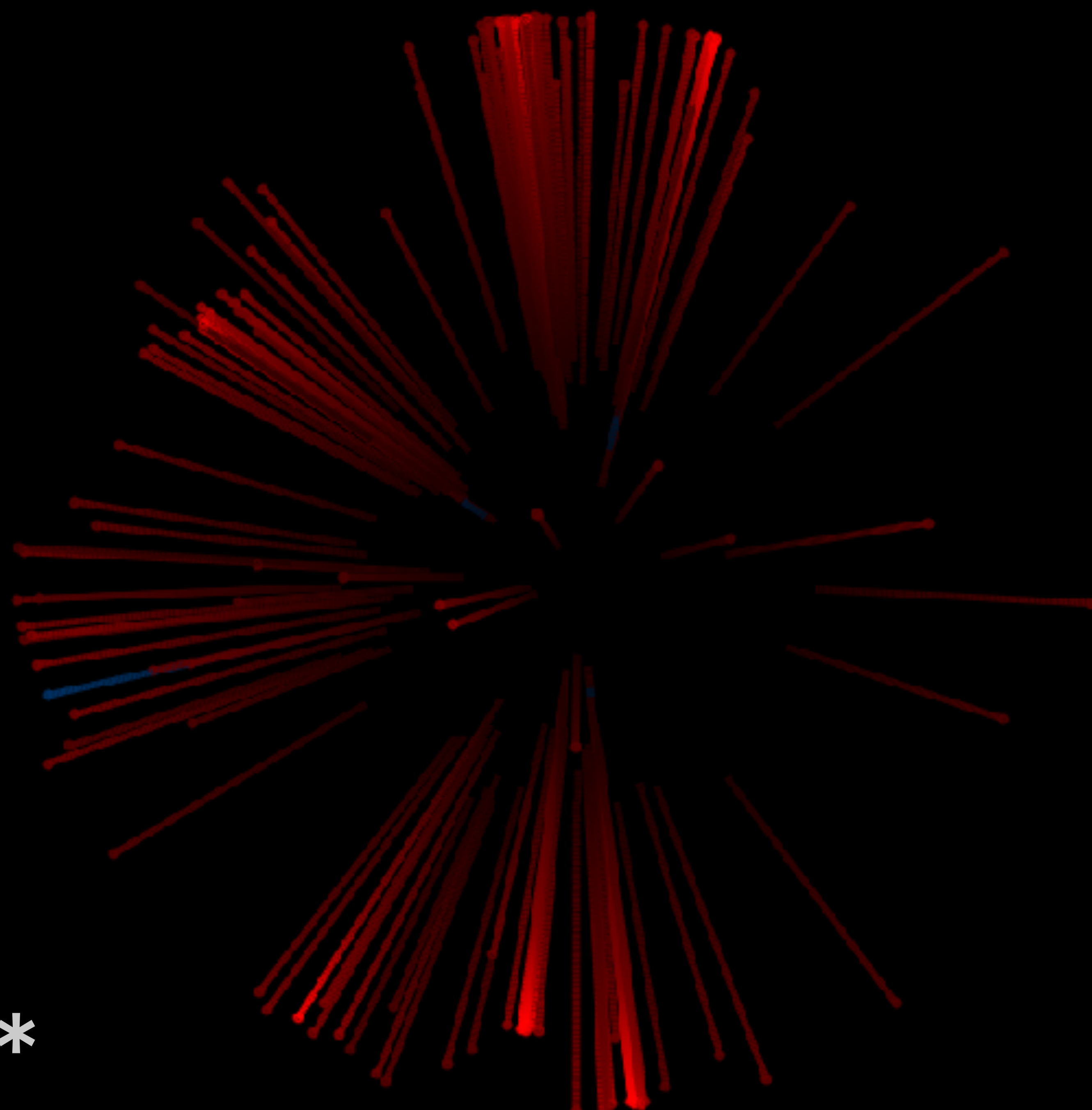
Jet Reconstruction Theory (1)

PREFIT20: PRecision Effective
FIeld Theory School
Hamburg, March 2020



Gavin Salam*

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

** on leave from CERN and CNRS*

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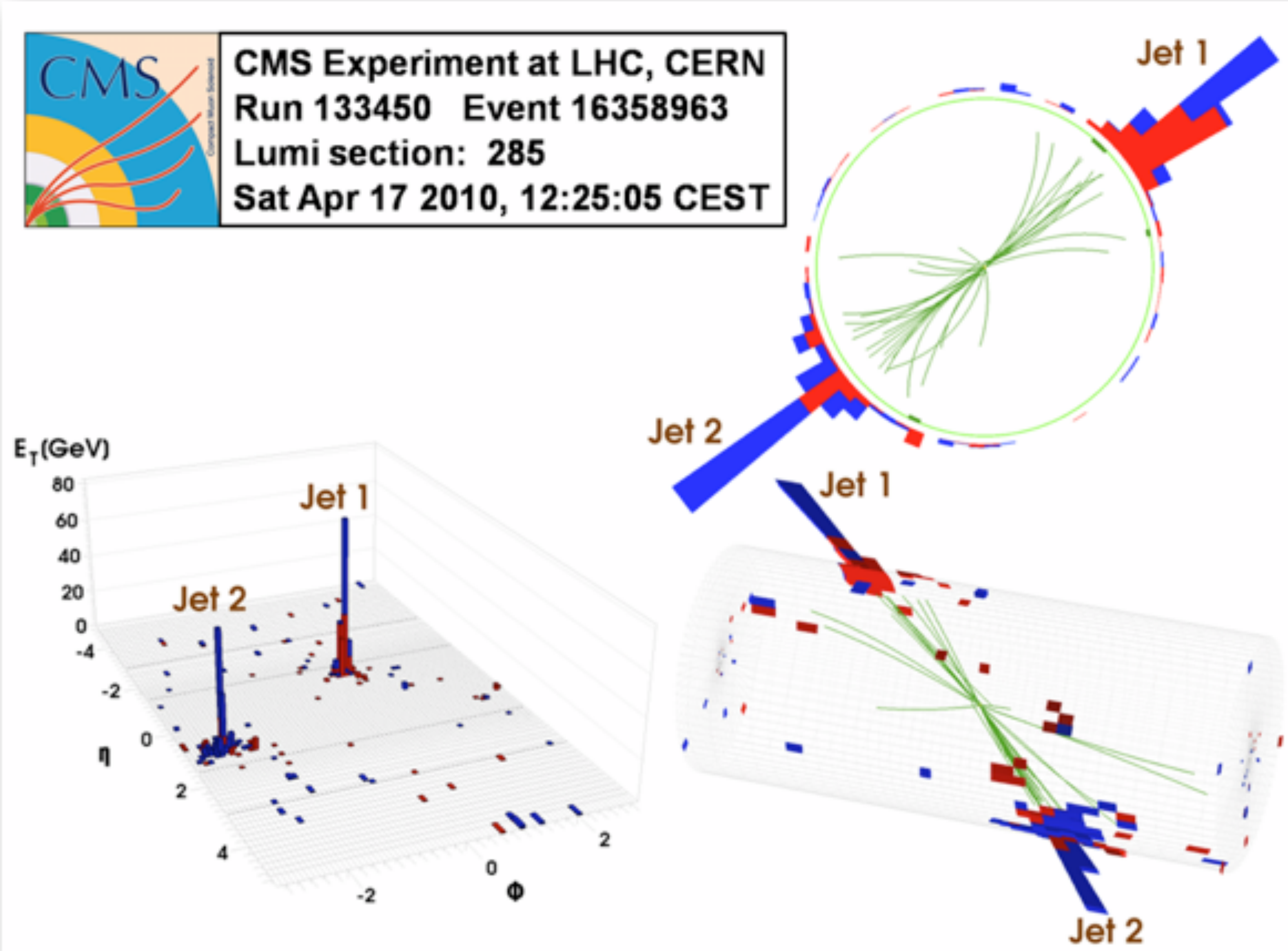

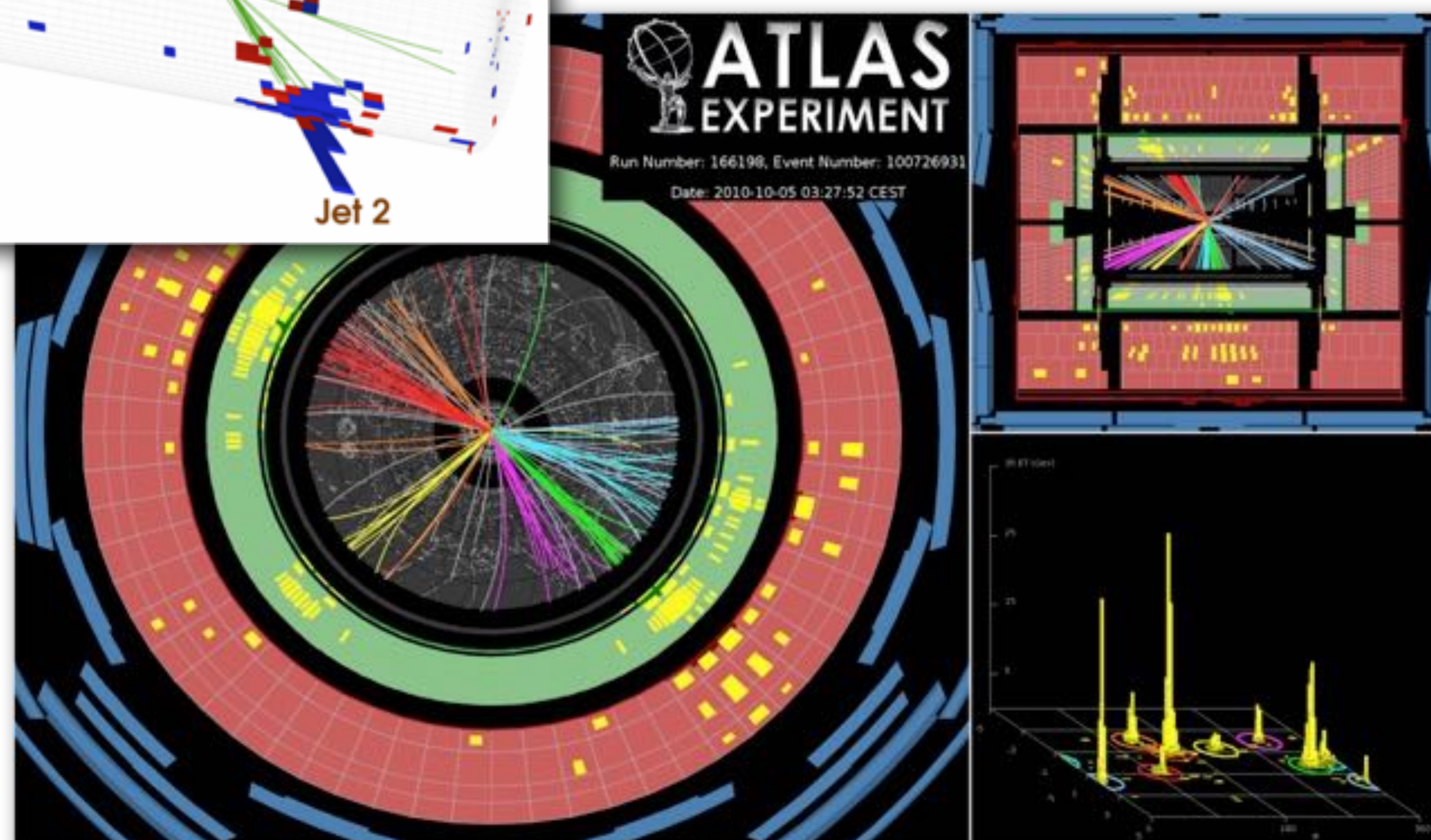

JETS

Collimated, energetic bunches of particles

Find all papers by ATLAS and CMS
2106 records found

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

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

Search on INSPIRE beta

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

Display results: 25 results | single list

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

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

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

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

1289 records found

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

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Search on INSPIRE beta

Sort by: latest first | desc. | - or rank by - Display results: 25 results | single list

> 60% of papers use jets!

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

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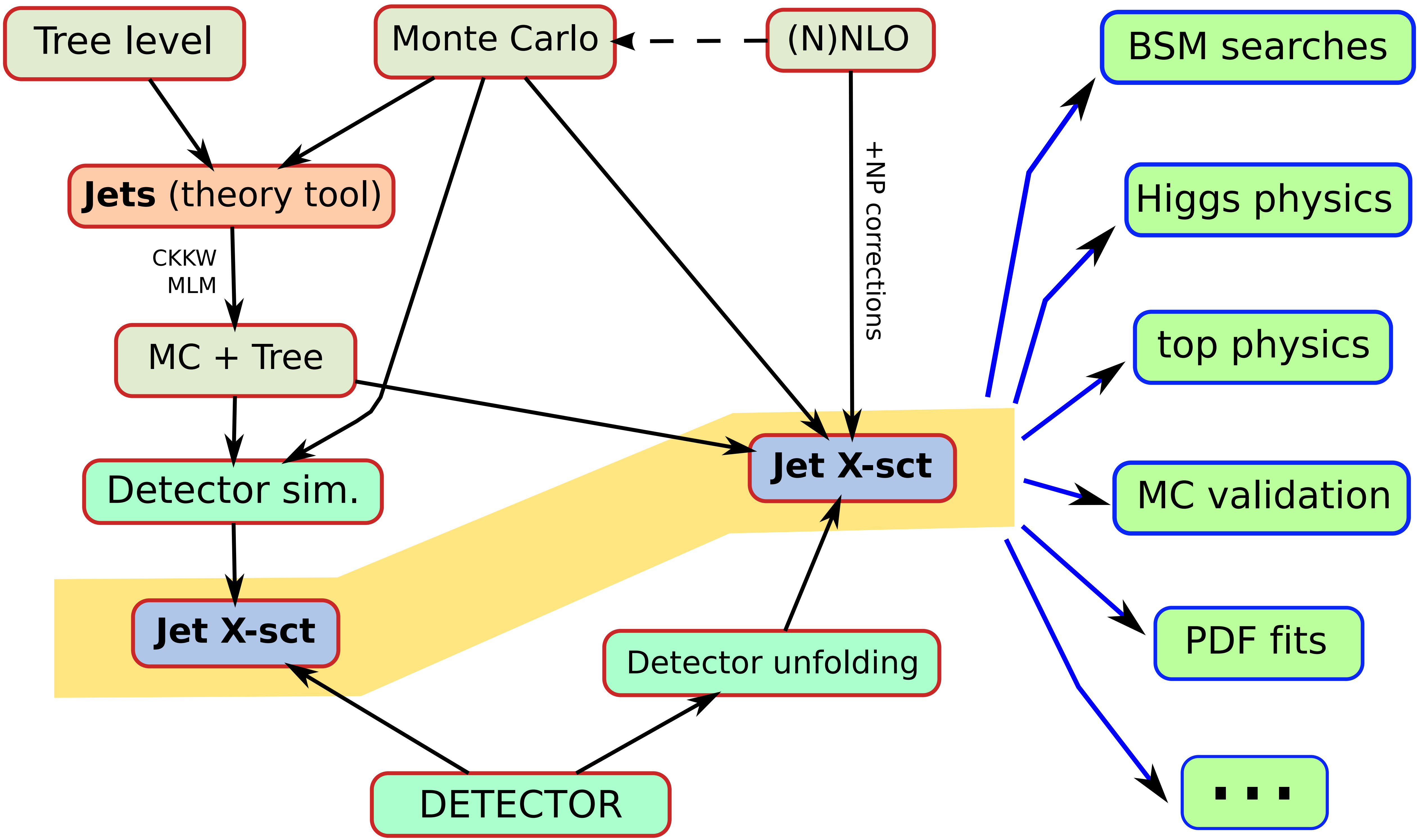
   ADS Abstract Service
   Detailed record

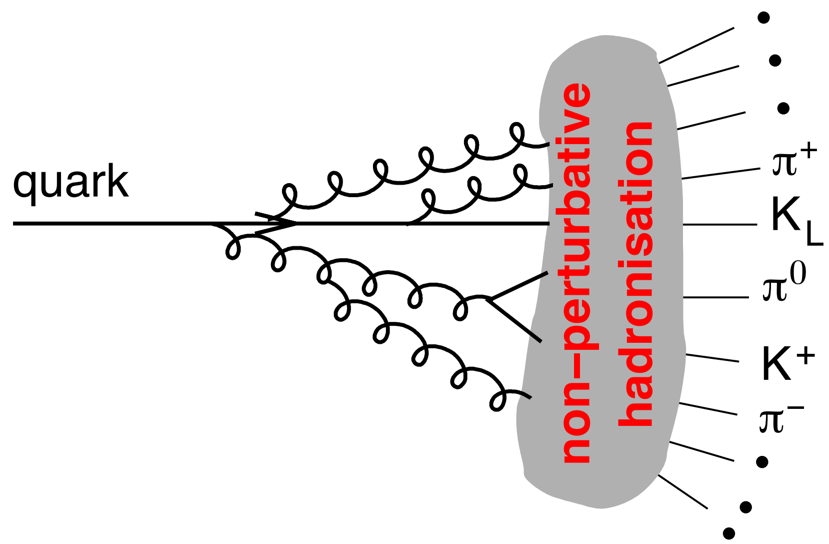
2. **Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ Te**
   ATLAS Collaboration (Georges Aad (Marseille, CPPM) *et al.*). Feb 18, 2020. 44 pp.
   CERN-EP-2019-273
   e-Print: **arXiv:2002.07546** [hep-ex] | PDF
   References | BibTeX | LaTeX(US)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

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

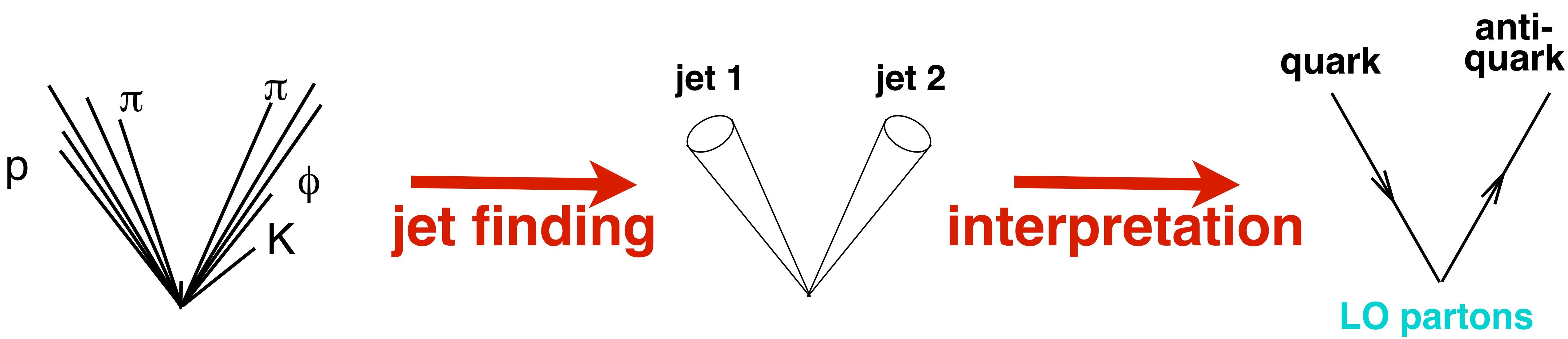
Jet usage at the LHC



How jets come to have the structure they do

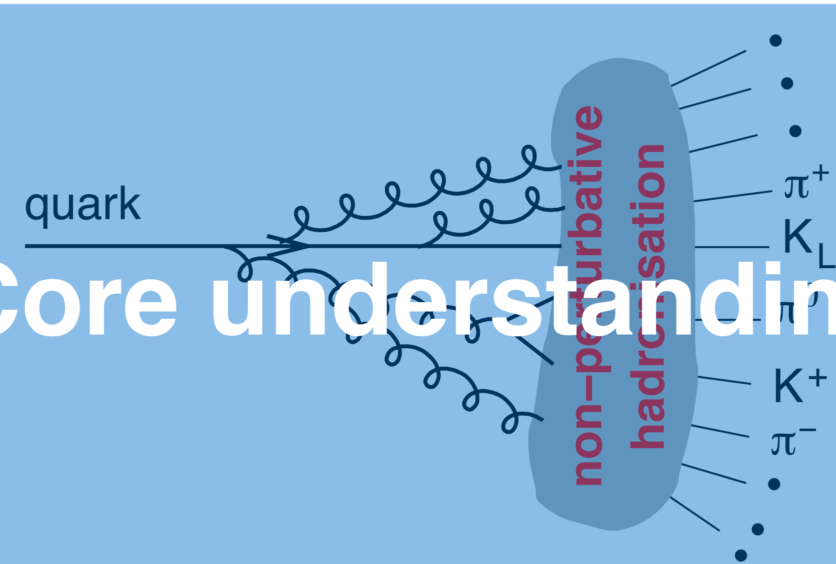


How we “reconstruct” and use jets



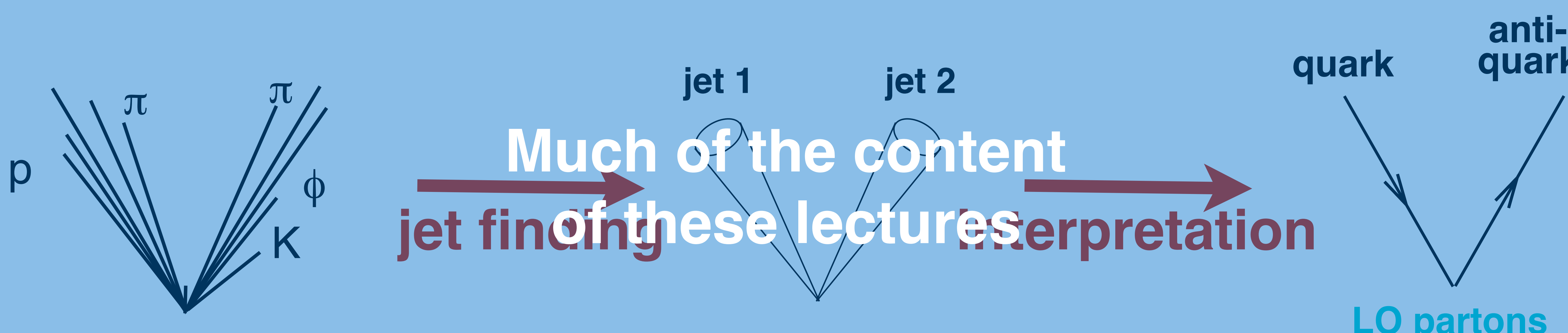
Two key aspects to discussing jets

How jets come to have the structure they do



Core understanding

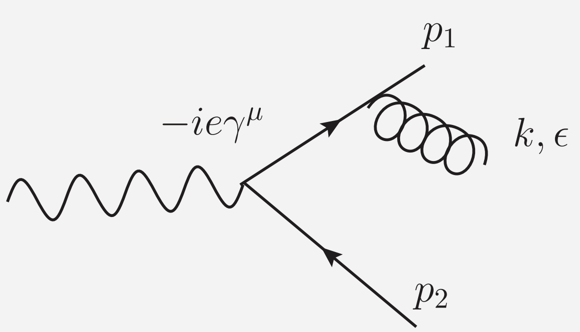
How we "reconstruct" and use jets



Much of the content of these lectures

soft singularities

Consider real emission diagrams in more detail:



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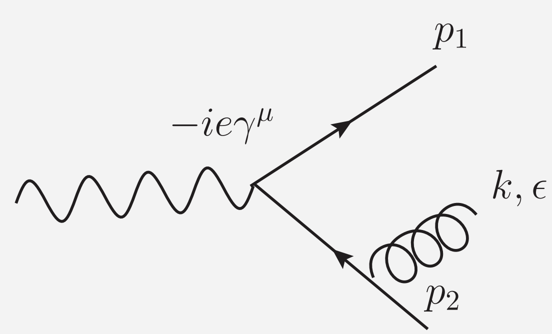


$=$

Gluon emission reduces to

$$\frac{2C_F\,\alpha_s}{\pi}\,\frac{dE}{E}\,\frac{d\theta}{\theta}$$

$$\mathcal{M}^\mu_{q\bar{q}g} = \bar{u}(p_1)\,(-igt^A\not{\epsilon})\,\frac{i(\not{p}_1+\not{k})}{(p_1+k)^2}\,(-ie\gamma^\mu)\,v(p_2)$$
$$+\quad \bar{u}(p_1)\,(-ie\gamma^\mu)\,\frac{-i(\not{p}_2+\not{k})}{(p_2+k)^2}\,(-igt^A\not{\epsilon})\,v(p_2)$$

If gluon becomes soft: neglect *k* except for linear terms in denominator:

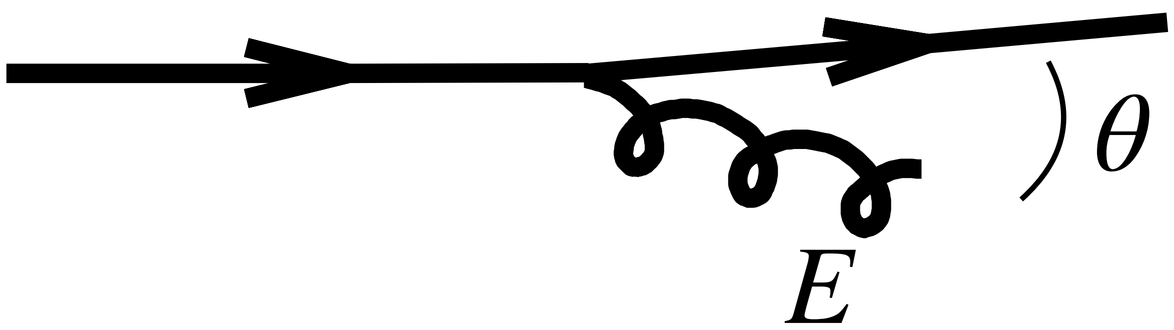
$$\mathcal{M}^\mu_{q\bar{q}g} \stackrel{soft}{=} -iegt^A\,\bar{u}(p_1)\,\gamma^\mu\left(\frac{\not{\epsilon}\not{p}_1}{2p_1k}-\frac{\not{p}_2\not{\epsilon}}{2p_2k}\right)\,v(p_2)$$

$$|\mathcal{M}_{q\bar{q}g}|^2 \stackrel{soft}{\to} |\mathcal{M}_{q\bar{q}}|^2\; g^2C_F\,\frac{p_1p_2}{(p_1k)(p_2k)}$$

Note: colour will in general **not** factorise in the soft limit

Factorisation into Born matrix element and Eikonal factor

Heinrich



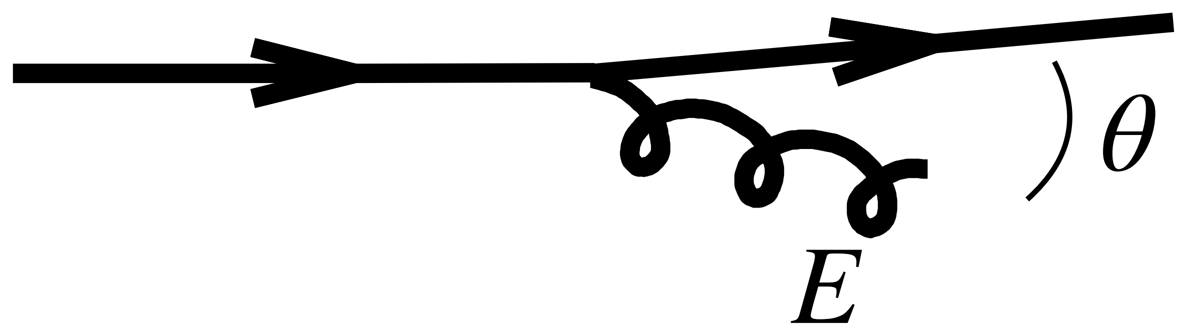
Gluon emission reduces to

$$\frac{2C_F \alpha_s}{\pi} \frac{dE}{E} \frac{d\theta}{\theta}$$

"soft" divergence for gluon energy $E \to 0$

"collinear" divergence when gluon is emitted parallel to the quark, $\theta \to 0$

NB: $\alpha_s \sim \frac{1}{\ln \Lambda_{\rm QCD}/Q}$



Gluon emission reduces to

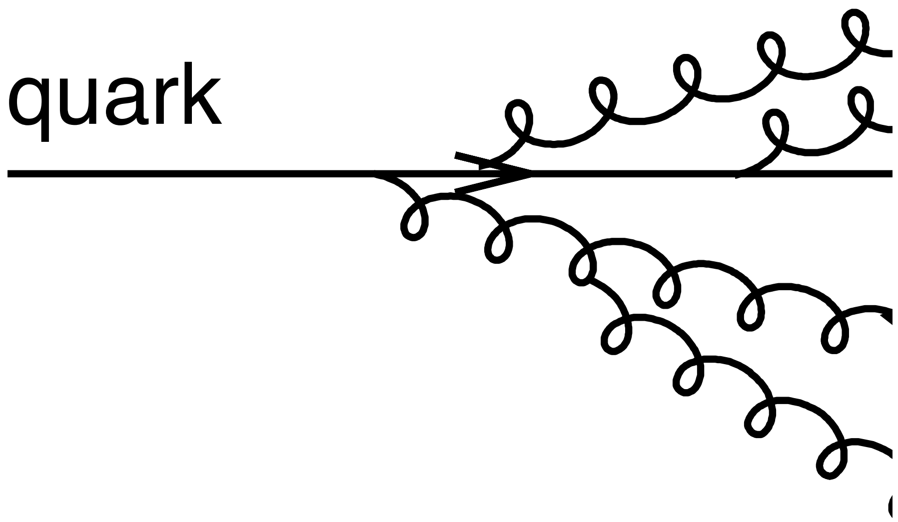
$$\frac{2C_F\,\alpha_s}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$

Estimate total probability P of emitting a gluon:

$$P \propto \alpha_s \int_{\Lambda_{\rm QCD}}^{Q} \frac{dE}{E} \int_{\frac{\Lambda_{\rm QCD}}{Q}}^{1} \frac{d\theta}{\theta} = \alpha_s \ln^2 \frac{Q}{\Lambda_{\rm QCD}} \sim \frac{1}{\alpha_s}$$

$\alpha_s \ll 1$ implies **high** gluon emission probability!

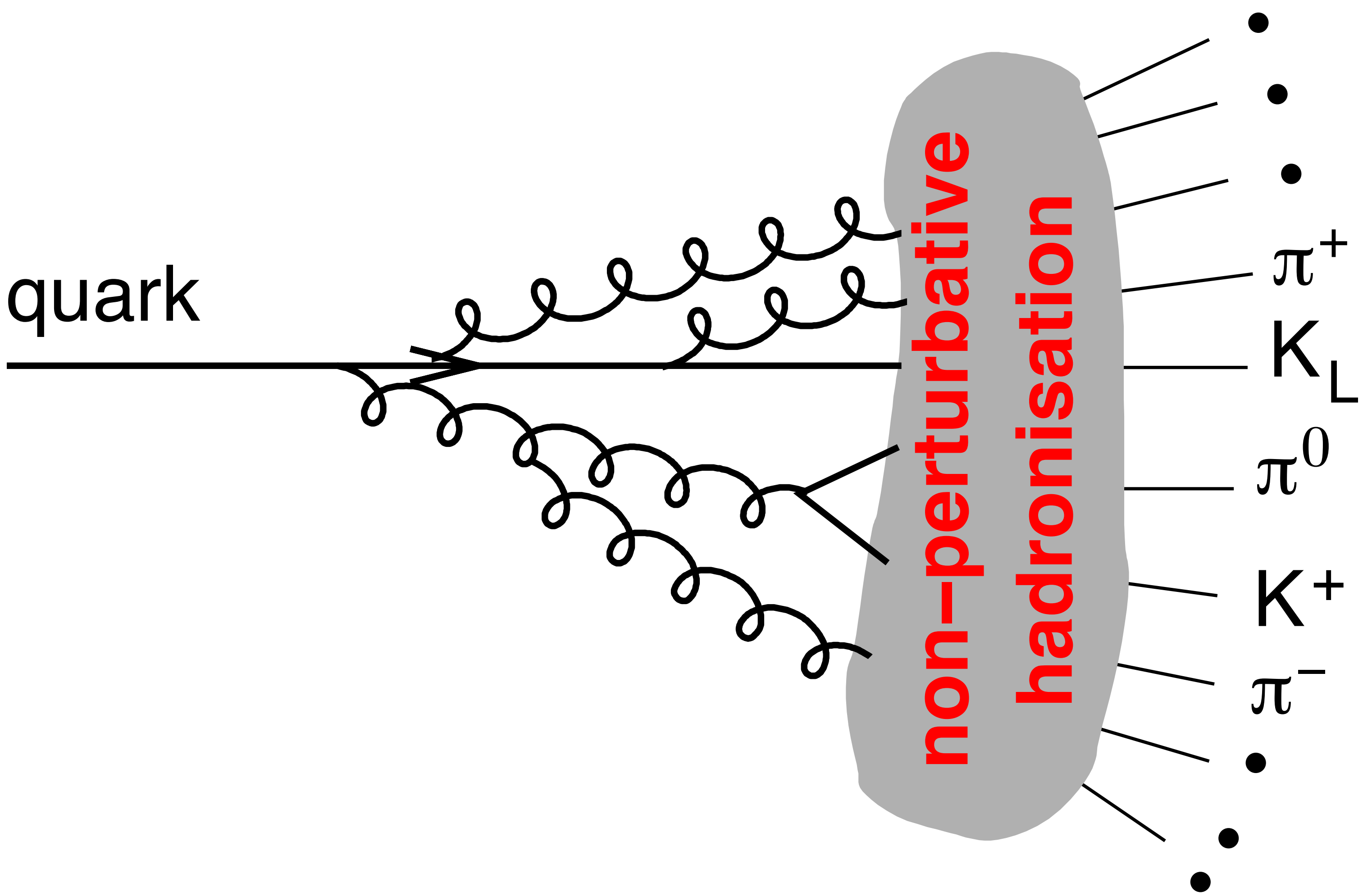
Why do we see jets?



Gluon emission

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

Why do we see jets?

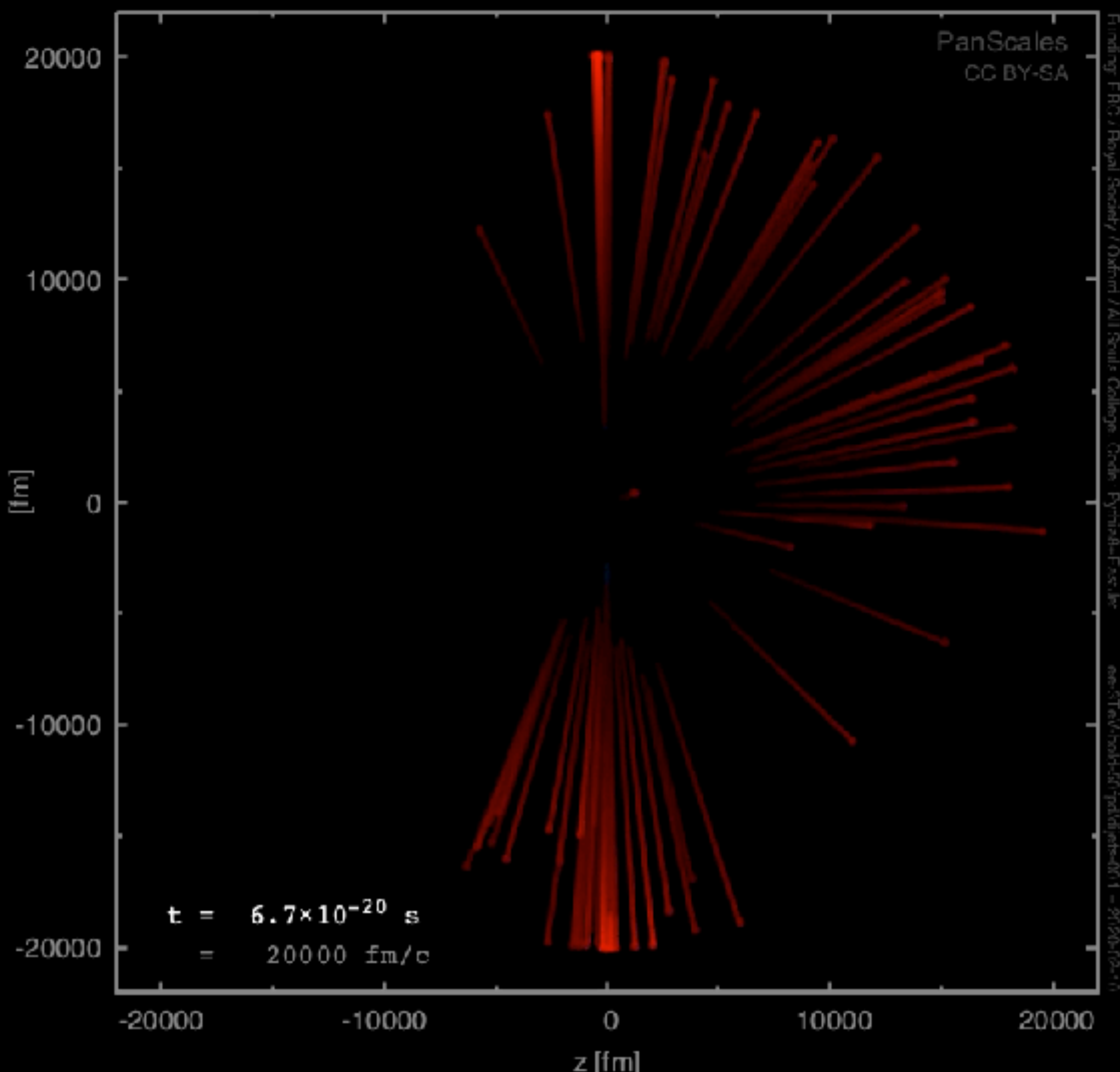


Gluon emission

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

Non-perturbative physics

$$\alpha_s \sim 1$$



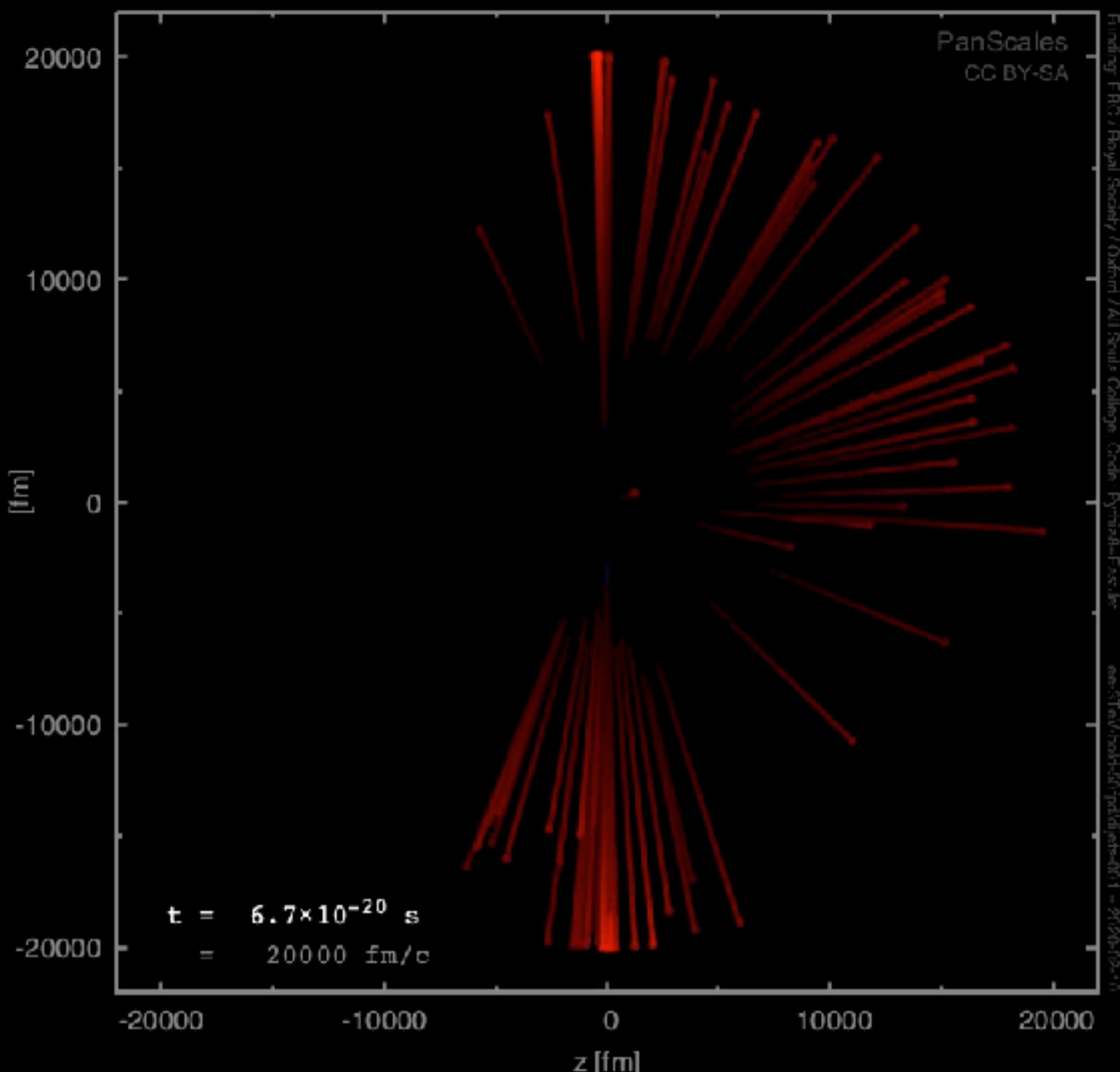
incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time

links to this video & more info



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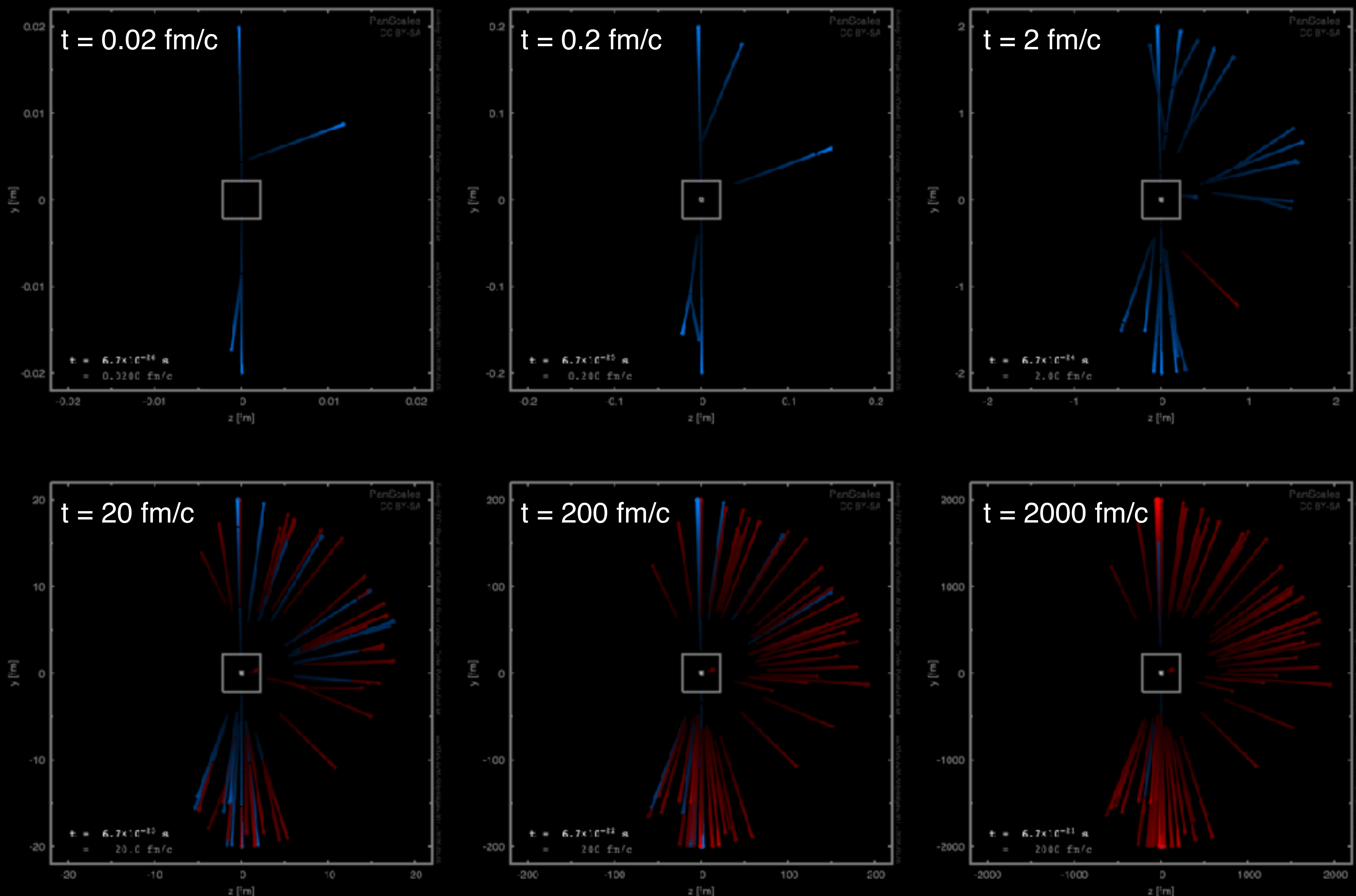
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PanScales
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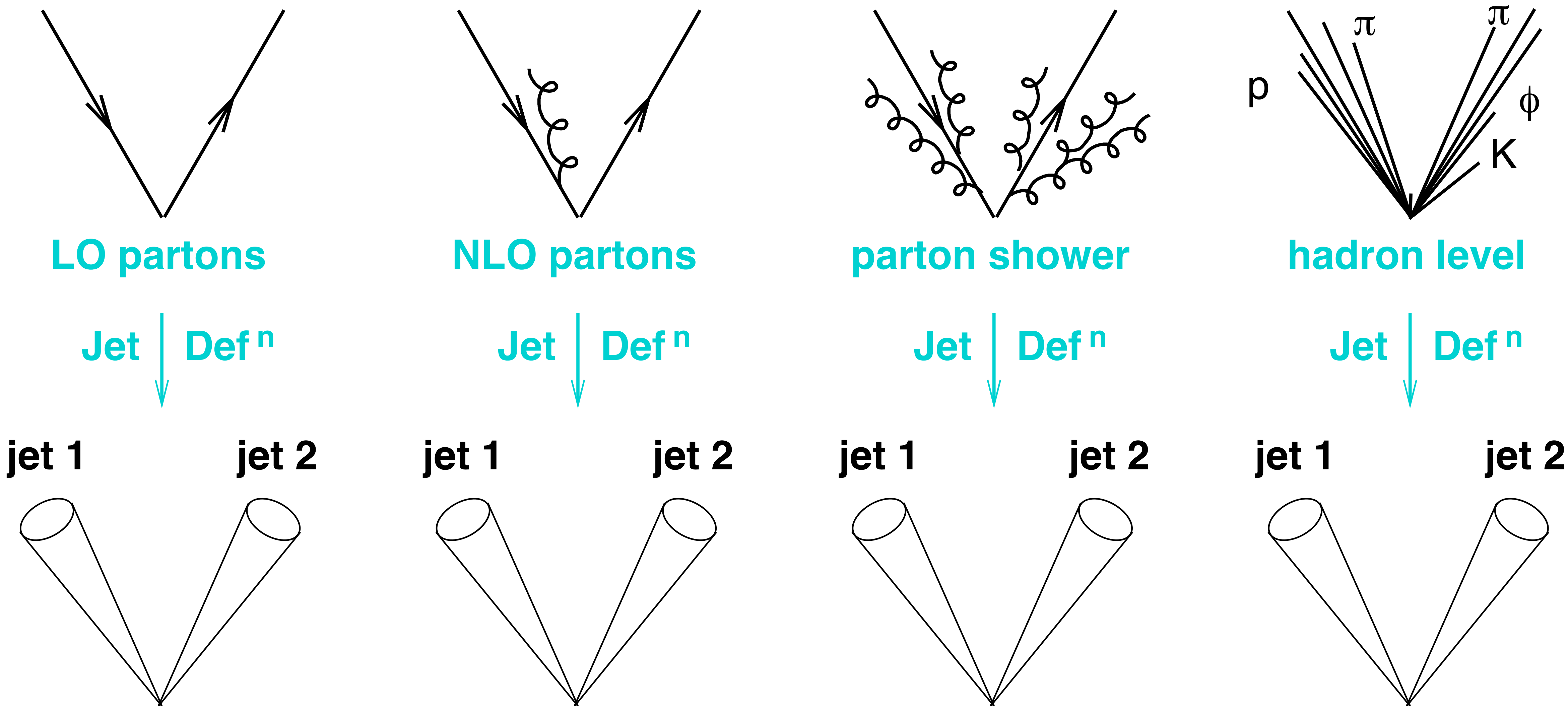
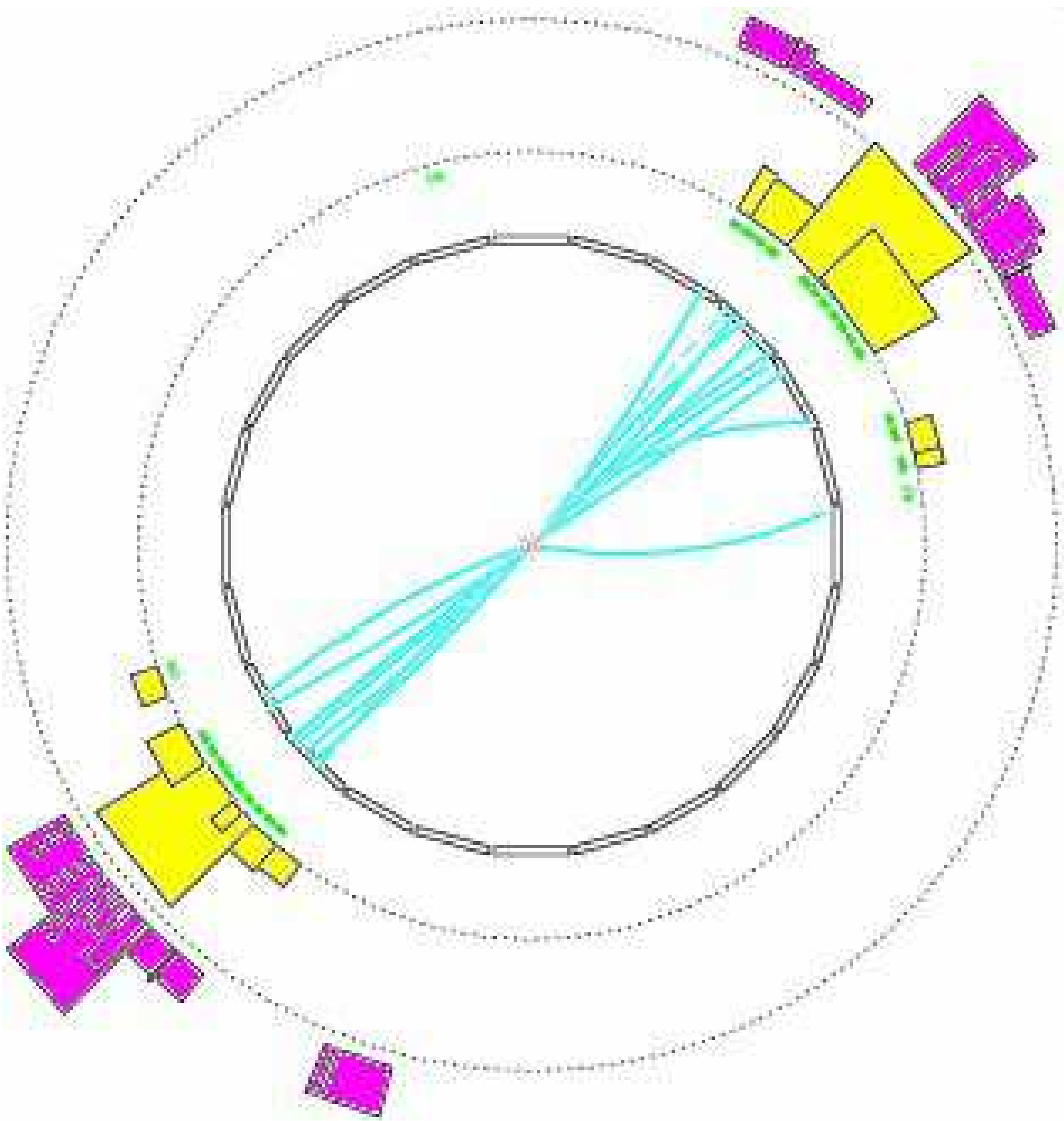
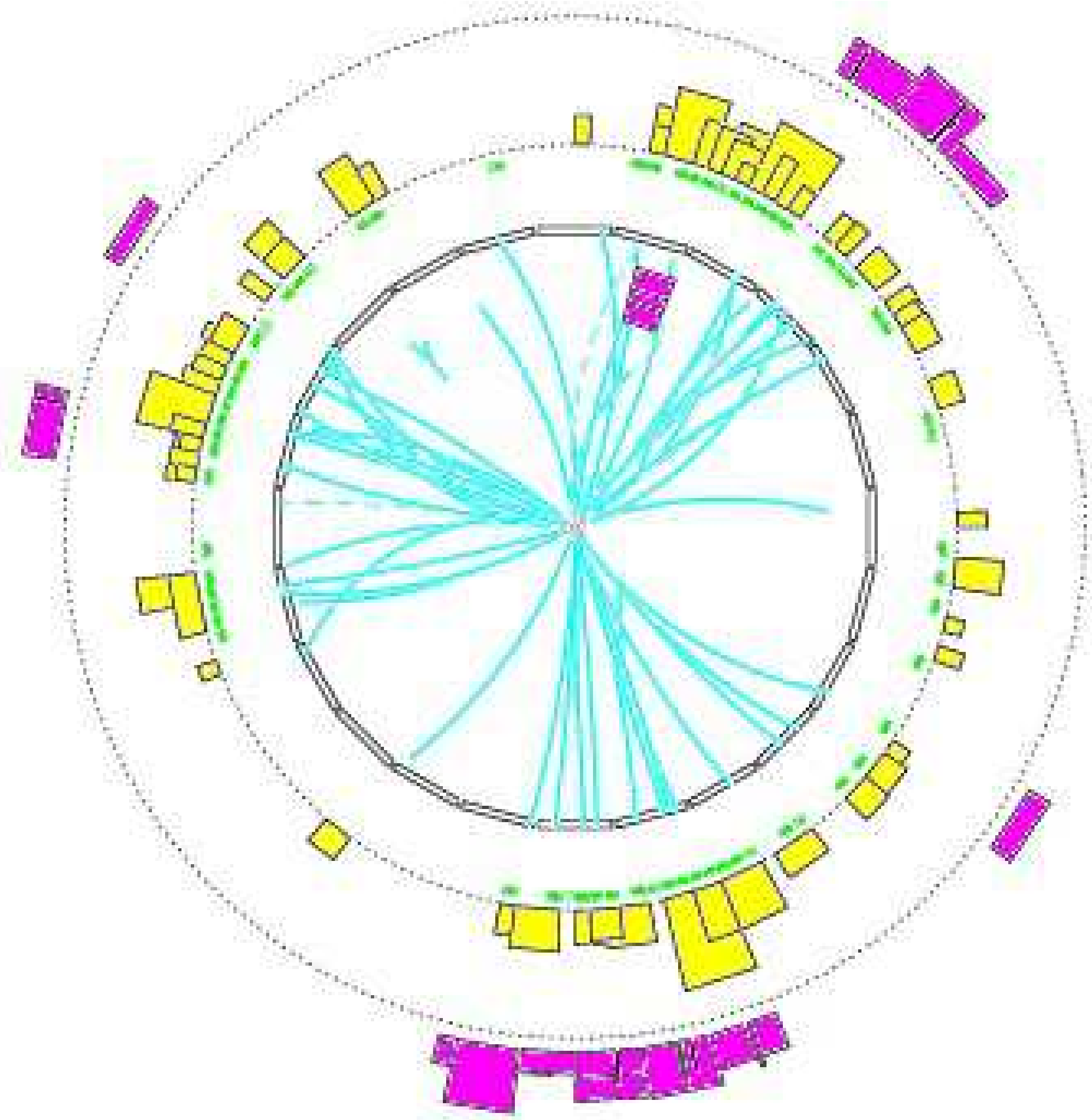
Jet finding as a form of projection

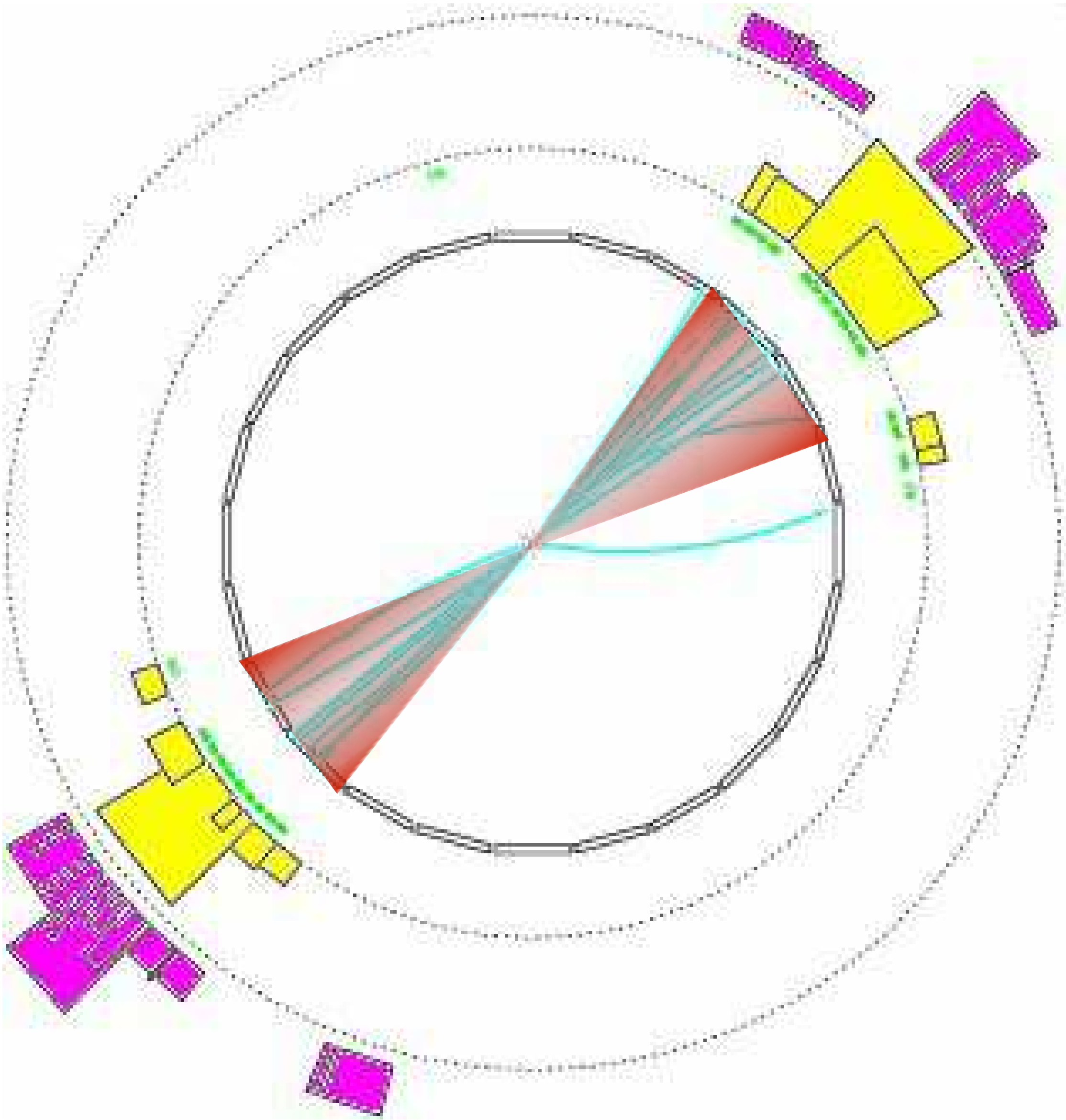


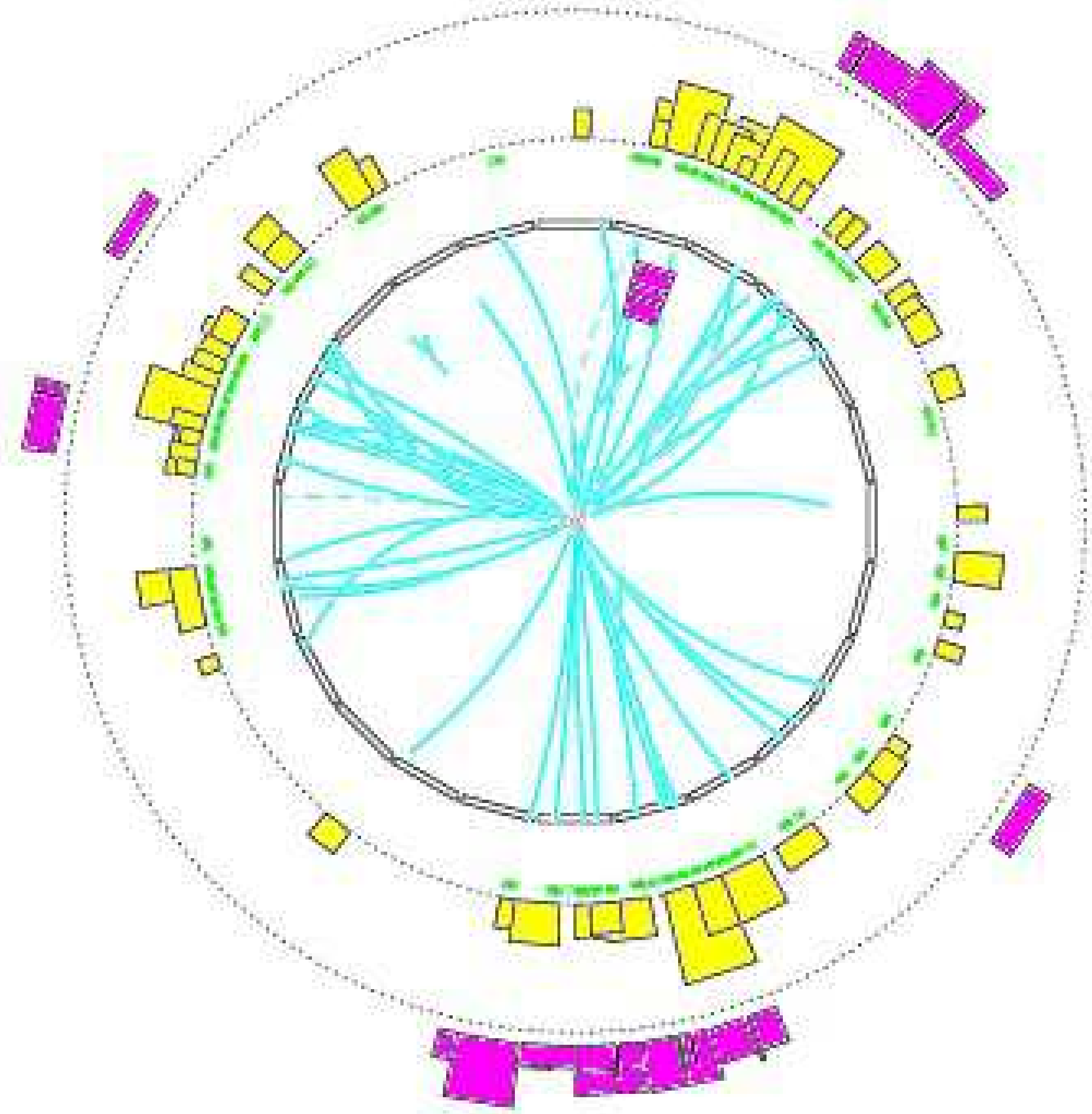
Projection to jets should be resilient to QCD effects





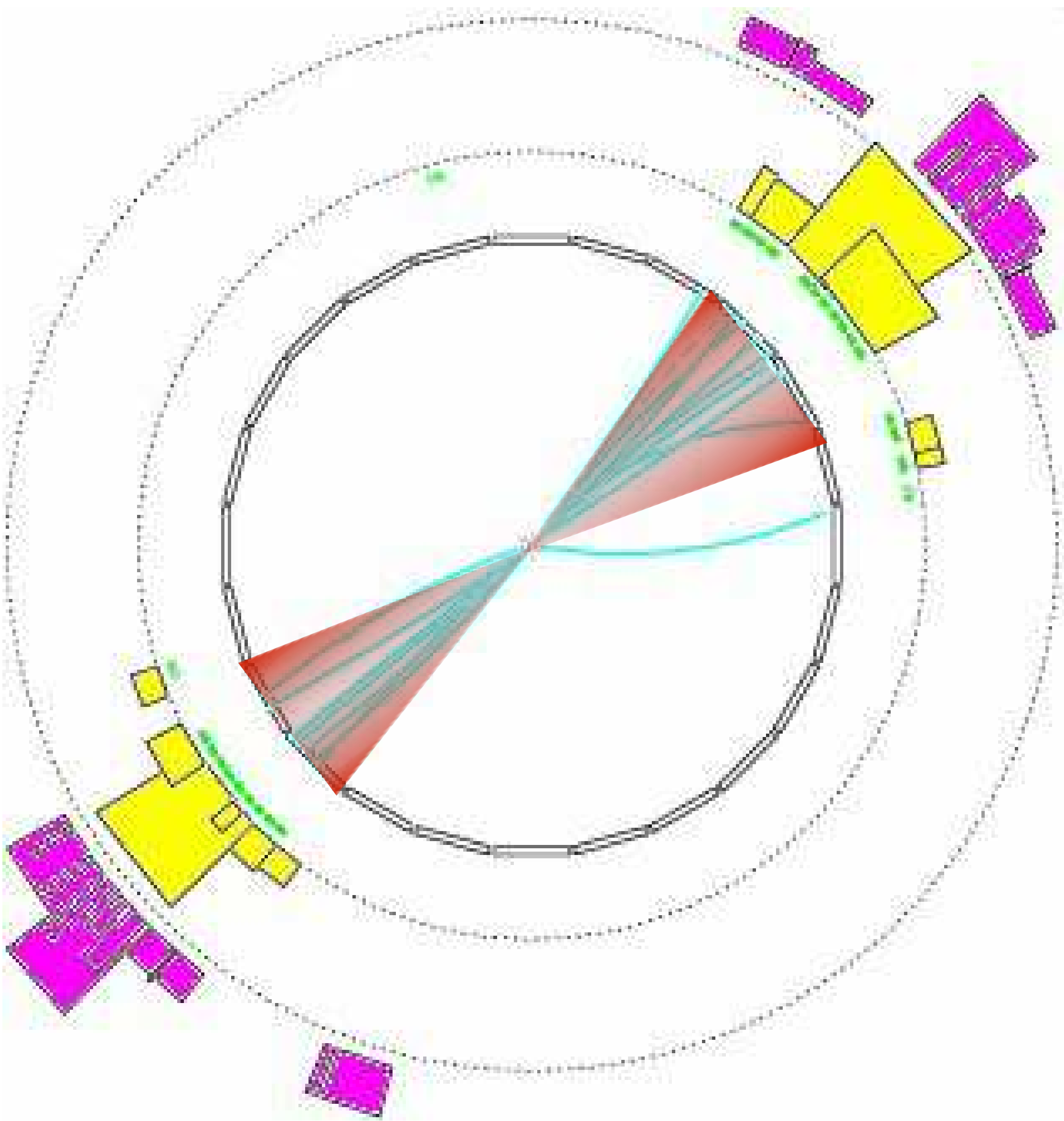
Reconstructing jets is an ambiguous task



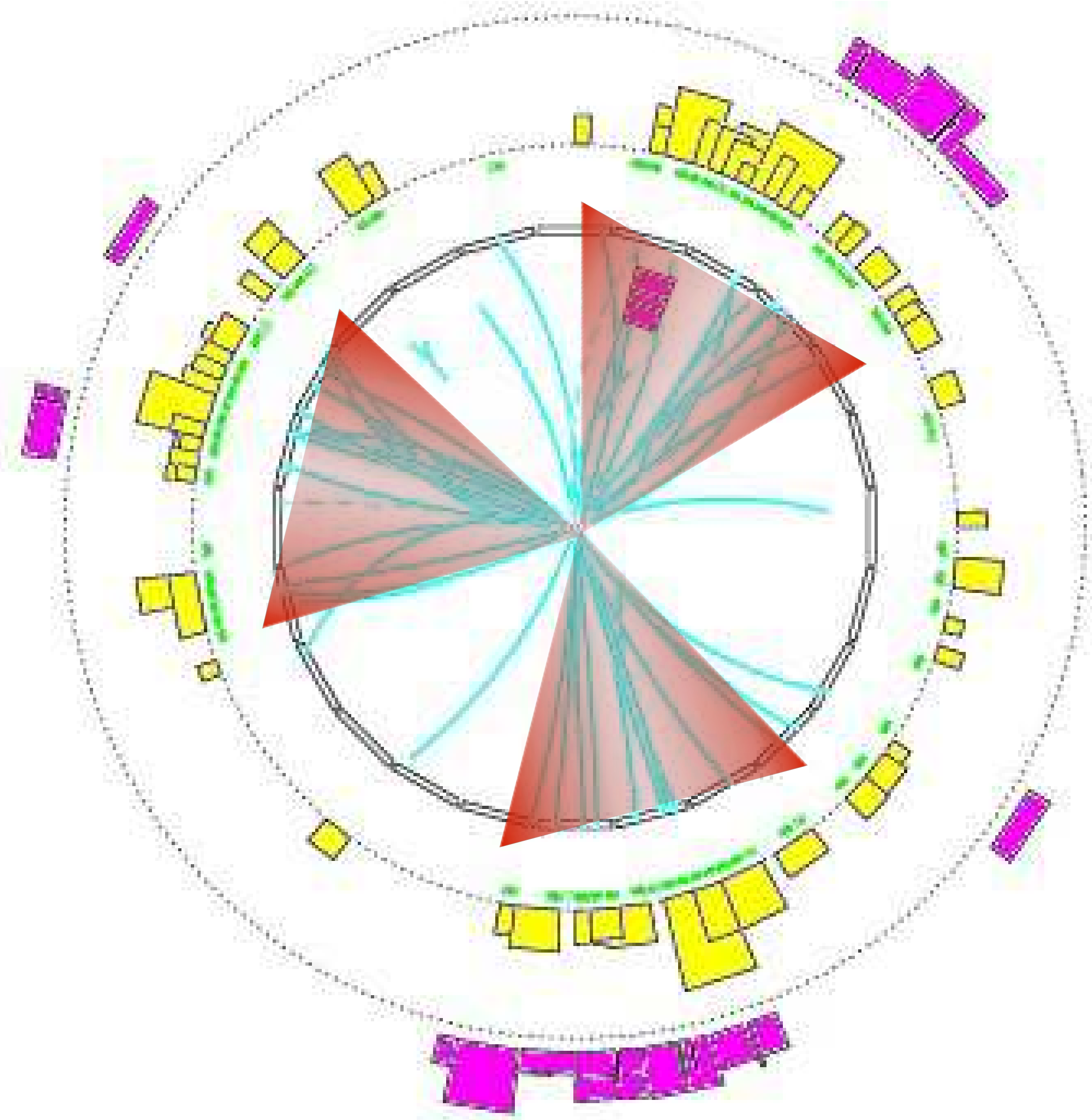


2 clear jets

Reconstructing jets is an ambiguous task

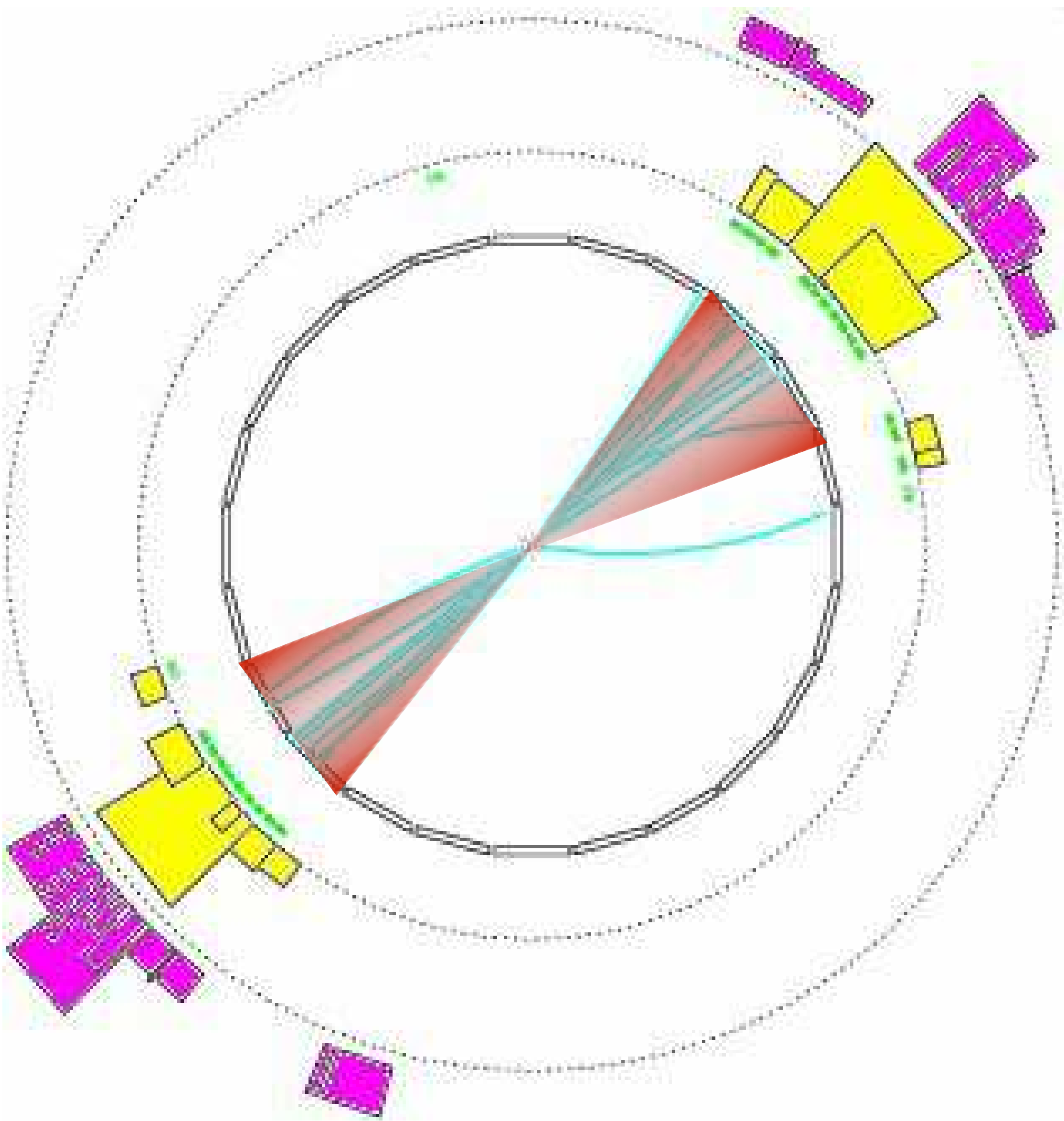


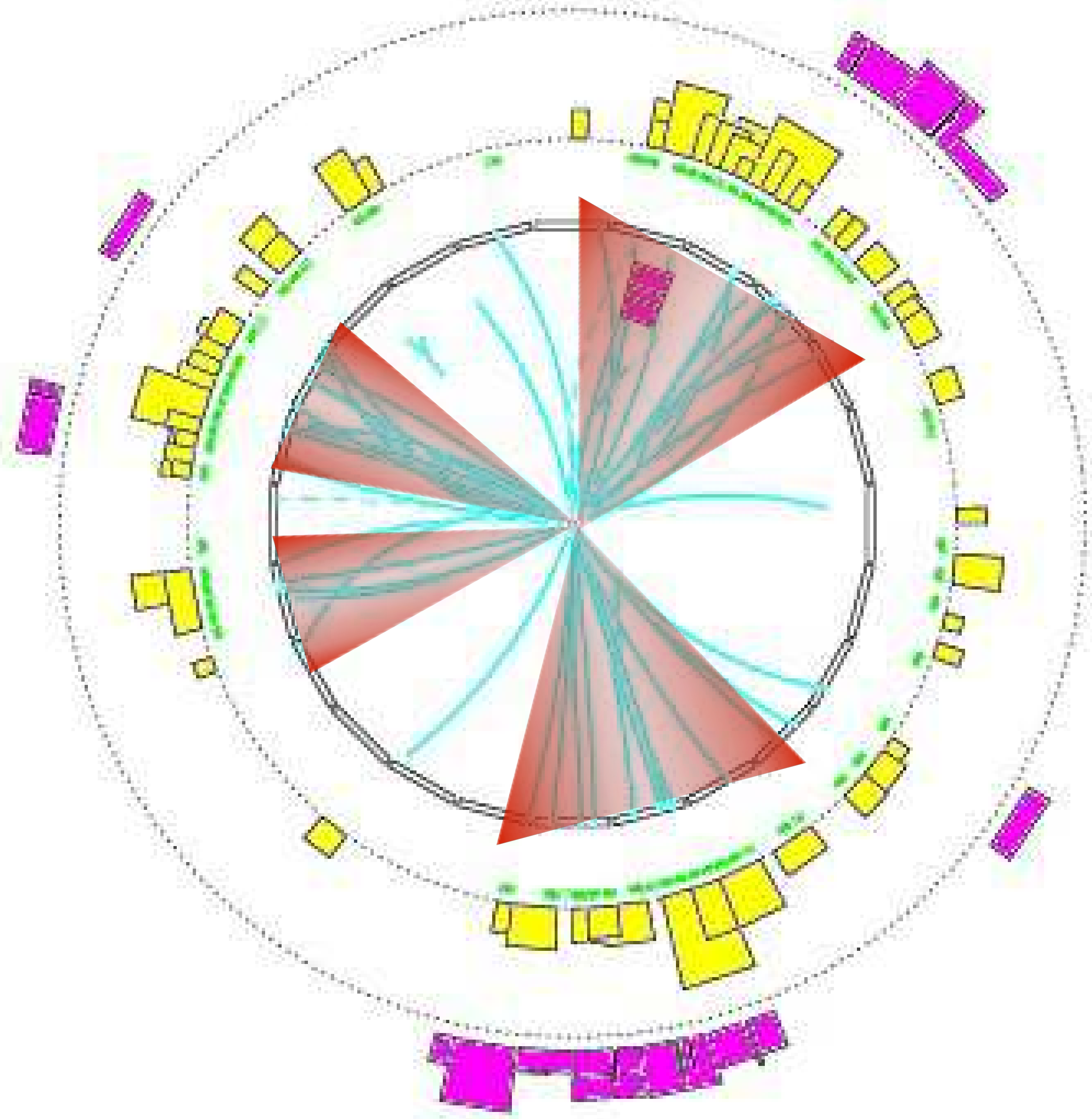
2 clear jets



3 jets?

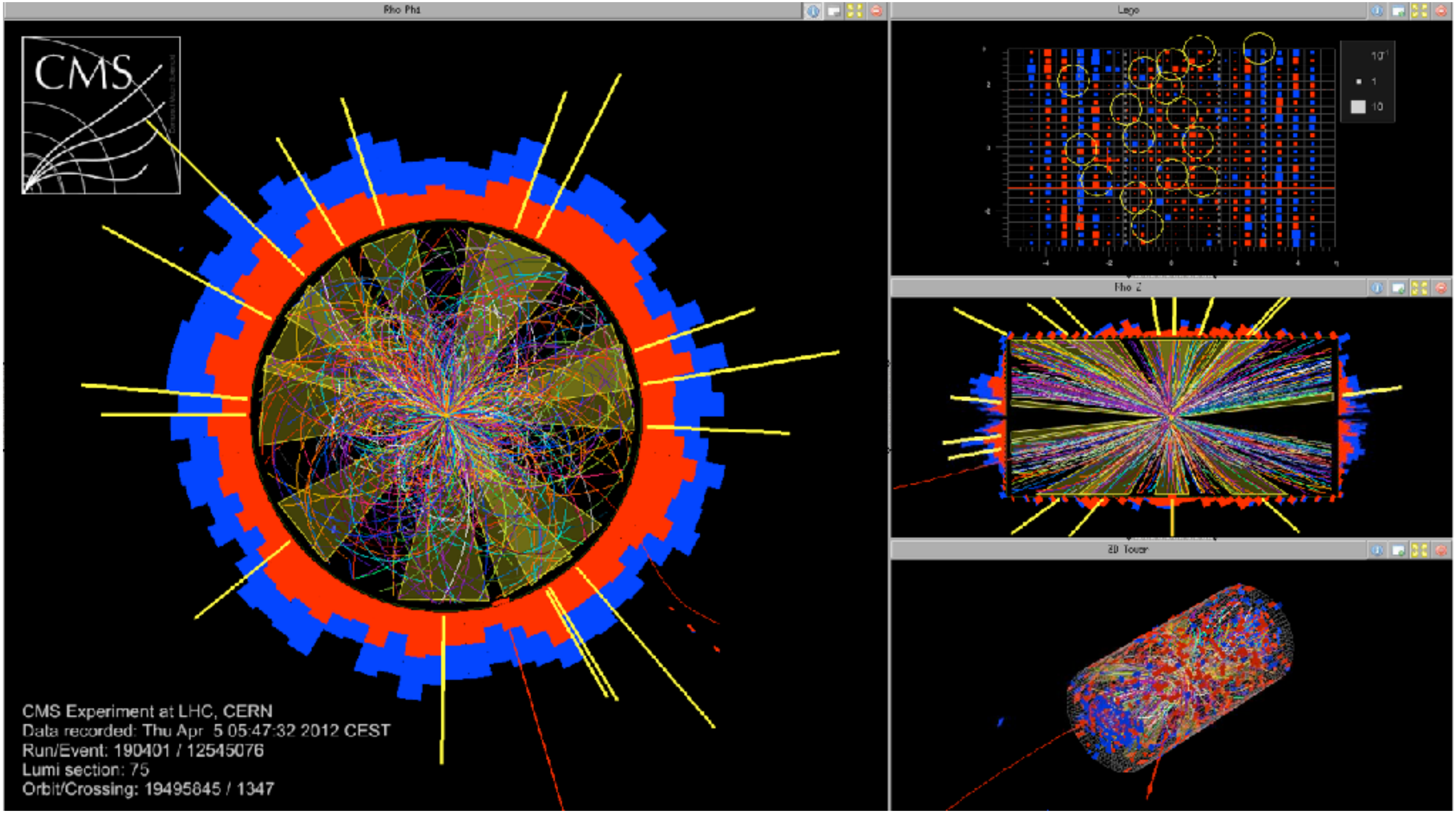
Reconstructing jets is an ambiguous task





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, ...

