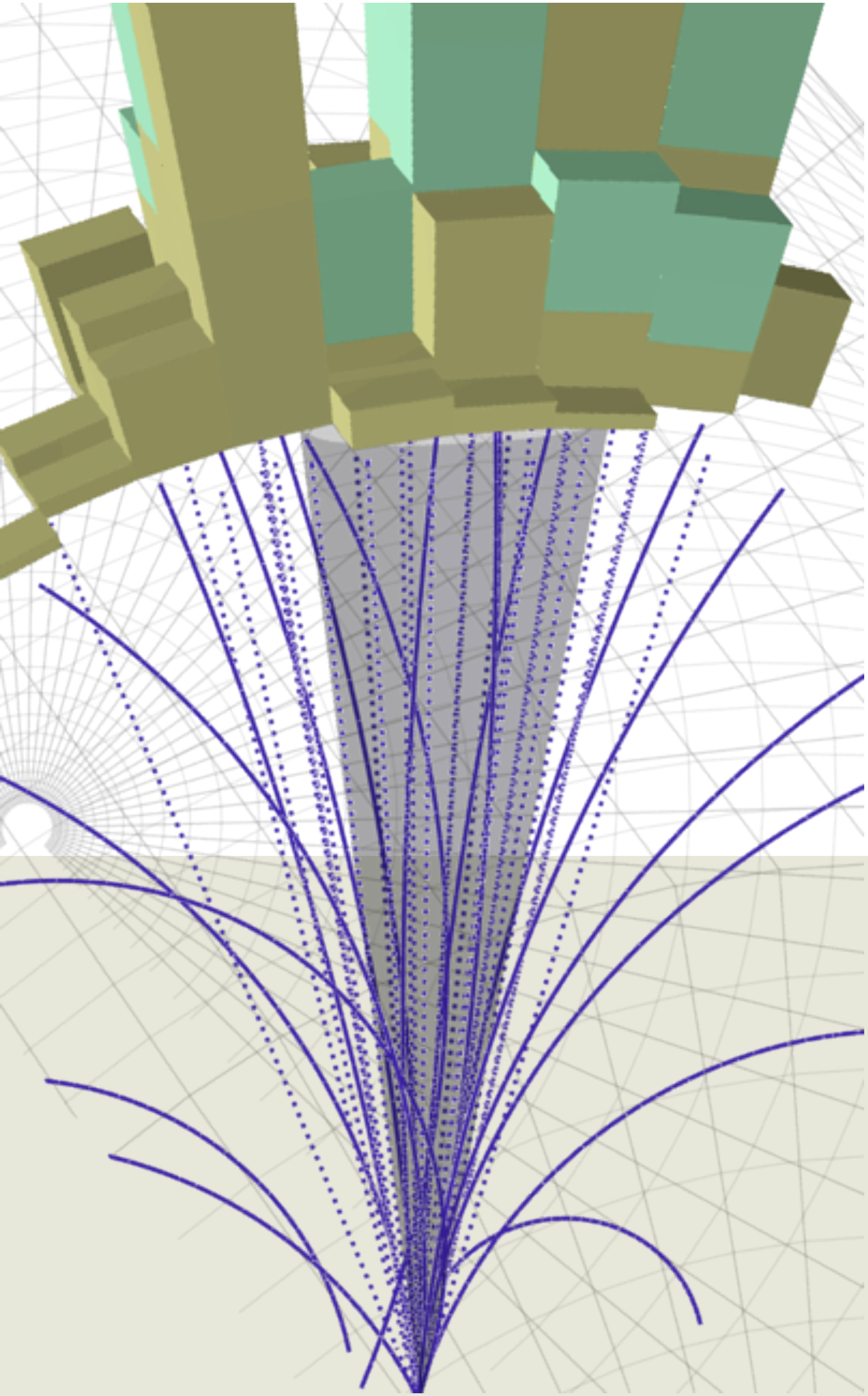

Jets and jet substructure 2: using jets

Gavin Salam (CERN)

with extensive use of material by Matteo Cacciari and Gregory Soyez

CFHEP, Beijing

April 2014

- 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

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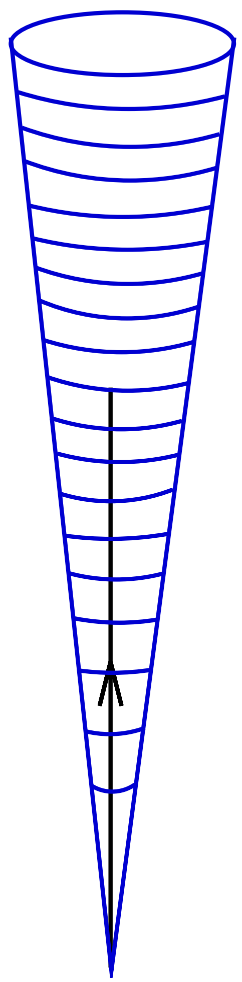
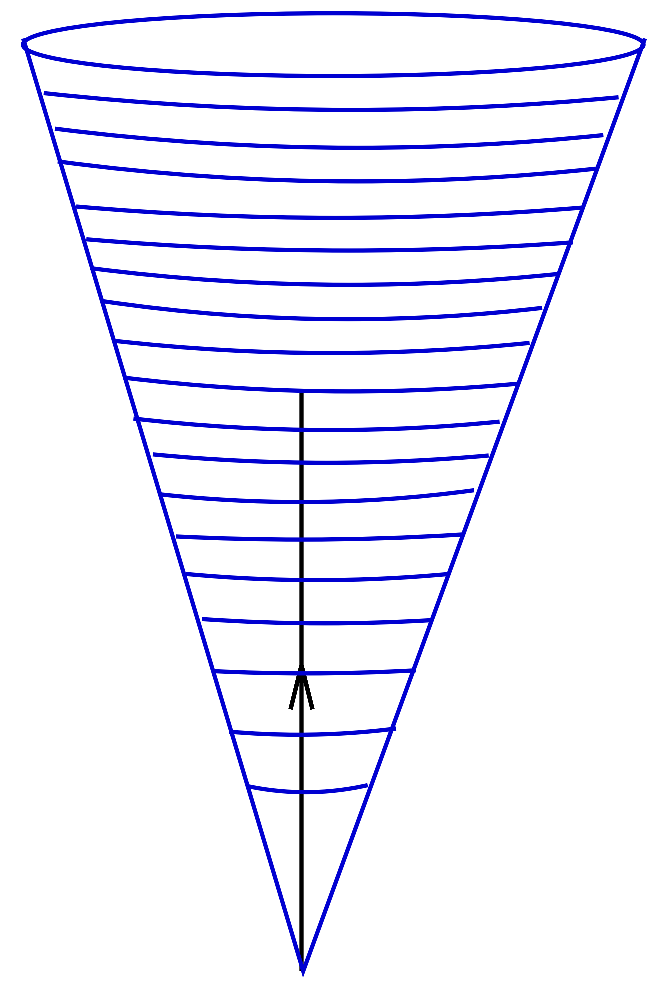
Small jet radius

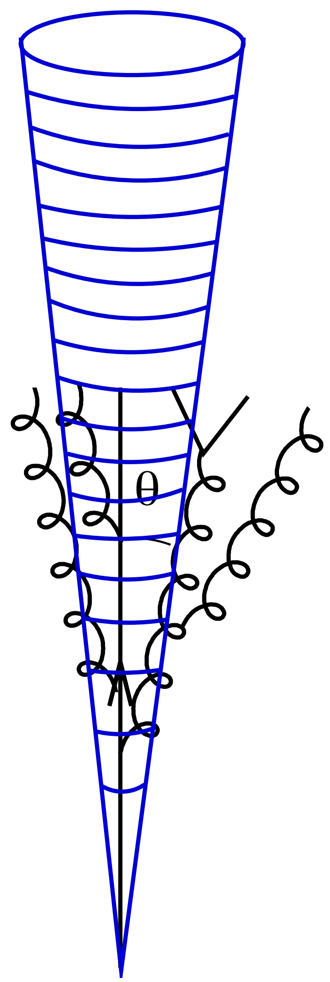


Large jet radius

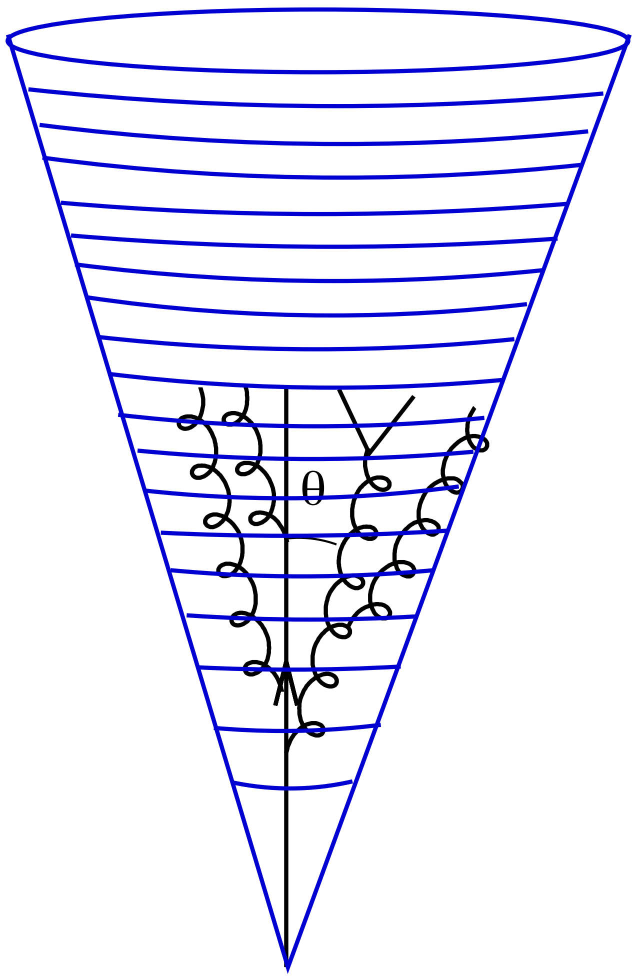


single parton @ LO: **jet radius irrelevant**

Small jet radius

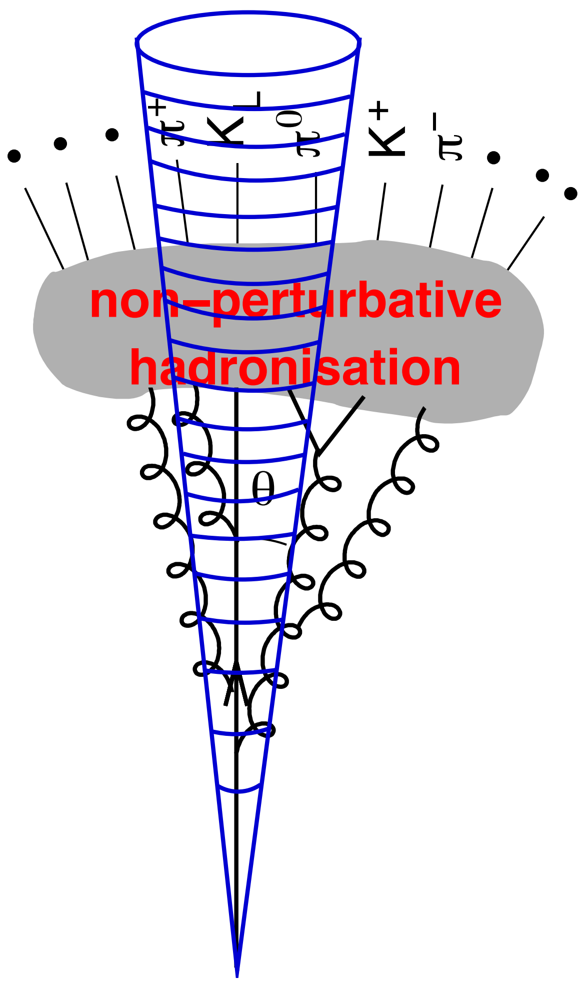


Large jet radius

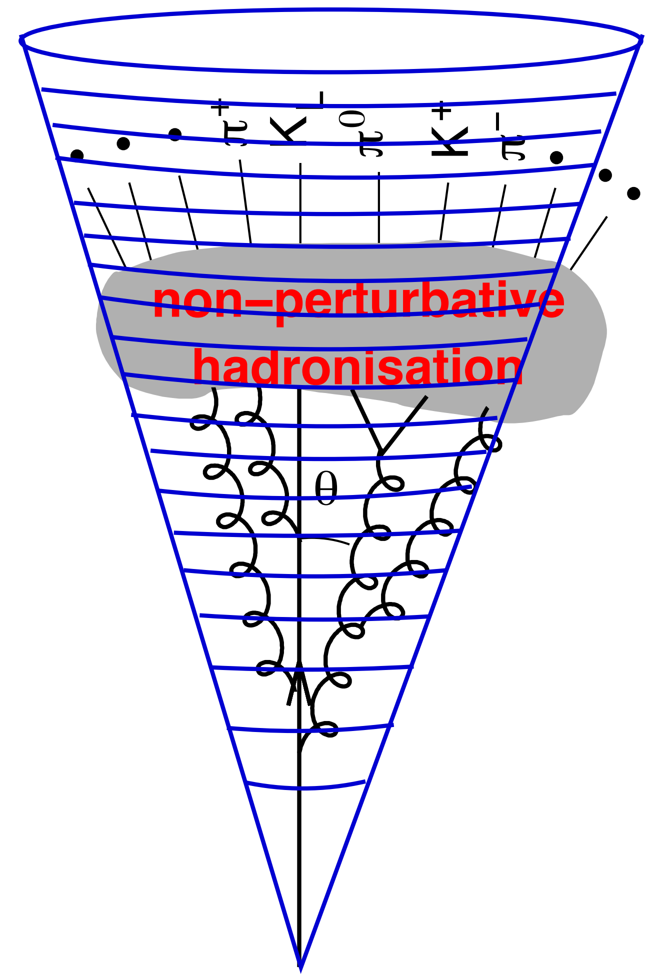


perturbative fragmentation: **large jet radius better**
(it captures more)

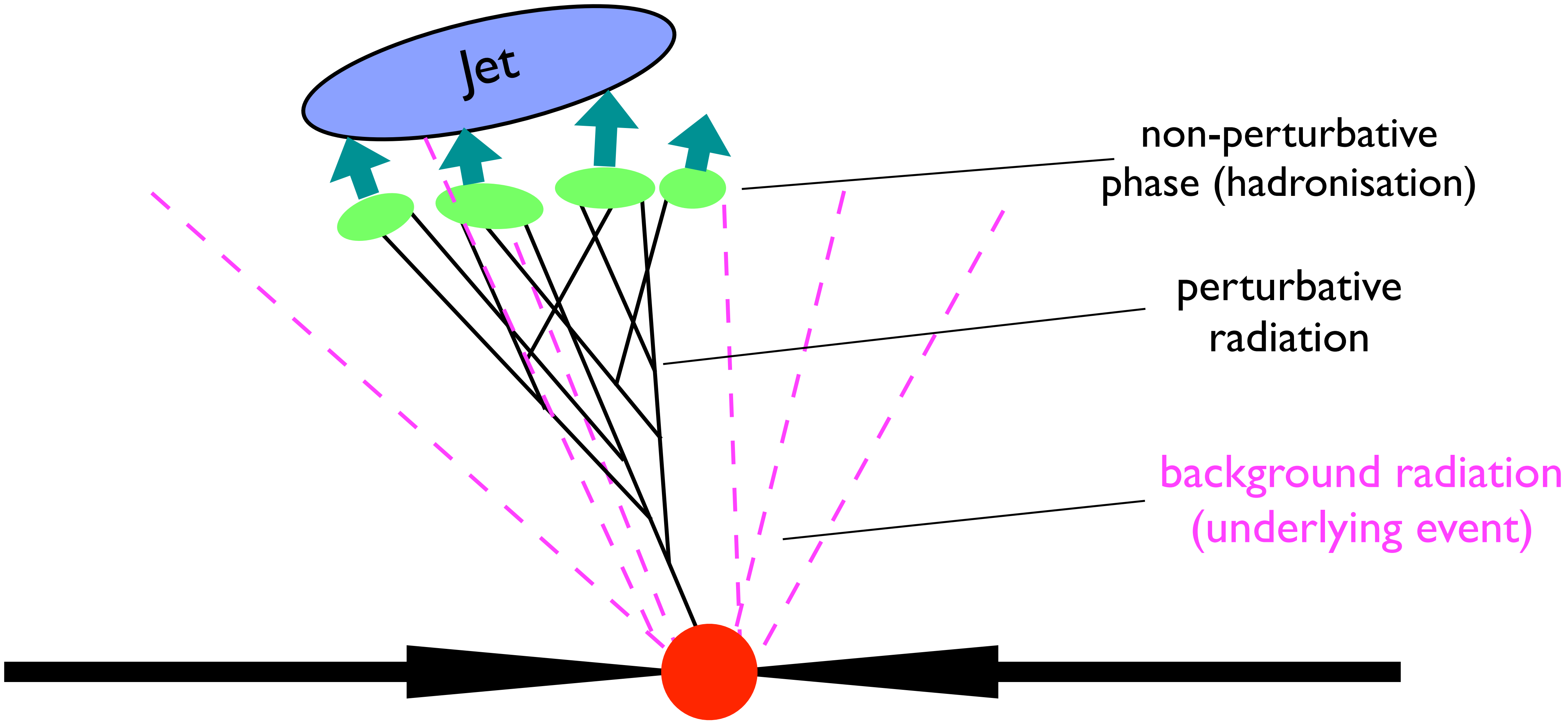
Small jet radius

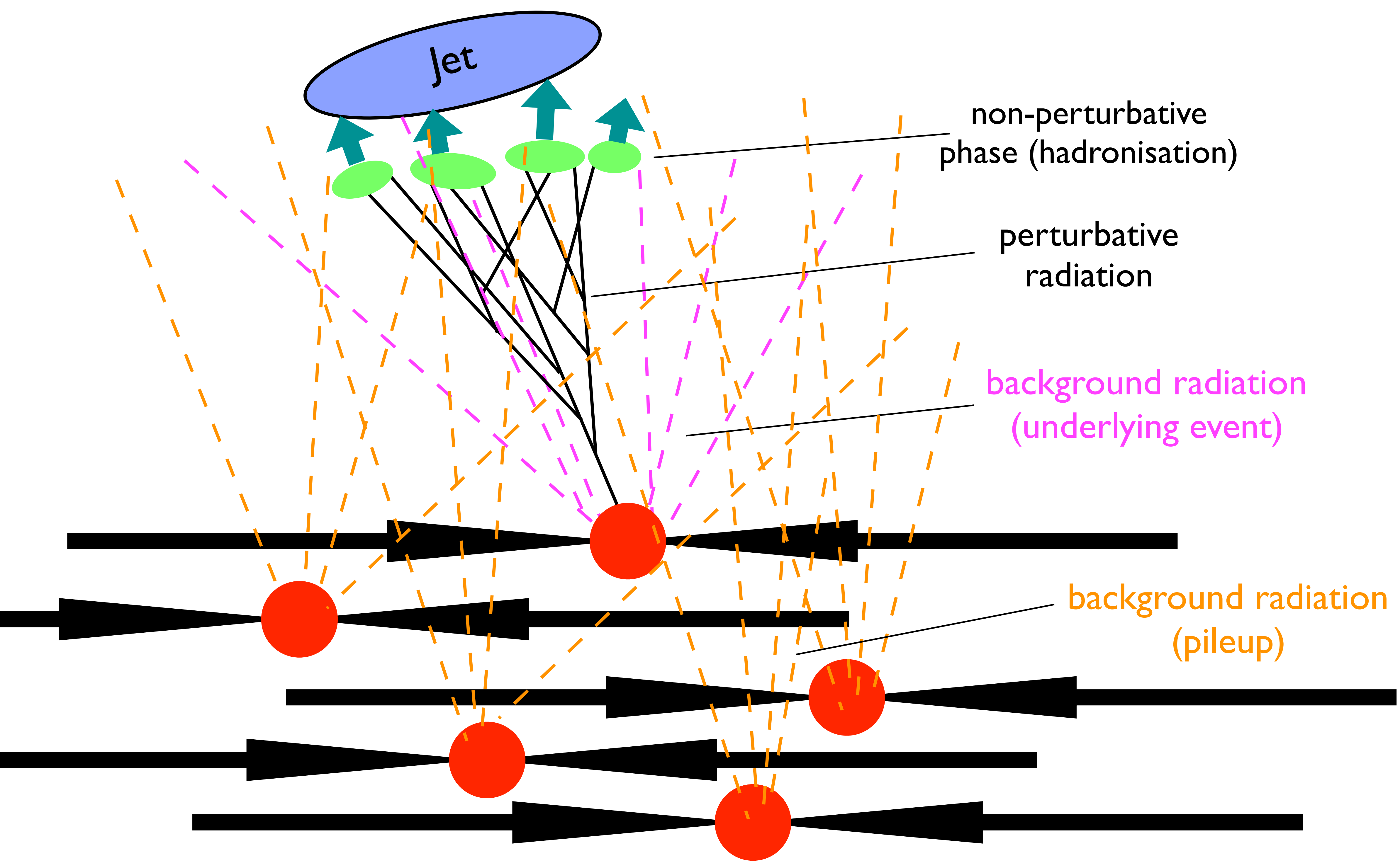


Large jet radius

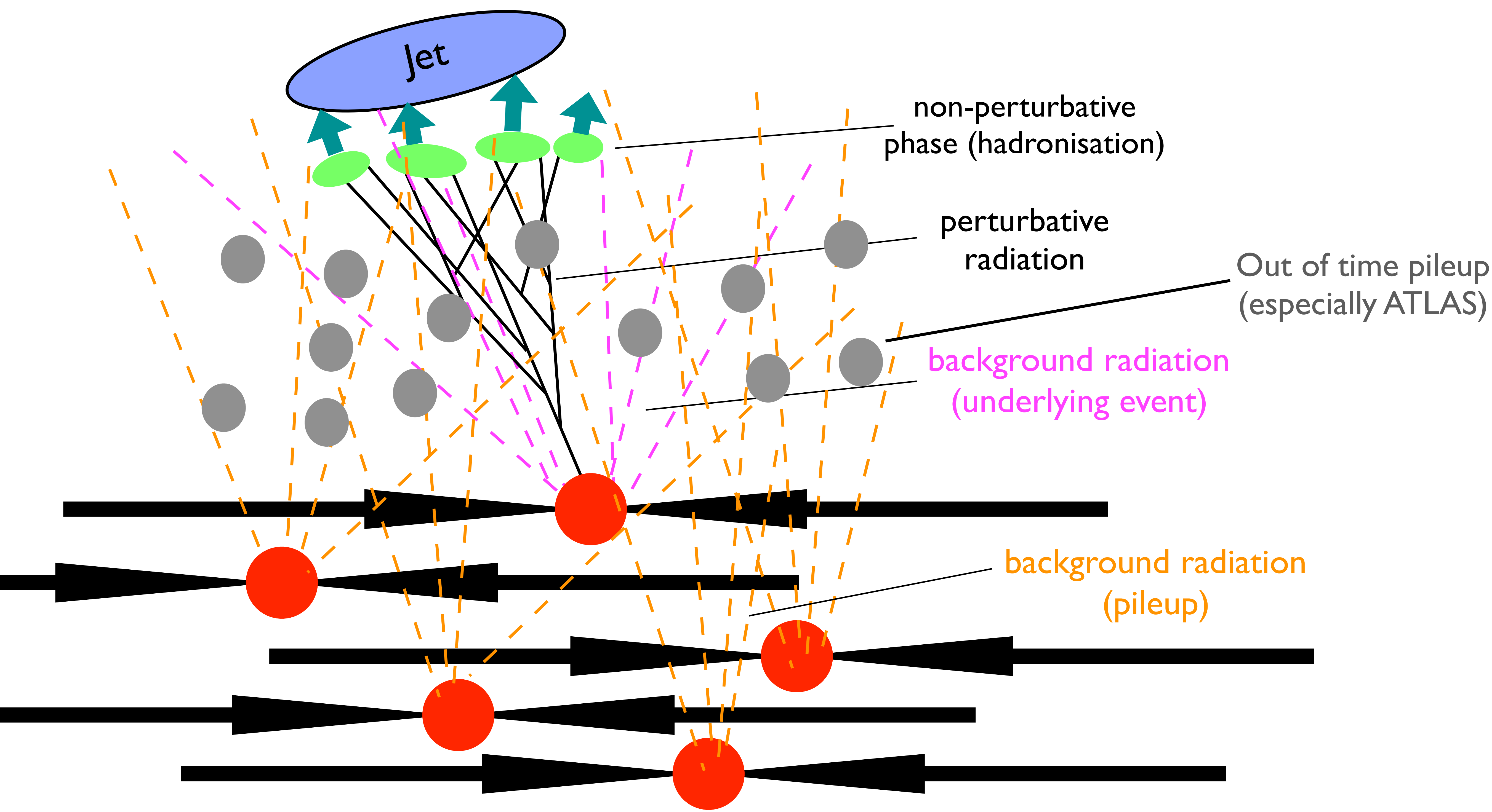


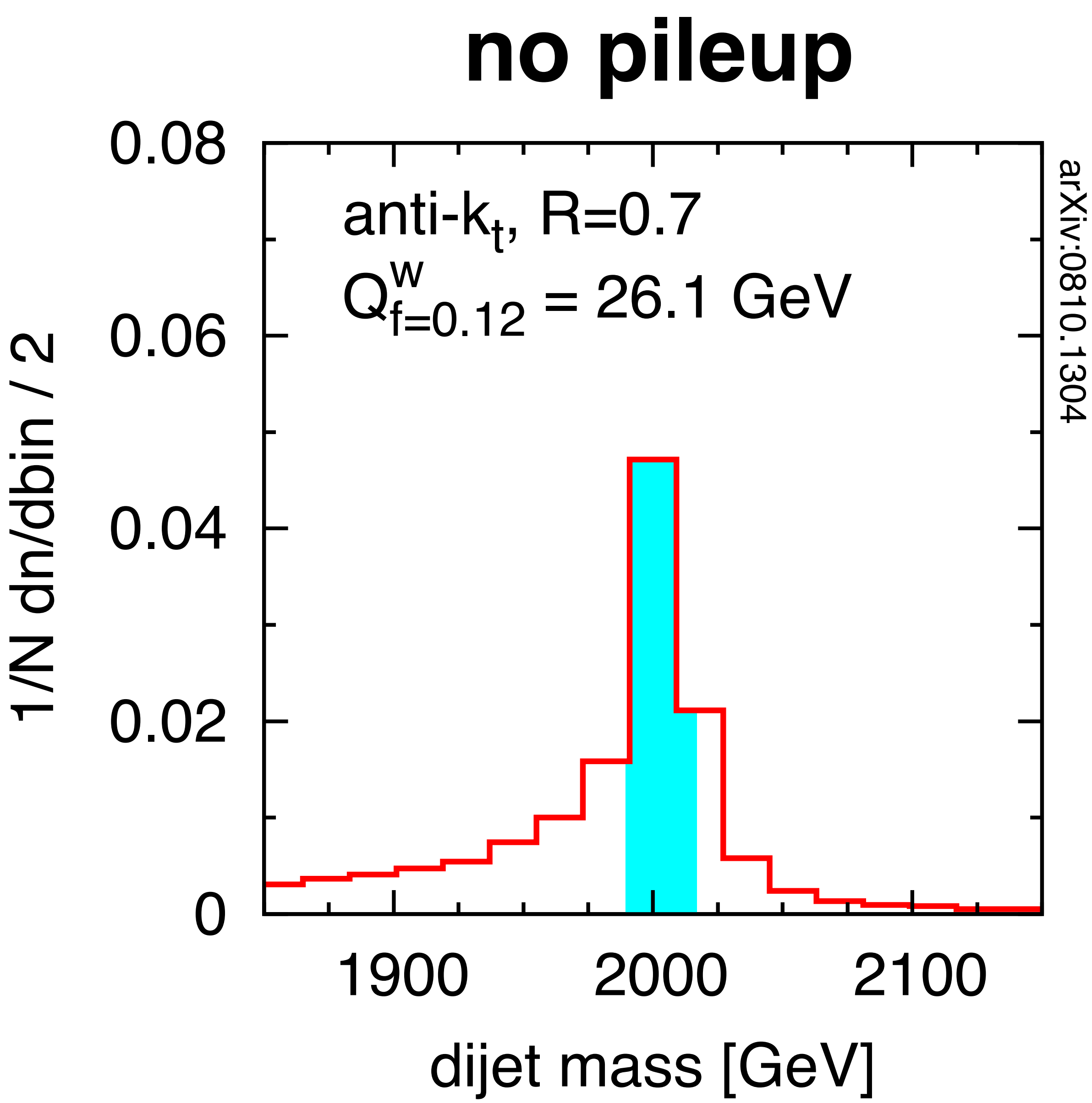
non-perturbative fragmentation: **large jet radius better**
(it captures more)


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

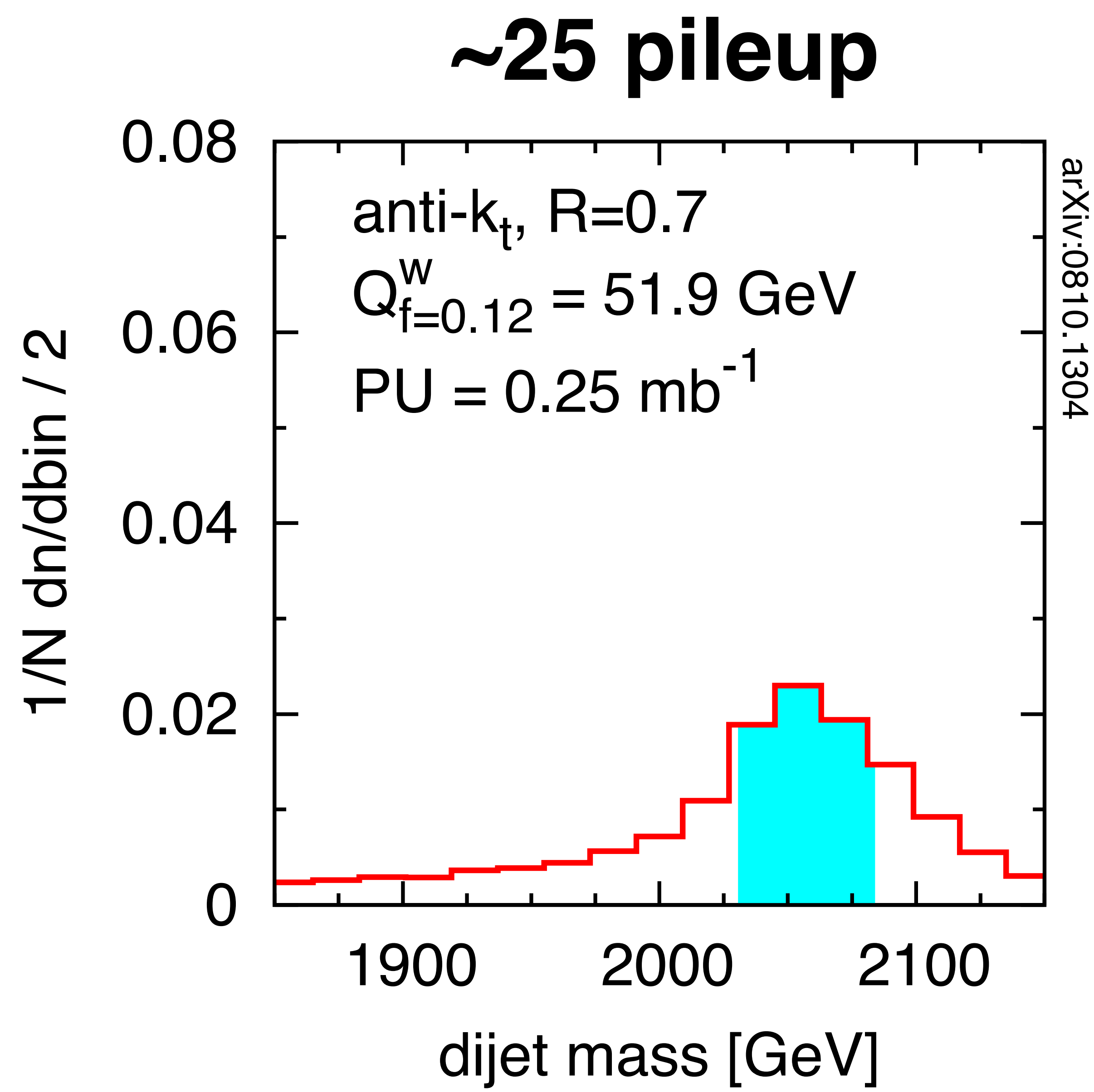

Jet
non-perturbative
phase (hadronisation)
perturbative
radiation
background radiation
(underlying event)
background radiation
(pileup)

Pileup


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



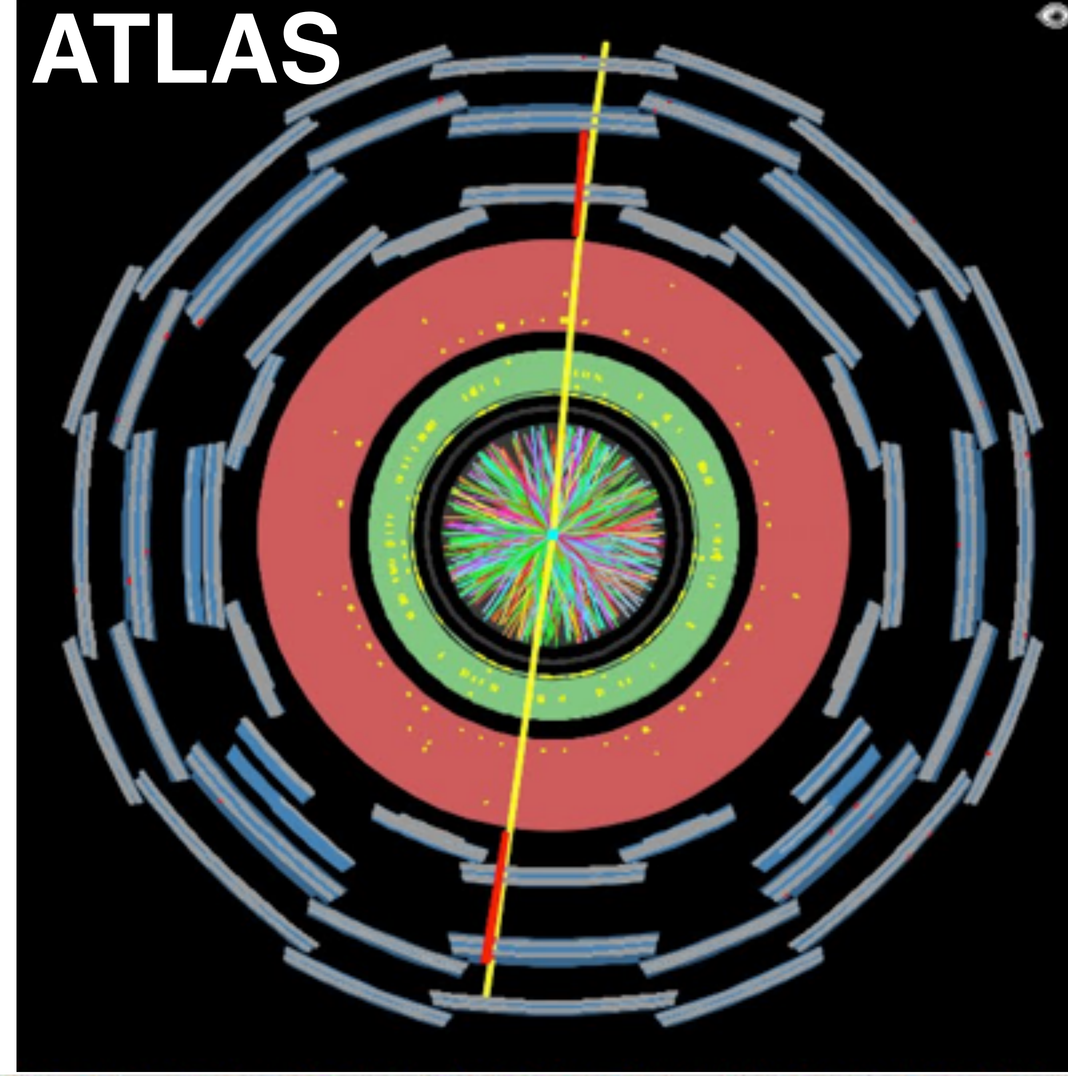
no pileup
anti-kt, R=0.7
Qwf=0.12 = 26.1 GeV
0.08
0.06
0.04
0.02
0
1/N dn/dbin / 2
1900
2000
2100
dijet mass [GeV]
arXiv:0810.1304



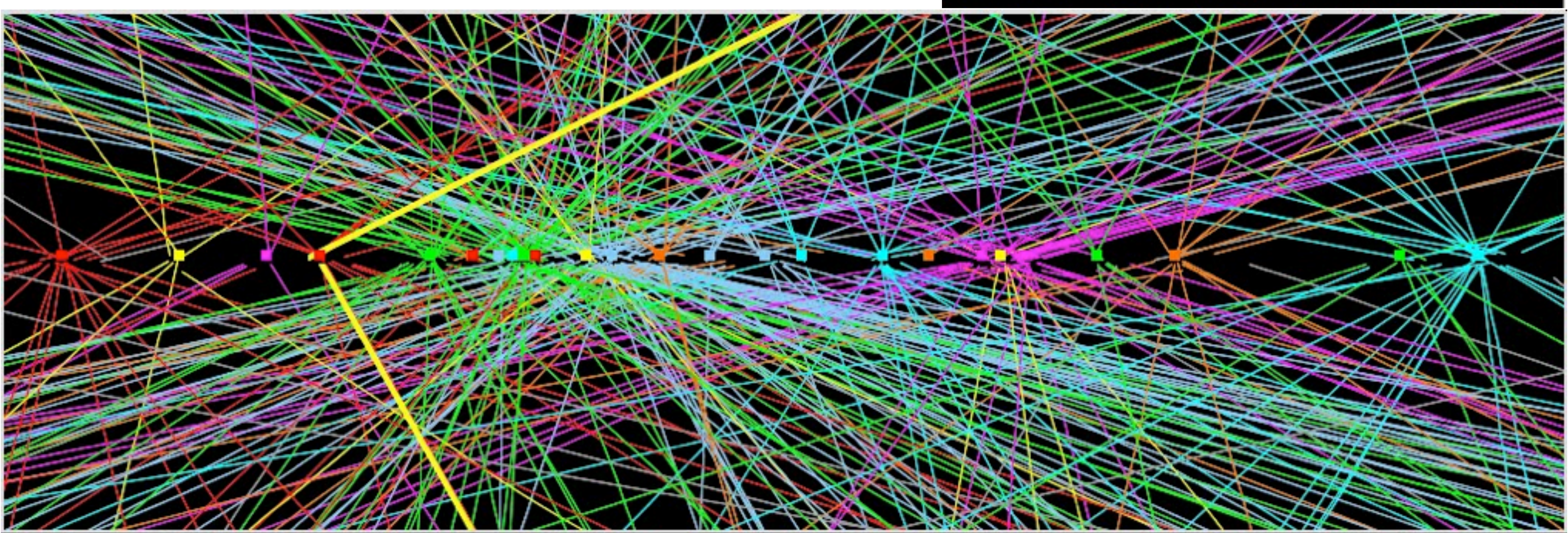
~25 pileup
anti-kt, R=0.7
Qwf=0.12 = 51.9 GeV
PU = 0.25 mb-1
0.08
0.06
0.04
0.02
0
1/N dn/dbin / 2
1900
2000
2100
dijet mass [GeV]
arXiv:0810.1304

Pileup for real

~ 20 m



a few cm



What goes into the jets?

ATLAS

Calorimeter towers, after pre-clustering them into "topoclusters"

CMS

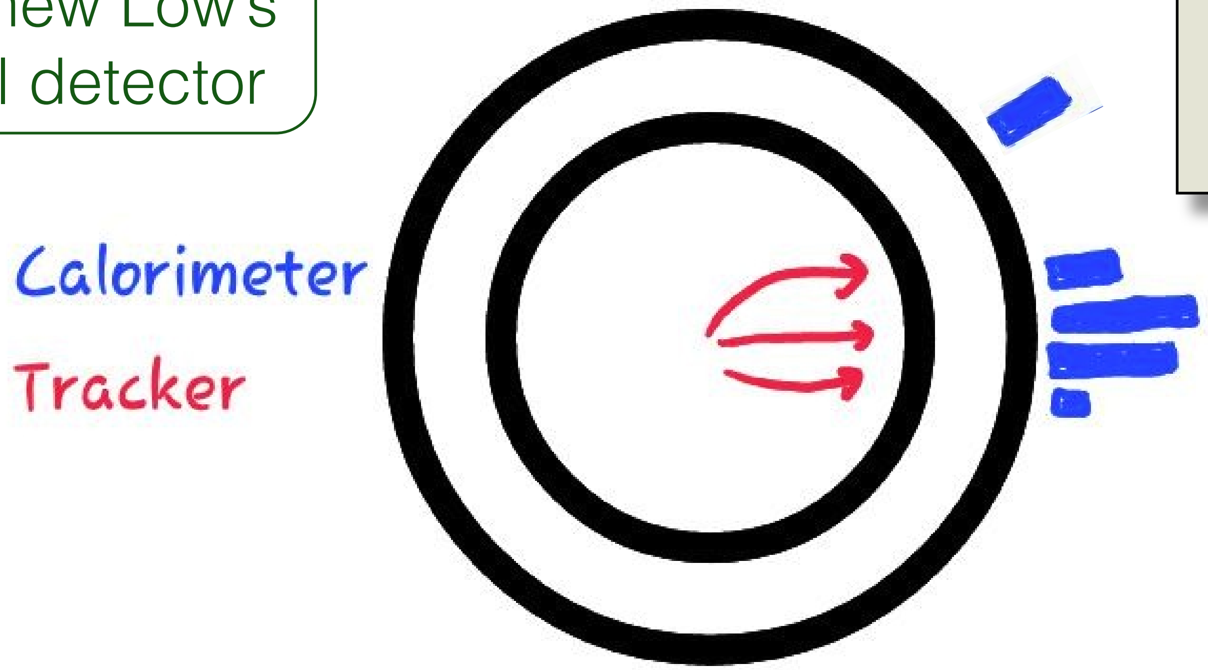
"**Particle flow**" objects ~

1) charged tracks

2) neutrals: calorimeter towers not associated with charged tracks

(or leftover bits of calo if $E_{calo} - E_{track} \gg \sqrt{E_{calo}}$)

Matthew Low's ideal detector



A CMS particle-flow expert would shudder at this description

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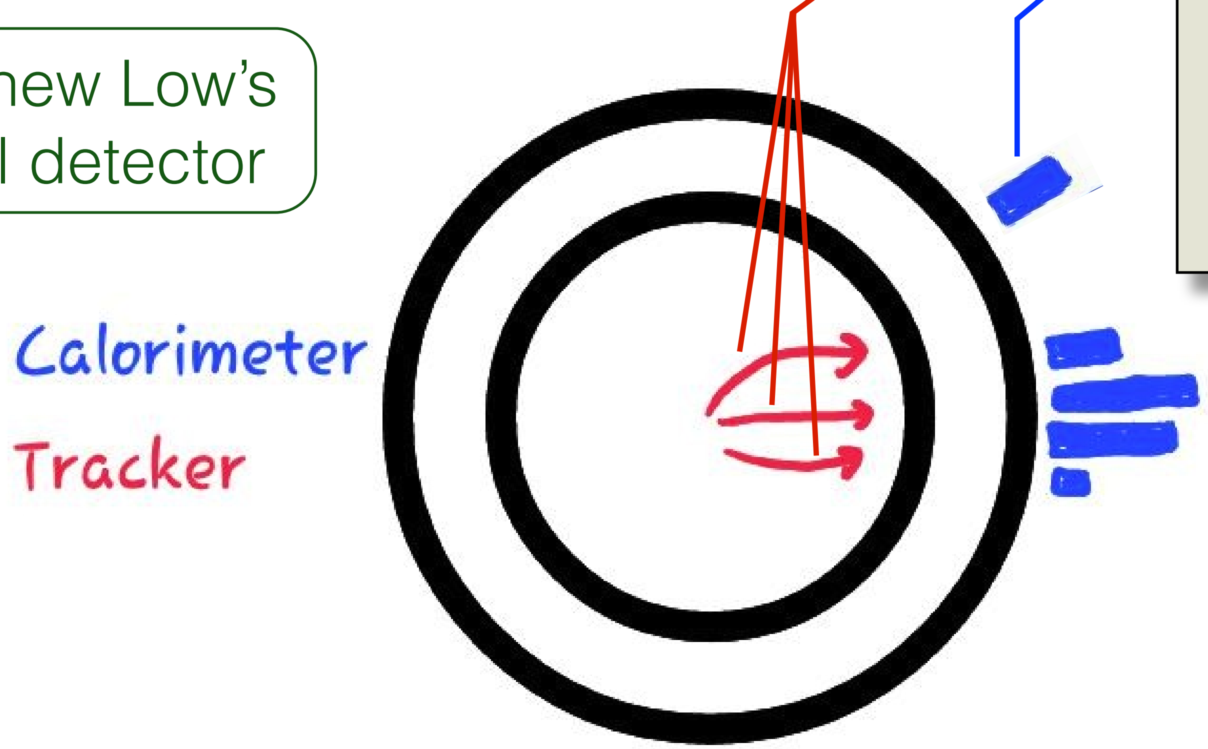


A CMS particle-flow expert would shudder at this description

How do you remove pileup (PU)?

1. Offset method

[Tevatron / old ATLAS]

Count # of pileup vertices (n_{pileup}):

$$p_{t,\text{jet}}^{\text{subtracted}} = p_{t,\text{jet}} - c \times n_{\text{pileup}}$$

$c \sim 0.5$ GeV

2. CMS

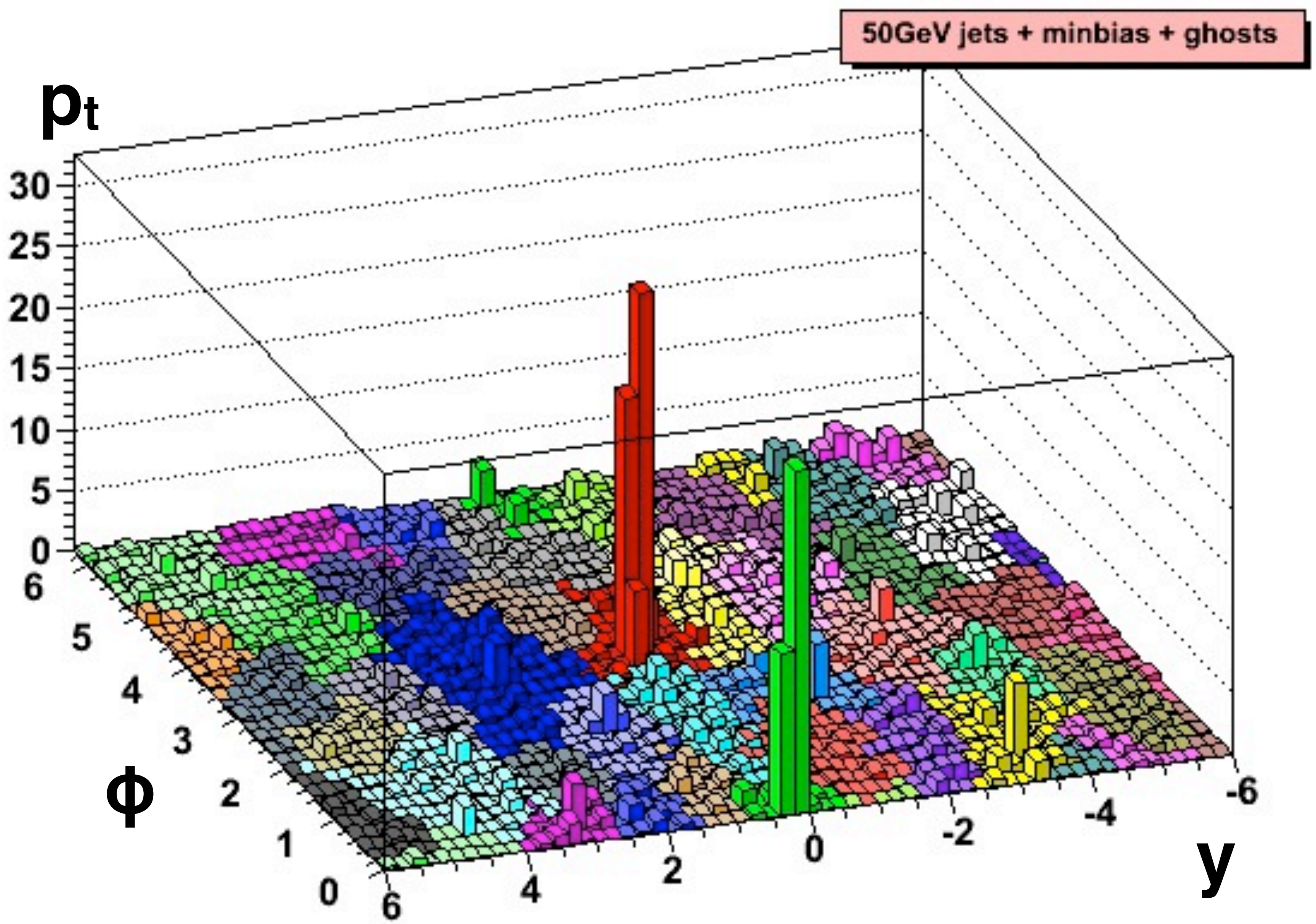
Throw out charged tracks not from the main primary vertex

Use area/median(FastJet) method for neutral PU

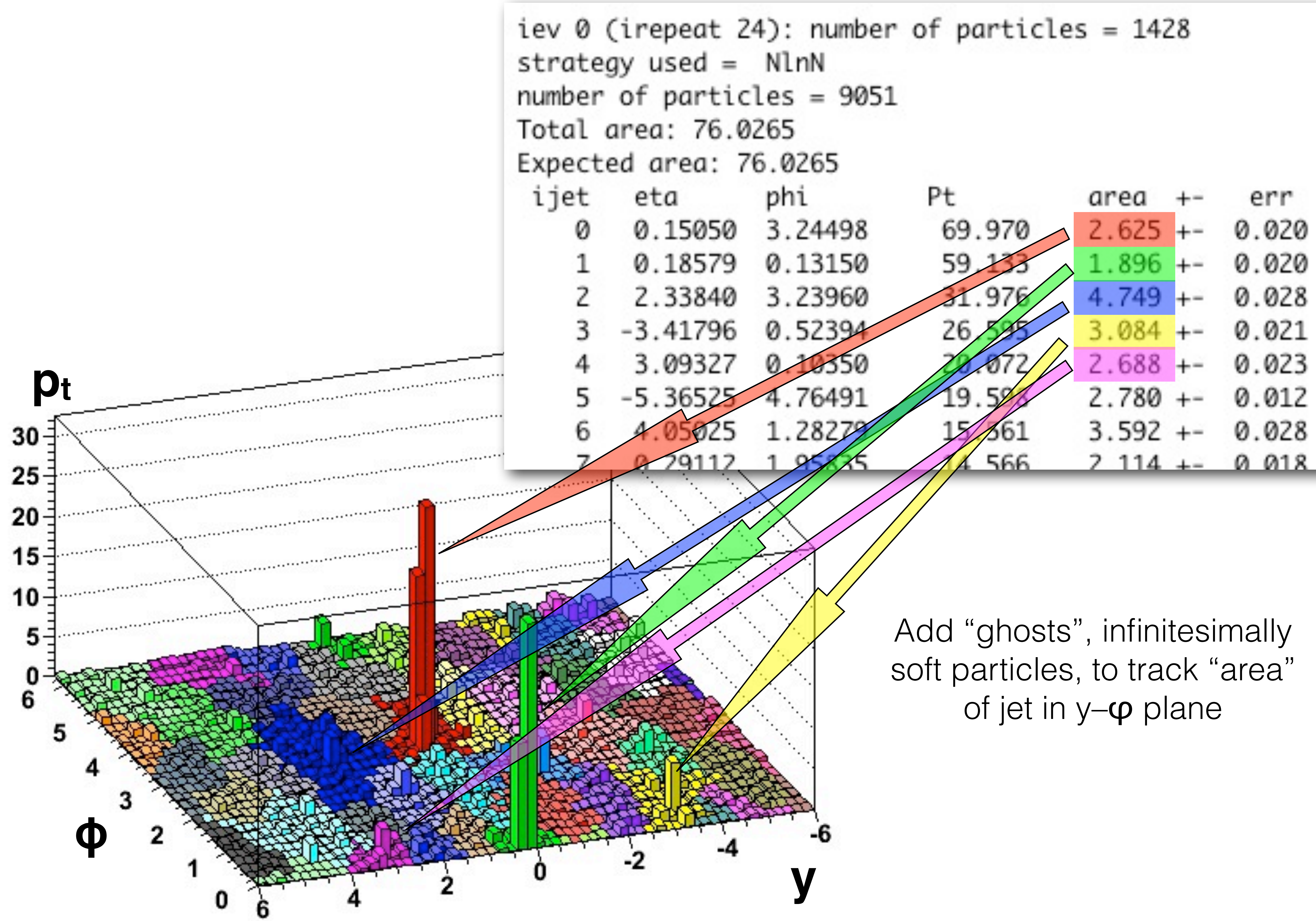
3. Area/median (FastJet) method

Determine density of pileup p_t / unit area $\equiv \rho$

$$p_{t,\text{jet}}^{\text{subtracted}} = p_{t,\text{jet}} - \rho \times A_{\text{jet}}$$



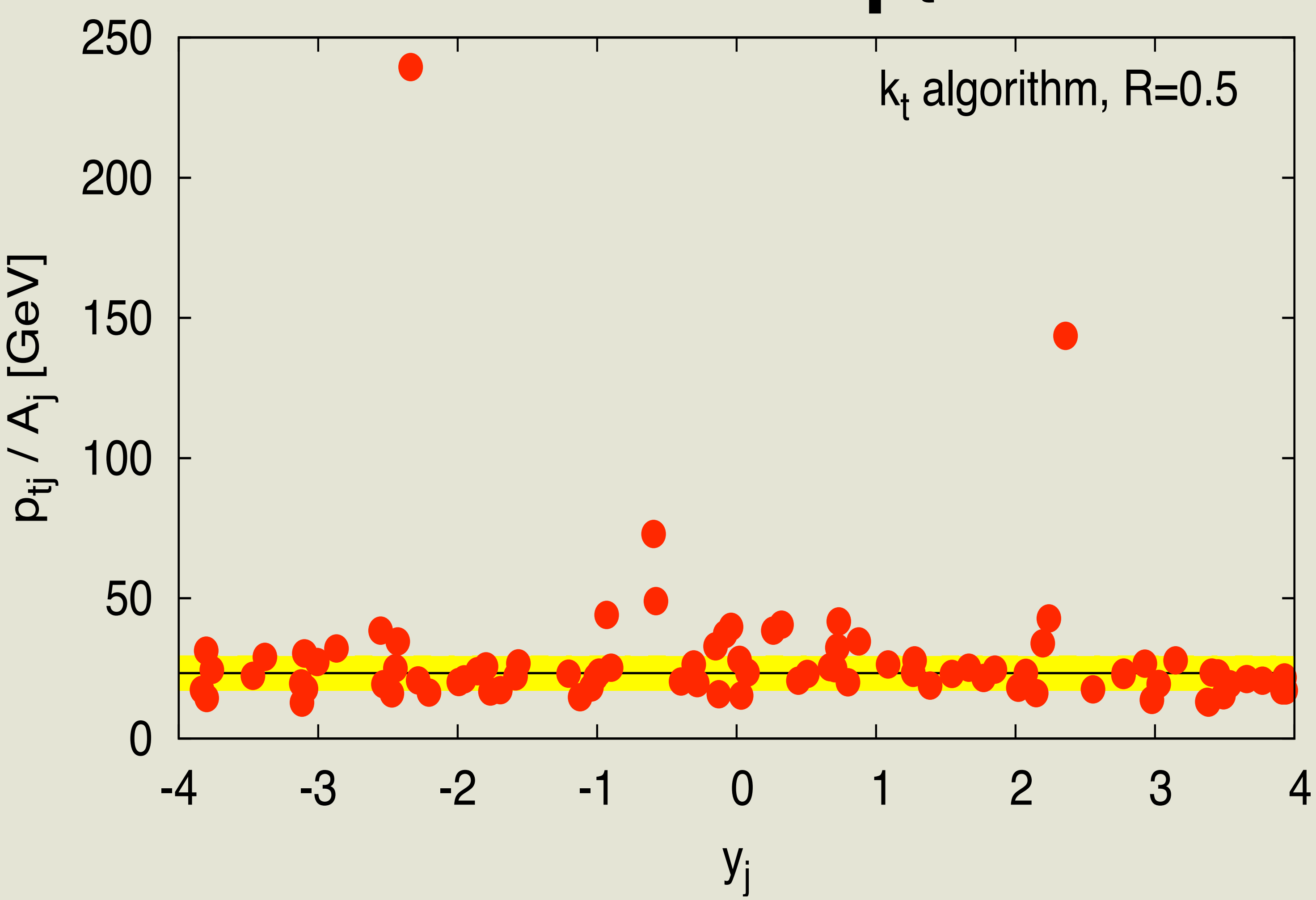
Add “ghosts”, infinitesimally soft particles, to track “area” of jet in y–φ plane



Add “ghosts”, infinitesimally soft particles, to track “area” of jet in y–φ plane

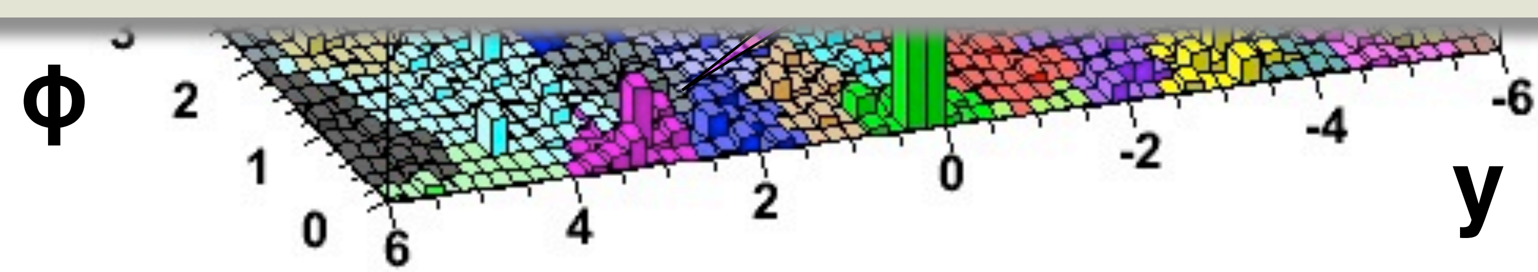
```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
```

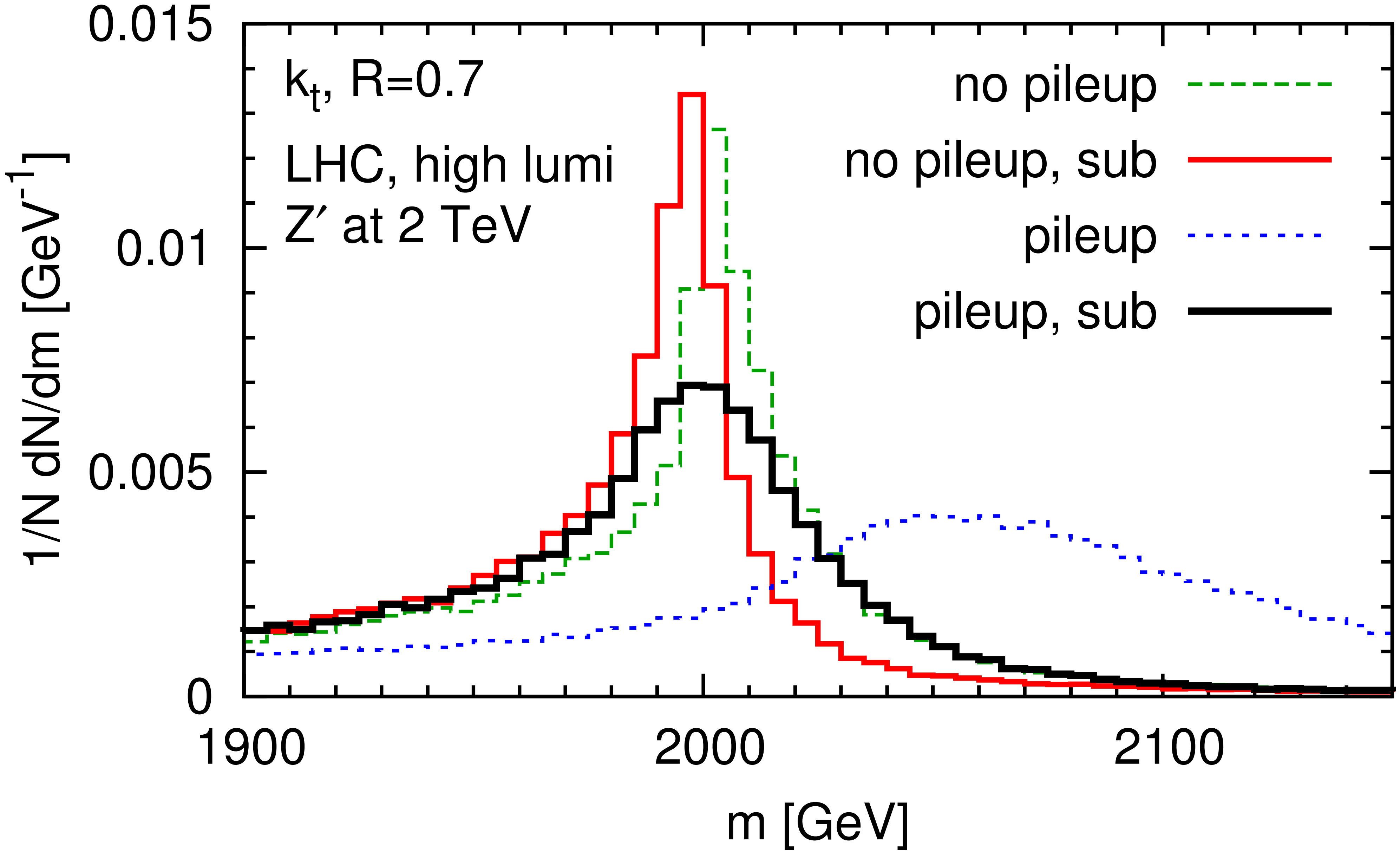
Most jets are from pileup; all have similar **p_t / area**



Estimate **ρ** for a given event as

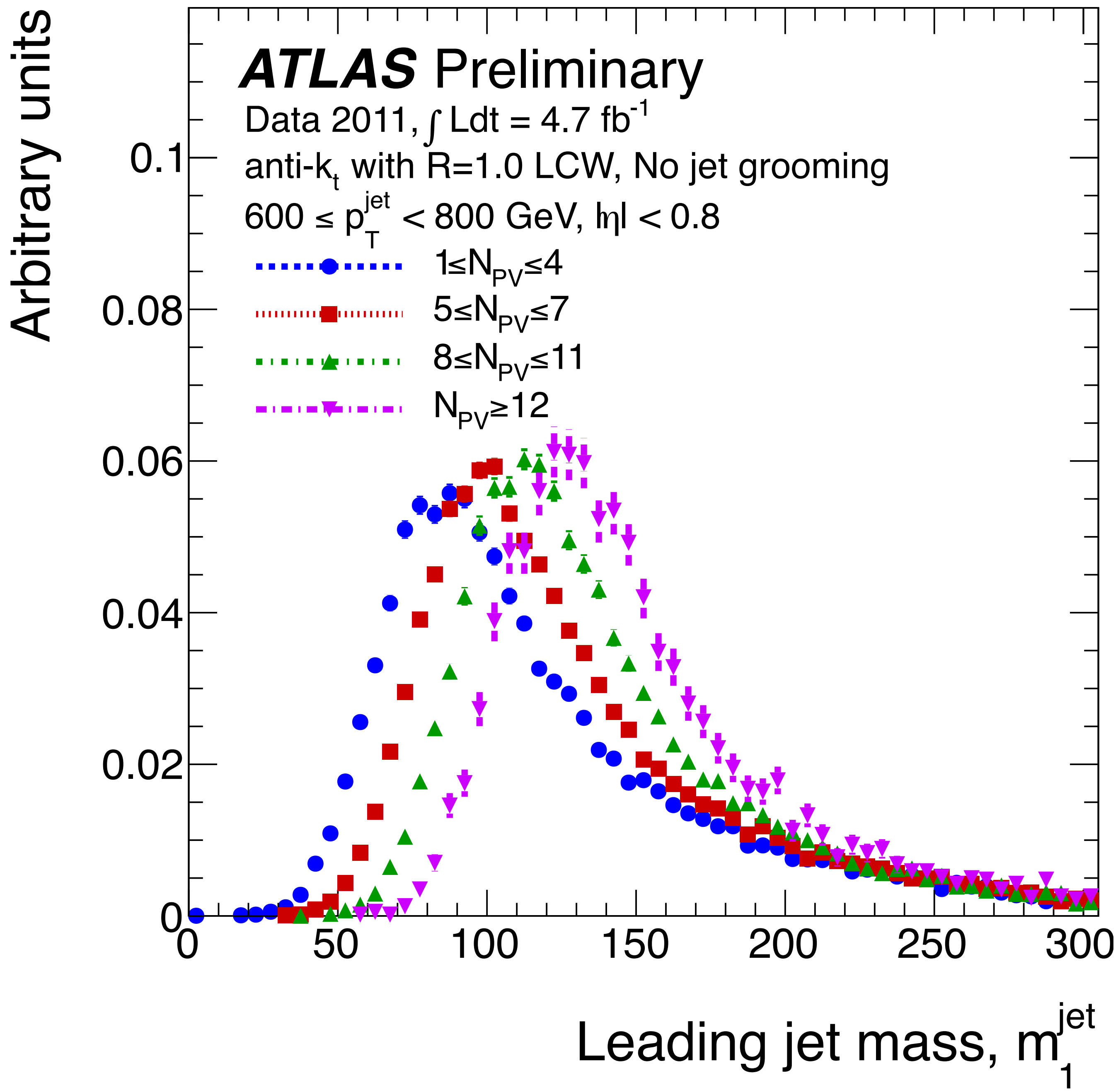
$$\rho = \underset{\text{jets}}{\text{median}} \left\{ \frac{p_{t,\text{jet}}}{A_{\text{jet}}} \right\}$$





Used in CMS for neutral part of PU, and (I think) for recent ATLAS results

Some observables particularly sensitive to PU



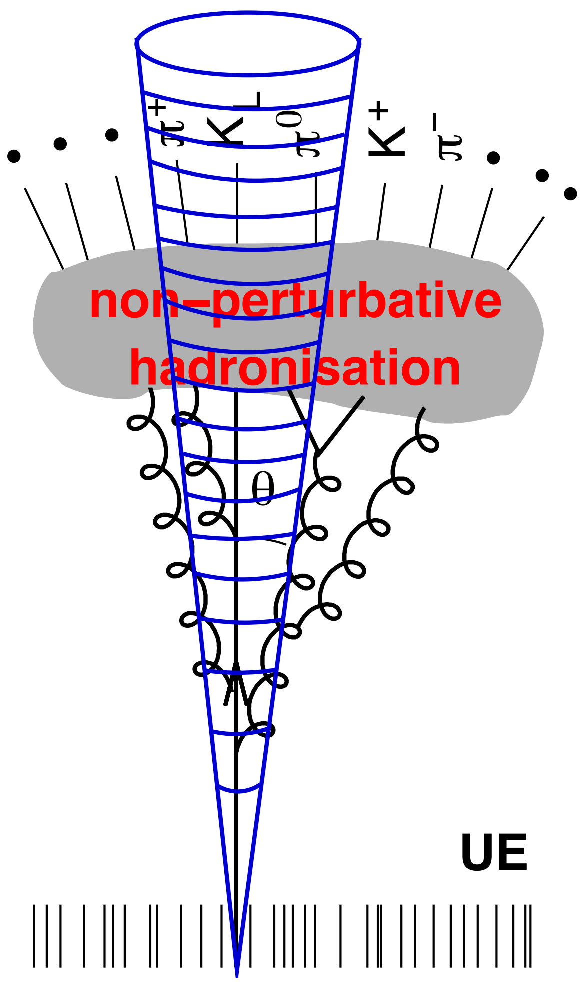
(a) Data: anti-k_t, $R = 1.0$: Ungroomed

E.g. **jet mass**

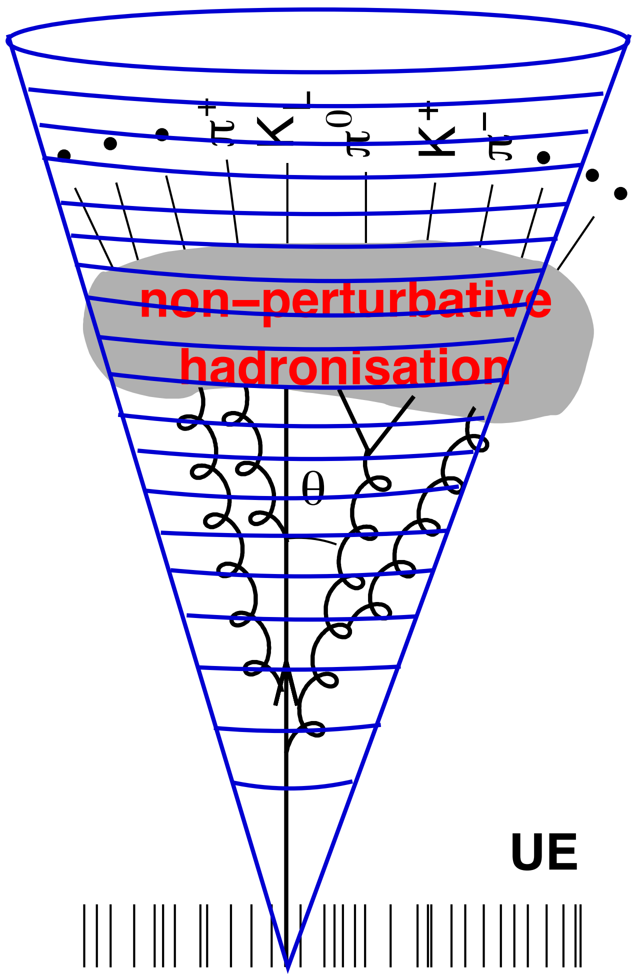
For these, plain pileup subtraction is only OKish

But why are we interested in the jet mass?

Small jet radius

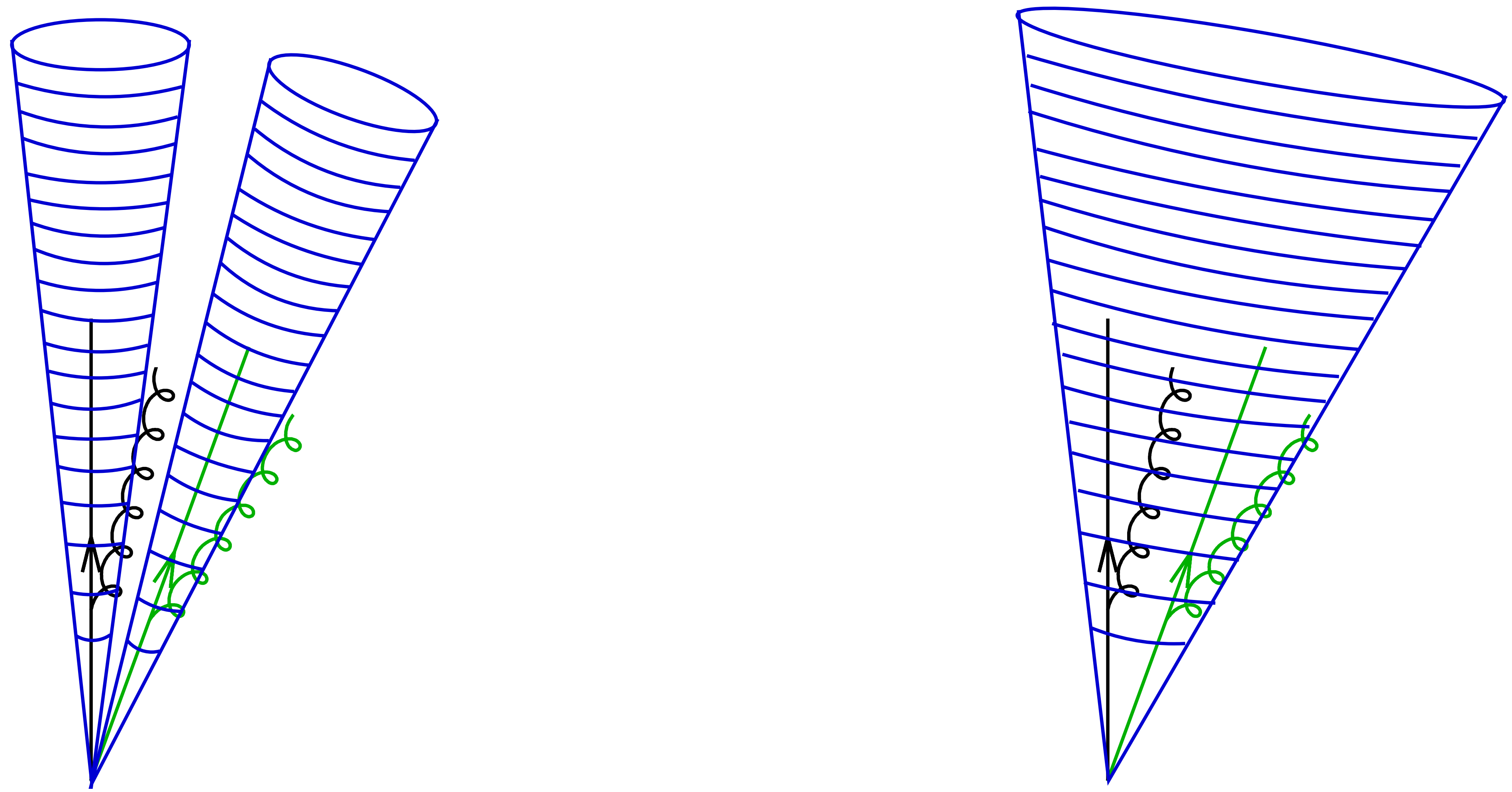


Large jet radius



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

Small jet radius **Large jet radius**



multi-hard-parton events: **small jet radius better**

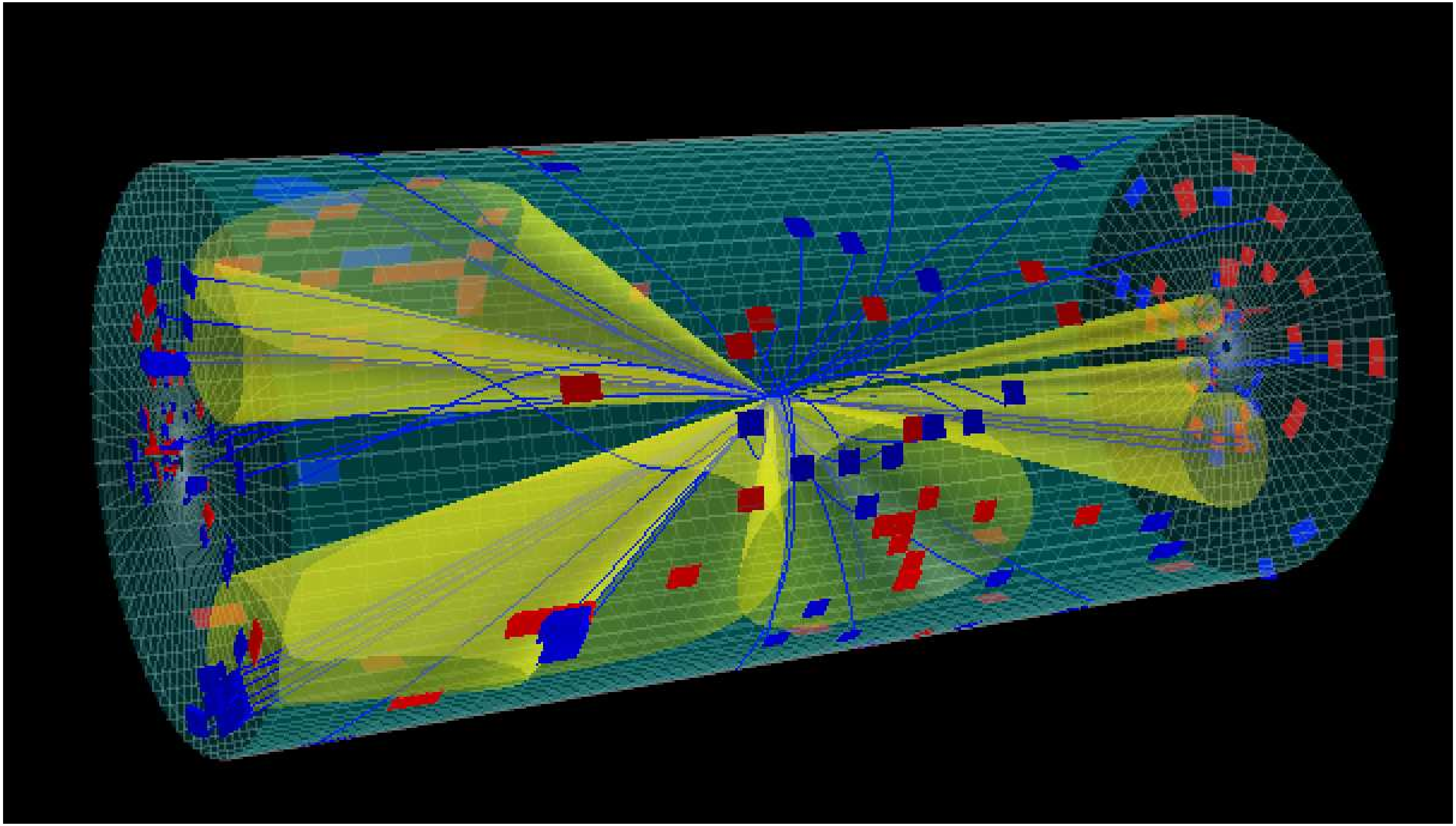
(it resolves partons more effectively)

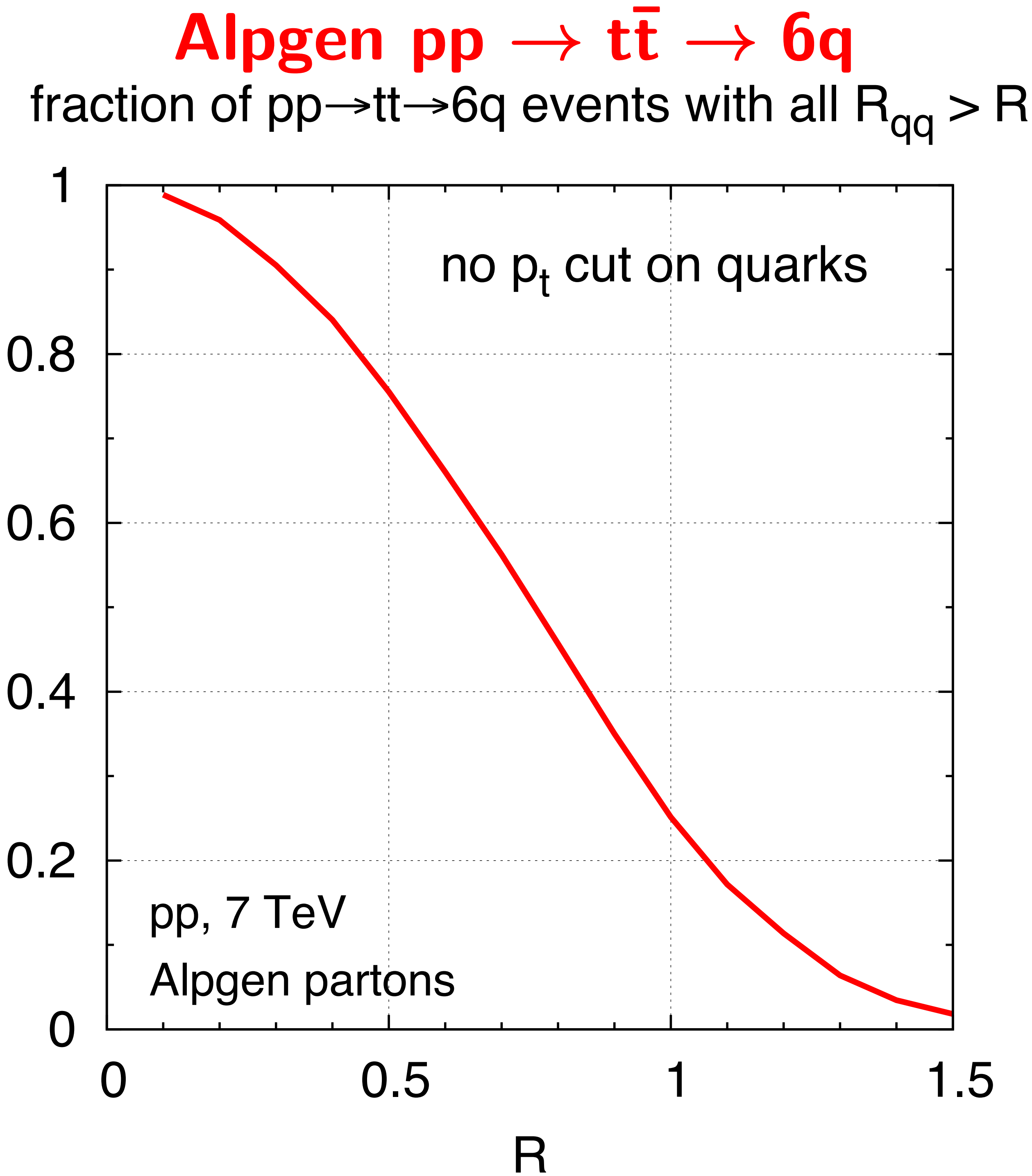
Can we capture all quarks and gluons?

