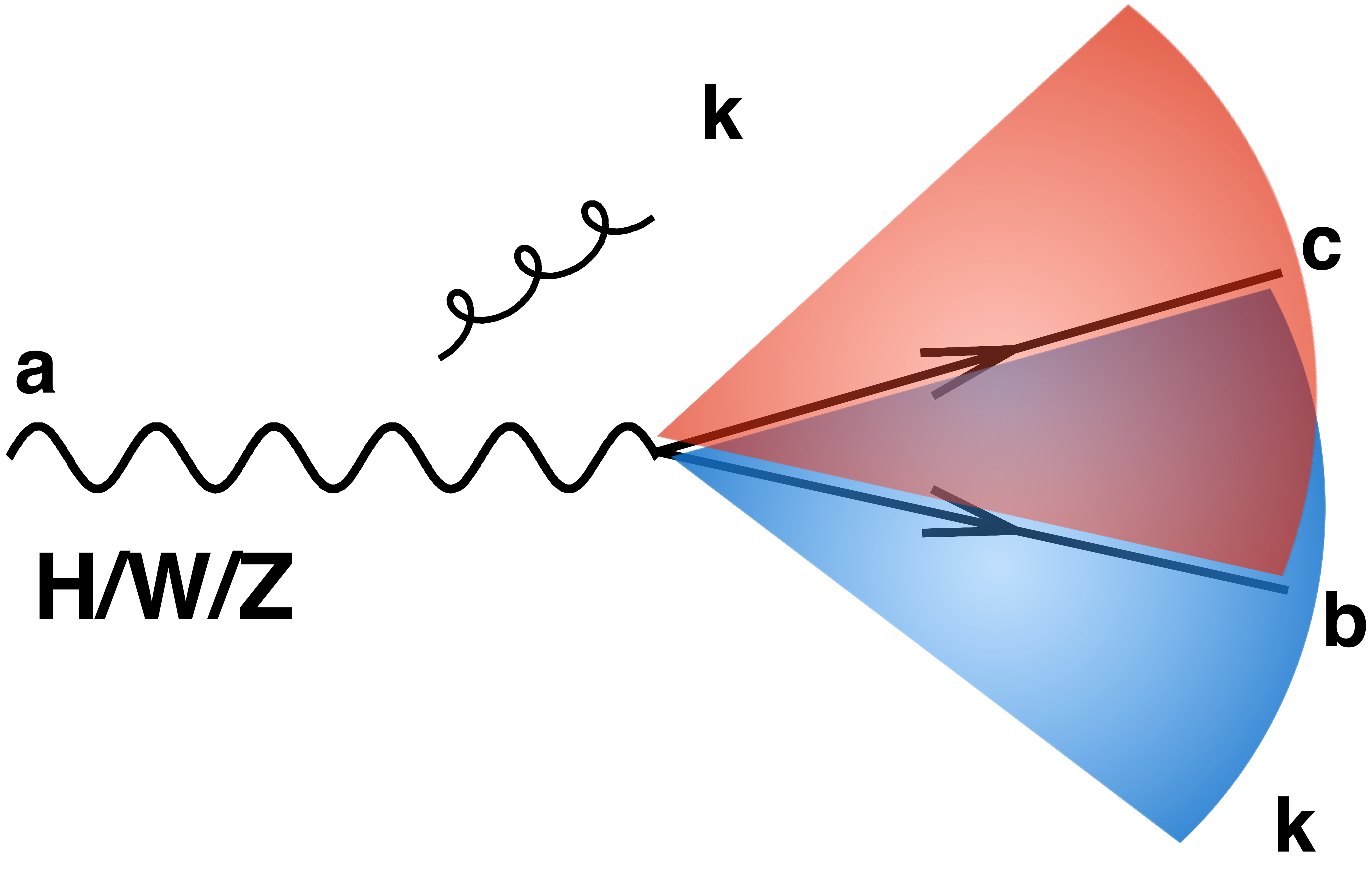


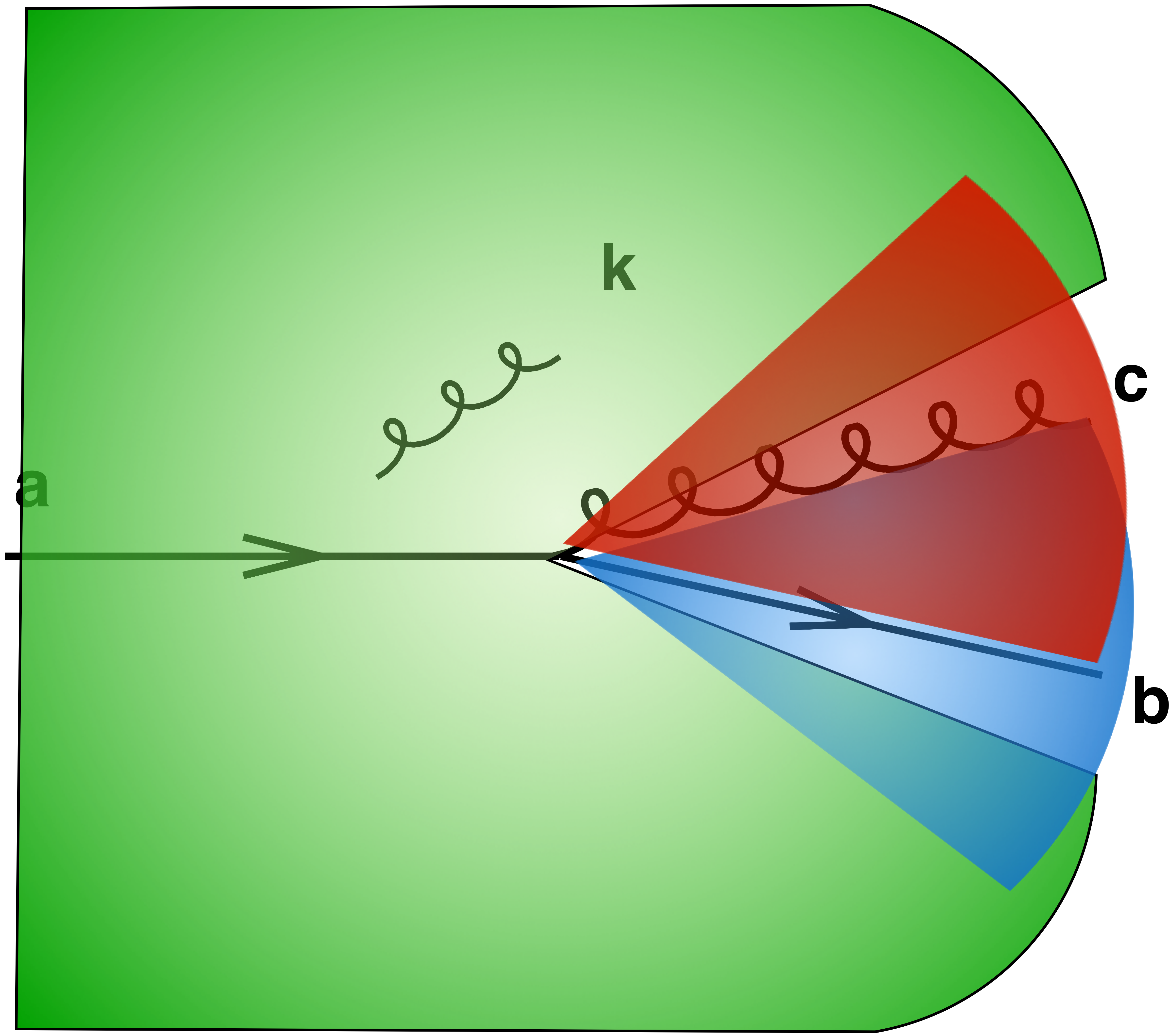
C_n, D_n, ${}_v e_n^{(\beta)}$, M_n, N_n, U_n, EFPs



etc.

signal vs. background radiation patterns (first practical exploitation, Thaler & van Tilburg, N-subjettiness, 1011.2268)