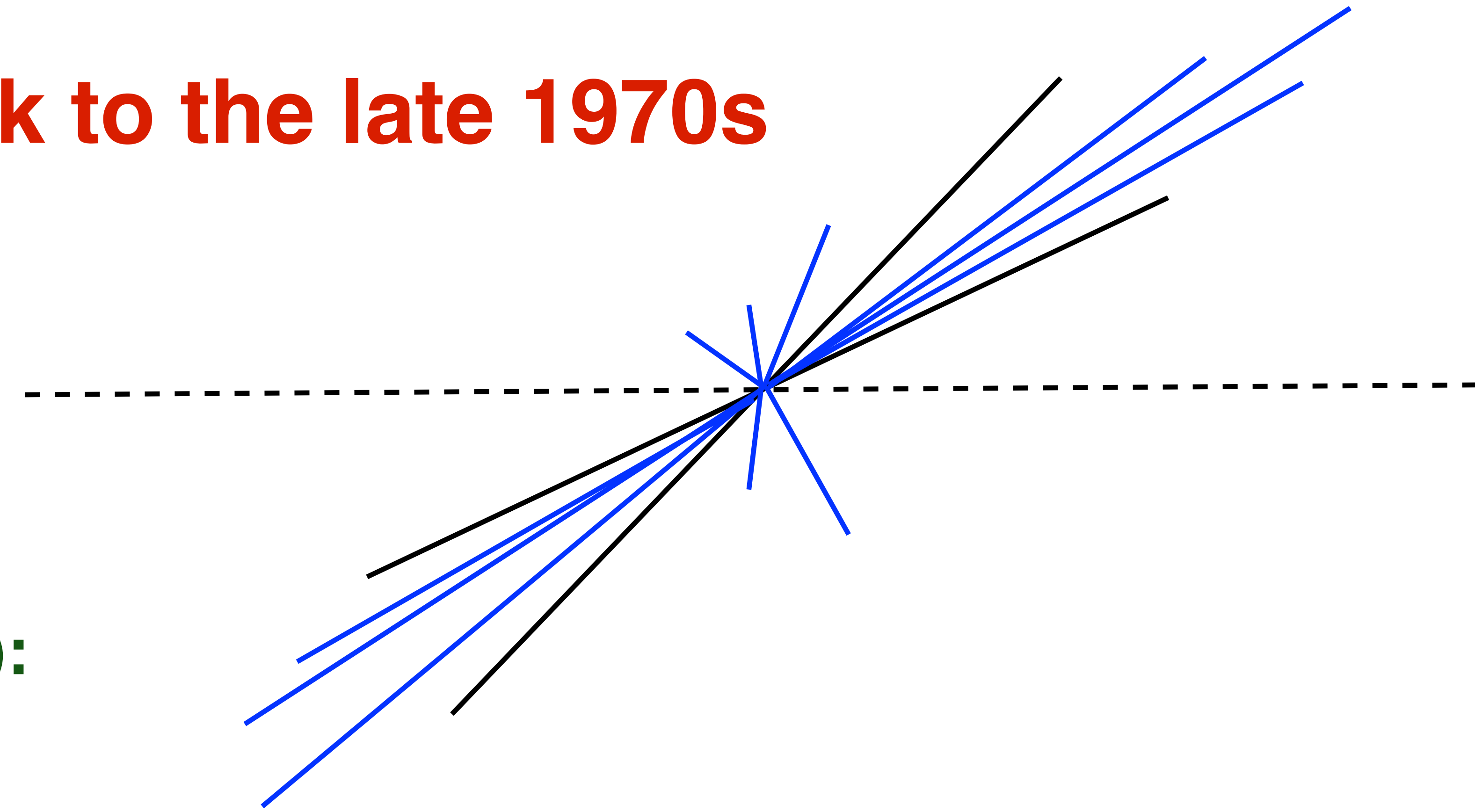
jets

- 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

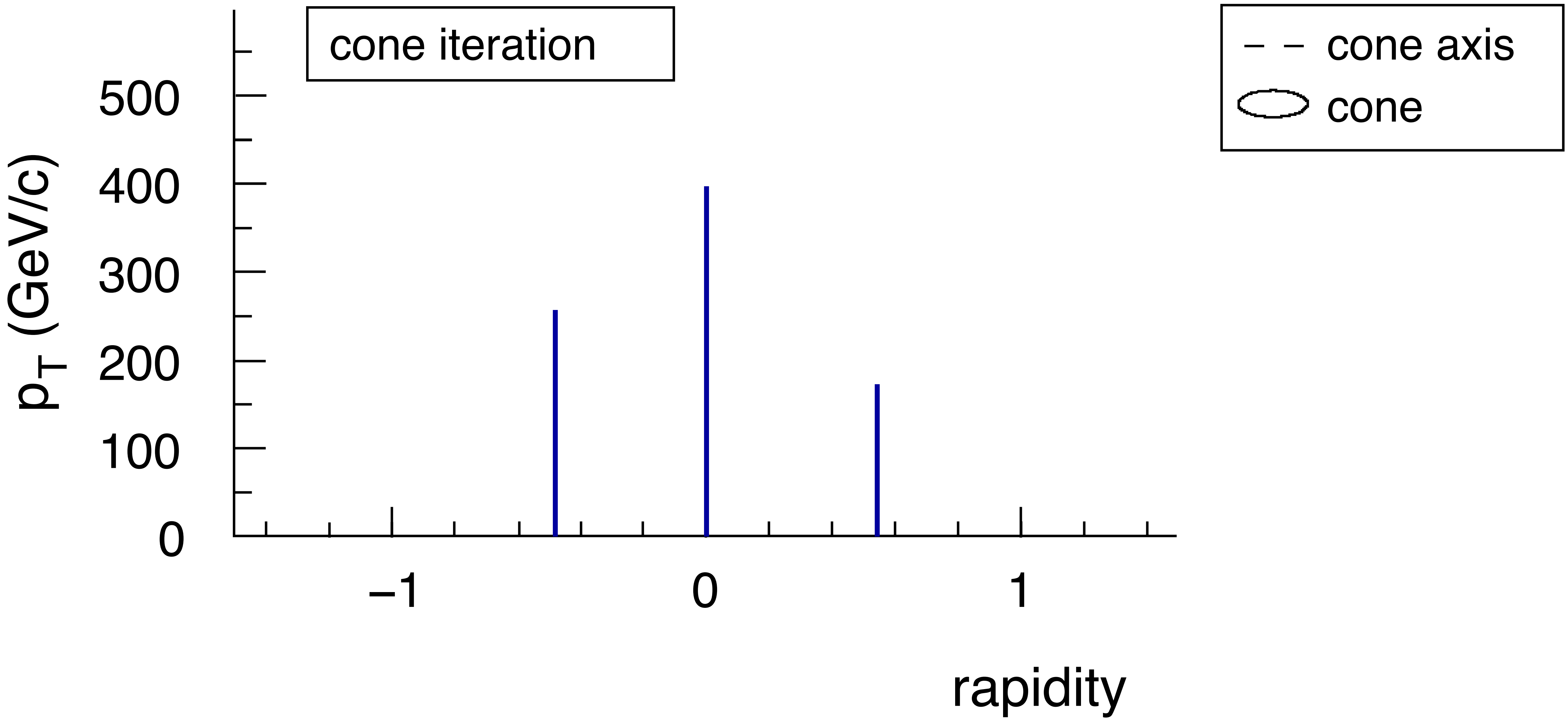
Jet definitions date back to the late 1970s



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-

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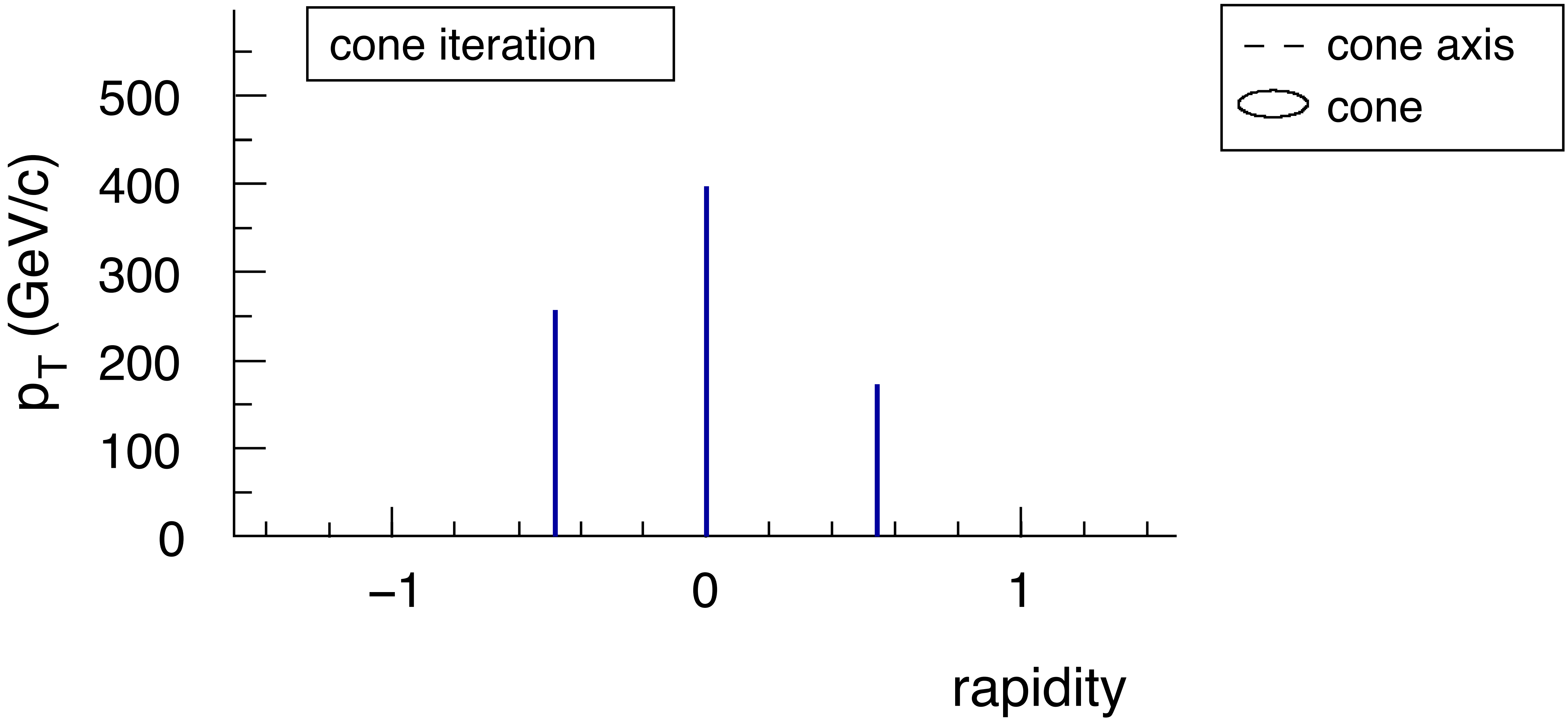
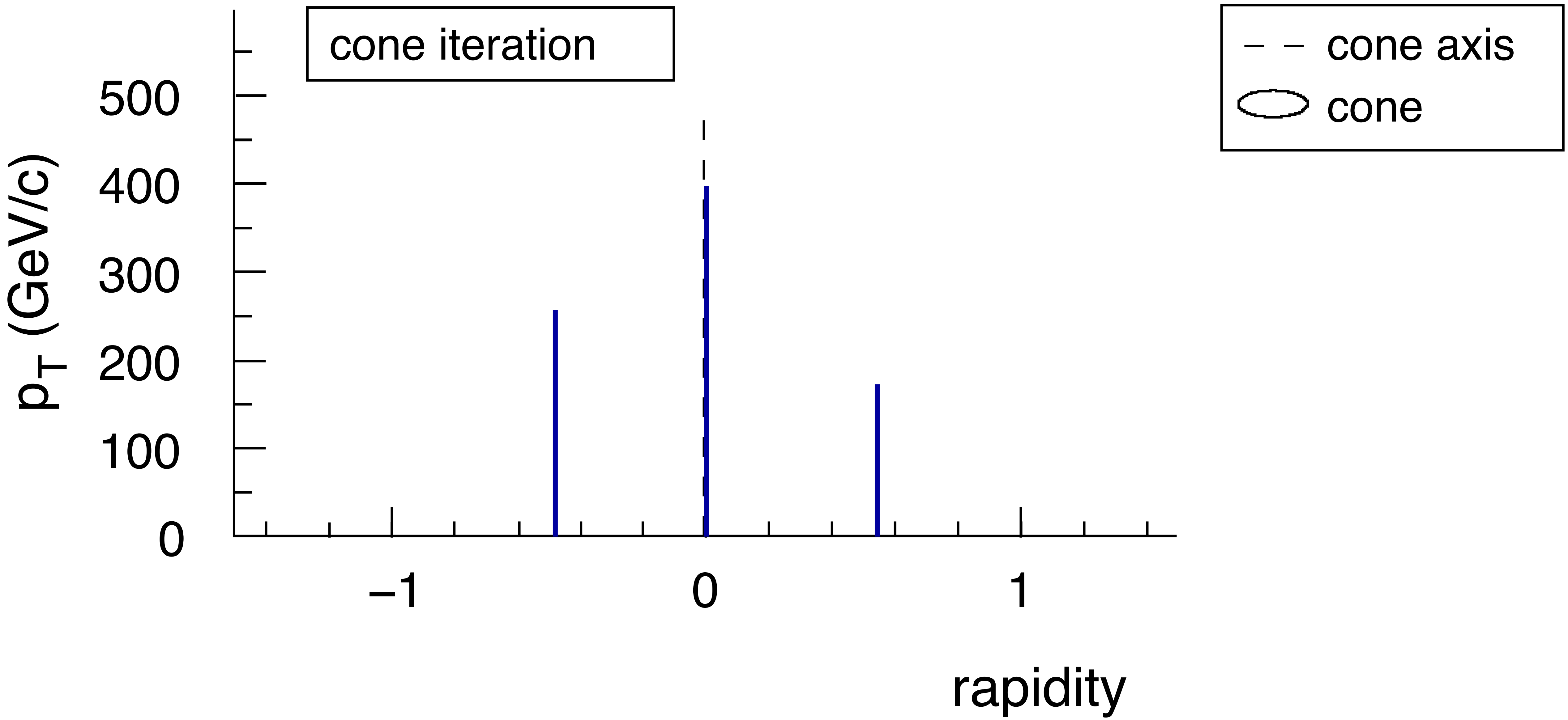
iterative cone issue

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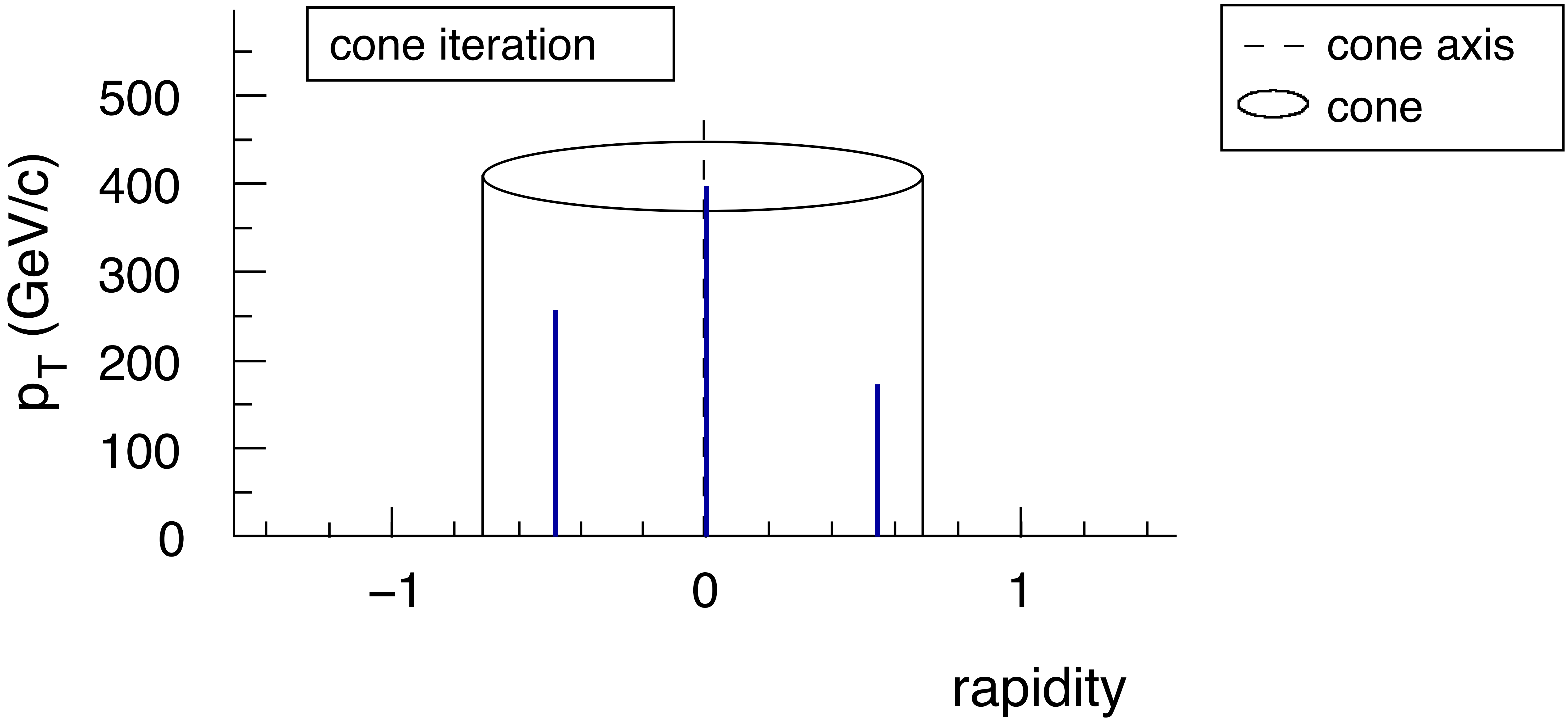

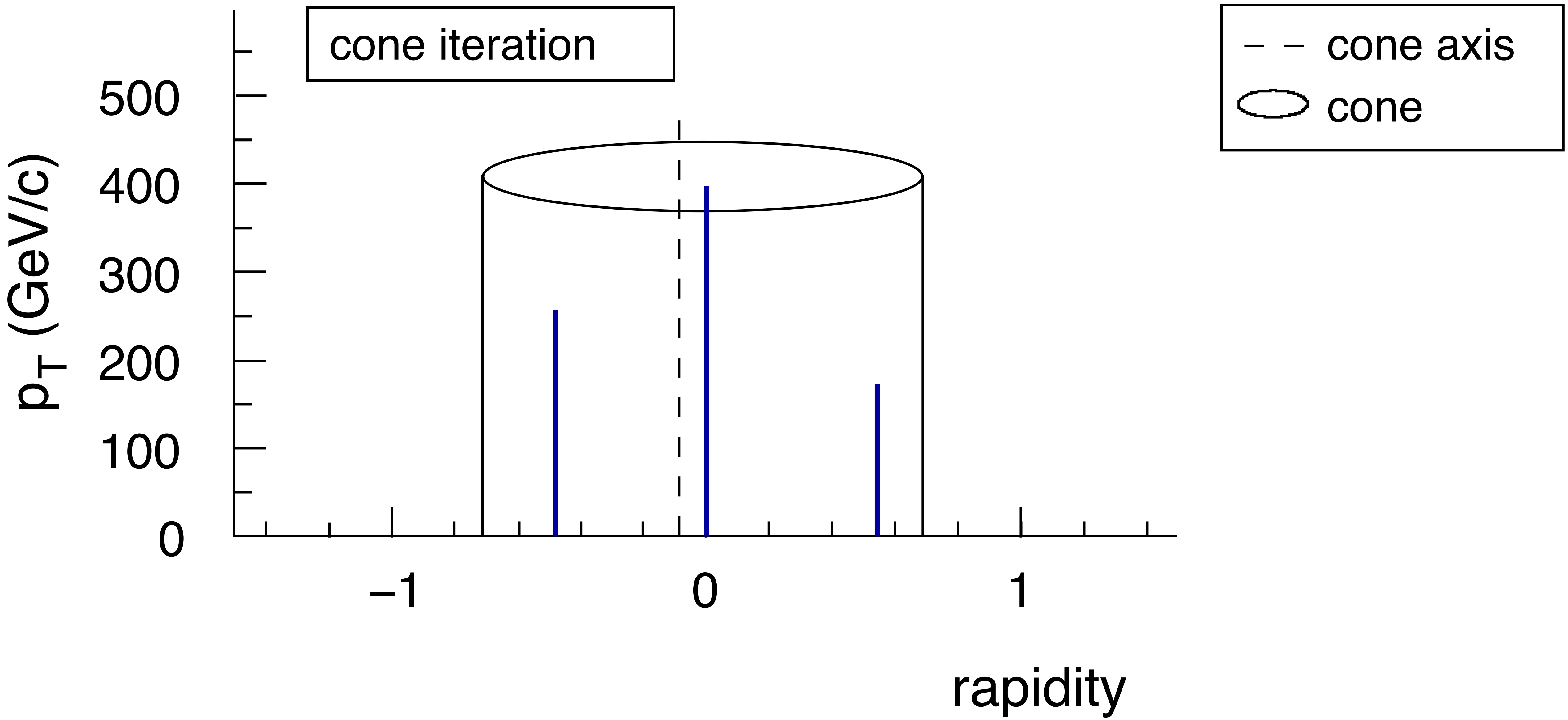
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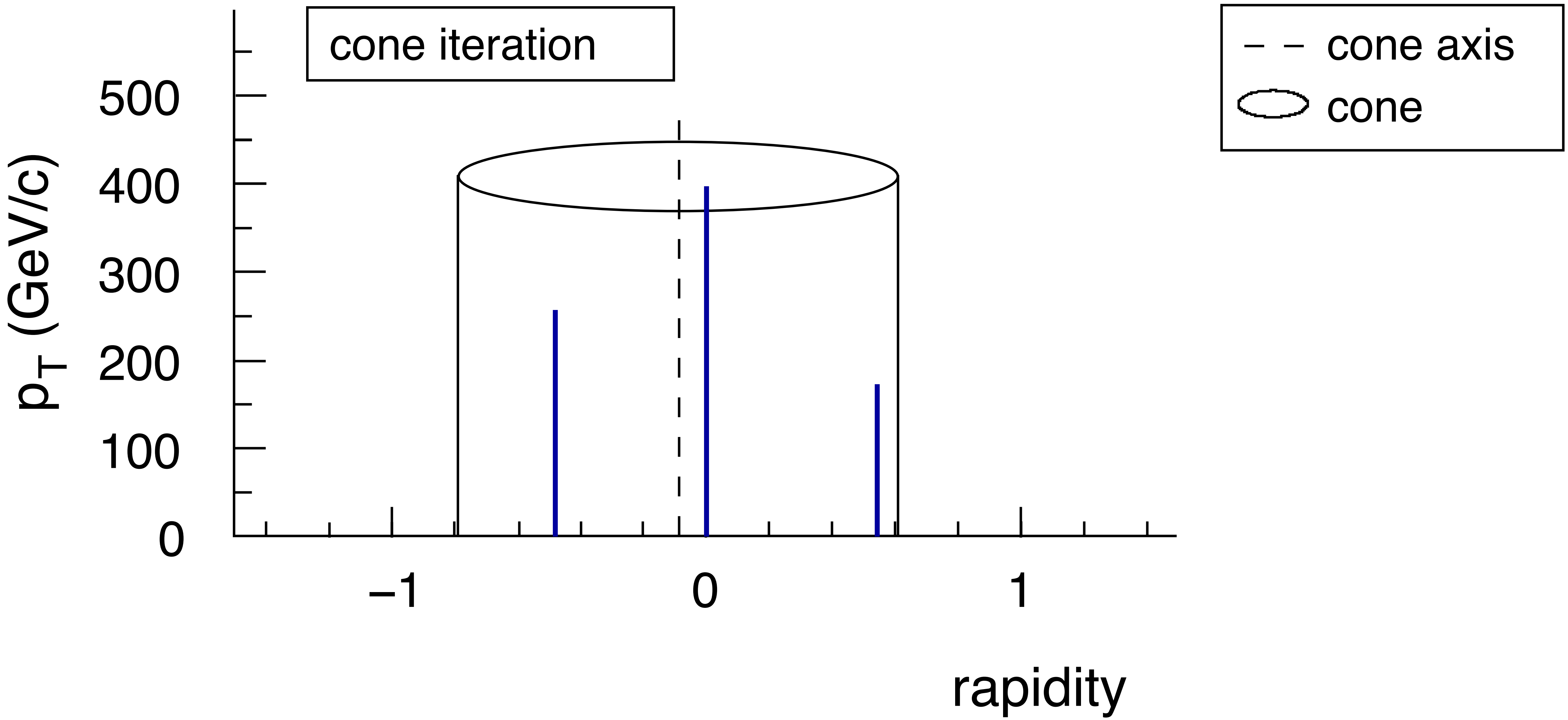

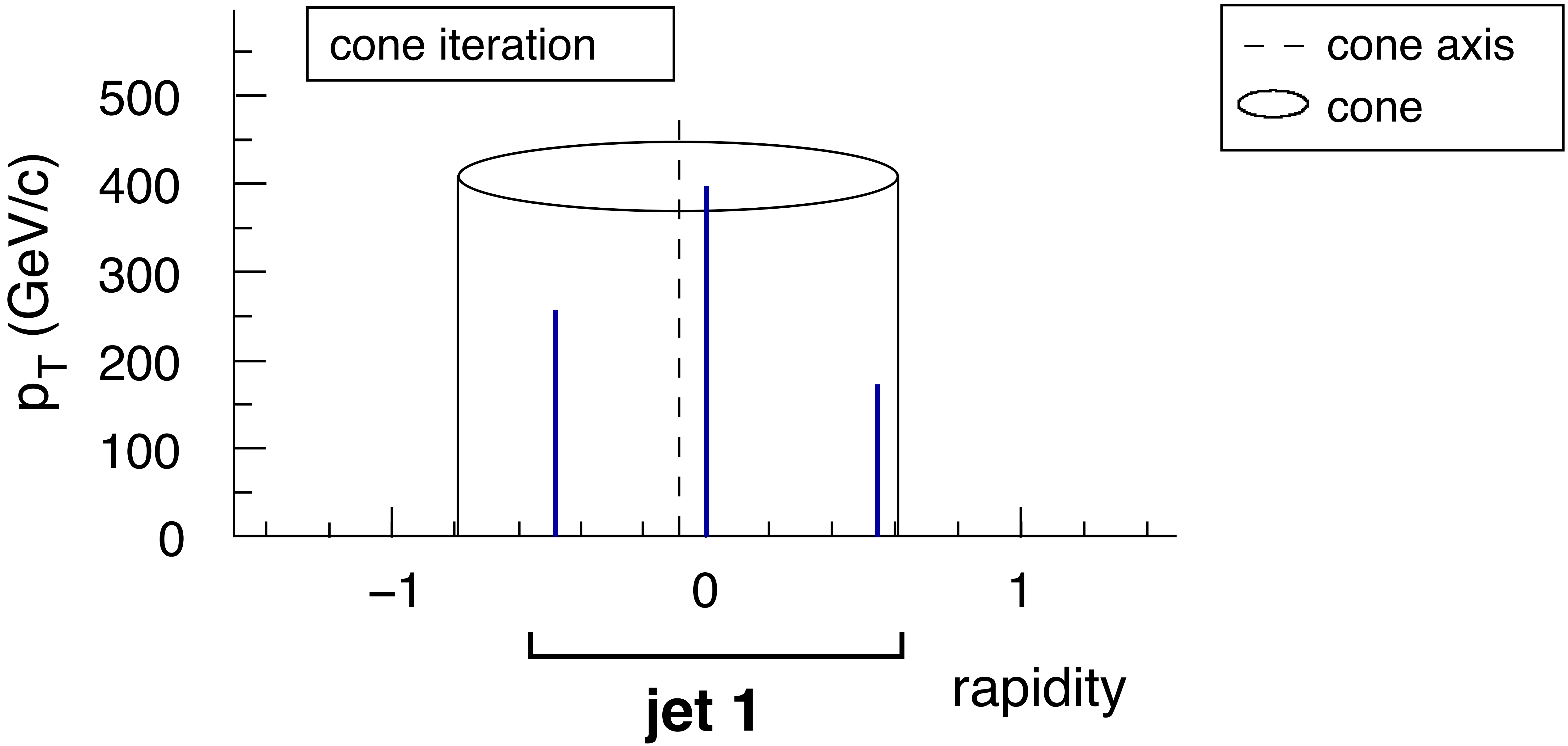

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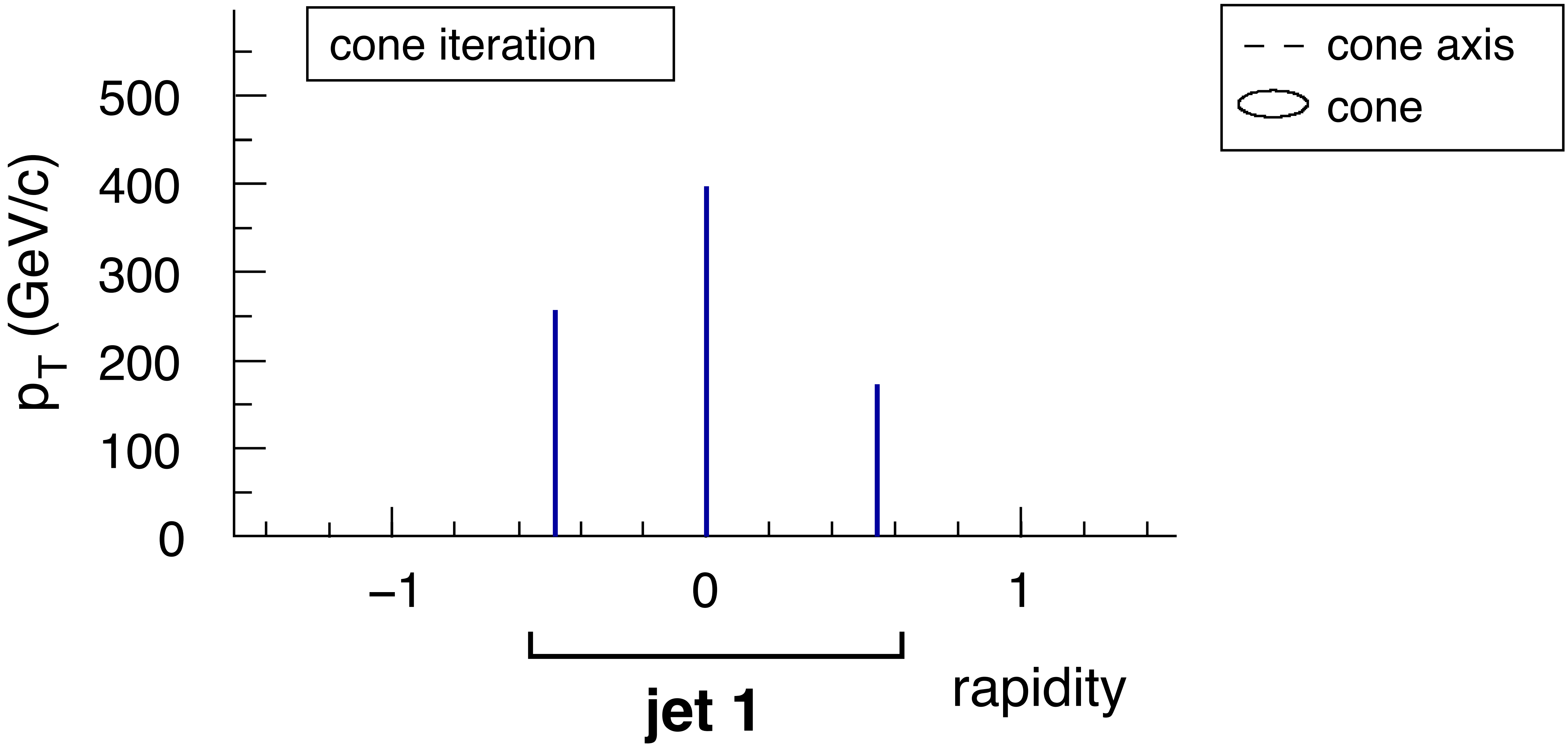
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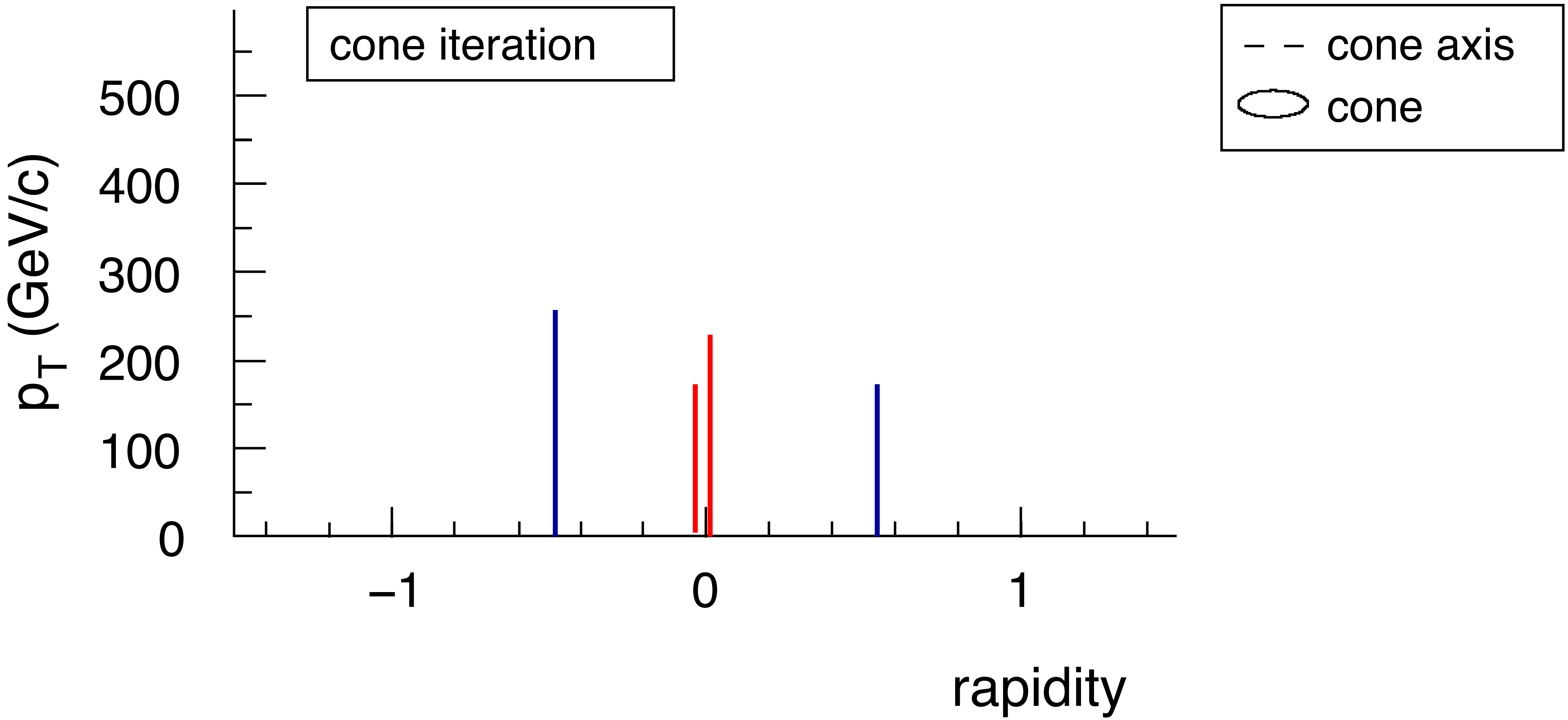

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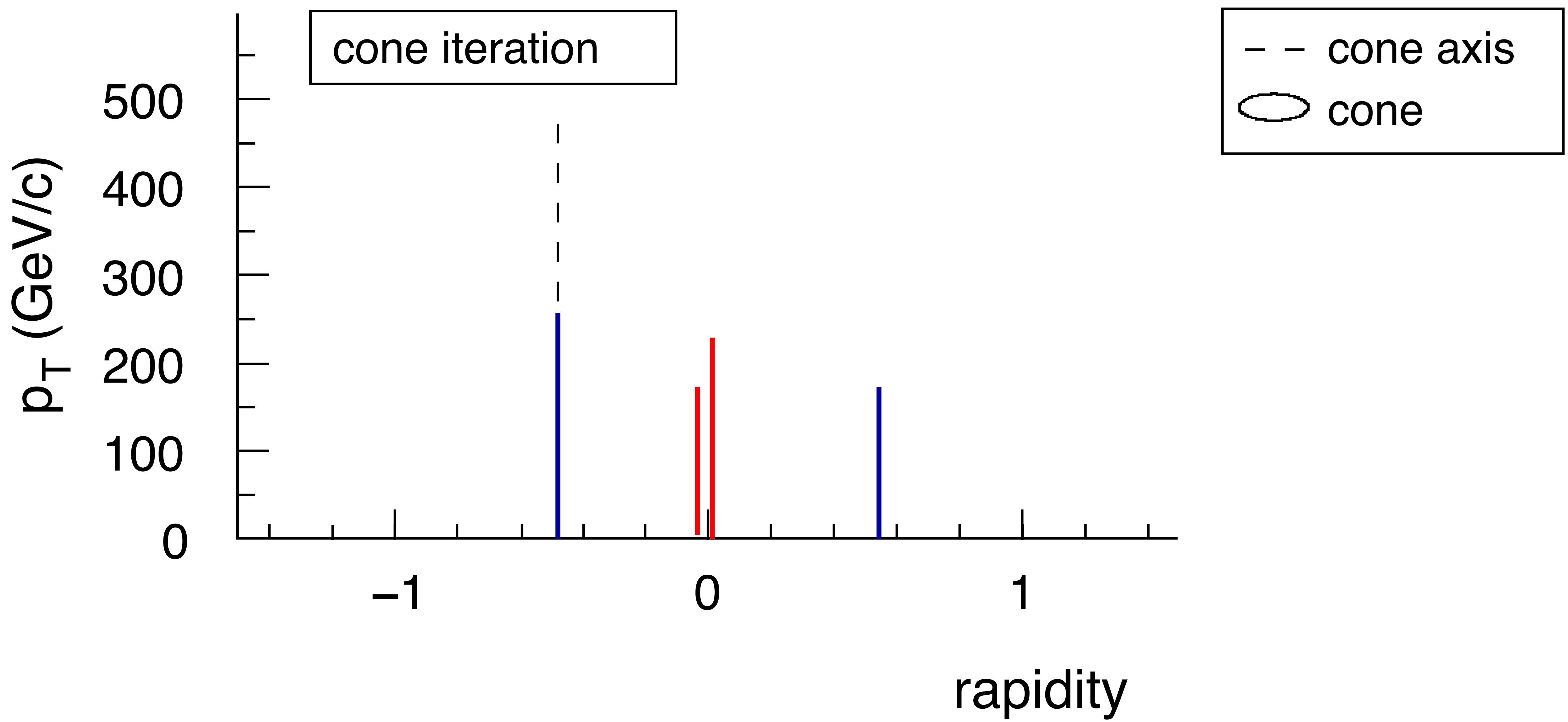

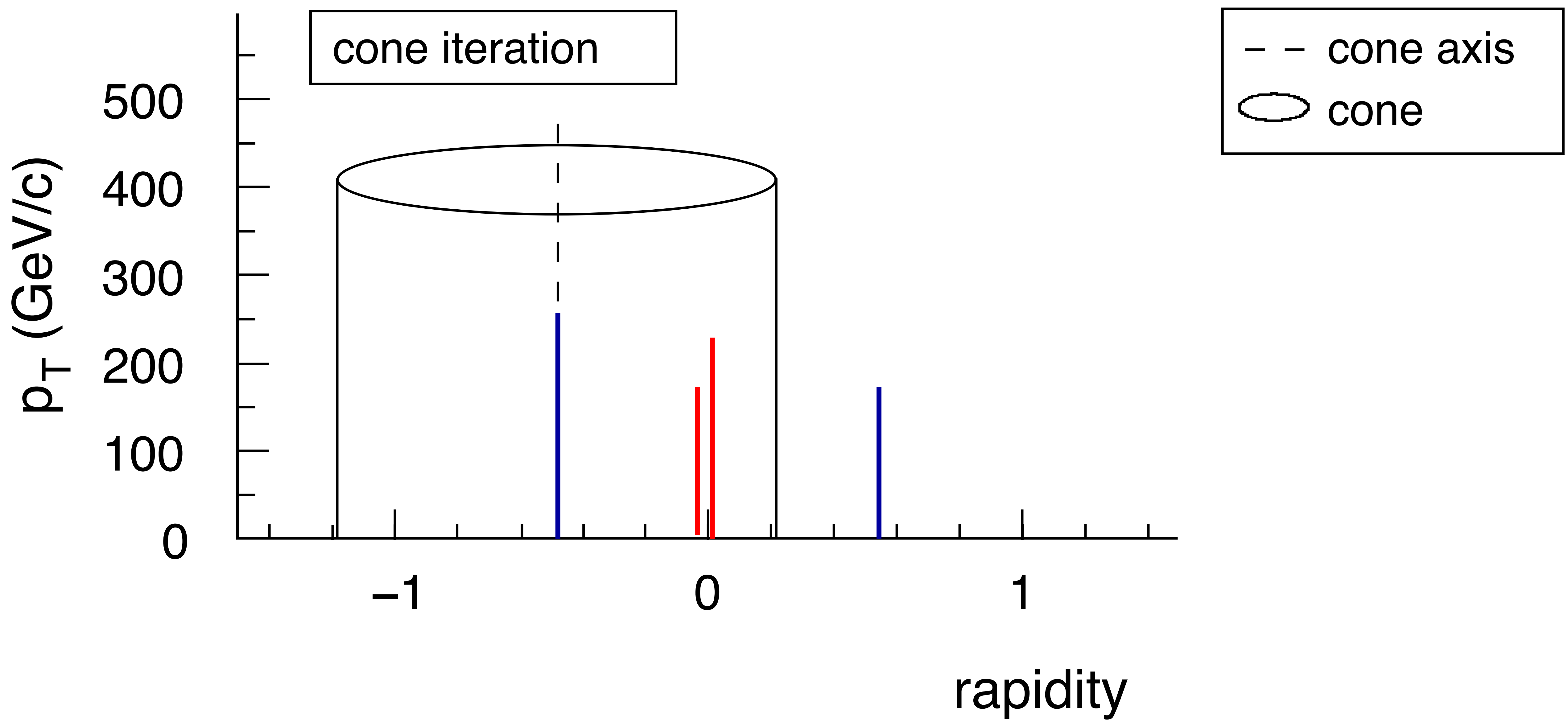
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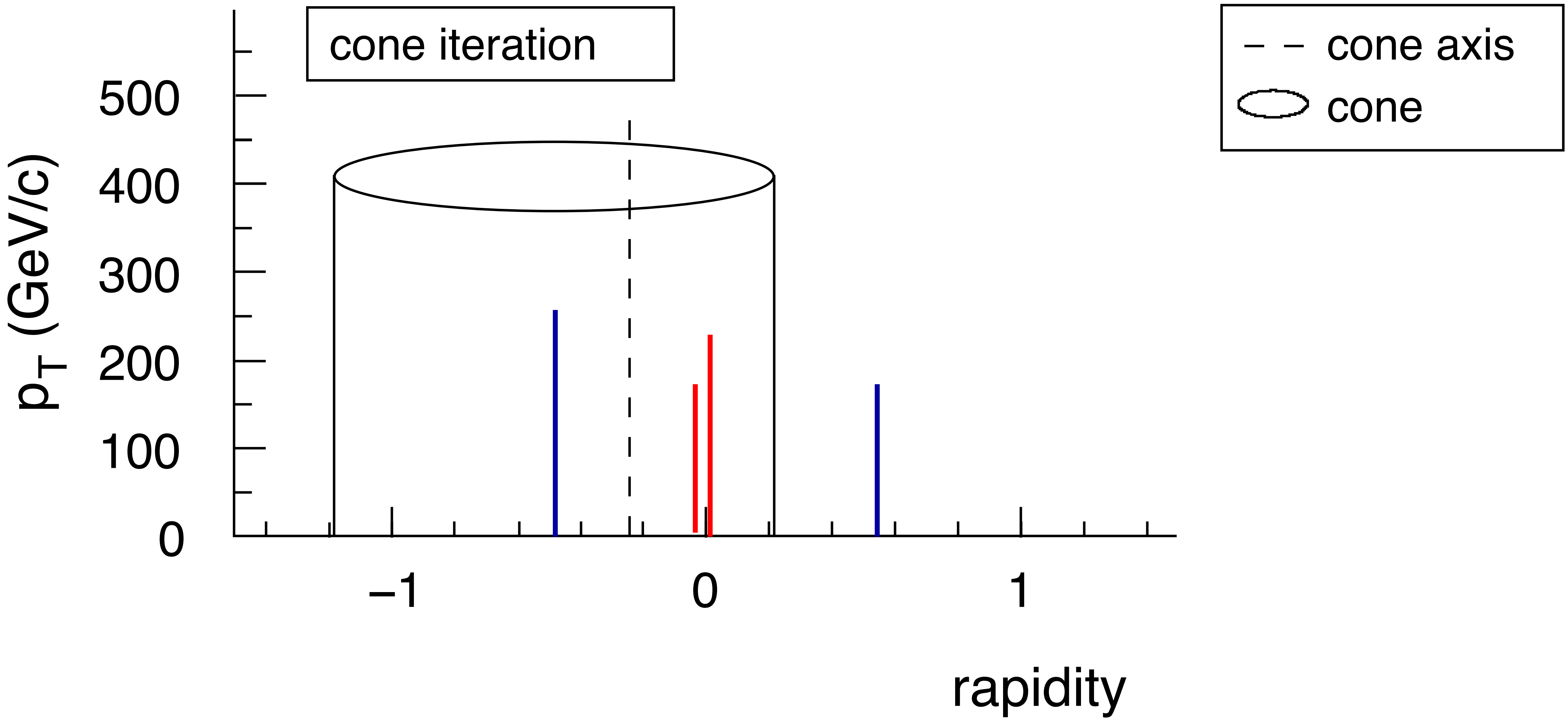
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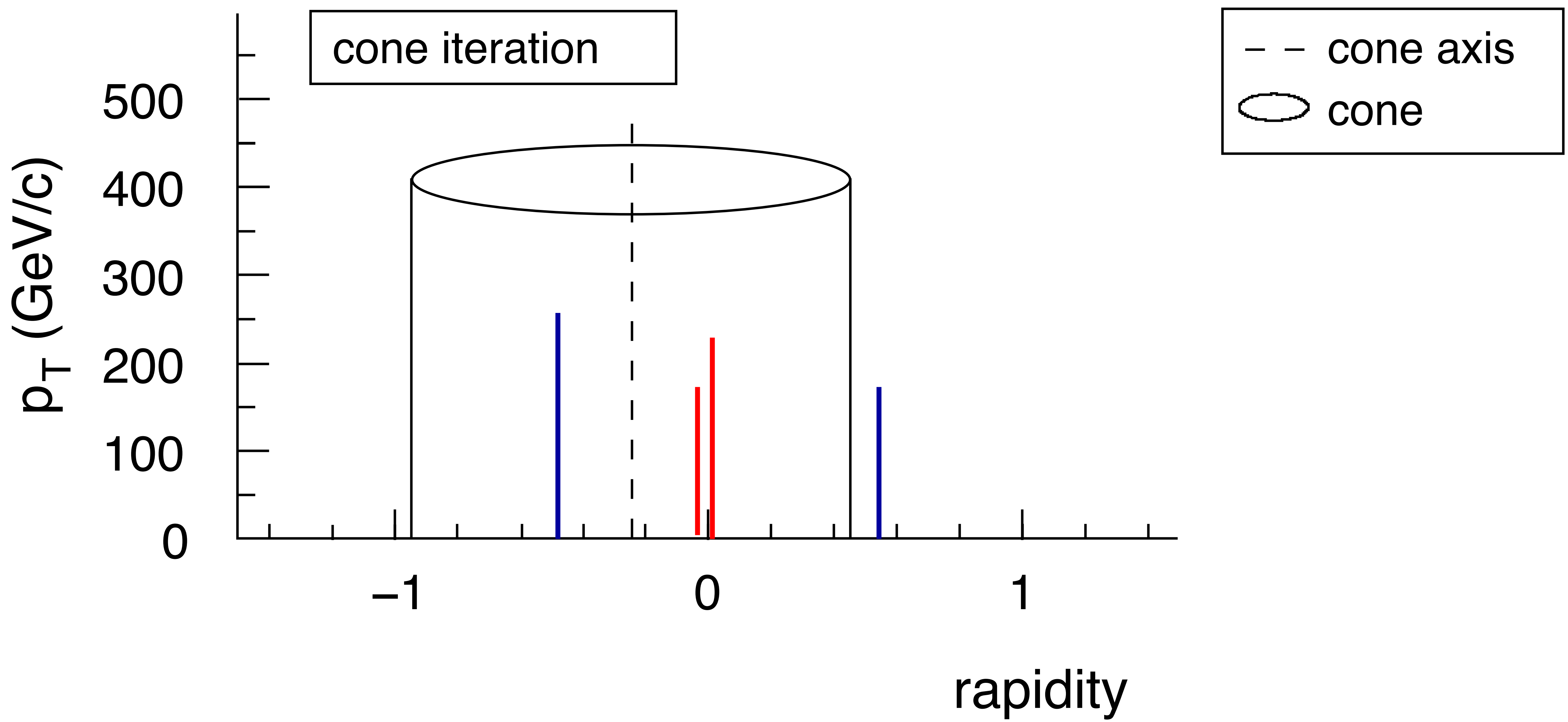

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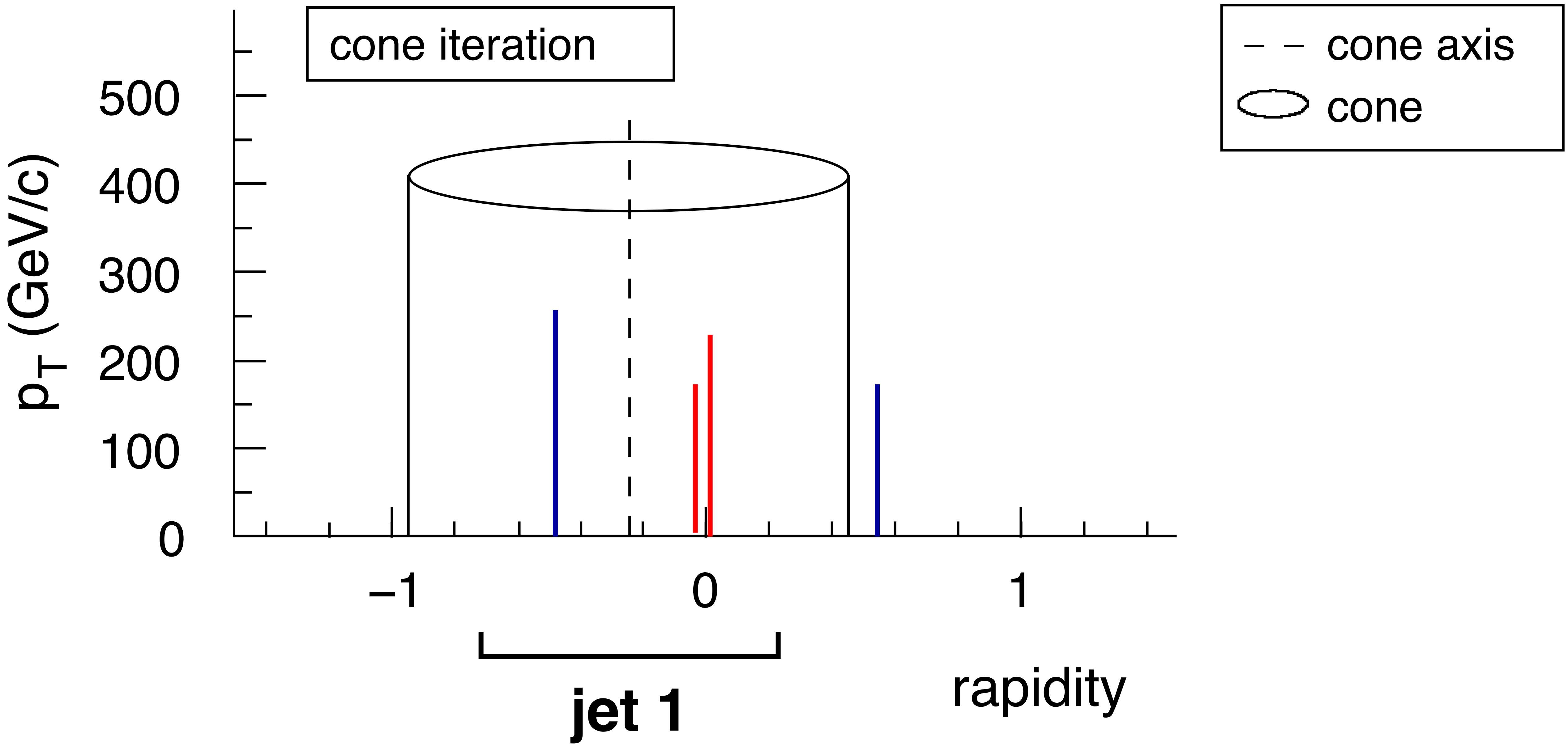
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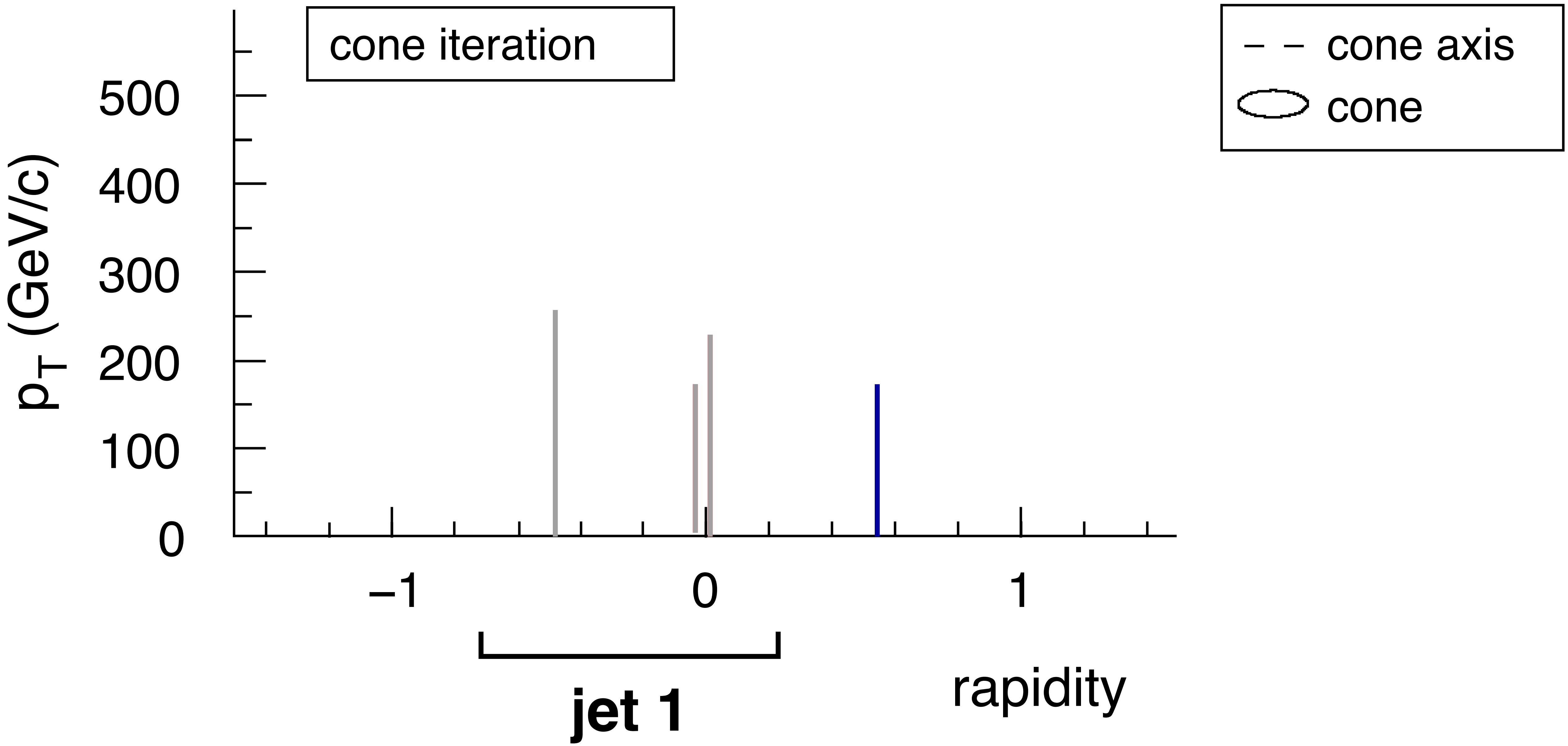
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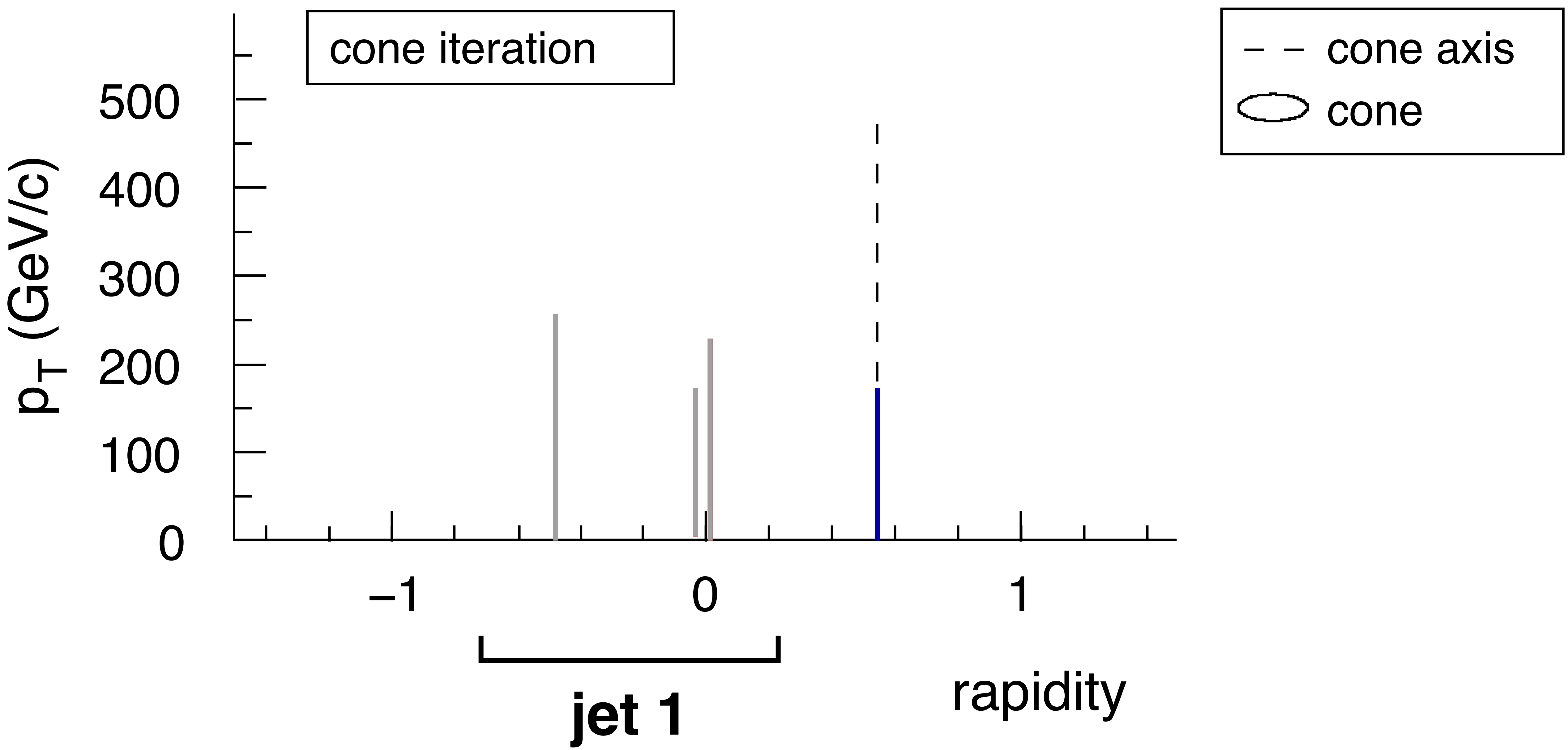

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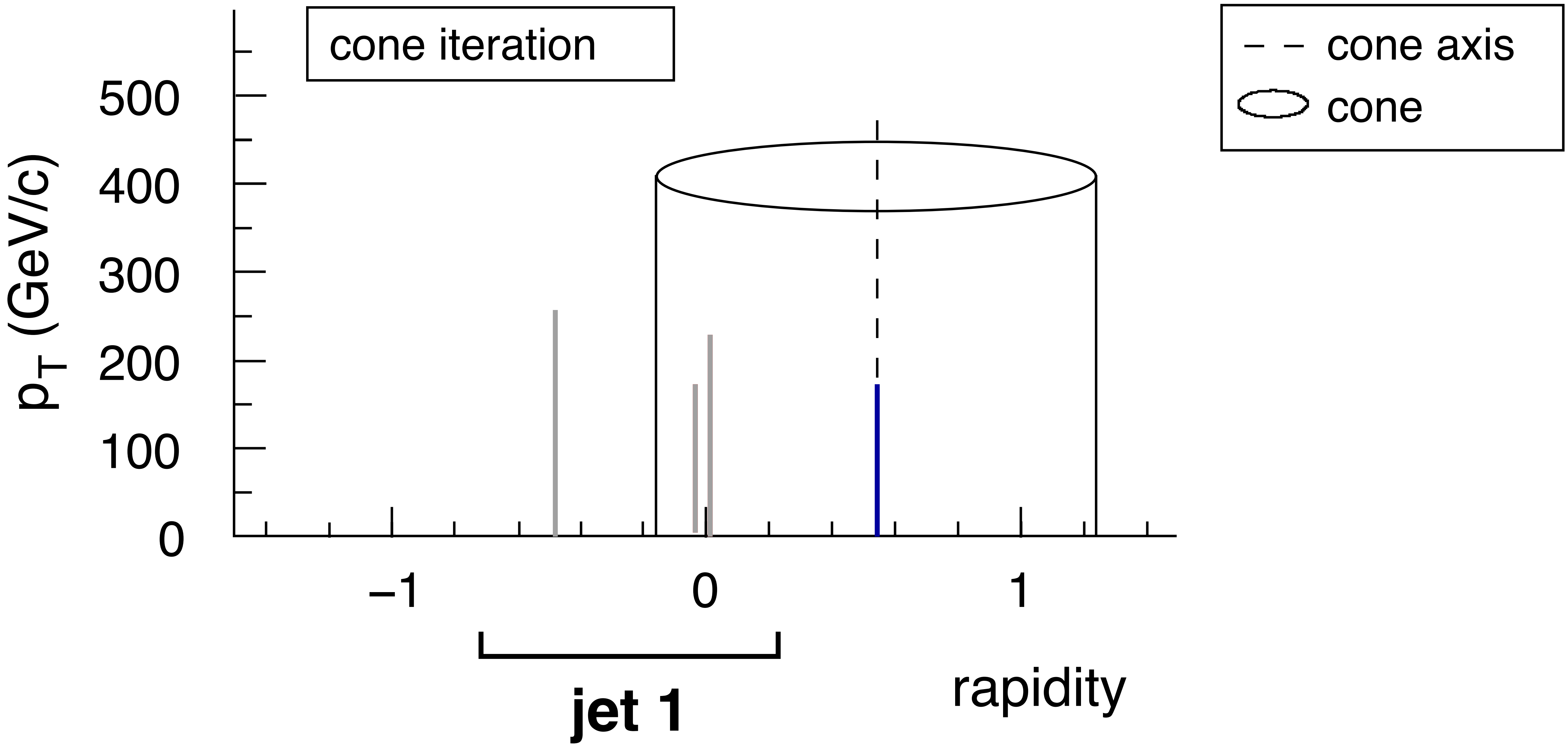

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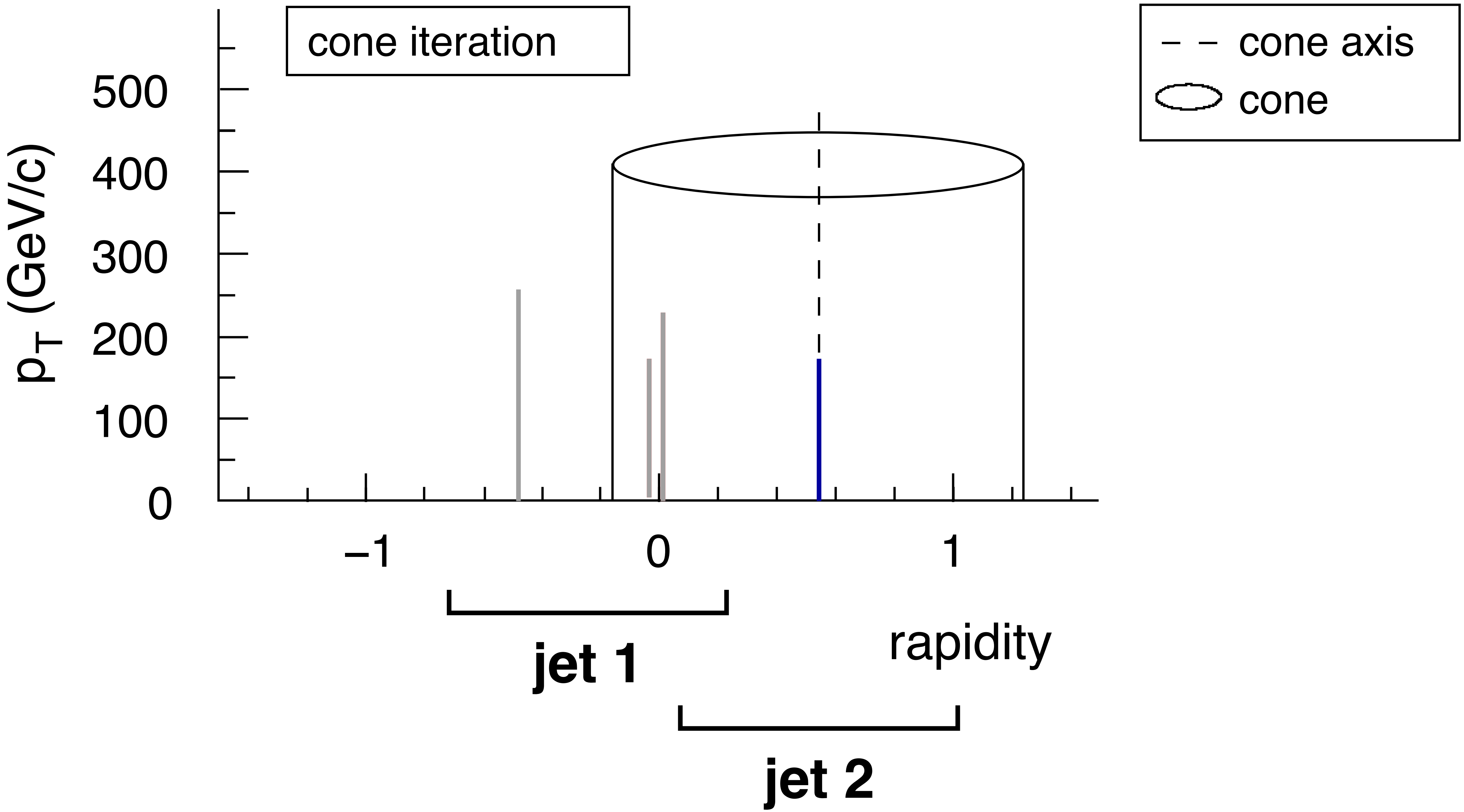
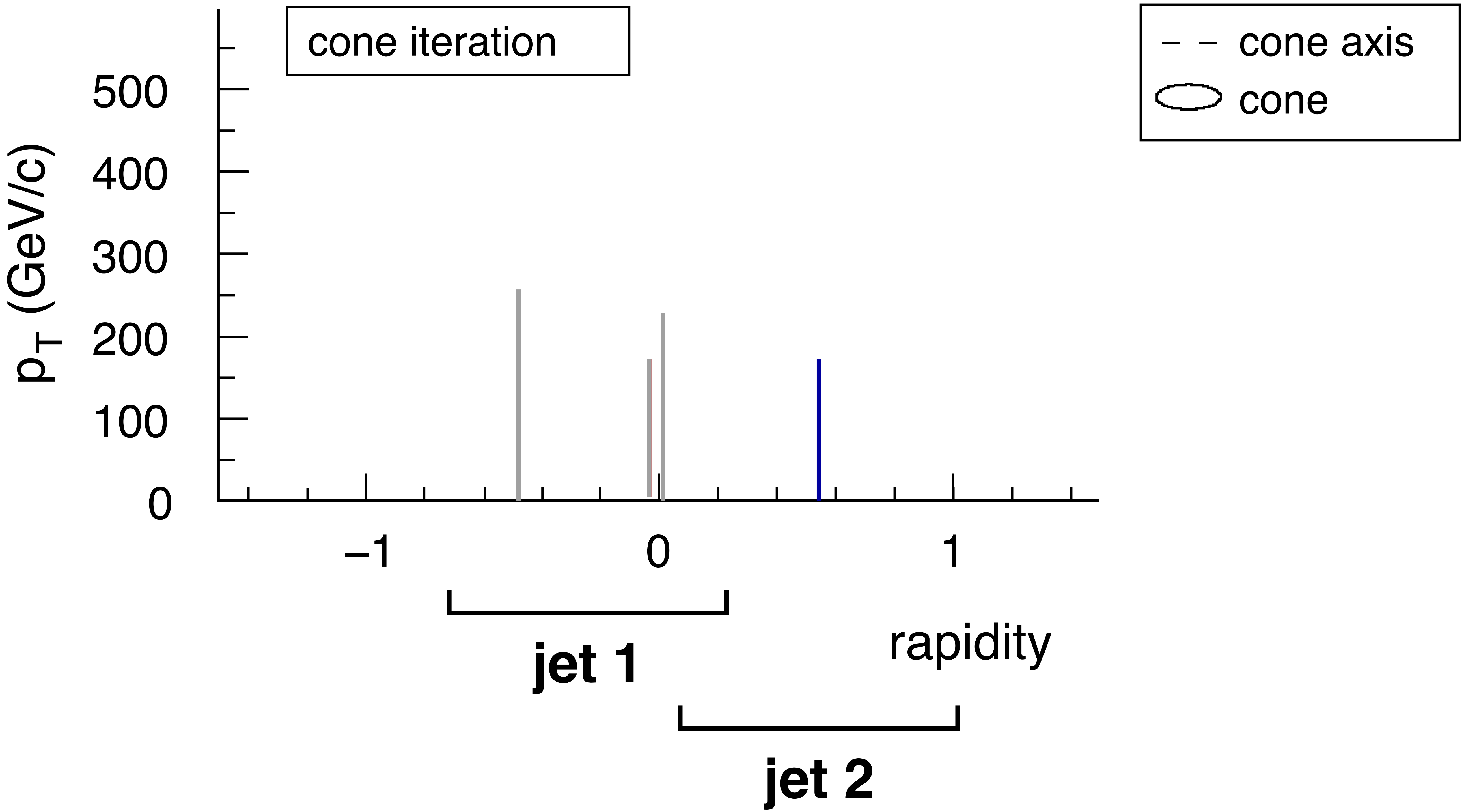
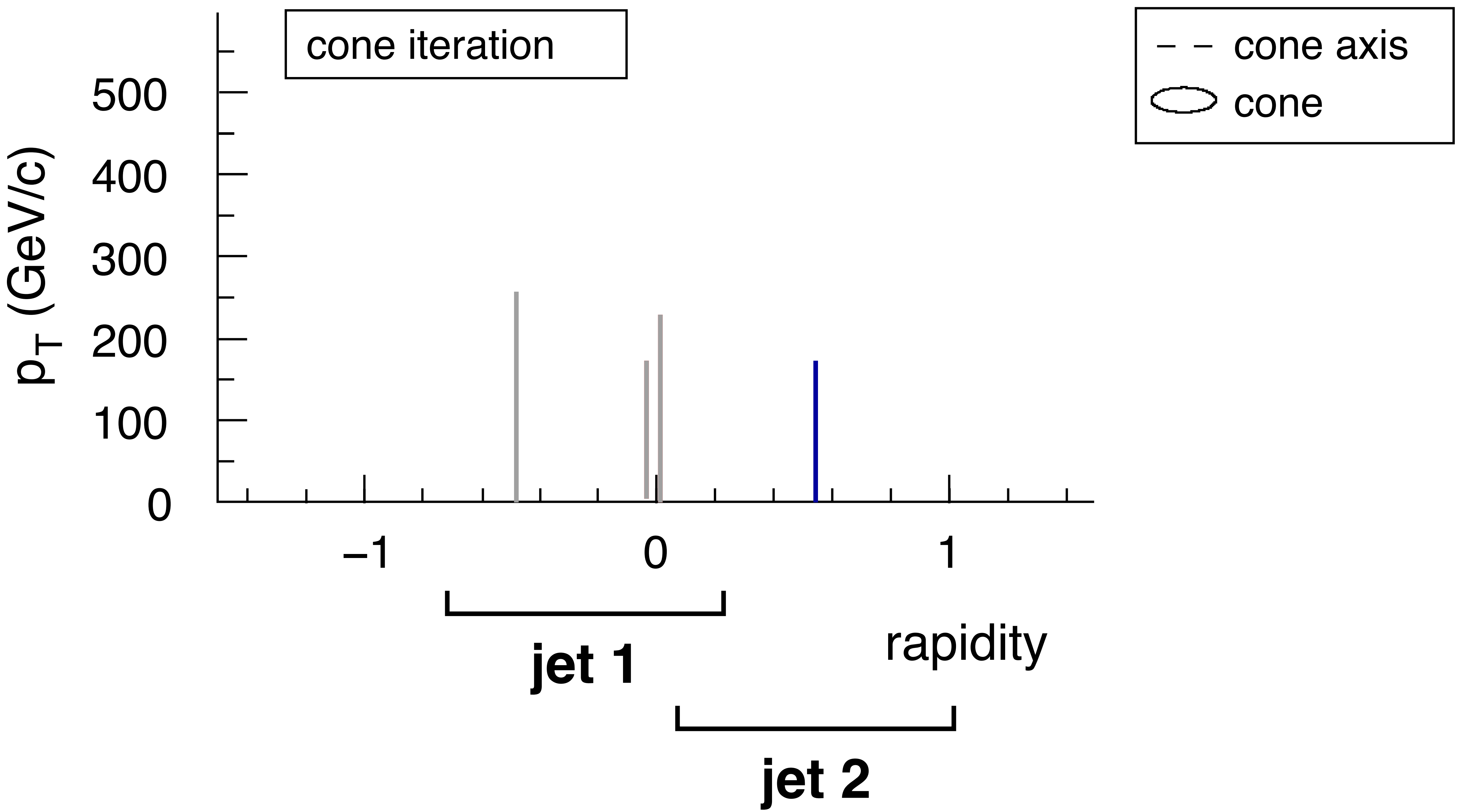


iterative cone issue



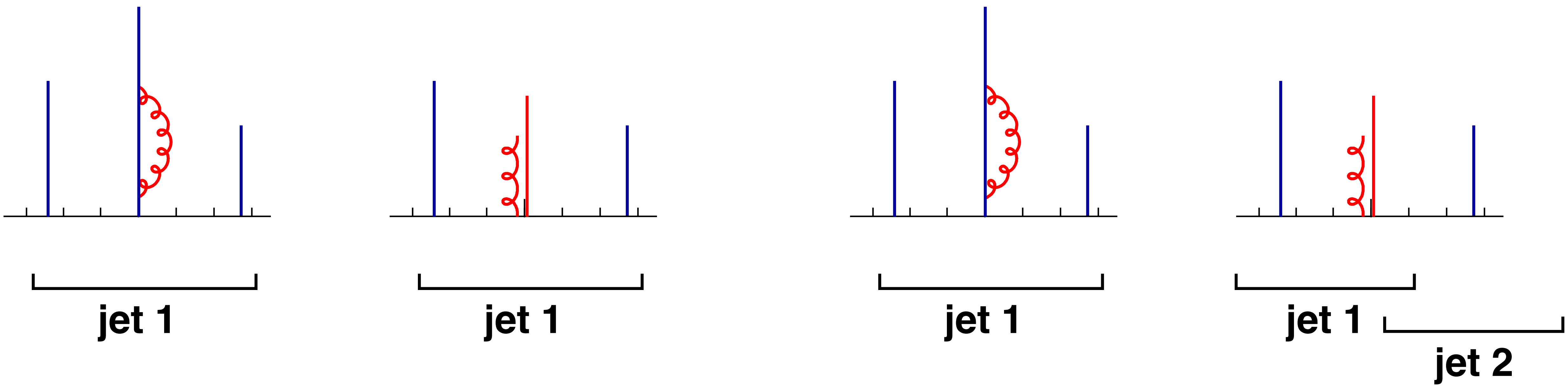


Collinear splitting can modify the final hard jets
The algorithm is **collinear unsafe**

Key requirement: infrared and collinear safety

Collinear Safe

Collinear Unsafe



$\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$ $\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$

Infinities cancel

Infinities do not cancel

Invalidates perturbation theory

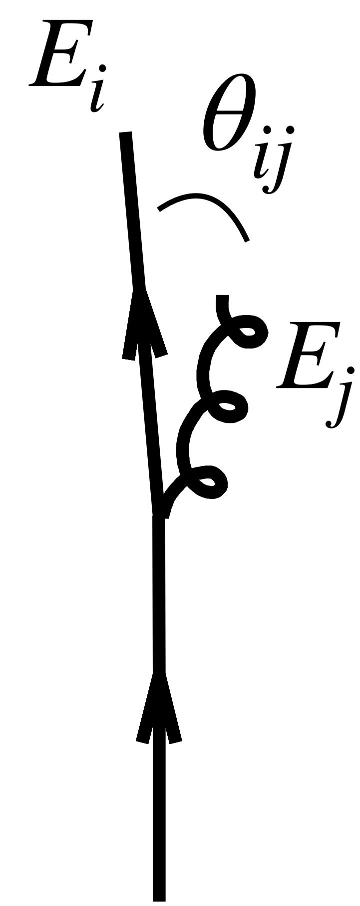
sequential recombination jet algorithms

[in clustering literature, known as pairwise agglomerative algorithms]

sequential recombination idea

- aim: undo the QCD branching that produced the jet
- two particles are likely to have come from a common parent if there is a strong divergence for the associated splitting
- divergence is

$$\frac{1}{\min(E_i, E_j)\theta_{ij}}$$



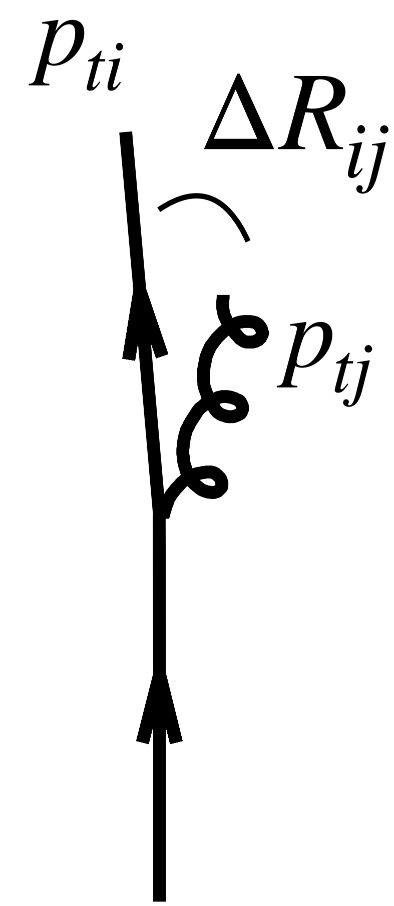
- i.e. when the softer particle has a small transverse momentum (k_t) with respect to the harder one

sequential recombination idea

- aim: undo the QCD branching that produced the jet

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- two particles are likely to have come from a common parent if there is a strong divergence for the associated splitting



- divergence is

$$\frac{1}{\min(E_i, E_j)\theta_{ij}} \sim \frac{1}{\min(p_{ti}, p_{tj})\Delta R_{ij}}$$

- i.e. when the softer particle has a small transverse momentum (k_t) with respect to the harder one

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

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

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

Sequential recombination algorithm

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

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

Inclusive k_t algorithm
S.D. Ellis & Soper, 1993
Catani, Dokshitzer, Seymour & Webber, 1993

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

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Sequential recombination algorithm

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

Mostly, the algorithm repeatedly recombines pairs of particles

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

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

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

Sequential recombination algorithm

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

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

k_t in action

k_t alg.: Find smallest of

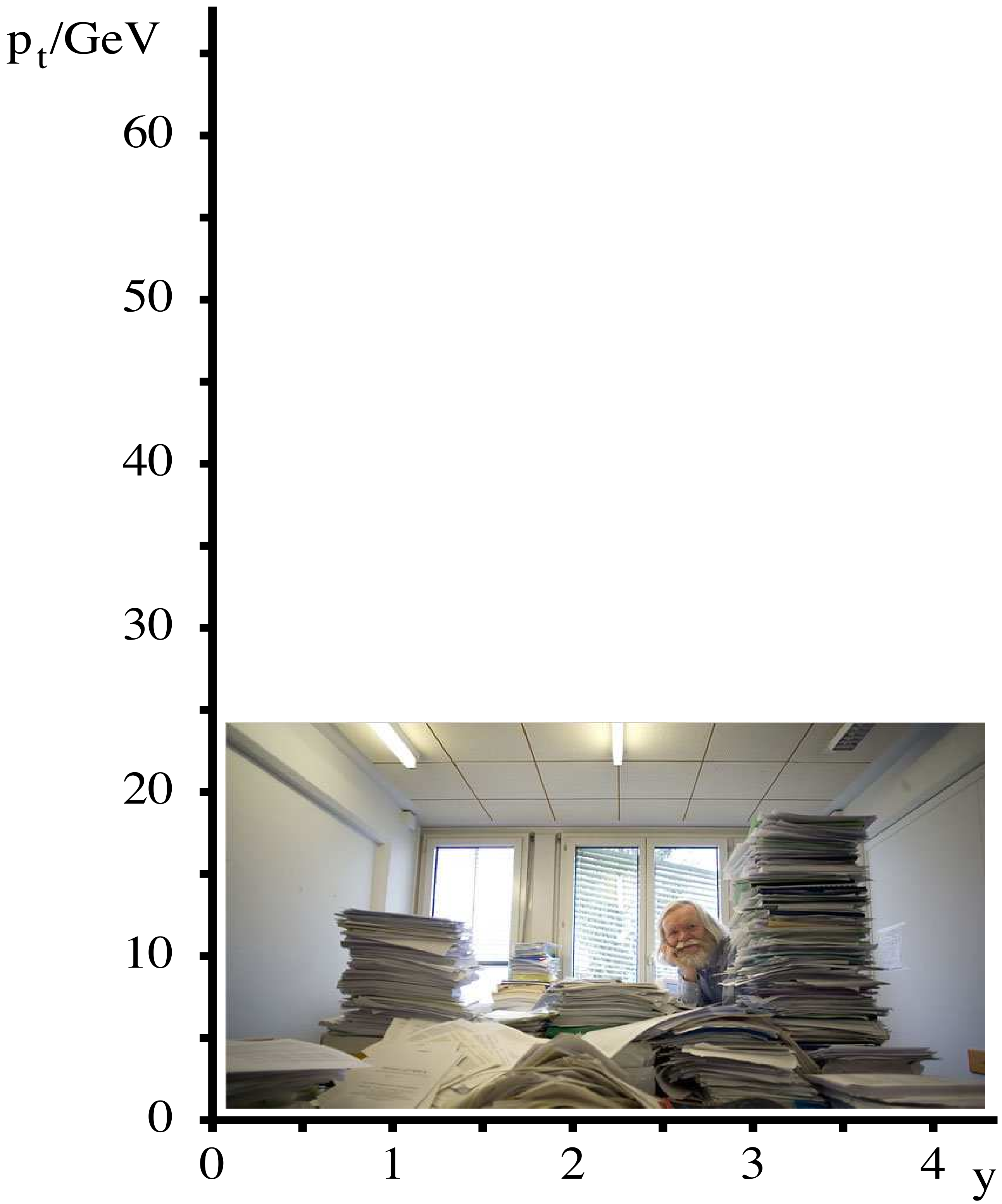
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

k_t in action



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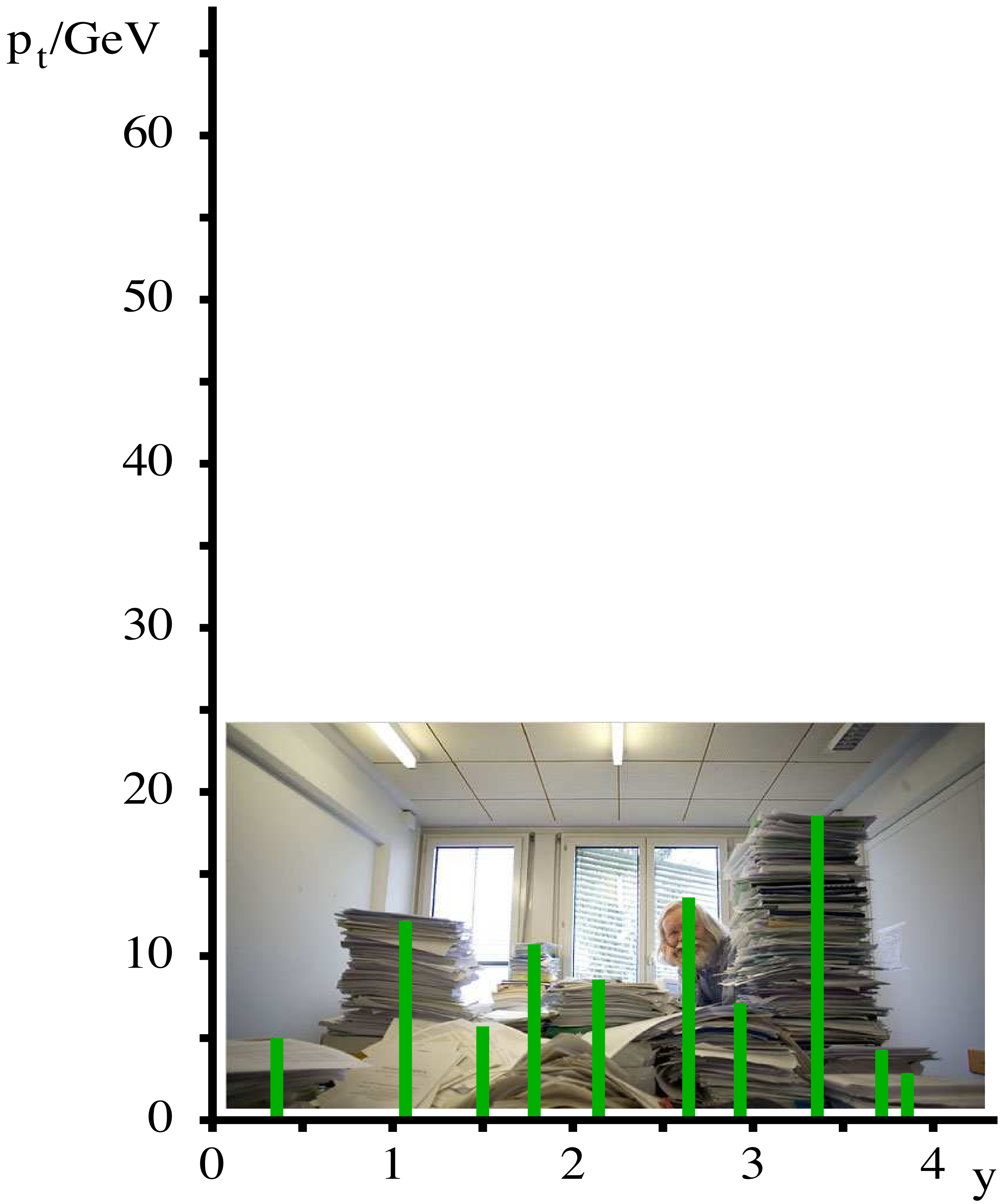