Should we capture all quarks and gluons?

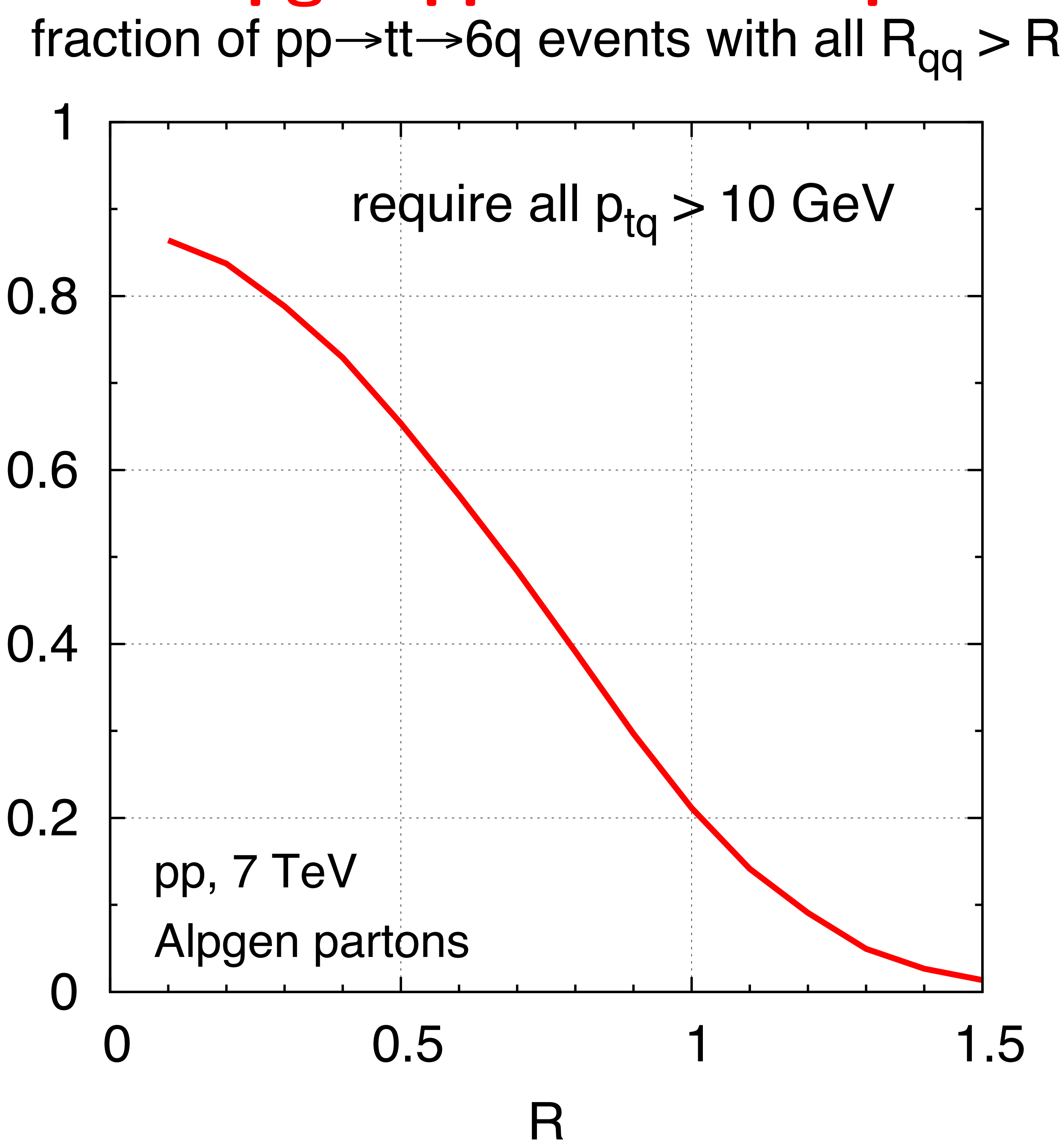
$pp \to t\bar{t}$

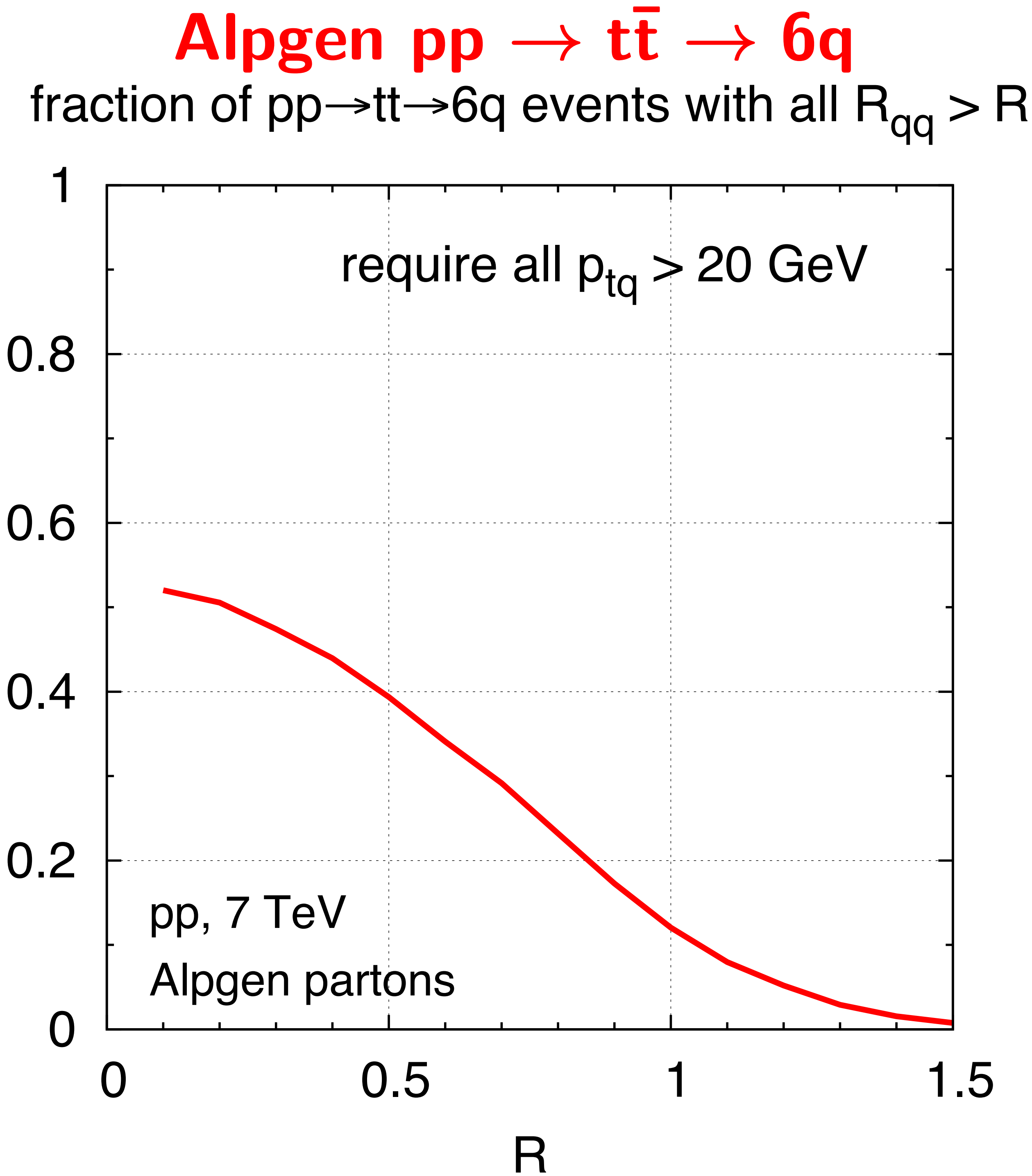
simulated with Pythia, displayed with Delphes



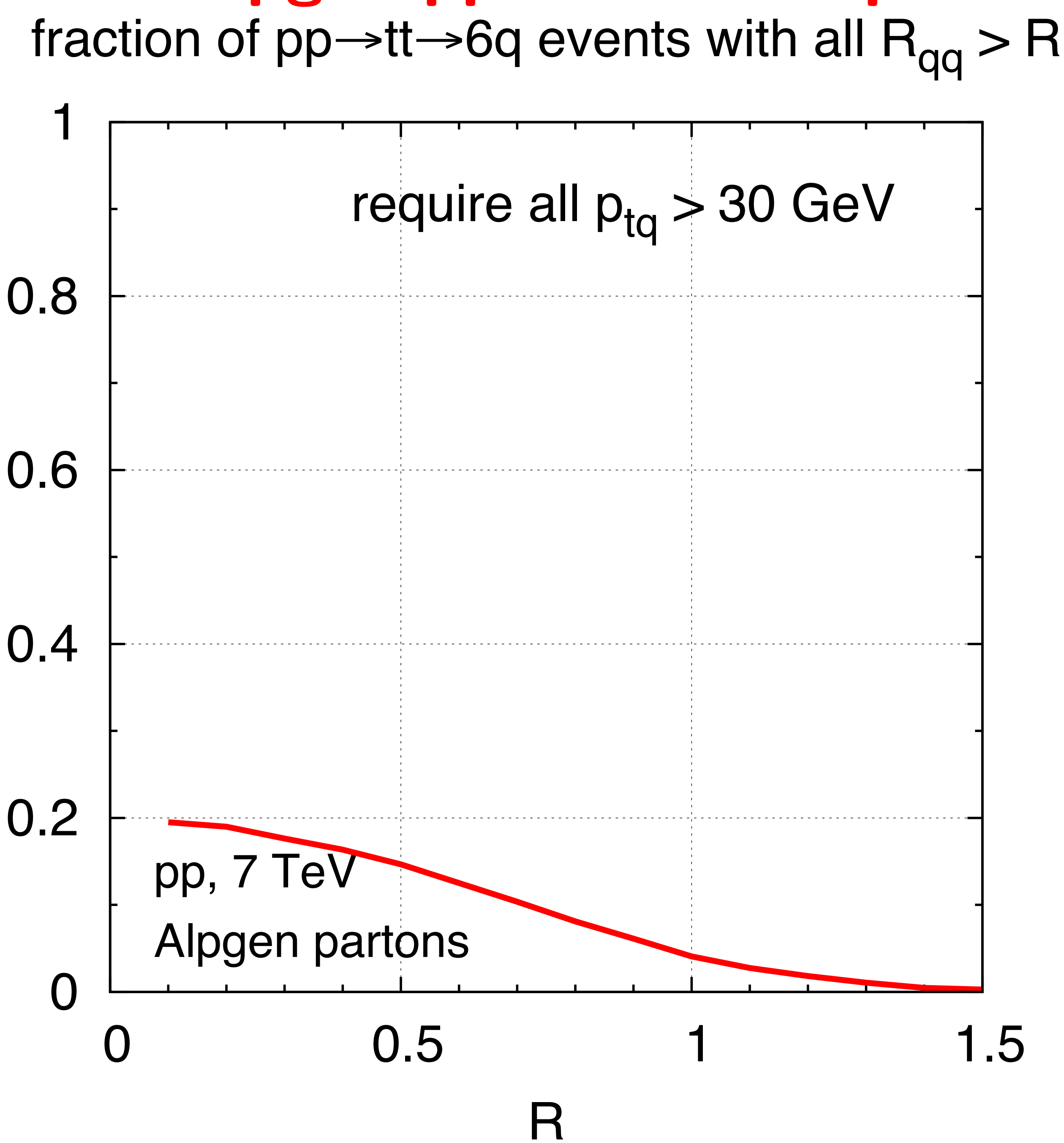

Alpgen pp → $t\bar{t}$ → 6q
fraction of pp→tt→6q events with all R_{qq} > R
no p_t cut on quarks
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

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

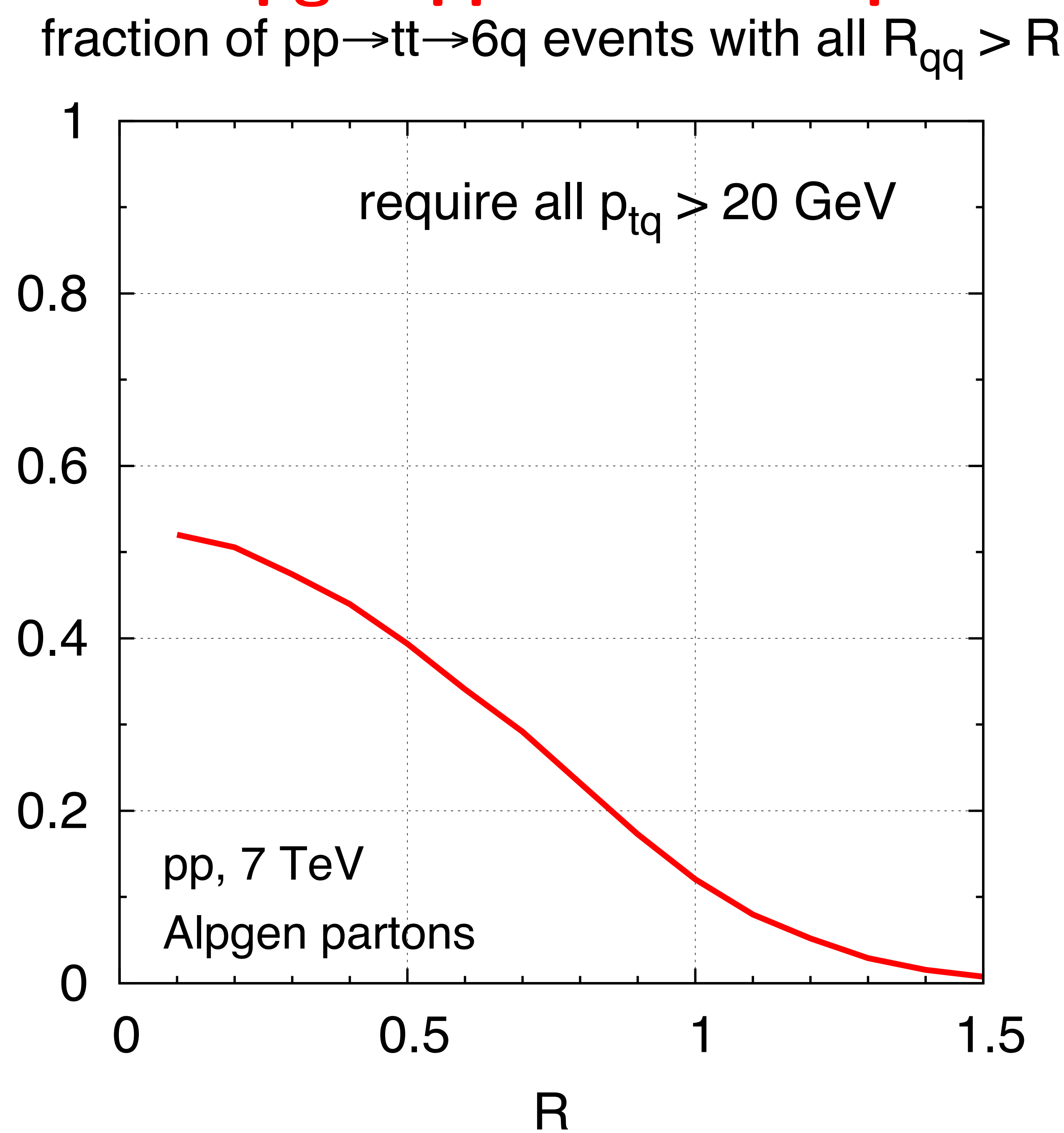



Alpgen pp → $t\bar{t}$ → 6q
fraction of pp→tt→6q events with all R_{qq} > R
require all p_{tq} > 20 GeV
pp, 7 TeV
Alpgen partons
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
R

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

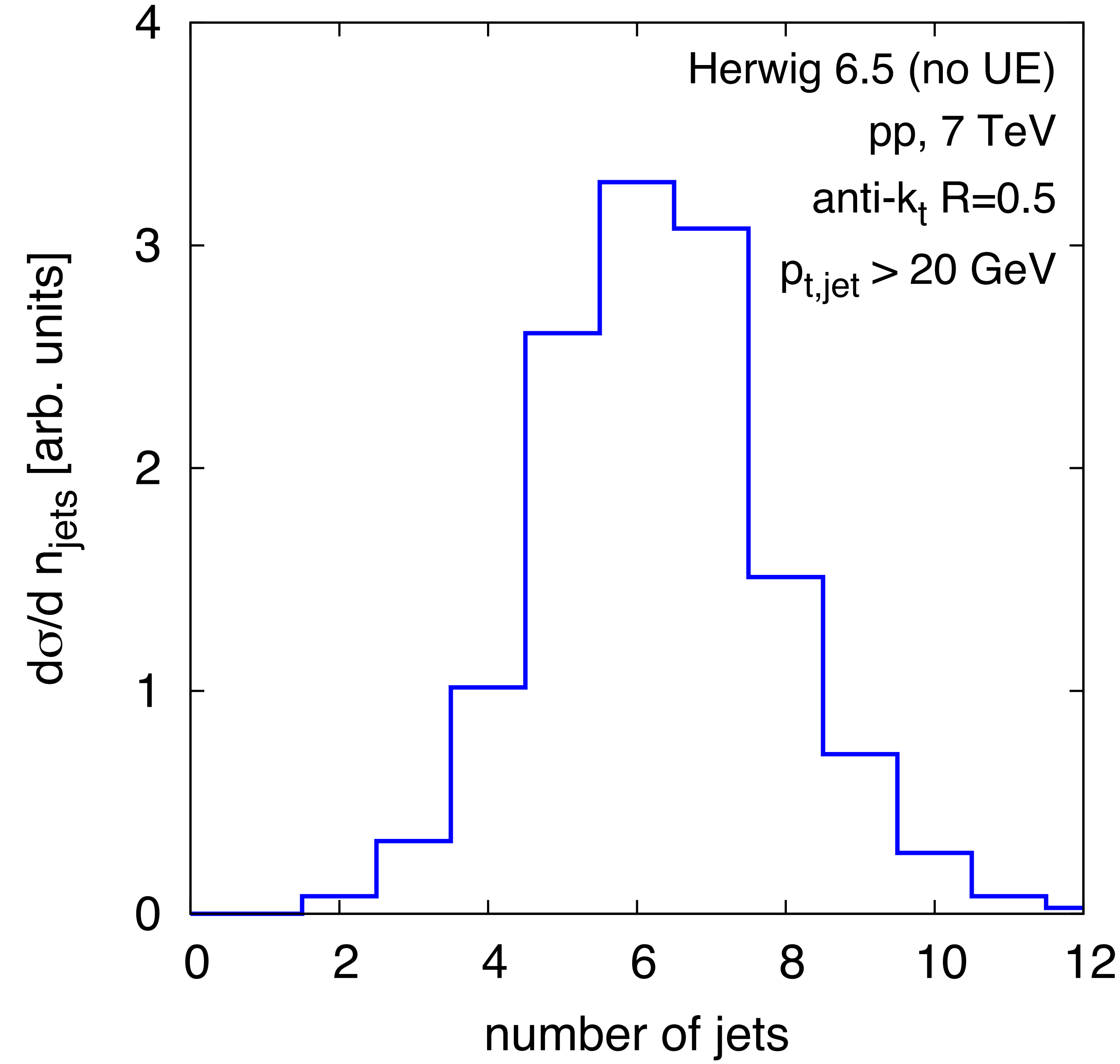


Alpgen $pp \to t\bar{t} \to 6q$



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

Distribution of number of jets



Why do the experiments have a $|\Delta\eta_{jj}| < 1.3$ cut?

see blackboard!

Why do the experiments have a $|\Delta\eta_{jj}| < 1.3$ cut?

see blackboard!

Bottom line: if you're looking for a hadronically decaying resonance, **never** use jets far in rapidity the CoM system of the resonance

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" $\to$ hadrons transition

Method:

- "infrared finite α_s" / infrared renormalons

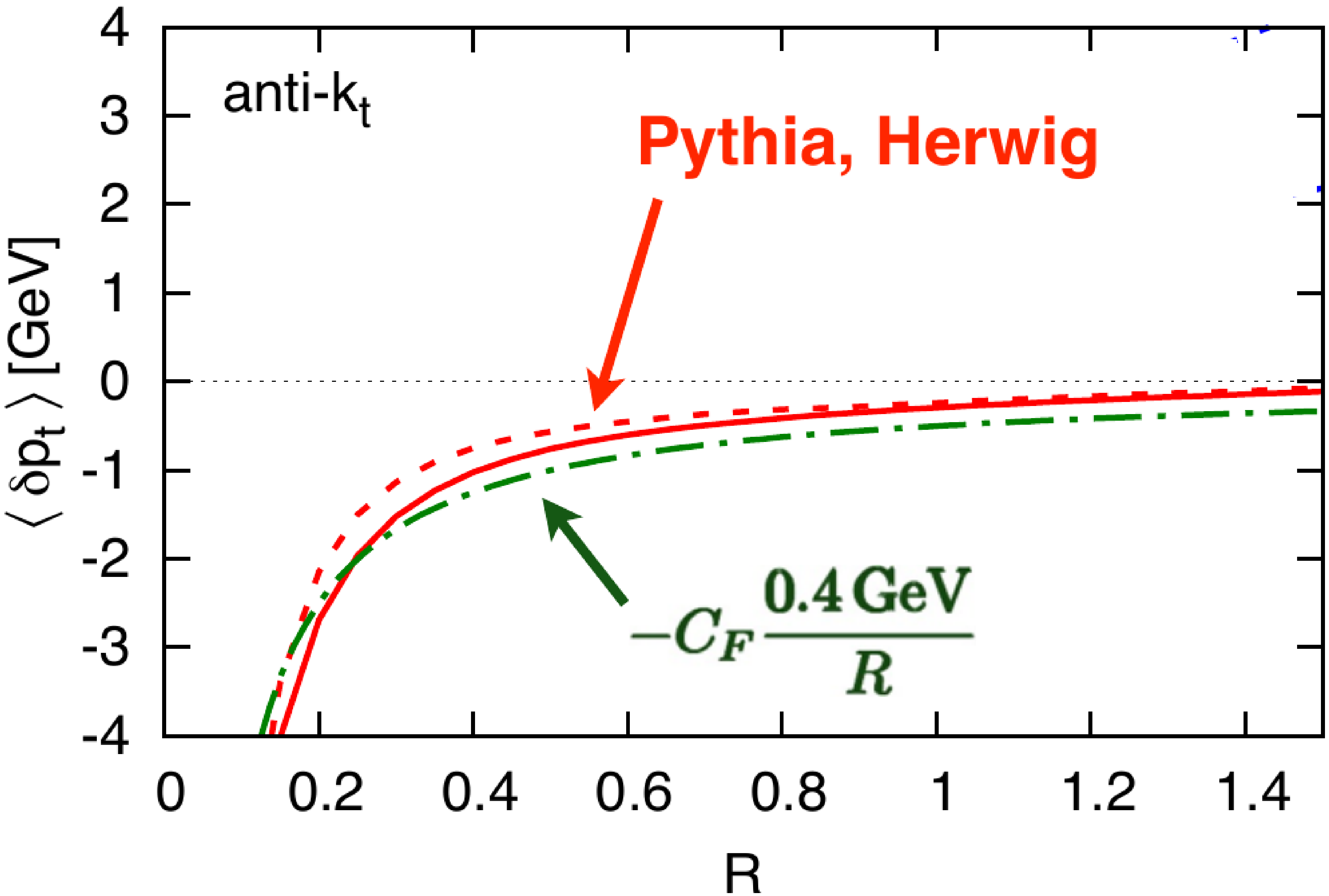
à la Dokshitzer & Webber '95
Korchemsky & Sterman '94
Seymour '97

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
coefficient holds for anti-k_t; see Dasgupta & Delenda '09 for k_t alg.

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?

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How does coefficient depend on algorithm?

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

What R is best for an isolated jet?

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

PT radiation:

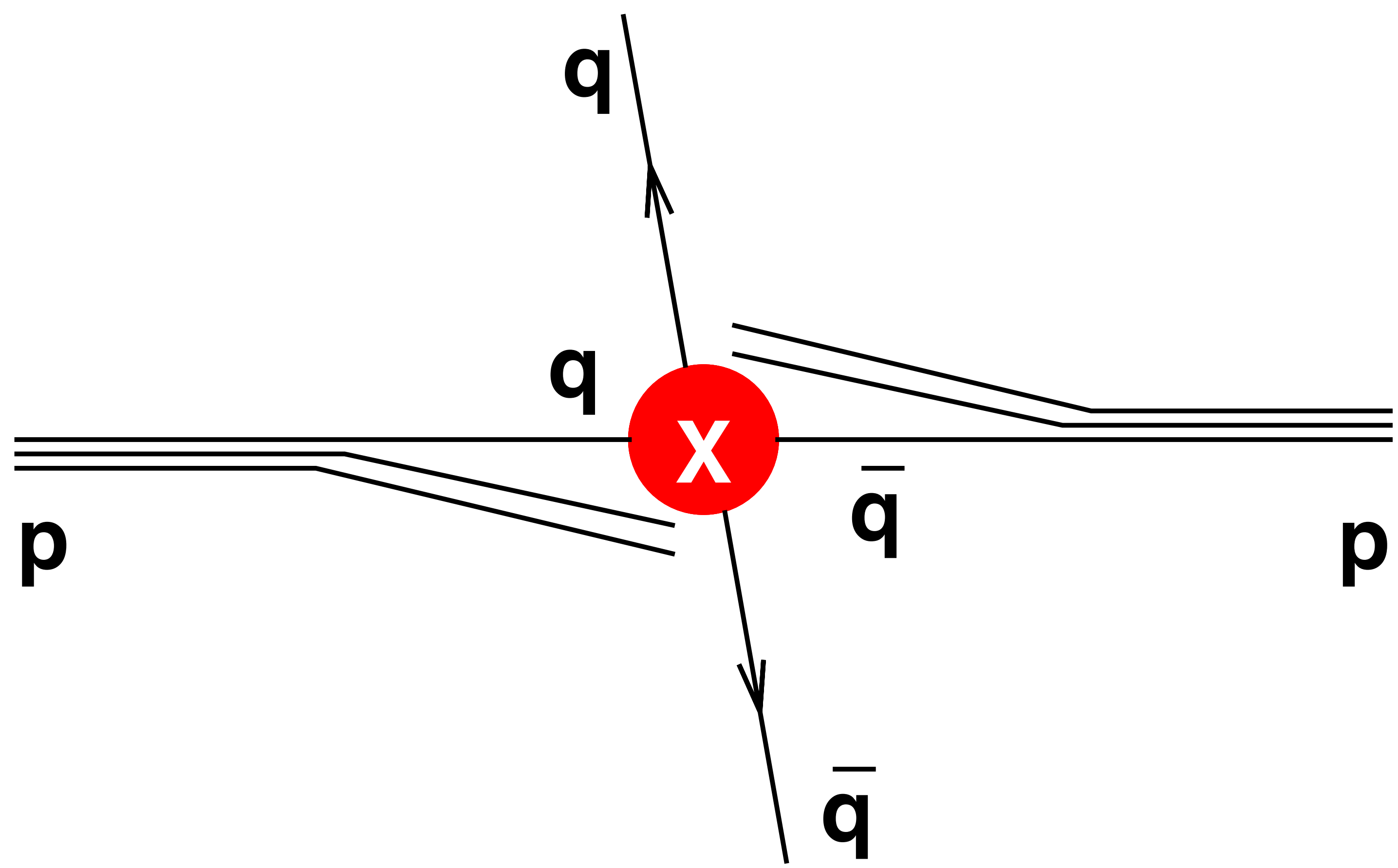
$$q: \quad \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

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:

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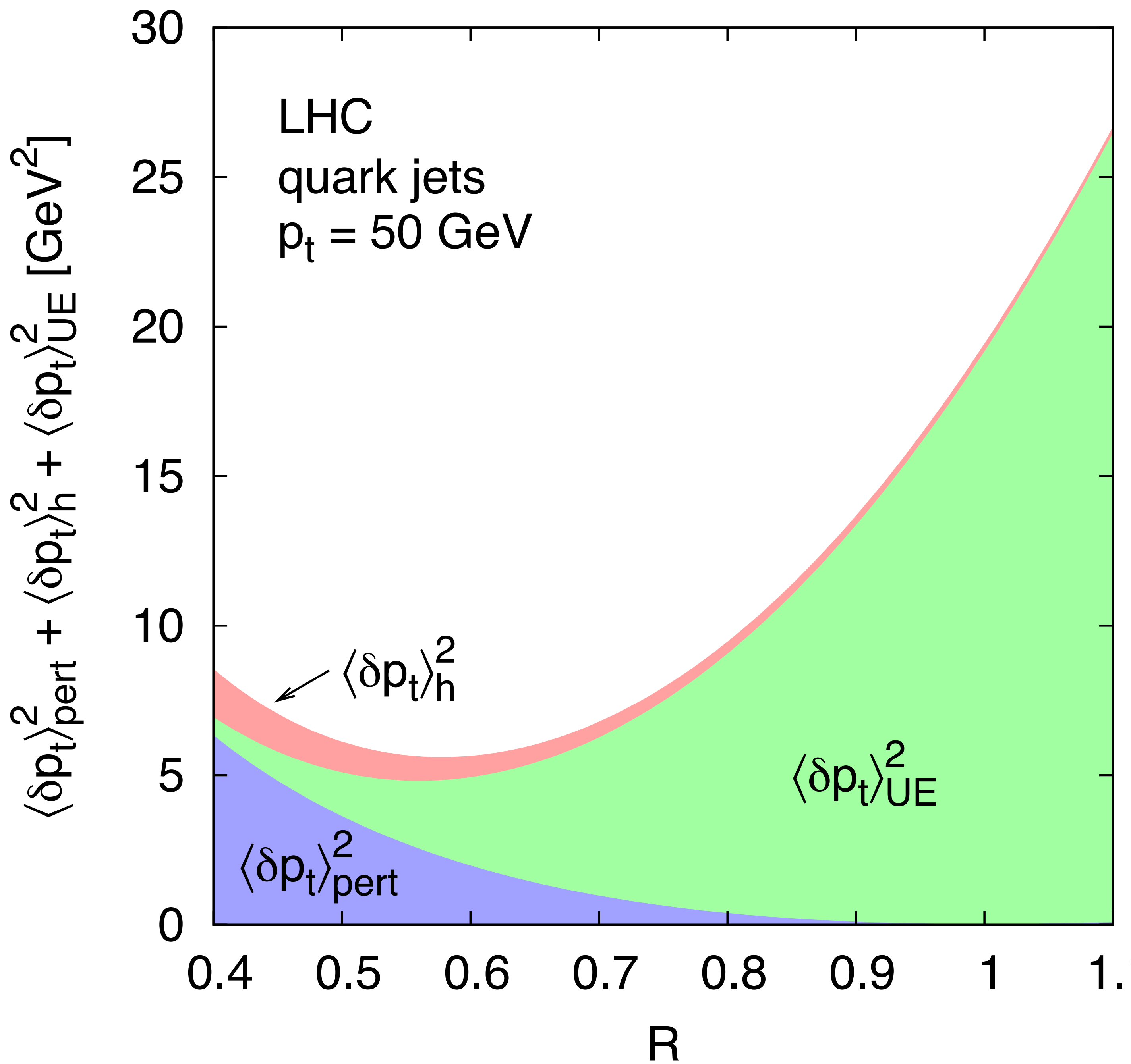
50 GeV quark jet



in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

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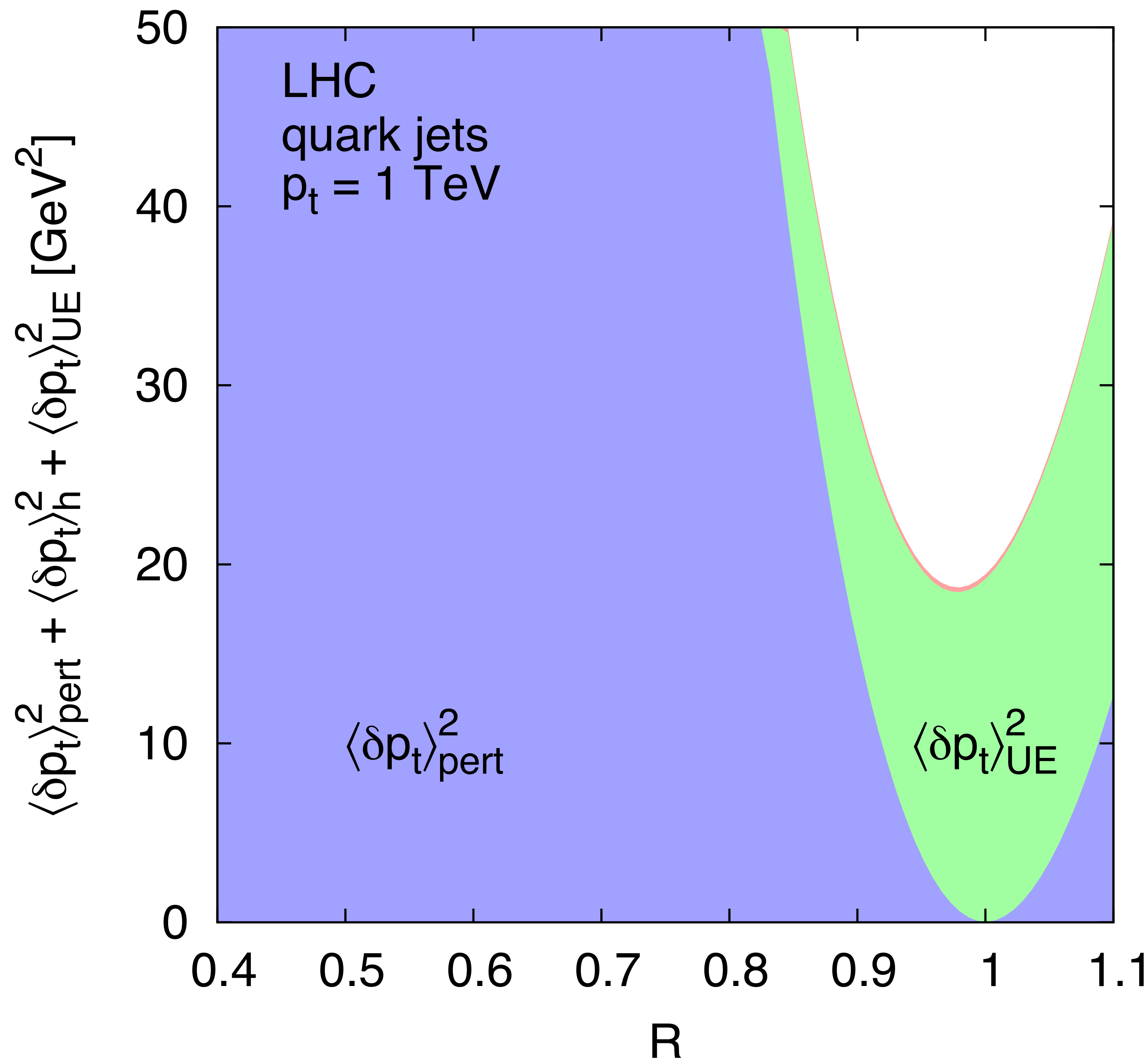
1 TeV quark jet



in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

PT radiation:

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

Hadr

$q:$

Underlying event:

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

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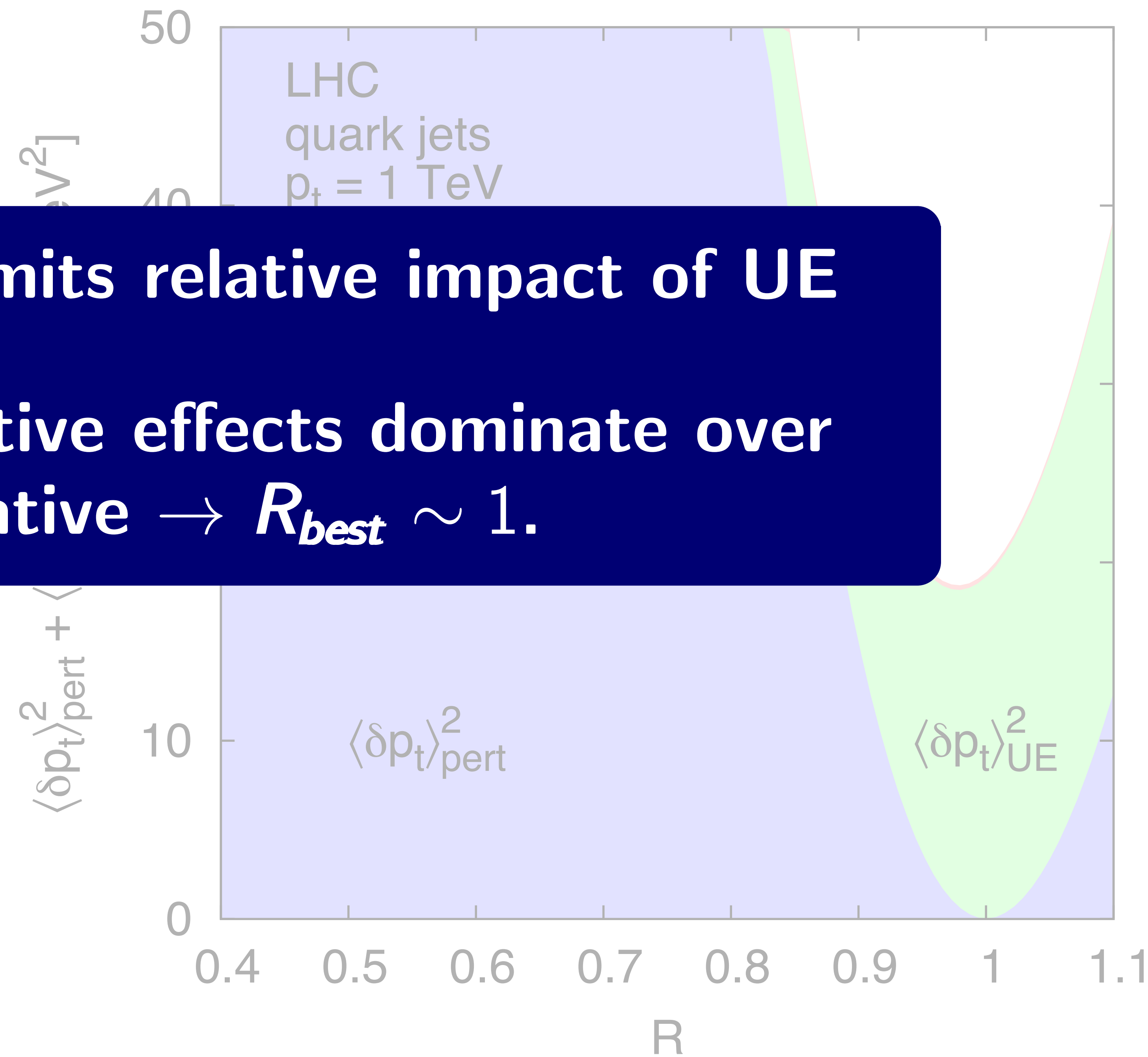


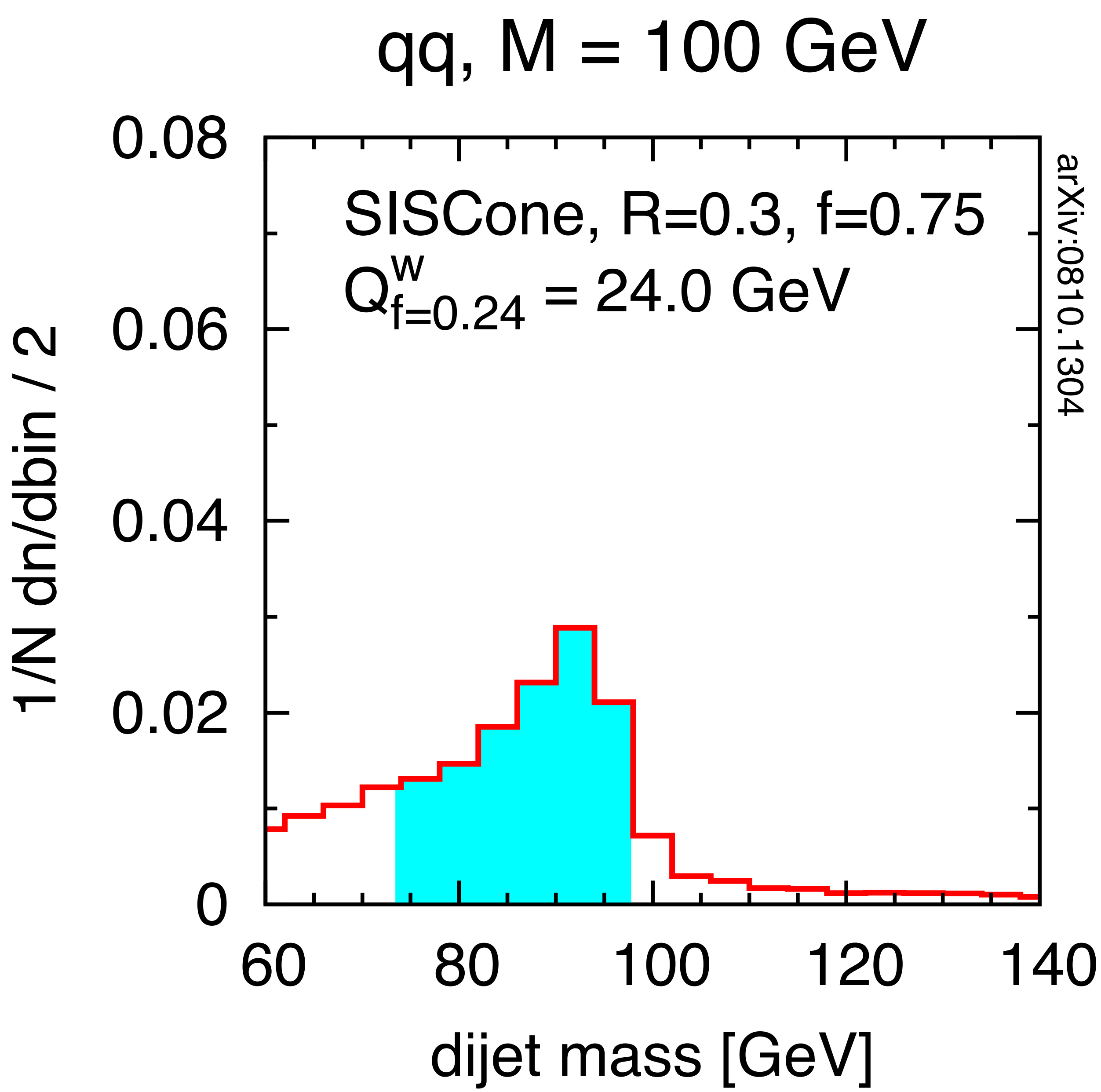
At low p_t, small R limits relative impact of UE

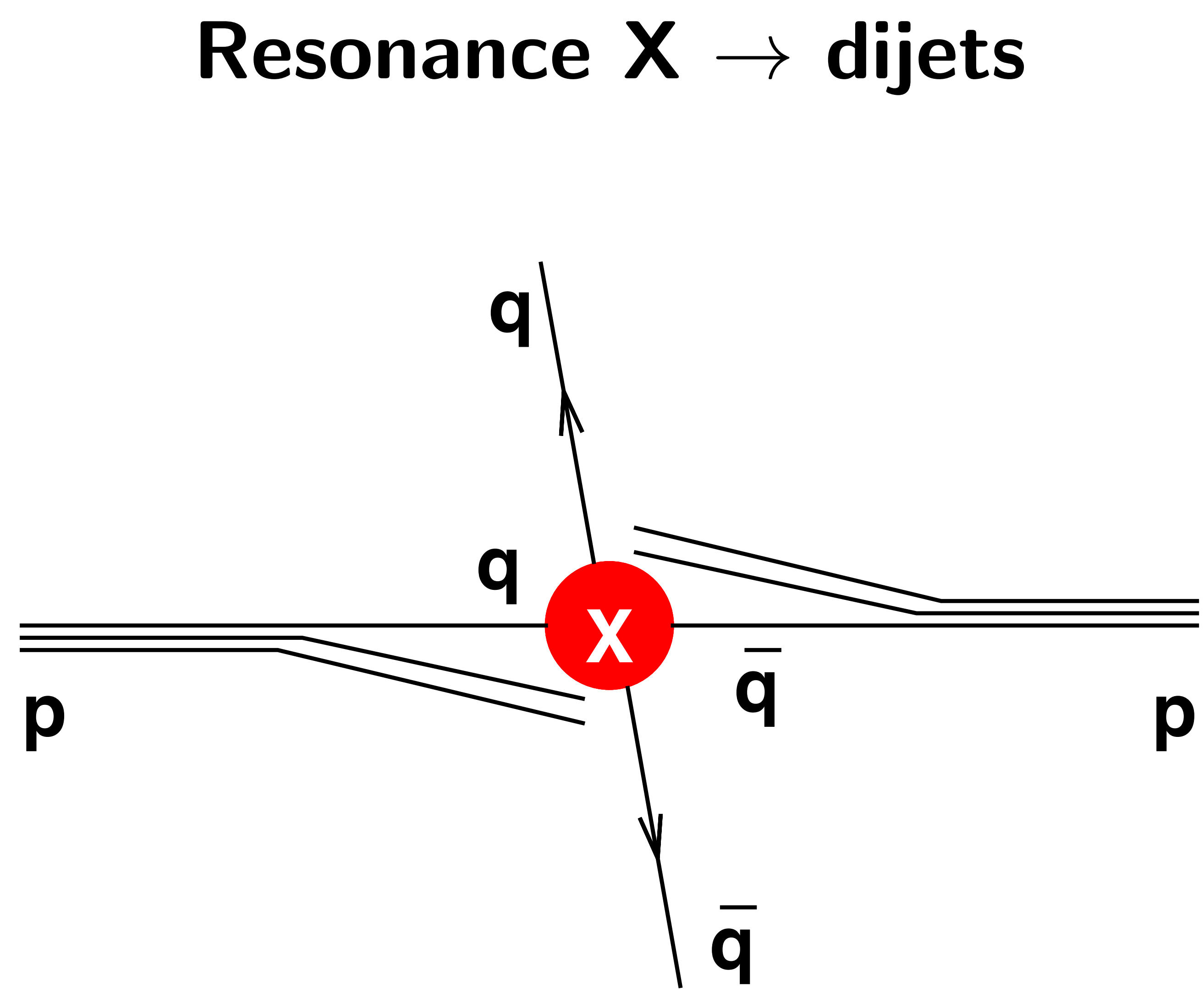
At high p_t, perturbative effects dominate over non-perturbative $\rightarrow R_{best} \sim 1$.

in small-R limit (!)

