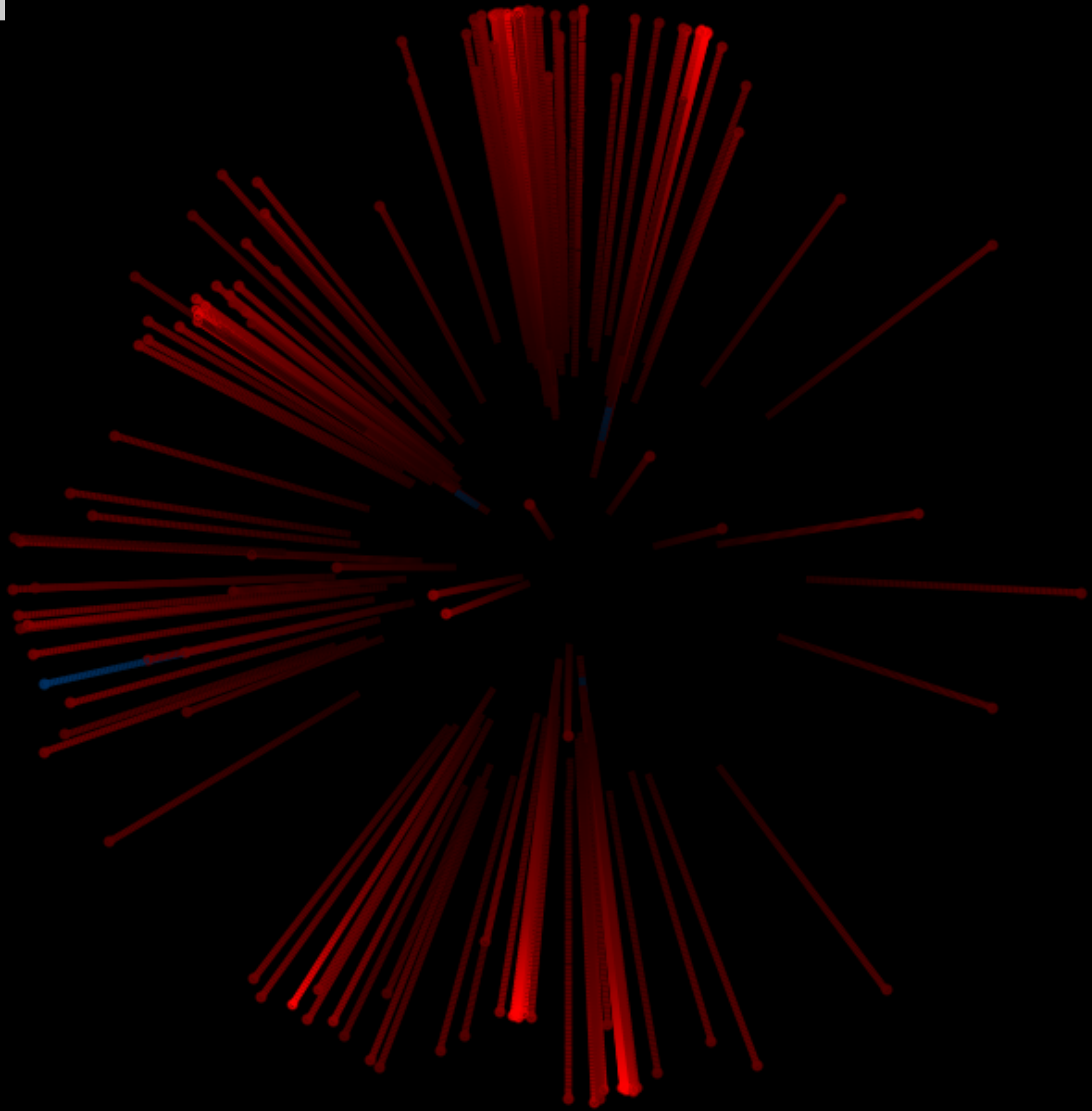
Jet Reconstruction Theory (2)

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

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

European Research Council
Established by the European Commission

- 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;
- default choices at ATLAS and CMS R=0.4 and p_t > O(20-30) GeV; good for many things, but not everything

Two things that make jets@LHC special

1. The large hierarchy of scales:

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

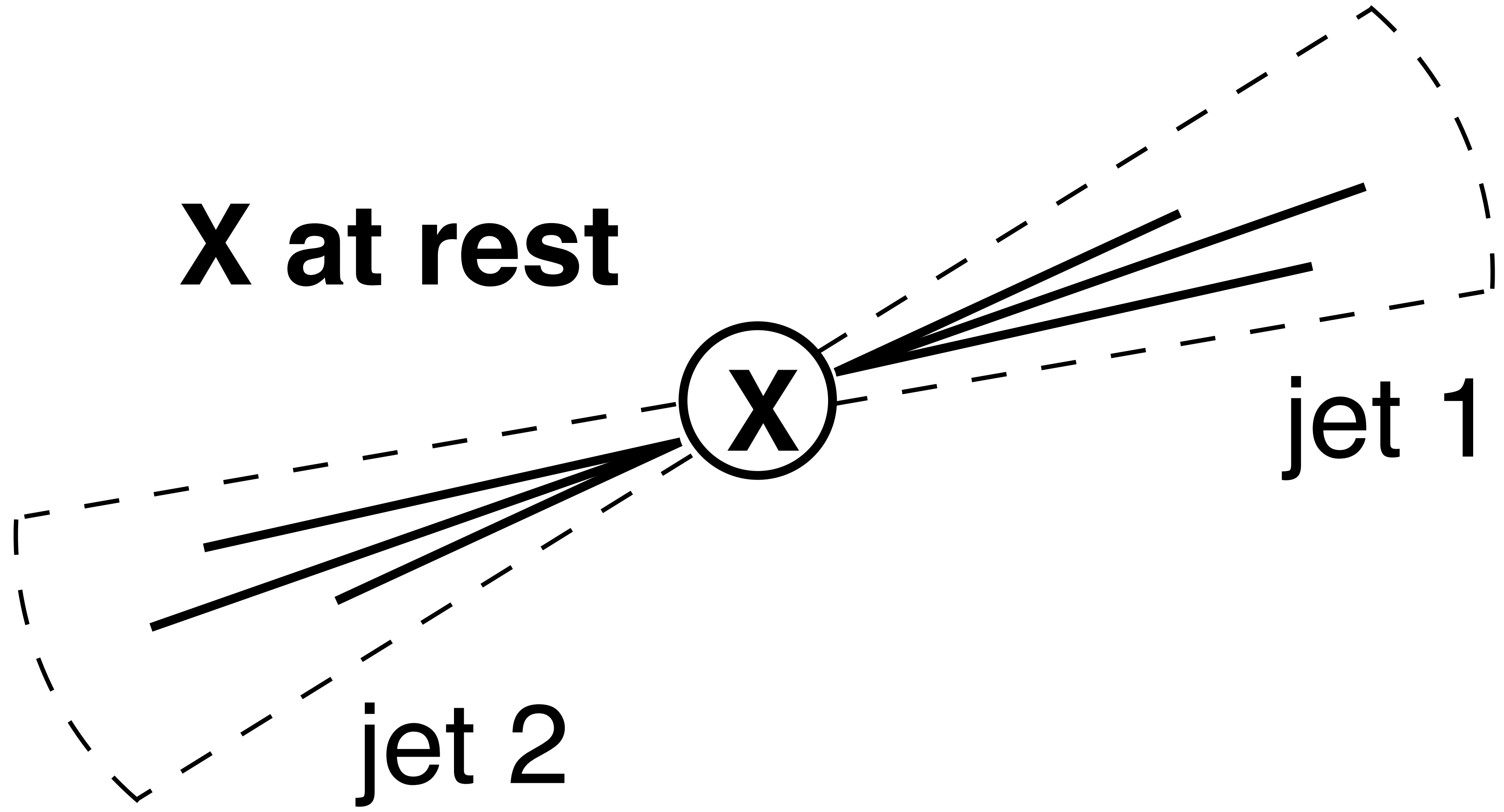
and associated **jet substructure** (this lecture)

2. The huge pileup (cf. Steven Schramm's lectures):

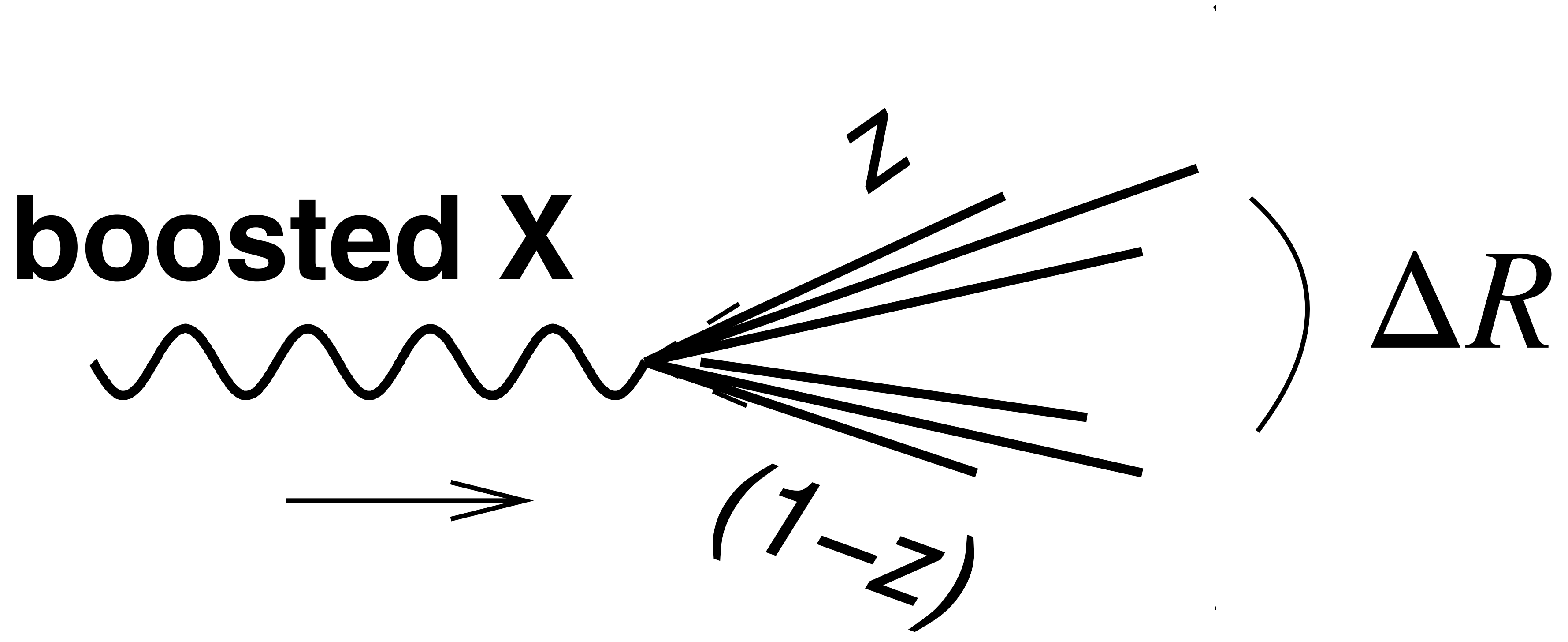
$$n_{\text{pileup}} \sim 20 - 60 \; (\rightarrow 140 \text{ at HL-LHC})$$

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

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



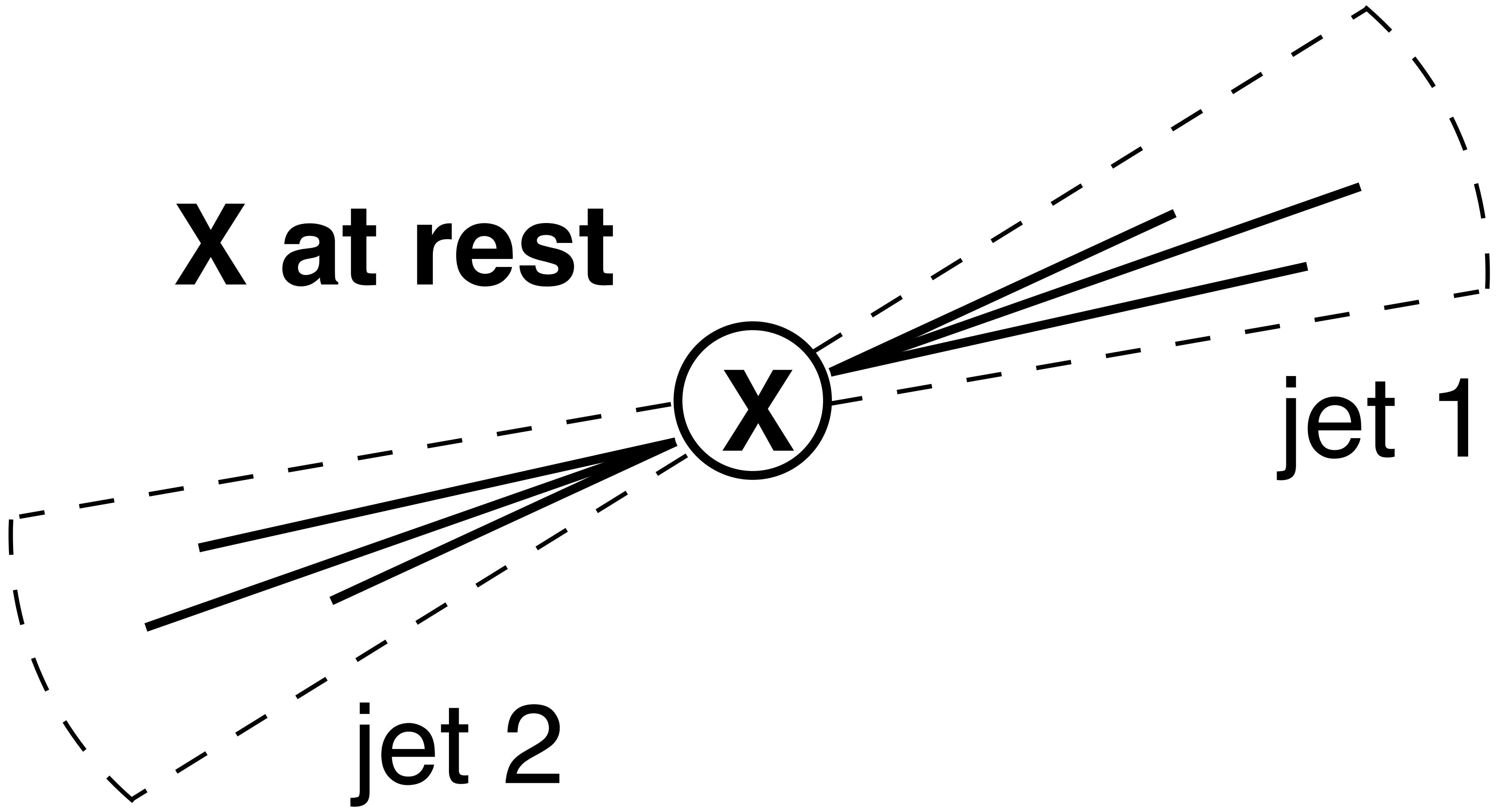
High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



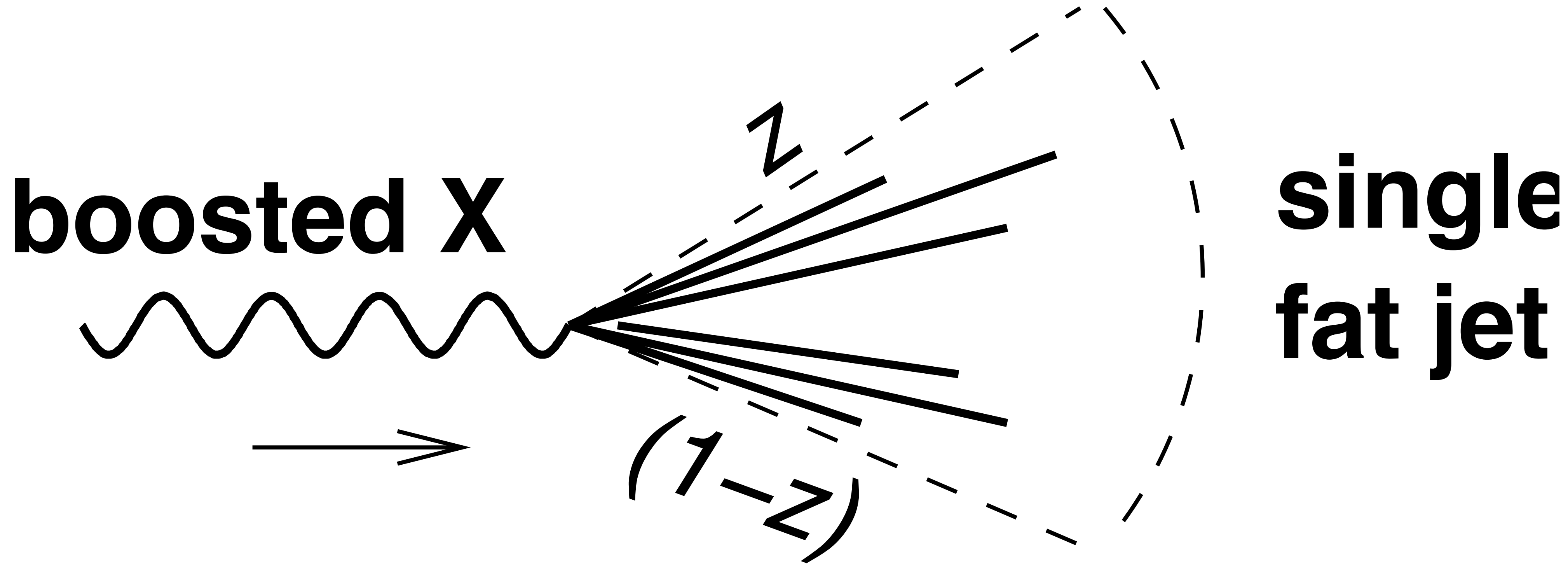
$$m_X^2 = 2\,zE_X(1-z)E_X(1-\cos\theta)$$
$$\simeq z(1-z)\,p_{tX}^2\,\Delta R^2$$

Boosted hadronic decays of EW-scale objects

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

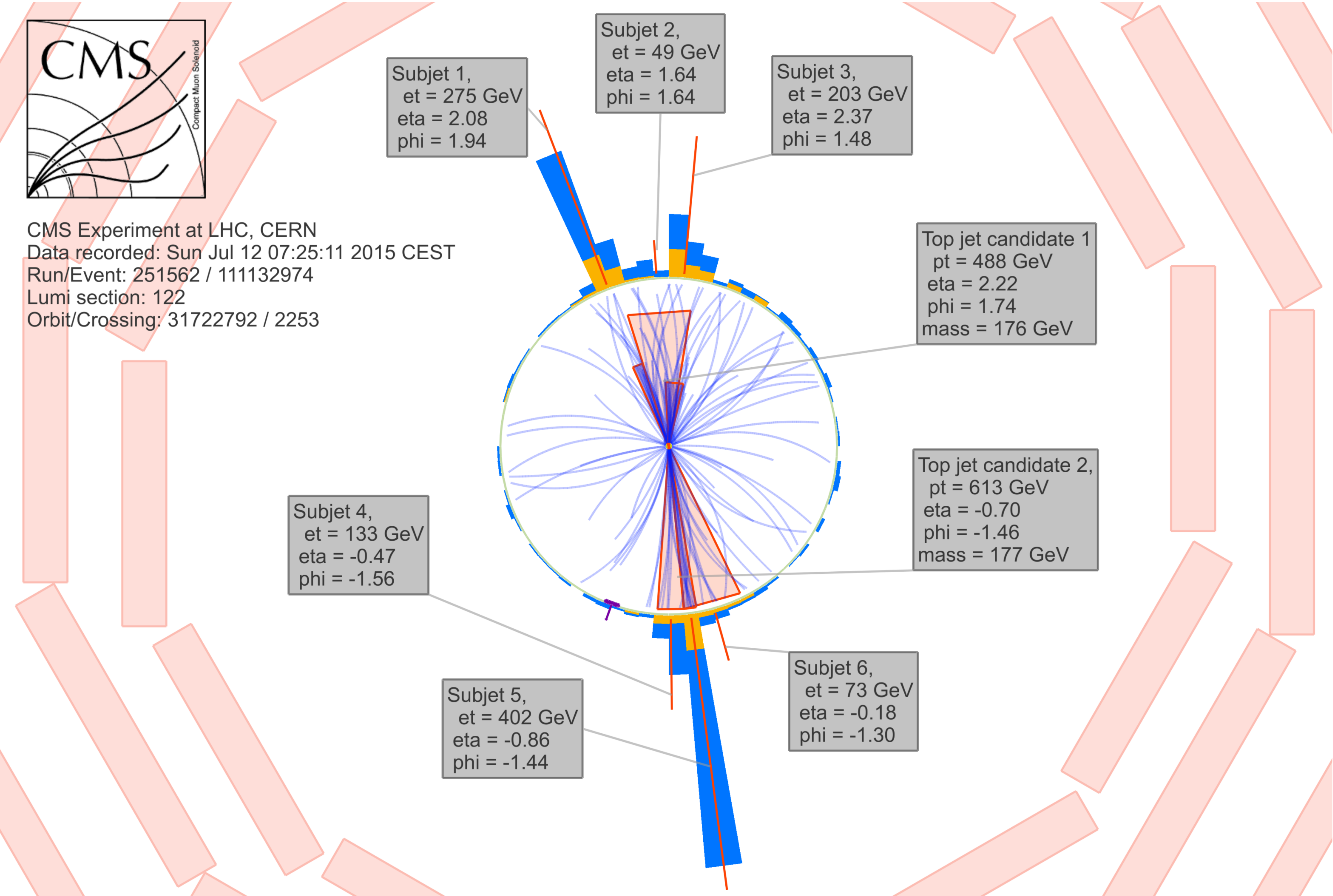


High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



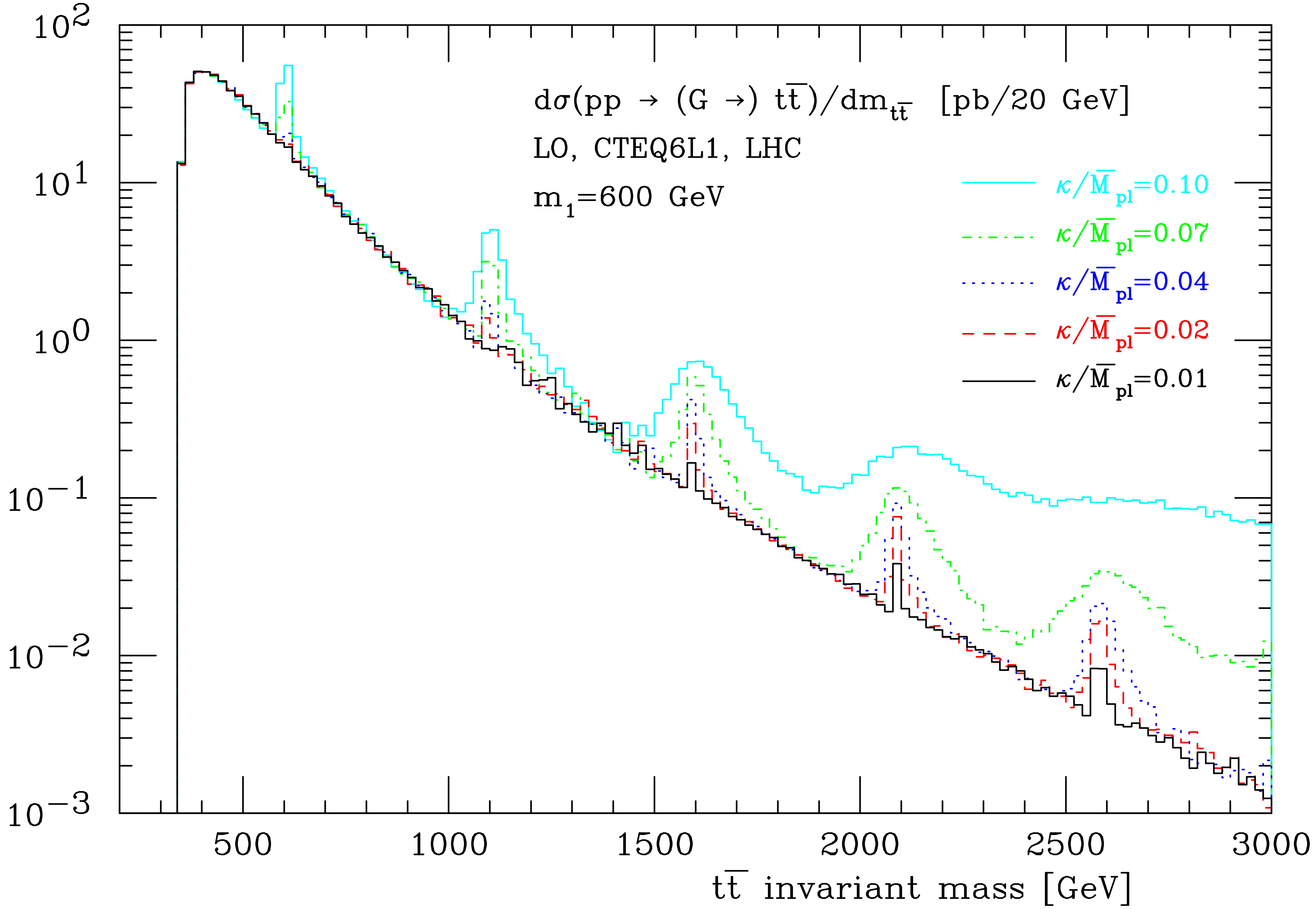
Happens for $p_{tX} > \frac{m_X}{R}\frac{1}{\sqrt{z(1-z)}} \gtrsim \frac{2m_X}{R}$

e.g. for a W boson, and R=0.4, $p_t \gtrsim 400$ GeV



a pp collision that produces a high p_t top-antitop pair, resulting in two "top-jets", each with subjets

Such events probe point-like nature of top quarks to TeV scale & allow you to search for new ttbar resonances



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

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

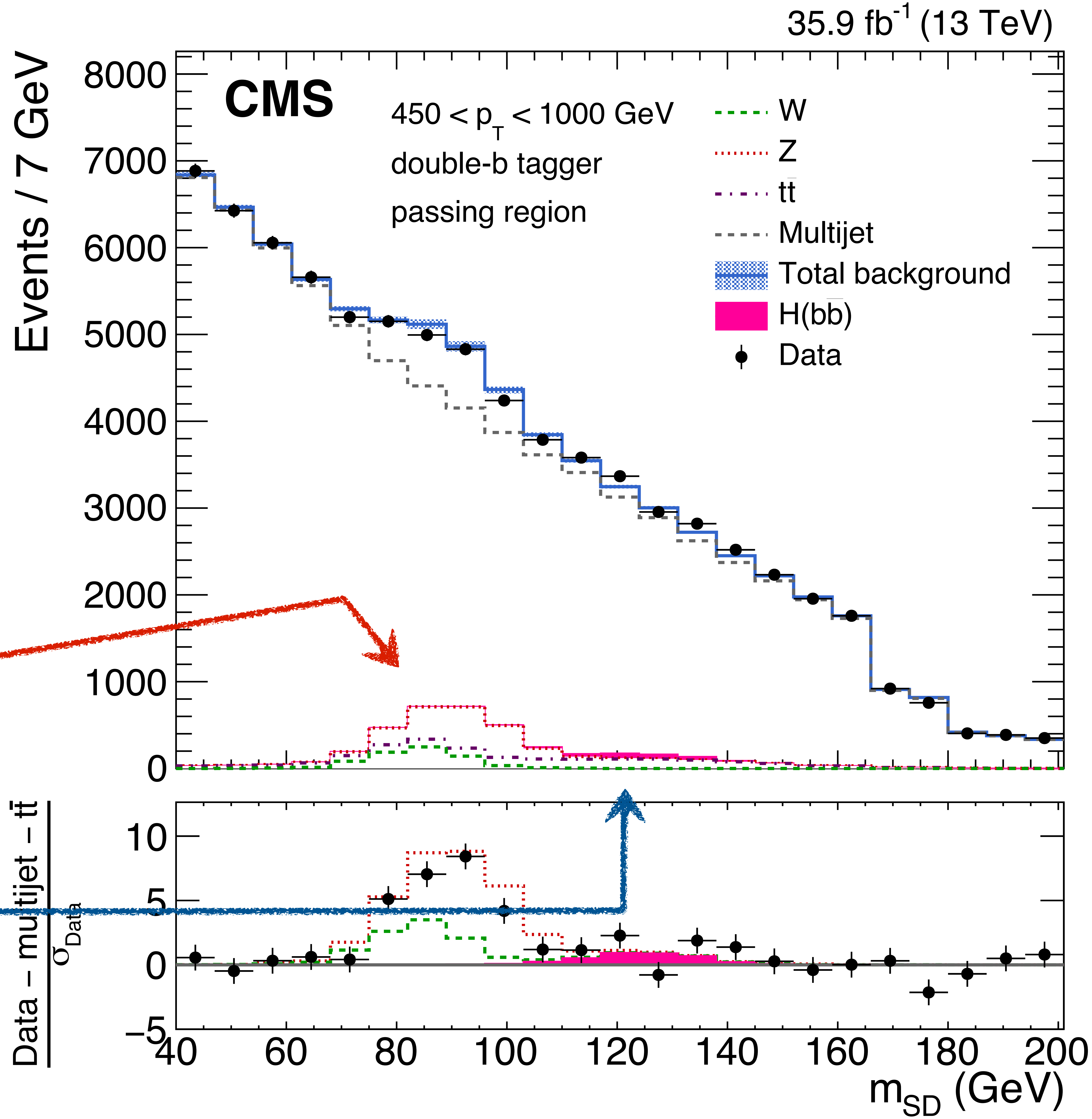
high p_T Higgs

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

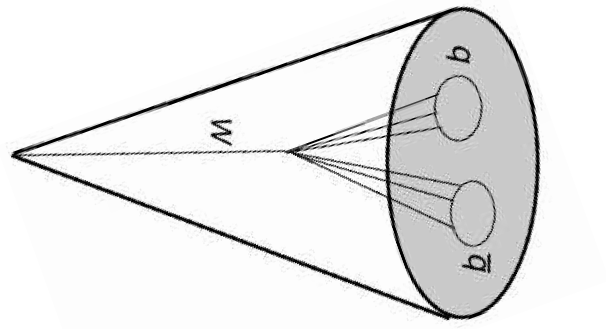
New Higgs interactions need testing at both low and (here) high momenta.

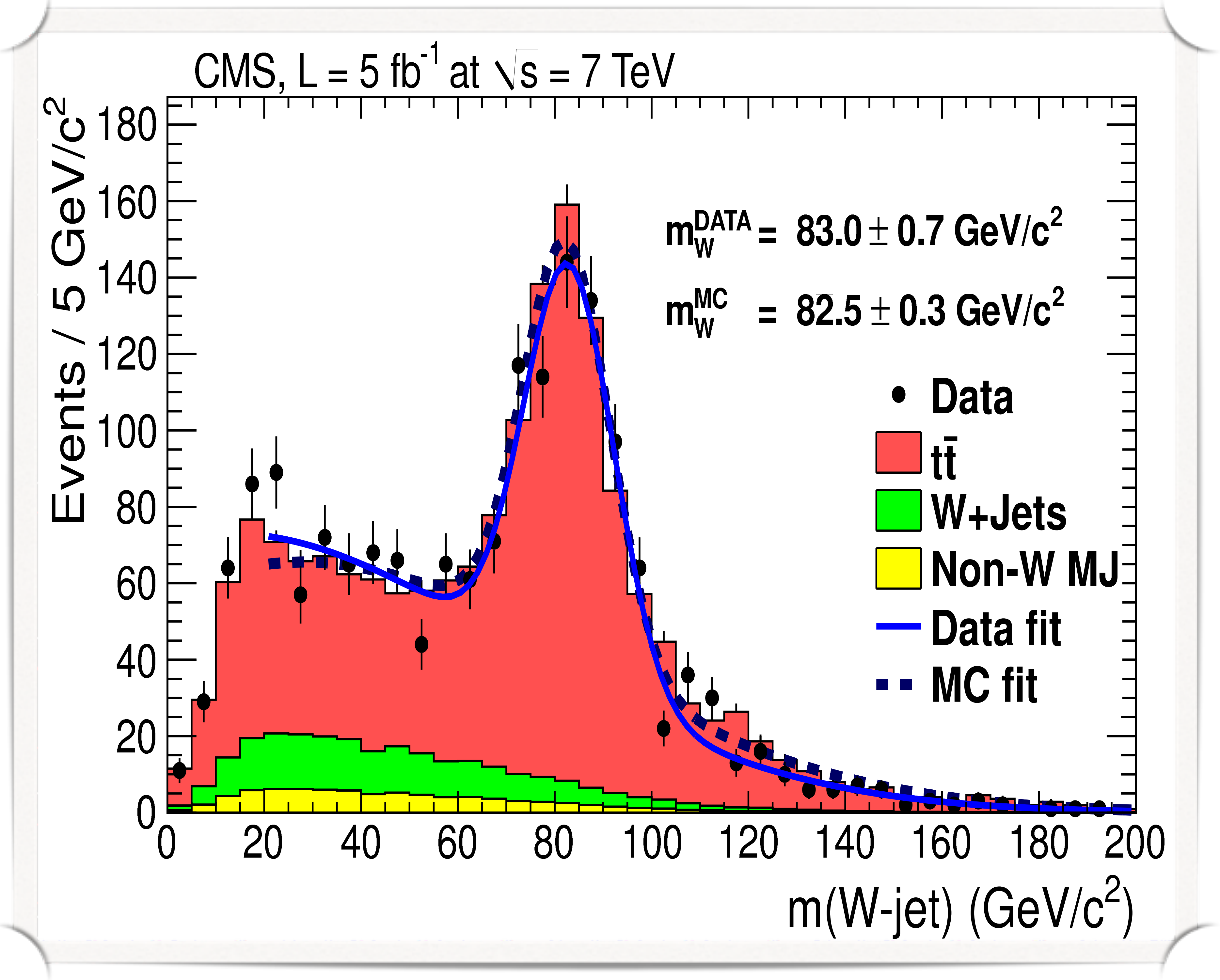
high-p_T Z → bb (5σ)

high-p_T H → bb (~ 1σ)

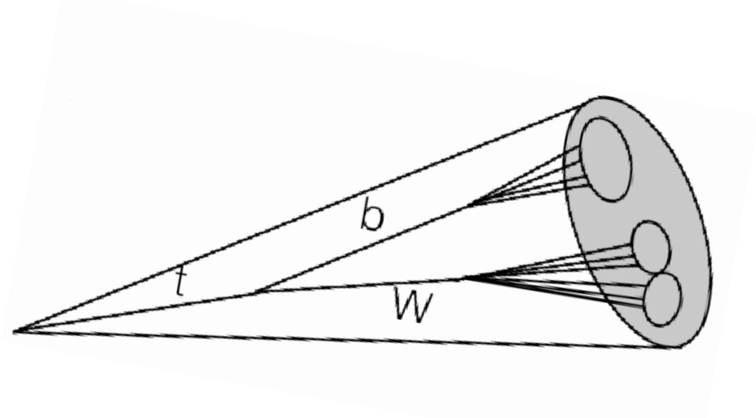


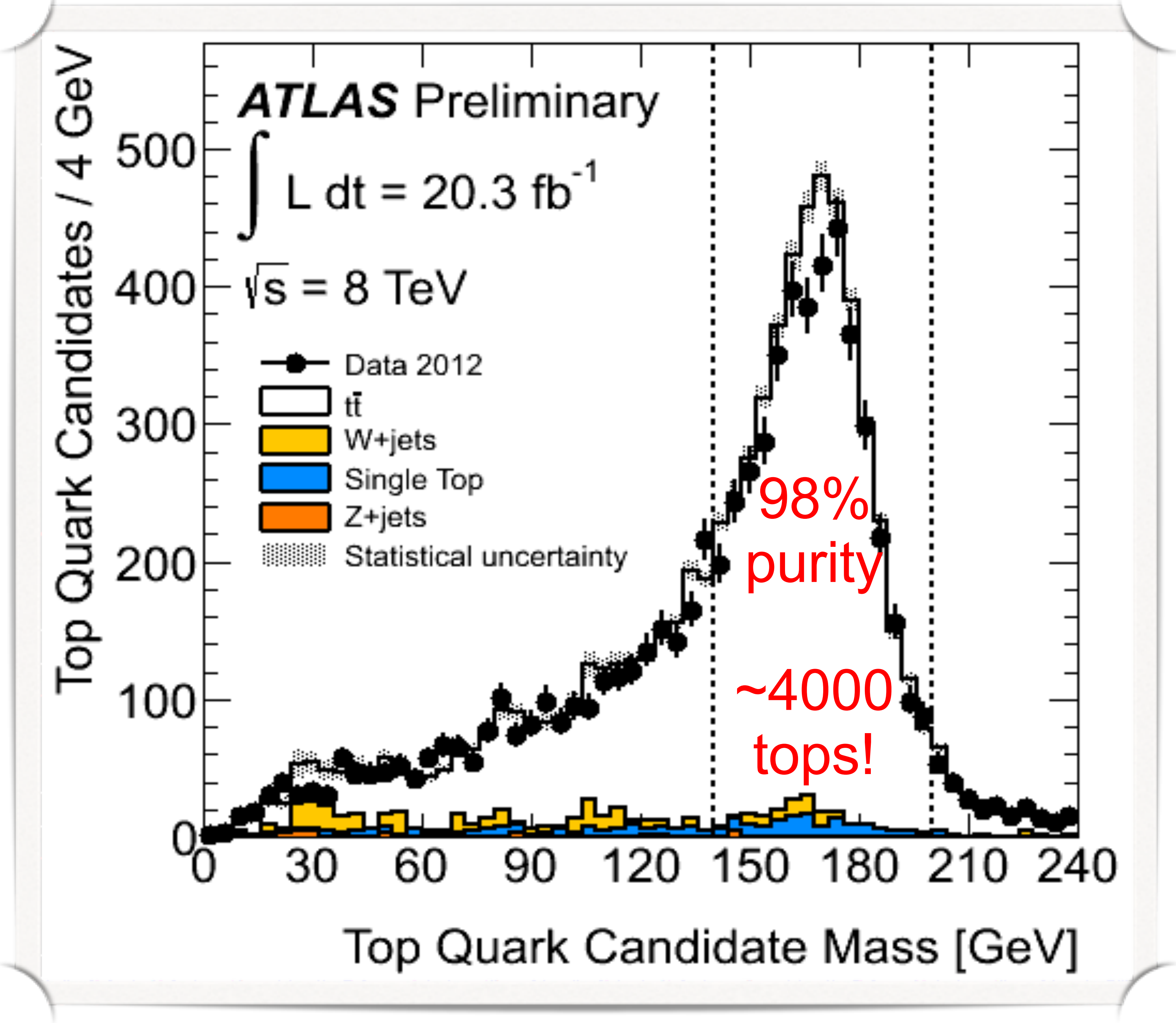
W's in a single jet





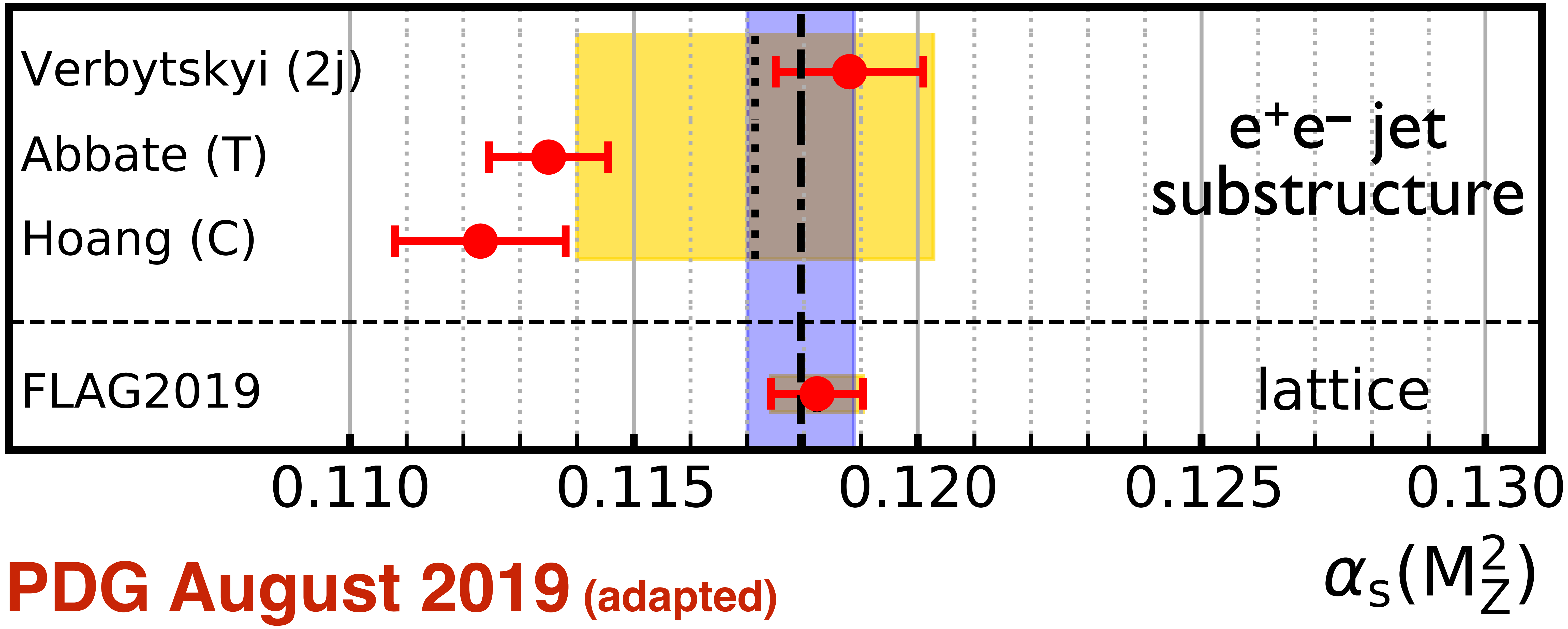
tops in a single jet





jet substructure & strong coupling determinations

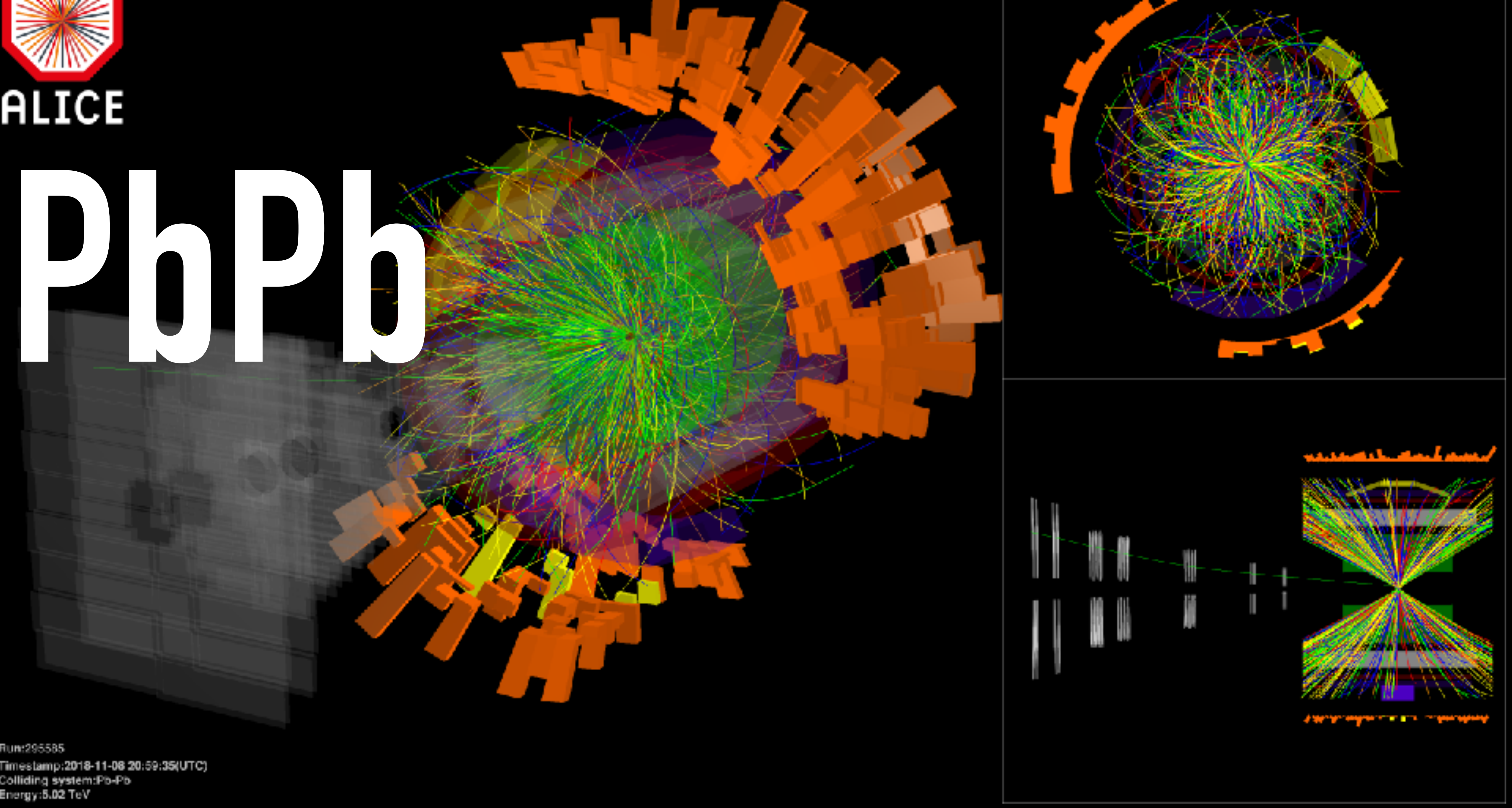
selected α_s determinations (most precise + lattice)