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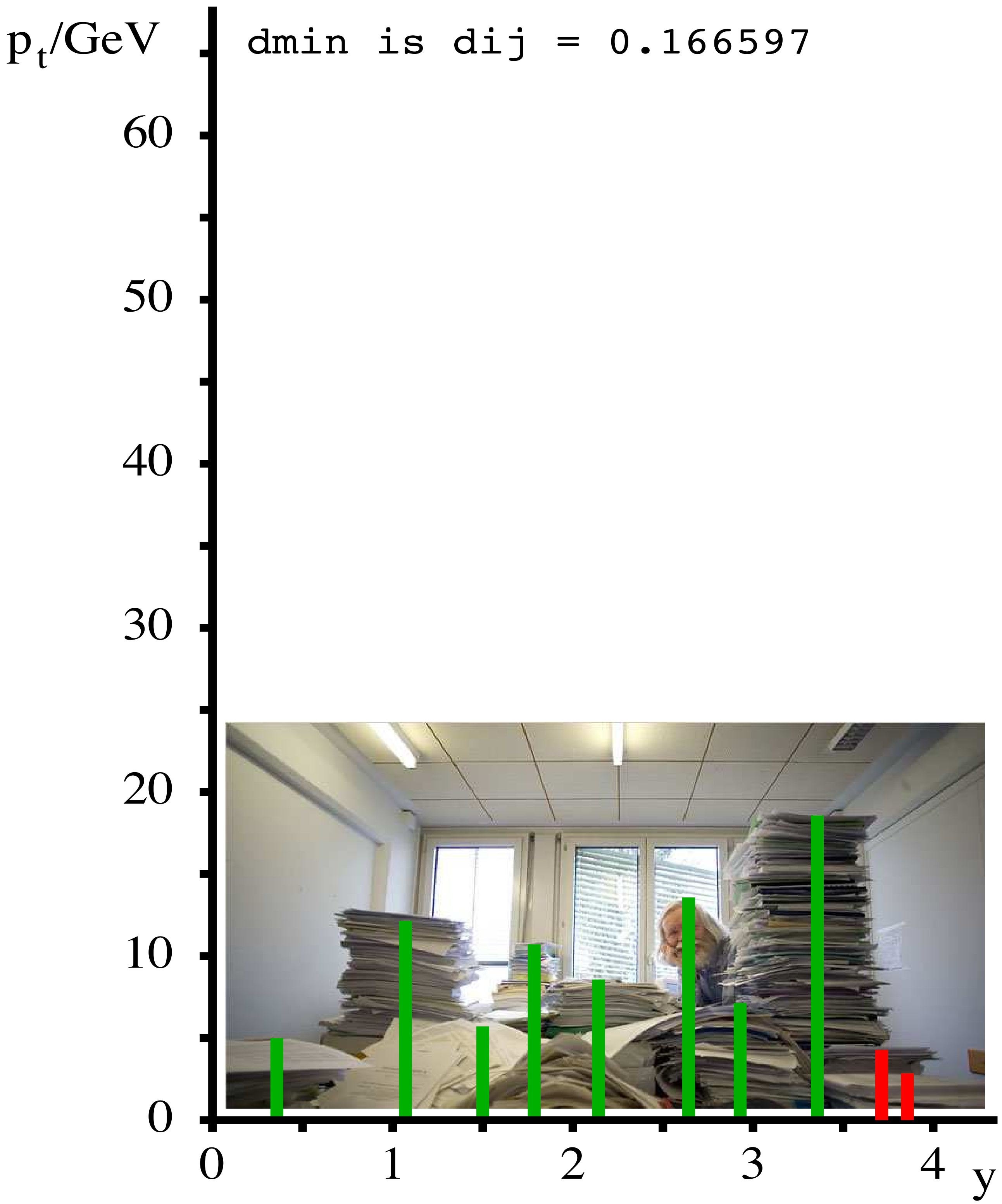

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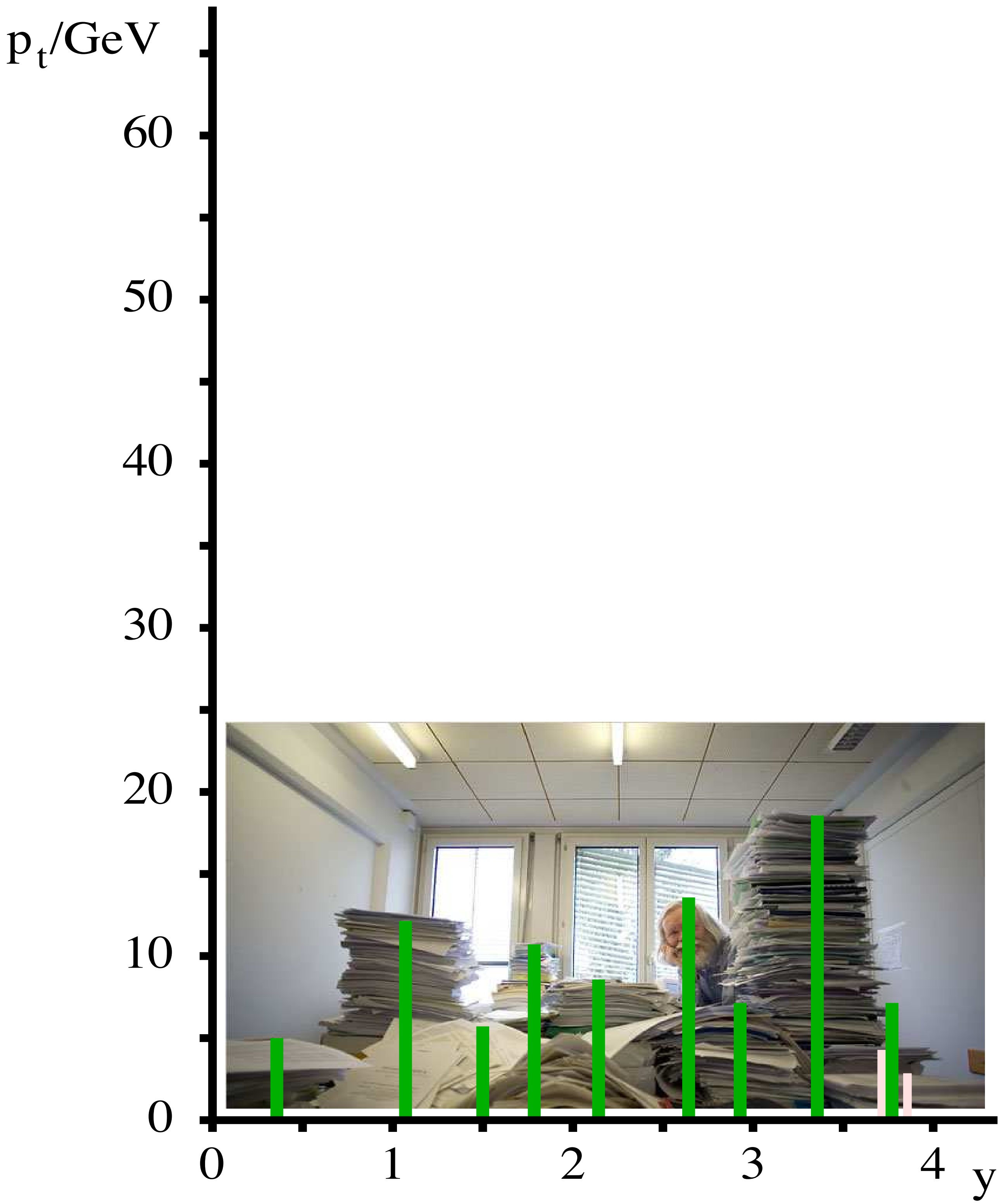

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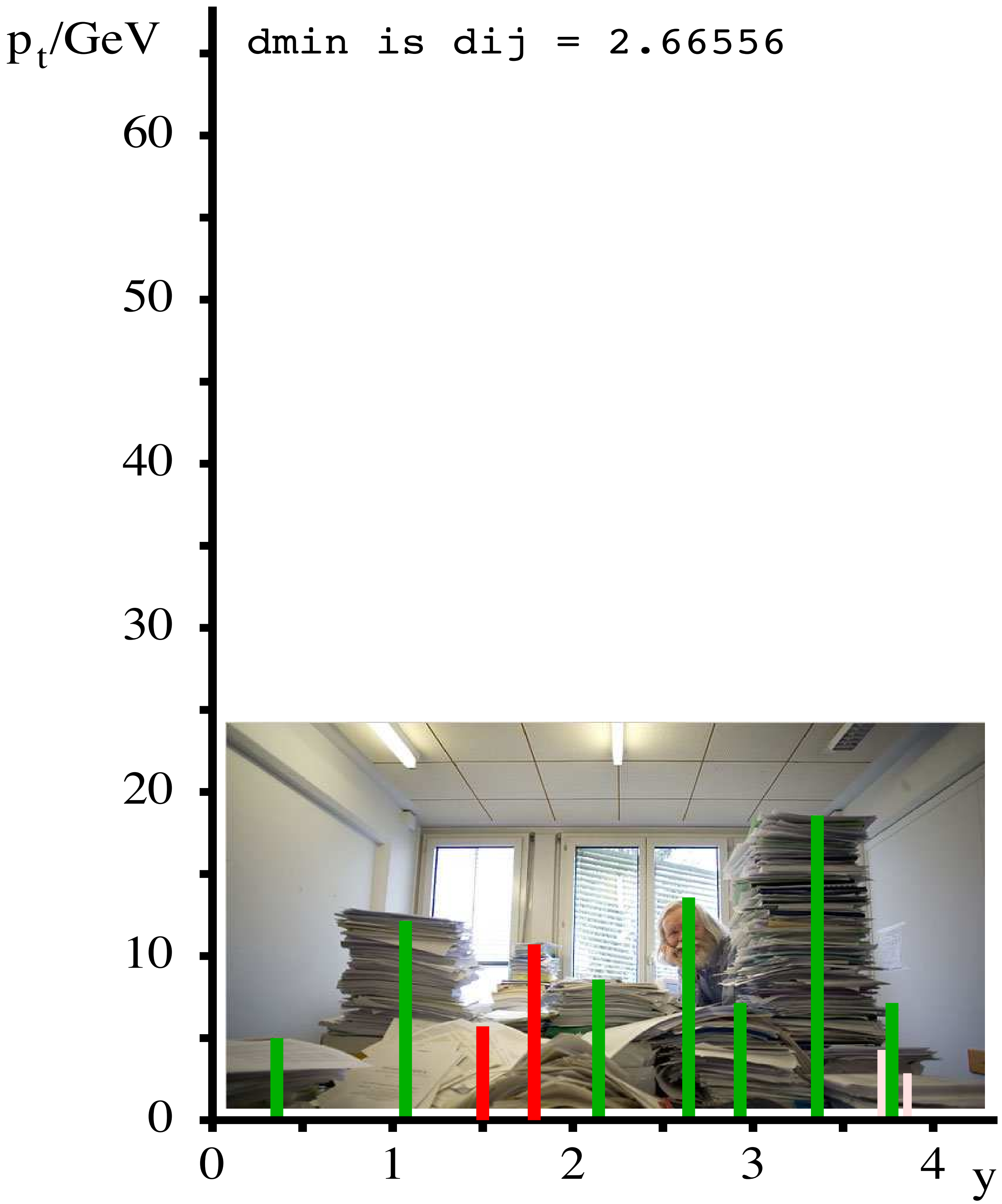

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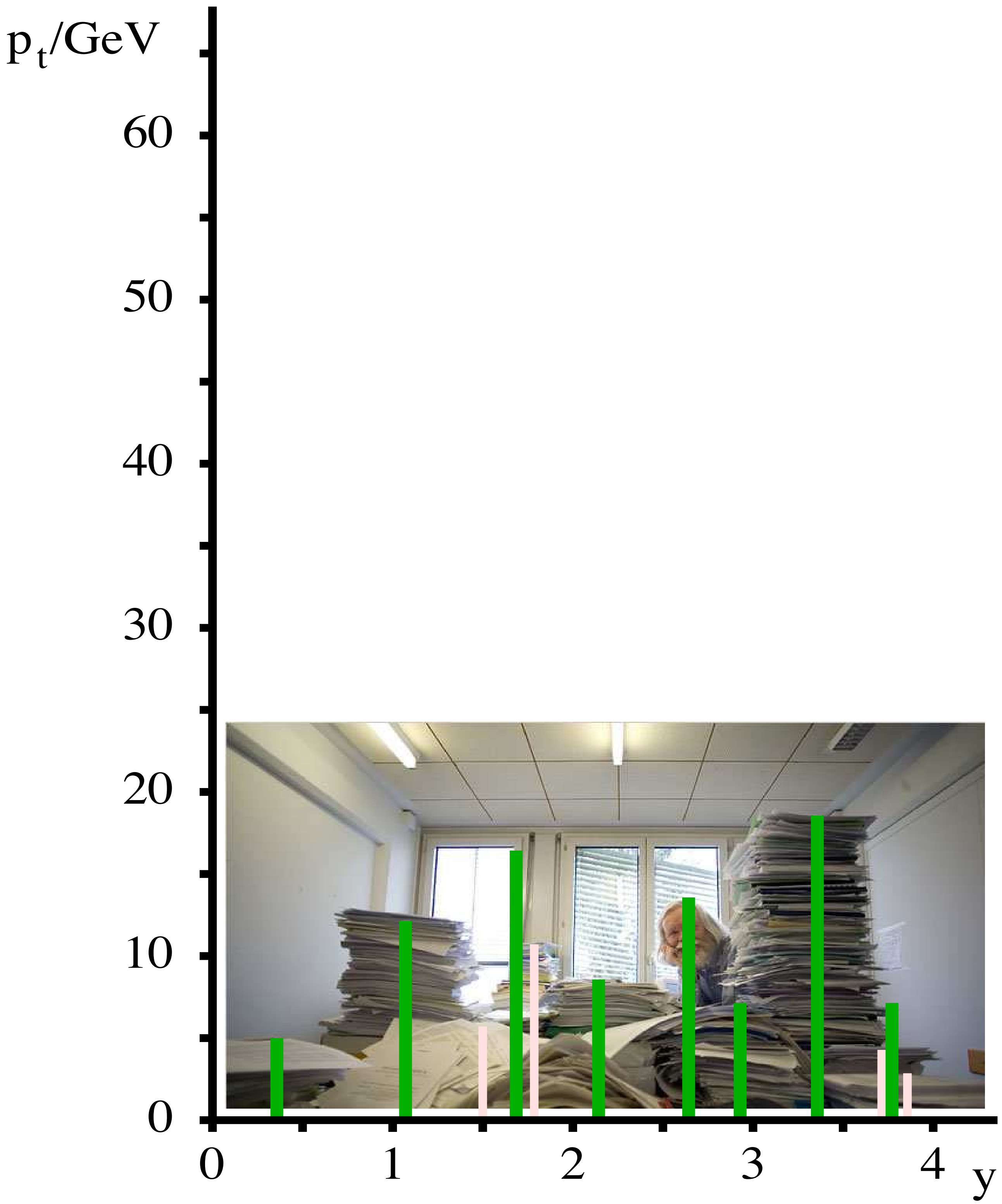

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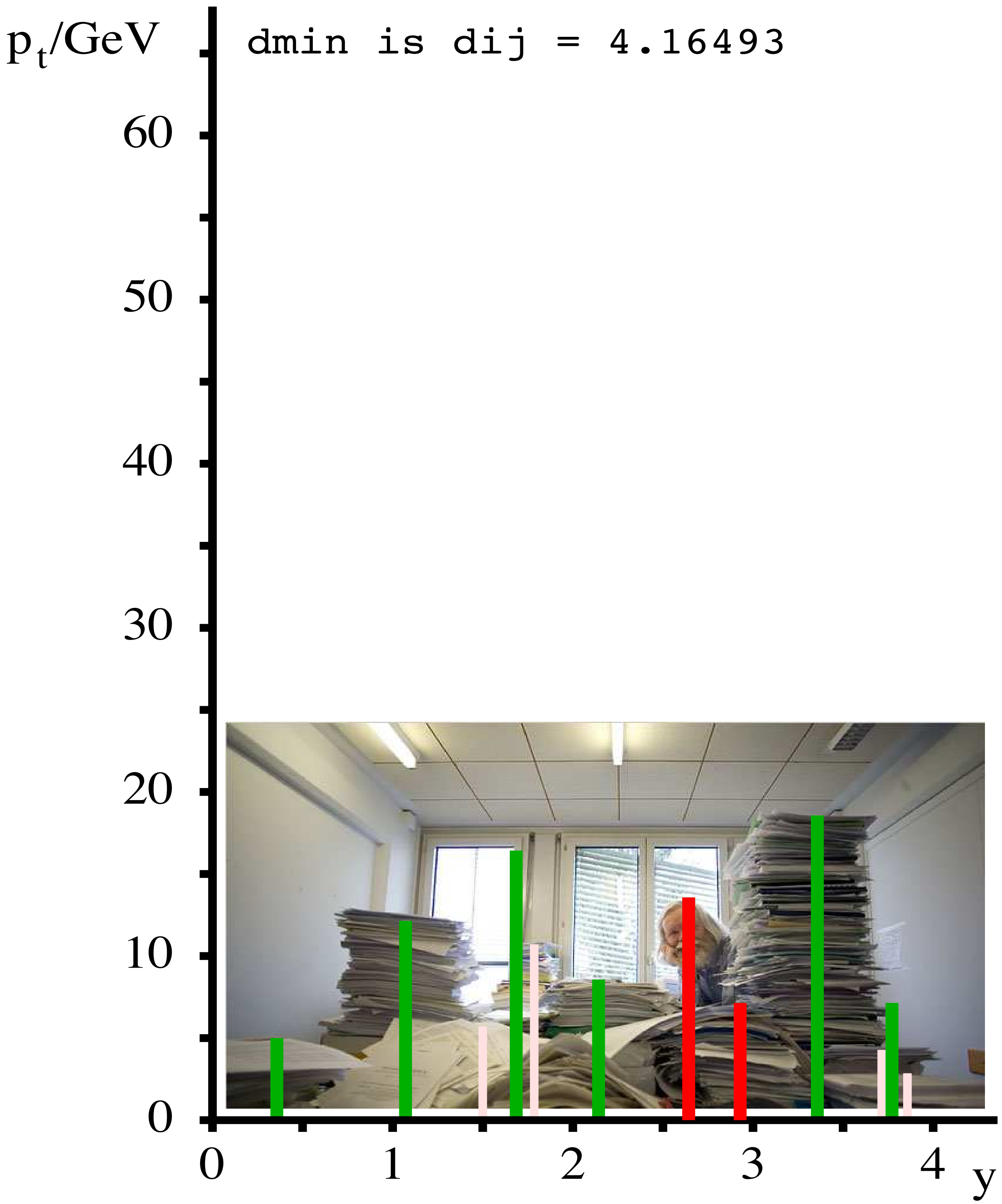

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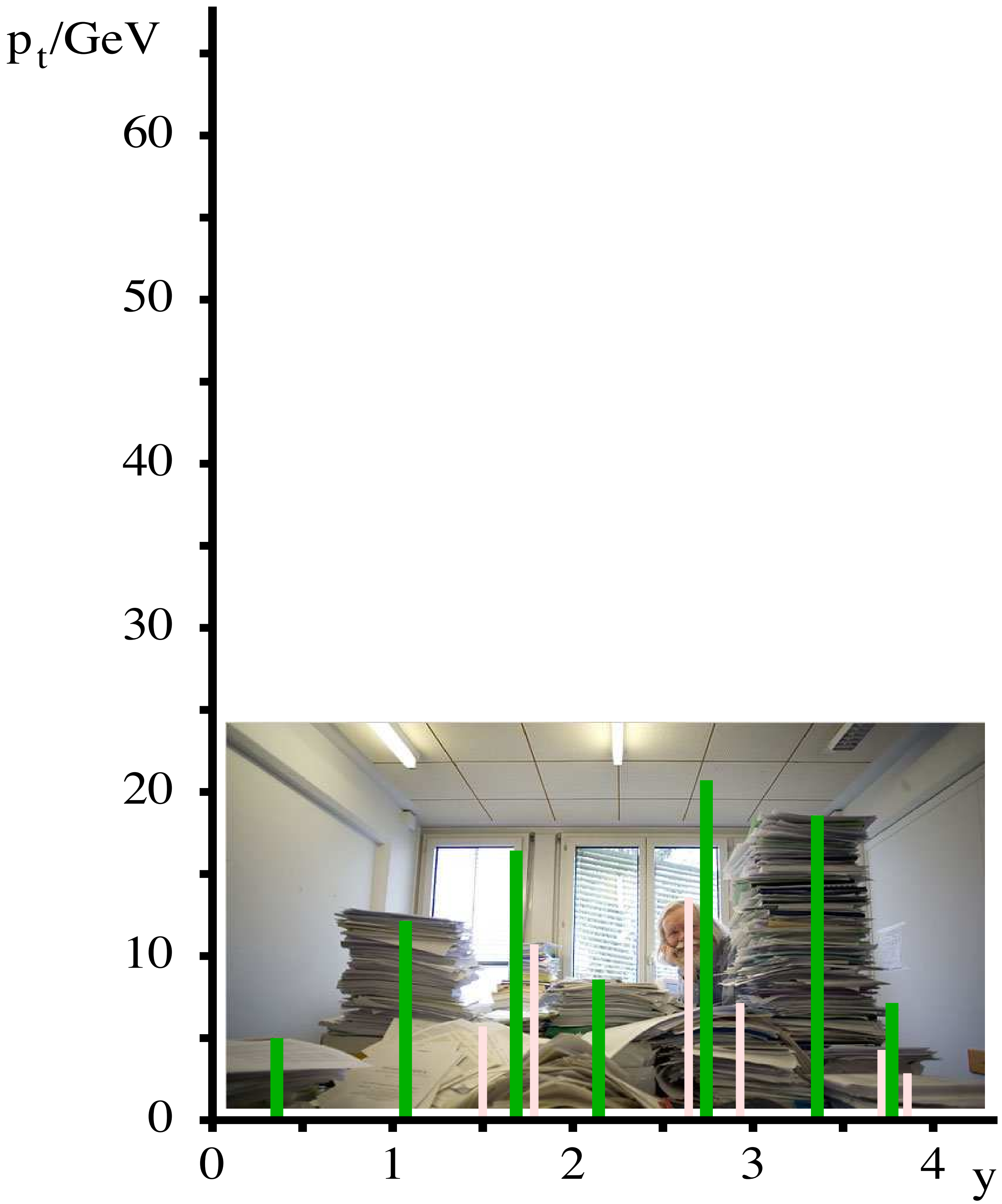

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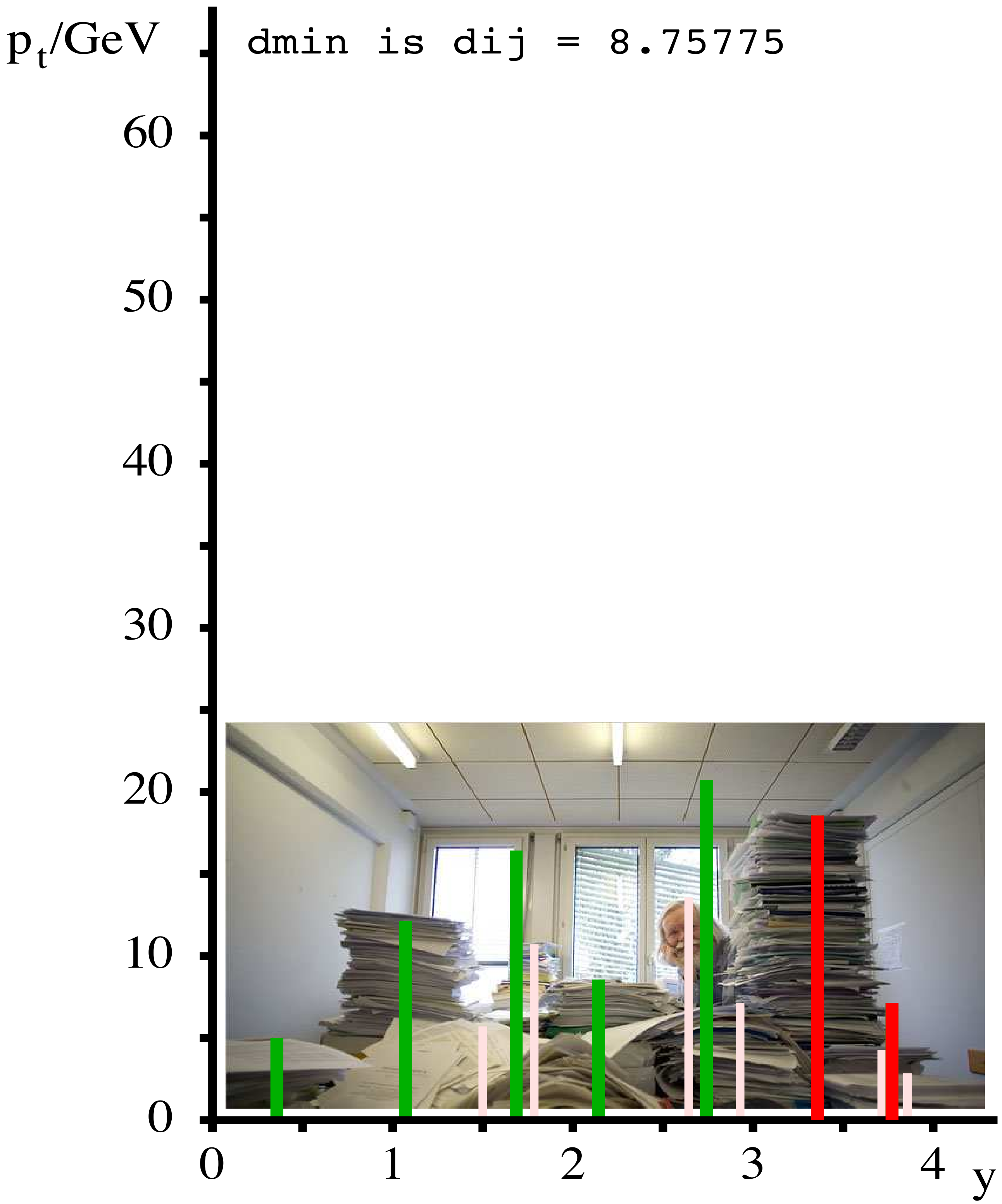

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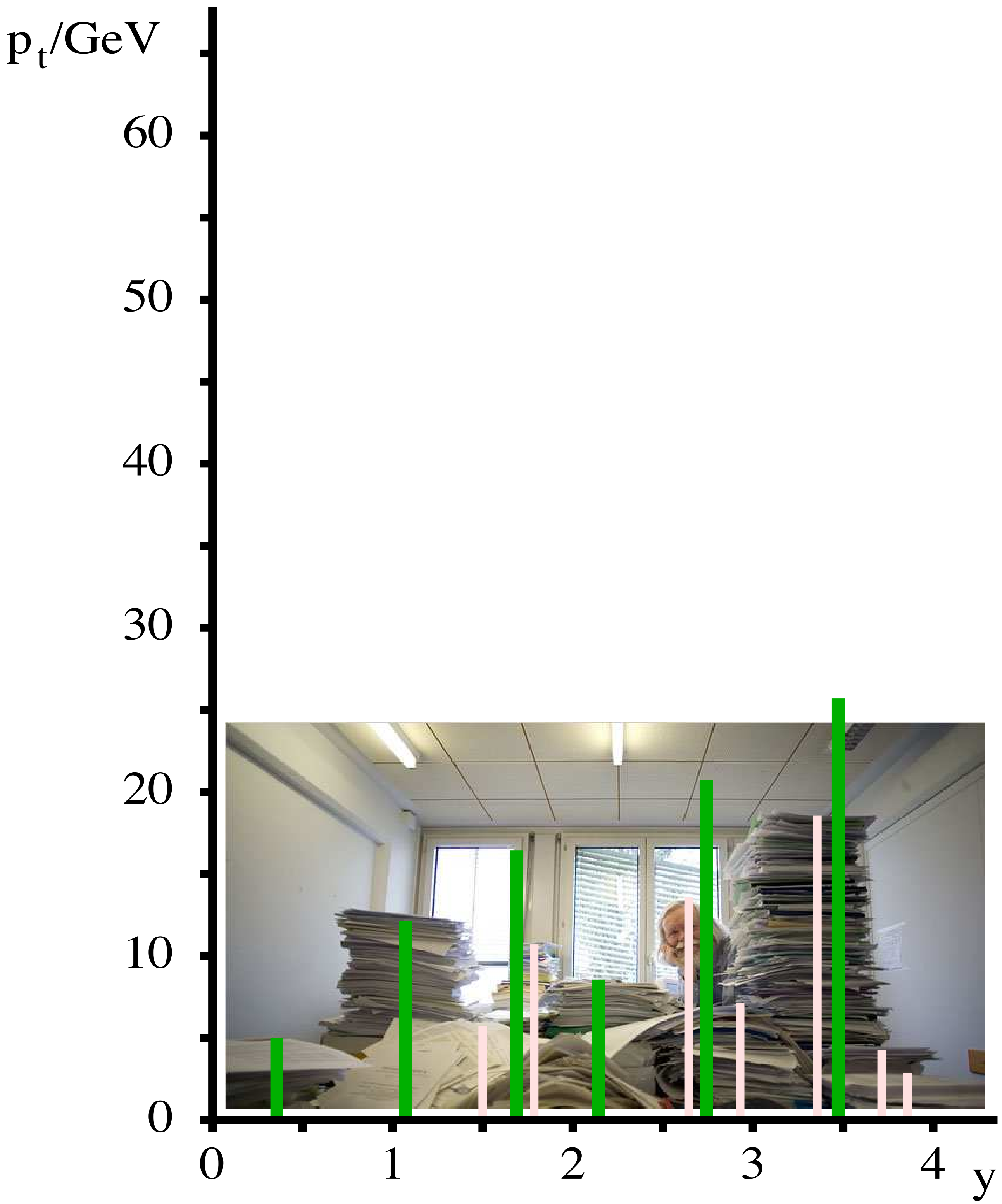

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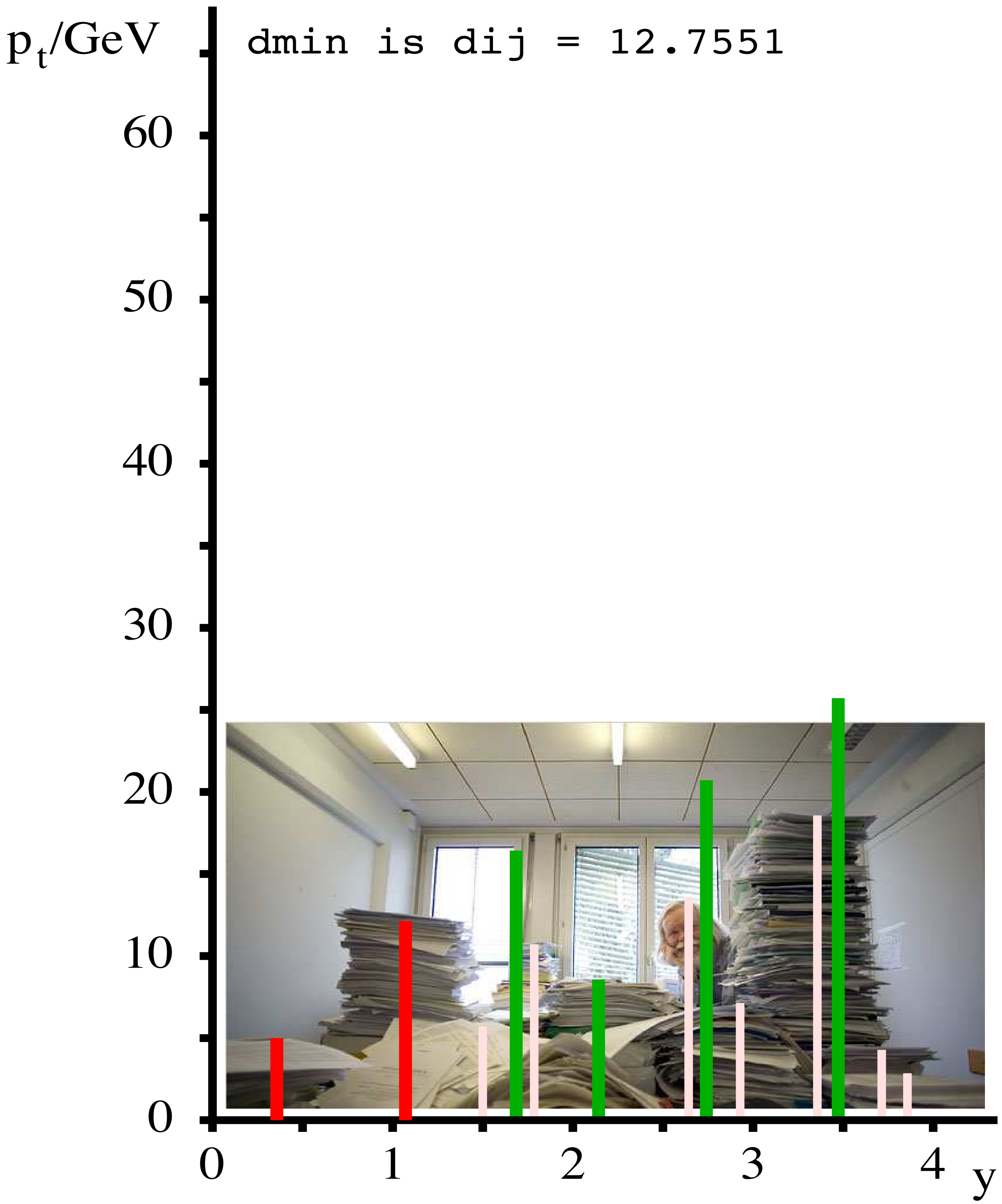

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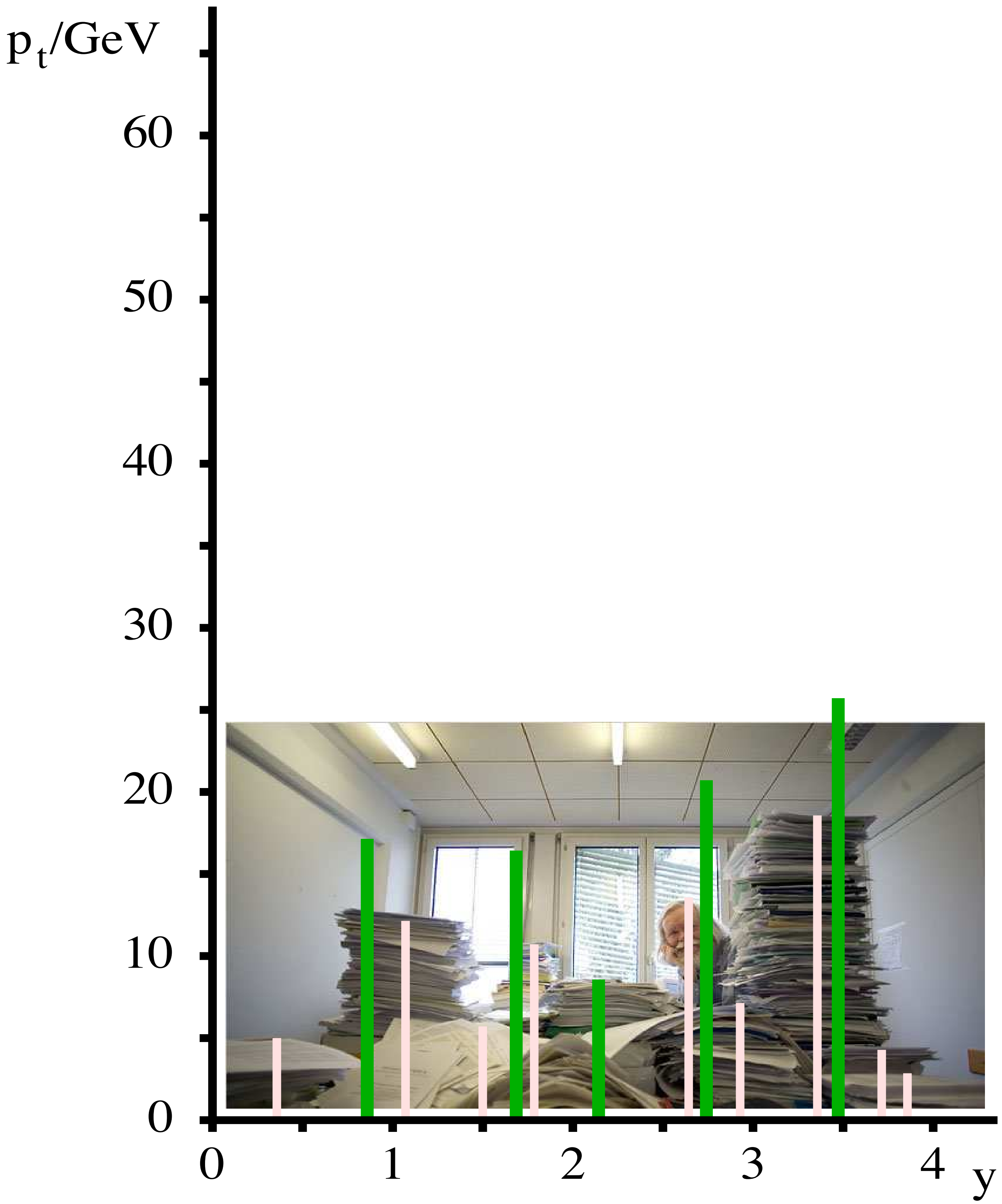

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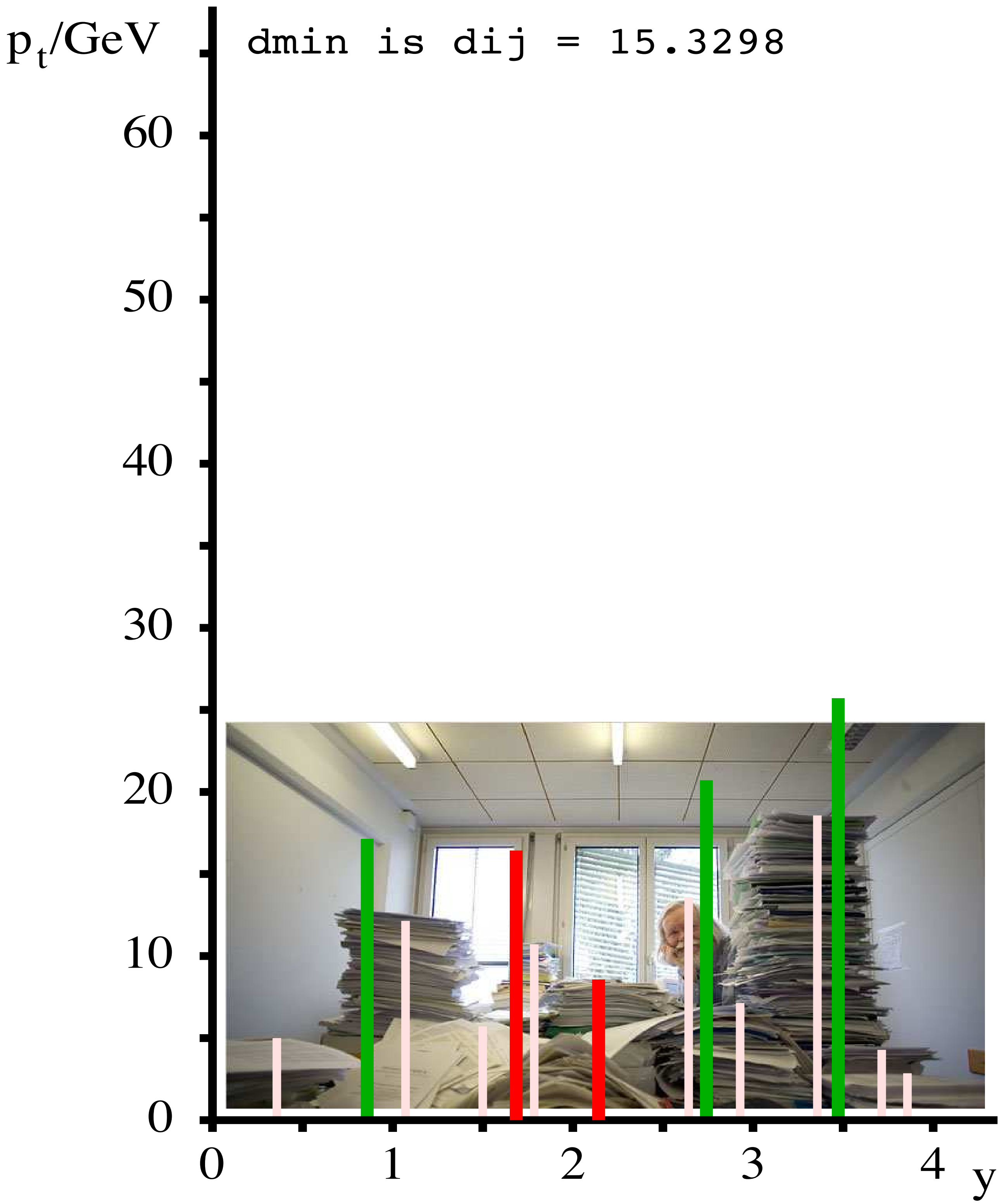

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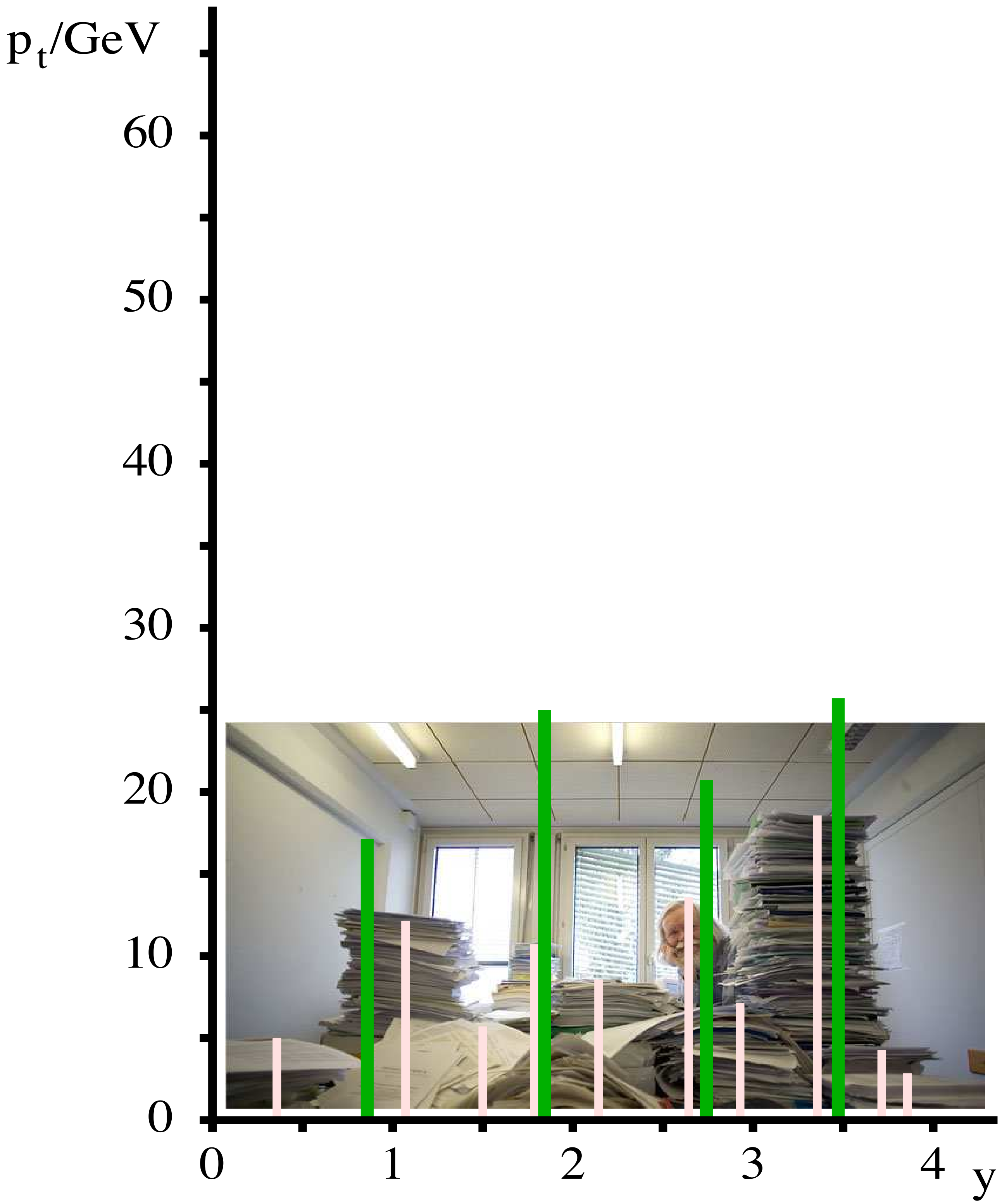

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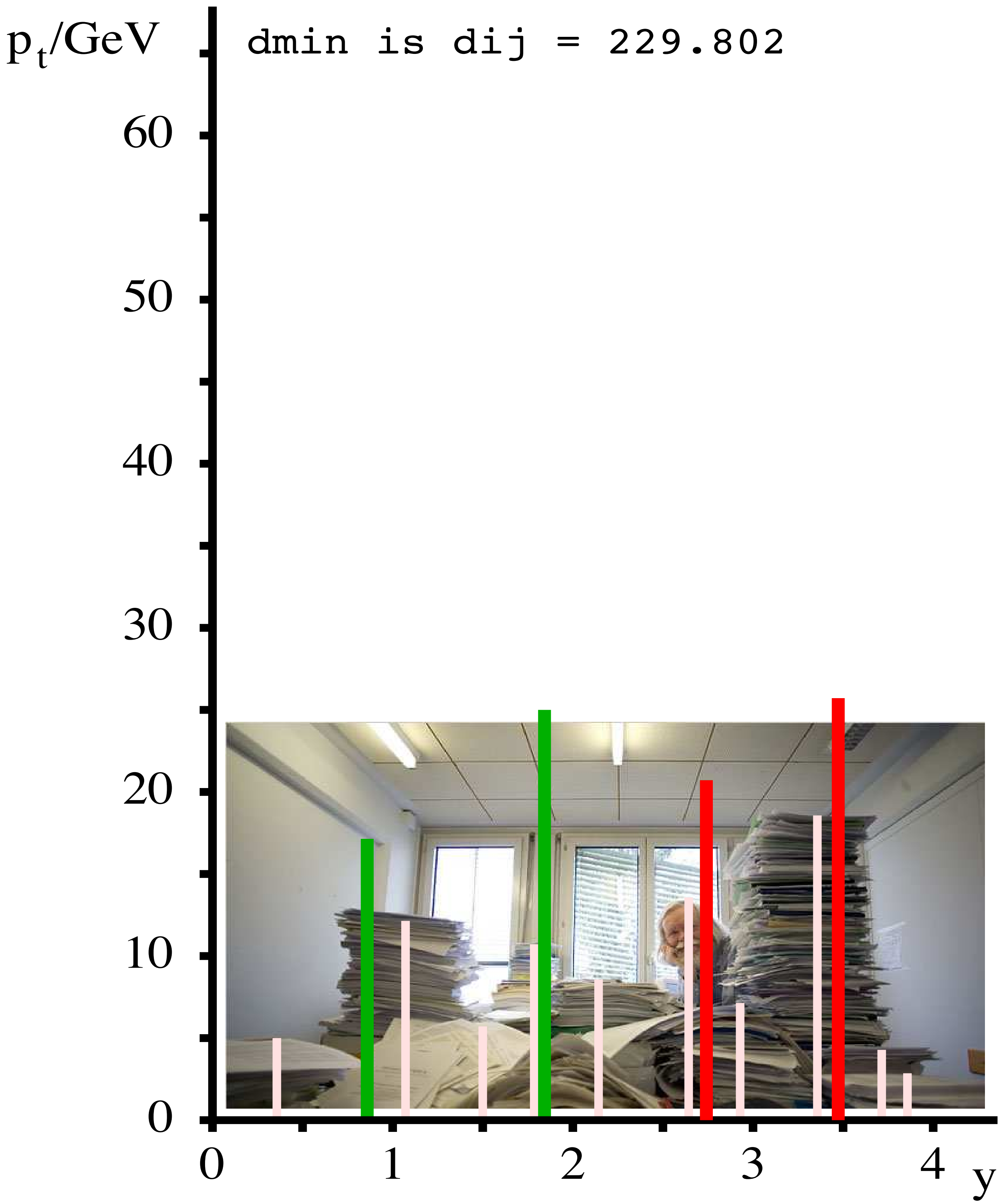

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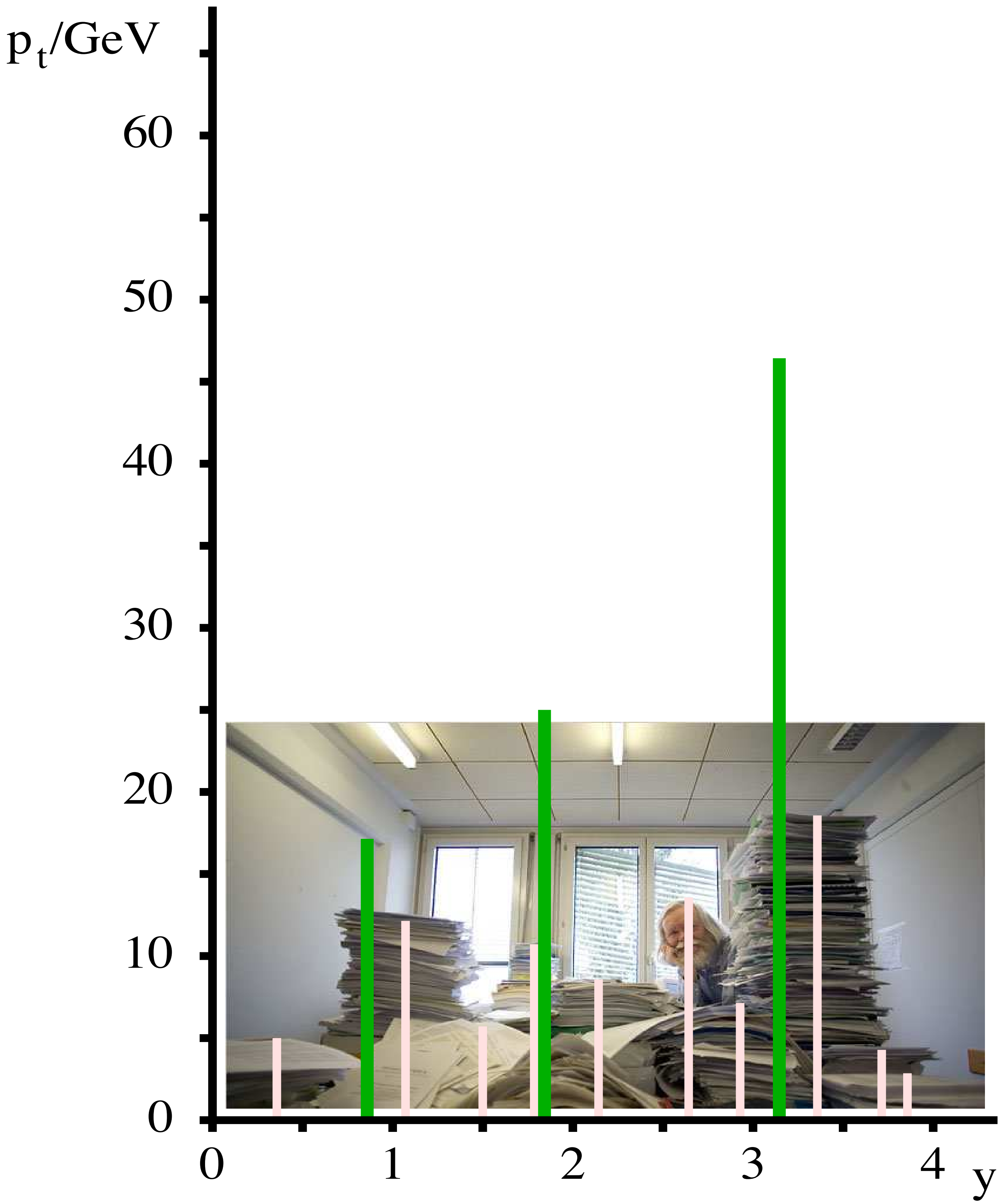

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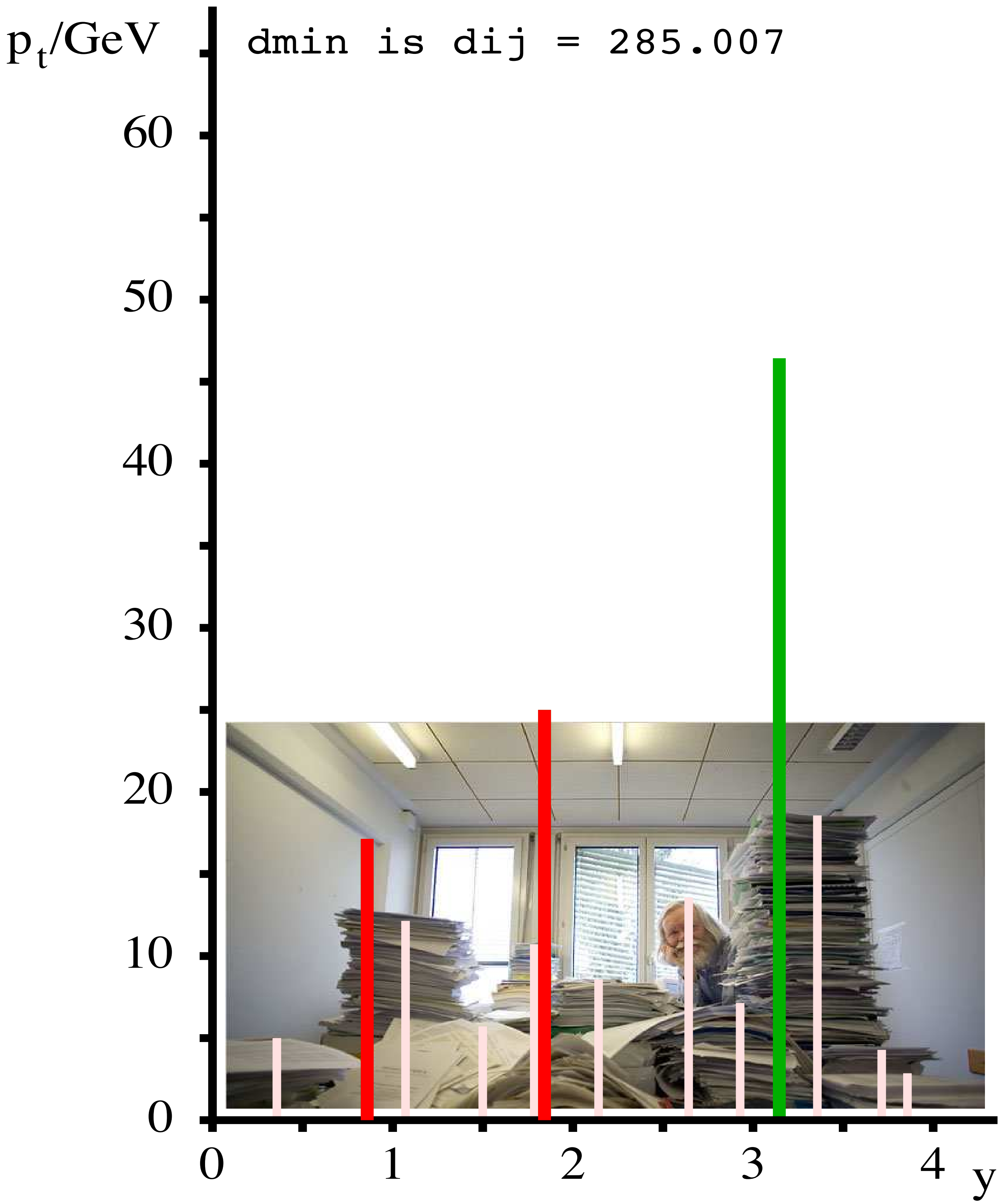

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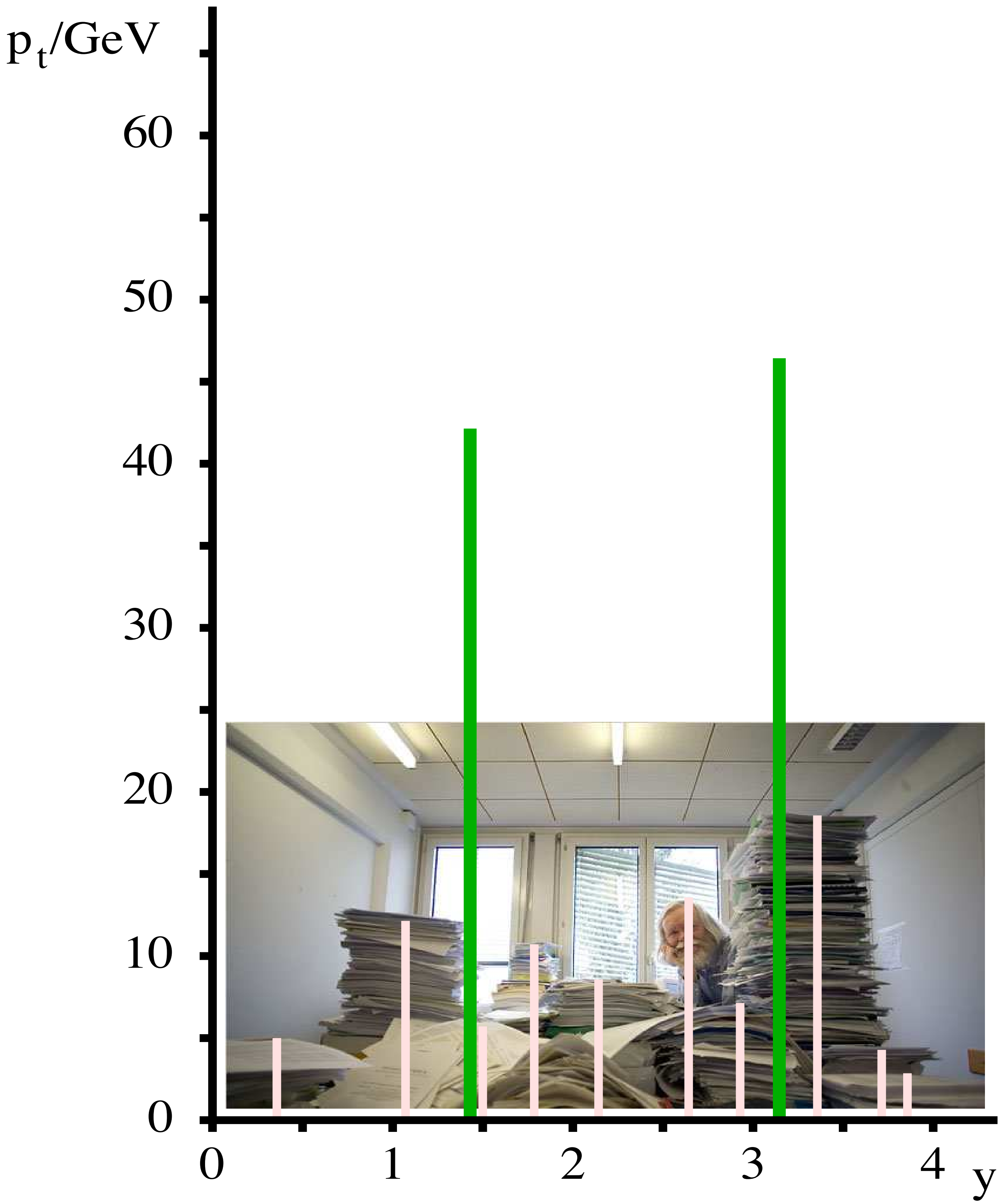

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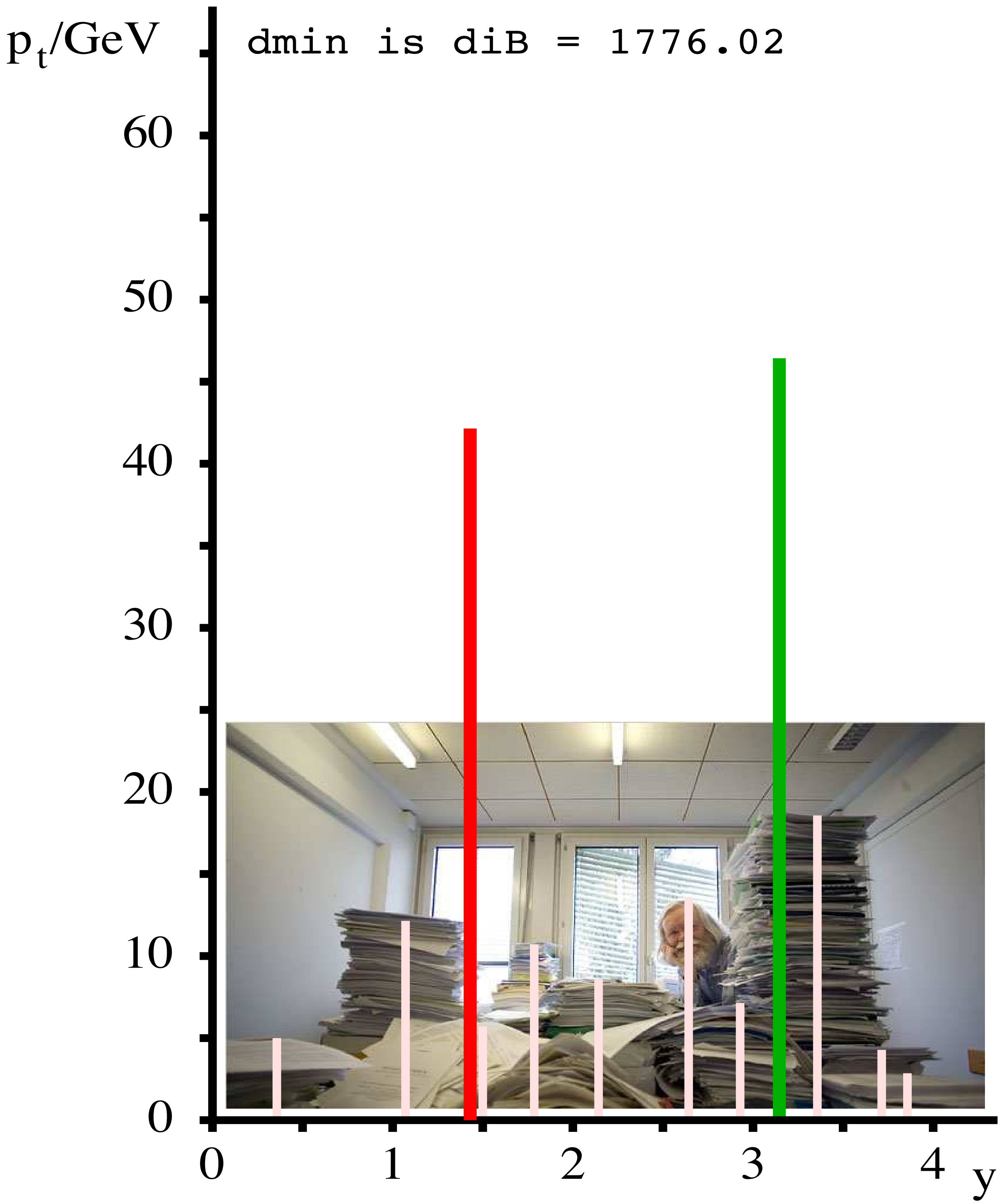

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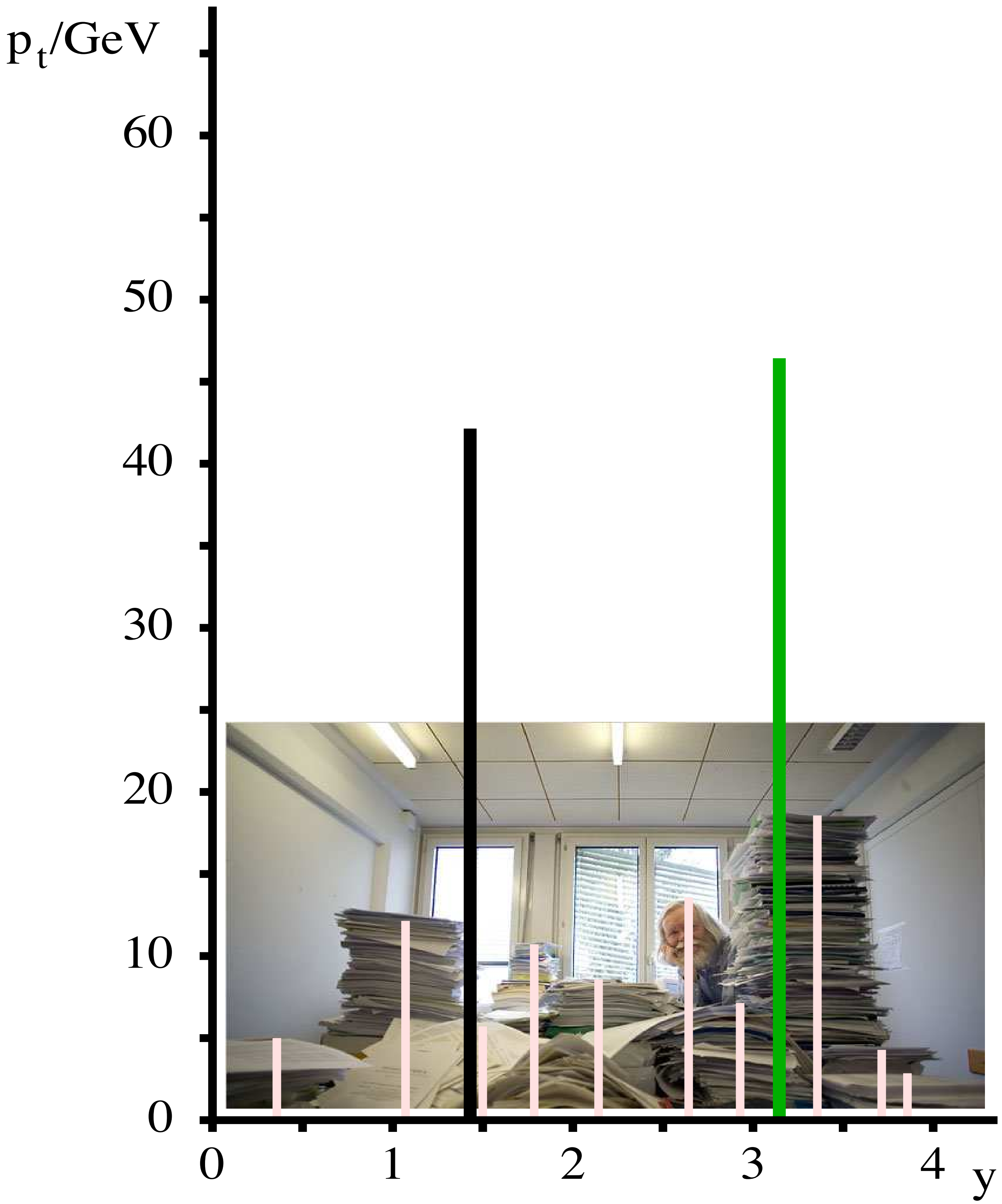

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Example clustering with k_t algorithm, $R = 1.0$

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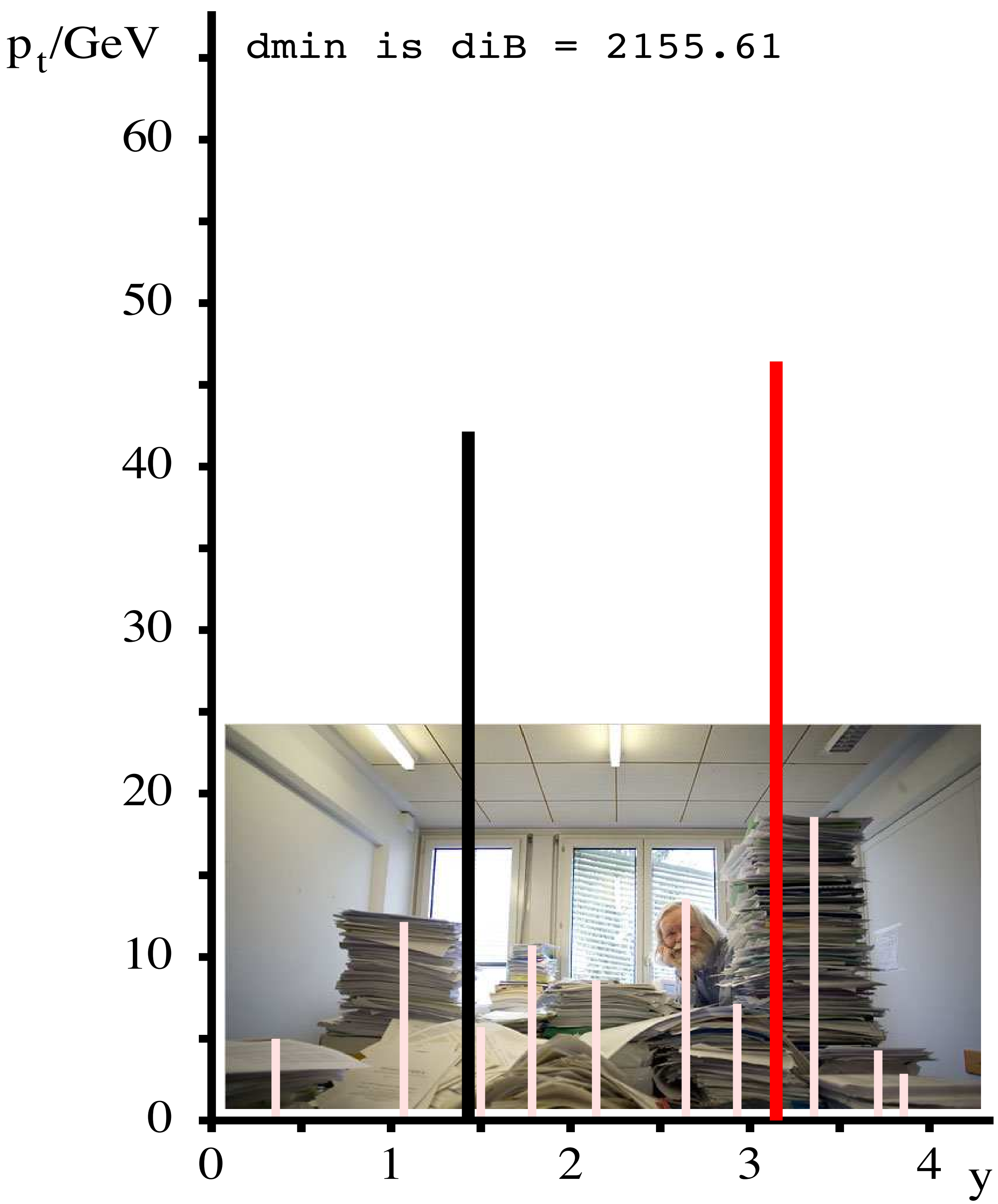
k_t in action



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Example clustering with k_t algorithm, $R = 1.0$

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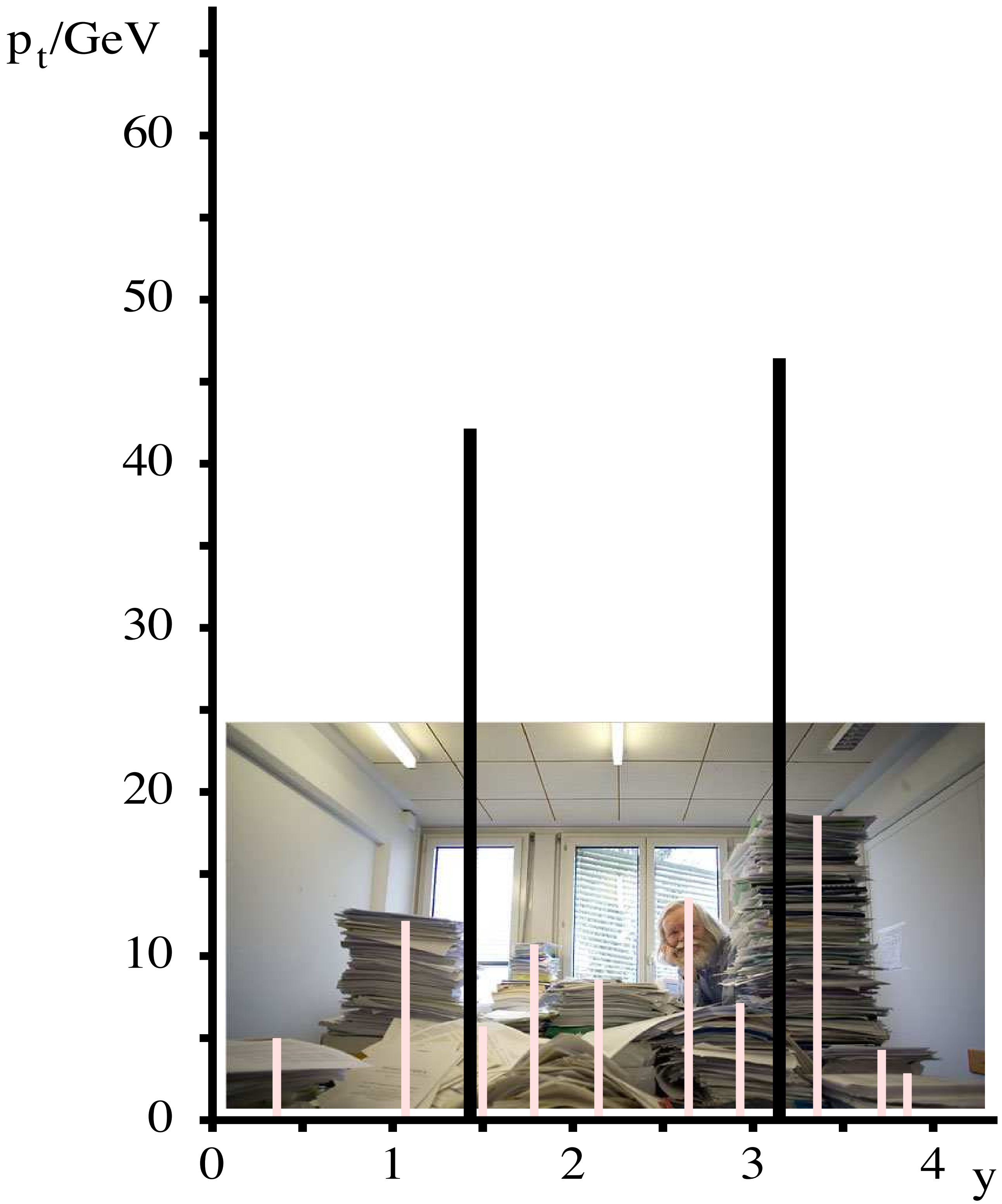
k_t in action



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Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination variants

Cambridge/Aachen: the simplest of hadron-collider algorithms

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

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

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

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

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

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

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

Most pairwise clusterings involve at least one hard particle

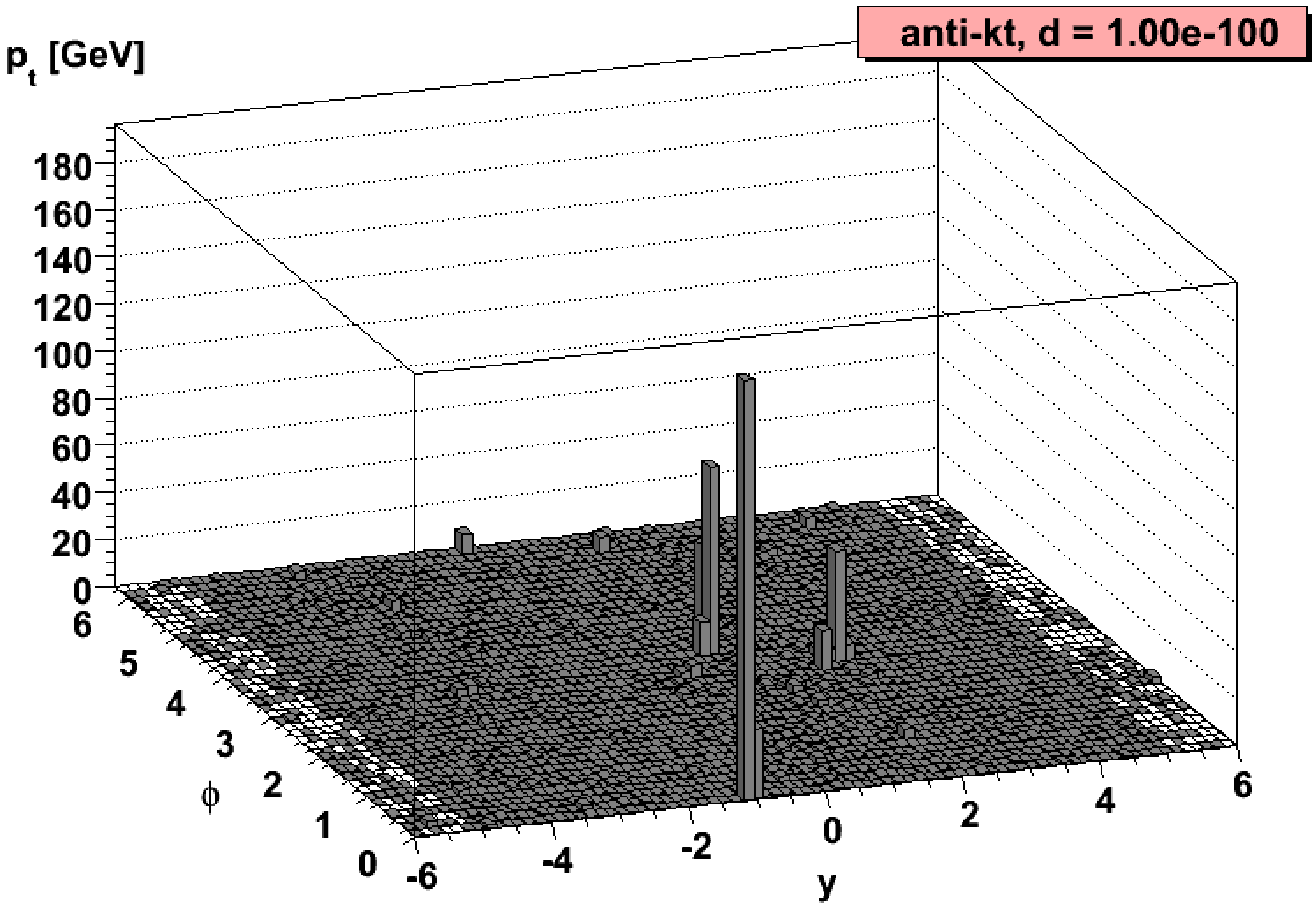
Anti-k_t in action

Clustering grows around hard cores

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

Clustering grows around hard cores

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



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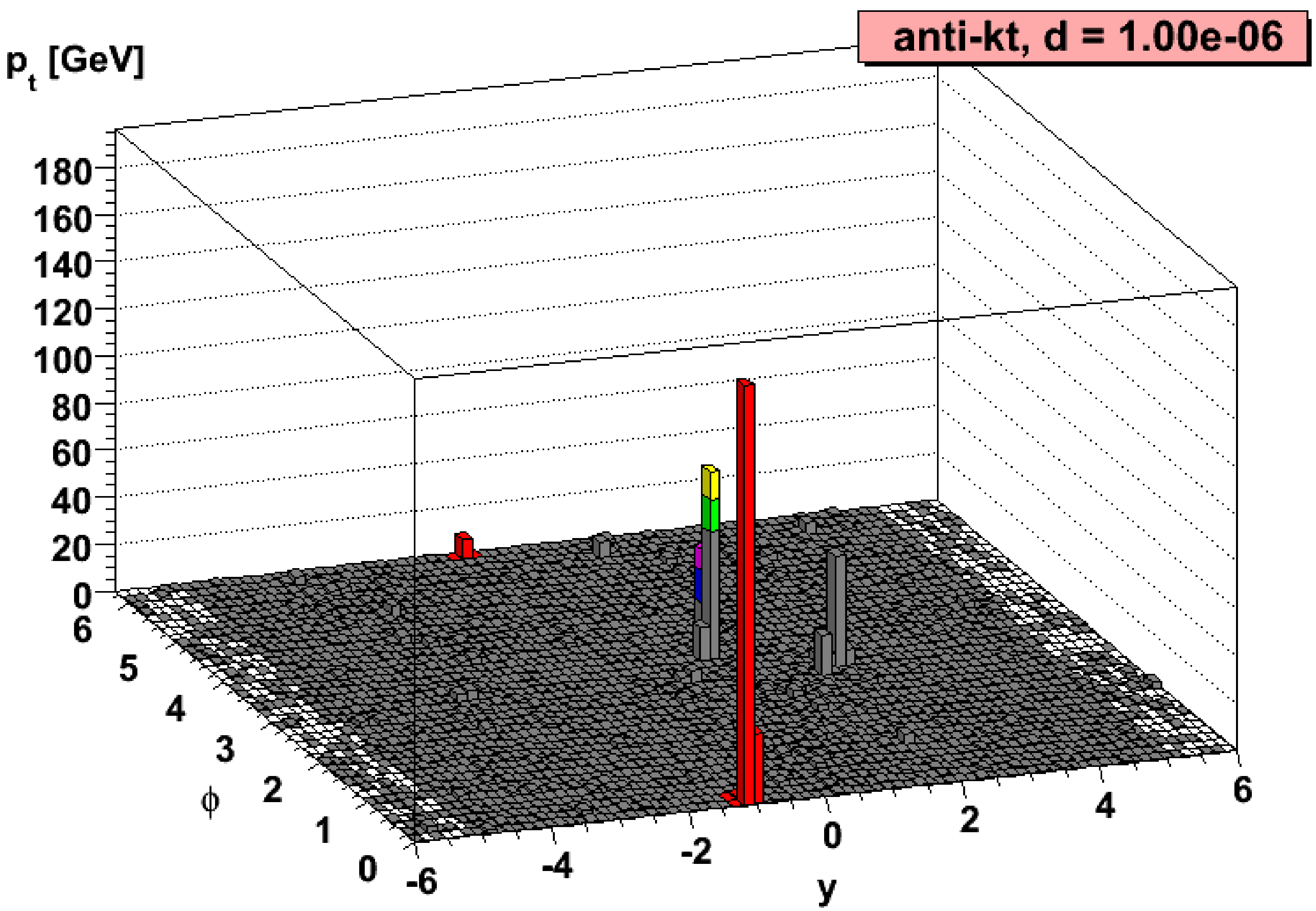