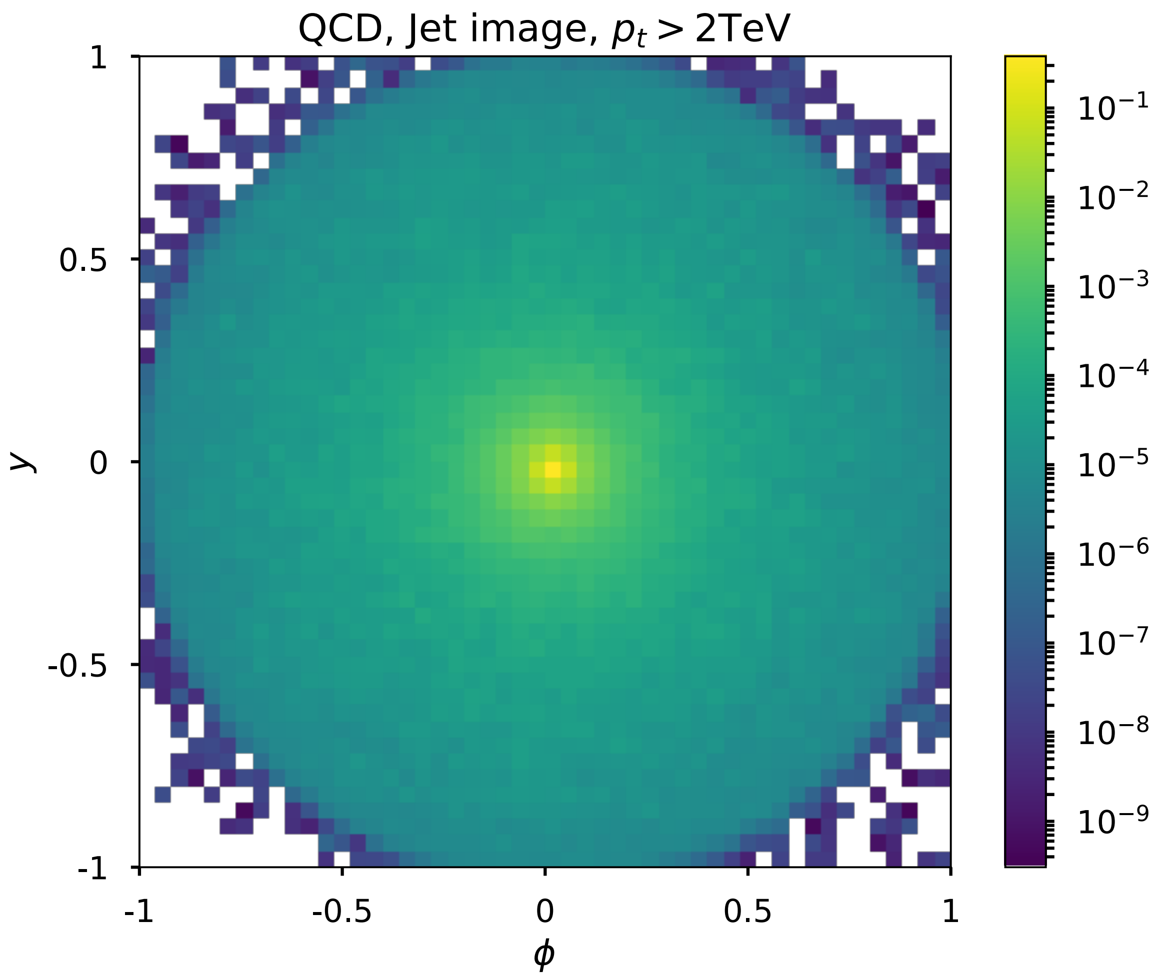


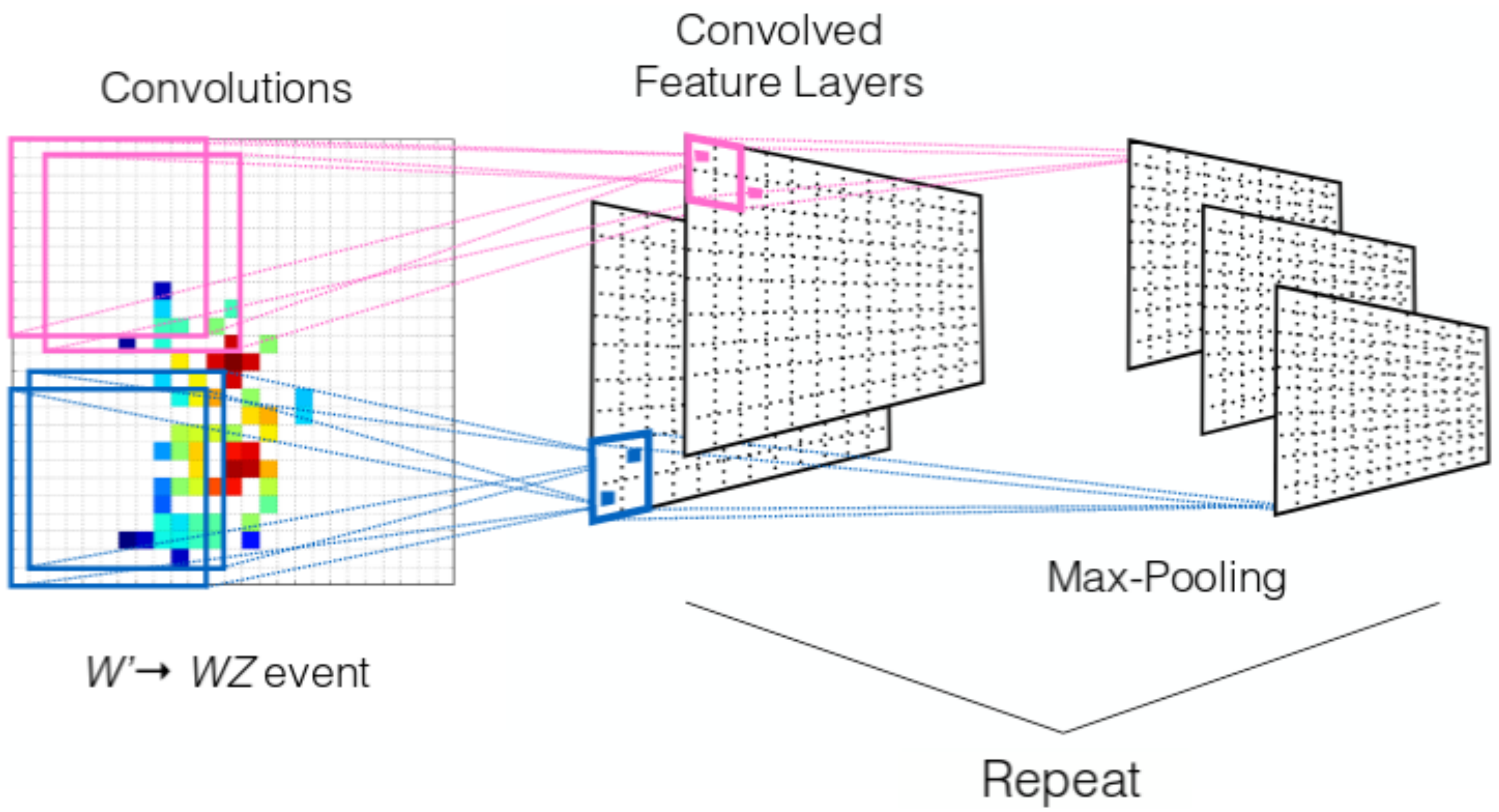
signal (H/W/Z → $q\bar{q}$)

background (q → qg)

Machine learning and jet/event structure

- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.