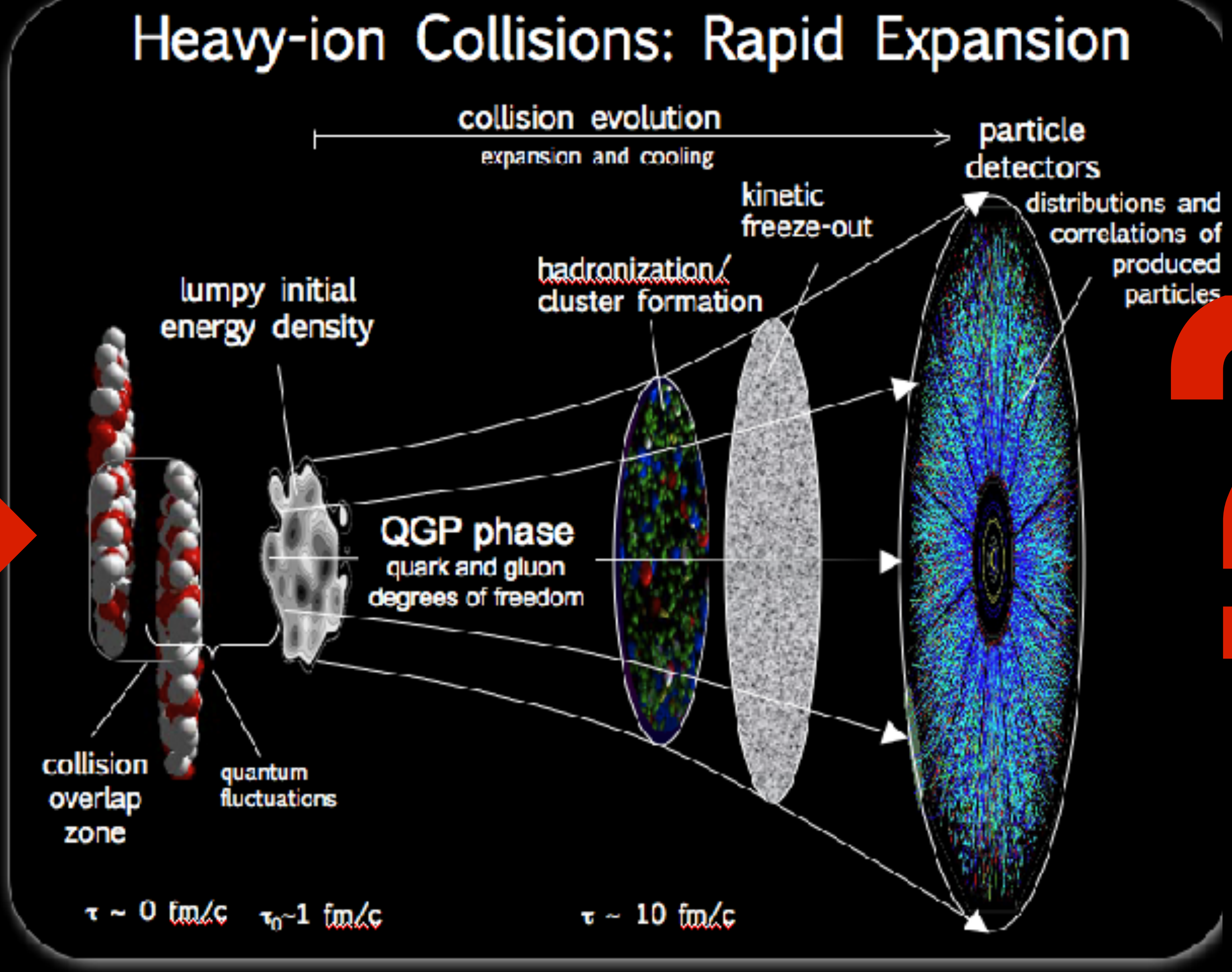


PDG August 2019 **(adapted)**

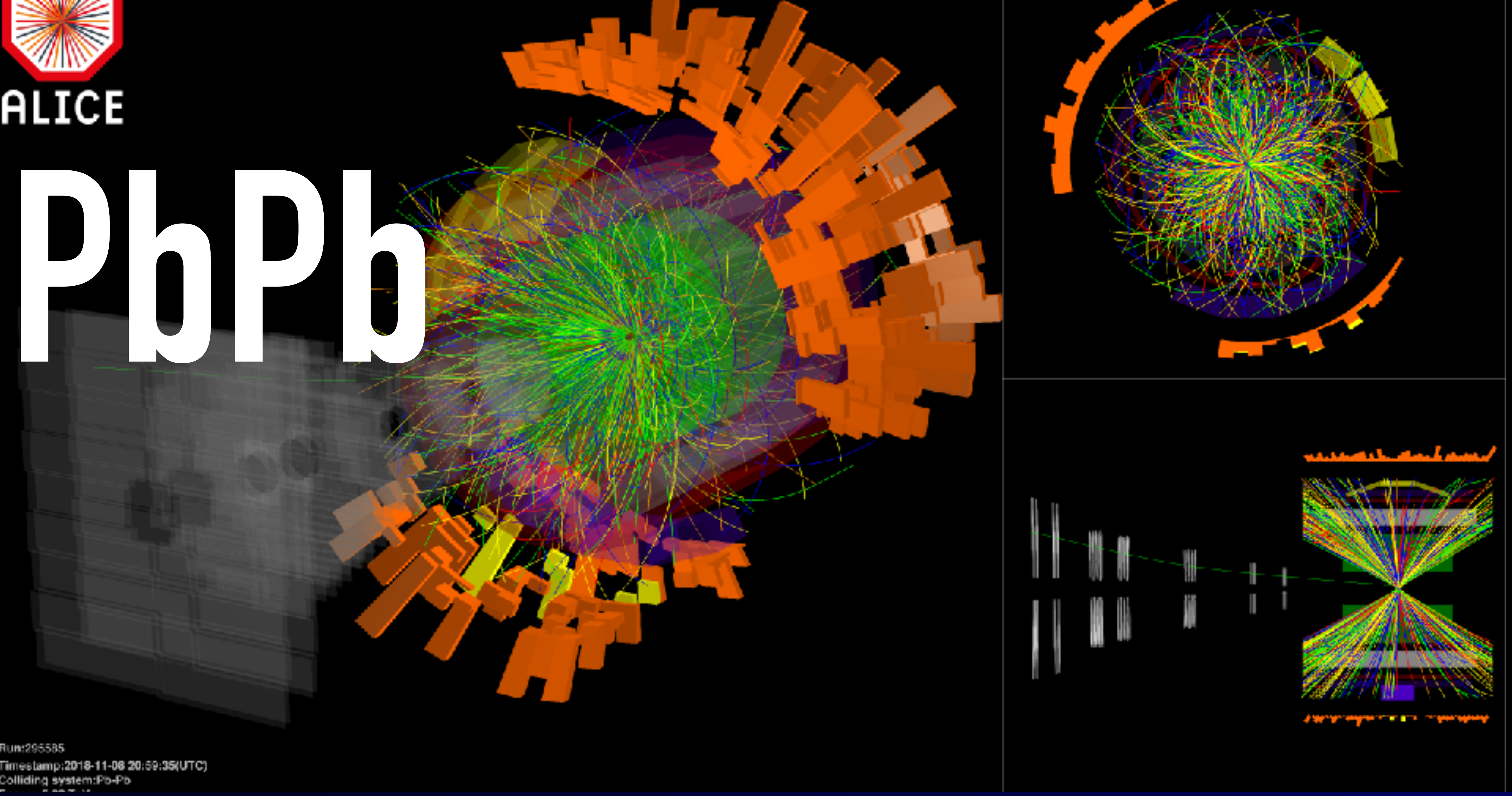
- some of the most smallest quoted errors come from e^+e^- jet substructure (better known as jet shapes and rates)
- though they don't agree with each other (and C & T don't agree with best lattice results)

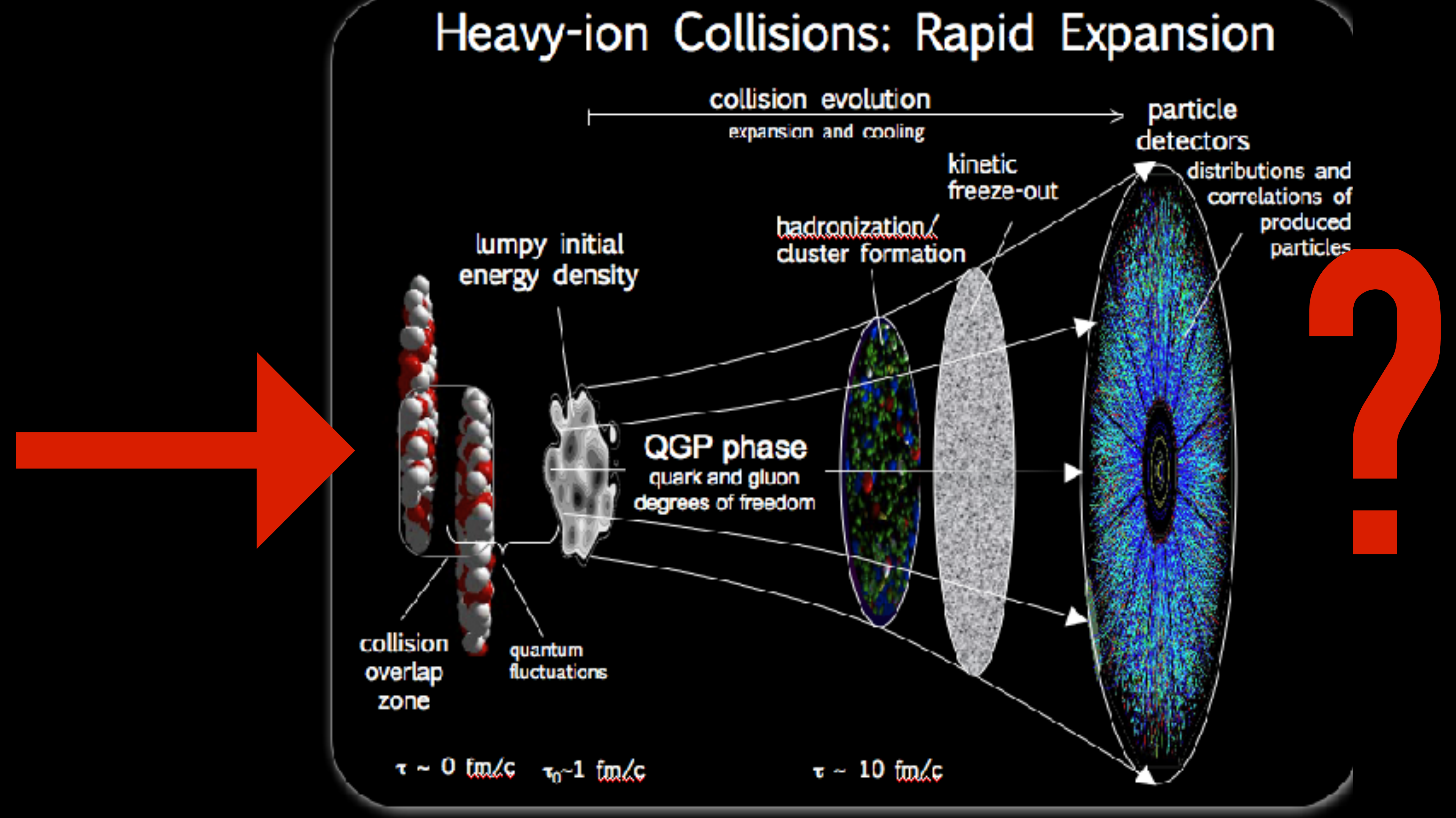
PbPb


ALICE
Run:295585
Timestamp:2018-11-08 20:59:35(UTC)
Colliding system:Pb-Pb
Energy:5.02 TeV

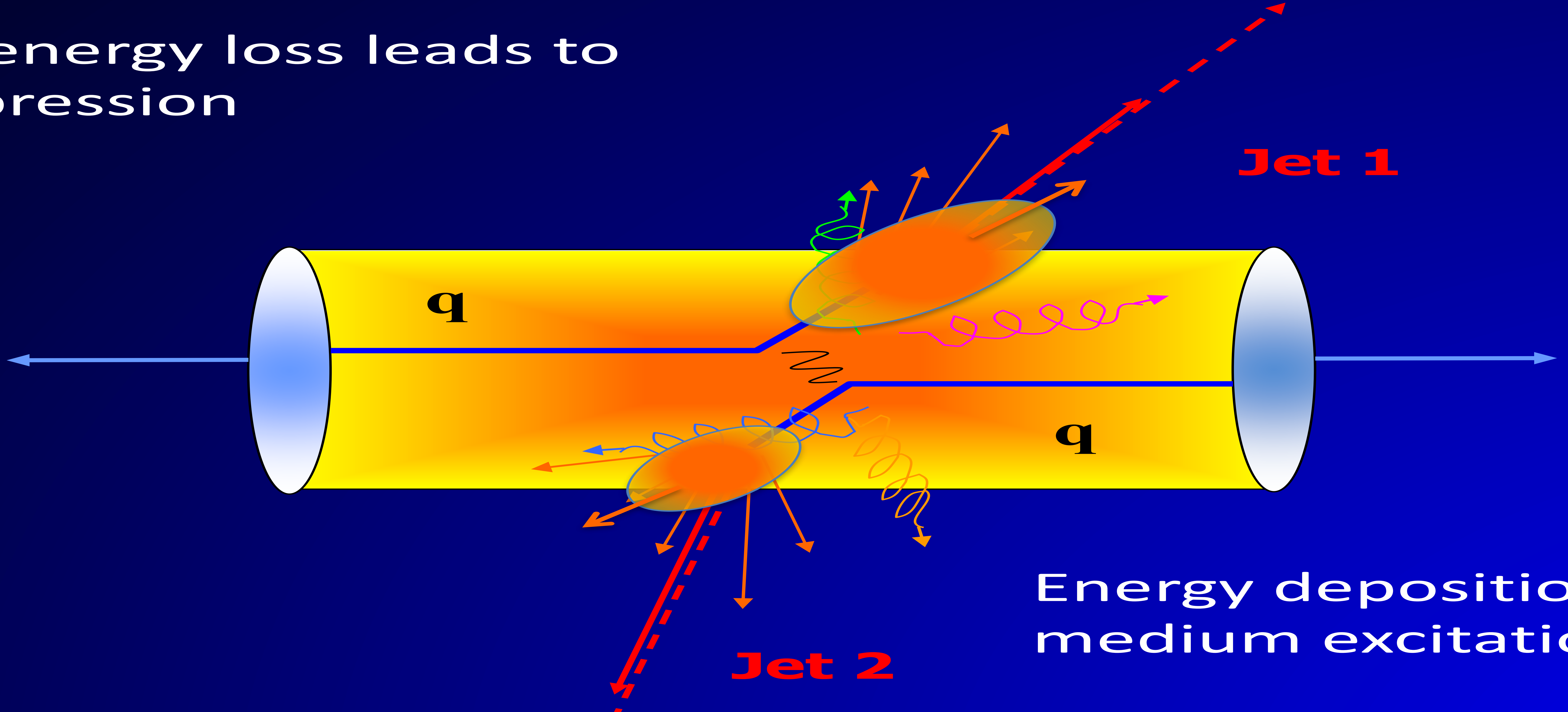

Heavy-ion Collisions: Rapid Expansion
collision evolution
expansion and cooling
particle detectors
distributions and correlations of produced particles
kinetic freeze-out
hadronization/ cluster formation
lumpy initial energy density
QGP phase
quark and gluon degrees of freedom
collision overlap zone
quantum fluctuations
τ ~ 0 fm/c
τ0~1 fm/c
τ ~ 10 fm/c

?





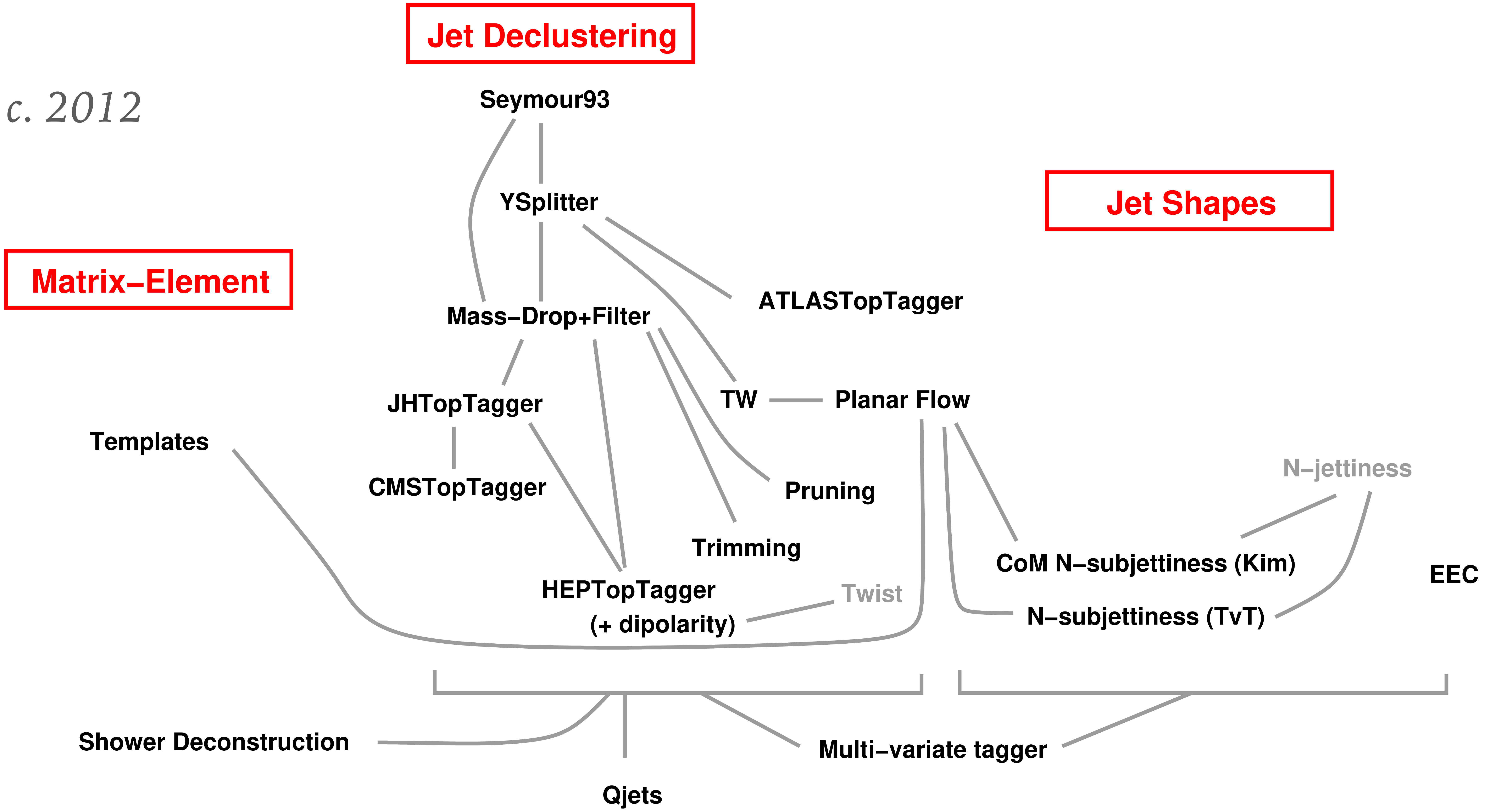
Parton energy loss leads to jet suppression



Energy deposition leads to medium excitation

from X-N. Wang

c. 2012


Jet Declustering
Seymour93
YSplitter
Jet Shapes
Matrix–Element
ATLASTopTagger
Mass–Drop+Filter
JHTopTagger
TW
Planar Flow
Templates
N–jettiness
CMSTopTagger
Pruning
Trimming
CoM N–subjettiness (Kim)
EEC
HEPTopTagger
(+ dipolarity)
Twist
N–subjettiness (TvT)
Shower Deconstruction
Multi–variate tagger
Qjets

jet substructure field is full of activity

c. 2018

Jet Declustering

Seymour93

YSplitter

ATLASTopTagger

Jet Shapes

Matrix–Element

Mass–Drop+Filter

modified mass drop
soft drop
iterated soft drop
recursive soft drop

Tagger

TW — Planar Flow

Tagger

Pruning

N–jettiness

Trimming

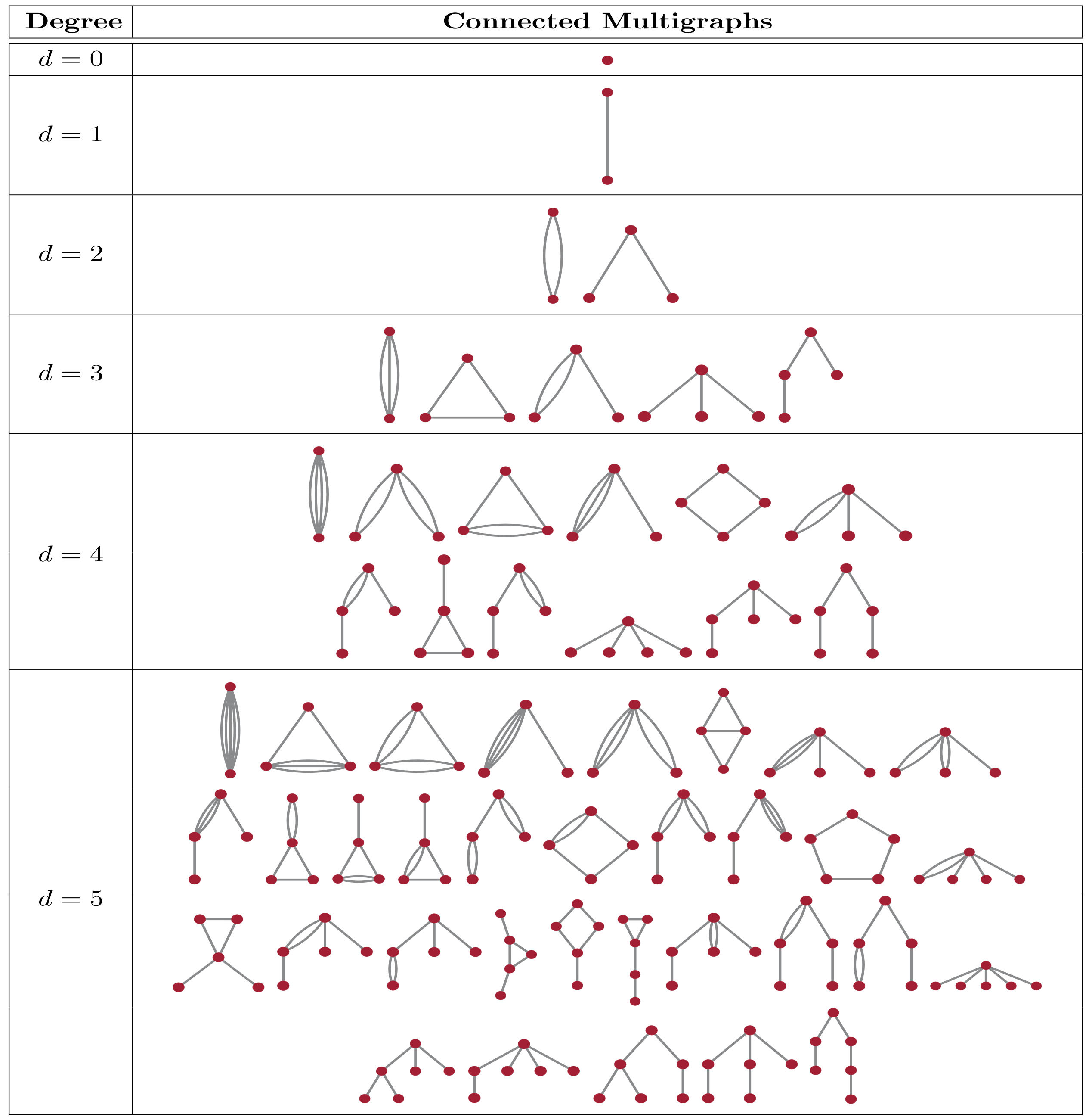
CoM N–subjettiness (Kim)

HEPTopTagger
(+ dipolarity)

Twist

N–subjettiness (TvT)

EEC



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

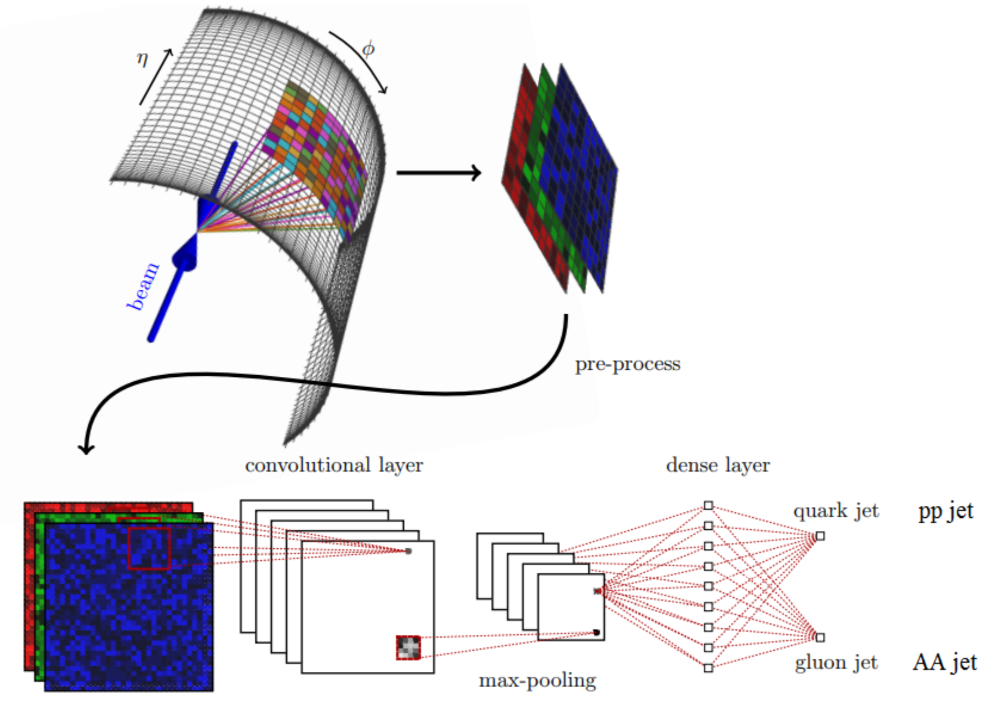
Shower Deconstruction

Multi–variate tagger

Qjets

machine learning
DNN, CNN,
RNN, LSTM, etc

classification without labels
weak supervision



etc.

Tagging on core n-prong structure

similar to asking for 2 jets in Z' search or 3 jets for a hadronic top

Tagging on energy flow pattern

not typically done in normal jet usage (closest analogue is jet veto in H→WW analyses)

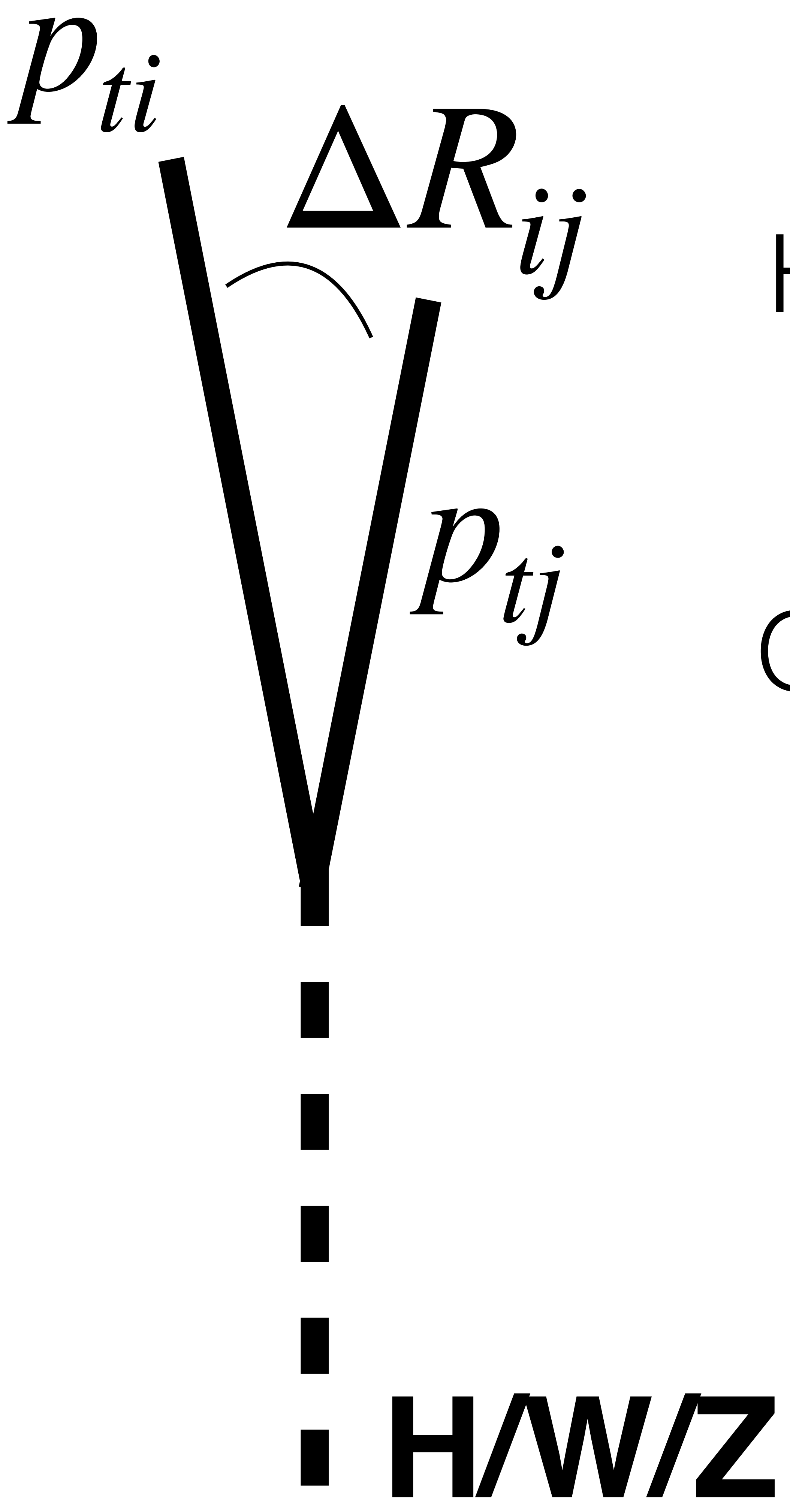
Grooming

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

Tagging two-prong decays

1. cutting on hard kinematics

“signals” (e.g. H decay) v. QCD backgrounds



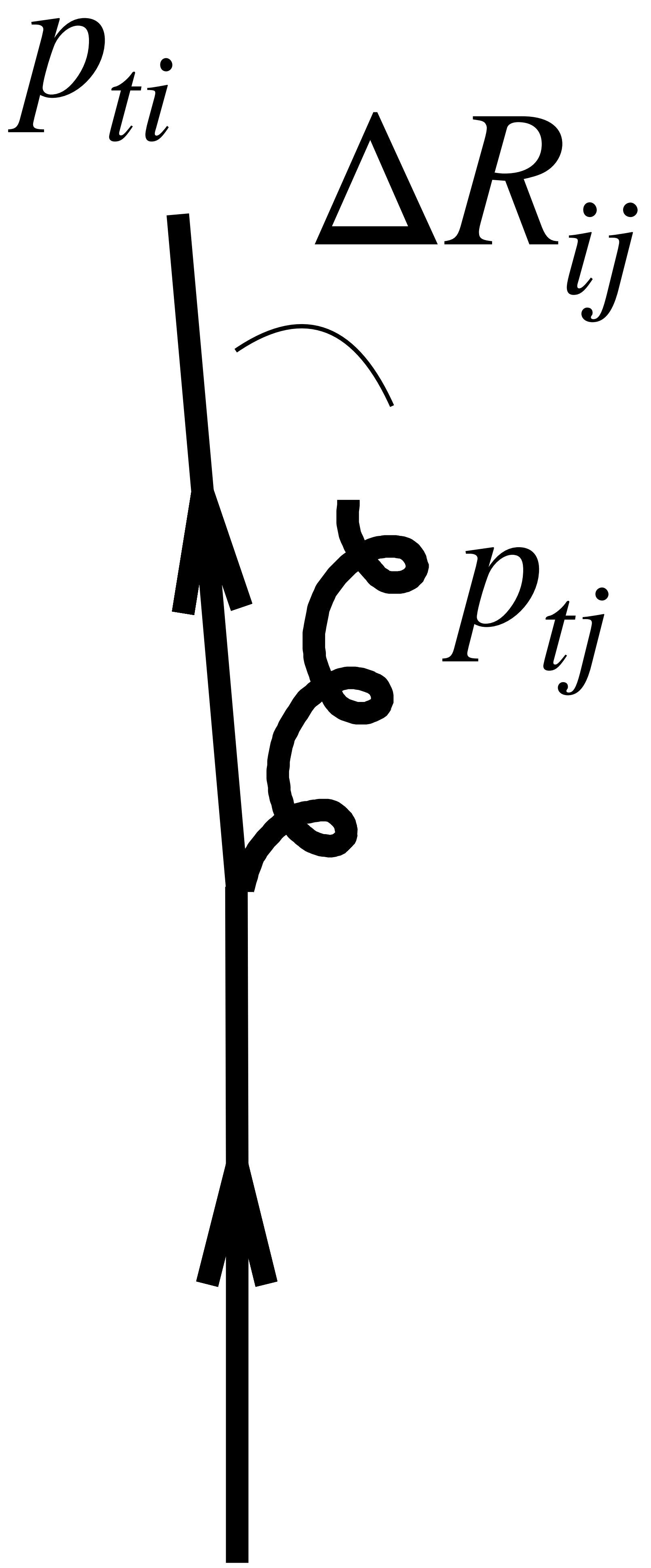
features in common

Higgs decay dominantly produces 2-prong structure.

Quark/gluon-induced jet can also branch to 2-prong structure

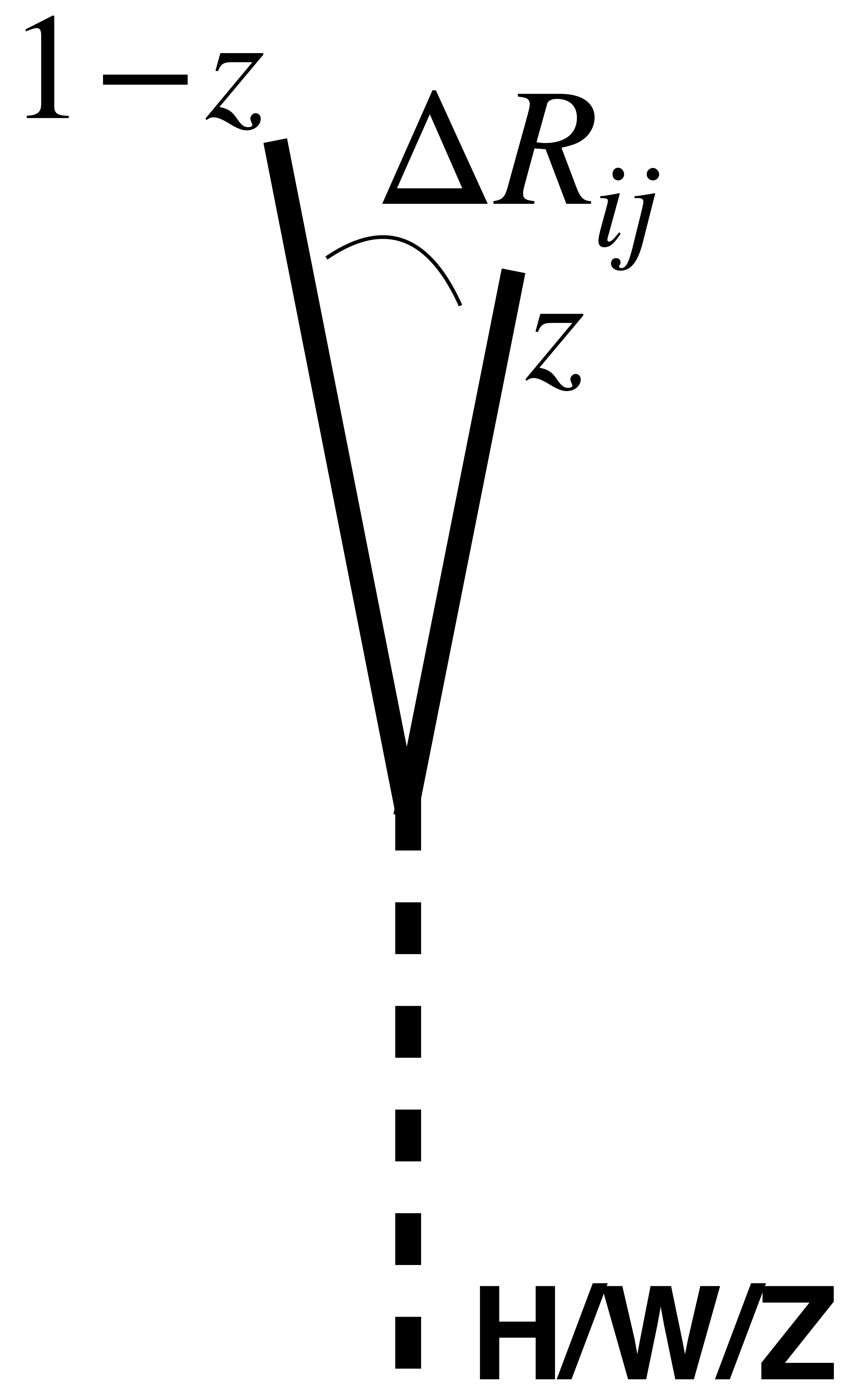
Resulting jet mass is

$$m^2 \simeq p_{ti} p_{tj} \Delta R_{ij}^2$$



[signal]

[background]