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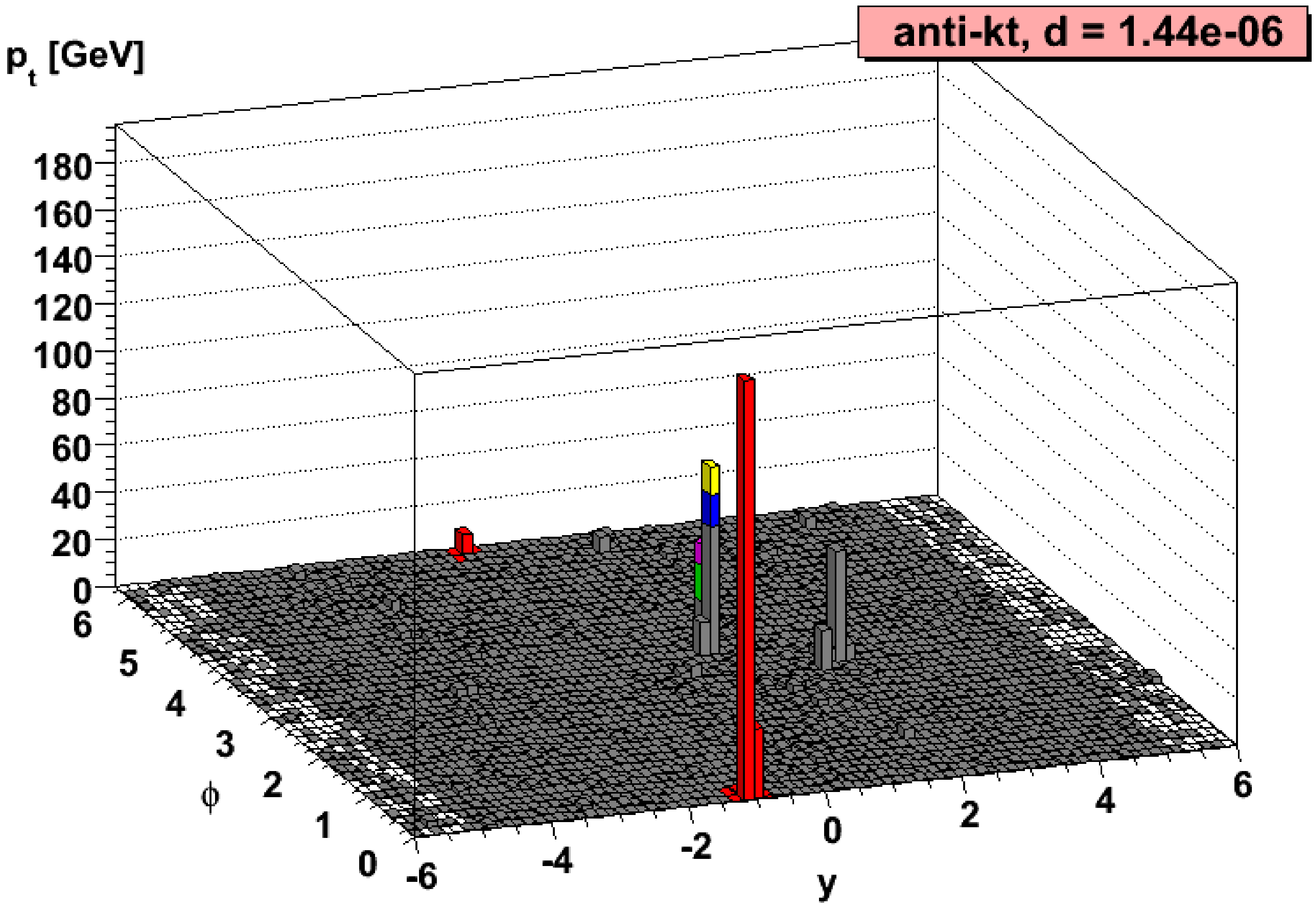

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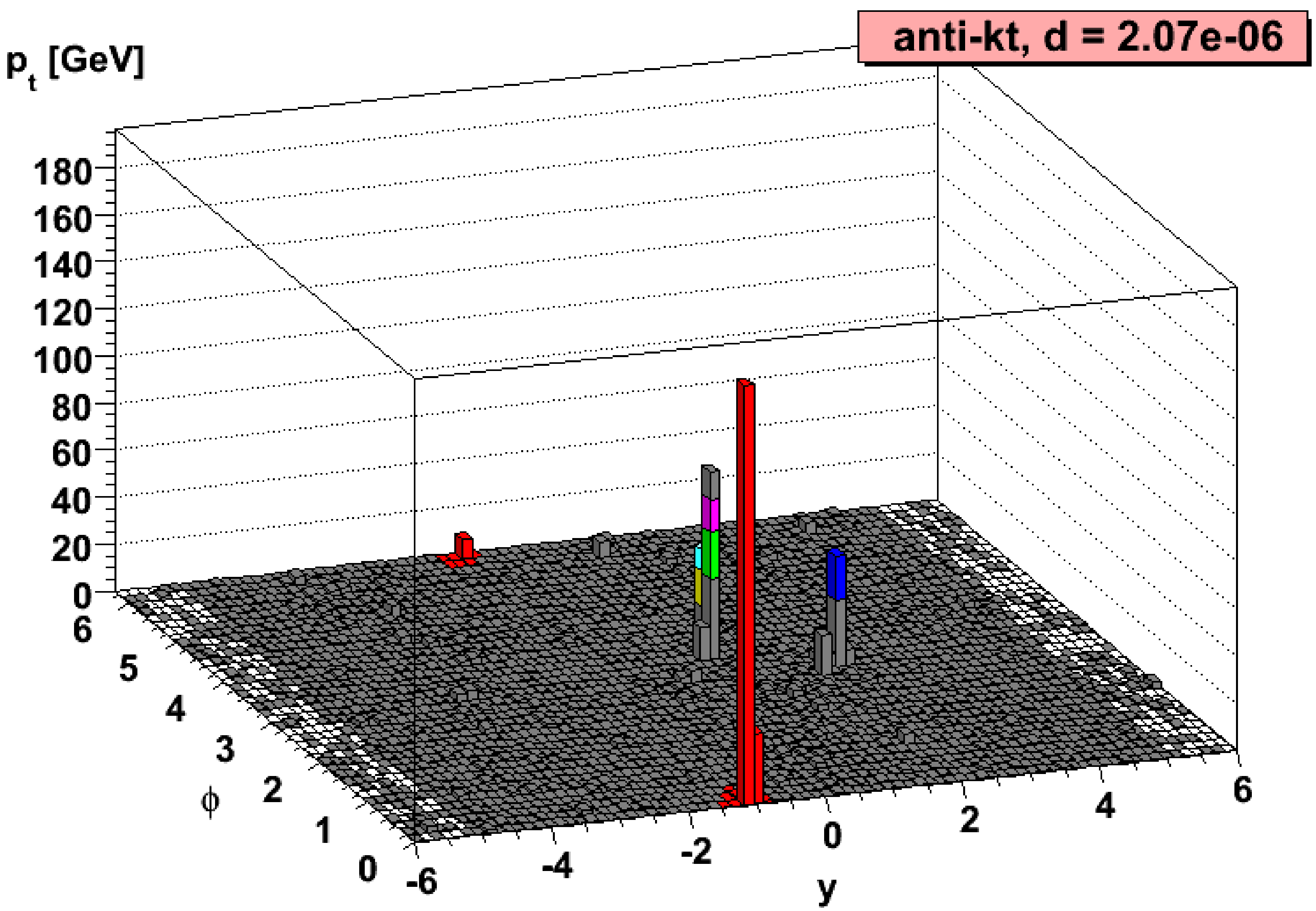

Anti-k_t in action

Clustering grows around hard cores

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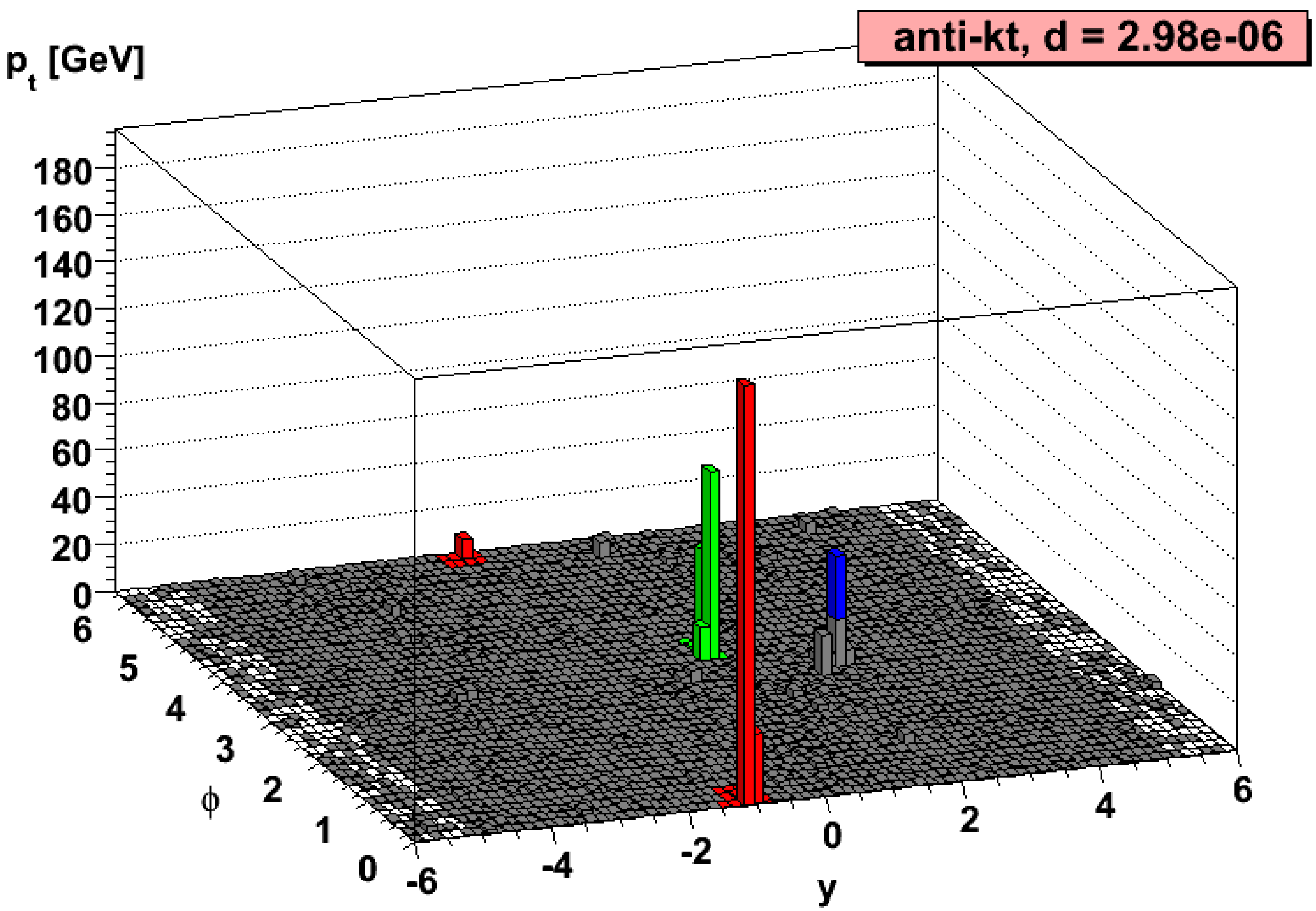

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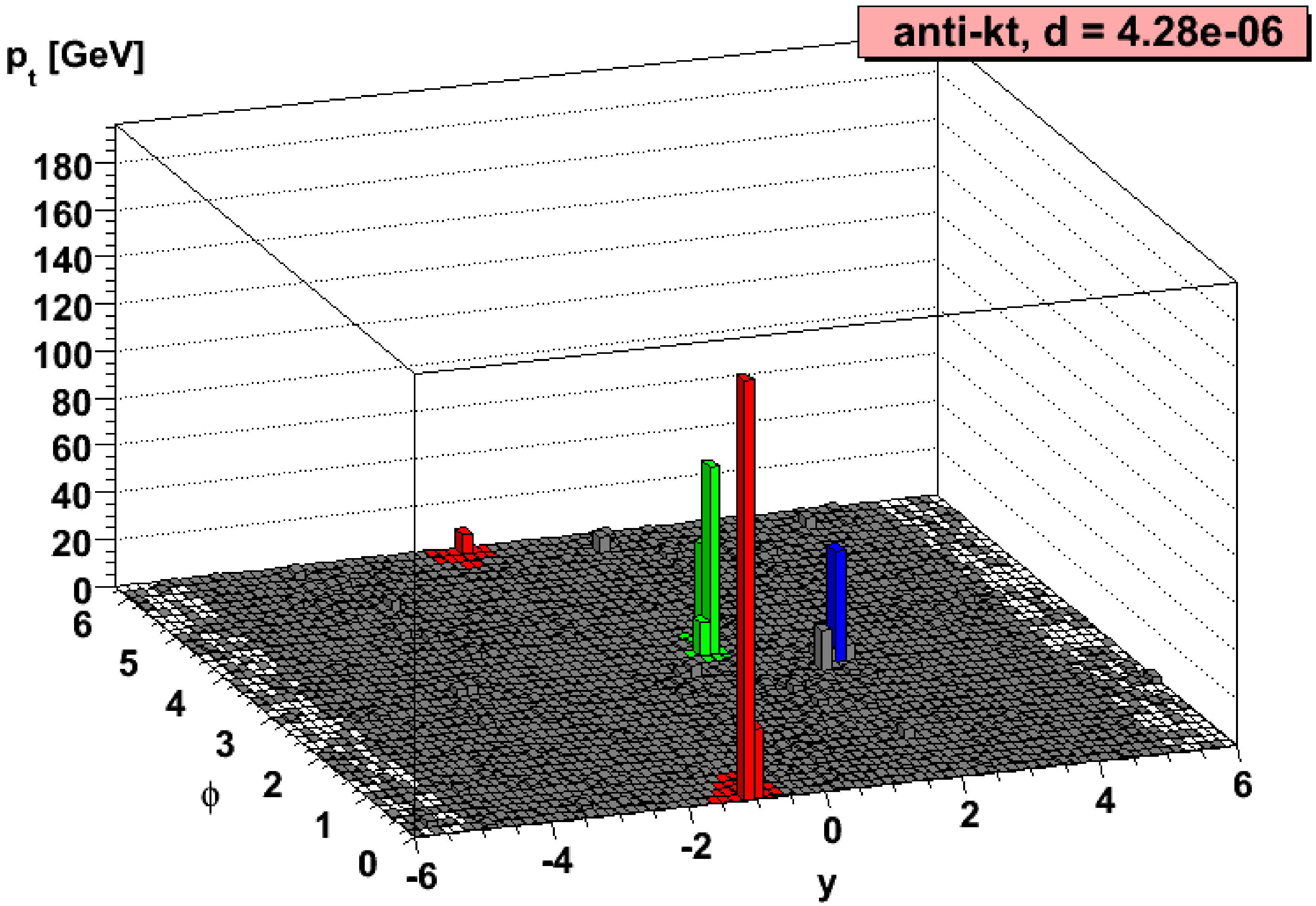
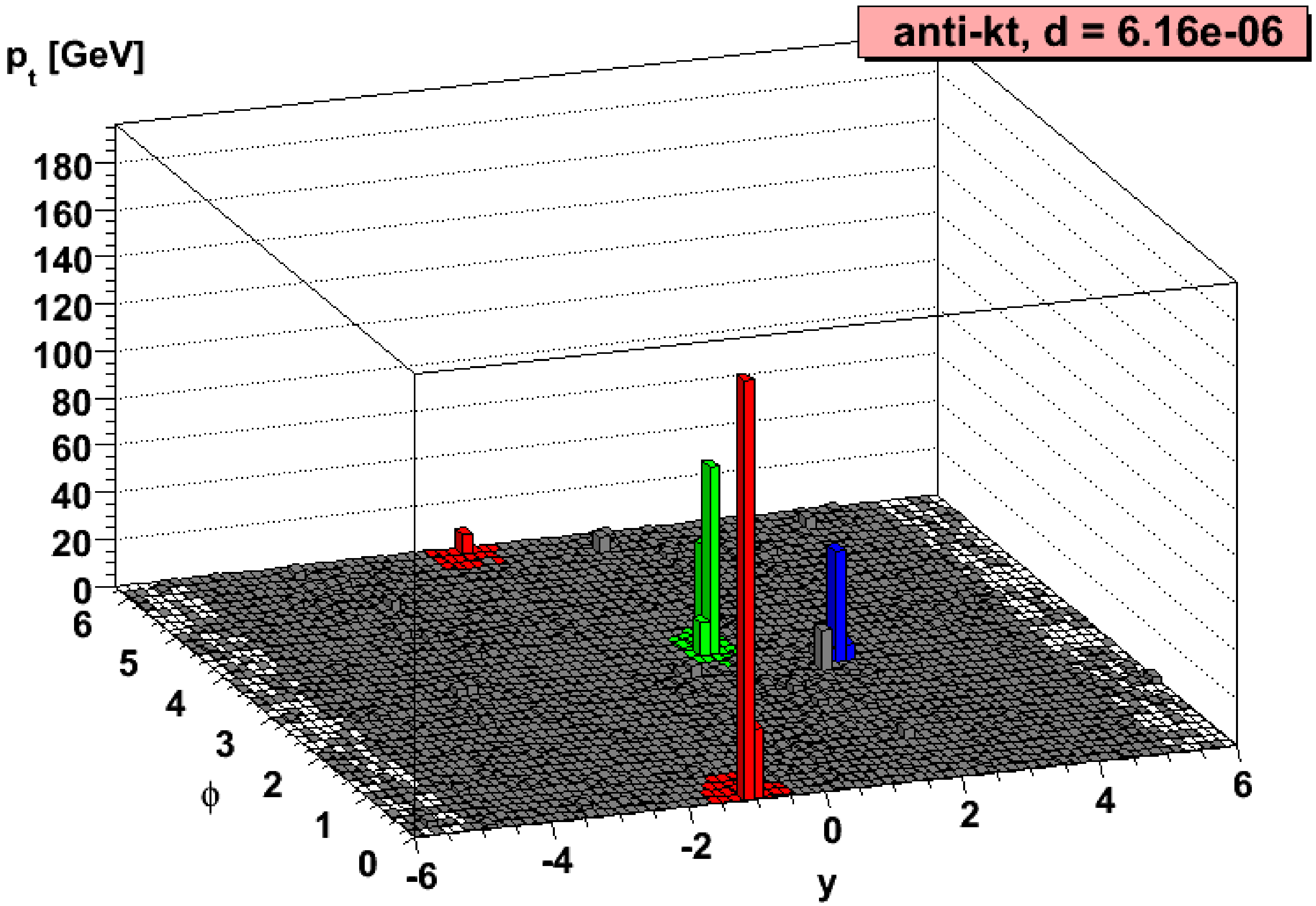


Clustering grows around hard cores

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



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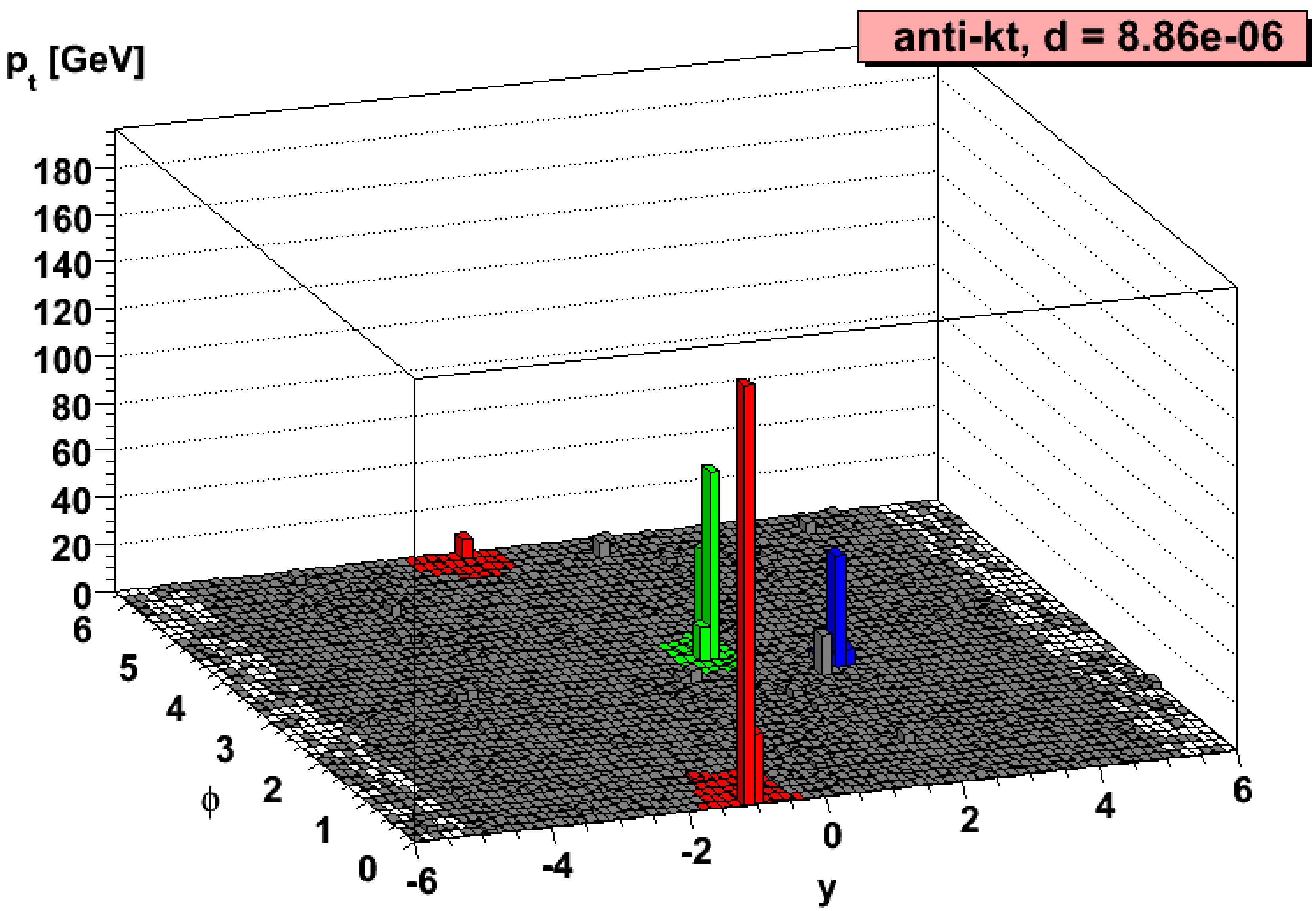
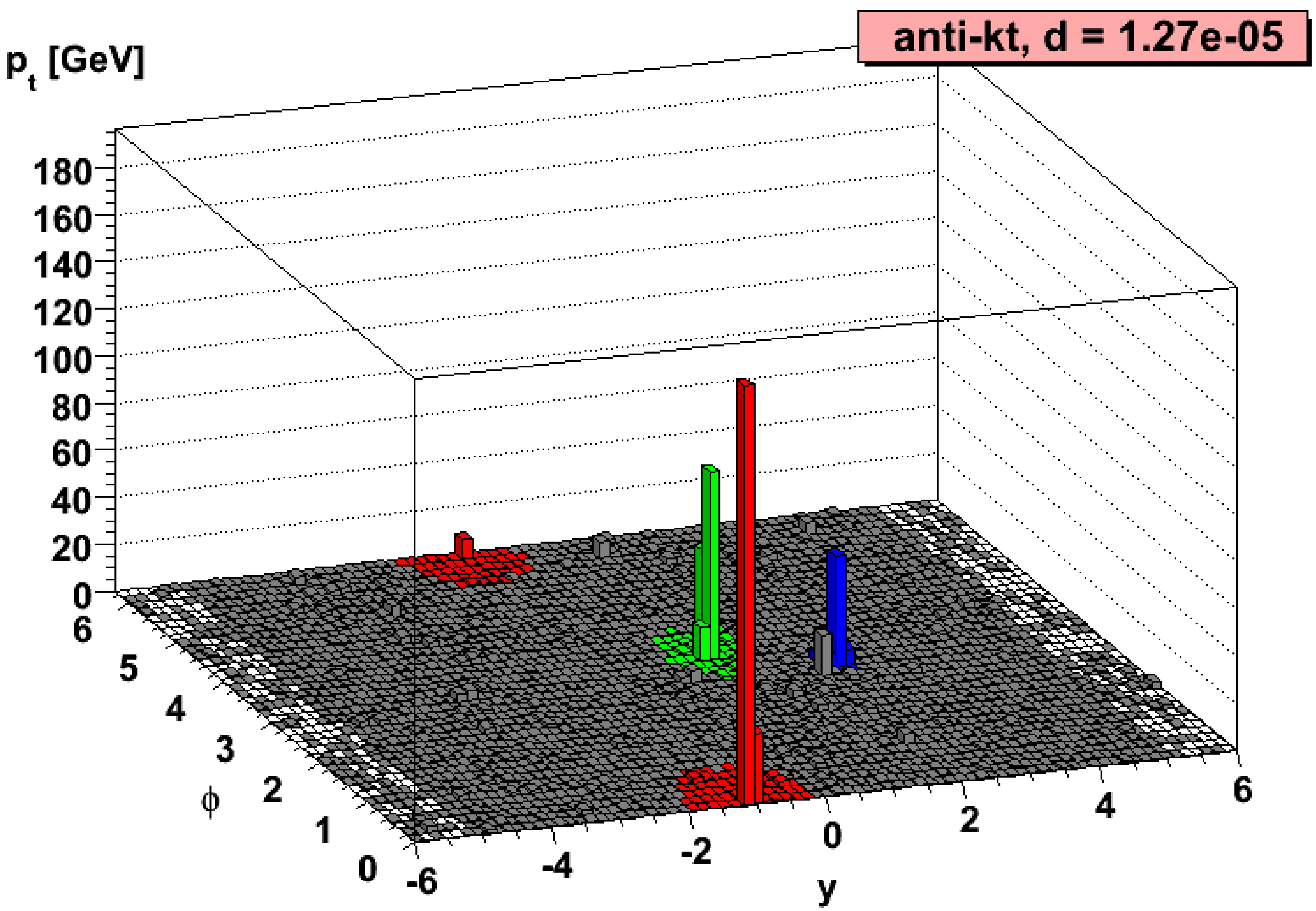


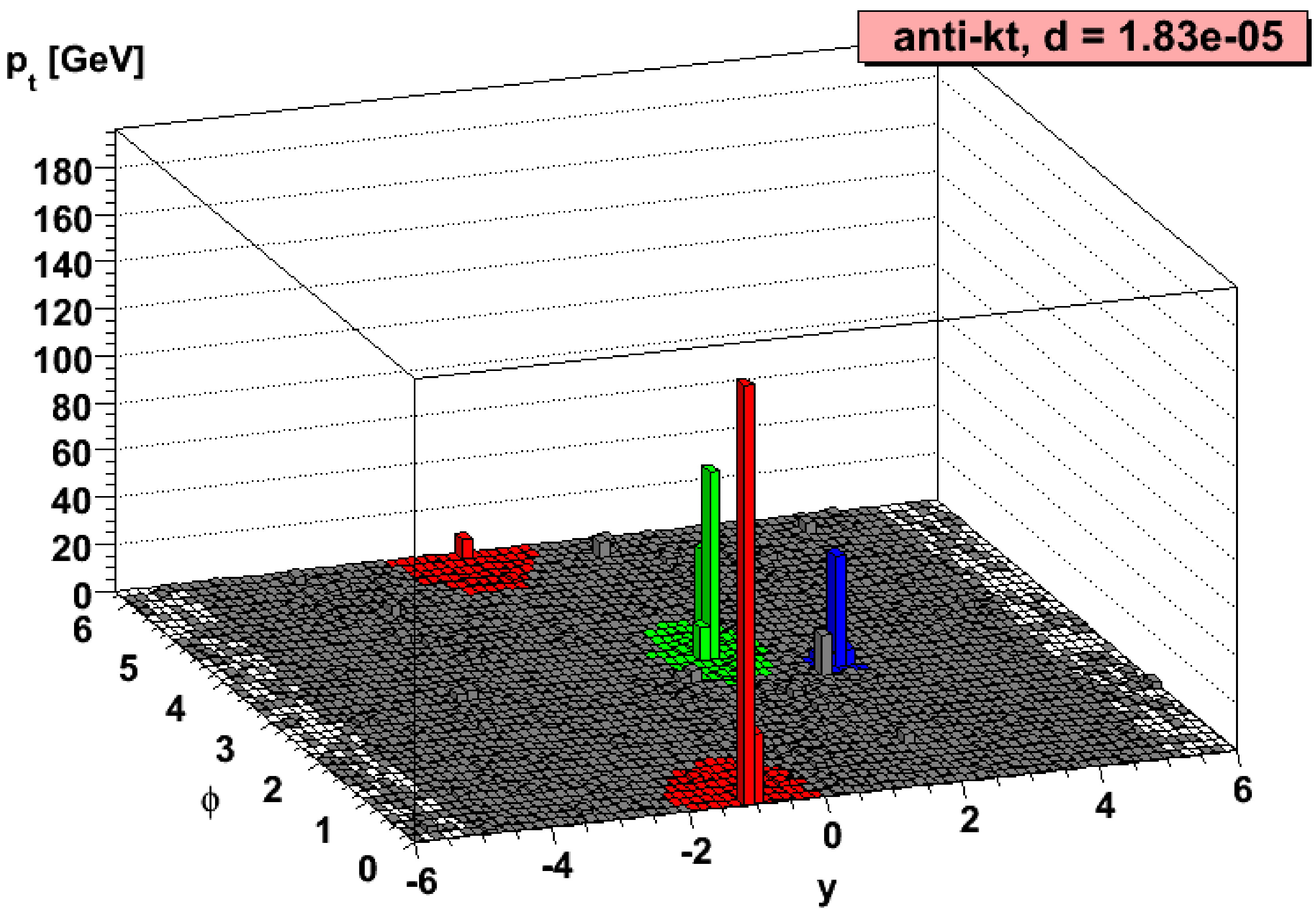
Clustering grows around hard cores

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



Clustering grows around hard cores

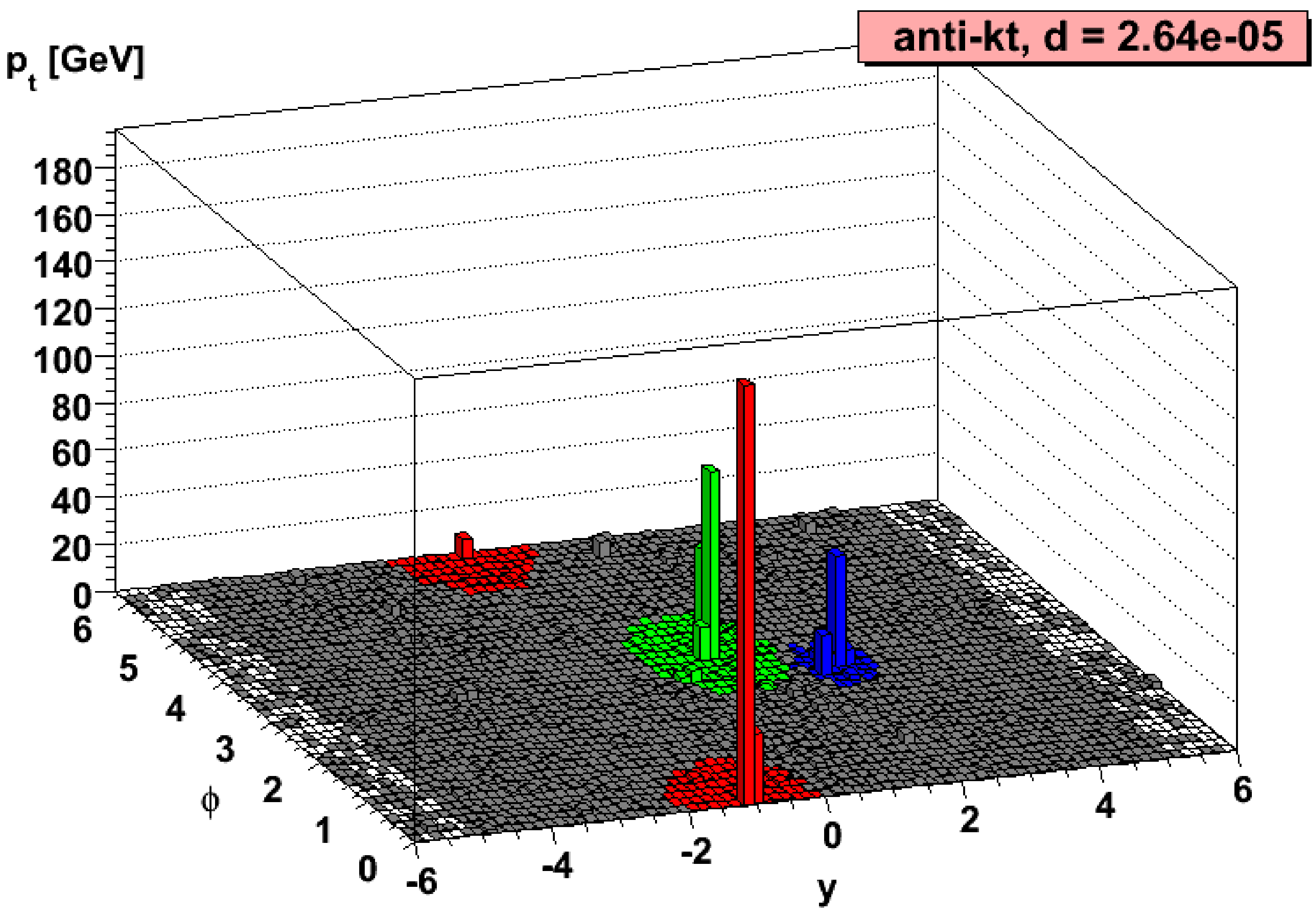
$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = \frac{1}{p_{ti}^2}$$



Anti-k_t in action

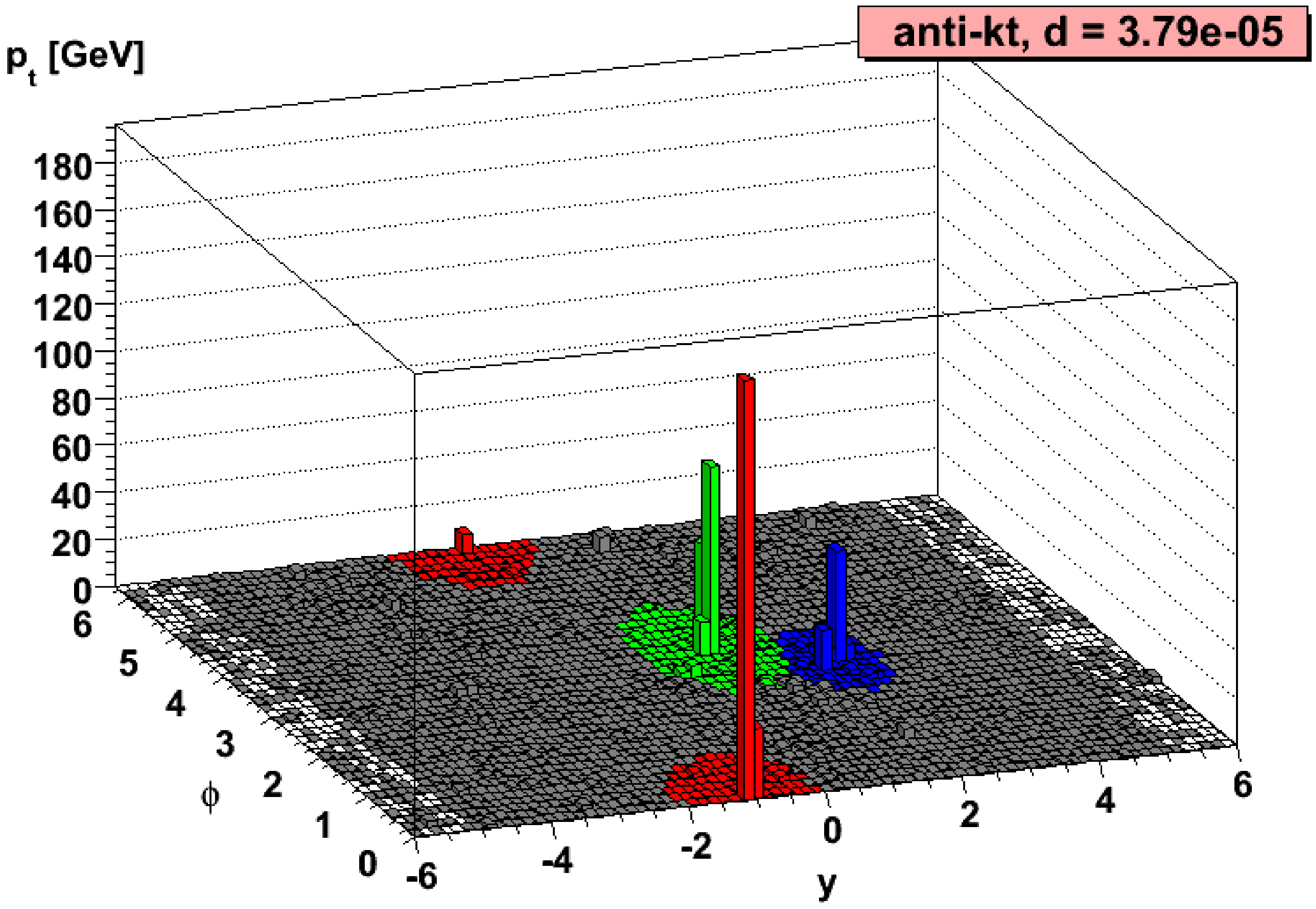
Clustering grows around hard cores

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



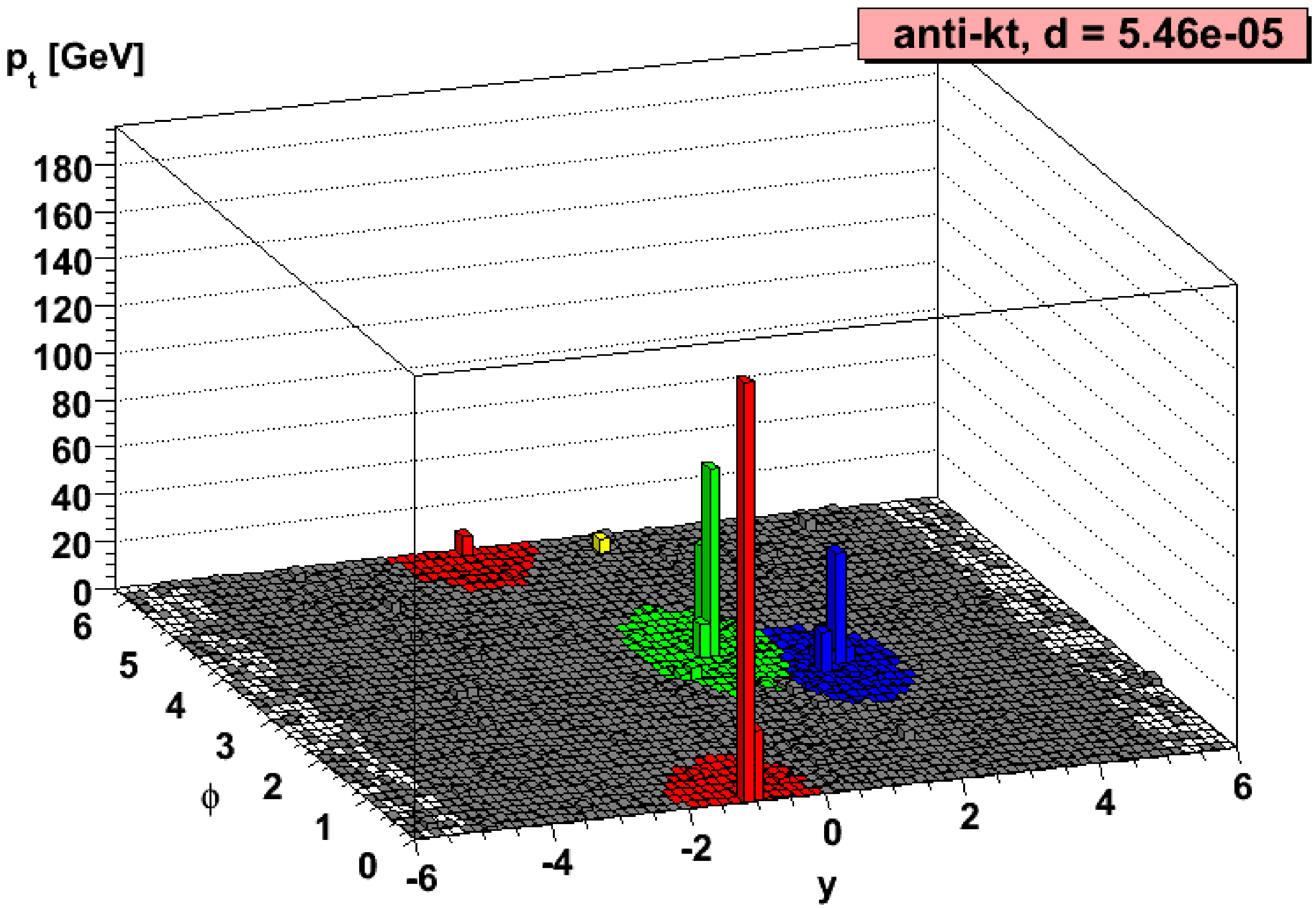
Clustering grows around hard cores

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



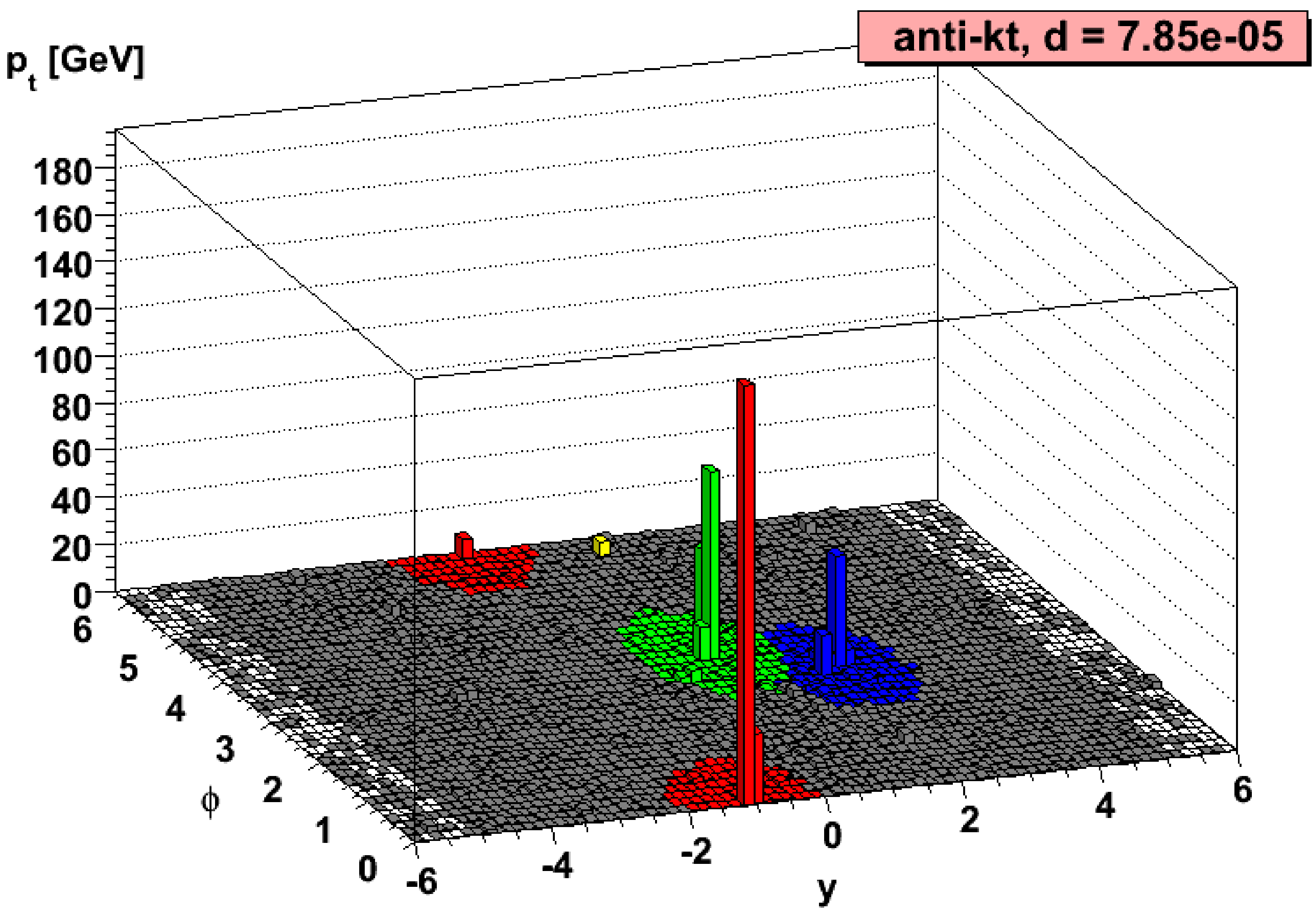
Clustering grows around hard cores

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



Clustering grows around hard cores

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



Clustering grows around hard cores

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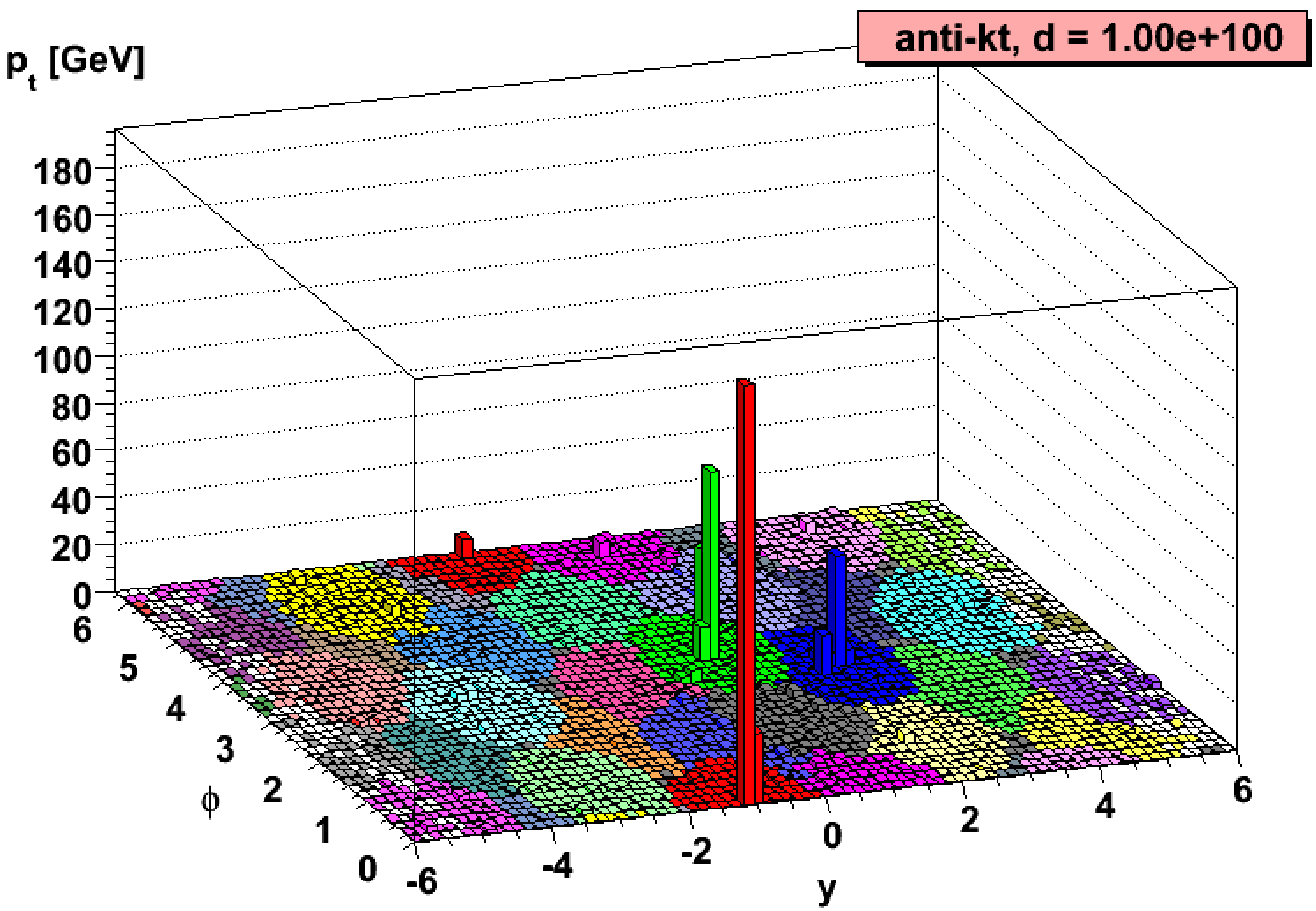
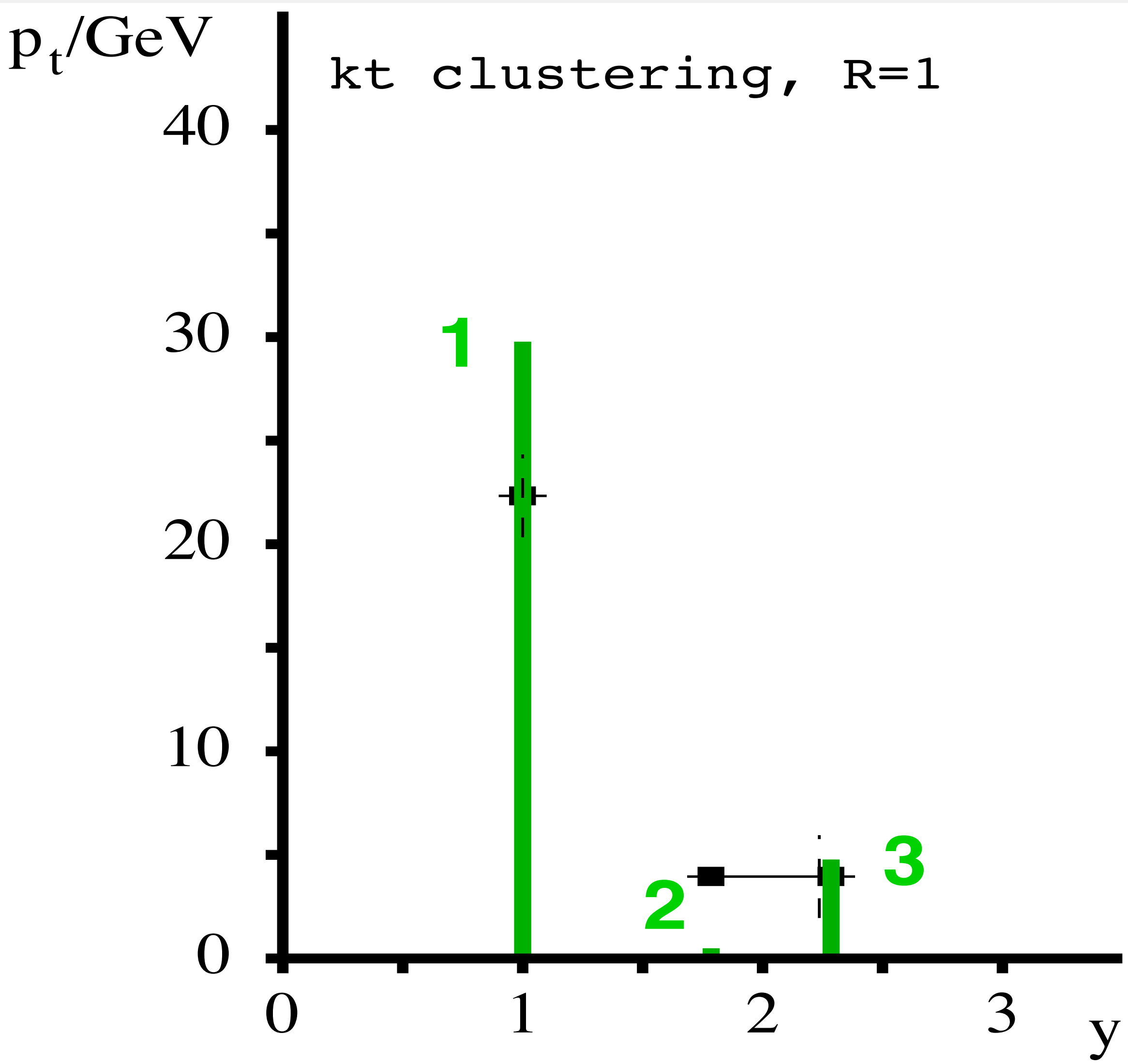
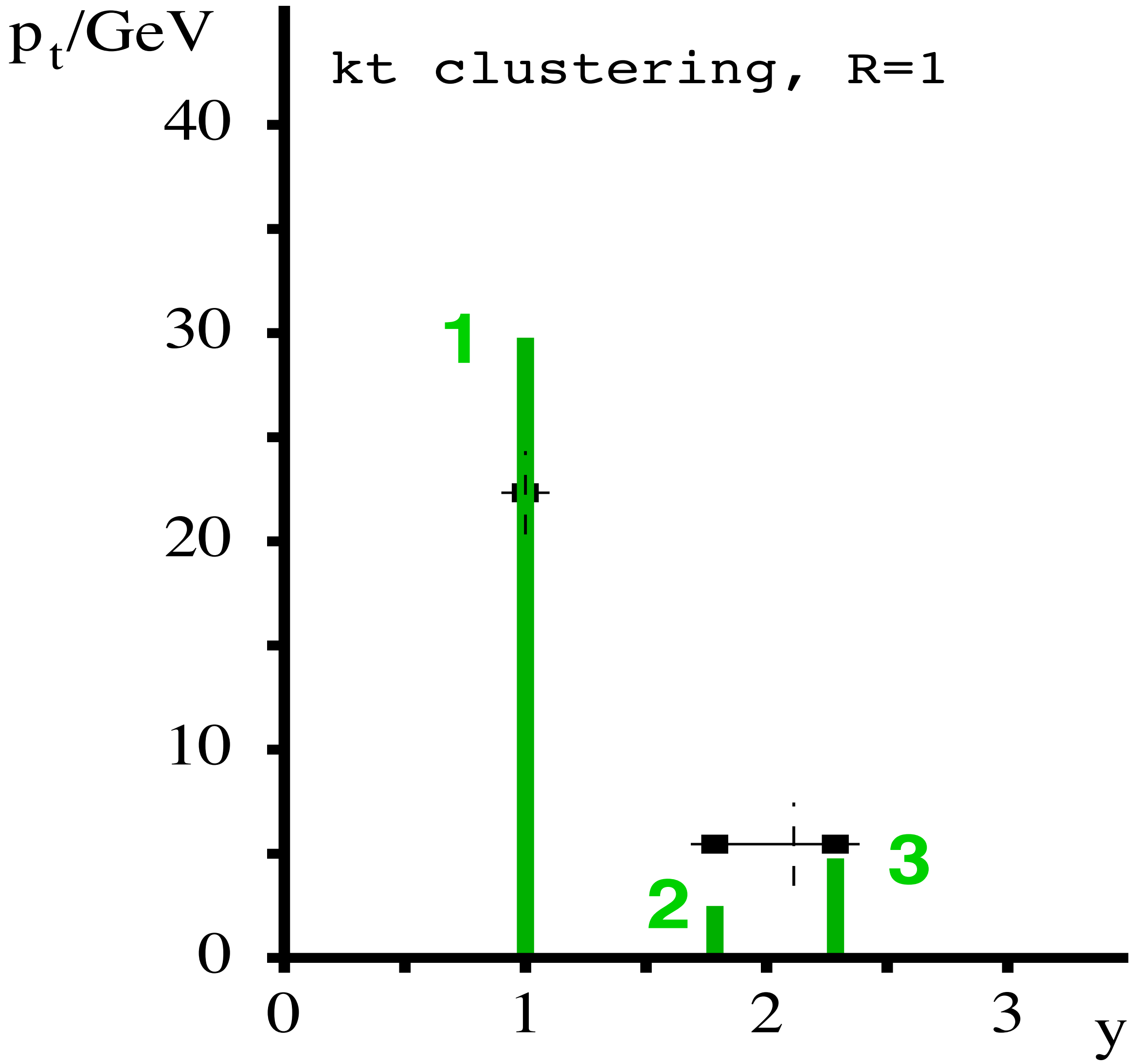


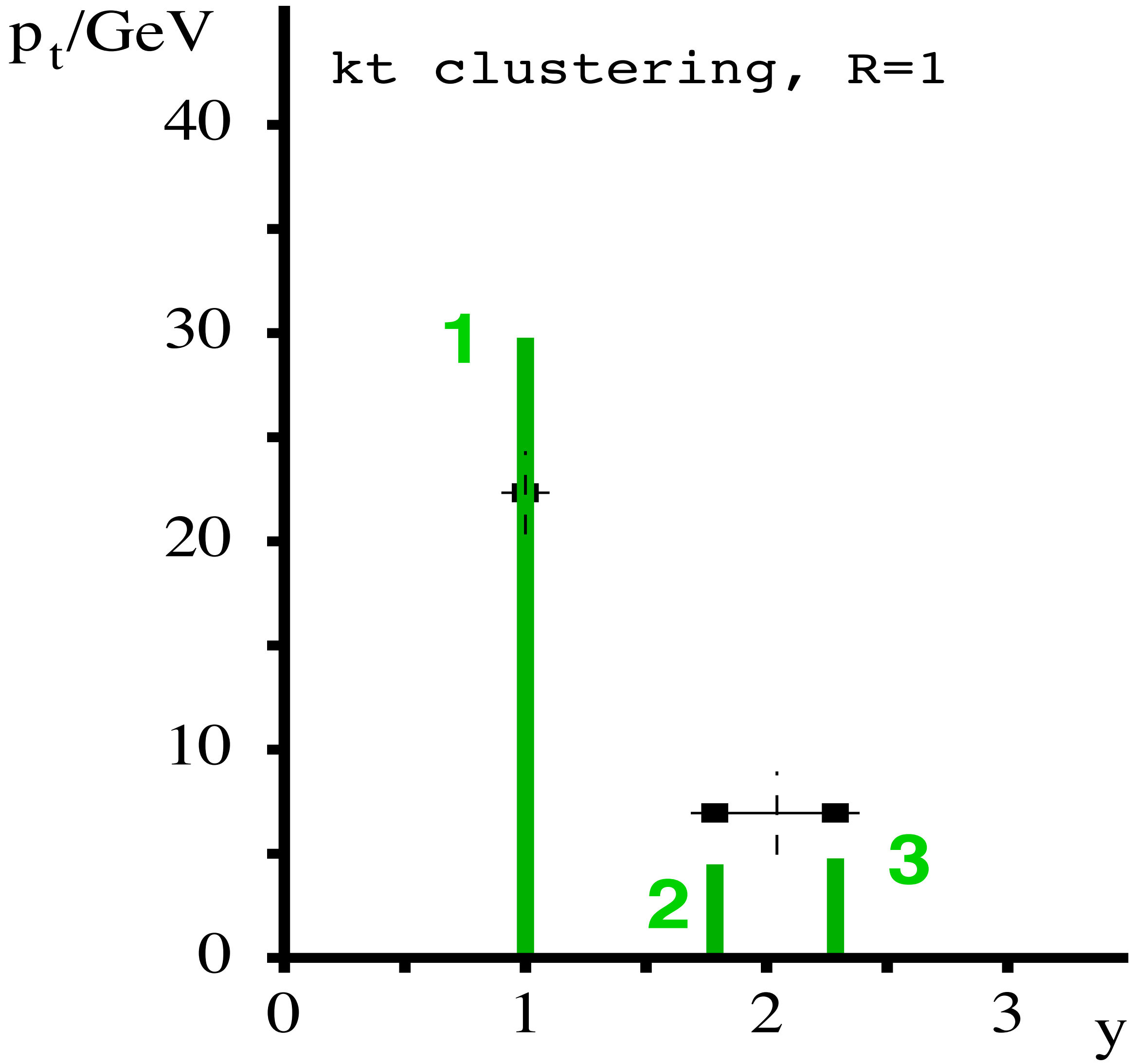
Anti-k_t gives circular jets ("cone-like") in a way that's infrared safe