NB: full calc, correct fluct: Soyez '10

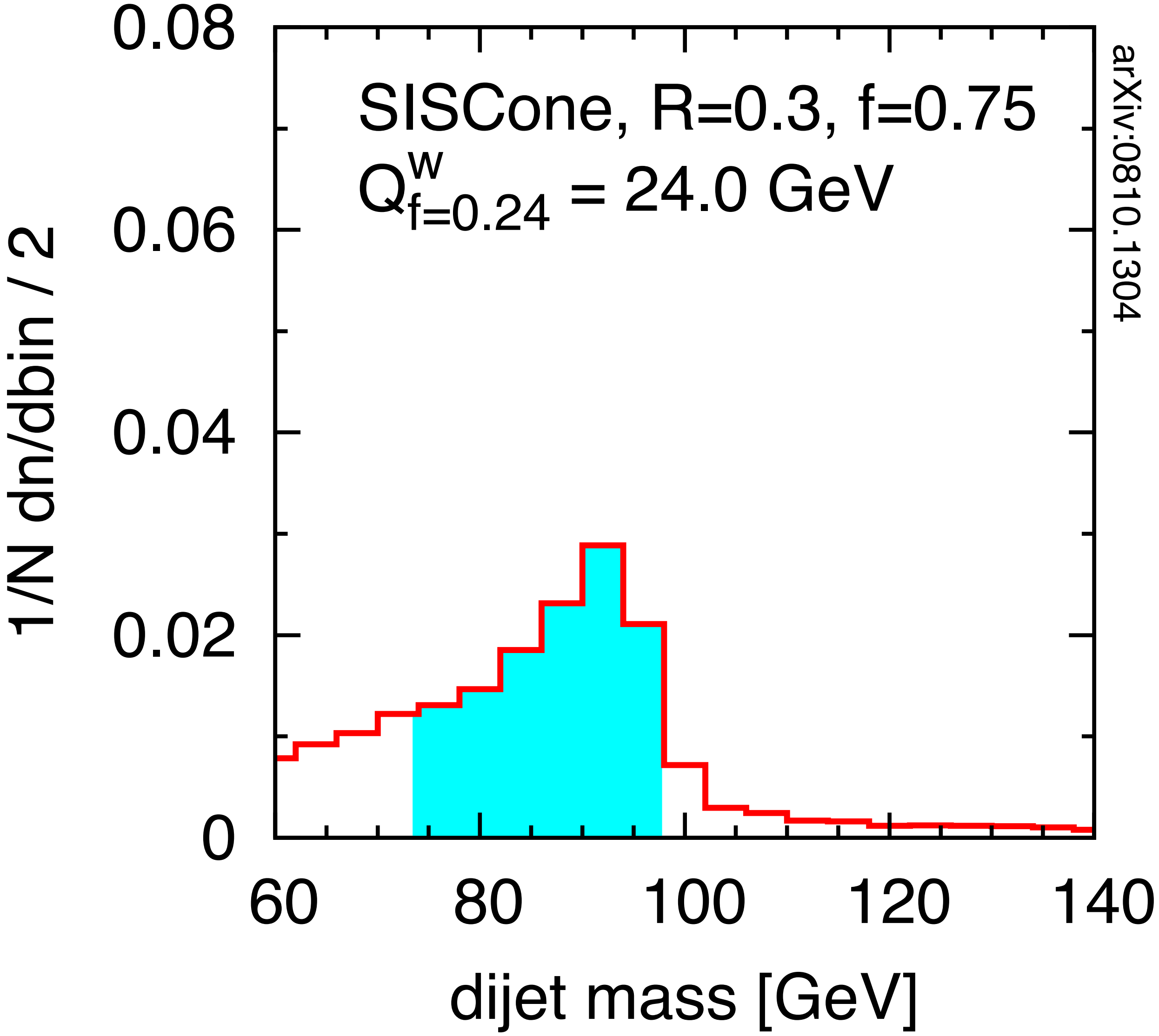
R = 0.3


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

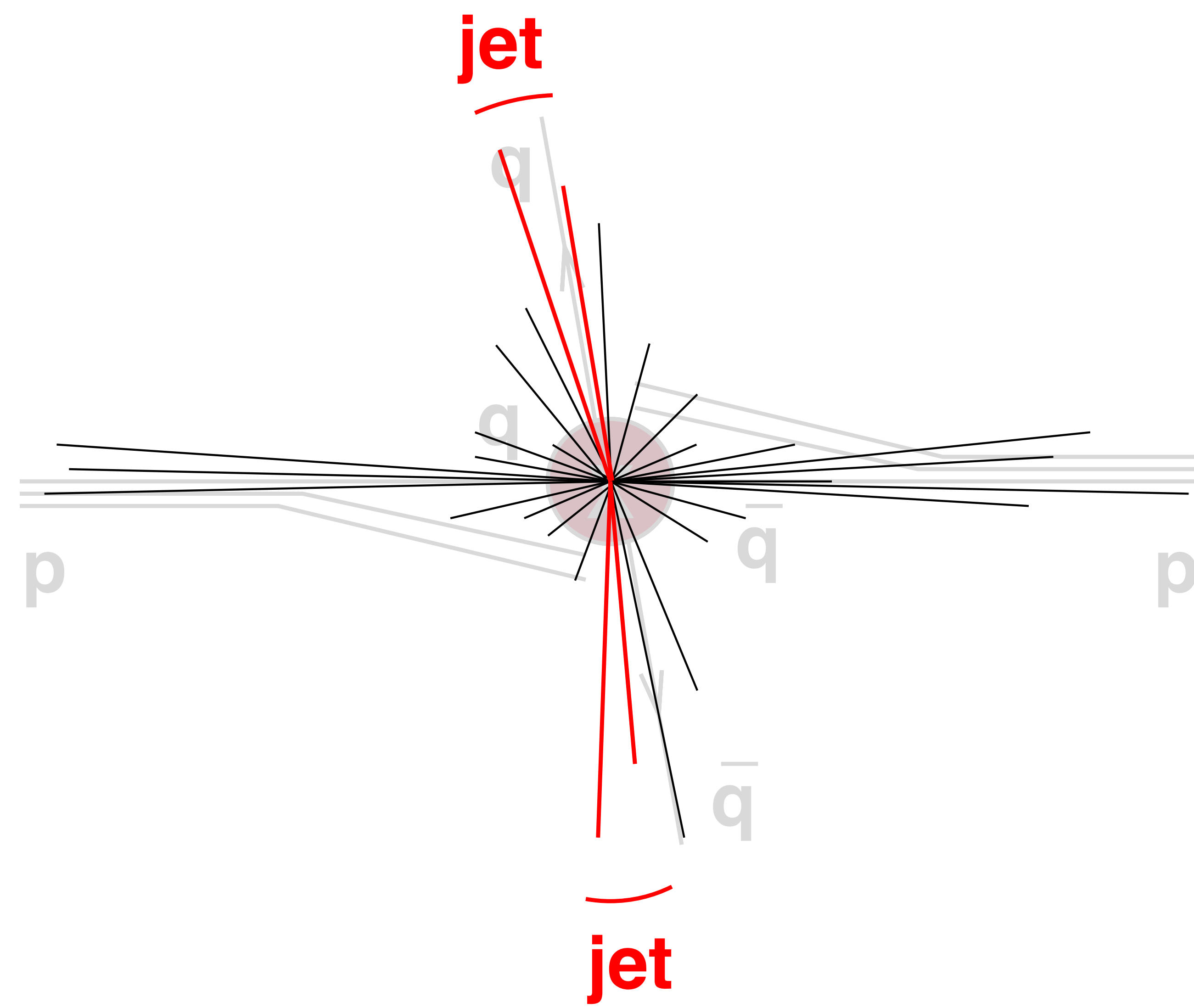

Resonance X → dijets
q
q
X
p
p
q̄
q̄

$R = 0.3$

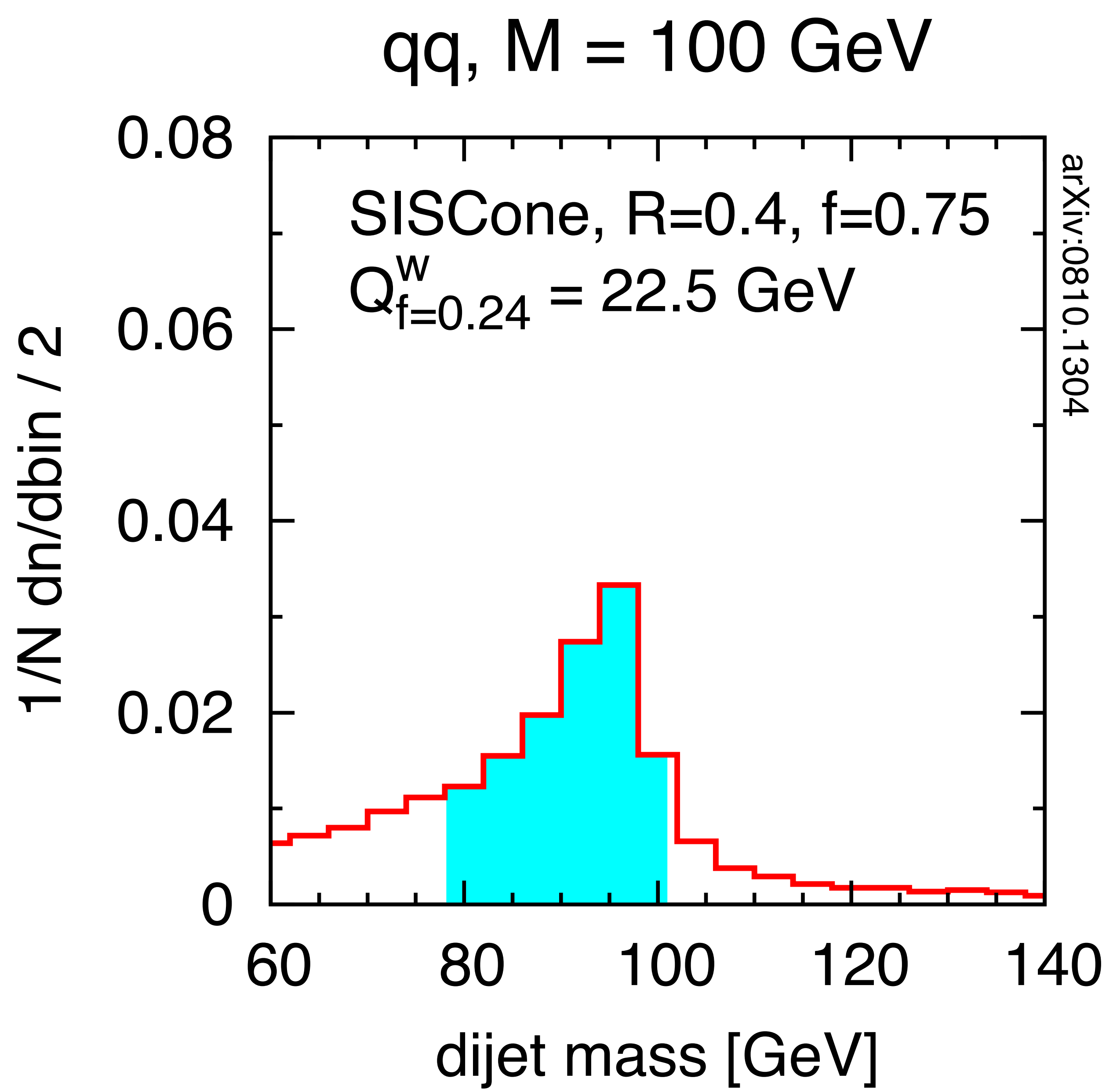
qq, M = 100 GeV



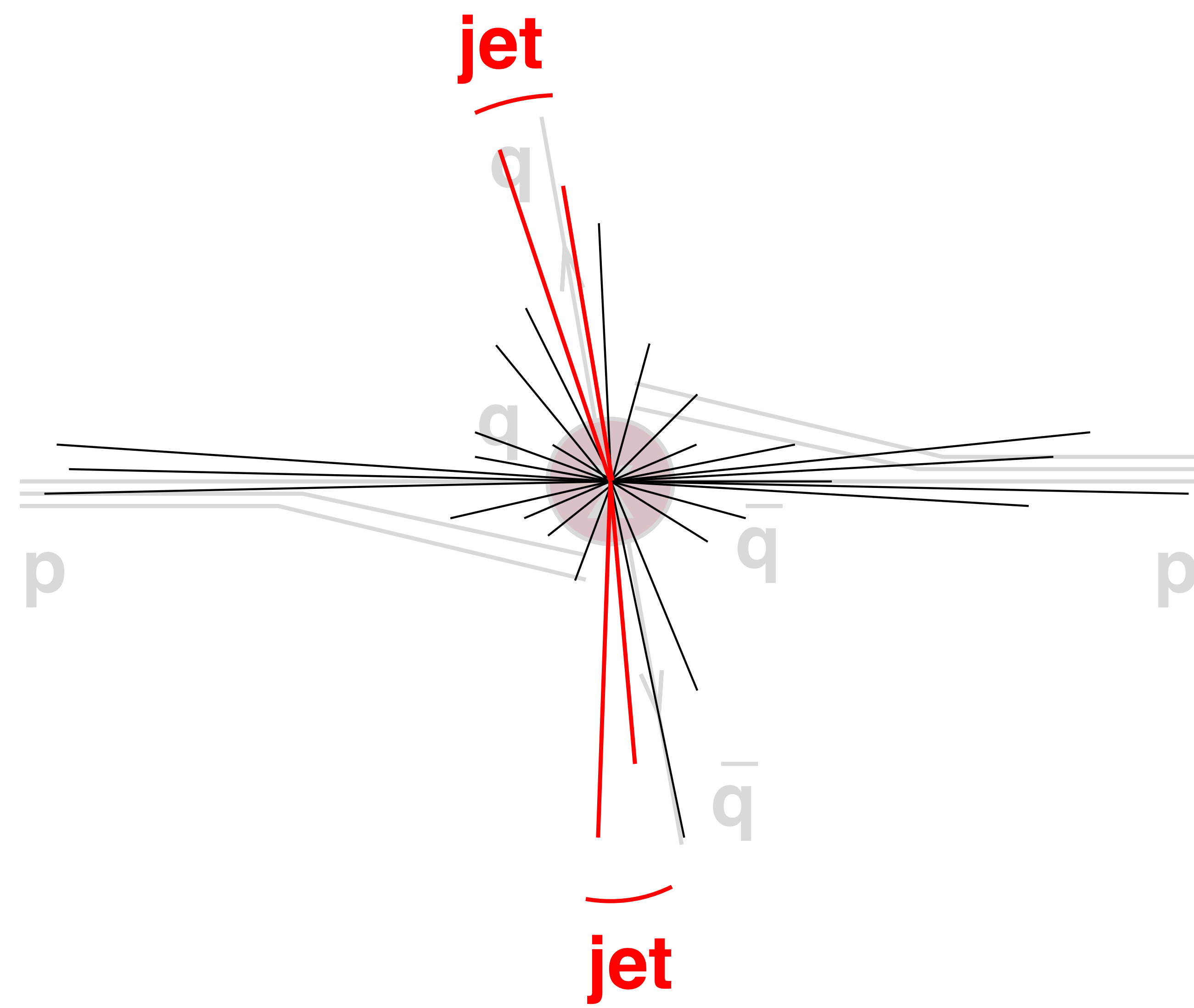
Resonance X → dijets



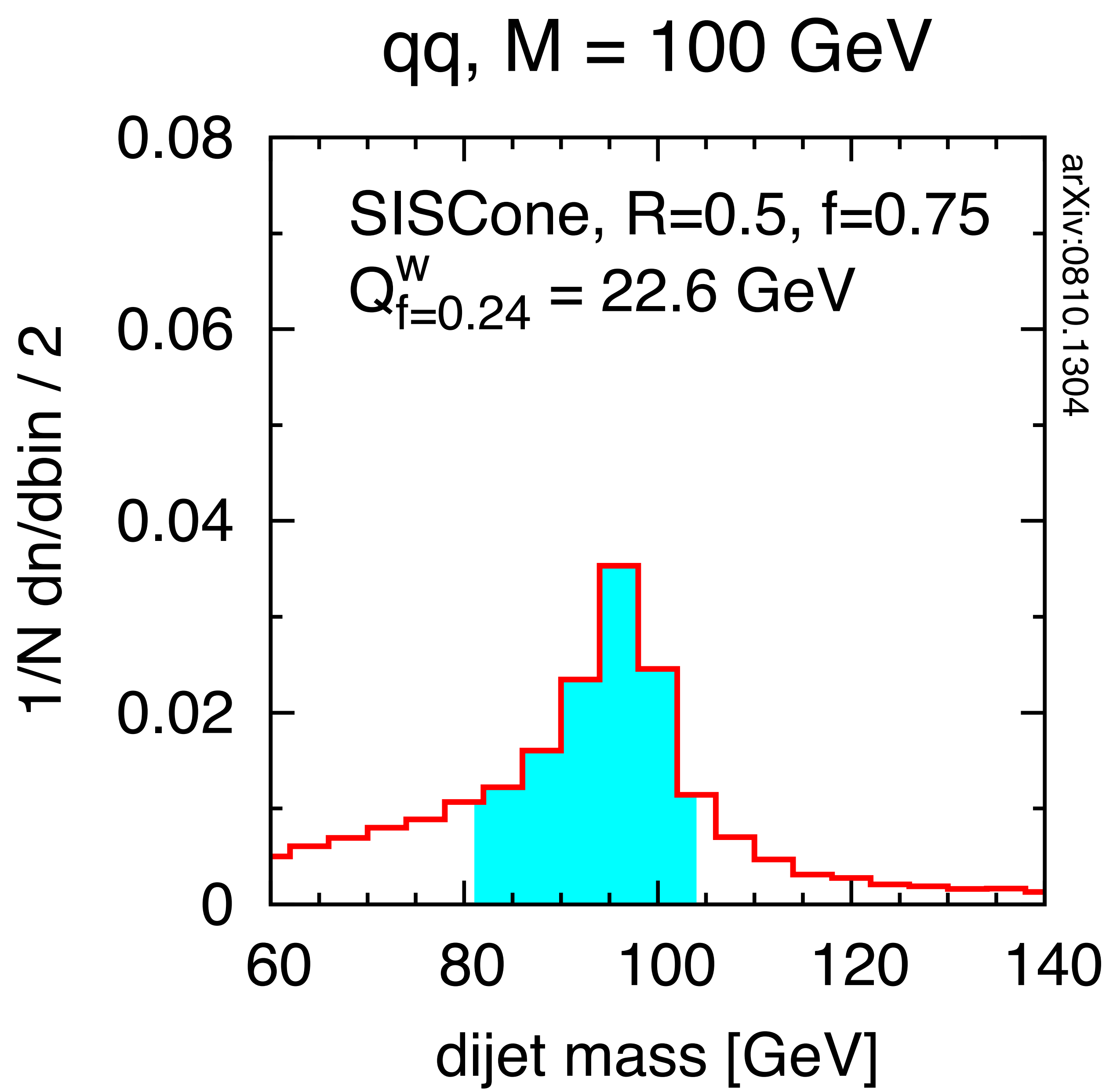
R = 0.4



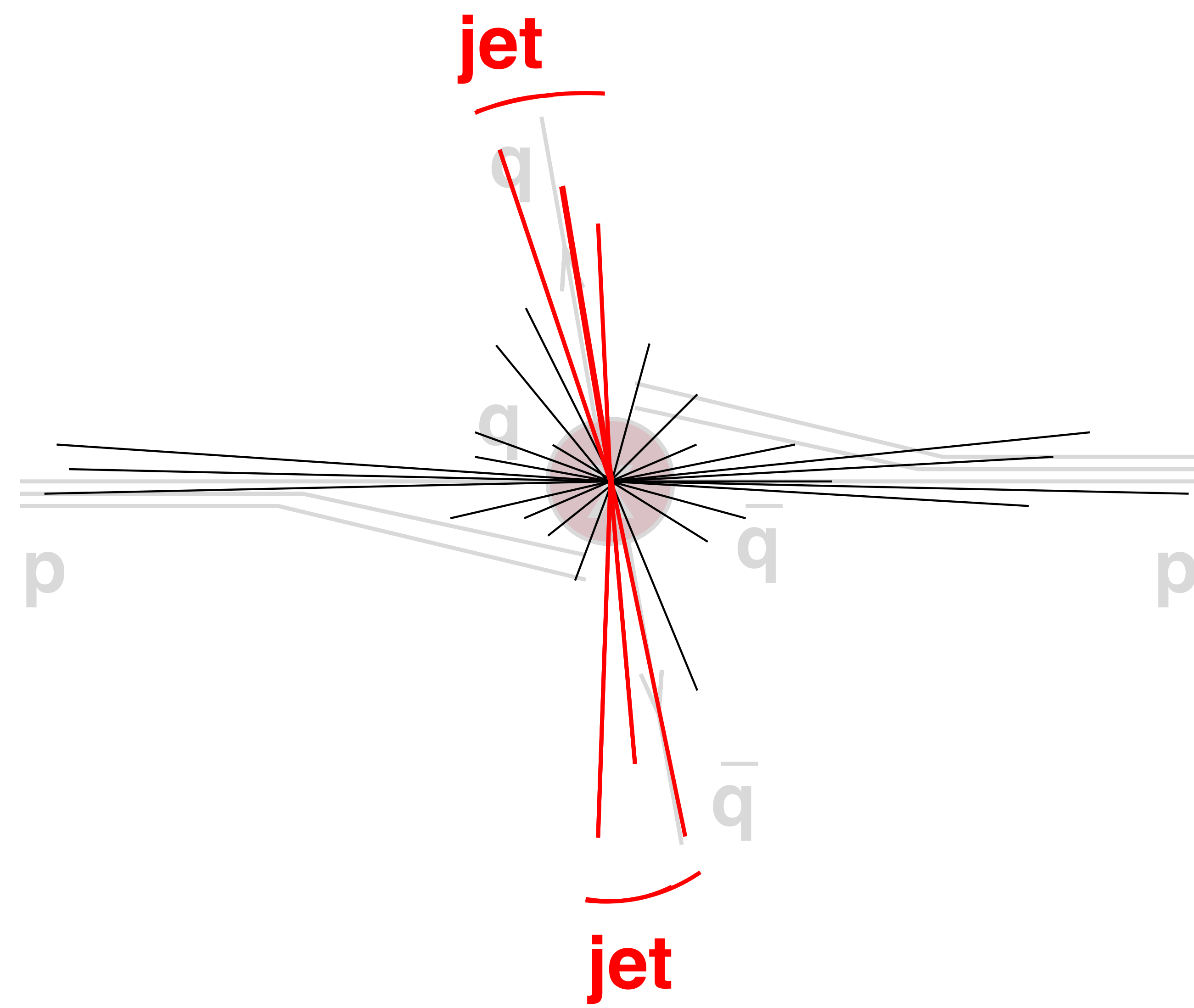
Resonance X → dijets



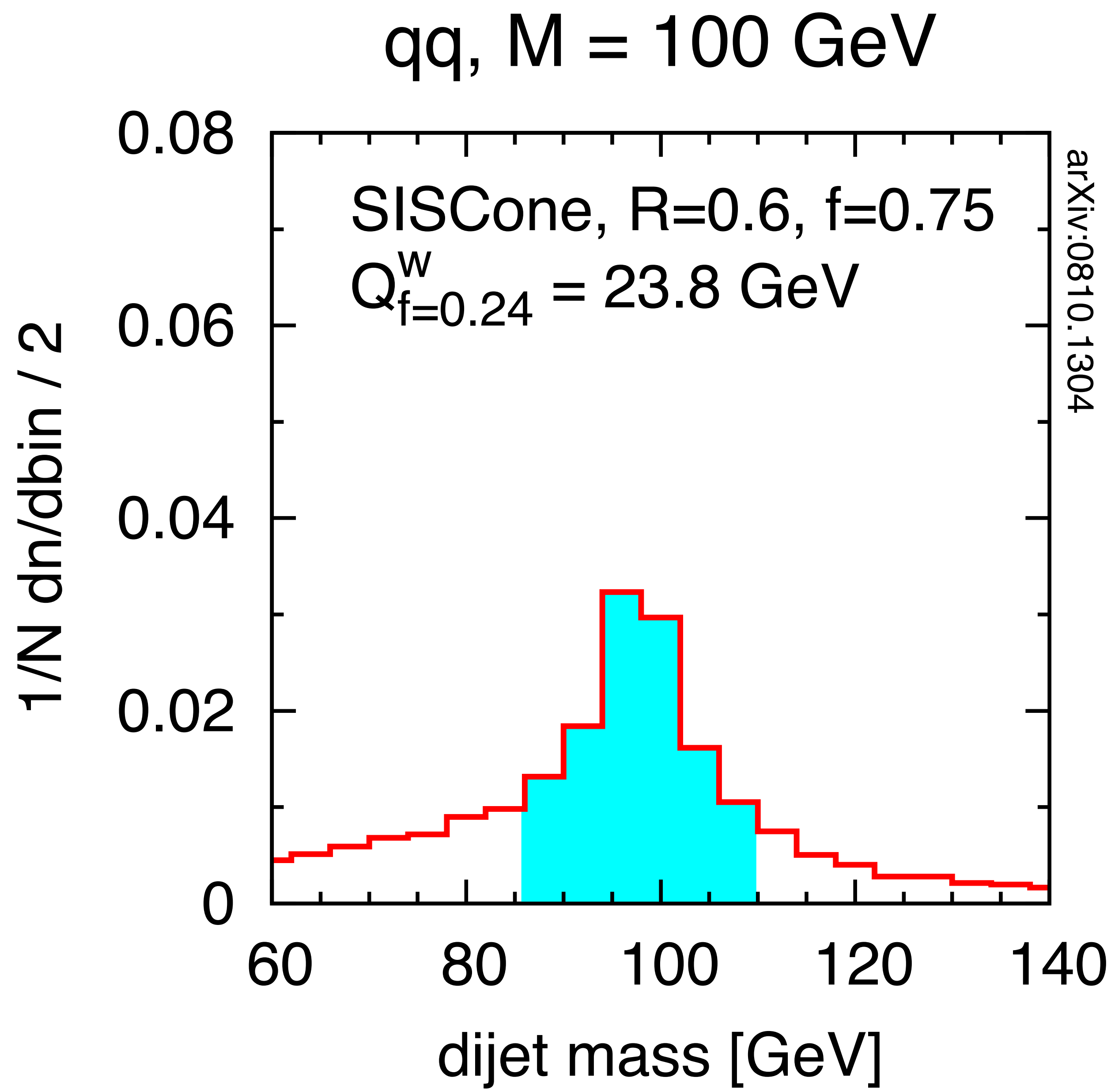
R = 0.5



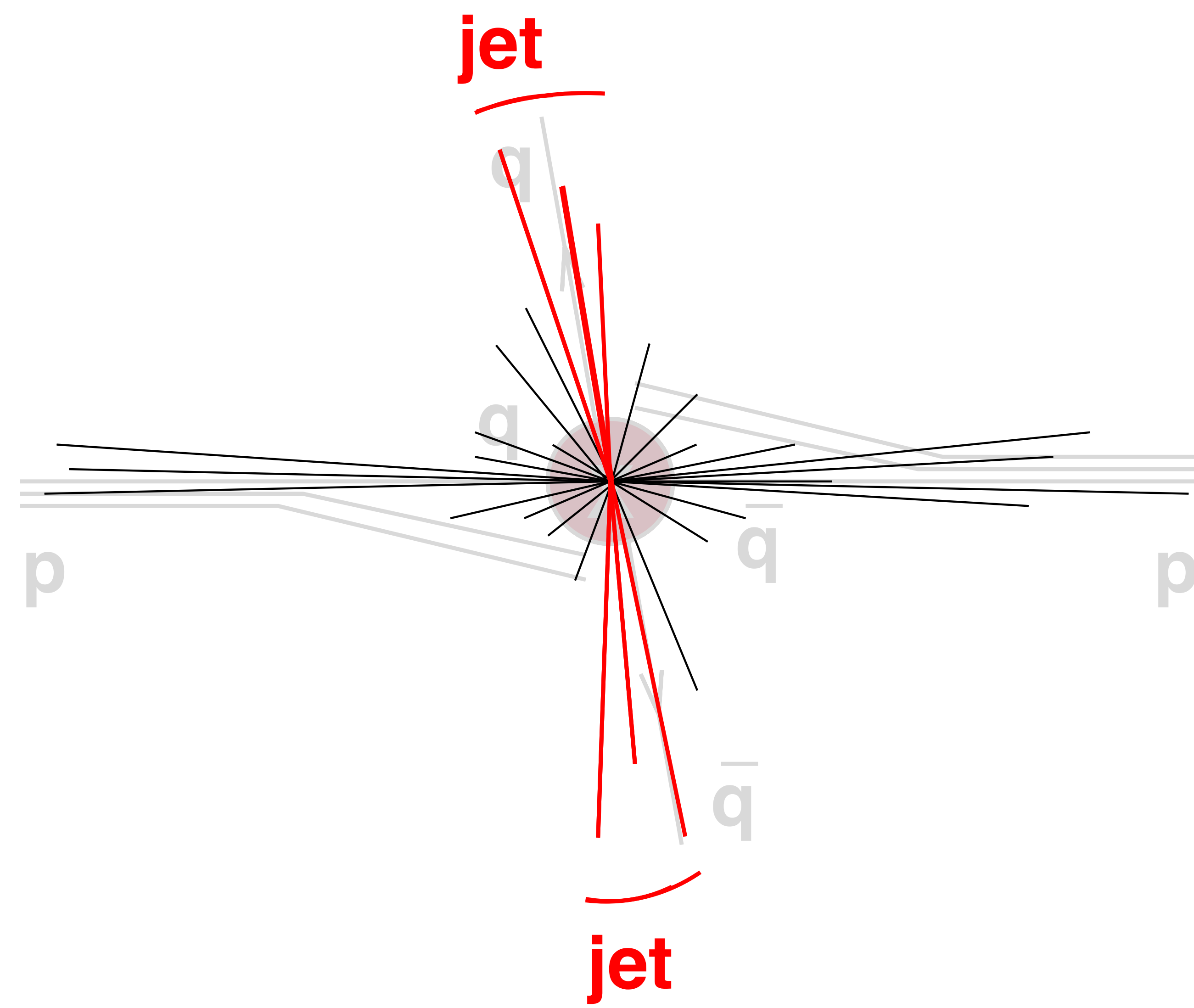
Resonance X → dijets



R = 0.6

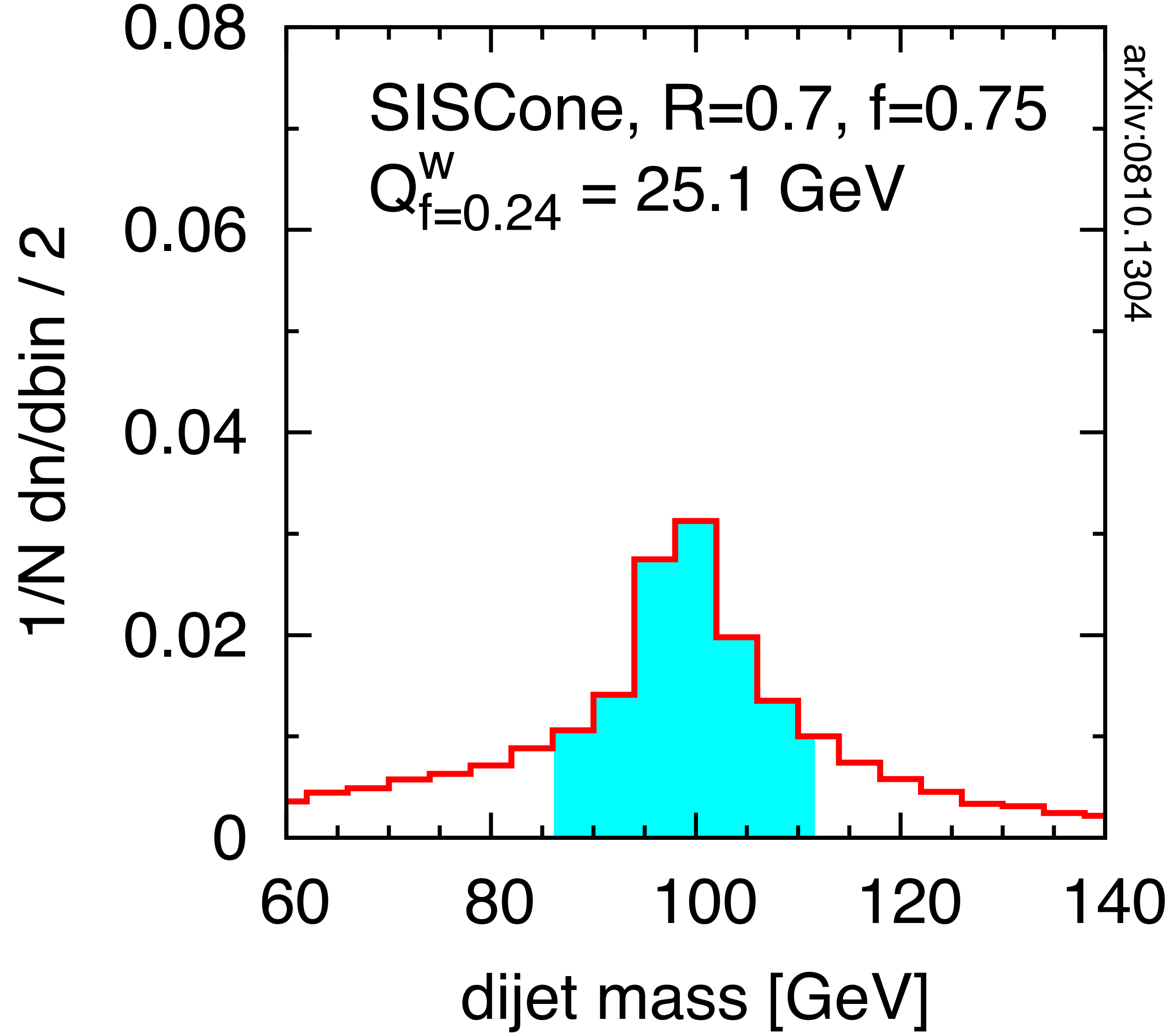


Resonance X → dijets

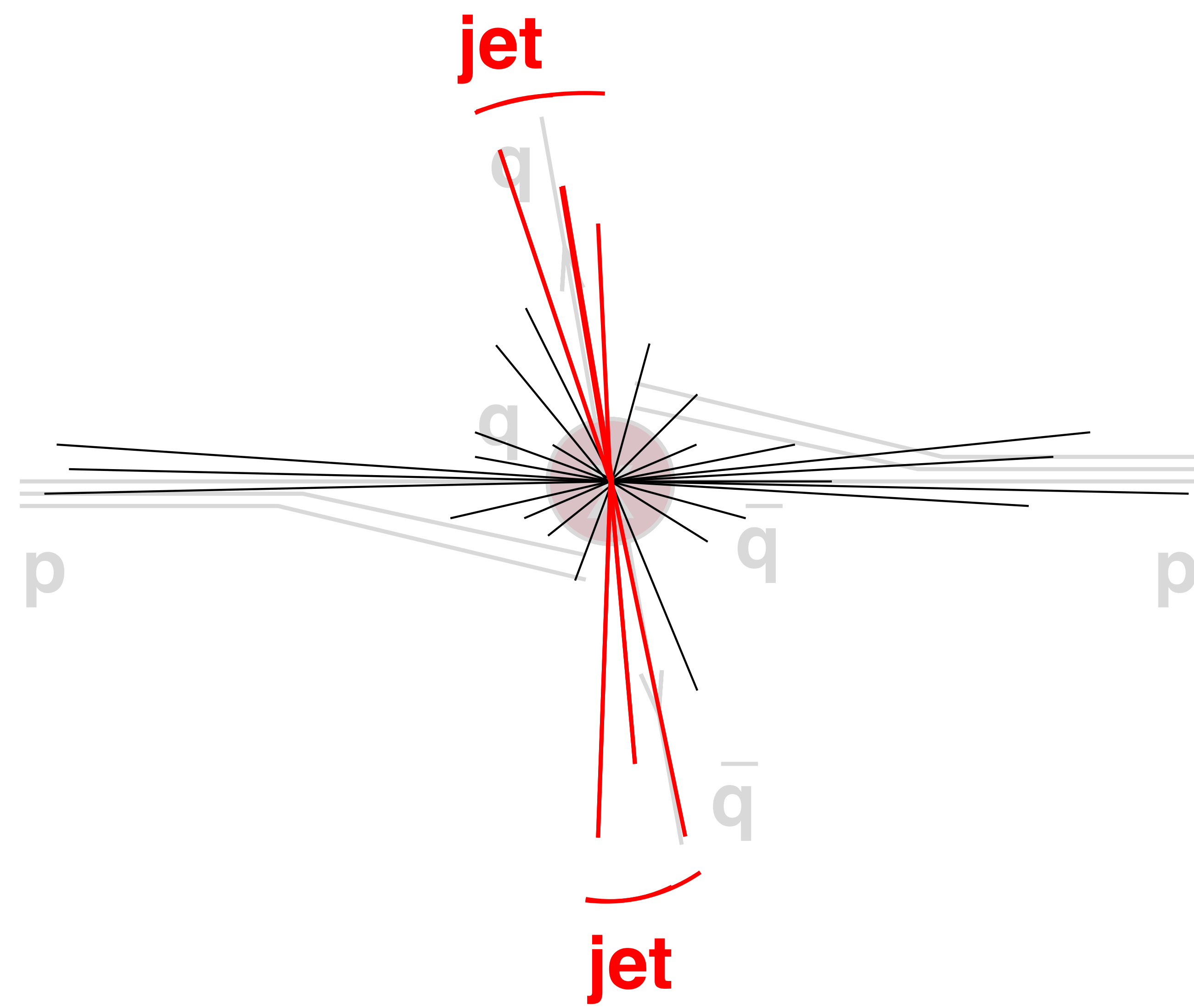


$R = 0.7$

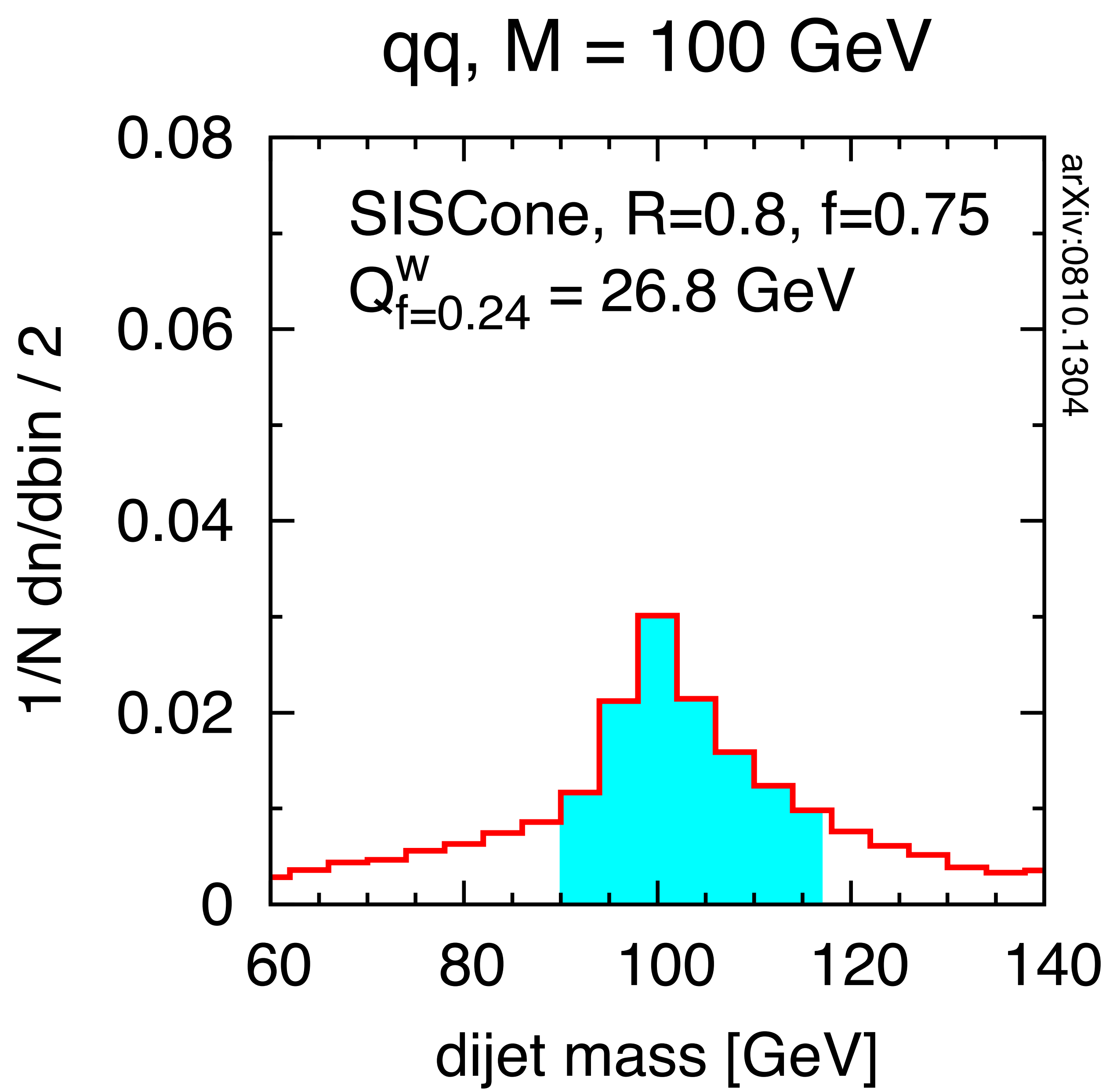
qq, M = 100 GeV



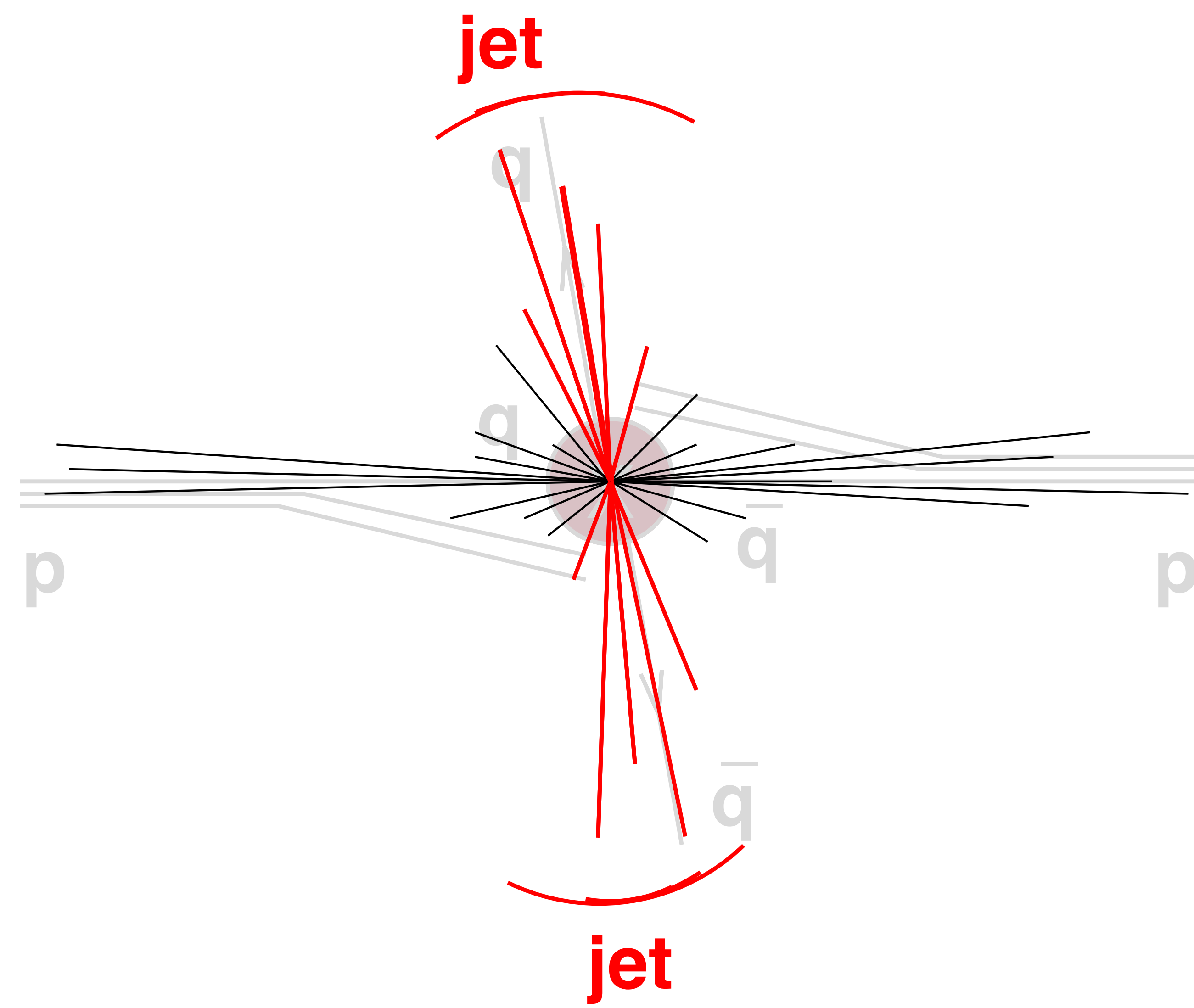
Resonance X → dijets



R = 0.8

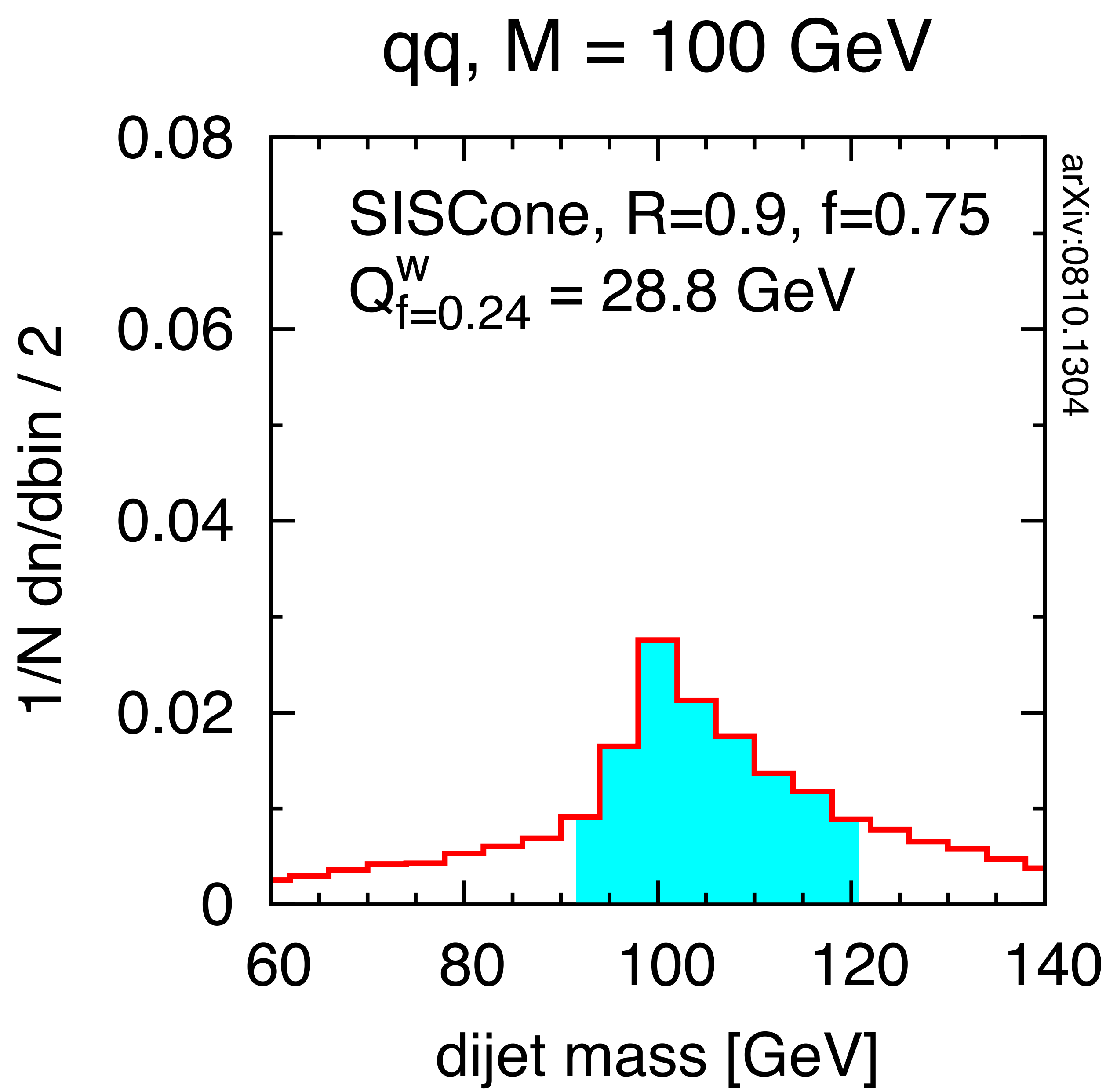


Resonance X → dijets

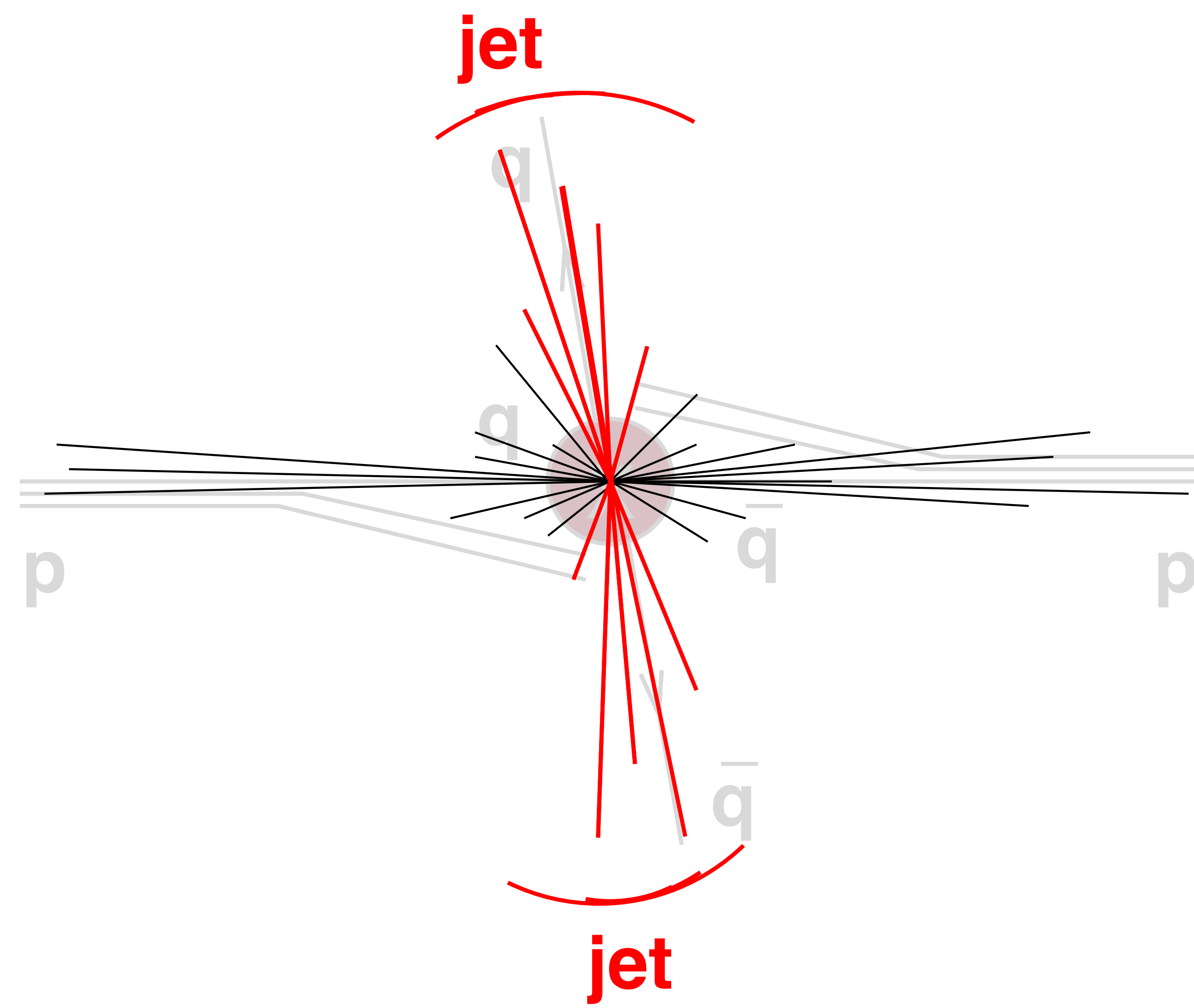


Dijet mass: scan over R [Pythia 6.4]

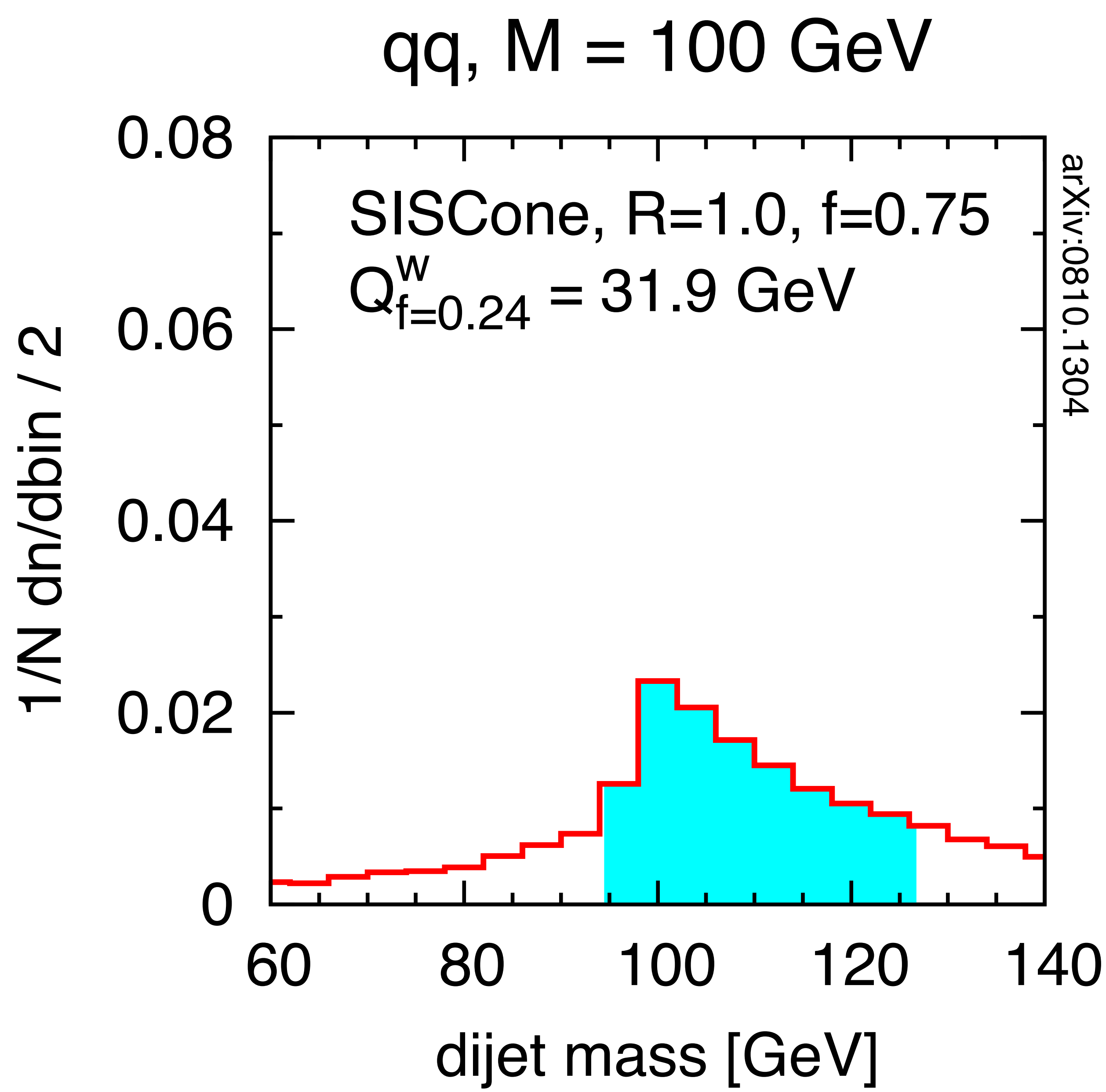
$R = 0.9$



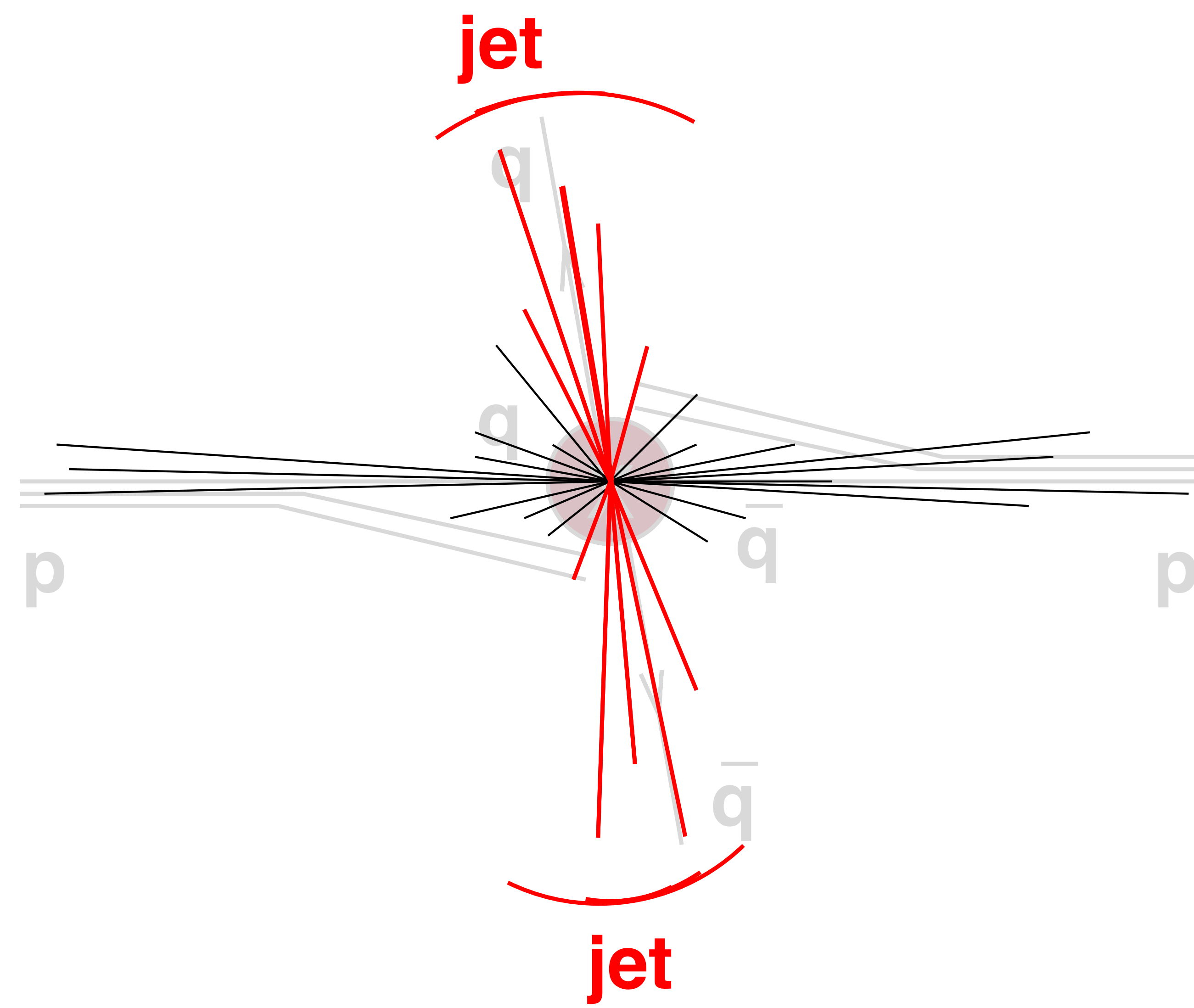
Resonance X → dijets

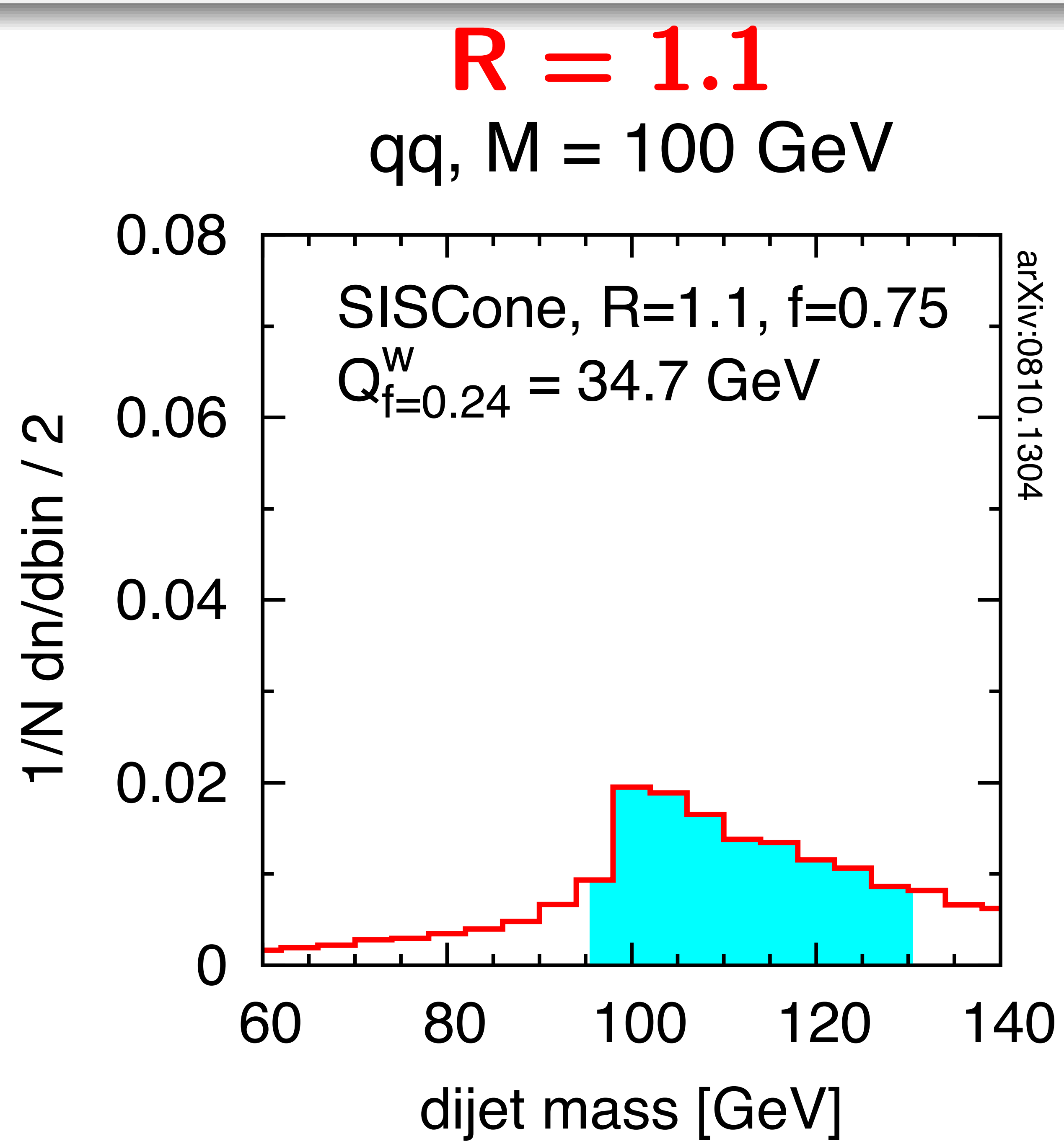


$R = 1.0$

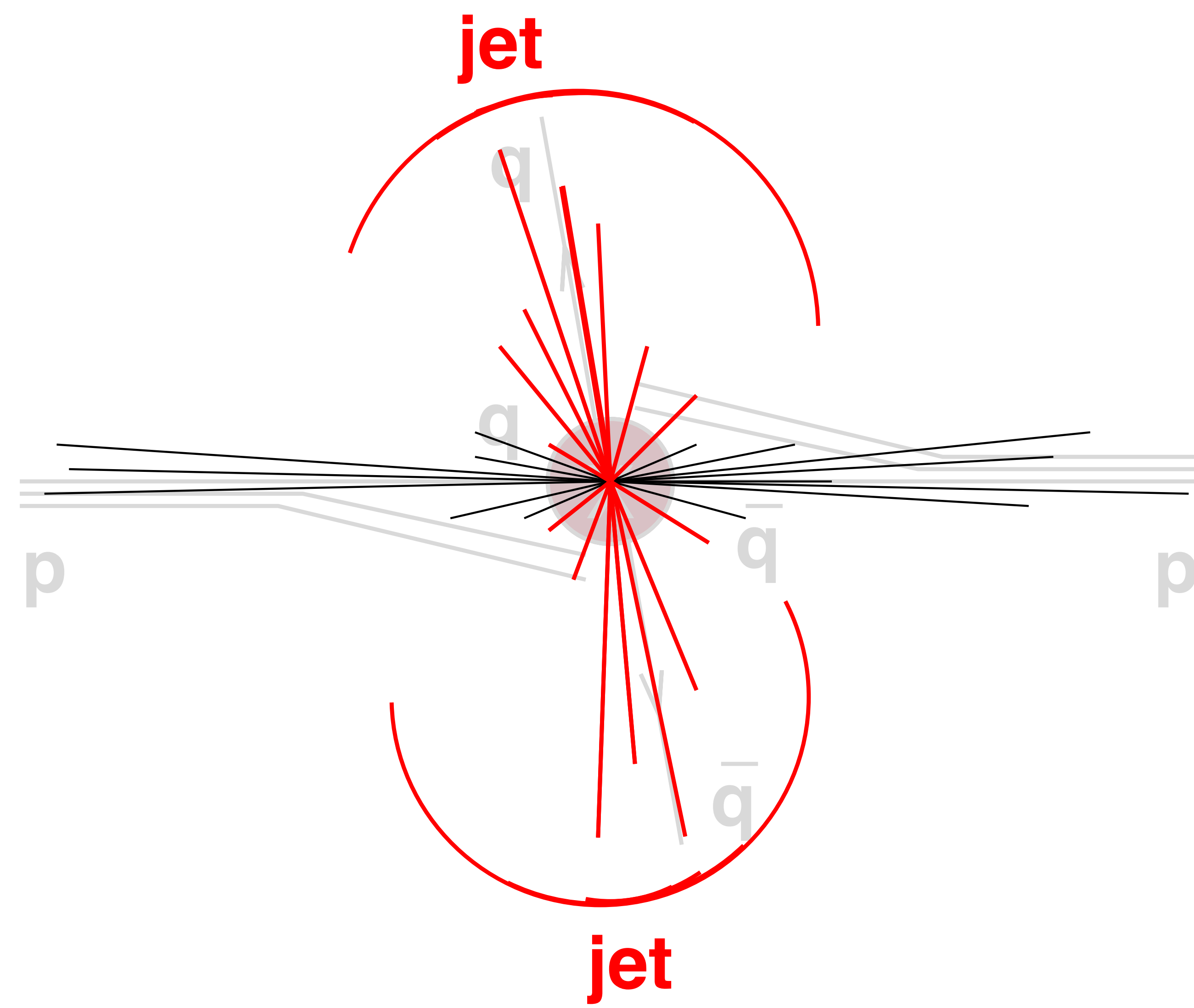


Resonance X → dijets

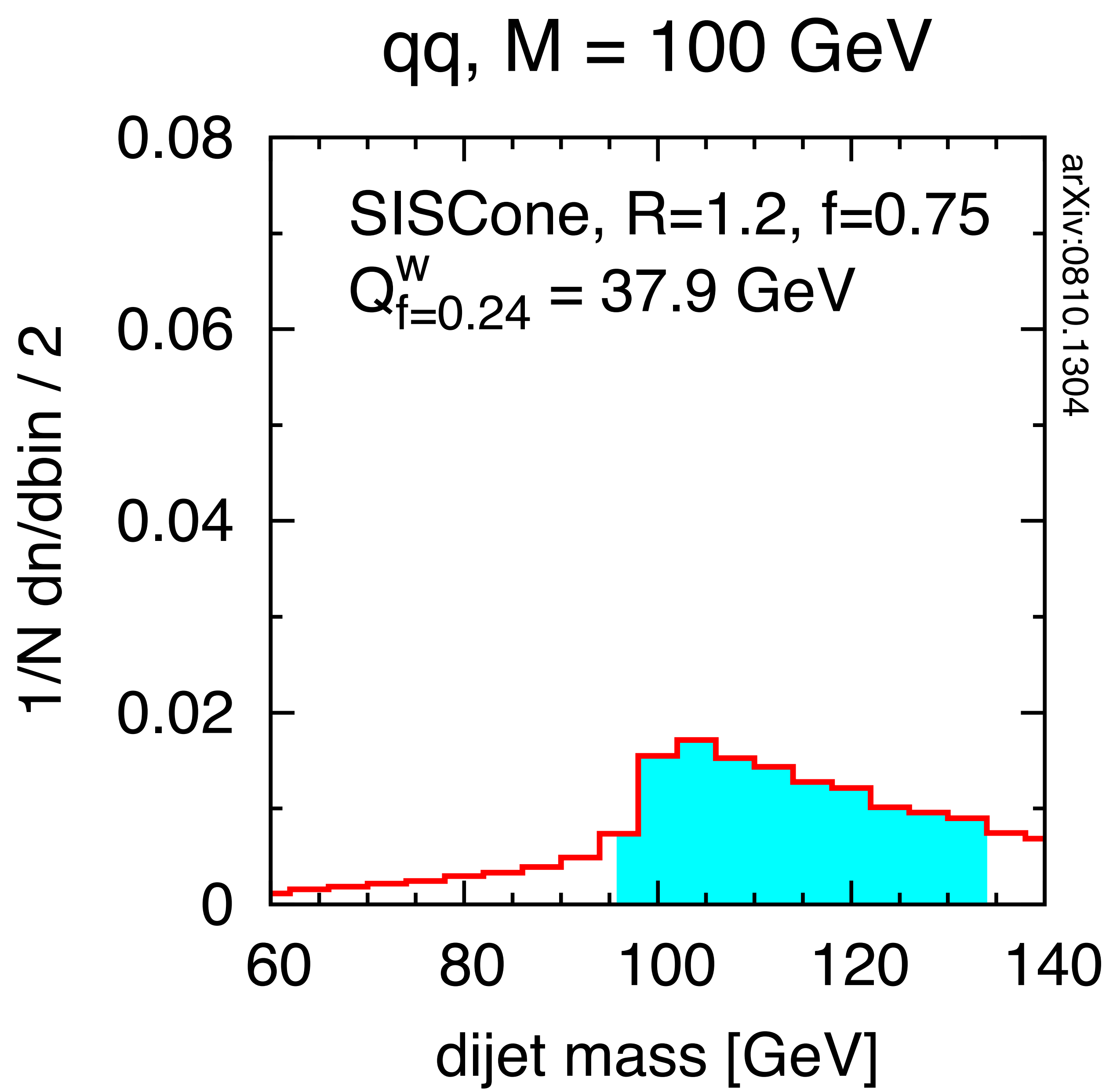




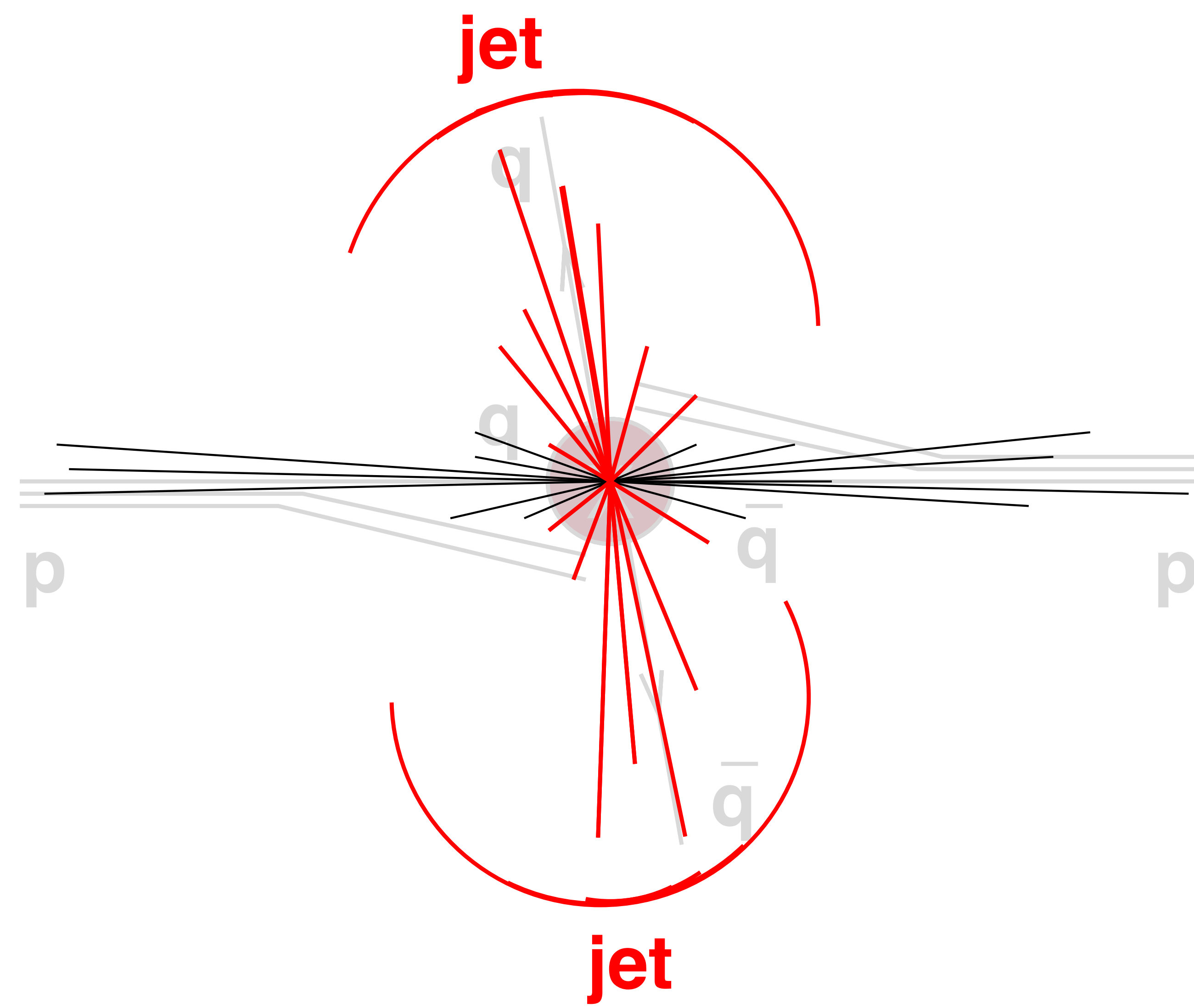
Resonance X → dijets



$R = 1.2$

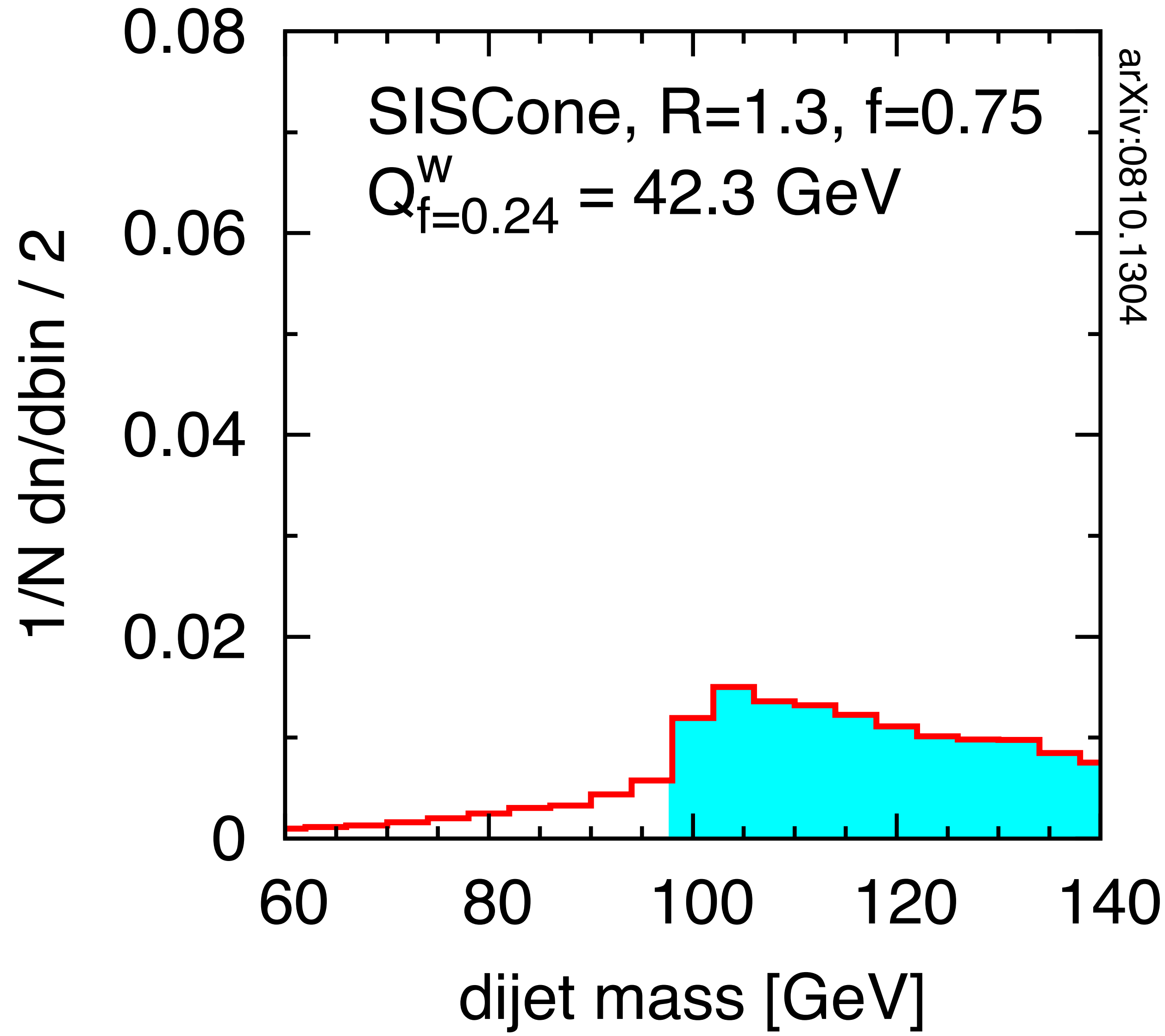


Resonance X → dijets

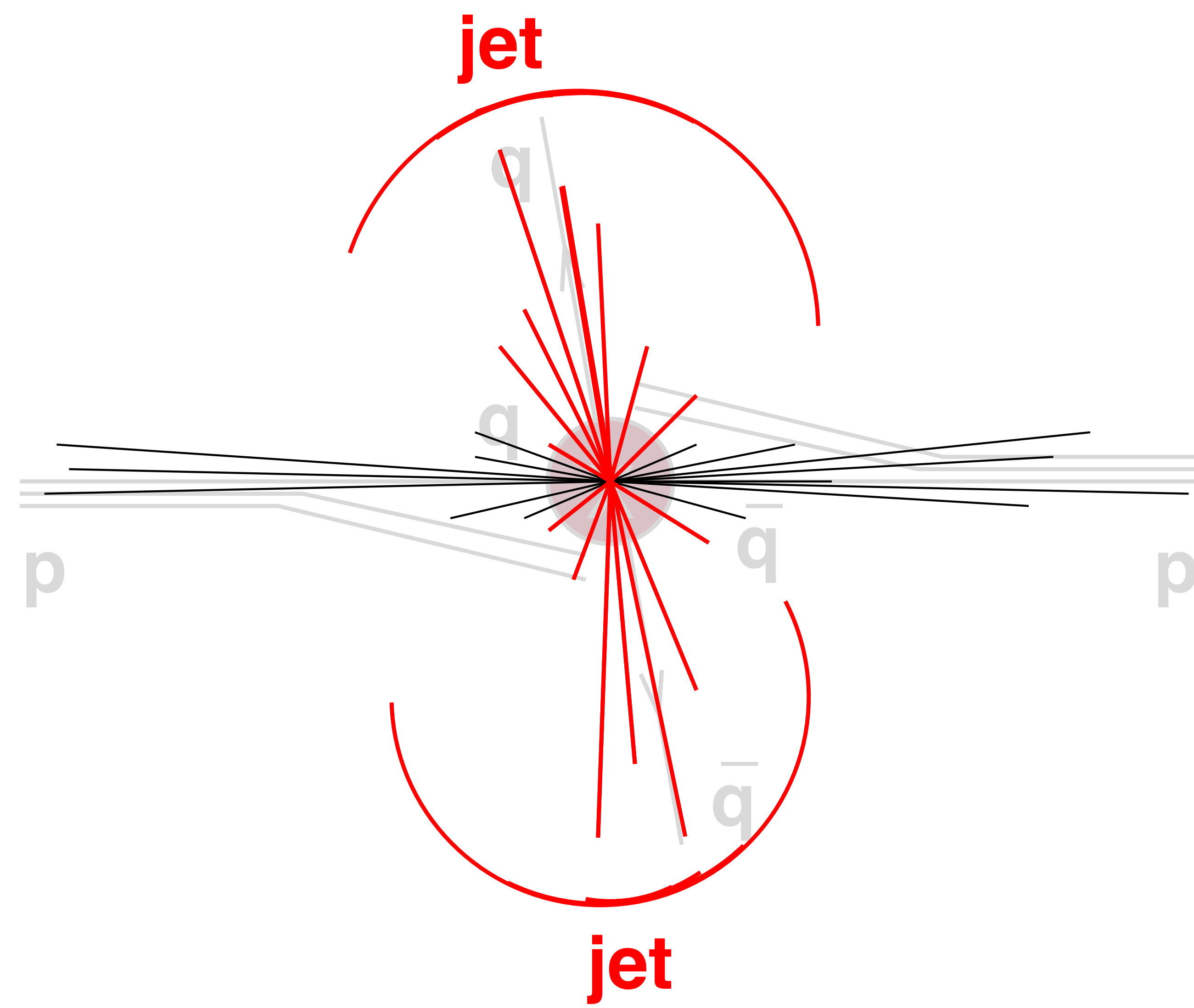


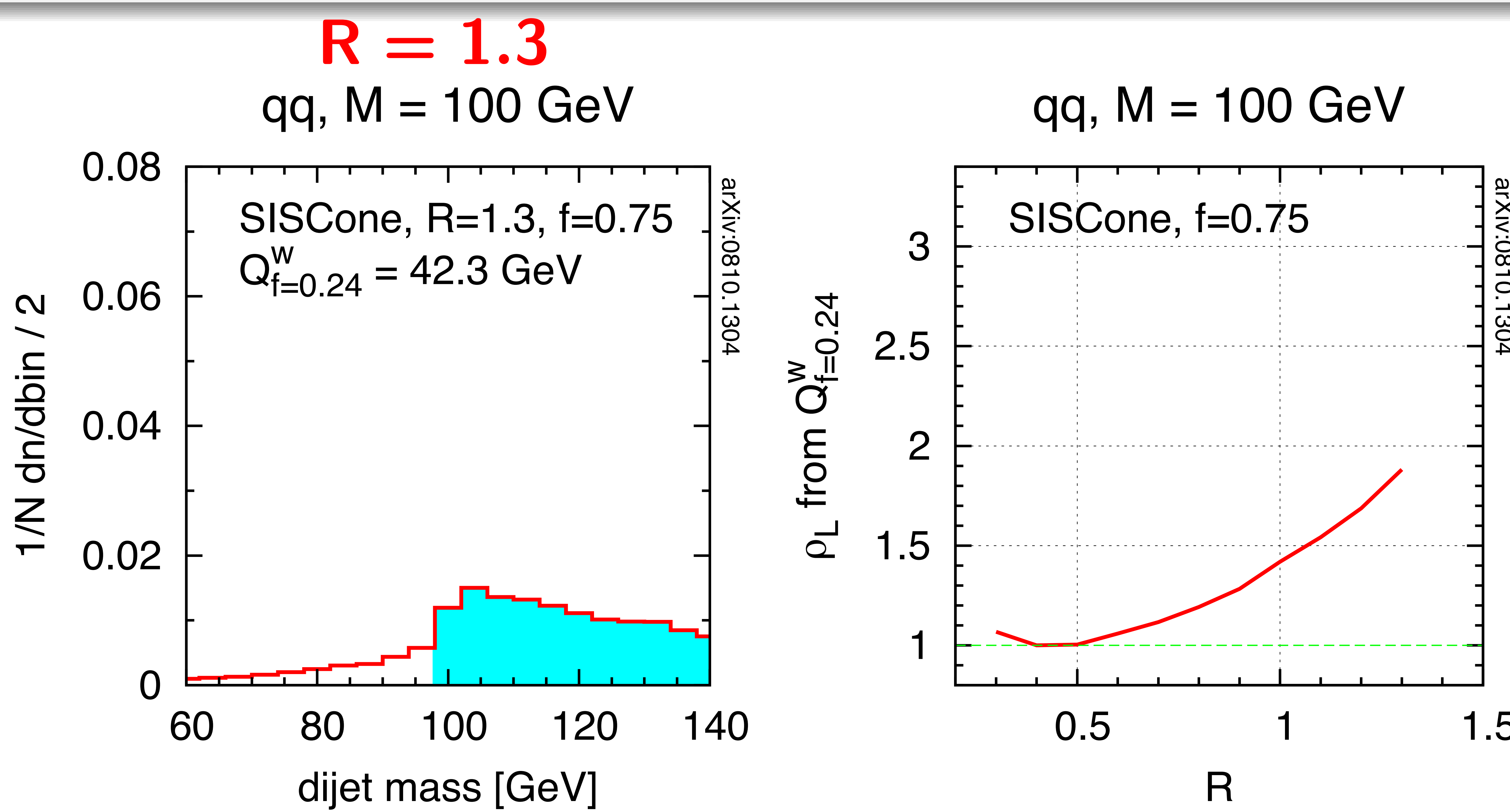
R = 1.3

qq, M = 100 GeV



Resonance X → dijets

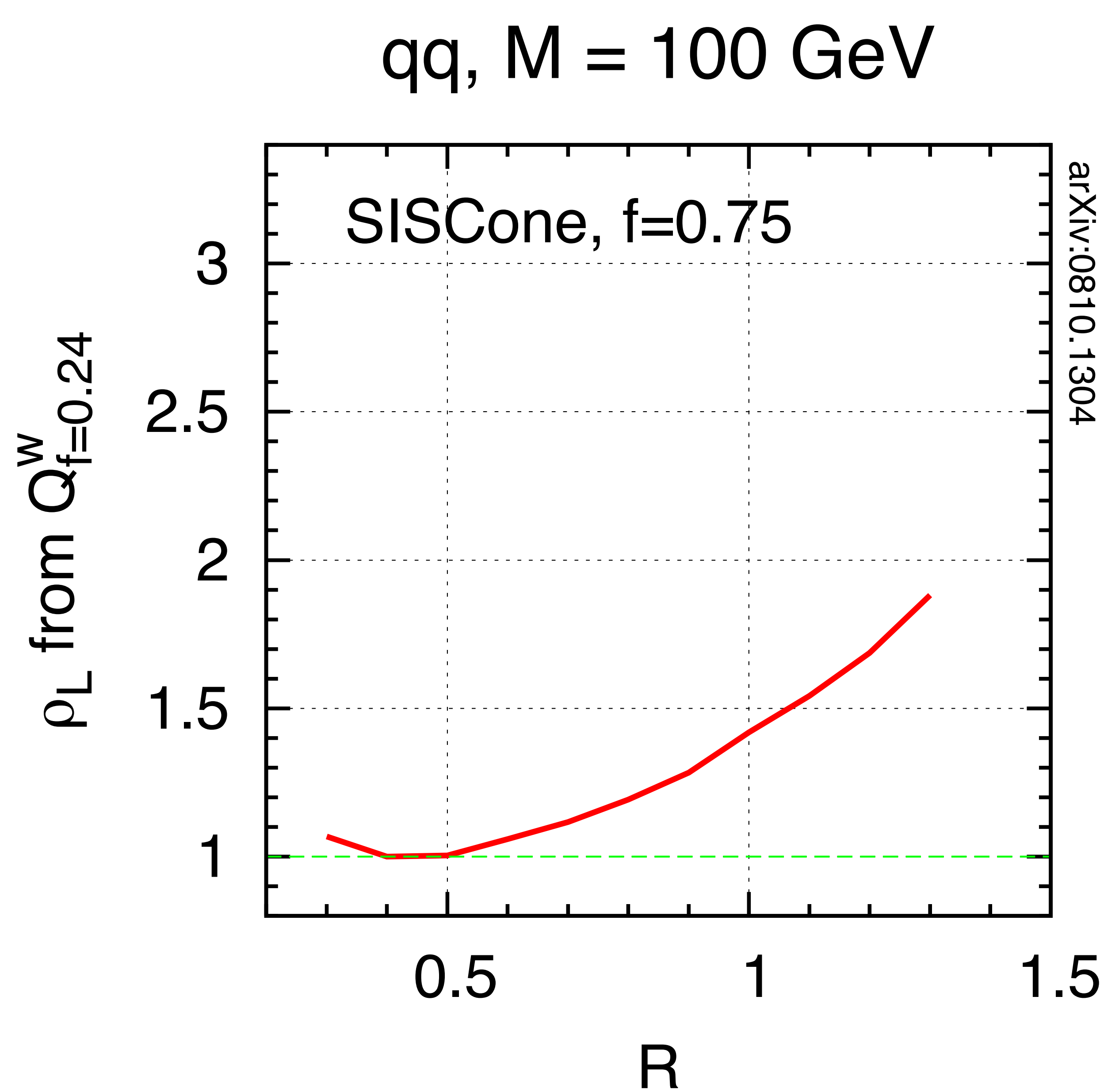




After scanning, summarise "quality" v. *R*. Minimum ≡ BEST

picture not so different from crude analytical estimate

$m_{qq} = 100$ GeV



Best R is at minimum of curve

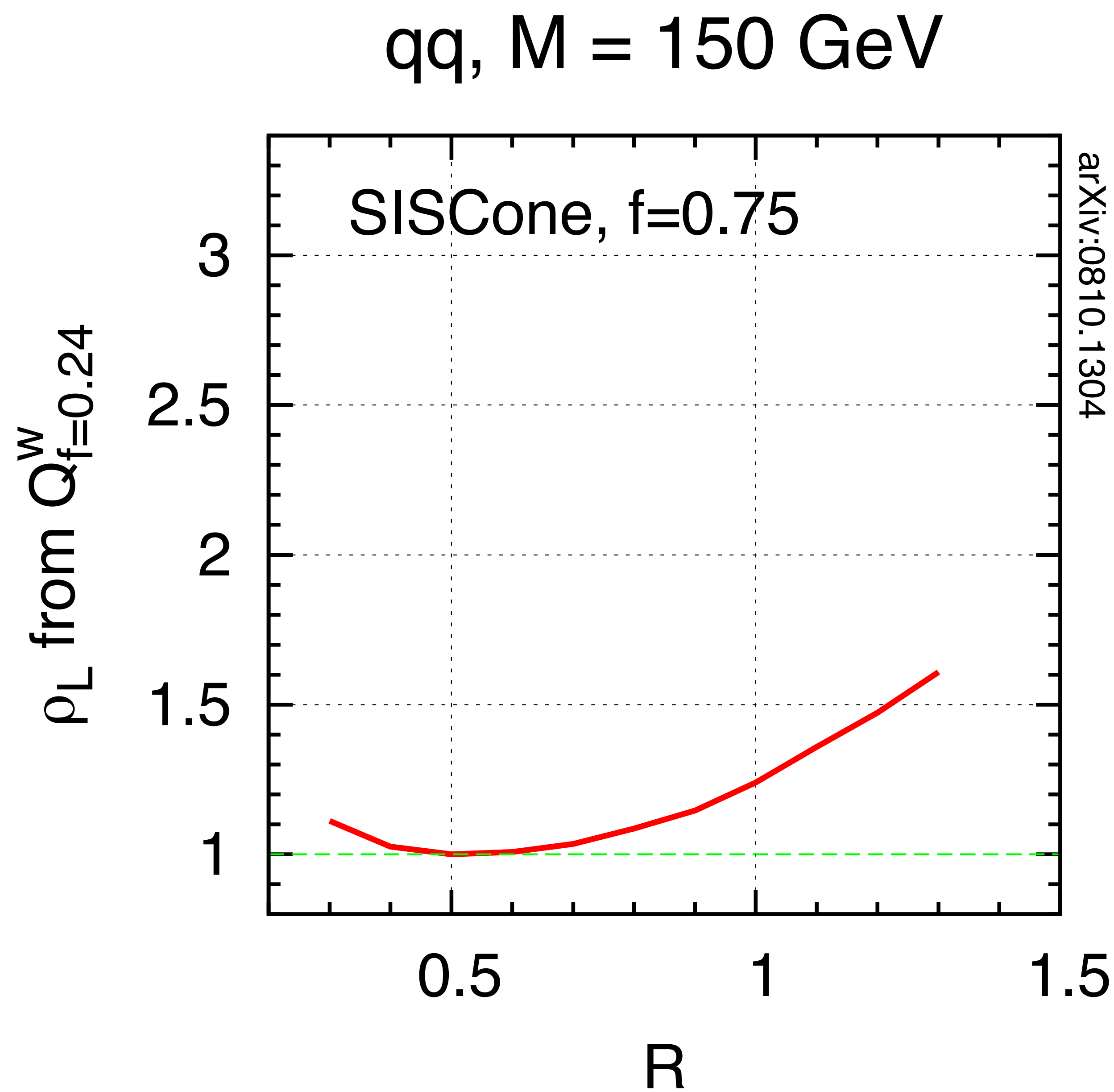
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

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

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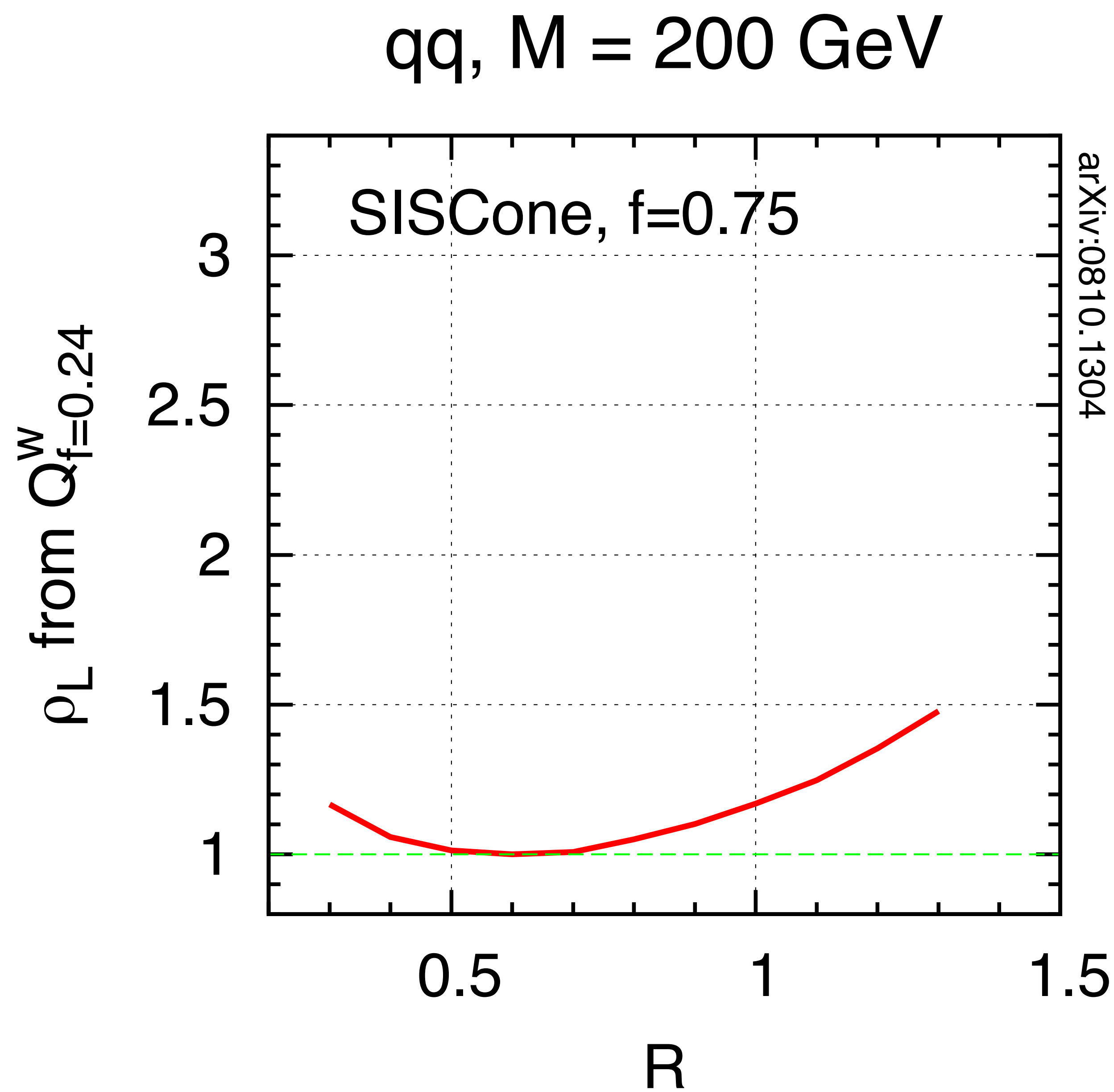
Other related work: Krohn, Thaler & Wang '09; Soyez '10

$m_{qq} = 200$ GeV



Best R is at minimum of curve

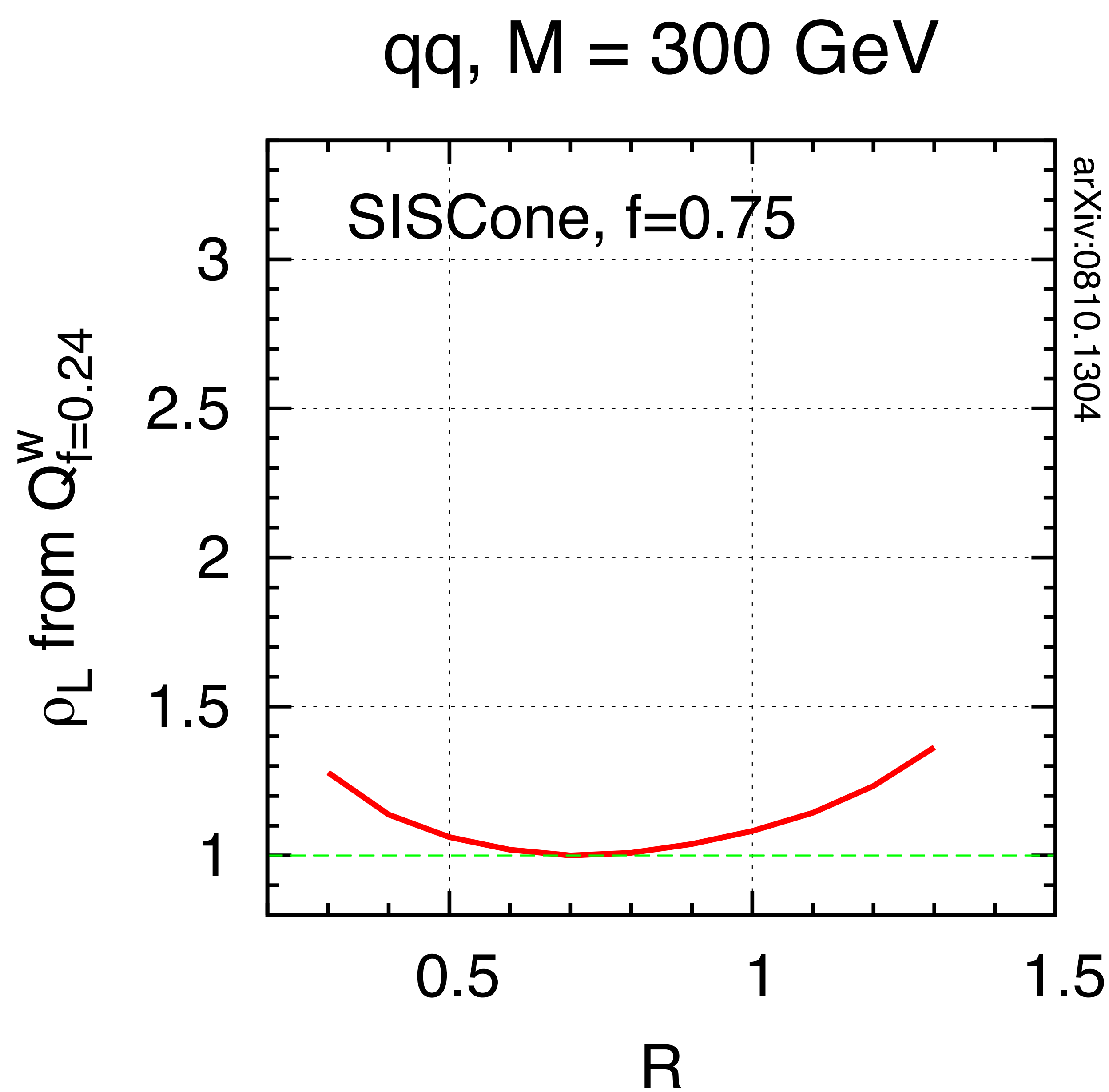
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  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

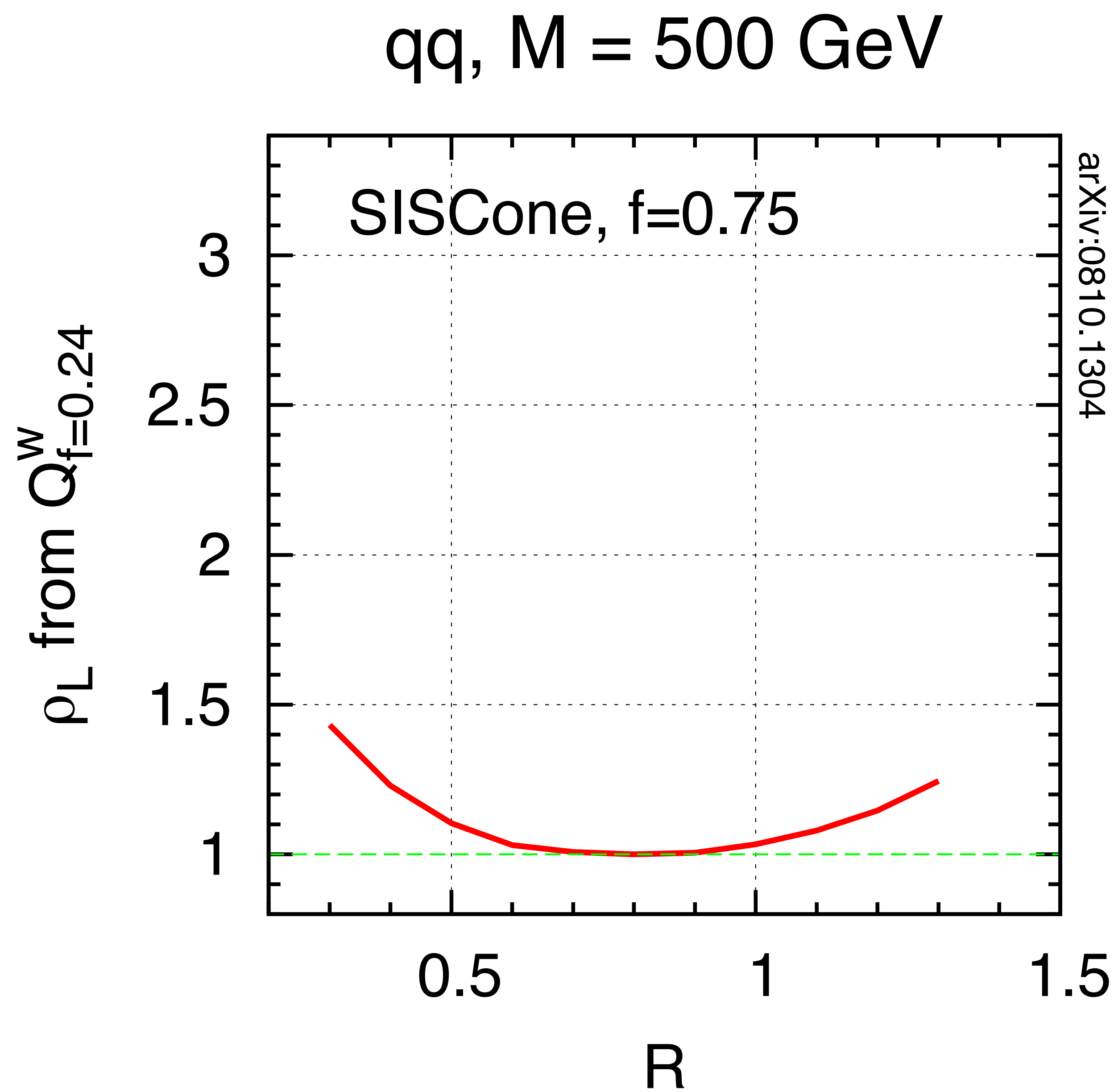
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  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

$m_{qq} = 500$ GeV



Best R is at minimum of curve

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

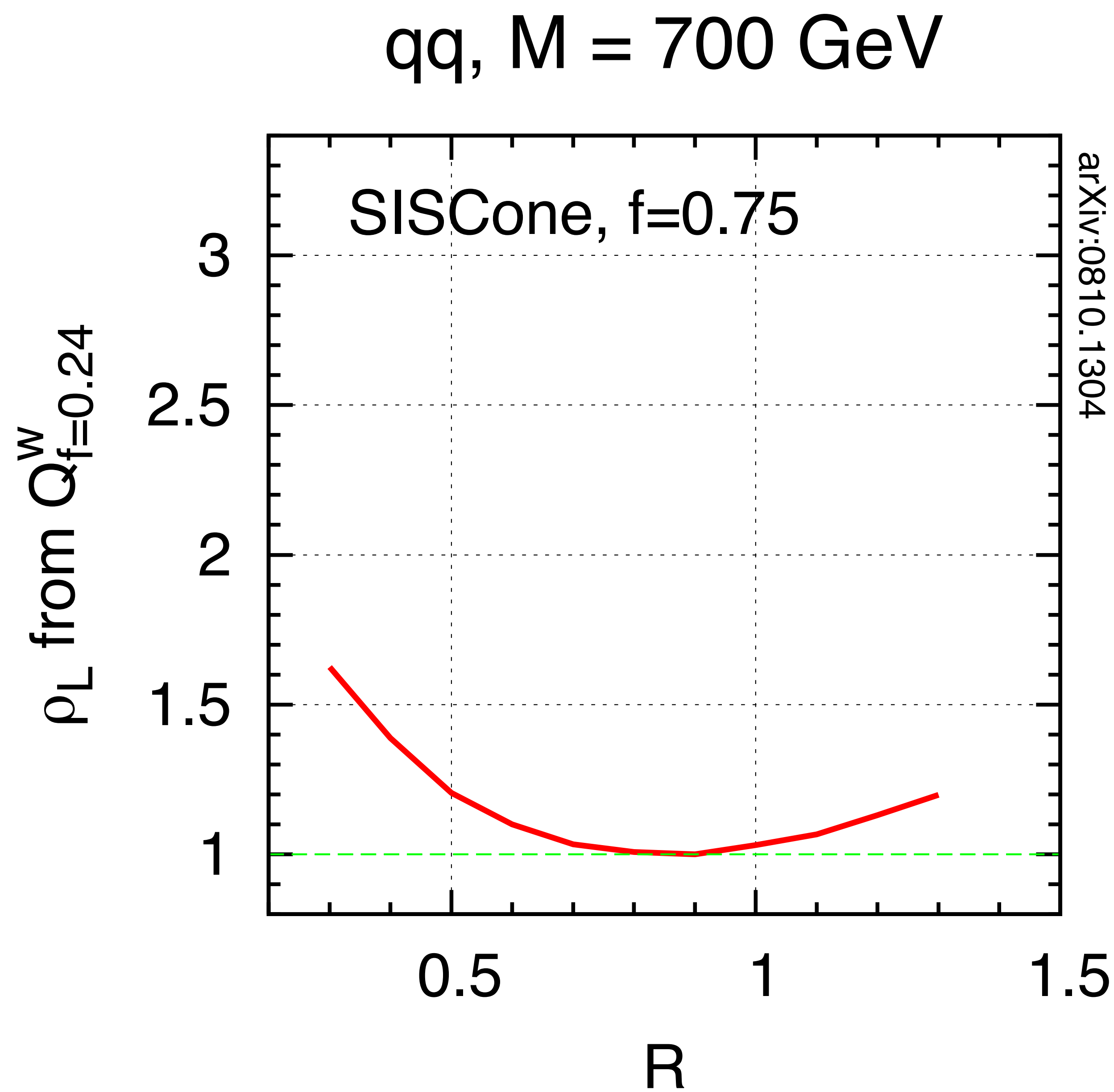
NB: current analytics too crude

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

m_{qq} = 700 GeV



Best R is at minimum of curve

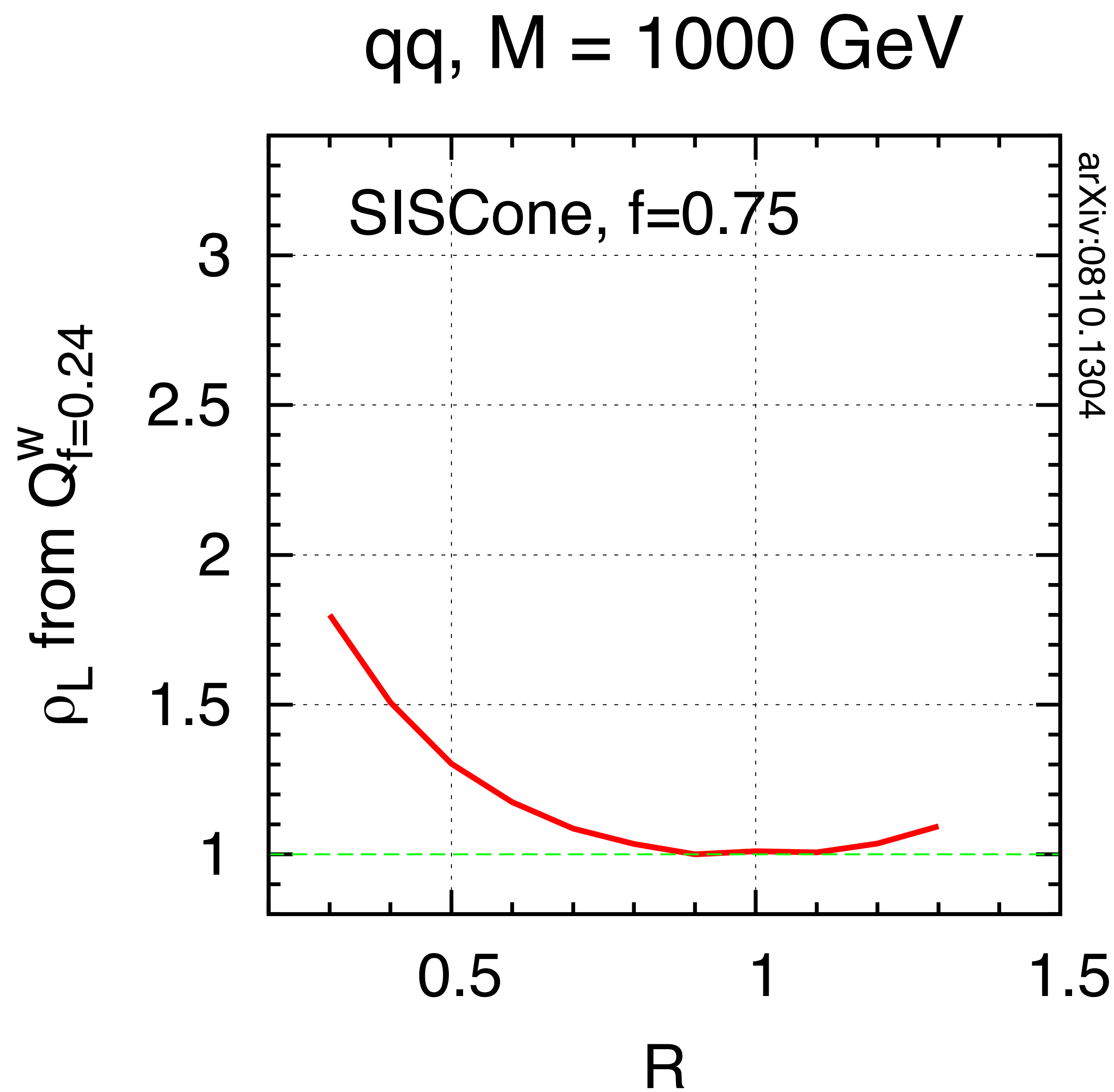
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  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

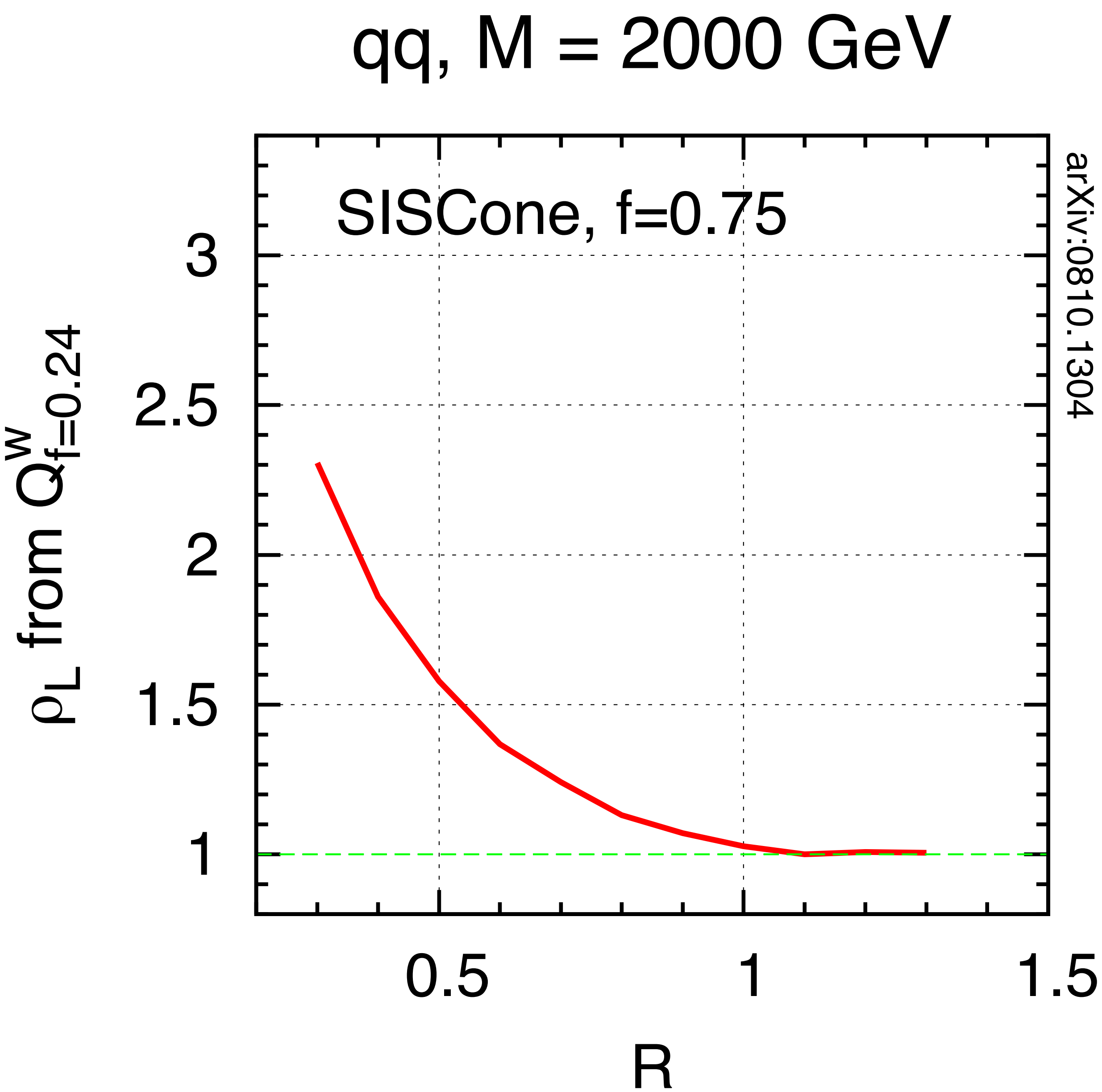
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  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

m_{qq} = 2000 GeV



Best R is at minimum of curve

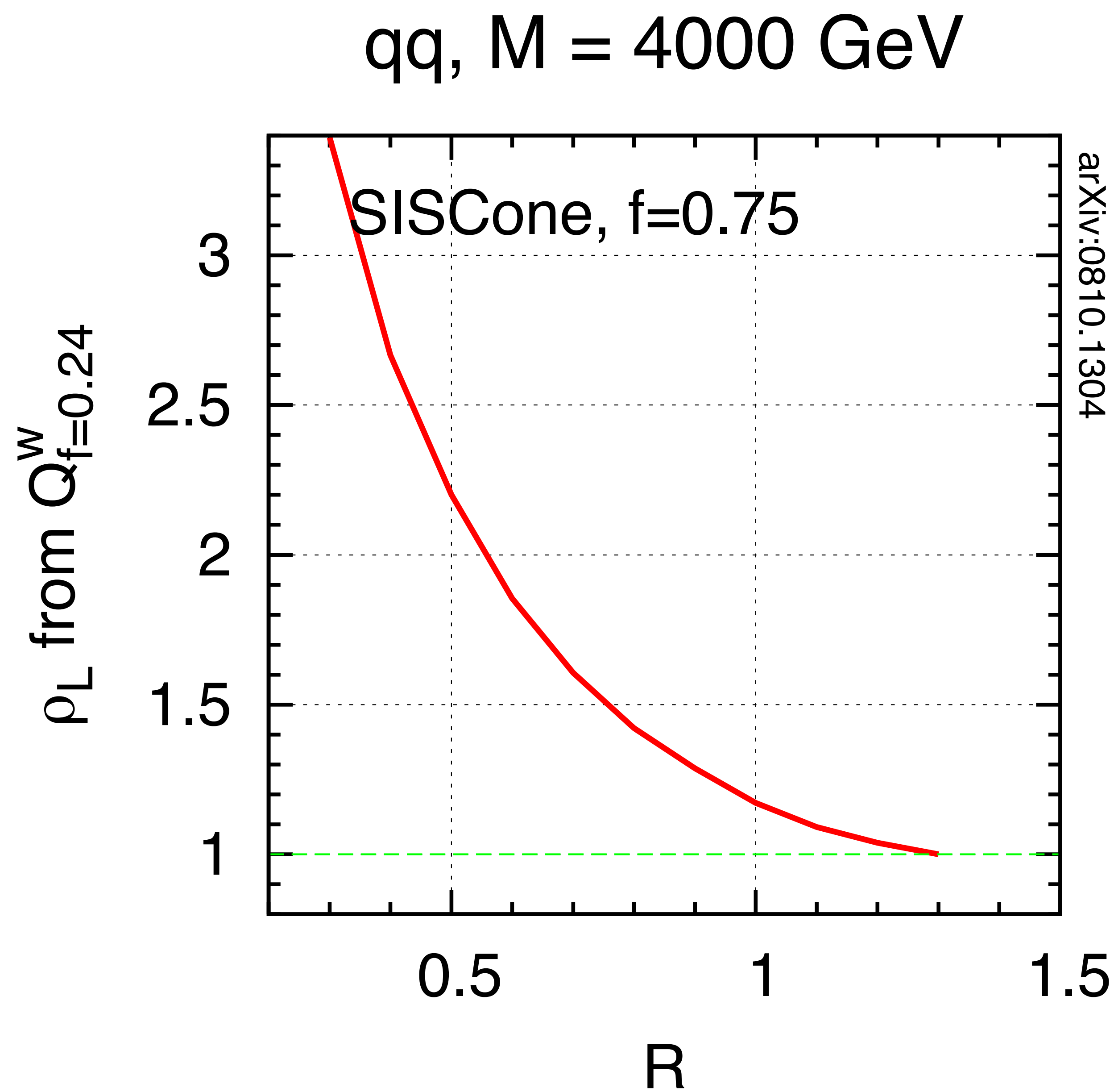
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