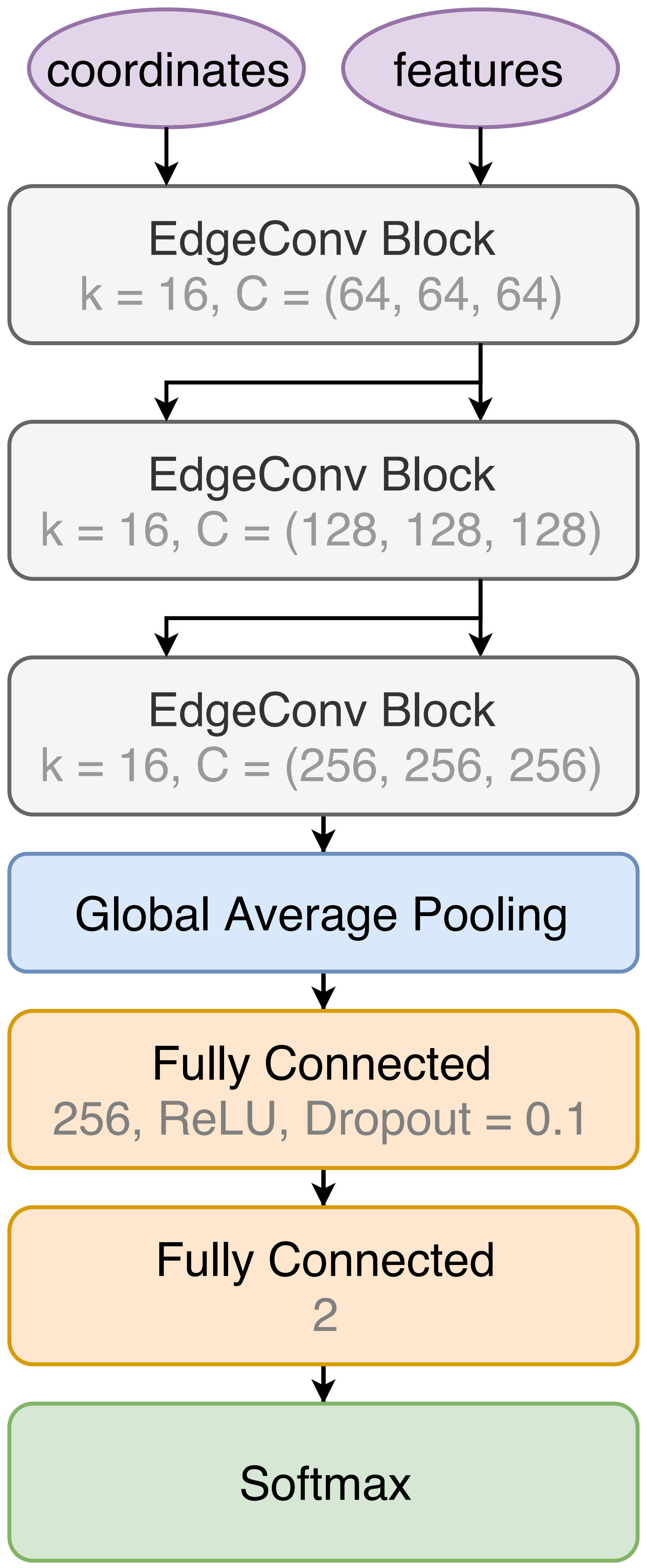


[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

↓

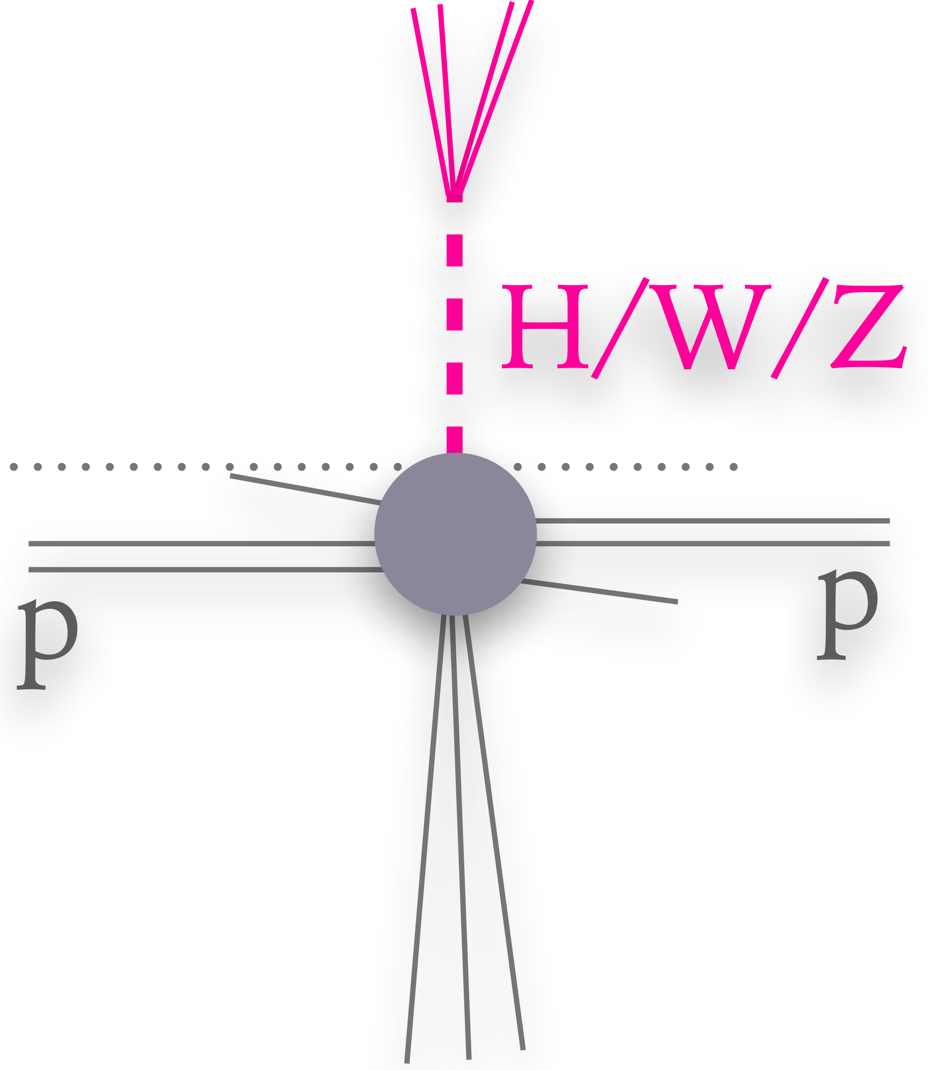
2021 Young Experimental Physicist Prize EPS HEPP prize