Linearity: k_t v. anti-k_t

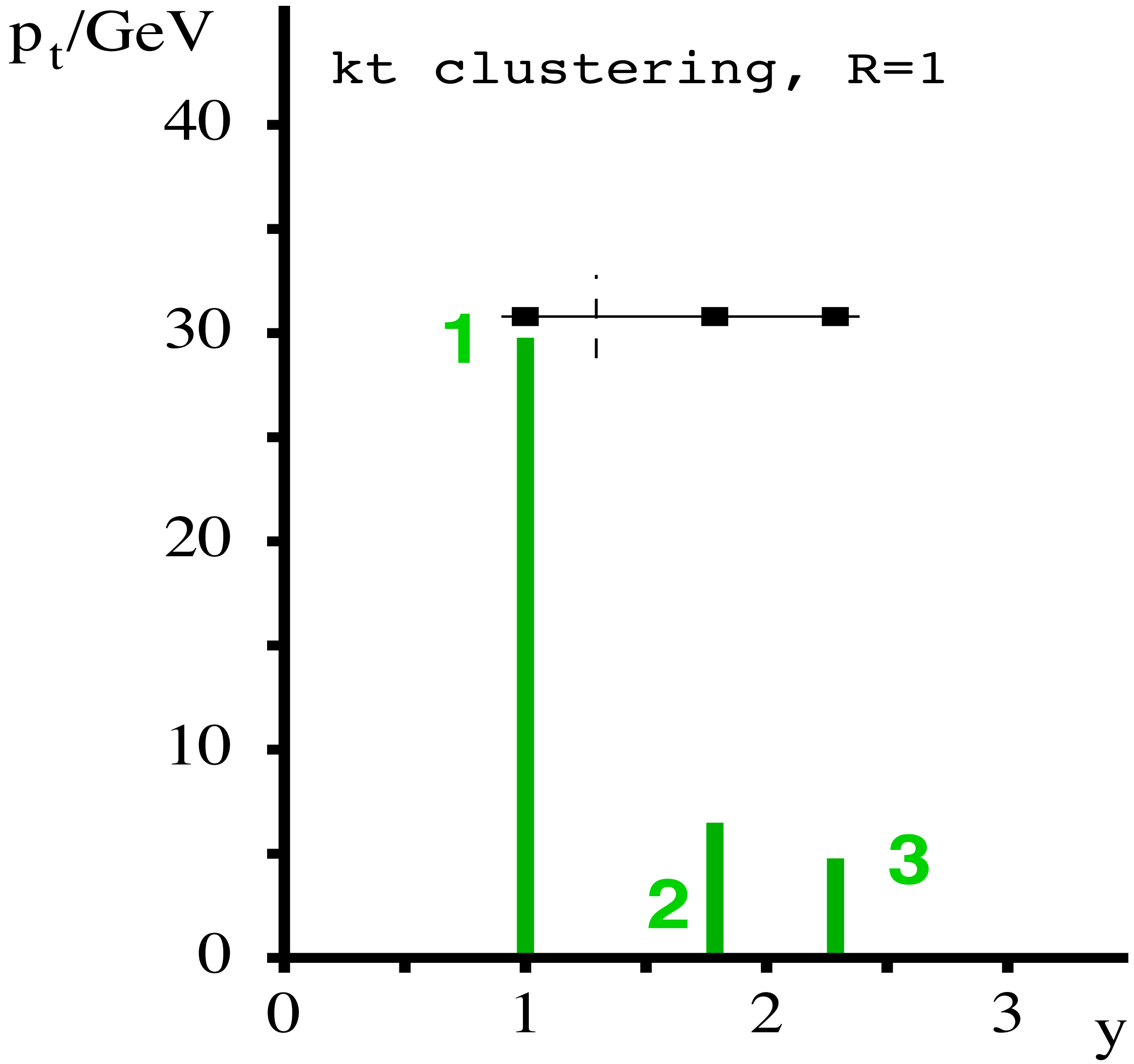



p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

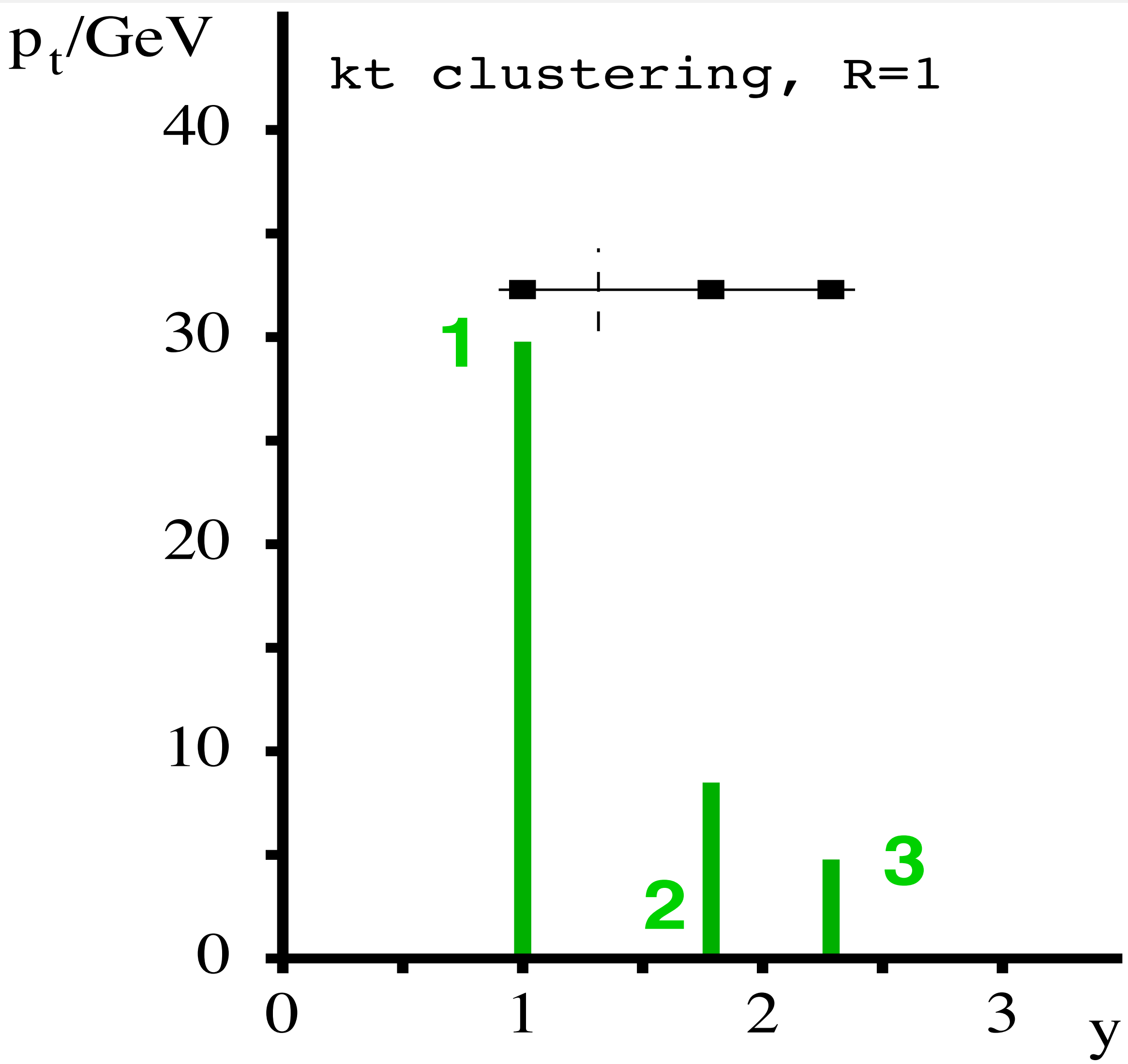
Linearity: k_t v. anti-k_t



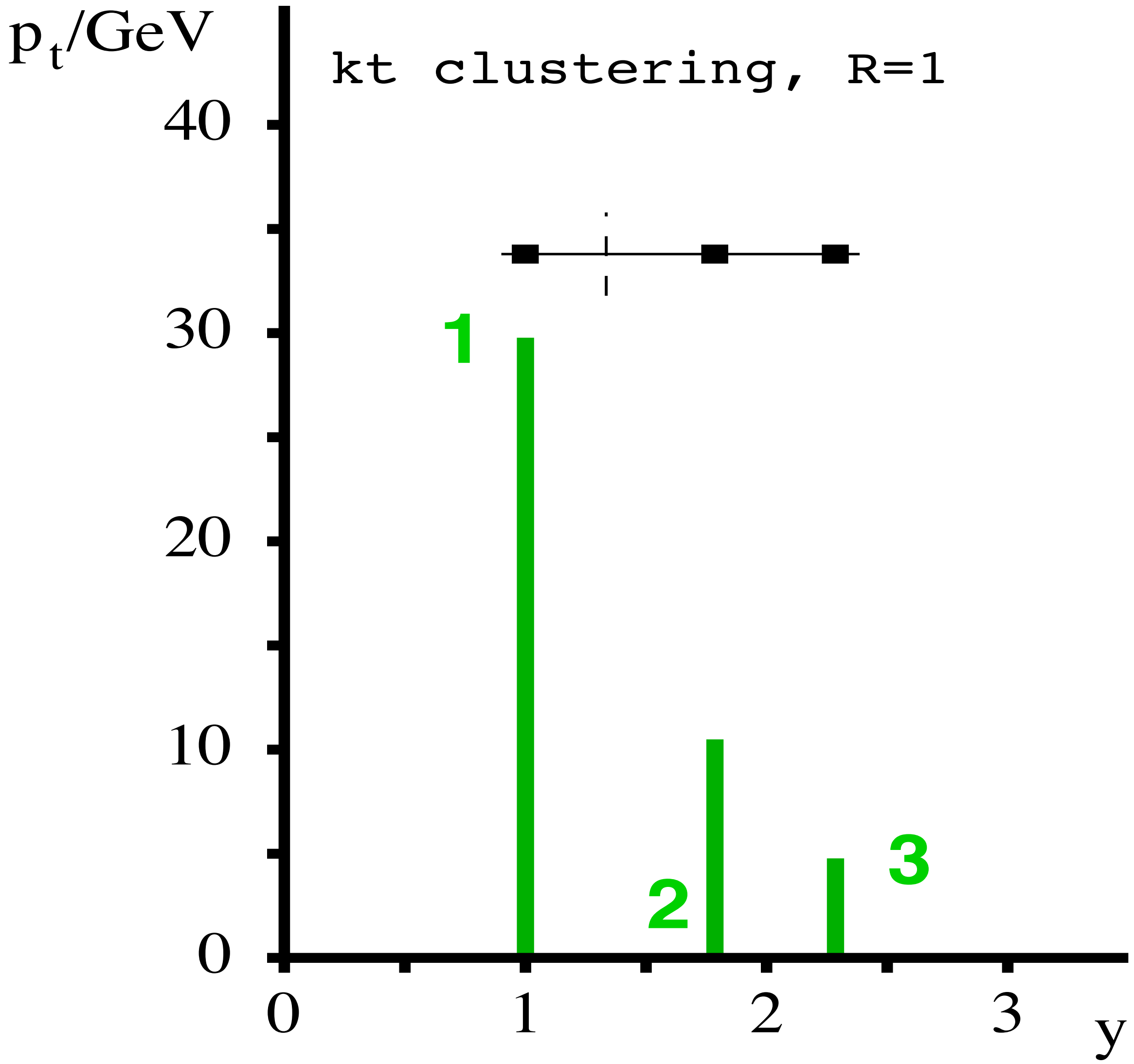
Linearity: k_t v. anti-k_t



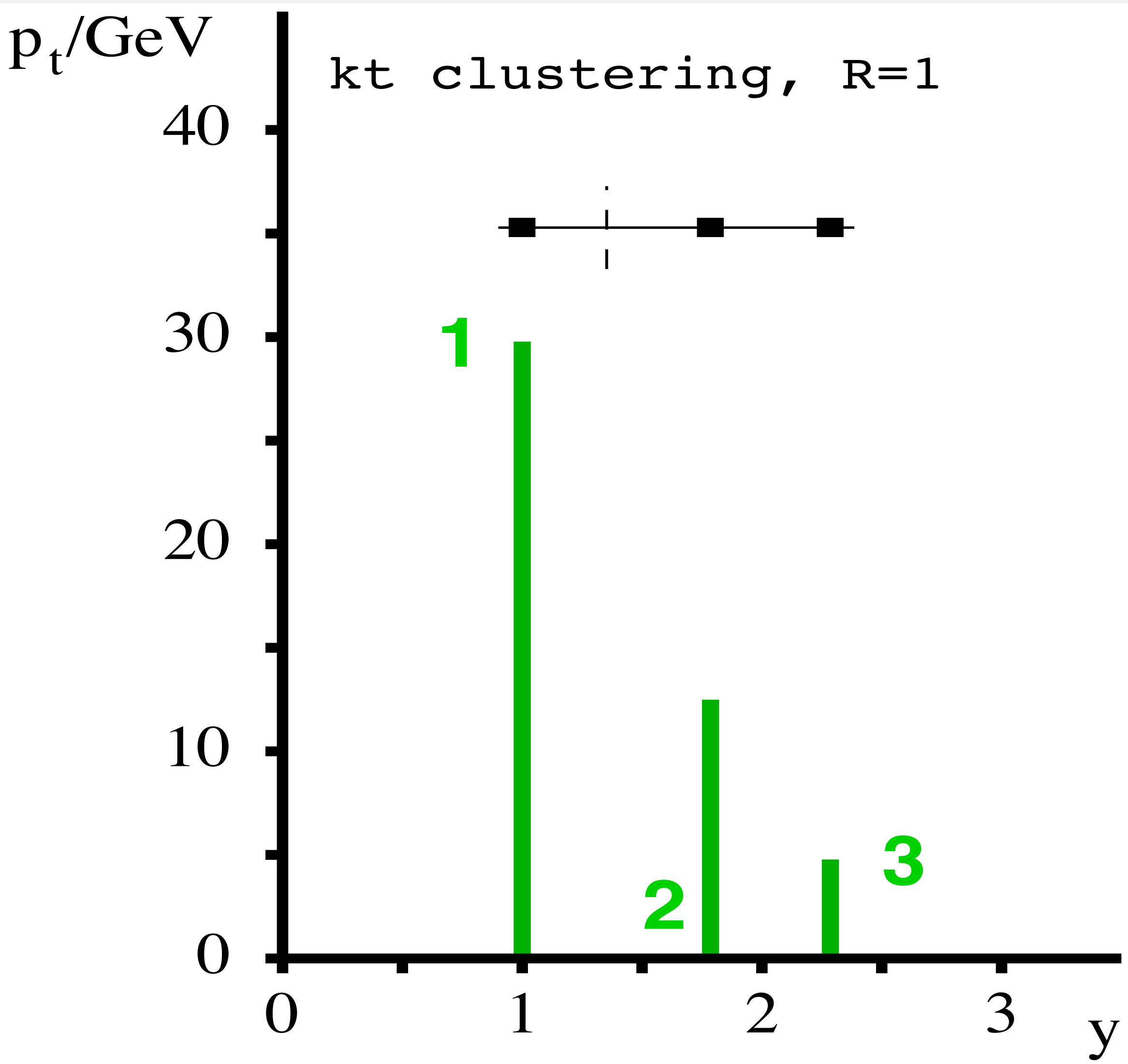
Linearity: k_t v. anti-k_t

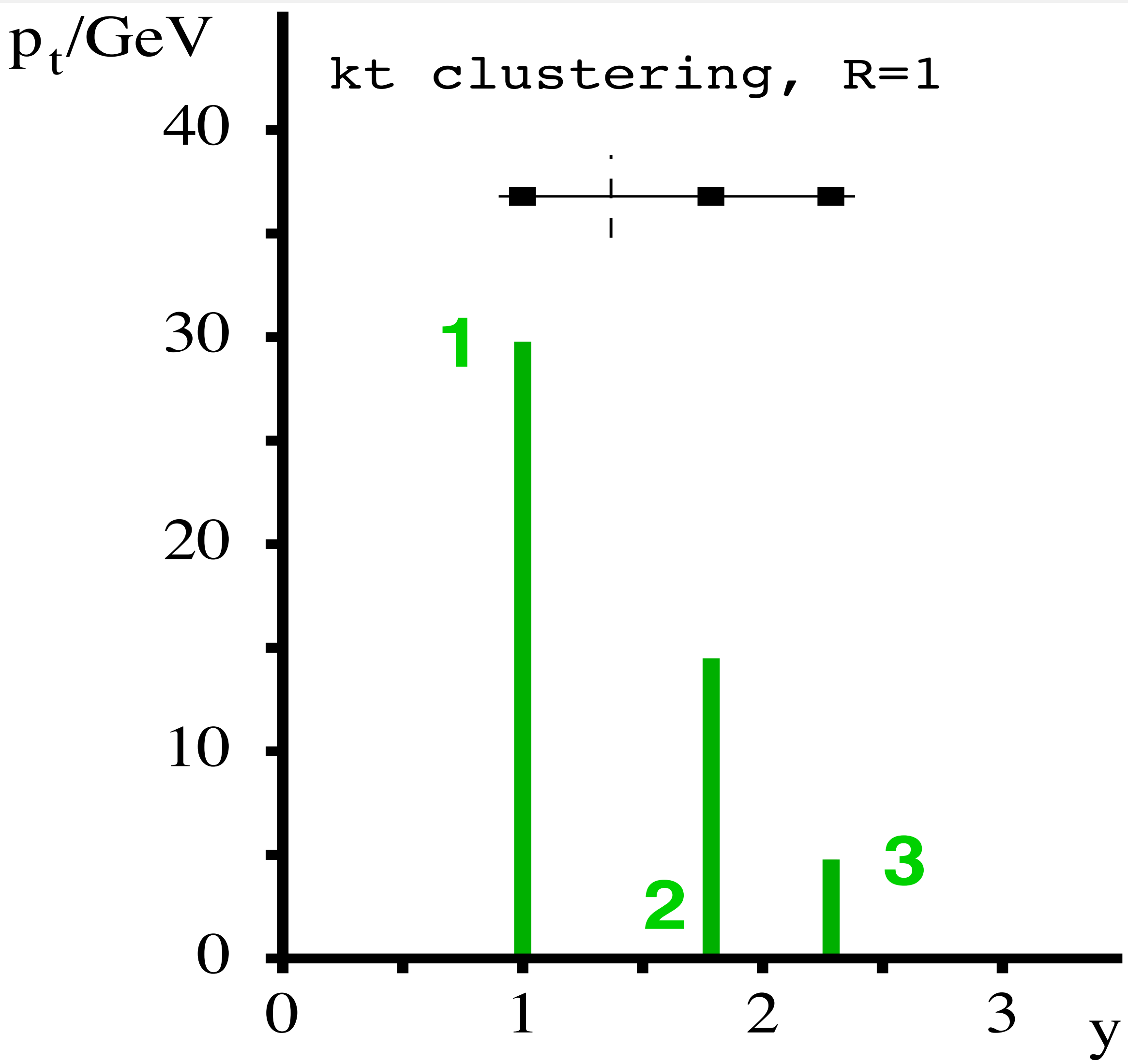


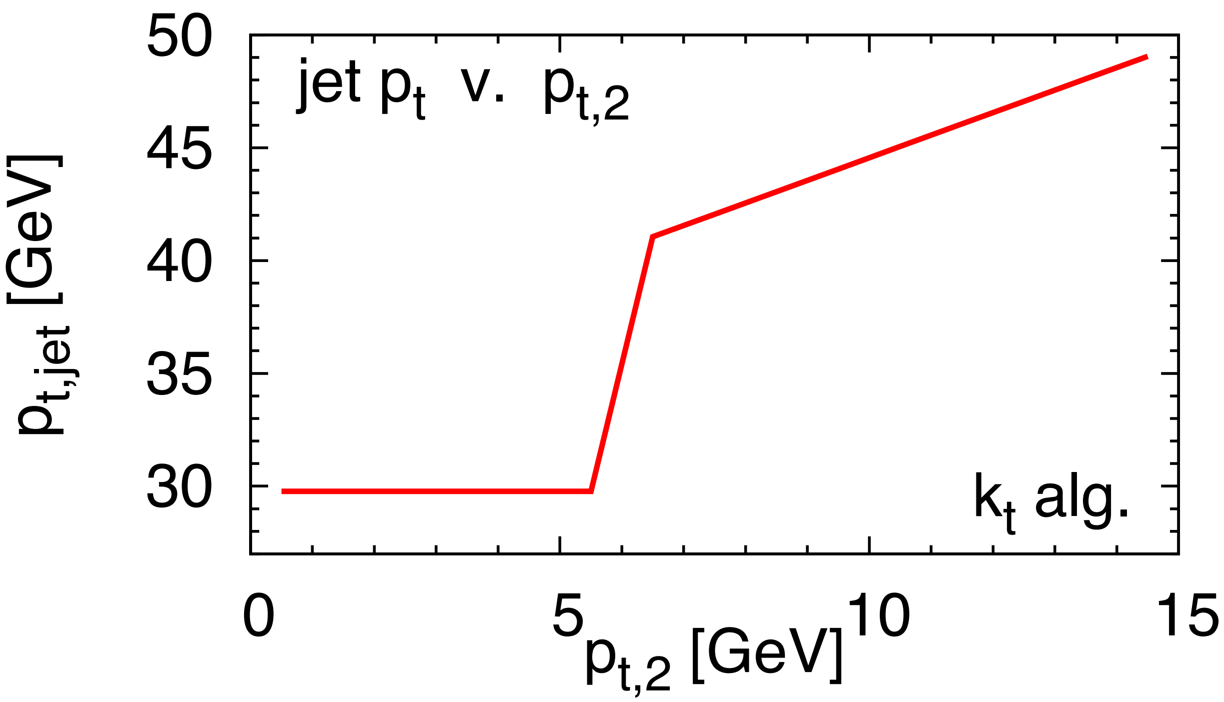
Linearity: k_t v. anti-k_t



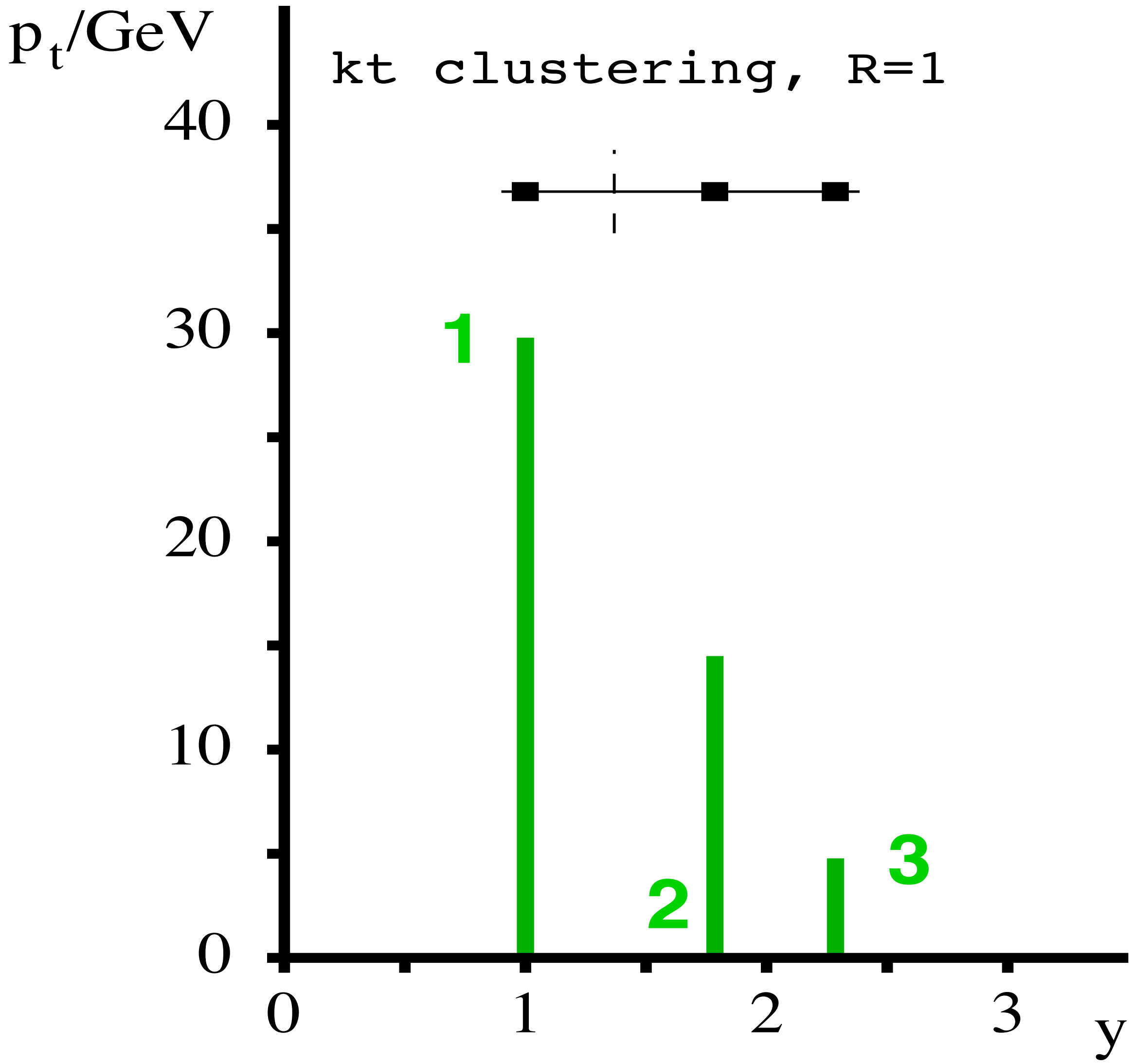
Linearity: k_t v. anti-k_t

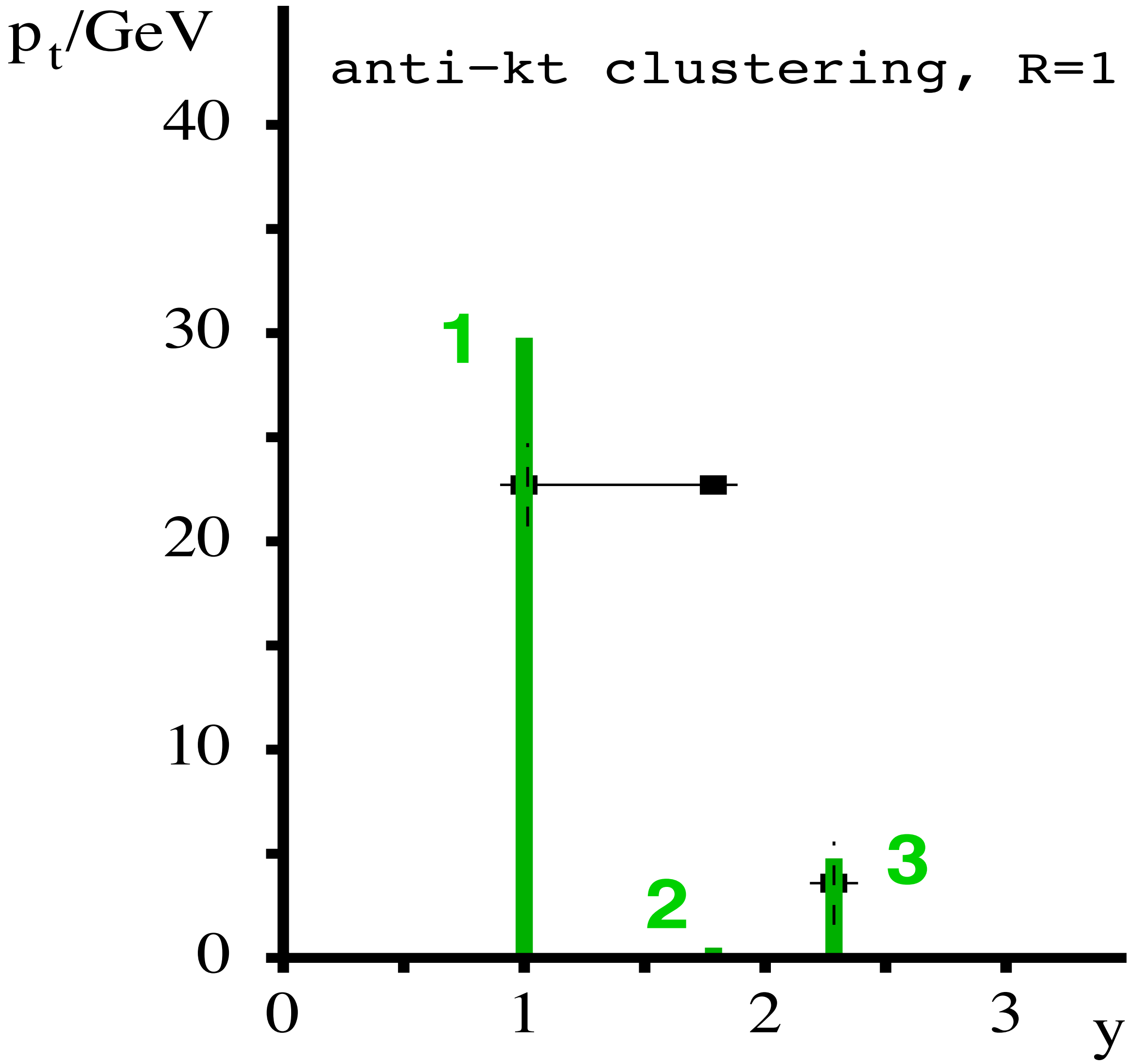


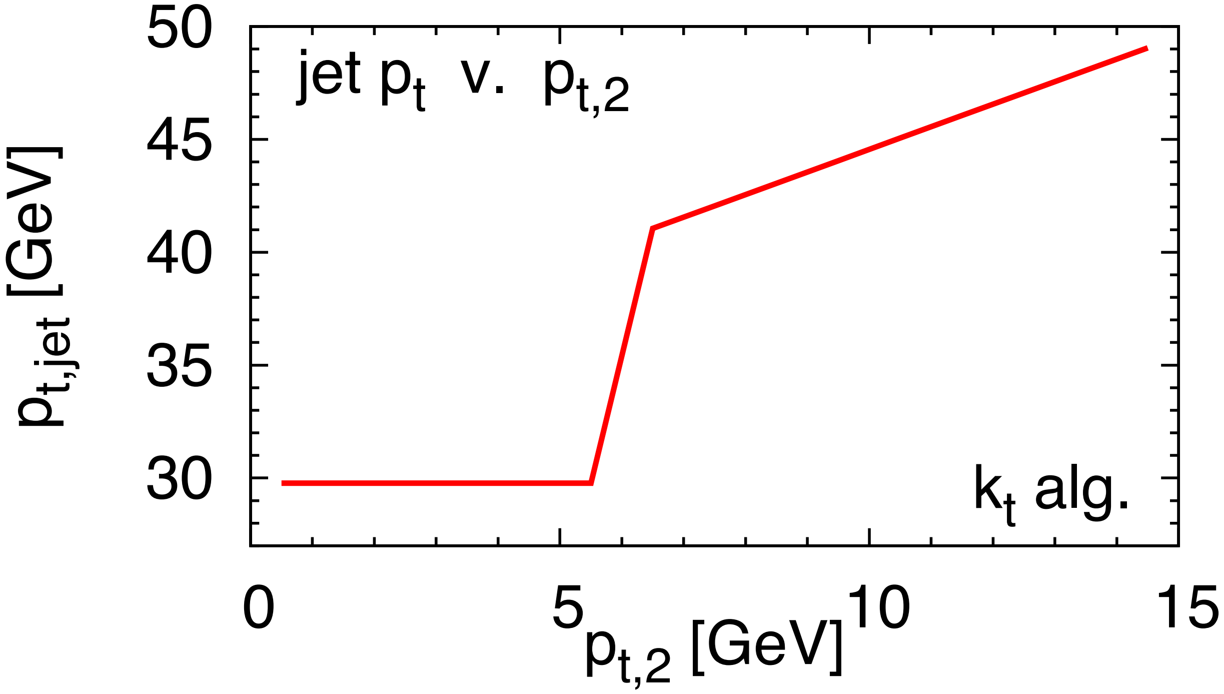

pt/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

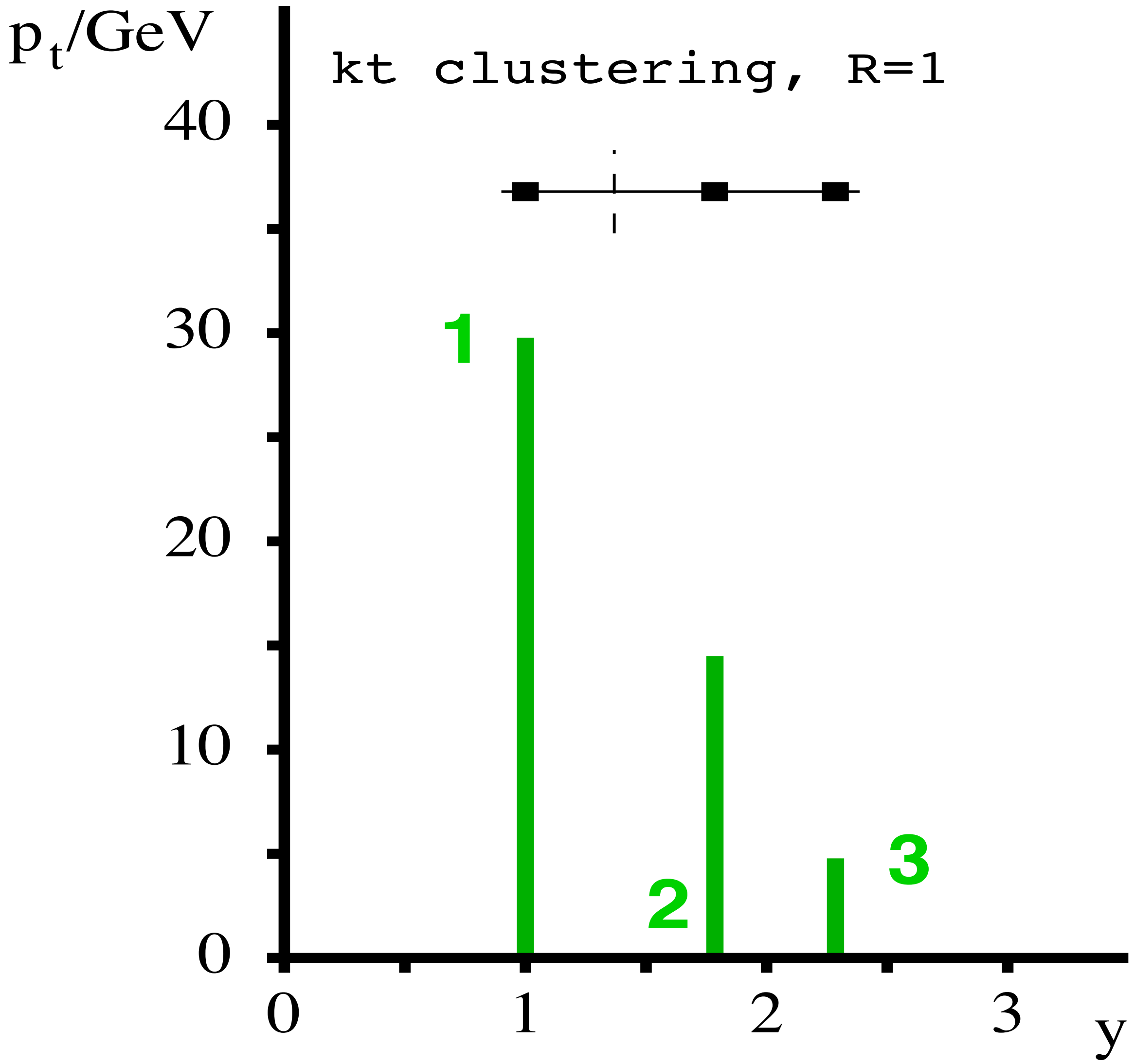

jet pt v. pt,2
kt alg.
pt,jet [GeV]
pt,2 [GeV]
50
45
40
35
30
0
5
10
15

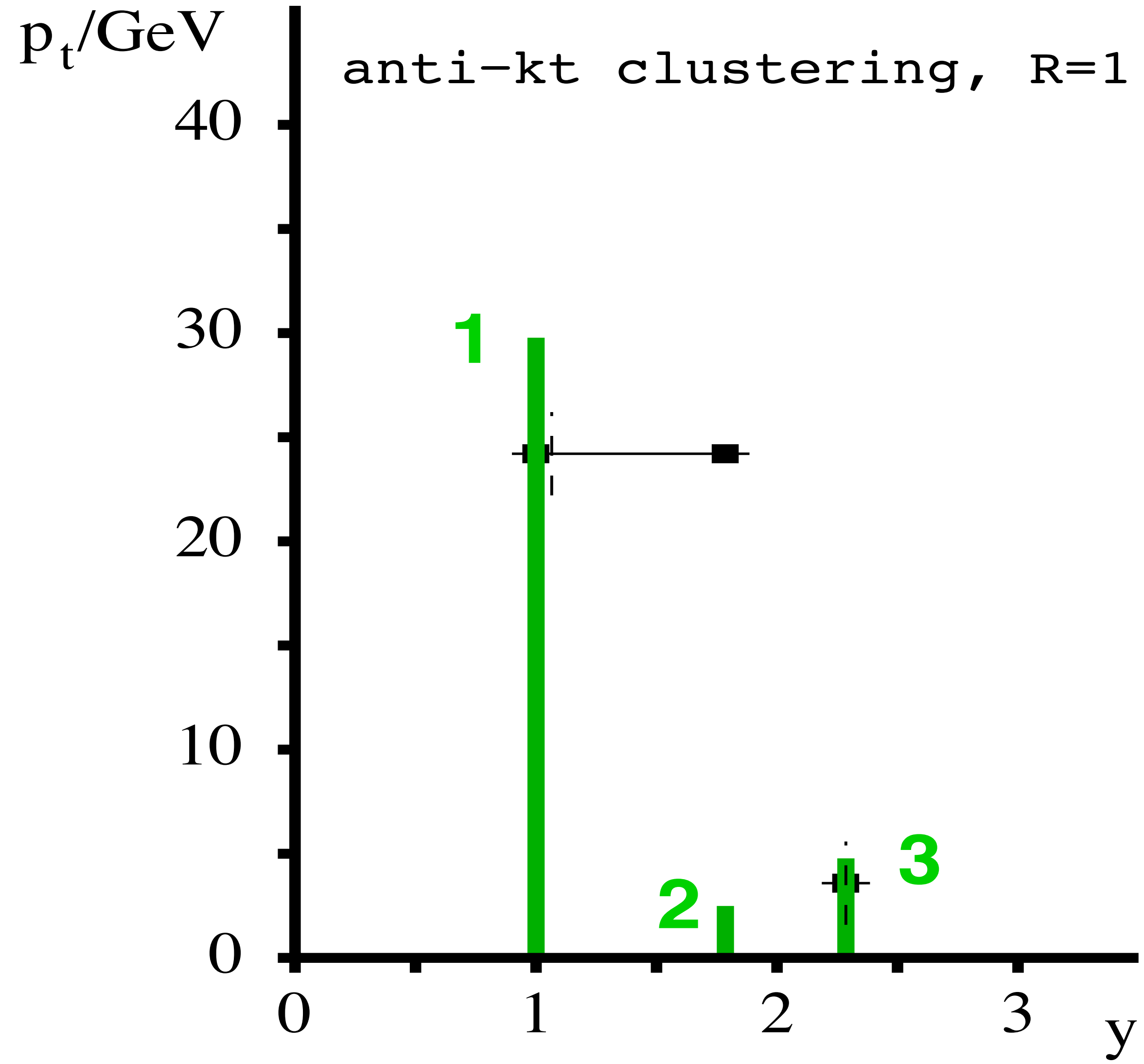
Linearity: k_t v. anti-k_t

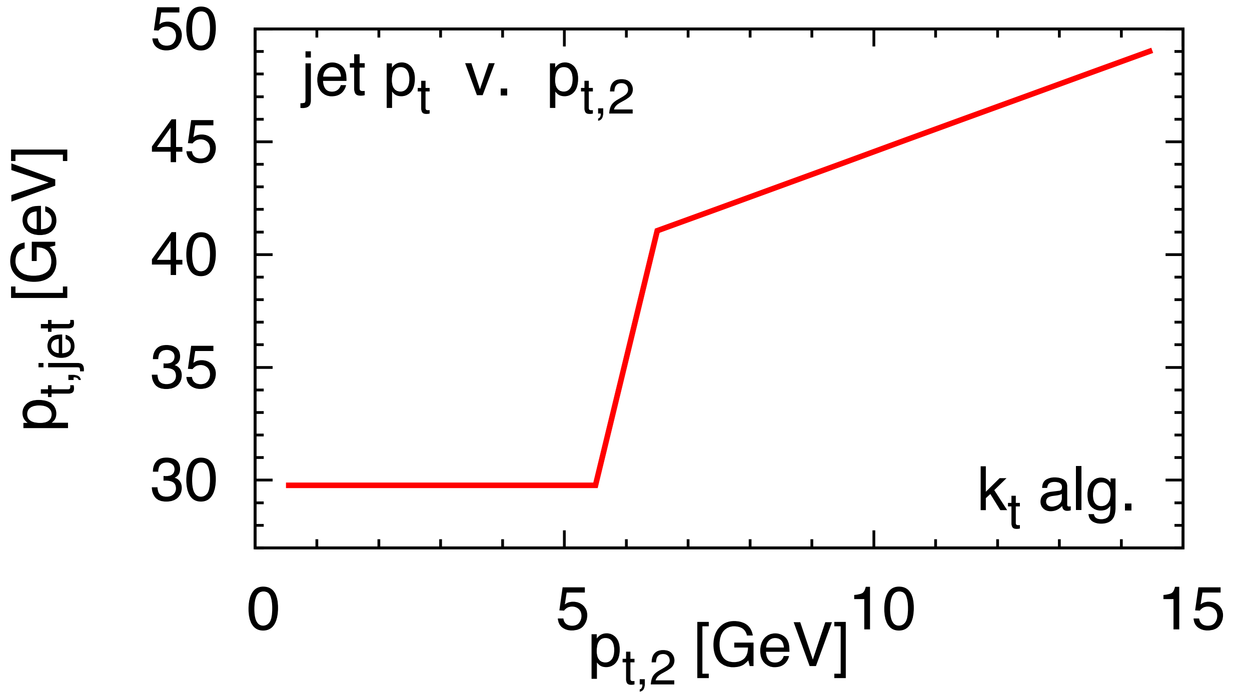


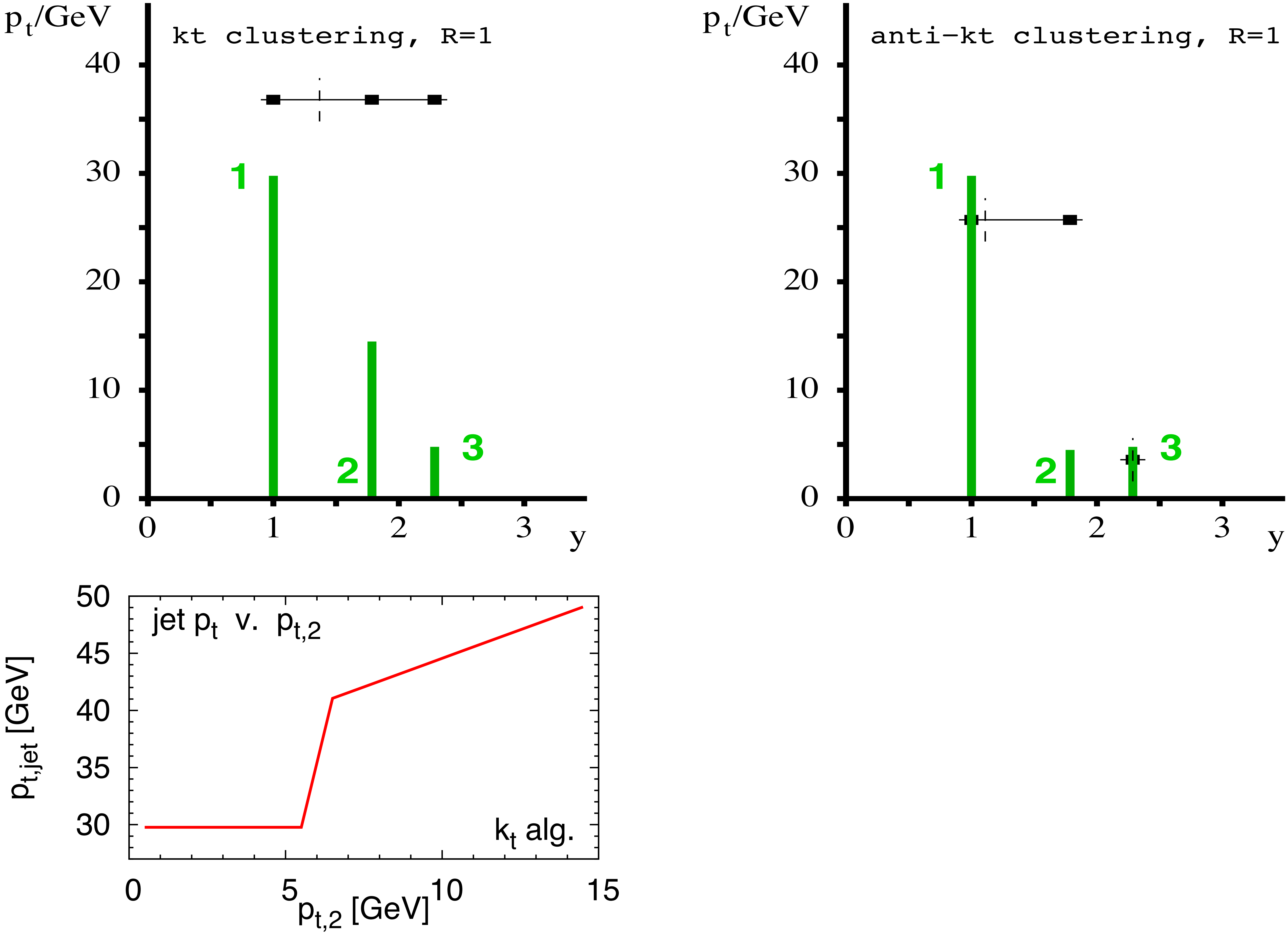




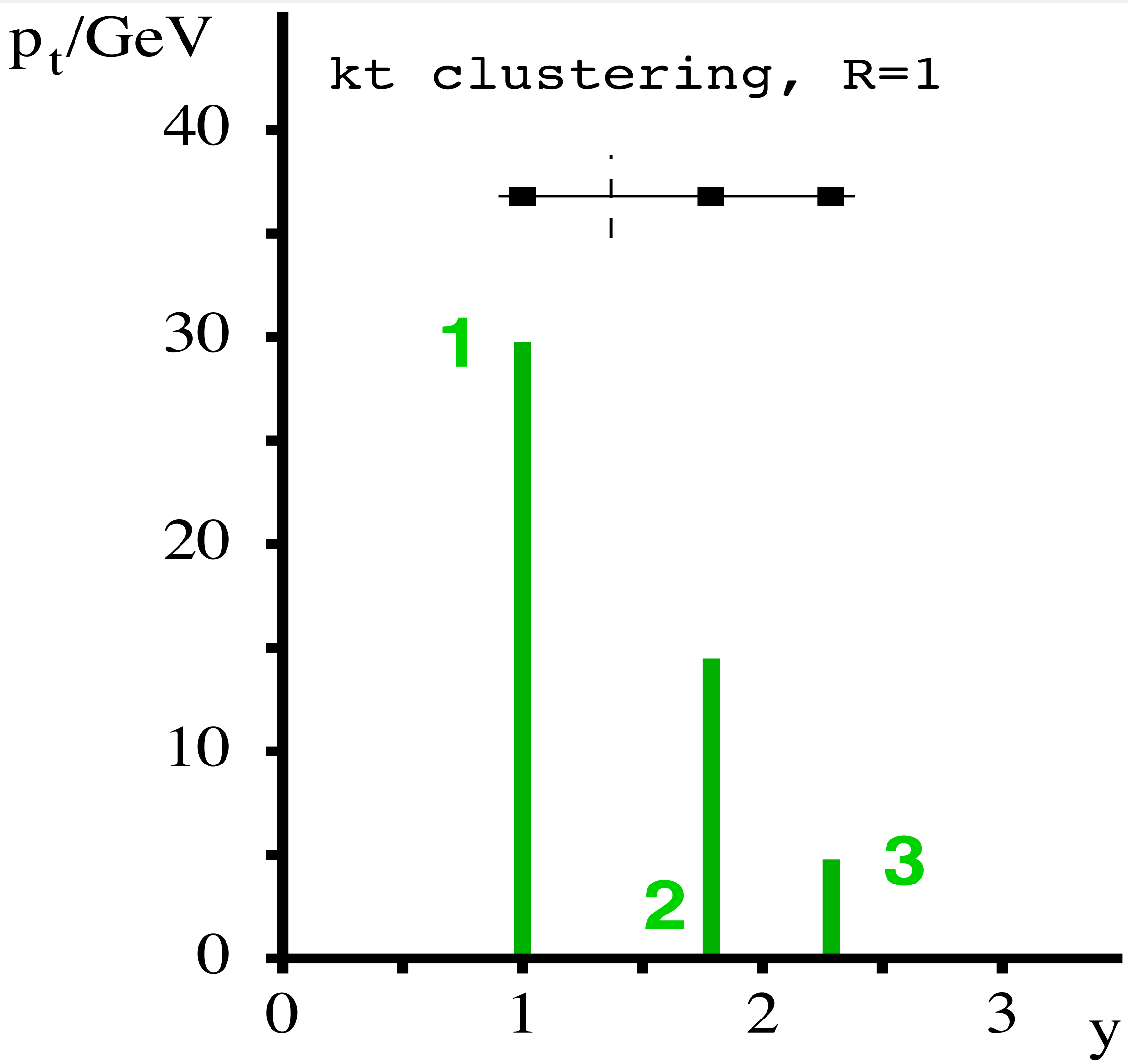

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

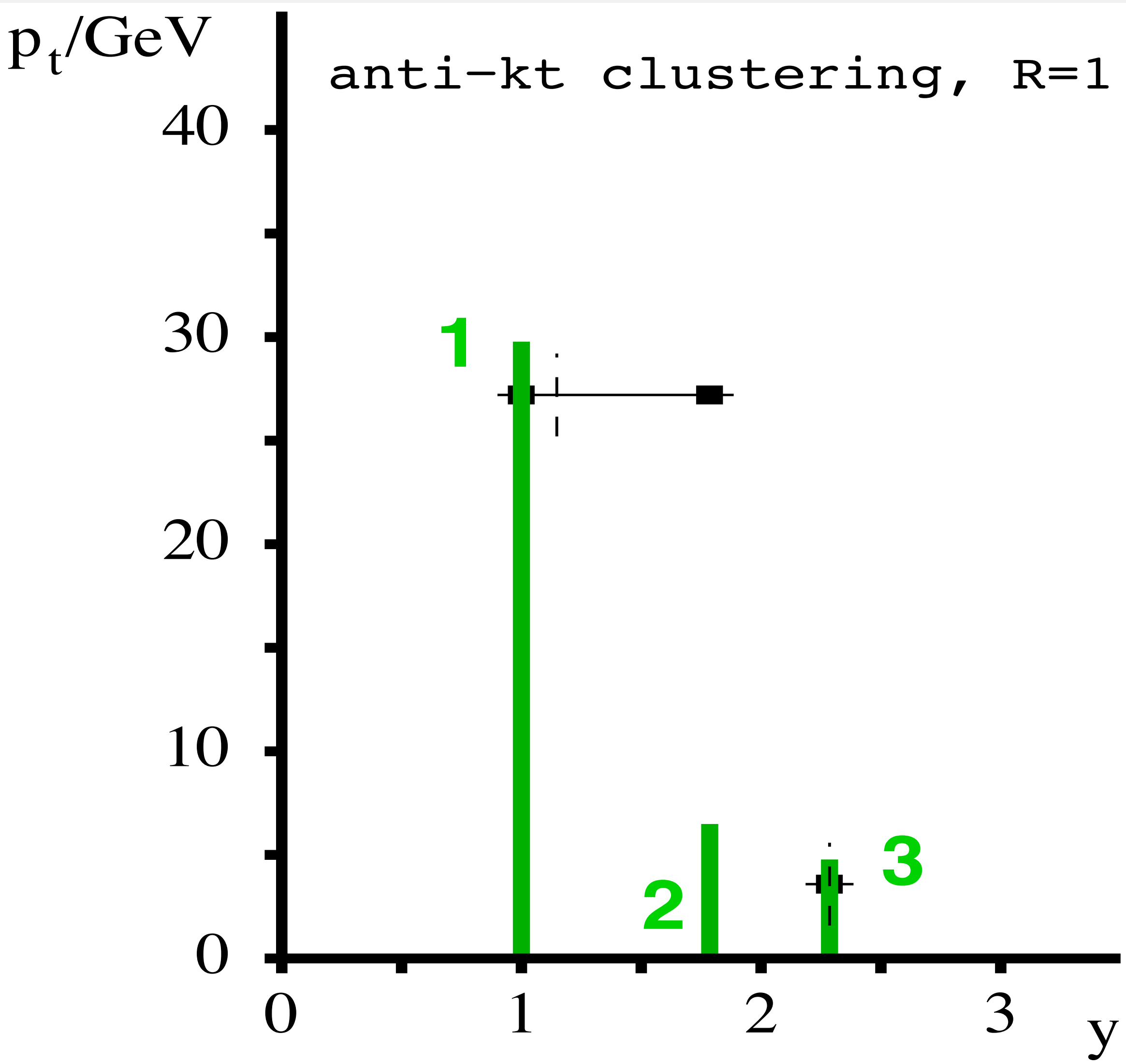

p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

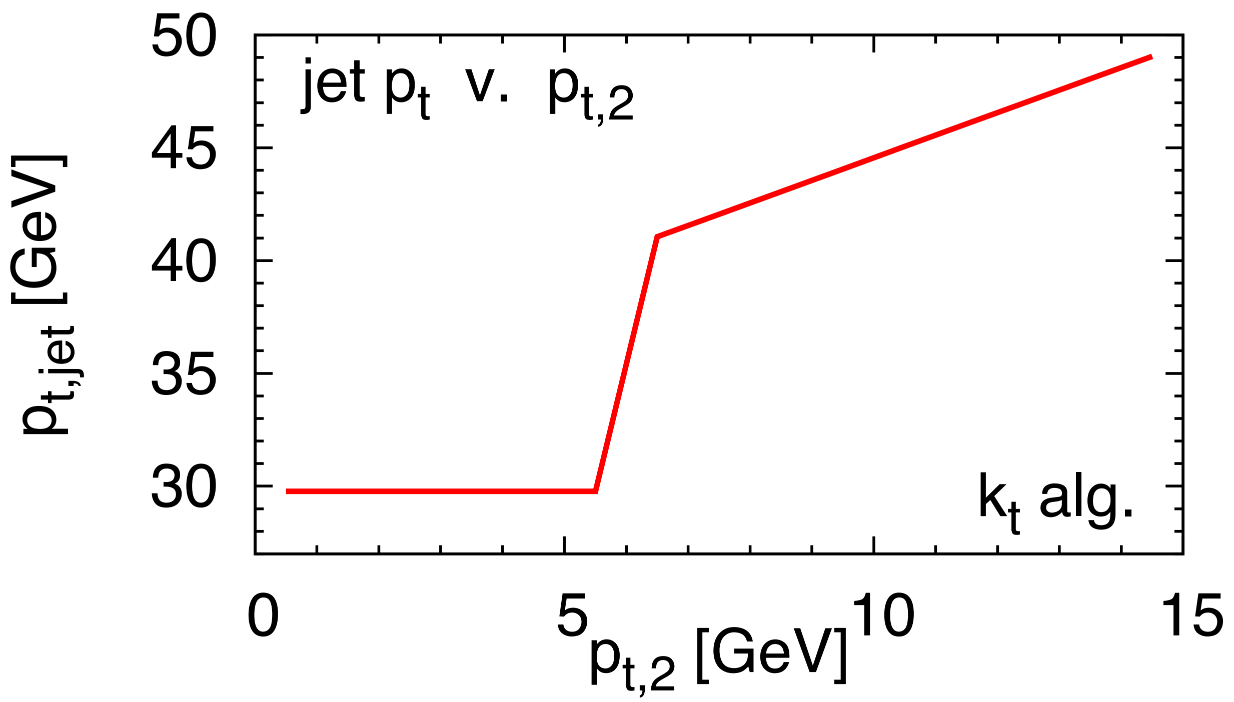

jet p_t v. p_t,2
k_t alg.
p_t,jet [GeV]
p_t,2 [GeV]
50
45
40
35
30
0
5
10
15



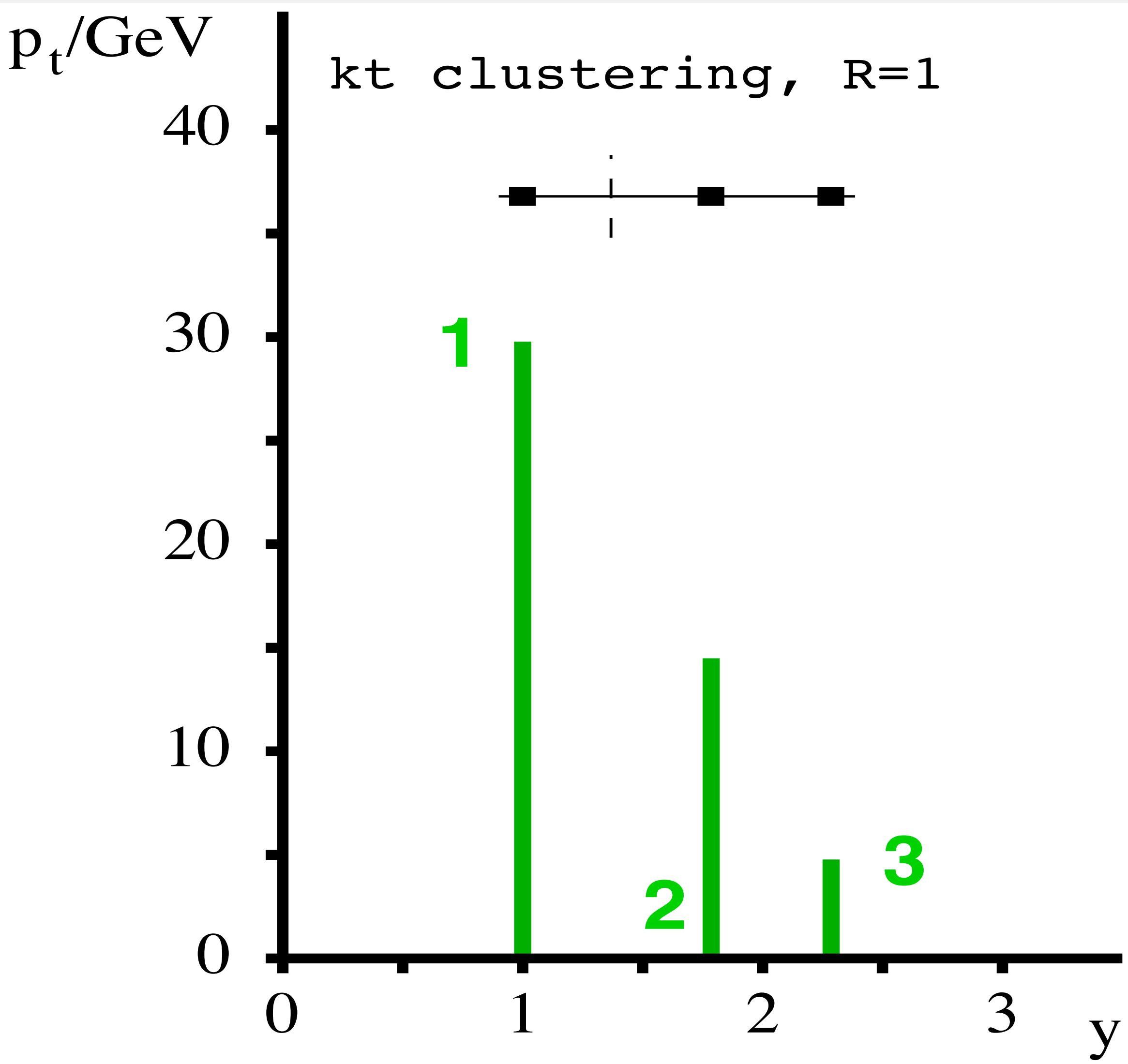
p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
p_t/GeV
anti-kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y
50
45
40
35
30
jet p_t v. p_t,2
k_t alg.
p_t,jet [GeV]
0
5
10
15
p_t,2 [GeV]

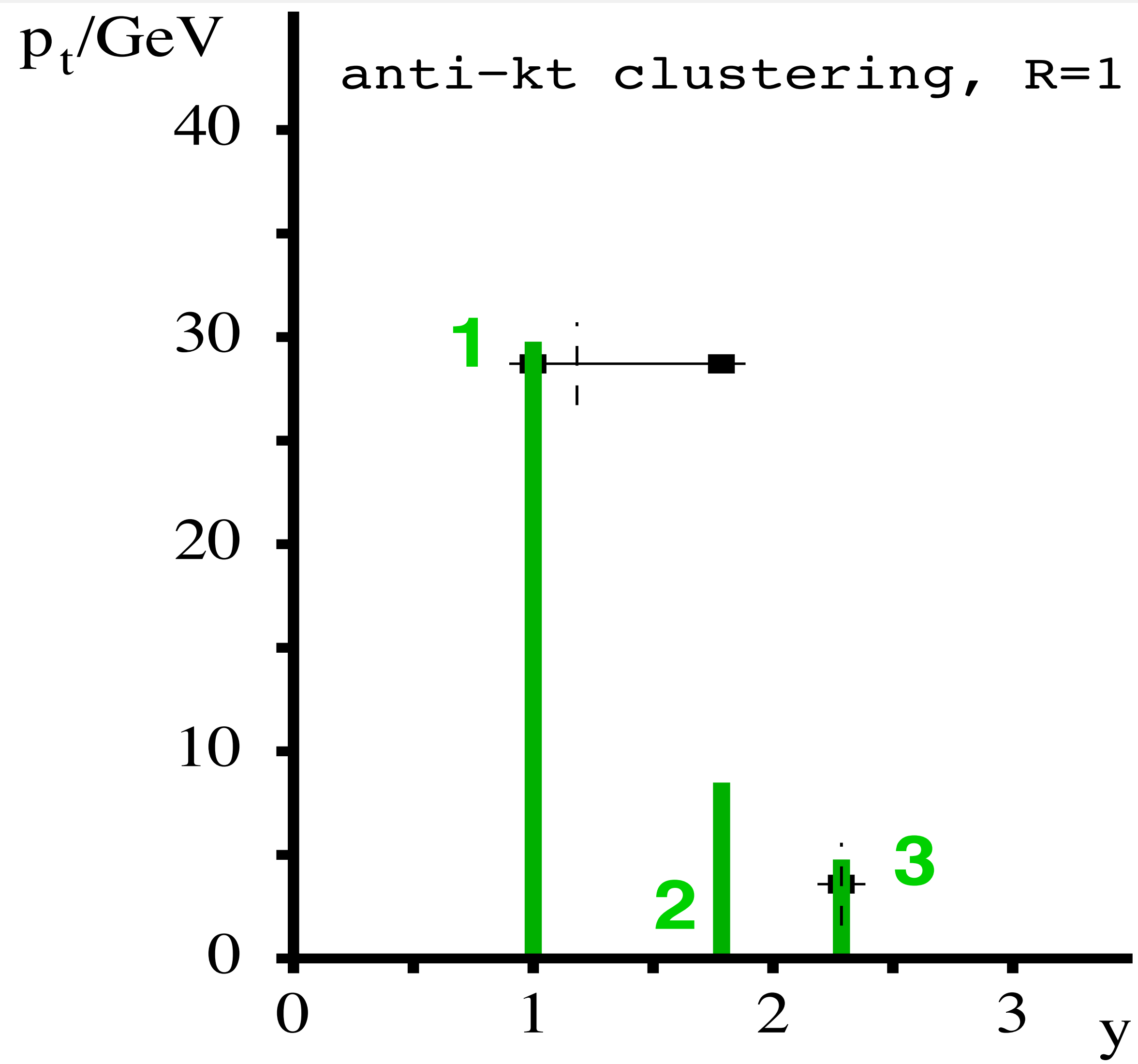

p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y

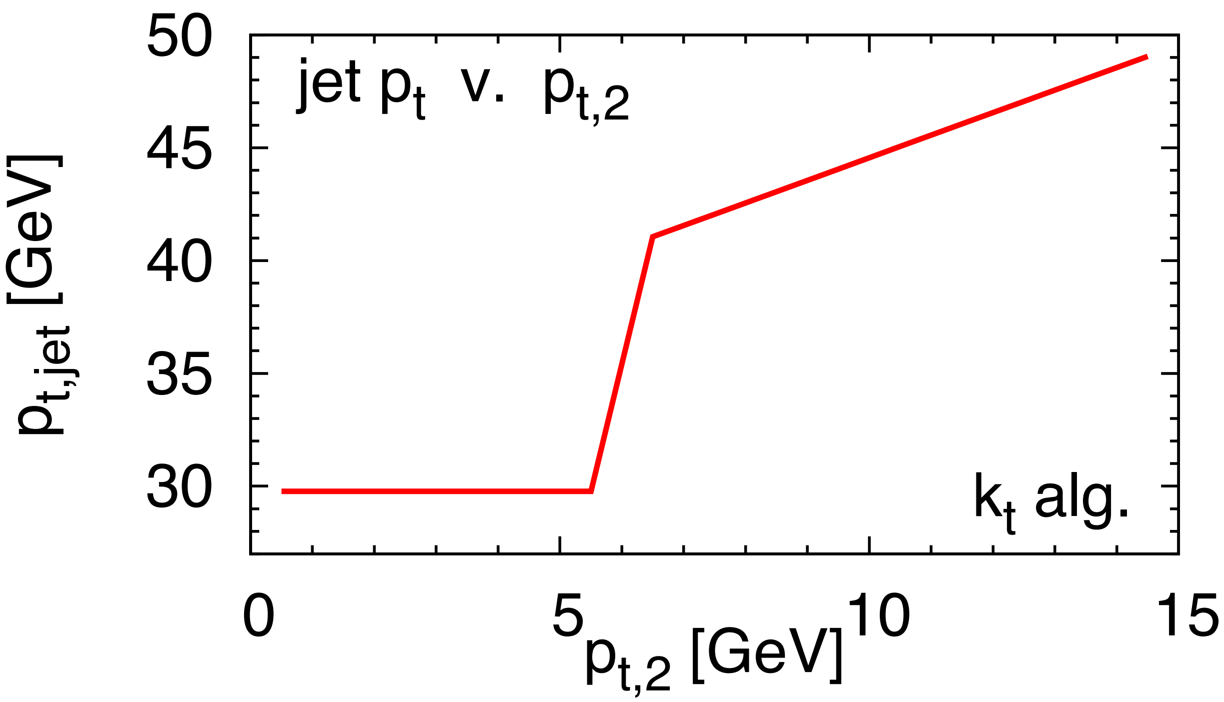

p_t/GeV
anti−kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y


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

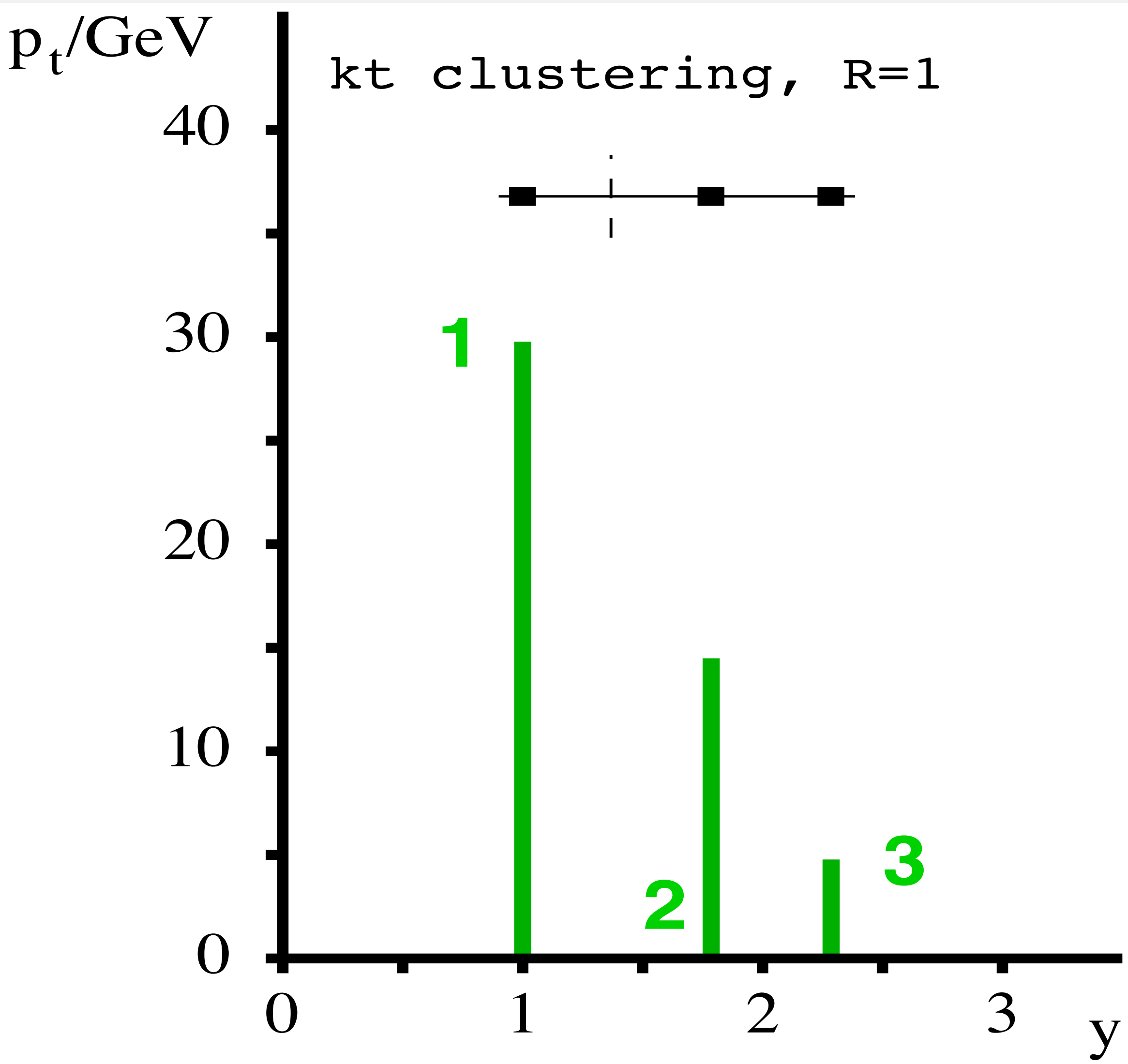
Linearity: k_t v. anti-k_t

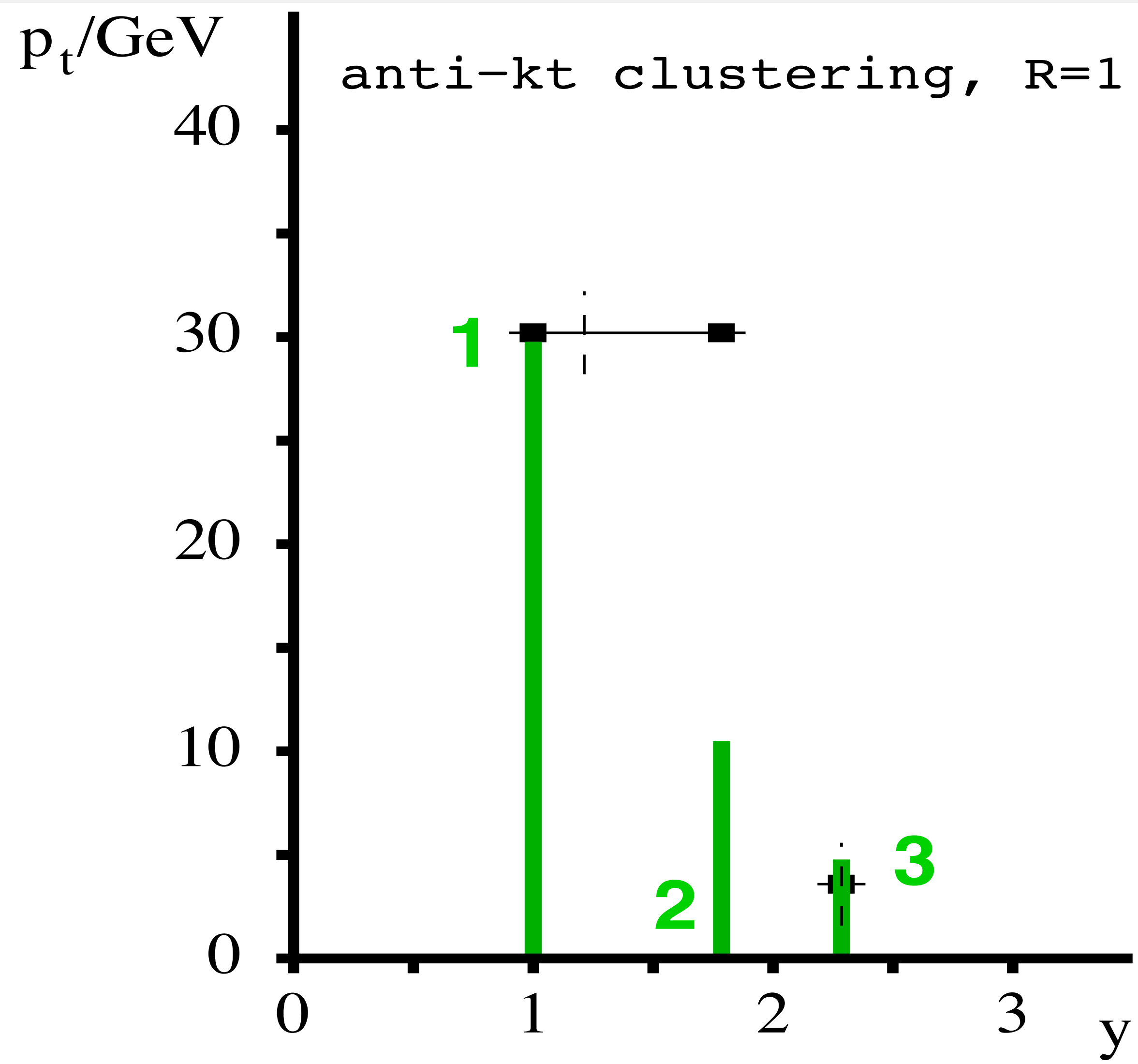


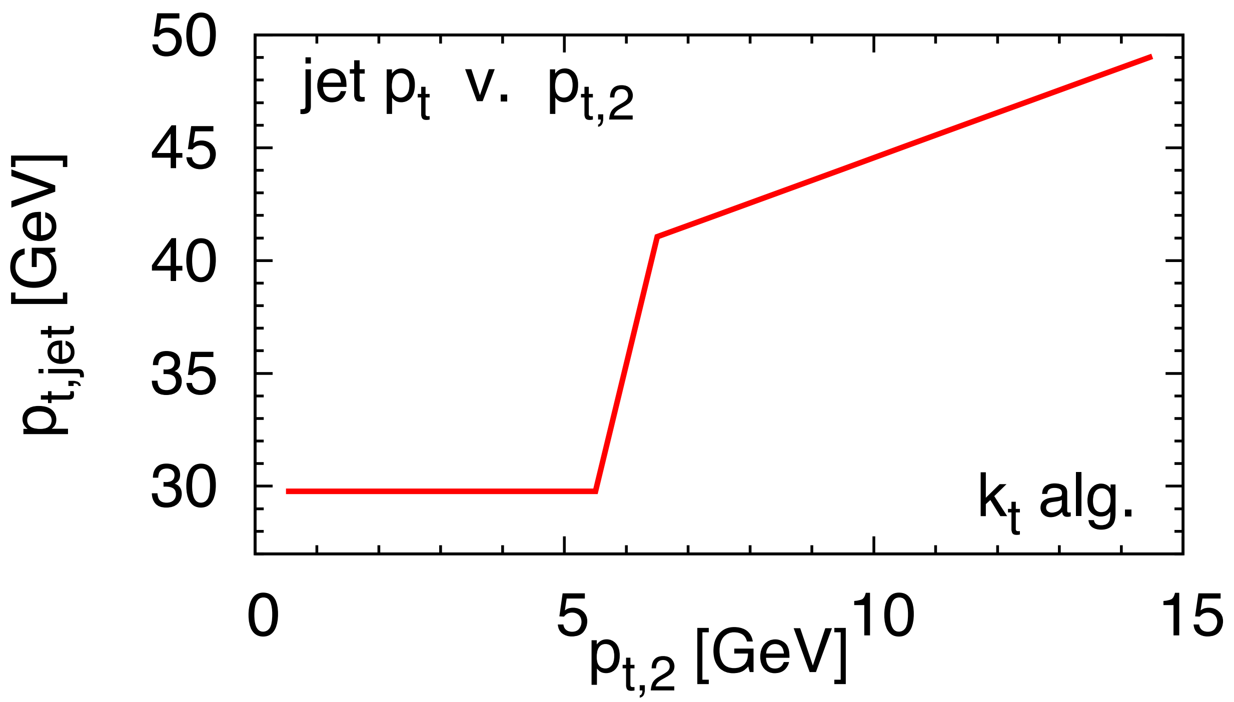


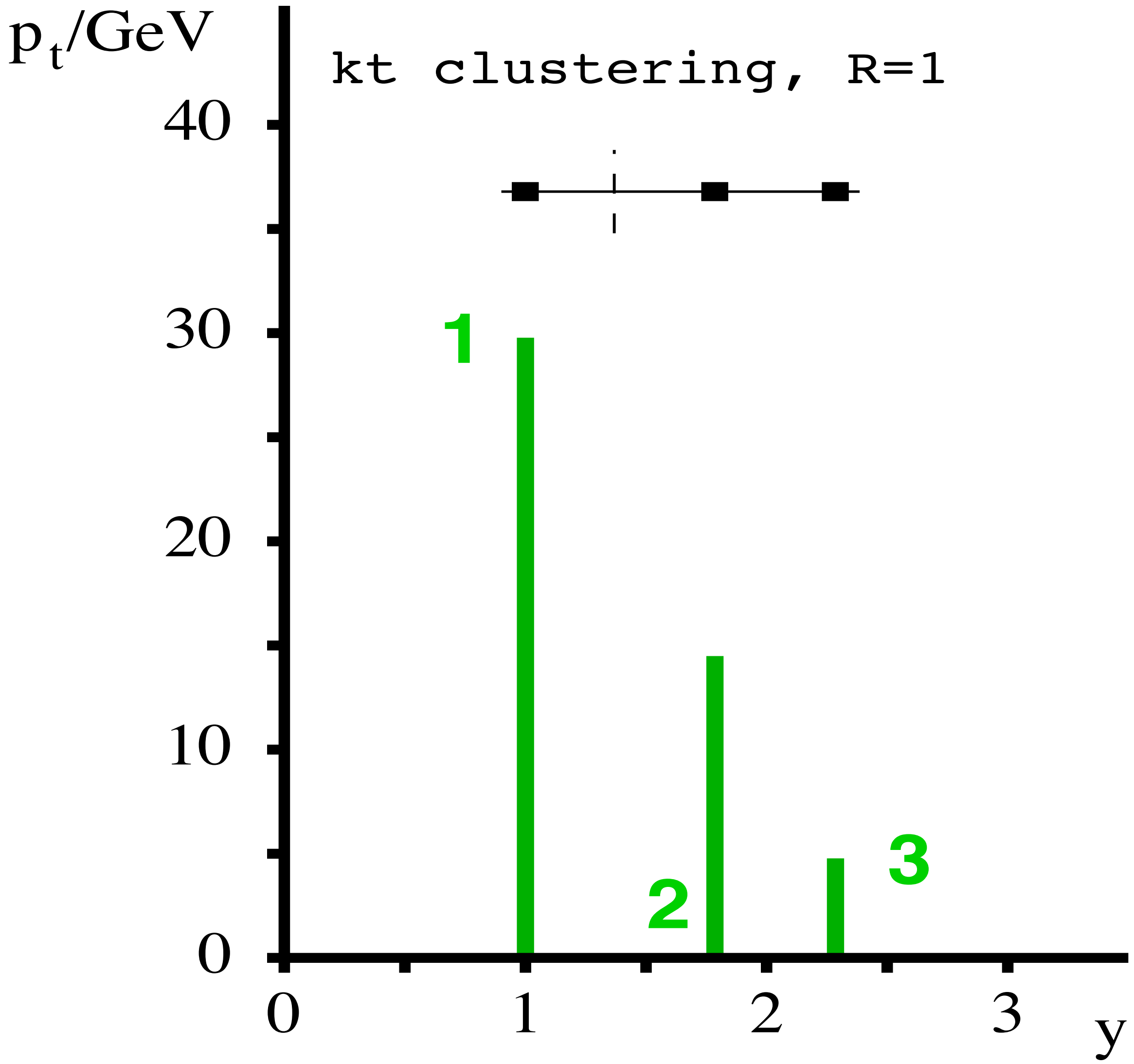


Linearity: k_t v. anti-k_t

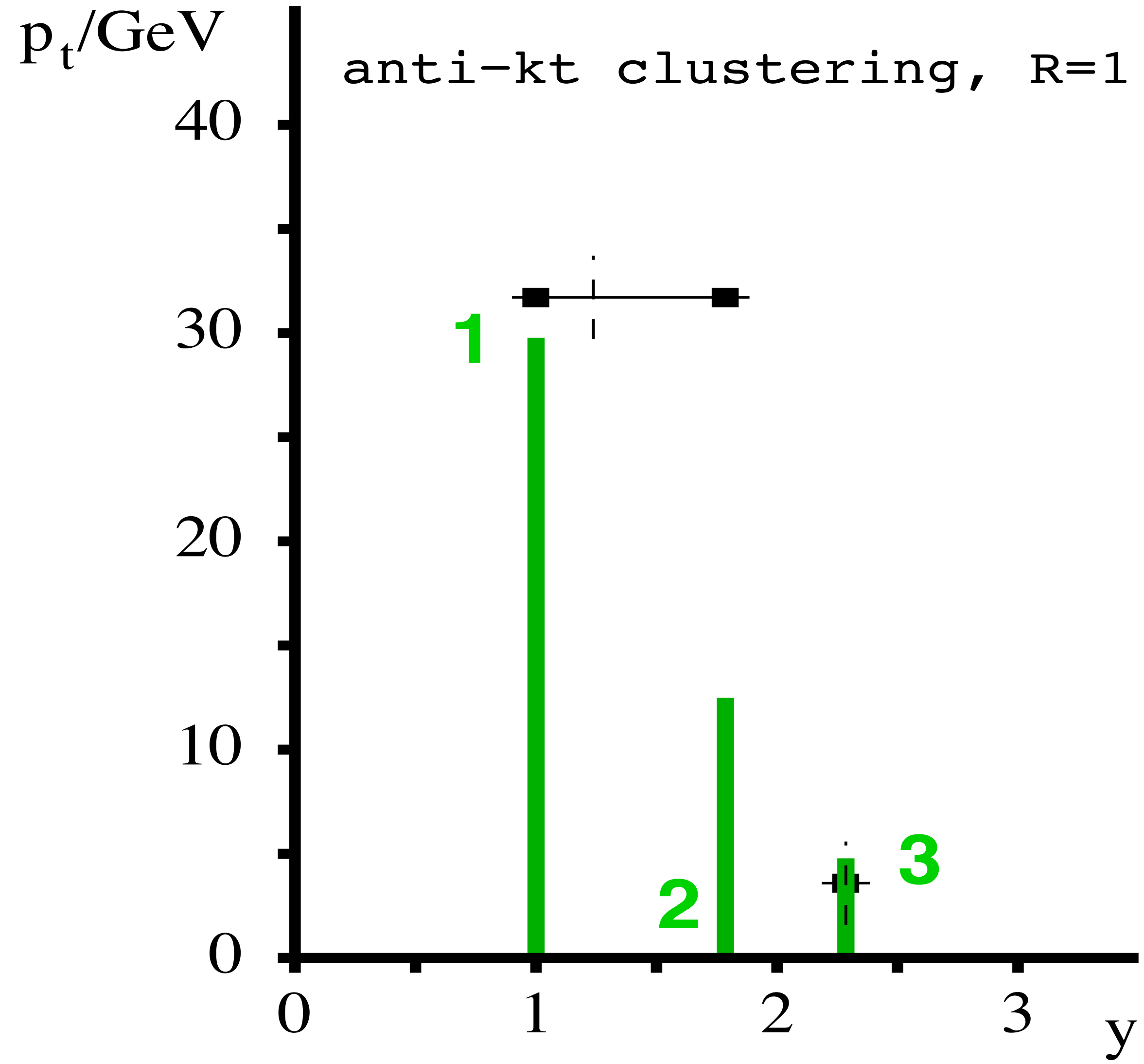








p_t/GeV
kt clustering, R=1
40
30
20
10
0
1
2
3
0
1
2
3
y



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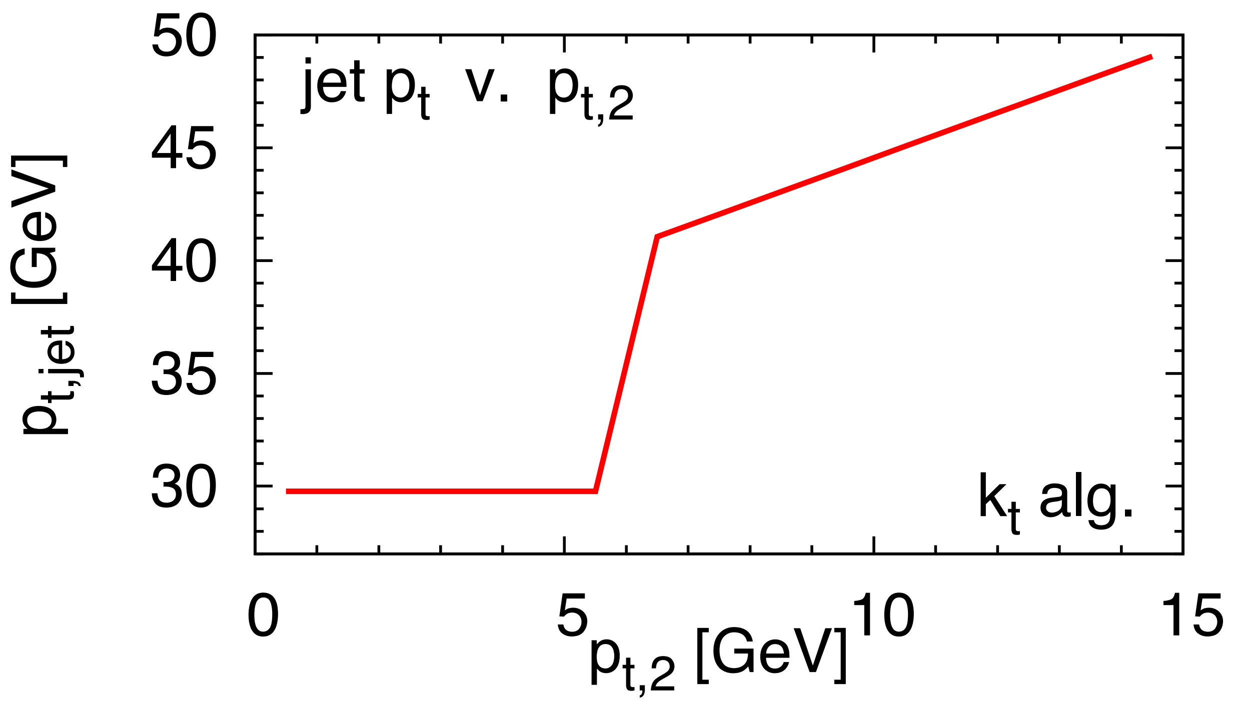
10
0
1
2
3
0
1
2
3
y



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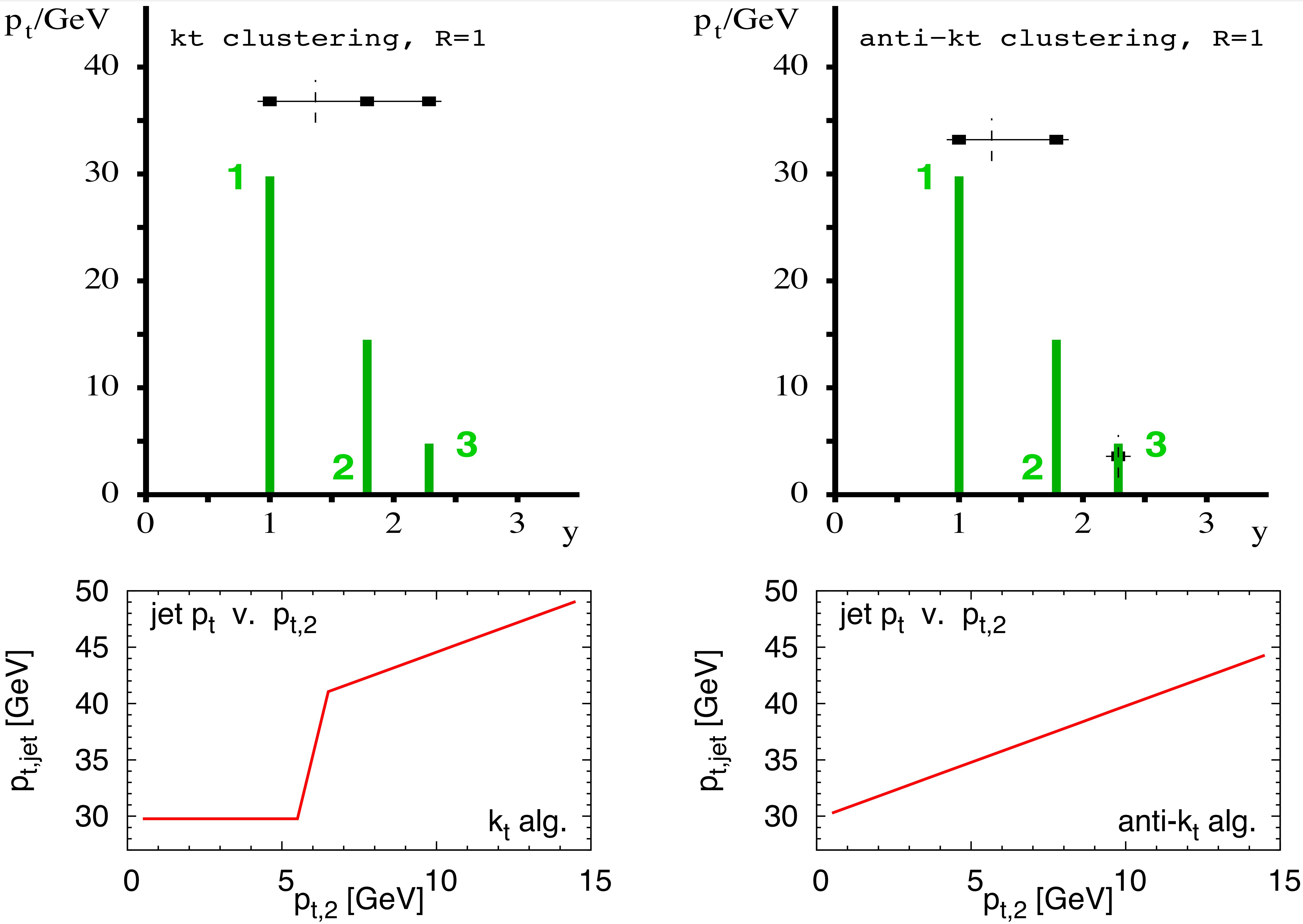
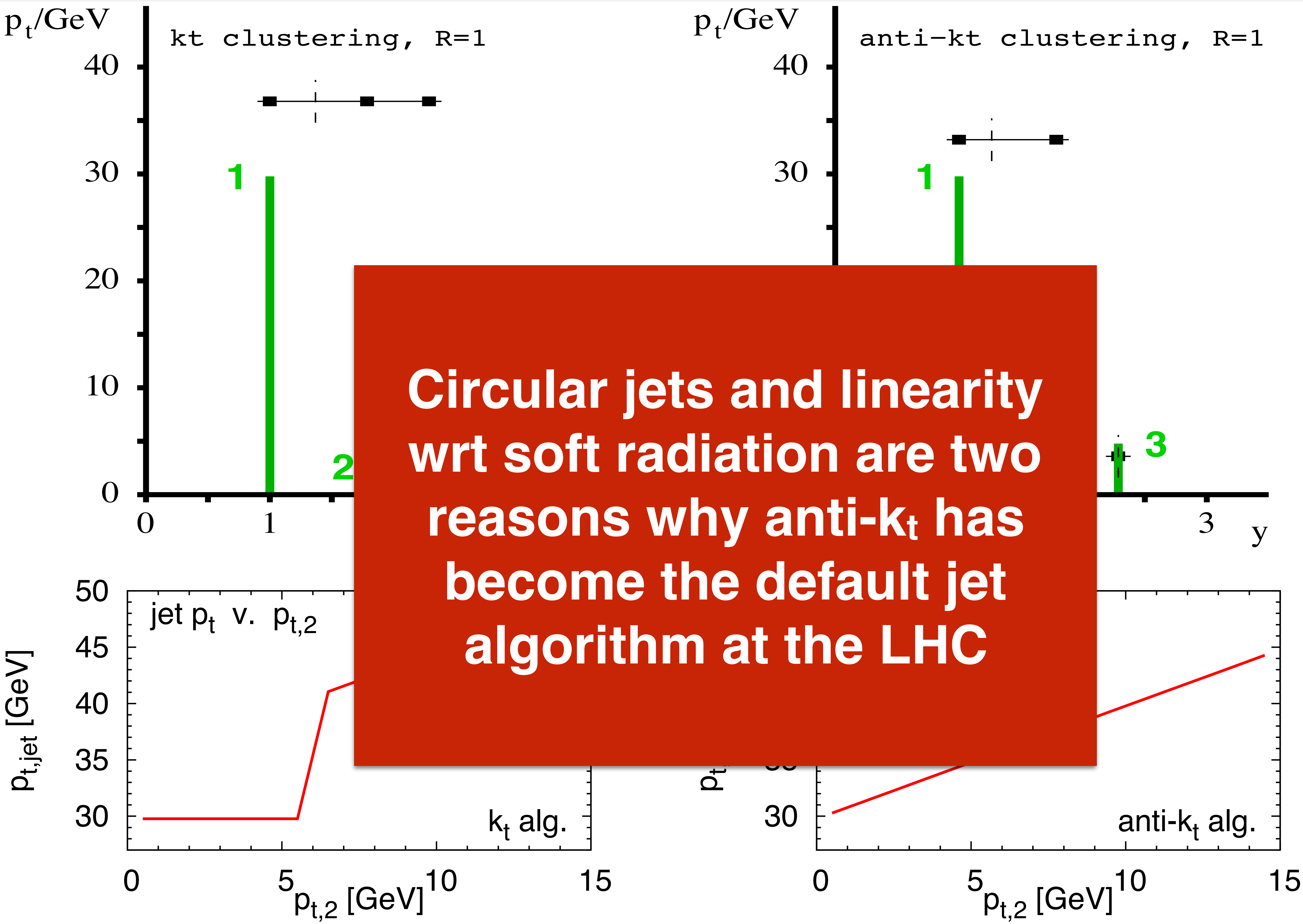
10
15
p_t,2 [GeV]

Linearity: k_t v. anti-k_t





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

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

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

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

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

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

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

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

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

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

when using jets, think about

(a) the hard partons

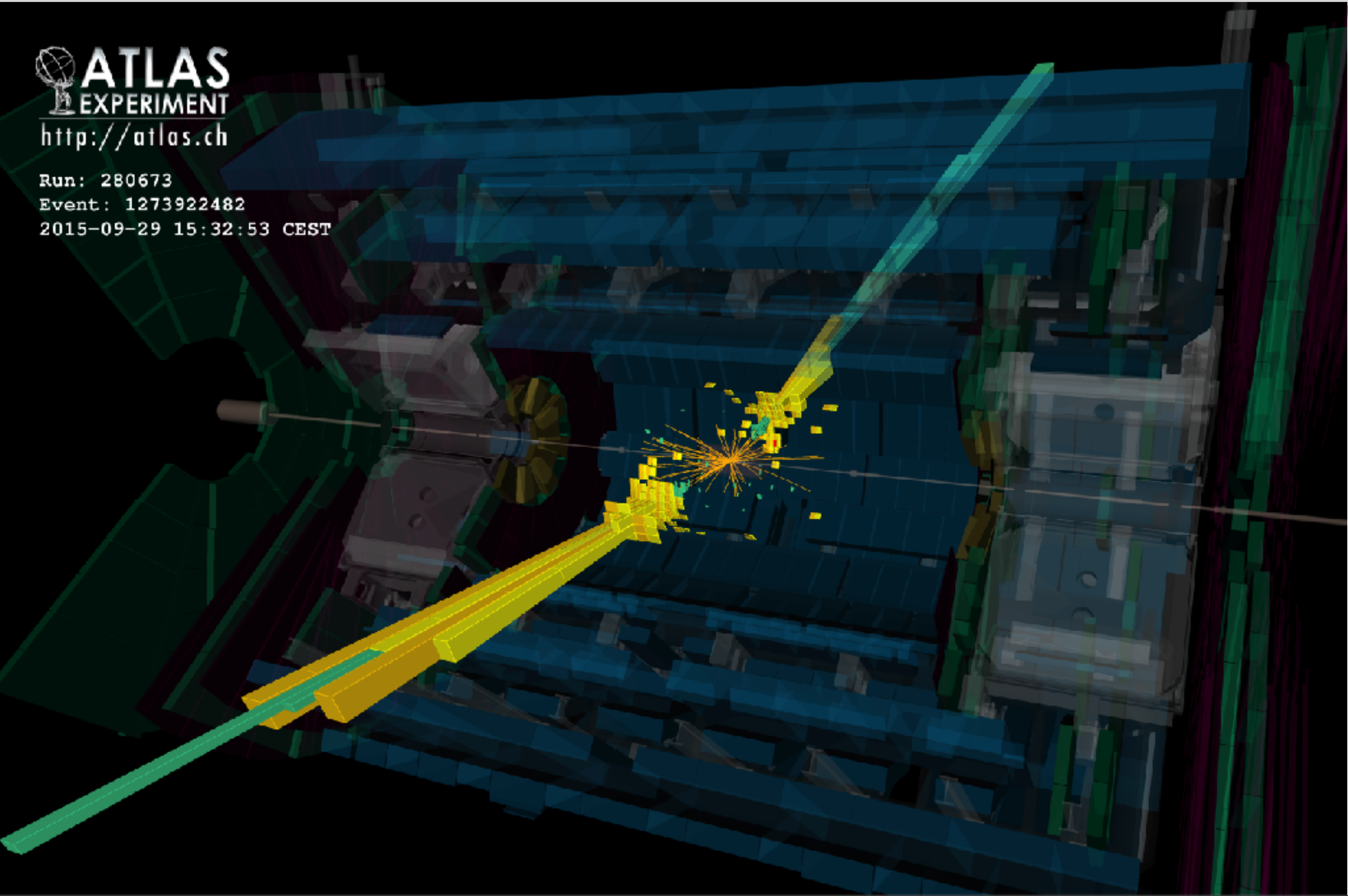
(b) relation between jets and hard partons

when using jets, think about

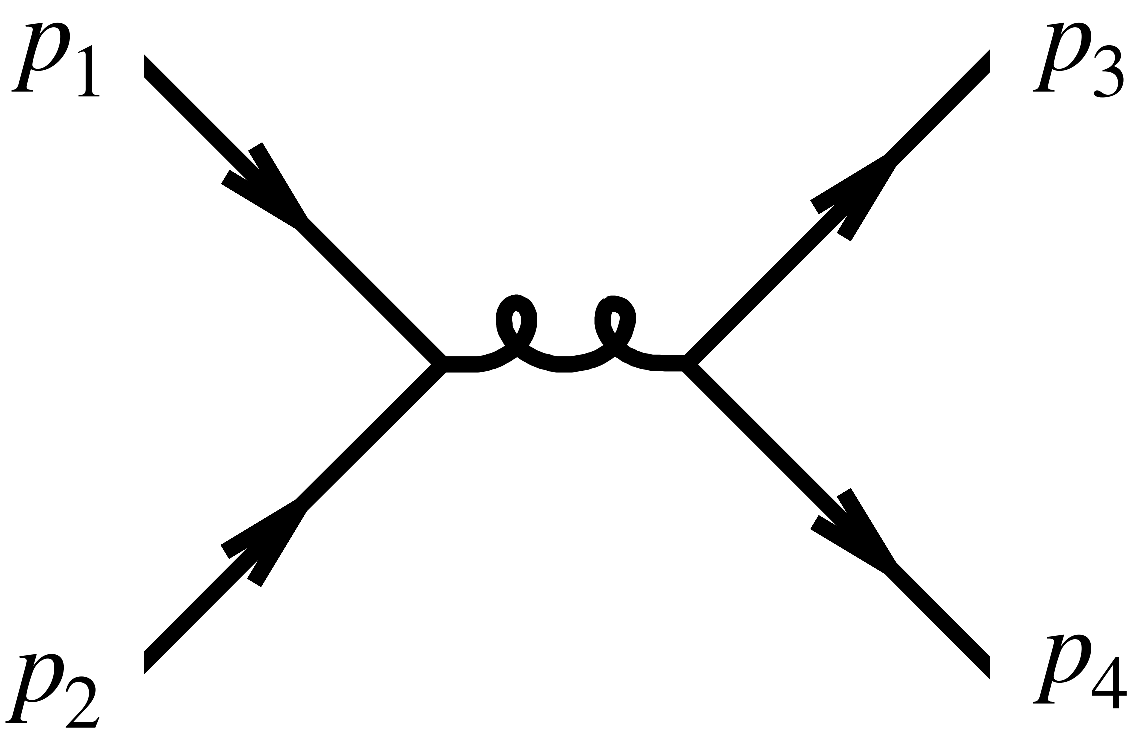
(a) the hard partons

(b) relation between jets and hard partons

dijet resonance reconstruction



Mandelstam variables & searches



s-channel

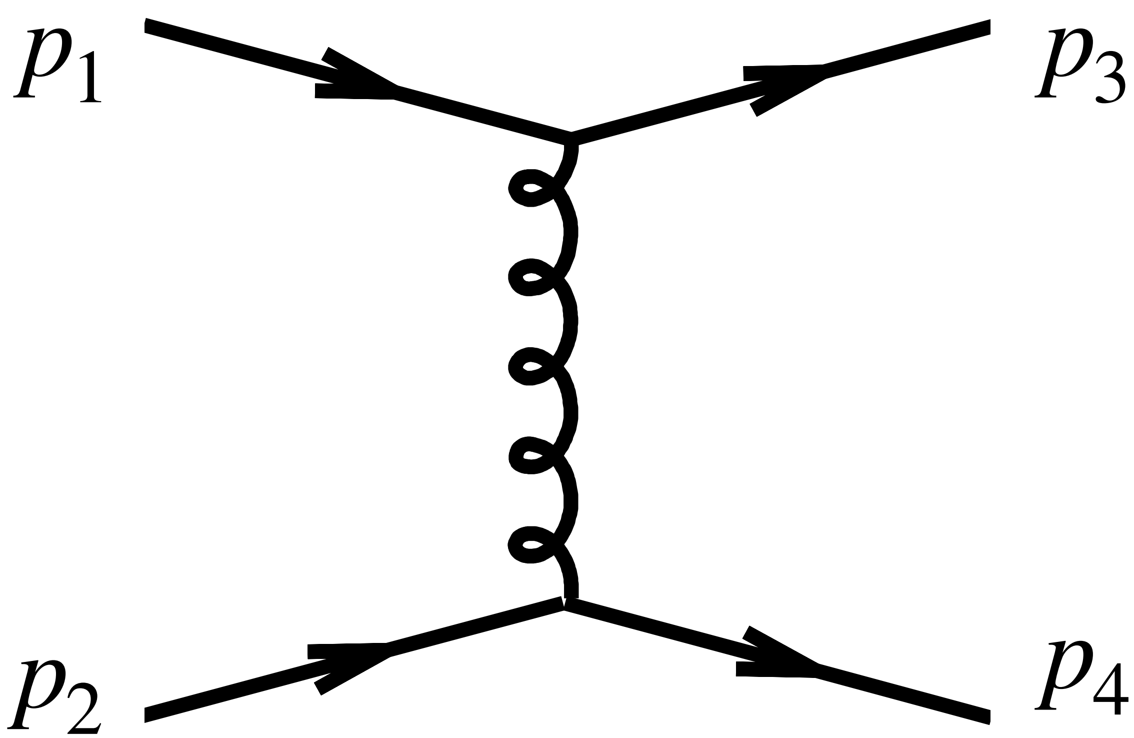
$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$\hat{t} = (p_3 - p_1)^2 = (p_4 - p_2)^2$$

$$\hat{u} = (p_4 - p_1)^2 = (p_3 - p_2)^2$$

$$q\bar{q} \to q'\bar{q}' : \mathcal{M}^2 = 16\pi^2\alpha_s^2 \, \frac{4}{9} \boxed{\frac{t^2 + u^2}{s^2}}$$

Mandelstam variables & searches



t-channel

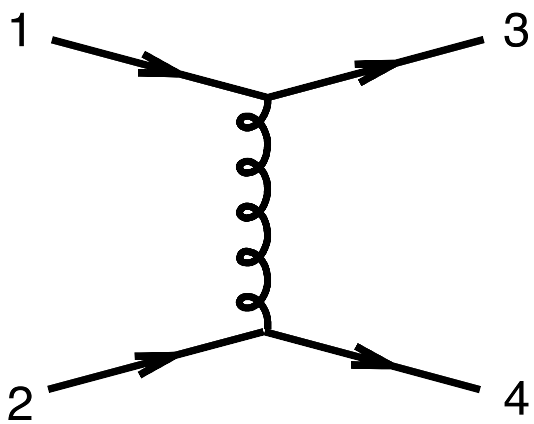
$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$\hat{t} = (p_3 - p_1)^2 = (p_4 - p_2)^2$$

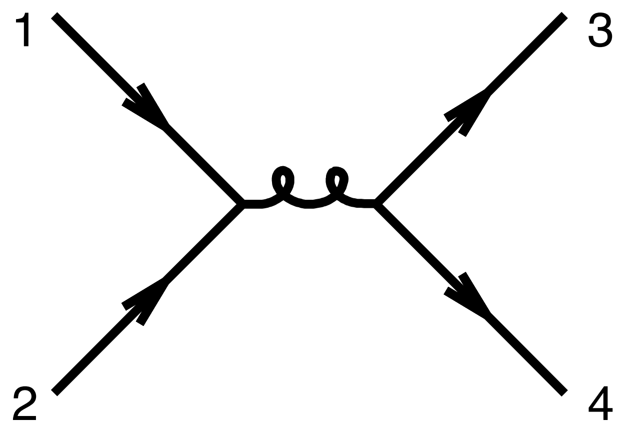
$$\hat{u} = (p_4 - p_1)^2 = (p_3 - p_2)^2$$

$$qq' \to qq' : \mathcal{M}^2 = 16\pi^2\alpha_s^2 \, \frac{4}{9} \boxed{\frac{s^2 + u^2}{t^2}}$$

Mandelstam variables & searches



$$\frac{s^2+u^2}{t^2}$$



$$\frac{t^2+u^2}{s^2}$$

$$\hat{s} = (p_1+p_2)^2 = (p_3+p_4)^2$$

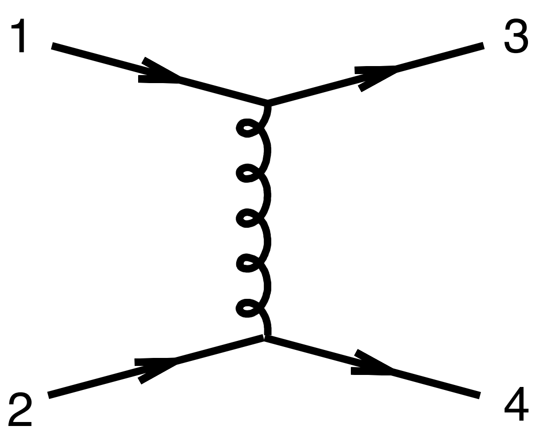
$$\hat{t} = (p_3-p_1)^2 = (p_4-p_2)^2$$

$$\hat{u} = (p_4-p_1)^2 = (p_3-p_2)^2$$

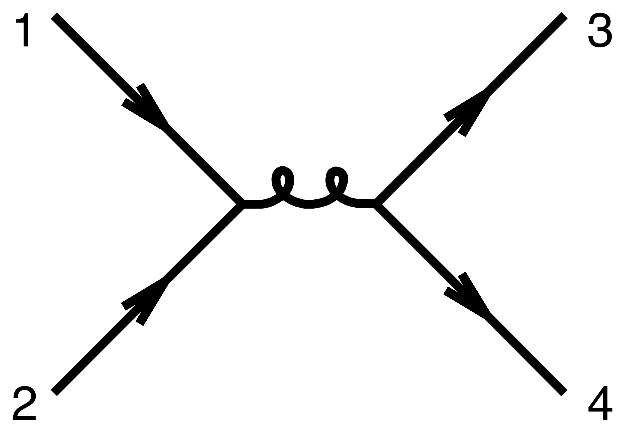
Fix $\hat{s} = m_{34}^2$ and write $\hat{t}$ as a function of rapidity separation between 3 and 4, Δy_{34}

$$\hat{t} = -\frac{\hat{s}}{2}\left(1 - \tanh\frac{\Delta y_{34}}{2}\right) \to -\,\hat{s}e^{-\Delta y_{34}} \text{ for large } \Delta y_{34}$$

Even if $\hat{s}$ is large **(new resonance)**, $\hat{t}$ can be small **(enhanced background)**



$$\frac{s^2+u^2}{t^2}$$



$$\frac{t^2+u^2}{s^2}$$

$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$\hat{t} = (p_3 - p_1)^2 = (p_4 - p_2)^2$$

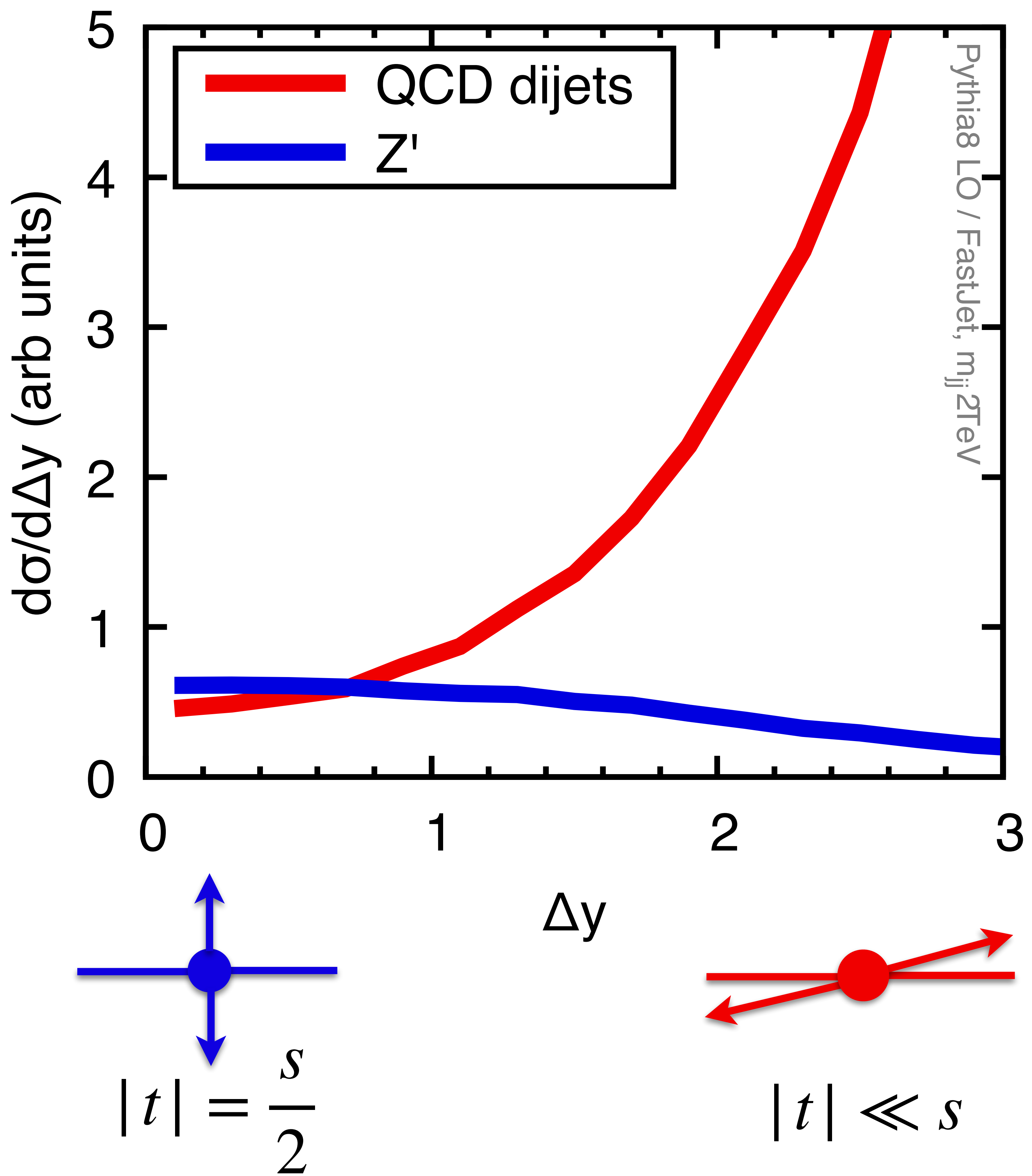
$$\hat{u} = (p_4 - p_1)^2 = (p_3 - p_2)^2$$

QCD background will predominantly come from the diagram with the smallest propagators

Without specific cuts, that usually means t-channel propagators

Even if $\hat{s}$ is large **(new resonance)**, $\hat{t}$ can be small **(enhanced background)**

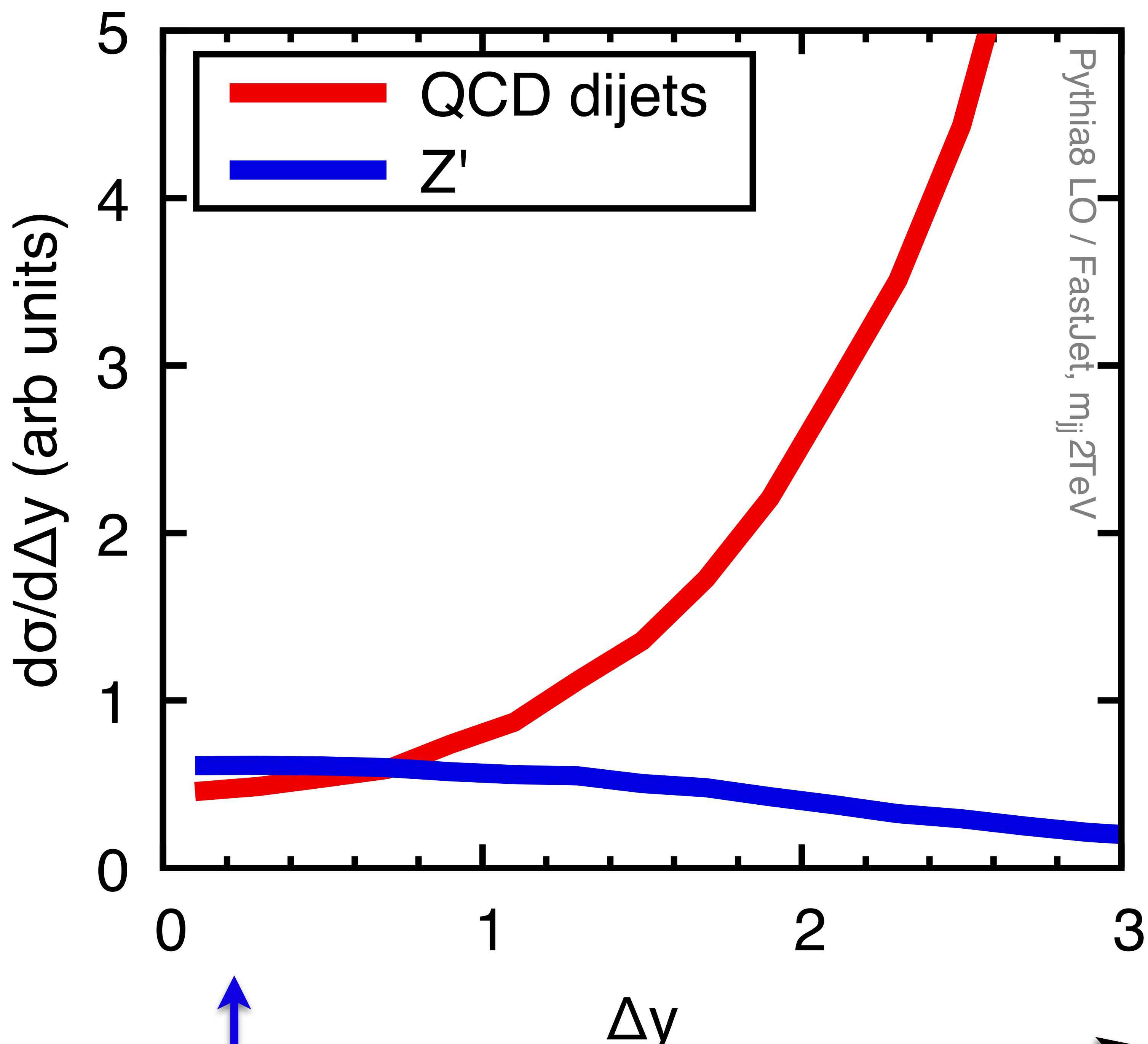
dijet rapidity difference: resonance v QCD

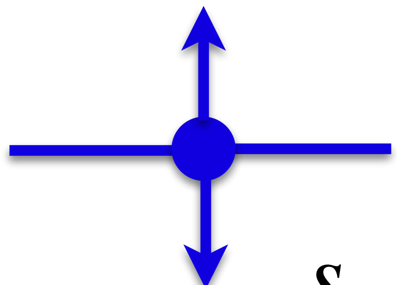


for a given dijet mass (or multijet mass), t-channel diagrams blow up for backgrounds when Δy gets large, because t gets small

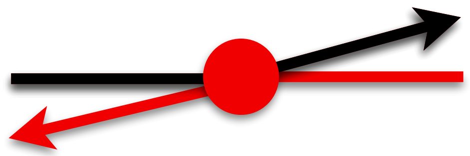
Lesson: always cut on Δy between jets

dijet rapidity difference: resonance v QCD





$$|t| = \frac{s}{2}$$



$$|t| \ll s$$

for a given dijet mass (or multijet mass), t-channel diagrams blow up for backgrounds when Δy gets large, because t gets small

Lesson: always cut on Δy between jets

e.g. CMS dijet search

The angular distribution of background from t-channel dijet events is similar to that for Rutherford scattering, approximately proportional to $1/[1-\tanh(|\Delta\eta|/2)]^2$, which peaks at large values of $|\Delta\eta|$. This background is suppressed by requiring the pseudorapidity separation of the two wide jets to satisfy $|\Delta\eta| < 1.3$.