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

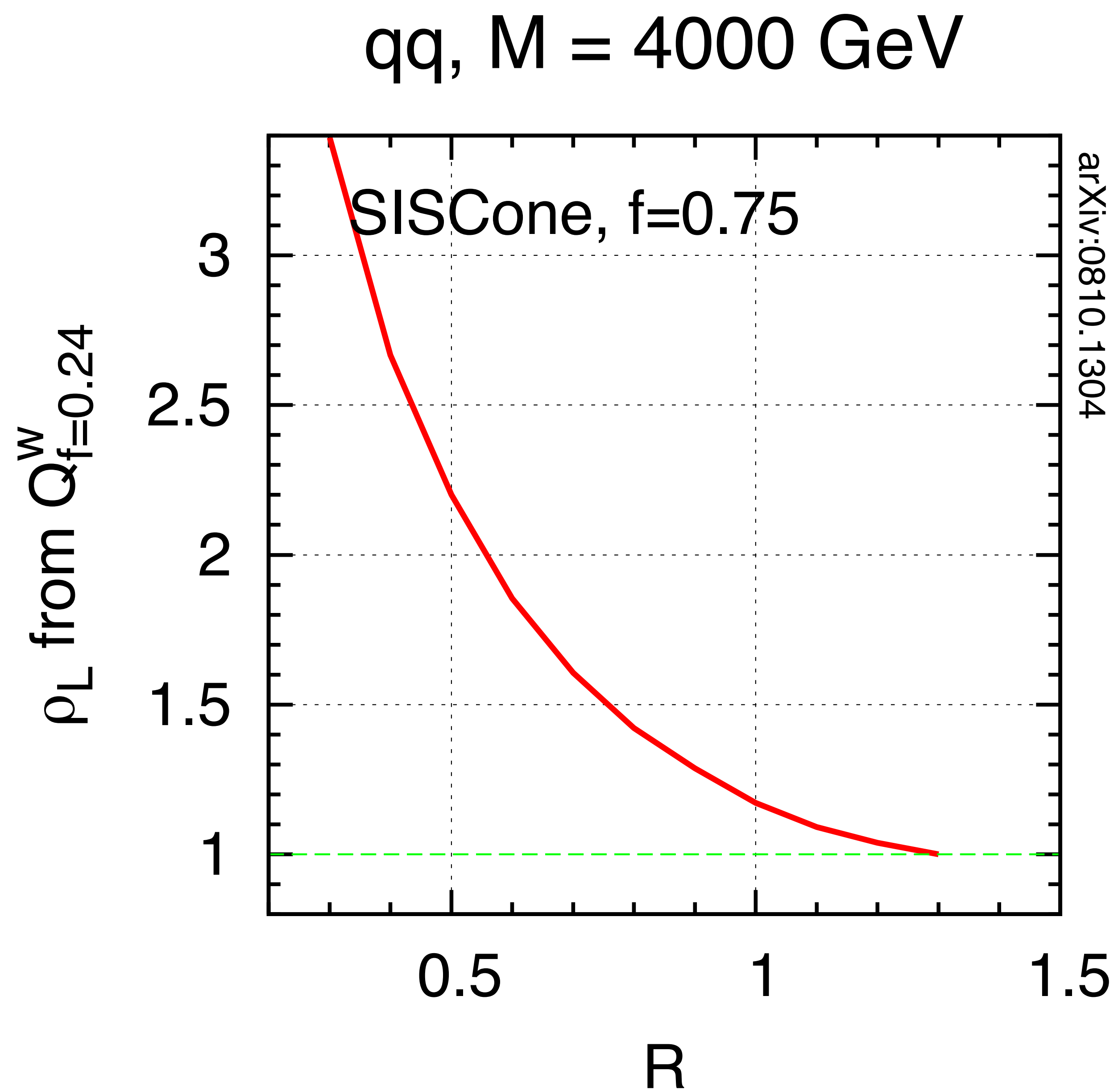
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

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

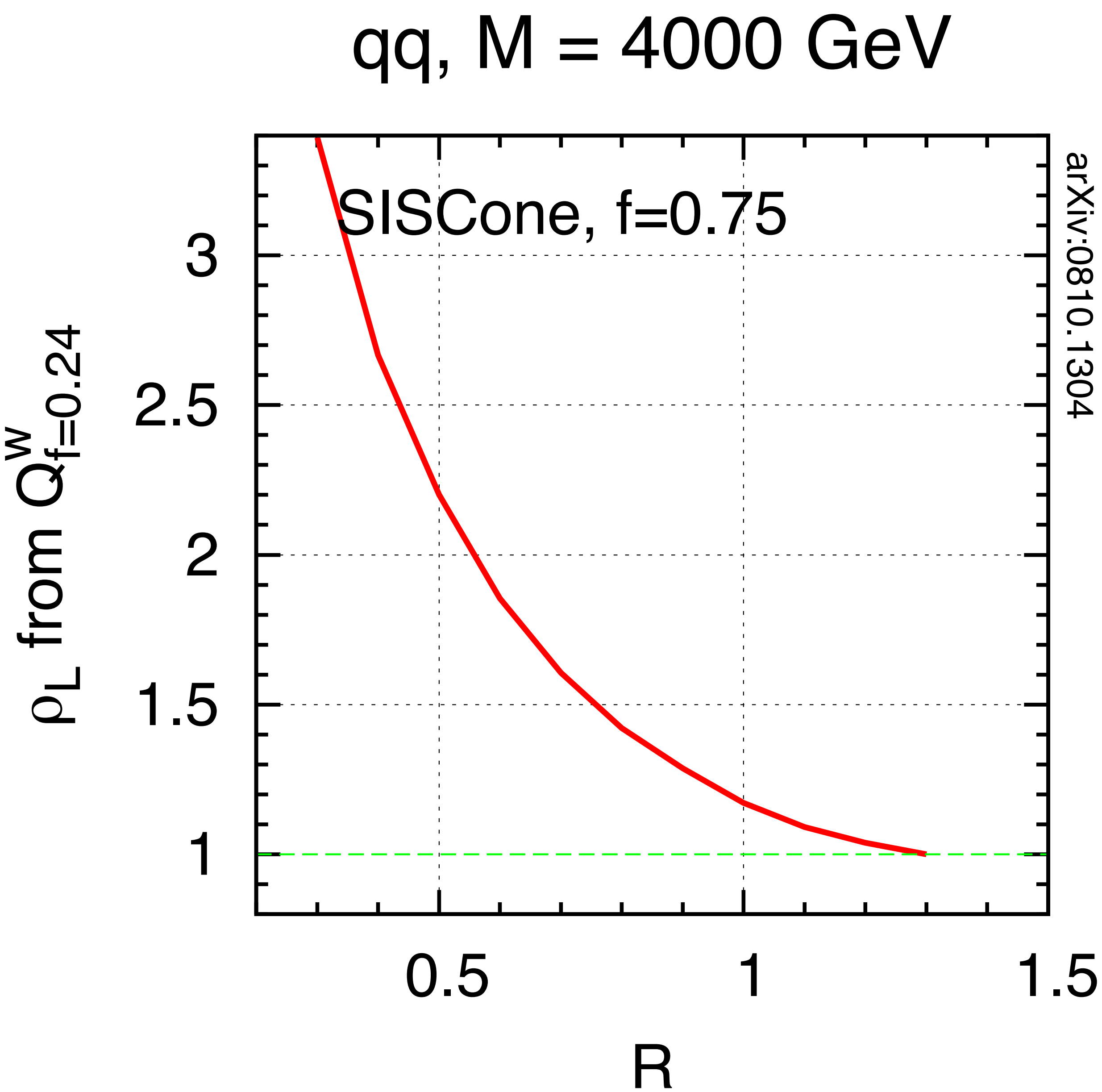
  NB: current analytics too crude

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

m_{qq} = 4000 GeV



Best R is at minimum of curve

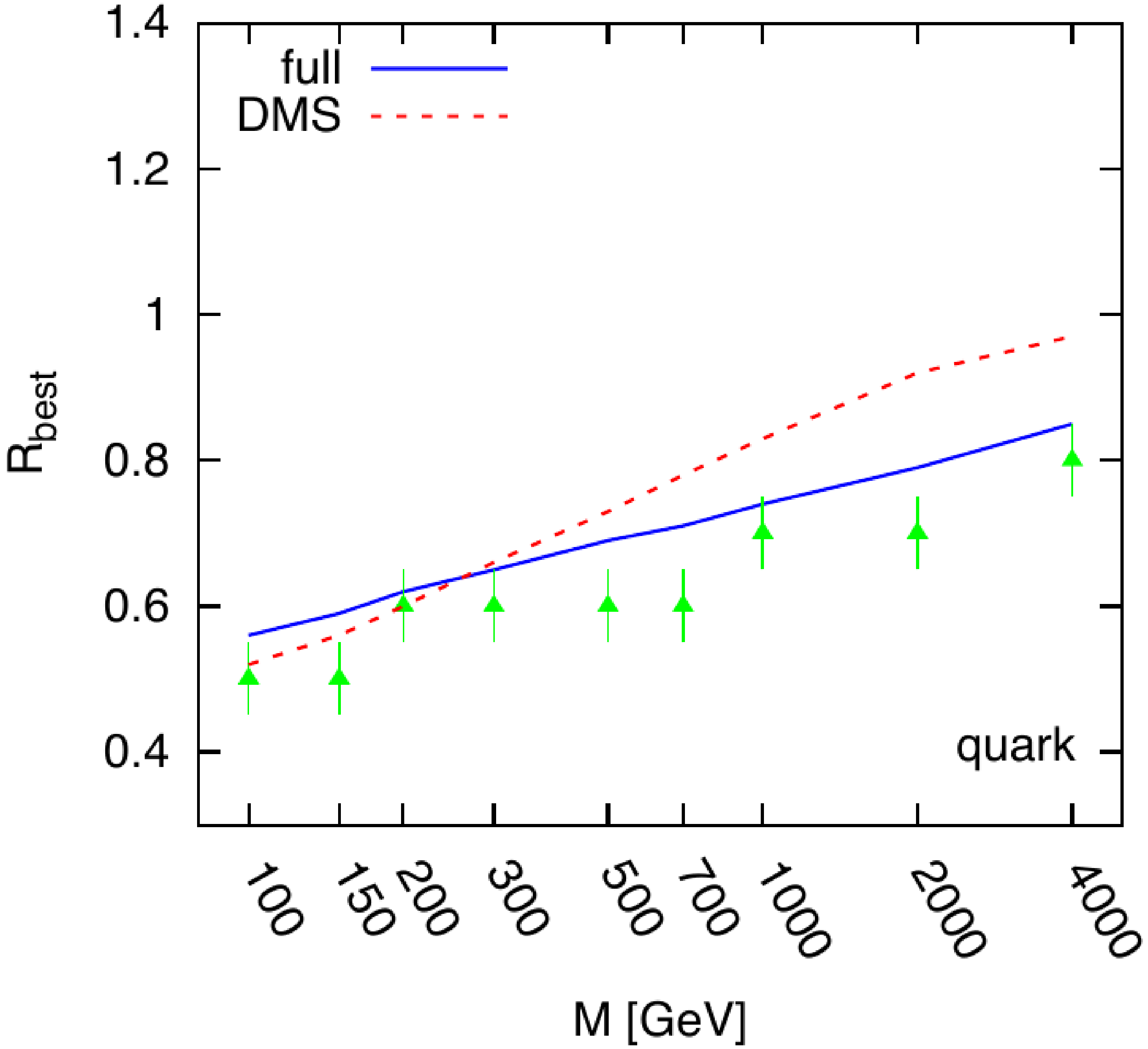
- Best R depends strongly on mass of system
- Increases with mass, just like crude analytical prediction

  NB: current analytics too crude

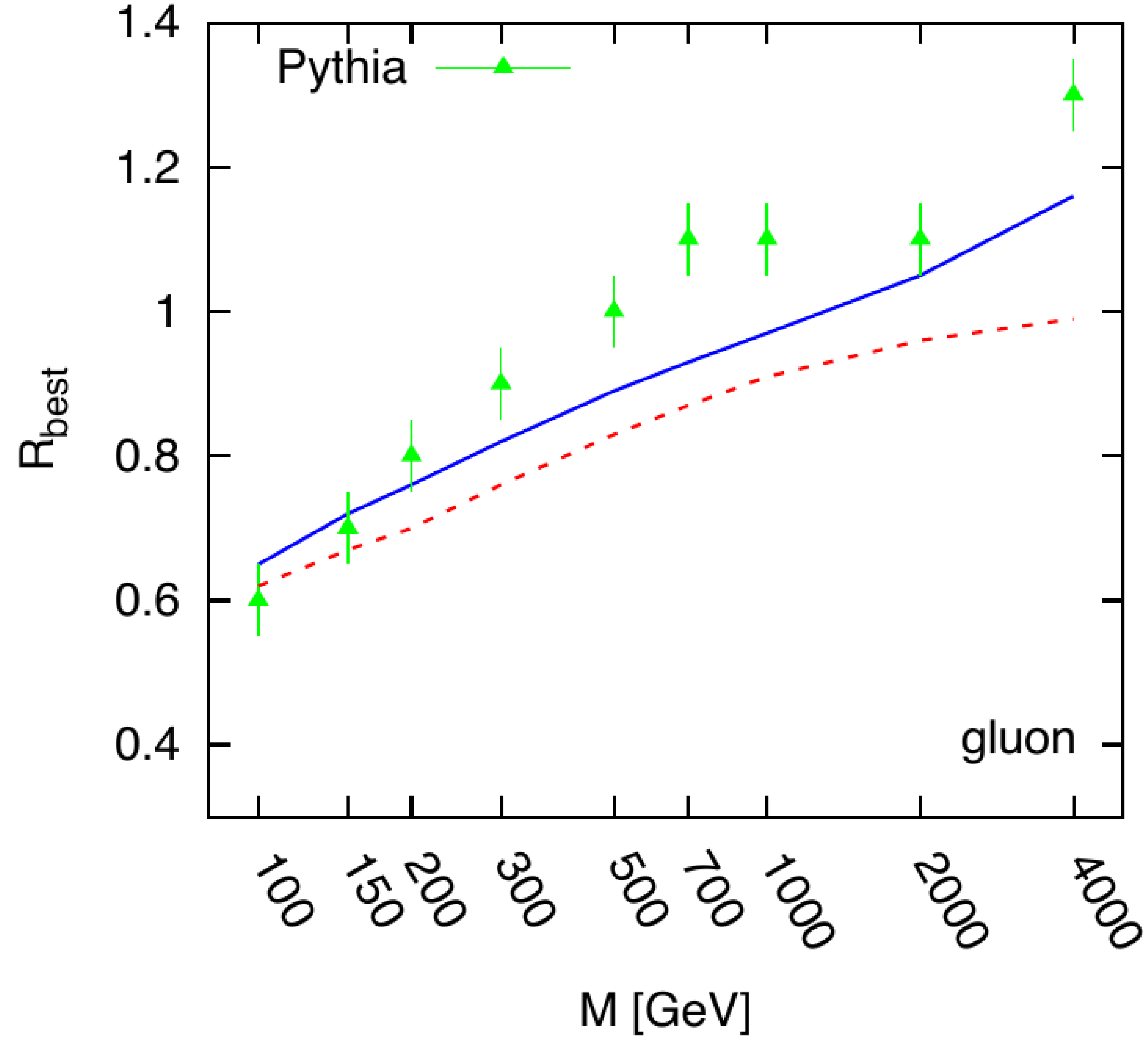
NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

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

Optimal R for $X \to q\bar{q}$

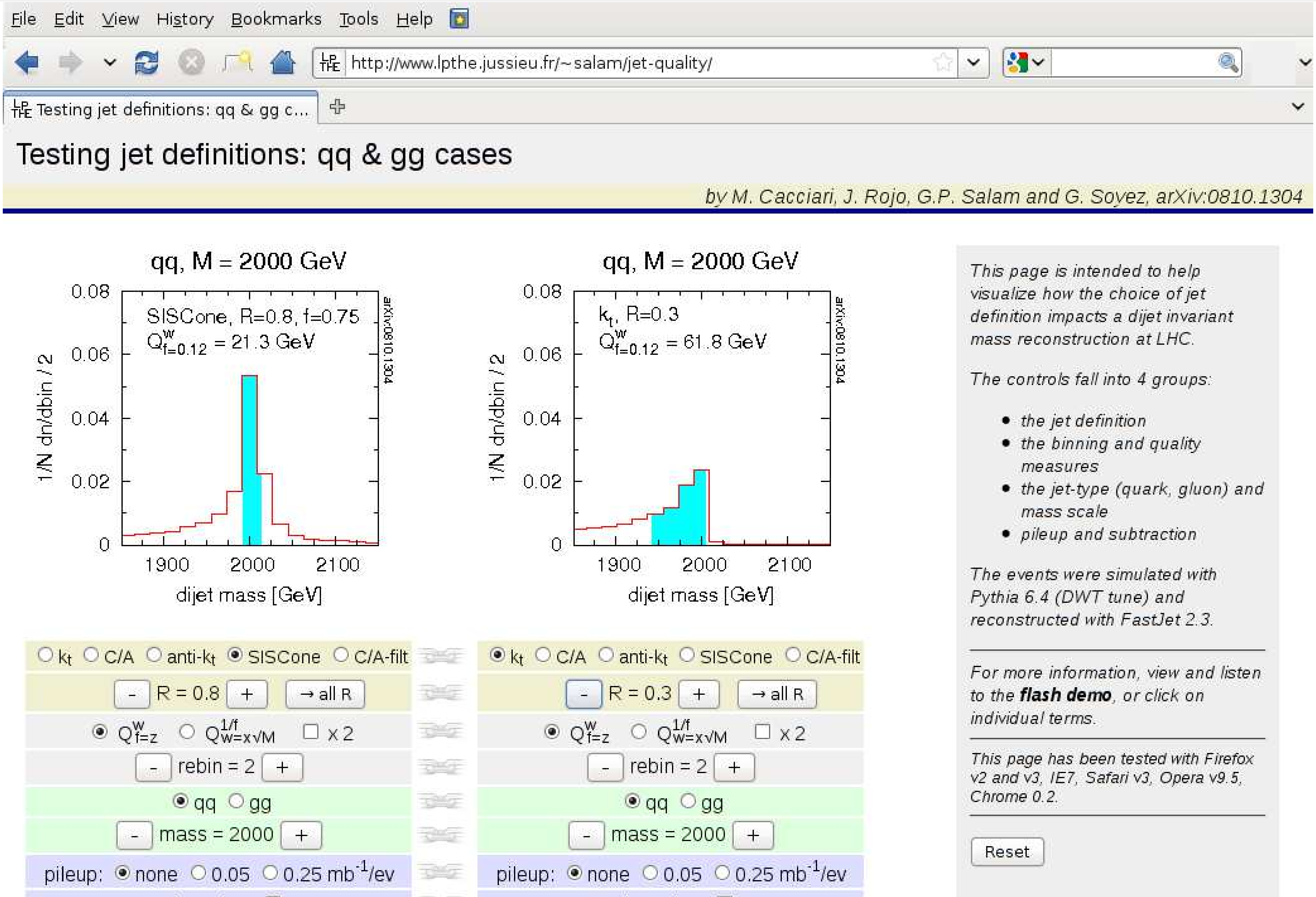


Optimal R for $X \to gg$

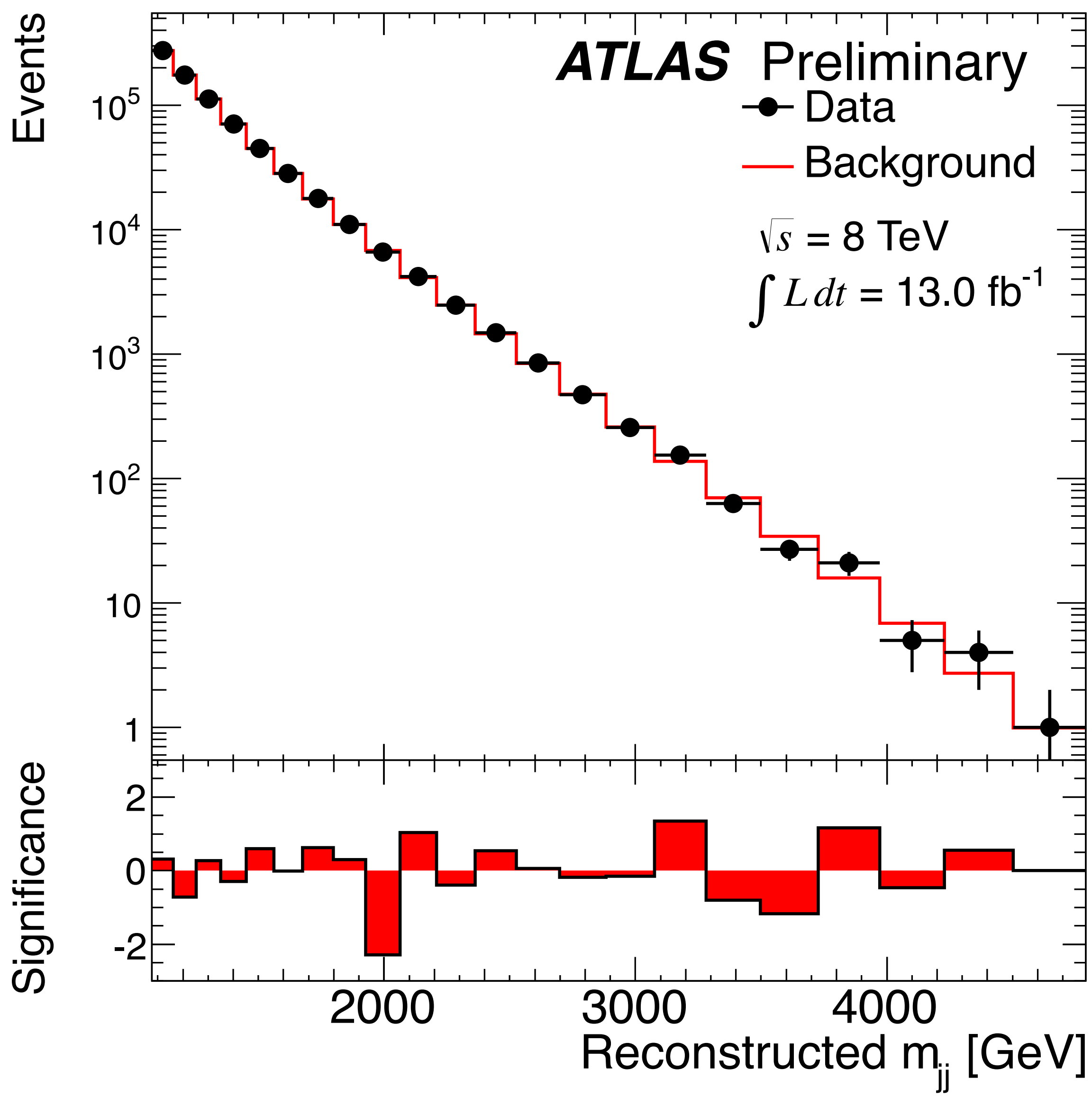


Soyez '10

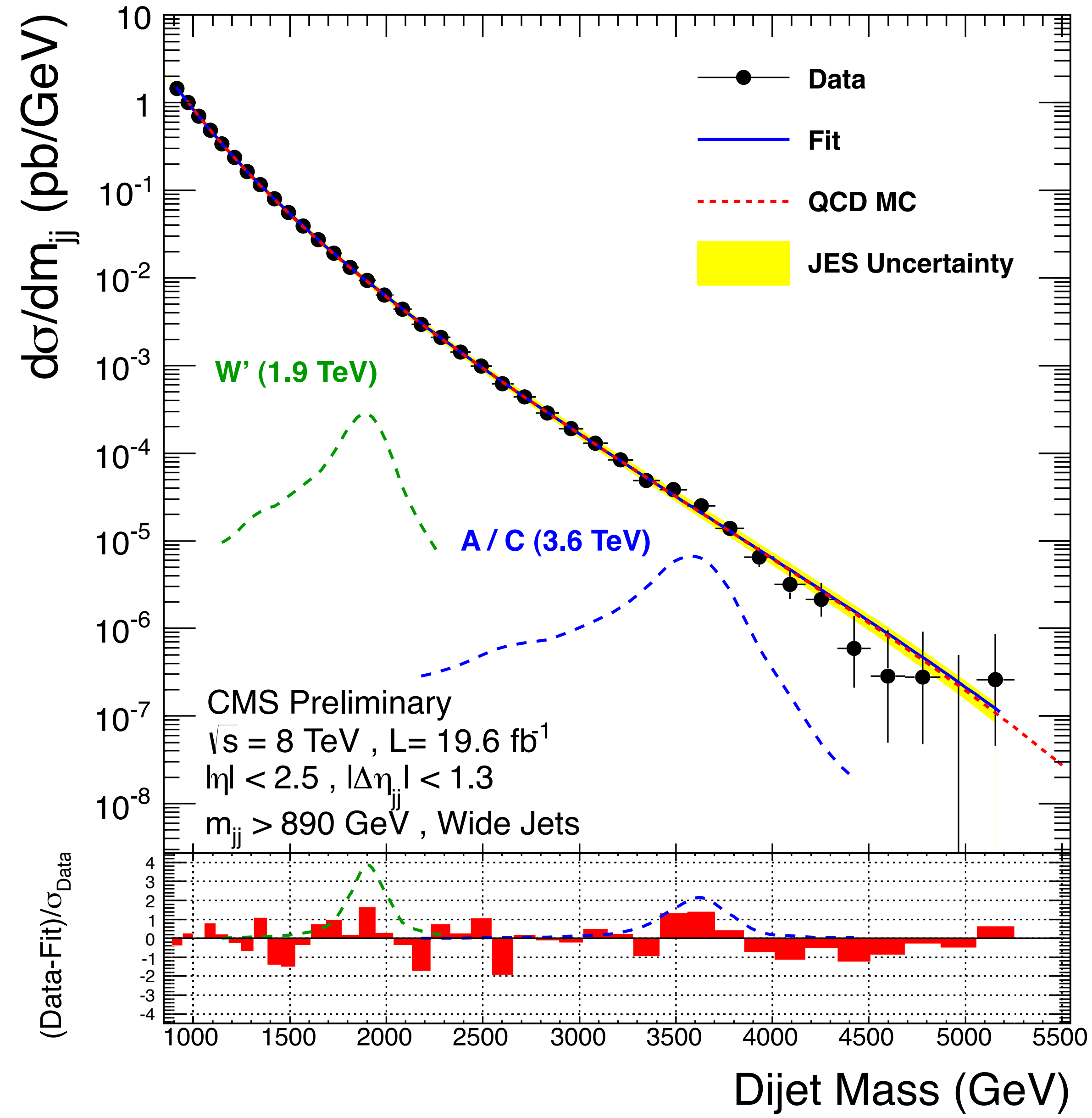
http://quality.fastjet.fr/

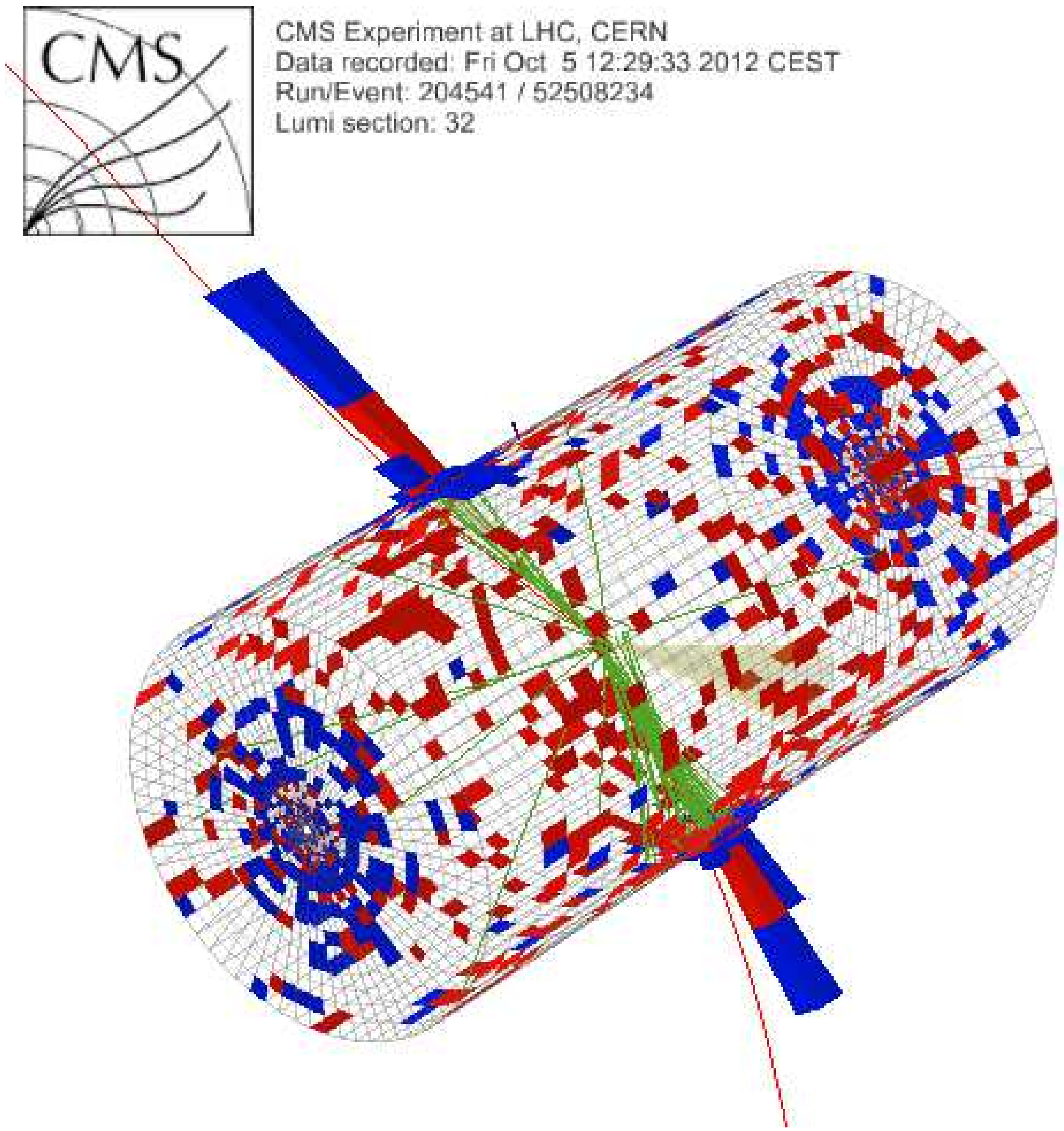


ATLAS dijet mass

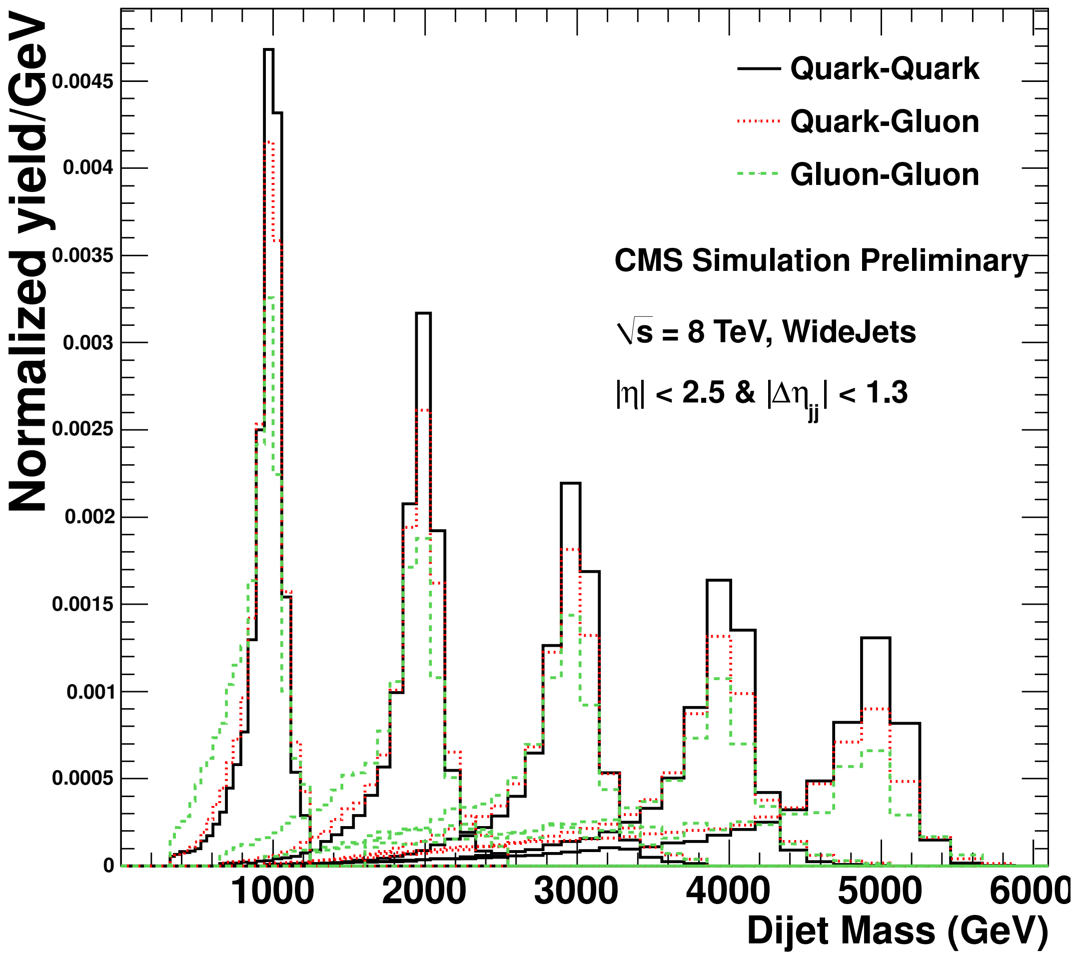


CMS dijet mass





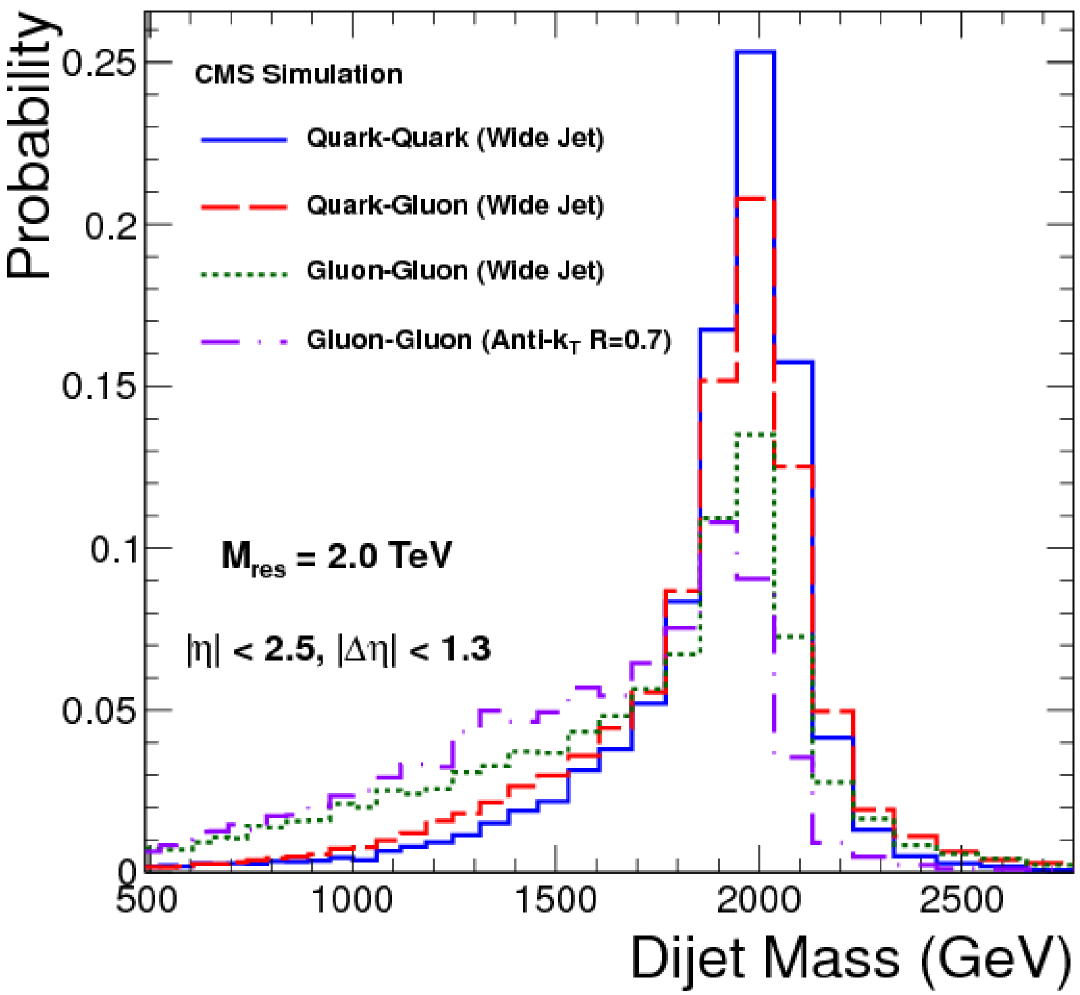
Highest mass central dijet event at the LHC: 5.15 TeV!



Expected resonance limits [TeV]

7 TeV, 5 fb^{-1}, published

X	$\rightarrow$	ATLAS ($R = 0.6$)	CMS (wide)
q^*	qg	2.94	3.05
string	qg	3.47	4.29
octet scalar	gg	1.97	2.24
W'	$q\bar{q}$	1.74	1.78



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octet scalar	gg	1.97	2.24
W'	$q\bar{q}$	1.74	1.78

CMS "wide jets":
We [...] select the two AK5 jets with the highest pT in the event (leading AK5 jets). Then we add the Lorentz vectors of all other AK5 jets with $p_T > 10$ GeV and $|\eta| < 2.5$ to the closest AK5 leading jet, if within $\Delta R =< 1.1$, to obtain the two leading wide jets. The parameter ΔR sets the maximum size of the wide jet.

- We can (sort of) calculate the relation between jet p_t and parton p_t
- That guides us in how to "focus" jets
  - generally want small R and low p_t, because UE is large
  - larger R at high p_t's
  - smaller R helps resolve multi jets, as in $t\bar{t}$, SUSY, black holes, etc.

ATLAS mostly uses $R = 0.4$; also $R = 0.6$

CMS mostly uses $R = 0.5$; also $R = 0.7$ & "wide" jets

- Large di/multi-jet mass is not enough when looking for signals — QCD very enhanced at small angles, signals aren't
- Relation between number of partons & number is non-trivial at high multiplicities

Two things that make jets@LHC special

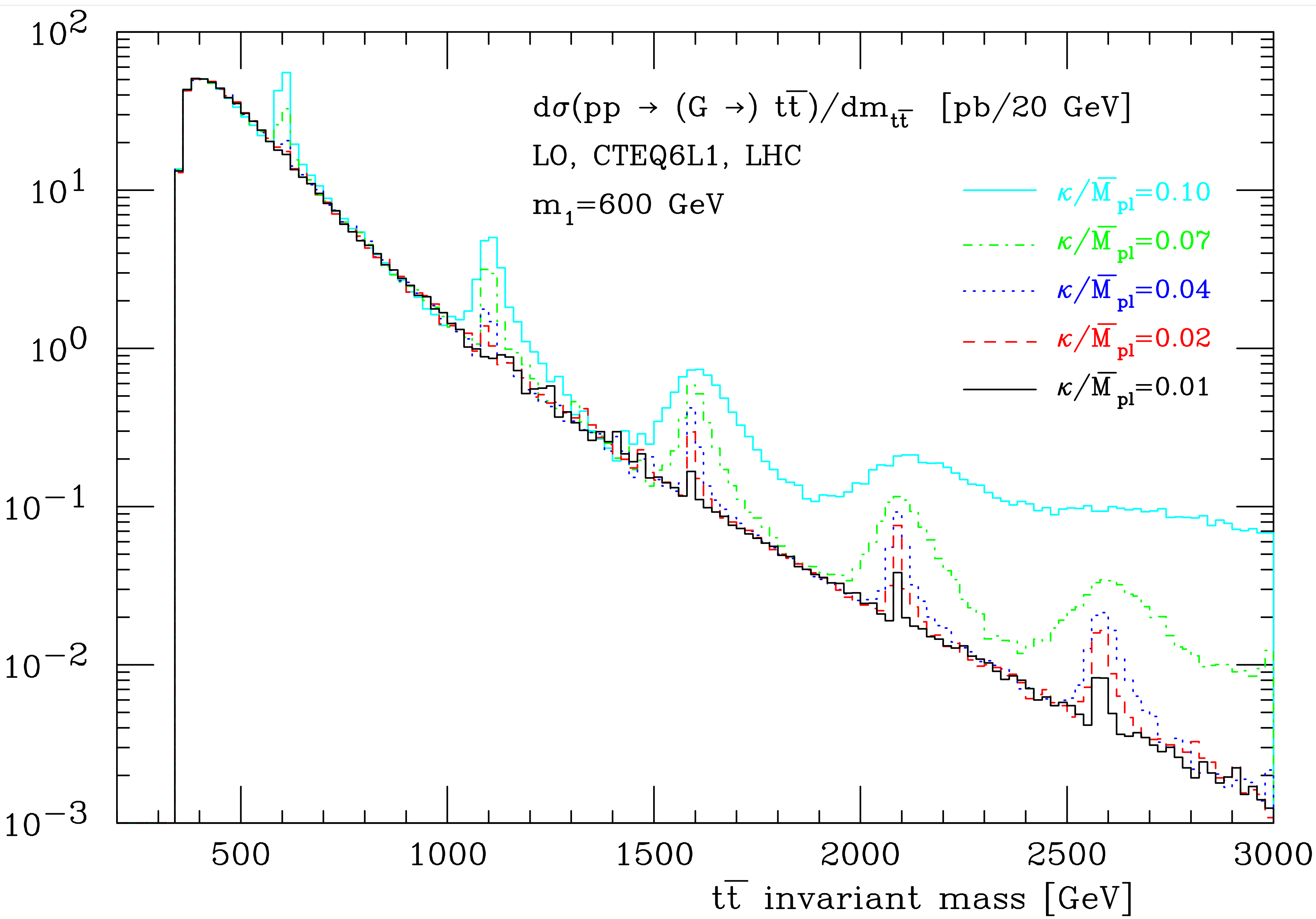
The large hierarchy of scales

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

The huge pileup

$n_{pileup} \sim 20 - 40$

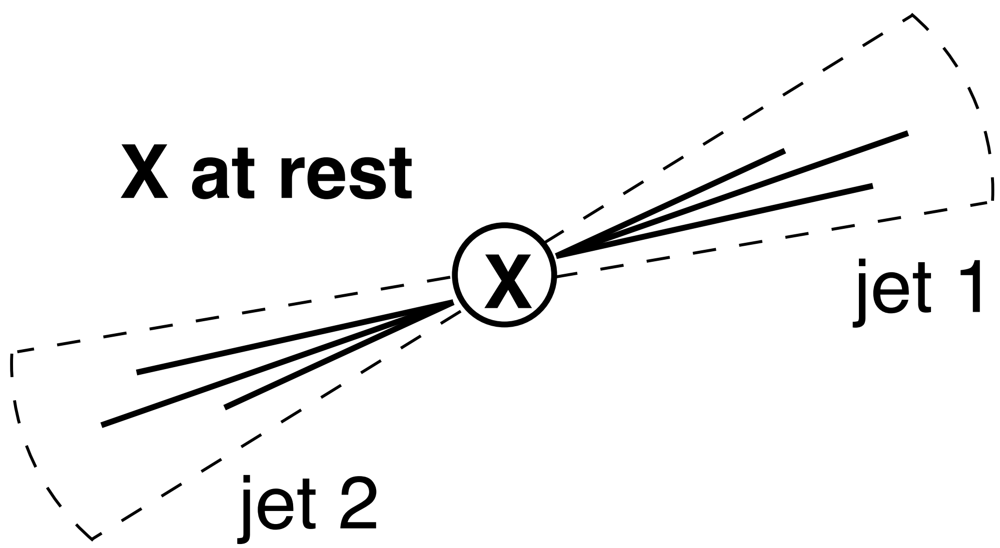
[These involve two opposite extremes: low p_t and high p_t, which nevertheless talk to each other]



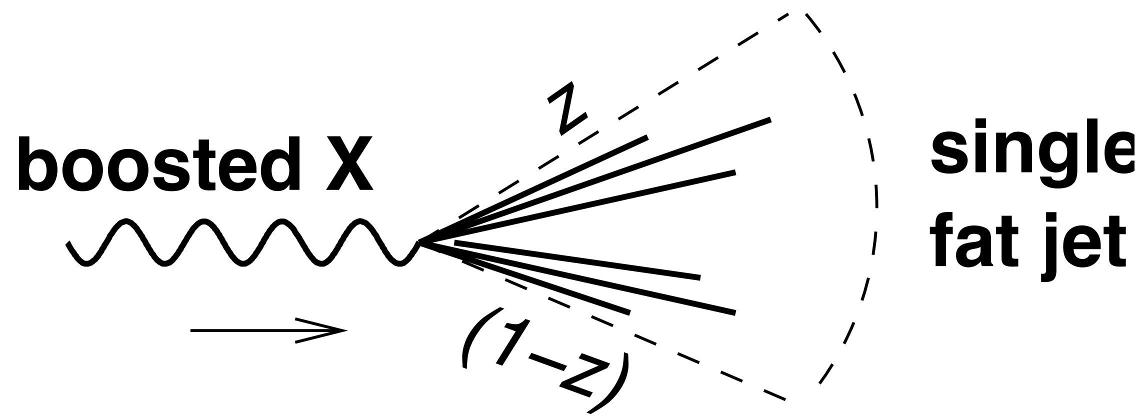
RS KK resonances $\to t\bar{t}$, from Frederix & Maltoni, 0712.2355

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

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



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

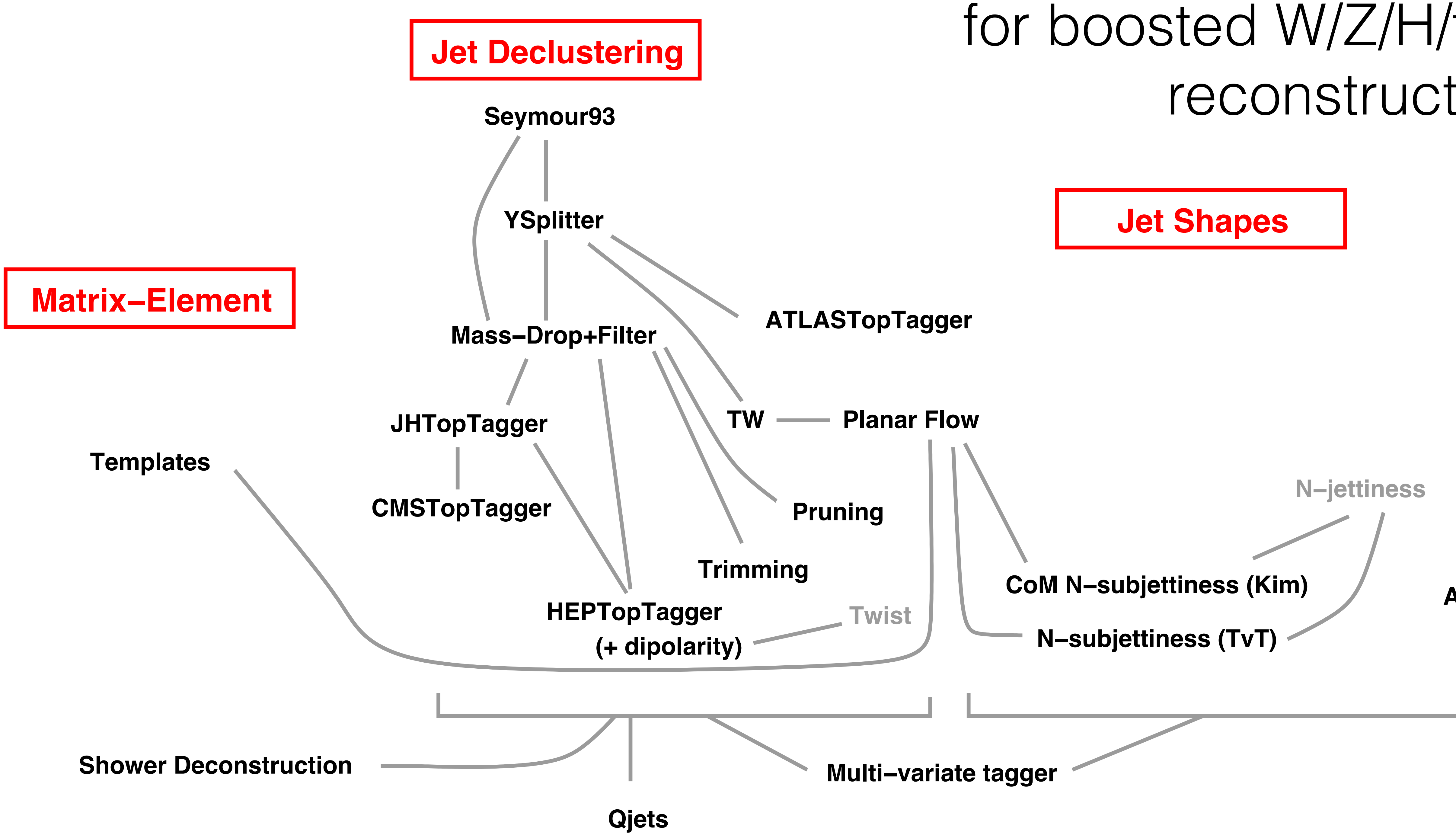


Happens for $p_t \gtrsim 2m/R$

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

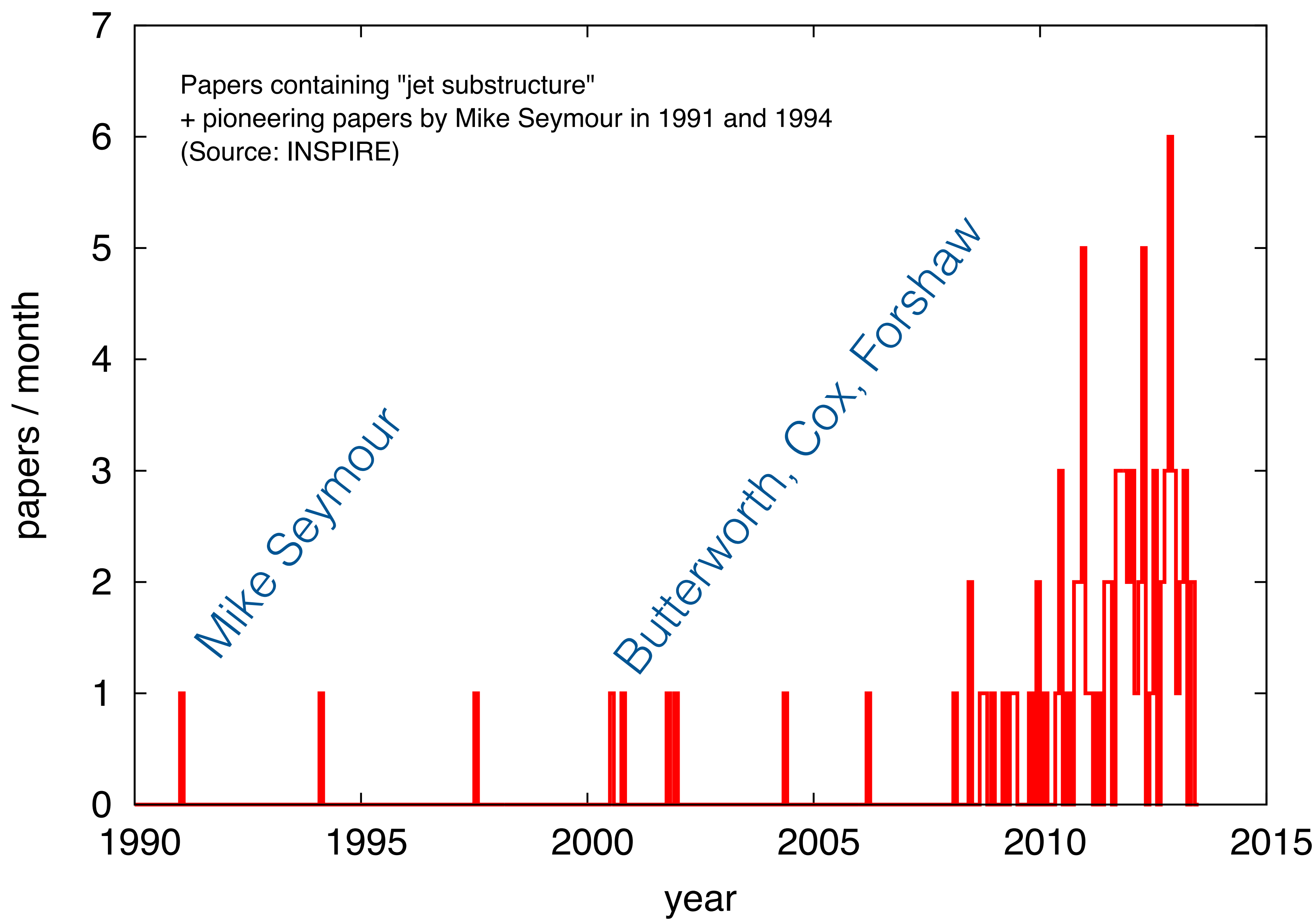
Very active research field

Some of the tools developed for boosted W/Z/H/top reconstruction



apologies for omitted taggers, arguable links, etc.

Number of papers containing
the words 'jet substructure'



More than 100 papers since 2008
(+ some background noise)

Pioneered by M. Seymour in the early '90s

Exploded around 2008

Extensive experimental work

ATLAS Public Results

- Large-R, groomed jets with pile-up
- Large-R jets with substructure
- Quark/gluon jets (see also this link)
- Jet substructure at LHC7
- Jet properties for boosted searches

Resonance searches

- Boosted top (hadronic)
- Boosted top (semileptonic)
- Three-jet resonance (gluino RPV)
- Two-jet resonance (sgluon)

CMS Public Results

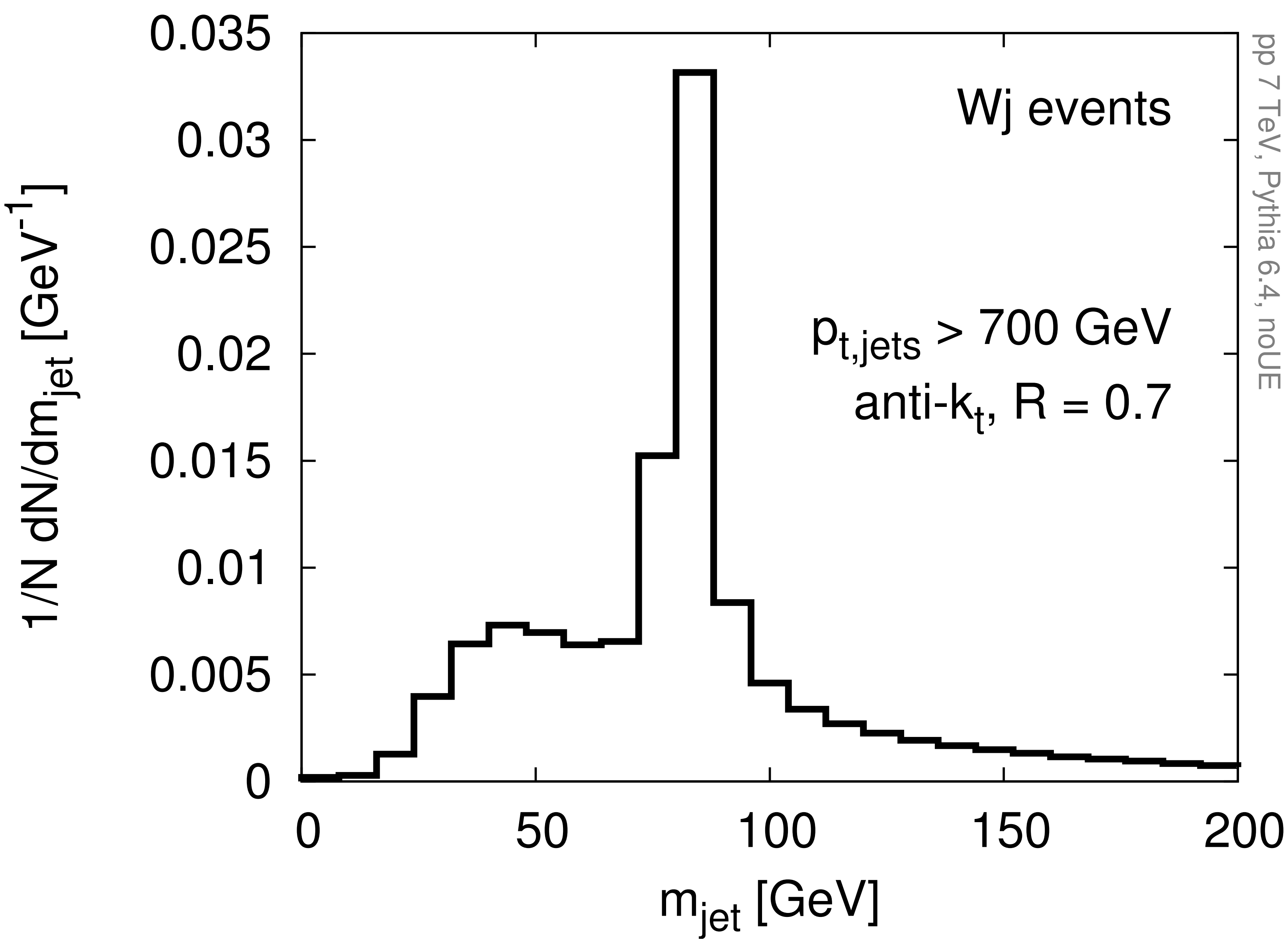
- Jet substructure in CMS
- Subjet multiplicity
- Jet mass and grooming

Resonance searches:

- Boosted top (hadronic)
- Boosted top (semileptonic)
- Boosted W/Z

From a list compiled for a recent workshop at Perimeter Institute

Many more analyses in the pipeline

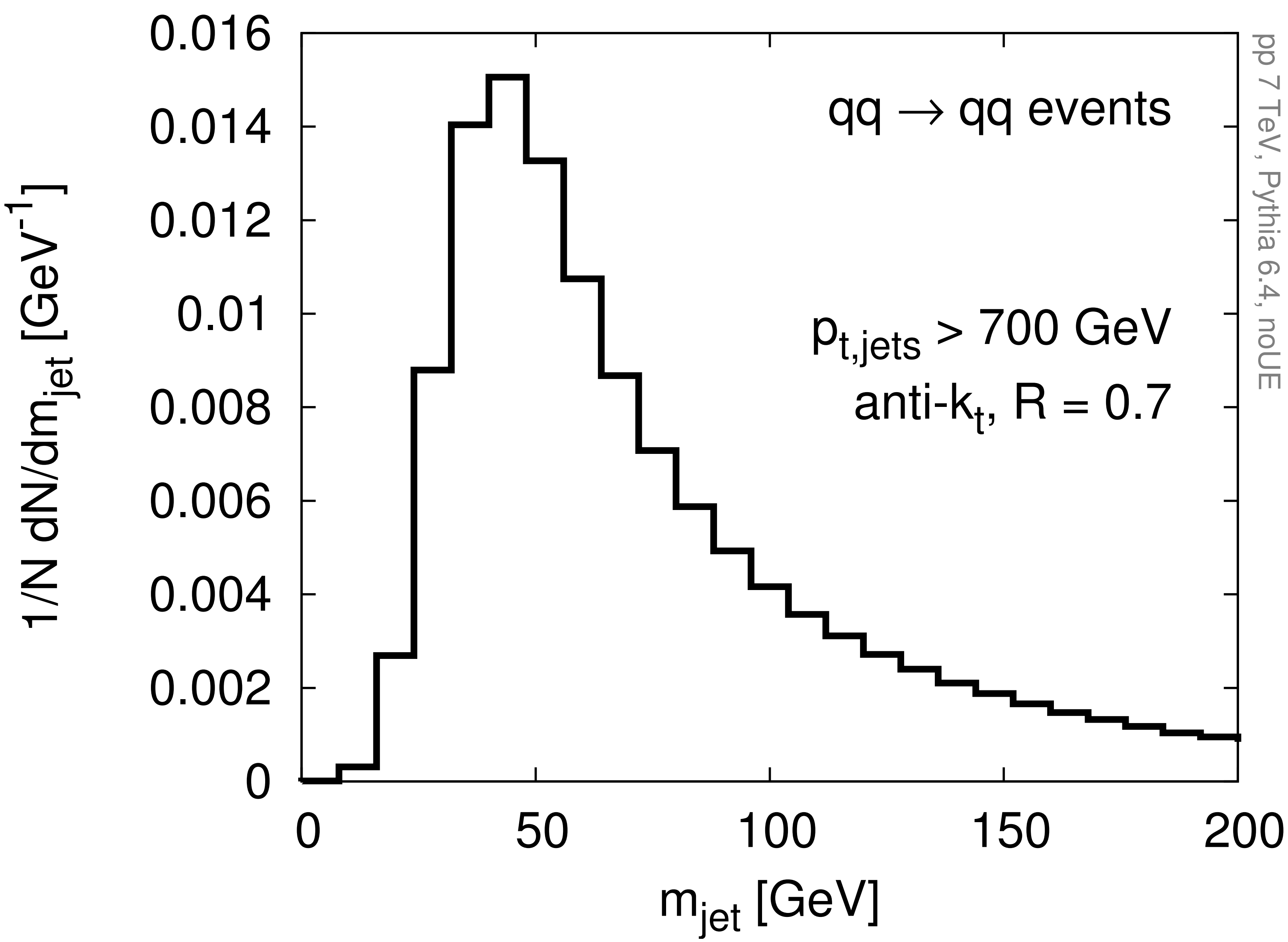


Look at jet mass distribution for 2 leading jets in

- pp → W+jet events

Pythia, underlying event switched off

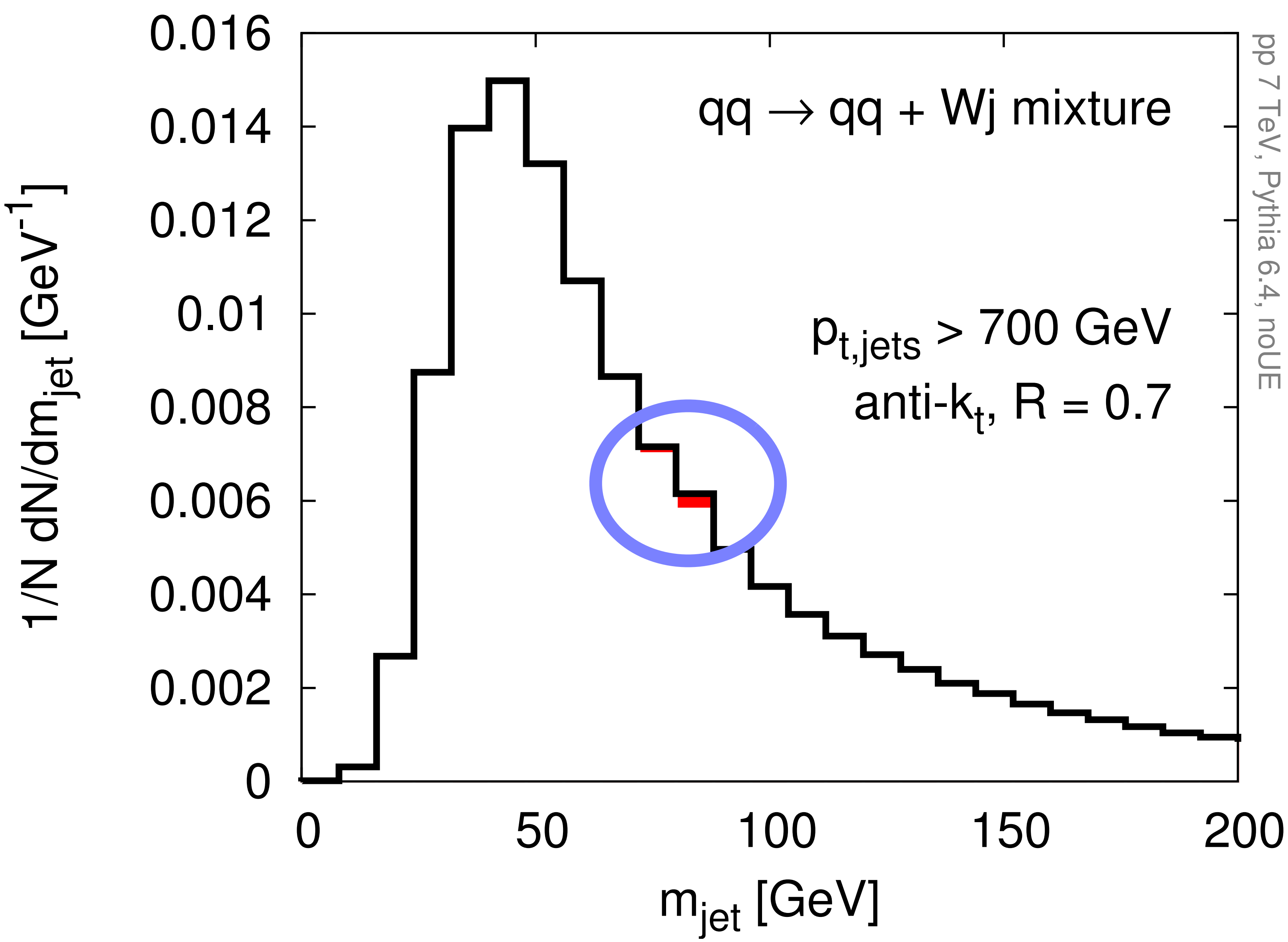
Problem #1$_a$: QCD jets have masses too



Look at jet mass distribution for 2 leading jets in

- pp → W+jet events
- qq → qq events

Problem #1b: there are lots of QCD jets

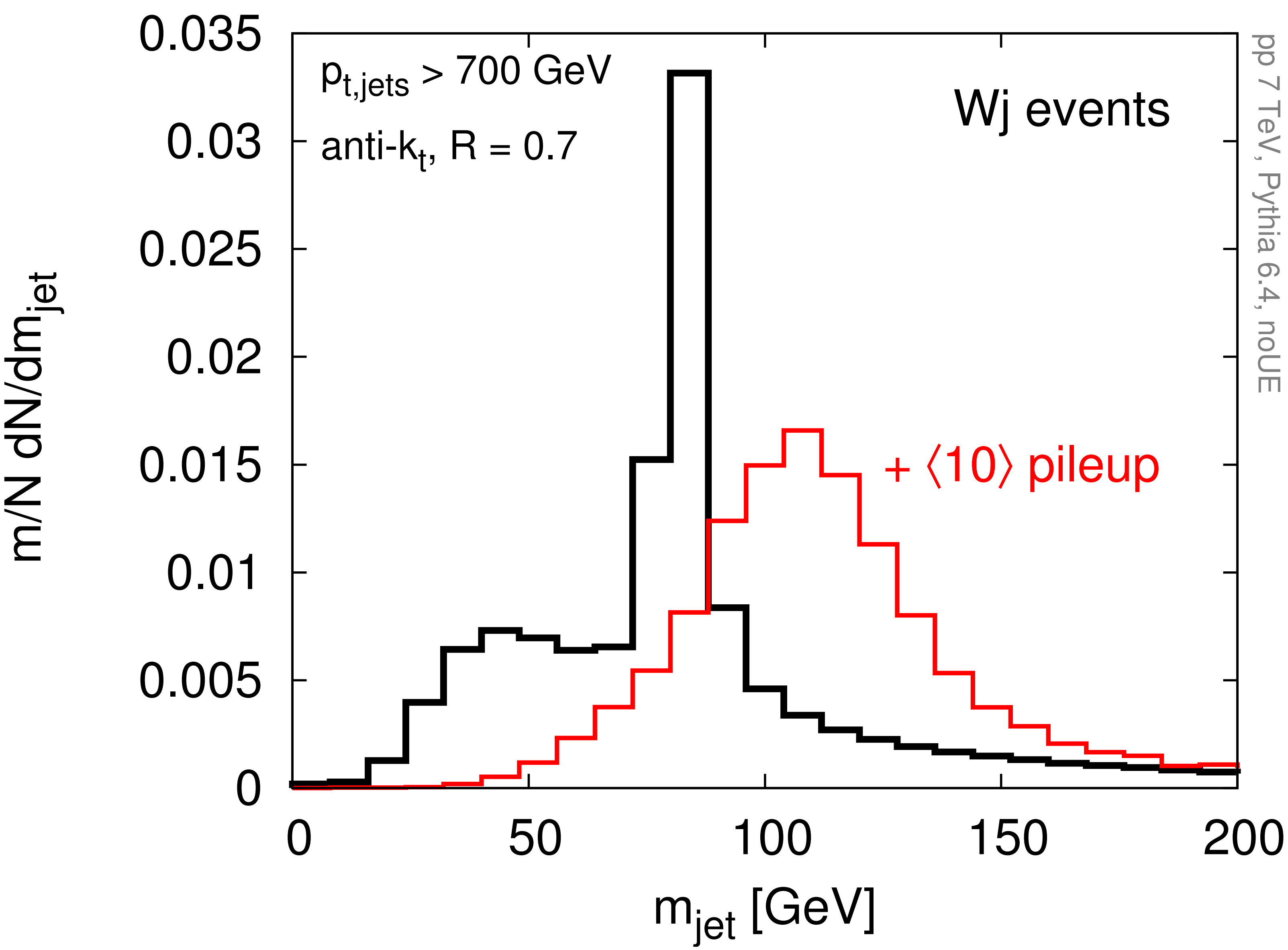


Look at jet mass distribution for 2 leading jets in

- pp → W+jet events
- qq → qq events
- mixture of the two, in rough proportion

Jet mass gives clear sign of massive particles inside the jet; but QCD jets are massive too — must learn to reject them

Problem #2: jet mass v. sensitive to PU



Jet mass is extremely sensitive to pileup

→ loss of mass resolution

→ loss of ability to find signals

Tagging & Grooming

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

Tagging

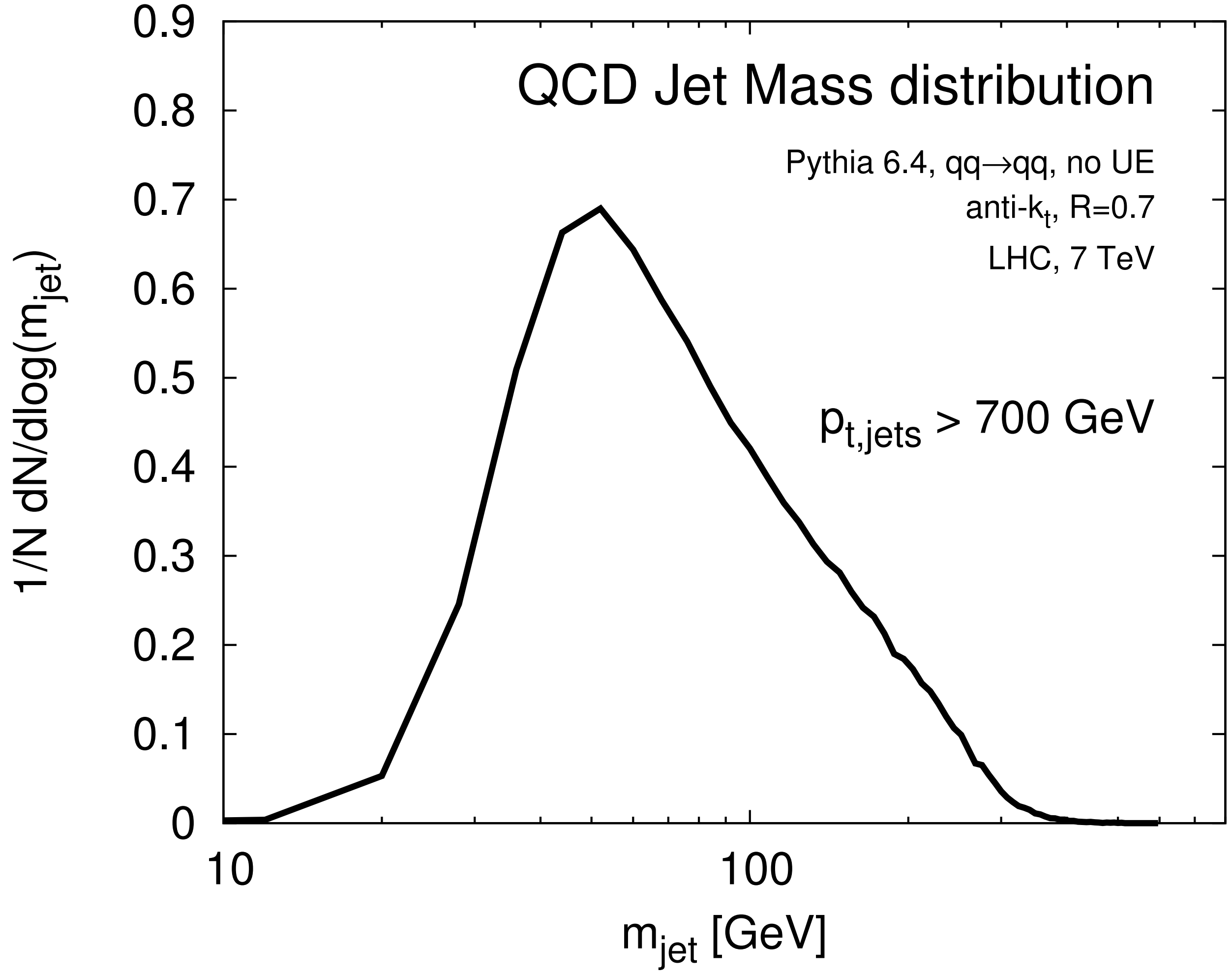
- reduces the background, leaves much of signal