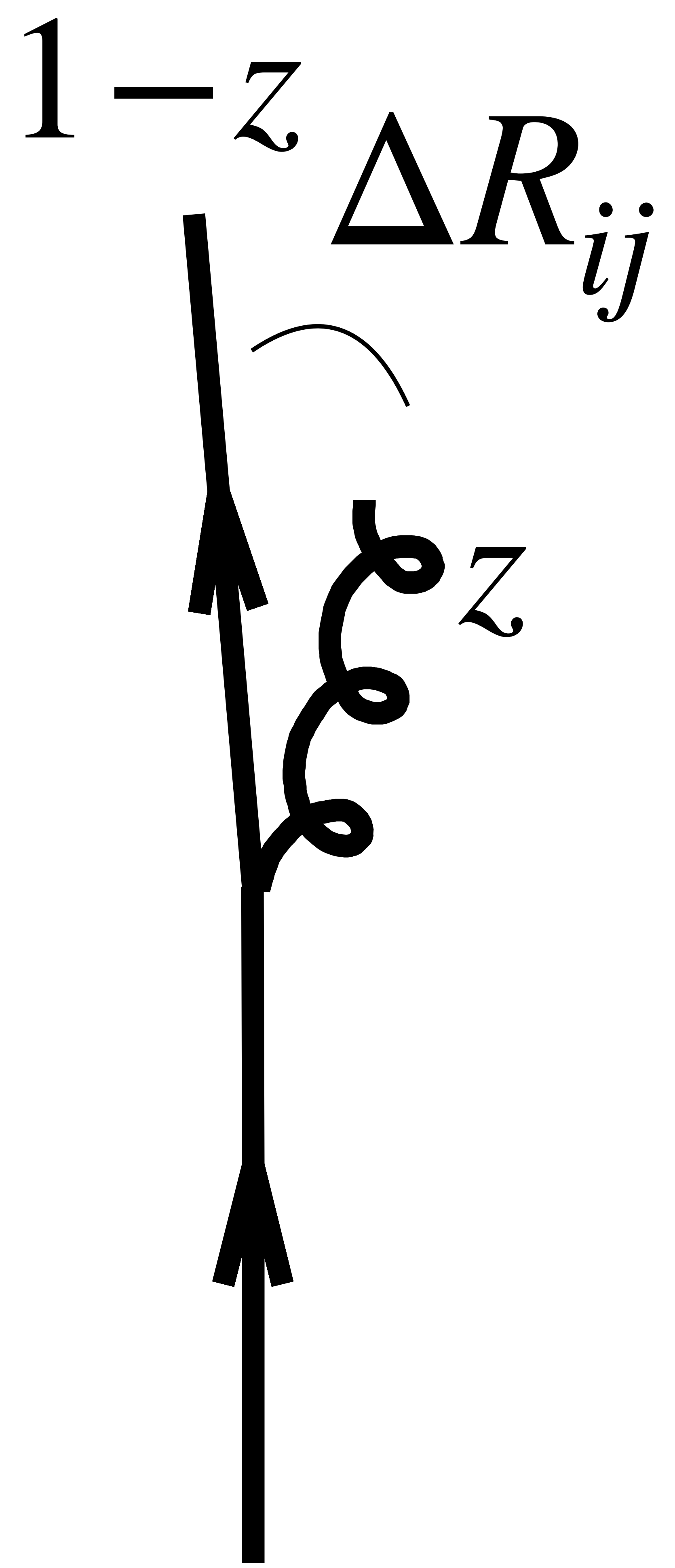
[signal]

features where they differ

energy-sharing between prongs

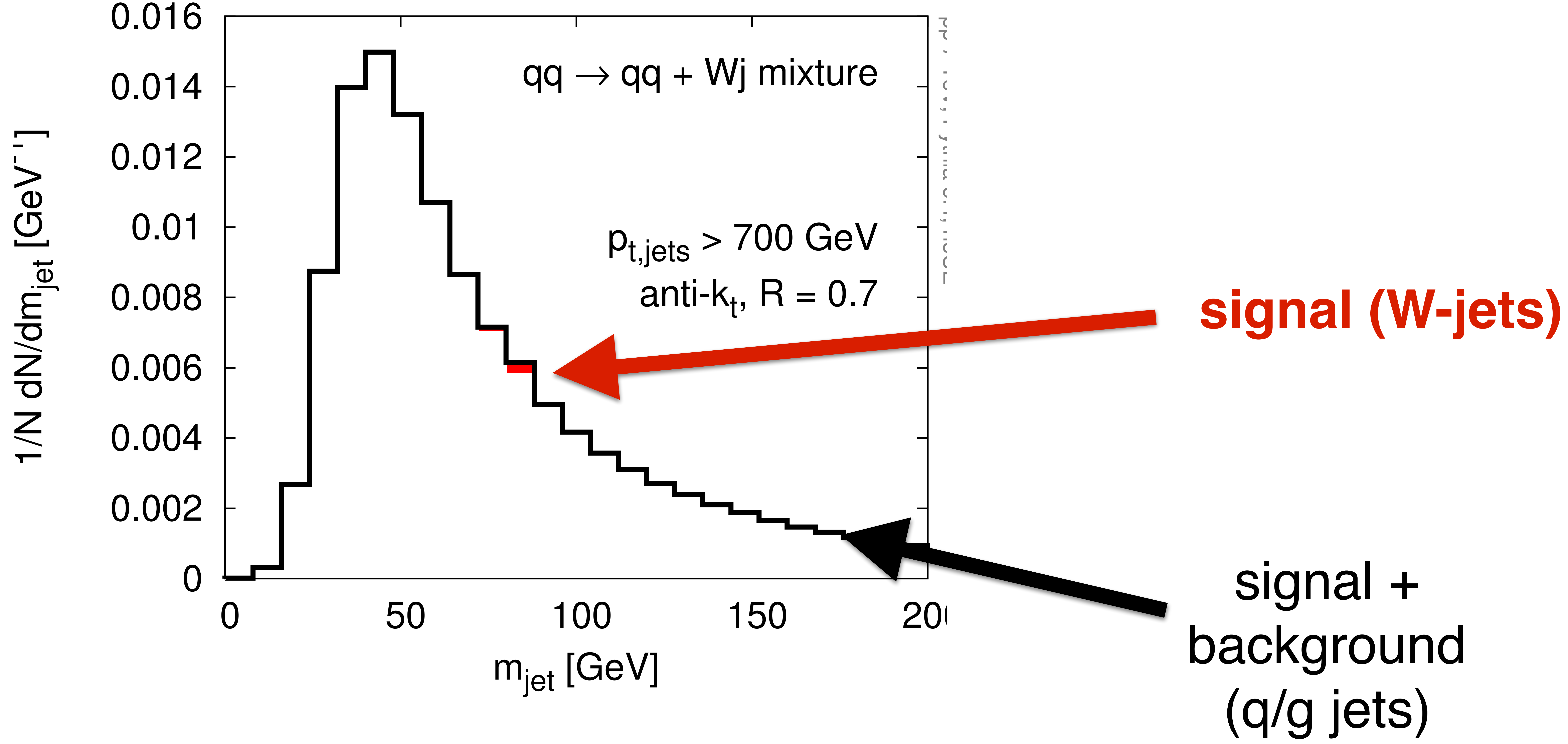
Higgs: $\frac{dP}{dz} \propto const$

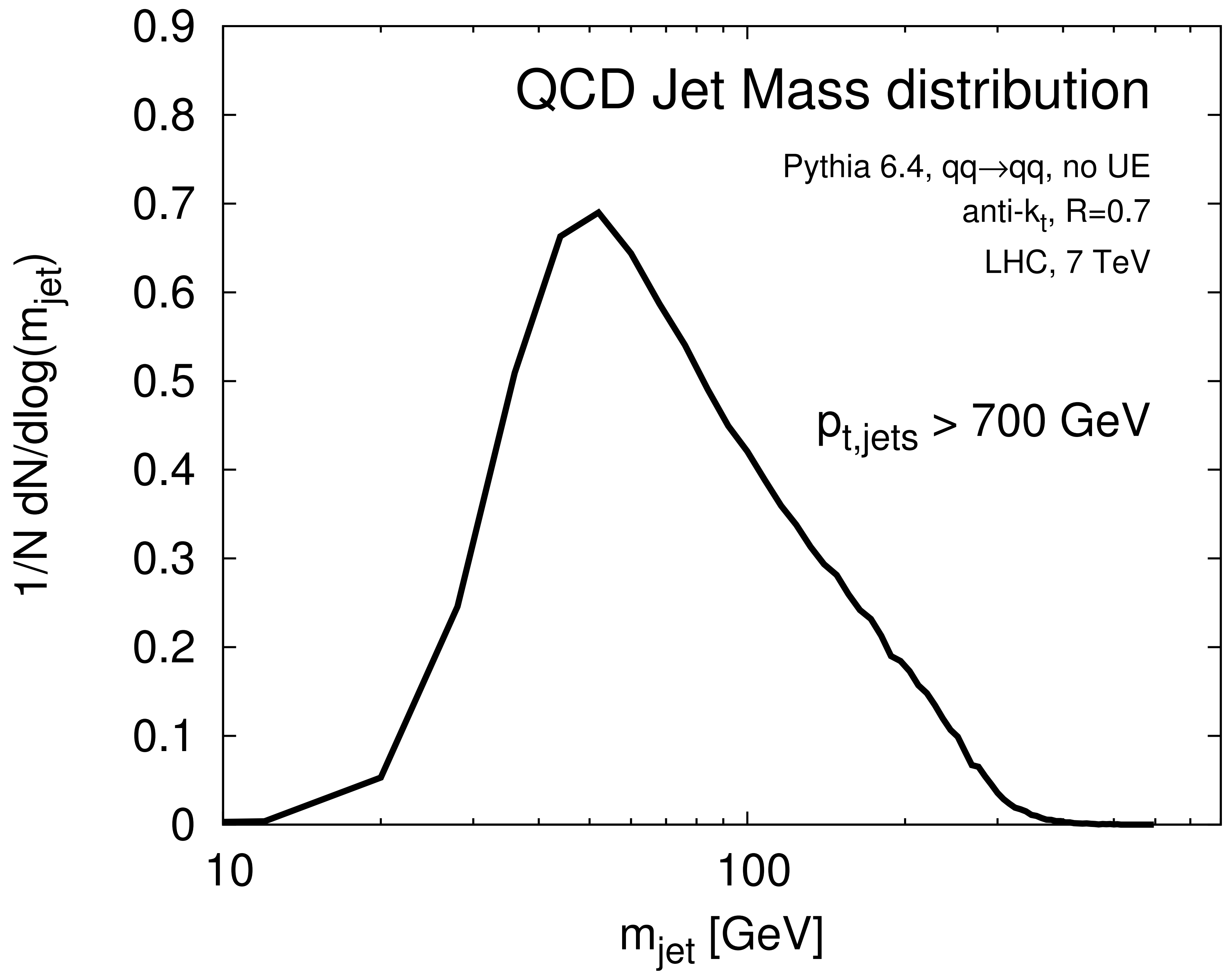
gluon emission: $\frac{dP}{dz} \propto \frac{1}{z}$



[background]

Look at a jet-mass distribution

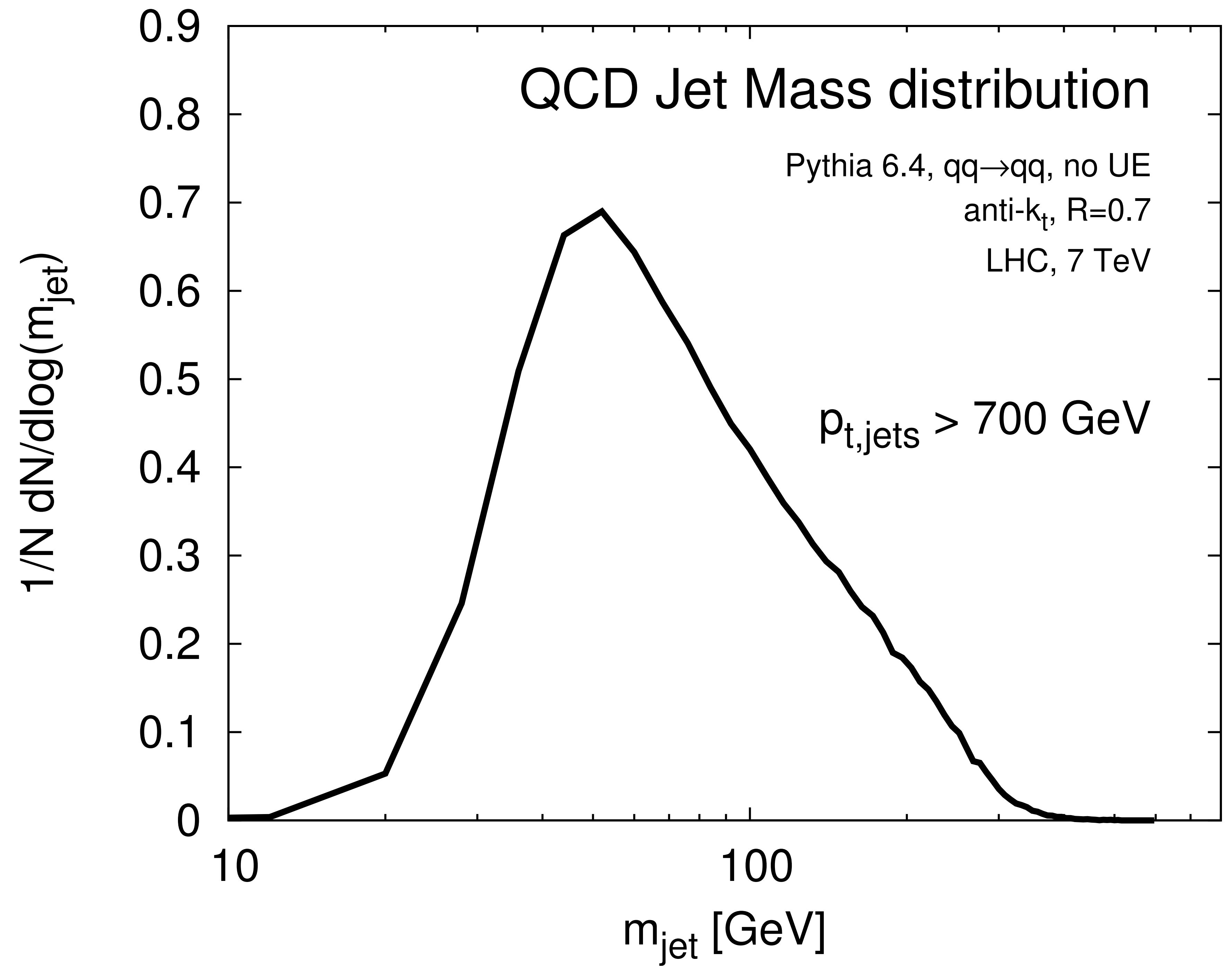


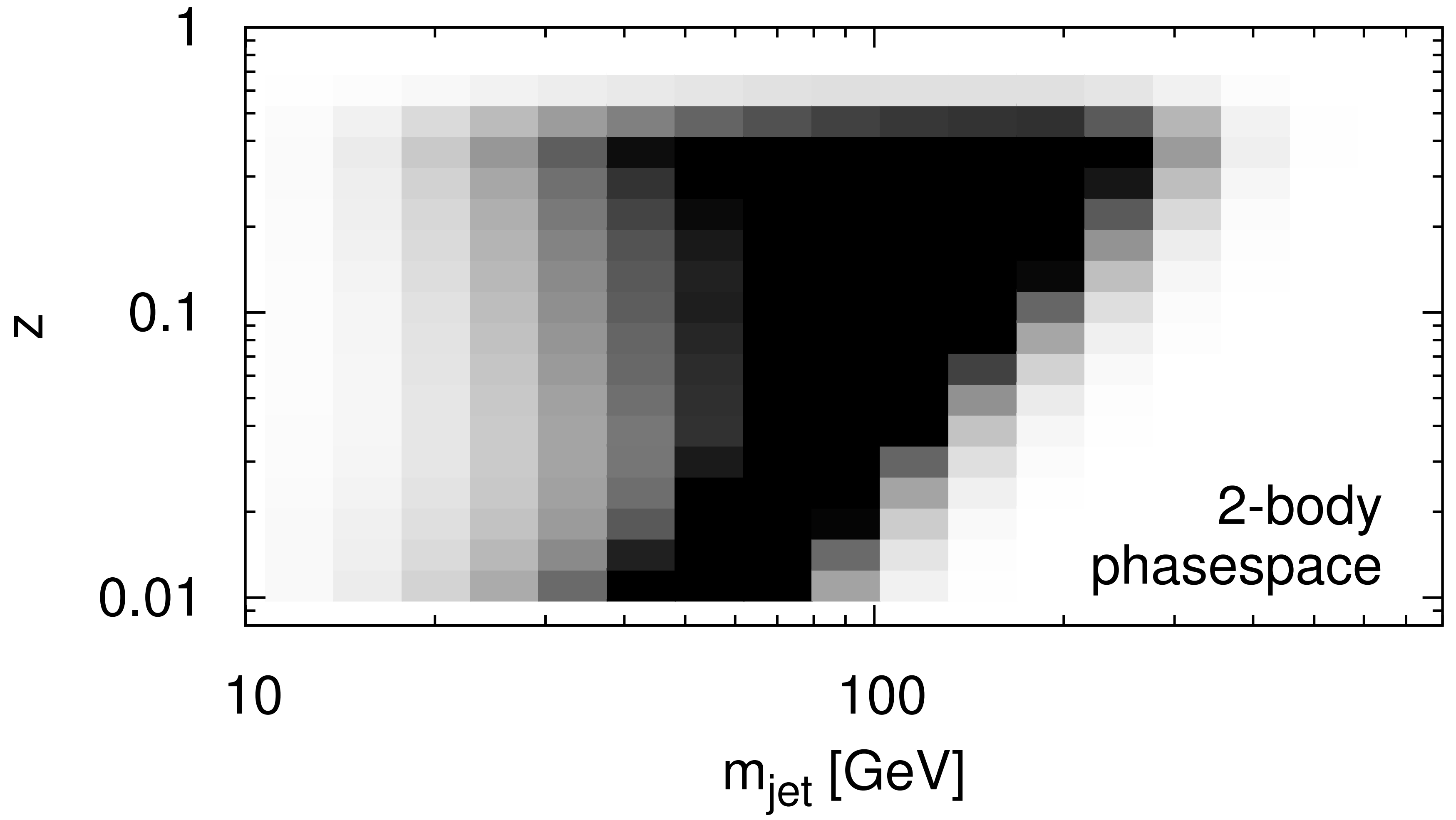


QCD jet mass distribution has the approximate

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

Work from '80s and '90s





QCD jet mass distribution has the approximate

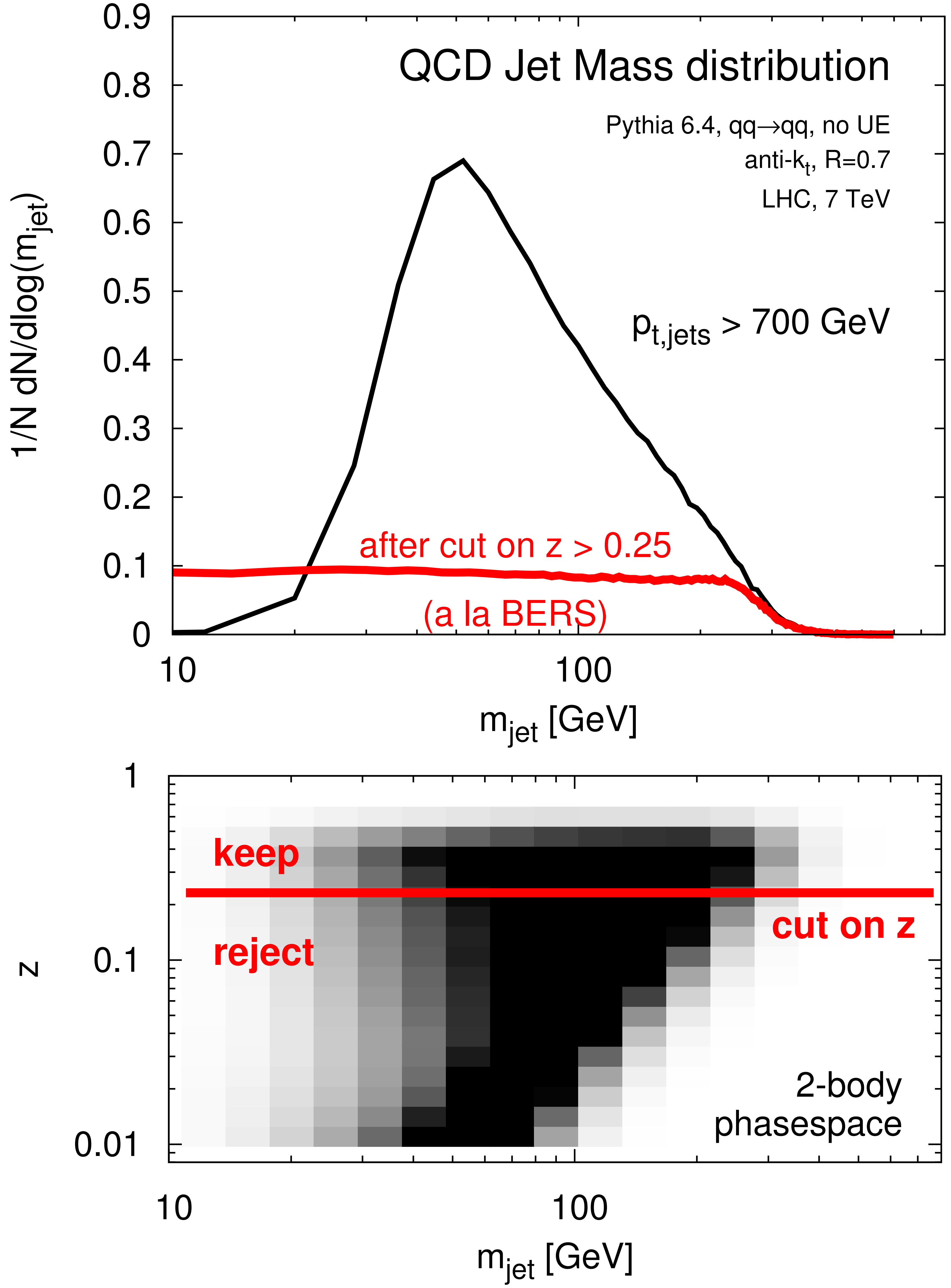
$$\frac{dN}{d\ln m} \sim \alpha_s \ln \frac{p_t R}{m} \times \text{Sudakov}$$

Work from '80s and '90s

The logarithm comes from integral over soft divergence of QCD:

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

Inside the jet mass



QCD jet mass distribution has the approximate

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

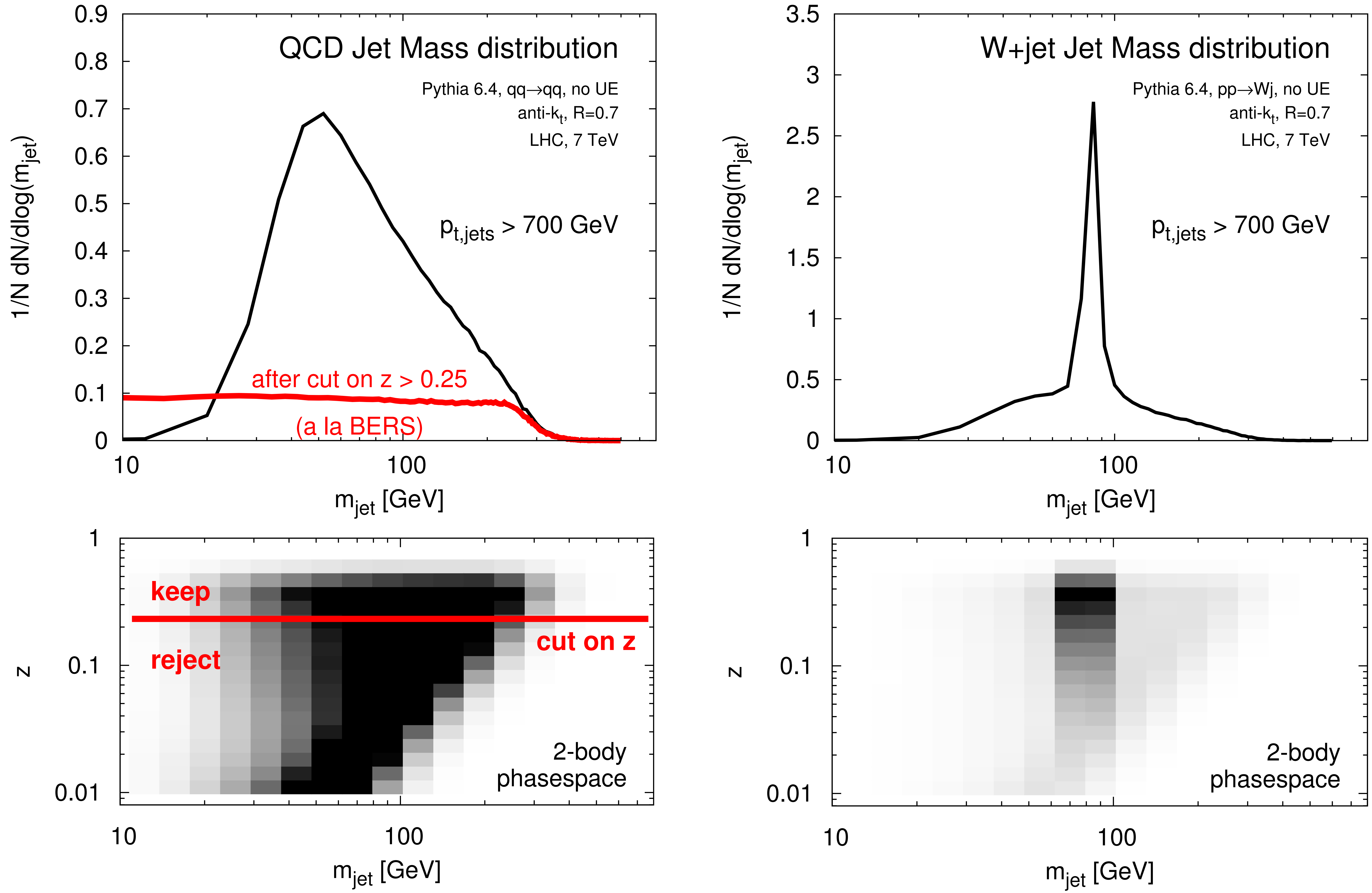
Work from '80s and '90s

The logarithm comes from integral over soft divergence of QCD:

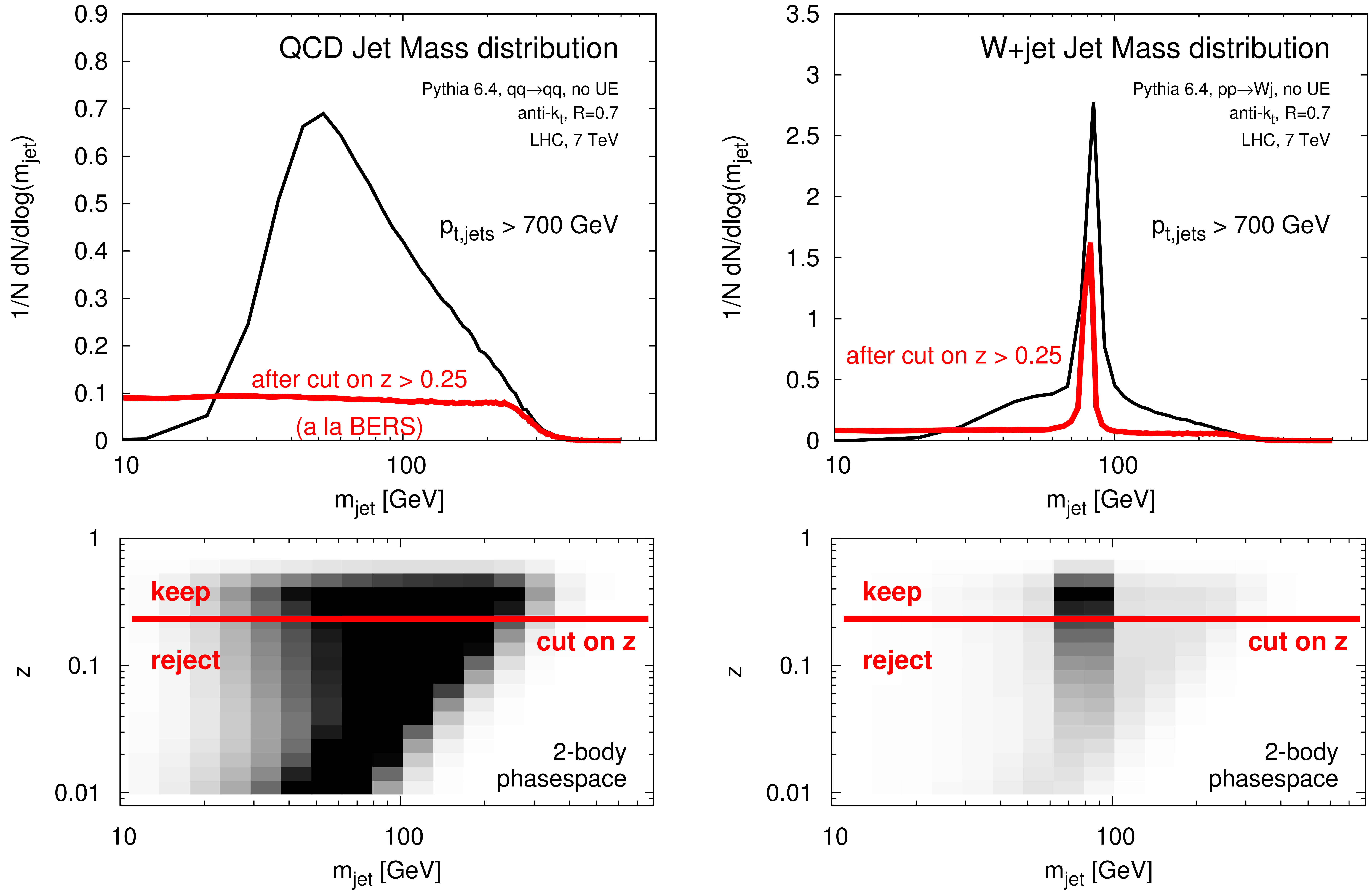
$$\int_{\frac{m^2}{p_t^2 R^2}}^{\frac{1}{2}} \frac{dz}{z}$$

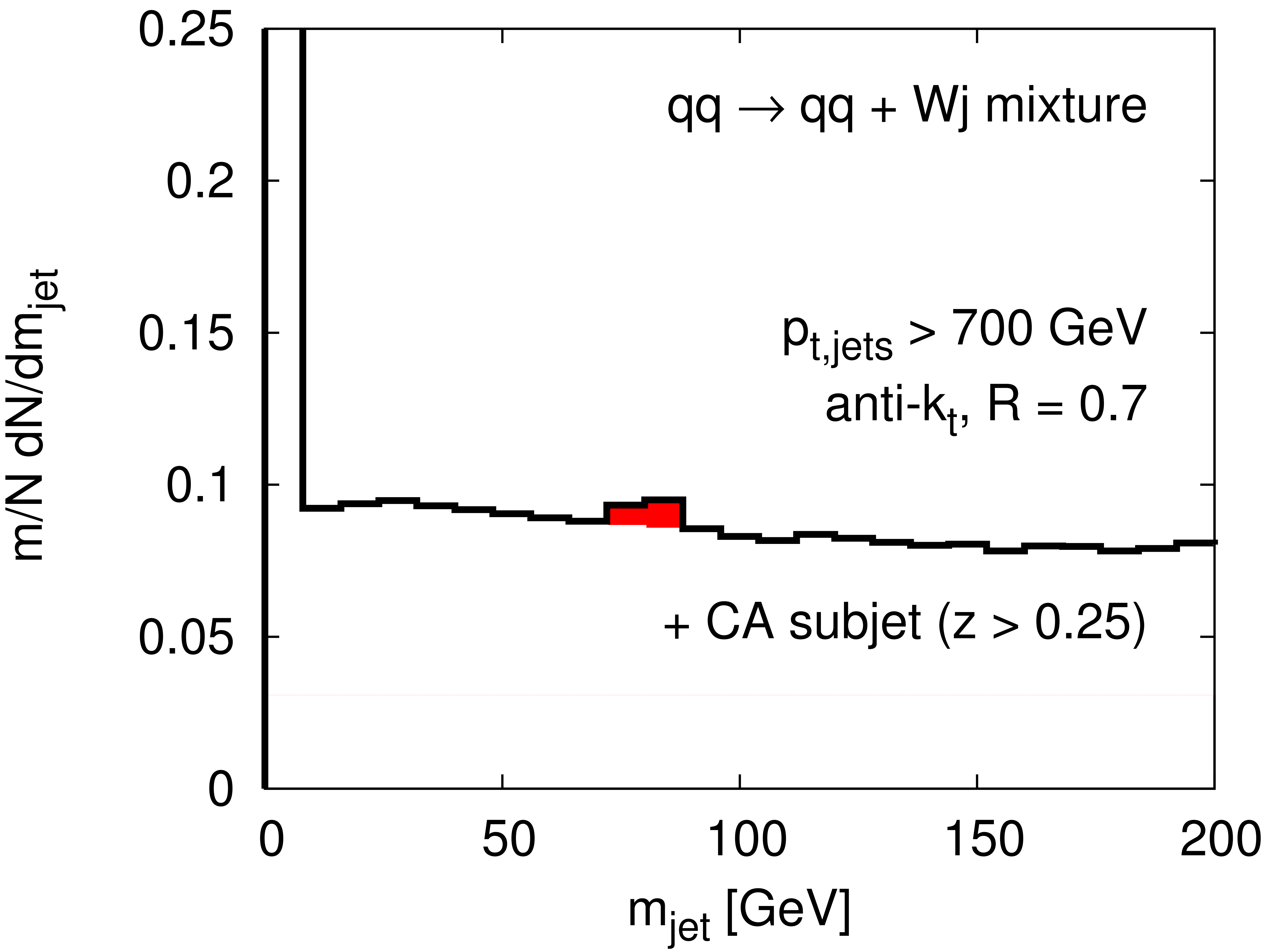
A hard cut on z reduces QCD background & simplifies its shape

Inside the jet mass



Inside the jet mass





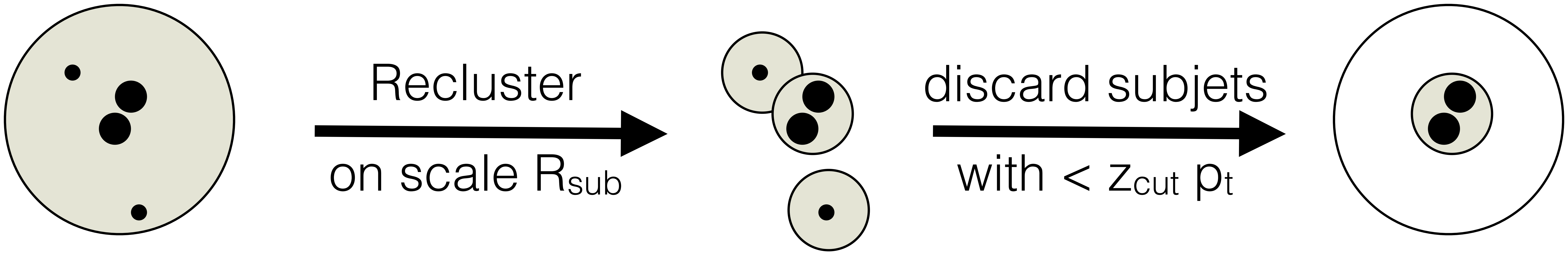
Signal + bkgd
after cut on z

cut on z helps “tag” the W-boson signal

Tagging two-prong decays

2. identifying hard kinematics

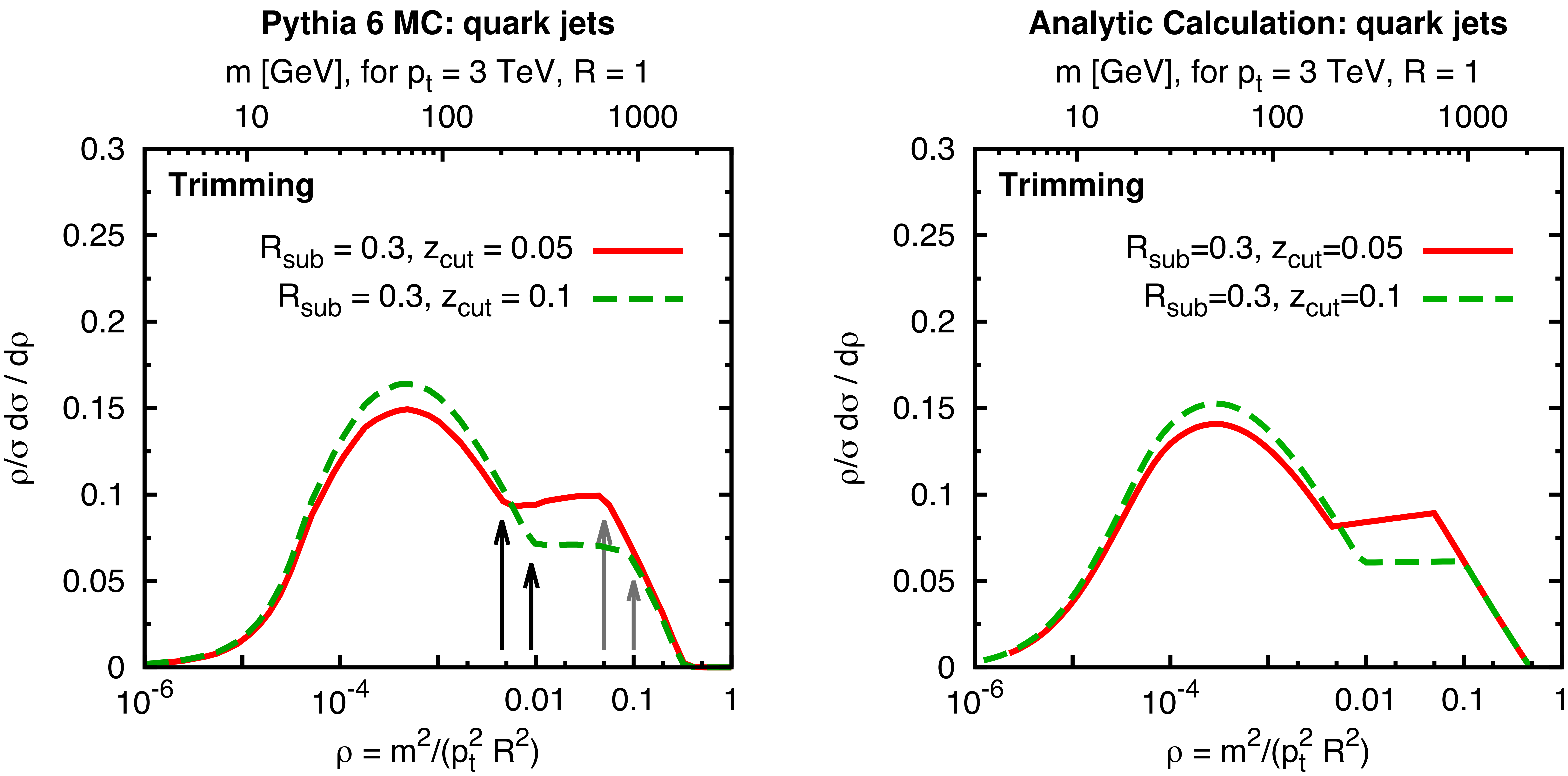
- Take all particles in a jet of radius R
- Recluster them into subjets with a jet definition using $R_{sub} < R$
- Keep only subjets with $p_t^{subjet} > z_{cut}\, p_t^{jet}$
- Recombine them into a single jet



Krohn, Thaler & Wang arXiv:0912.1342

widely used in ATLAS

Trimming: QCD jet mass distribution



arXiv:1307.0007
Dasgupta,
Fregoso,
Marzani & GPS

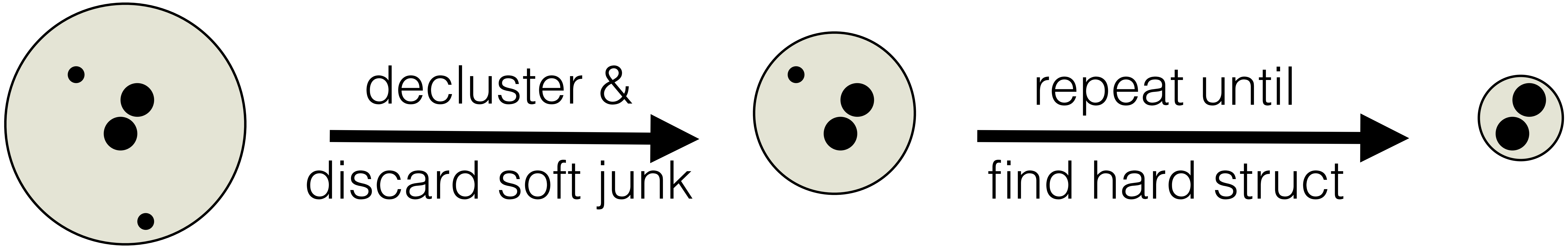
3 scales: two kinks (from z_{cut} & R_{sub}) and one Sudakov peak

Soft Drop (β=0 variant)

1. Recluster jet with Cambridge/Aachen algorithm
2. Undo last step of clustering to give two subjets i, j (with $p_{ti} < p_{tj}$)
3. If $p_{ti} > z_{cut}(p_{ti} + p_{tj})$ stop
4. otherwise discard i, go back to step 2 to decluster j

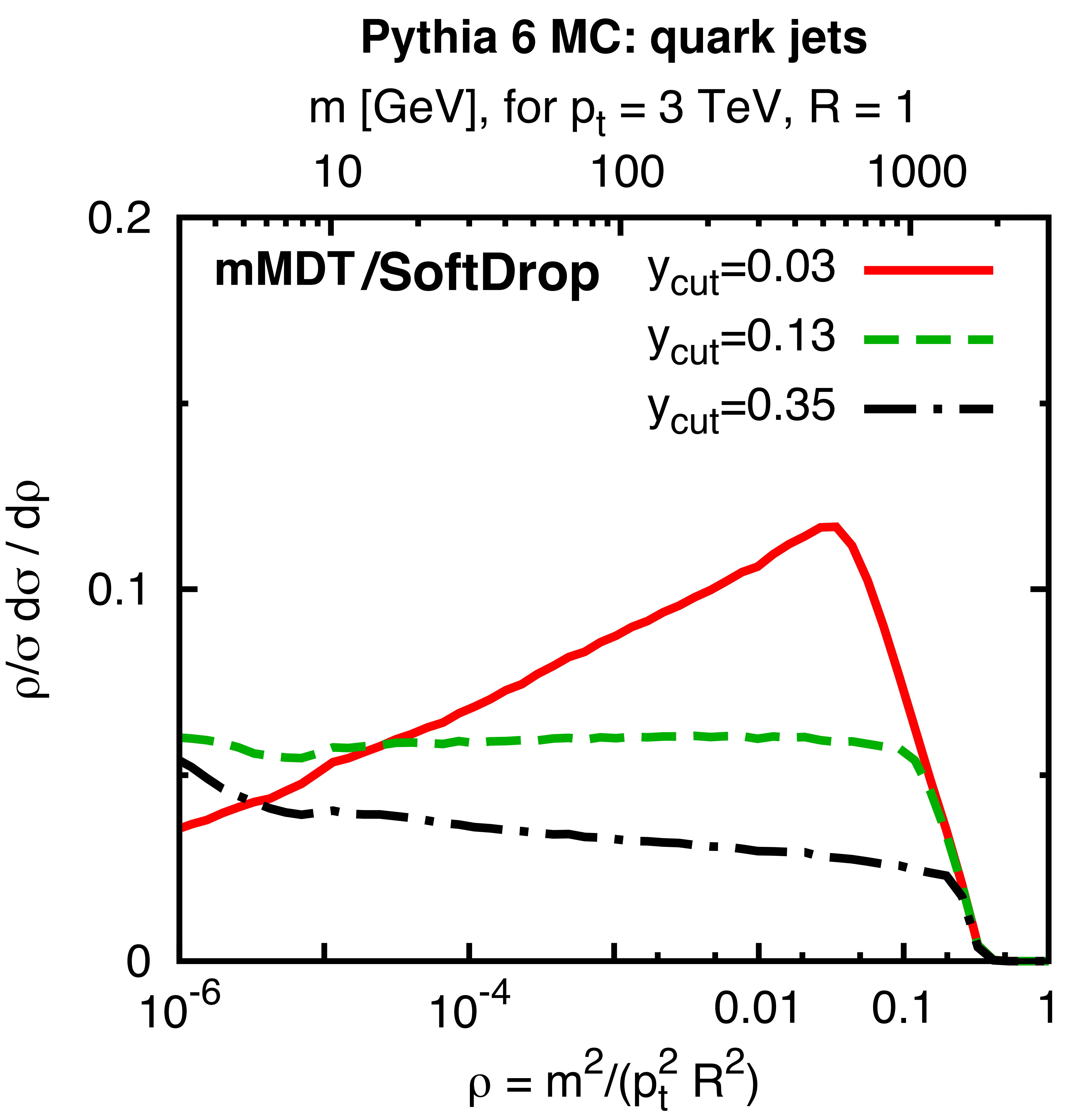
no manually specified Rcut

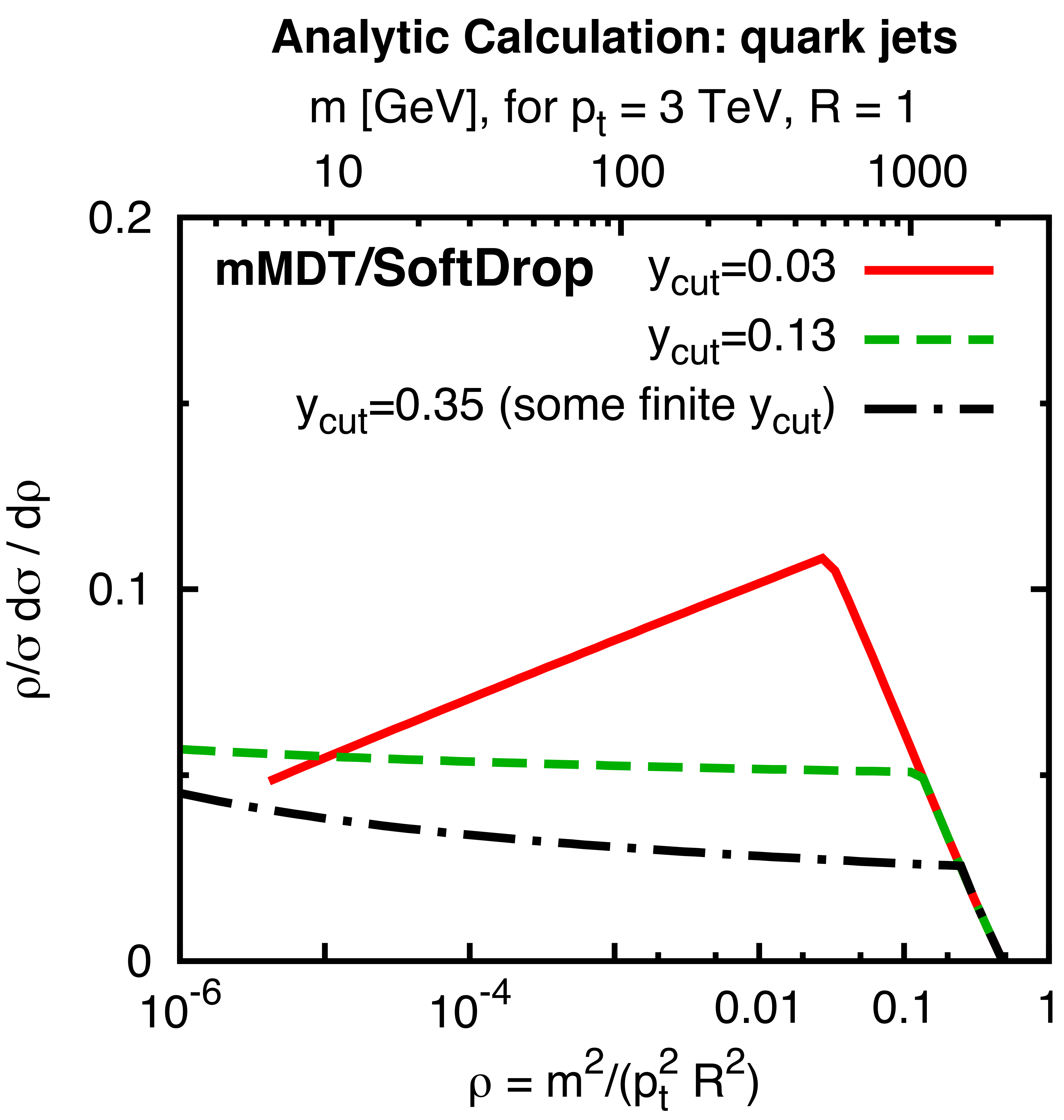
uses internal structure of jet to auto-zoom into right angular scale