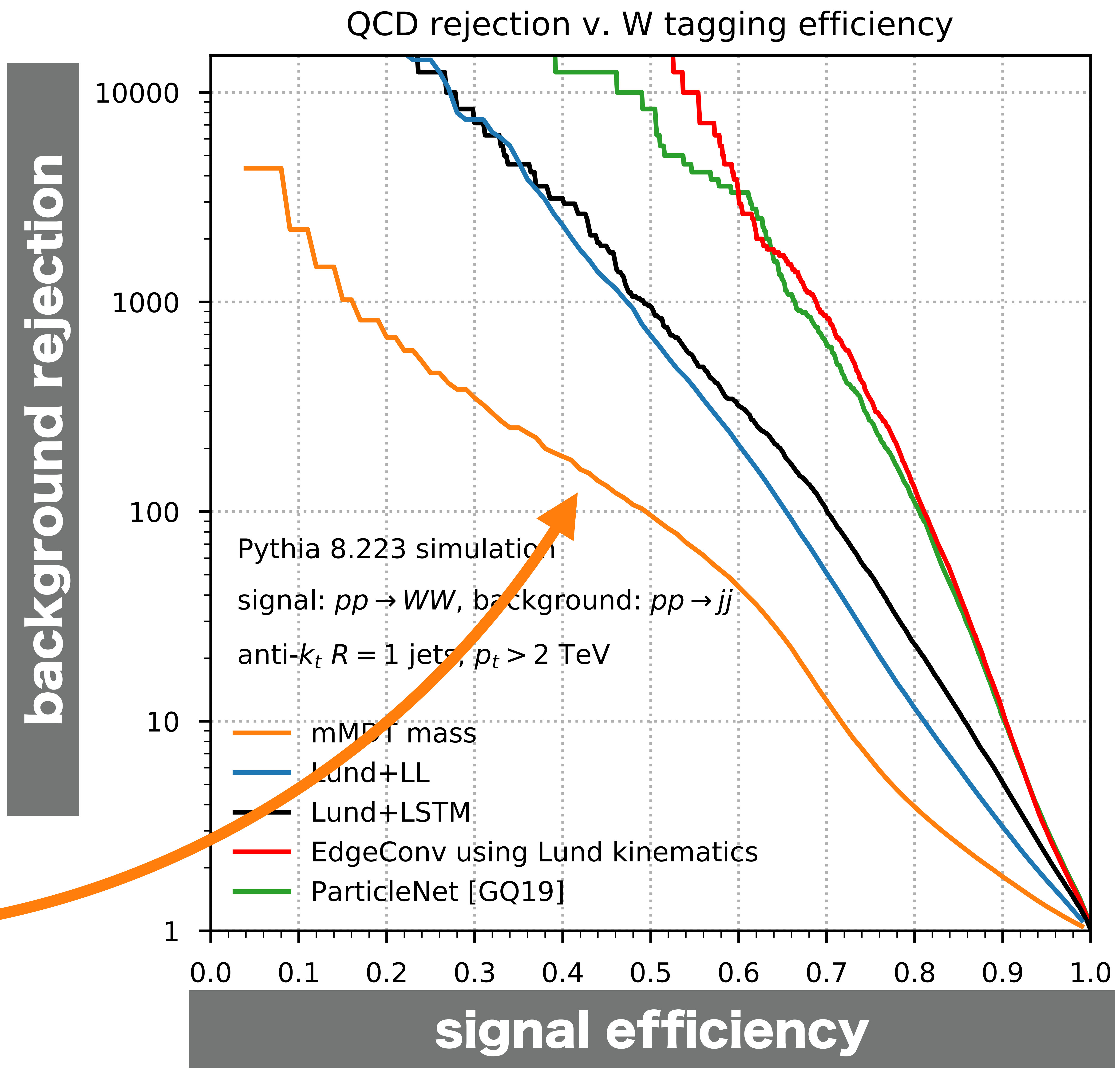
(a) ParticleNet

Qu & Guskos, arXiv:1902.08570

using full jet/event information for H/W/Z-boson tagging

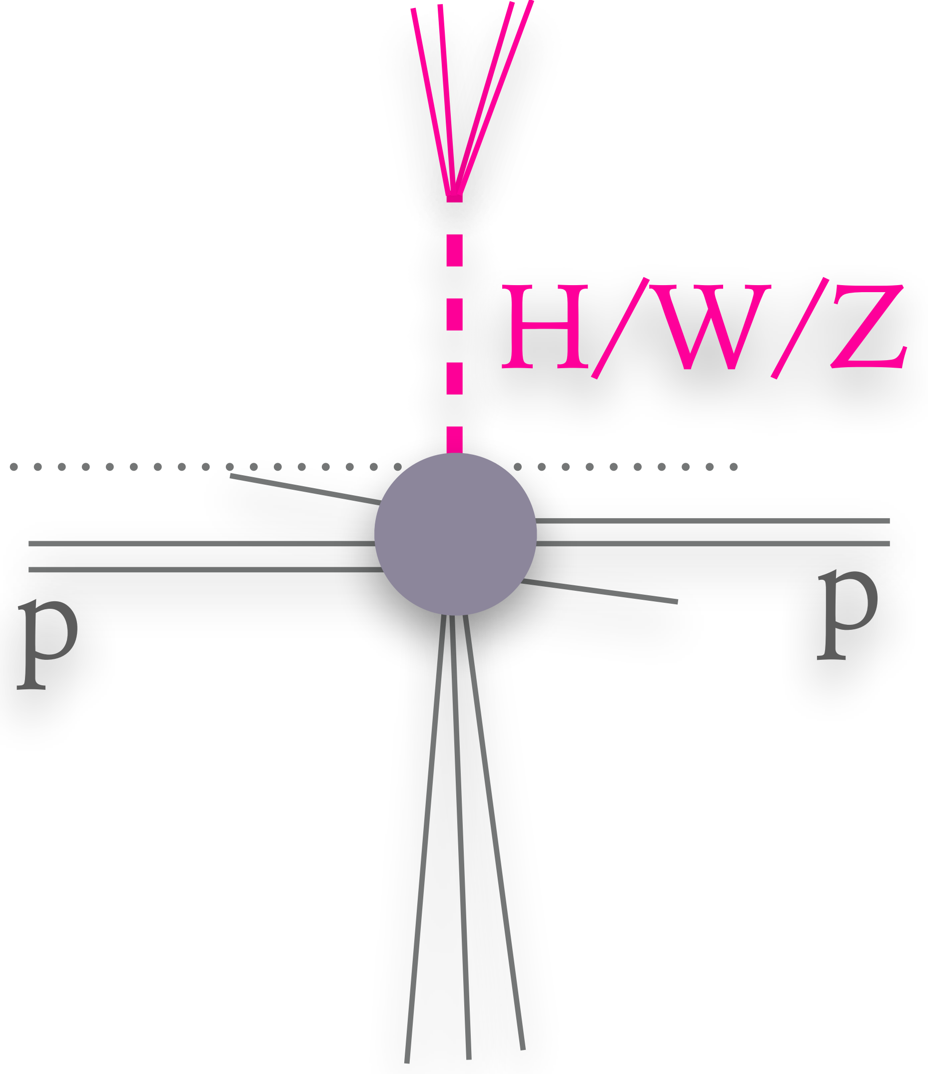


adapted from Dreyer & Qu
2012.08526

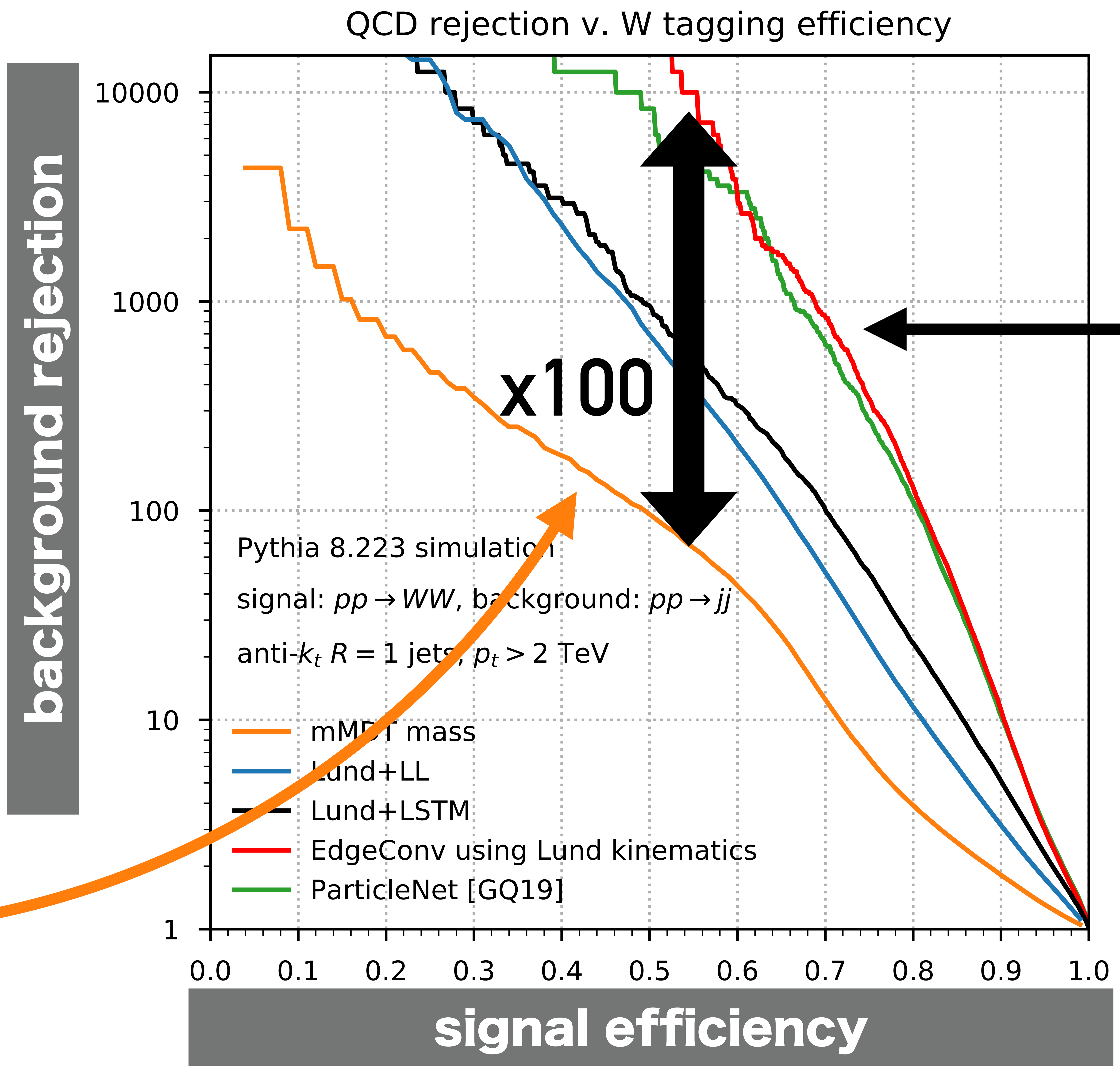


QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

using full jet/event information for H/W/Z-boson tagging



adapted from Dreyer & Qu 2012.08526



QCD rejection with use of full jet substructure (2021 tools)

100x better

QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

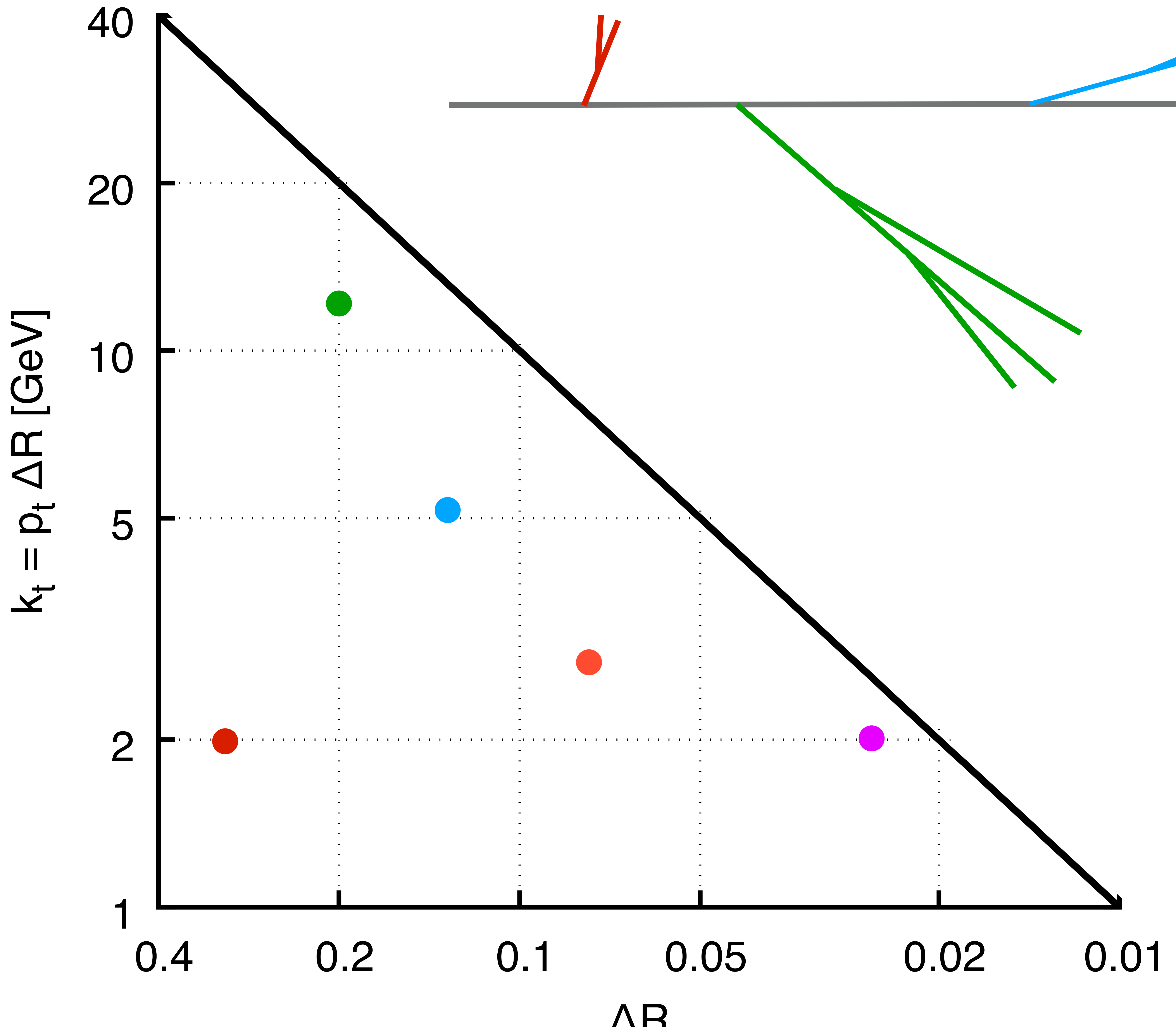
can we trust machine learning? A question of confidence in the training…