Grooming

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

One core idea for tagging

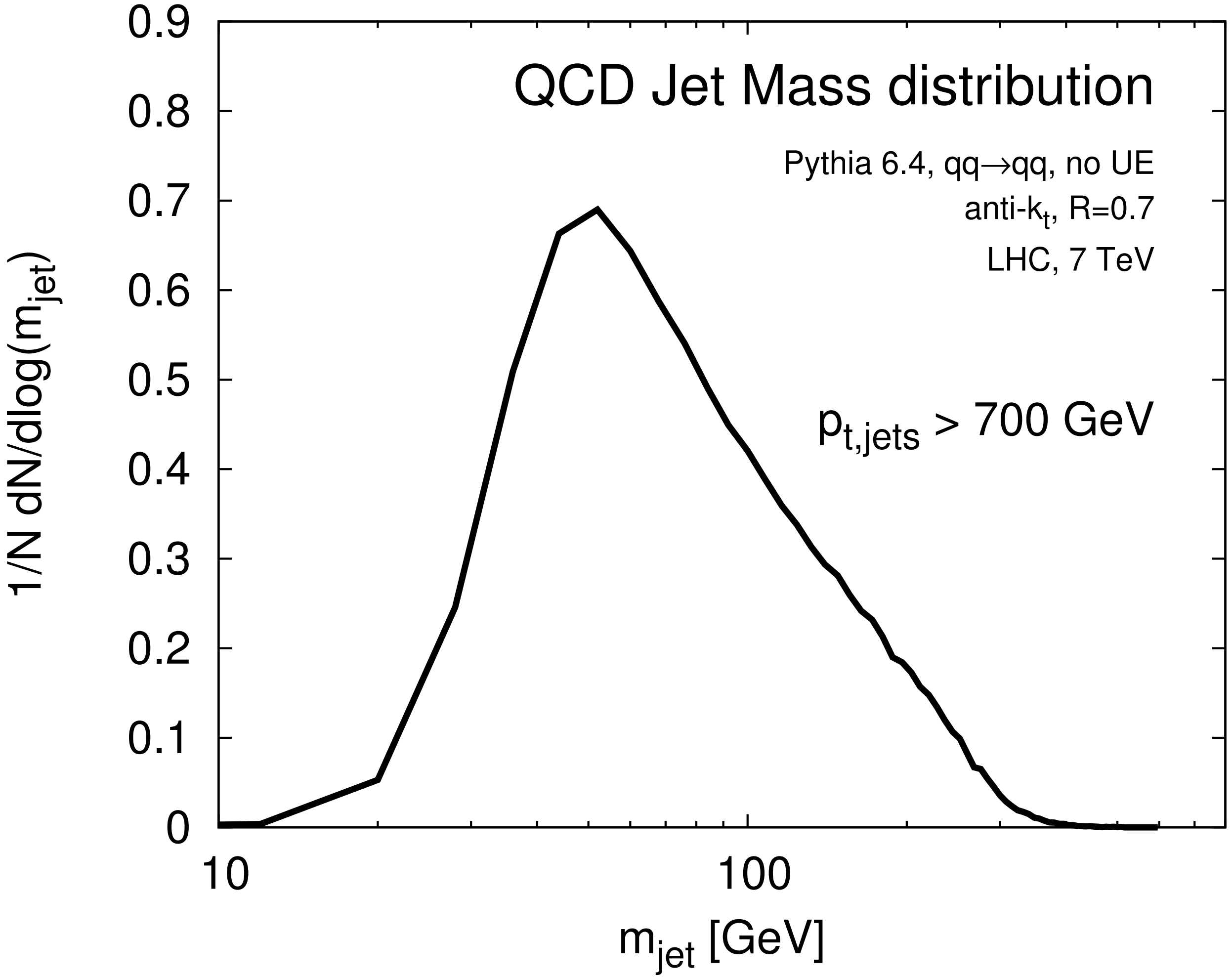
Inside the jet mass

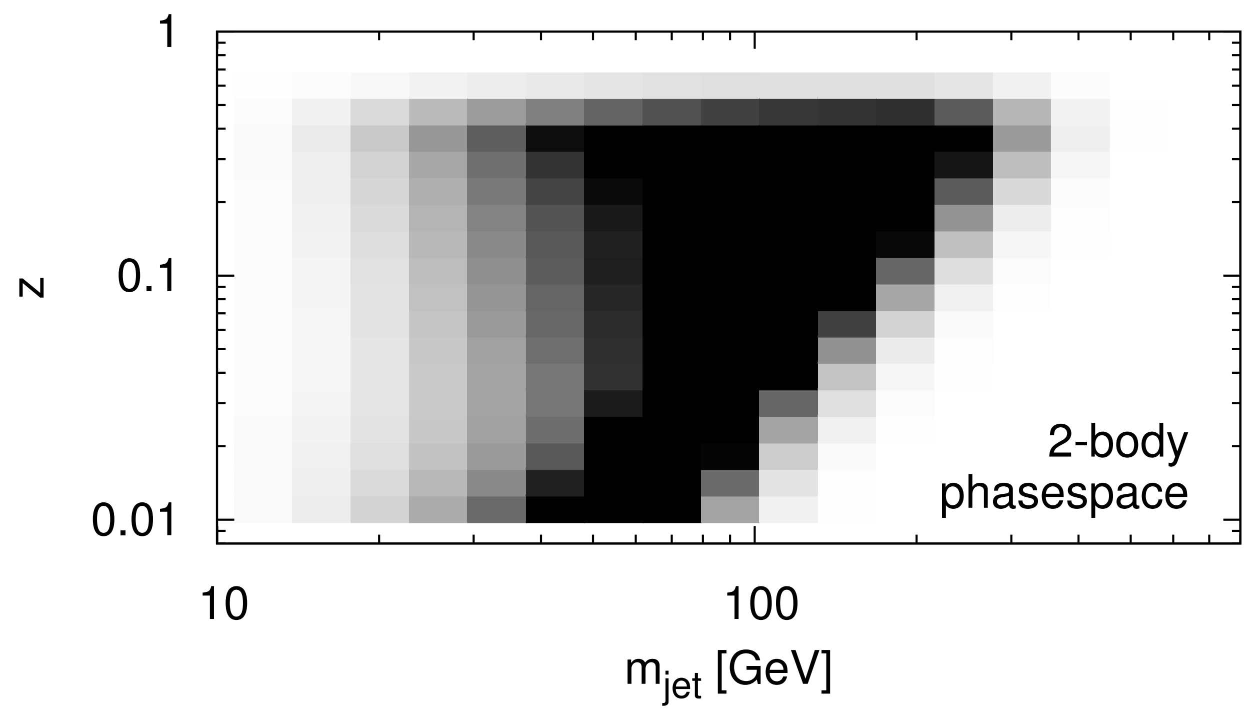


QCD jet mass distribution has the approximate

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

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





QCD jet mass distribution has the approximate

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

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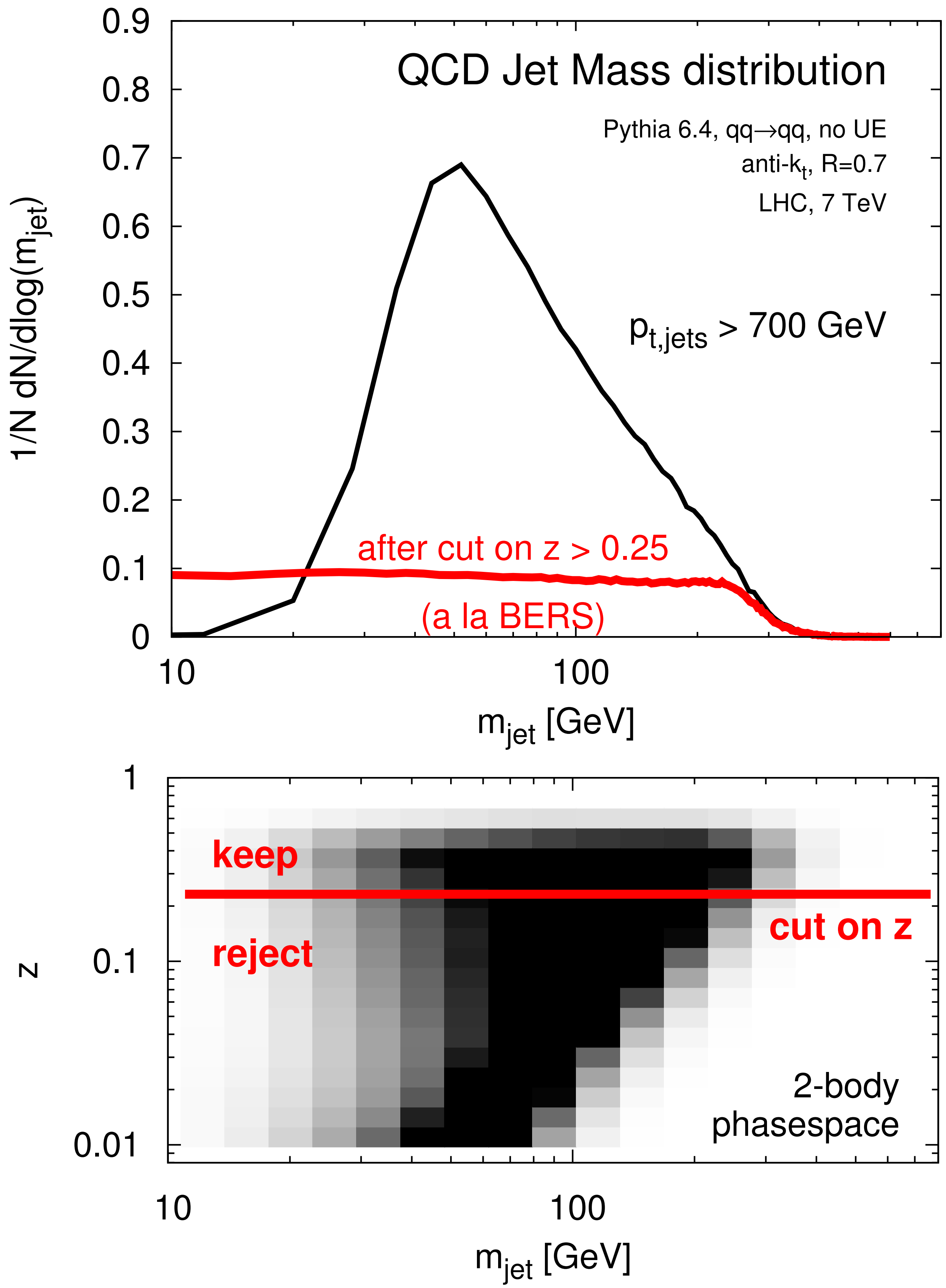
The logarithm comes from integral over soft divergence of QCD:

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



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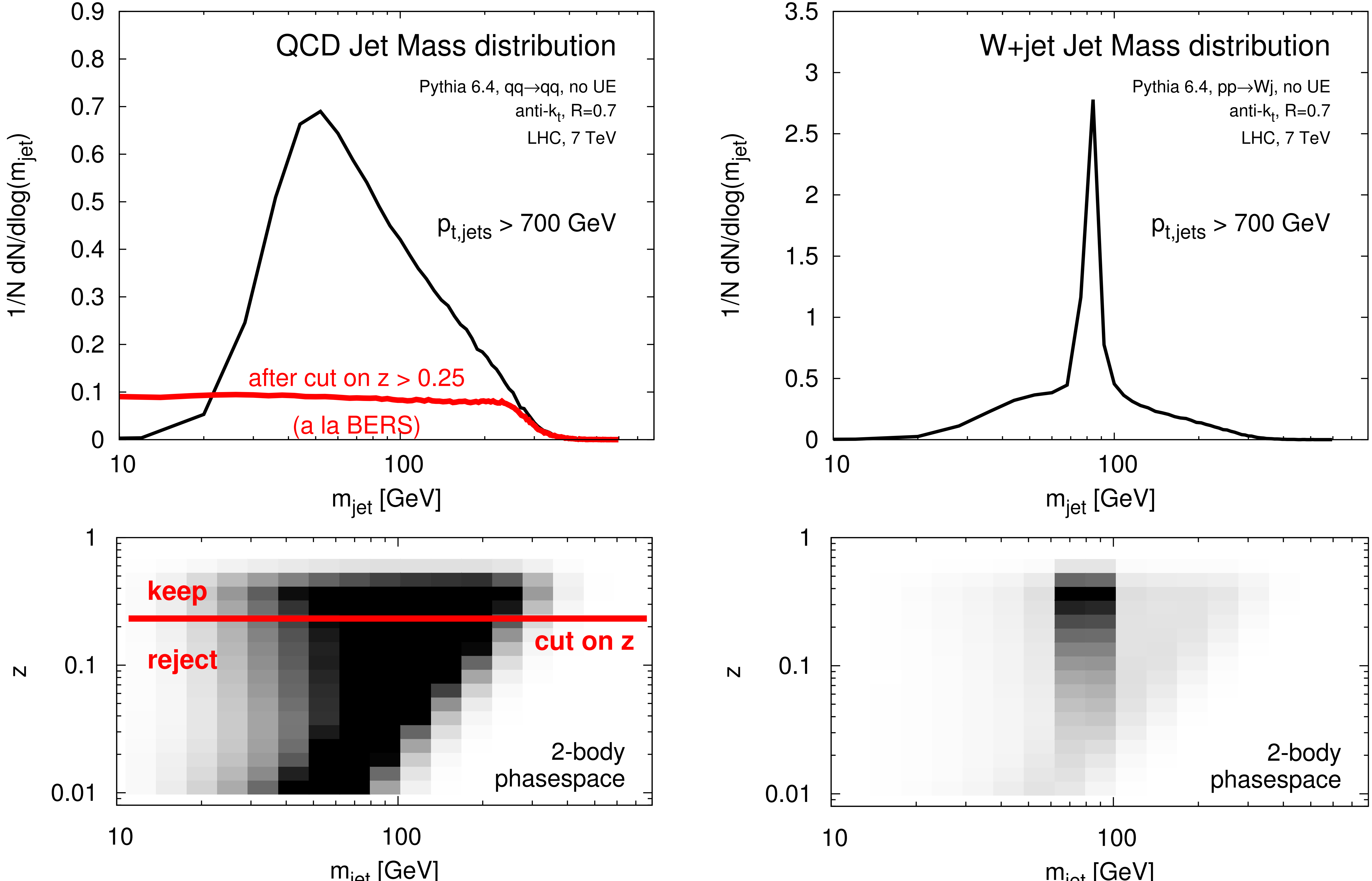
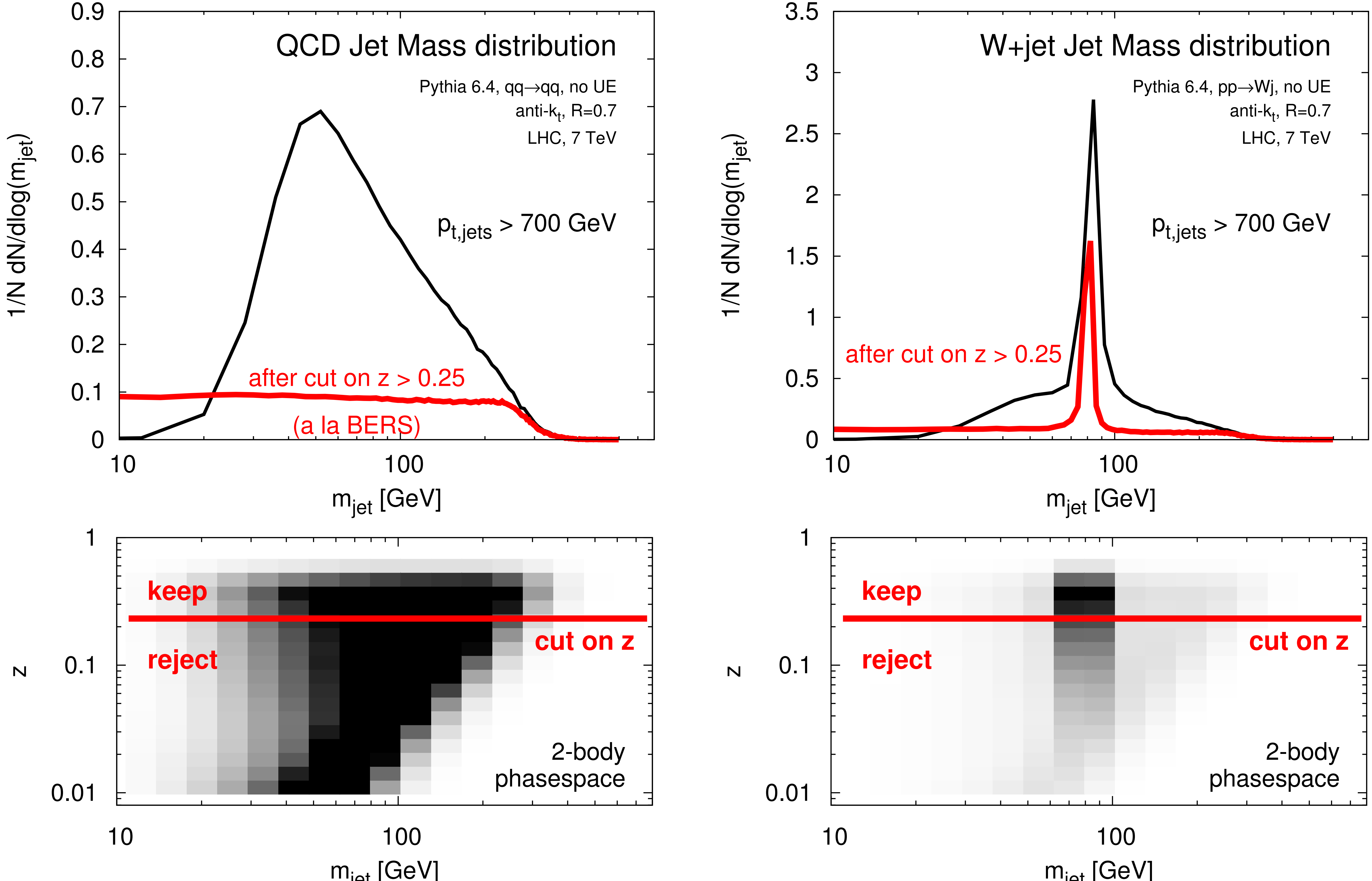
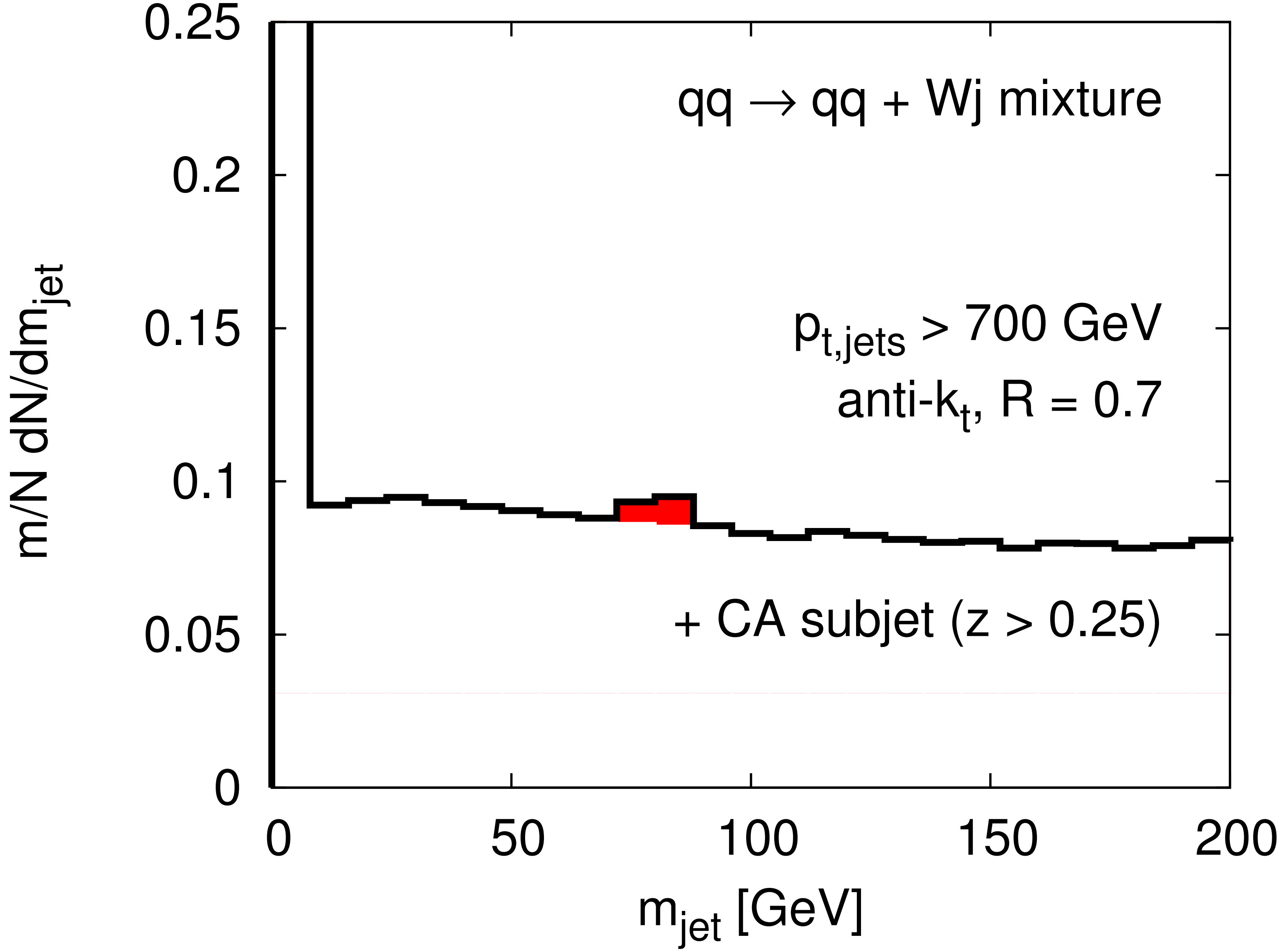
A hard cut on z reduces QCD background & simplifies its shape

Inside the jet mass



Inside the jet mass

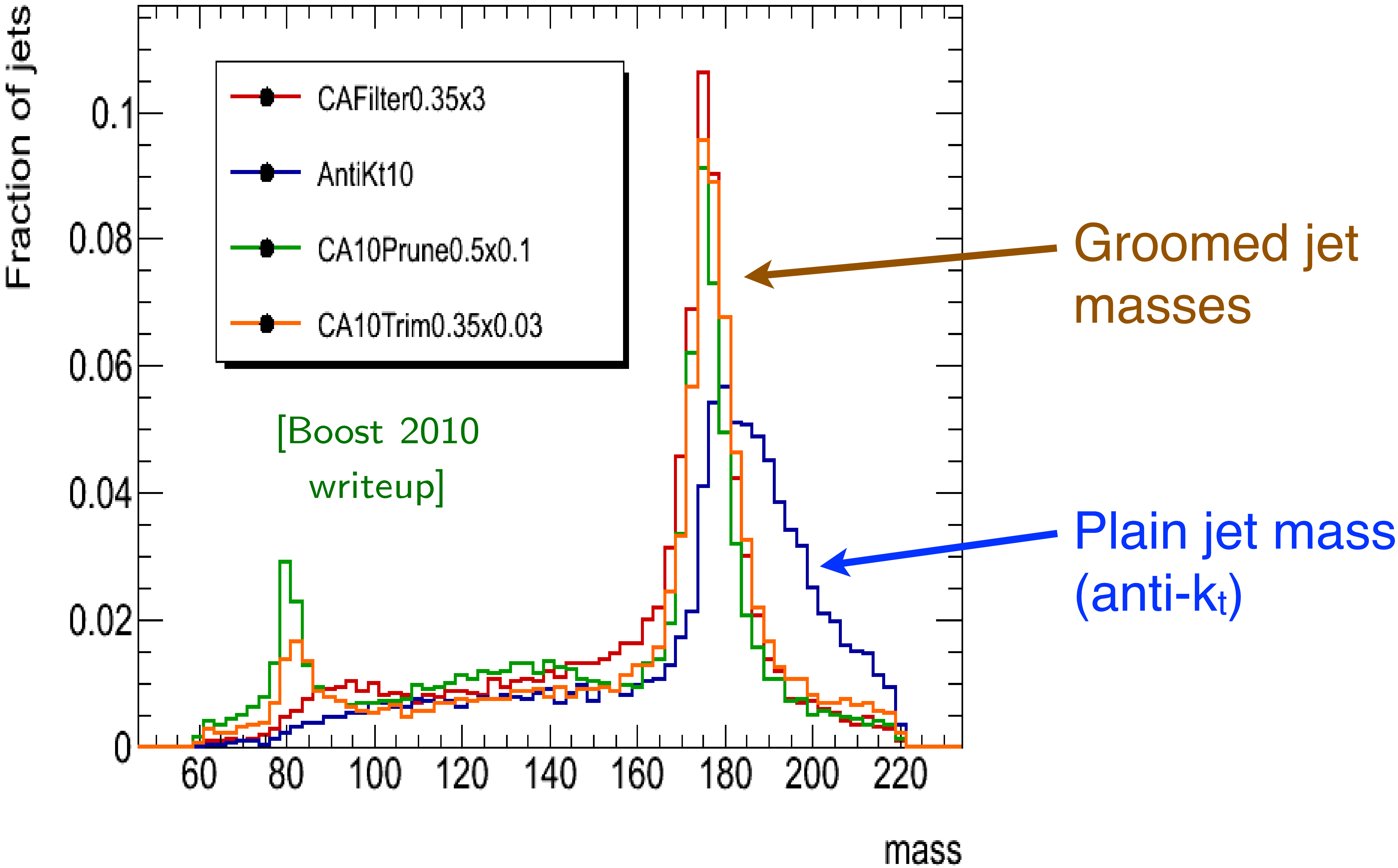




Signal + bkgd after cut on z

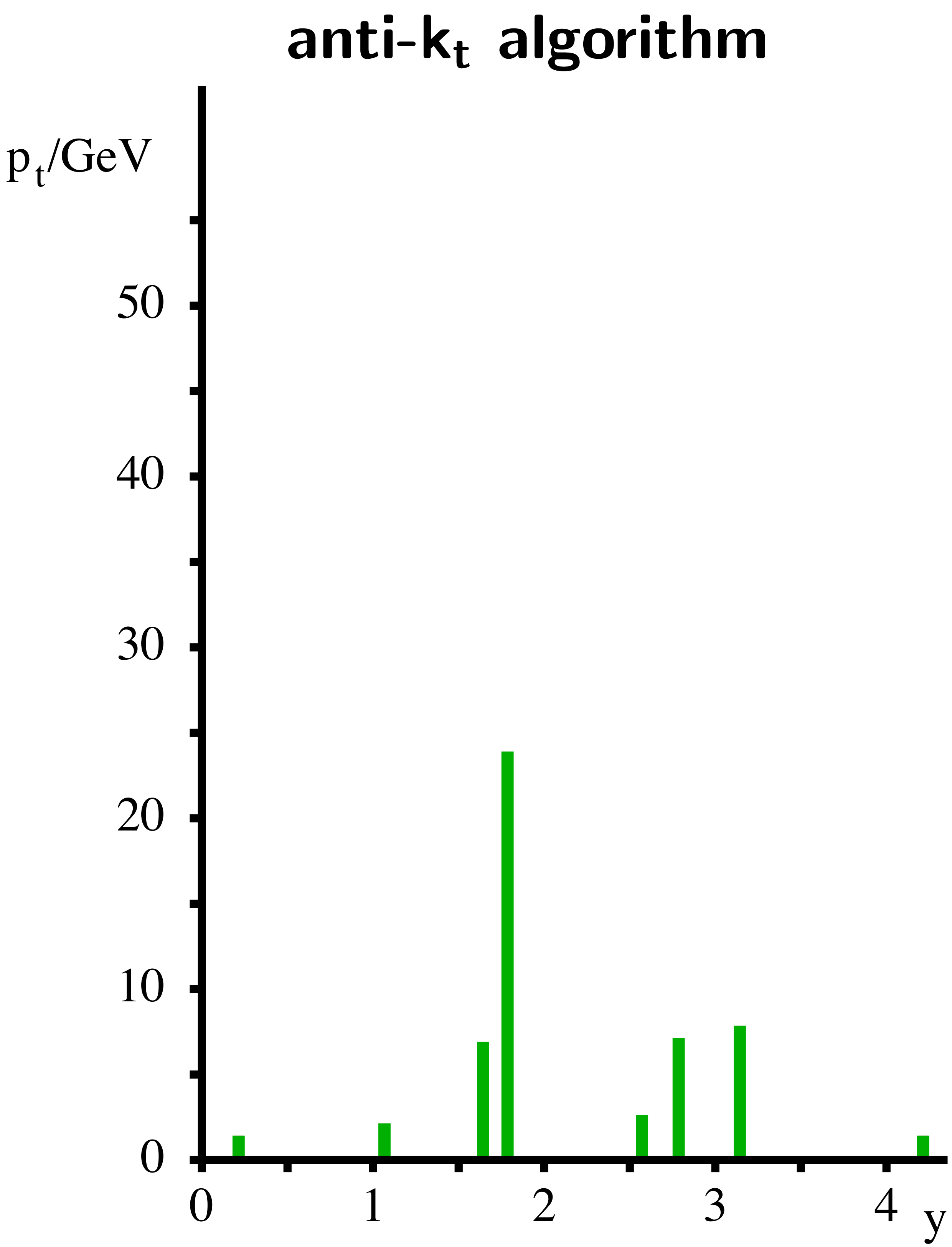
One core idea for grooming

[see blackboard]


Fraction of jets
0.1
0.08
0.06
0.04
0.02
0
60
80
100
120
140
160
180
200
220
mass
CAFilter0.35x3
AntiKt10
CA10Prune0.5x0.1
CA10Trim0.35x0.03
[Boost 2010
writeup]
Groomed jet
masses
Plain jet mass
(anti-kt)

How do the tools work in practice?

Identifying jet substructure: try out anti-k_t



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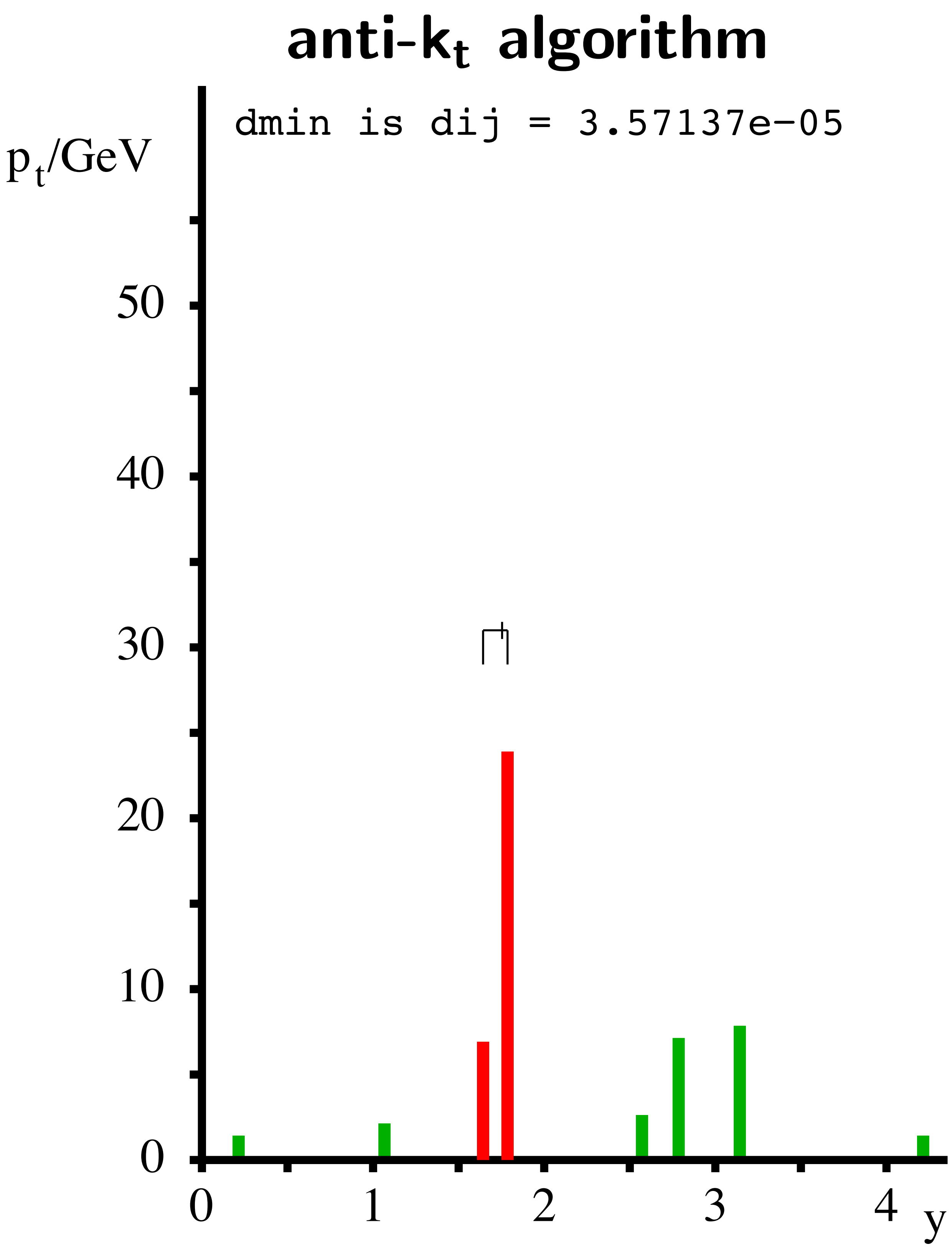
This is crucial for identifying the kinematic variables of the partons in the jet (e.g. z).



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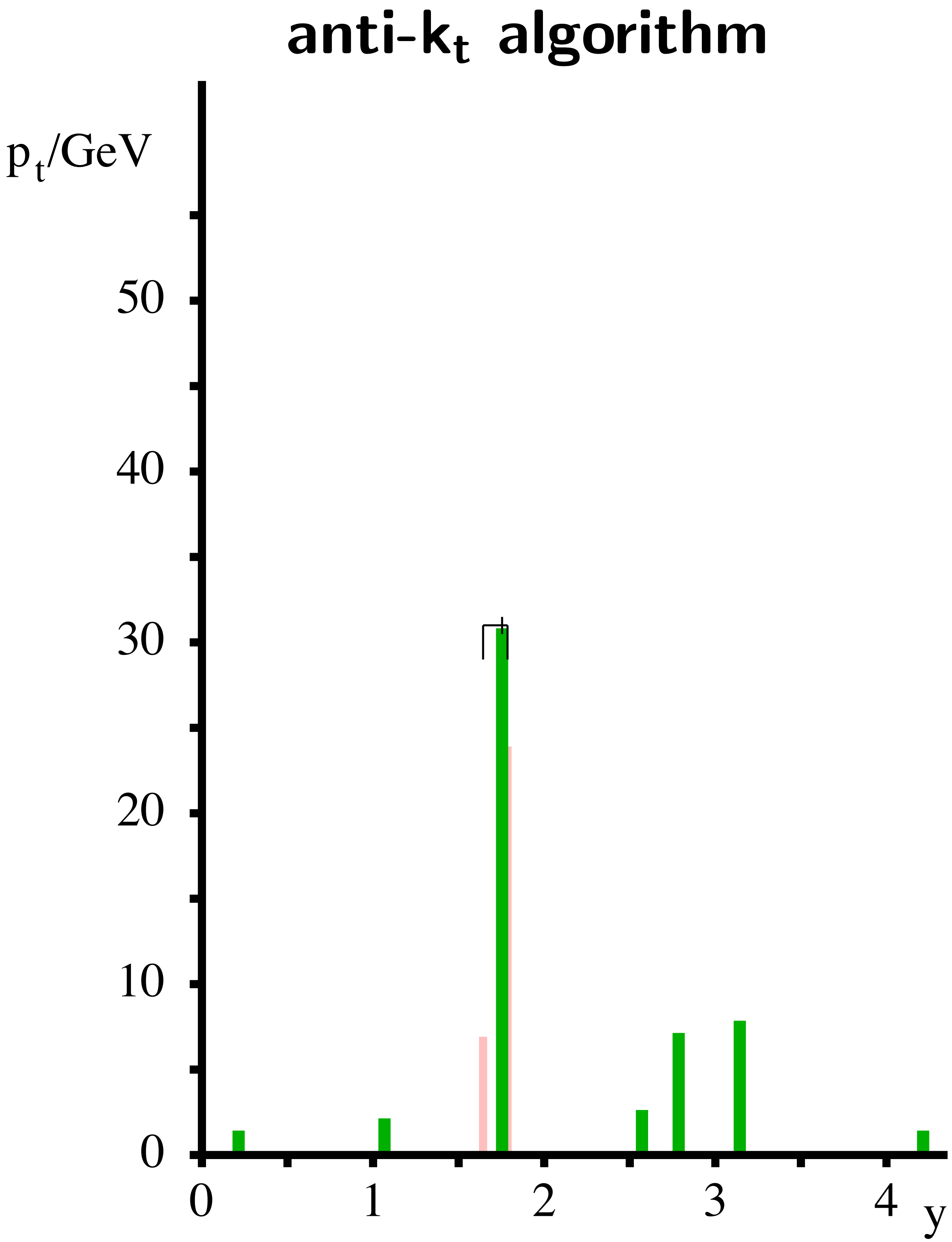

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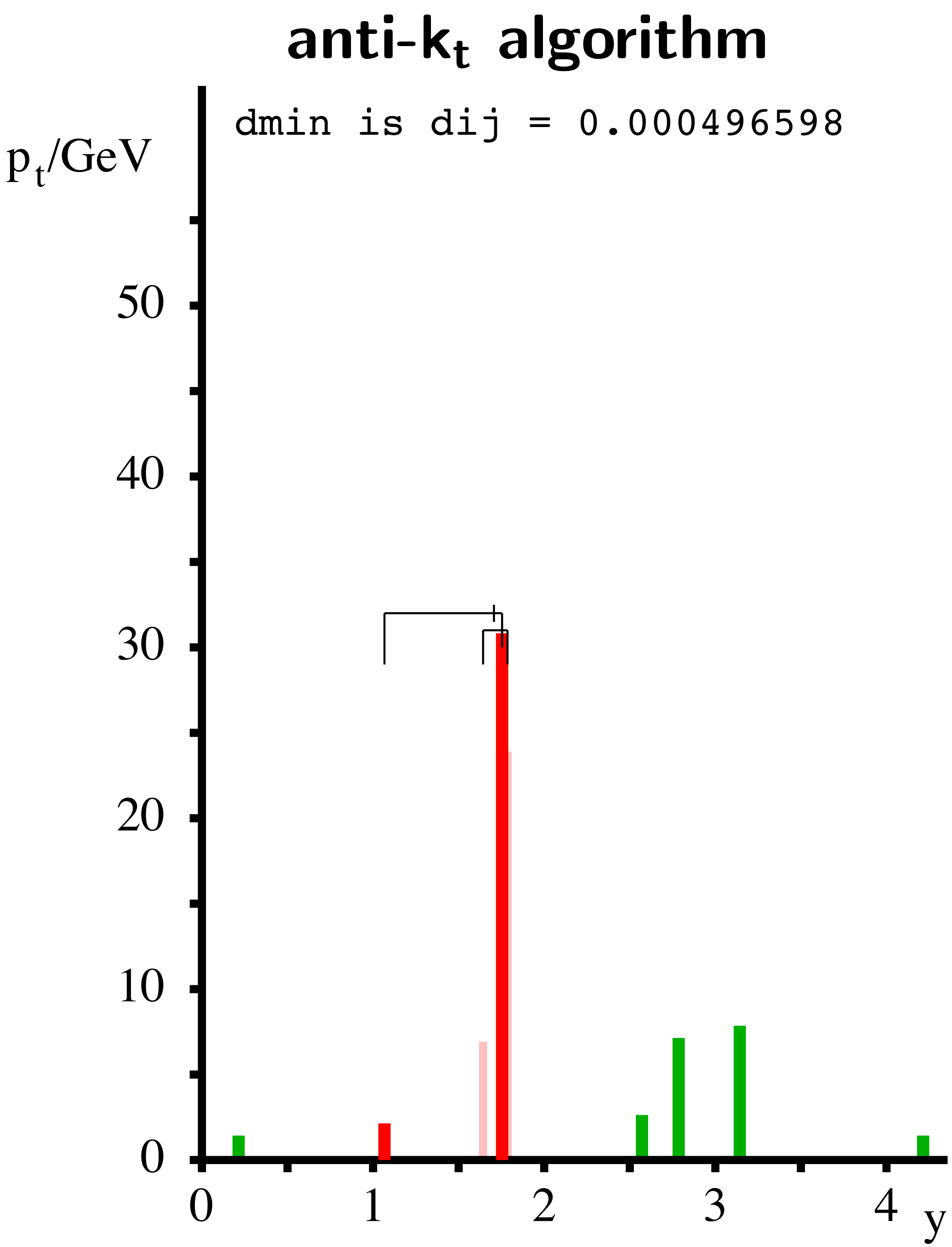

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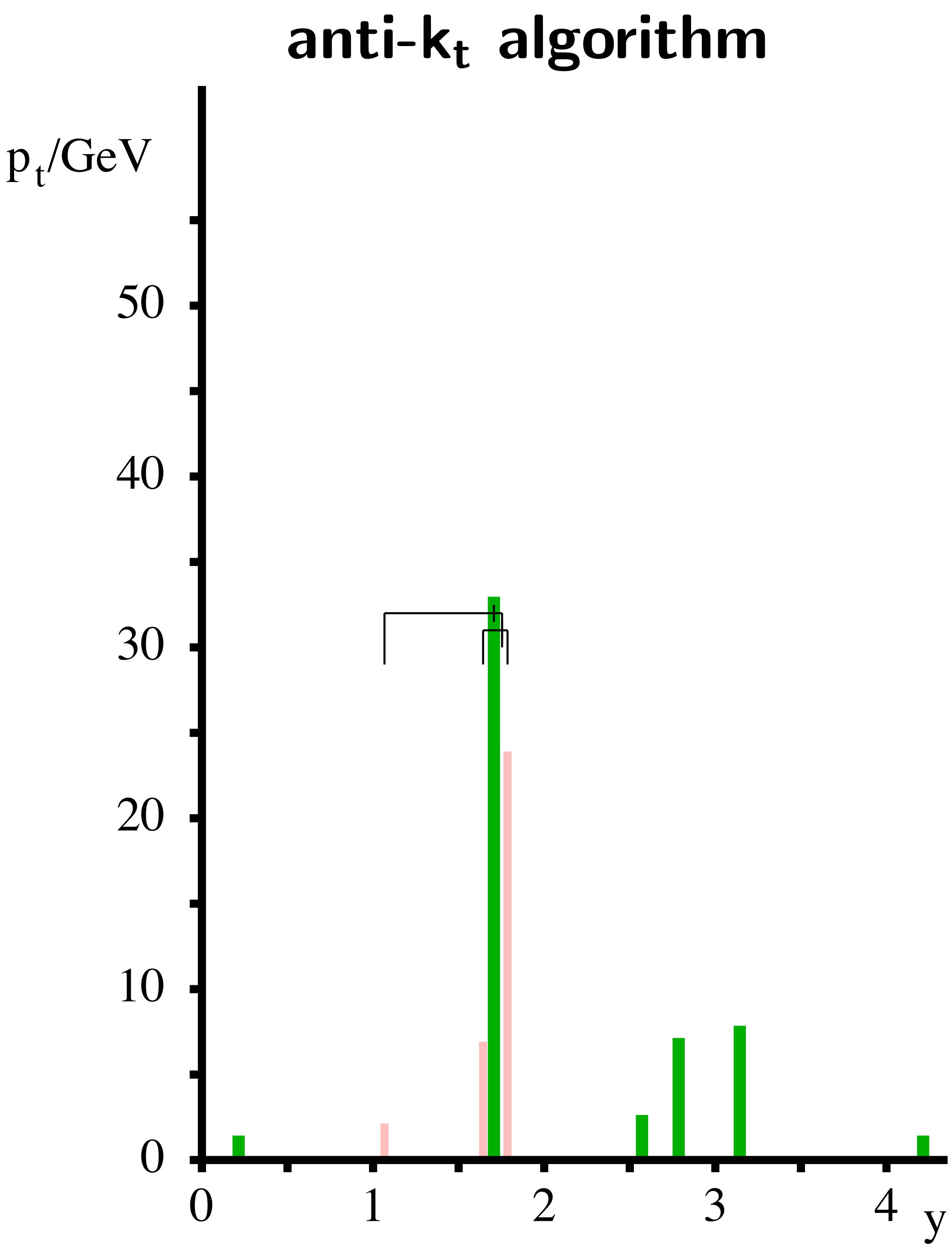

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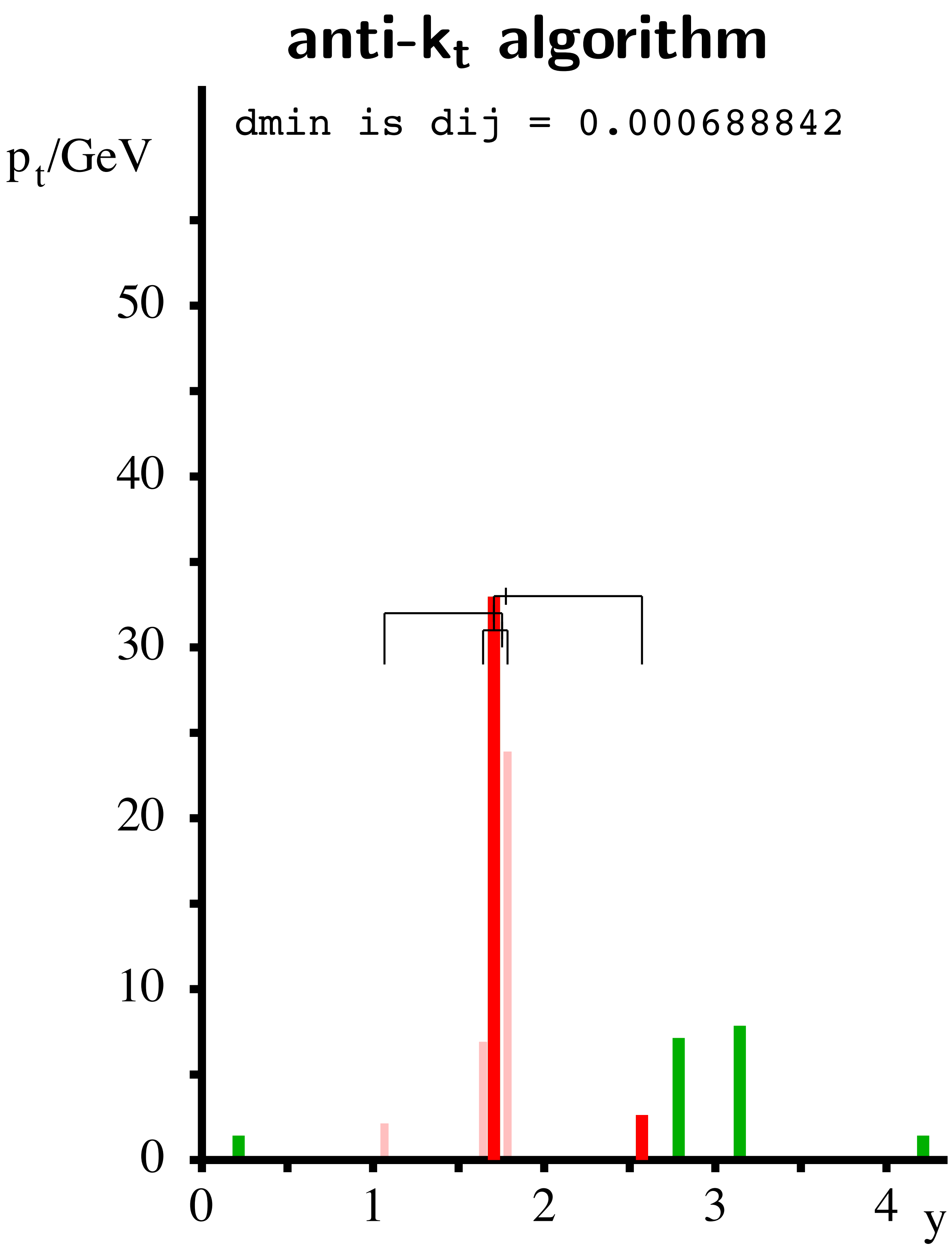

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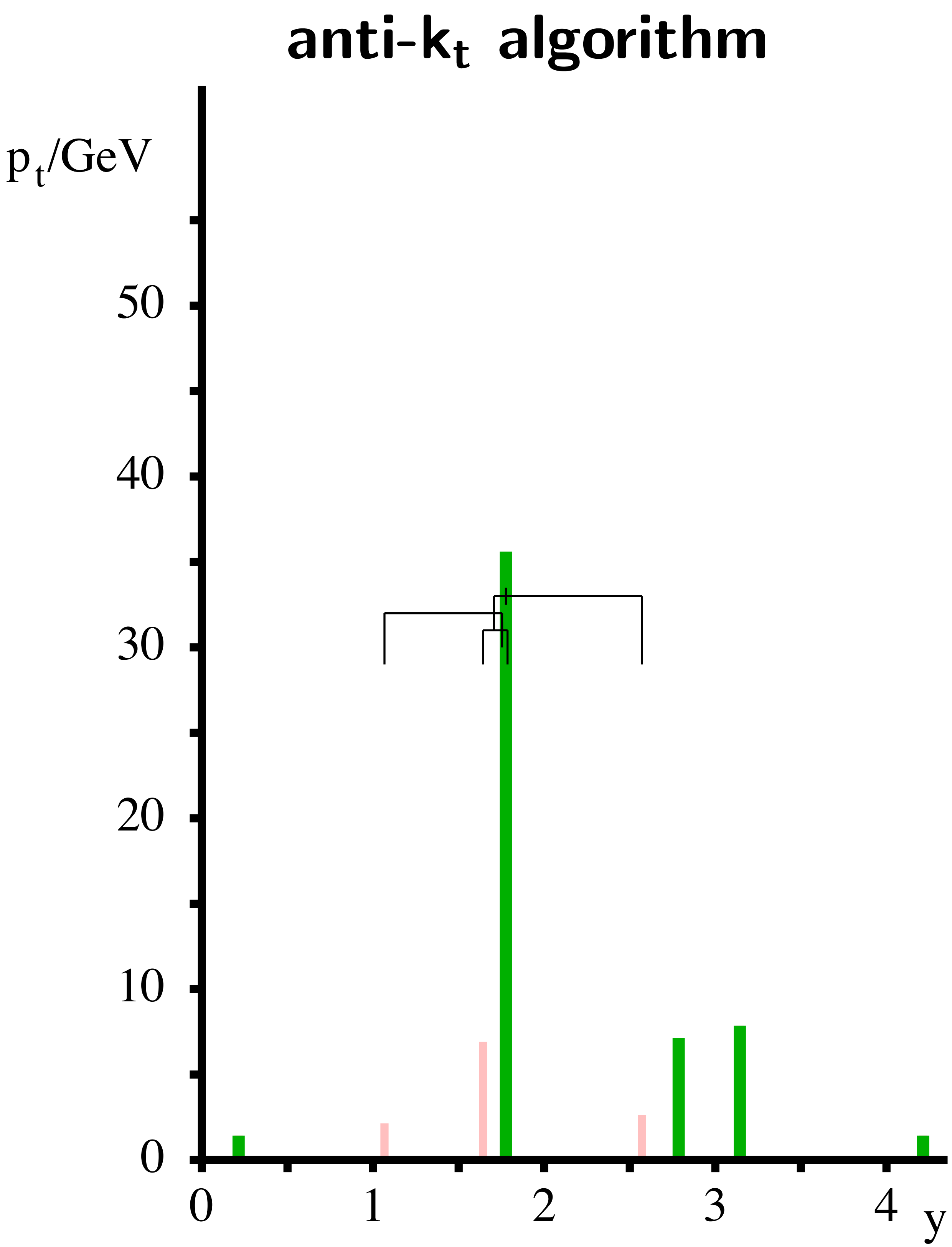

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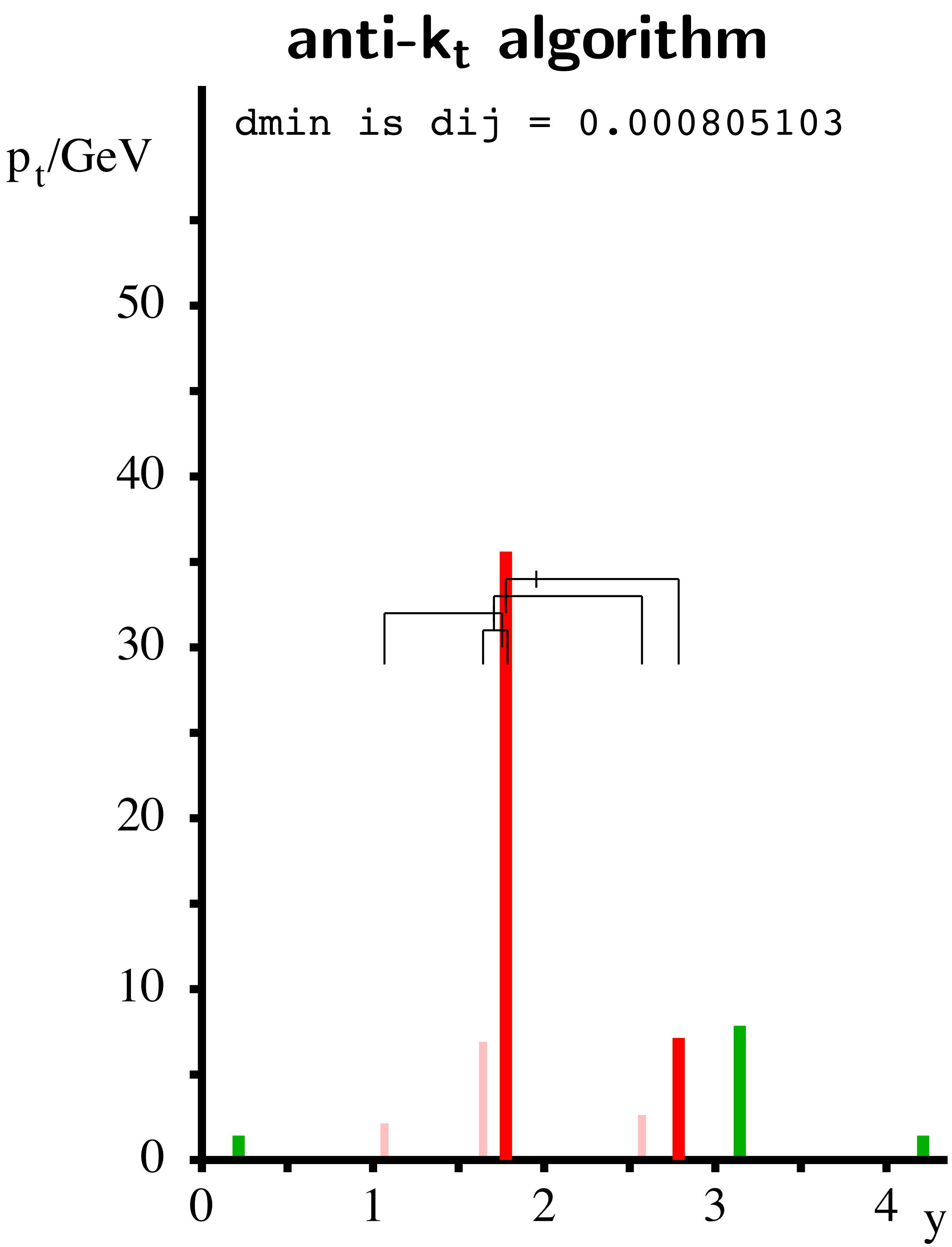

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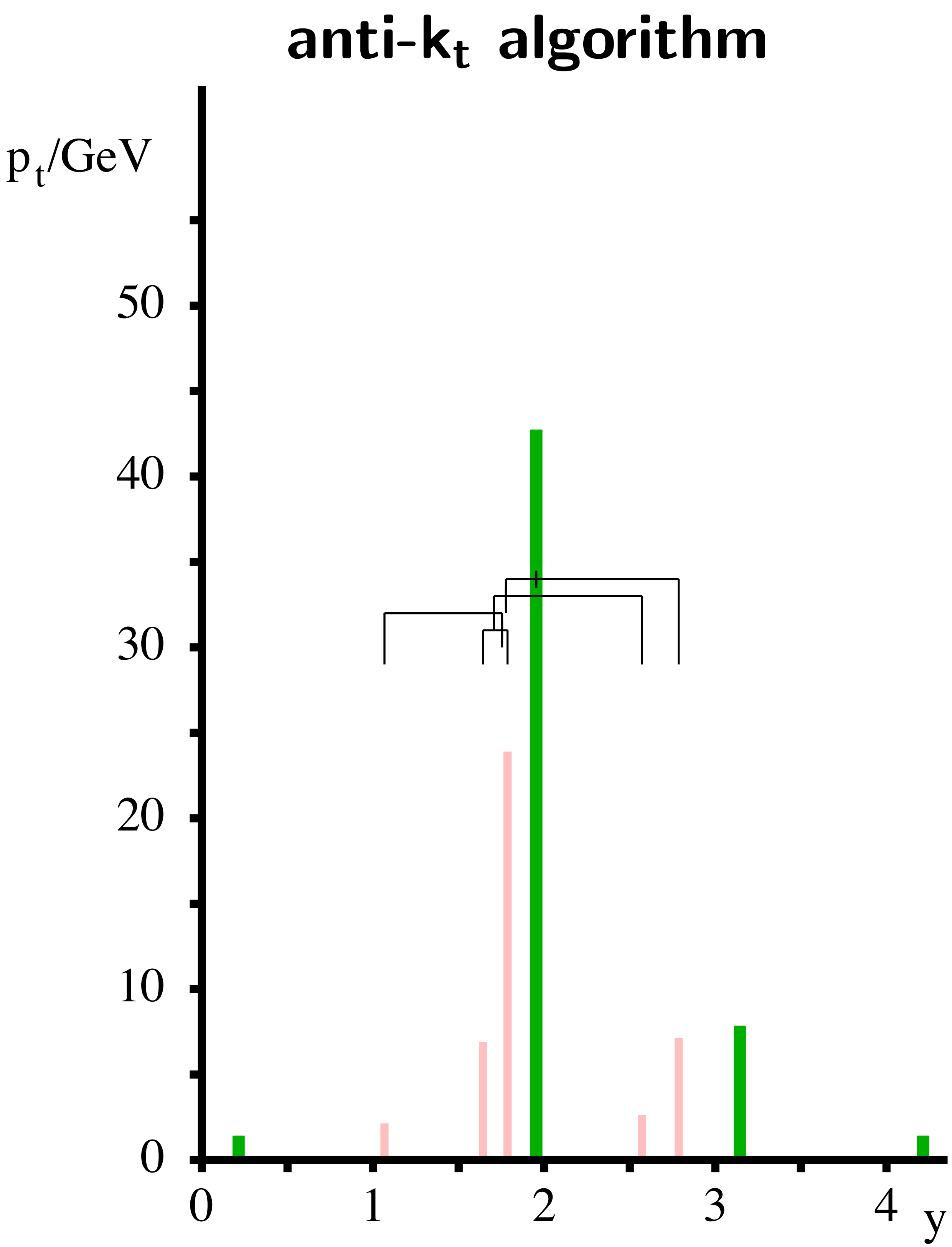

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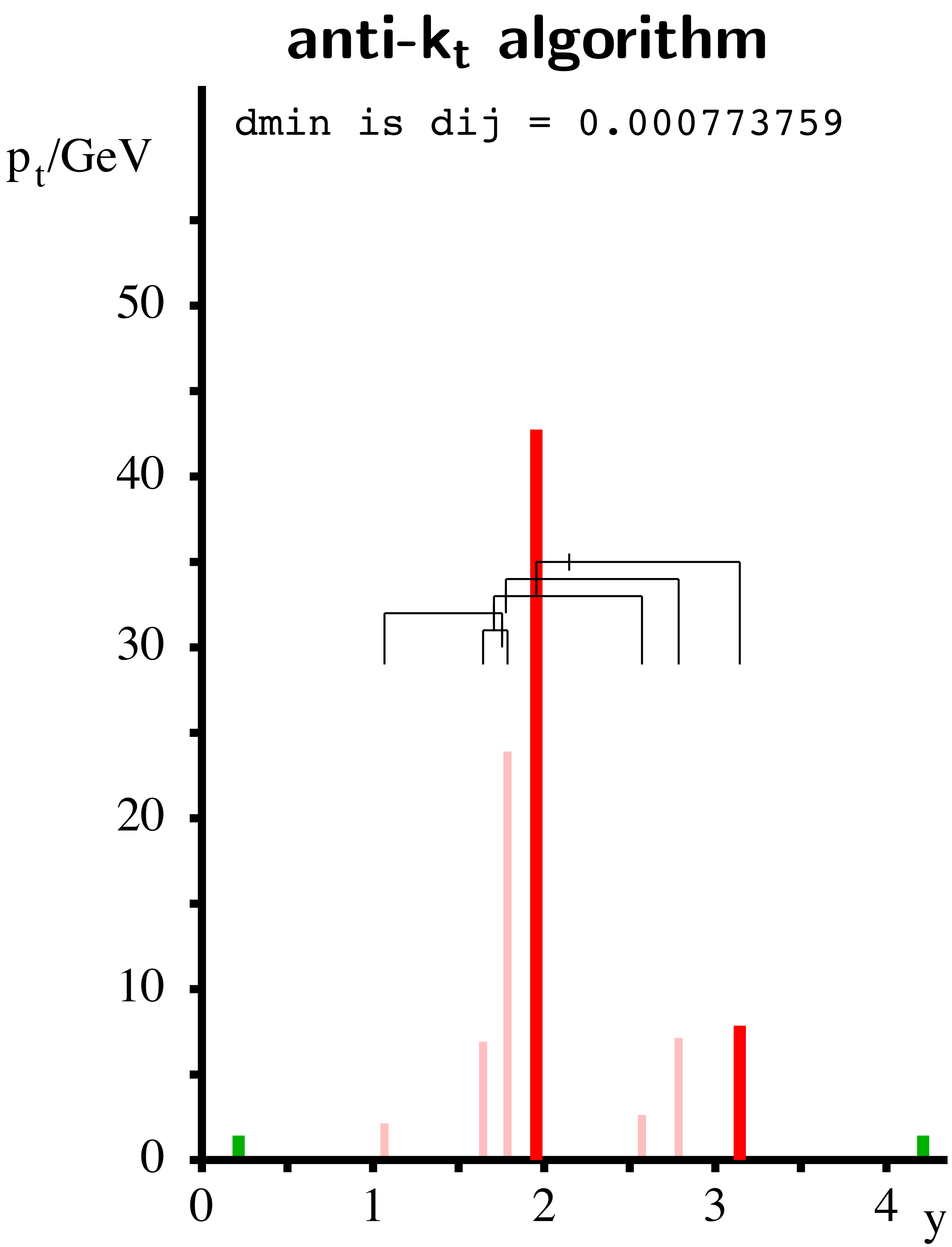

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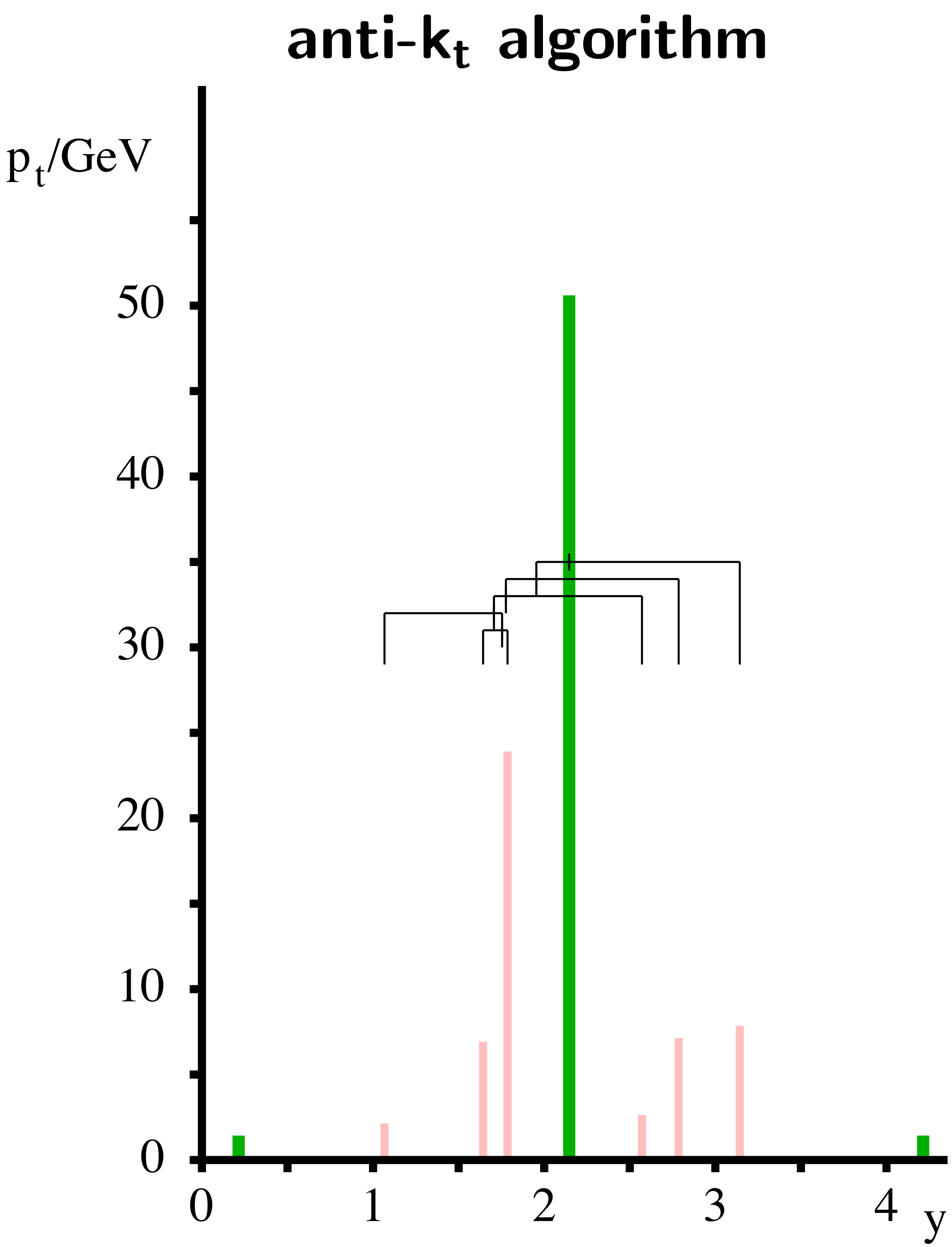

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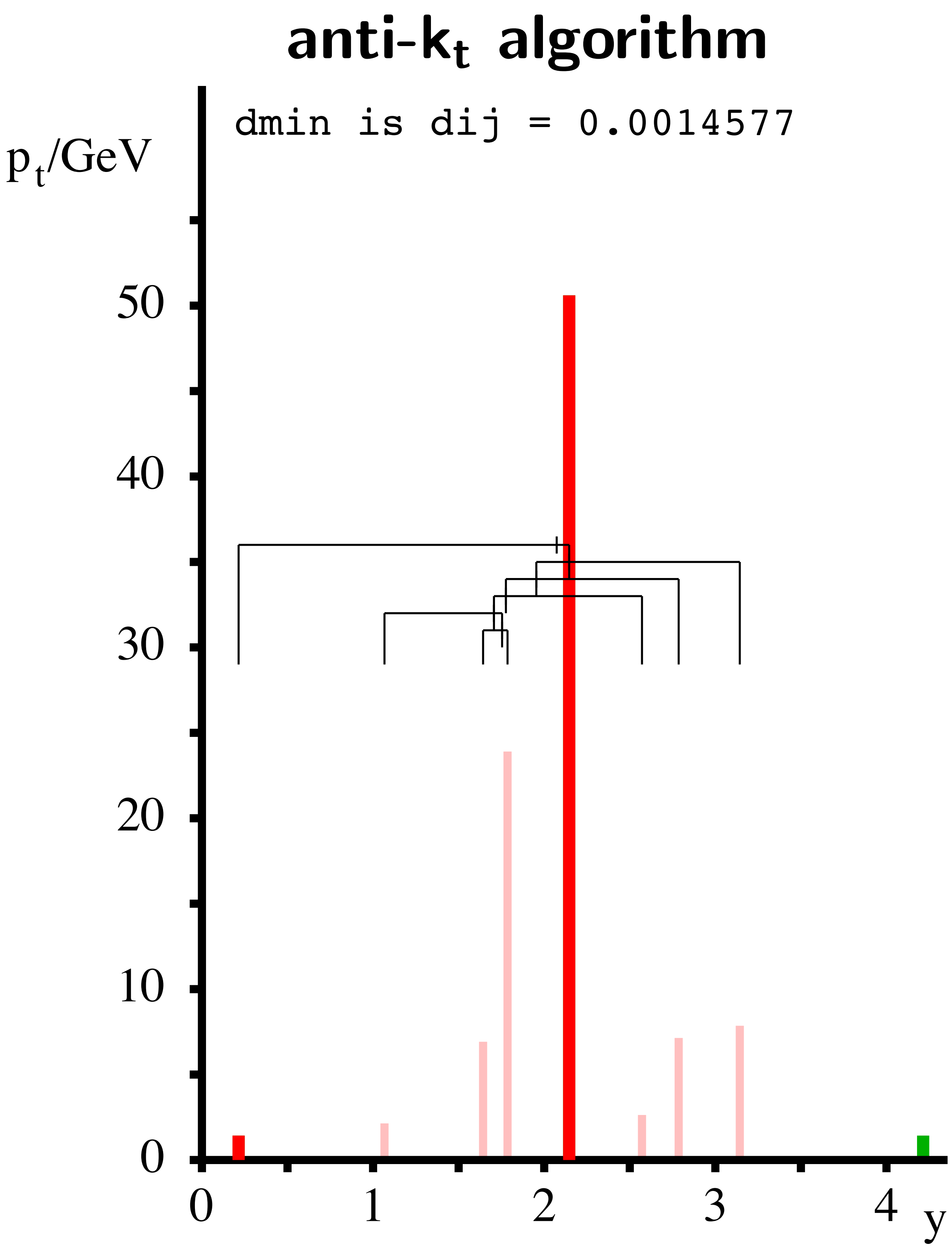

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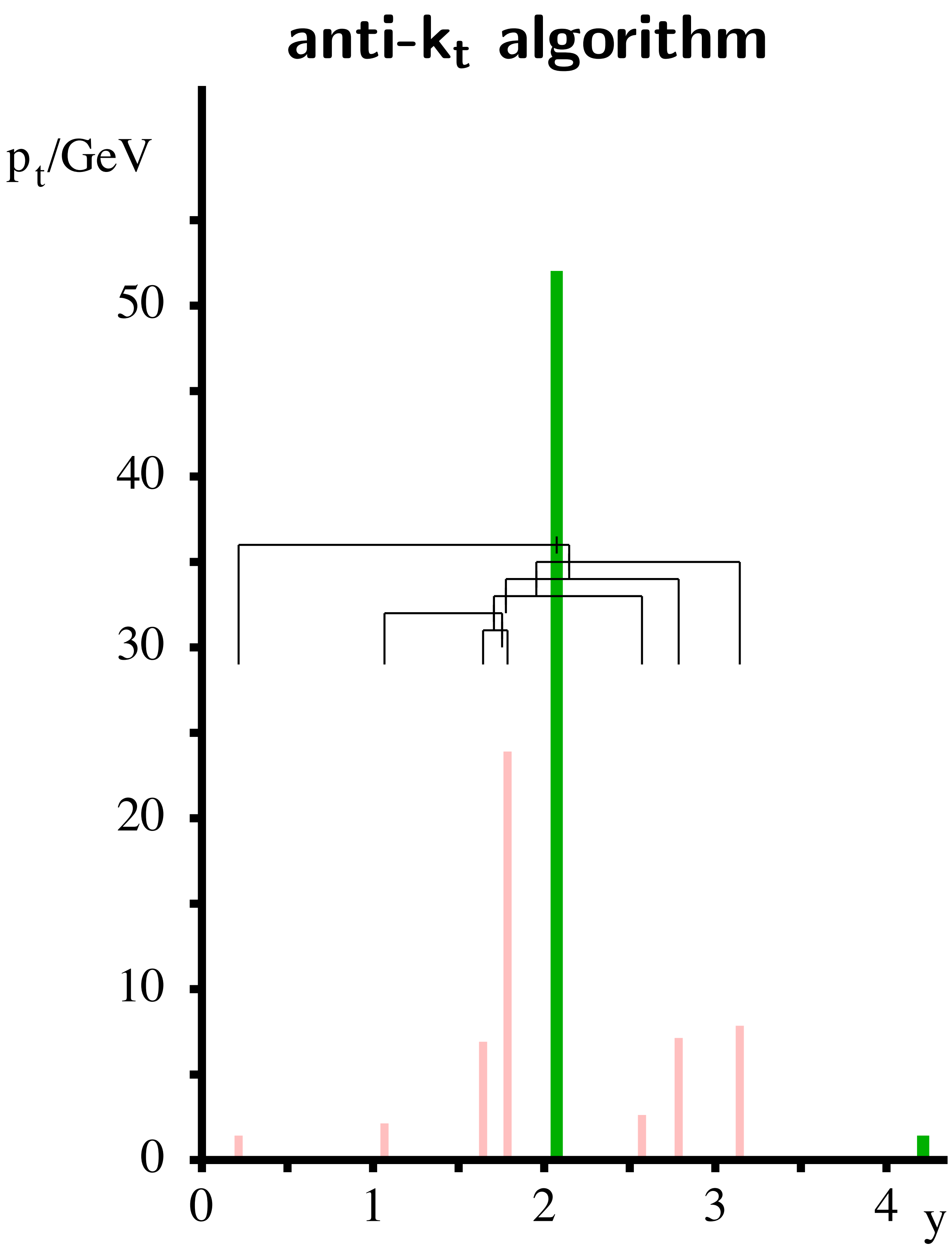

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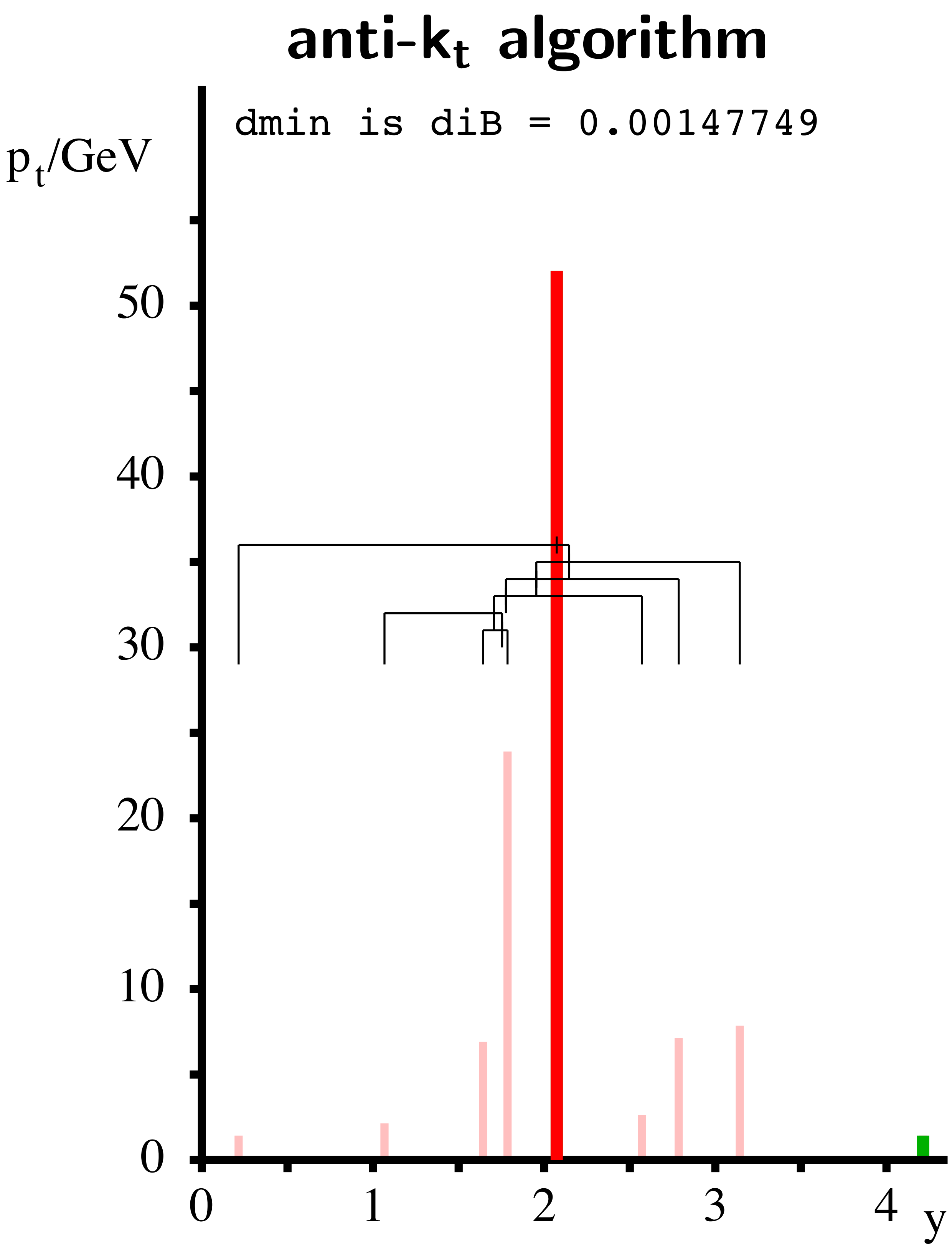

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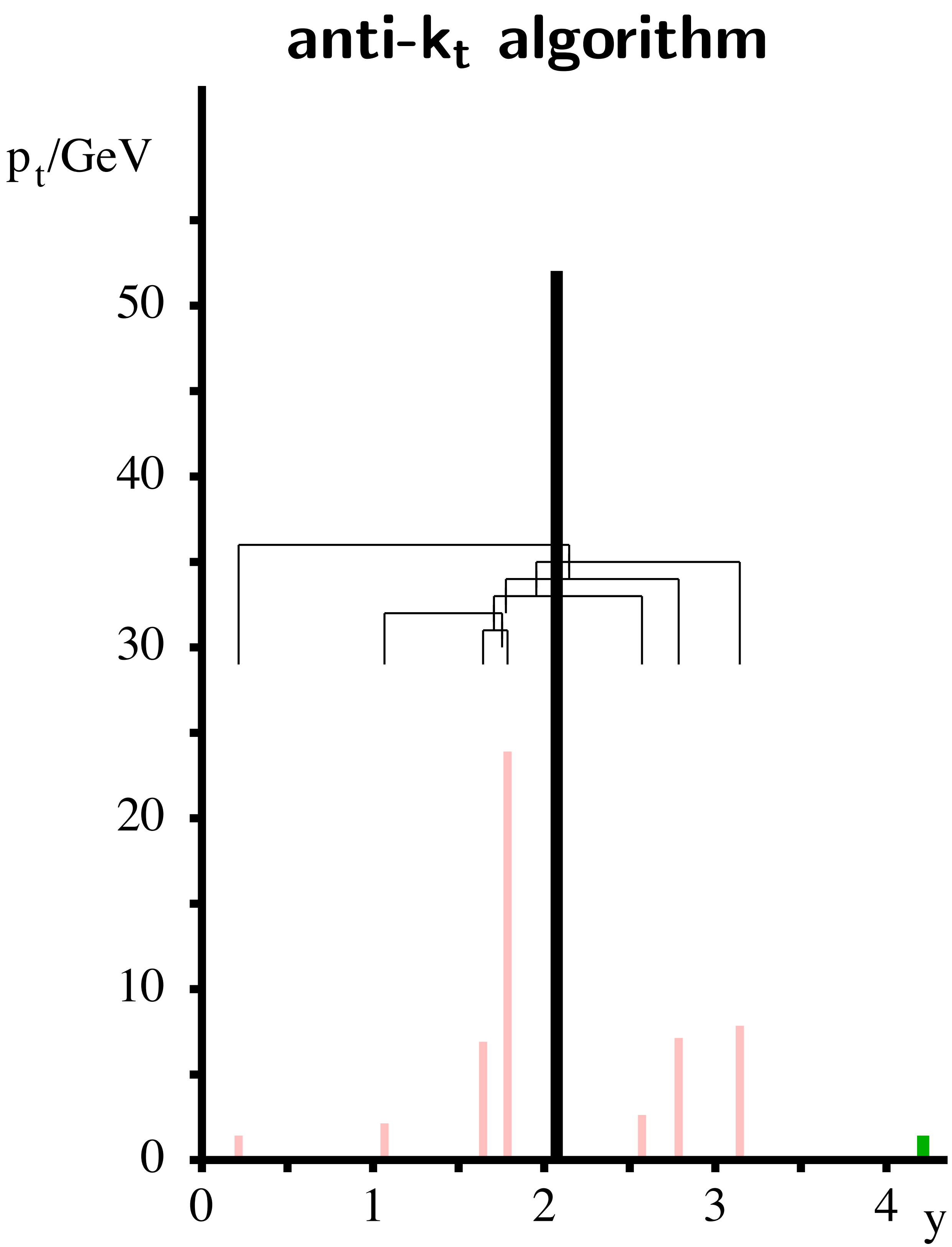

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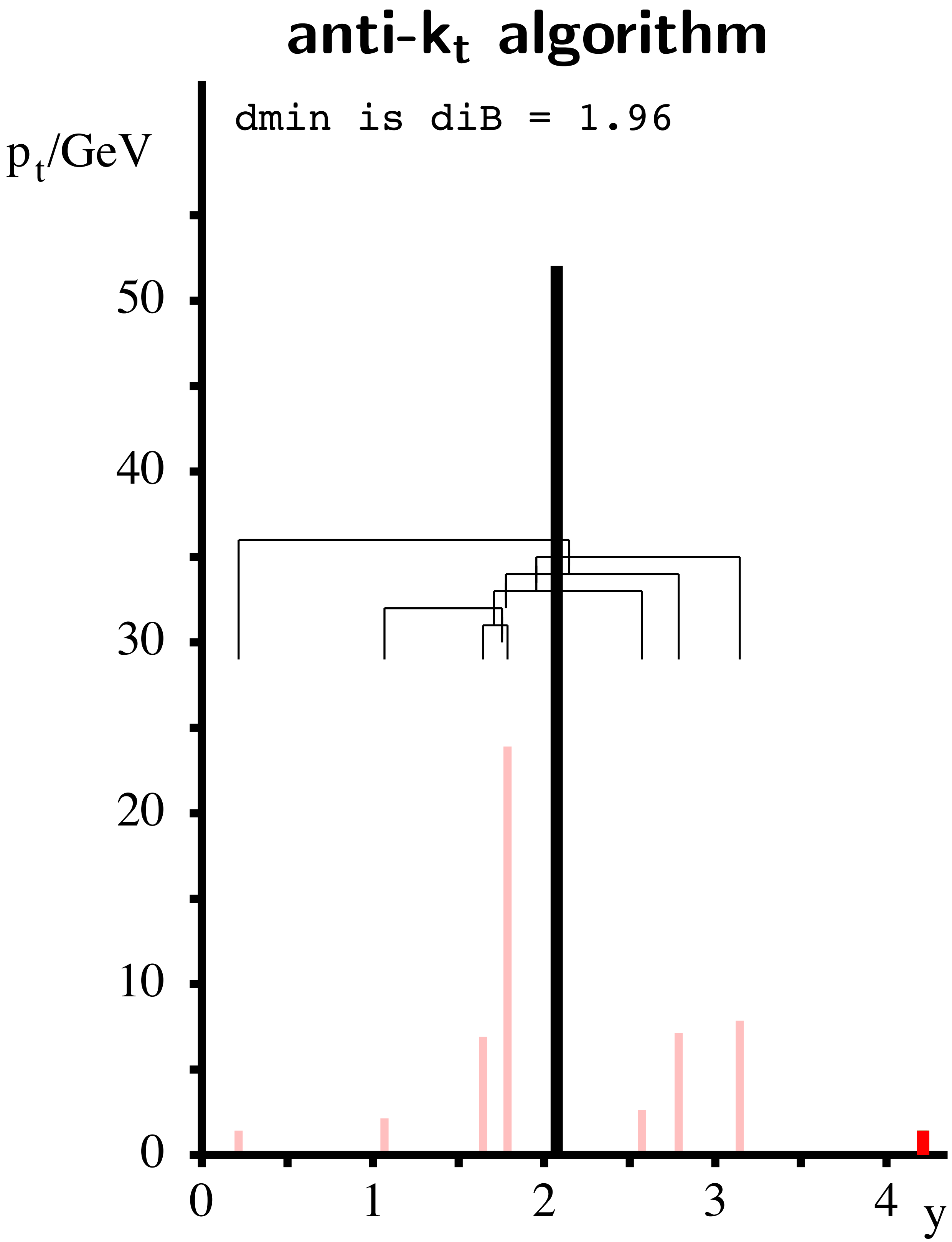