Dasgupta, Fregoso, Marzani & GPS [arXiv:1307.0007],
descended from mass-drop tagger, Butterworth, Davison, Rubin & GPS [arXiv:0802.2470]

widely used in CMS





smooth distribution, apart from one kink (induced by z_{cut})

Plain jet mass

$$\Sigma(\rho) = e^{-D(\rho)} \cdot \frac{e^{-\gamma_E D'(\rho)}}{\Gamma(1 + D'(\rho))} \cdot \mathcal{N}(\rho)$$

$$D(\rho) \simeq \frac{\alpha_s C_F}{\pi} \left[\frac{1}{2}\ln^2\frac{1}{\rho} - \frac{3}{4}\ln\frac{1}{\rho} + \mathcal{O}(1)\right], \qquad \text{(fixed coupling approx.)}\,,$$

Note $\ln^2 \rho$

SoftDrop(mMDT) jet mass

$$\Sigma^{(\text{mMDT})}(\rho) = \exp\left[-\frac{\alpha_s C_F}{\pi}\left(\ln\frac{y_{\text{cut}}}{\rho}\ln\frac{1}{y_{\text{cut}}} - \frac{3}{4}\ln\frac{1}{\rho} + \frac{1}{2}\ln^2\frac{1}{y_{\text{cut}}}\right)\right], \quad (\text{for } \rho < y_{\text{cut}})\,,$$

Note $\ln \rho$

in fixed-coupling approximation for simplicity

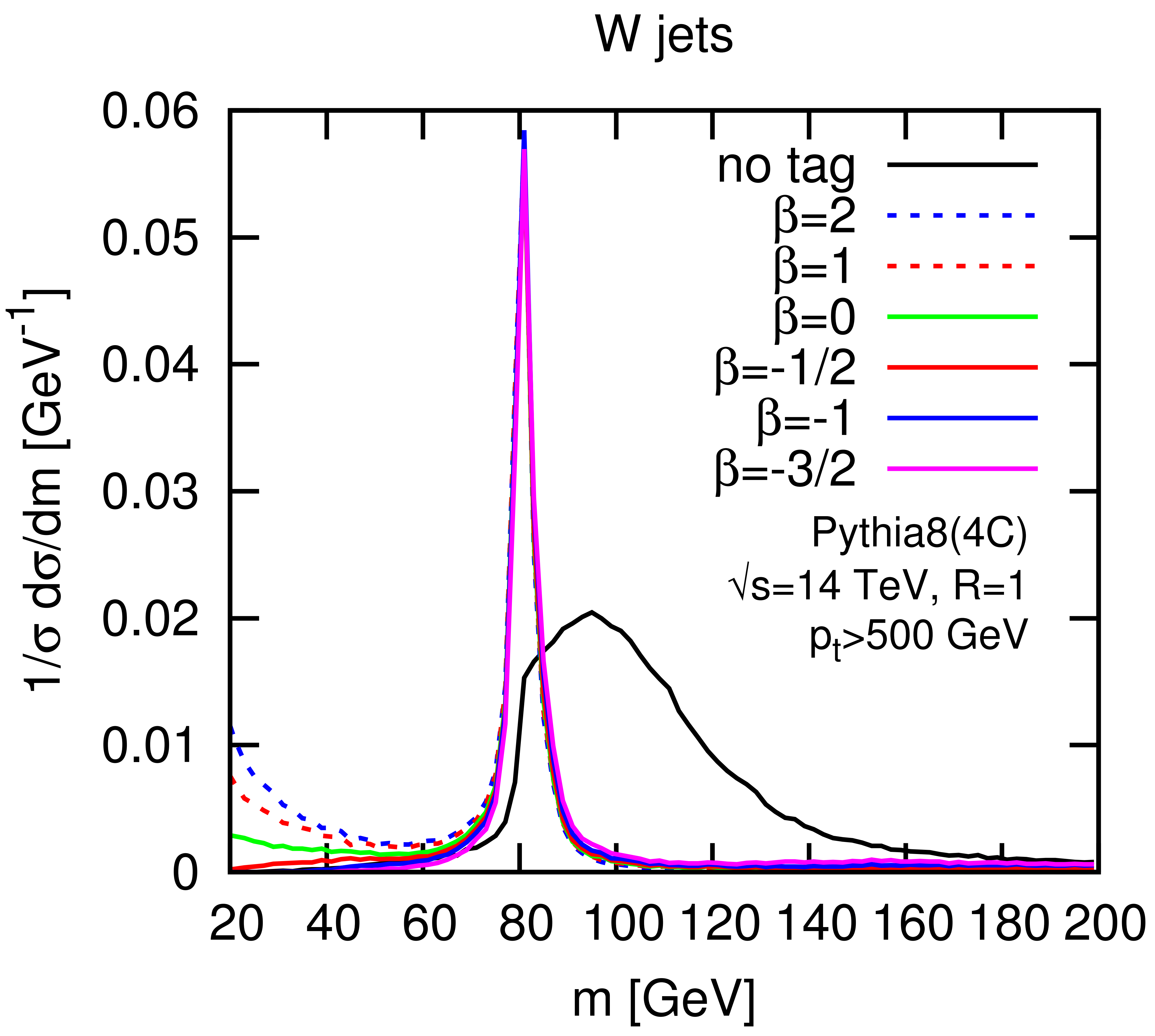
Soft Drop (with β)

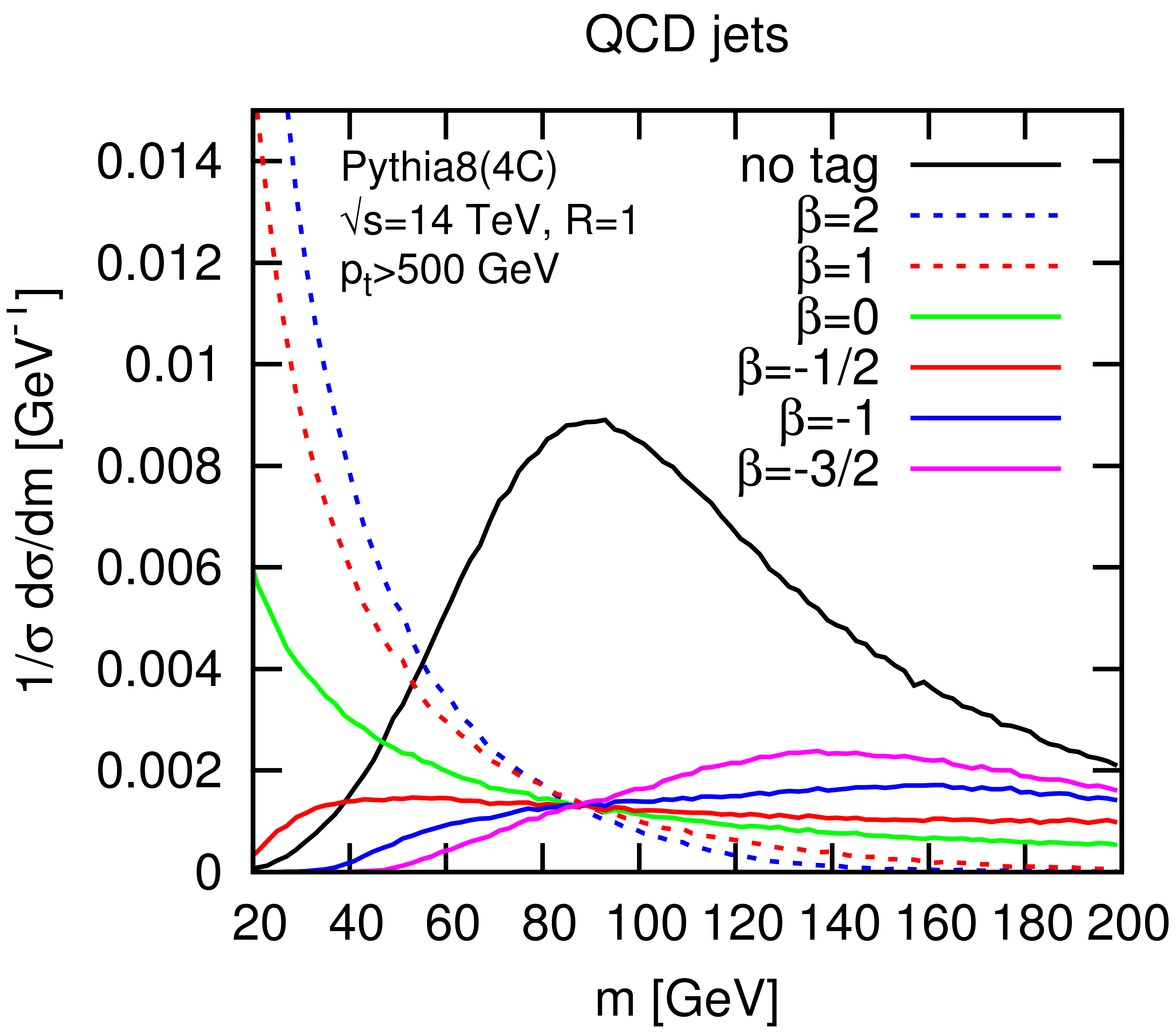
1. Recluster jet with Cambridge/Aachen algorithm
2. Undo last step of clustering to give two subjets i, j (with $p_{ti} < p_{tj}$)
3. If $p_{ti} > z_{cut}(p_{ti} + p_{tj}) \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$
4. otherwise discard i, and go back to step 2, now with j
5. If j is a singleton either discard it (tagging mode) or leave j as the final "groomed" jet

β > 0 cuts less aggressively as angles decrease

β < 0 cuts more aggressively as angles decrease

Larkoski, Marzani, Soyez & Thaler arXiv:1402.2657





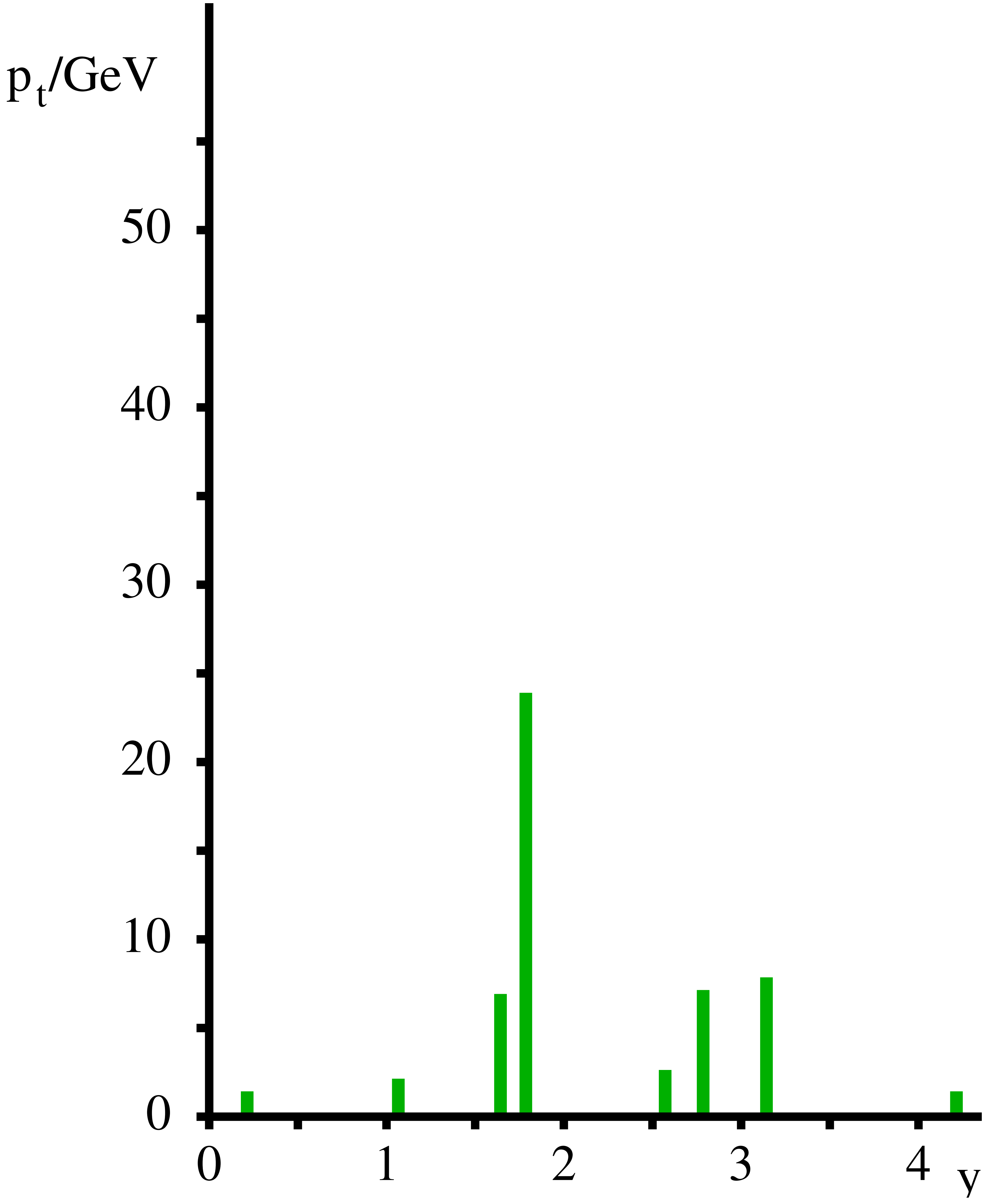
NB: z_{cut} chosen to keep signal efficiency fixed at 35% for all β

Larkoski, Marzani, Soyez & Thaler arXiv:1402.2657

Tagging two-prong decays

3. why the Cambridge/ Aachen algorithm?

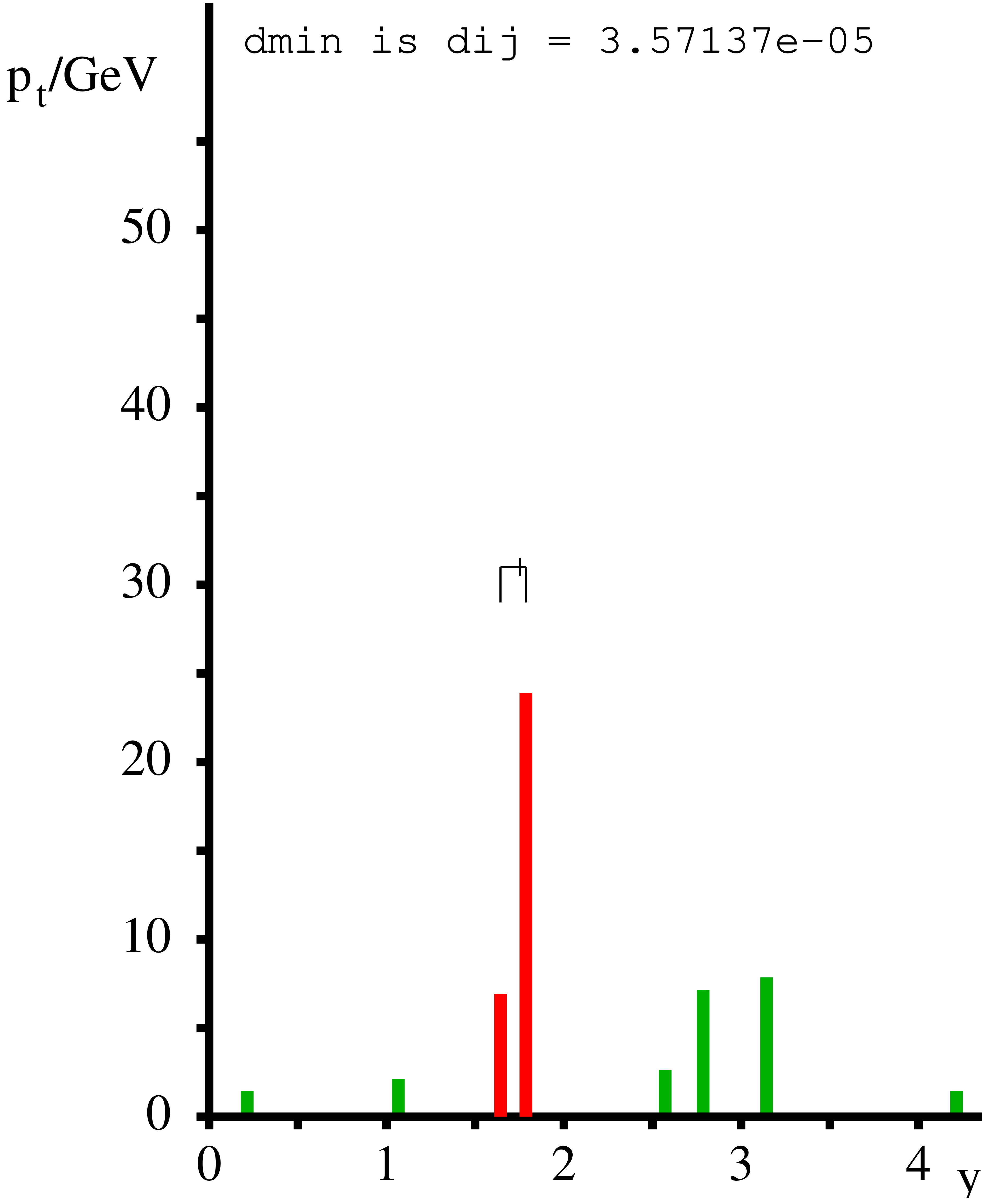
Identifying jet substructure: try out anti-k_t



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

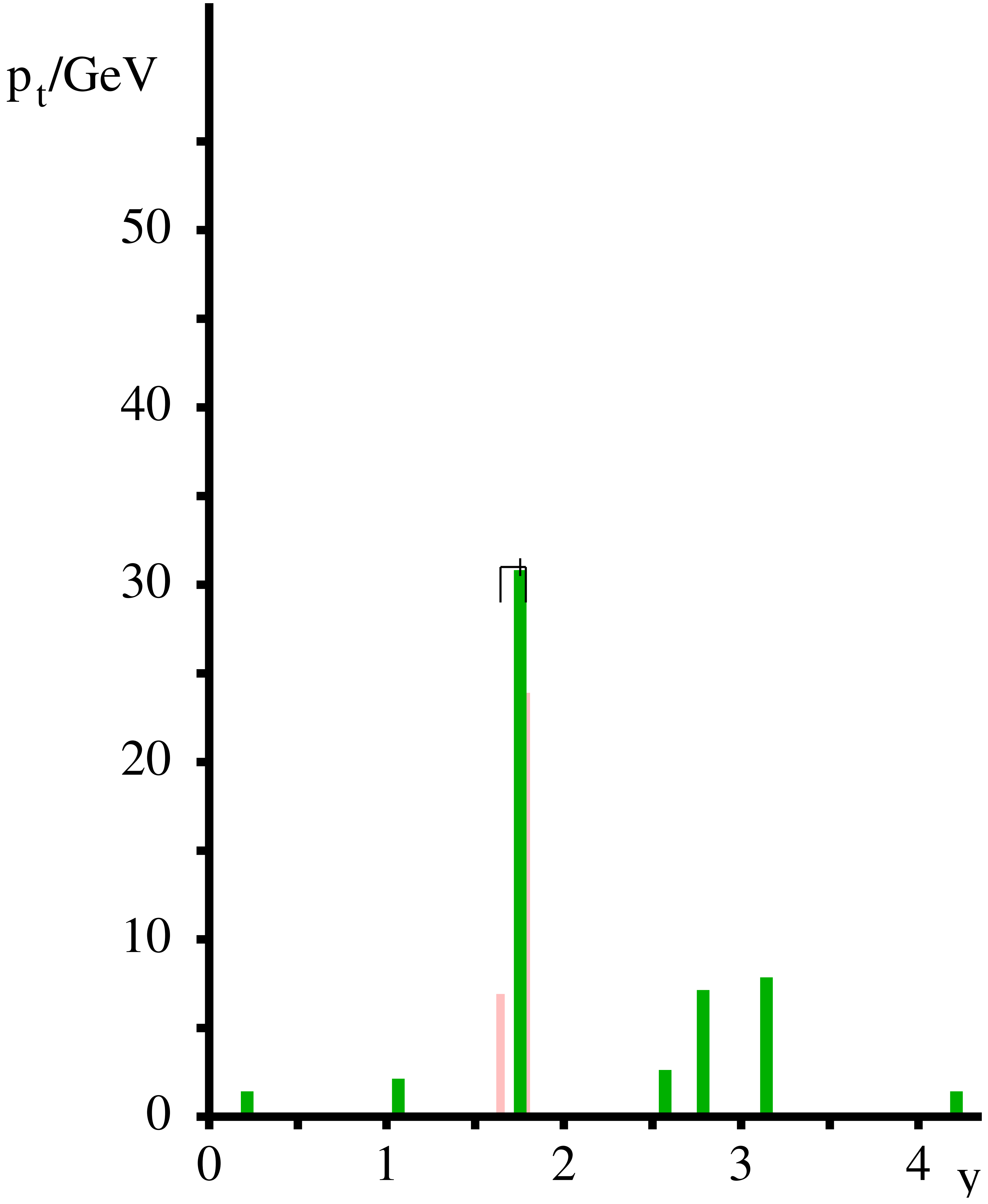
This is crucial for identifying the kinematic variables of the partons in the jets

Identifying jet substructure: try out anti-k_t



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

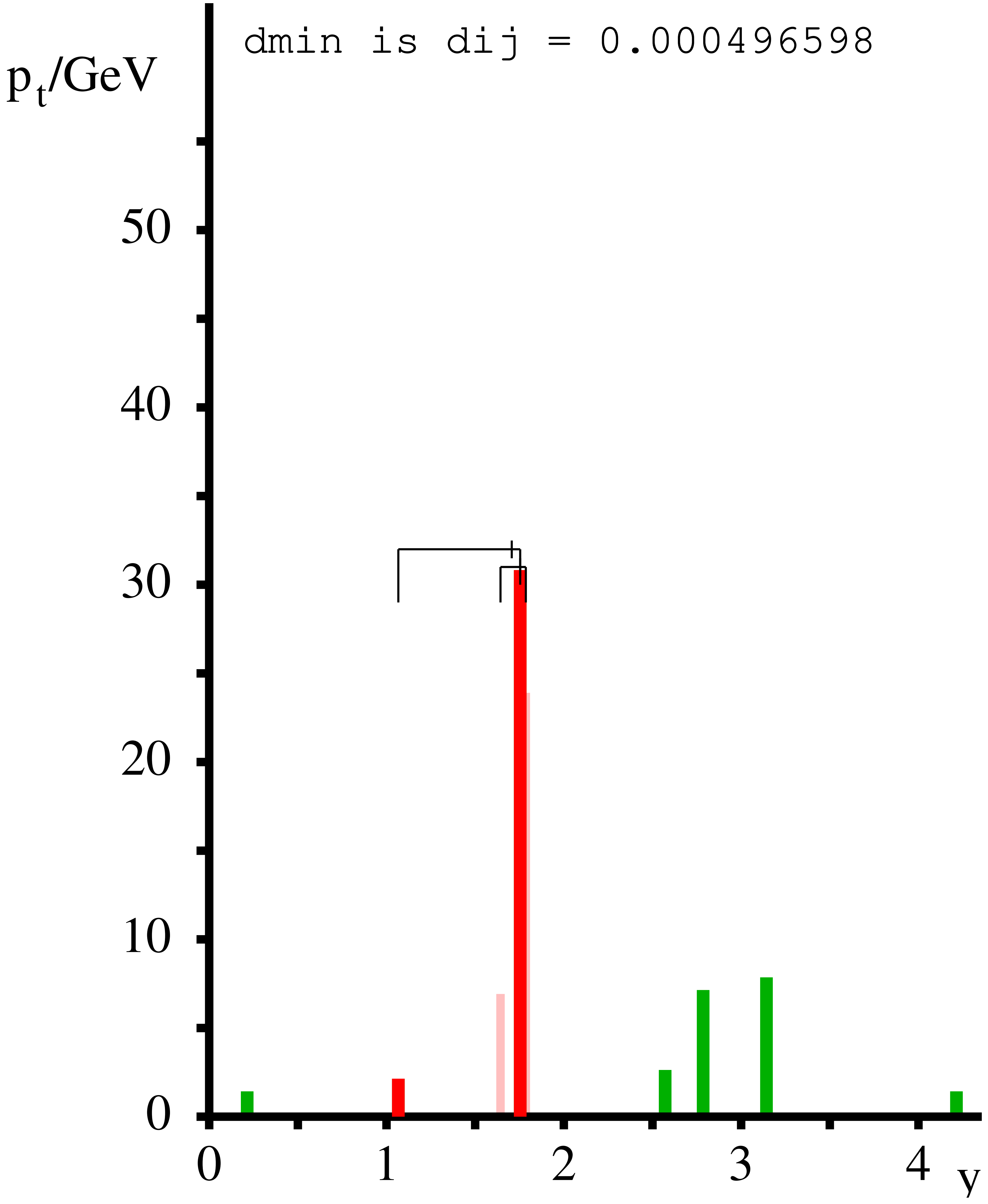
This is crucial for identifying the kinematic variables of the partons in the jets



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

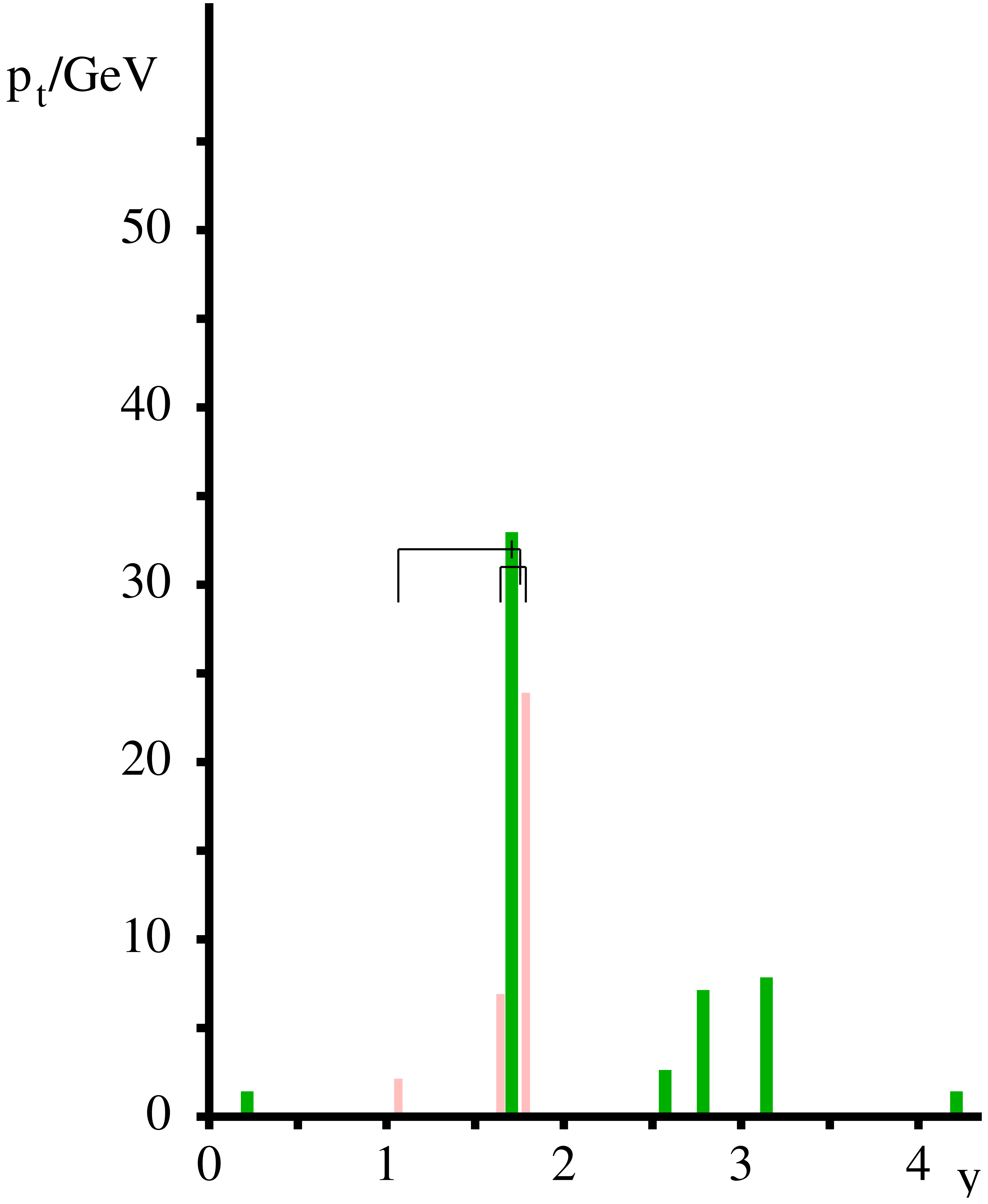
This is crucial for identifying the kinematic variables of the partons in the jets

Identifying jet substructure: try out anti-k_t



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

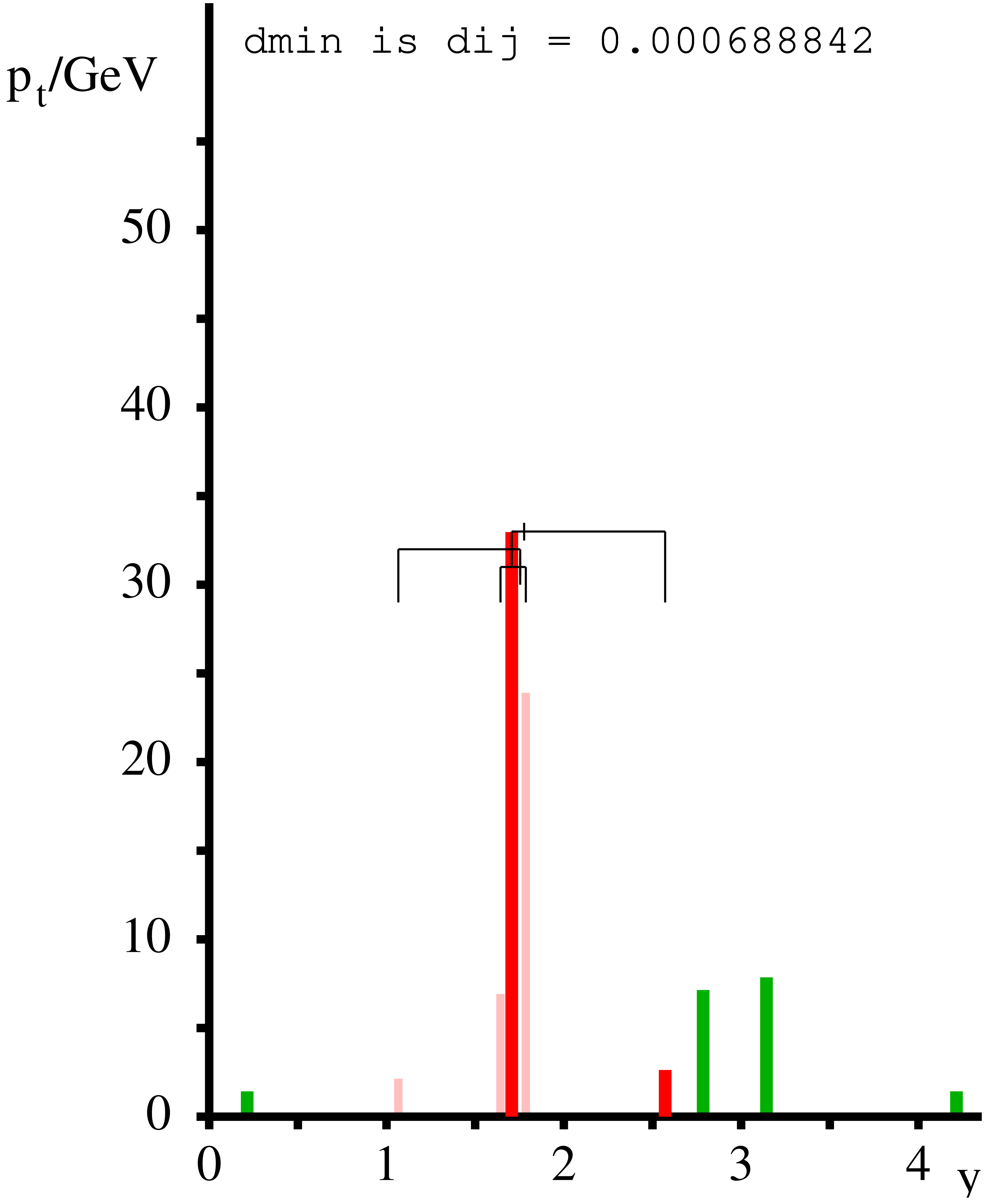
This is crucial for identifying the kinematic variables of the partons in the jets



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

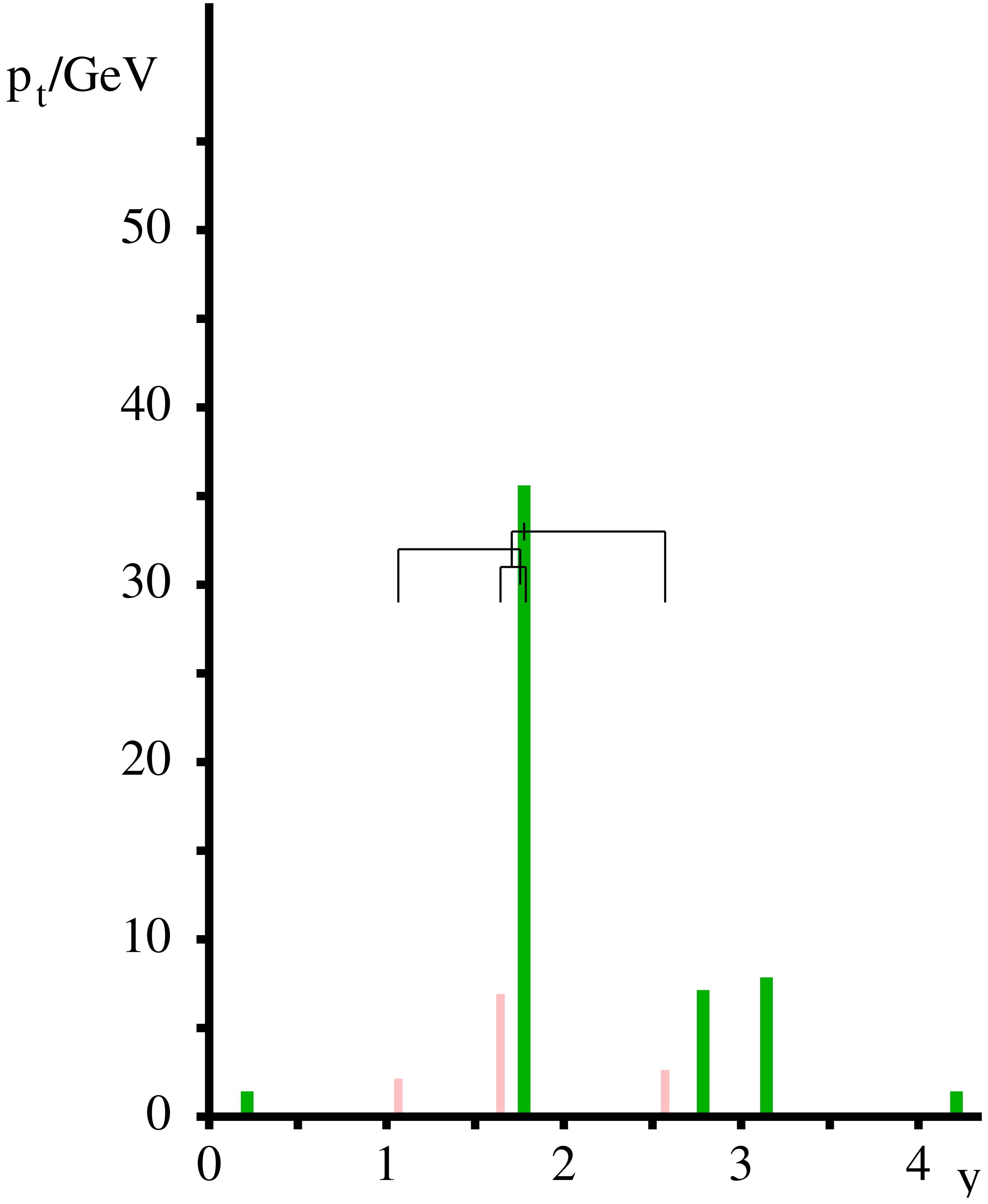
This is crucial for identifying the kinematic variables of the partons in the jets

Identifying jet substructure: try out anti-k_t



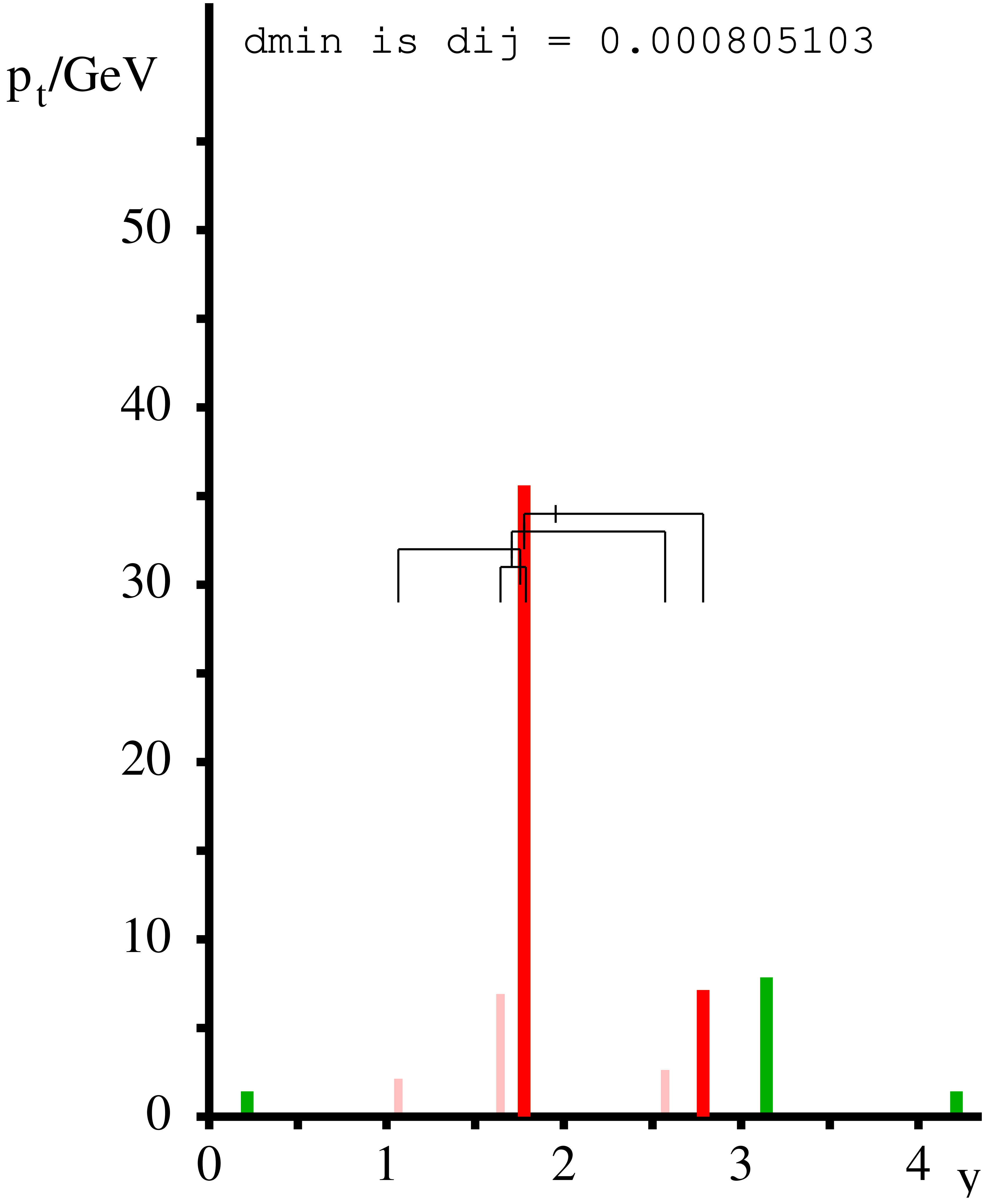
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jets



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

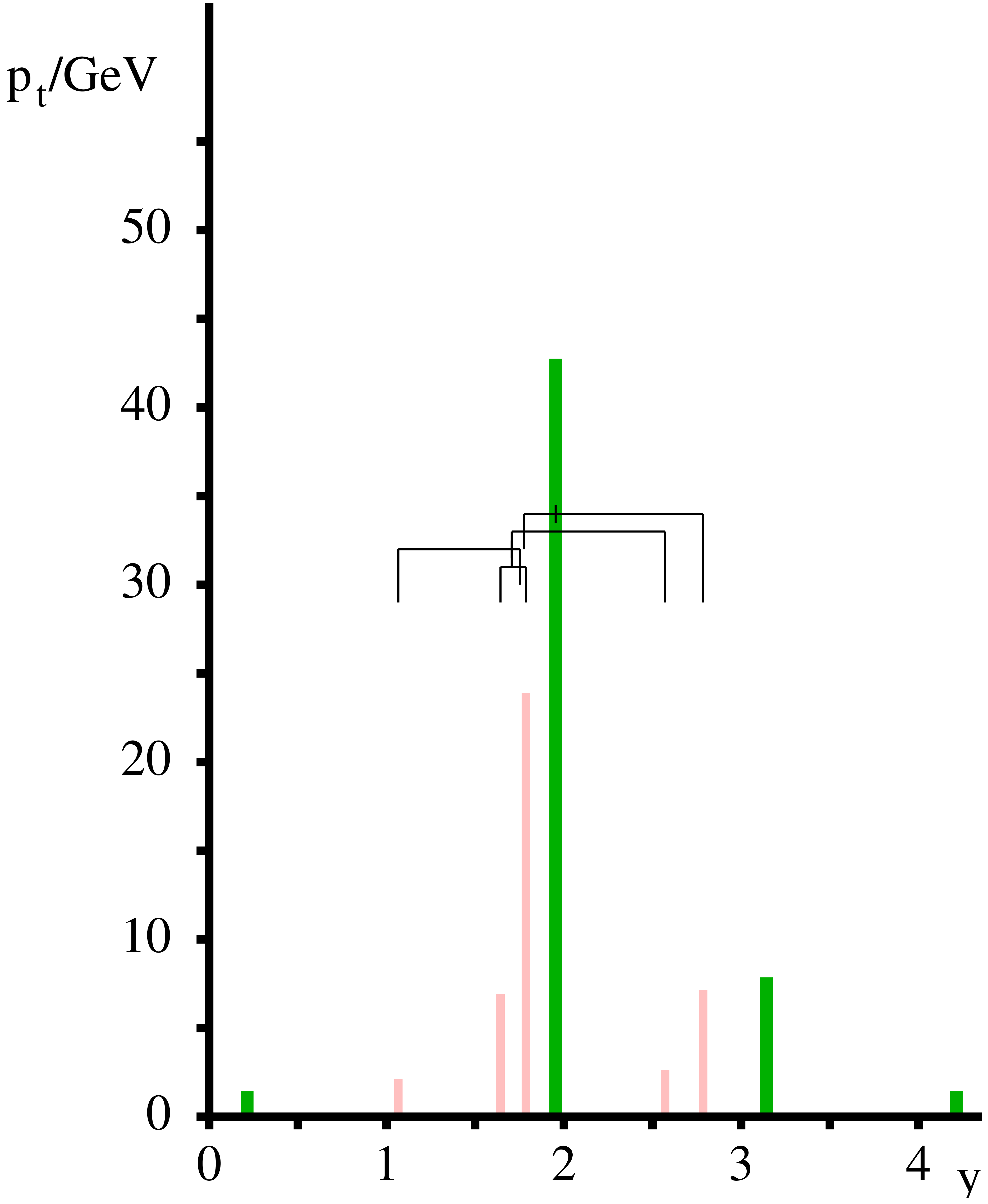
This is crucial for identifying the kinematic variables of the partons in the jets