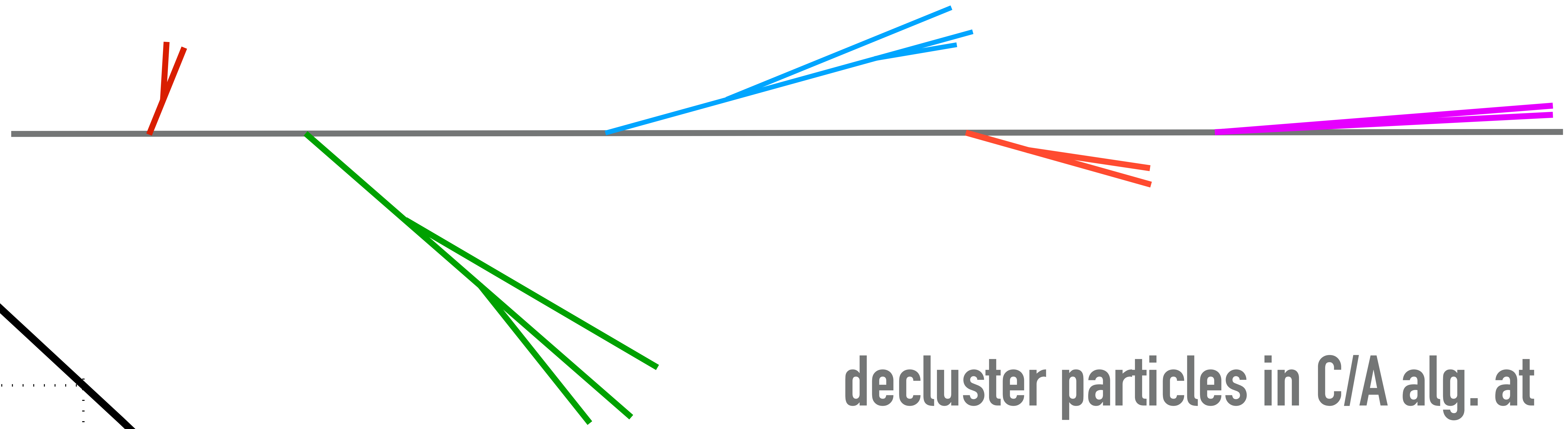
Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

can we organise phase space to work for tagging and validation?





decluster particles in C/A alg. at successively smaller angles:

at each step record $\theta (= \Delta R), k_t$

Lund plane & declustering

simple and robust

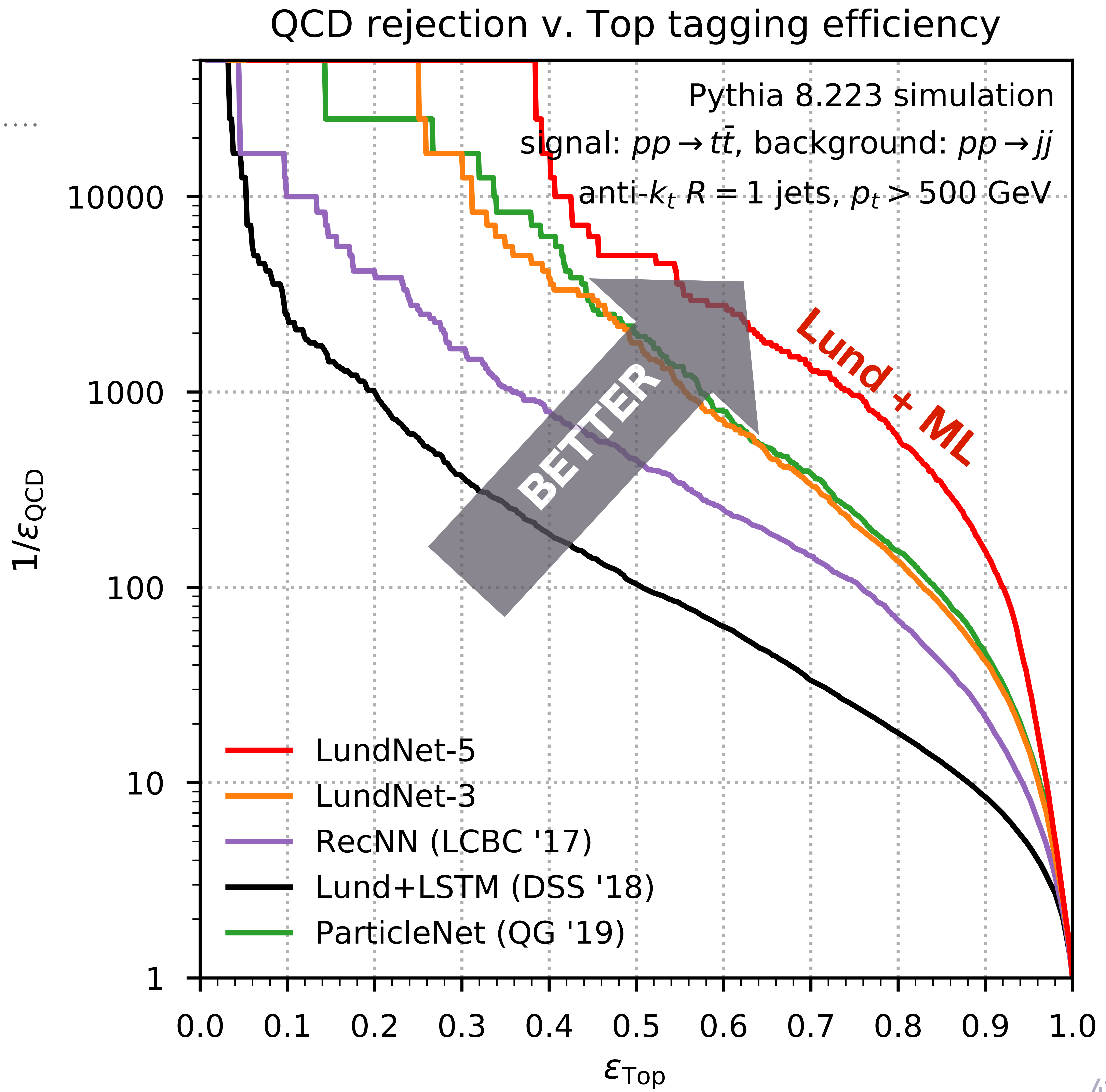
B. Andersson, G. Gustafson, L. Lonnblad and Pettersson 1989
Dreyer, GPS & Soyez, 1807.04758
& 5th heavy-ion workshop @ CERN, 1808.03689