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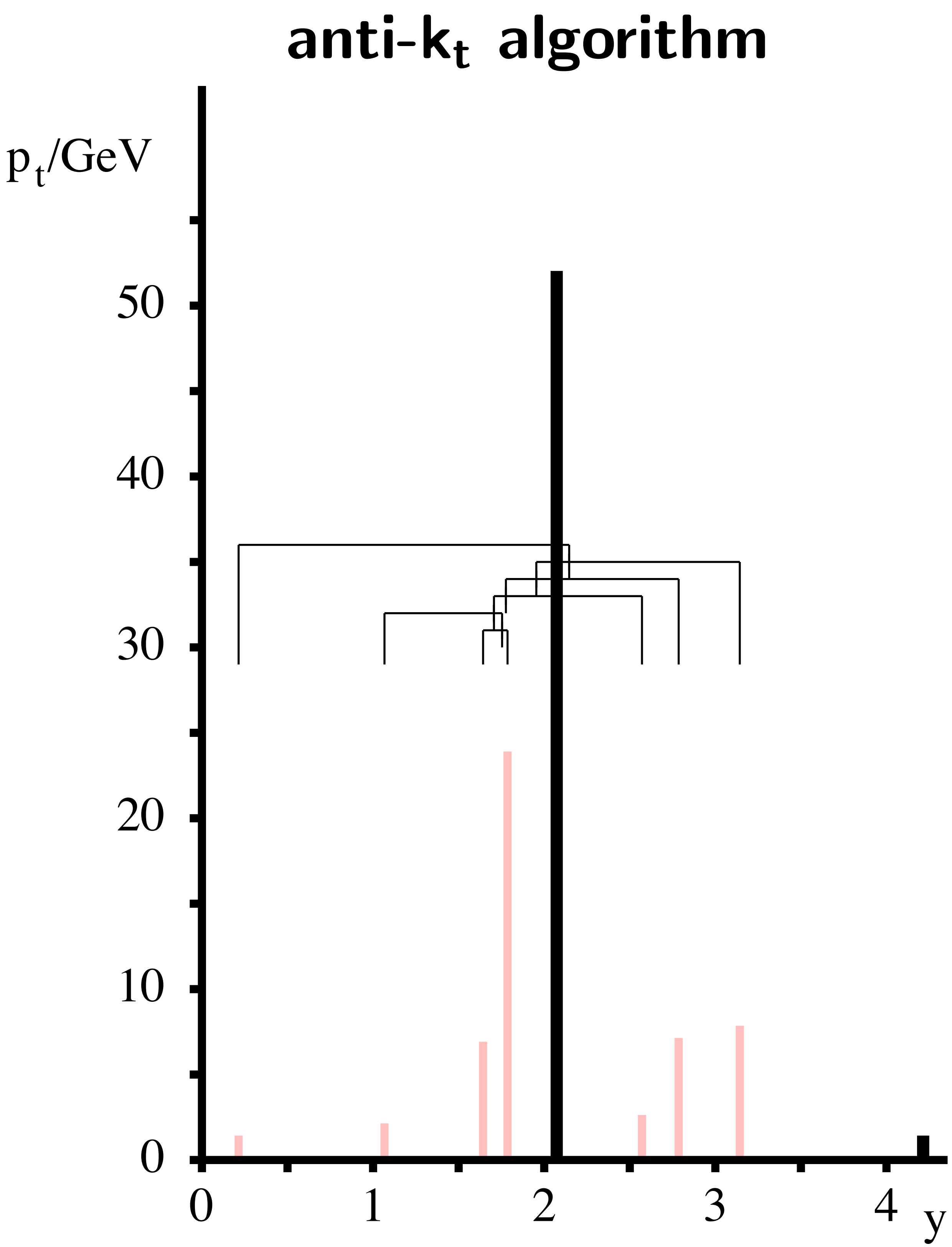

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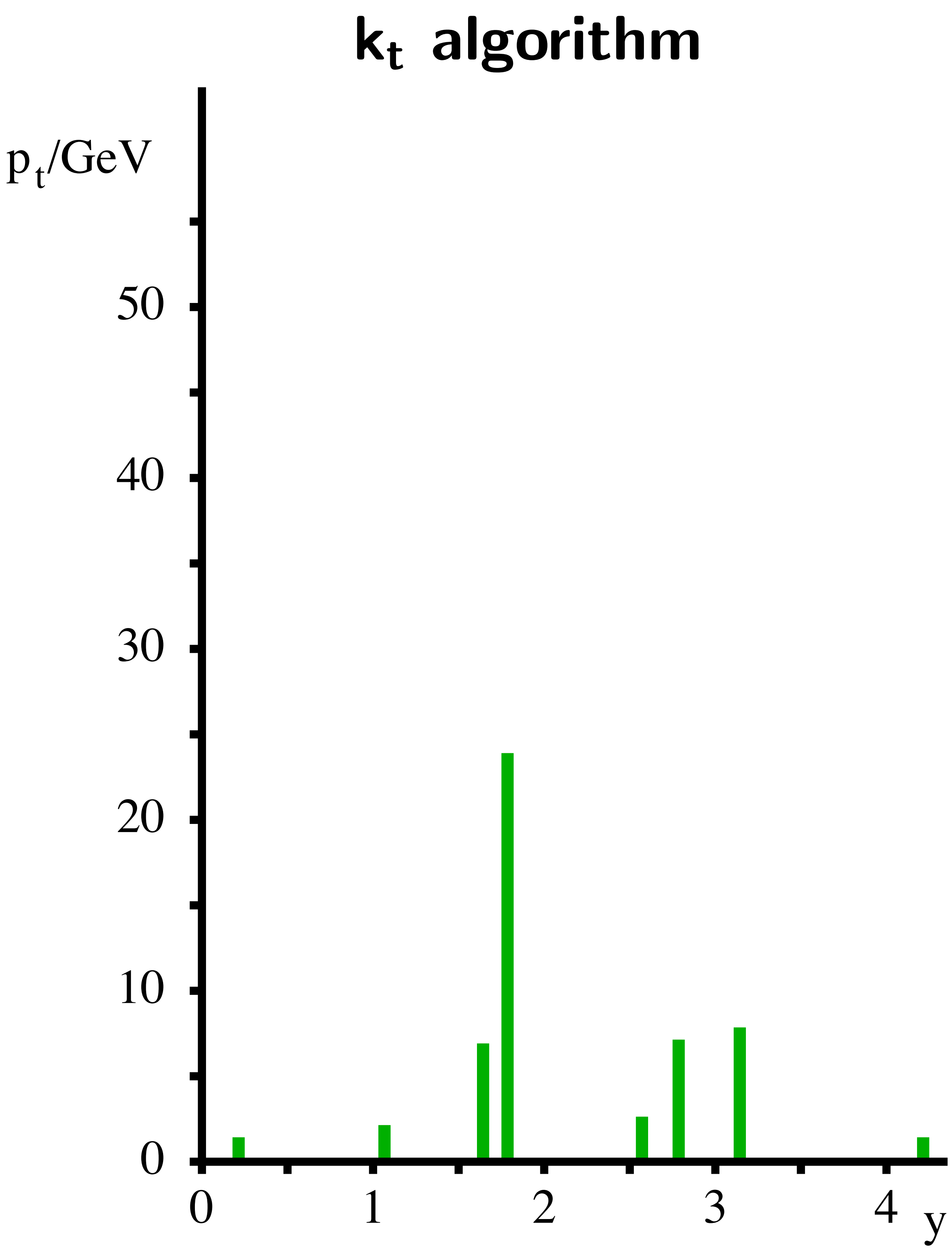

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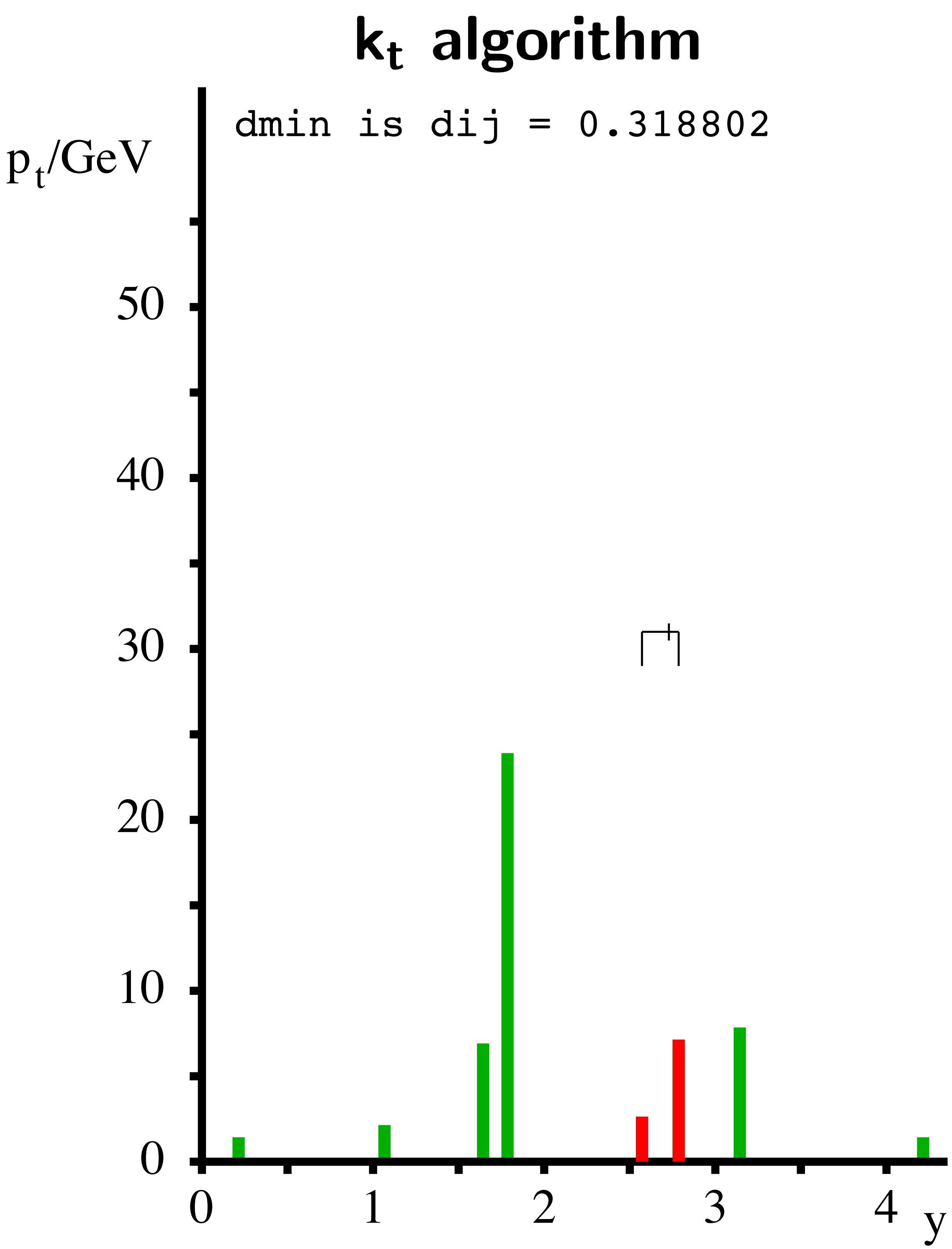

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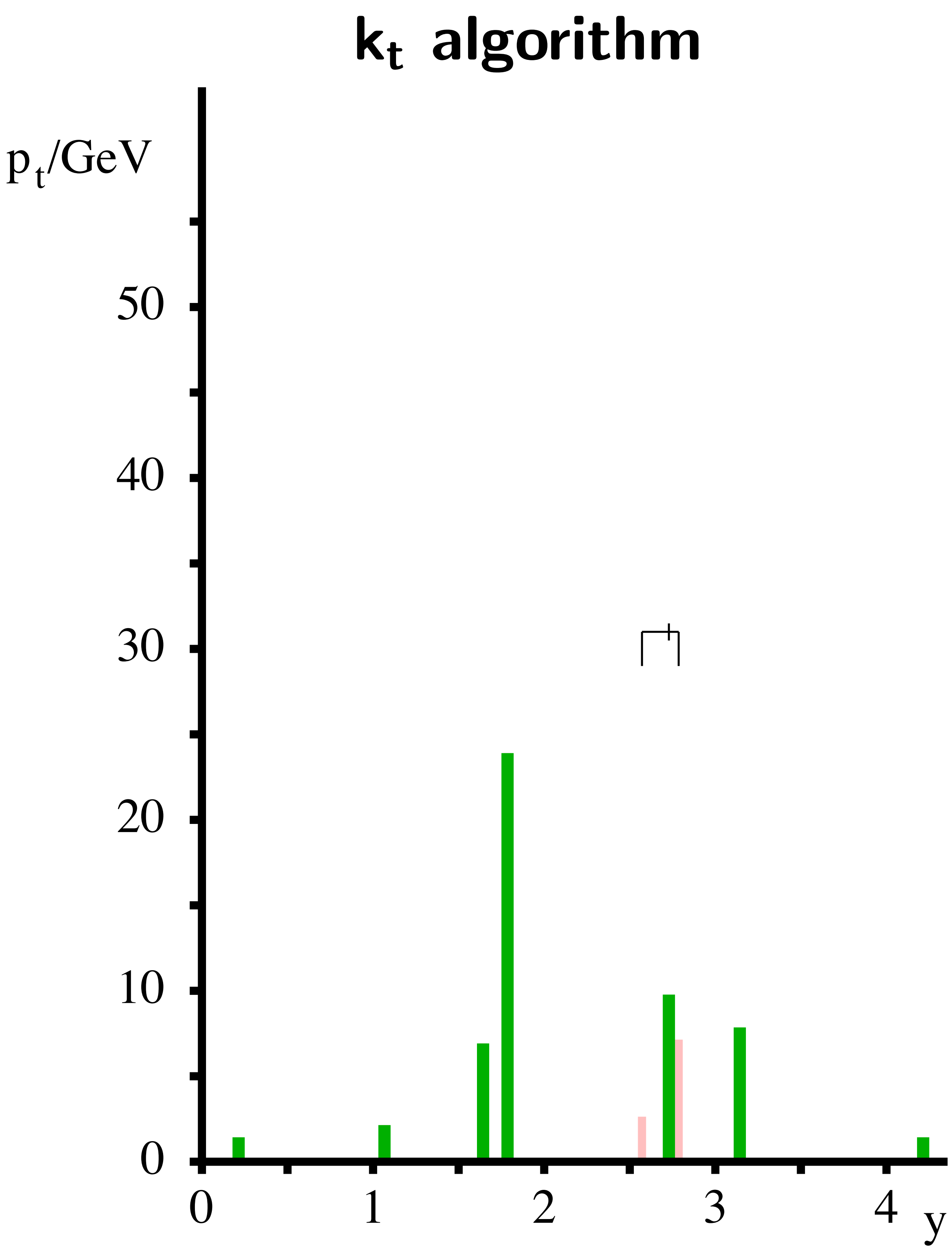

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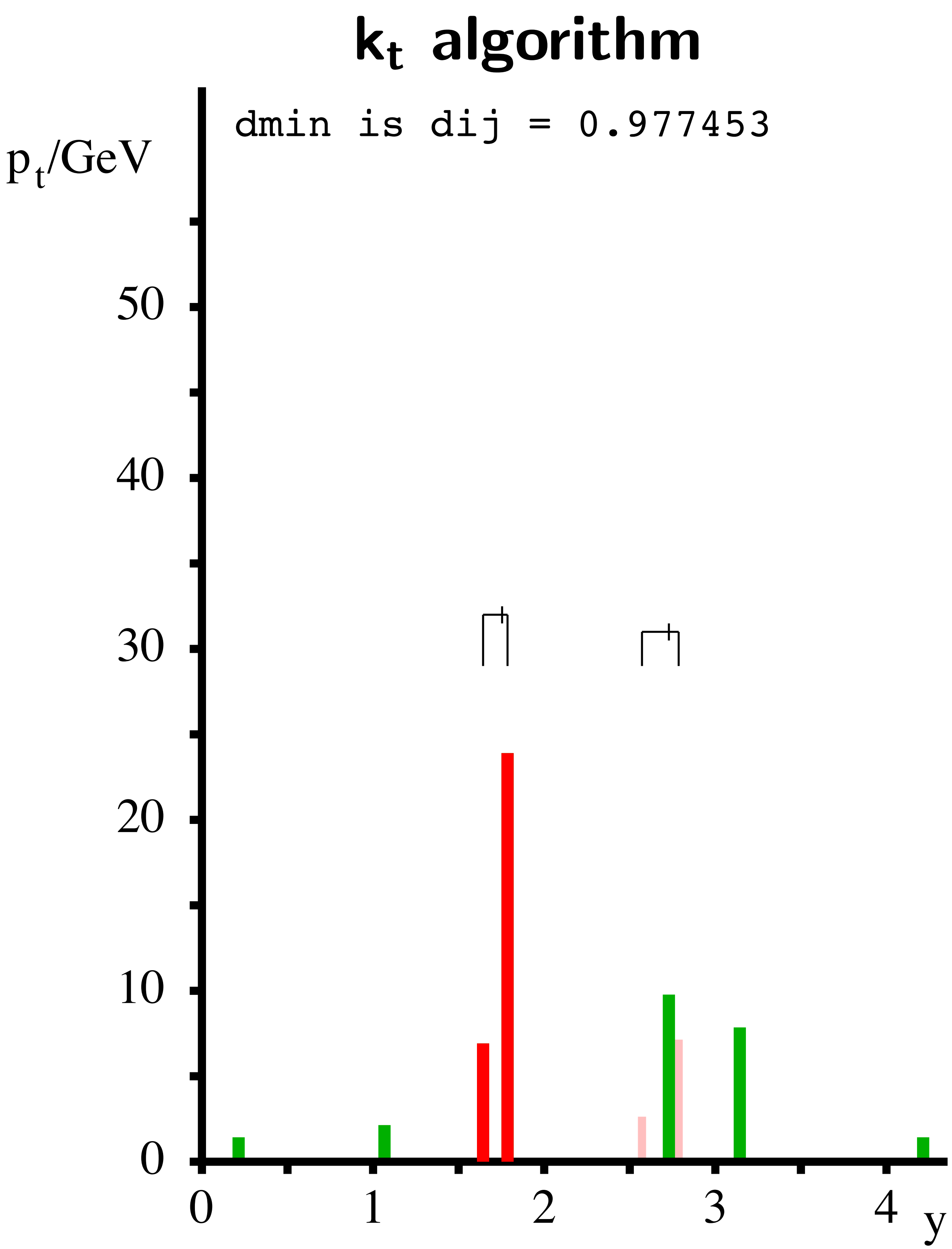

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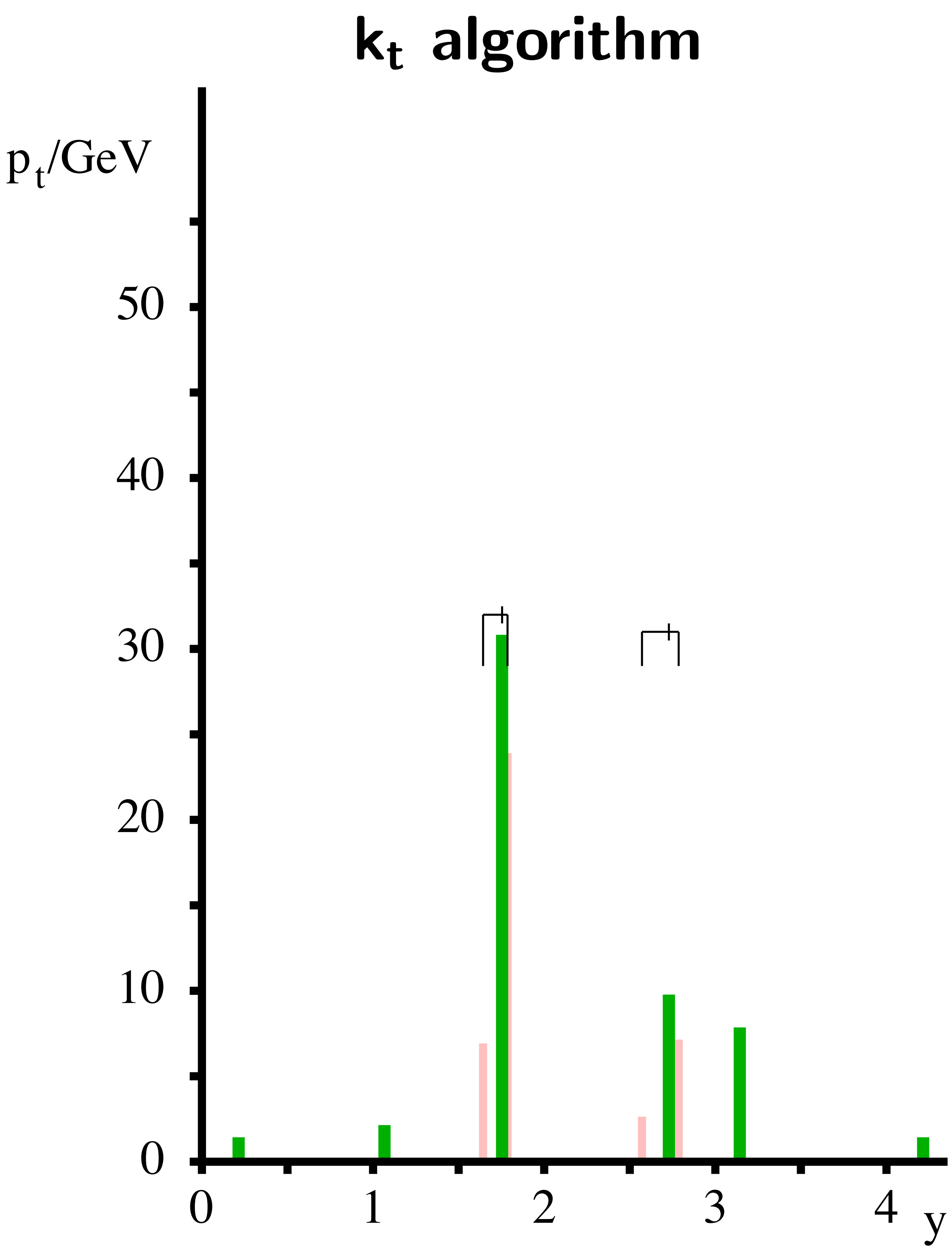

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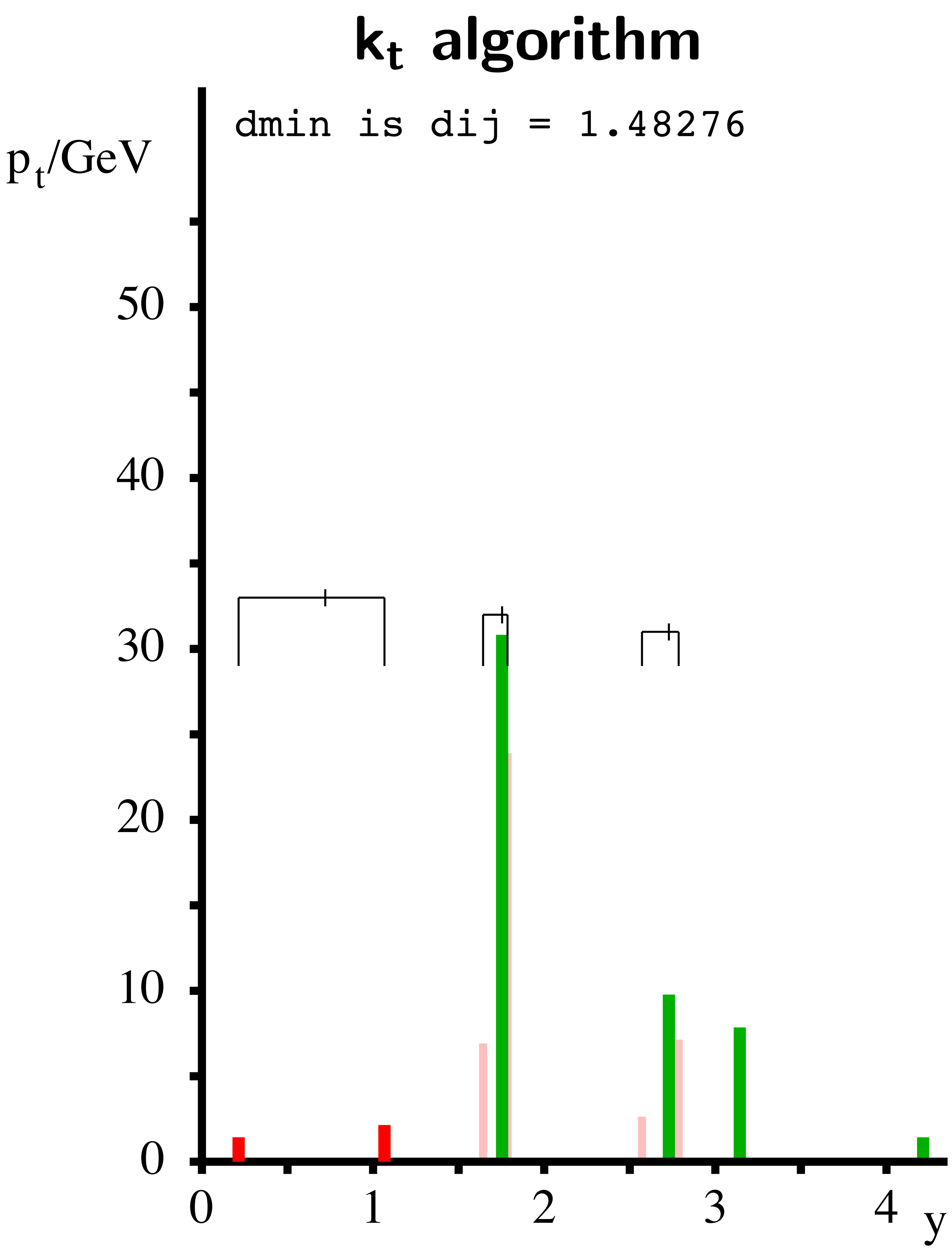

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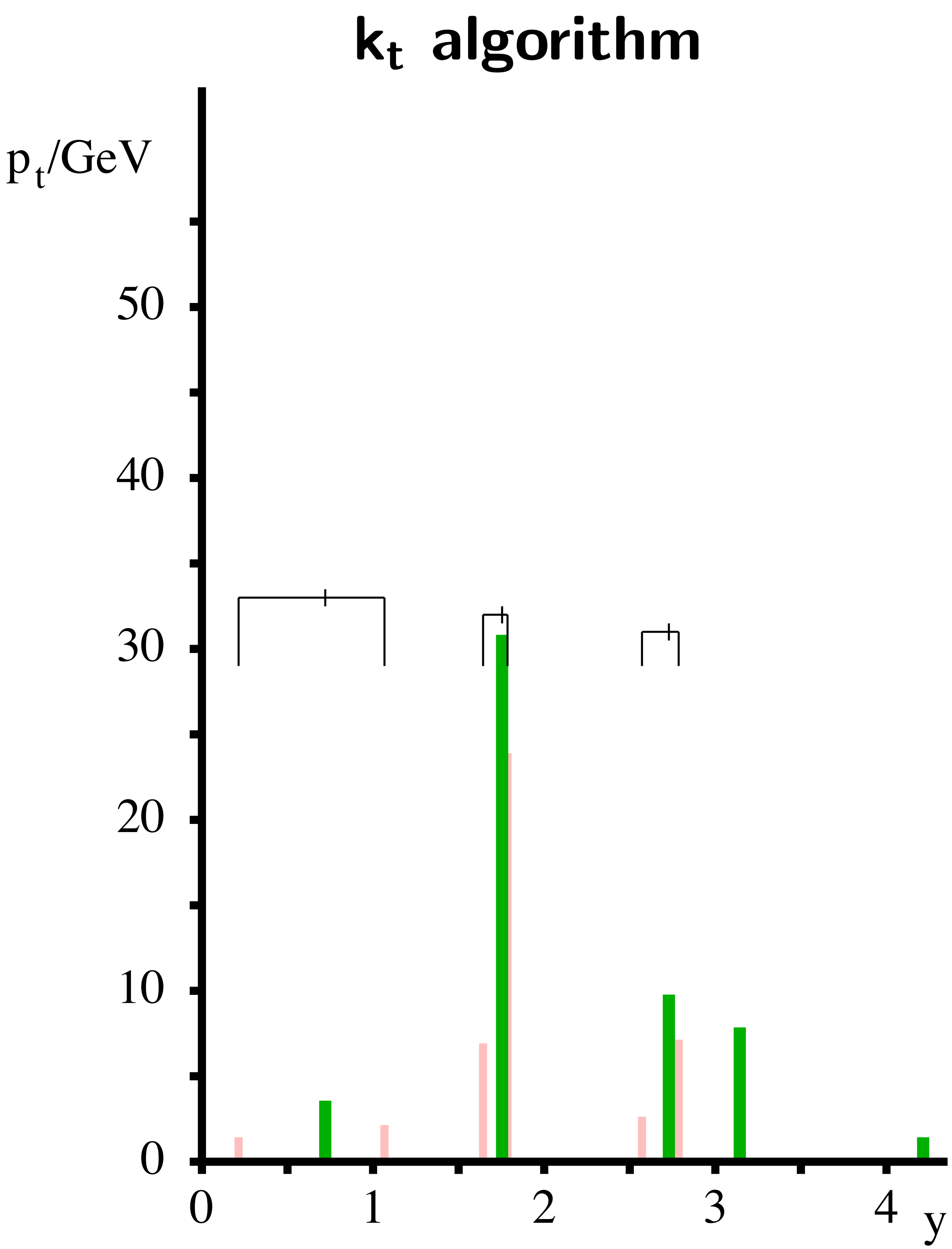

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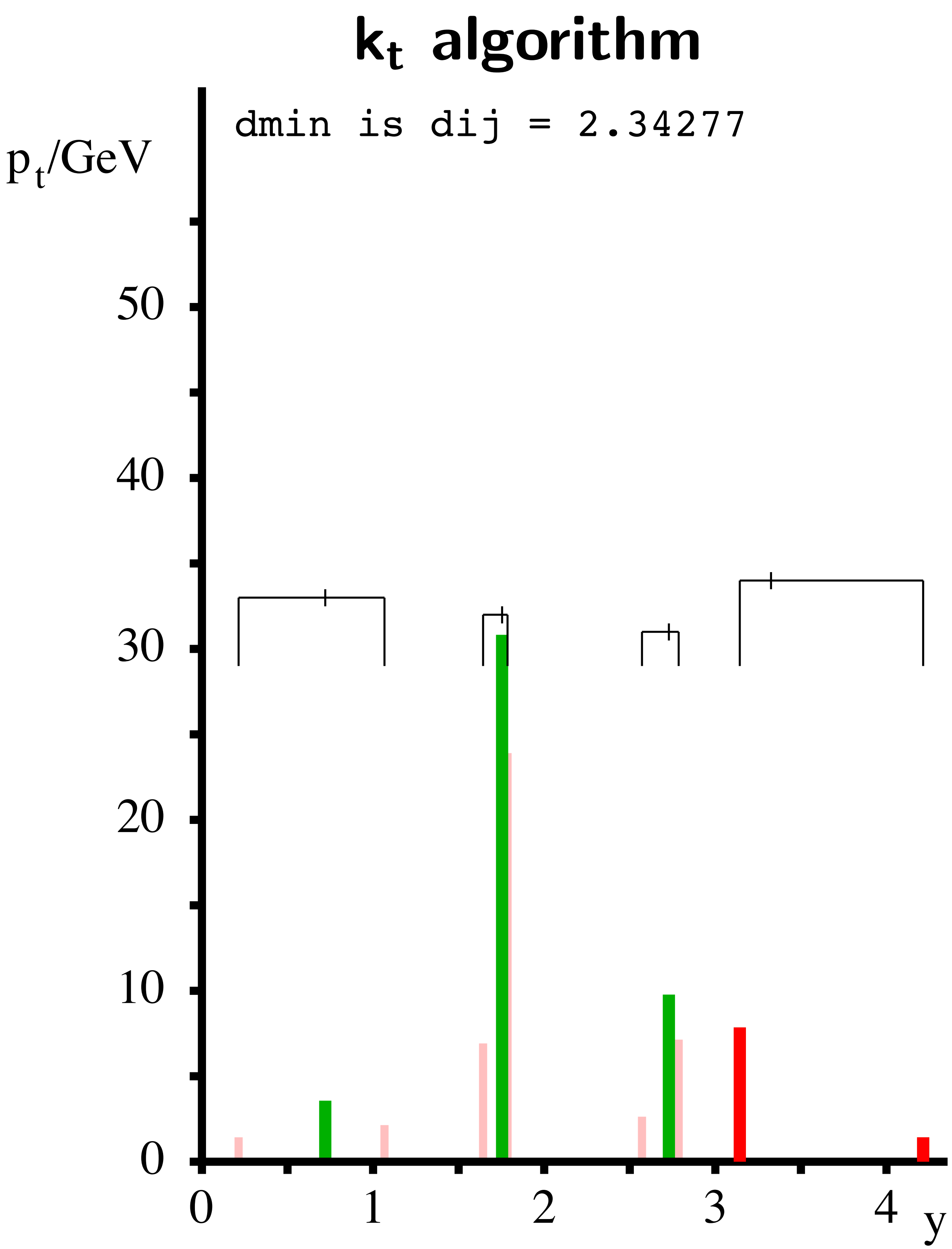

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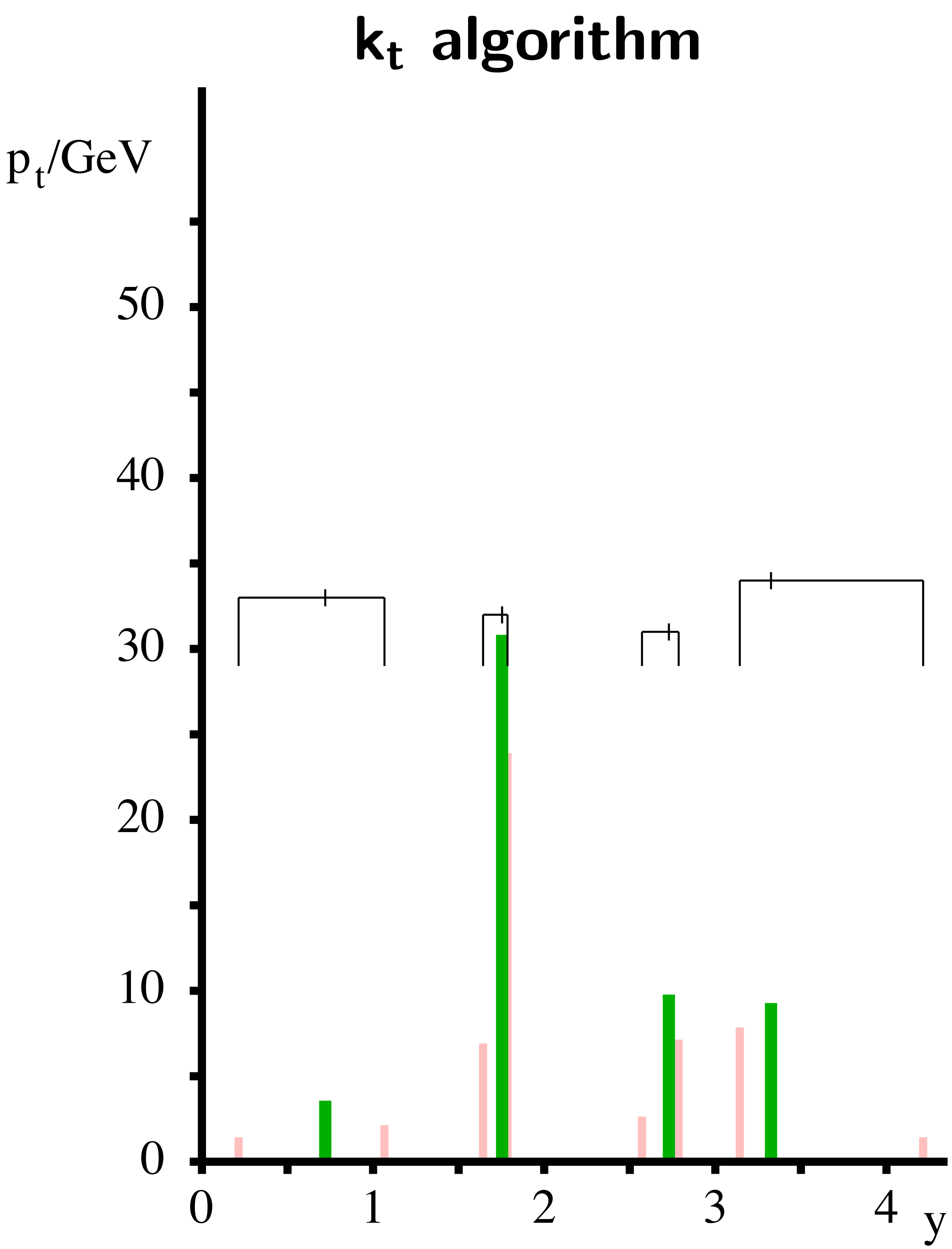

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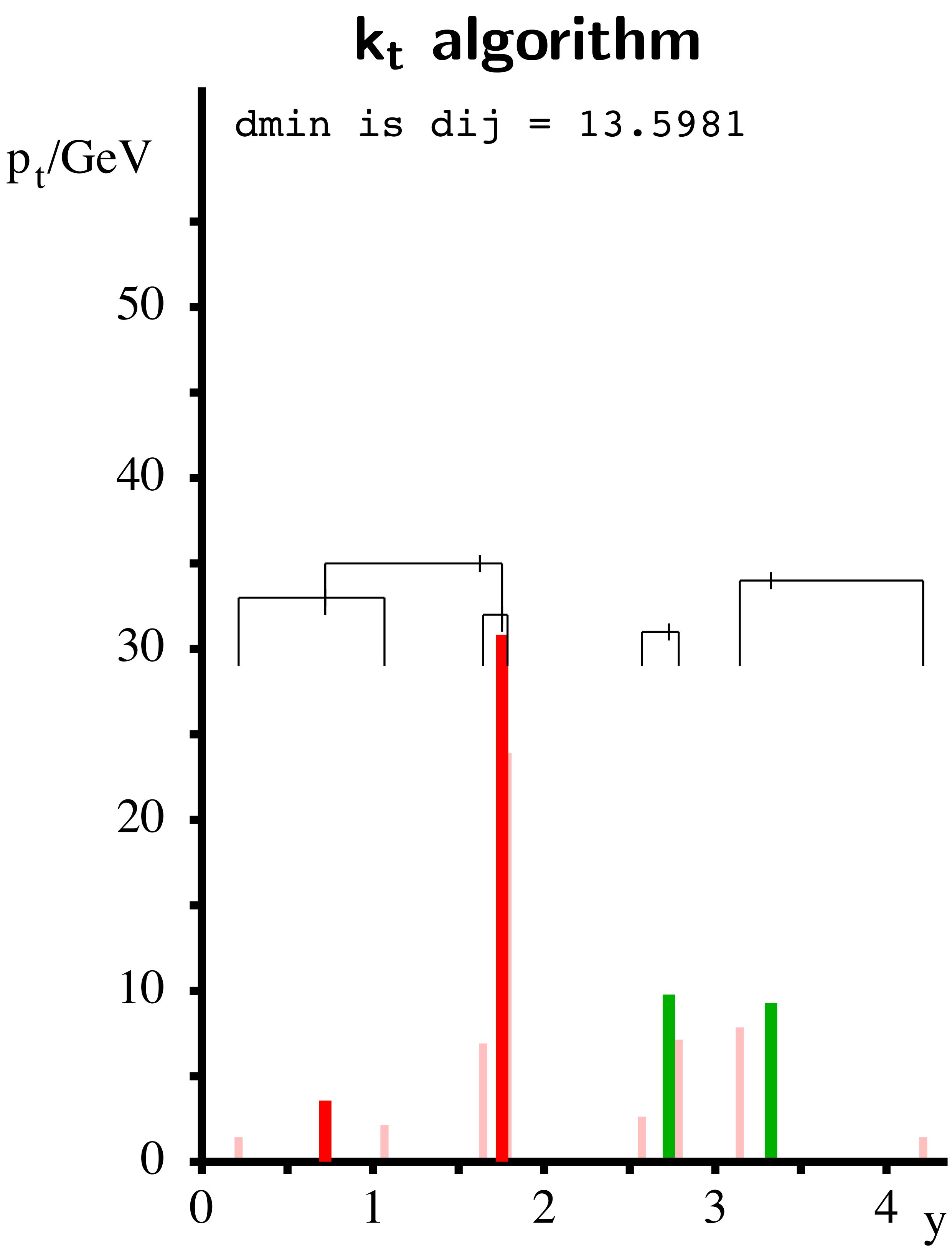

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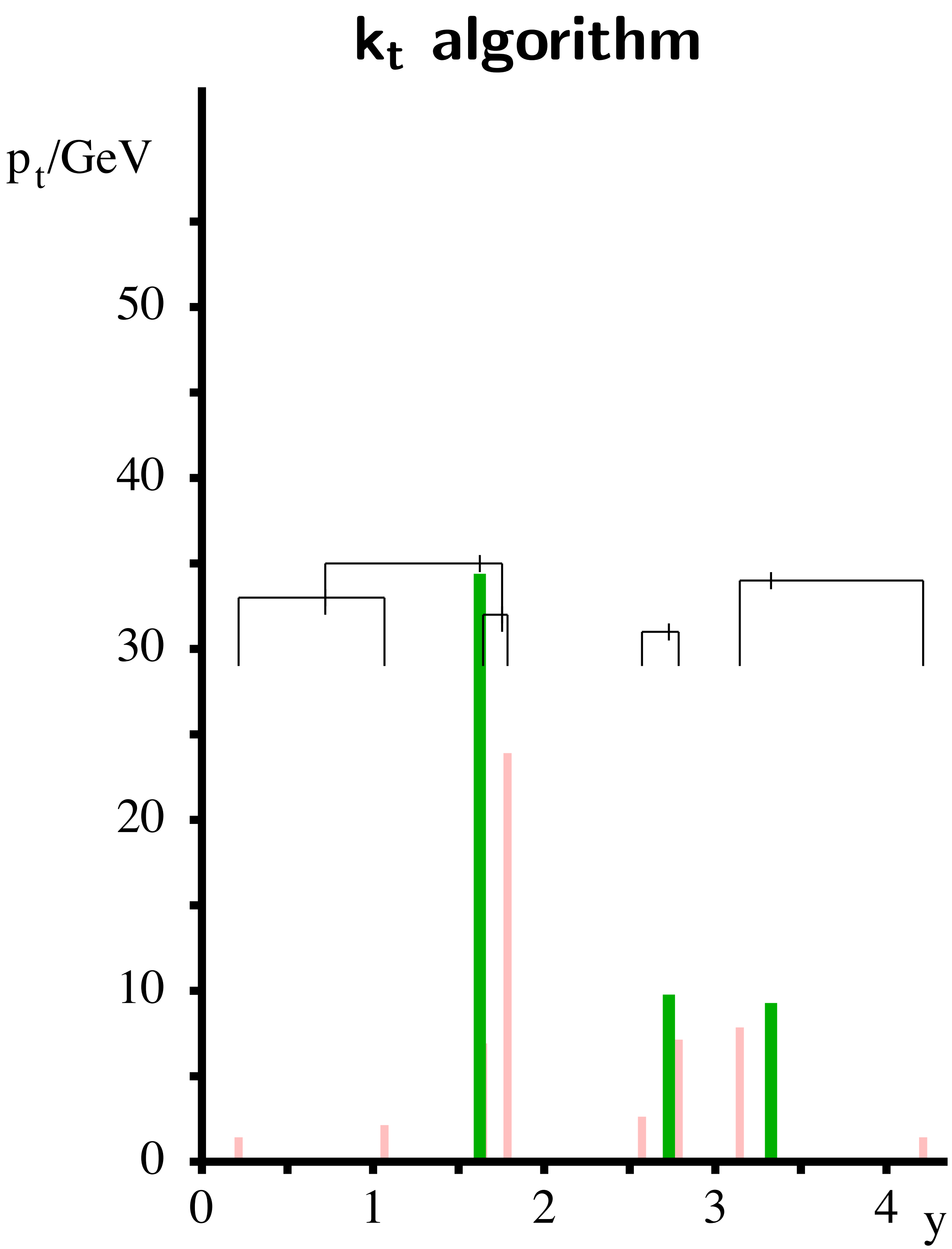

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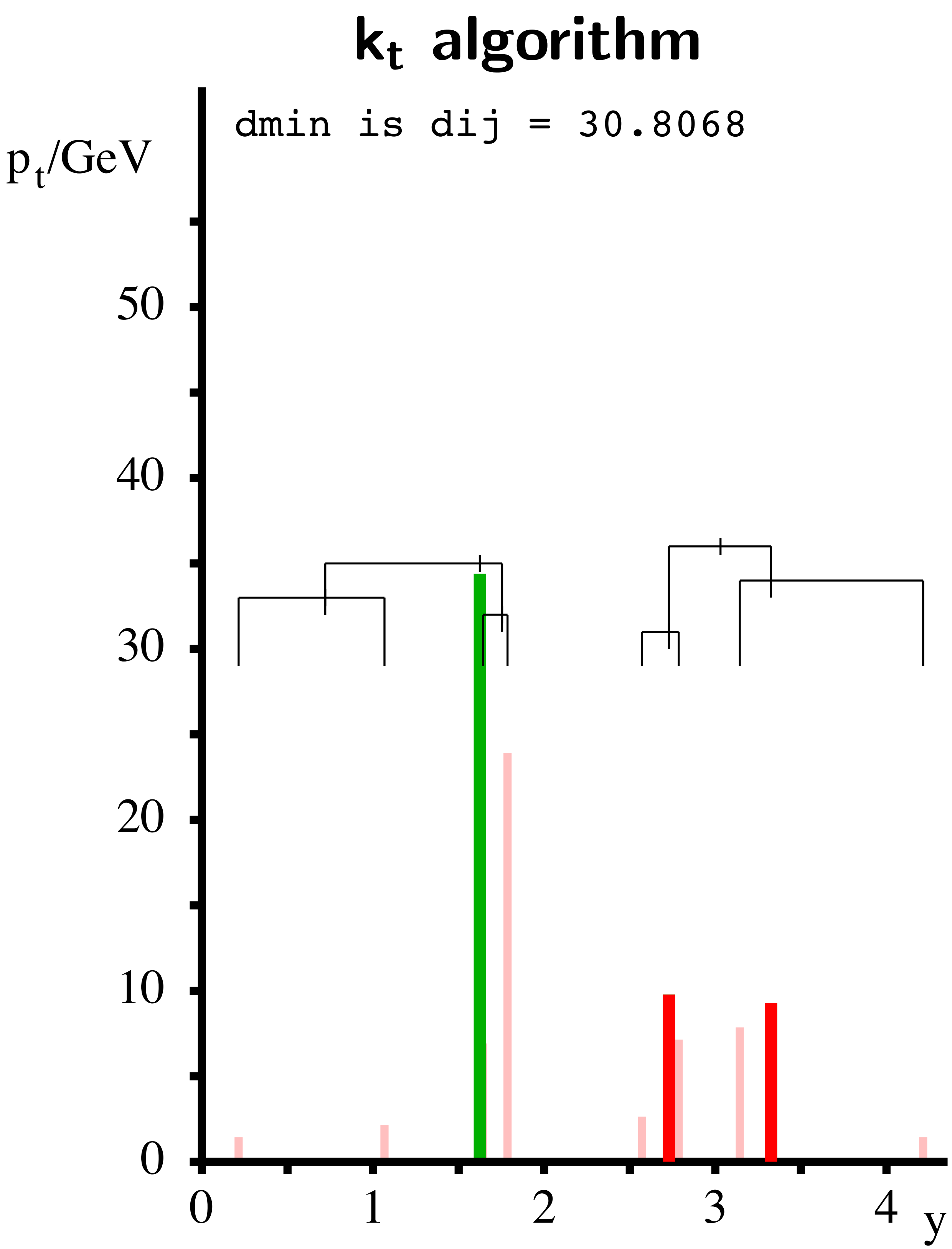

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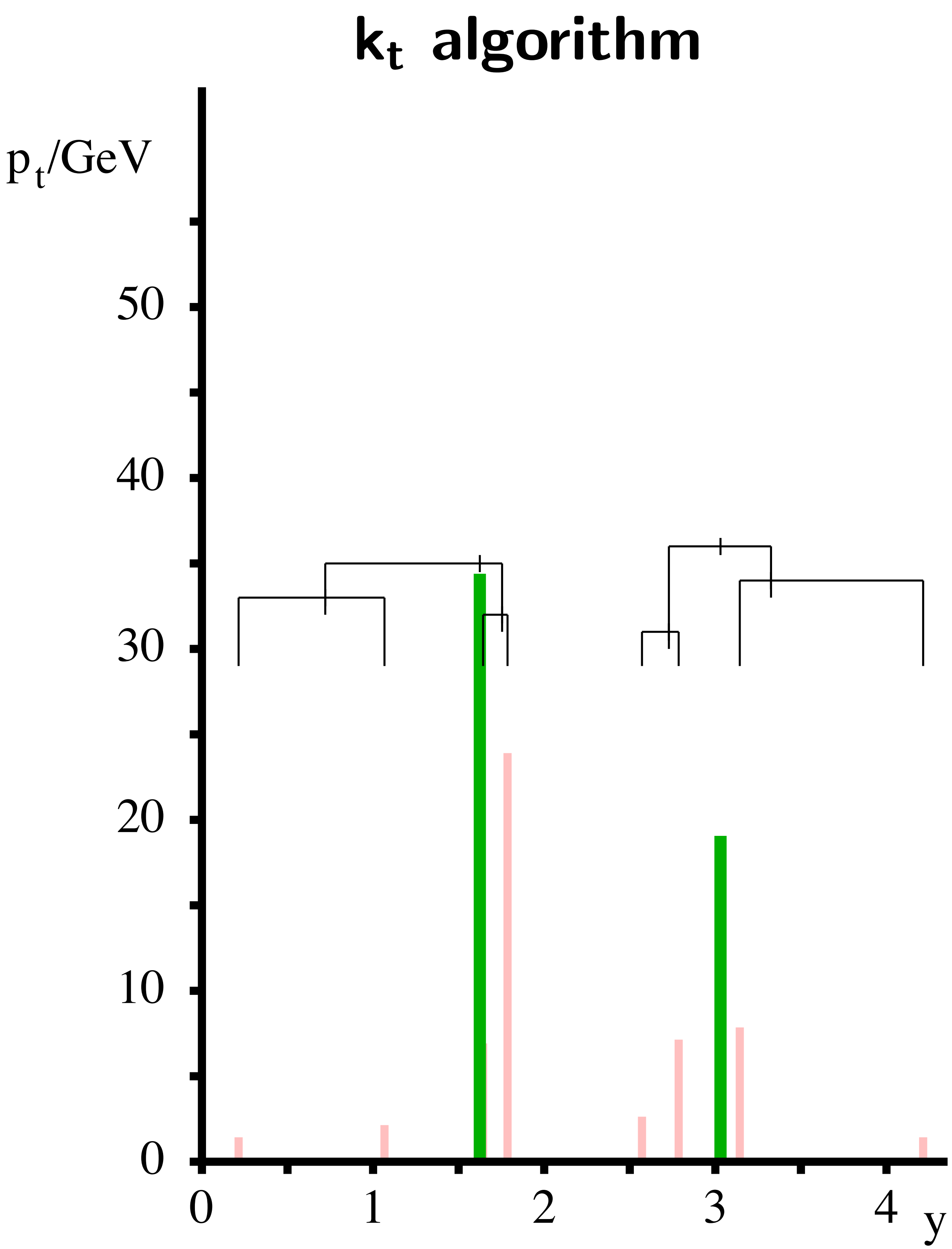

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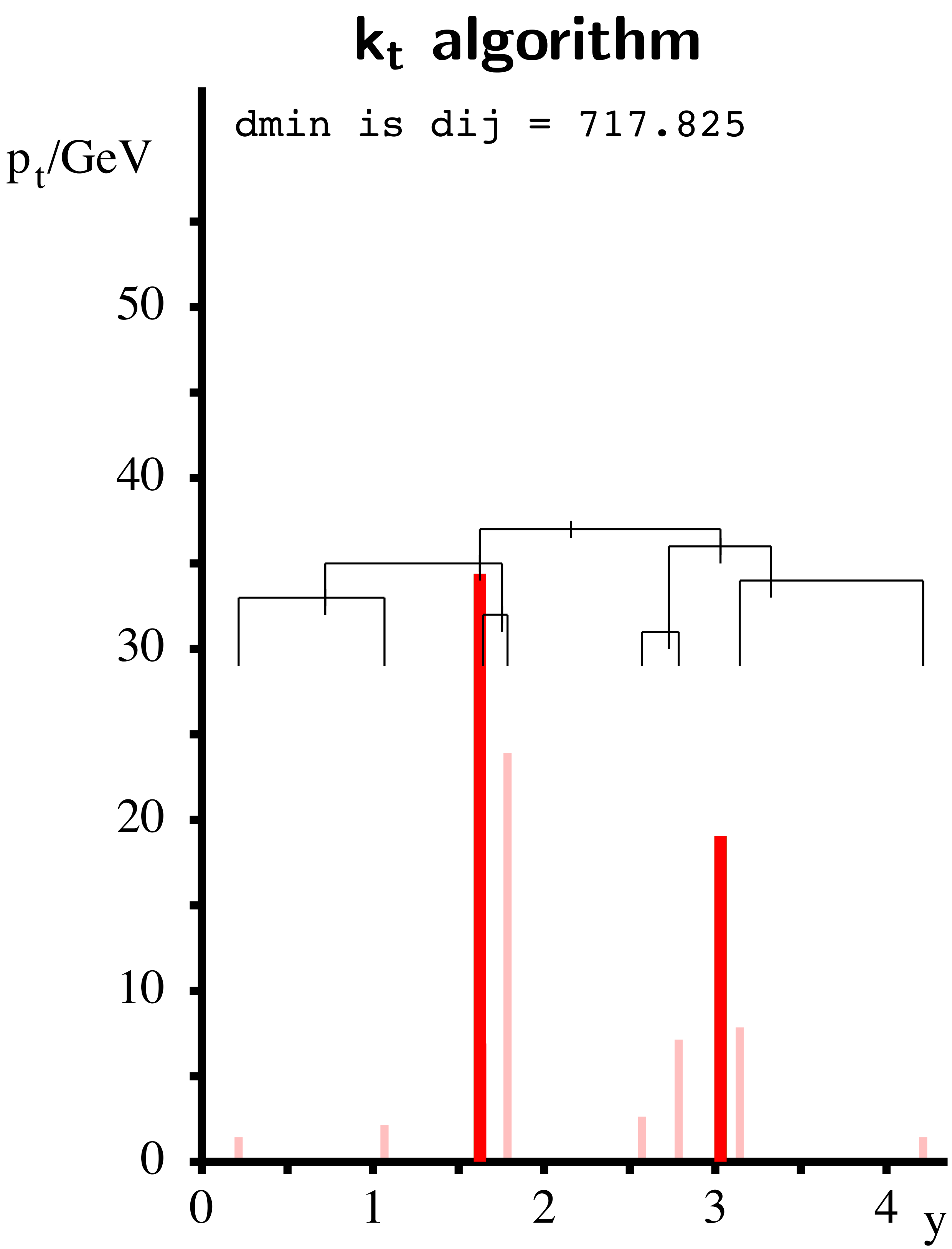

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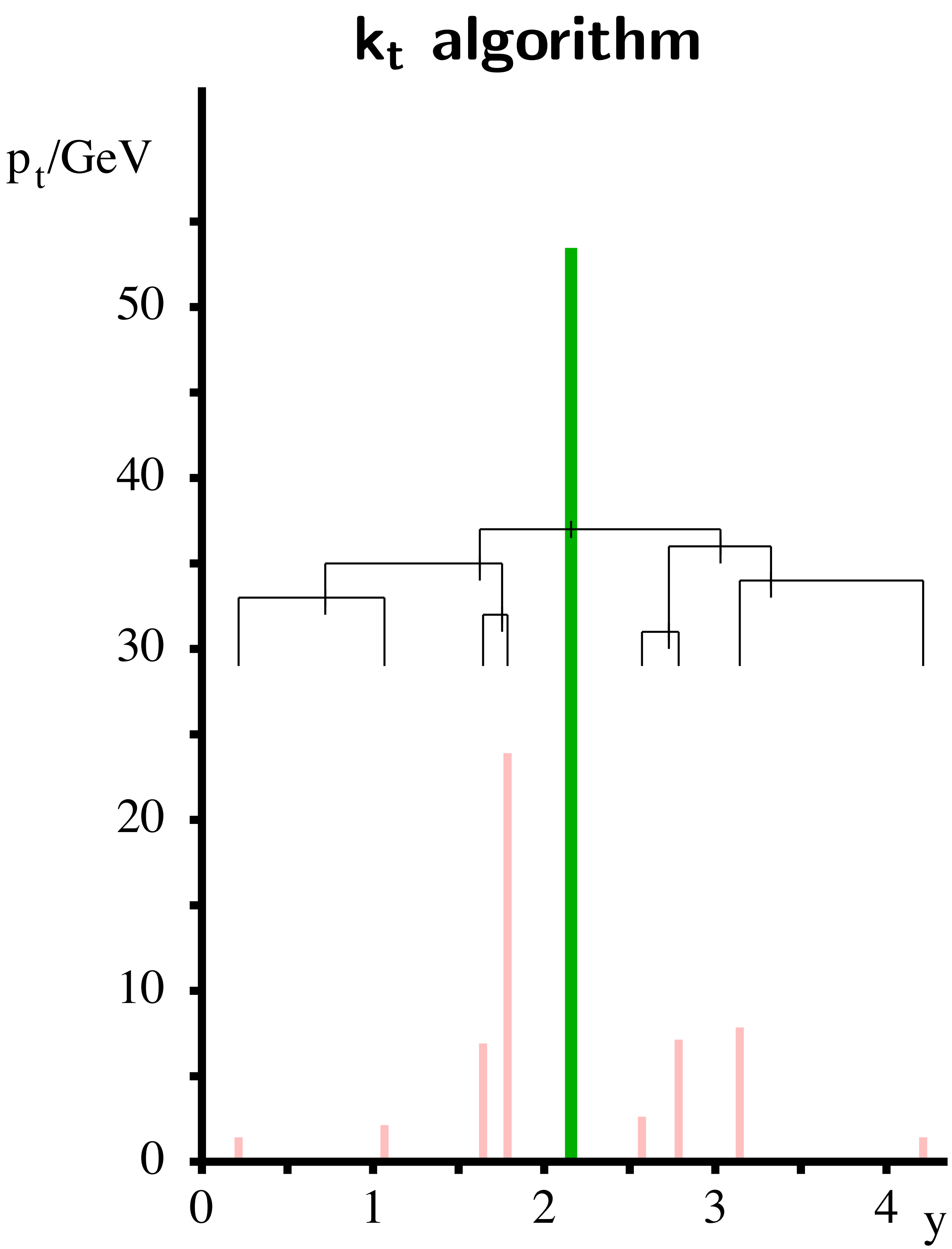

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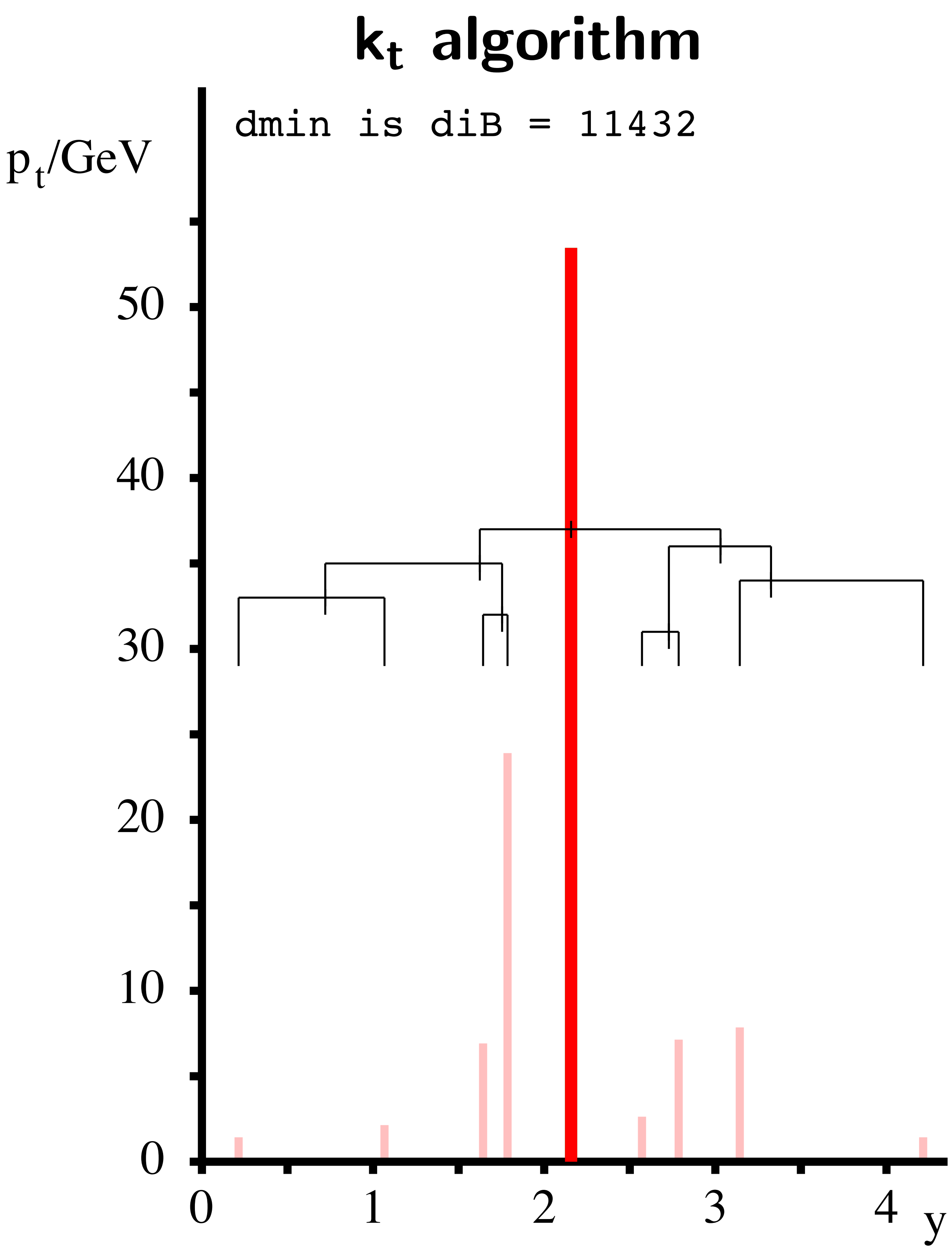

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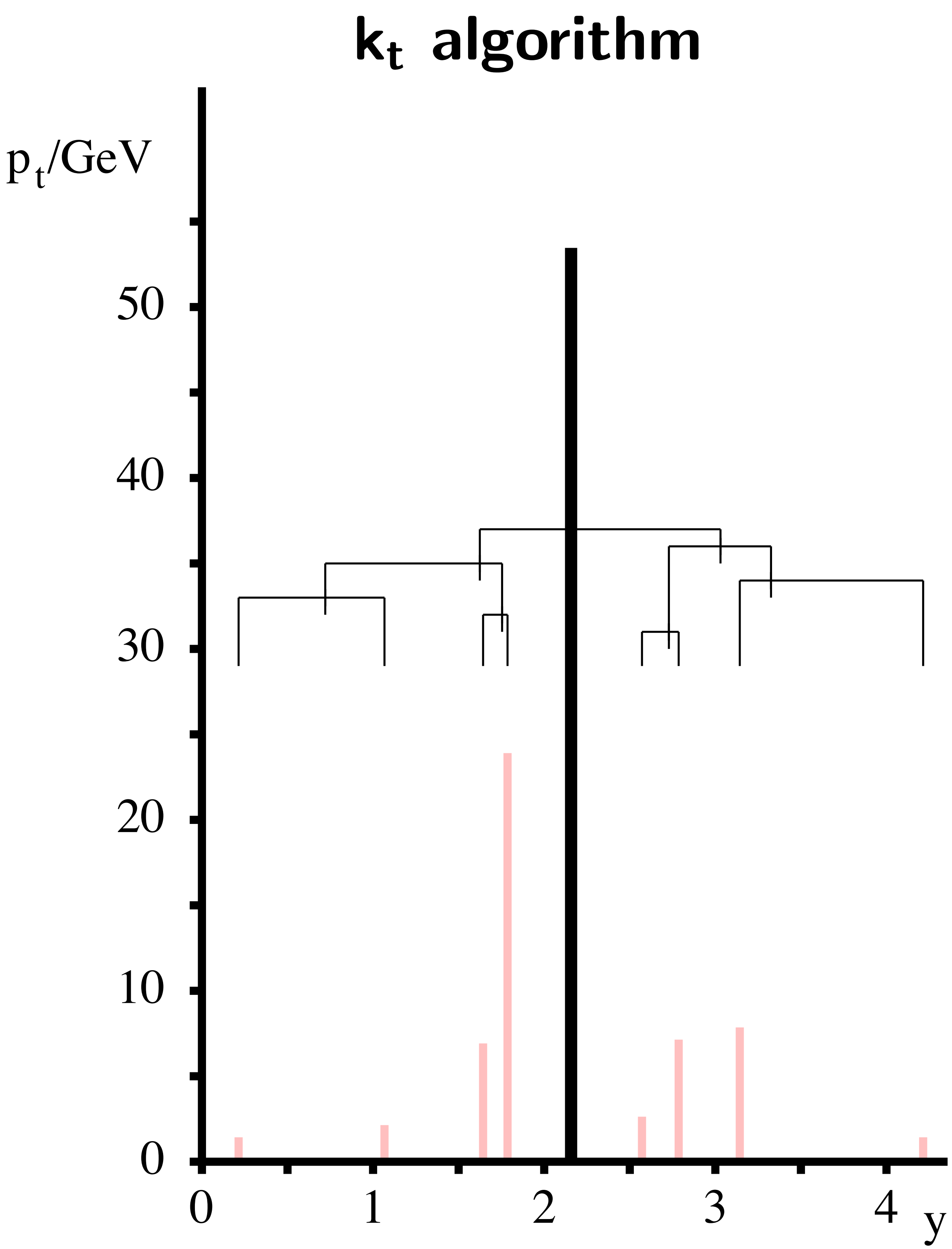

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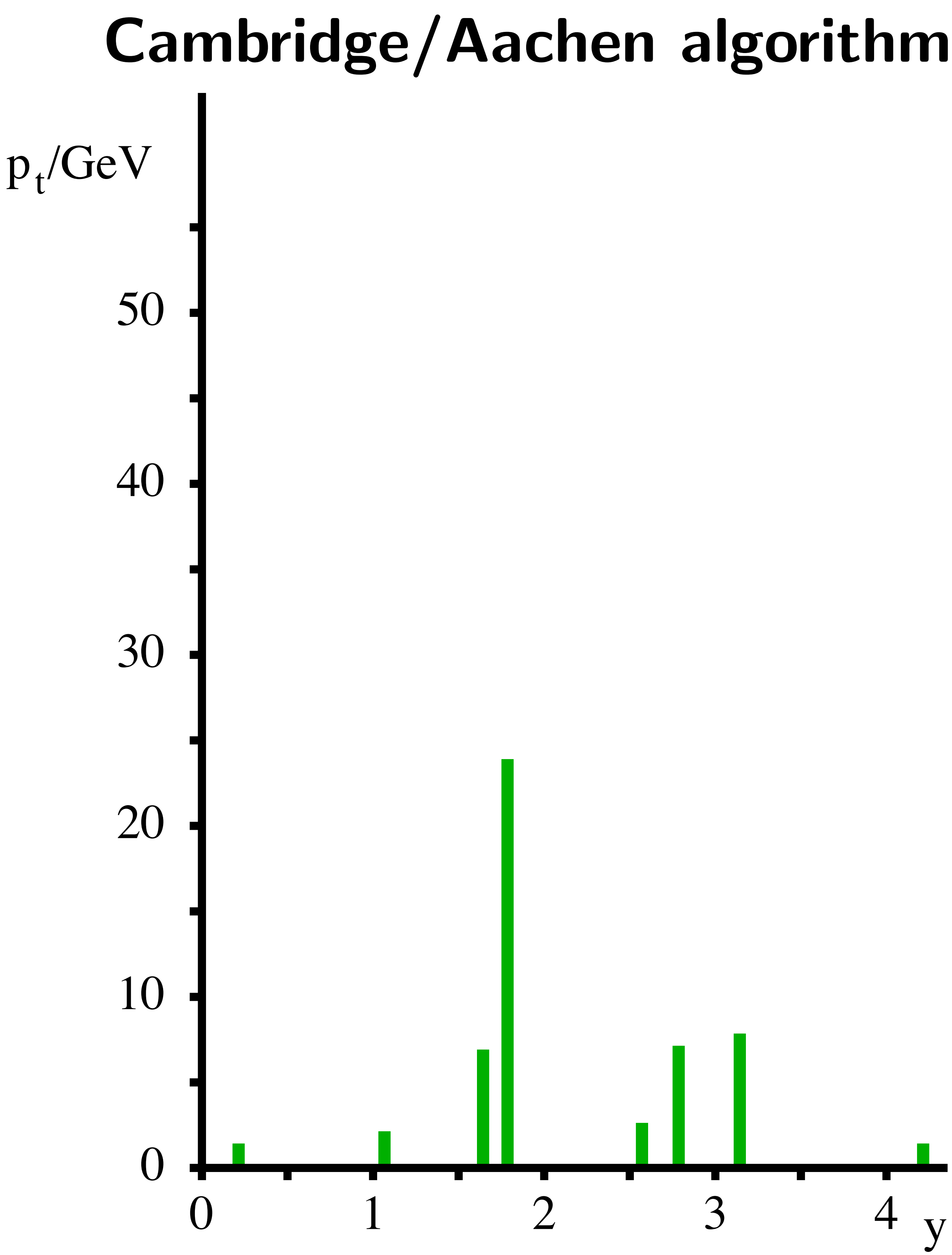
This meant it was the first algorithm to be used for jet substructure.

Seymour '93

Butterworth, Cox & Forshaw '02



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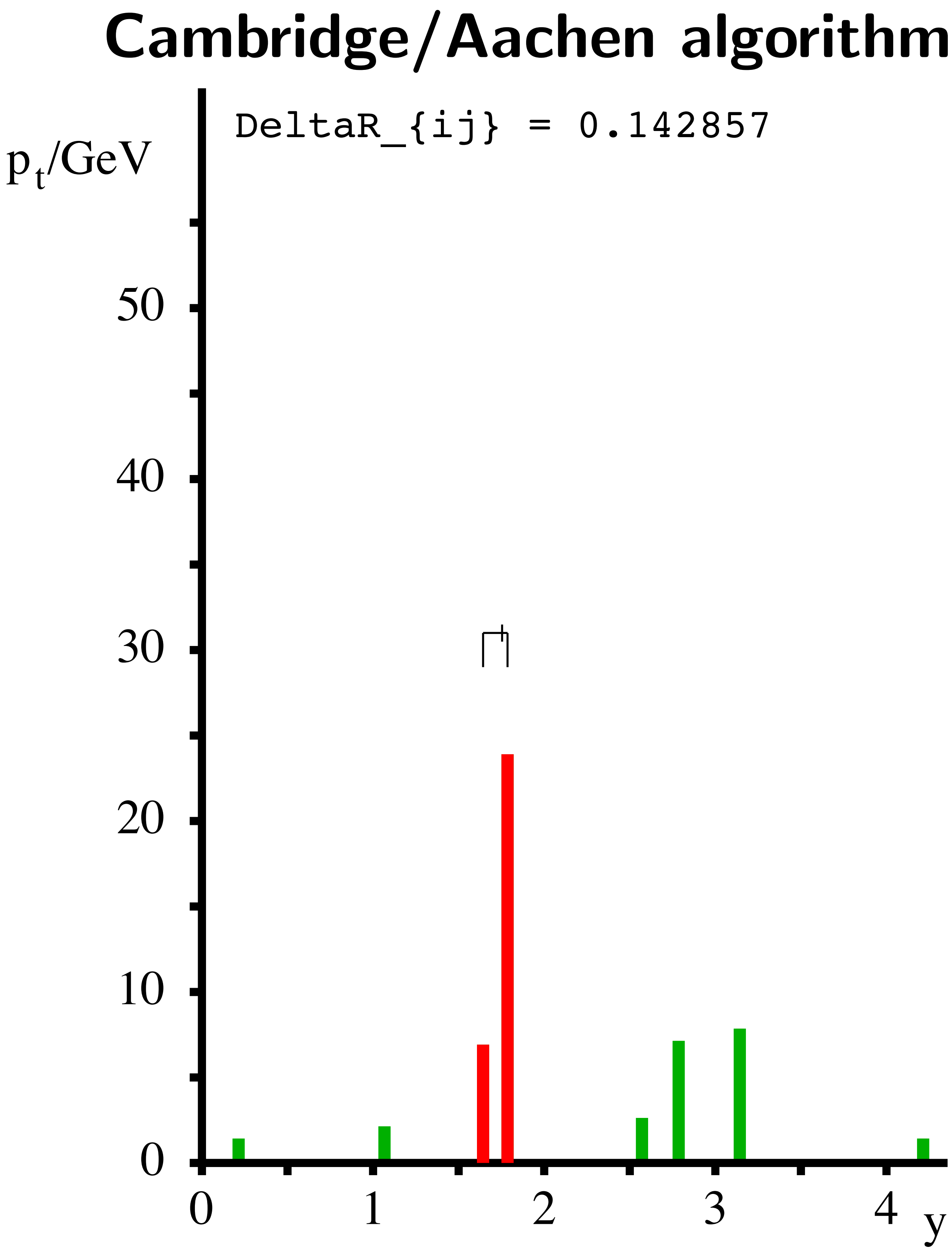

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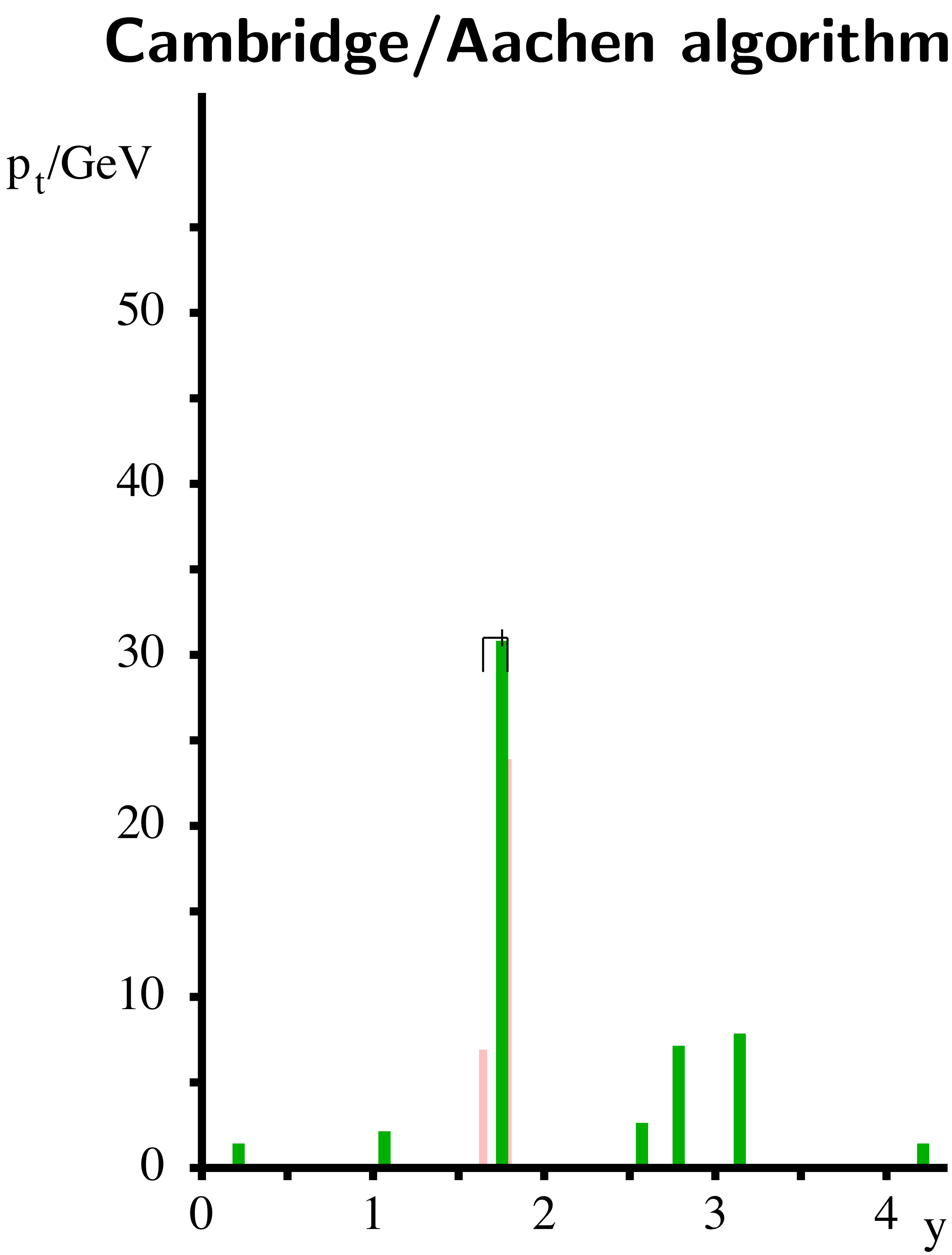

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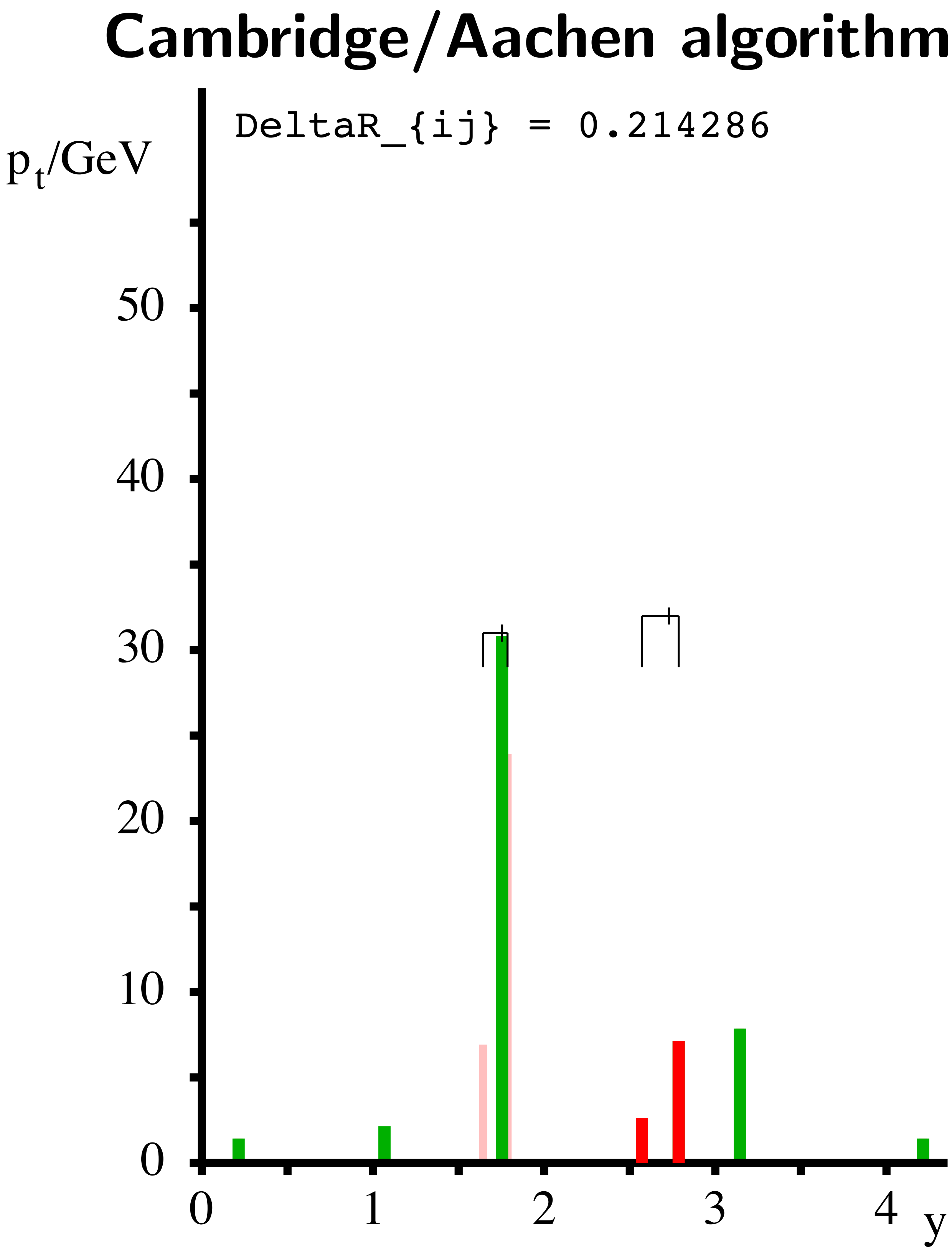