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

This is crucial for identifying the kinematic variables of the partons in the jets

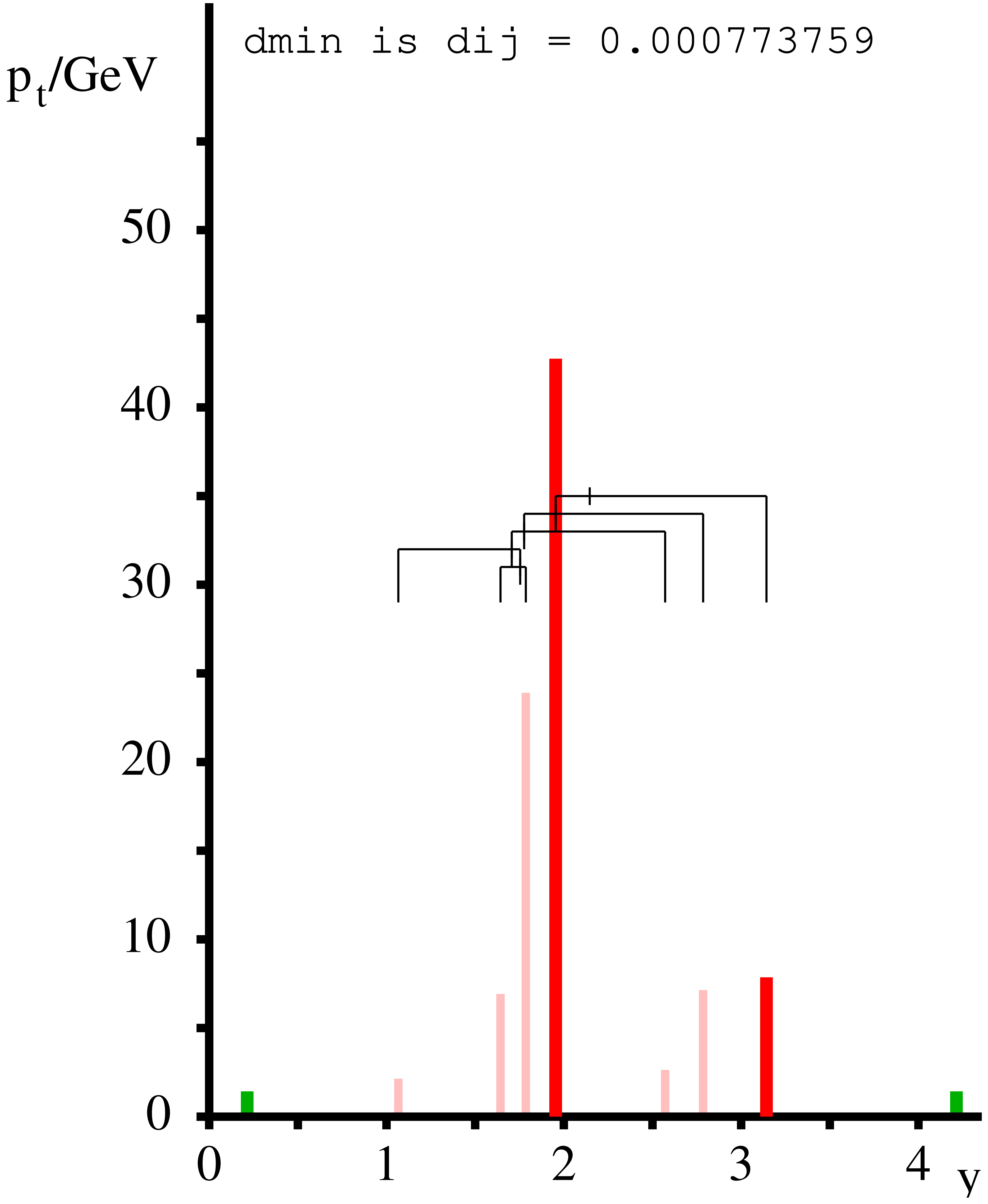
Identifying jet substructure: try out anti-k_t



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

This is crucial for identifying the kinematic variables of the partons in the jets

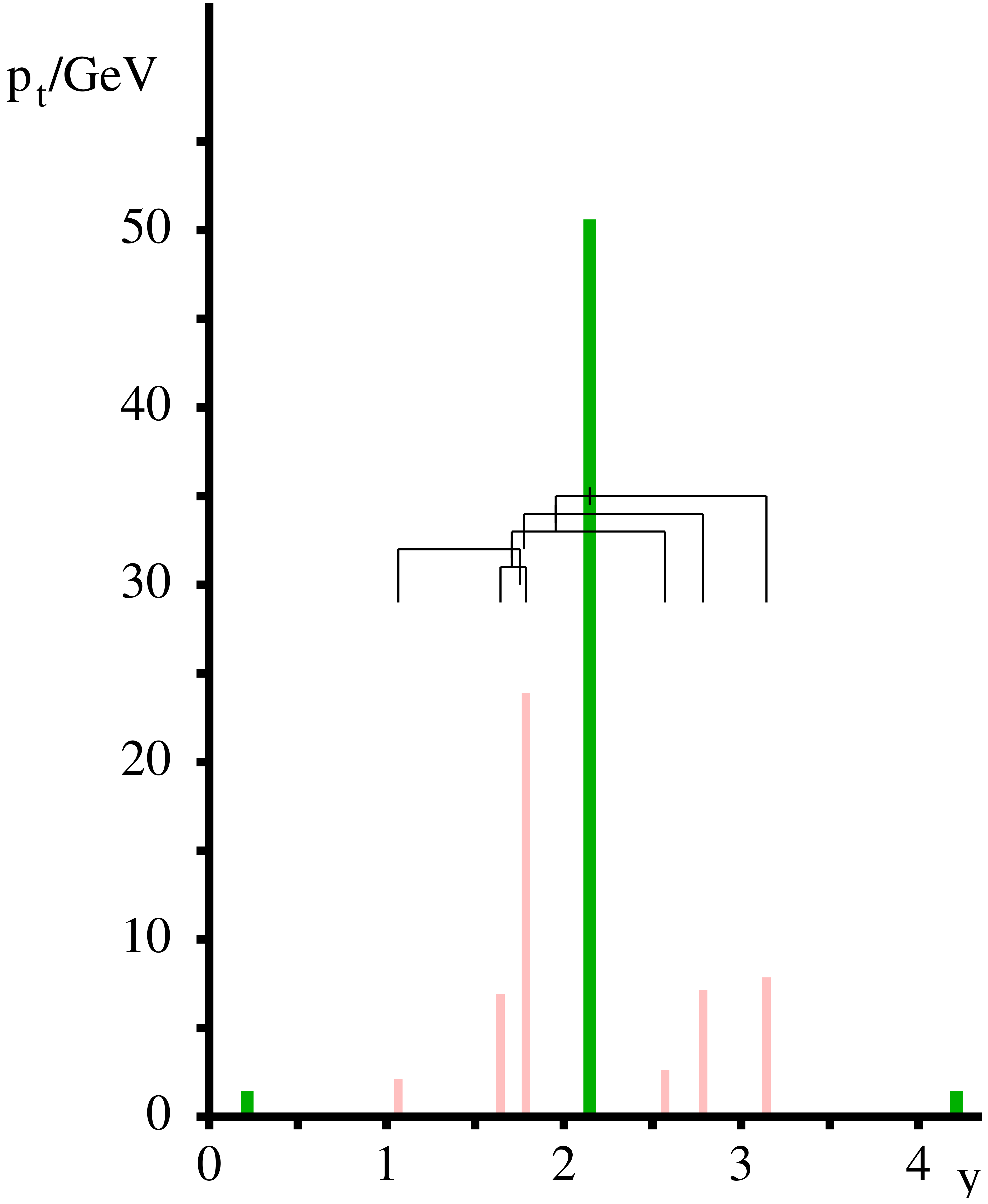
Identifying jet substructure: try out anti-k_t



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

This is crucial for identifying the kinematic variables of the partons in the jets

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

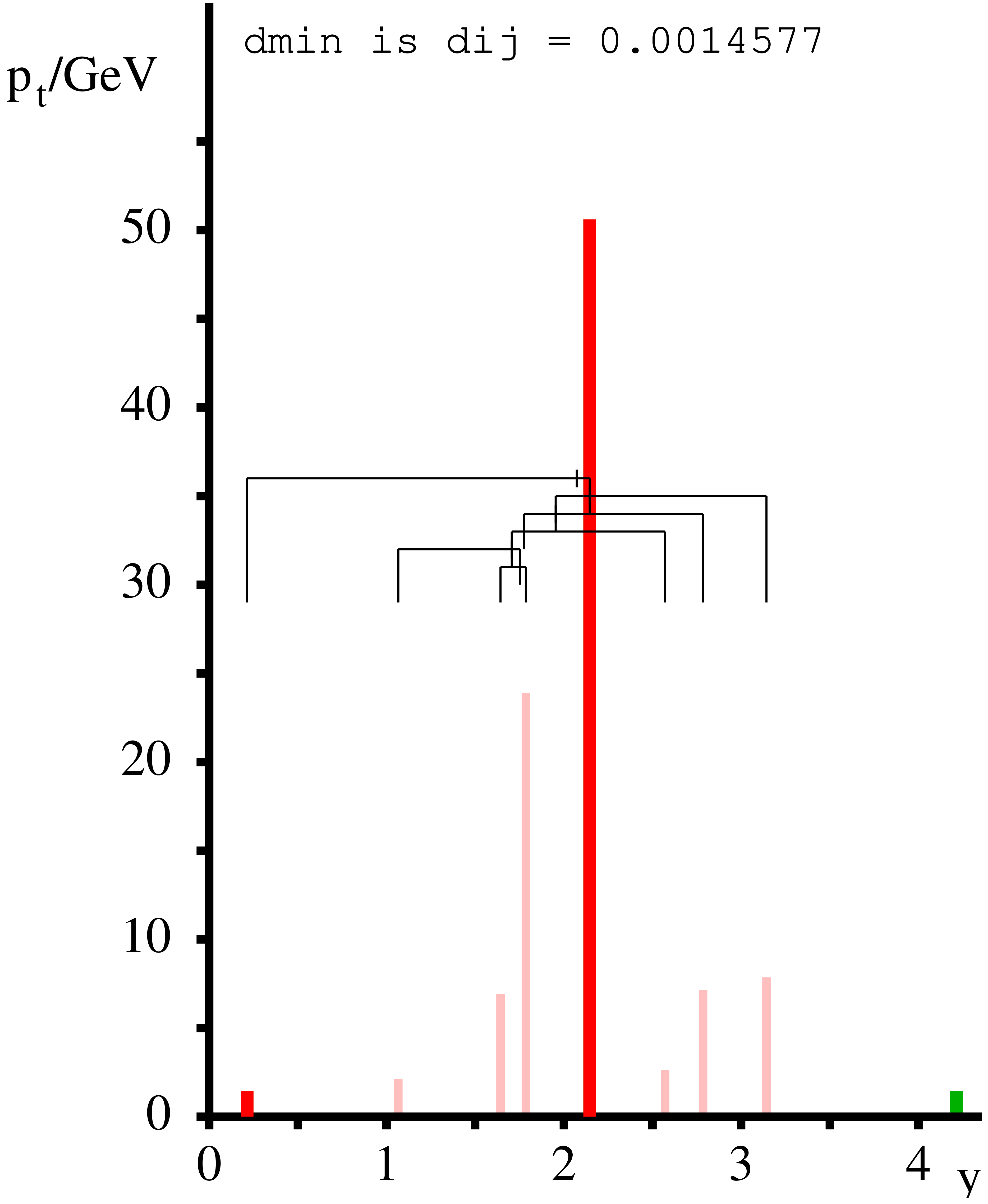


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jets

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

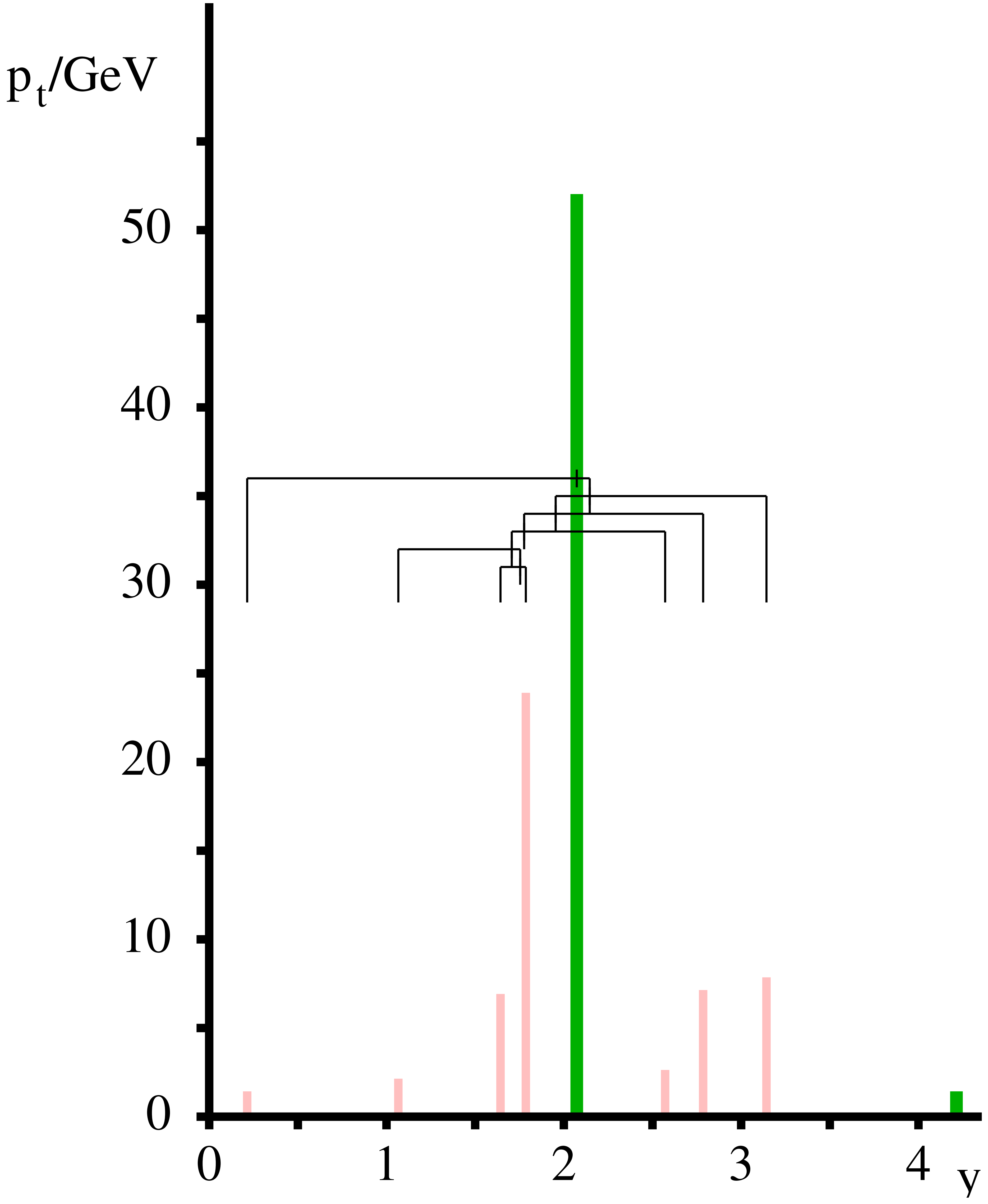
Identifying jet substructure: try out anti-k_t



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

This is crucial for identifying the kinematic variables of the partons in the jets

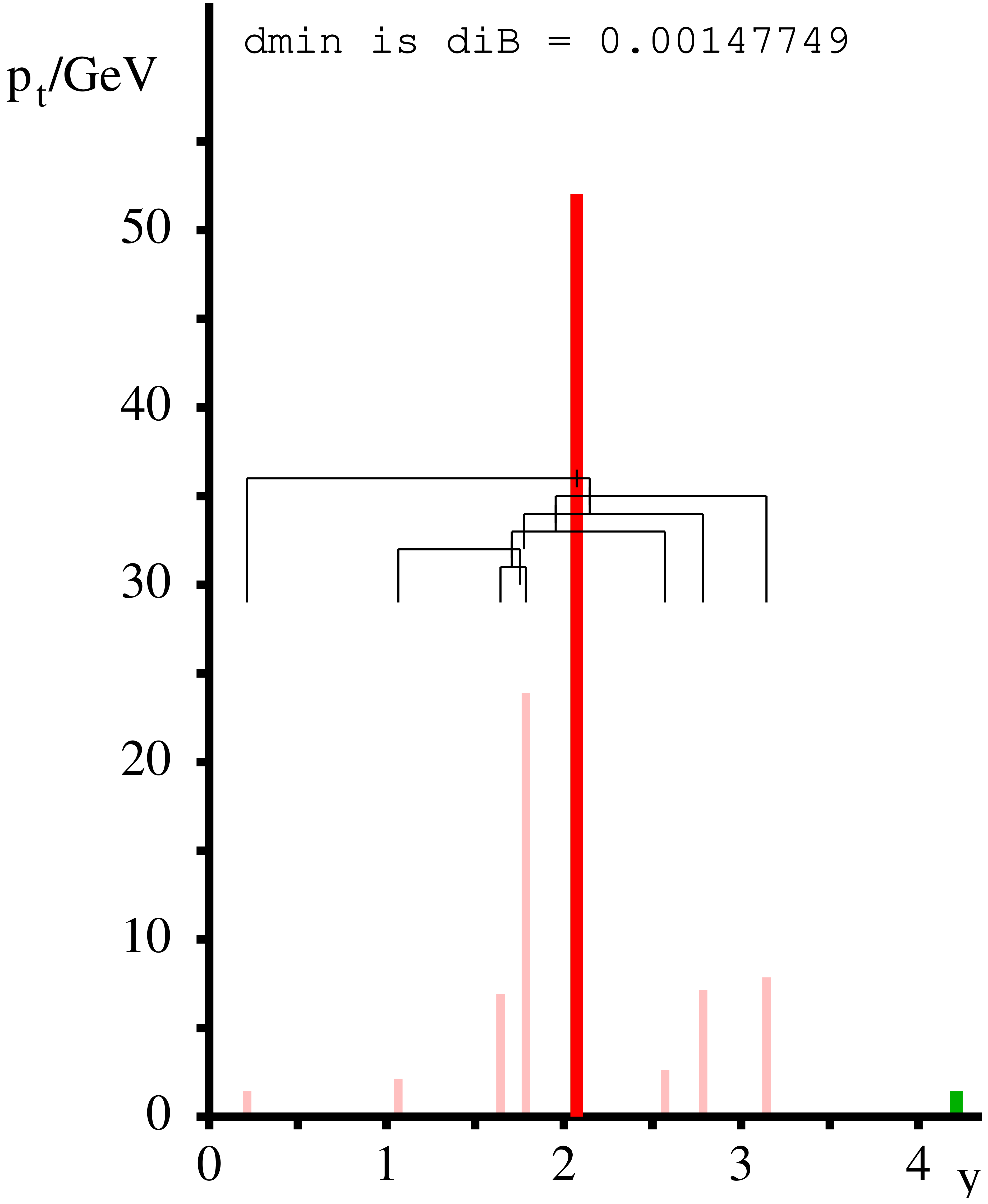
Anti-k_t gradually makes its way through the secondary blob → no clear ID of substructure associated with 2nd parton



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

This is crucial for identifying the kinematic variables of the partons in the jets

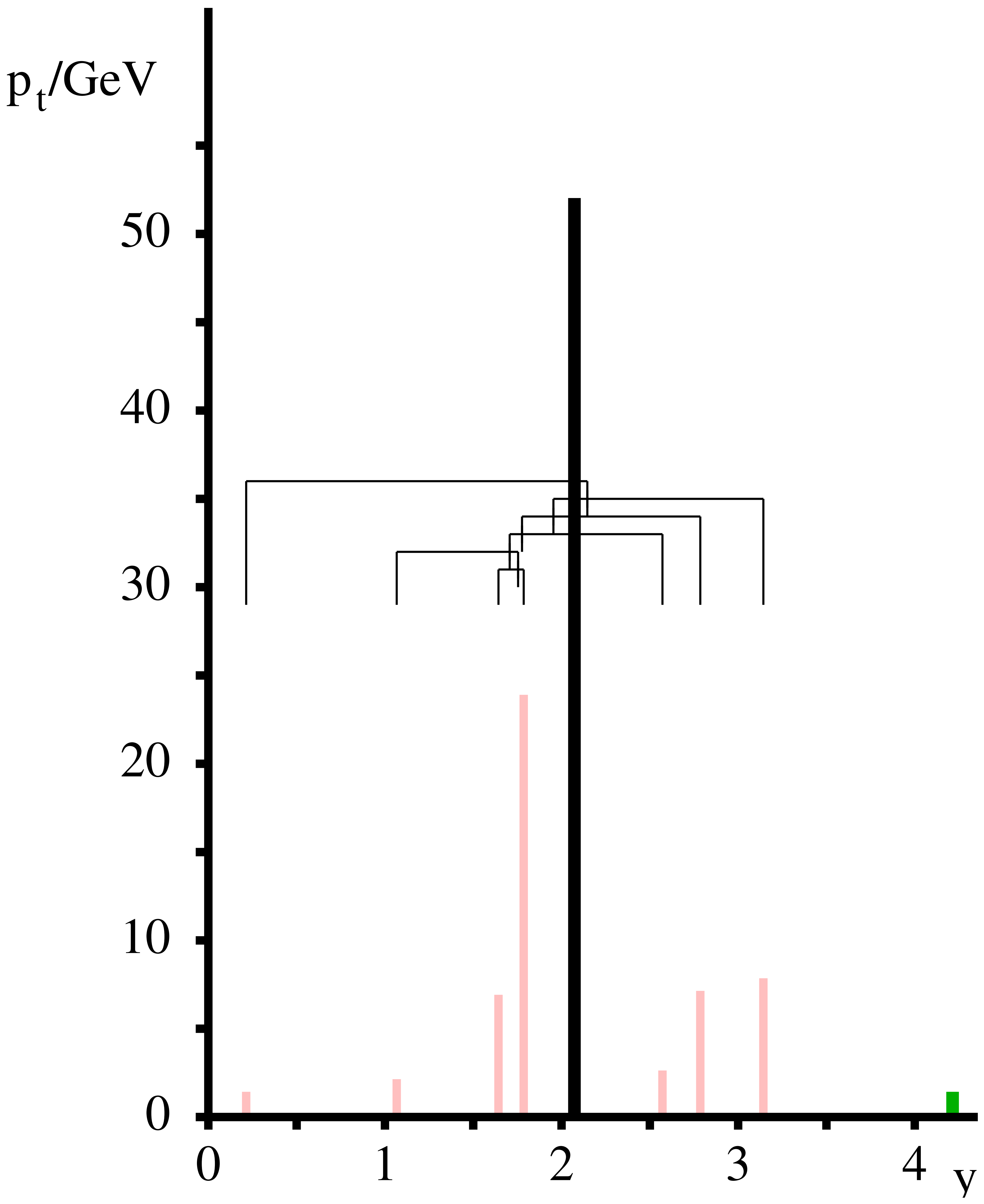
Anti-k_t gradually makes its way through the secondary blob → no clear ID of substructure associated with 2nd parton



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

This is crucial for identifying the kinematic variables of the partons in the jets

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

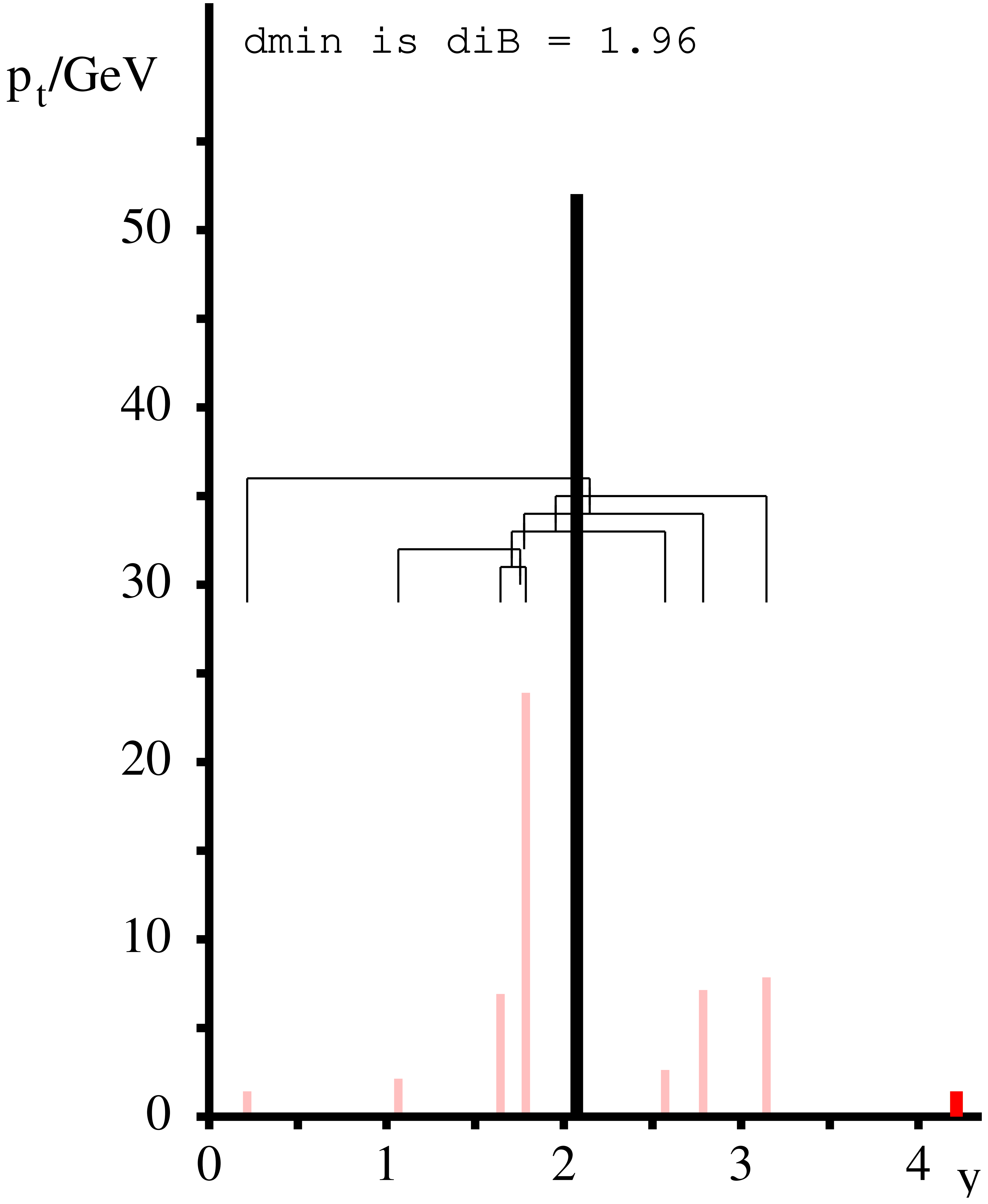


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jets

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

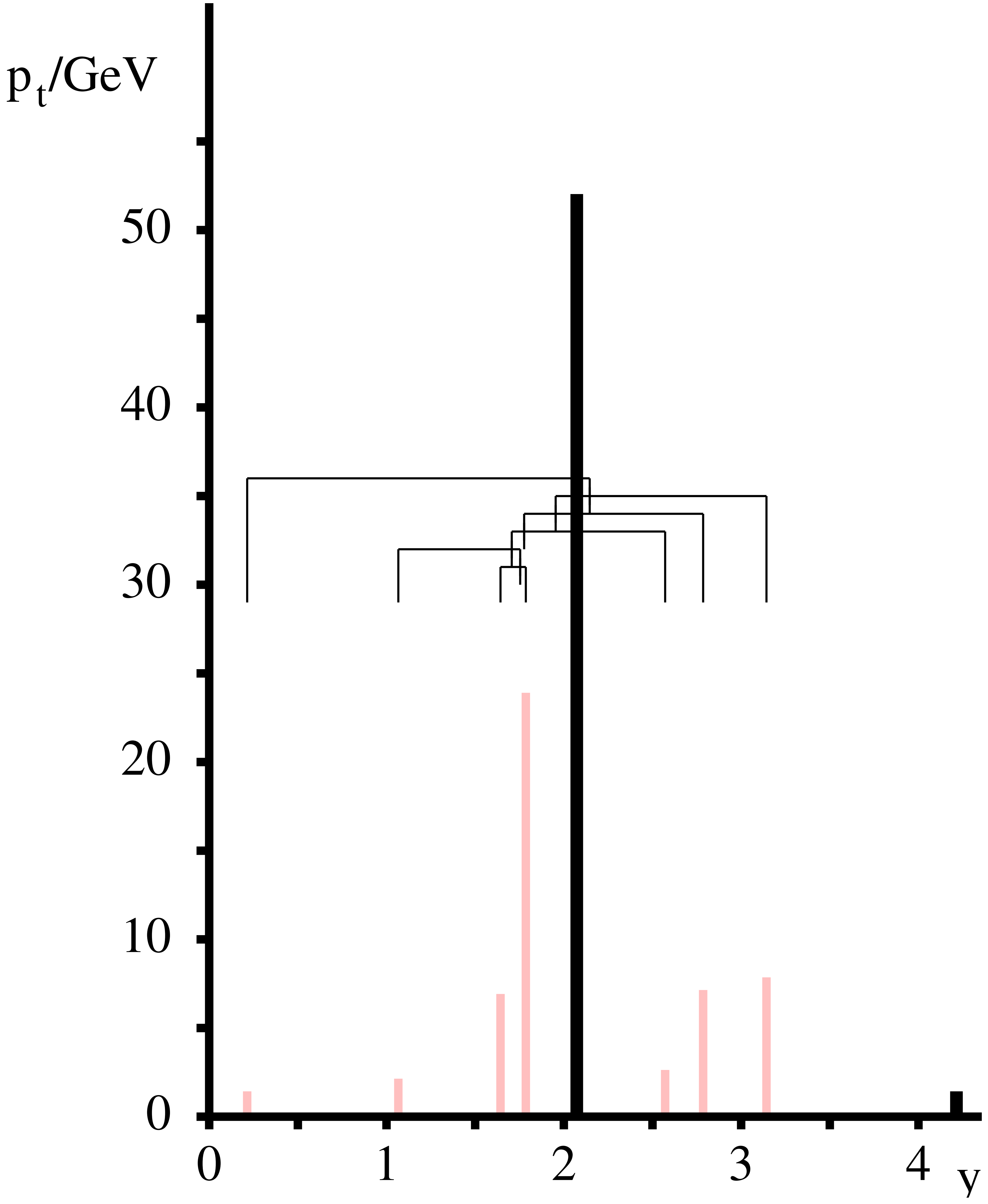
Identifying jet substructure: try out anti-k_t



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

This is crucial for identifying the kinematic variables of the partons in the jets

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

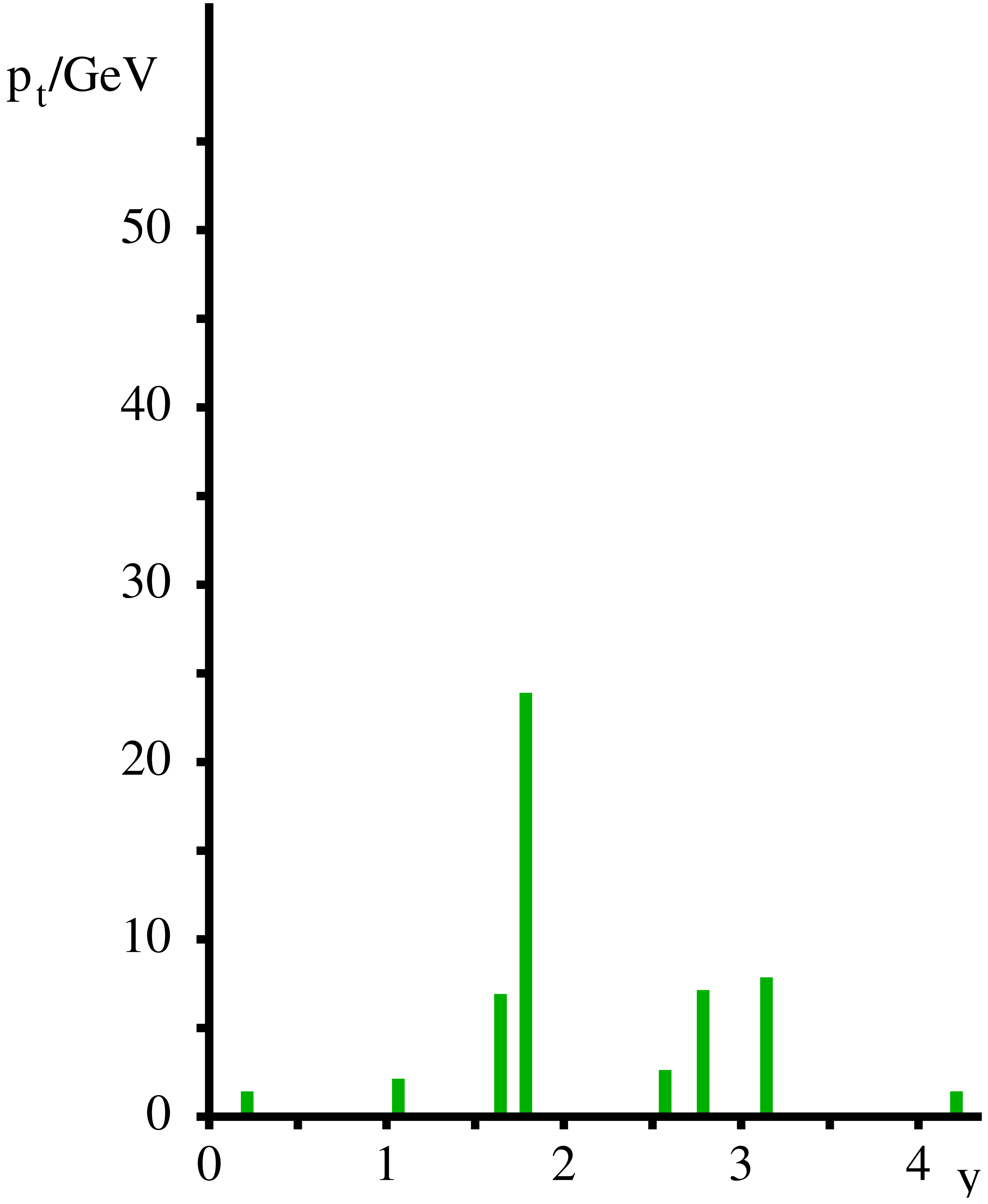


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

This is crucial for identifying the kinematic variables of the partons in the jets

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

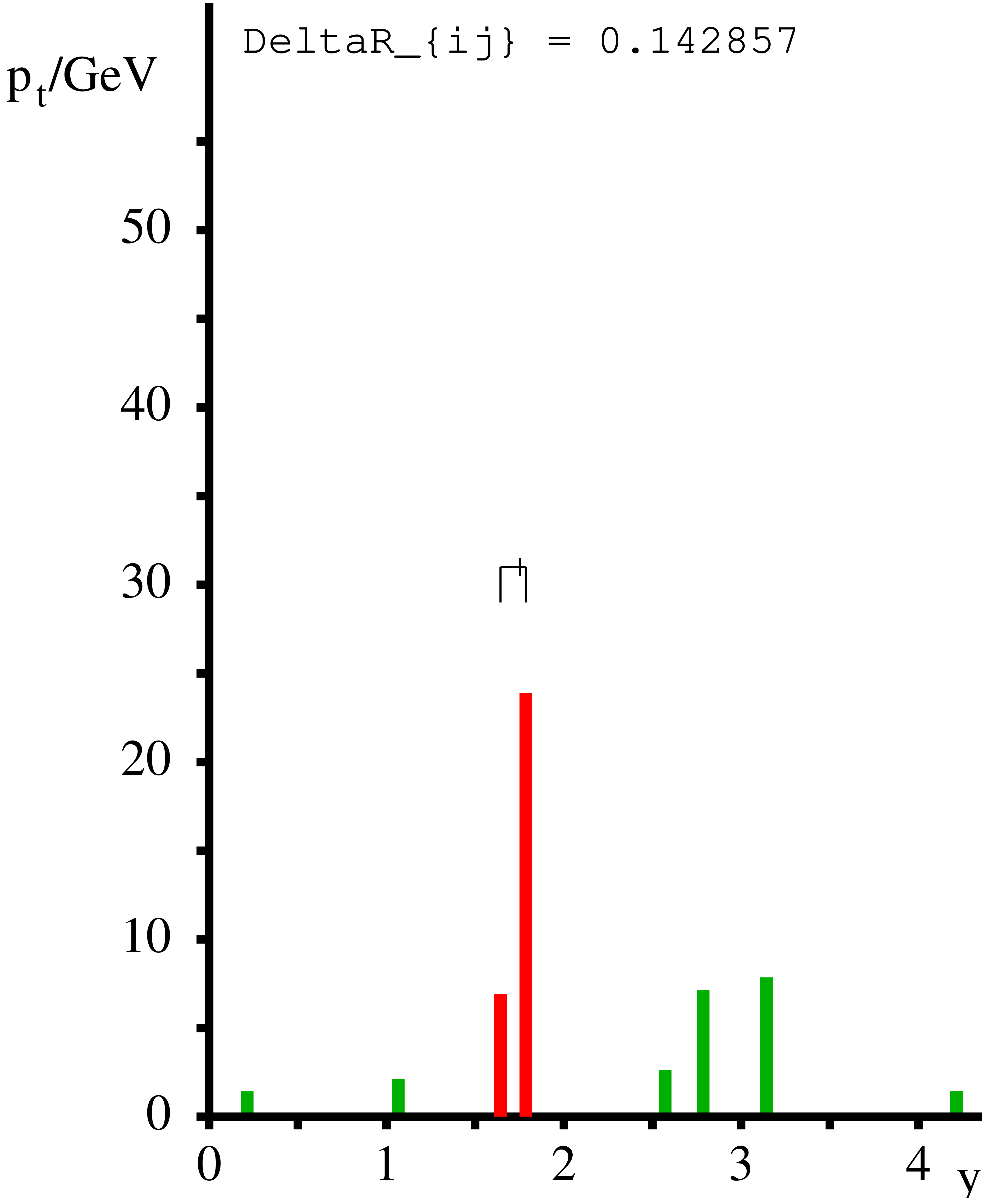
Identifying jet substructure: Cam/Aachen



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

C/A algorithm works hierarchically in angle

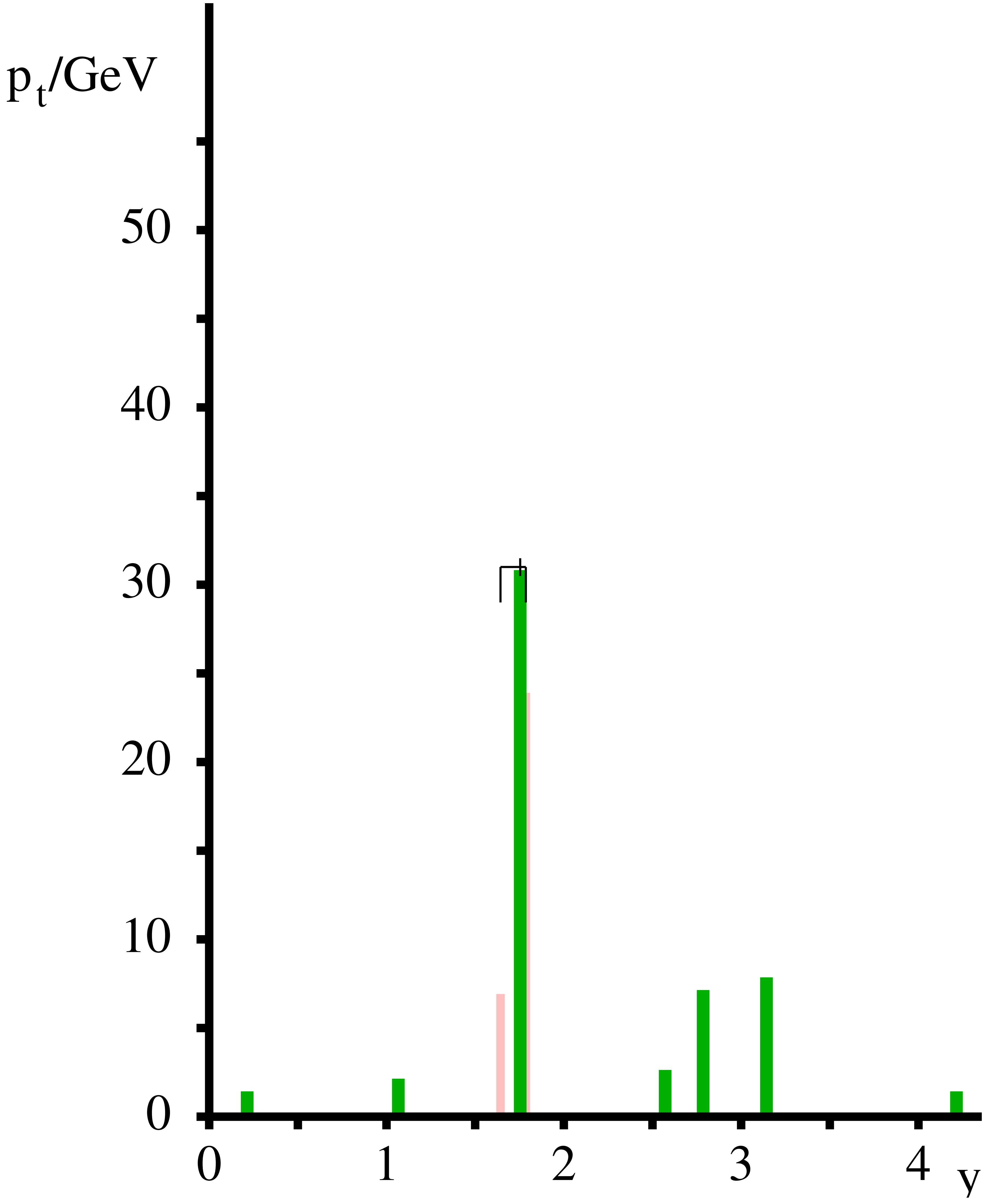
Identifying jet substructure: Cam/Aachen