Use as input to machine-learning

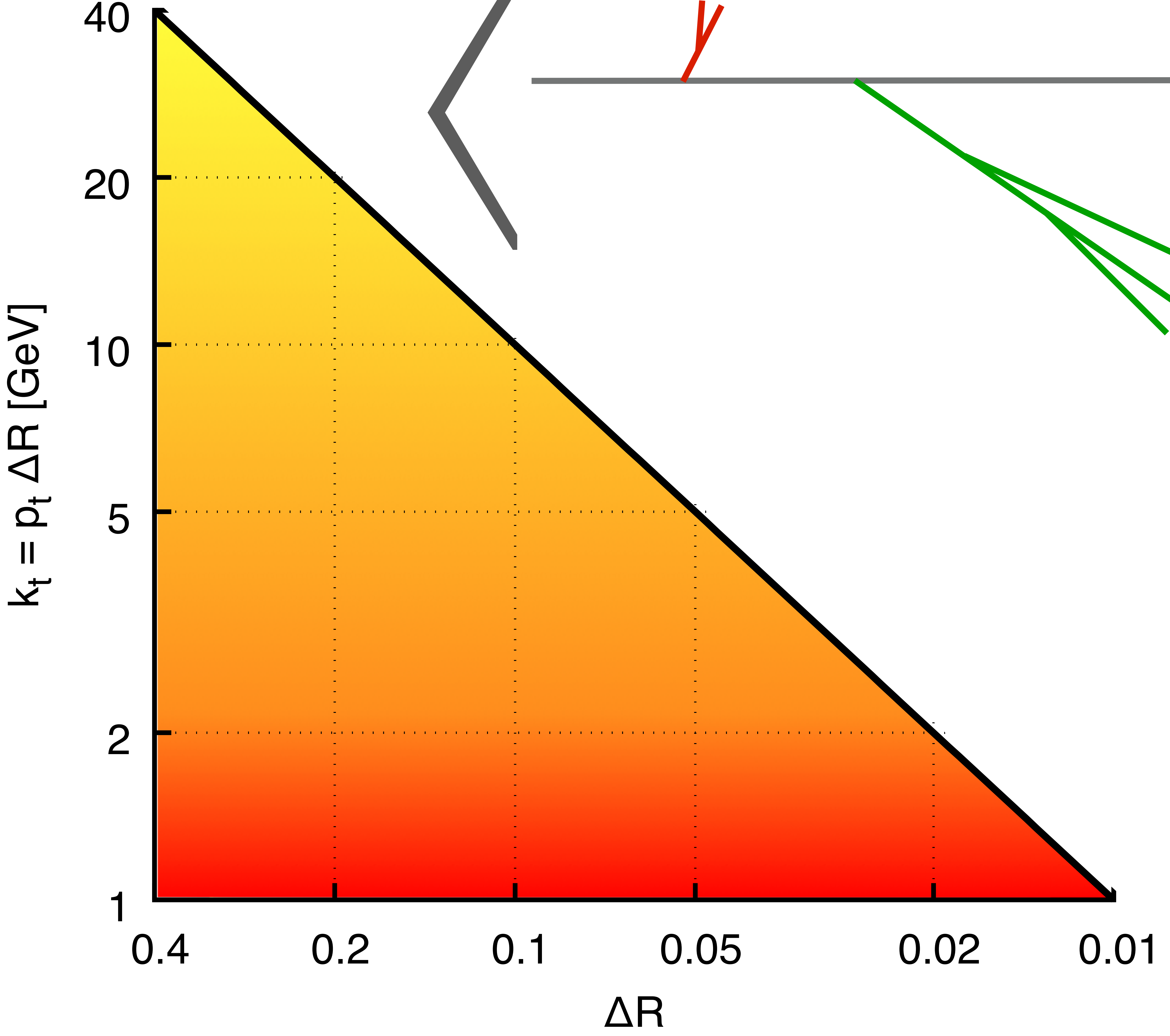
Dreyer & Qu, arXiv:2012.08526

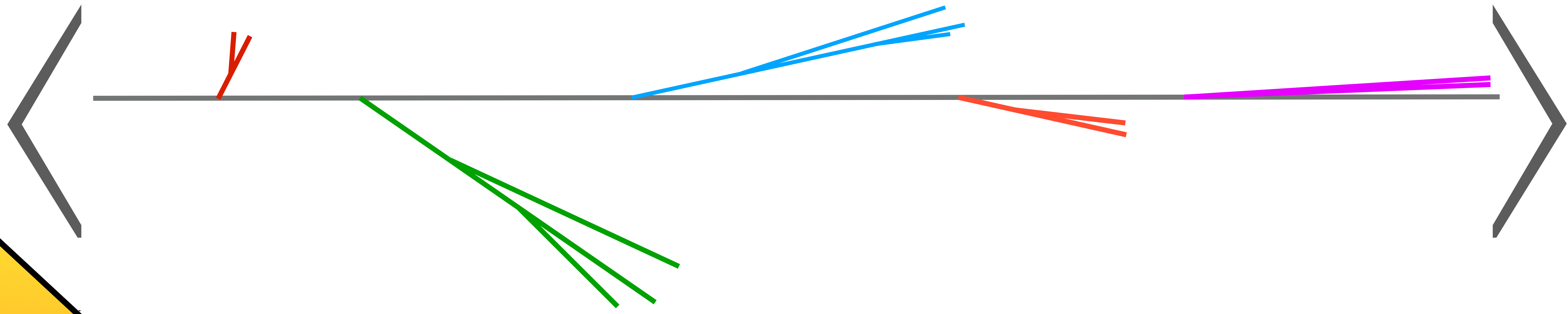
- ML with Lund inputs gives signal/background separation as good as, or better than other methods
- faster to train and to use
- these advantages probably come because the Lund diagram frames the physically relevant info in a way that makes it easier for machines to "learn"

	Number of parameters	Training time [ms/sample/epoch]	Inference time [ms/sample]
LundNet	395k	0.472	0.117
ParticleNet	369k	3.488	1.036
Lund+LSTM	67k	0.424	0.131



Same input used for ML can also be measured directly (validate / study QCD rad^n pattern)

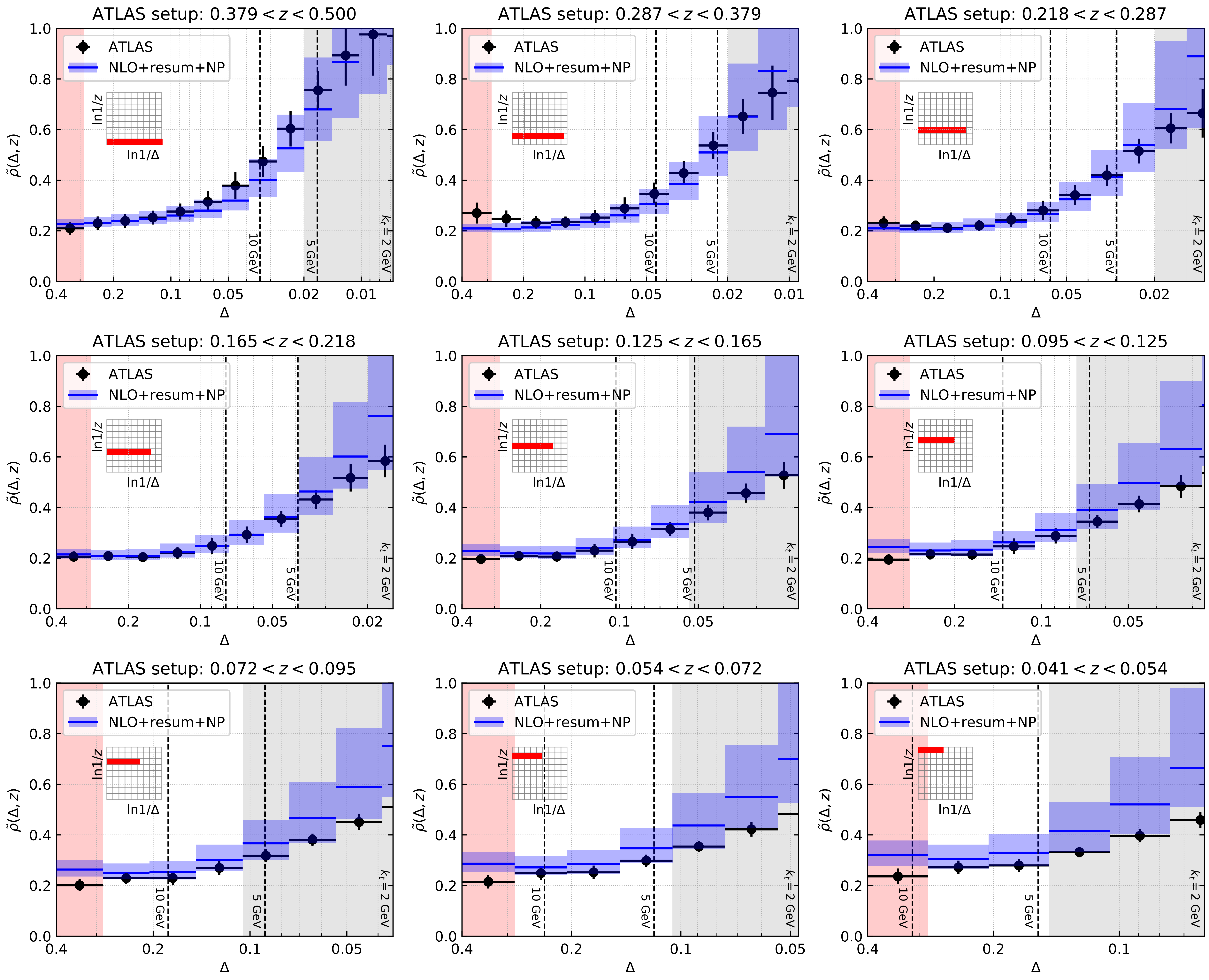




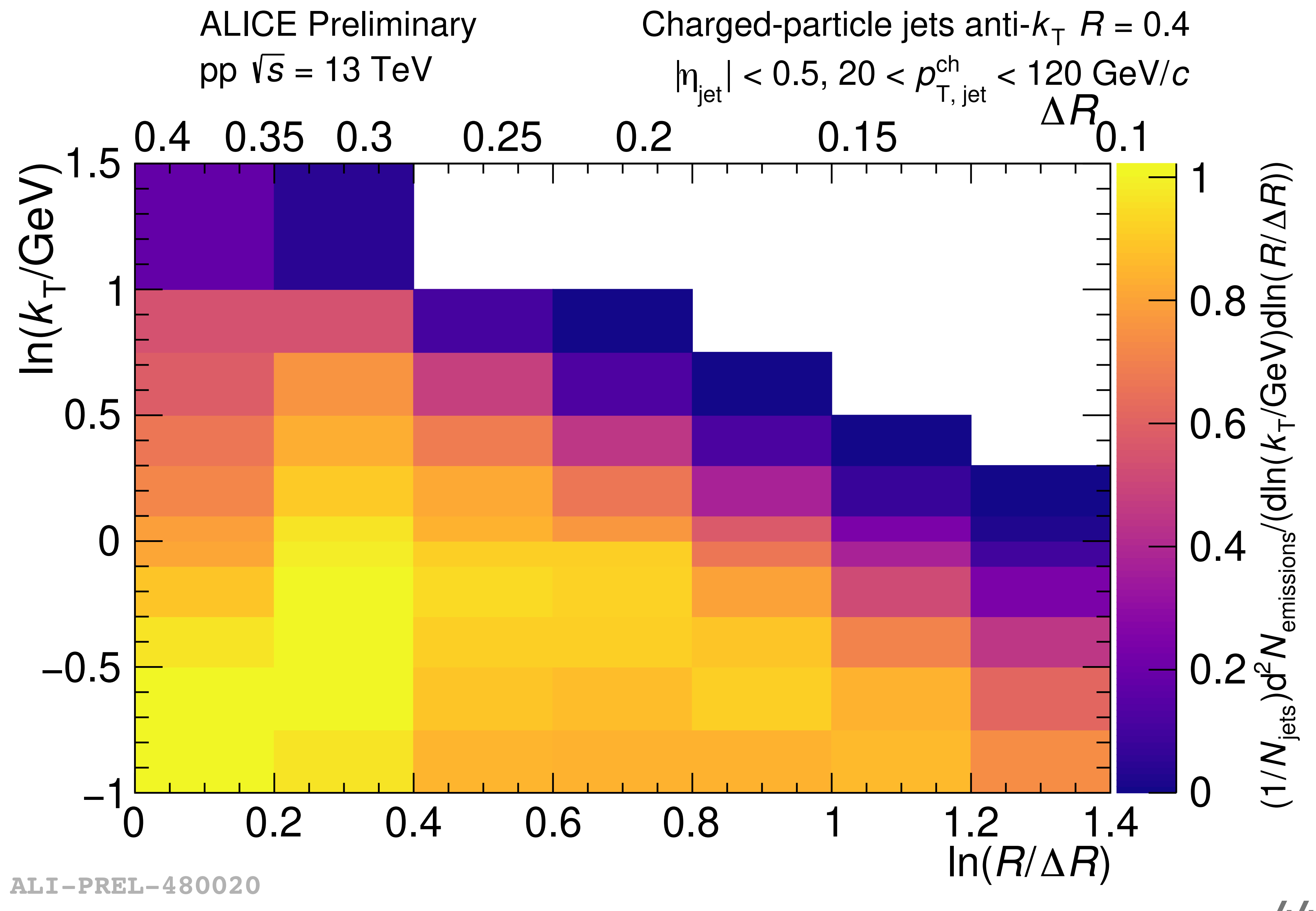
average over many jets:

Lund plane density

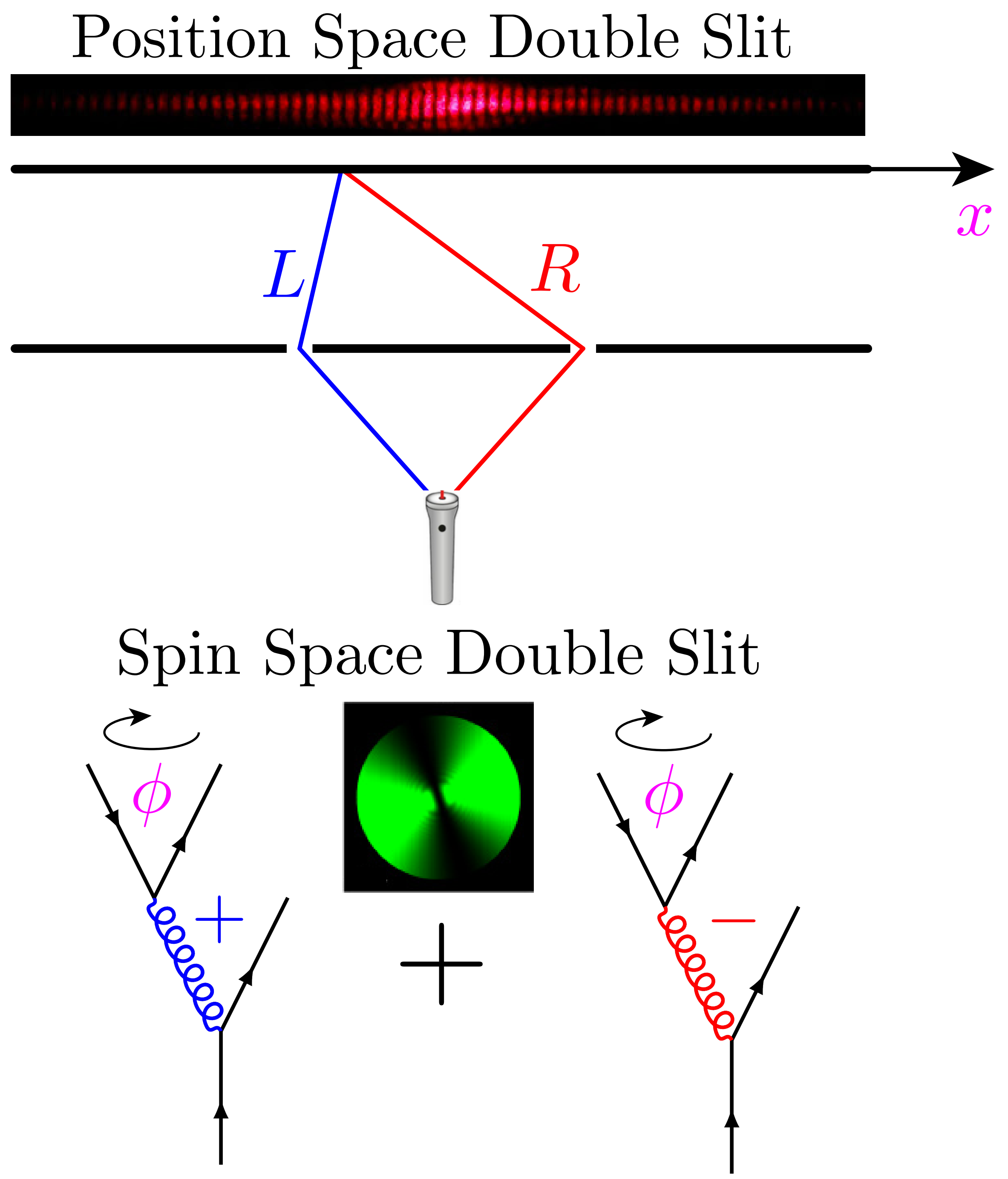
Lund plane: measured & calculated

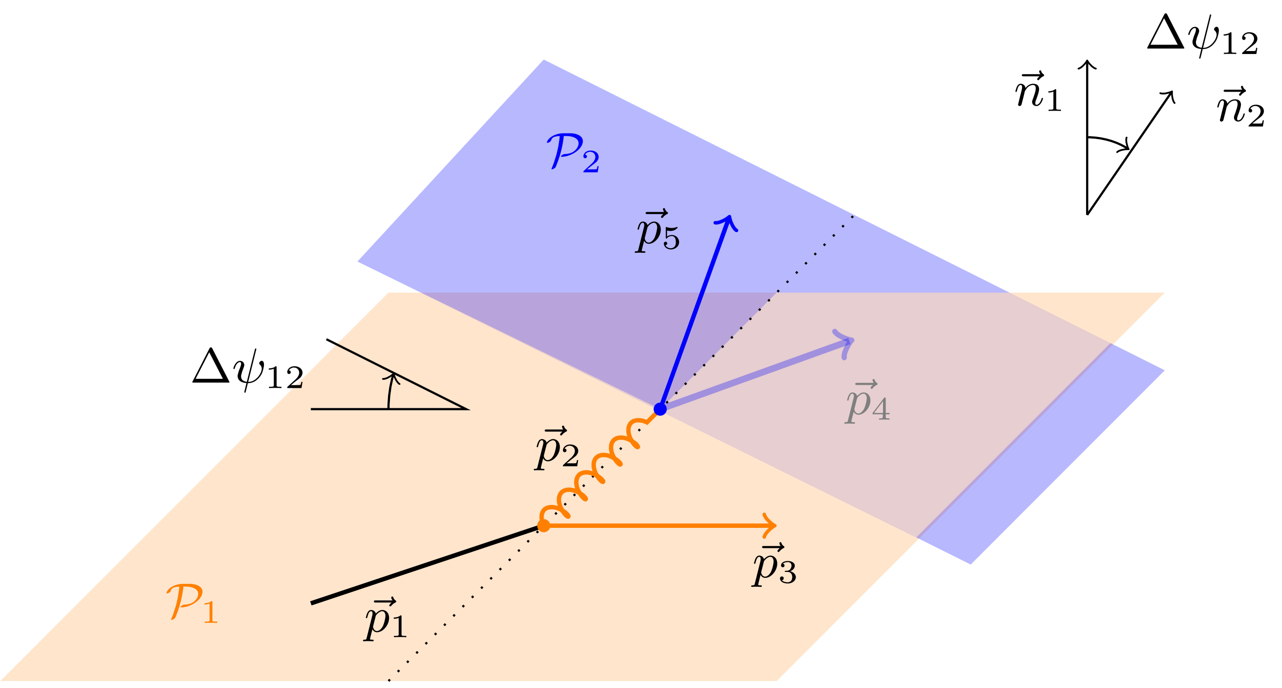


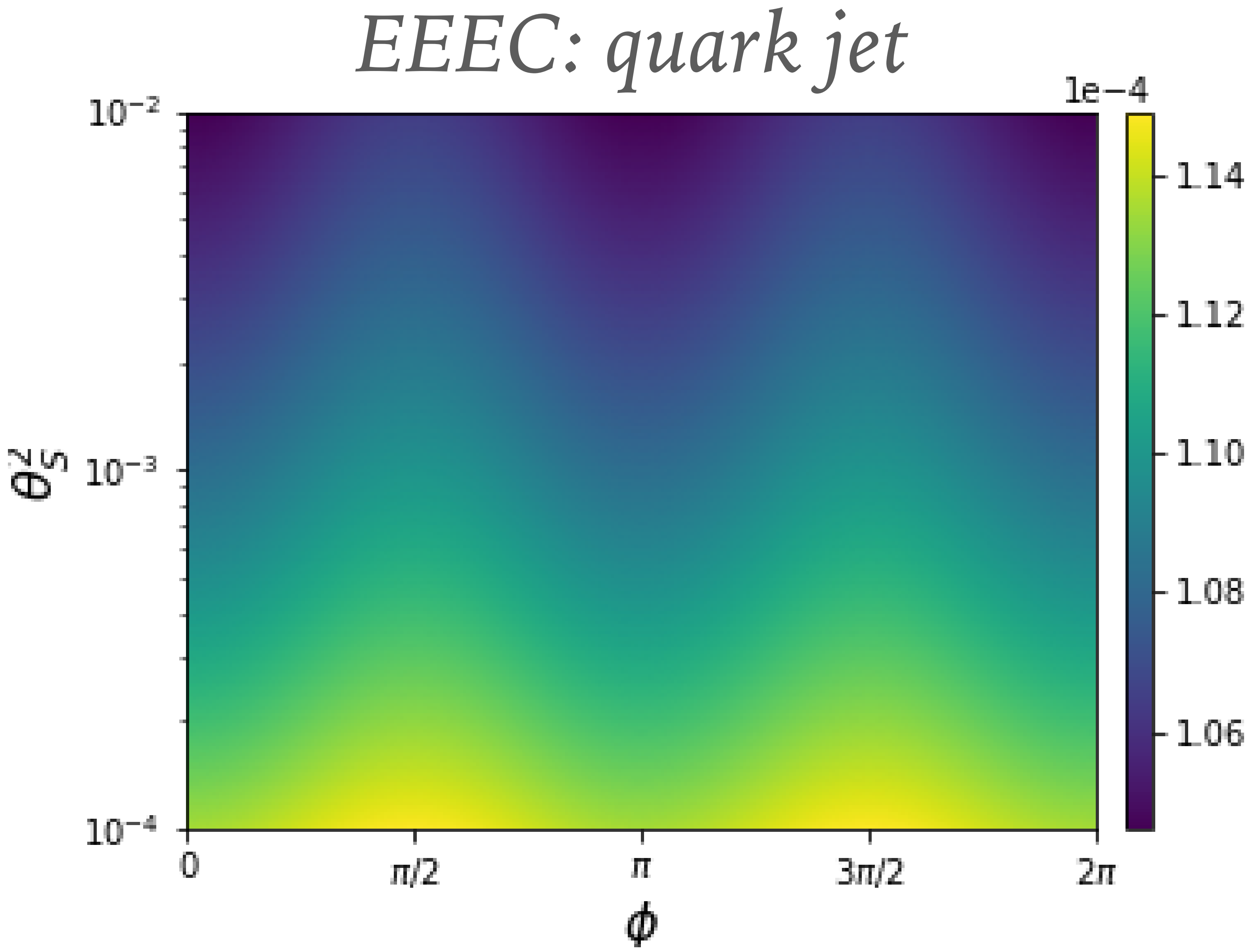
- ➤ measurements by ATLAS & ALICE
- ➤ Good agreement between ATLAS & Lifson, GPS & Soyez, arXiv:2007.06578
- ➤ powerful tests also of Monte Carlos