CMS, Search for narrow and broad dijet resonances
1806.00843

if you're looking for a hadronically decaying resonance, (or contact interactions) don't use jets far apart in rapidity

NB: in general, prefer rapidities (y) to pseudorapidities (η). For massive objects Δy is long. boost invariant, $\Delta\eta$ is not.

when using jets, think about

(a) the hard partons

(b) relation between jets and hard partons

- Fine detail on boarding pass — shoot from close up, focus = 40cm

[look for gate]

- Keep focus at 40cm
- Reset focus to 3m

Catch correct plane

- Fine detail on boarding pass — shoot from close up, focus = 40cm

  [look for gate]

- Keep focus at 40cm
- Reset focus to 3m

  Catch correct plane

- Fine detail on boarding pass — shoot from close up, focus = 40cm

  [look for gate]

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- Reset focus to 3m

  Catch correct plane

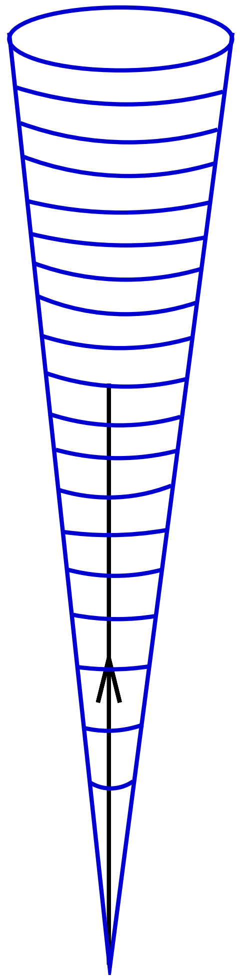
- Fine detail on boarding pass — shoot from close up, focus = 40cm

  [look for gate]

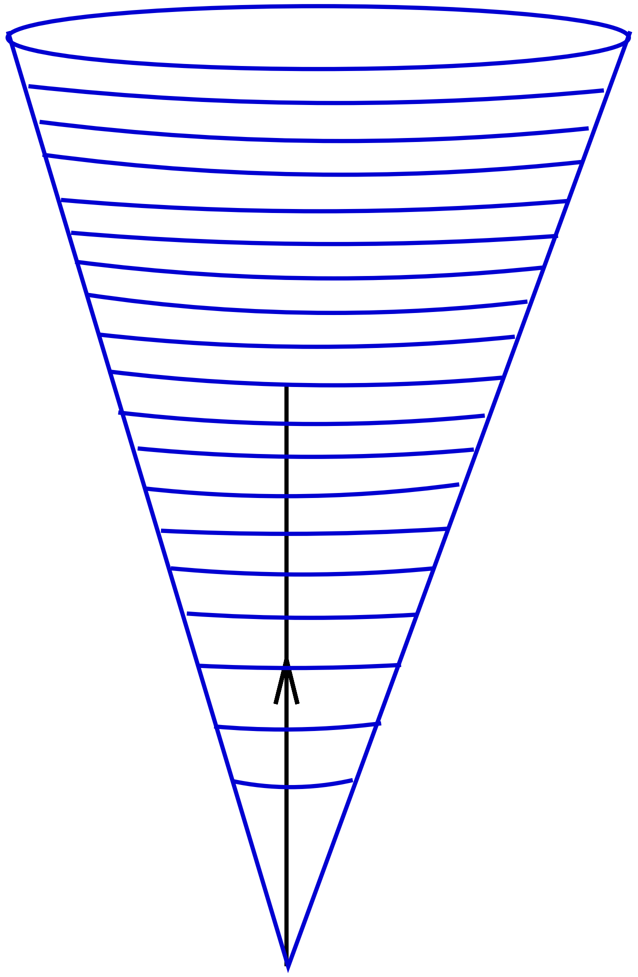
- Keep focus at 40cm
- Reset focus to 3m

  Catch correct plane

Small jet radius

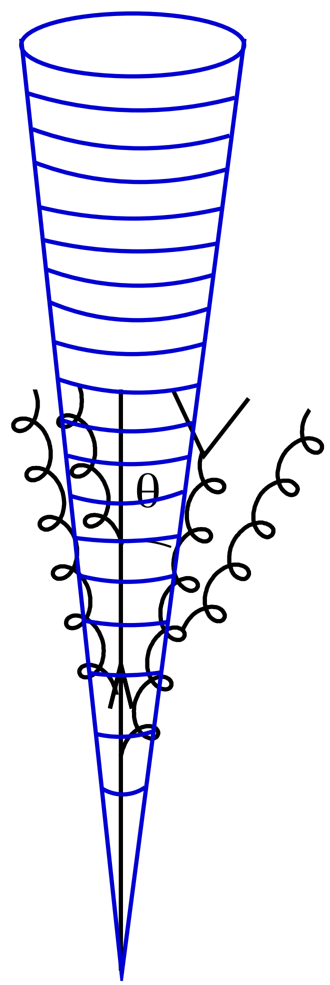


Large jet radius

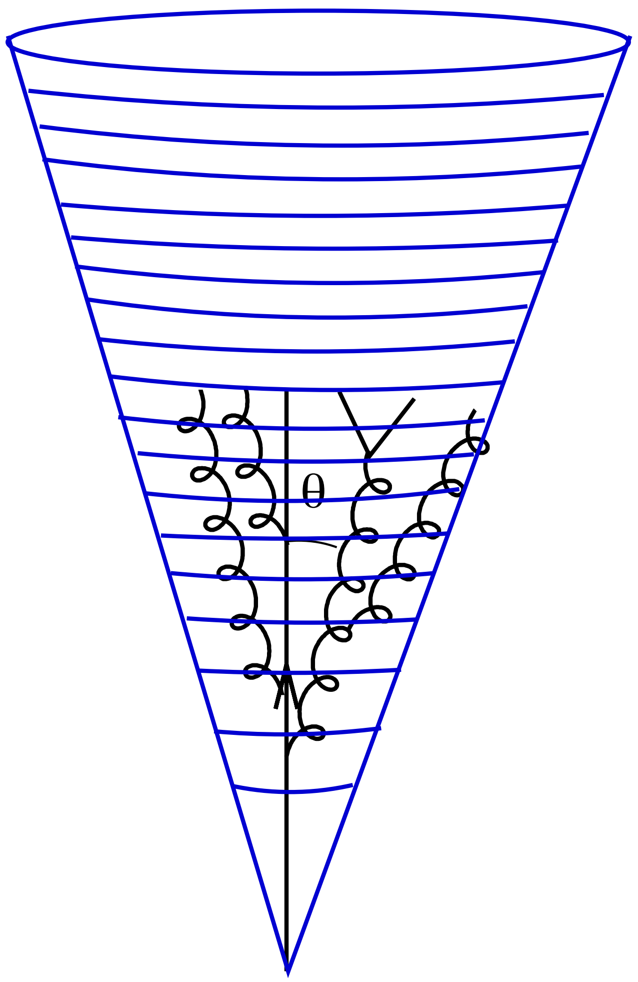


single parton @ LO: **jet radius irrelevant**

Small jet radius



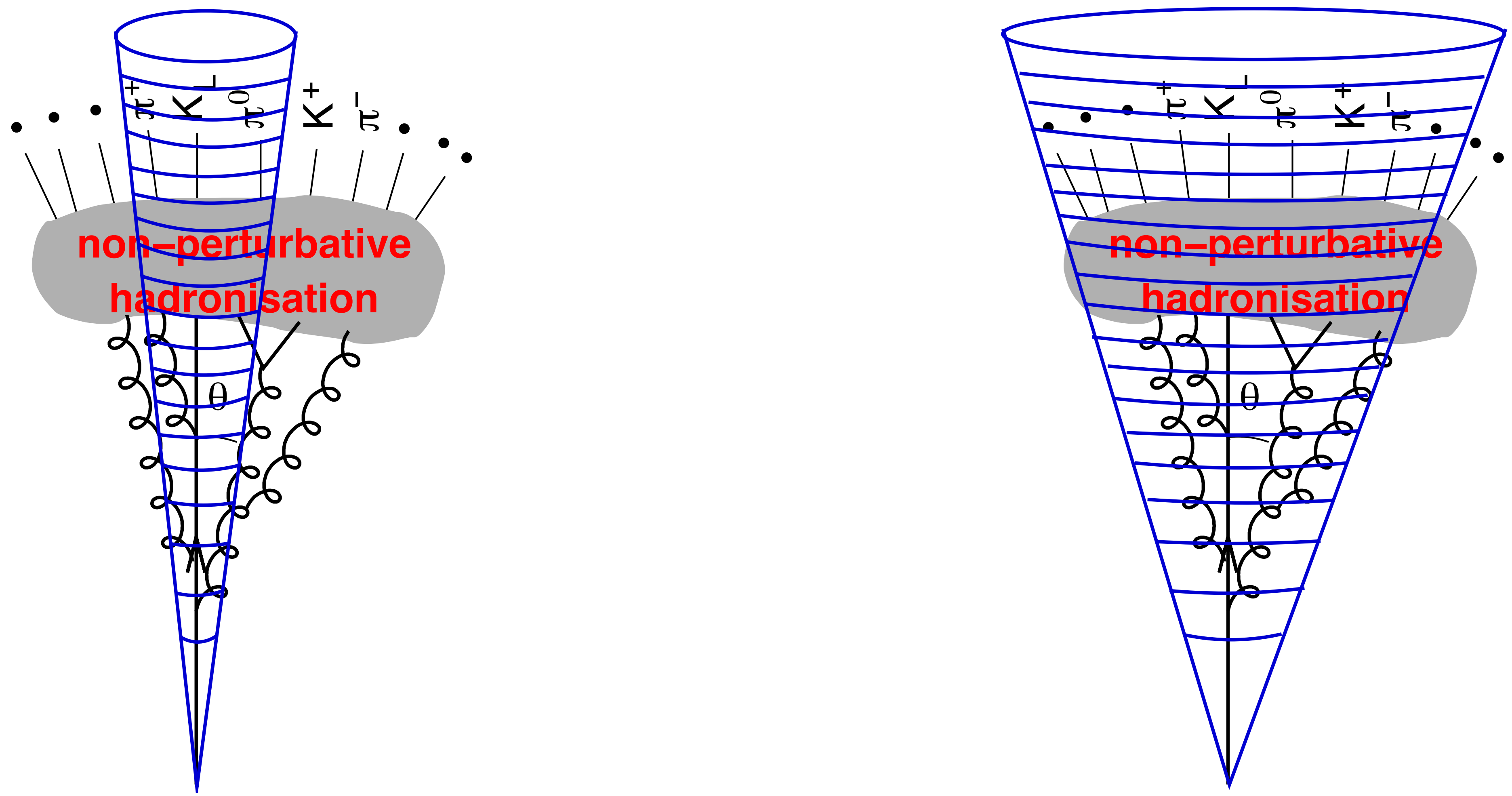
Large jet radius



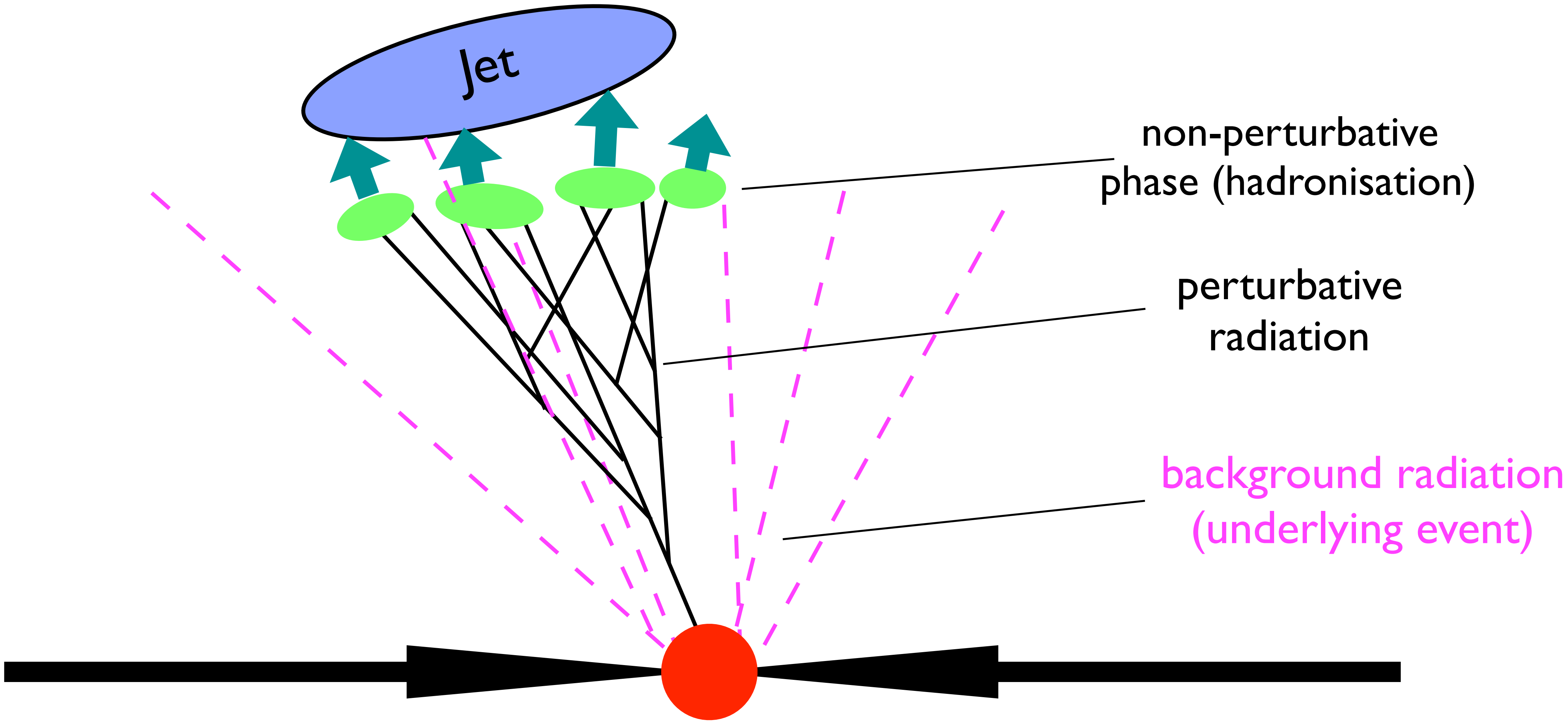
perturbative fragmentation: **large jet radius better**

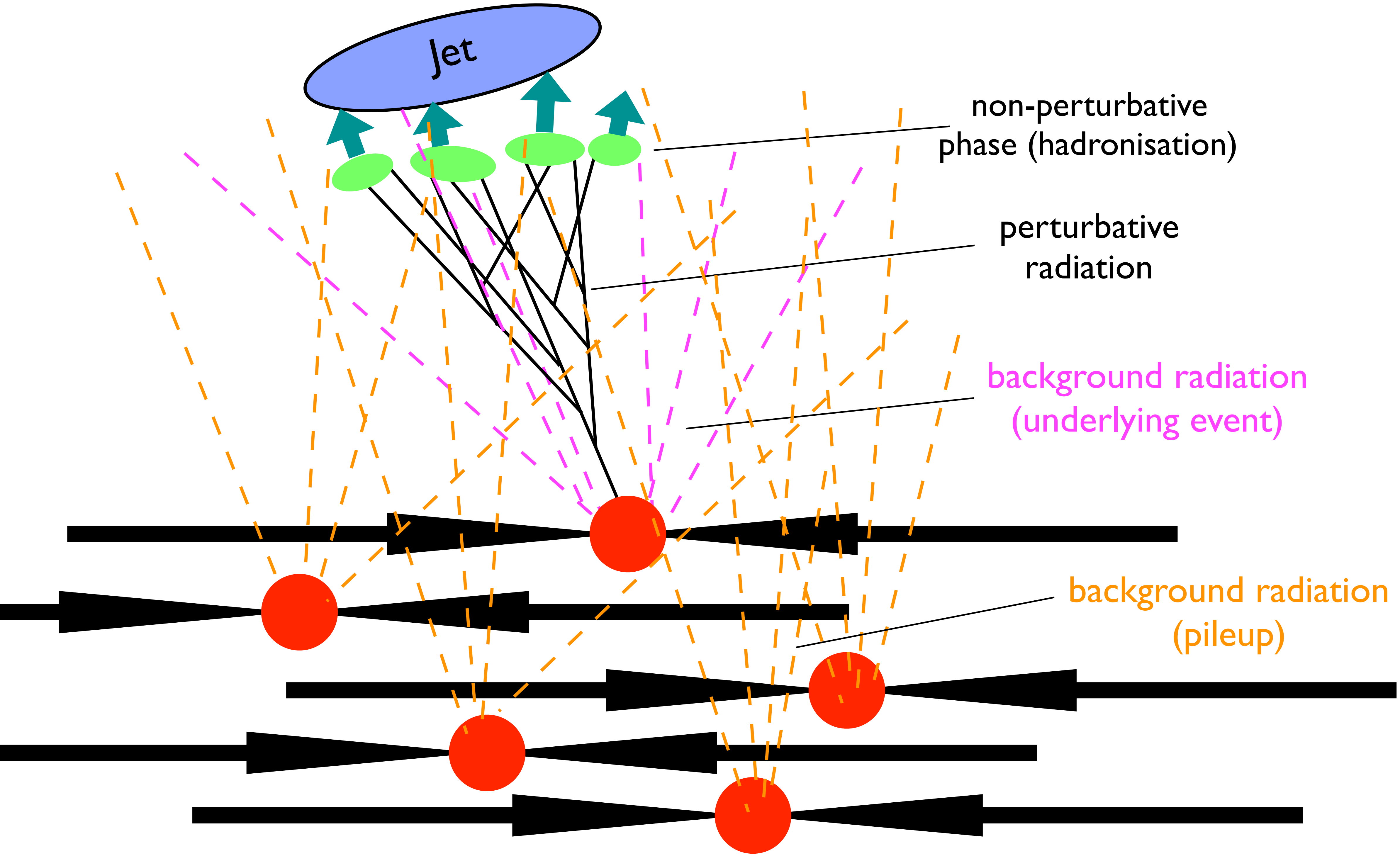
(it captures more)

Small jet radius **Large jet radius**

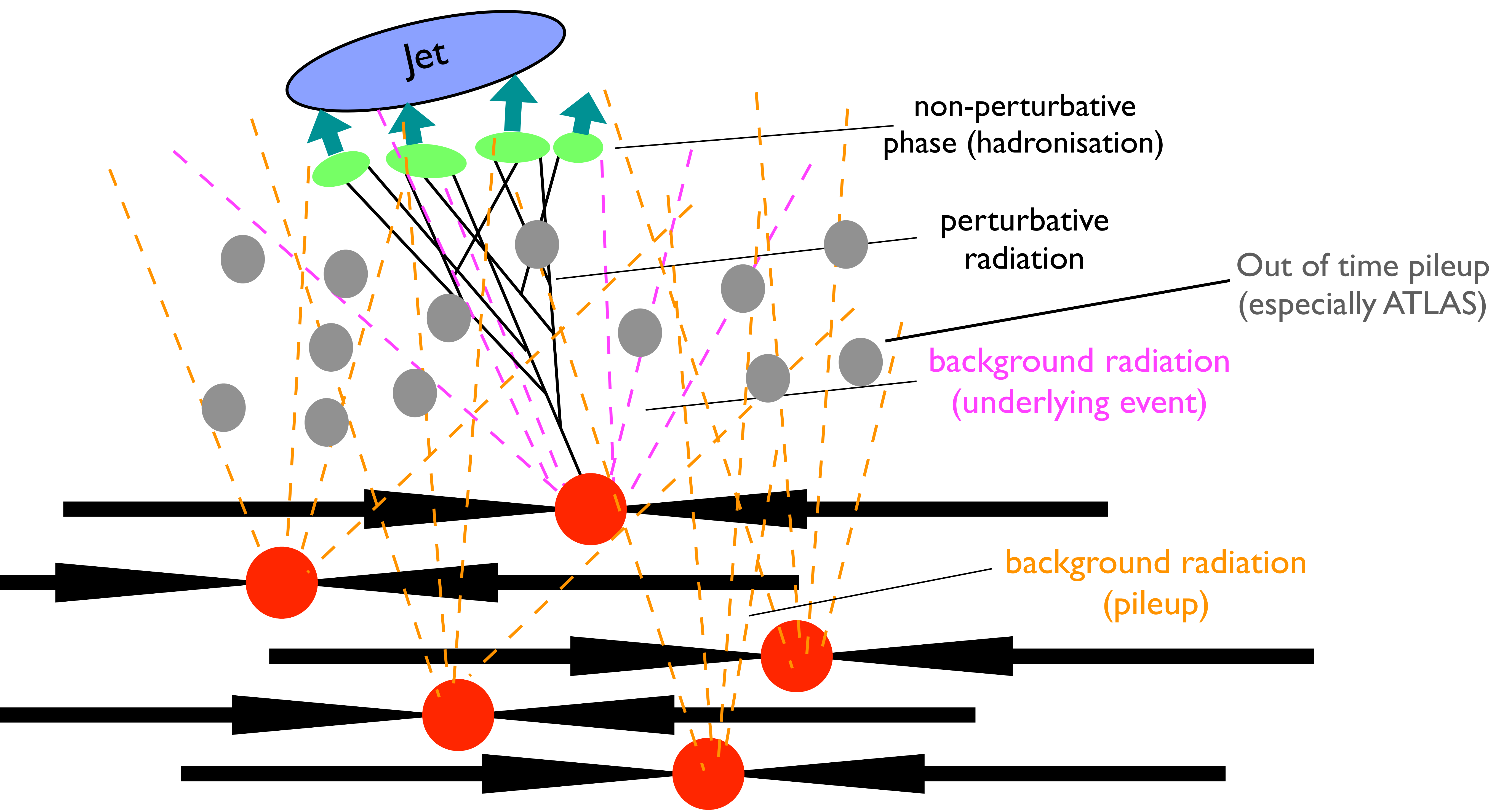


non-perturbative fragmentation: **large jet radius better**
(it captures more)


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


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

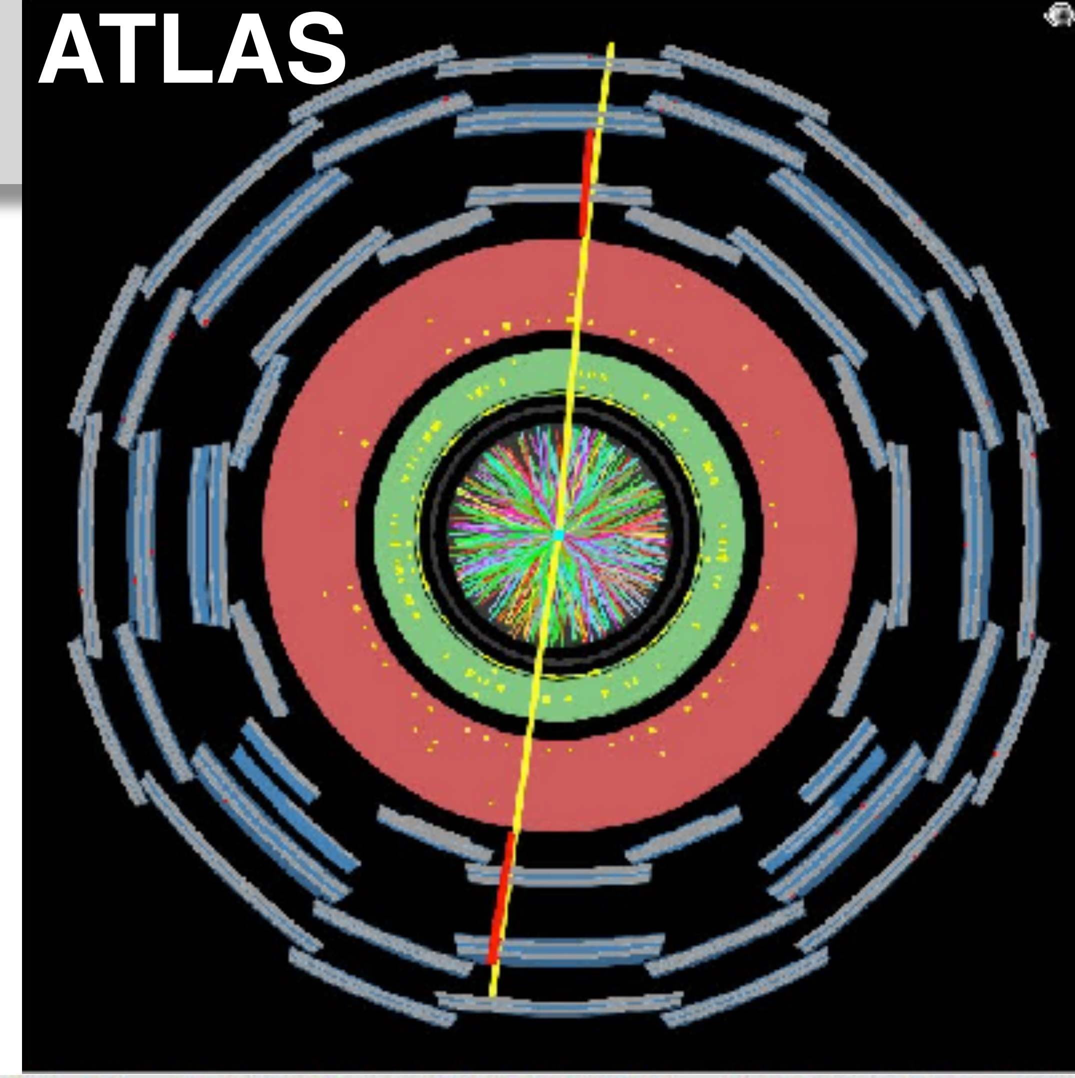
Pileup



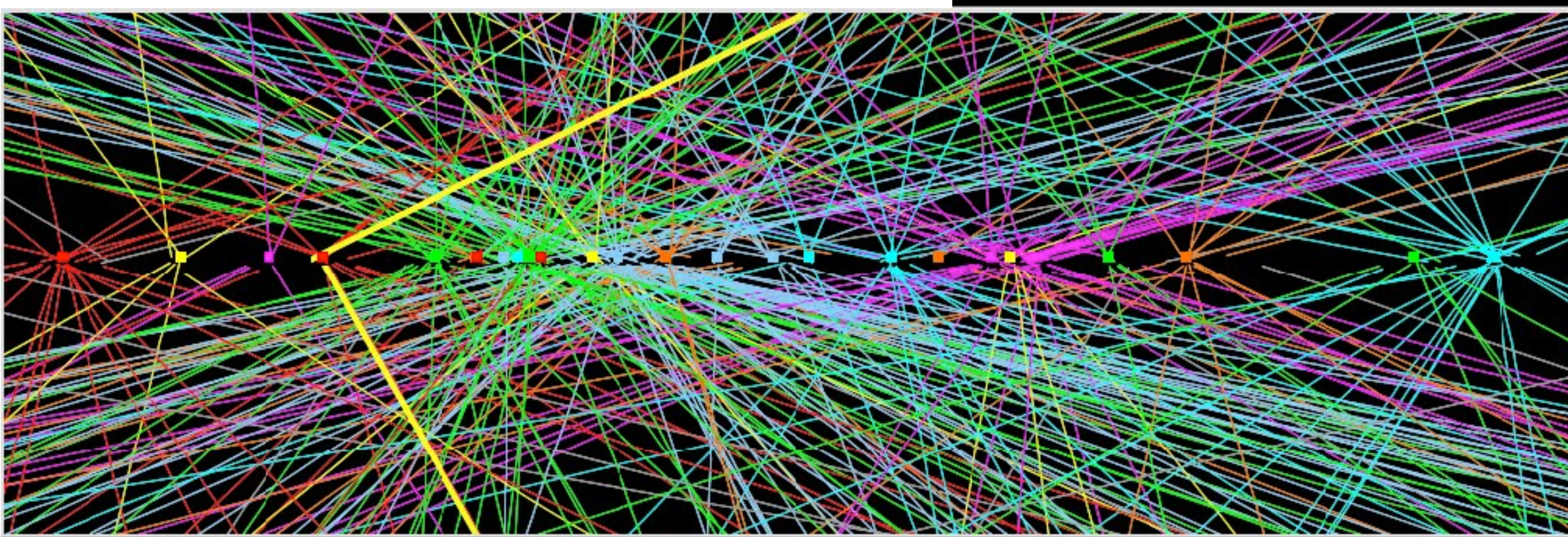
Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
Out of time pileup
(especially ATLAS)
background radiation
(underlying event)
background radiation
(pileup)

Pileup for real

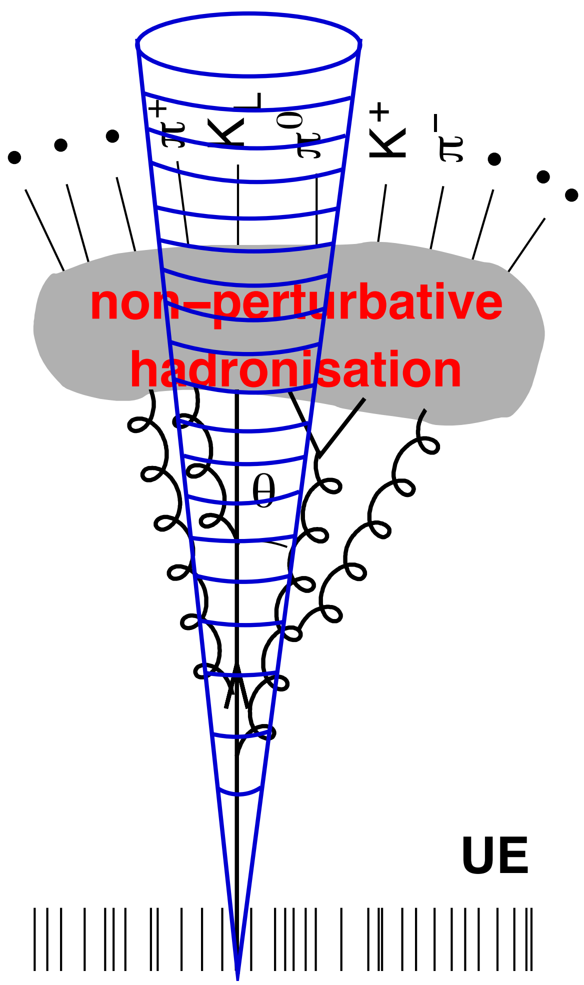
~ 20 m



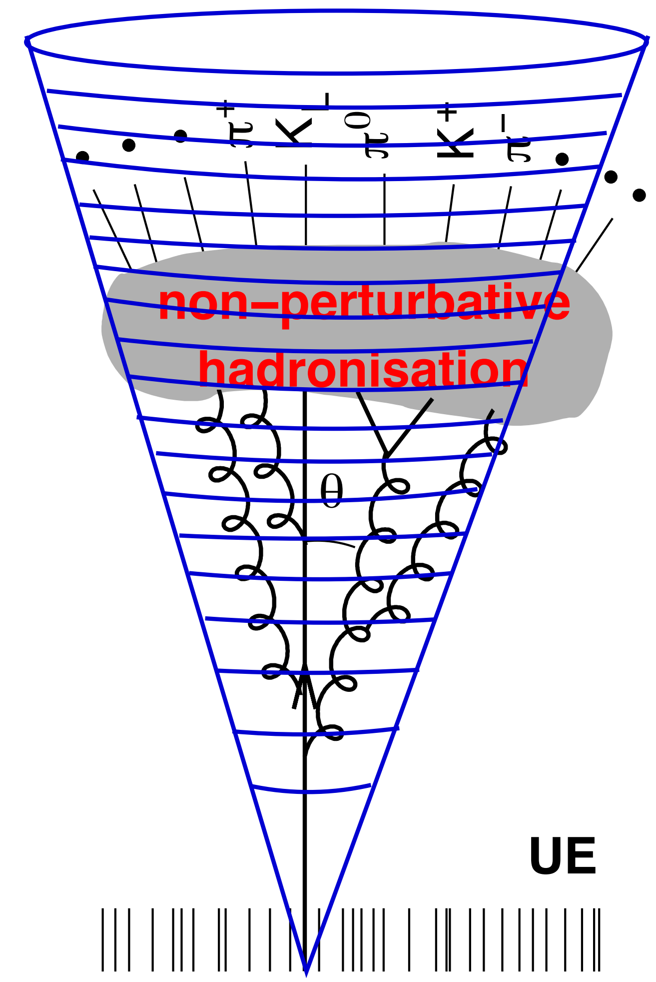
a few cm



Small jet radius



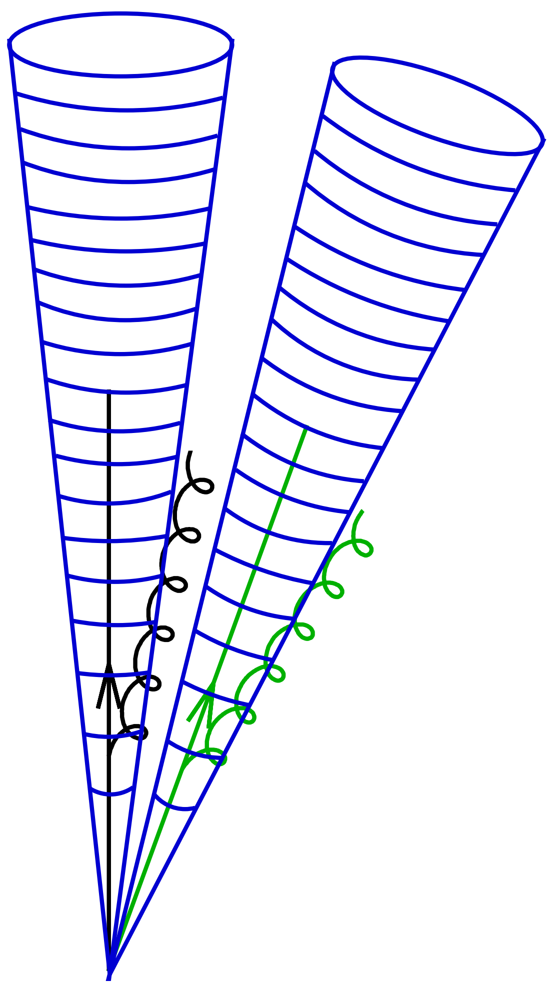
Large jet radius

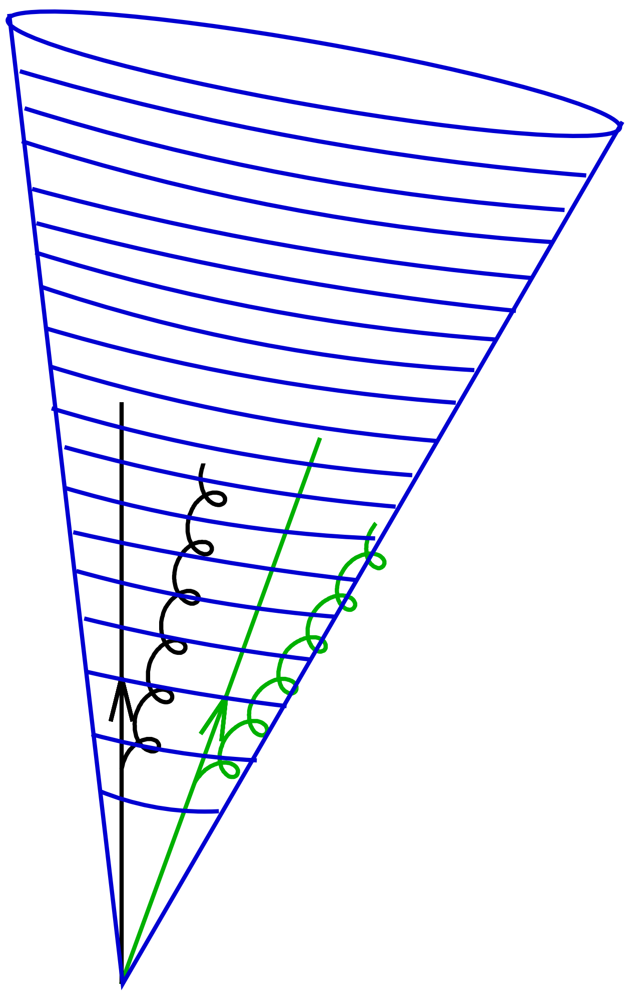


underlying ev. & pileup "noise": **small jet radius better**
(it captures less)

Small jet radius

Large jet radius





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

The question's dangerous: a "parton" is an ambiguous concept

Three limits can help you:

- Threshold limit — e.g. de Florian & Vogelsang '07
- Parton from color-neutral object decay (Z')
- Small-R (radius) limit for jet

One simple result (small-R limit)

$$\frac{\langle p_{t,jet} - p_{t,parton} \rangle}{p_t} = \frac{\alpha_s}{\pi} \ln R \times \begin{cases} 1.01\, C_F & \textit{quarks} \\ 0.94\, C_A + 0.07\, n_f & \textit{gluons} \end{cases} + \mathcal{O}(\alpha_s)$$

only $\mathcal{O}(\alpha_s)$ depends on algorithm & process

cf. Dasgupta, Magnea & GPS '07

Hadronisation: the "parton-shower" → hadrons transition

Method:

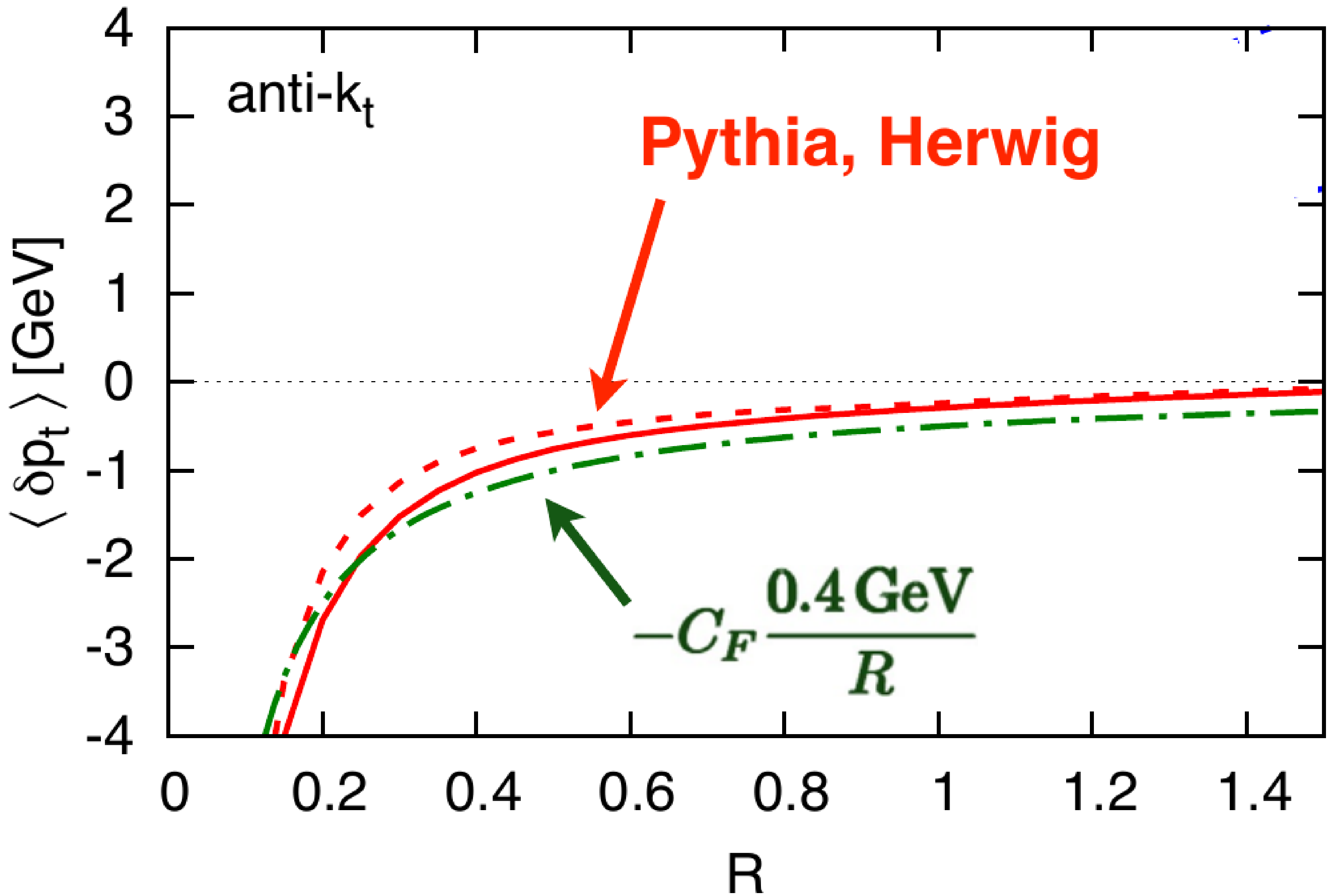
- "infrared finite α_s" / infrared renormalons — à la Dokshitzer & Webber '95, Korchemsky & Sterman '94, Seymour '97

Main result

$$\langle p_{t,jet} - p_{t,parton-shower} \rangle \simeq -\frac{0.4\text{ GeV}}{R} \times \begin{cases} C_F & \textit{quarks} \\ C_A & \textit{gluons} \end{cases}$$

cf. Dasgupta, Magnea & GPS '07

Change in jet p_t due to hadronisation



"Naive" prediction (UE $\simeq$ colour dipole between pp):

$$\Delta p_t \simeq 0.4 \text{ GeV} \times \frac{R^2}{2} \times \begin{cases} C_F & q\bar{q} \text{ dipole} \\ C_A & \text{gluon dipole} \end{cases}$$

Perugia 2011 Pythia tune:

$$\Delta p_t \simeq \mathbf{5-10\ GeV} \times \frac{R^2}{2}$$

This big coefficient motivates special effort to understand interplay between jet algorithm and UE: "jet areas"

How does coefficient depend on algorithm?

How does it depend on jet p_t? How does it fluctuate?

"Naive" prediction (UE $\simeq$ colour dipole between pp):

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How does coefficient depend on algorithm?

How does it depend on jet p_t? How does it fluctuate?

E.g. to reconstruct $m_X \sim (p_{tq} + p_{t\bar{q}})$

PT radiation:

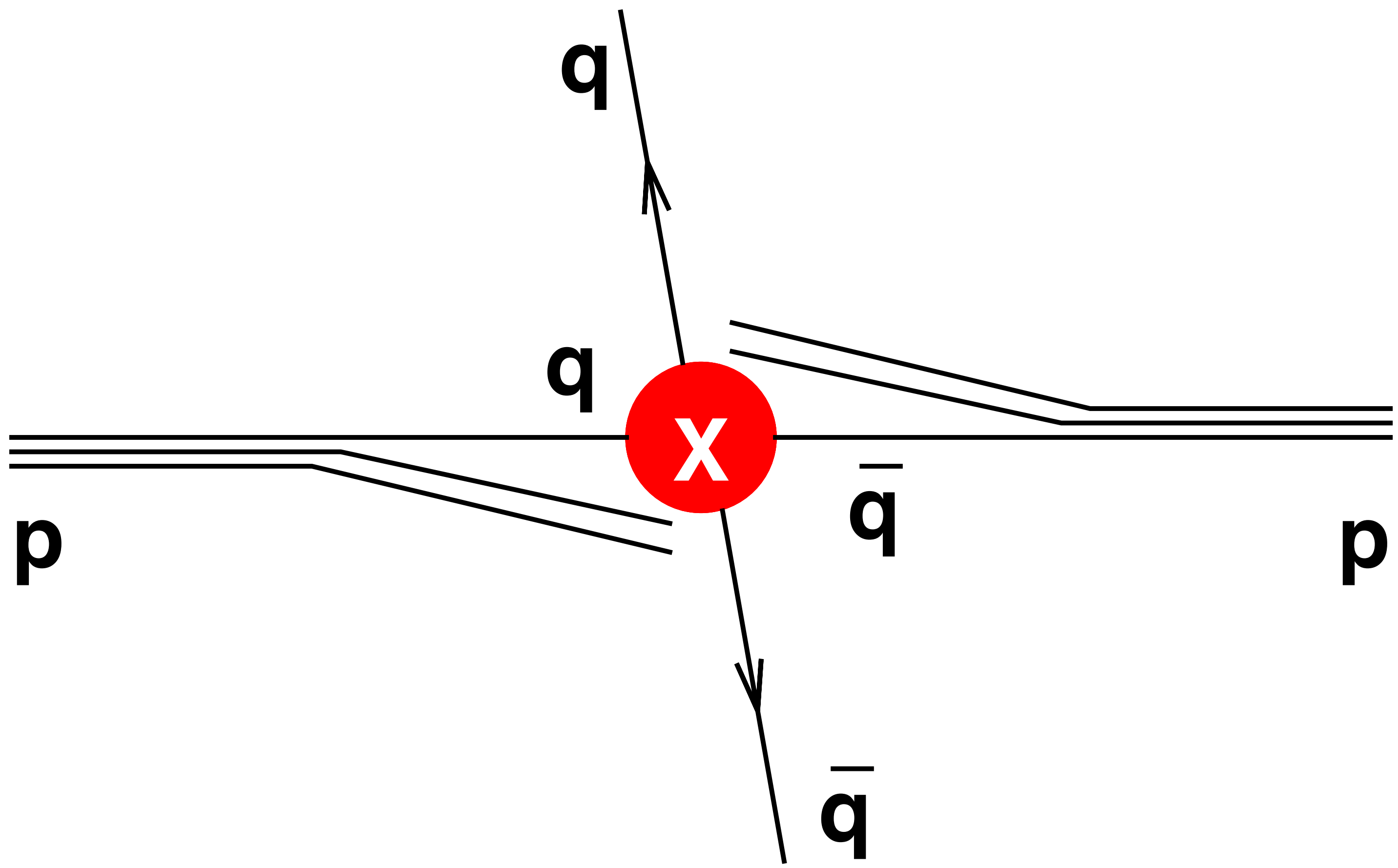
$$q: \quad \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

Hadronisation:

$$q: \quad \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4\ \text{GeV}$$

Underlying event:

$$q, g: \quad \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5\text{–}15\ \text{GeV}$$



Minimise fluctuations in p_t

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

PT radiation:

$$q: \quad \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

Hadronisation:

$$q: \quad \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4 \text{ GeV}$$

Underlying event:

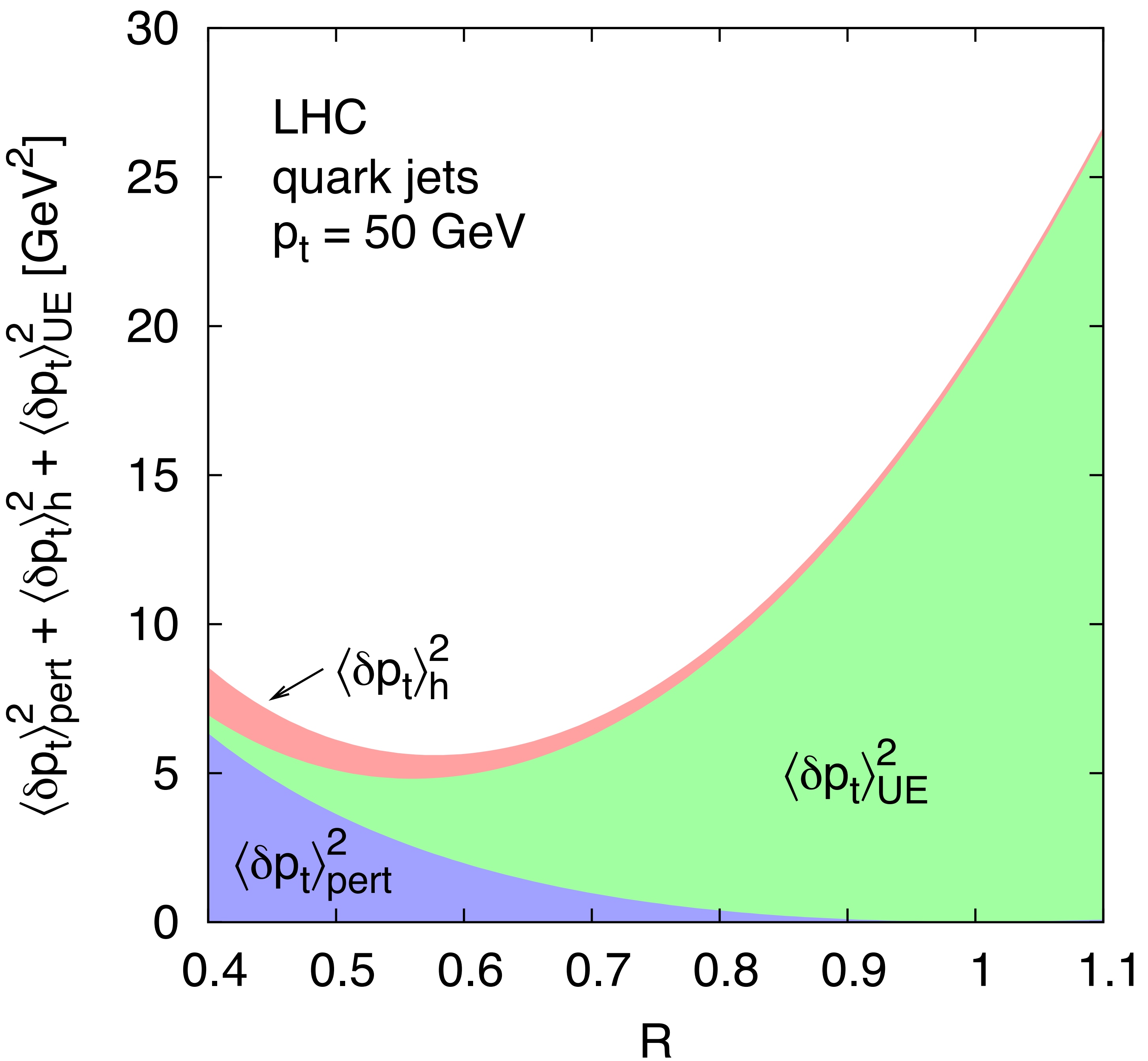
$$q, g: \quad \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5\text{–}15 \text{ GeV}$$

Minimise fluctuations in p_t

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

50 GeV quark jet



in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

PT radiation:

$$q: \quad \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

Hadronisation:

$$q: \quad \langle \Delta p_t \rangle \simeq -\frac{C_F}{R} \cdot 0.4 \text{ GeV}$$

Underlying event:

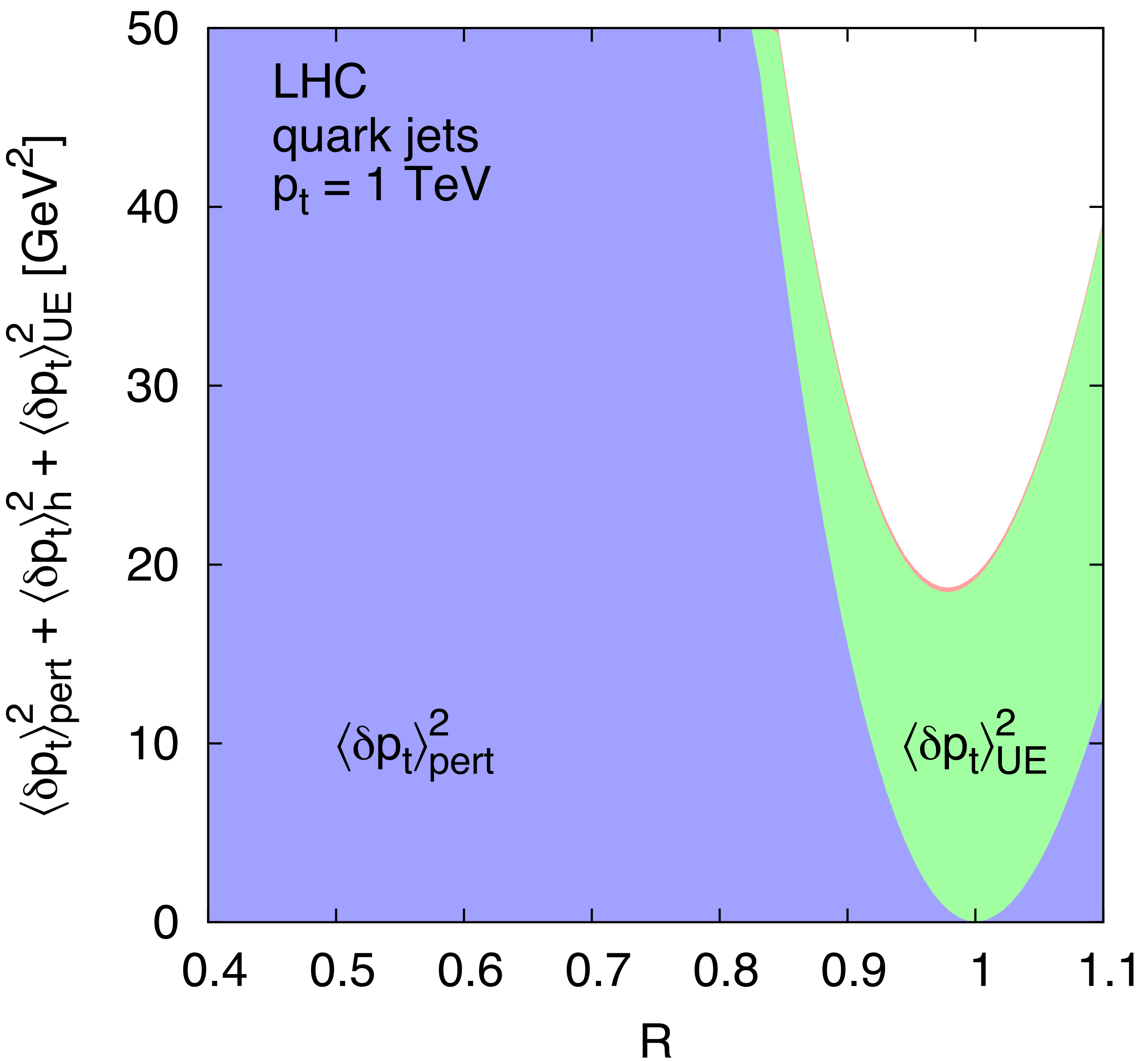
$$q, g: \quad \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5\text{–}15 \text{ GeV}$$

Minimise fluctuations in p_t

Use crude approximation:

$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

1 TeV quark jet



in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

What R is best for an isolated jet?

PT radiation:

$$q: \quad \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

Hadr

$q:$

Underlying event:

$$q, g: \quad \langle \Delta p_t \rangle \simeq \frac{R^2}{2} \cdot 2.5\text{–}15 \text{ GeV}$$

At low $\mathrm{p_t}$, small R limits relative impact of UE

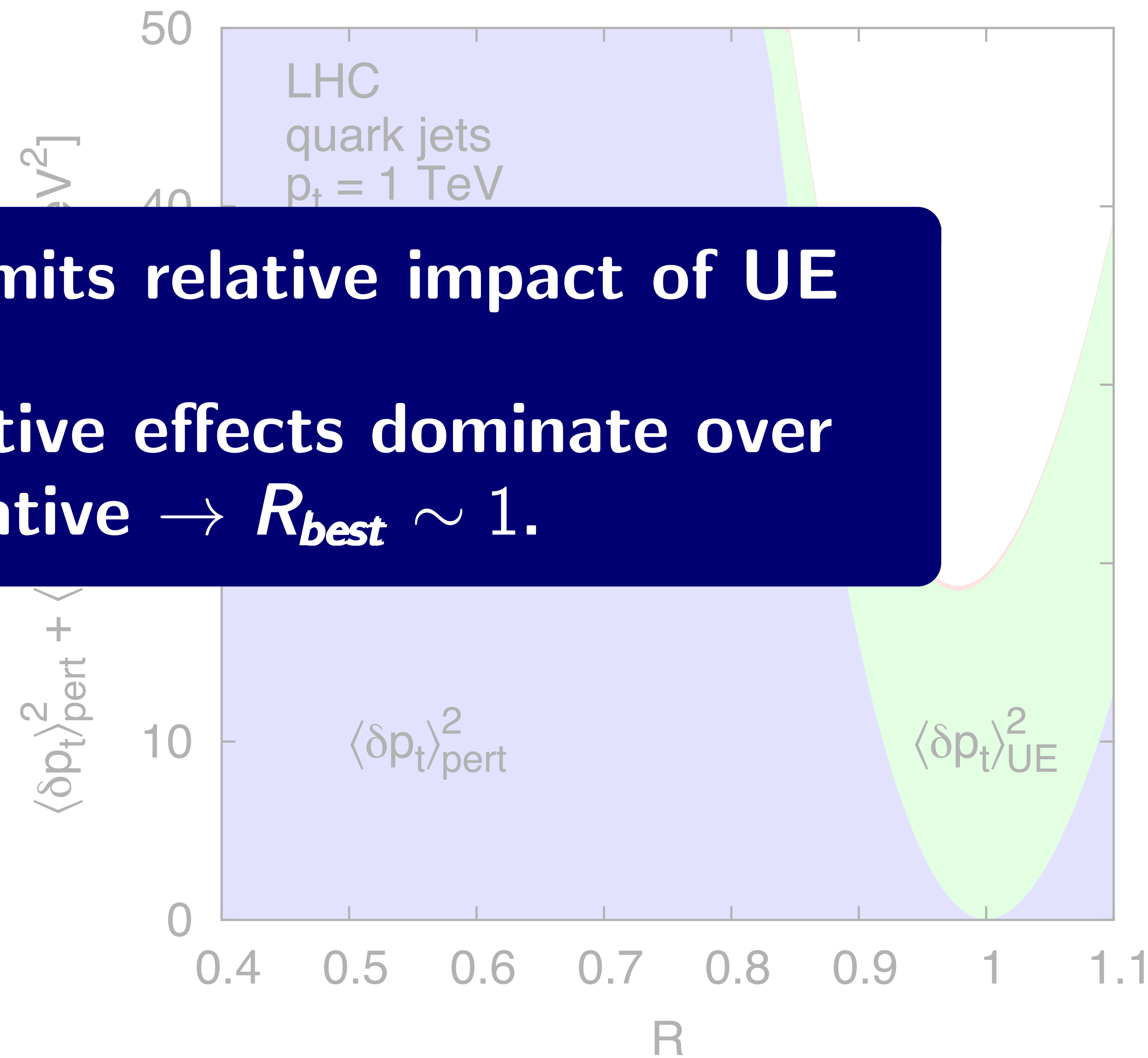
At high $\mathrm{p_t}$, perturbative effects dominate over non-perturbative $\to R_{best} \sim 1$.

Minimise fluctuations in p_t

Use crude approximation:

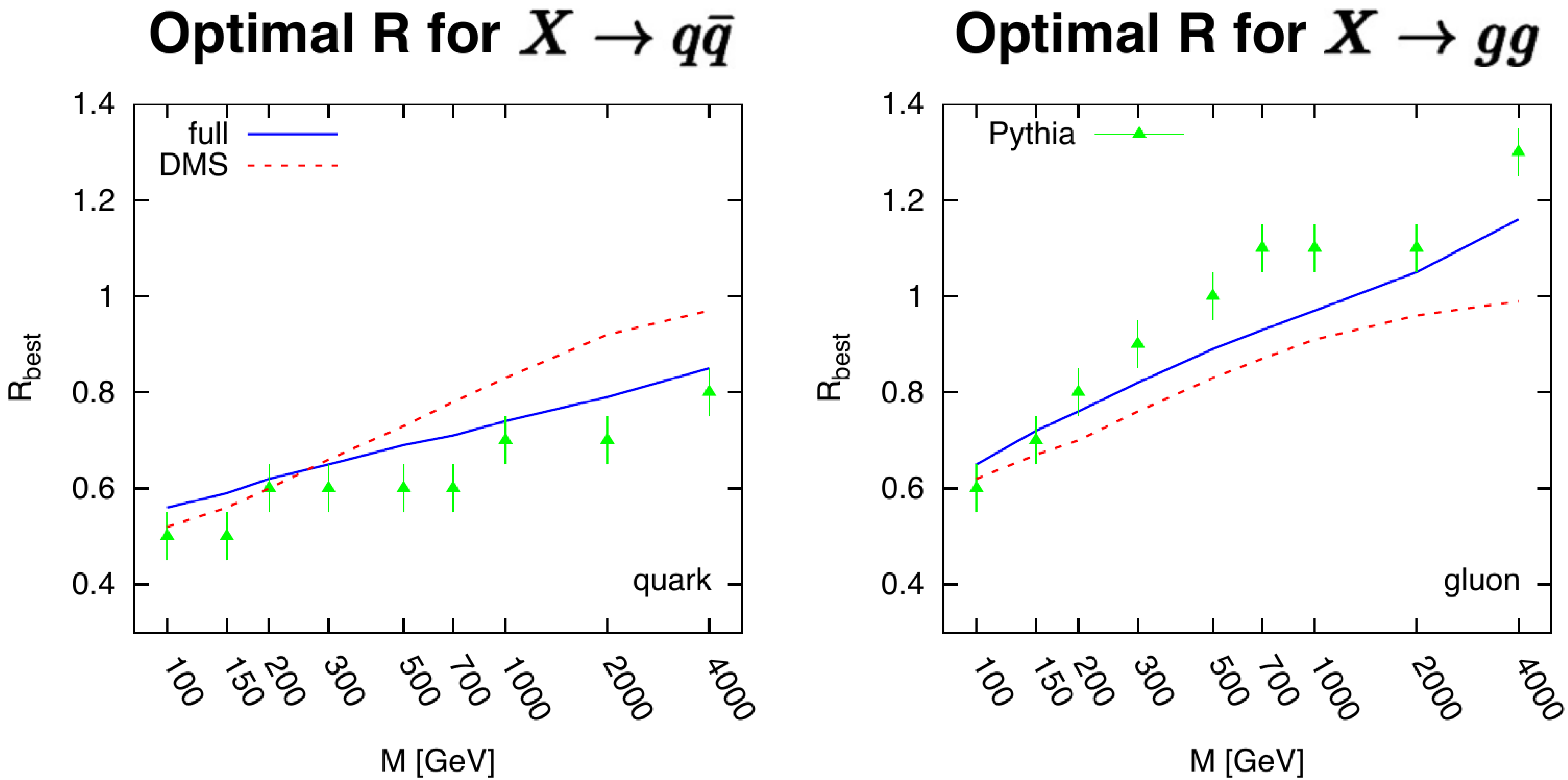
$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

1 TeV quark jet



in small-R limit (!)