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

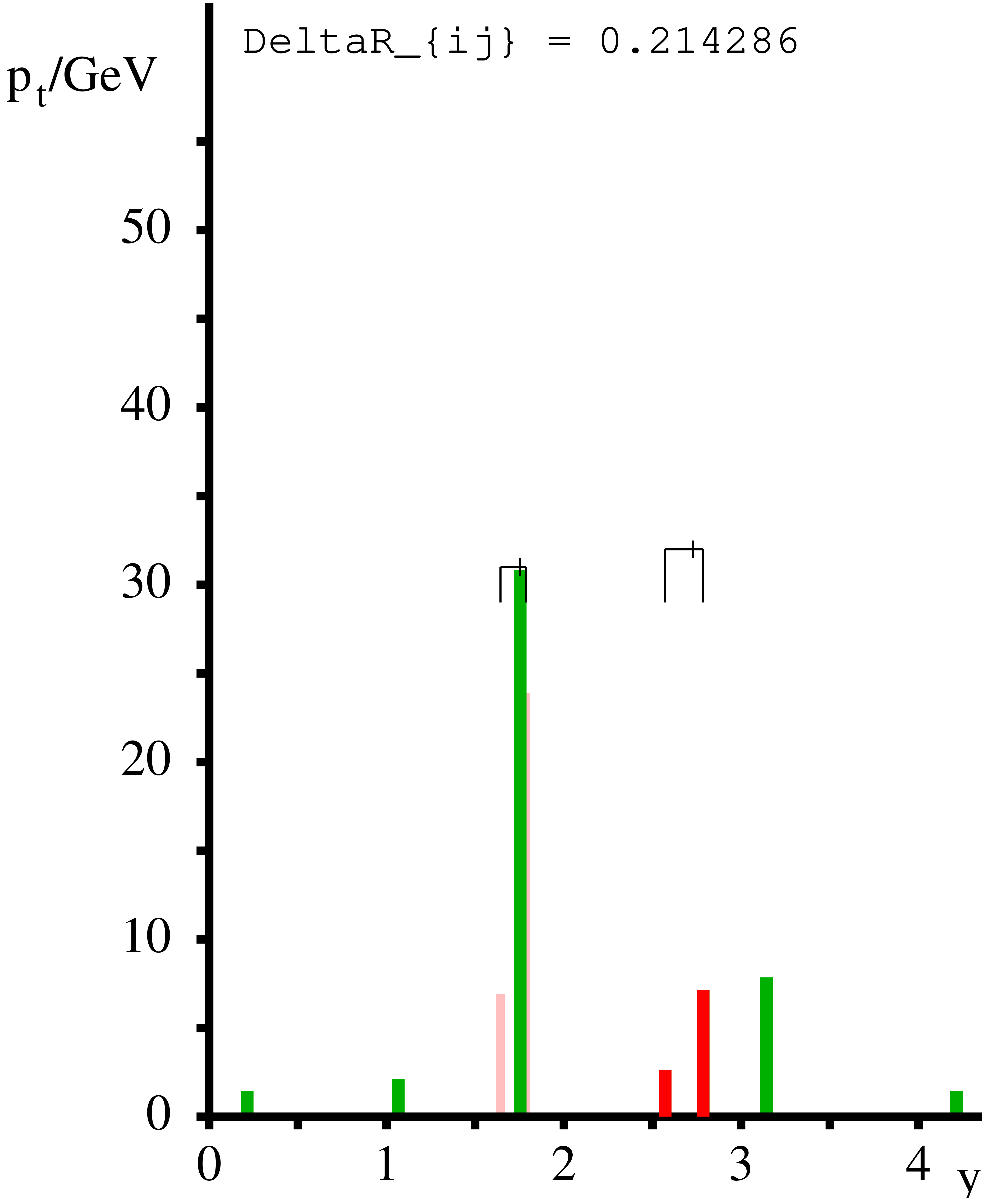
C/A algorithm works hierarchically in angle

Identifying jet substructure: Cam/Aachen



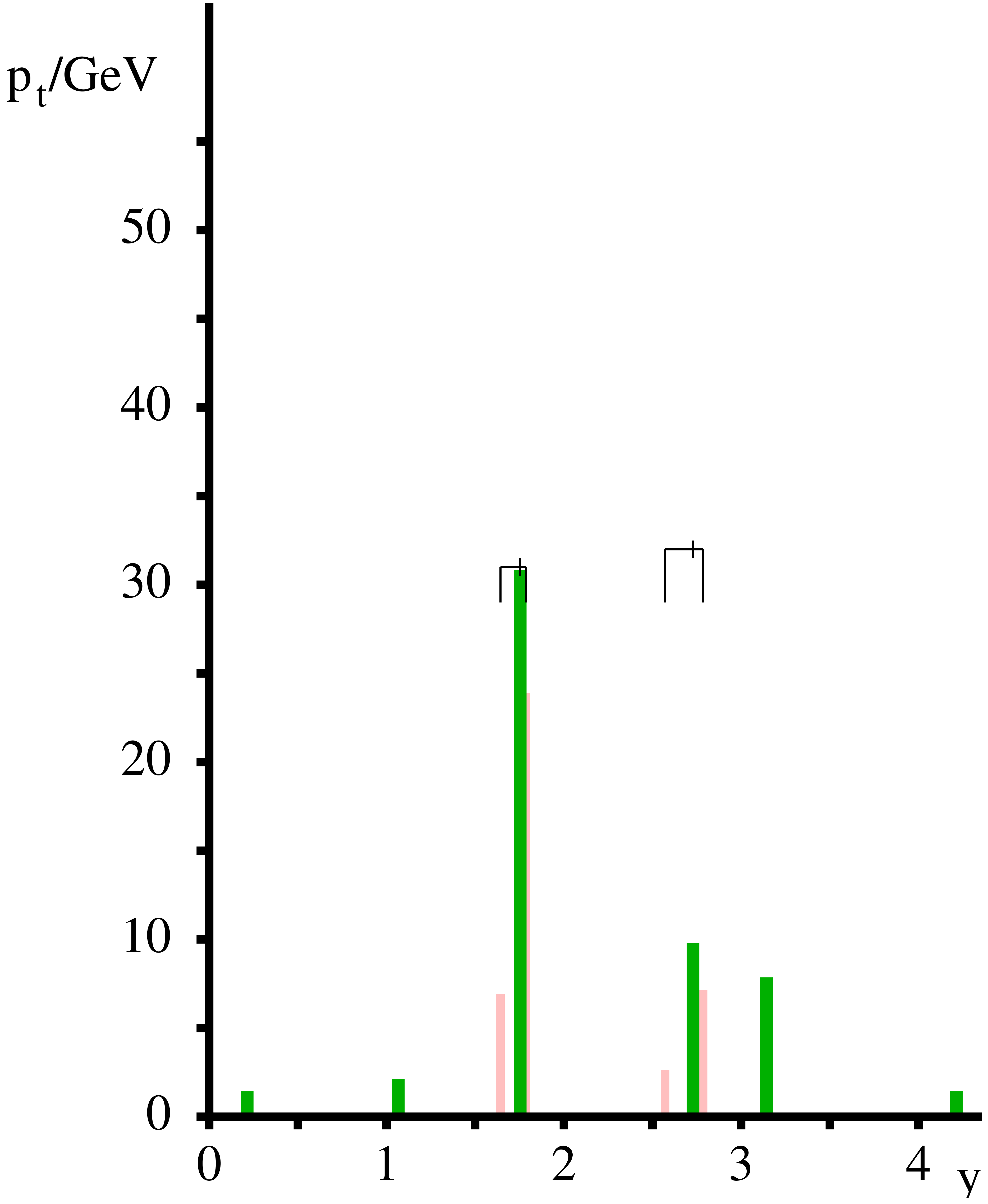
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle



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

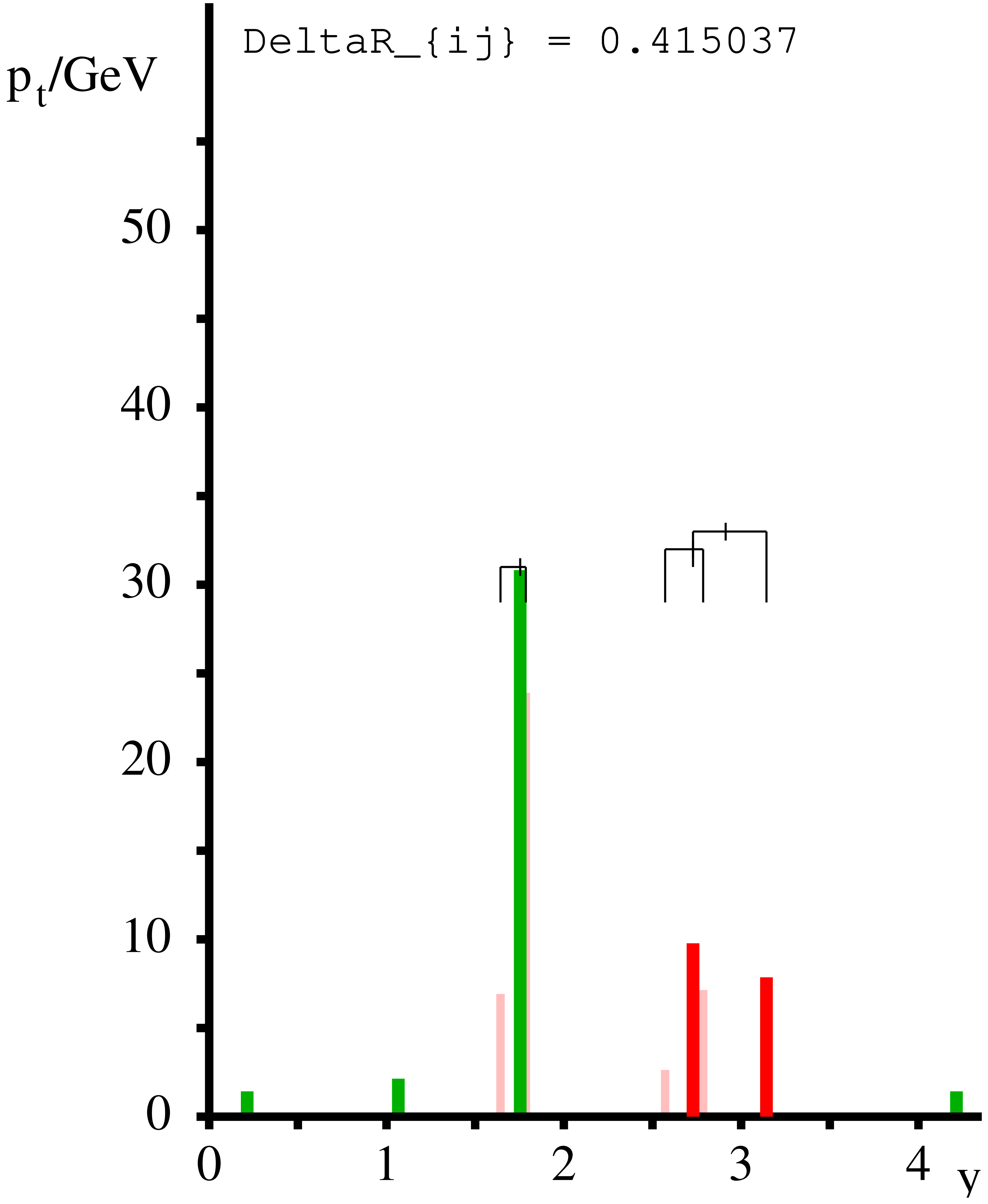
C/A algorithm works hierarchically in angle



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

C/A algorithm works hierarchically in angle

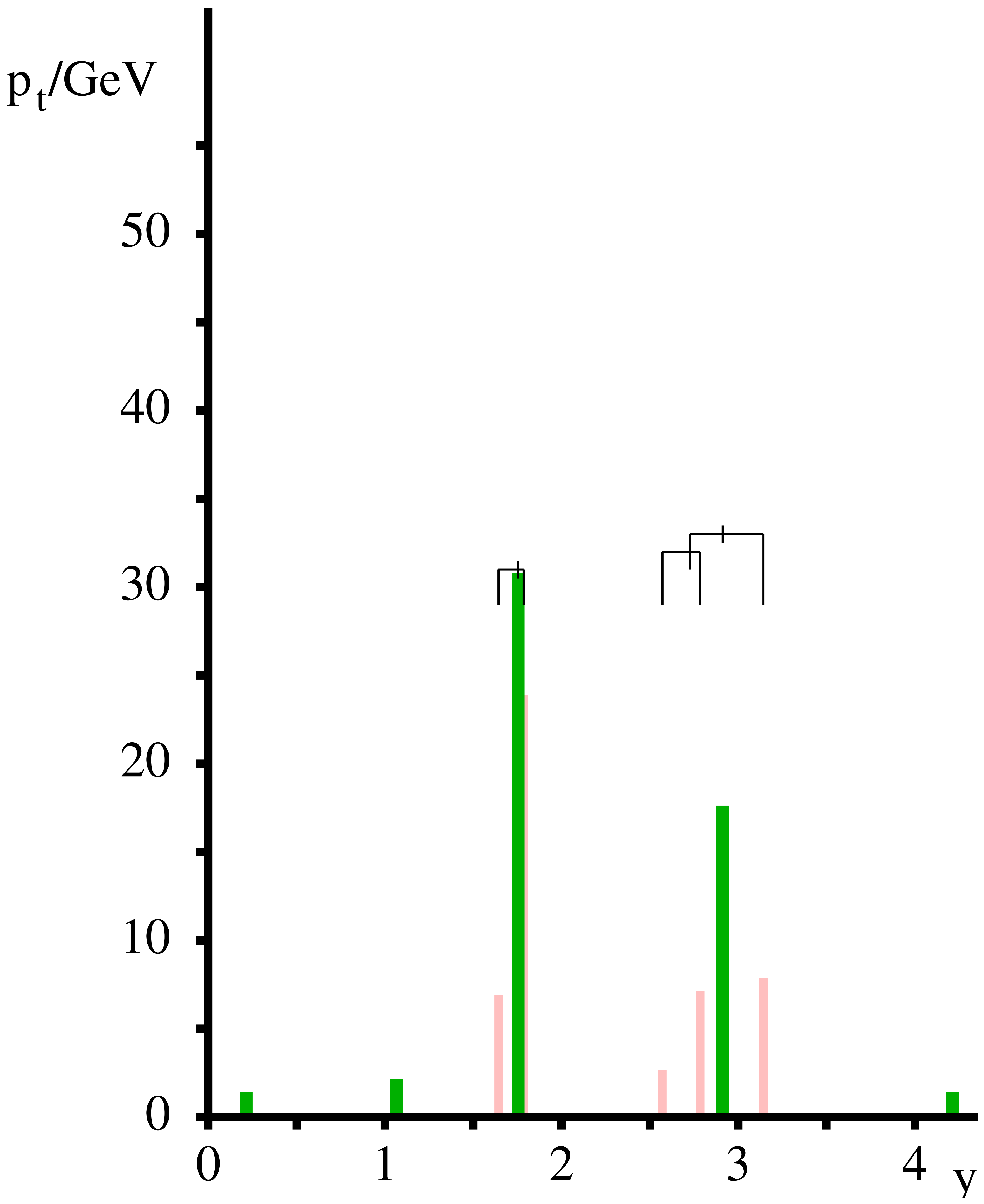
Identifying jet substructure: Cam/Aachen



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

C/A algorithm works hierarchically in angle

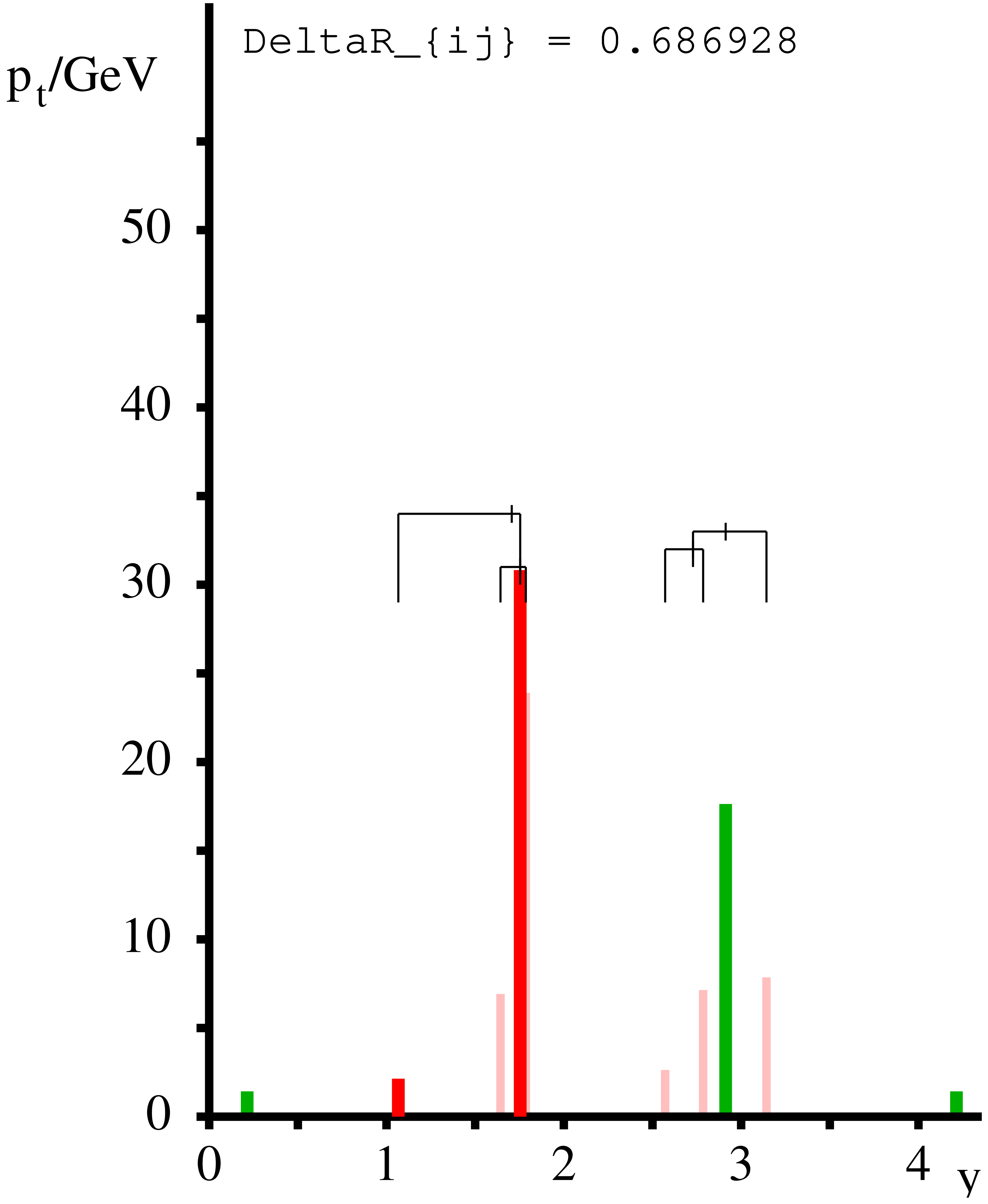
Identifying jet substructure: Cam/Aachen



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

C/A algorithm works hierarchically in angle

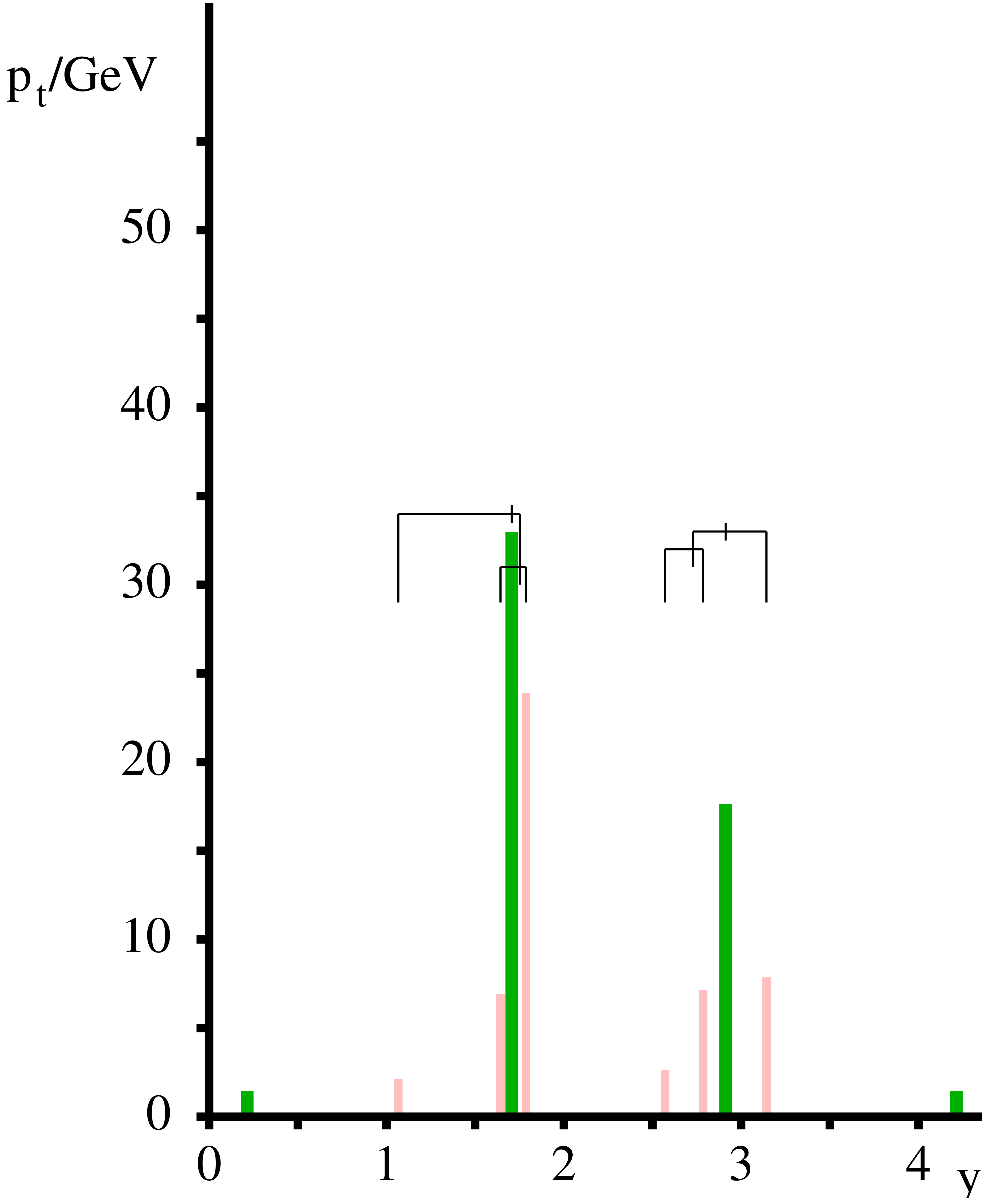
Identifying jet substructure: Cam/Aachen



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

C/A algorithm works hierarchically in angle

Identifying jet substructure: Cam/Aachen

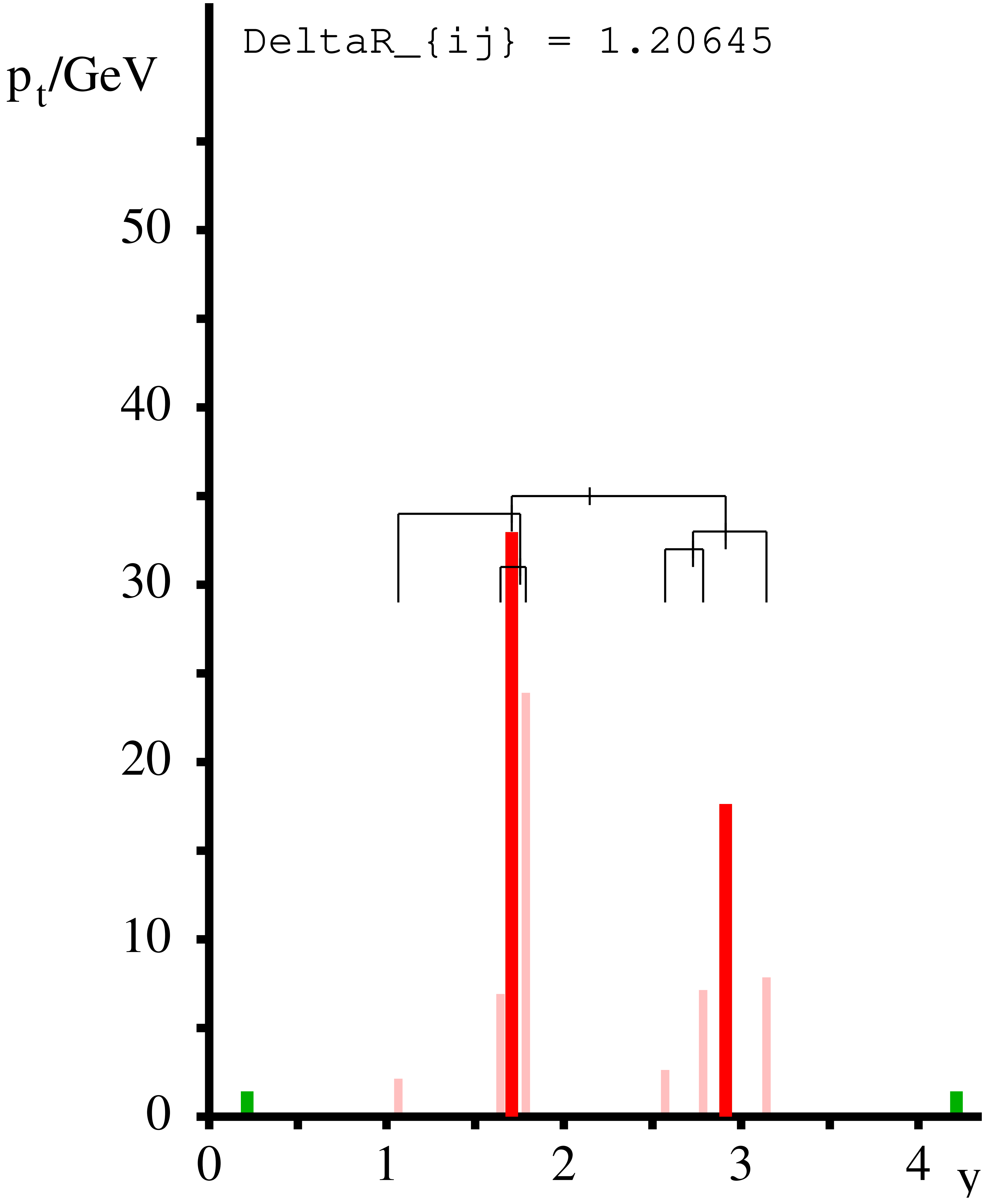


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Identifying jet substructure: Cam/Aachen

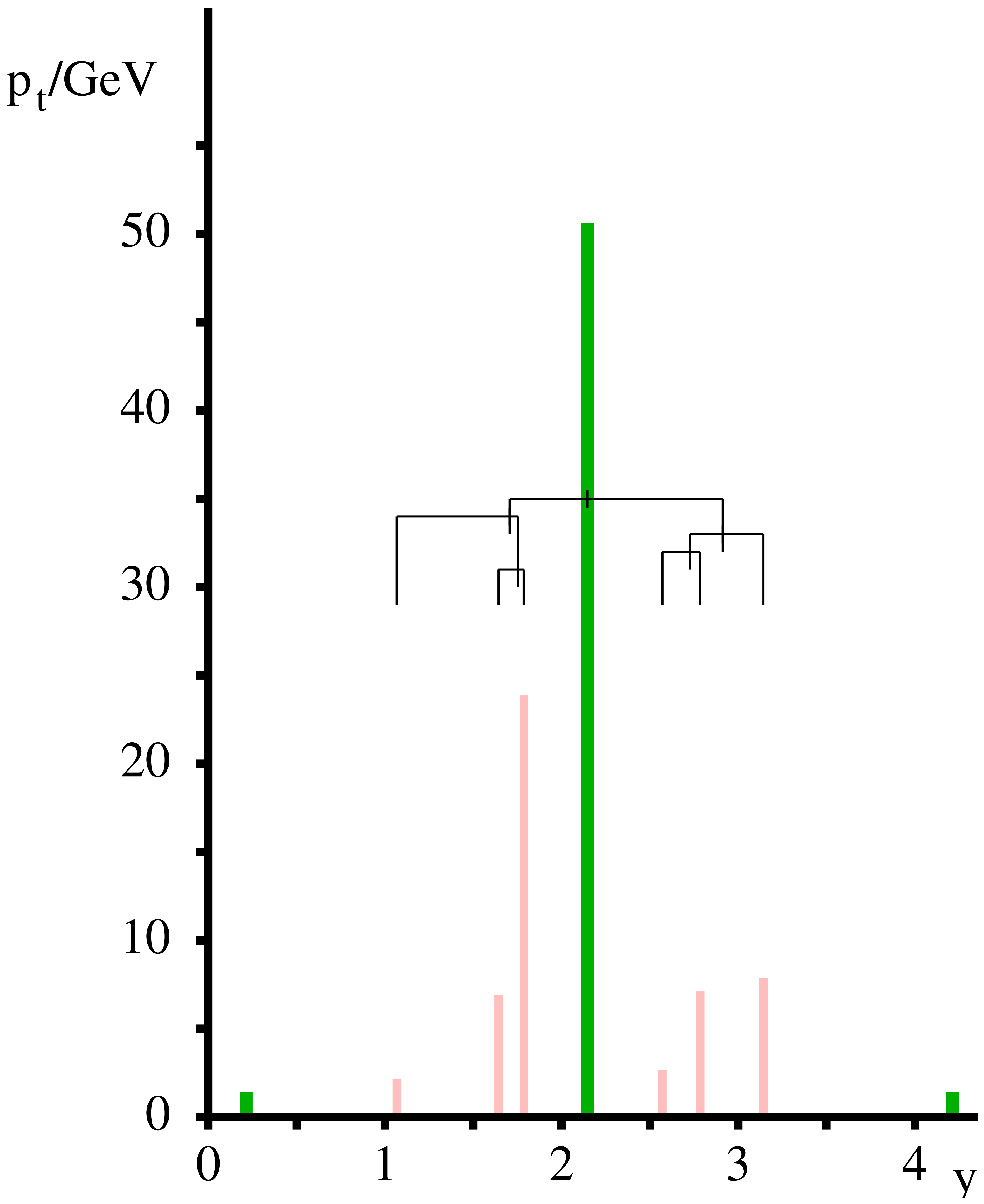


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Identifying jet substructure: Cam/Aachen

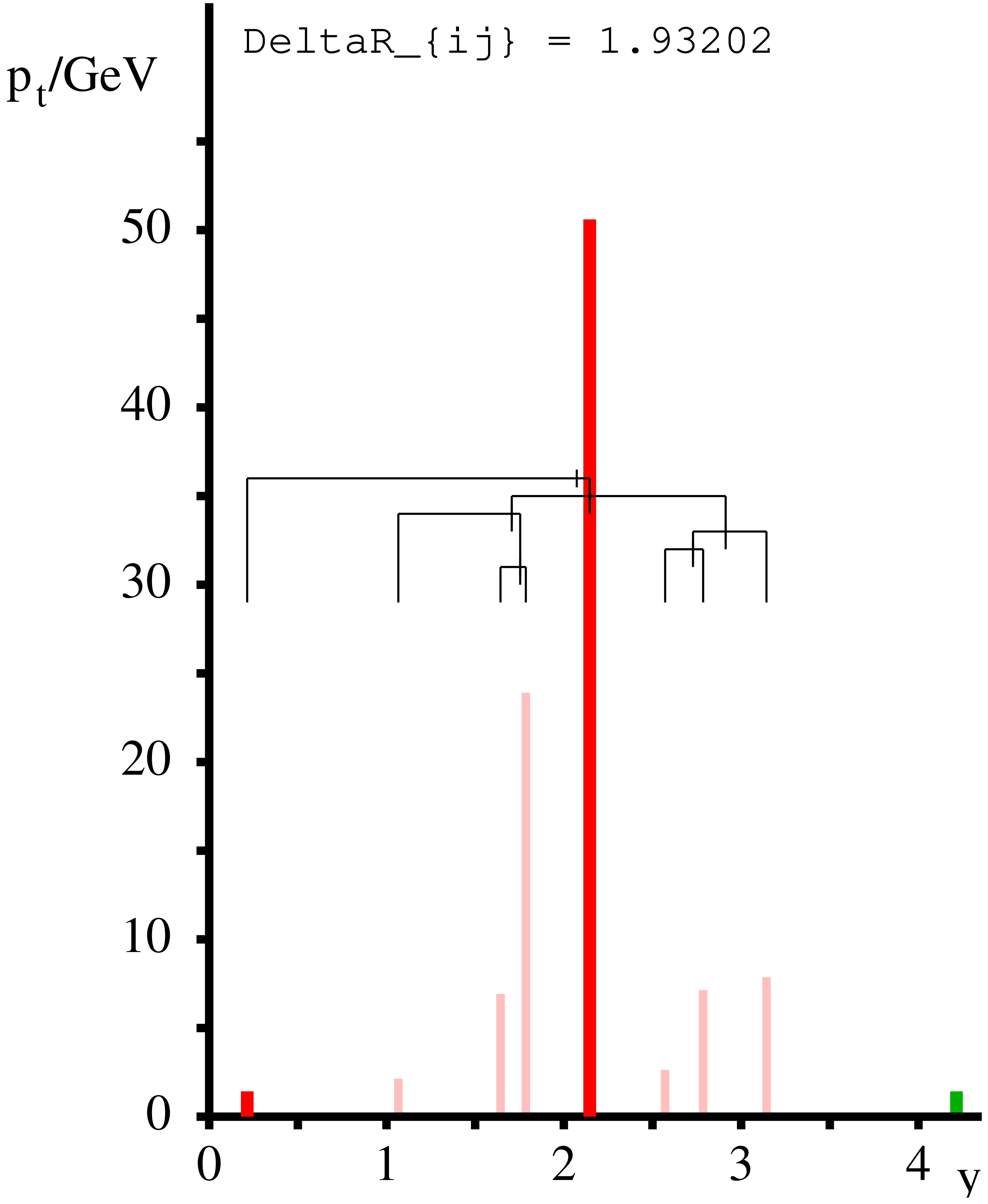


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Identifying jet substructure: Cam/Aachen

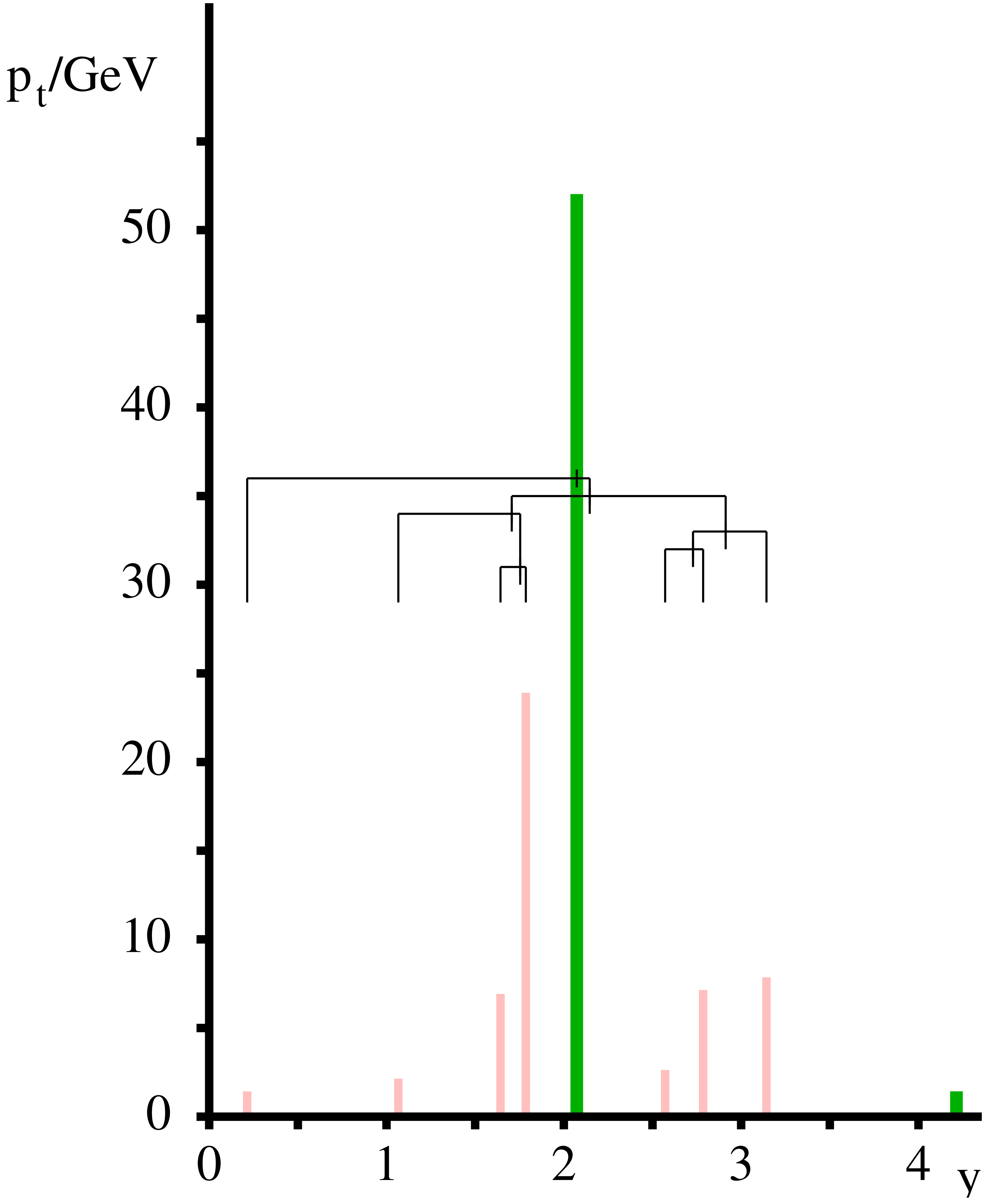


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

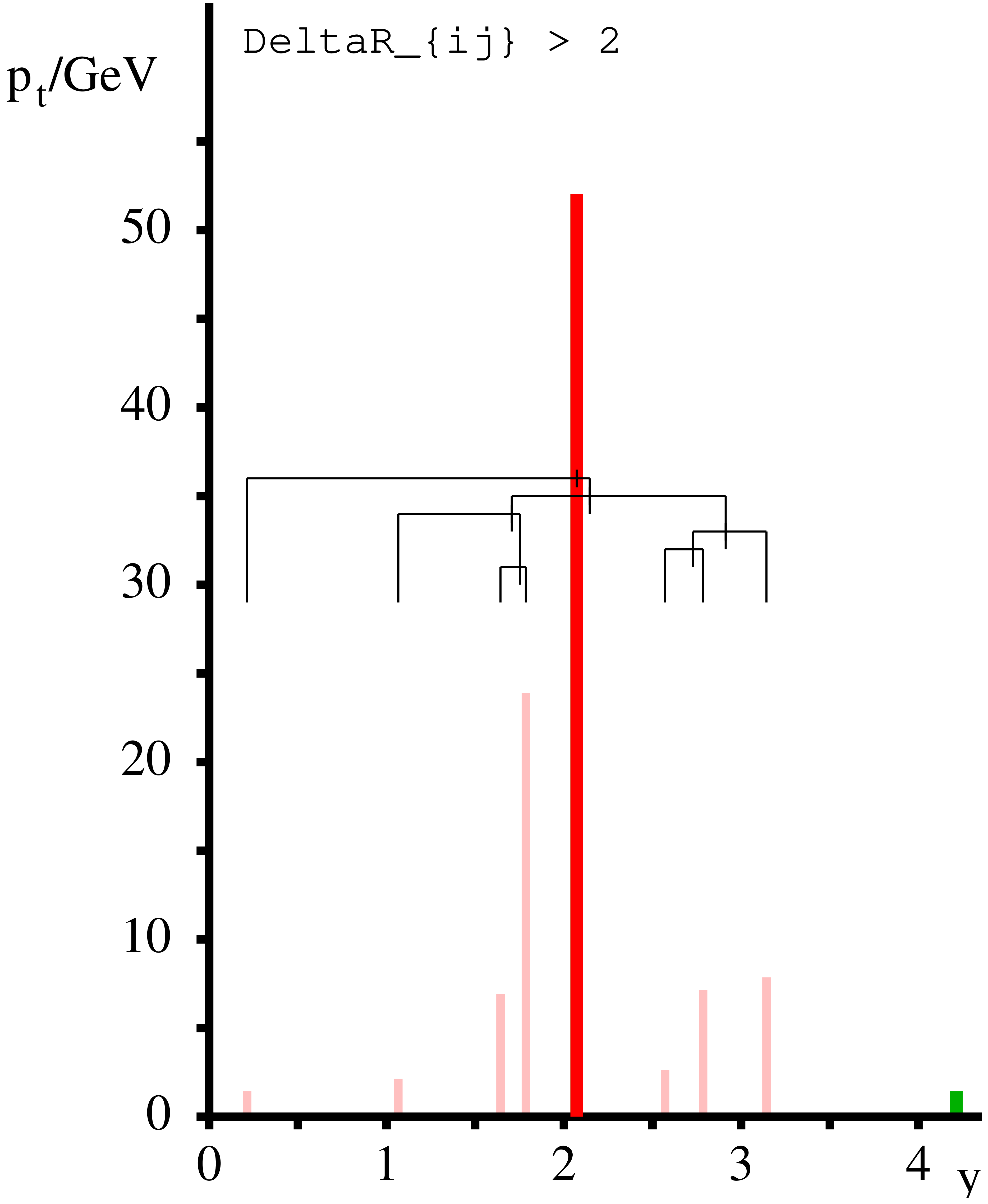
Identifying jet substructure: Cam/Aachen



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

C/A algorithm works hierarchically in angle

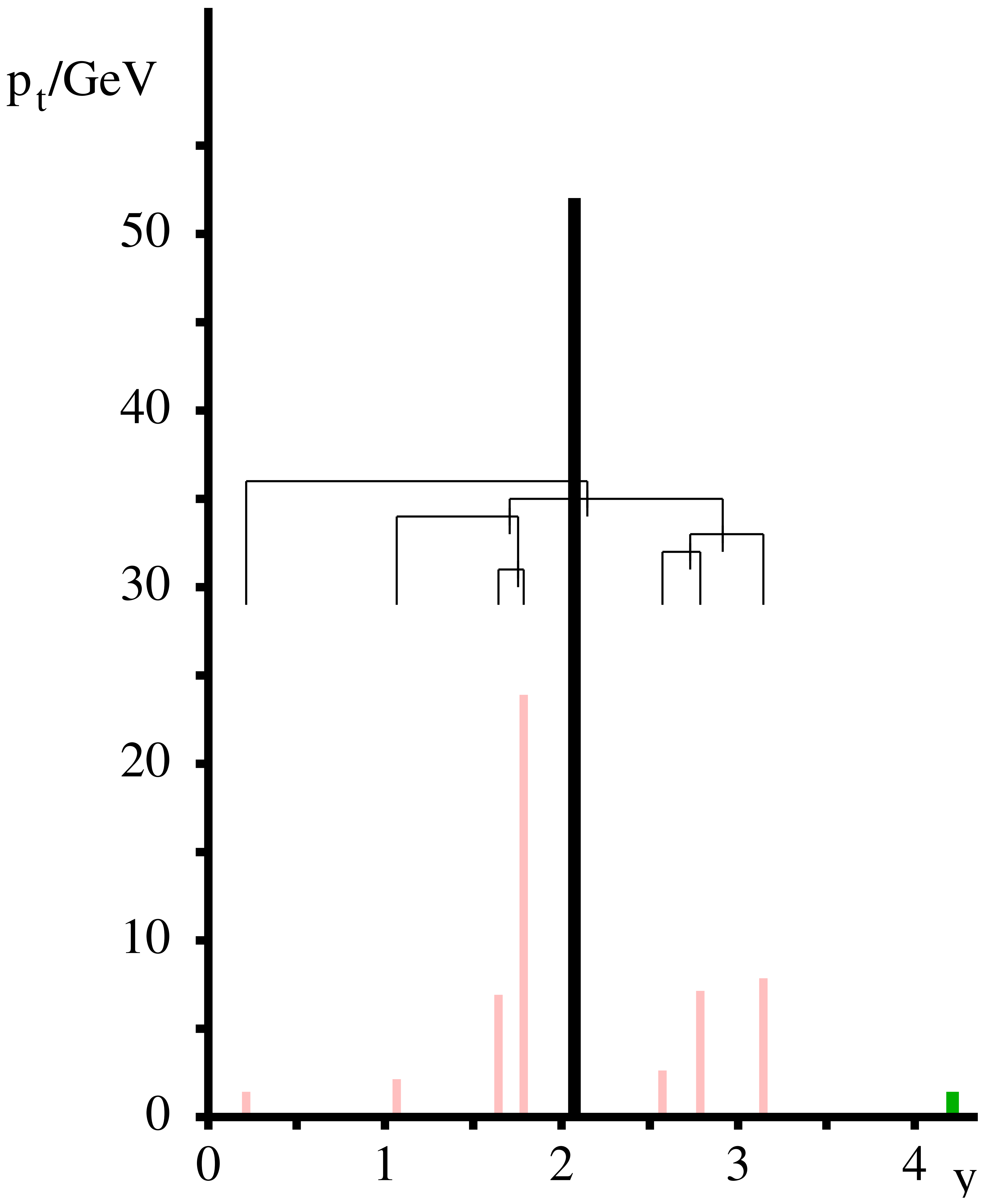
Clear ID of two separate hard “blobs”