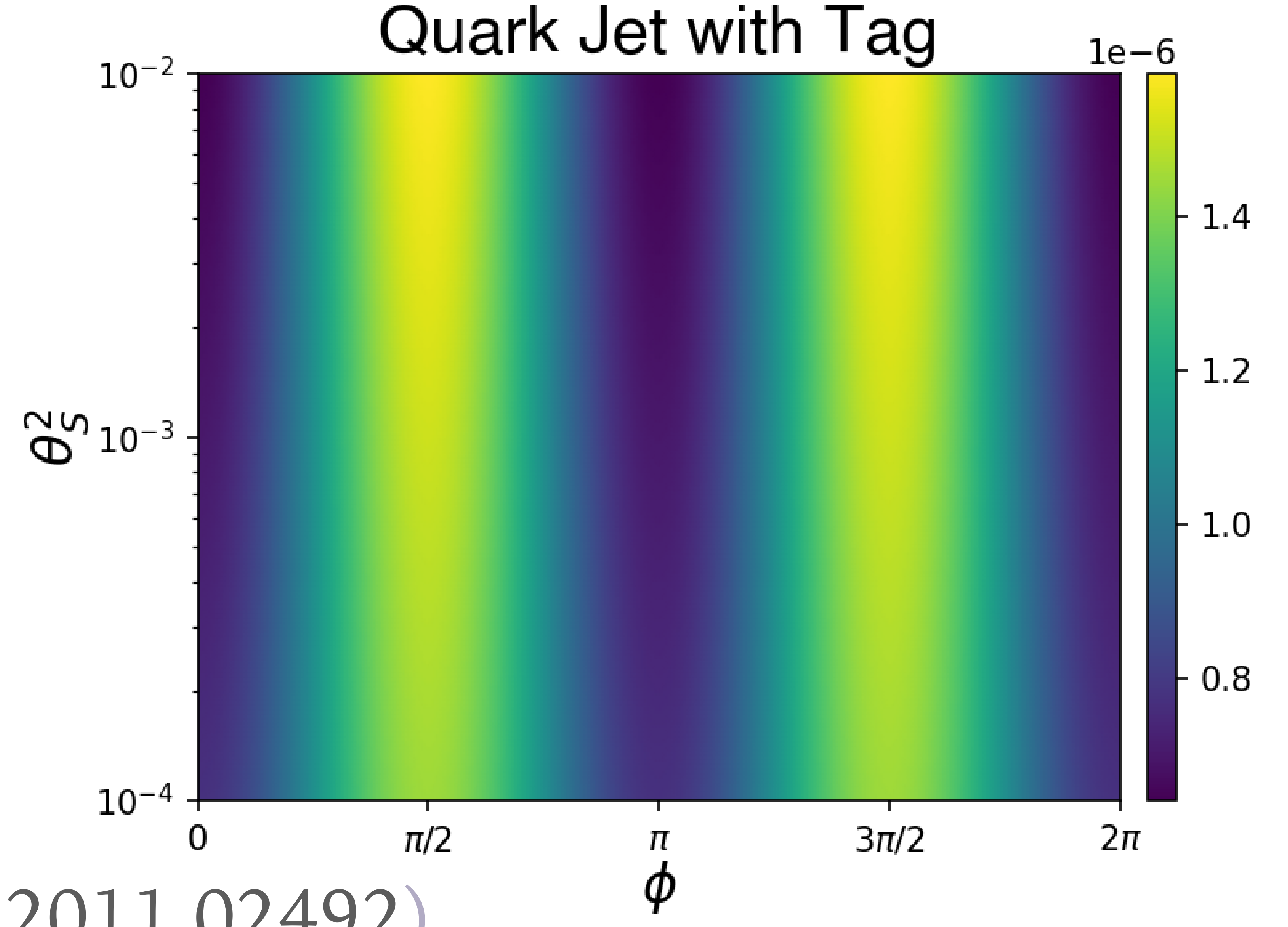


Collinear spin correlations within jets

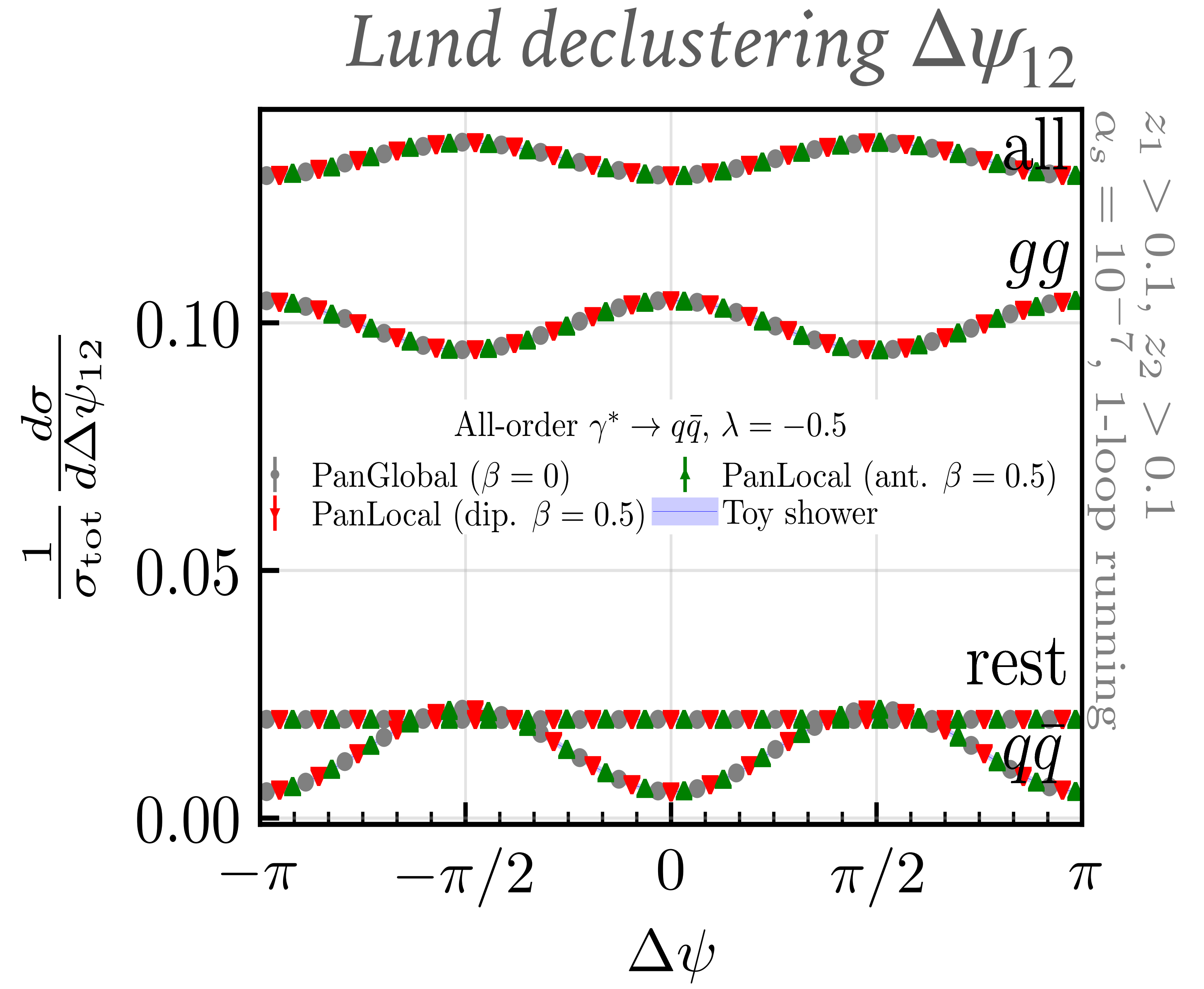








(Chen, Moult & Zhu, 2011.02492)



magnitude of spin correlation effects	
EEEC	-0.008
$\Delta\psi_{12},\ z_1, z_2 > 0.1$	-0.025
$\Delta\psi_{12},\ z_1 > 0.1,\ z_2 > 0.3$	-0.042

Karlberg, GPS, Scyboz & Verheyen, 2103.16526

conclusions

Conclusions

- Jets are a crucial part of collider physics
  Including broad programme to study new Higgs interactions and search for BSM physics
- Basic jet finding (1 quark = 1 jet) has simple, fast tools (anti-k_t, FastJet) that continue to work well 10-15 years since their inception
- Incredible how much information is hiding in jet substructure — every couple of years, people find that there is yet more info to be extracted
  - Lund declustering is one physical, powerful way of doing that (another is energy-flow polynomials)
- Will undoubtedly play major role in next 15 years of LHC, and at future e^+e^-/pp/μμ colliders
- The challenge is also on to make sure we can reliably predict the internal structure of jets and so make confident use of the associated information