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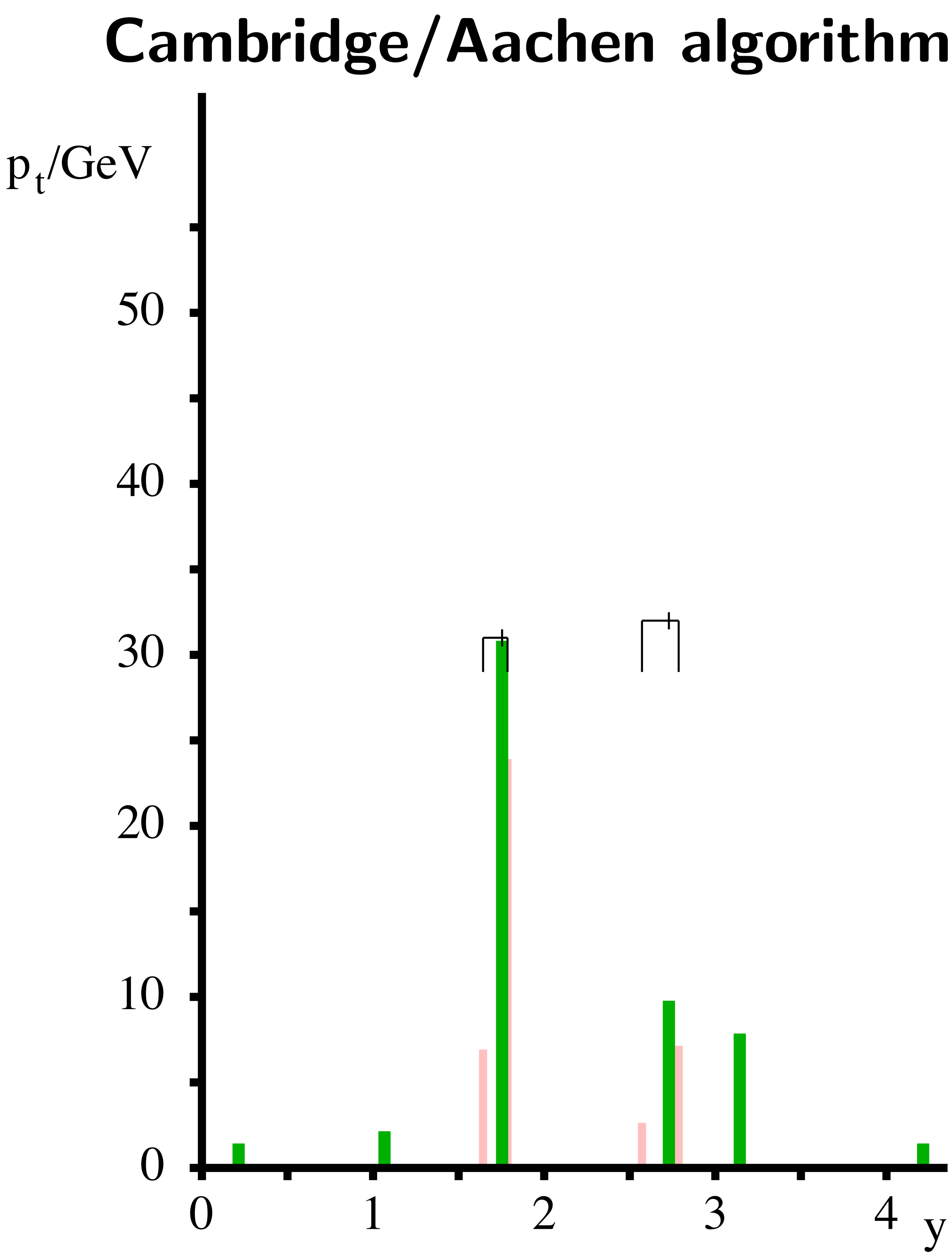

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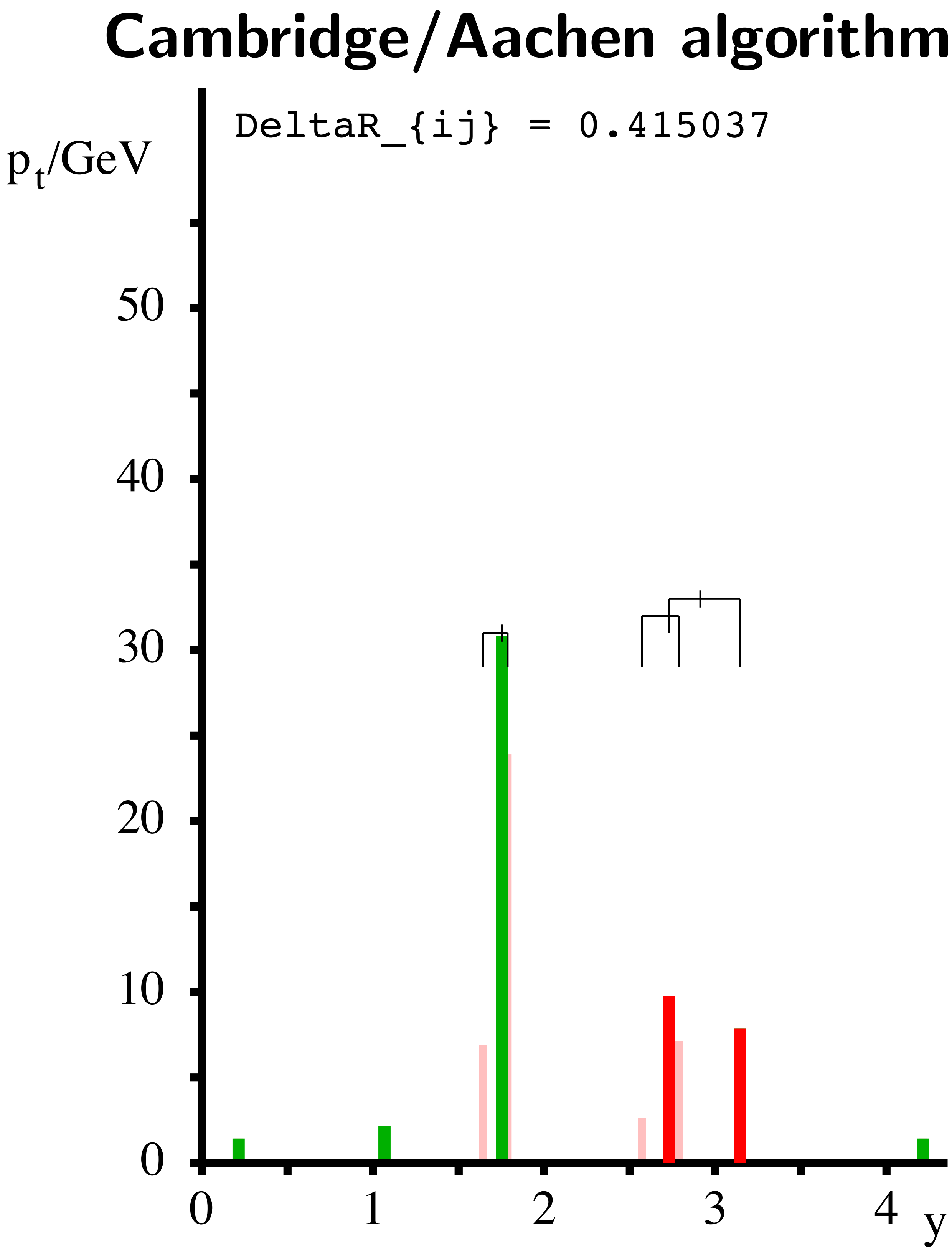

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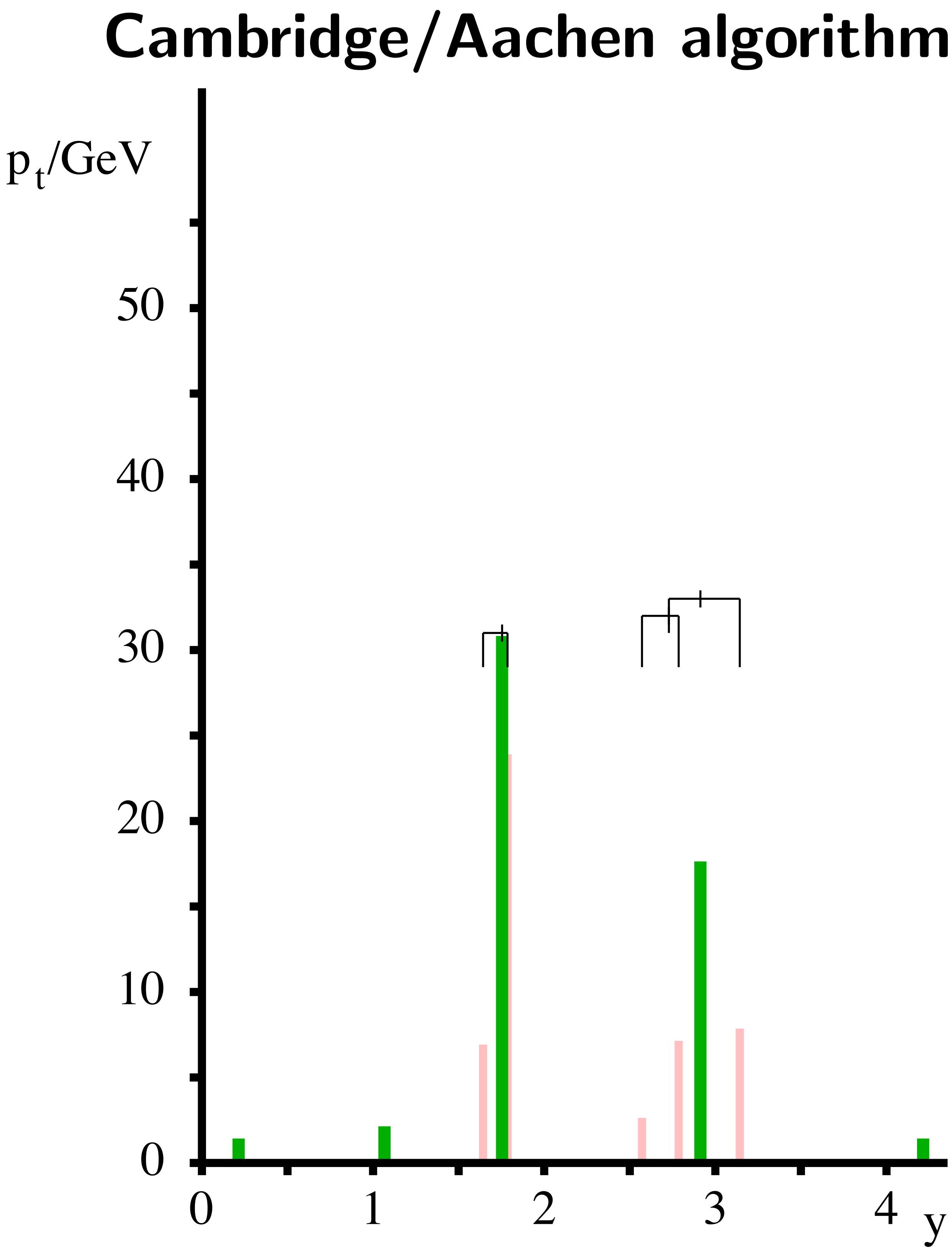

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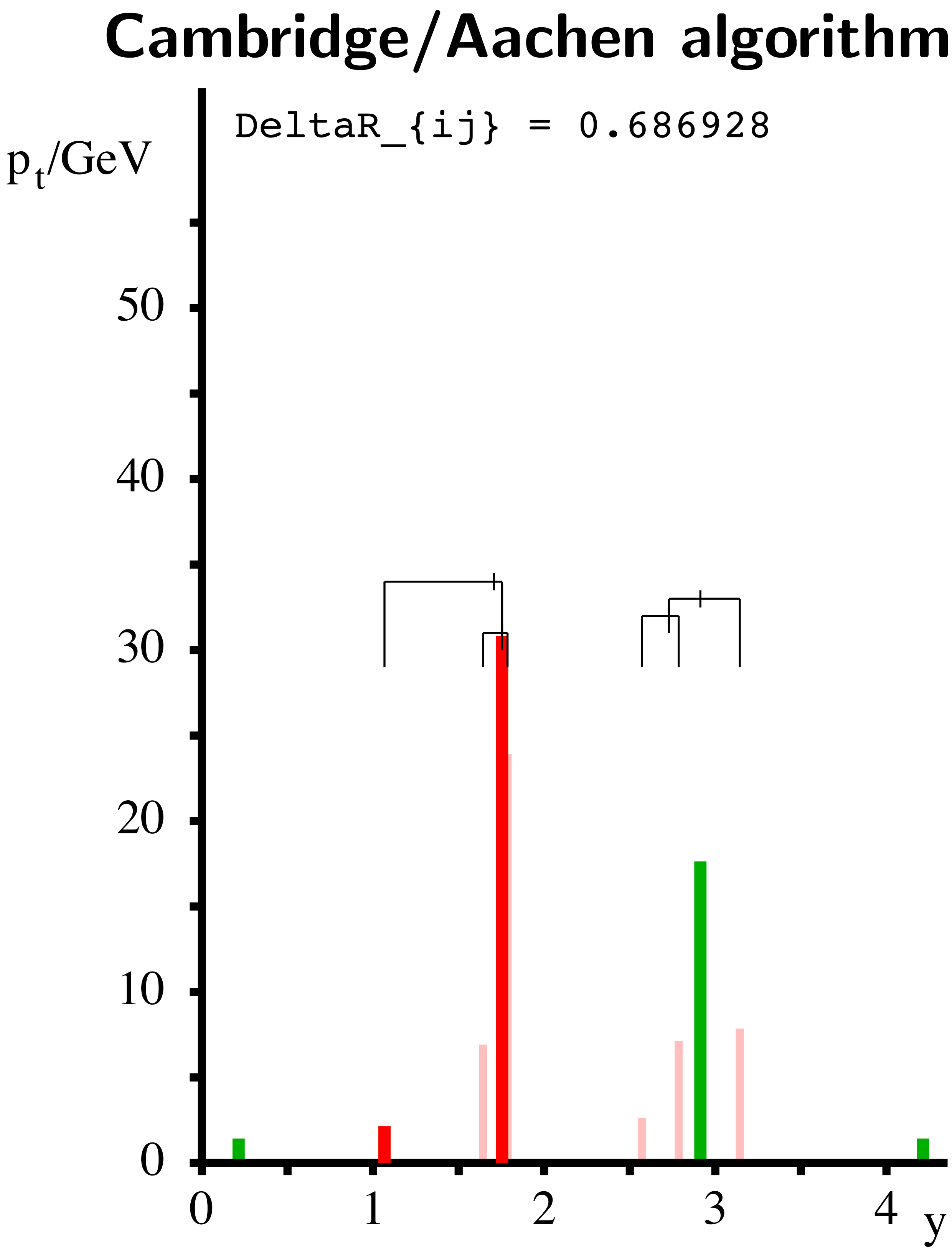

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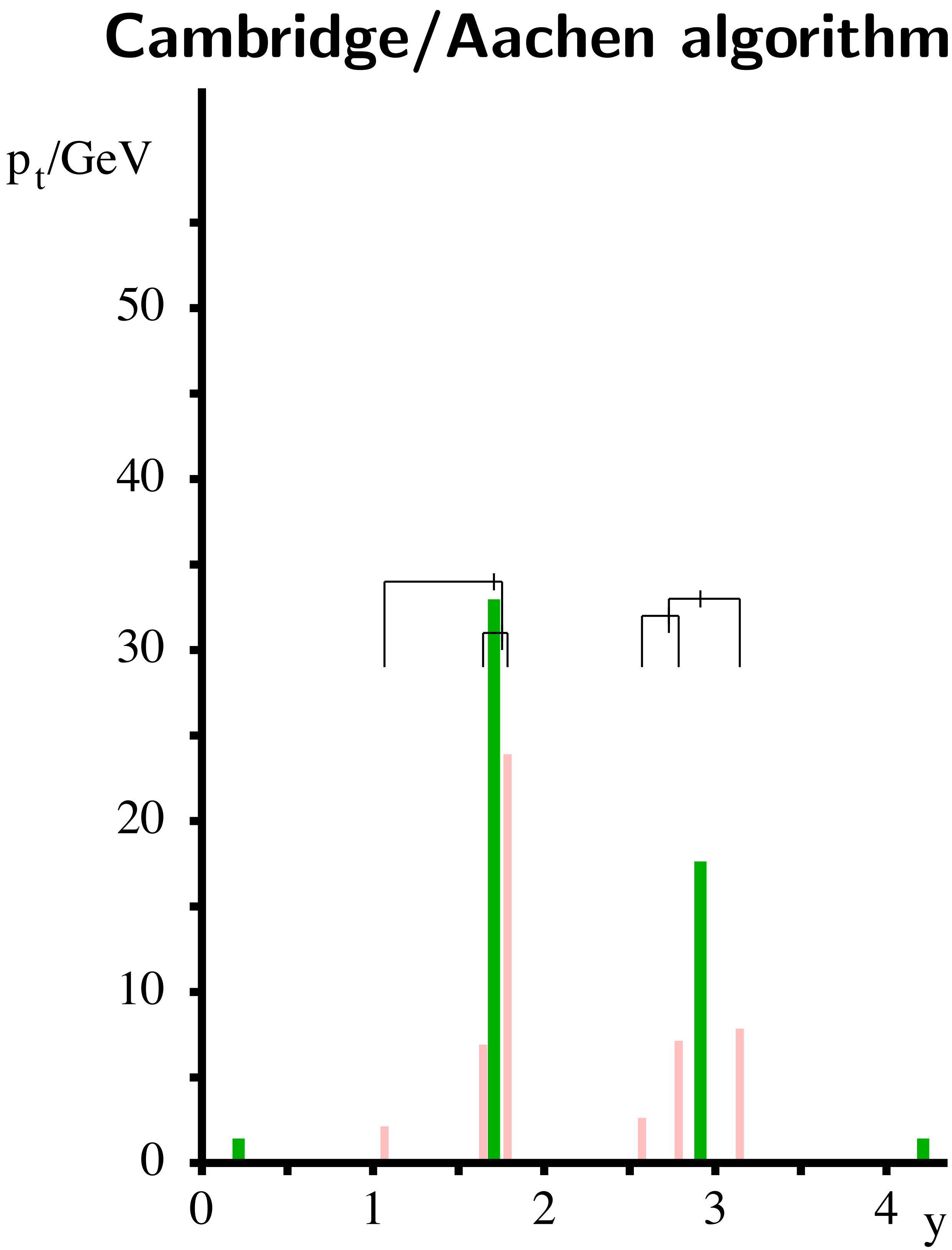
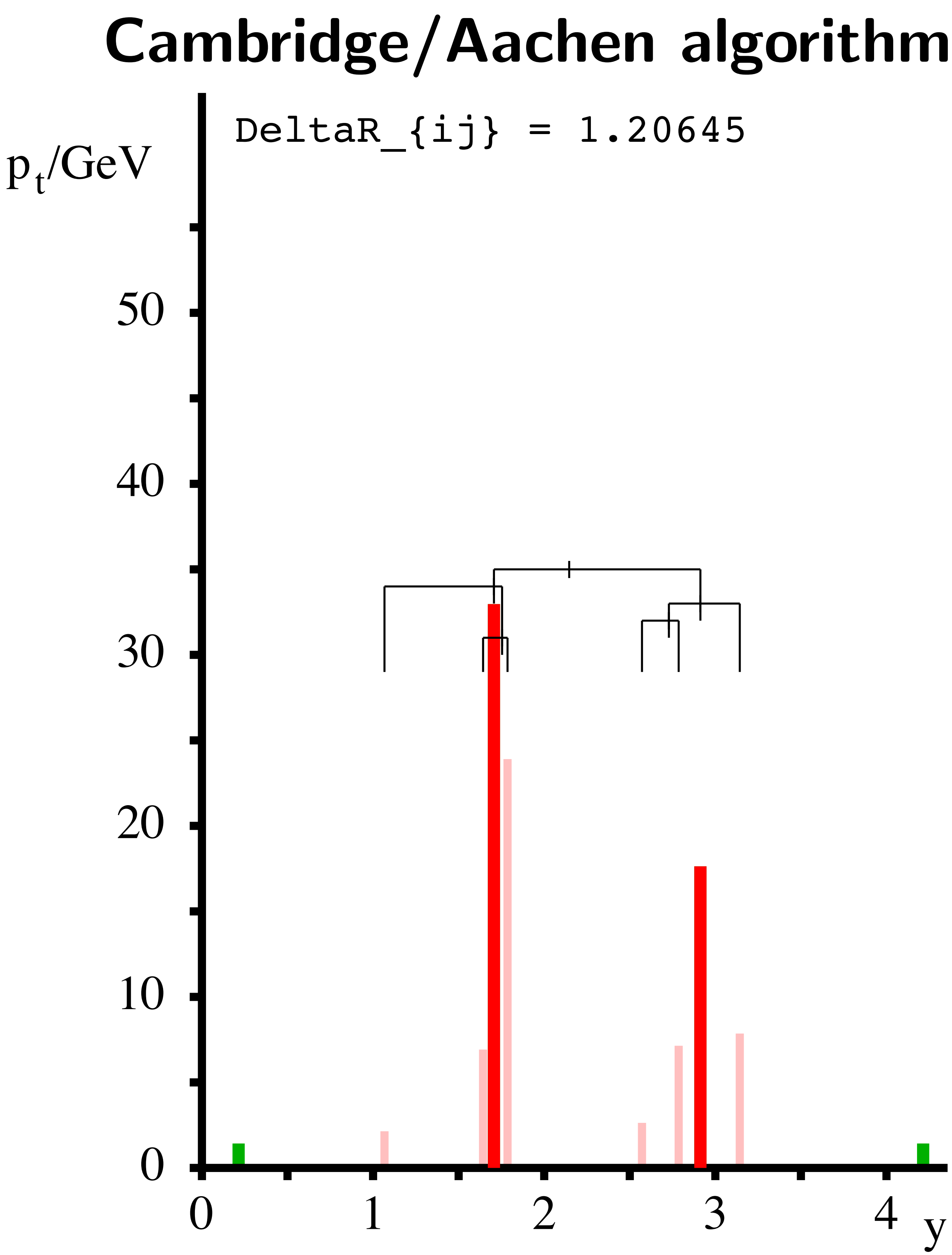


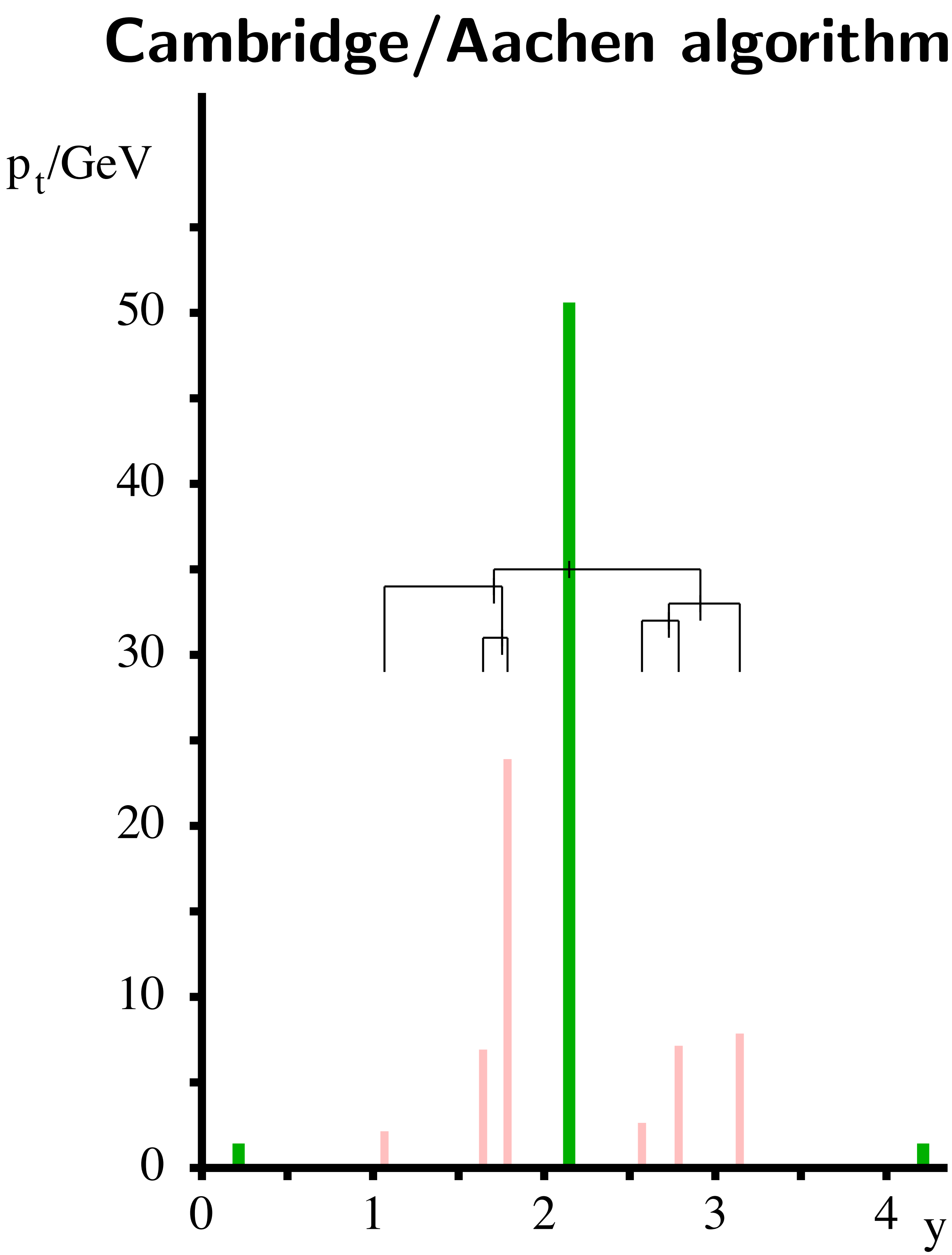
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A identifies two hard blobs with limited soft contamination



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

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



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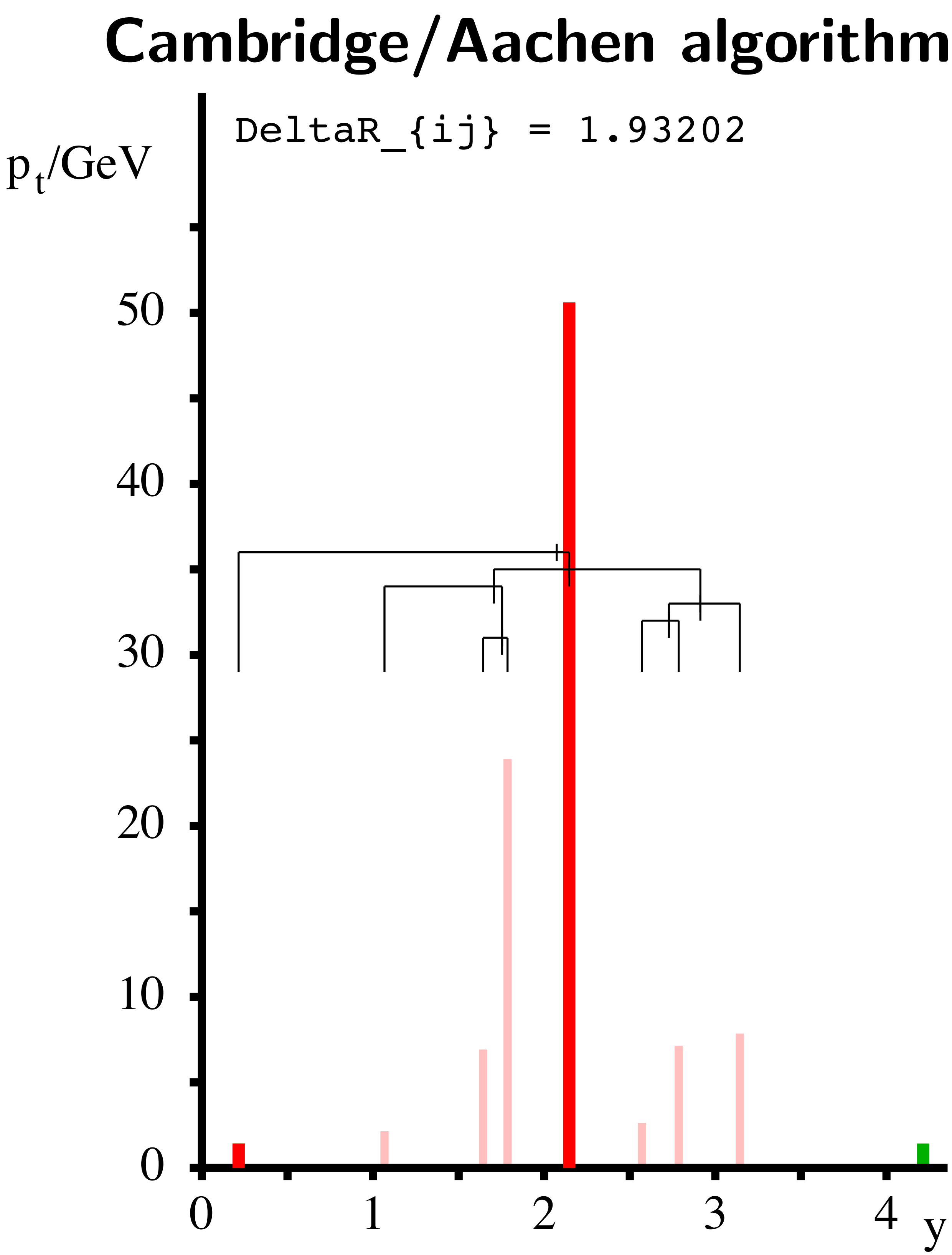
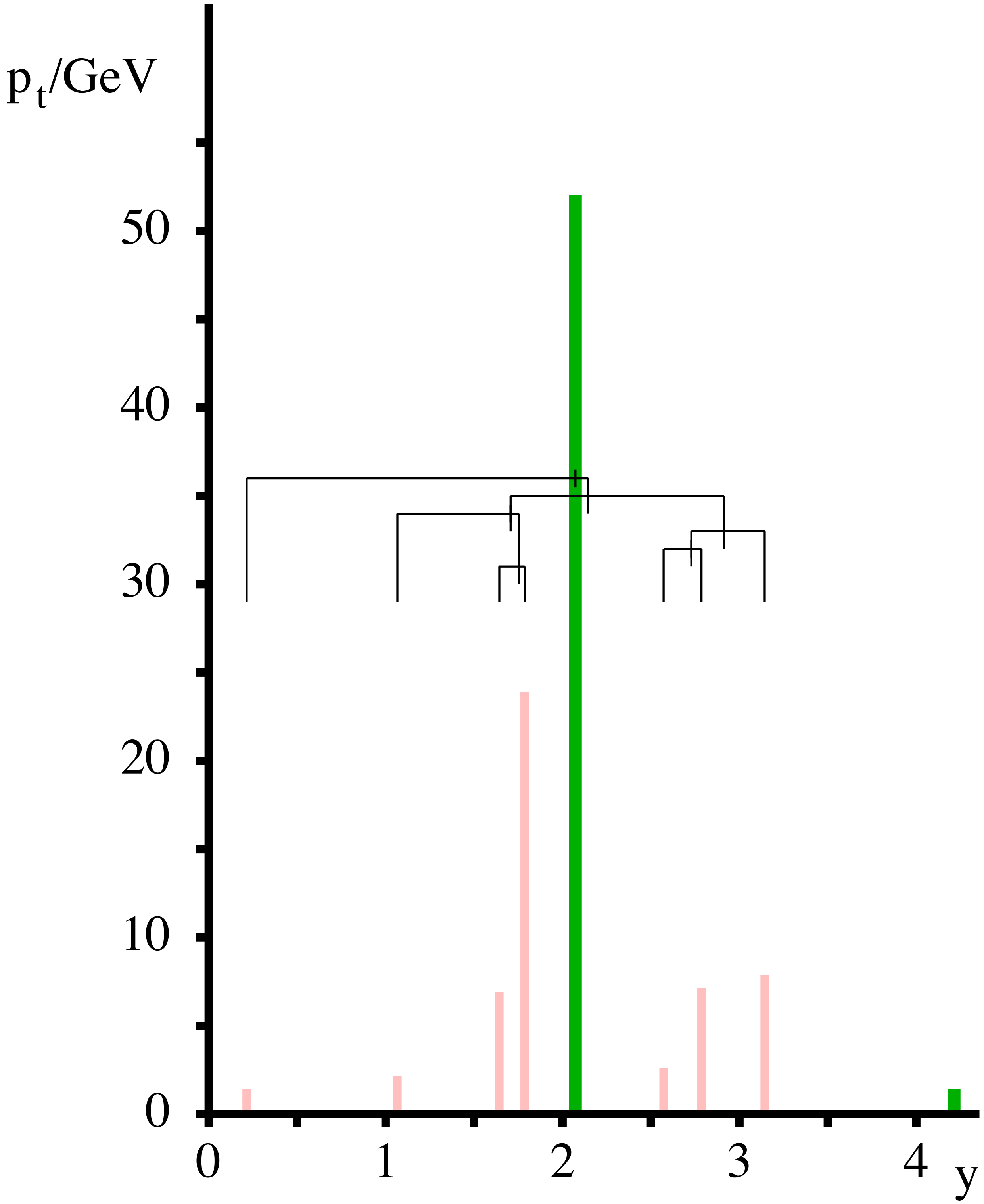


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

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

Cambridge/Aachen algorithm



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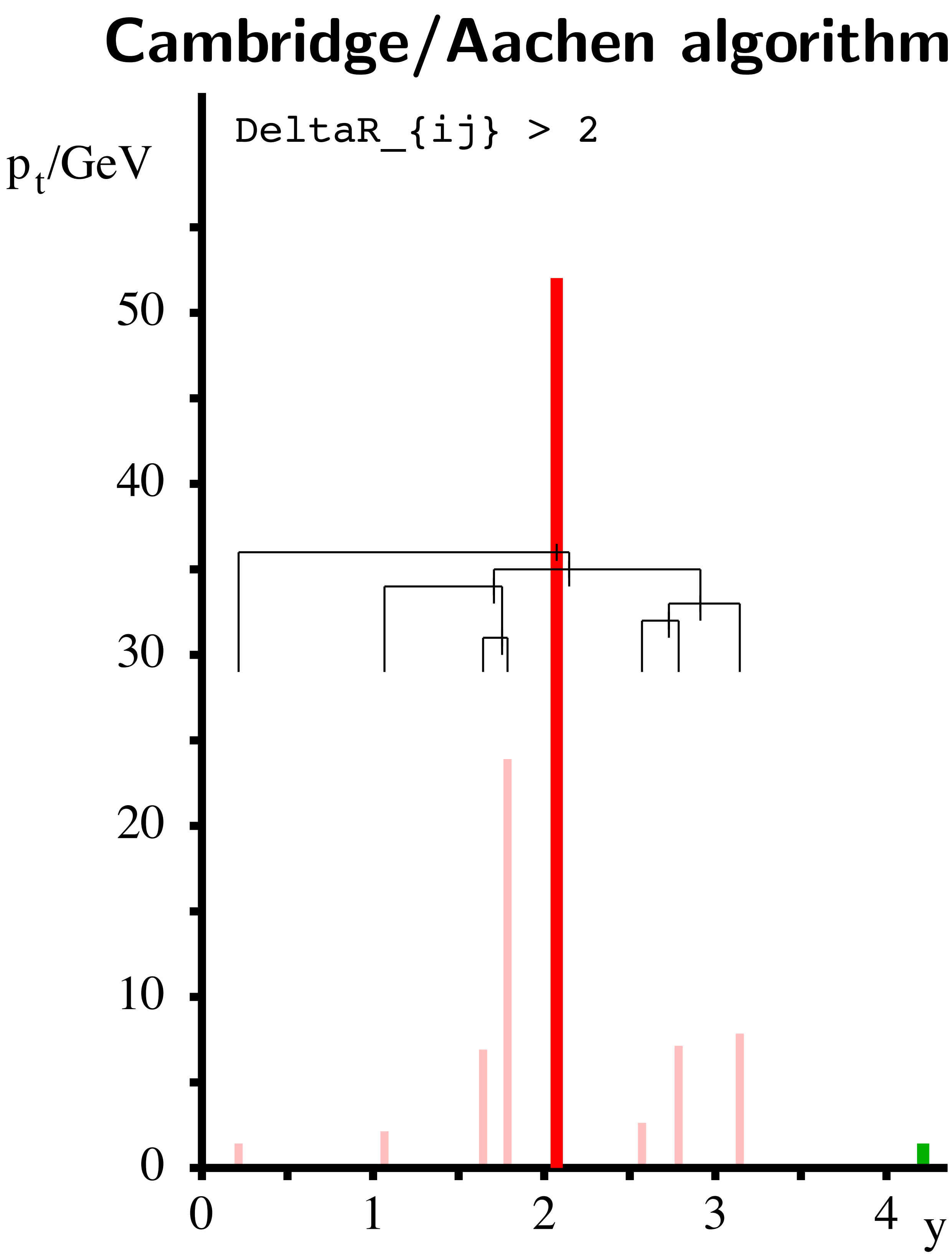

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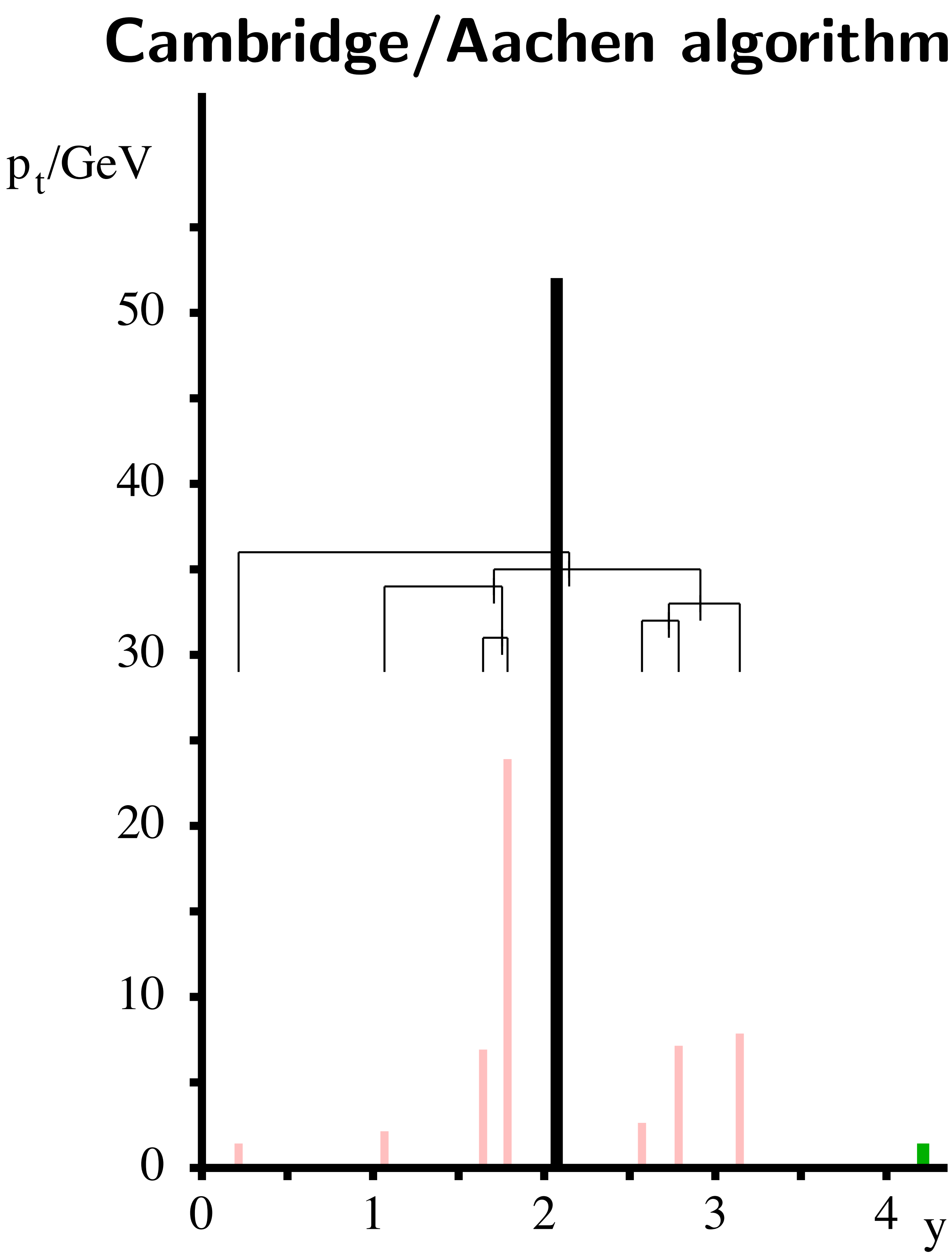

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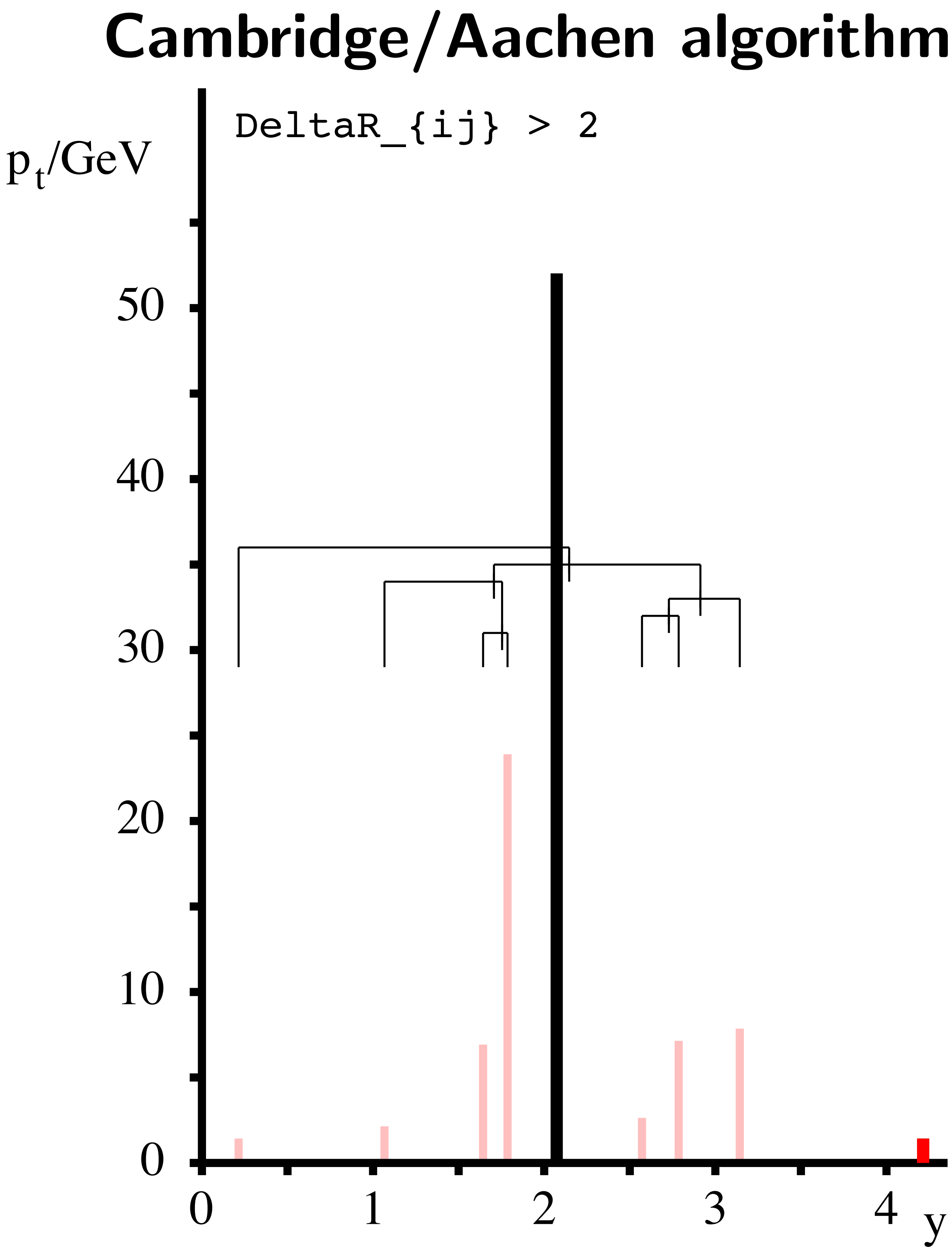

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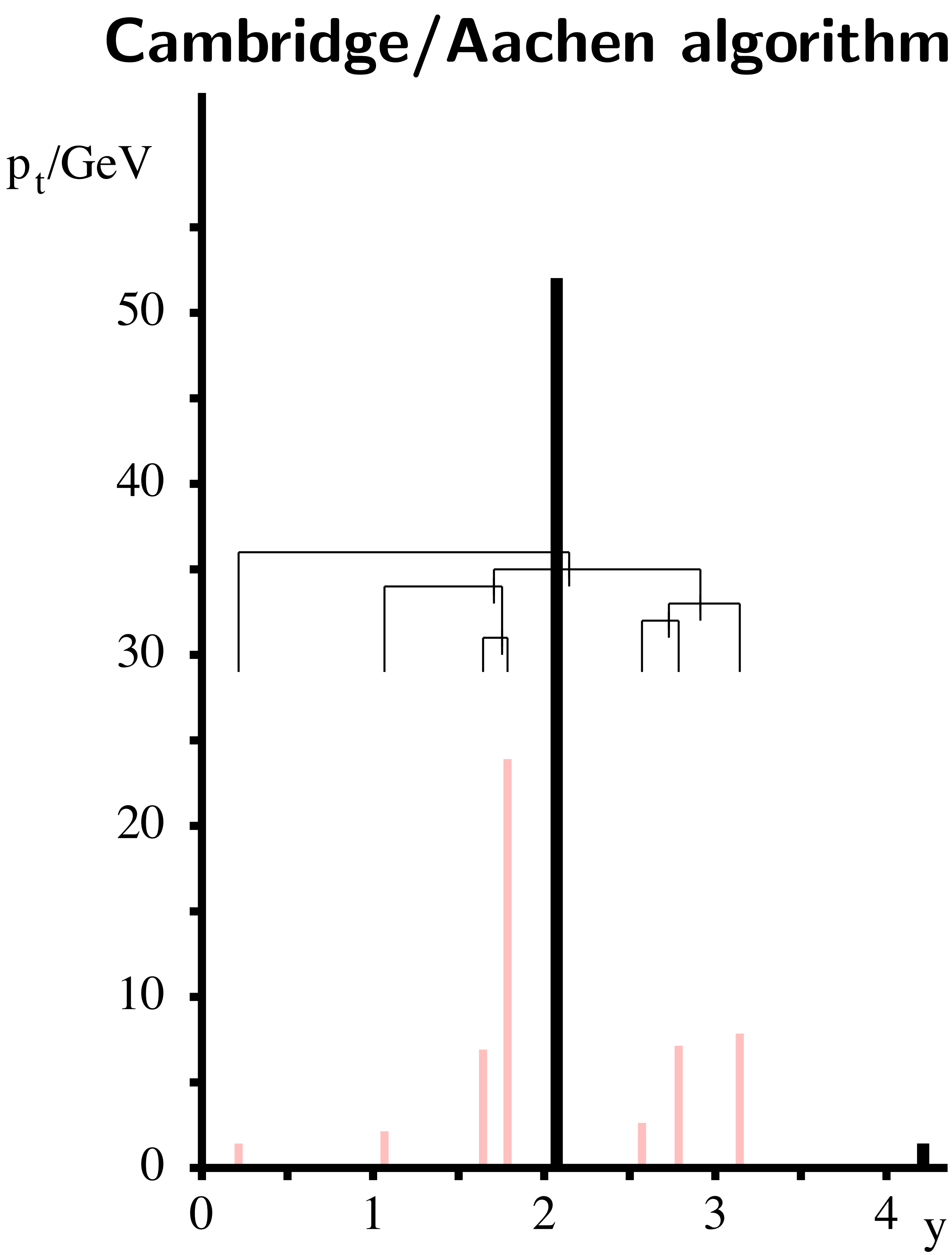


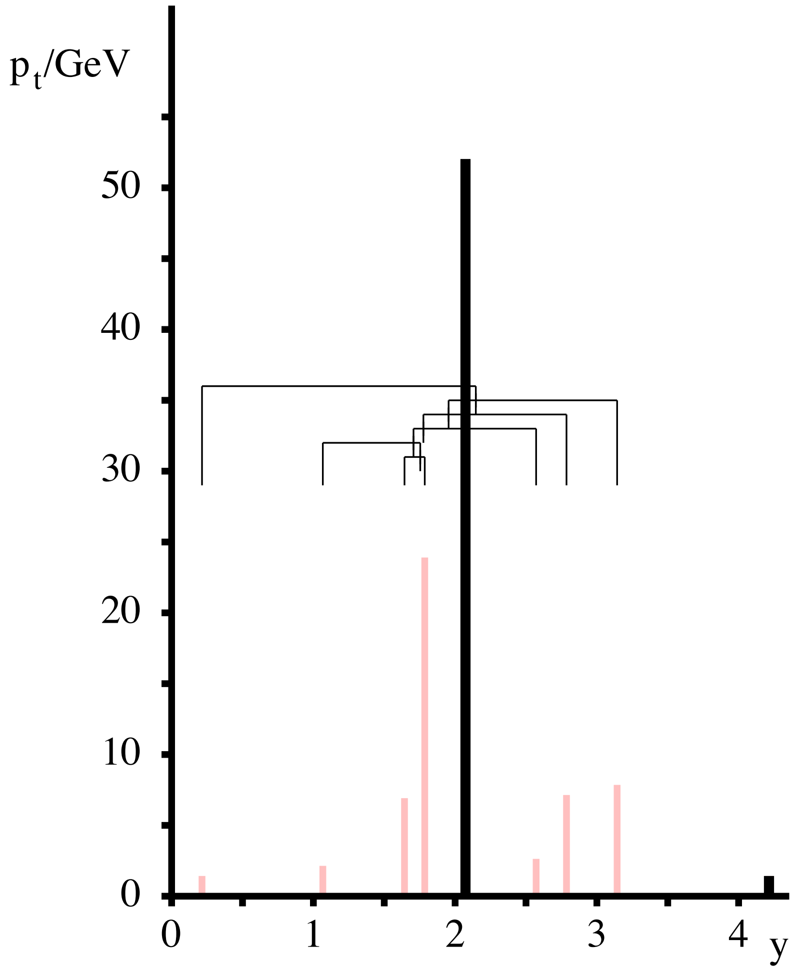
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

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

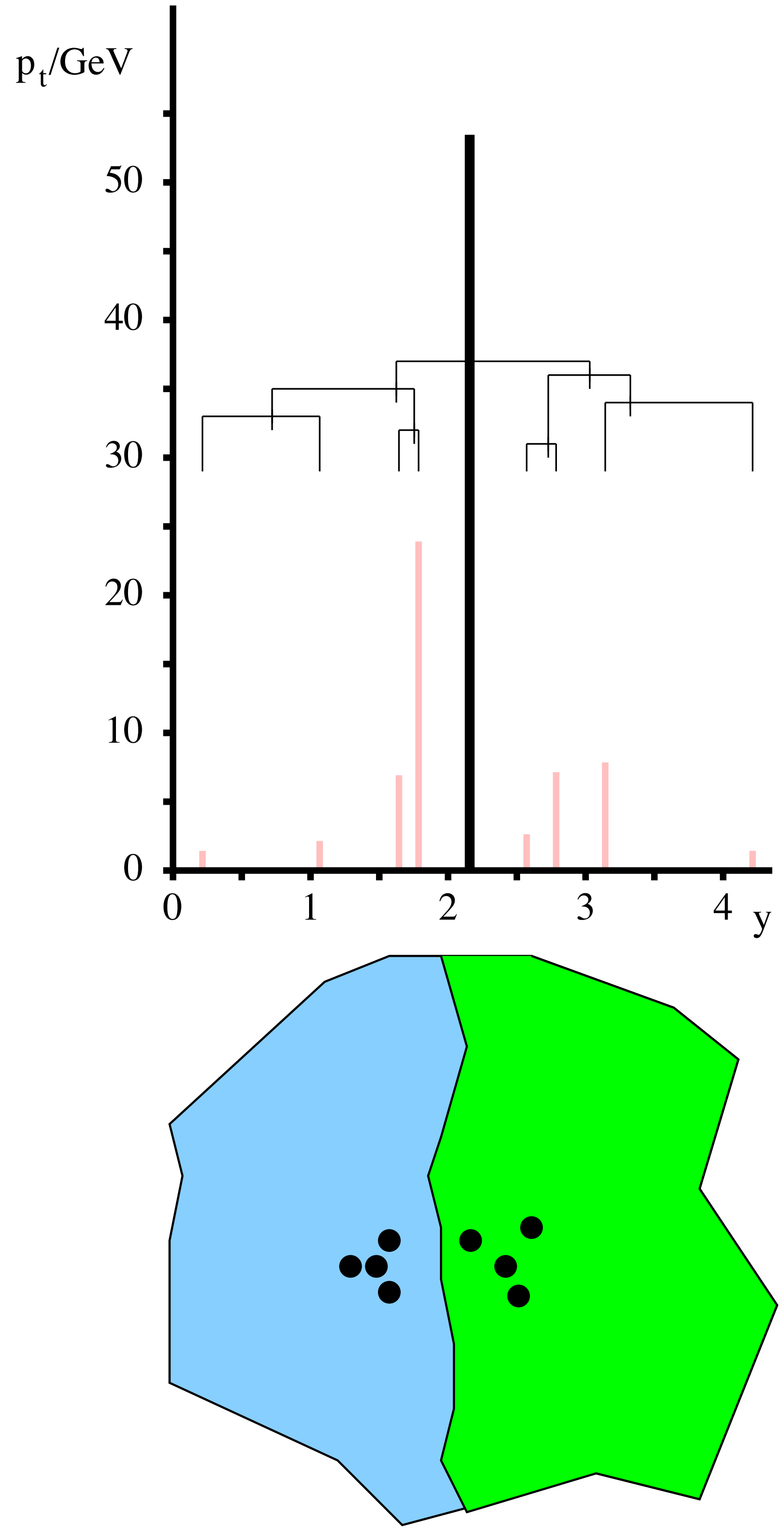
The interesting substructure is buried inside the clustering sequence — it's less contaminated by soft junk, but needs to be pulled out with special techniques

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

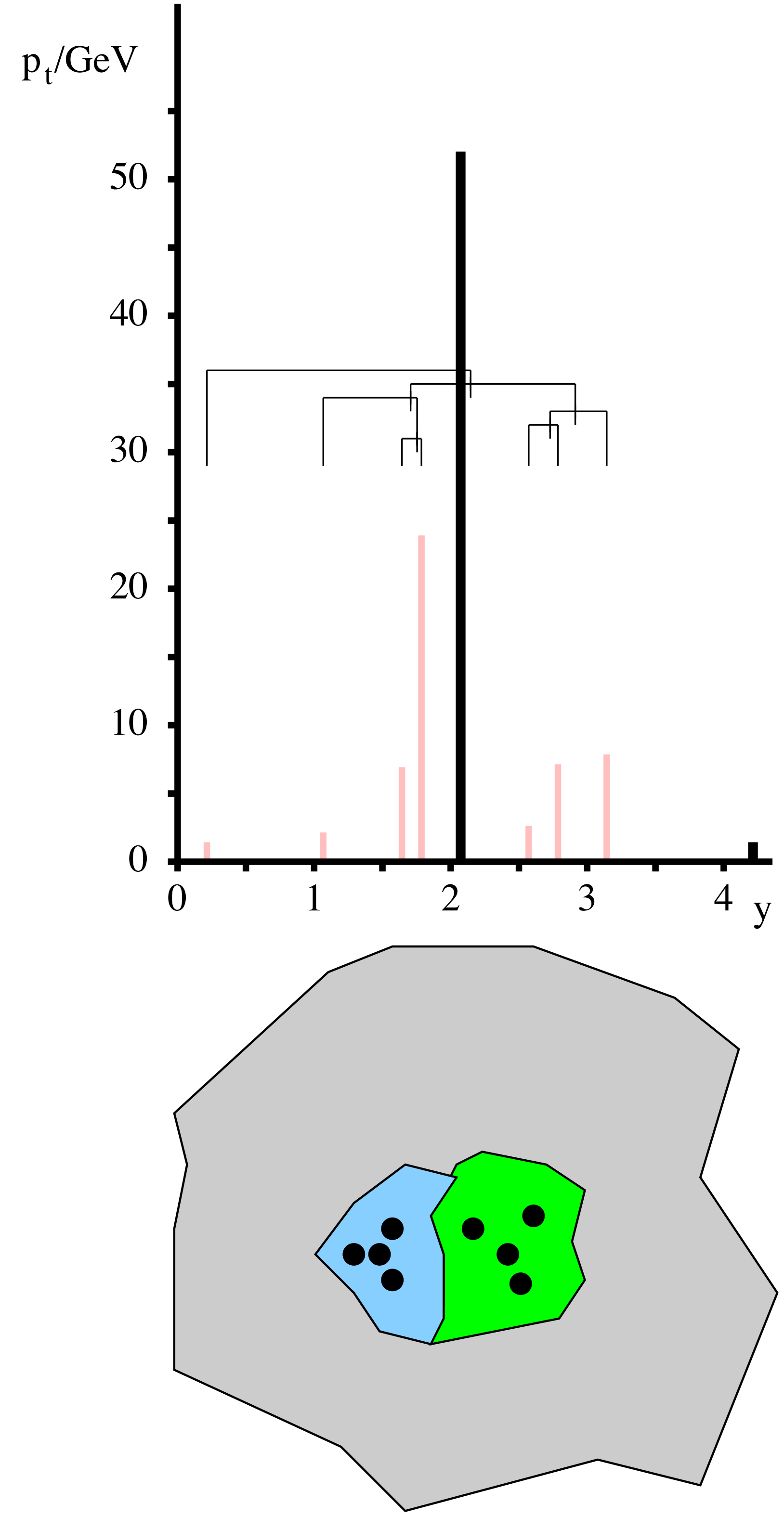
anti-k_t algorithm



k_t algorithm



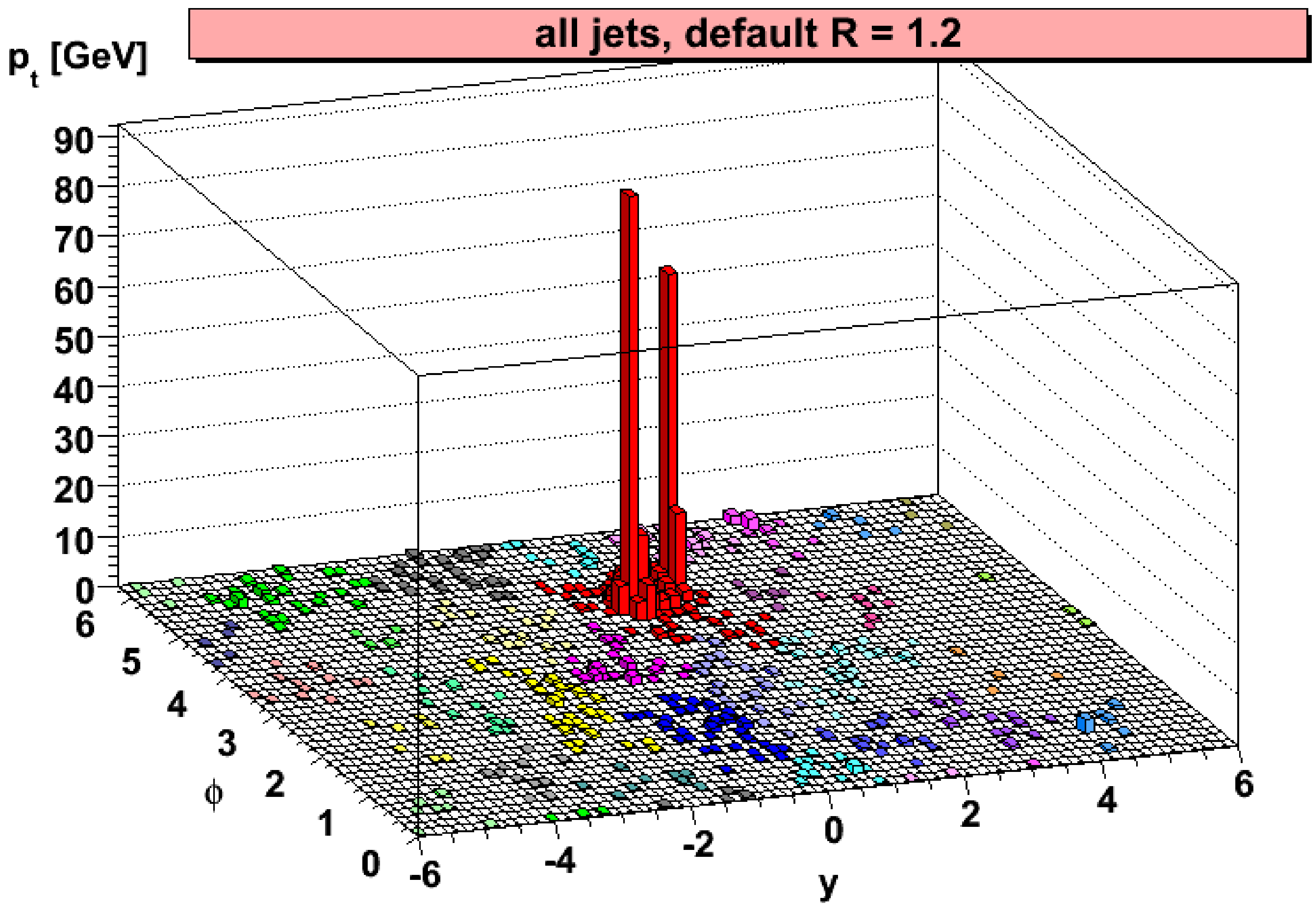
Cambridge/Aachen



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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

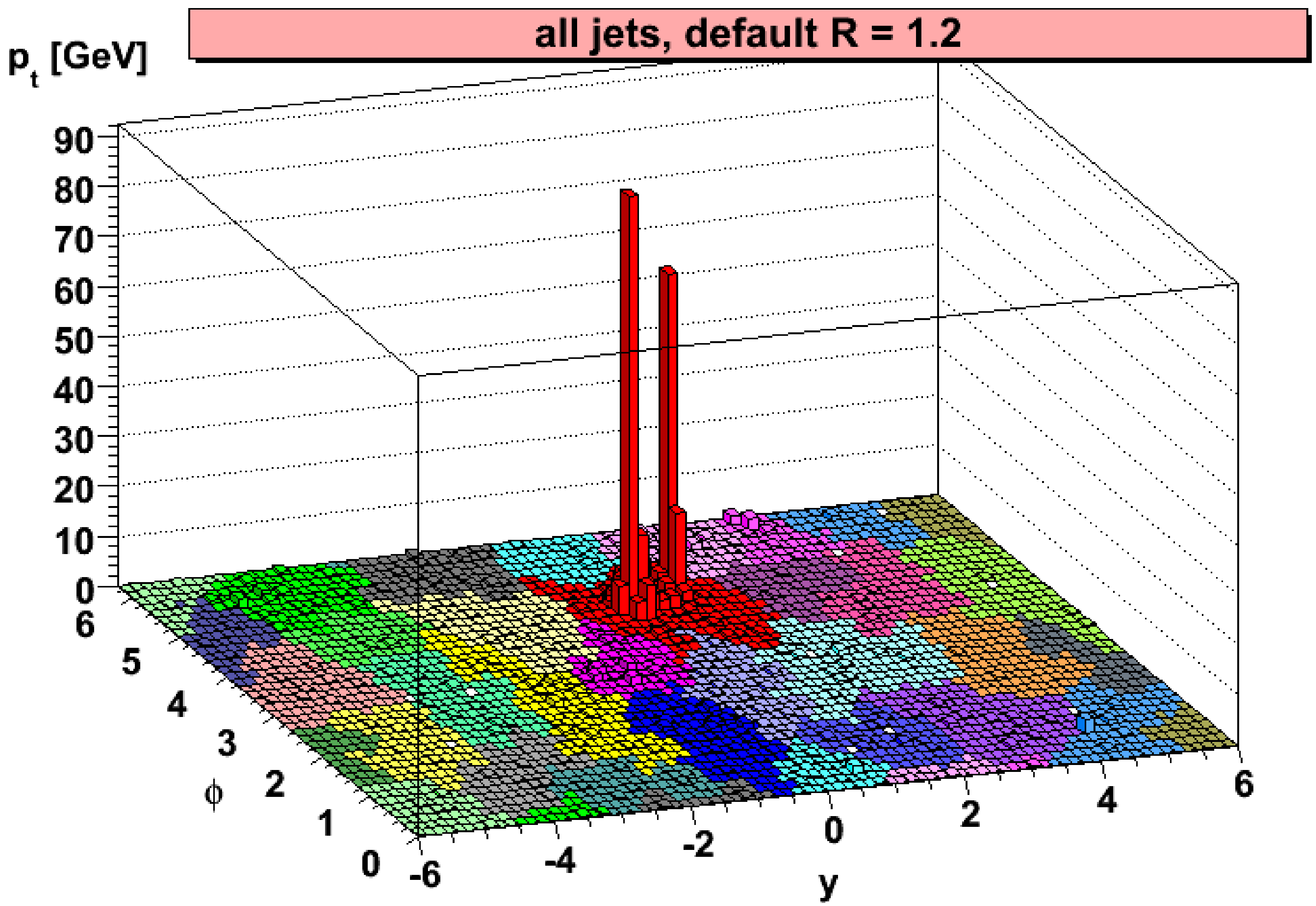
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

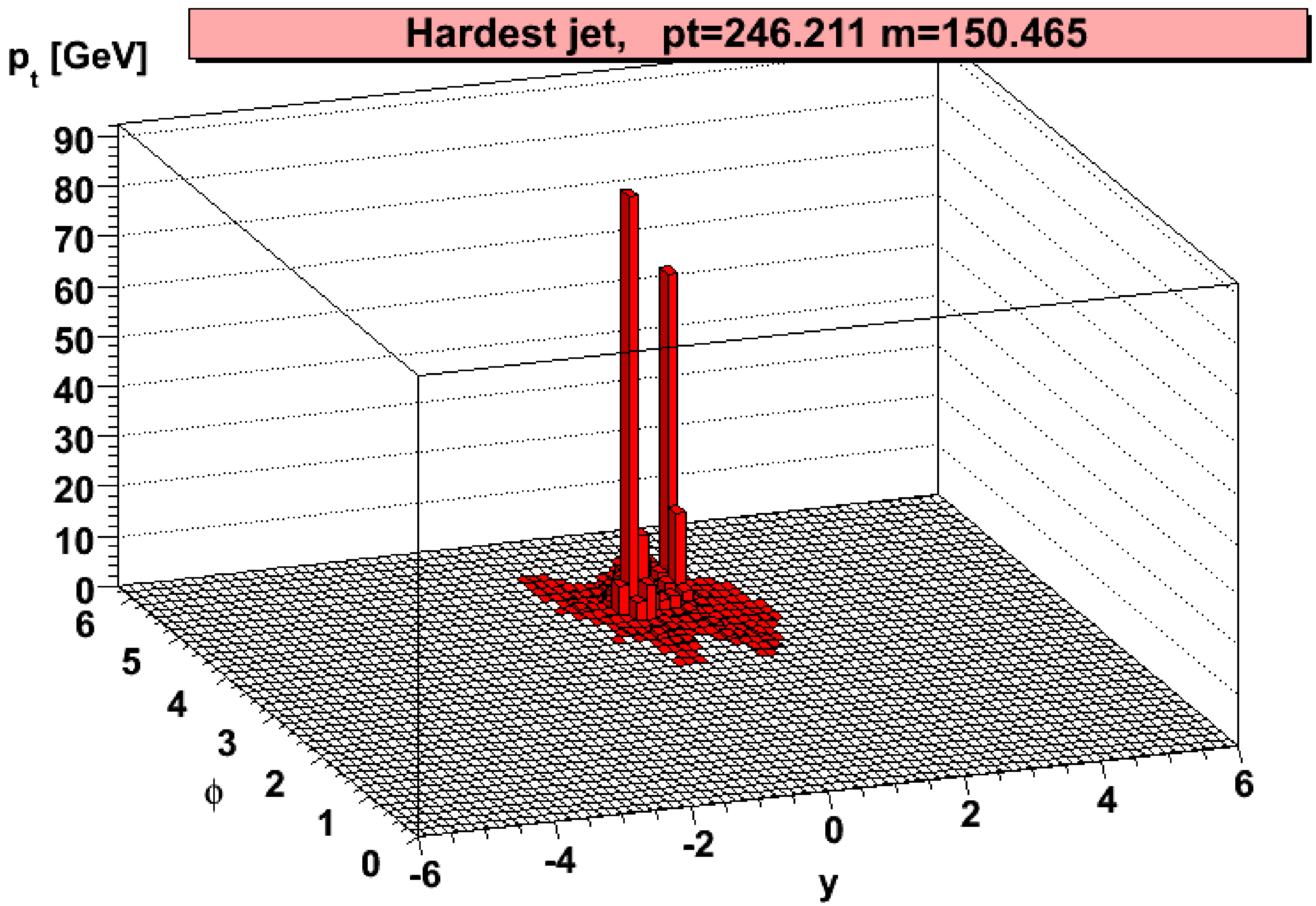
Fill it in, $\to$ show jets more clearly

Butterworth, Davison, Rubin & GPS '08

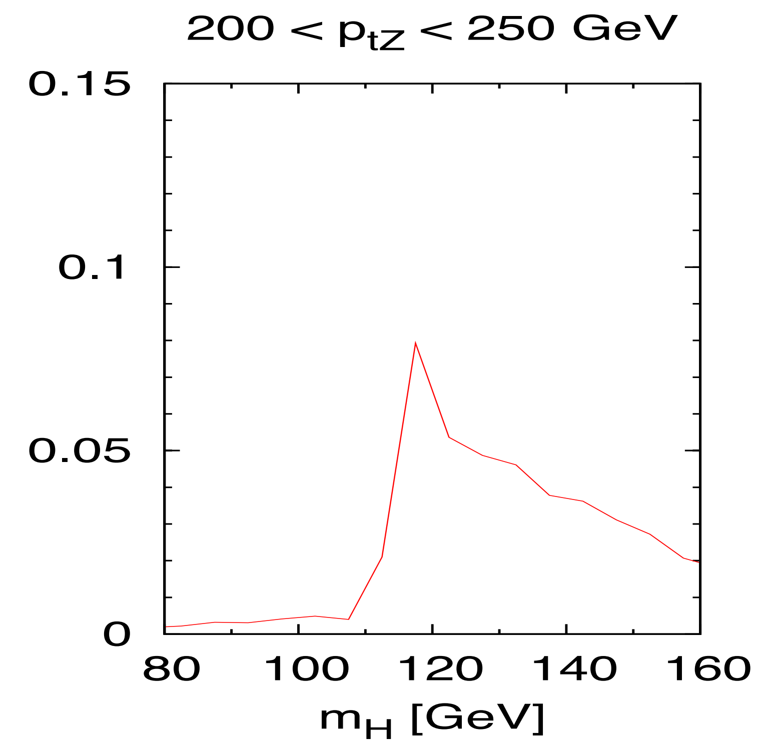
arbitrary norm.

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

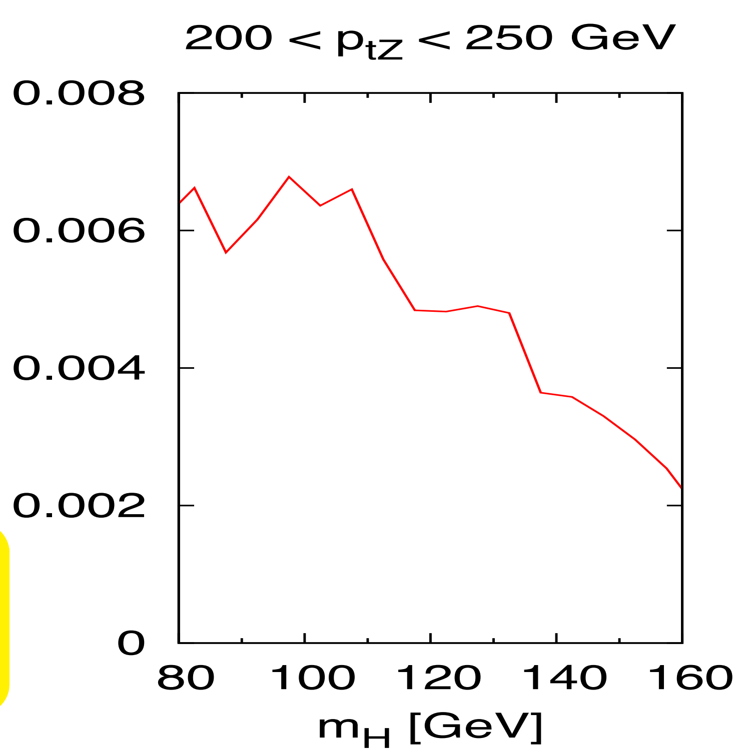
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



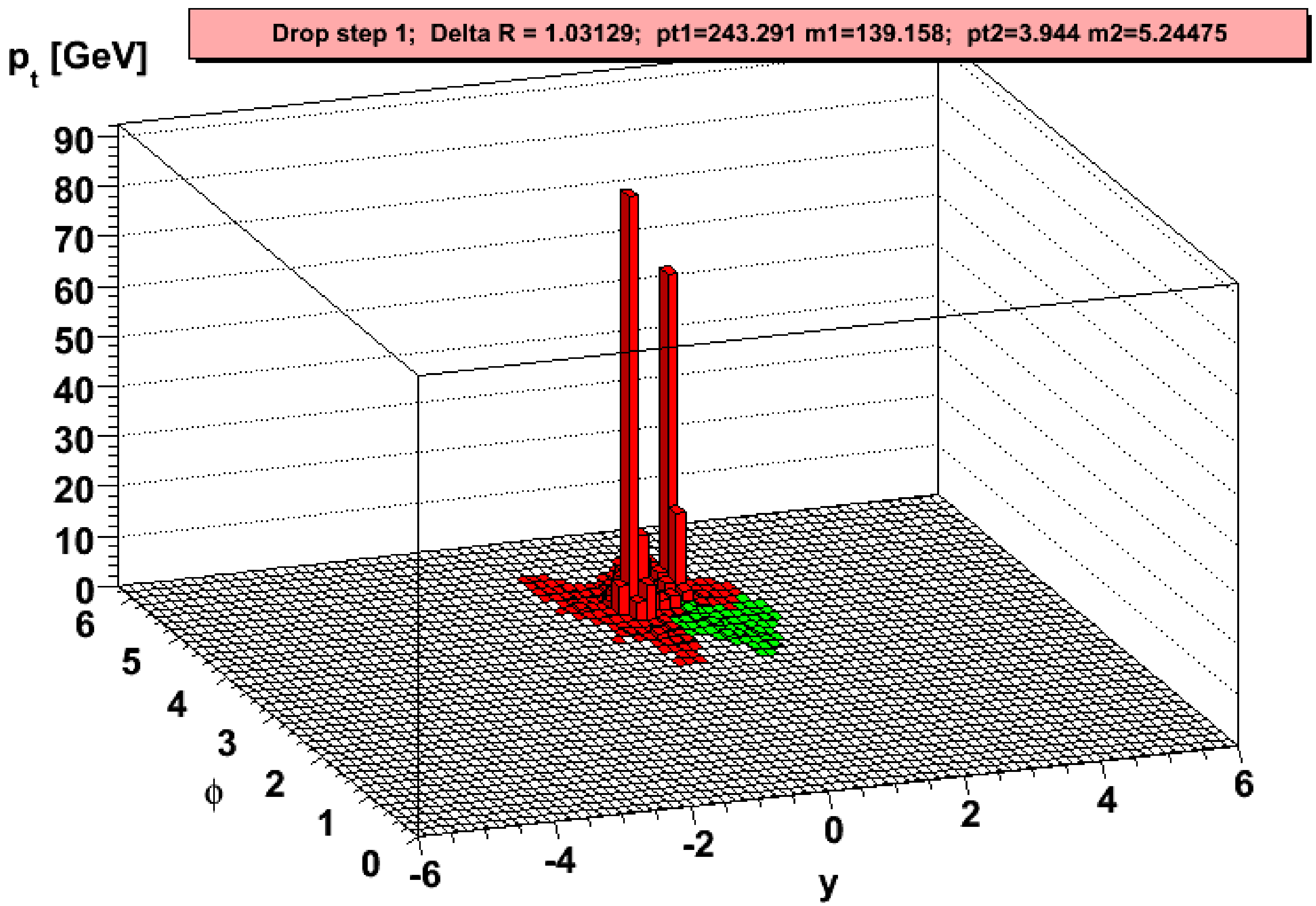
Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

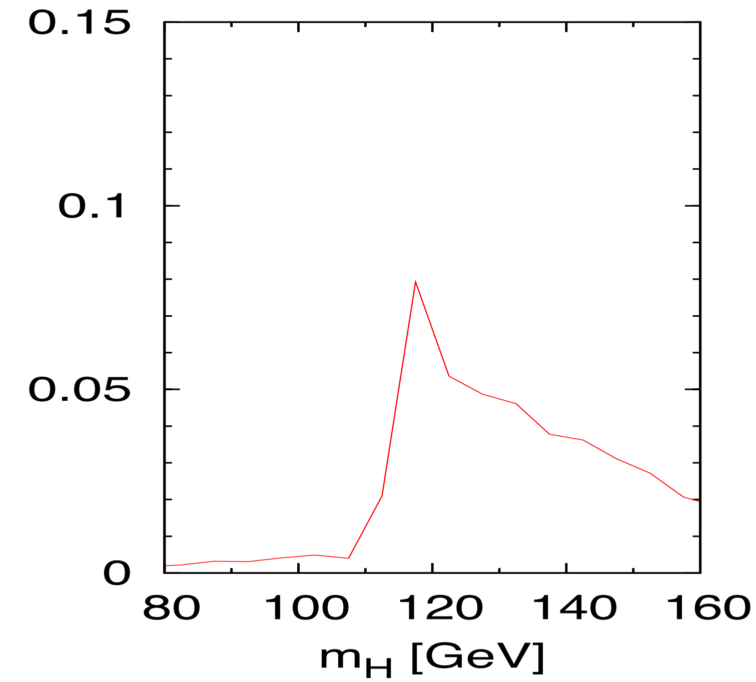
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



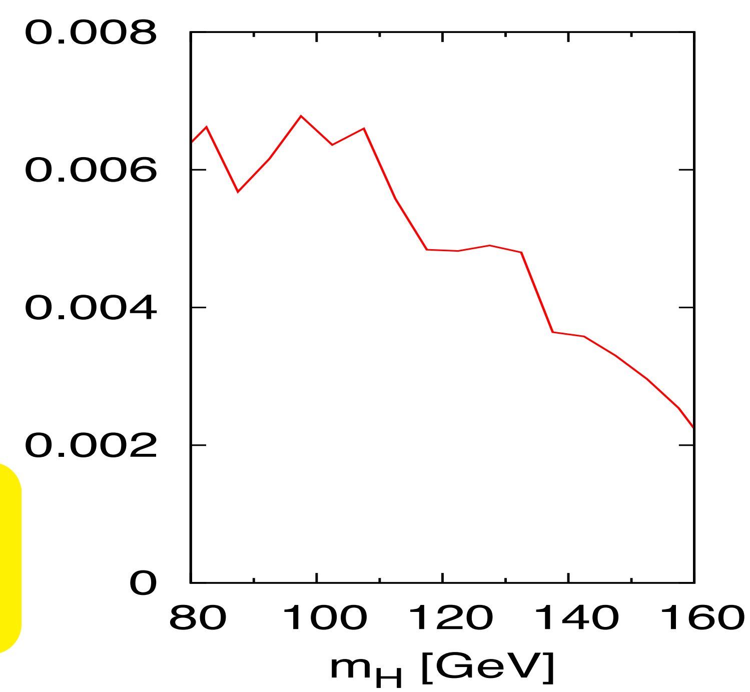
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



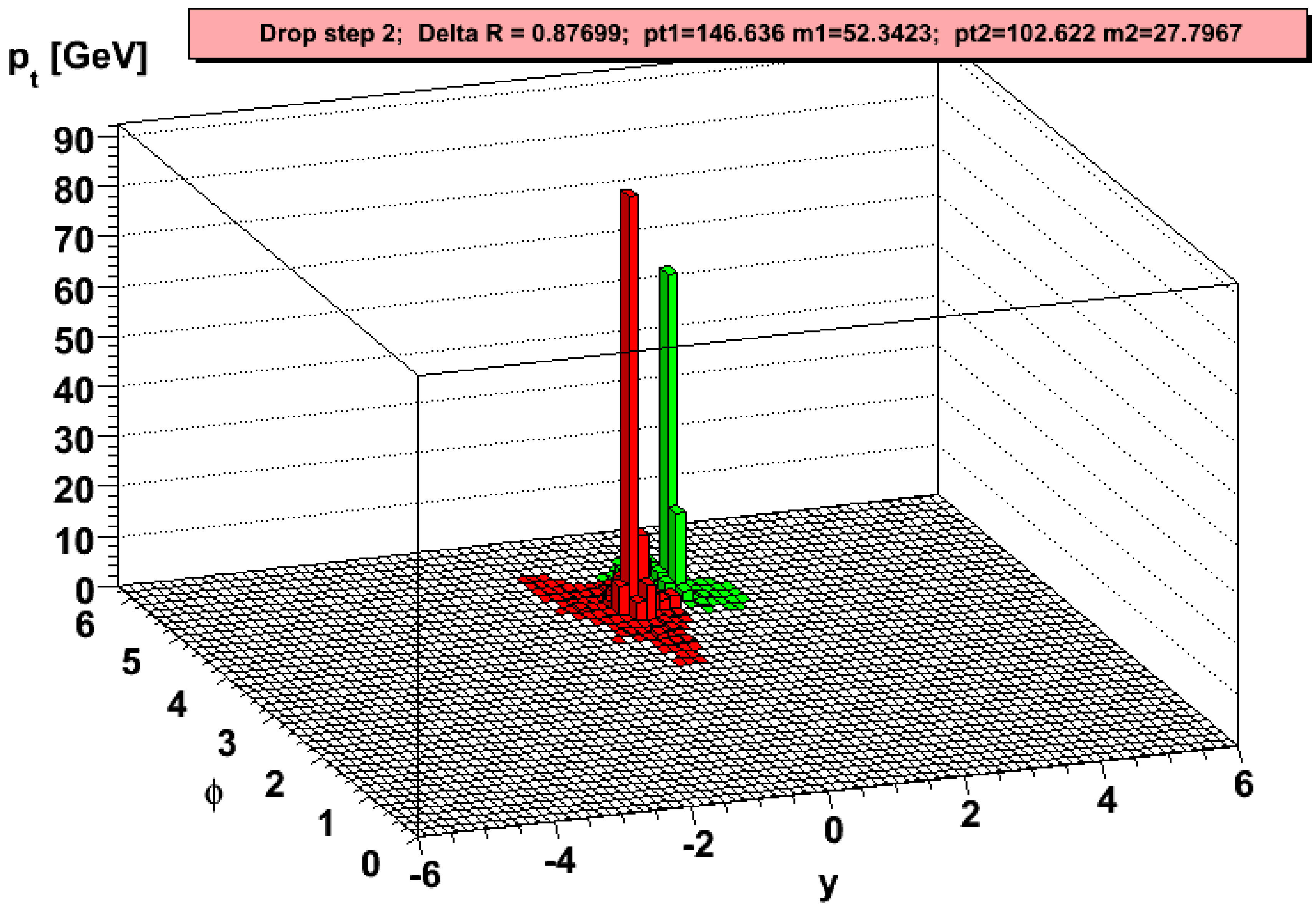
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

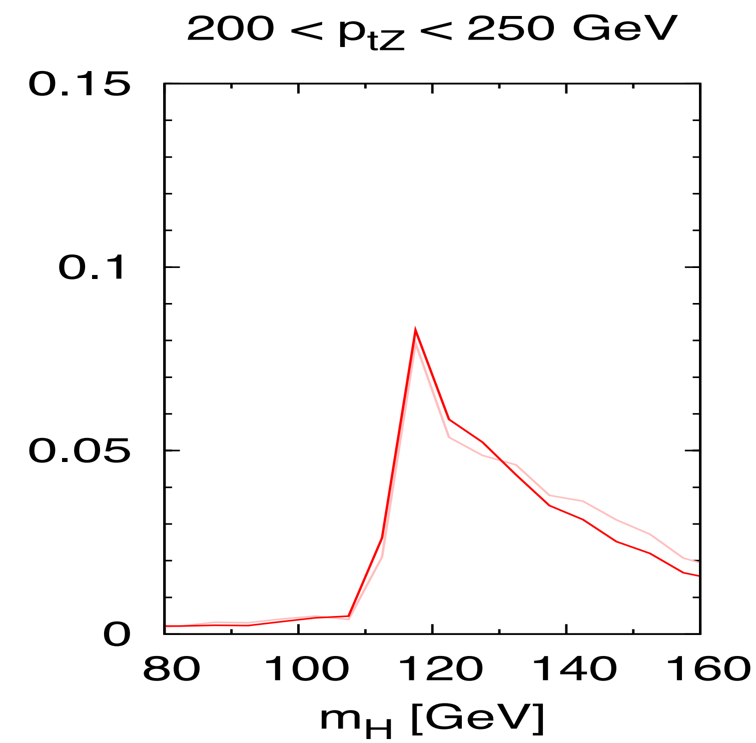
arbitrary norm.