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

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

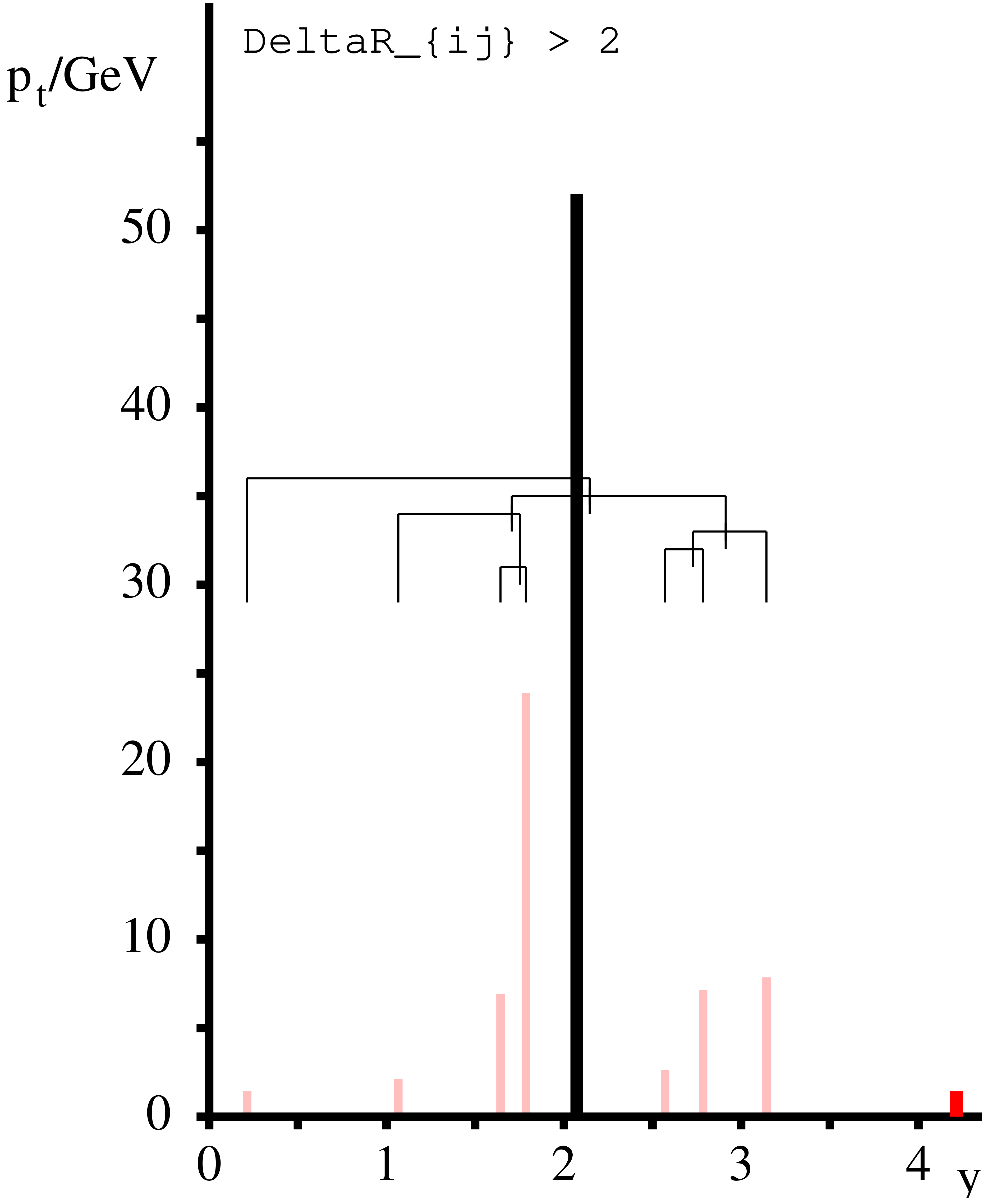


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Identifying jet substructure: Cam/Aachen

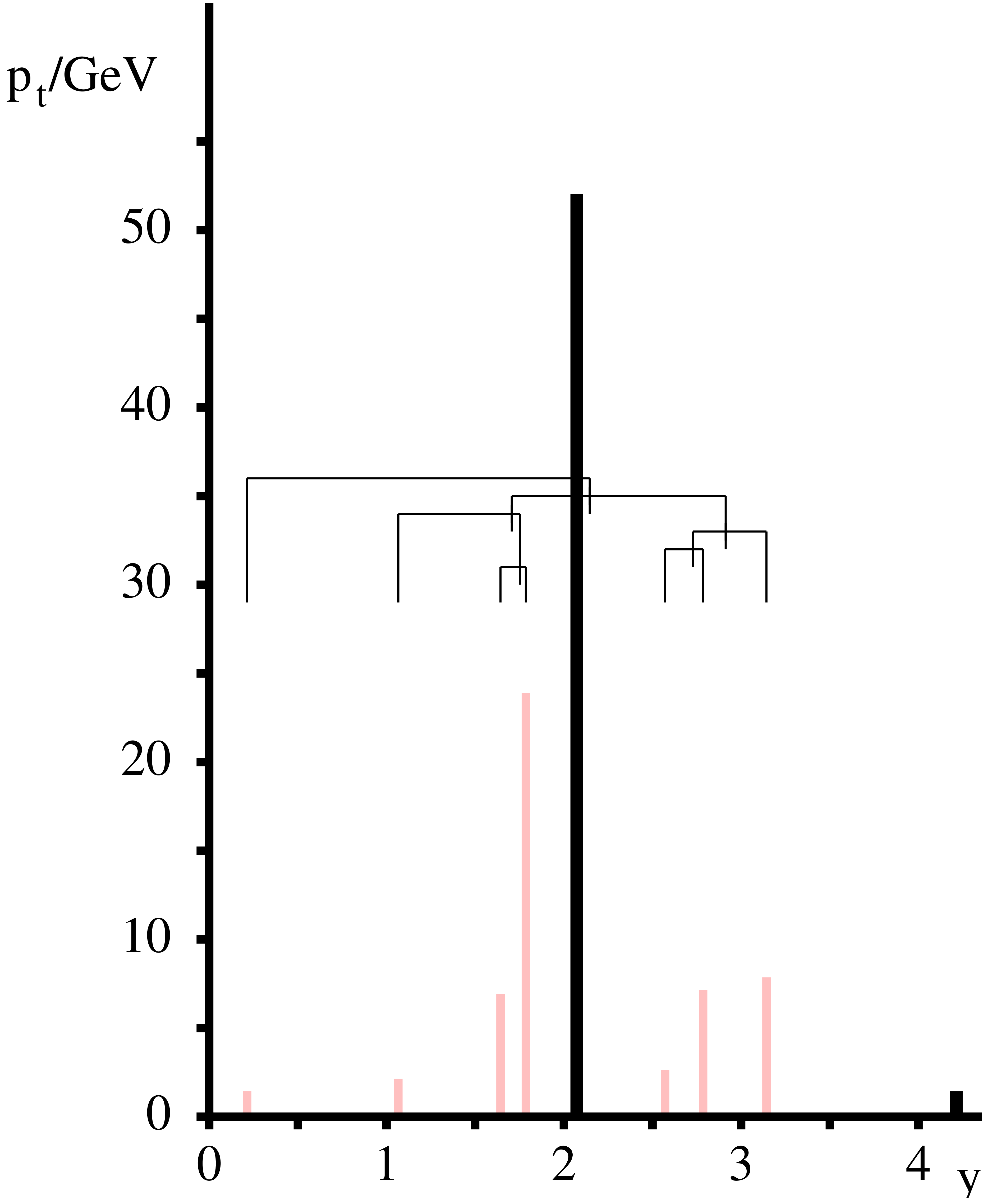


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Identifying jet substructure: Cam/Aachen

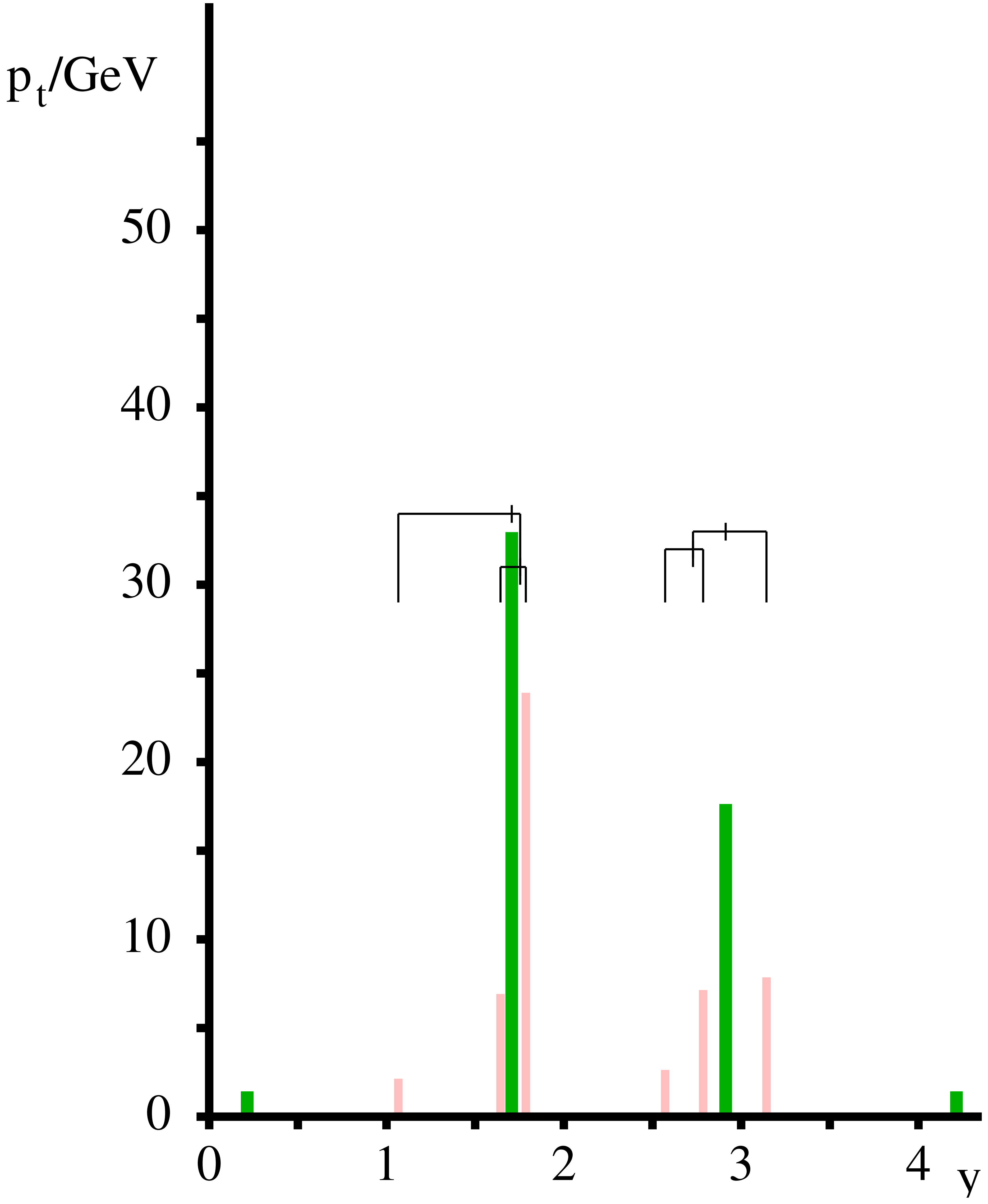


How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Identifying jet substructure: Cam/Aachen



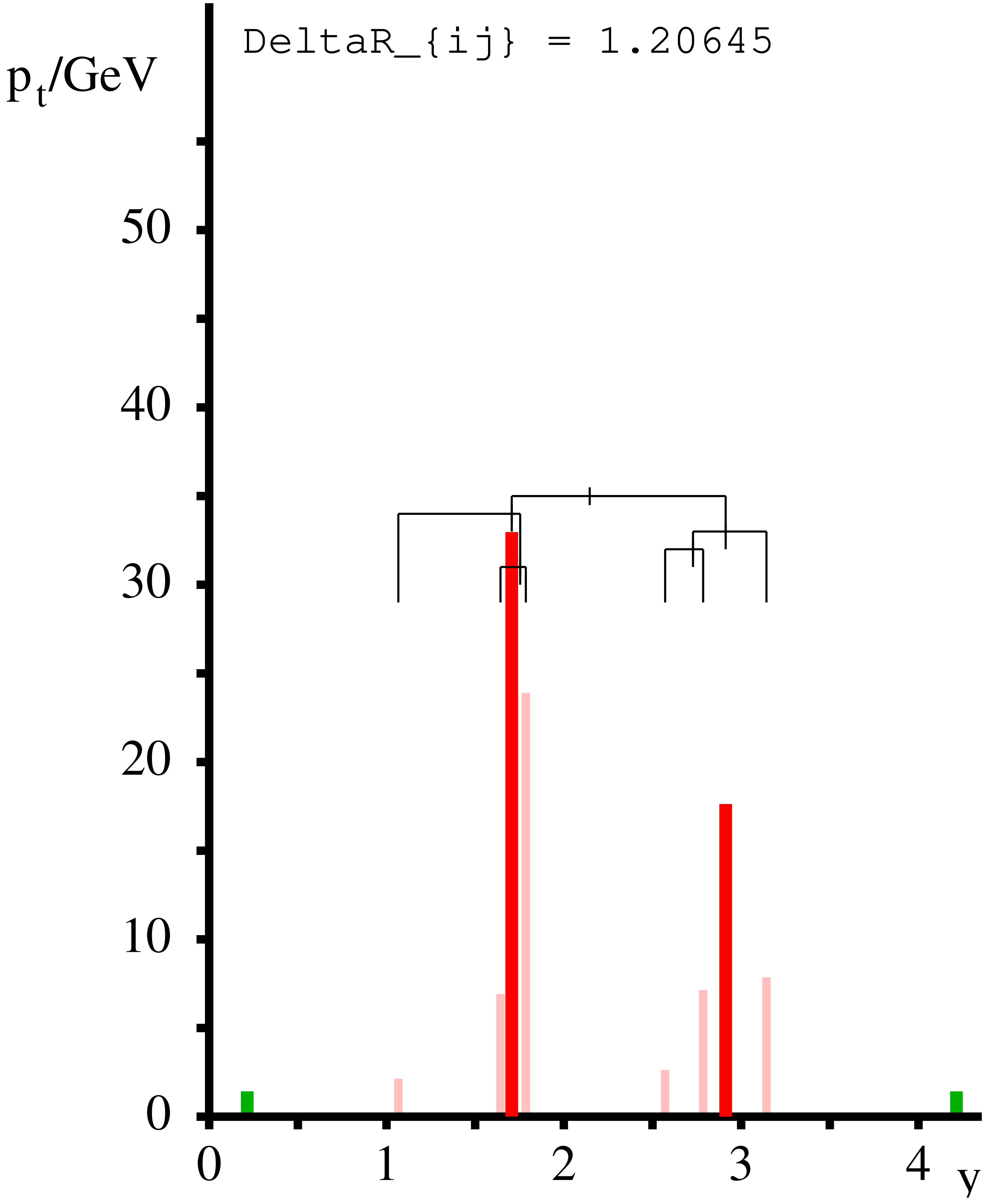
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



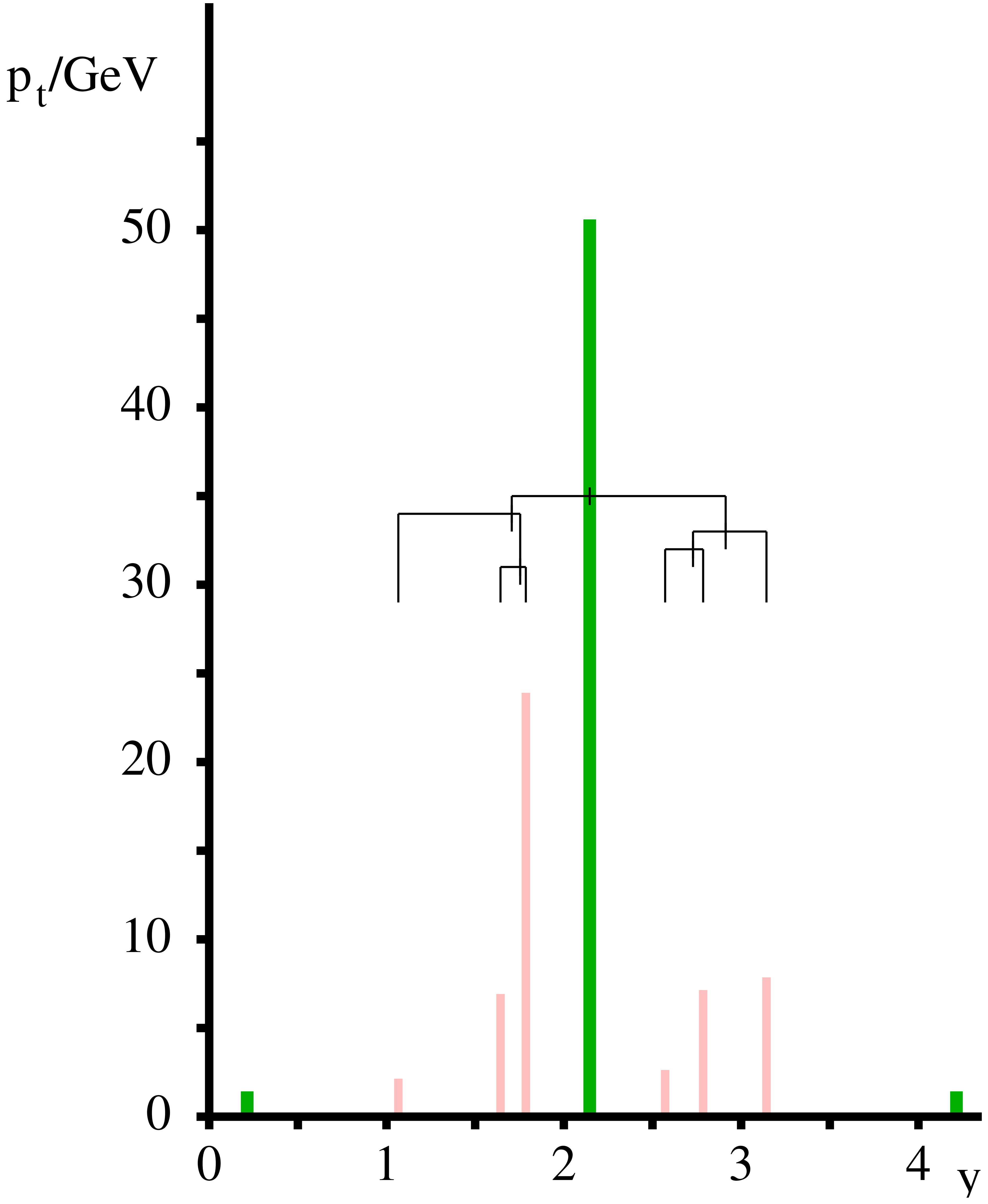
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



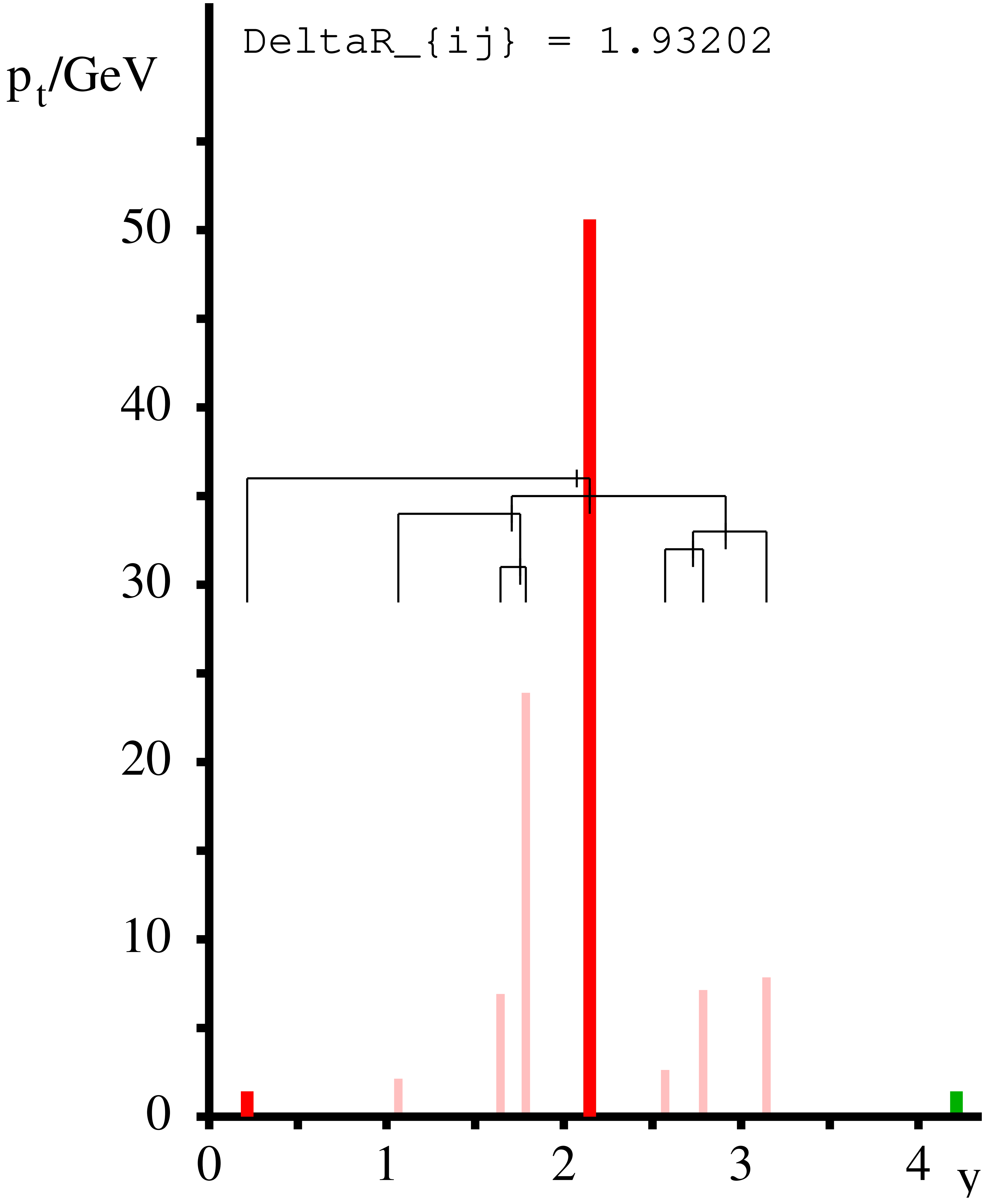
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



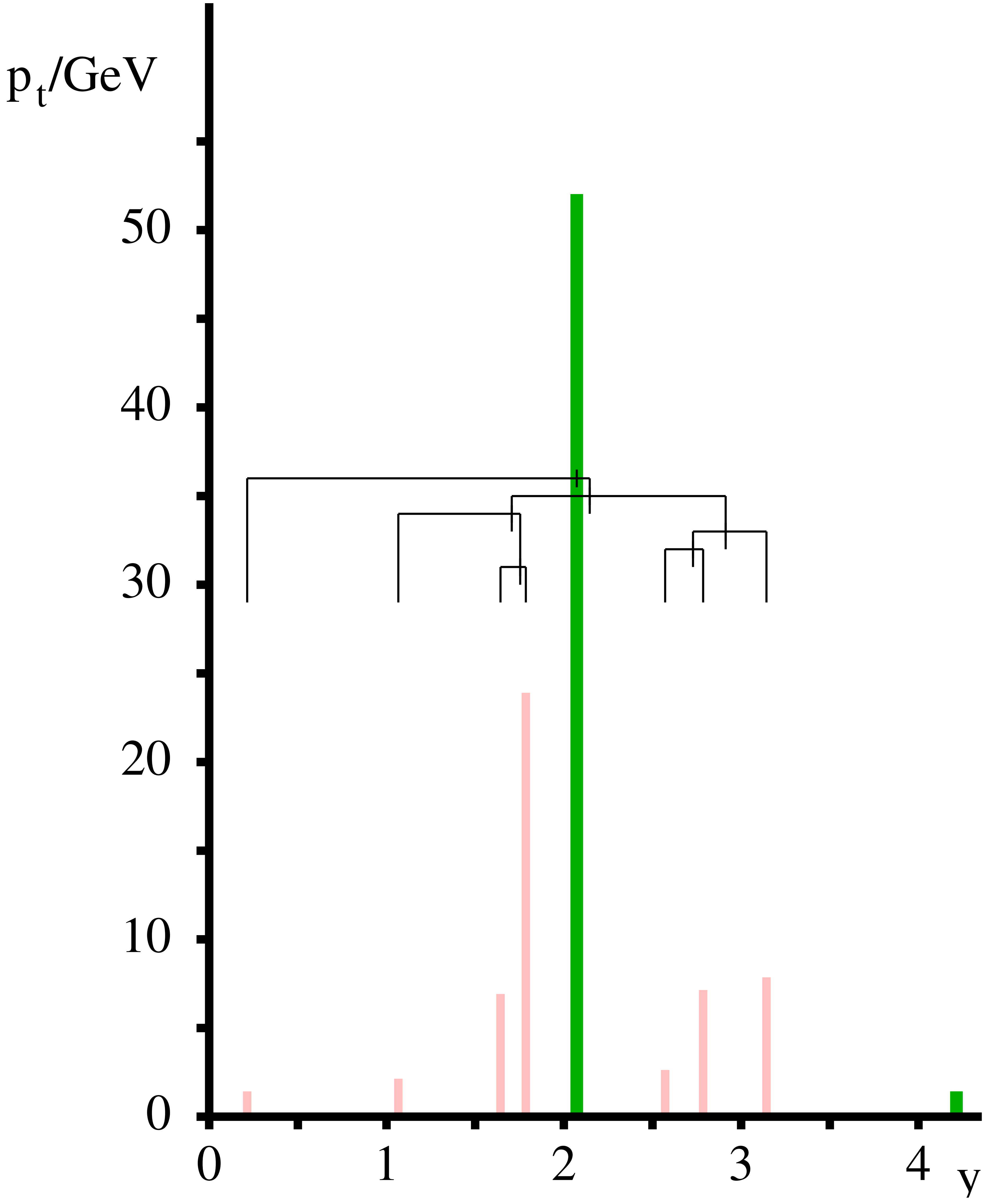
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



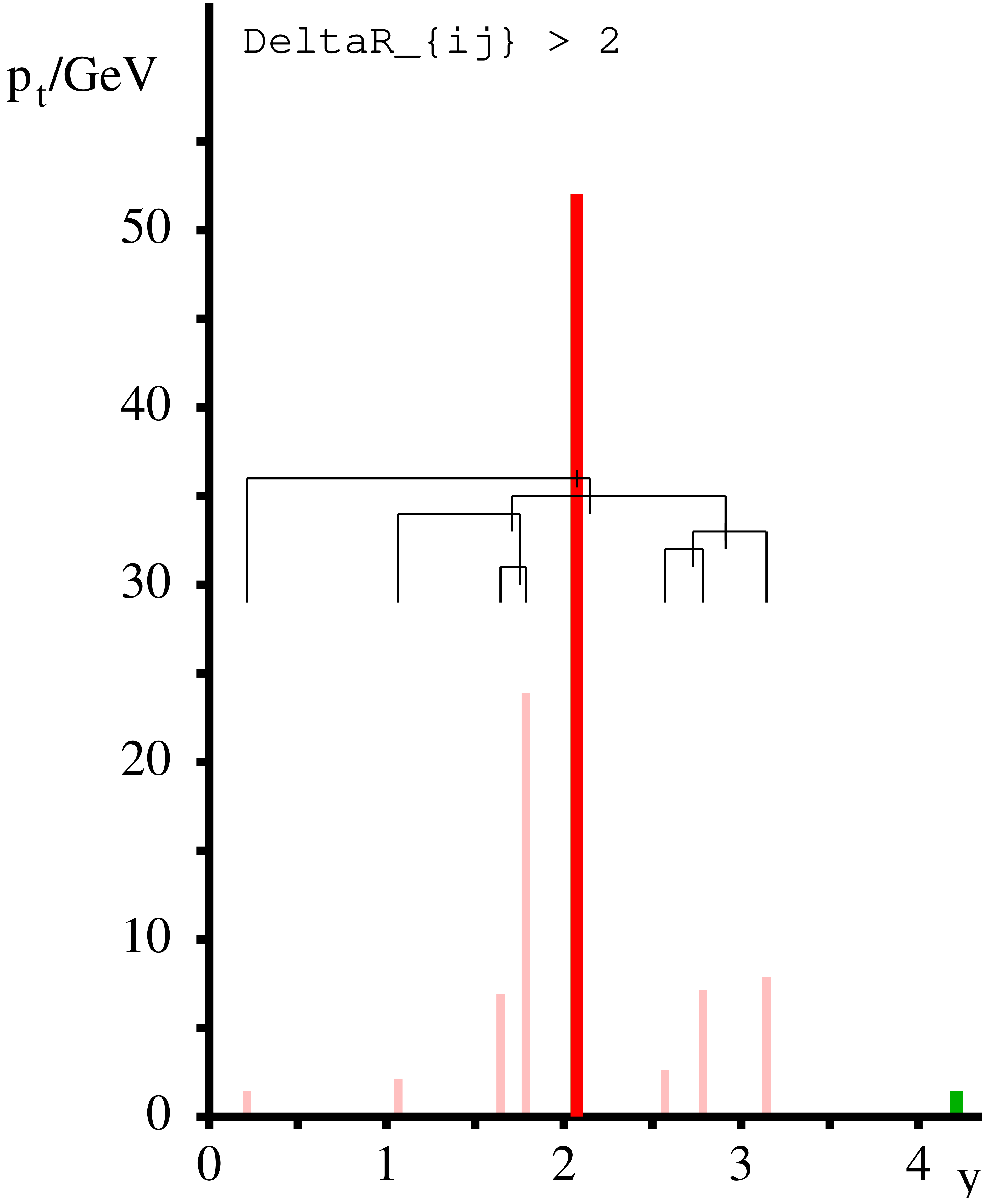
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



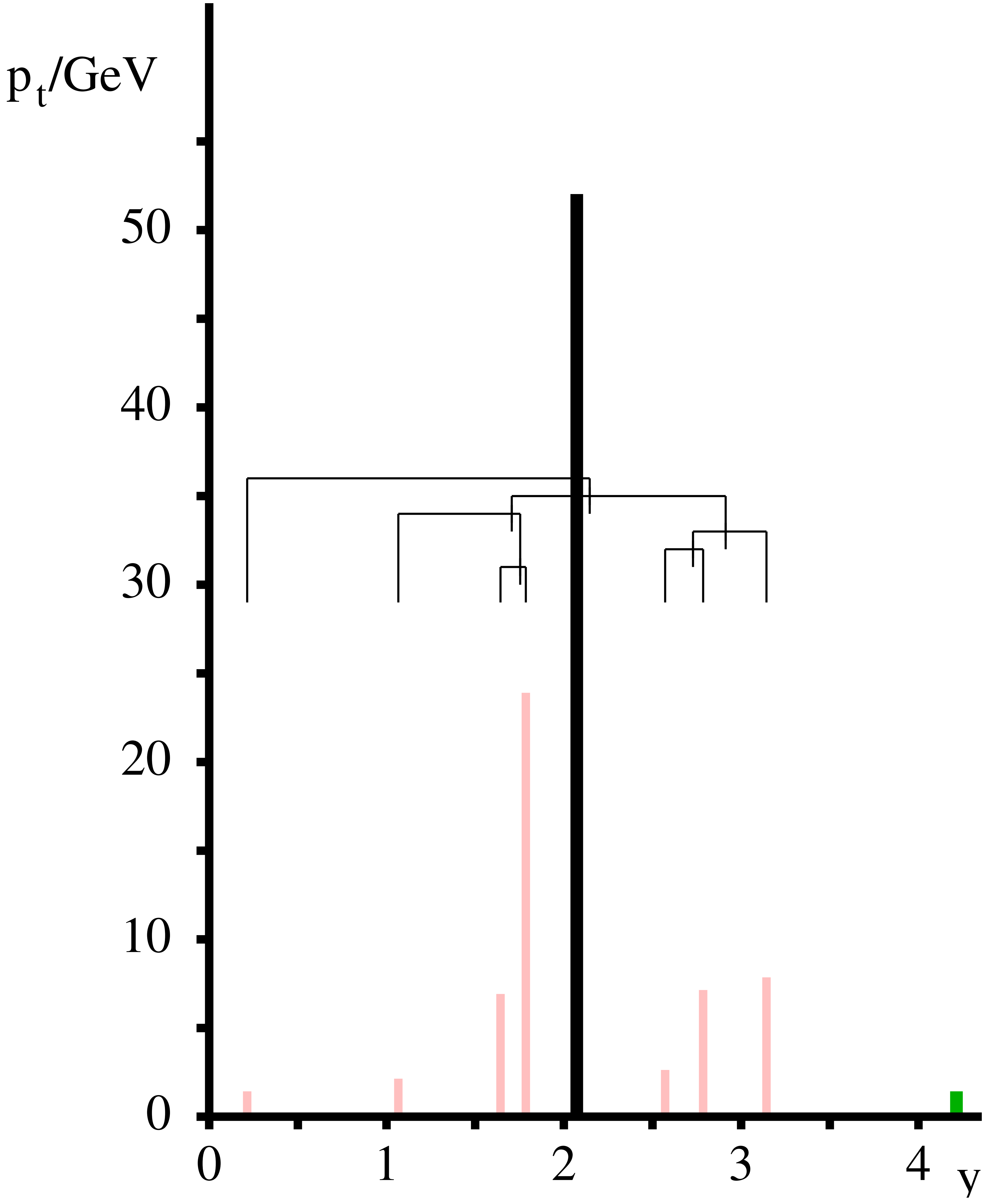
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



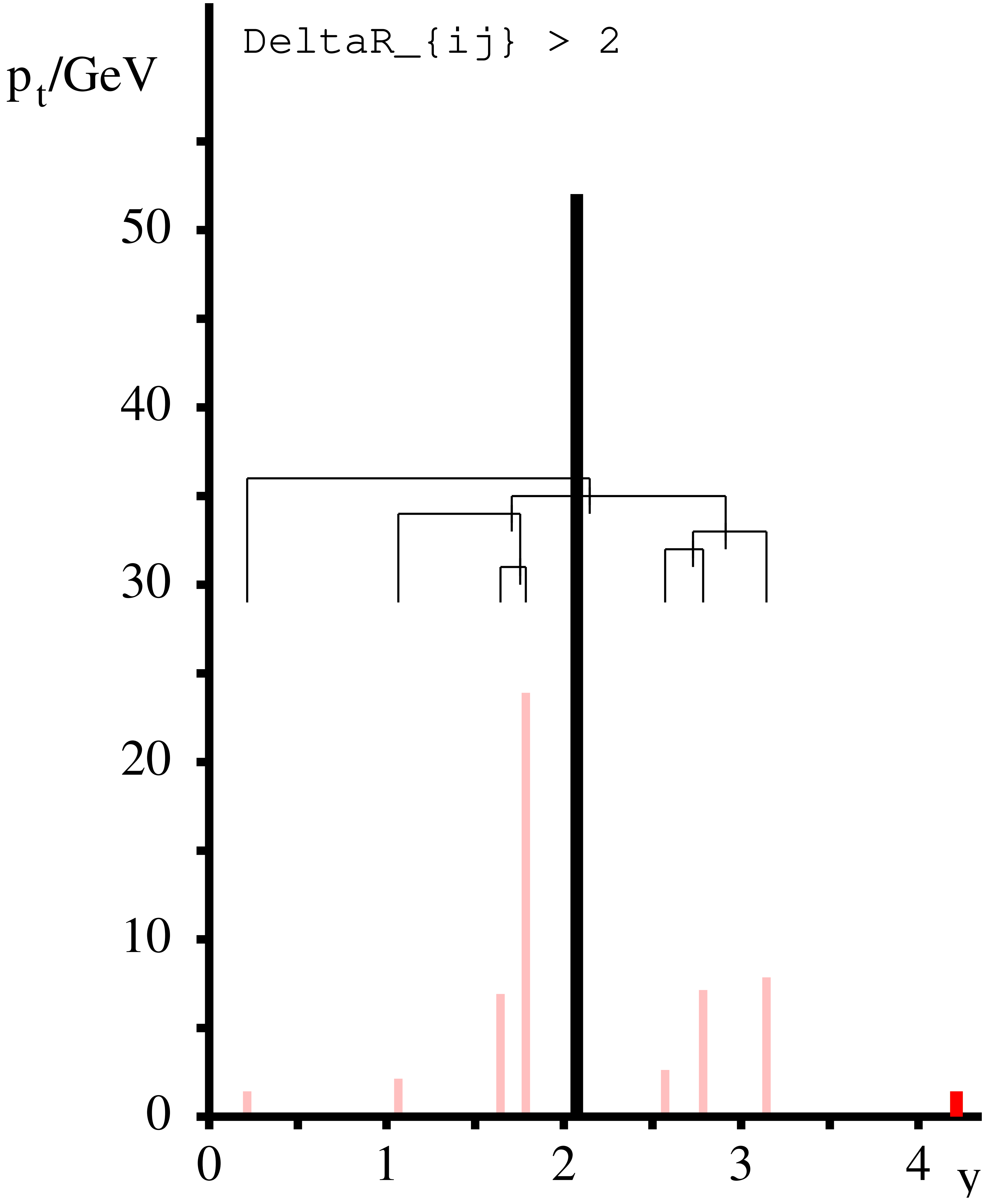
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



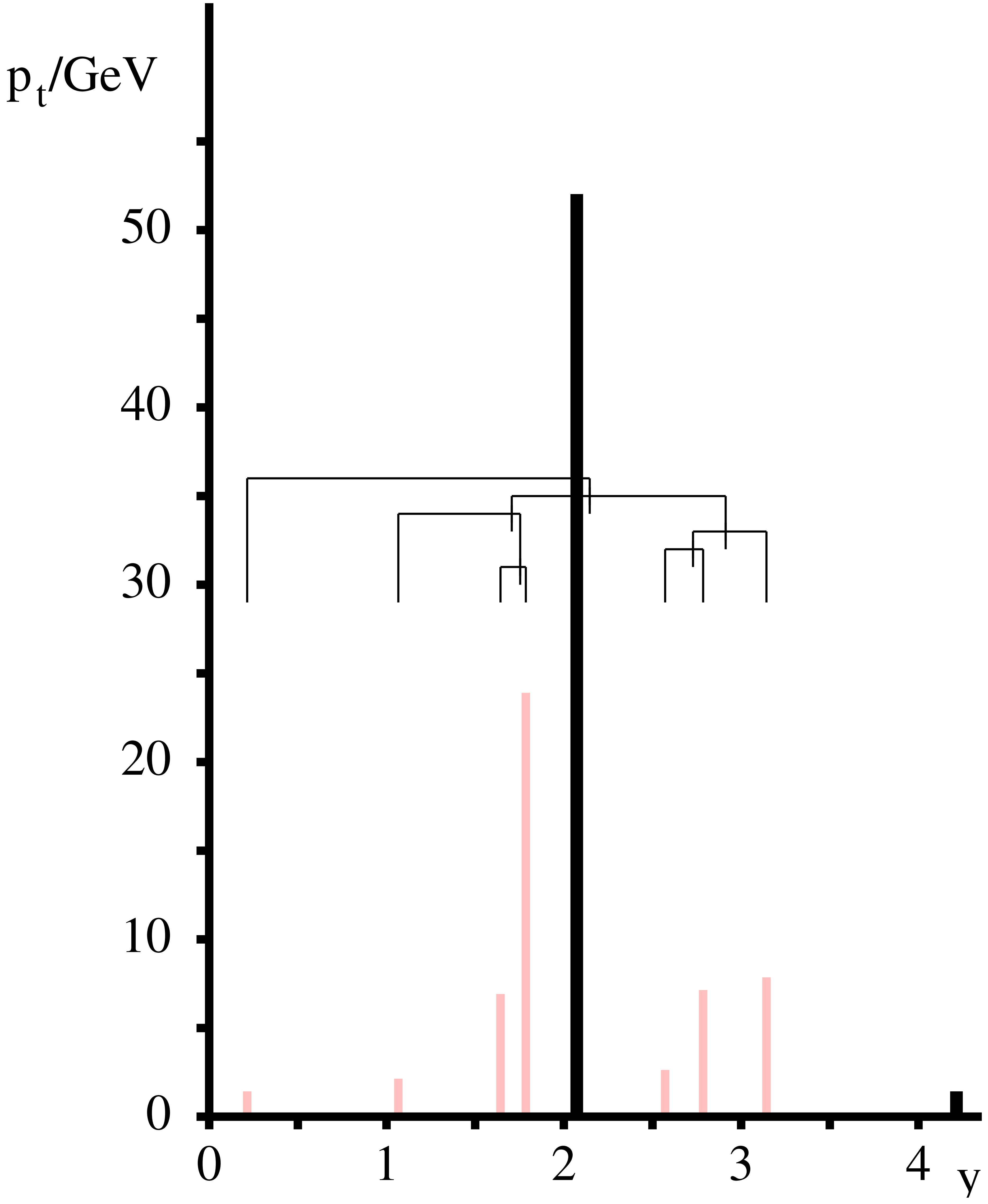
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



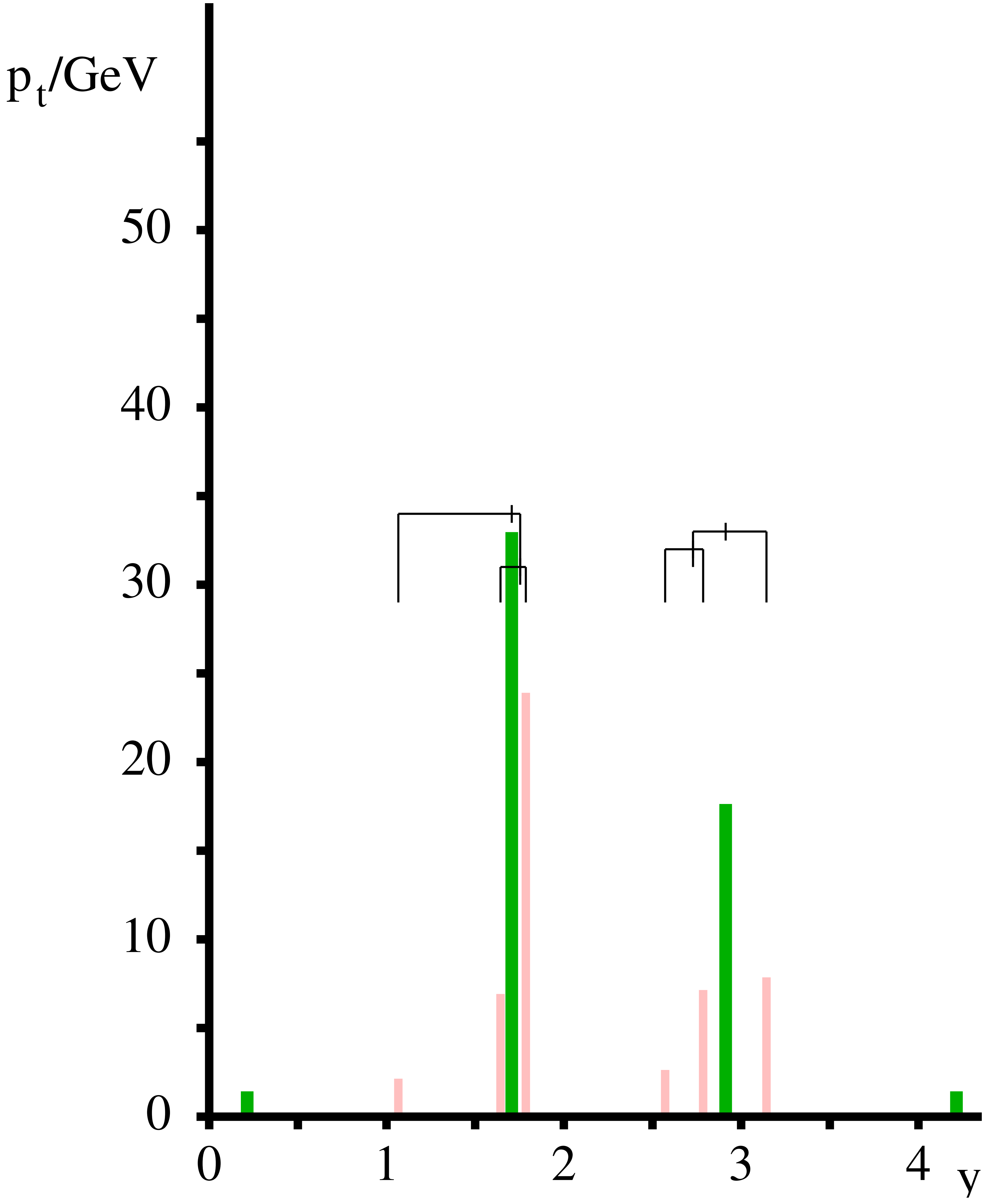
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard “blobs”