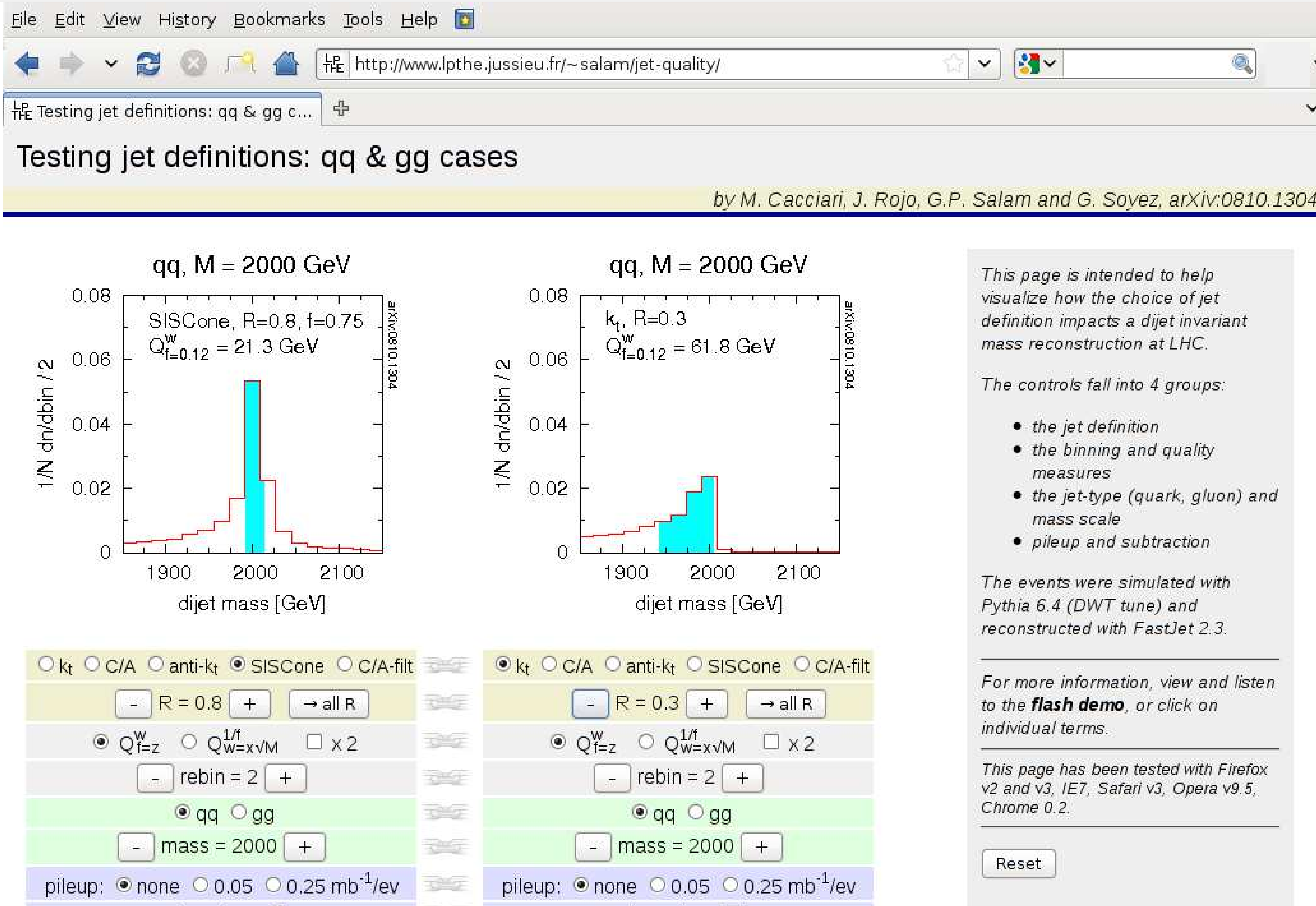
NB: full calc, correct fluct: Soyez '10



Optimal R for $X \to q\bar{q}$
Optimal R for $X \to gg$
full
DMS
Pythia
quark
gluon
R_{best}
M [GeV]
1.4
1.2
1
0.8
0.6
0.4
100
150
200
300
500
700
1000
2000
4000

Soyez '10

http://quality.fastjet.fr/



2.5 Wide jet reconstruction and event selection

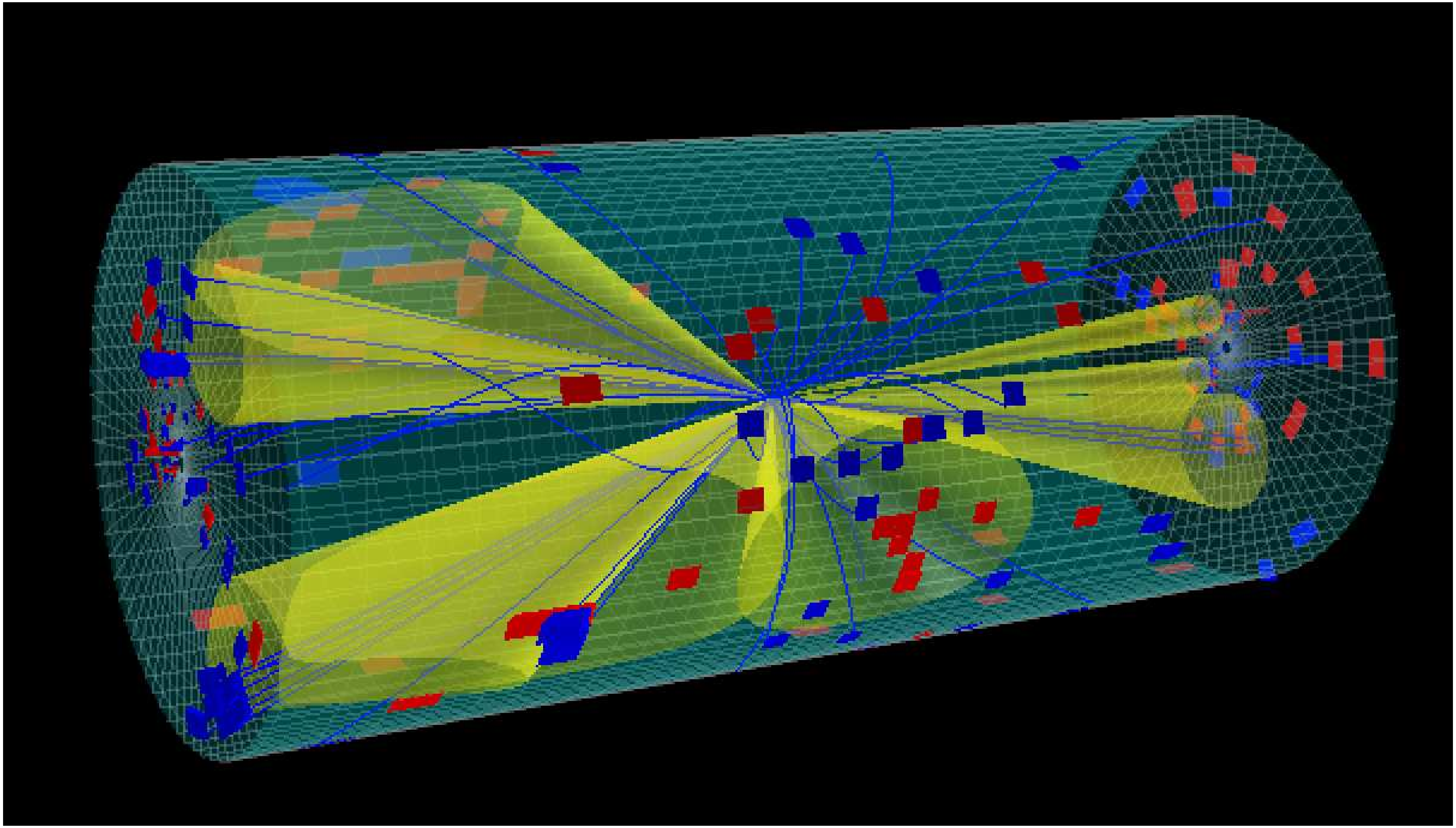
Spatially close jets are combined into "wide jets" and used to determine the dijet mass, as in the previous CMS searches [5, 6, 8, 9, 11, 12, 15]. The wide-jet algorithm, designed for dijet resonance event reconstruction, reduces the analysis sensitivity to gluon radiation from the final-state partons. The two leading jets are used as seeds and the four-vectors of all other jets, if within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$, are added to the nearest leading jet to obtain two wide jets, which then form the dijet system. The dijet mass is the magnitude of the momentum-energy 4-vector of the dijet system, which is the invariant mass of the two wide jets. The

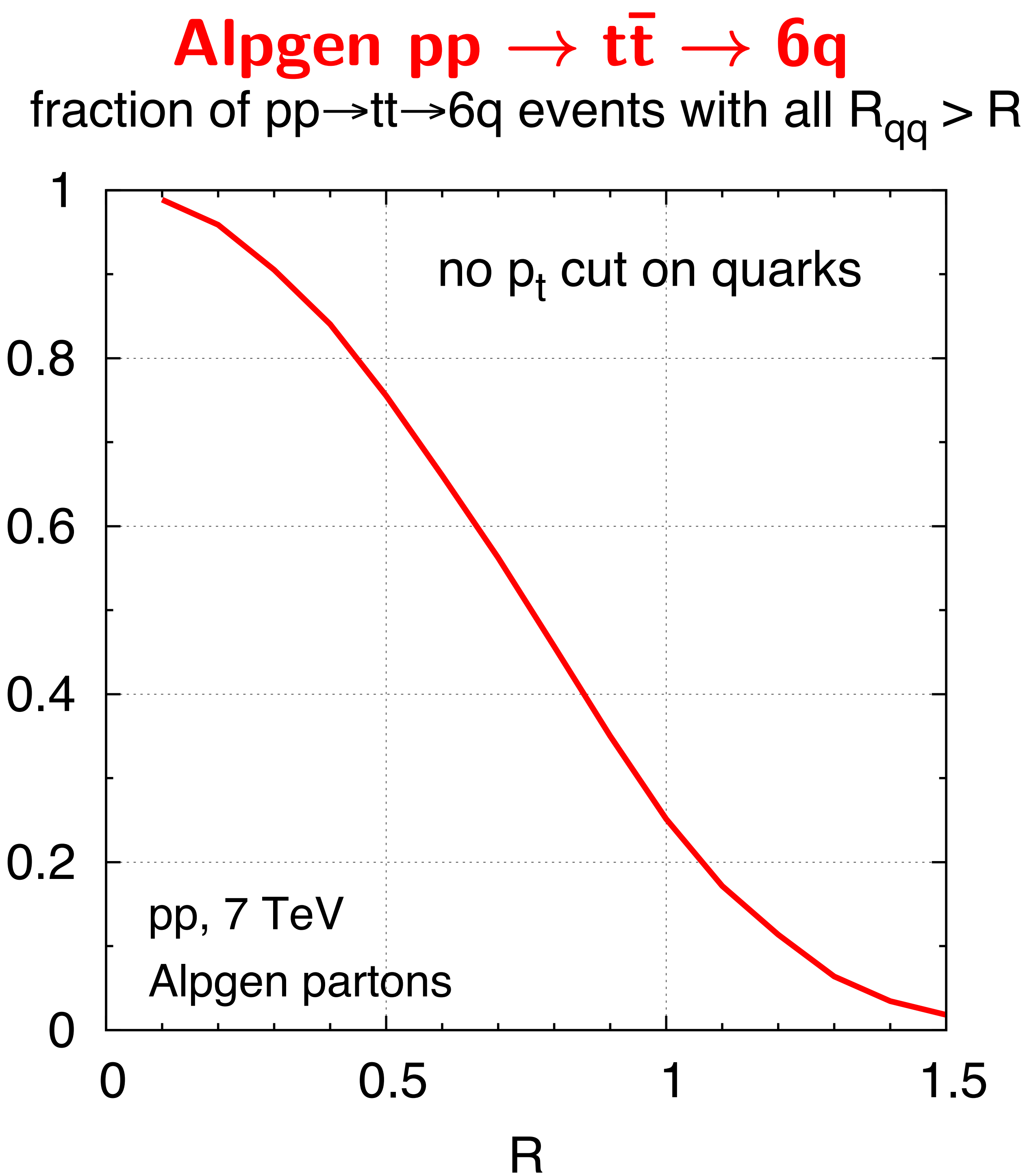
CMS, Search for narrow and broad dijet resonances
1806.00843

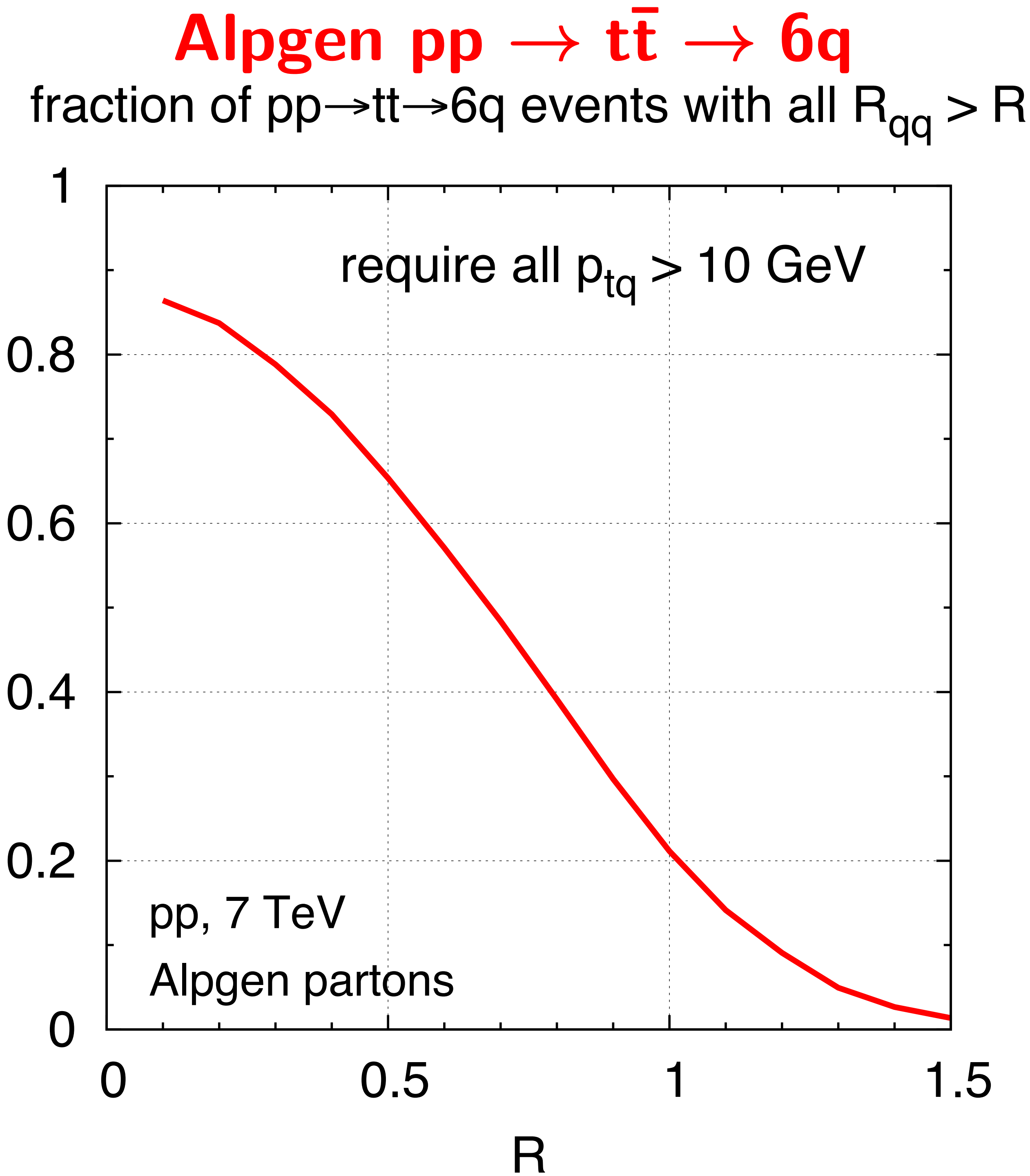
Jet radius and p_t cut choice in more complex events

$pp \to t\bar{t}$

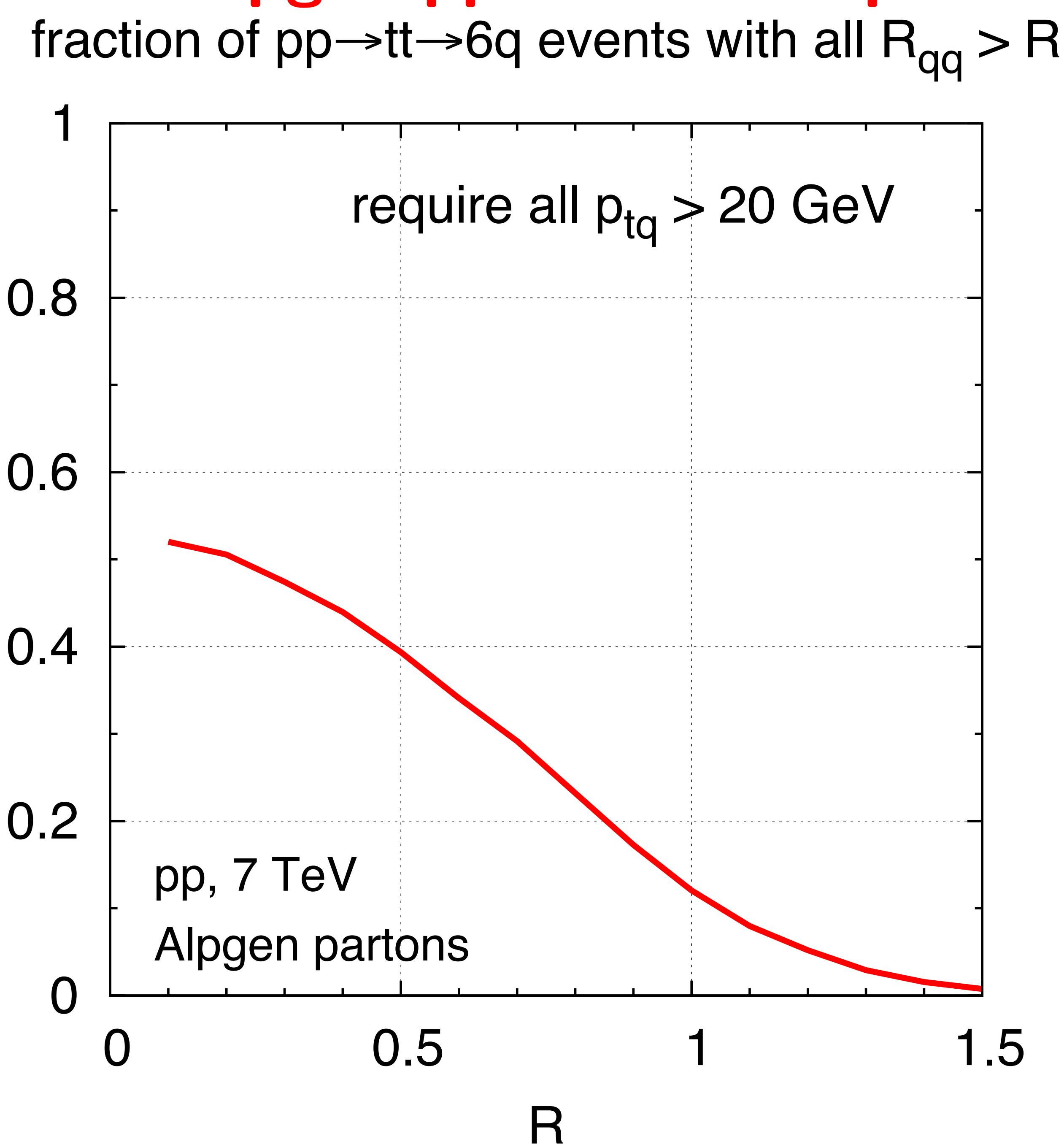
simulated with Pythia, displayed with Delphes

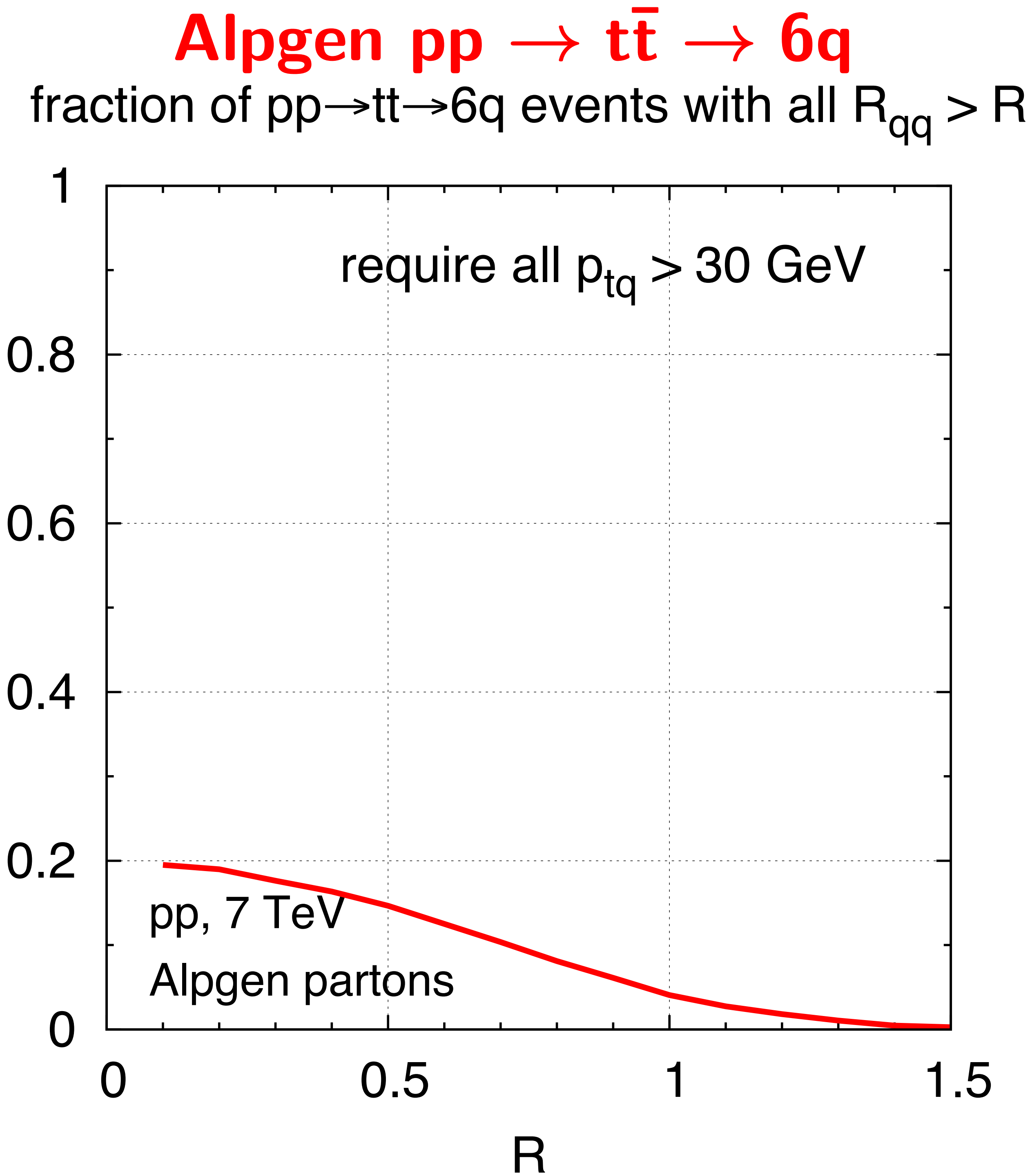



Alpgen pp → tt̄ → 6q
fraction of pp→tt→6q events with all R_qq > R
no p_t cut on quarks
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R


Alpgen pp → $t\bar{t}$ → 6q
fraction of pp→tt→6q events with all R_{qq} > R
require all p_{tq} > 10 GeV
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

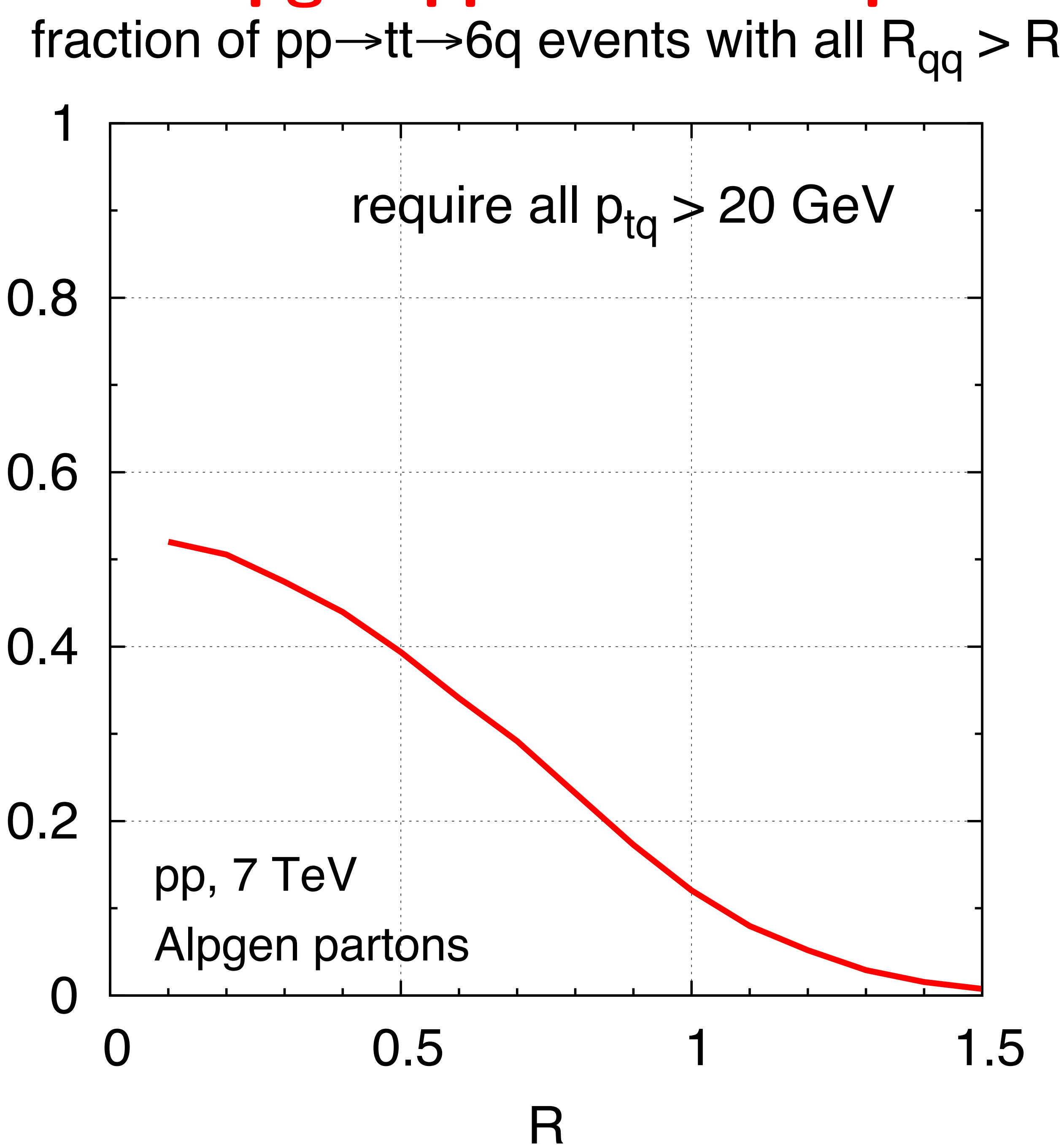
Alpgen $pp \to t\bar{t} \to 6q$





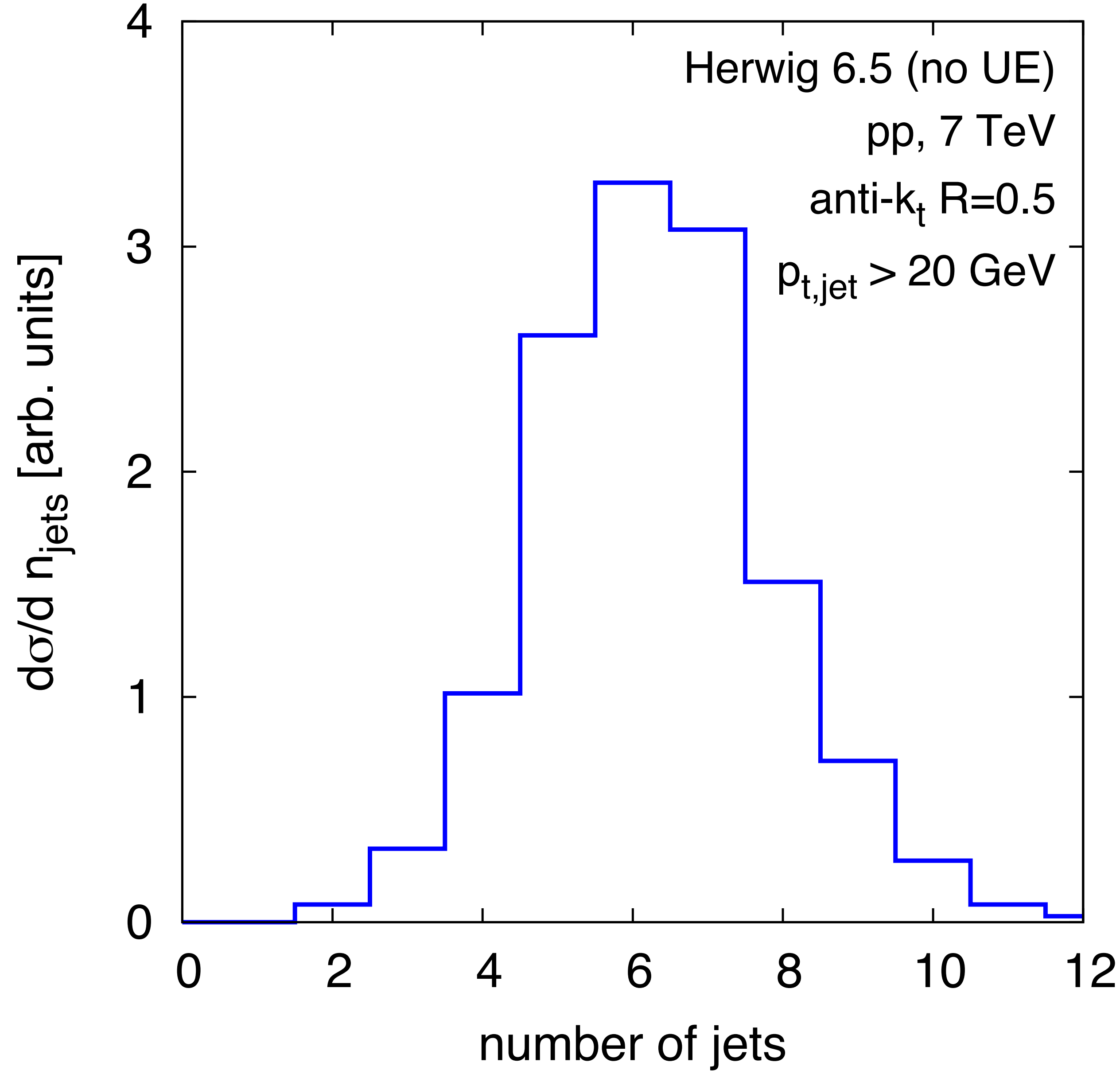
Alpgen pp $\rightarrow t\bar{t} \rightarrow$ 6q
fraction of pp→tt→6q events with all R_{qq} > R
require all p_{tq} > 30 GeV
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

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

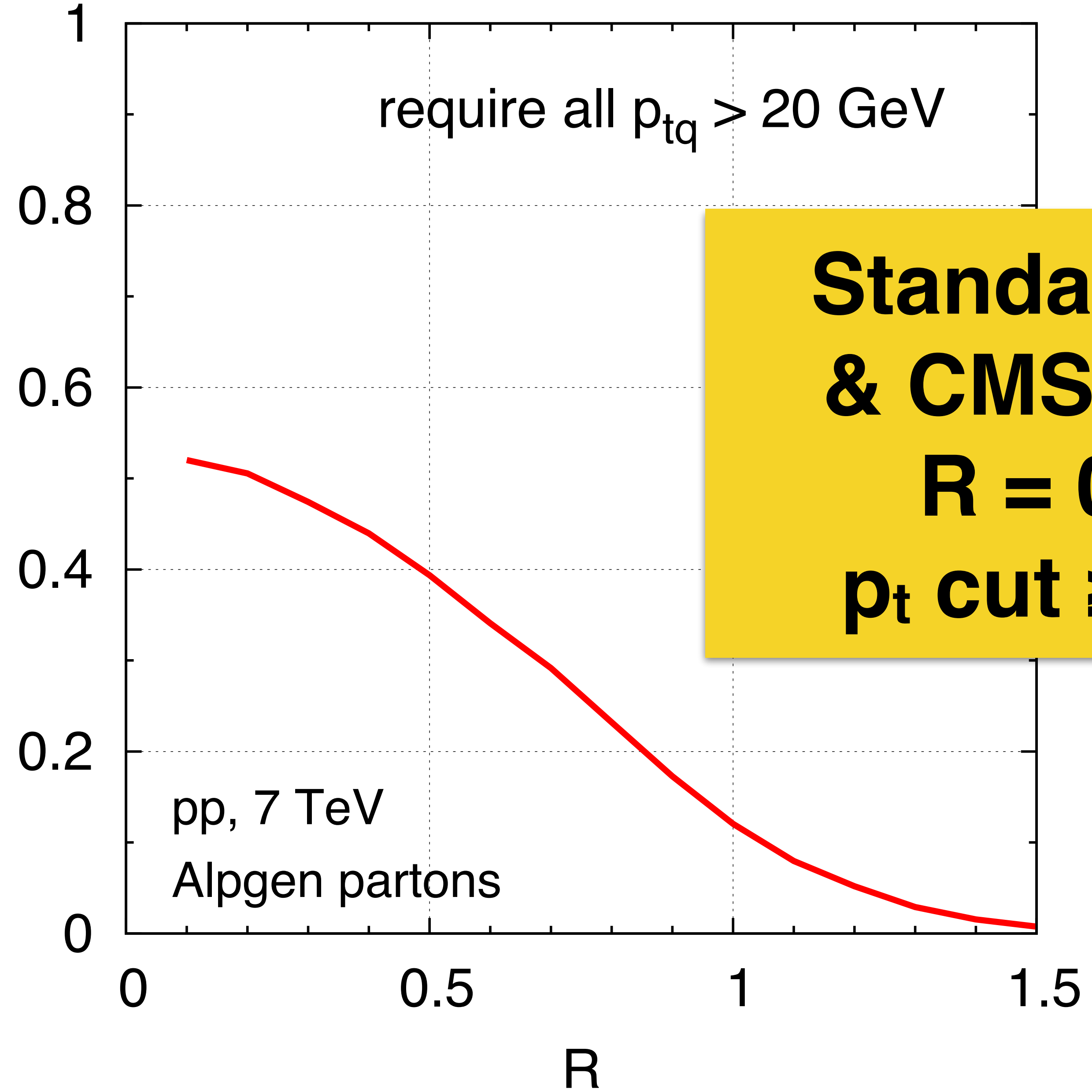


Herwig pp $\to t\bar{t} \to$ hadrons

Distribution of number of jets

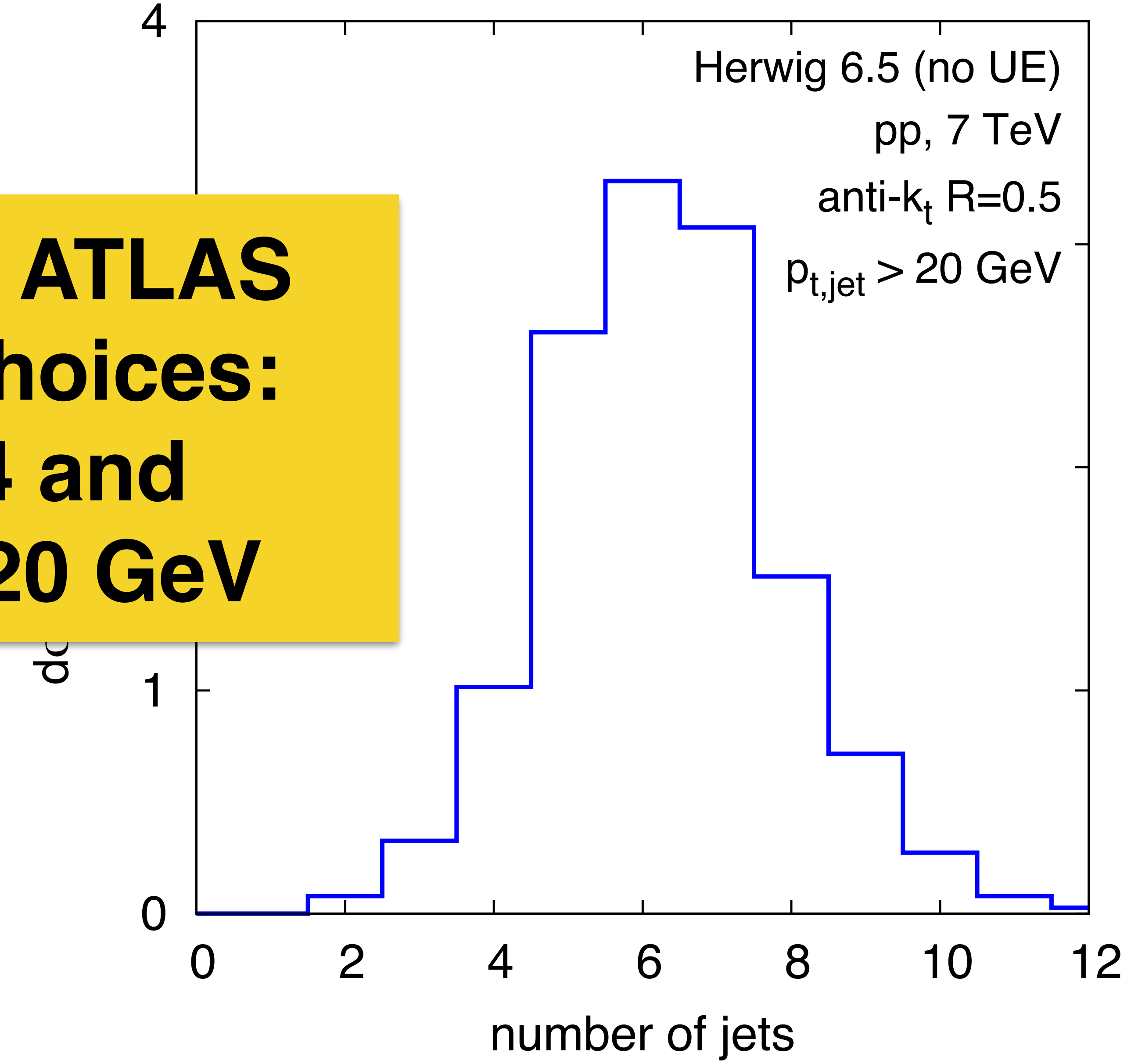


Alpgen pp $\to t\bar{t} \to$ 6q



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

Distribution of number of jets



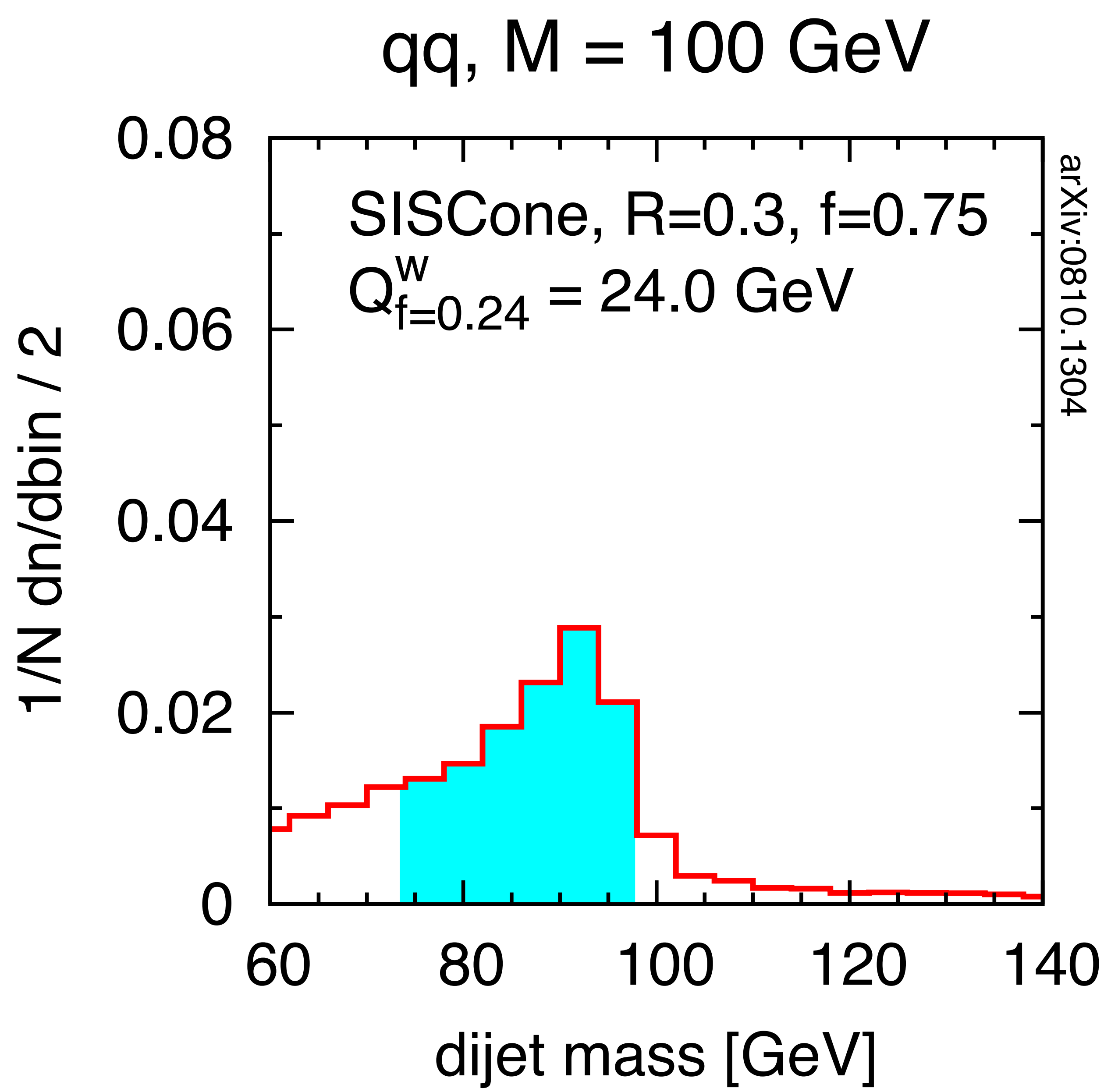
Standard ATLAS & CMS choices: R = 0.4 and p_t cut ≥ 20 GeV

messages from lecture 1

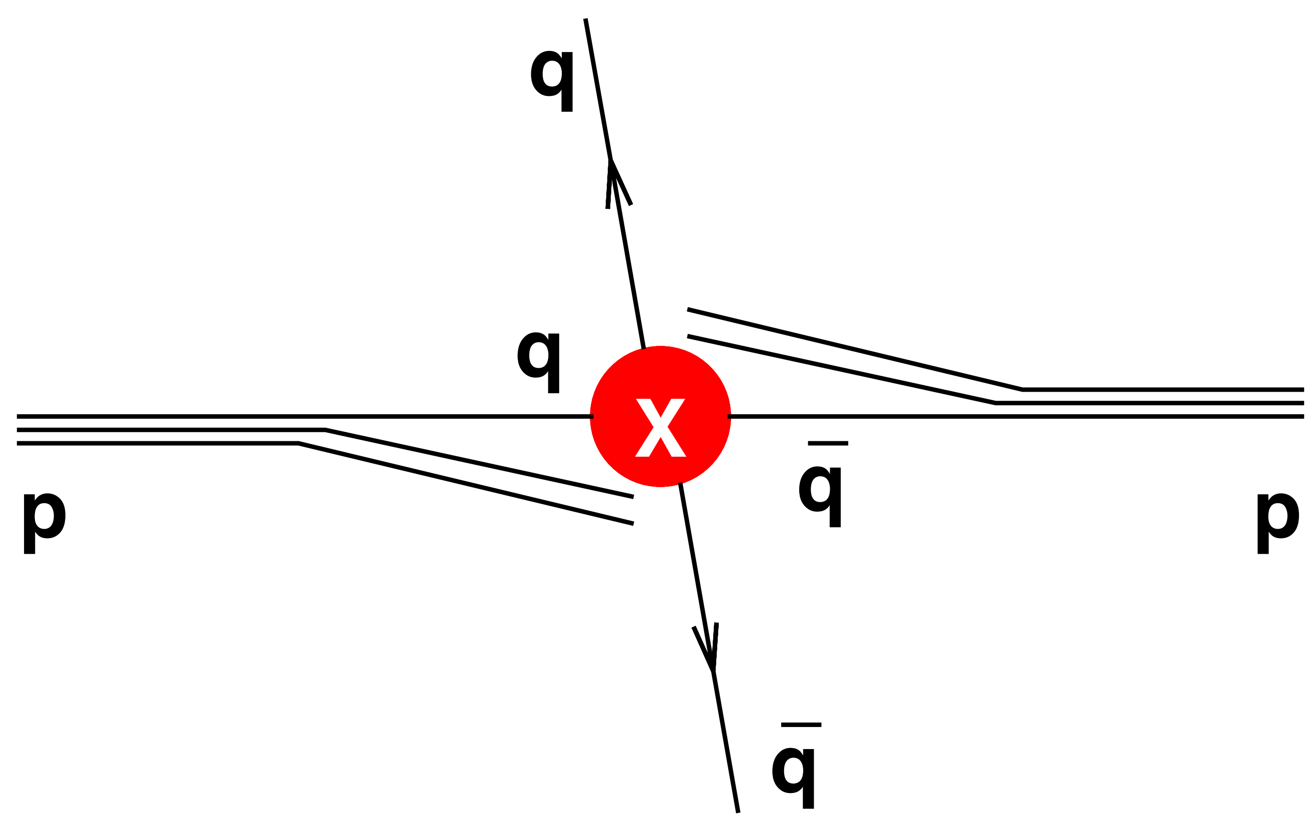
- jets come about because of soft-collinear fragmentation & hadronisation
- today's jet reconstruction algorithms are (almost always) sequential recombination algorithms
- when using jets, think about the underlying scattering processes in signal and background (e.g. s- v. t-channel)
- be aware of how jet radius and p_t cuts may have been optimised for specific processes

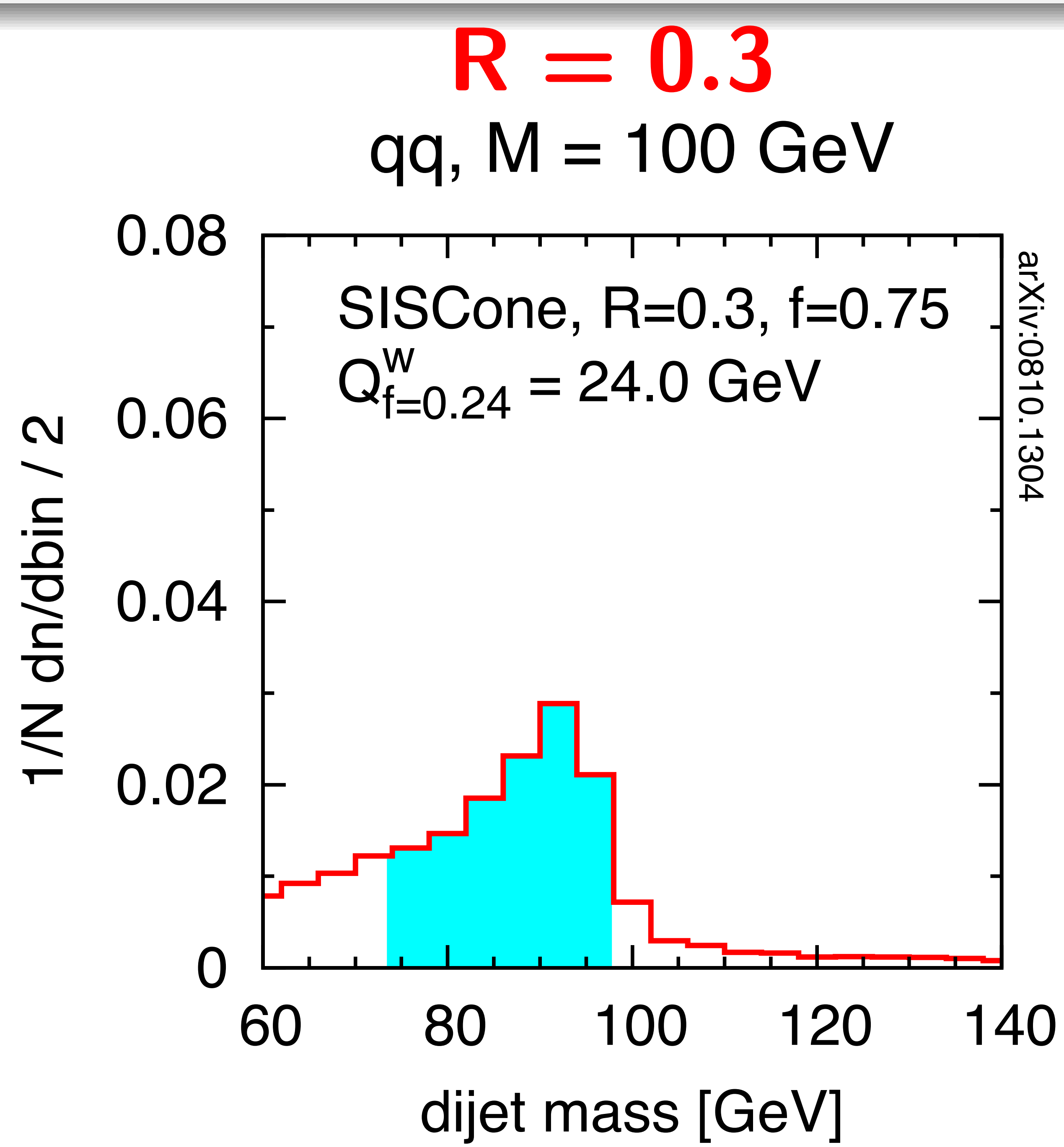
EXTRA SLIDES

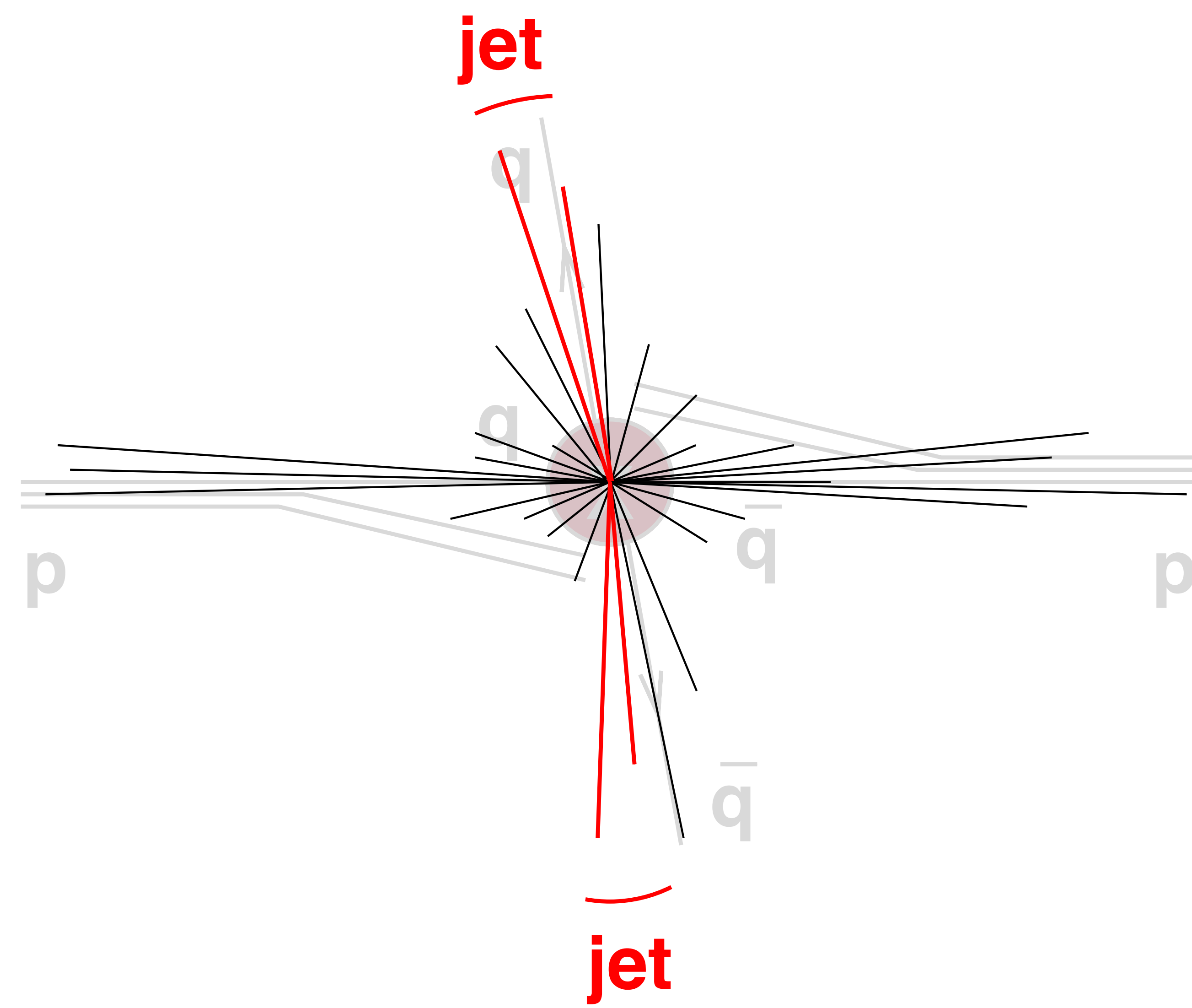
$R = 0.3$



Resonance X → dijets

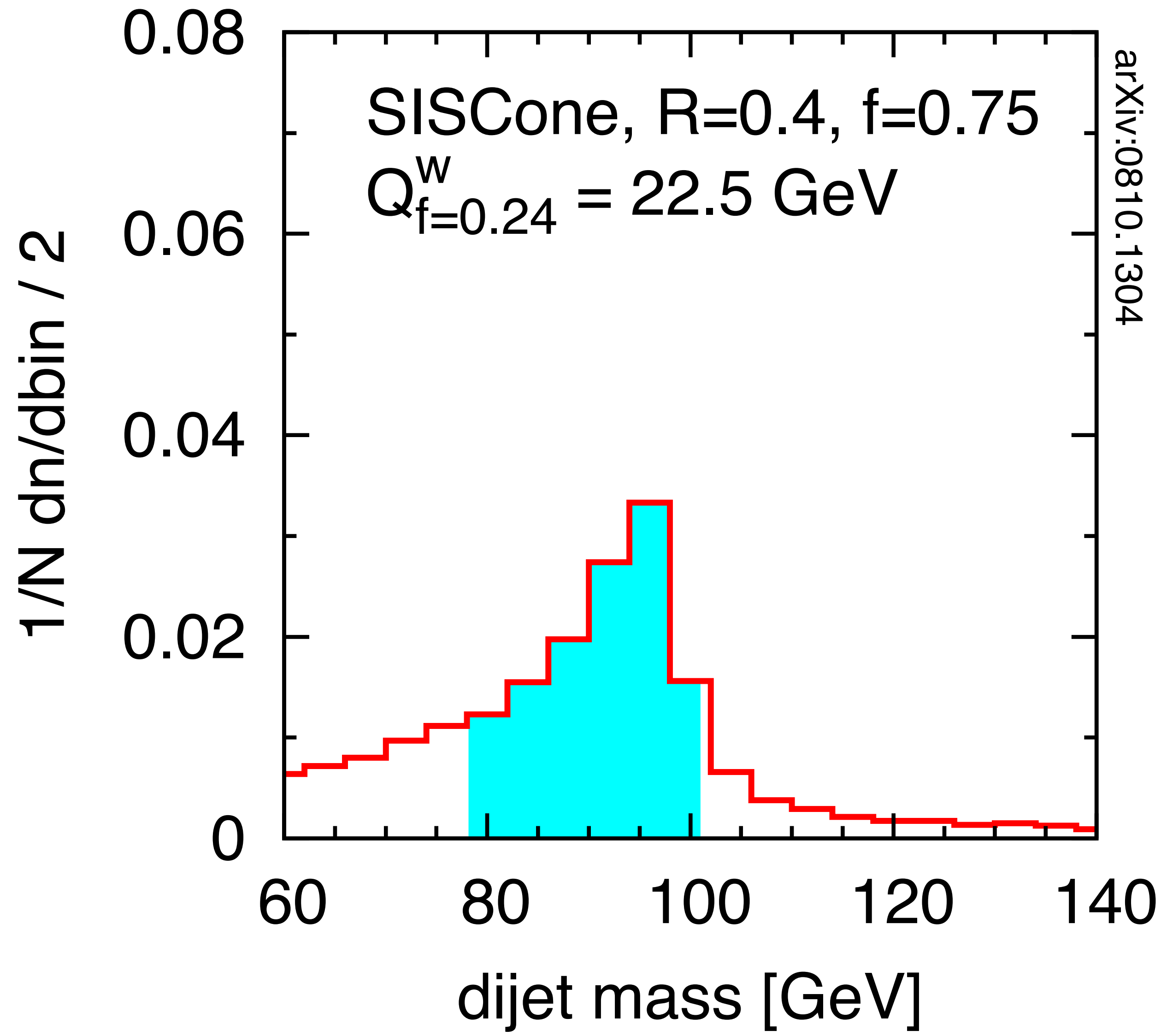



R = 0.3
qq, M = 100 GeV
SISCone, R=0.3, f=0.75
$Q^{w}_{f=0.24}$ = 24.0 GeV
arXiv:0810.1304
1/N dn/dbin / 2
0.08
0.06
0.04
0.02
0
60
80
100
120
140
dijet mass [GeV]

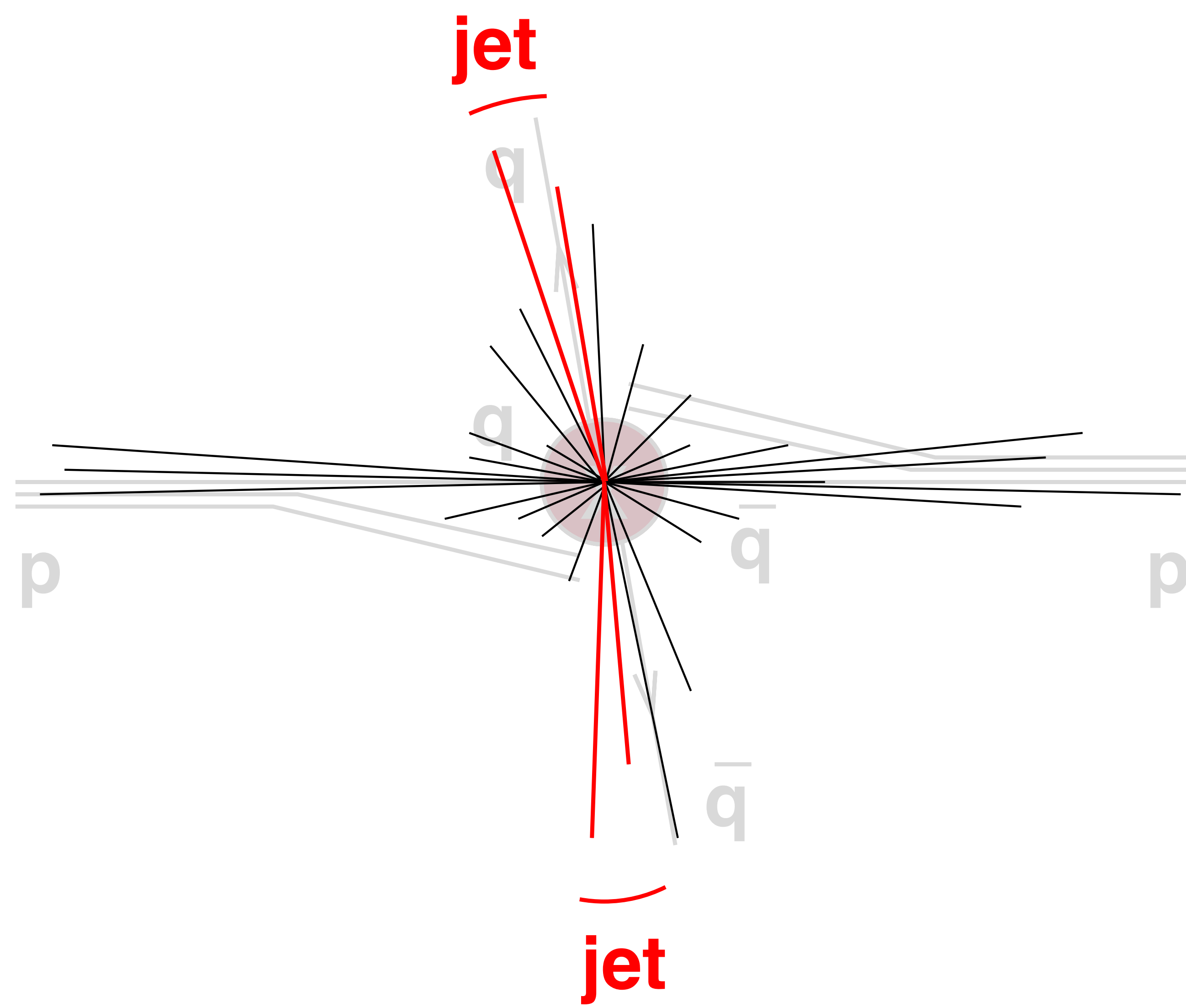

Resonance X → dijets
jet
q
q
p
$\bar{q}$
$\bar{q}$
p
jet

R = 0.4

qq, M = 100 GeV

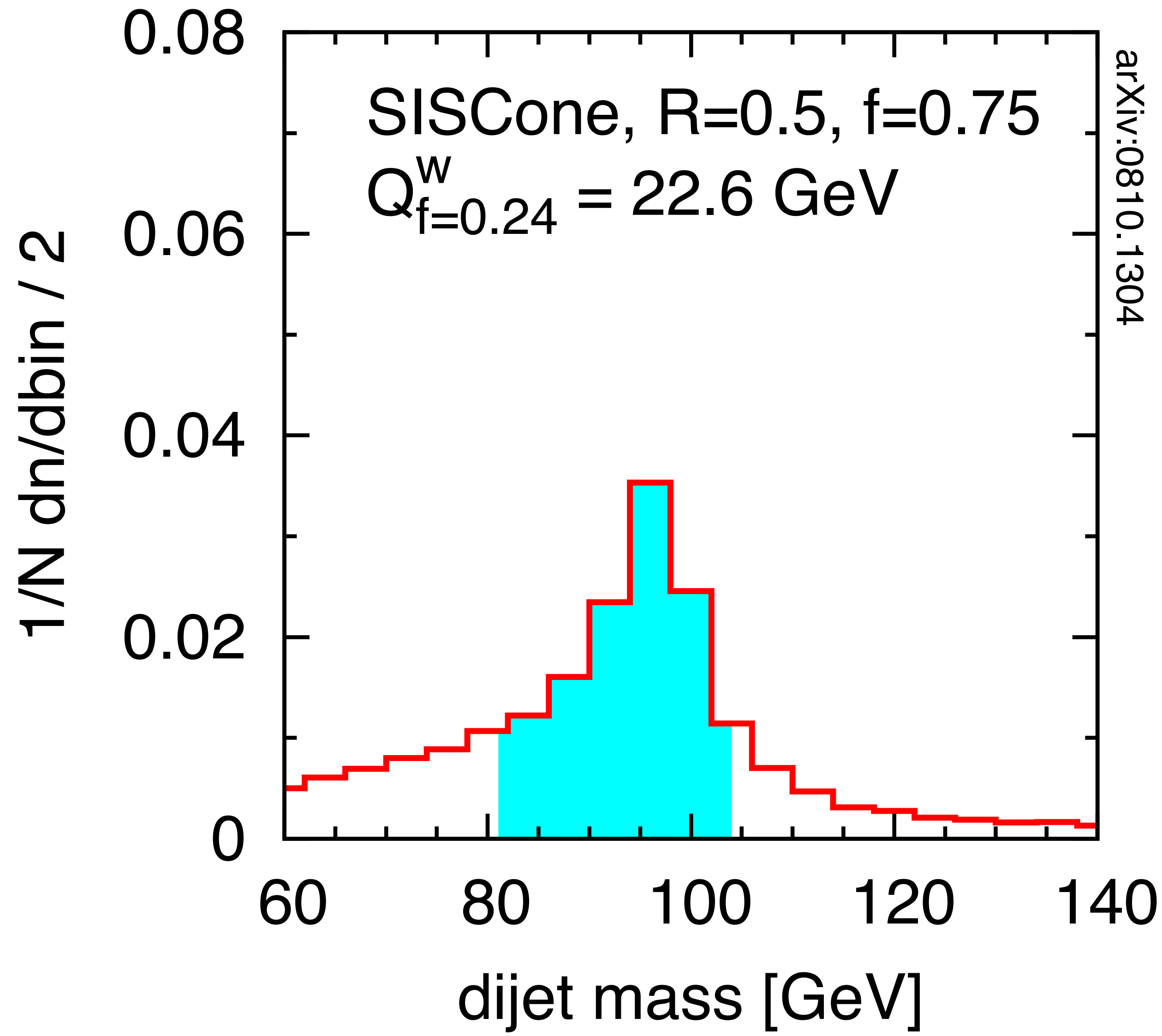


Resonance X → dijets

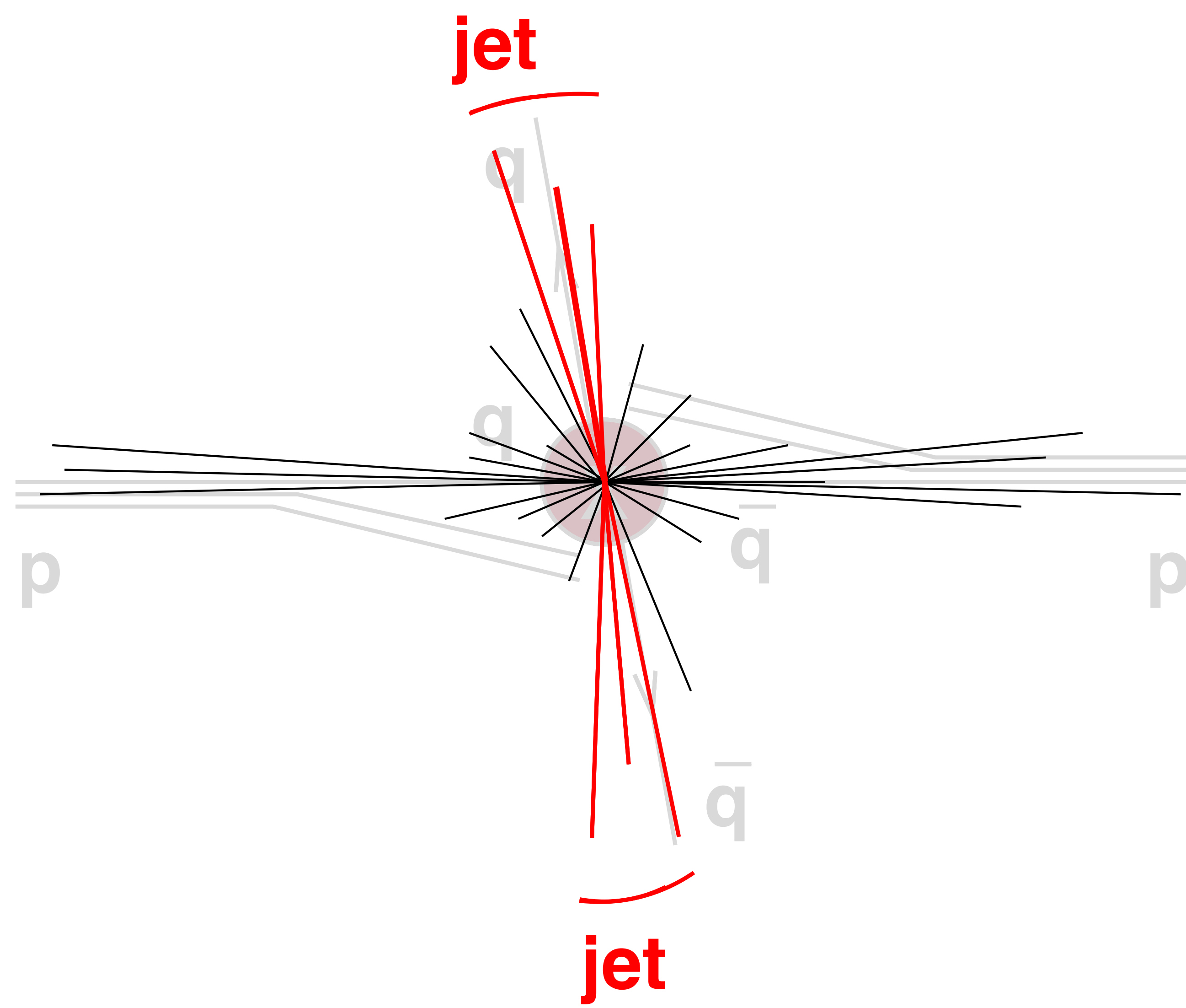


$R = 0.5$

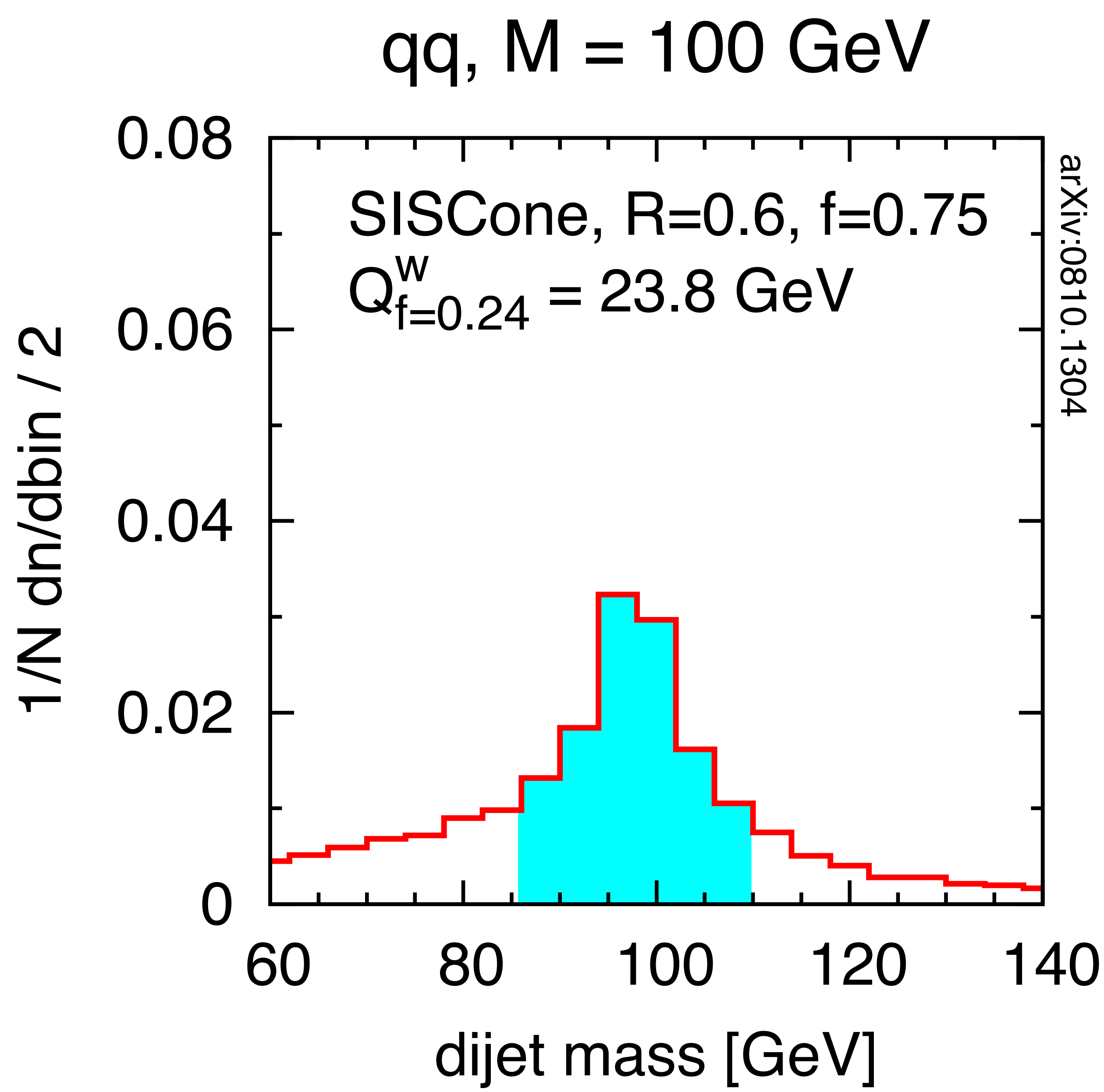
qq, M = 100 GeV



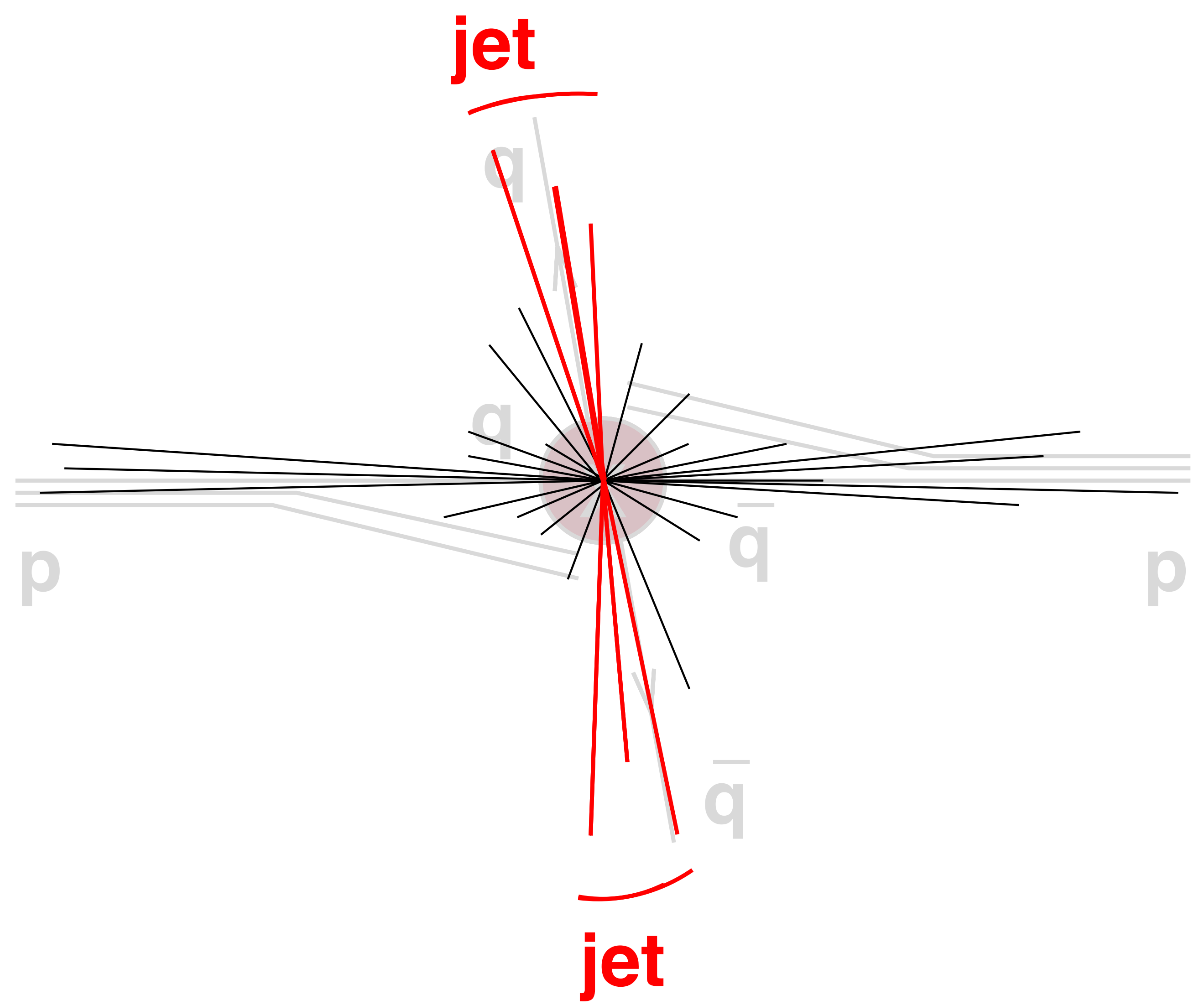
Resonance X → dijets

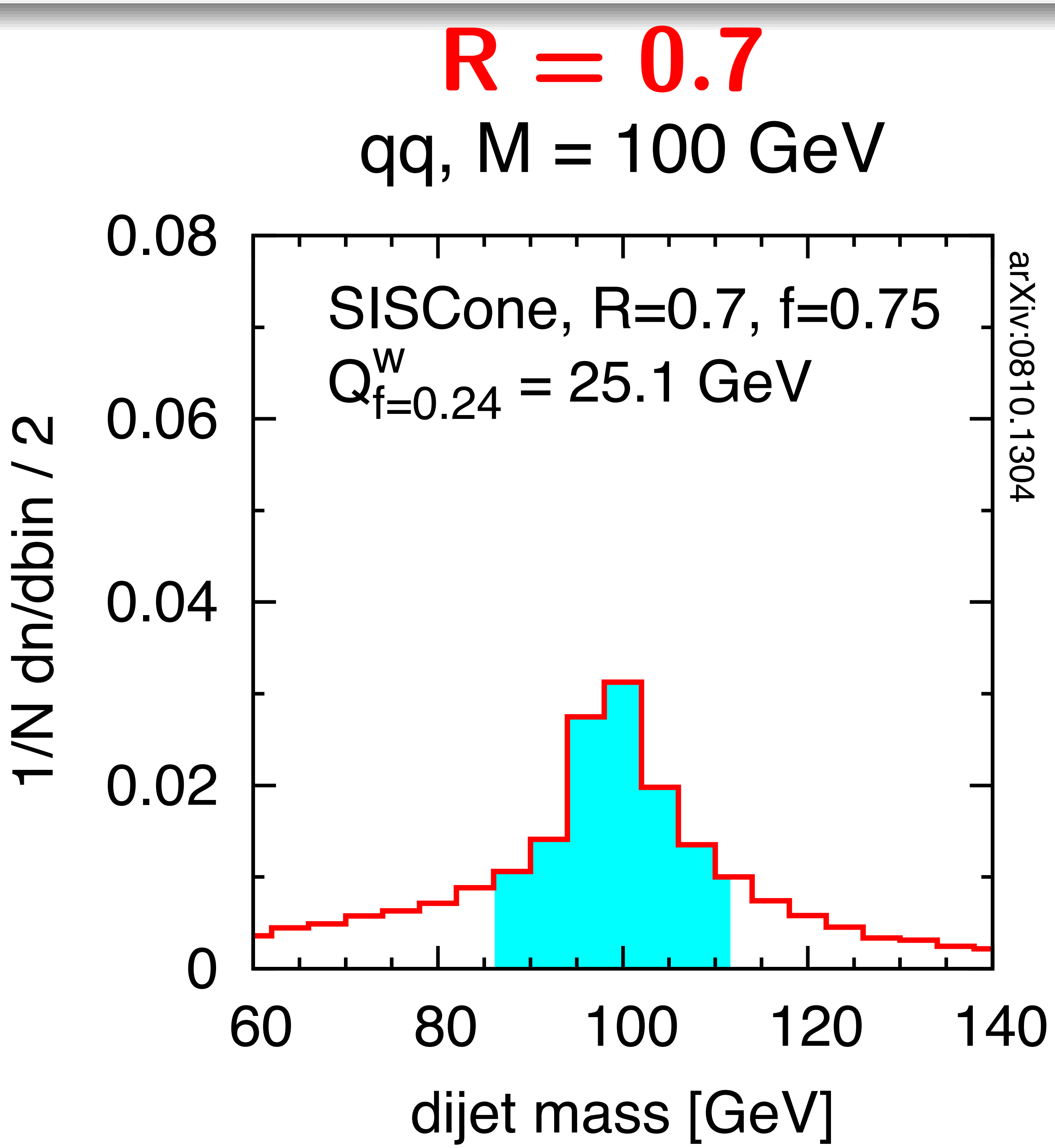


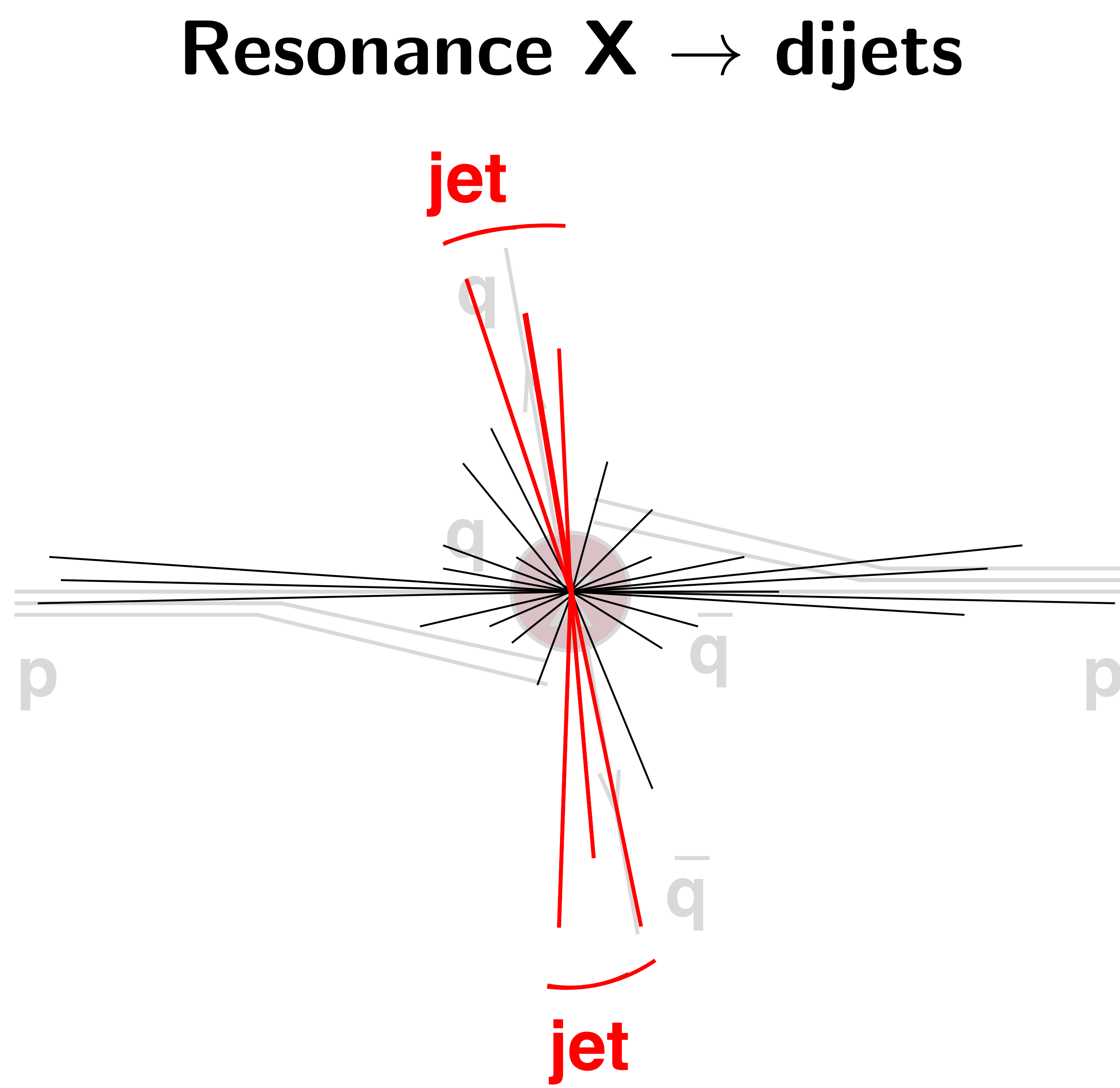
$R = 0.6$



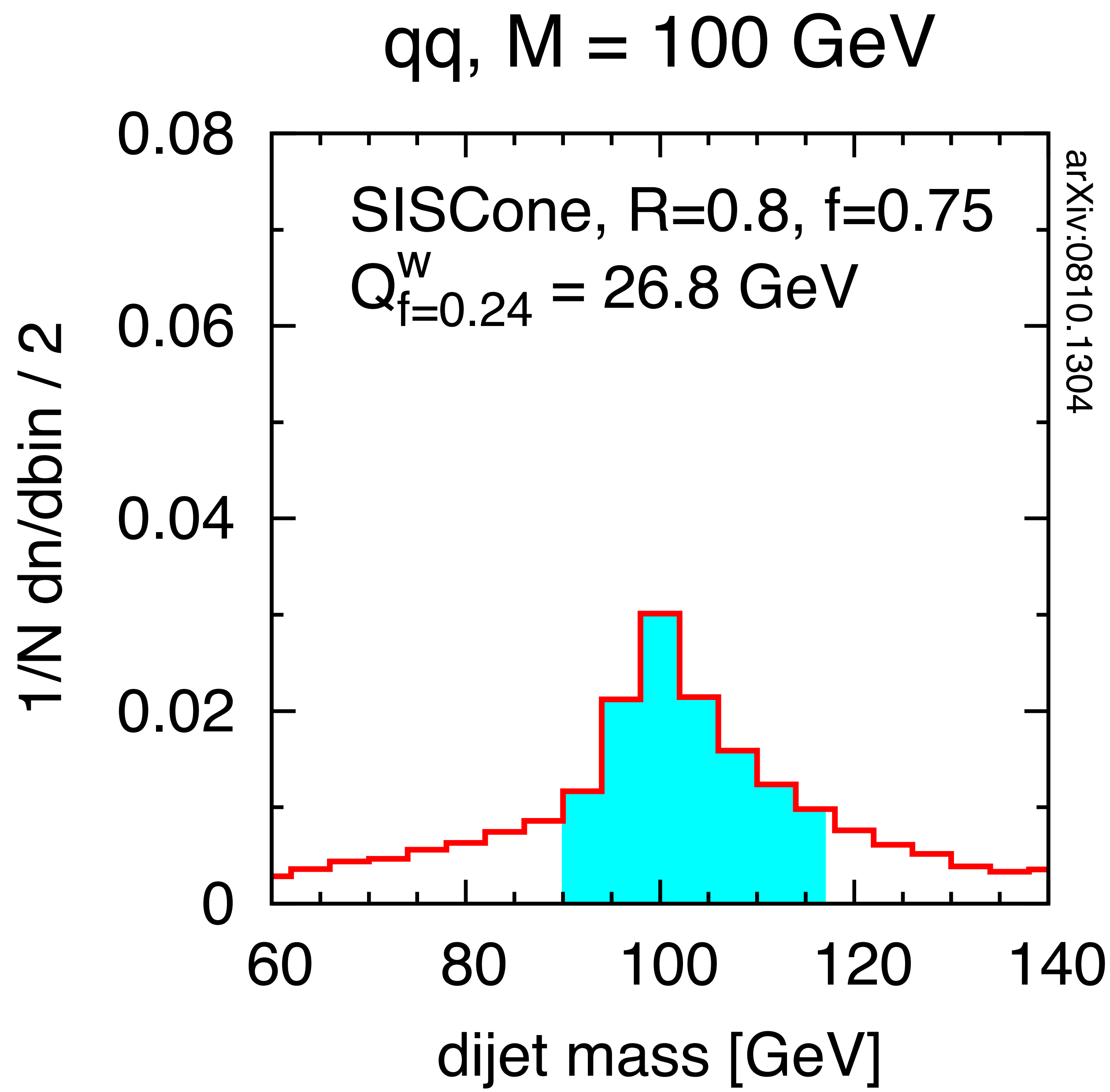
Resonance X → dijets



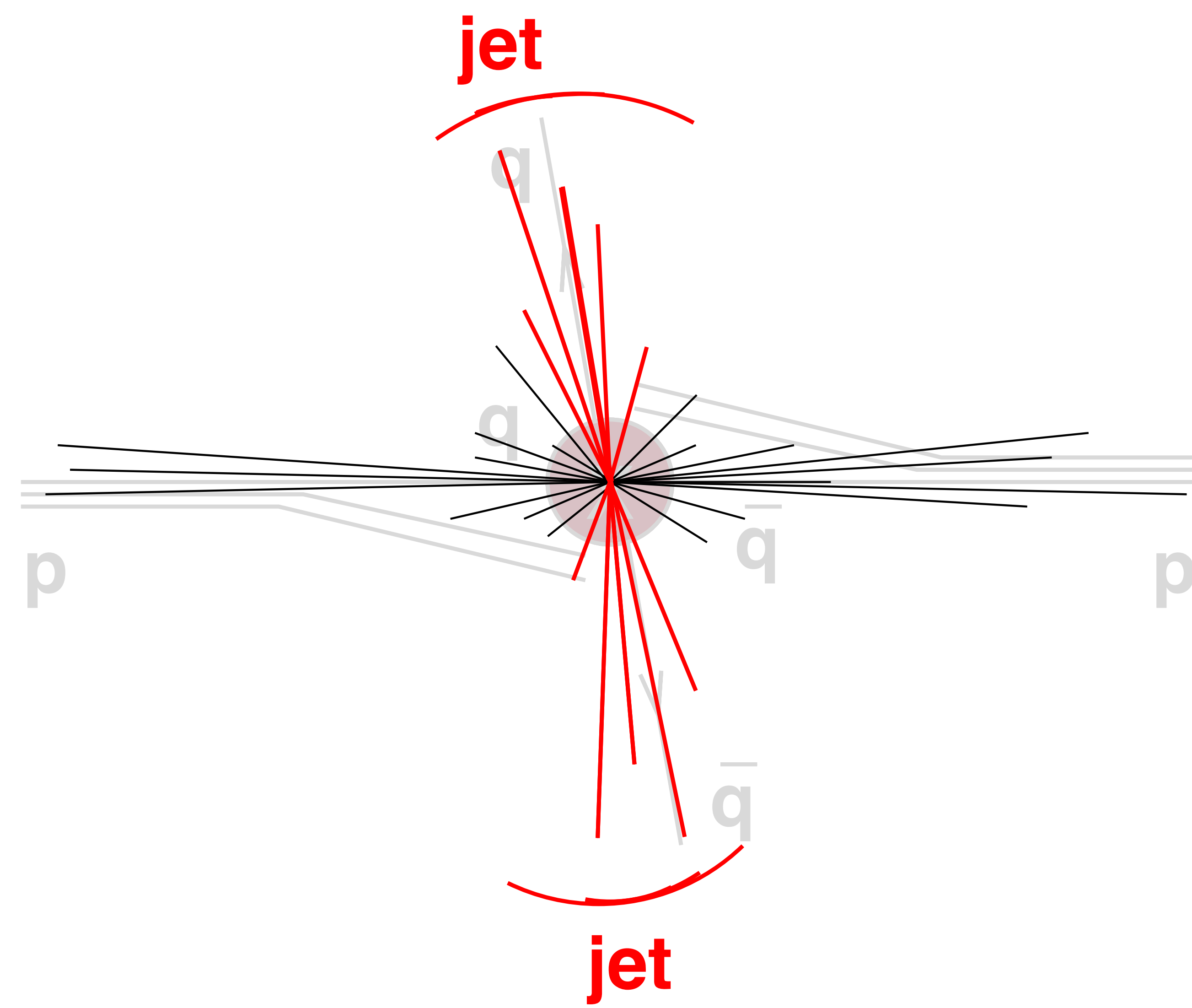

R = 0.7
qq, M = 100 GeV
SISCone, R=0.7, f=0.75
$Q^{w}_{f=0.24}$ = 25.1 GeV
arXiv:0810.1304
1/N dn/dbin / 2
0.08
0.06
0.04
0.02
0
60
80
100
120
140
dijet mass [GeV]