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

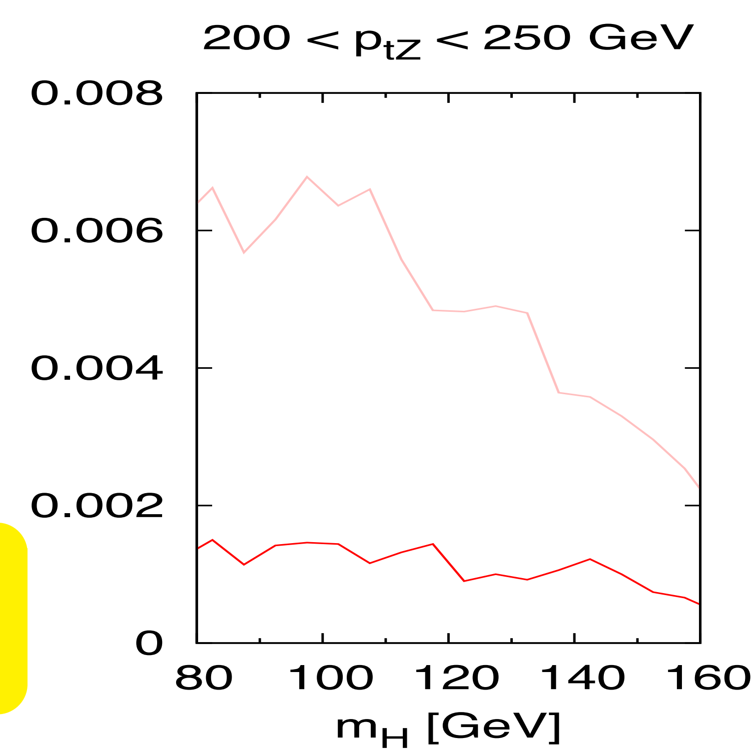
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



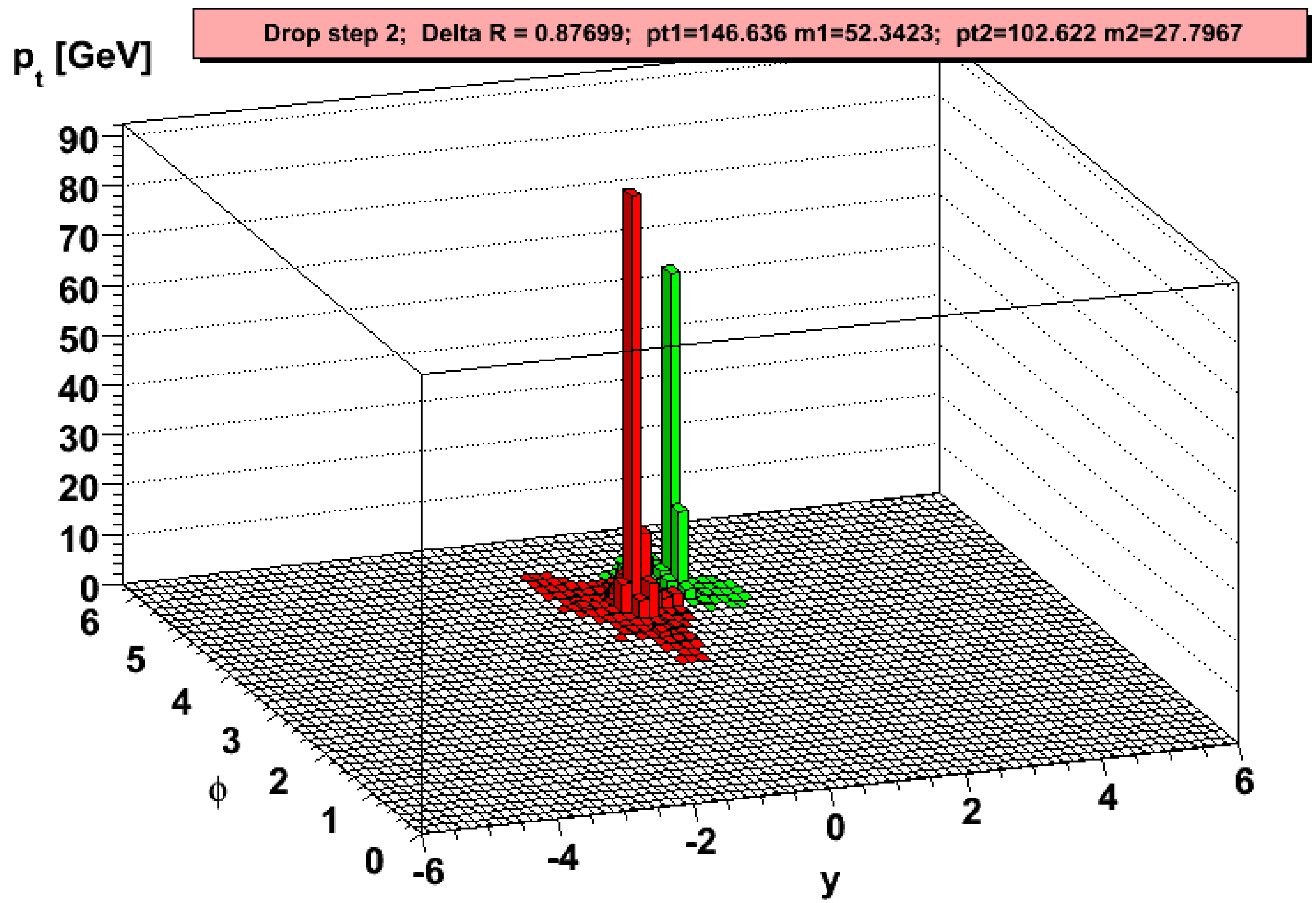
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

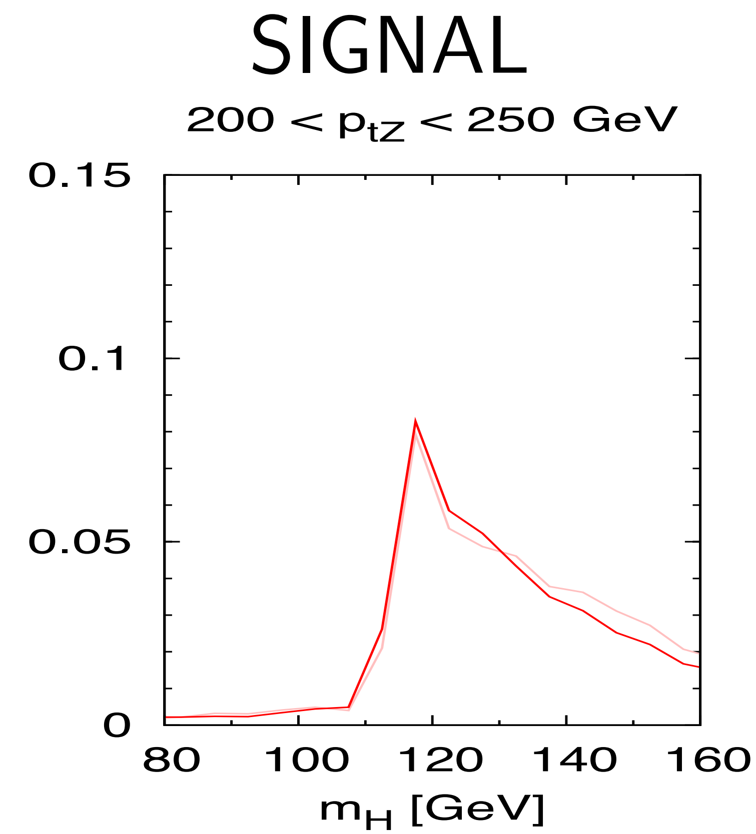
Butterworth, Davison, Rubin & GPS '08

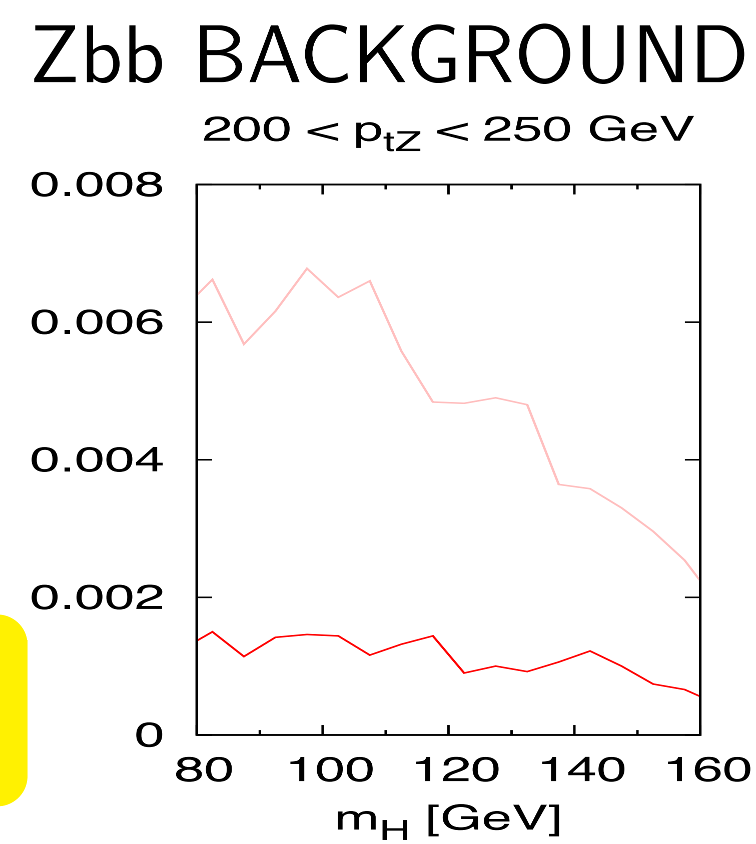
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







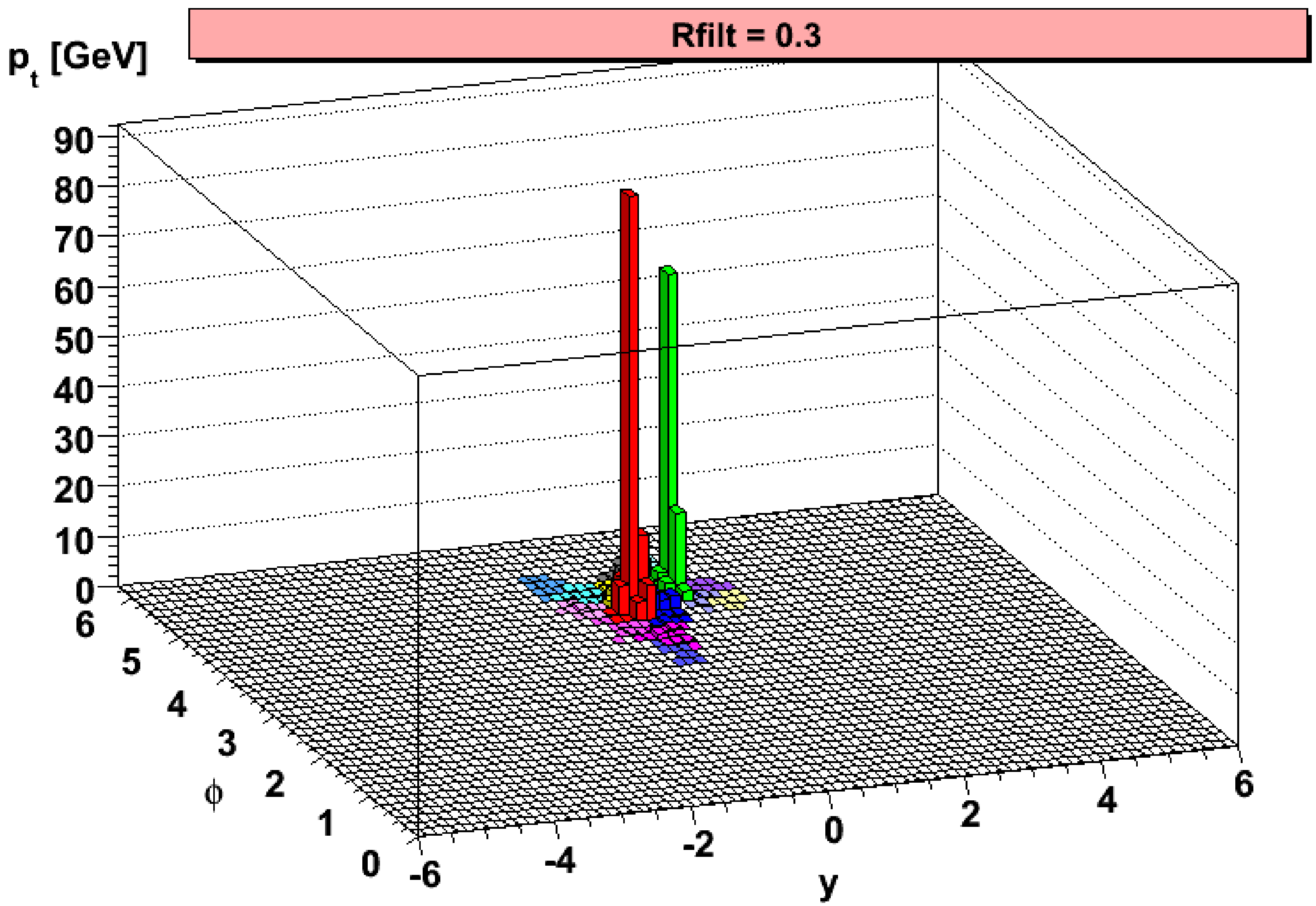
check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

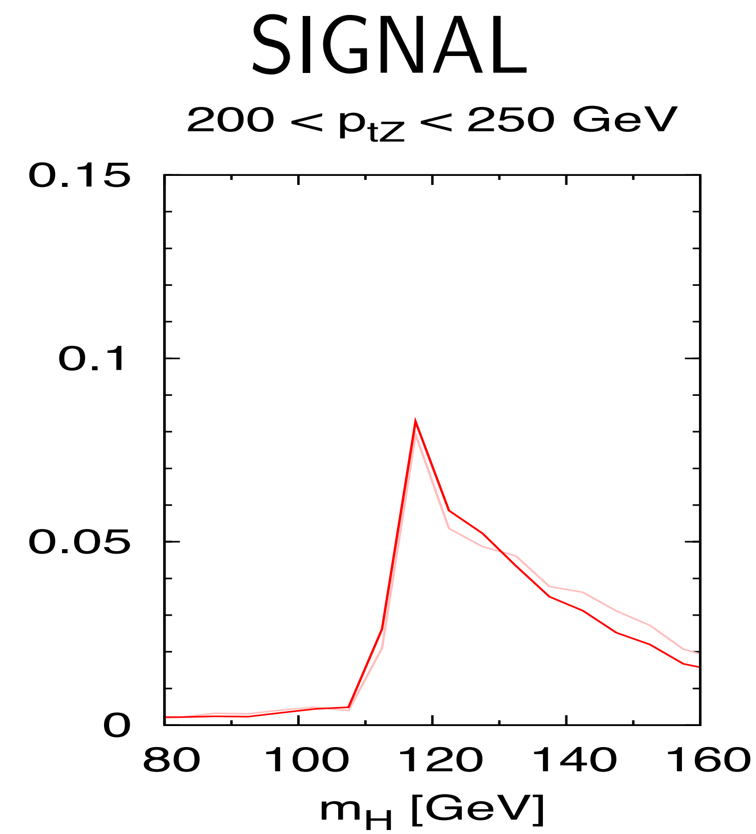
Butterworth, Davison, Rubin & GPS '08

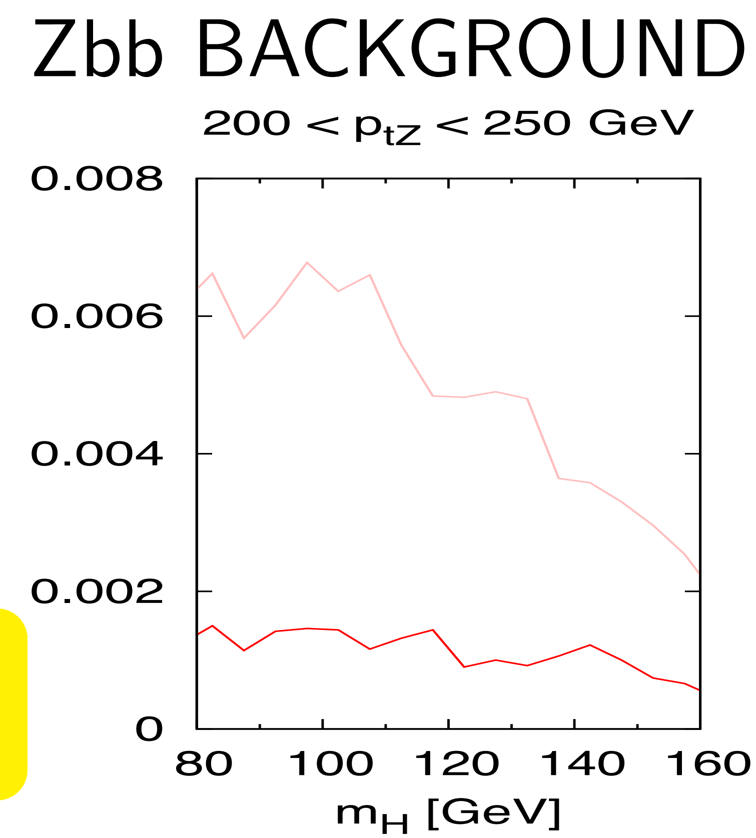
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







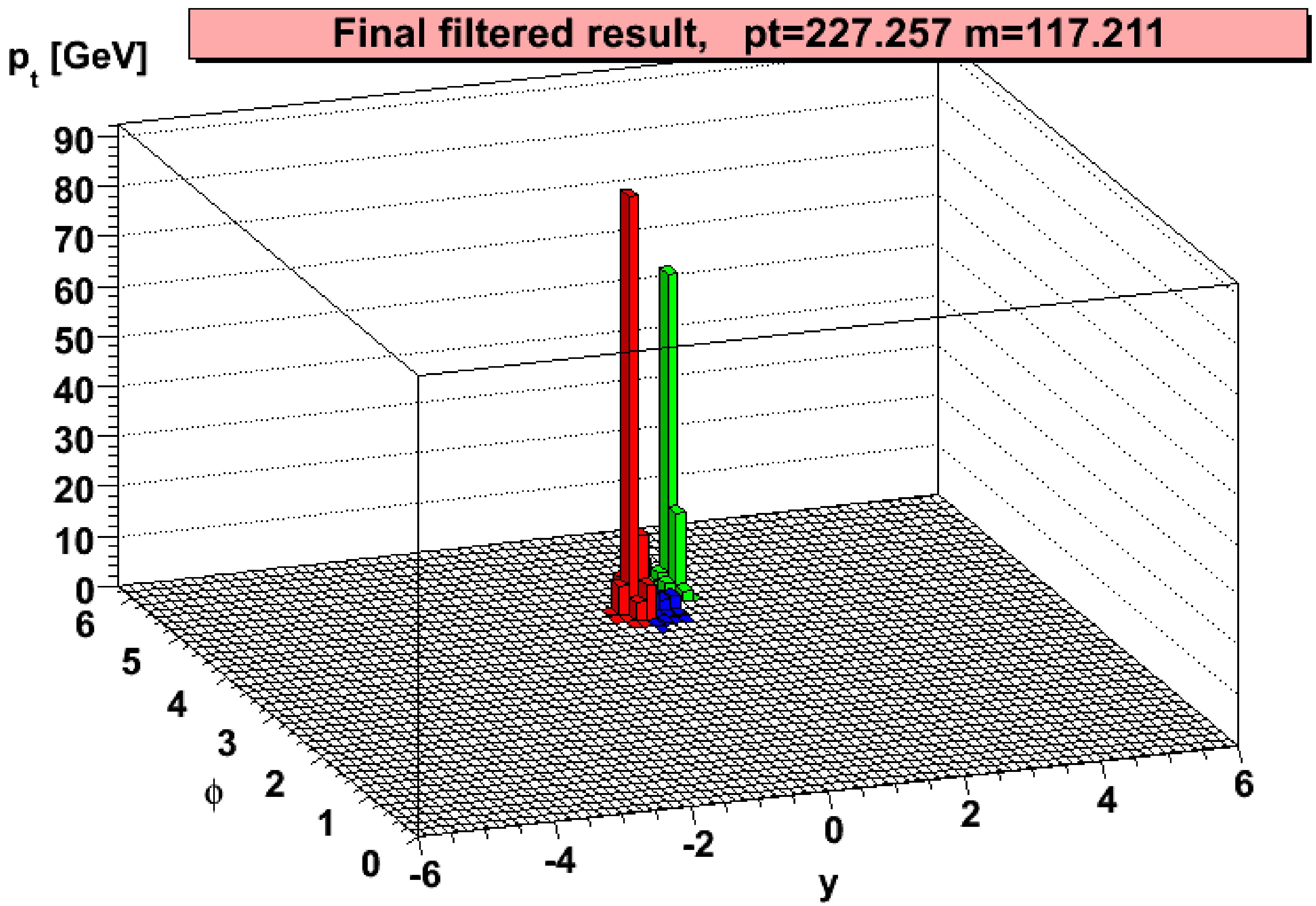
$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

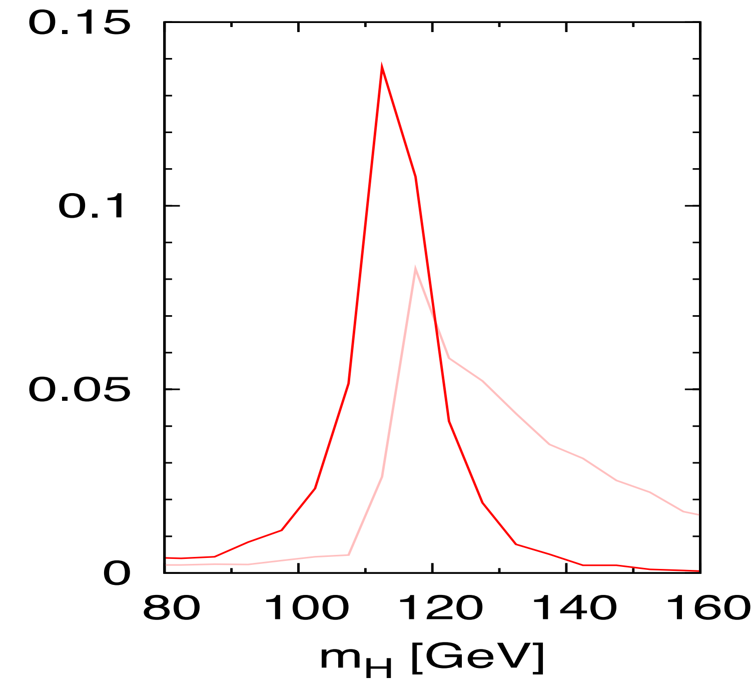
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



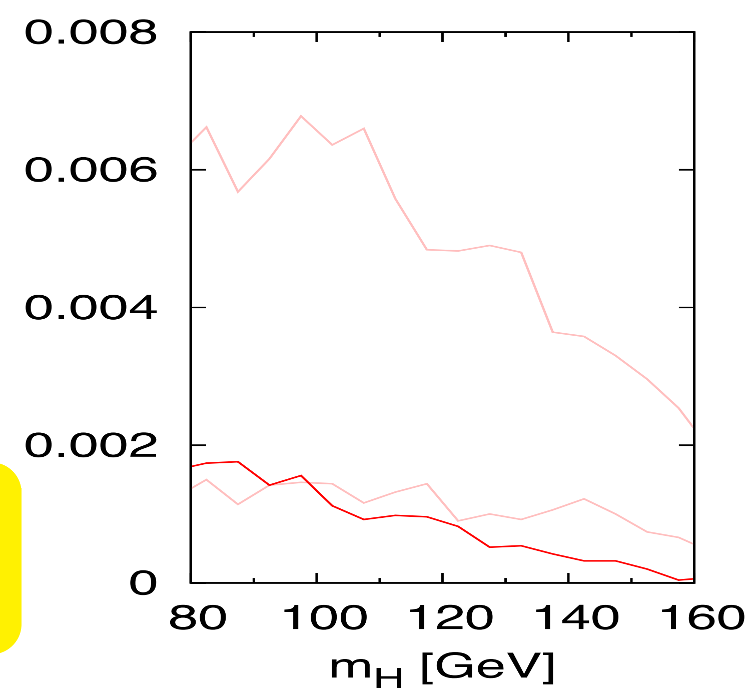
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



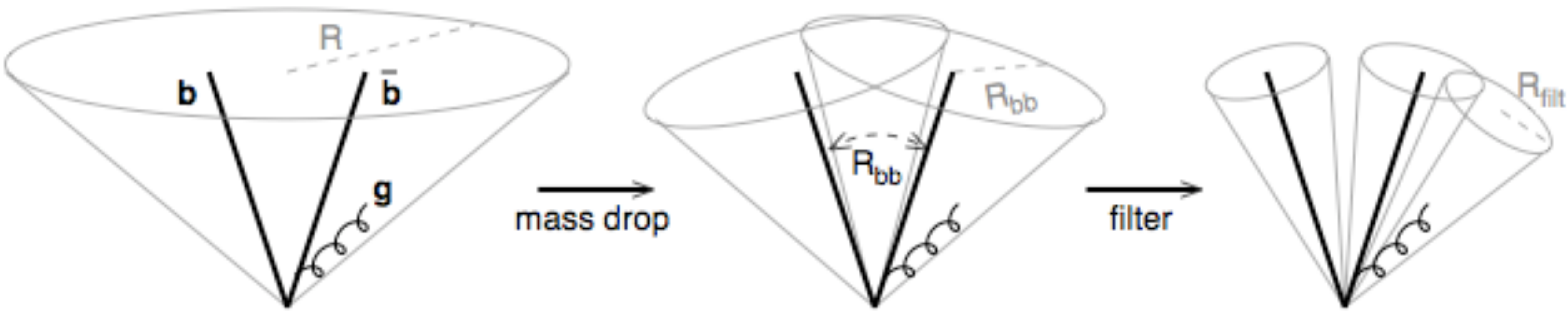
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

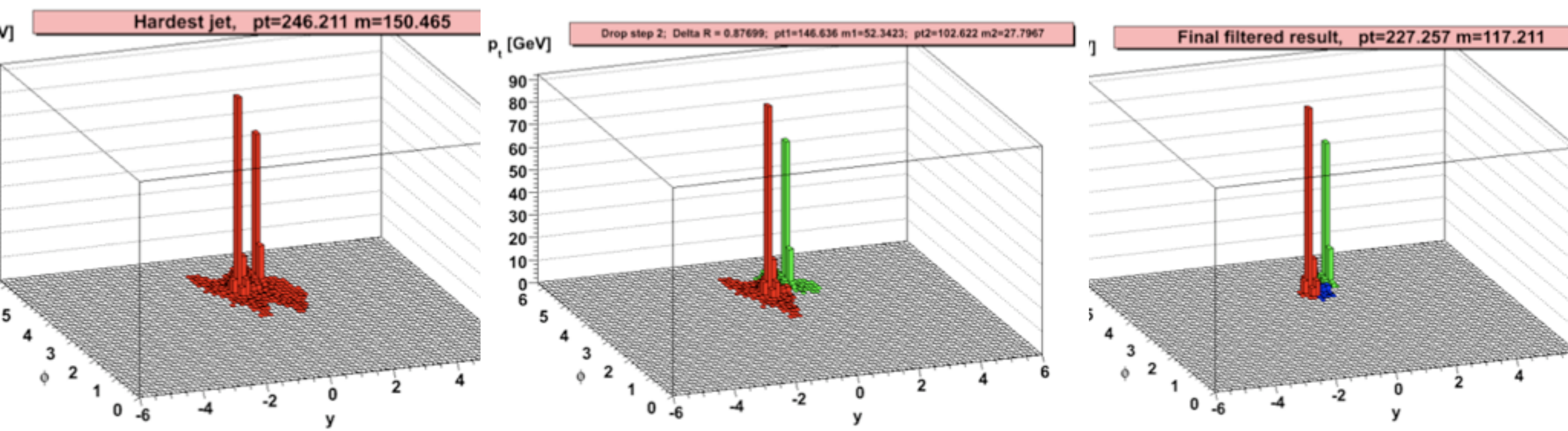
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

Boosted Higgs analysis

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





Cluster with a large R

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

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

Mass-Drop Tagger + Filtering in FastJet

```
#include “fastjet/tools/MassDropTagger.hh”
#include “fastjet/tools/Filter.hh”

JetDefinition jet_def(cambridge_algorithm, 1.2);
ClusterSequence cs(input_particles, jet_def);
jets = sorted_by_pt(cs.inclusive_jets());

// define the tagger and use it
double mu = 0.667, ycut = 0.09;
MassDropTagger md_tagger(mu, ycut);
PseudoJet tagged = md_tagger(jets[0]);
// check it was tagged OK by verifying (tagged != 0)

// define the filter and use it
Filter filter(0.3,SelectorNHardest(3));
PseudoJet filtered = filter(tagged);  // this is the Higgs!!
```

The real analysis is slightly more refined (b-tagging, dynamical filter radius, etc) but the main features are already present here

Pruning

Pruning [7, 8] takes an initial jet, and from its mass deduces a pruning radius $R_{\text{prune}} = R_{\text{fact}} \cdot \frac{2m}{p_t}$, where R_{fact} is a parameter of the tagger. It then reclusters the jet and for every clustering step, involving objects a and b, it checks whether $\Delta_{ab} > R_{\text{prune}}$ and $\min(p_{ta}, p_{tb}) < z_{\text{cut}} p_{t,(a+b)}$, where z_{cut} is a second parameter of the tagger. If so, then the softer of the a and b is discarded. Otherwise a and b are recombined as usual. Clustering then proceeds with the remaining objects, applying the pruning check at each stage.

```
#include "fastjet/tools/Pruner.hh"

// define pruner
double zcut = 0.1, Rfact = 0.5;
Pruner pruner(cambridge_algorithm, zcut, Rfact);

PseudoJet pruned_jet = pruner(jet);
```

Trimming

1. Cluster all cells/tracks into jets using any clustering algorithm. The resulting jets are called the seed jets.

2. Within each seed jet, recluster the constituents using a (possibly different) jet algorithm into subjets with a characteristic radius R_{sub} smaller than that of the seed jet.

3. Consider each subjet, and discard the contributions of subjet i to the associated seed jet if $p_{Ti} < f_{\text{cut}} \cdot \Lambda_{\text{hard}}$, where f_{cut} is a fixed dimensionless parameter, and Λ_{hard} is some hard scale chosen depending upon the kinematics of the event.

4. Assemble the remaining subjets into the trimmed jet.

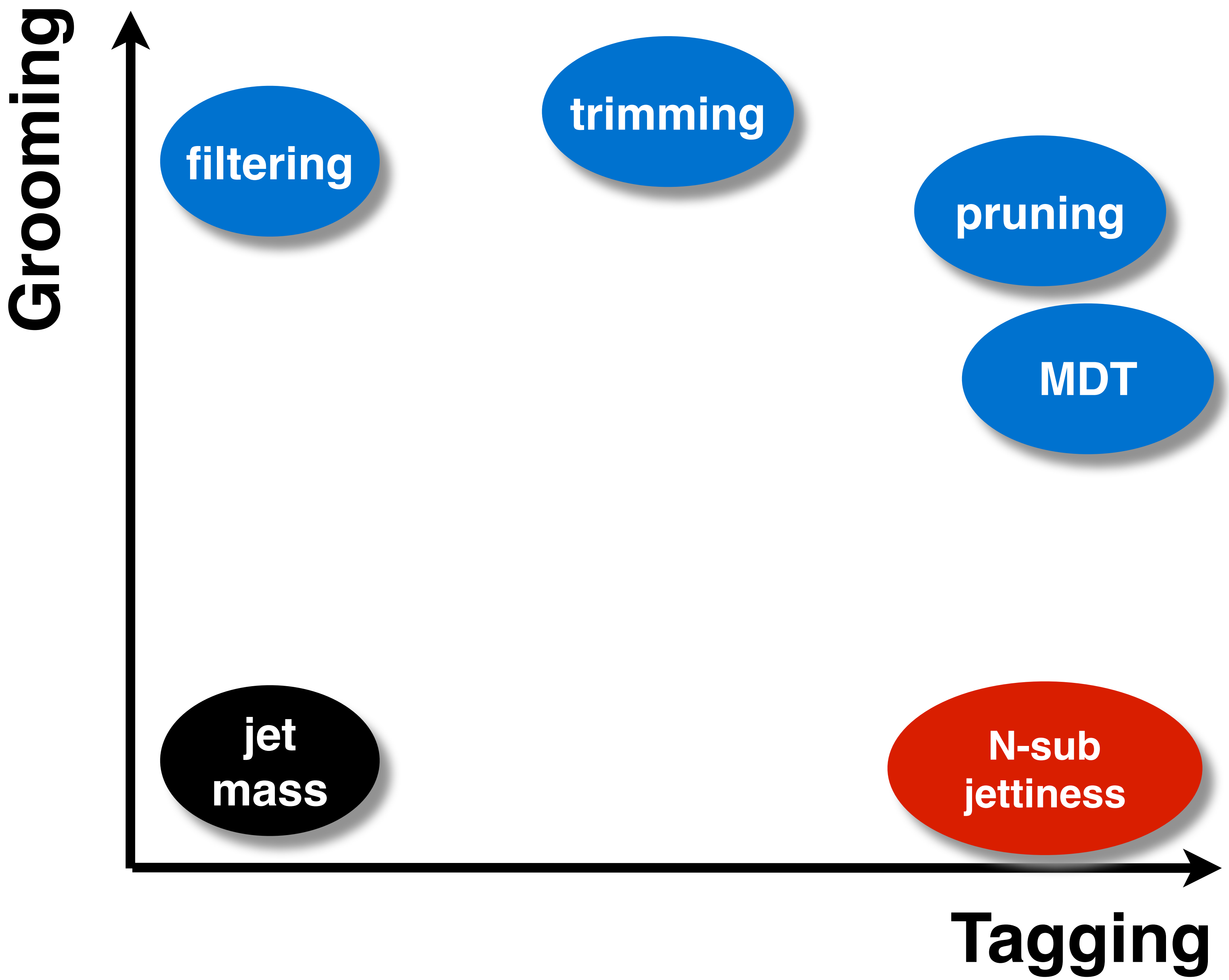
Different condition for retaining jets (p_T-cut rather than n_{filt} hardest) with respect to filtering, but otherwise identical

```
#include "fastjet/tools/Filter.hh"

// define trimmer
Filter trimmer(0.3,SelectorPtFractionMin(0.03));
```

different (2-body) substructure tools

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



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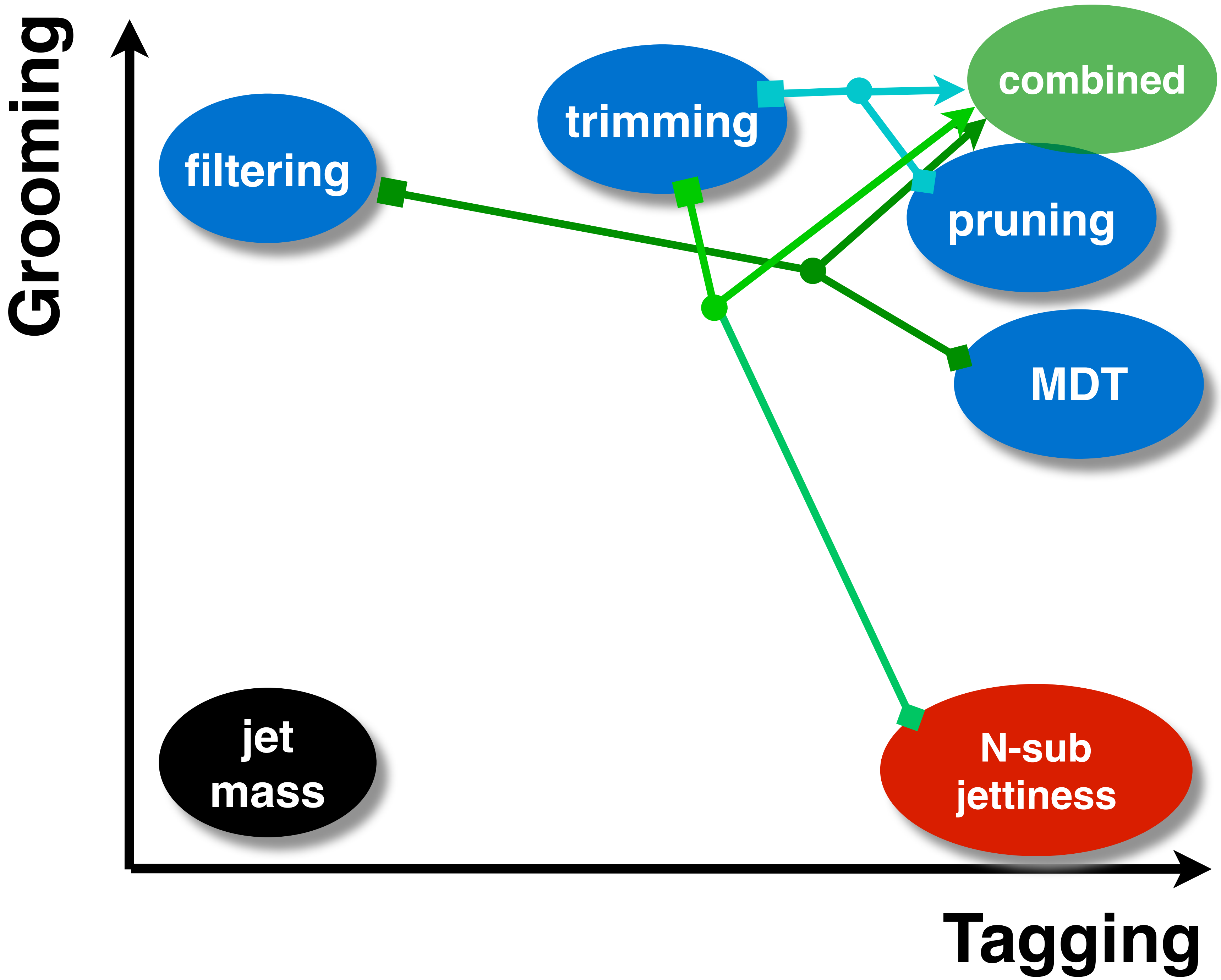

Detailed relative positions depend on physics context
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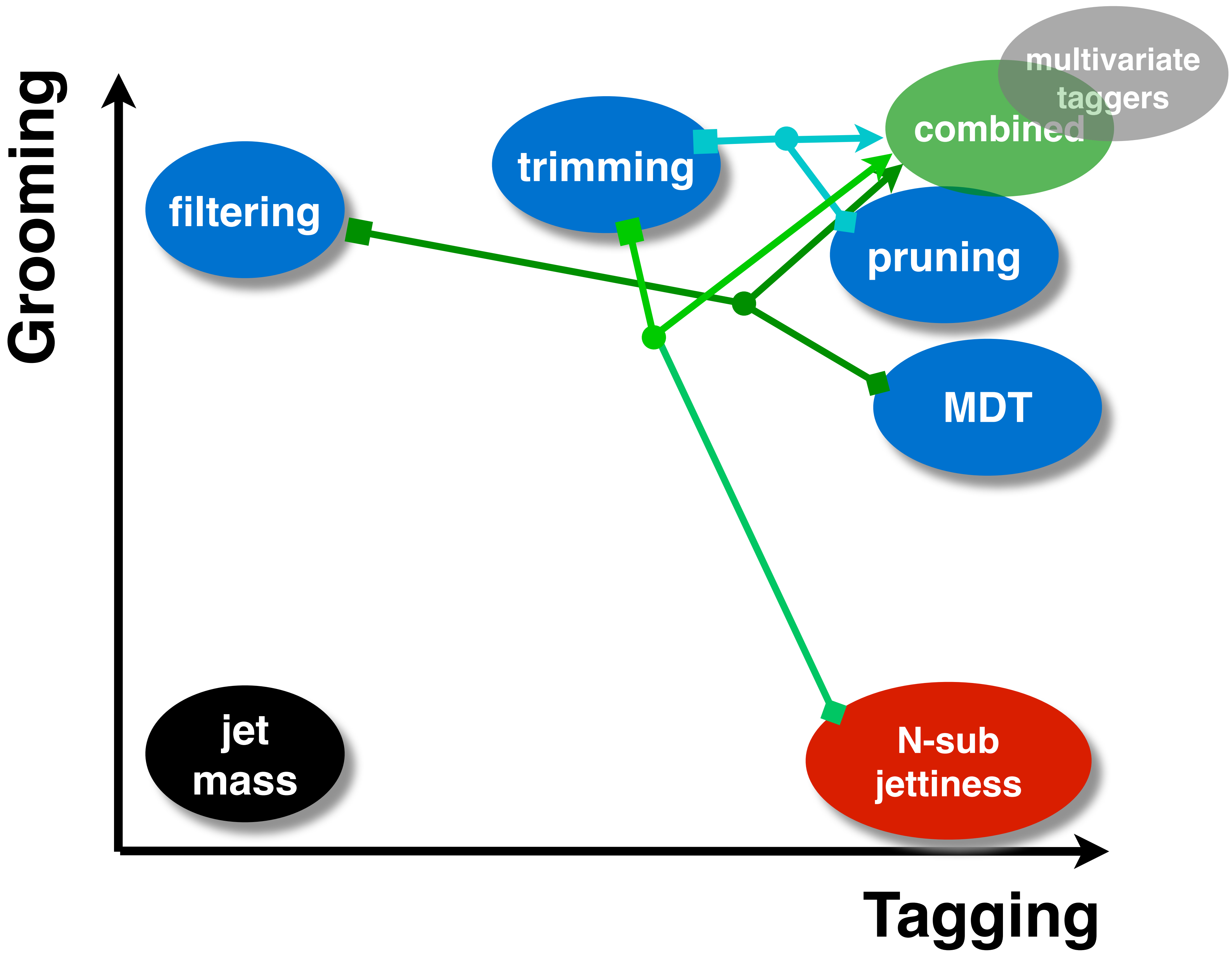

Detailed relative positions depend on physics context
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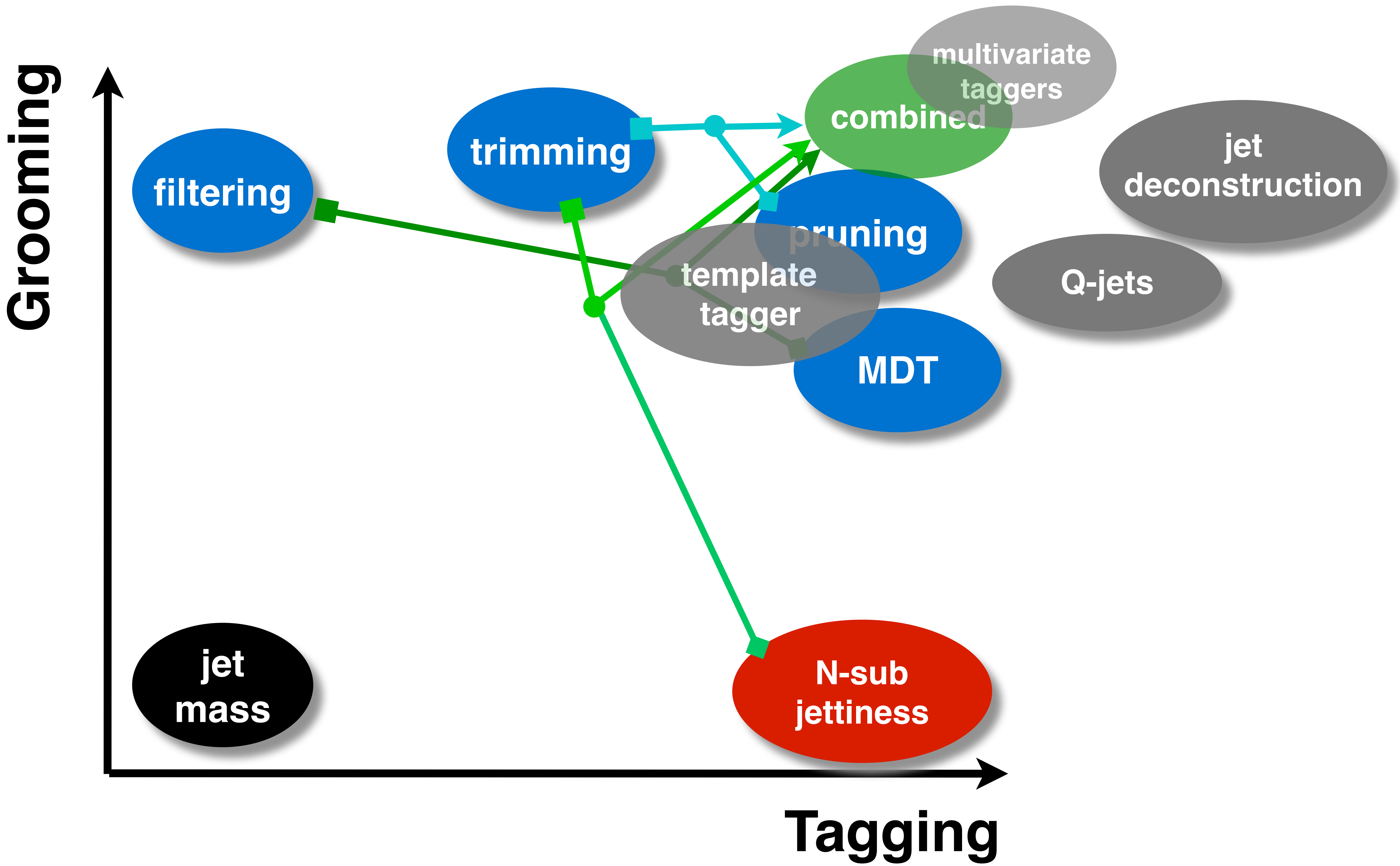


3rd party tools for FastJet

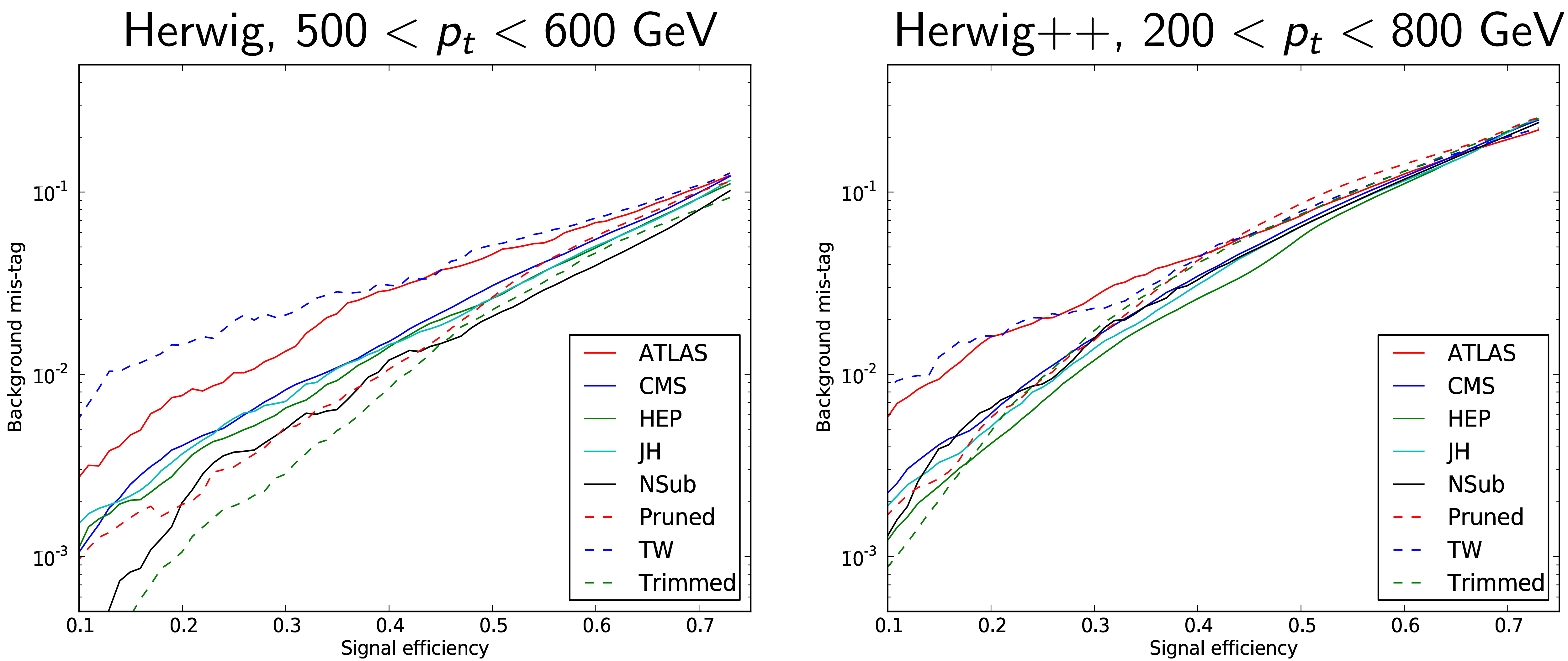
3rd party tools (external code)

Code	Authors	Comment	Available in FastJet Contrib
		Plugins	
Variable R	Krohn, Thaler and Wang	arXiv:0903.0392	Y
ScJet	Jeff Tseng and Hannah Evans	arXiv:1304.1025	Y
YSplitter	Butterworth, Cox and Forshaw	Just call the ClusterSeq method on you	
HEPTopTagger	Plehn, Salam, Spannowsky and Takeuchi	based on arXiv	
multivariate W-jet	Cui, Han and Schwartz	arXiv:1012.207	
N-subjettiness	Jesse Thaler and Ken Van Tilburg	based on arXiv	
Qjets	Ellis, Hornig, Krohn, Roy and Schwartz	arXiv:1201.191	
TemplateTagger	Backovic, Juknevic and Perez	arXiv:1212.297	
JetFFMoments	Cacciari, Quiroga, Salam, Soyez	arXiv:1209.608	
GenericSubtractor	Soyez, Dutta, Kim, Salam, Cacciari	arXiv:1211.281	
EnergyCorrelator	Larkoski, Salam, Thaler	arXiv:1305.0007	

Version 1.011 of FastJet Contrib is distributed with the following packages

Package	Version	Information
ConstituentSubtractor	1.0.0	README NEWS
EnergyCorrelator	1.0.1	README NEWS
GenericSubtractor	1.2.0	README NEWS
JetCleanser	1.0.0	README NEWS
JetFFMoments	1.0.0	README NEWS
JetsWithoutJets	1.0.0	README NEWS
Nsubjettiness	1.0.3	README NEWS
ScJet	1.1.0	README NEWS
SubjetCounting	1.0.1	README NEWS
VariableR	1.0.1	README NEWS

Comparing top taggers

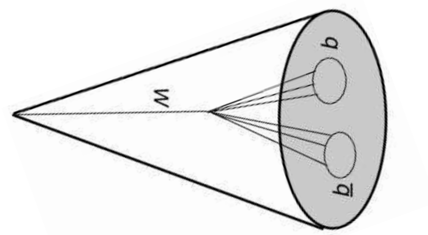


From the extensive "Boost 2011" report, which reviewed taggers discussed software, determined performance on MC, etc.

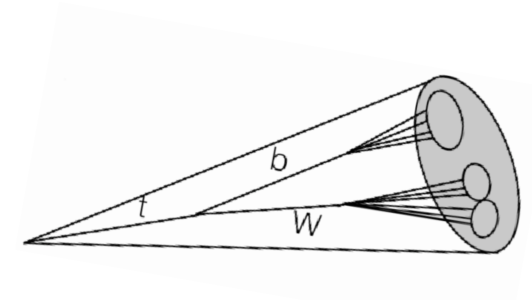
Bottom line: some taggers clearly better than others.
But many taggers behave similarly & details depend on analysis (+ MC choice)

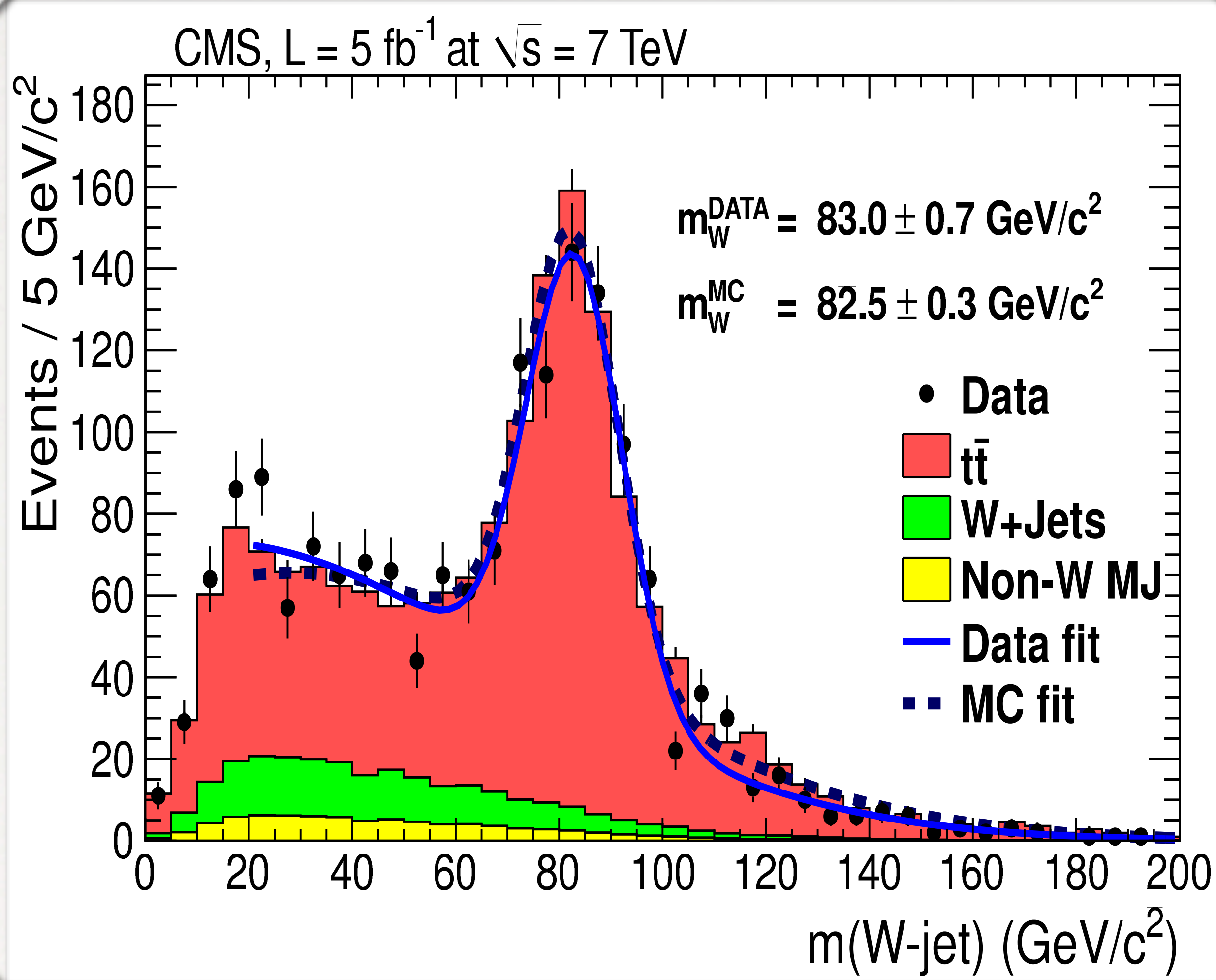
Seeing W's and tops in a single jet

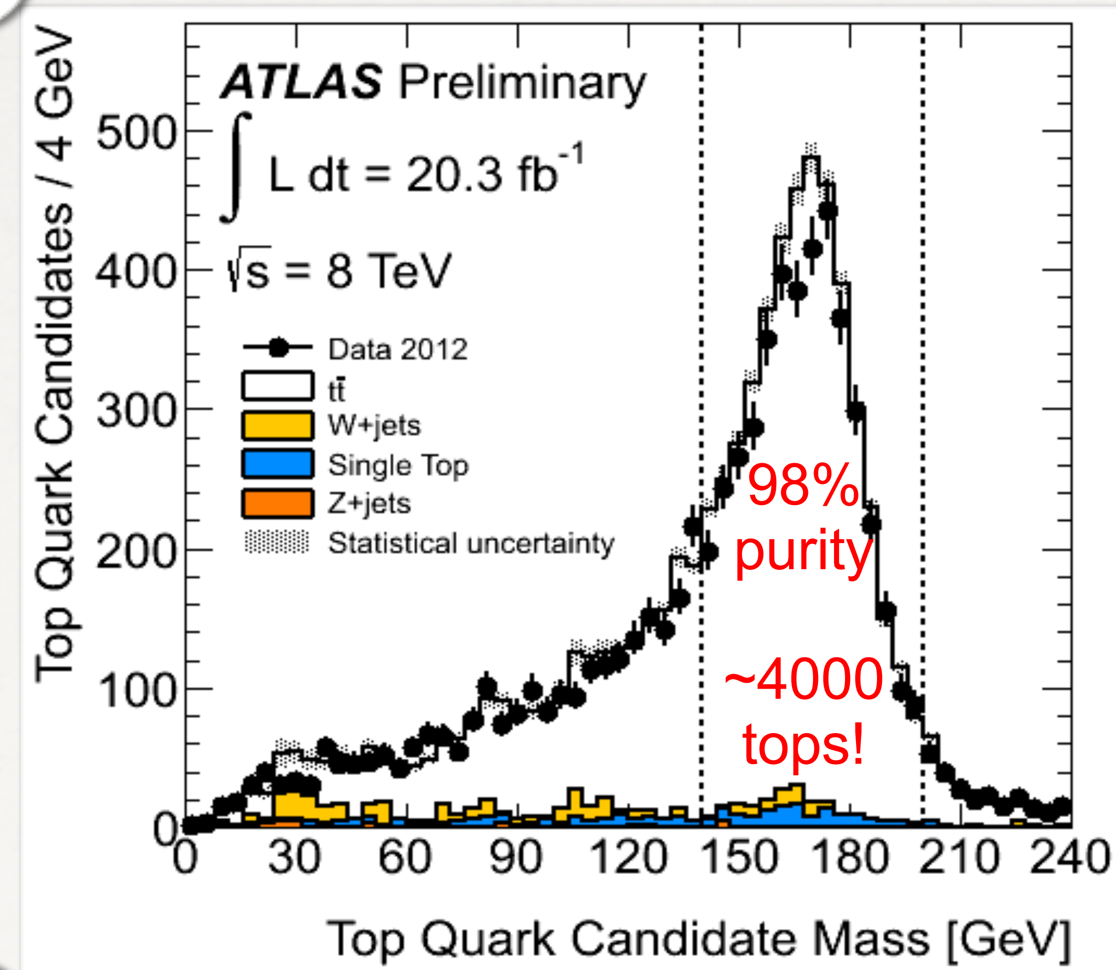
W's in a single jet



tops in a single jet







Recent ATLAS & CMS preprints citing jet substructure work

Jet Cross-Section Measurements In CMS
CMS Collaboration
Inspire. arXiv:1306.6604 (ps, pdf). Int.J.Mod.Phys. A28 (2013) 1330030.

Performance of jet substructure techniques for large-R jets in proton-proton collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1306.4945 (ps, pdf). JHEP 1309 (2013) 076. 16 cites [co]

Measurement of jet shapes in top pair events at $\sqrt{s}$ = 7 TeV using the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1307.5749 (ps, pdf).

Searches for New Physics in Multijet Final States
for the CMS Collaboration
Inspire. arXiv:1307.2518 (ps, pdf).

Search for Single and Pair-Production of Dijet Resonances with the CMS Detector
CMS Collaboration
Inspire. arXiv:1307.1400 (ps, pdf). J.Phys.Conf.Ser. 455 (2013) 012034. 1 cites [co]

Search for dark matter in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1309.4017 (ps, pdf). 5 cites [co]

Searches for anomalous ttbar production in pp collisions at $\sqrt{s}$=8 TeV
CMS Collaboration
Inspire. arXiv:1309.2030 (ps, pdf). 6 cites [co]

Search for heavy resonances decaying to top quarks
for the CMS Collaboration
Inspire. arXiv:1310.8183 (ps, pdf).

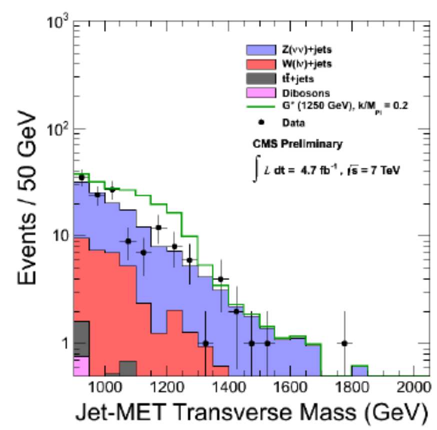
Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks
CMS Collaboration
Inspire. arXiv:1310.3687 (ps, pdf). 3 cites [co]

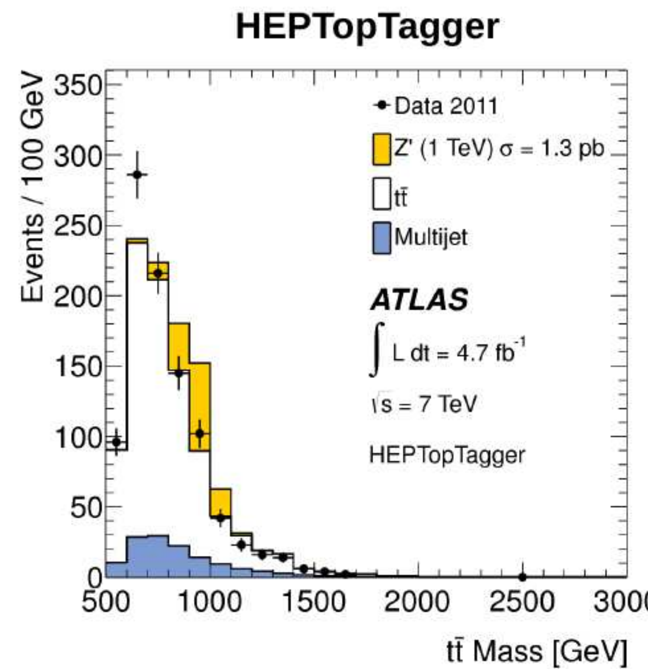
Search for the SM Higgs Boson Produced in Association with a Vector Boson and Decaying to Bottom Quarks
for the CMS Collaboration
Inspire. arXiv:1310.3551 (ps, pdf).

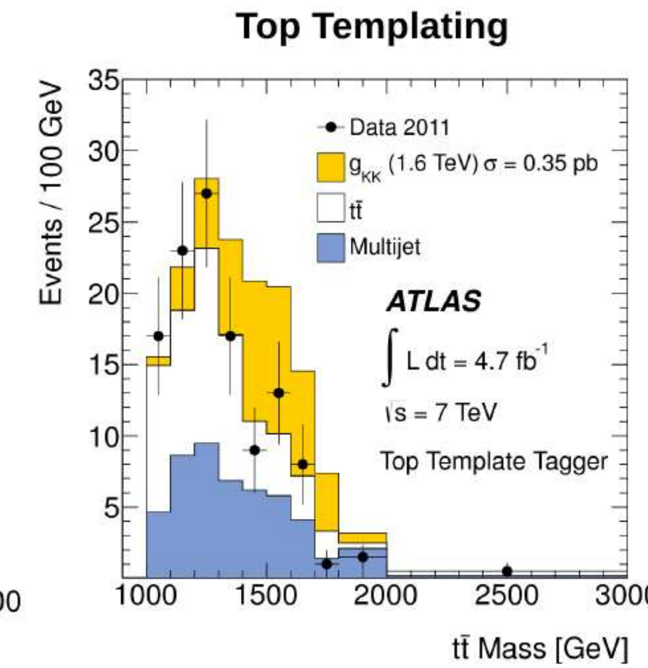
Inclusive search for a vector-like T quark with charge 2/3 in pp collisions at $\sqrt{s}$=8 TeV
CMS Collaboration
Inspire. arXiv:1311.7667 (ps, pdf).

Search for top-quark partners with charge 5/3 in the same-sign dilepton final state
CMS Collaboration
Inspire. arXiv:1312.2391 (ps, pdf).

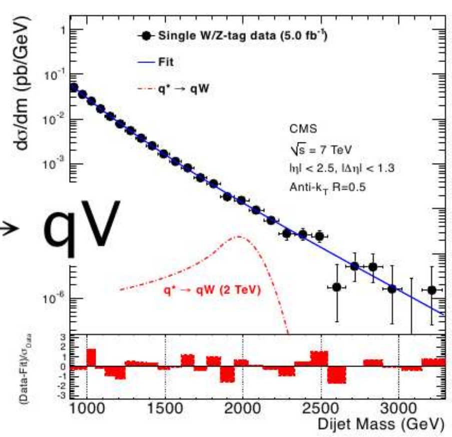
$X \to ZZ \to 2\nu 2q$

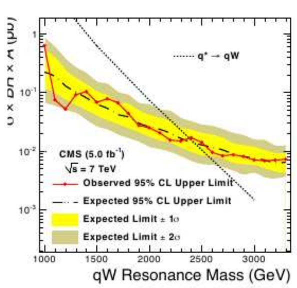


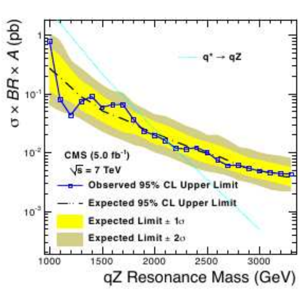


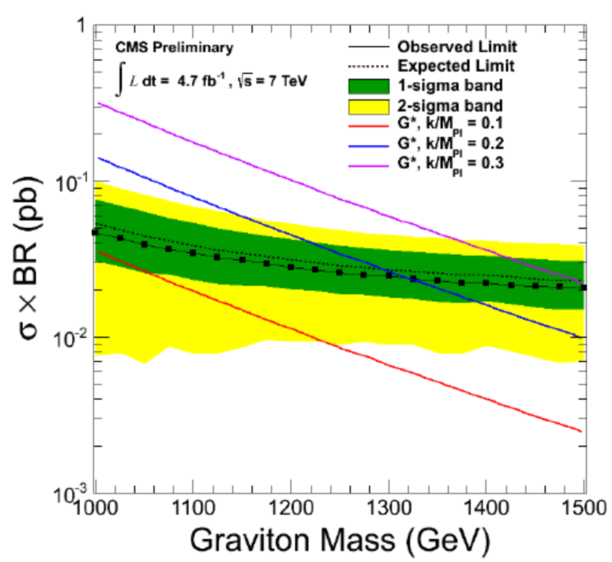


$X \to qV$









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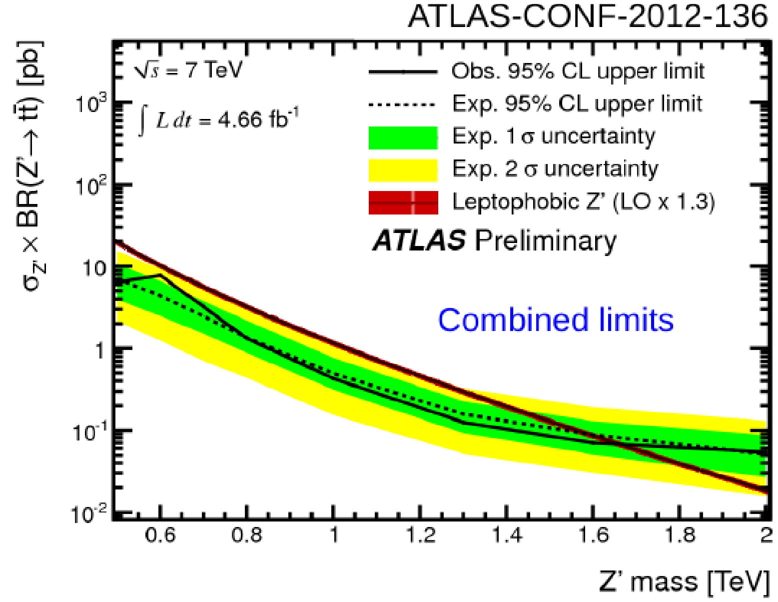


A range of techniques being used for varied BSM scenarios

EXTRA MATERIAL

What do we know currently?

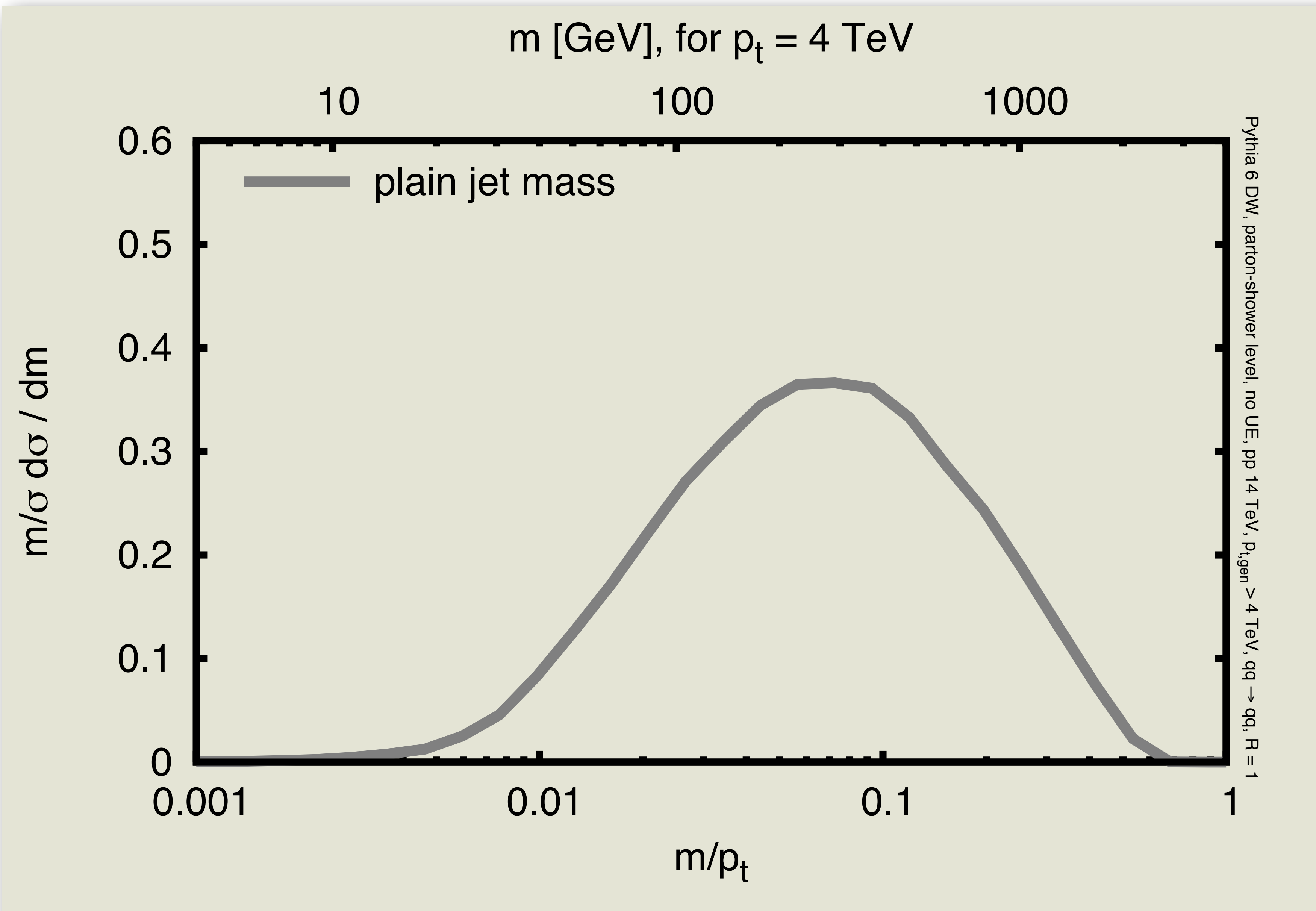
Boost 2010 proceedings:

The [Monte Carlo] findings discussed above indicate that while [pruning, trimming and filtering] have qualitatively similar effects, there are important differences. For our choice of parameters, pruning acts most aggressively on the signal and background followed by trimming and filtering.

At the time:

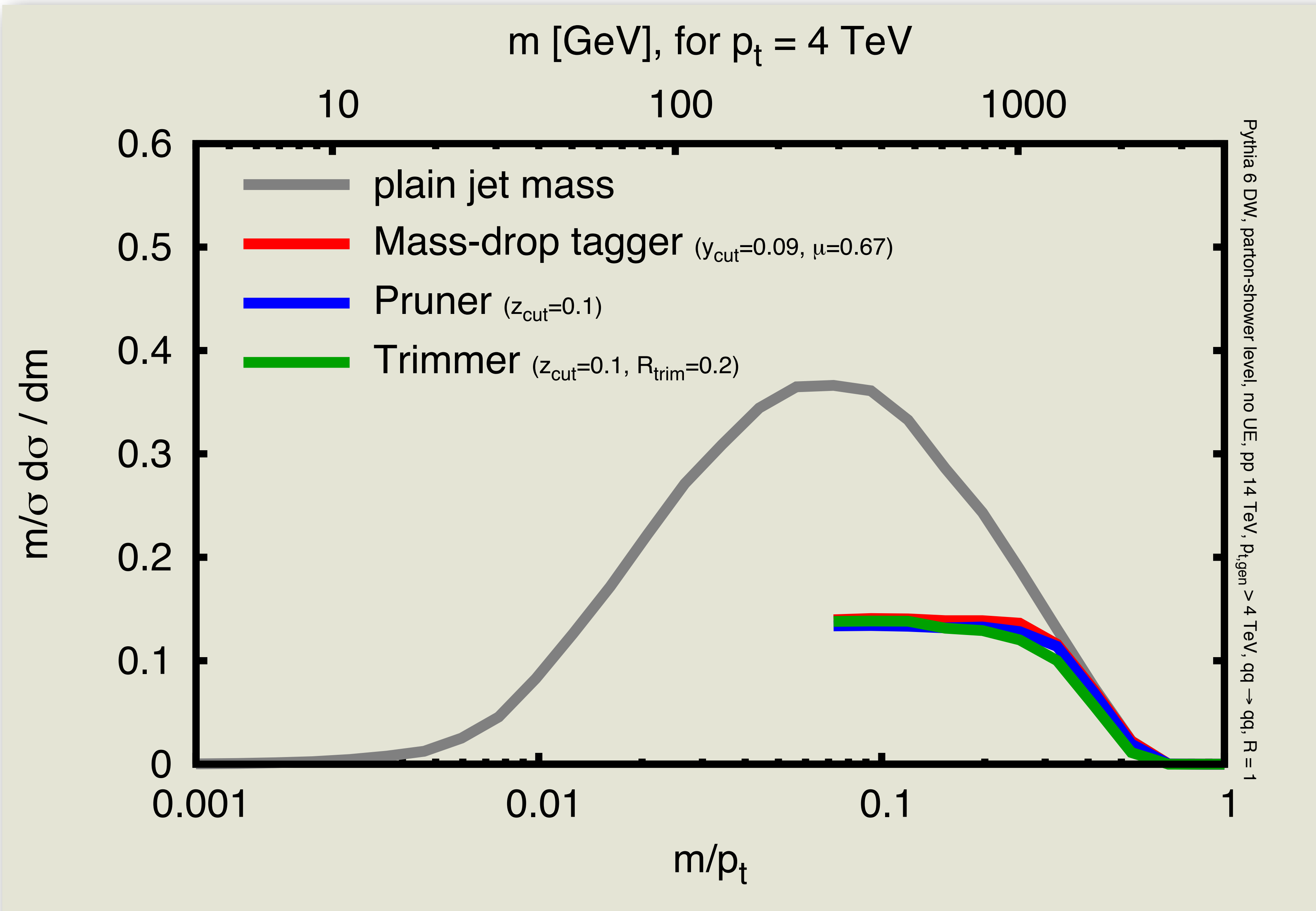
- No clear picture of why the taggers might be similar or different
- No clear picture of how the parameter choices affect the taggers

The “right” MC study can already be instructive
(testing on background [quark] jets)



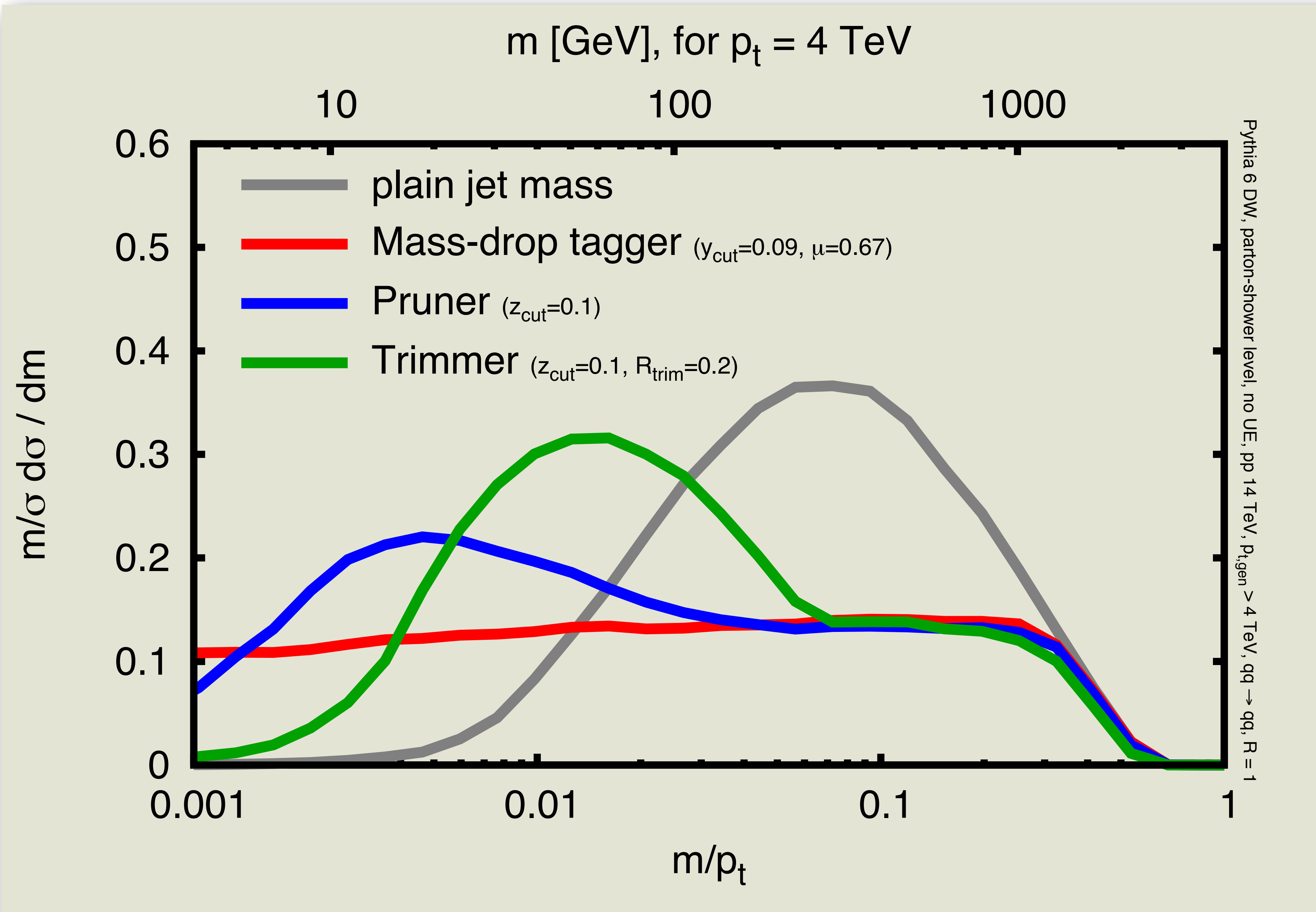
The “right” MC study can already be instructive

(testing on background [quark] jets)



Different taggers are apparently quite similar

The “right” MC study can already be instructive
(testing on background [quark] jets)



But only for a limited range of masses