Resonance X → dijets
jet
q
q
p
$\bar{q}$
$\bar{q}$
p
jet

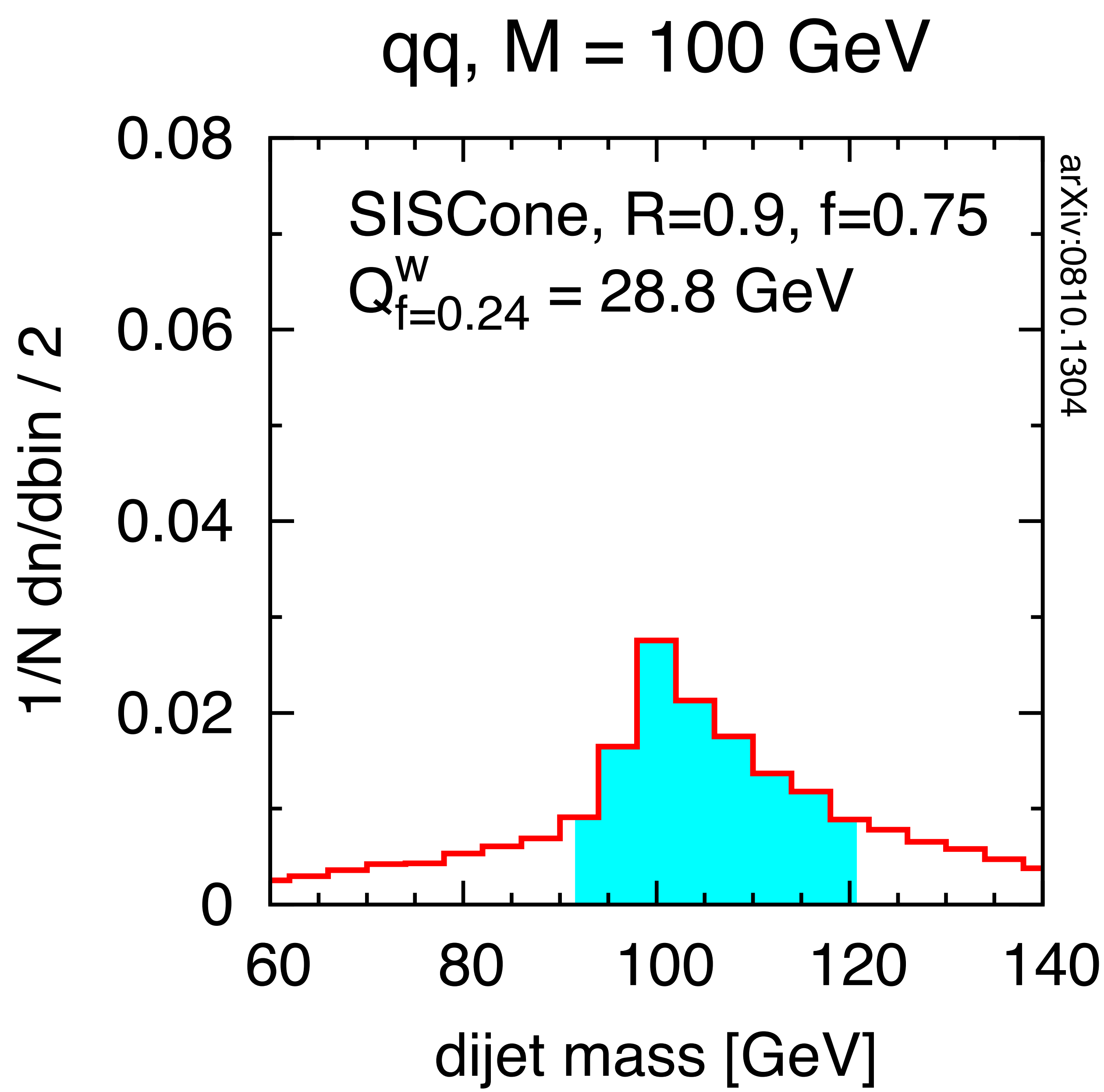
R = 0.8



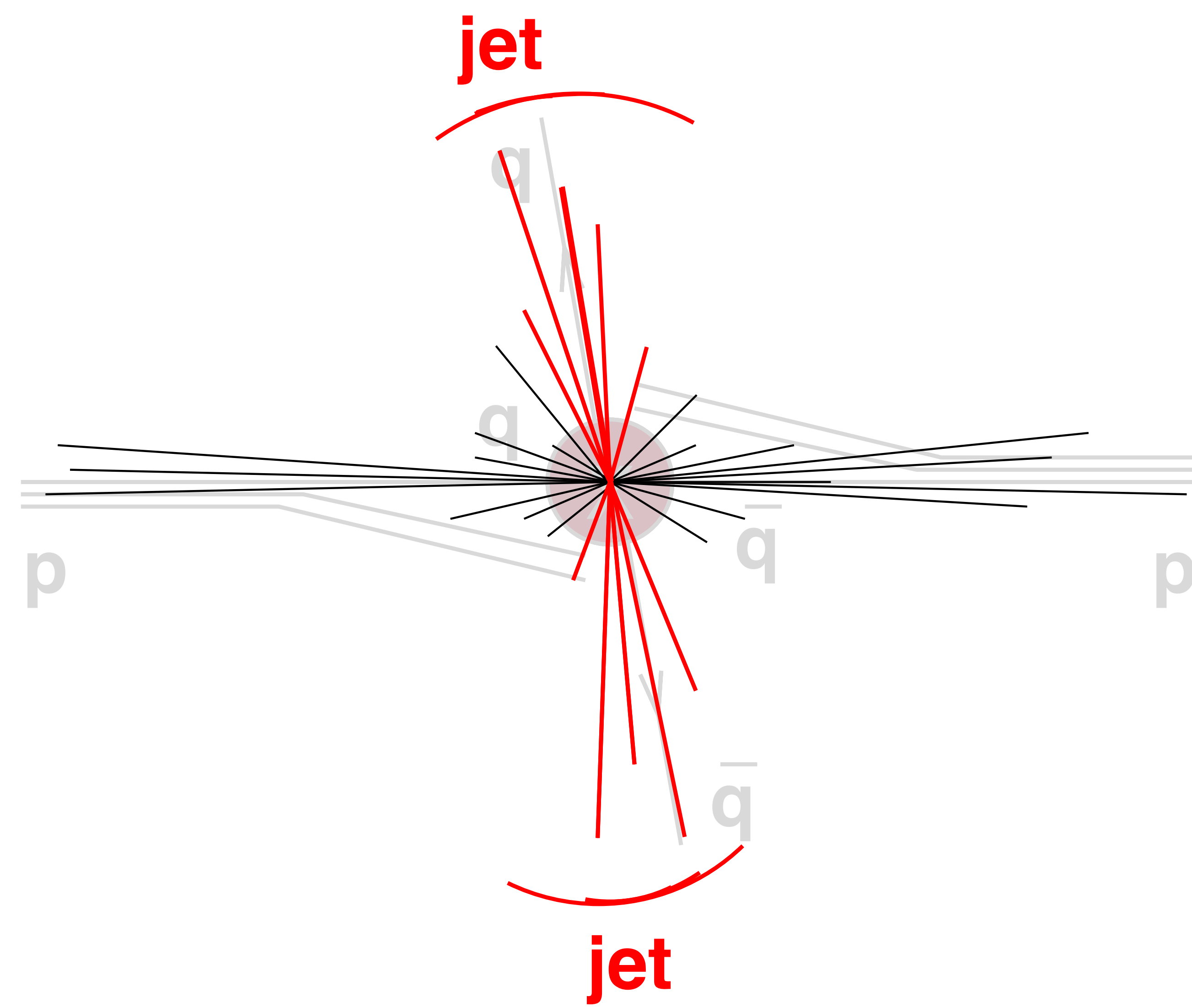
Resonance X → dijets

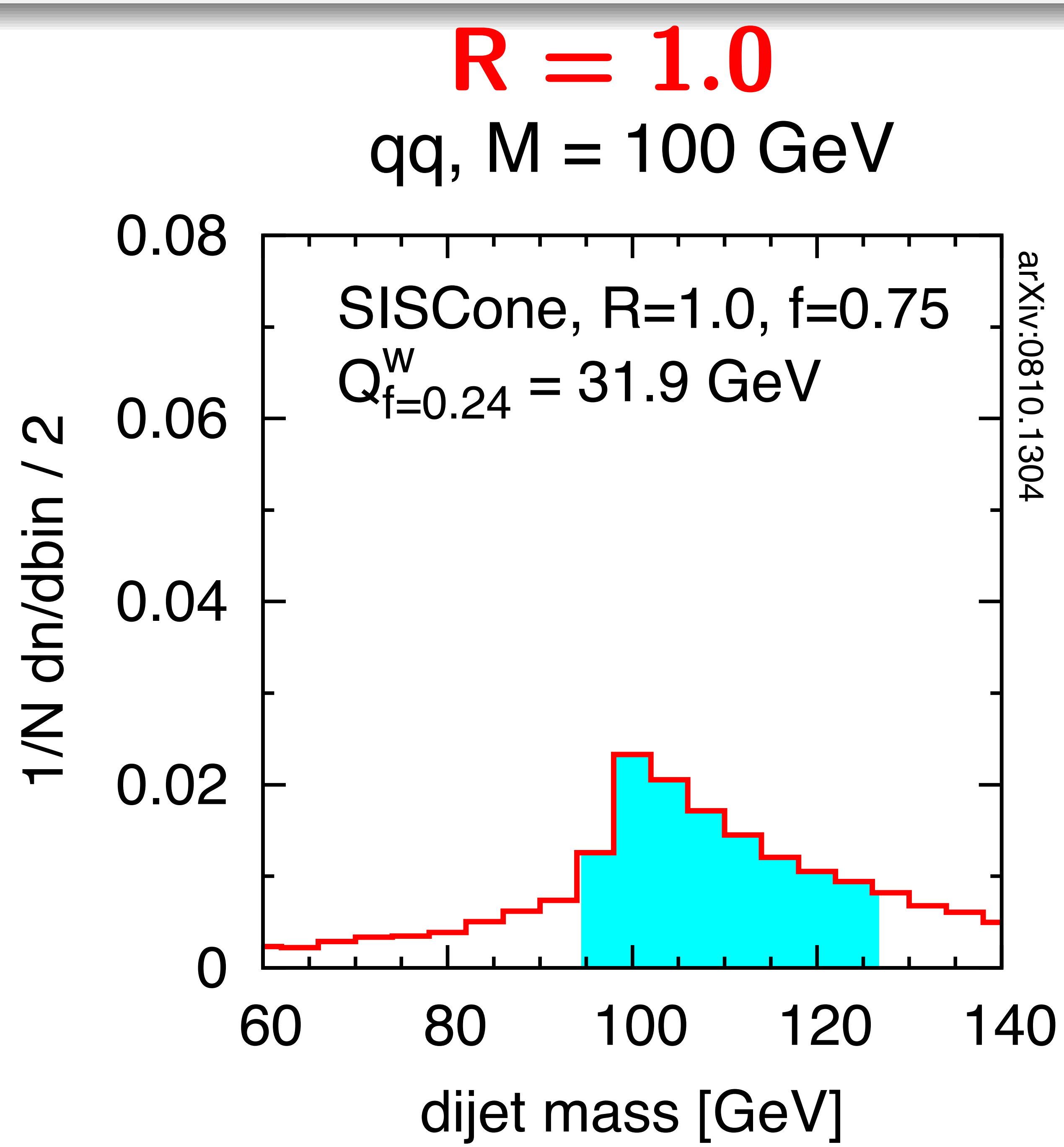


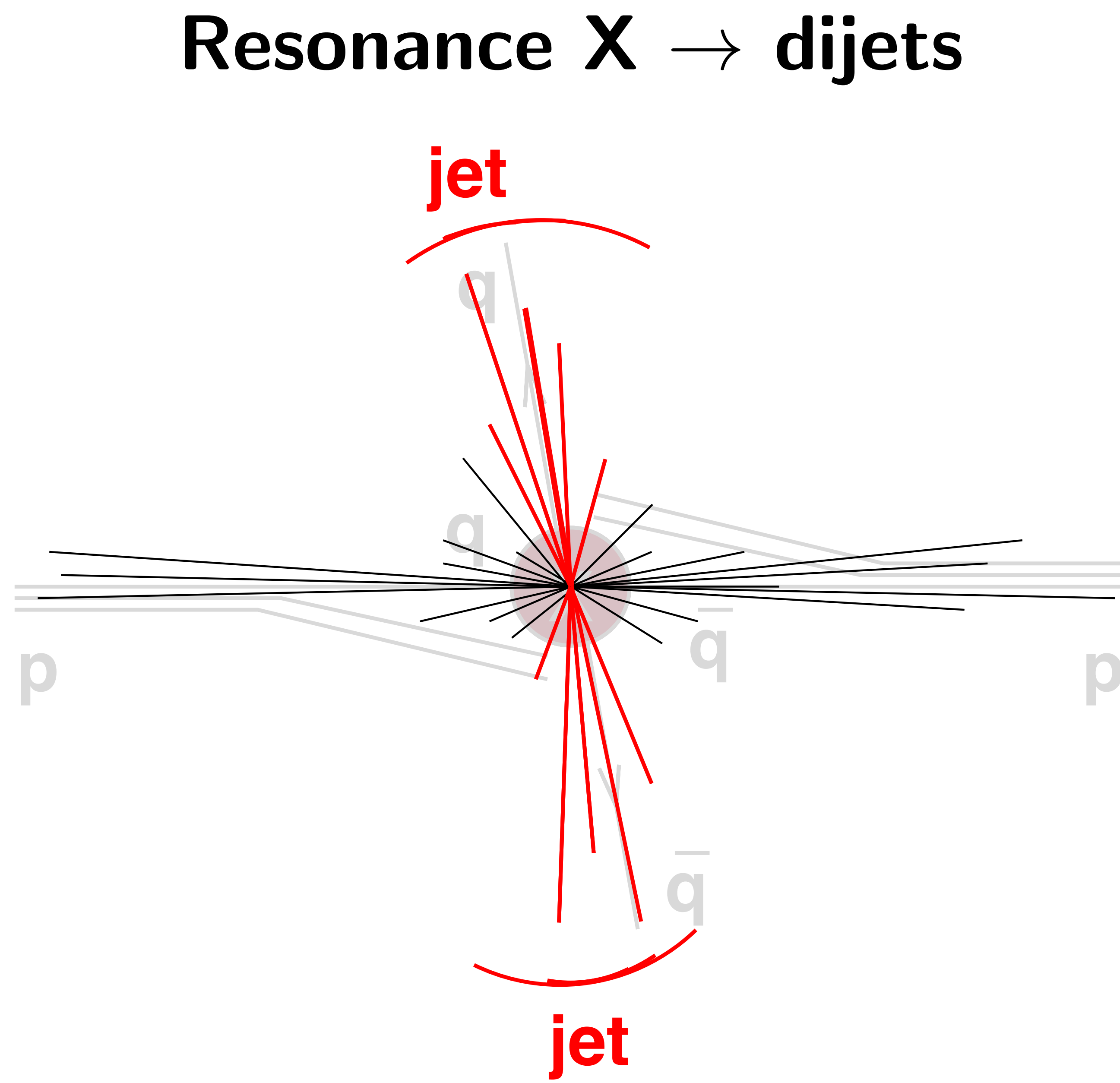
$R = 0.9$



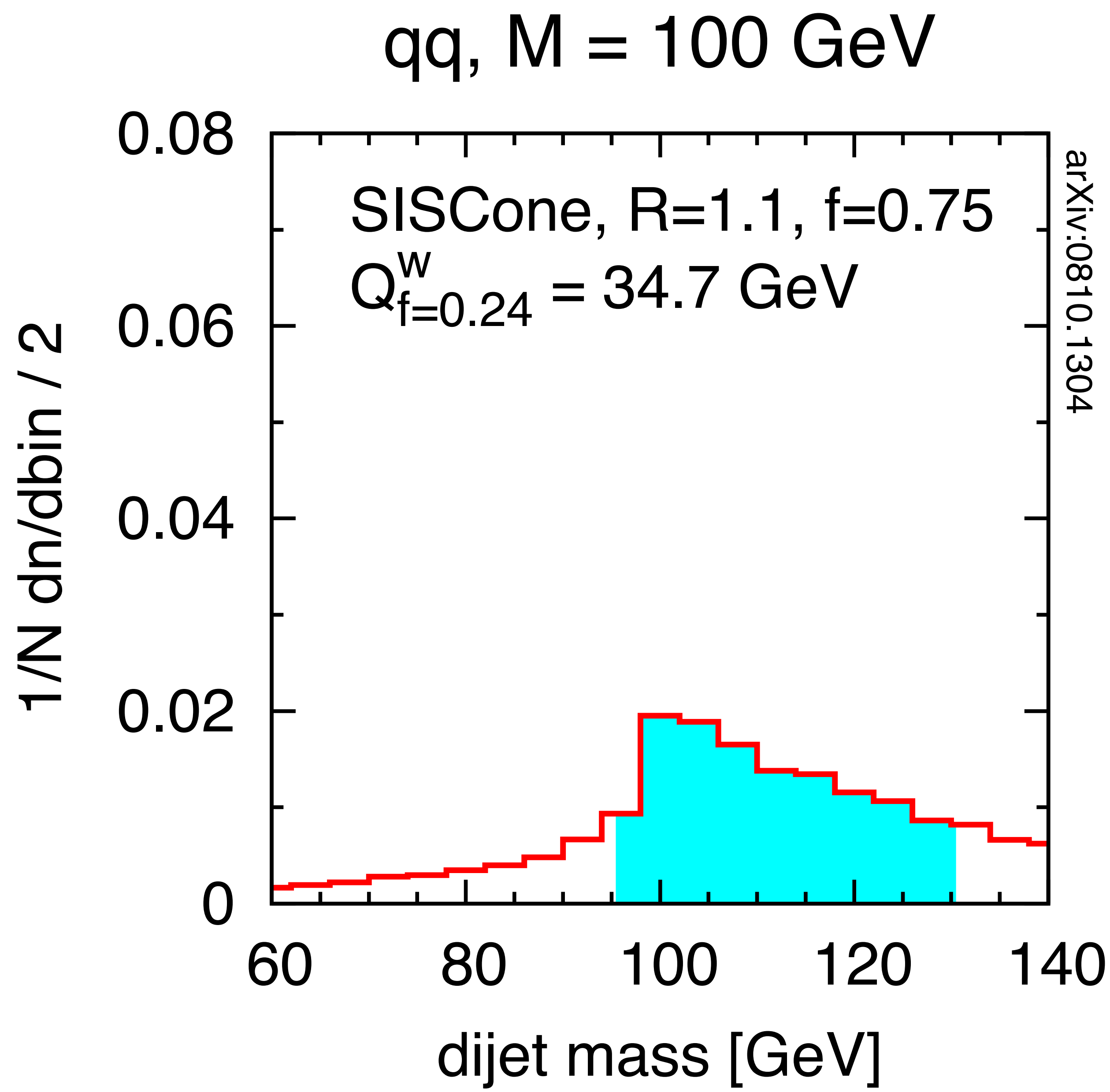
Resonance X → dijets



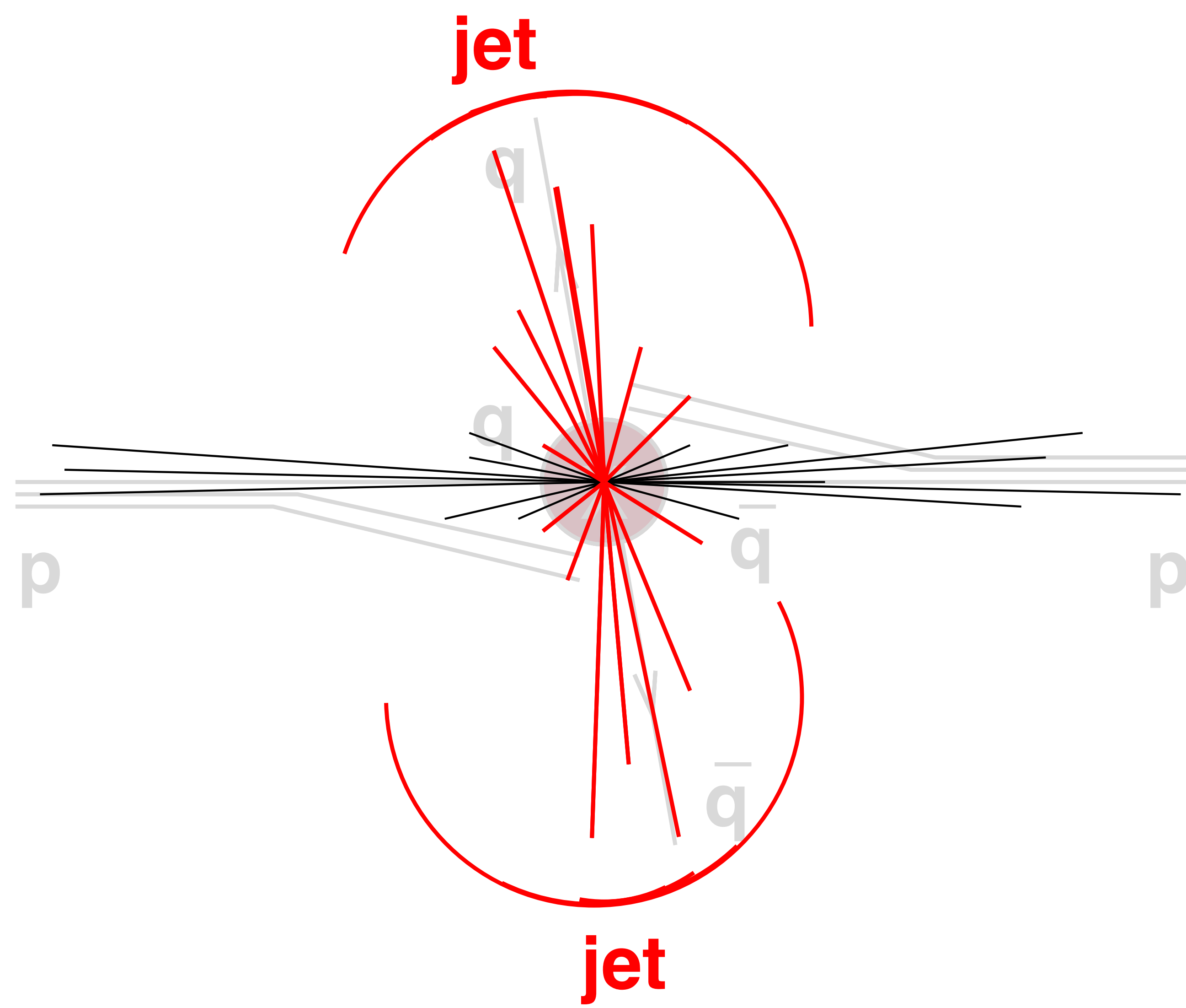

R = 1.0
qq, M = 100 GeV
SISCone, R=1.0, f=0.75
$Q^{w}_{f=0.24}$ = 31.9 GeV
arXiv:0810.1304
0.08
0.06
0.04
0.02
0
60
80
100
120
140
1/N dn/dbin / 2
dijet mass [GeV]


Resonance X → dijets
jet
q
q
$\bar{q}$
$\bar{q}$
p
p
jet

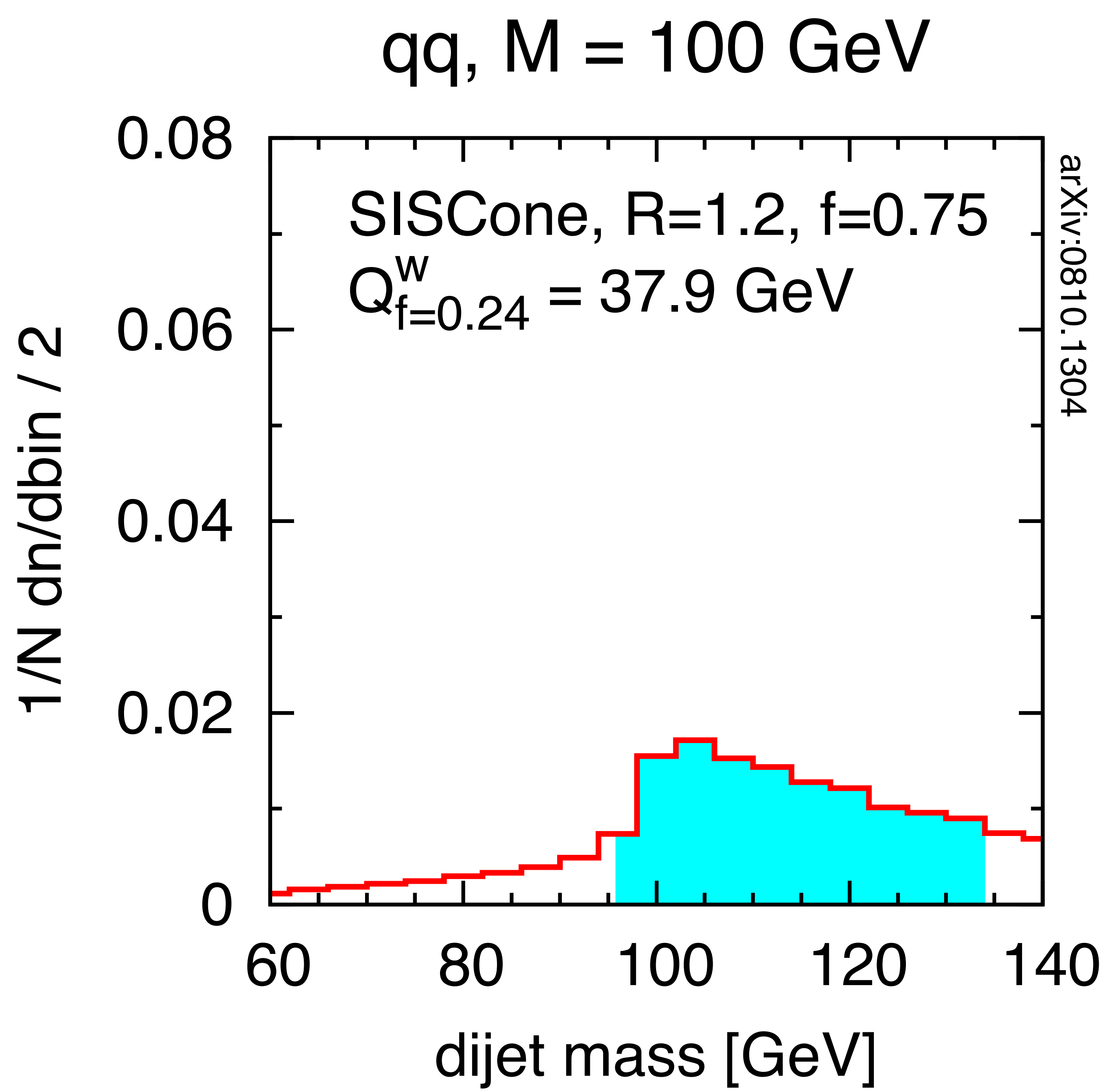
$R = 1.1$



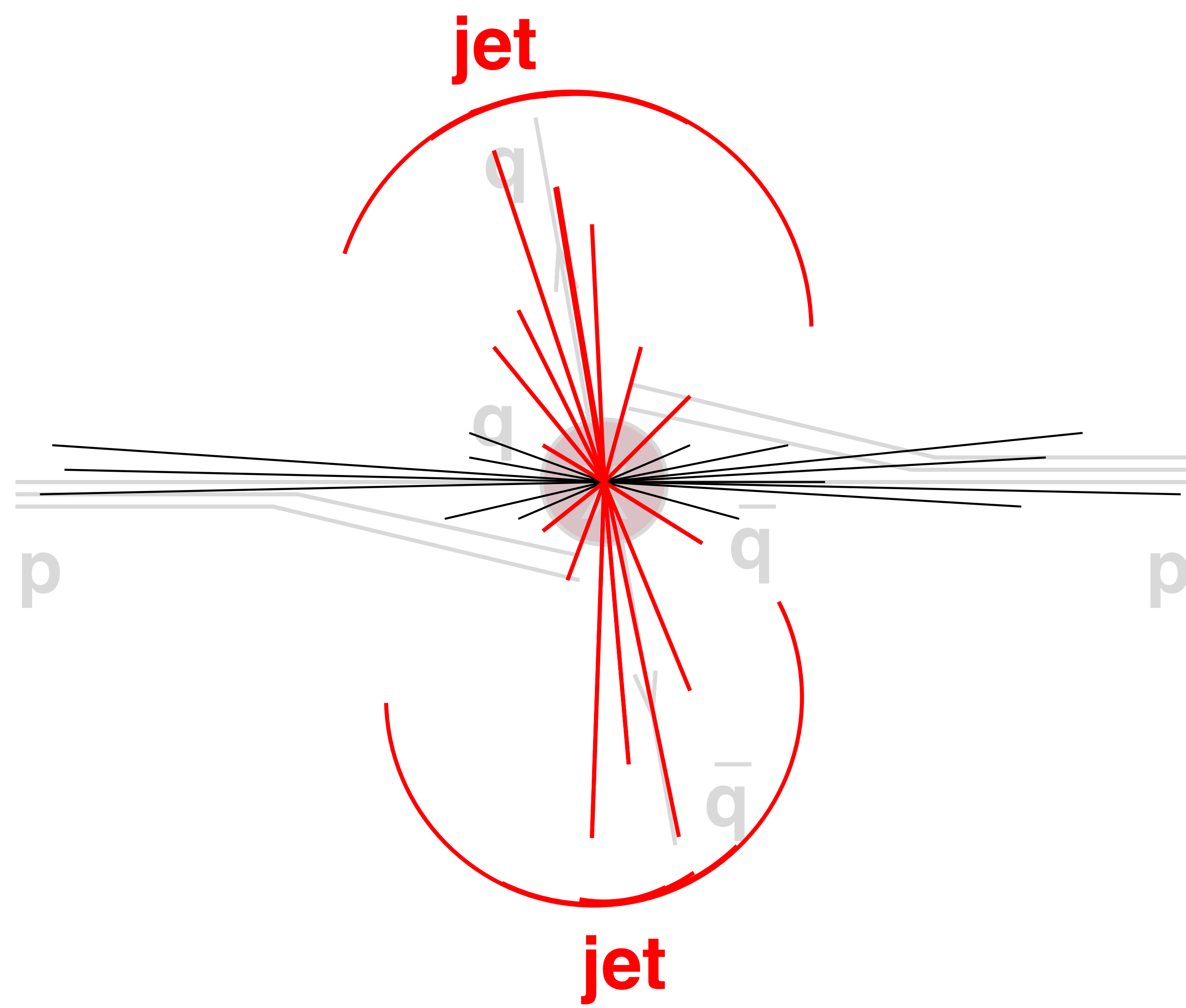
Resonance X → dijets

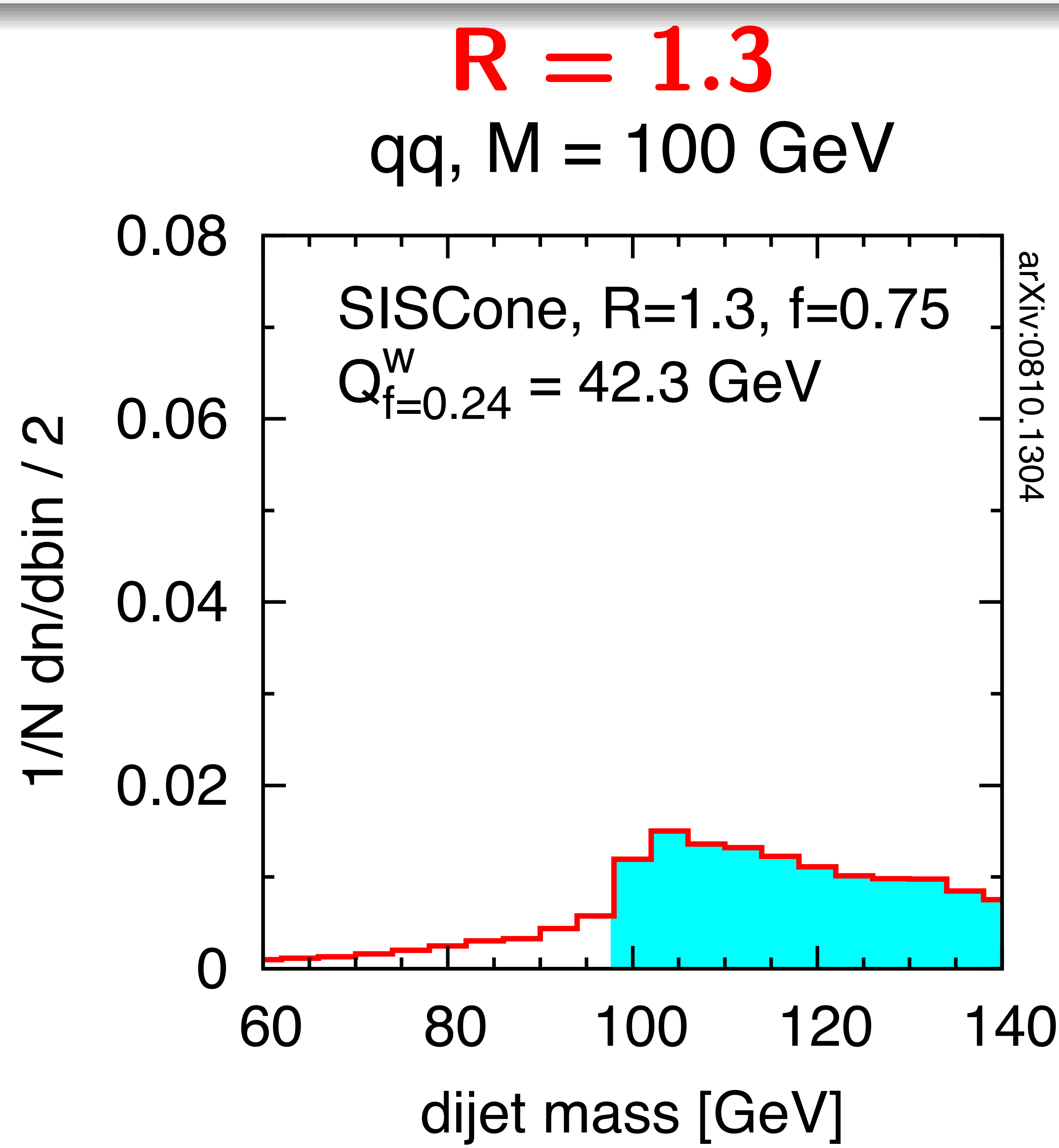


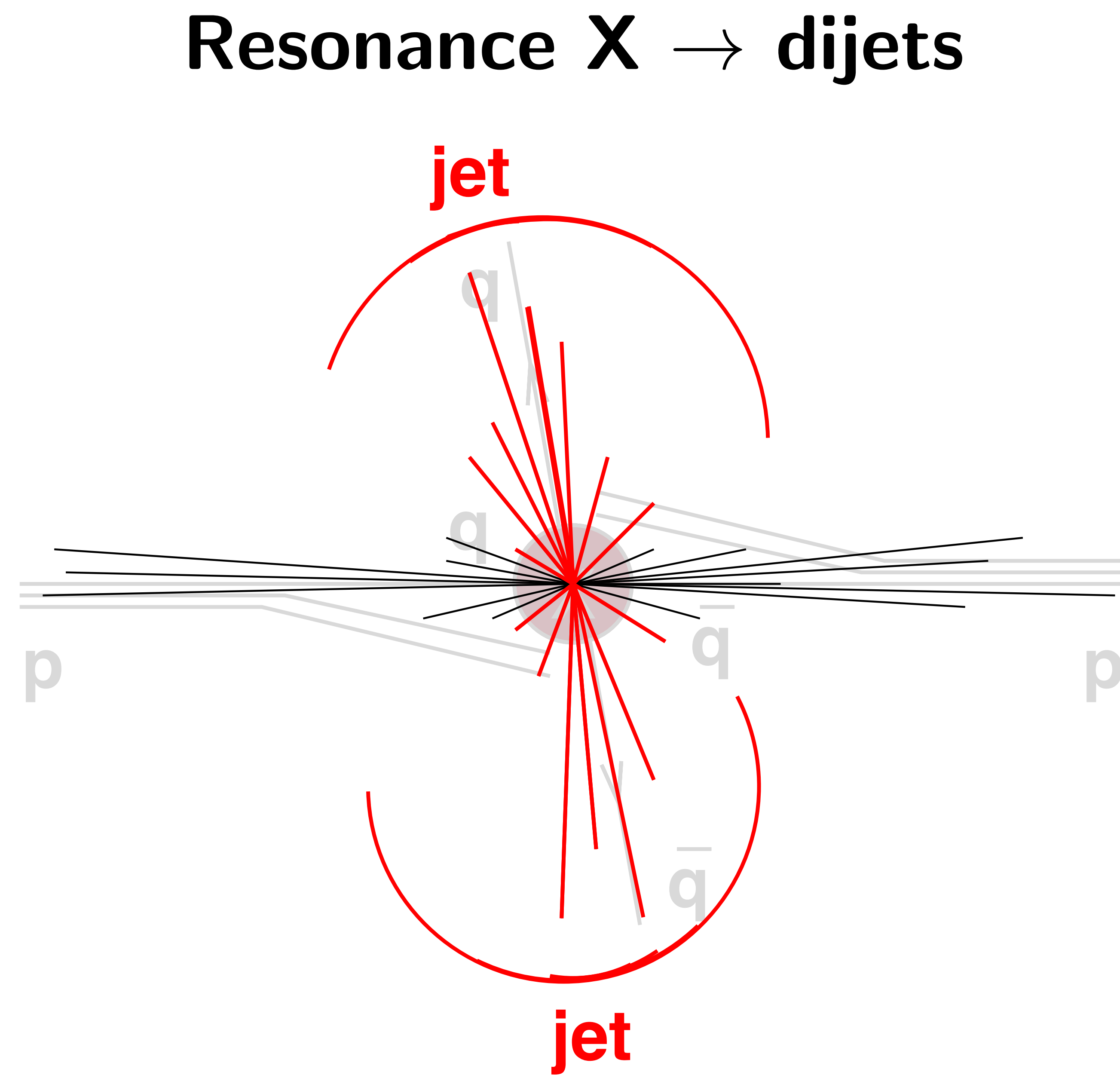
$R = 1.2$



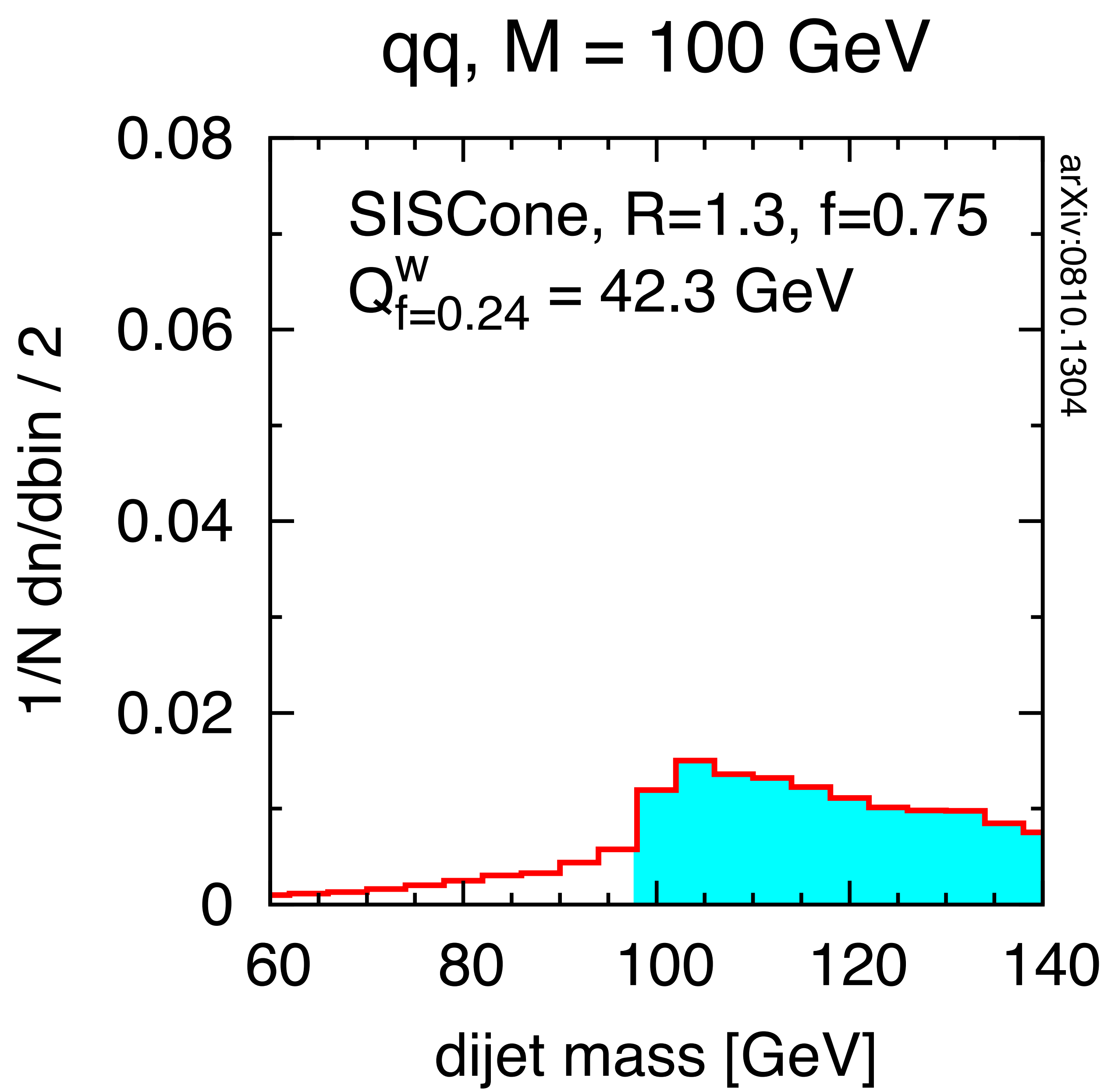
Resonance X → dijets

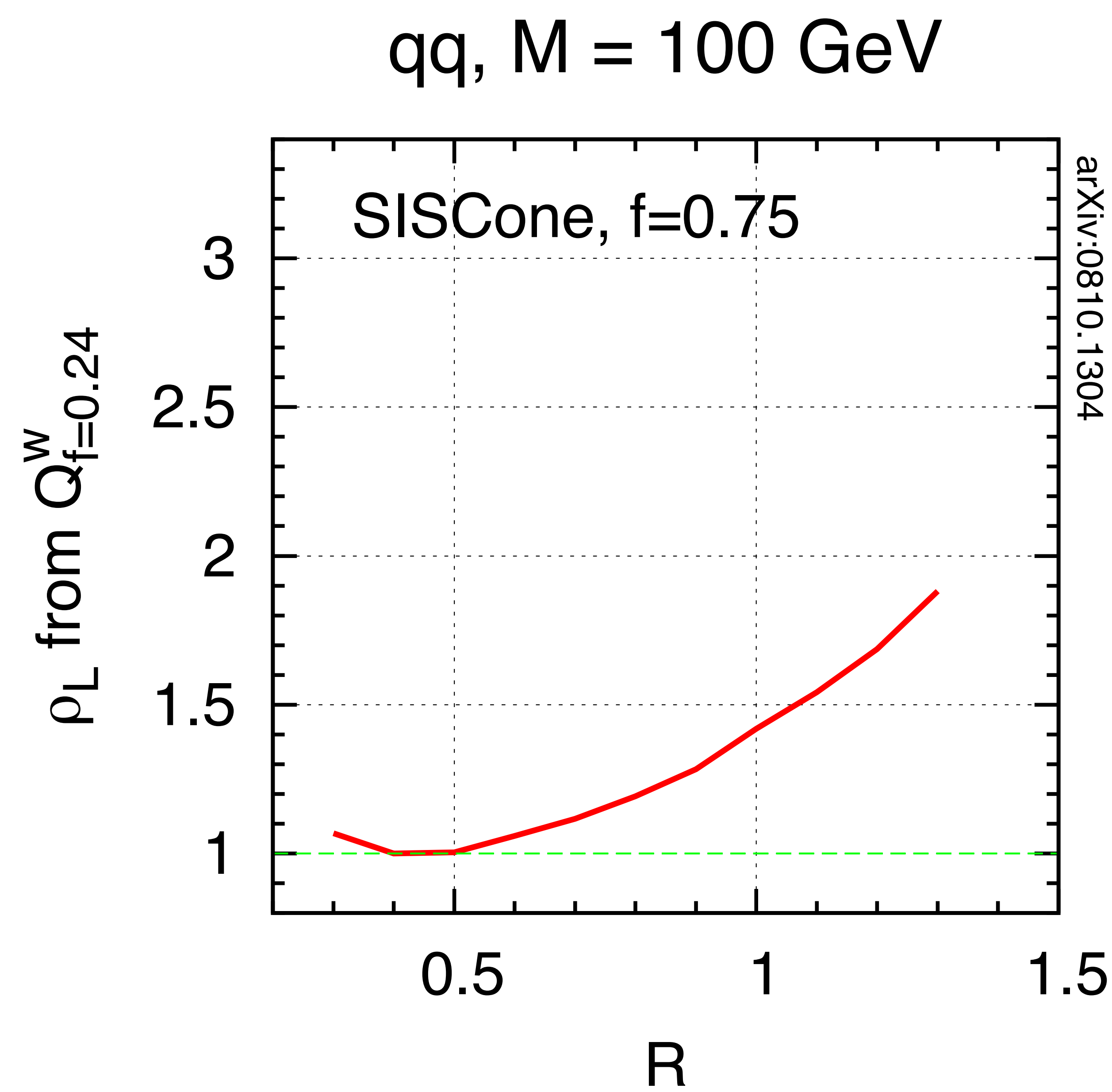



R = 1.3
qq, M = 100 GeV
0.08
0.06
0.04
0.02
0
1/N dn/dbin / 2
SISCone, R=1.3, f=0.75
$Q^{w}_{f=0.24}$ = 42.3 GeV
arXiv:0810.1304
60
80
100
120
140
dijet mass [GeV]


Resonance X → dijets
jet
q
q
$\bar{q}$
$\bar{q}$
p
p
jet

R = 1.3



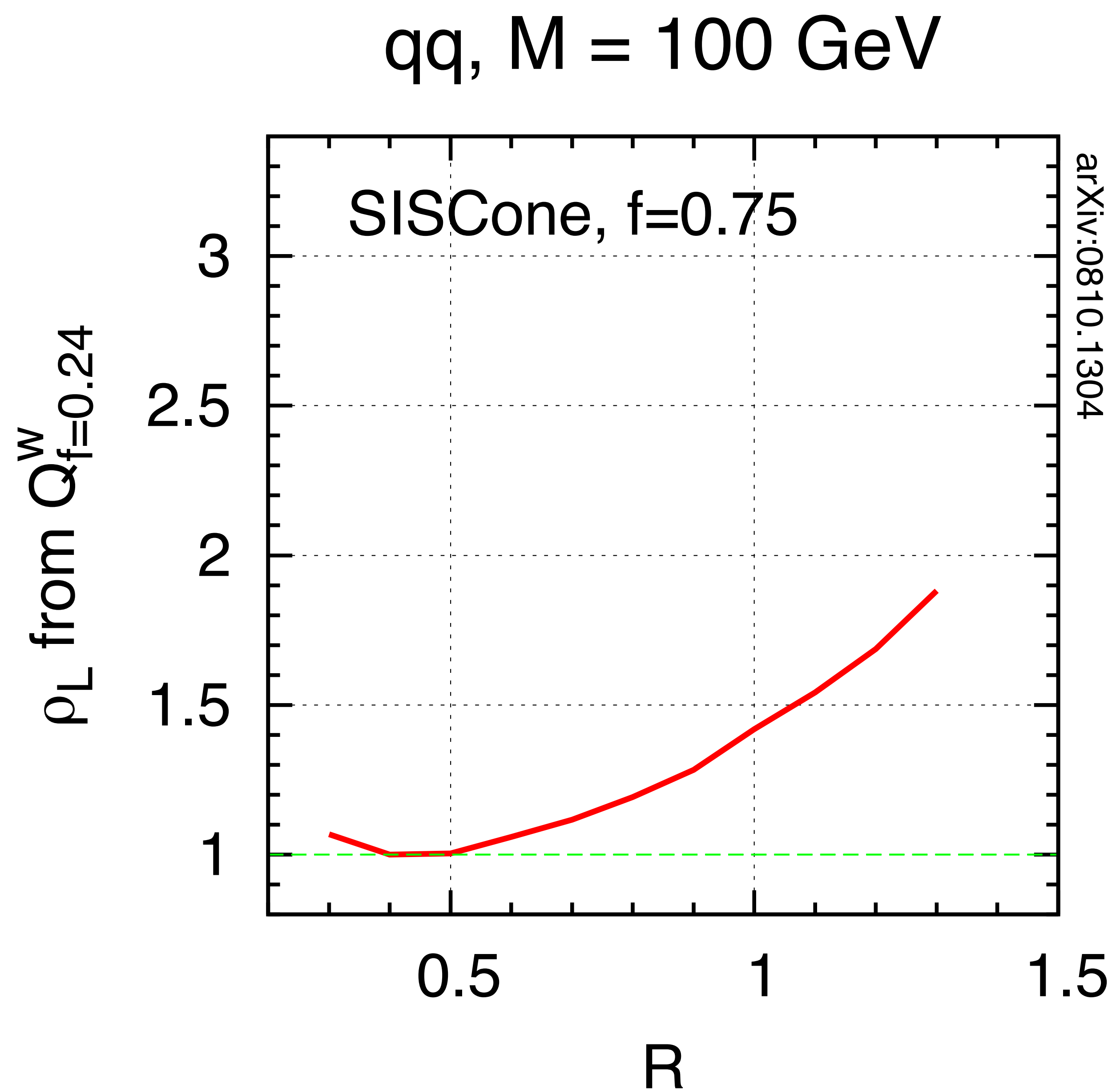


After scanning, summarise "quality" v. *R*. Minimum ≡ BEST

picture not so different from crude analytical estimate

Scan through $q\bar{q}$ mass values

$\mathbf{m_{qq} = 100}$ GeV



Best R is at minimum of curve

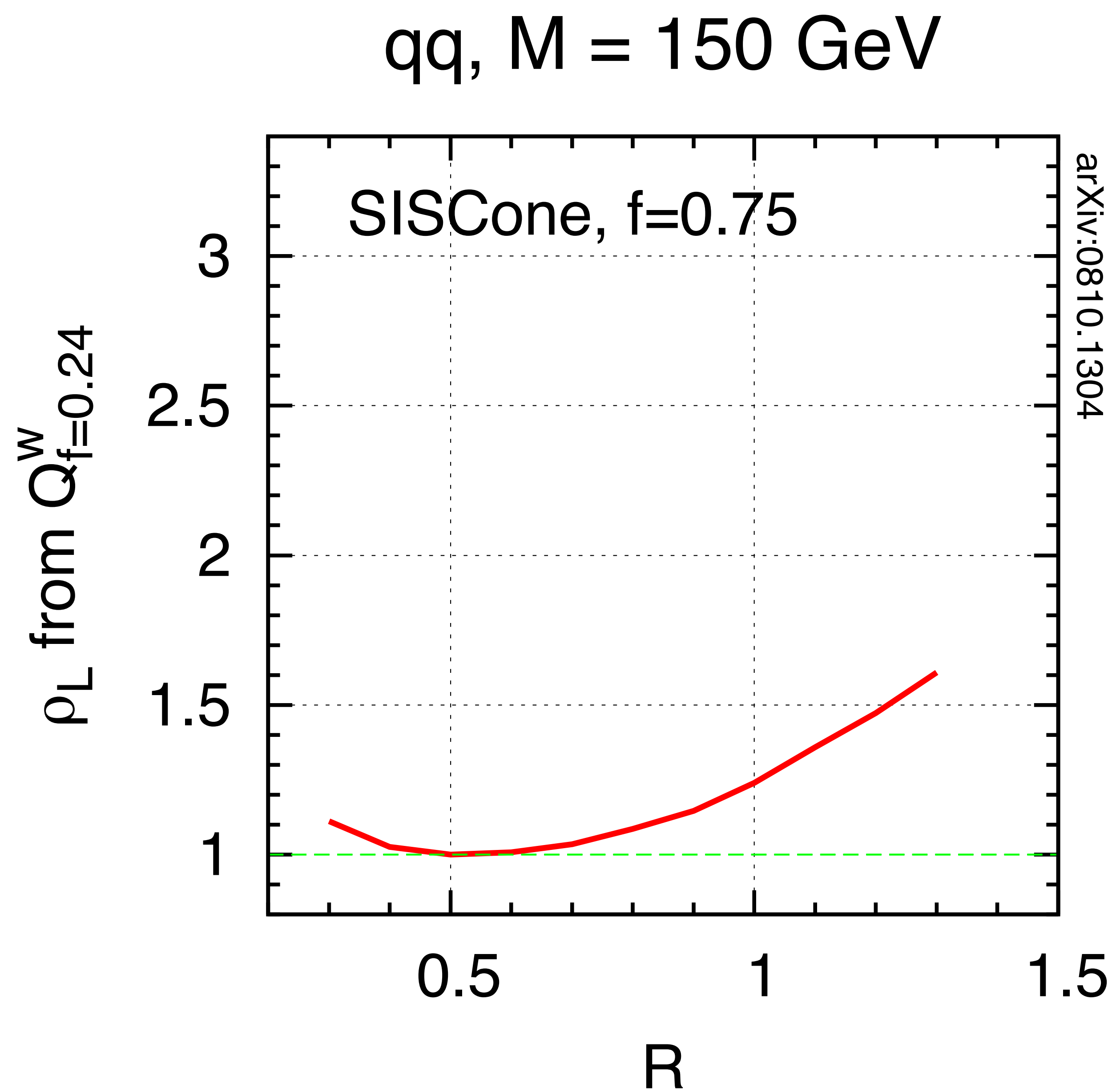
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$m_{qq} = 150$ GeV



Best R is at minimum of curve

- Best R depends strongly on mass of system
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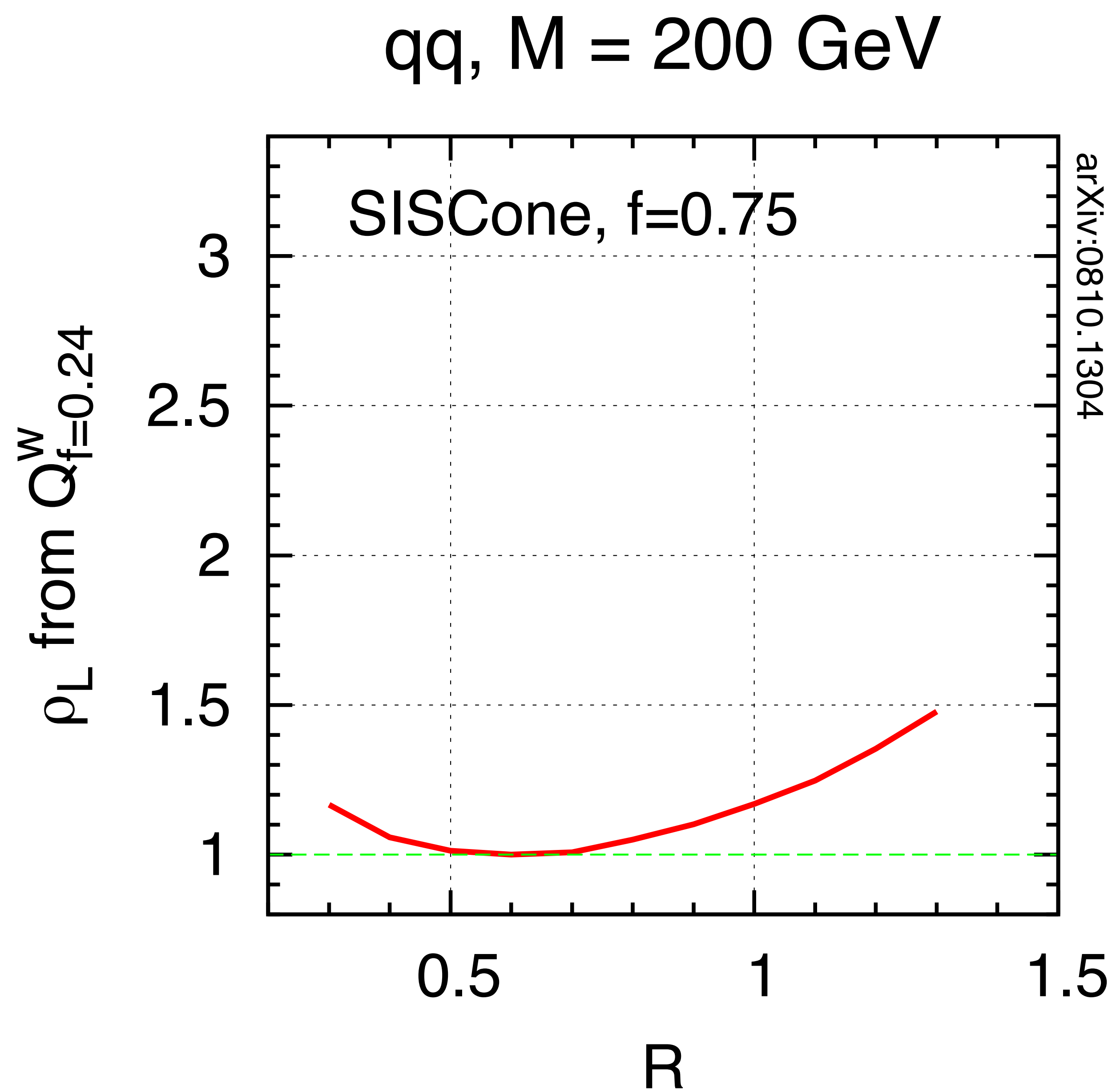
NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq} = 200}$ GeV



Best R is at minimum of curve

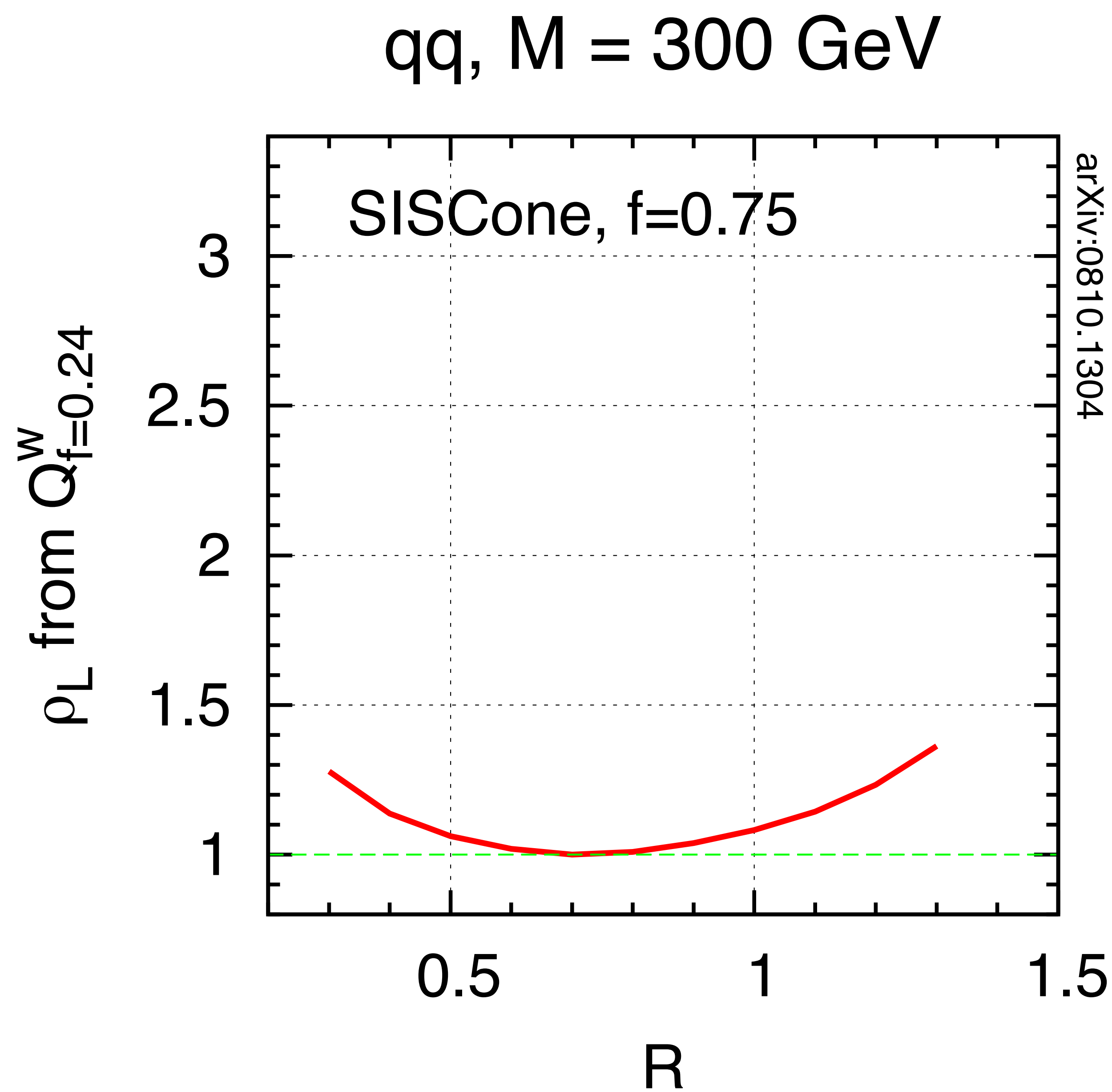
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq} = 300\ GeV}$



Best R is at minimum of curve

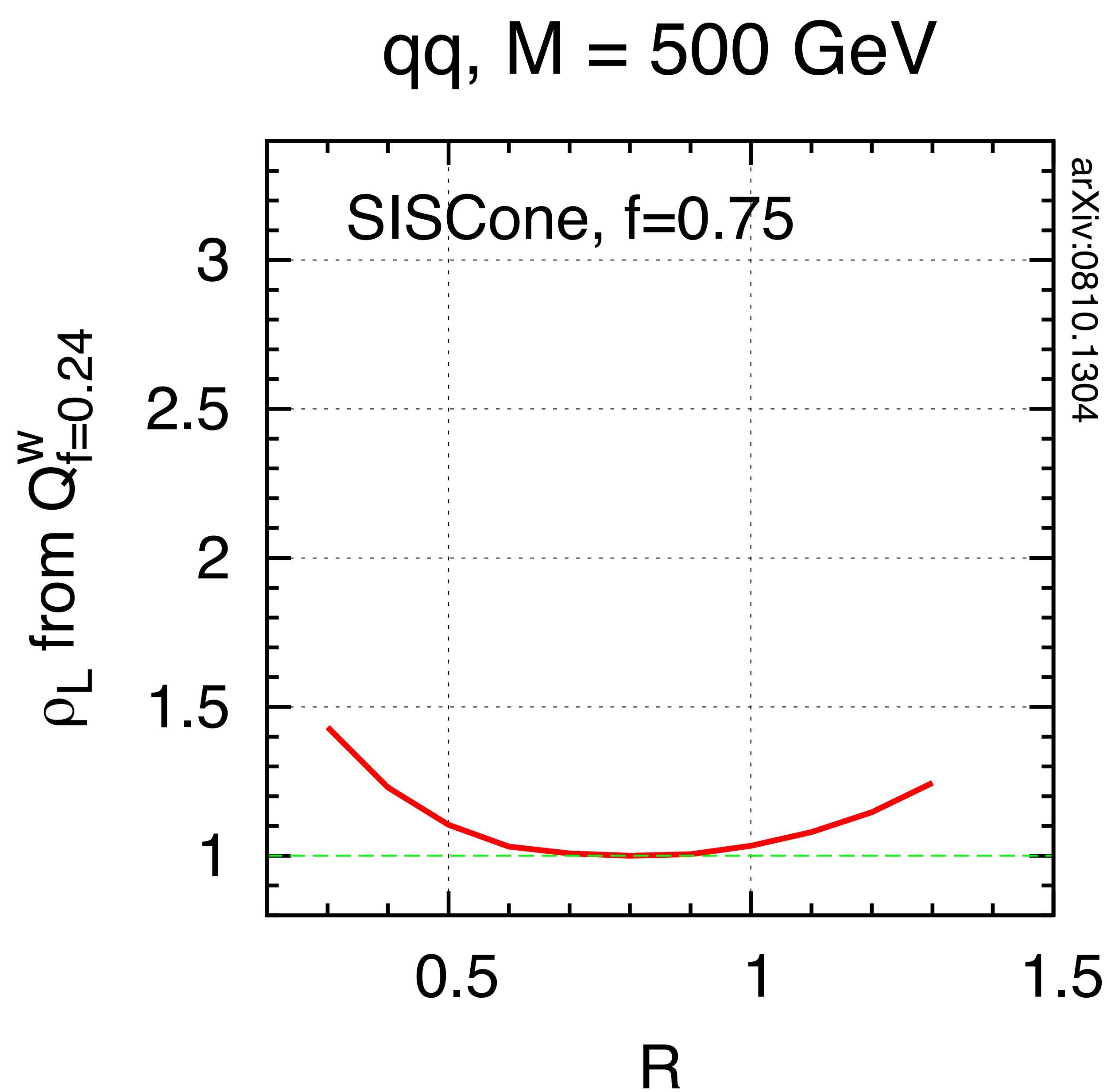
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq} = 500}$ GeV



Best R is at minimum of curve

- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

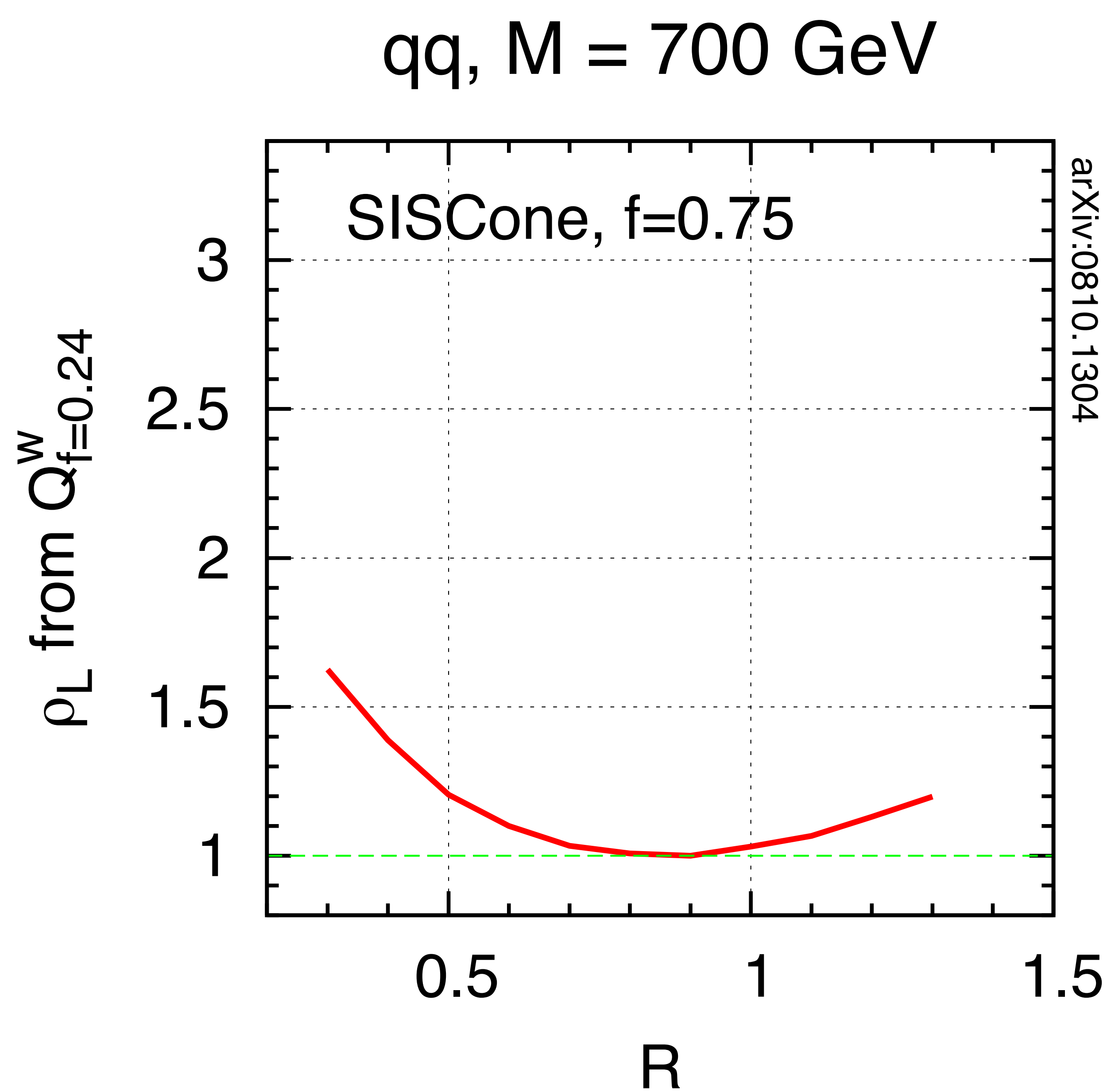
NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr`

Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq}}$ = 700 GeV



Best R is at minimum of curve

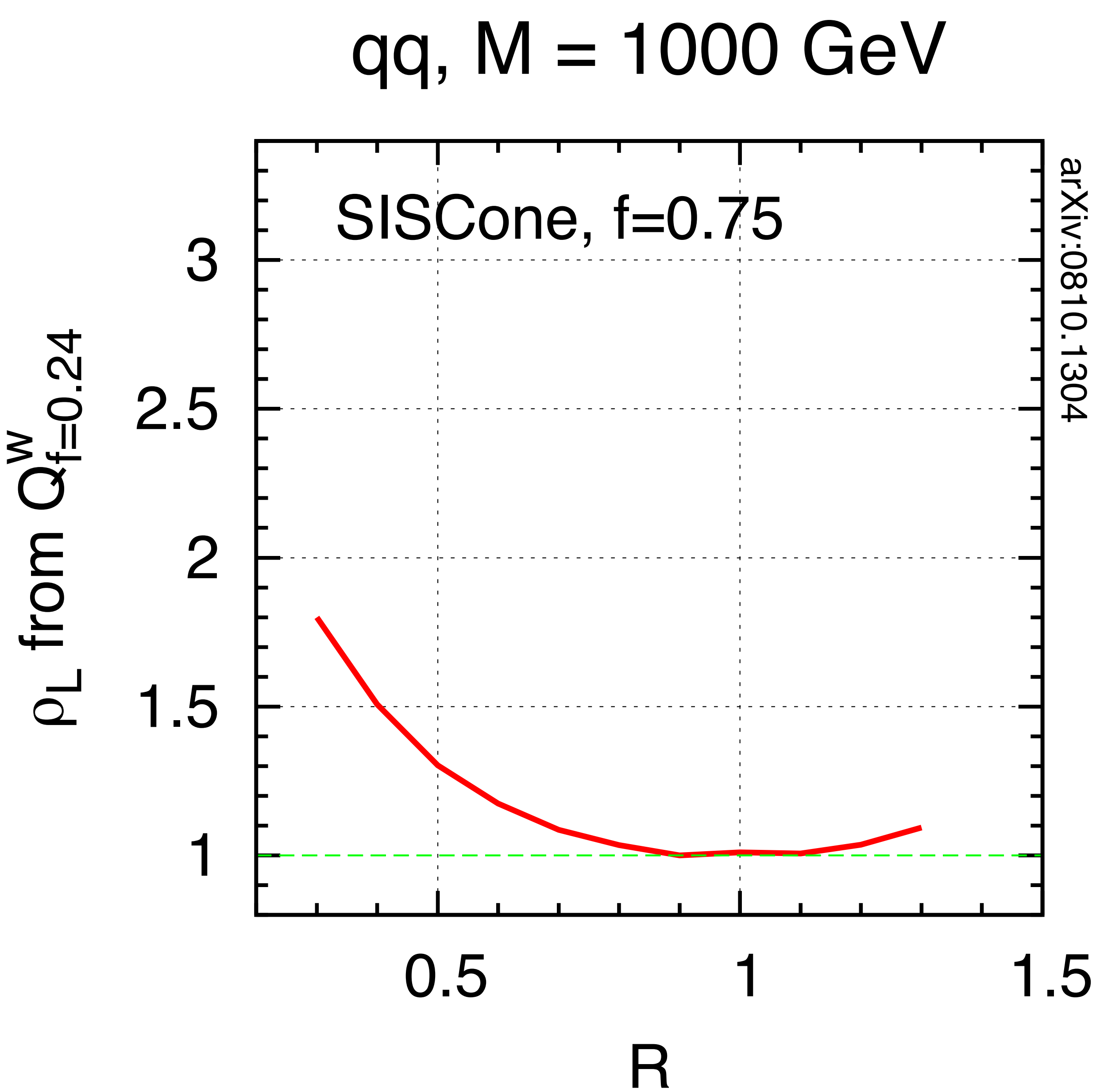
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from http://quality.fastjet.fr Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

m_{qq} = 1000 GeV



Best R is at minimum of curve

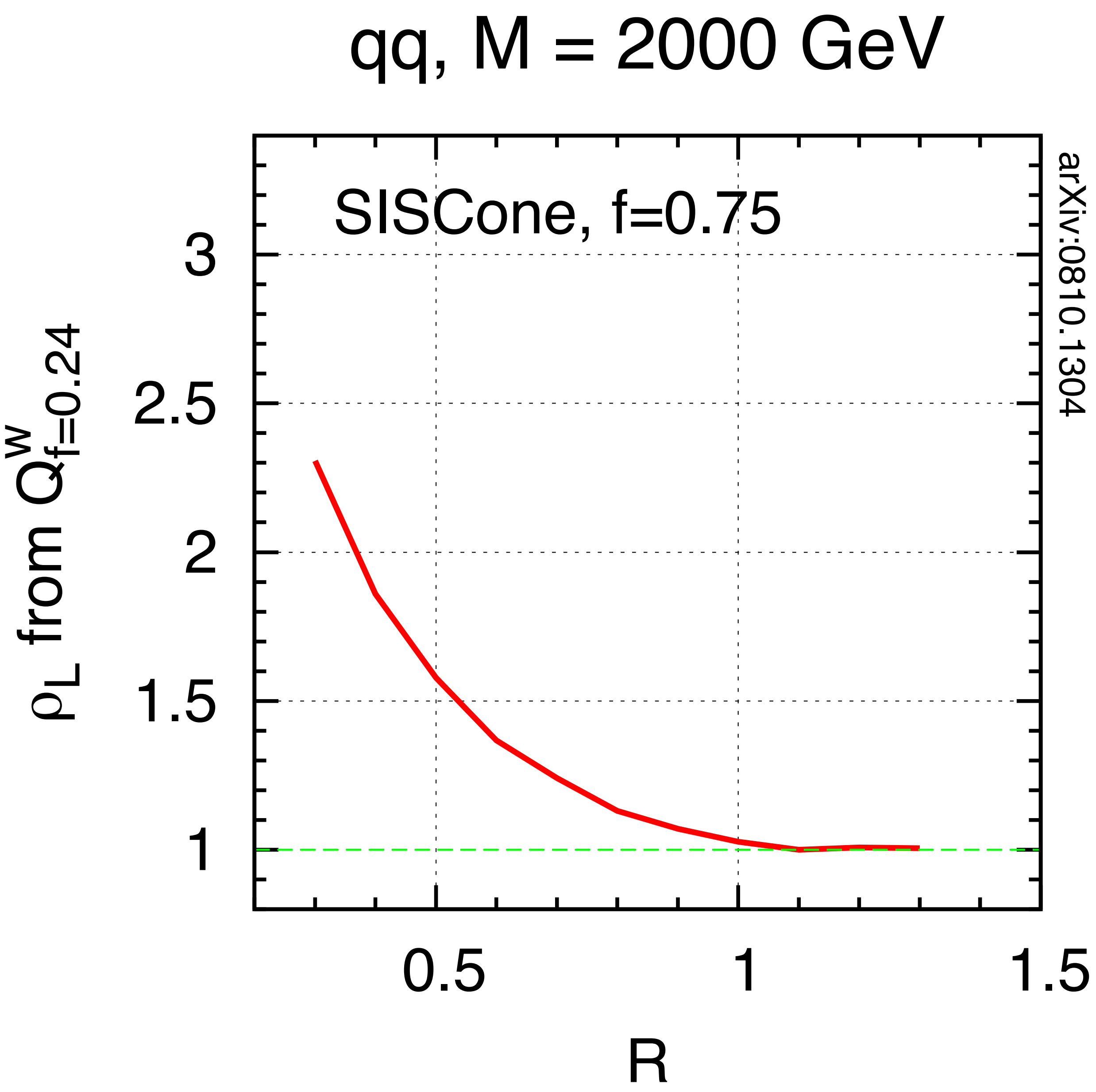
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq} = 2000}$ GeV



Best R is at minimum of curve

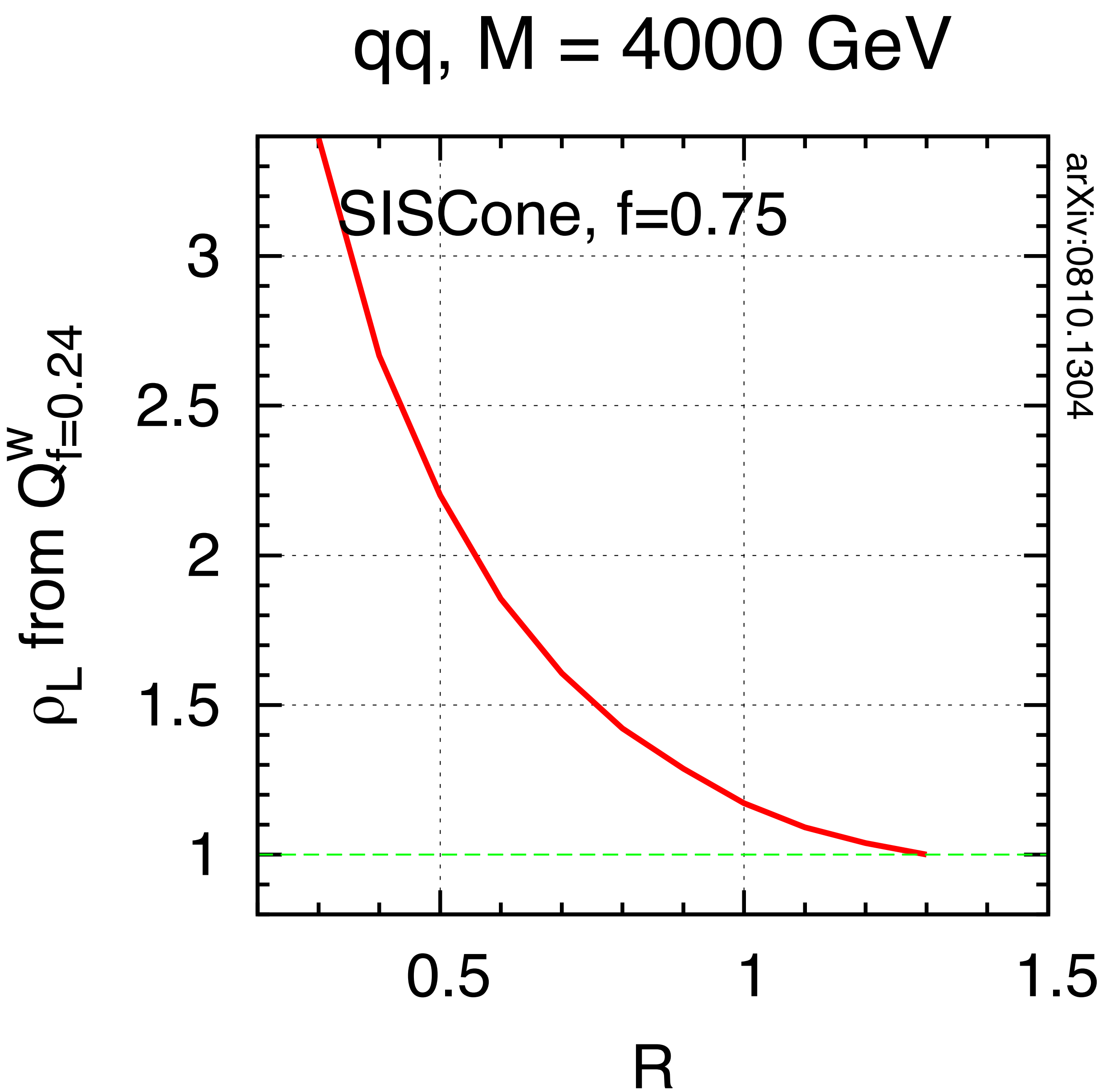
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

m_{qq} = 4000 GeV



Best *R* is at minimum of curve

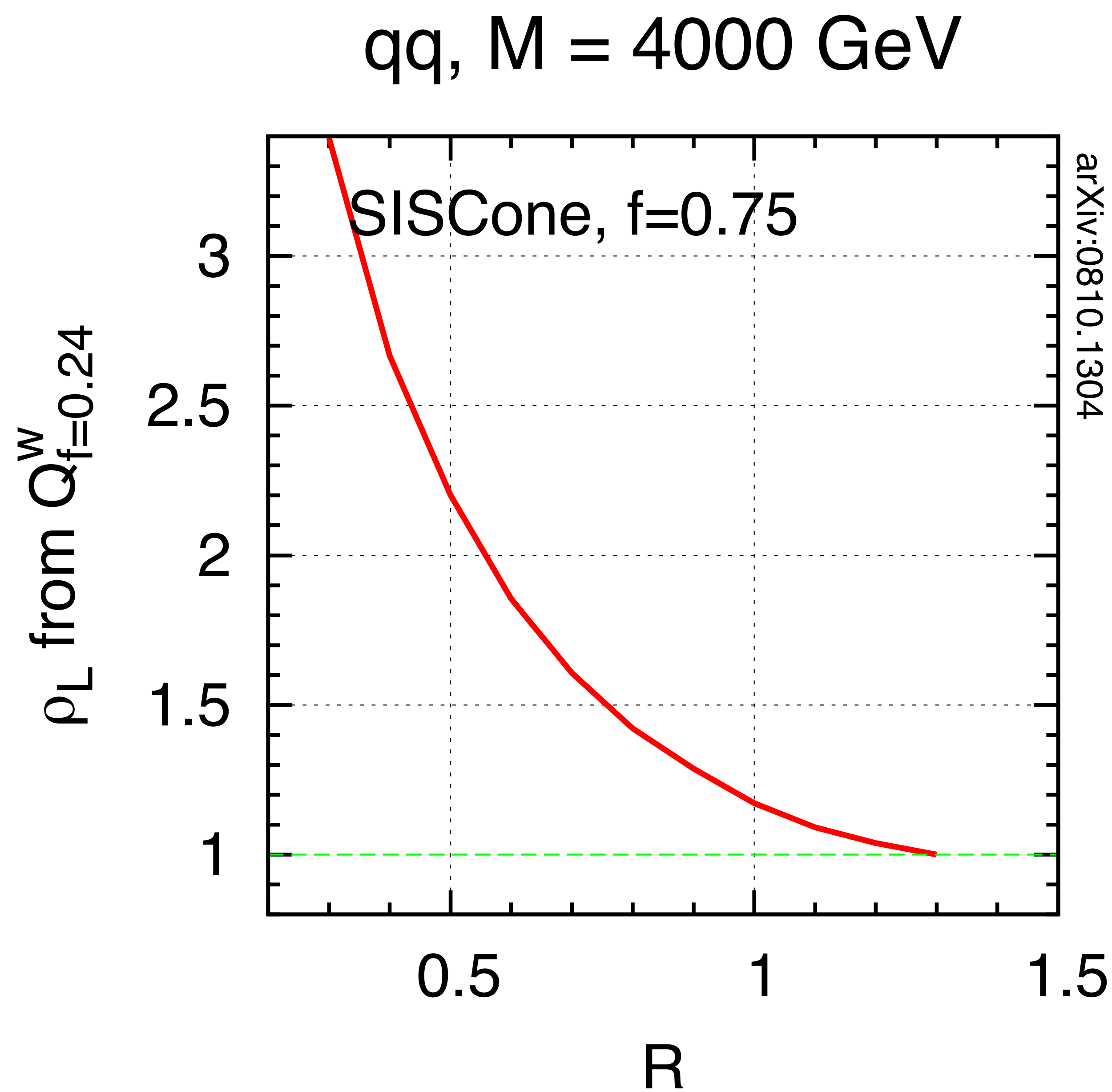
- Best *R* depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow *qq* and *gg* resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$m_{qq} = 4000$ GeV



Best R is at minimum of curve

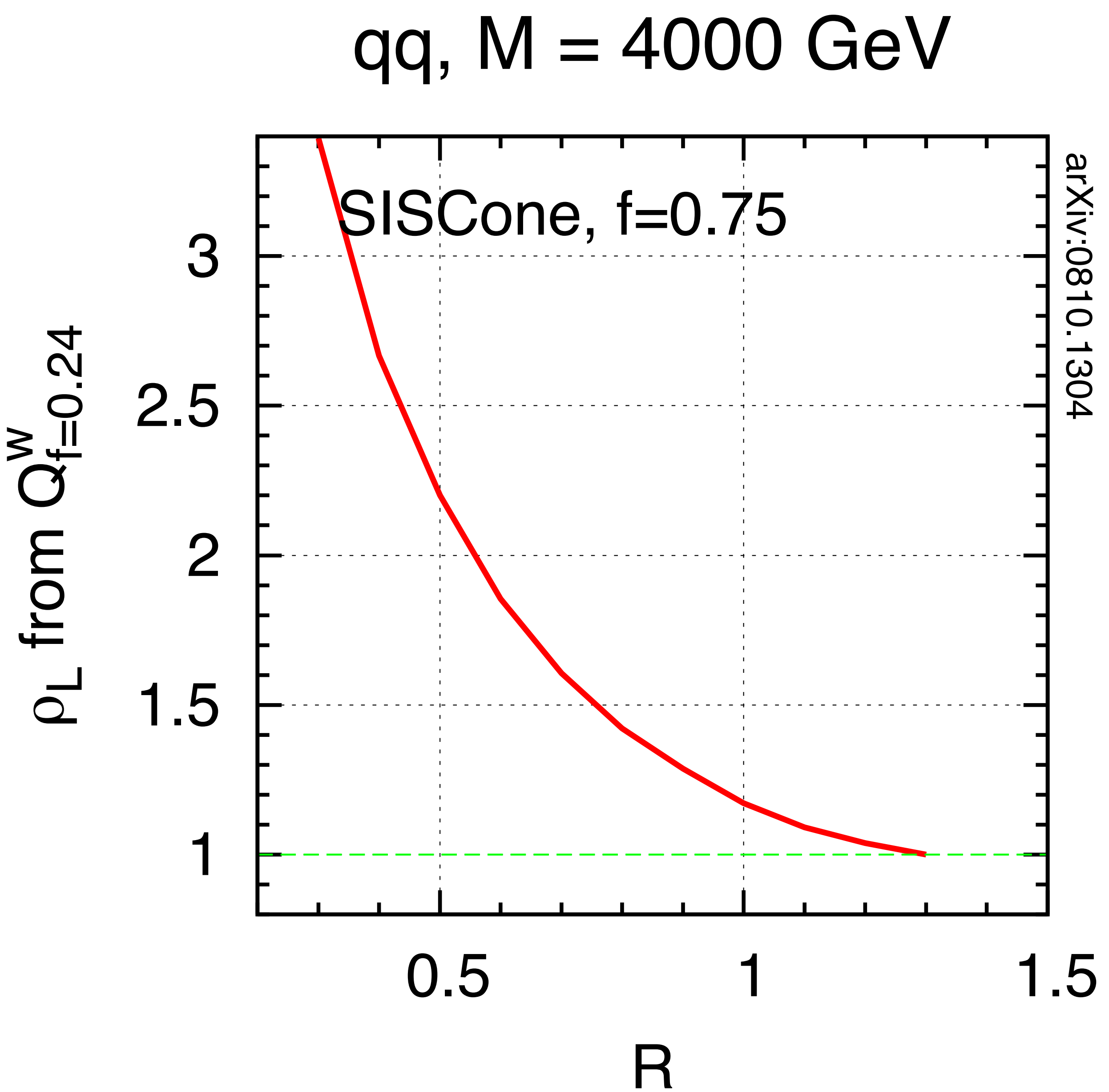
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09; Soyez '10

$\mathbf{m_{qq} = 4000\ GeV}$



Best R is at minimum of curve

- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction
  NB: current analytics too crude

NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

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