Soft junk gets added in at the end

Identifying jet substructure: Cam/Aachen



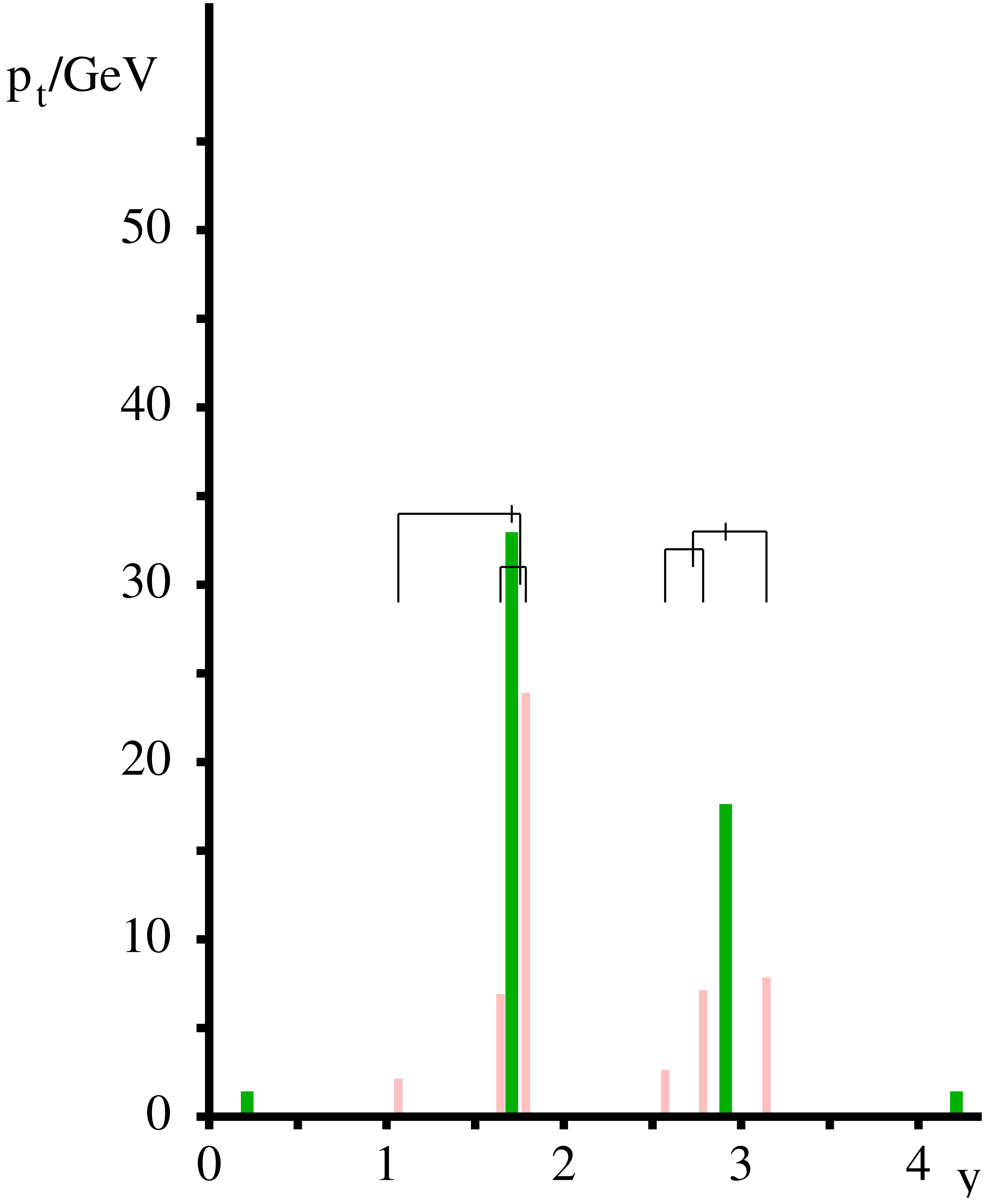
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end (and is what SoftDrop removes)

Identifying jet substructure: Cam/Aachen



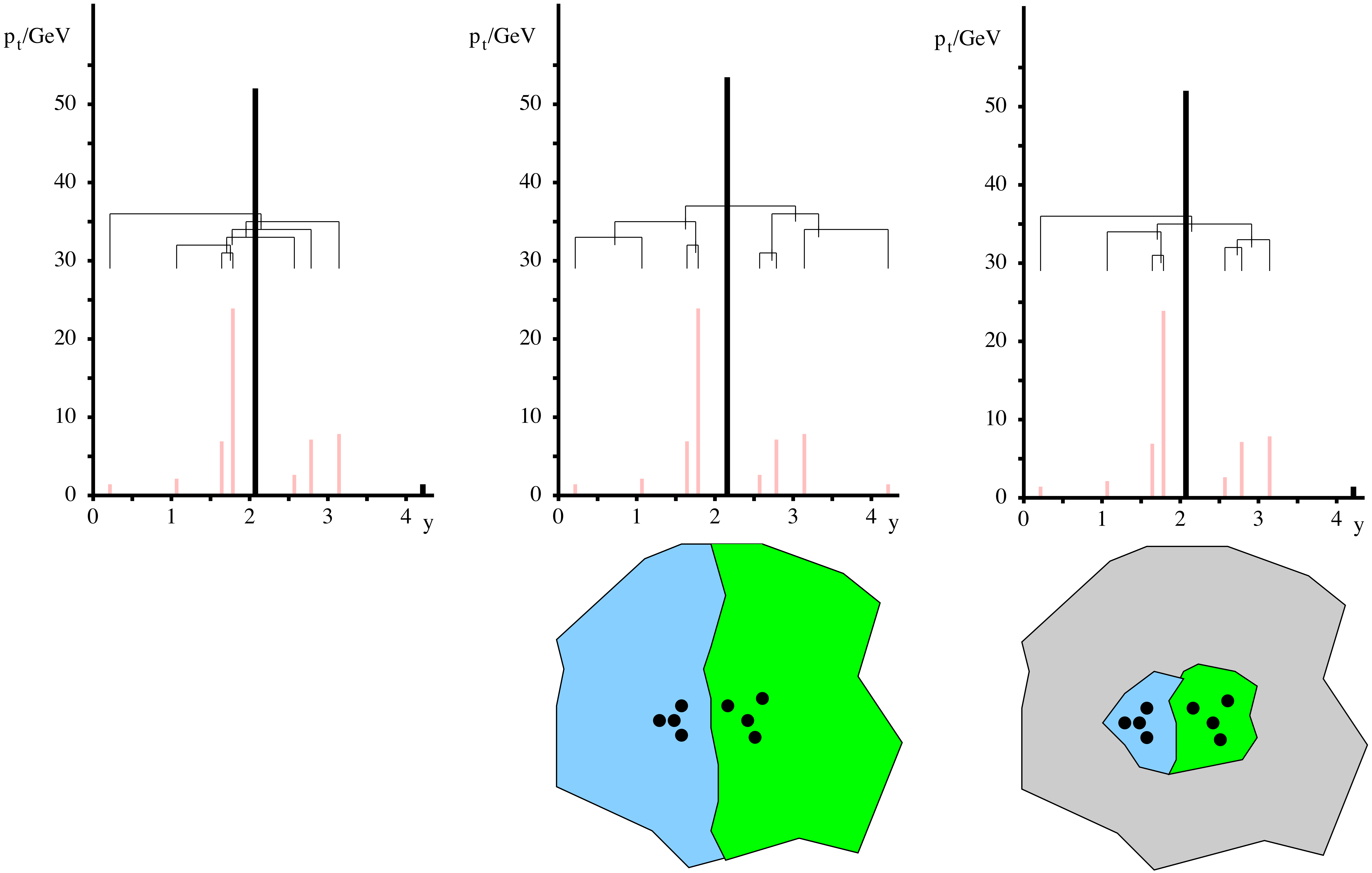
How well can an algorithm identify the "blobs" of energy inside a jet that come from different partons?

C/A algorithm works hierarchically in angle

Clear ID of two separate hard "blobs"

Soft junk gets added in at the end (and is what SoftDrop removes)

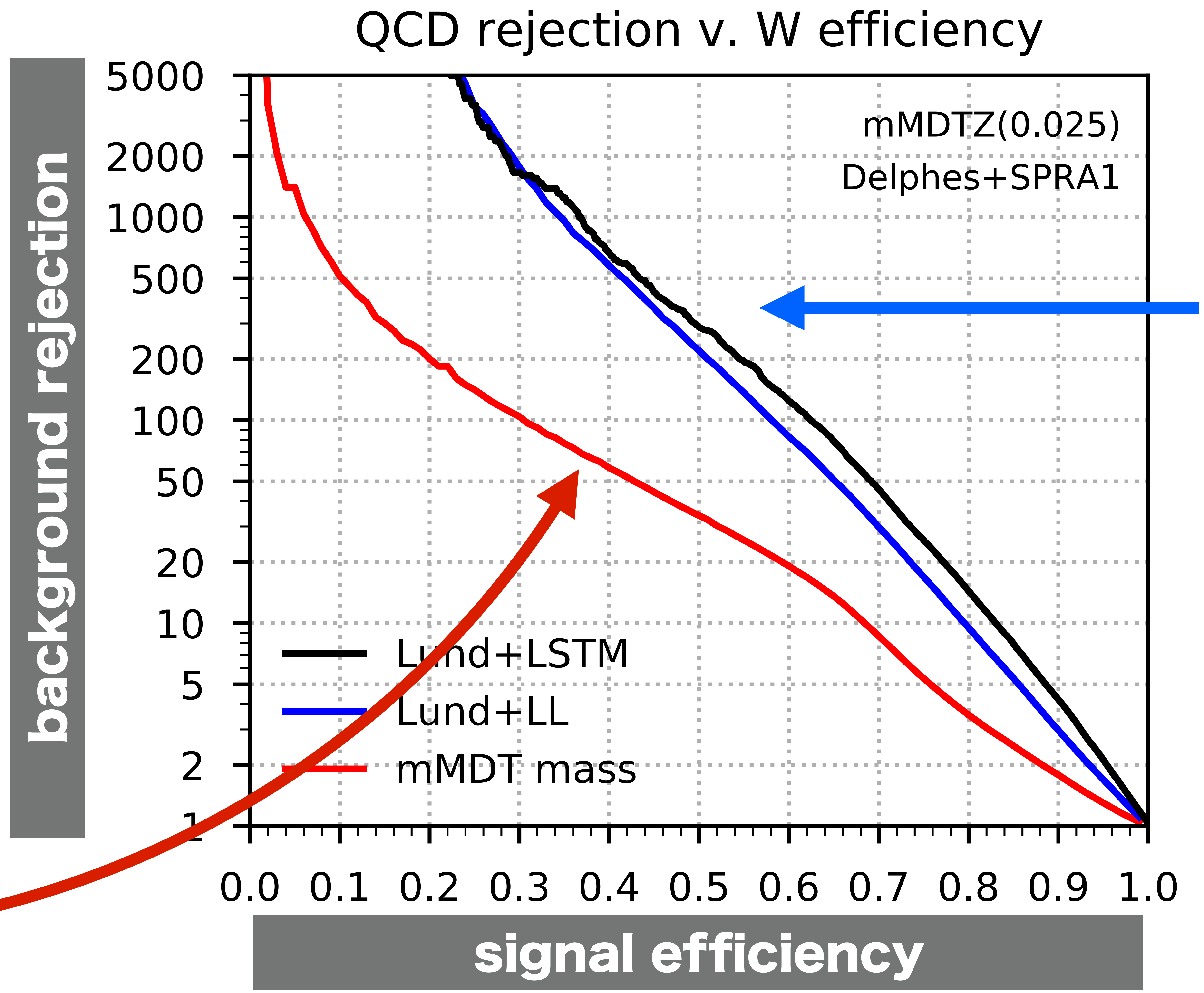
anti-k_t algorithm **k_t algorithm** **Cambridge/Aachen**



Tagging two-prong decays

4. Looking beyond hard substructure

Figure from
Frédéric Dreyer



QCD rejection with use of full jet substructure (2018 ML tools)

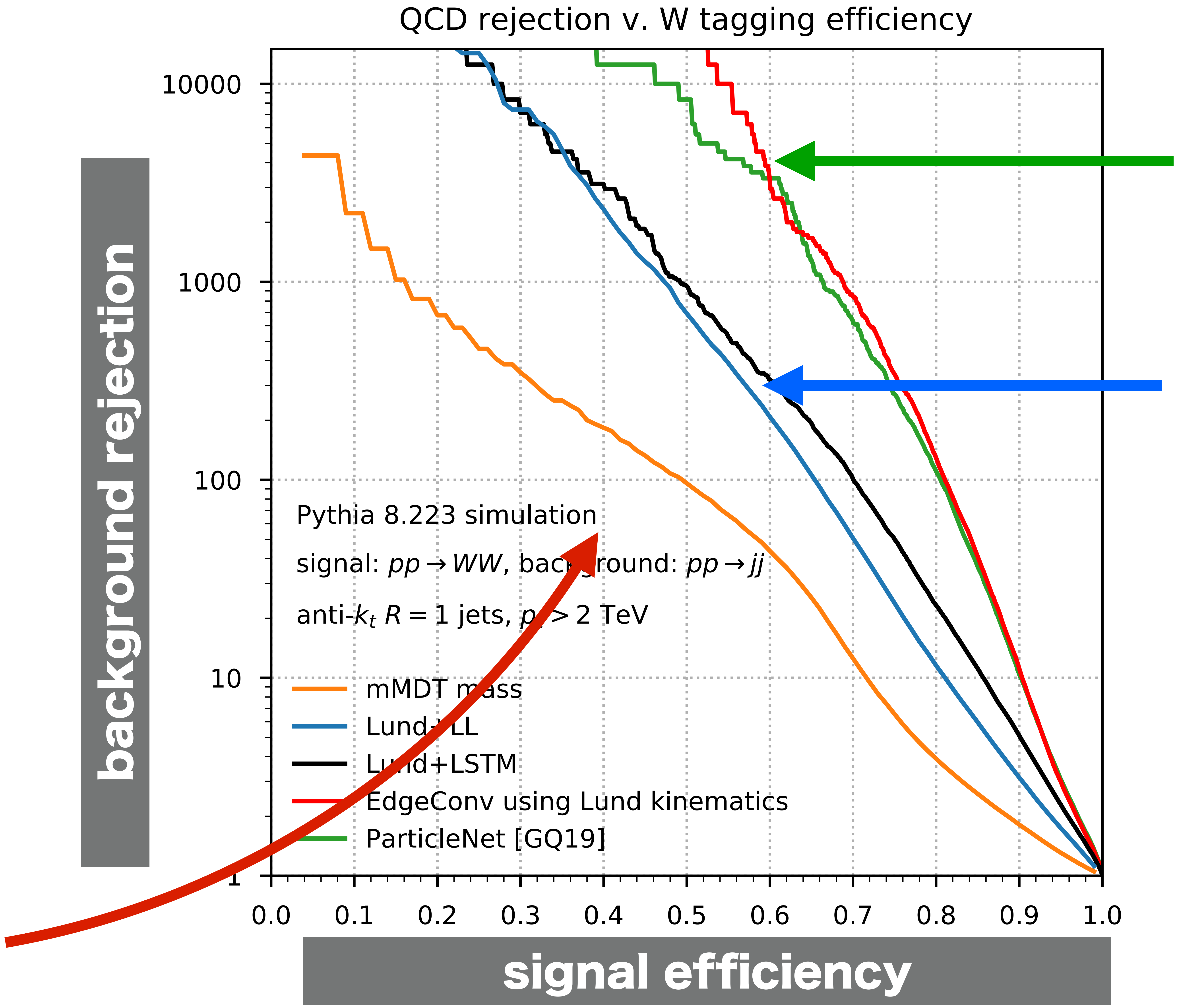
5–10x better

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

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

using full jet information for W boson tagging

Figure from
Frédéric Dreyer



2019/20 ML tools another x10

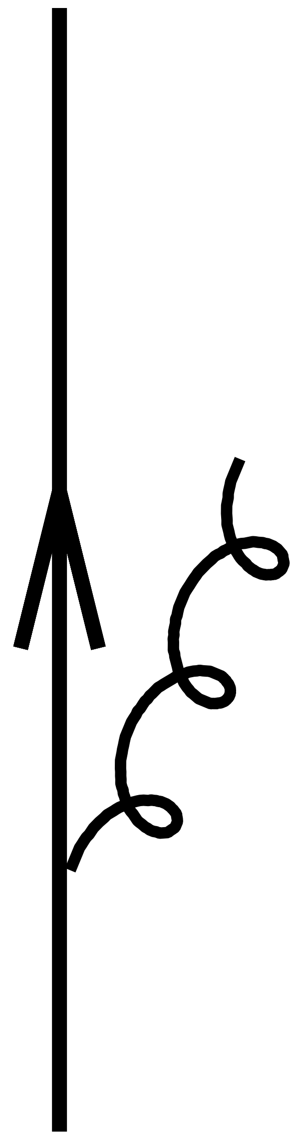
QCD rejection with use of full jet substructure (2018 ML tools)

5–10x better

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

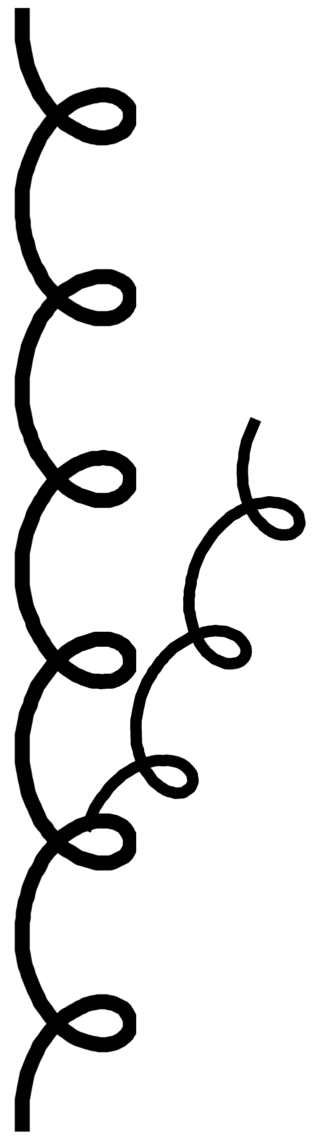
First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

Intensity of gluon radiation from a single parton



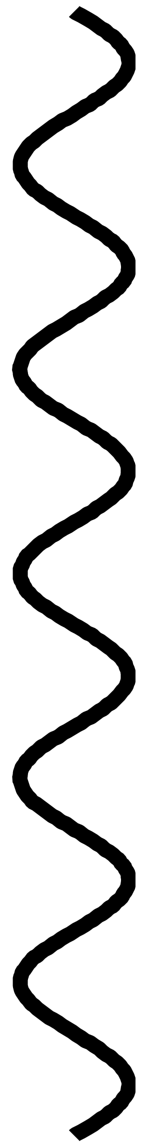
$$\frac{\boxed{C_F}\,\alpha_s}{\pi}\,\frac{dE}{E}\,\frac{d\theta^2}{\theta^2}$$

$$C_F = \frac{4}{3}$$



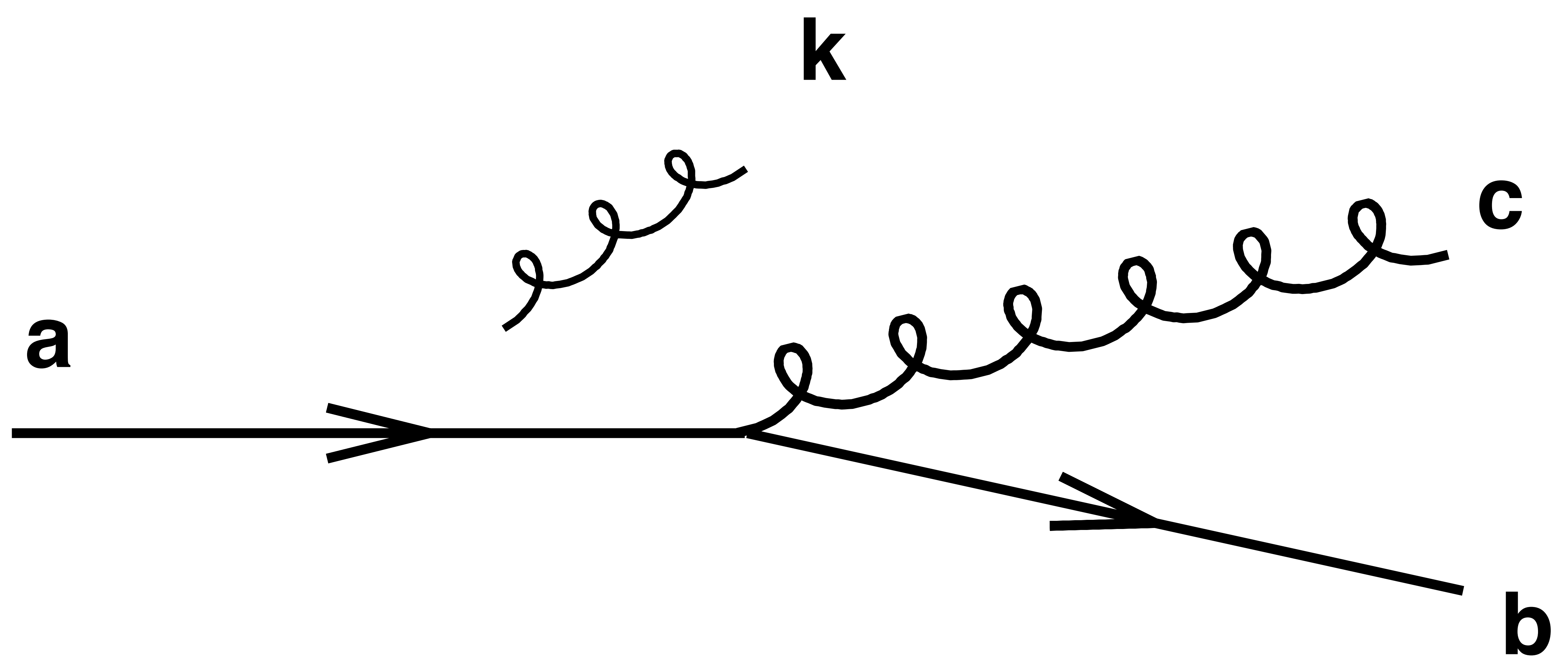
$$\frac{\boxed{C_A}\,\alpha_s}{\pi}\,\frac{dE}{E}\,\frac{d\theta^2}{\theta^2}$$

$$C_A = 3$$



$$\boxed{0}$$

Z/W/H don't radiate gluons

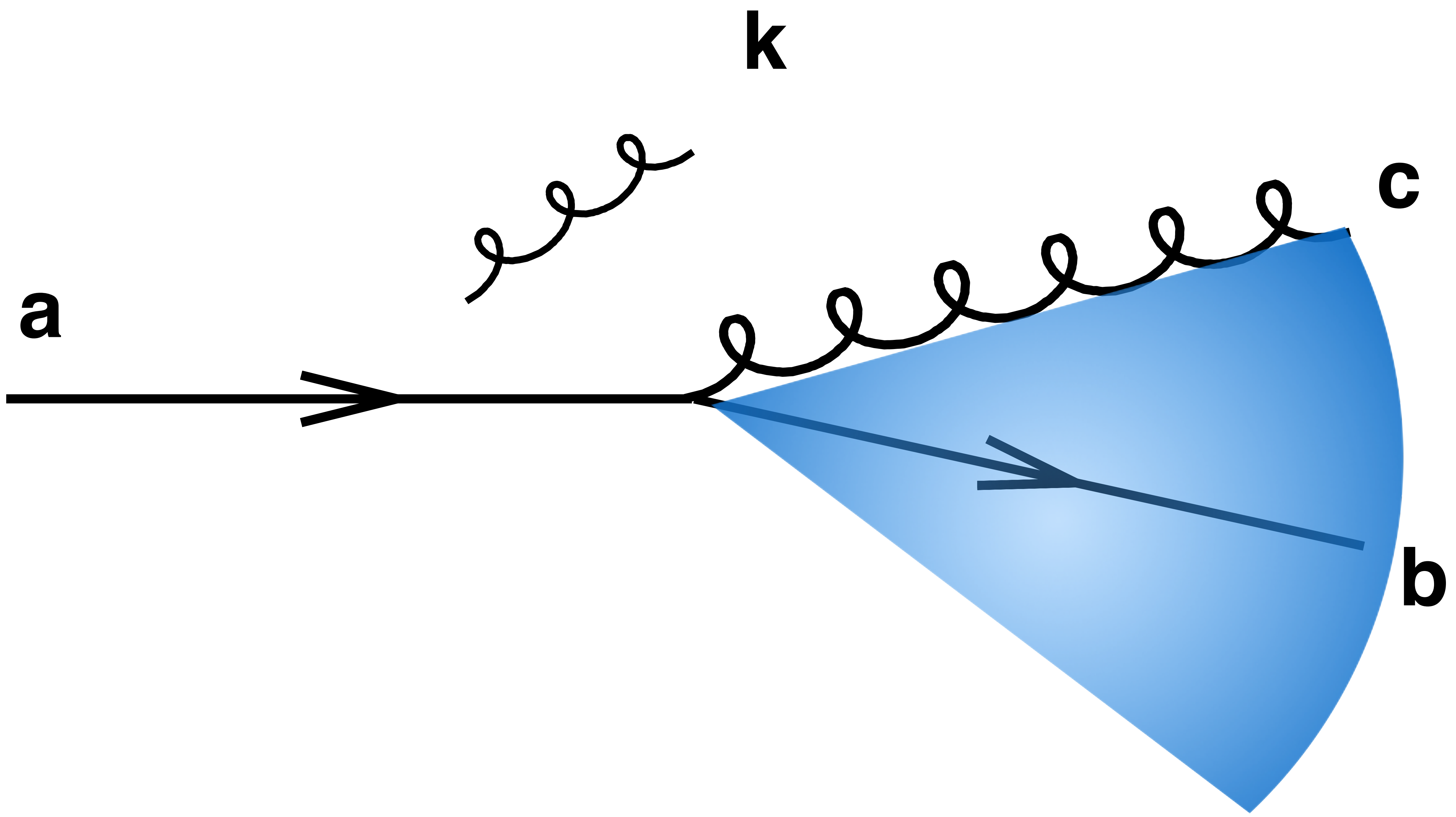


$$C_F \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_A \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation

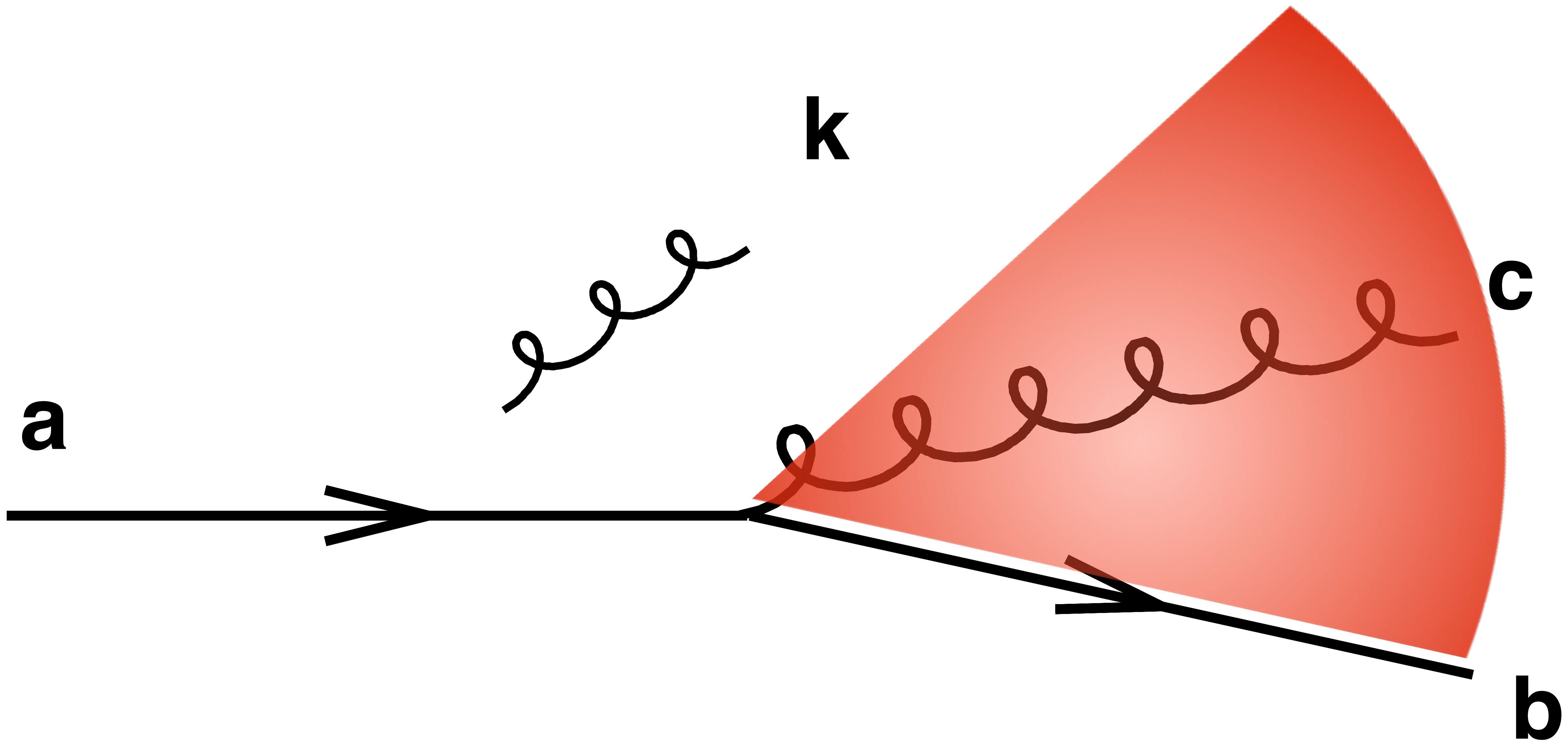


$$C_F \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_A \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation

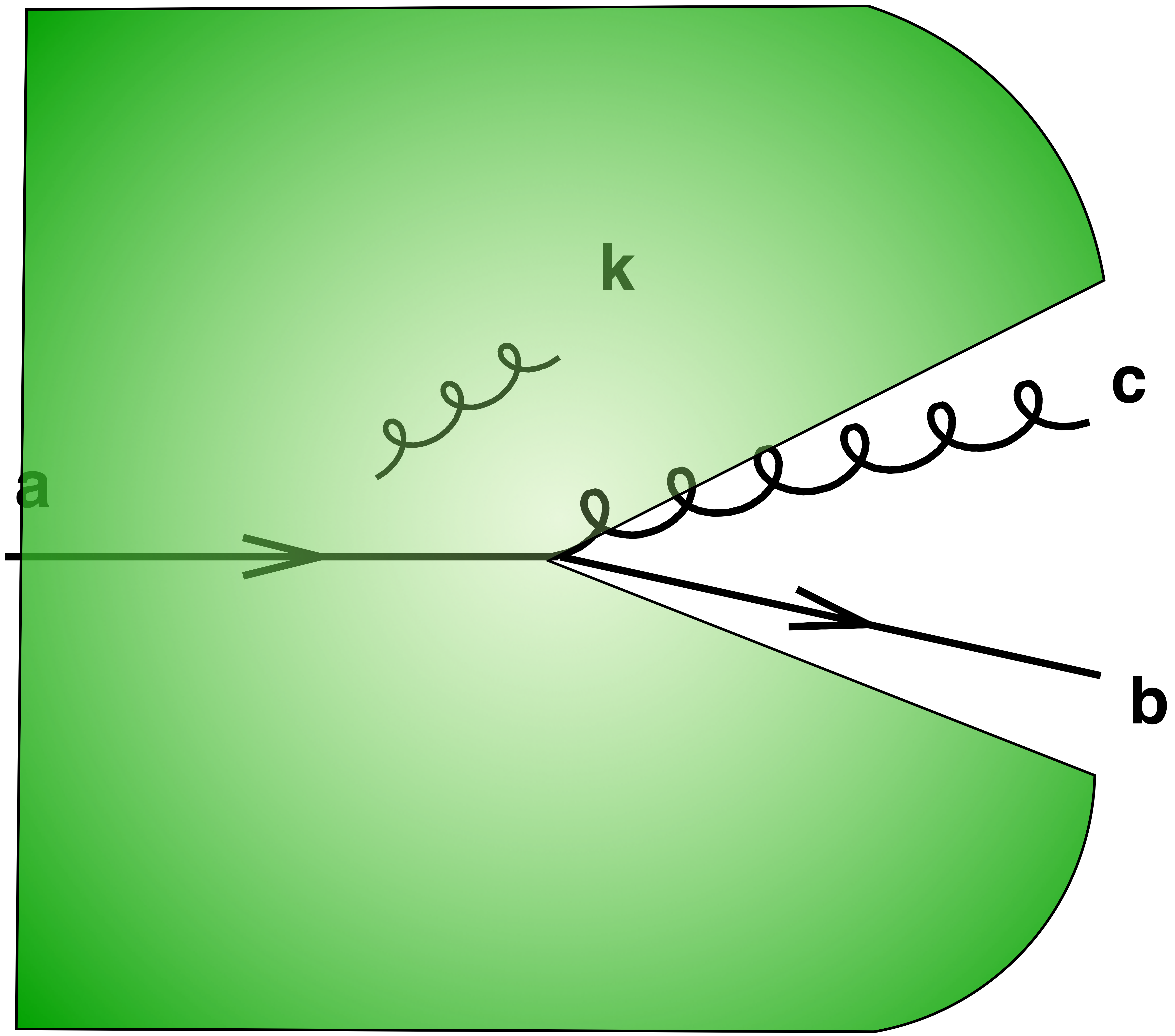


$$C_F \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_A \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation

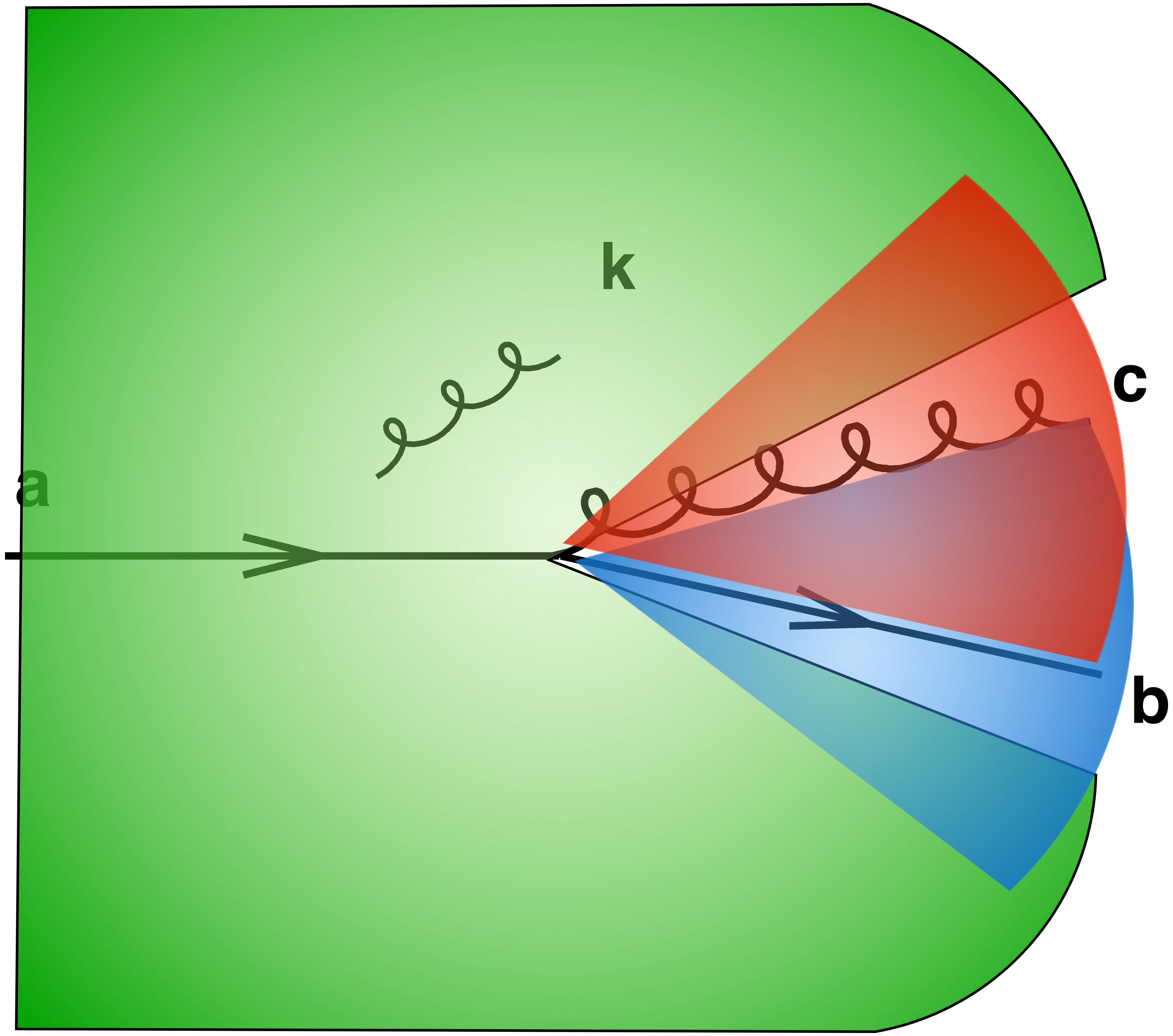


$$C_F \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_A \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation



$$C_F \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_A \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

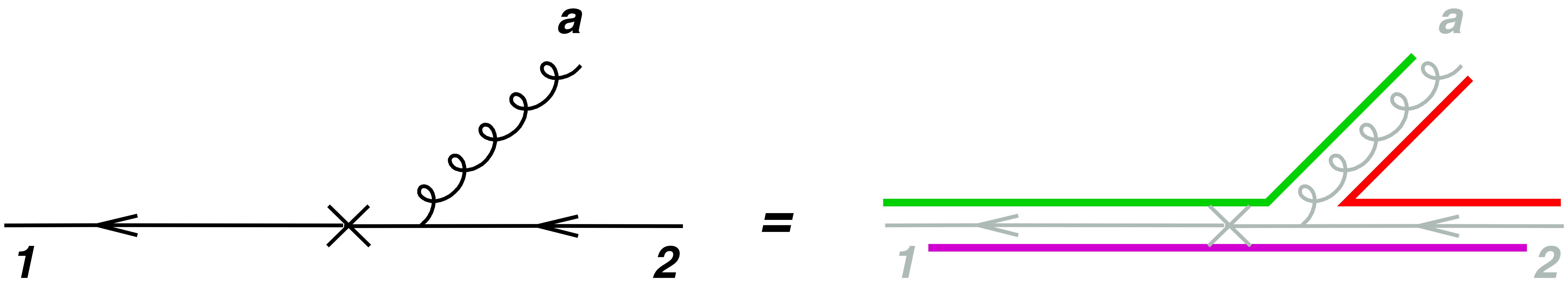
angular ordering approximation

expression without angular ordering approximation

Write as $|M^2_{q\bar{q}a}| \times$ (emission of b)

$$|M_{q\bar{q}ab}|^2 = |M_{q\bar{q}a}|^2 2g_s^2 \left(-\frac{1}{2N_c}\frac{(12)}{(1b)(b2)} + \frac{N_c}{2}\frac{(a1)}{(ab)(b1)} + \frac{N_c}{2}\frac{(a2)}{(ab)(b2)} \right)$$

Note structure as *incoherent sum over dipoles*



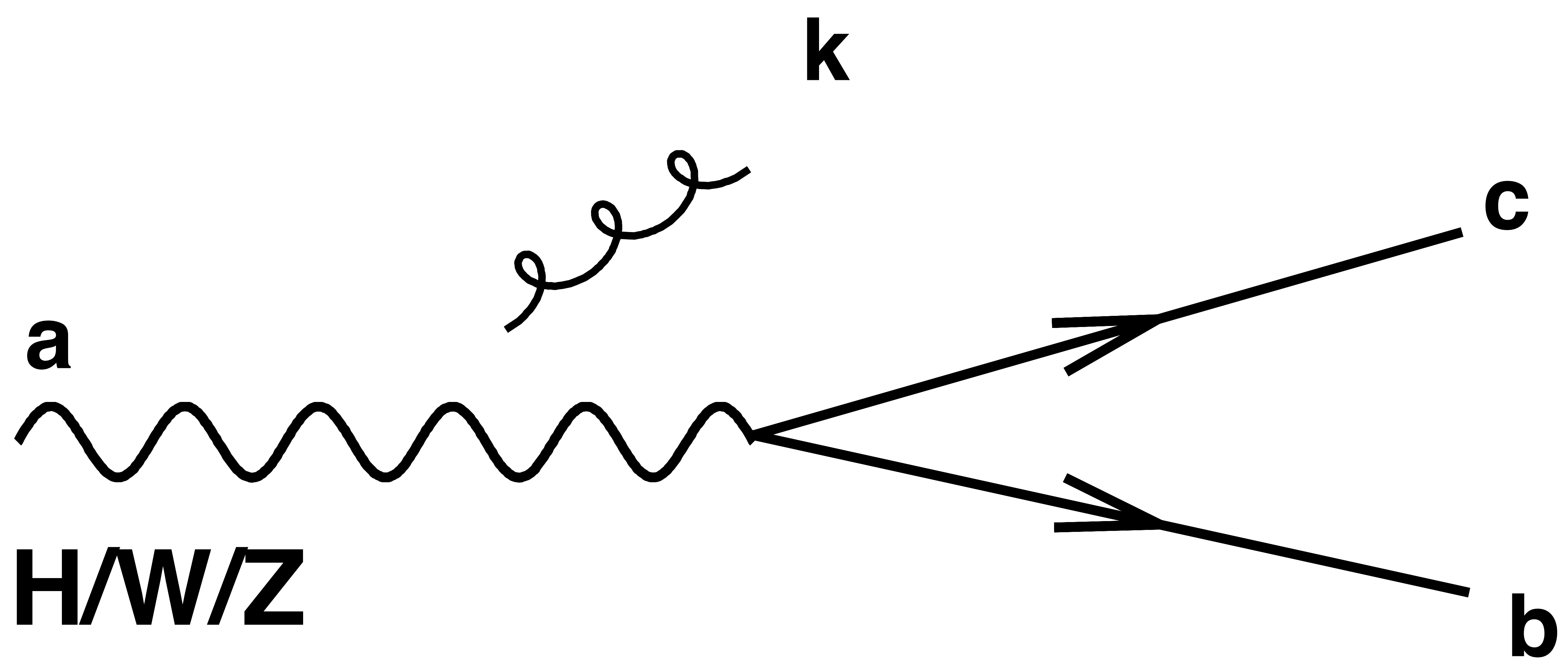
Consistency: off each quark we have

$$-\frac{1}{2N_C} + \frac{N_C}{2} = -\frac{1}{2N_C} + \frac{N_C}{2} = C_F$$

For gluon

$$\frac{N_C}{2} + \frac{N_C}{2} = C_A$$

radiation from a **colour-singlet** multi-parton system



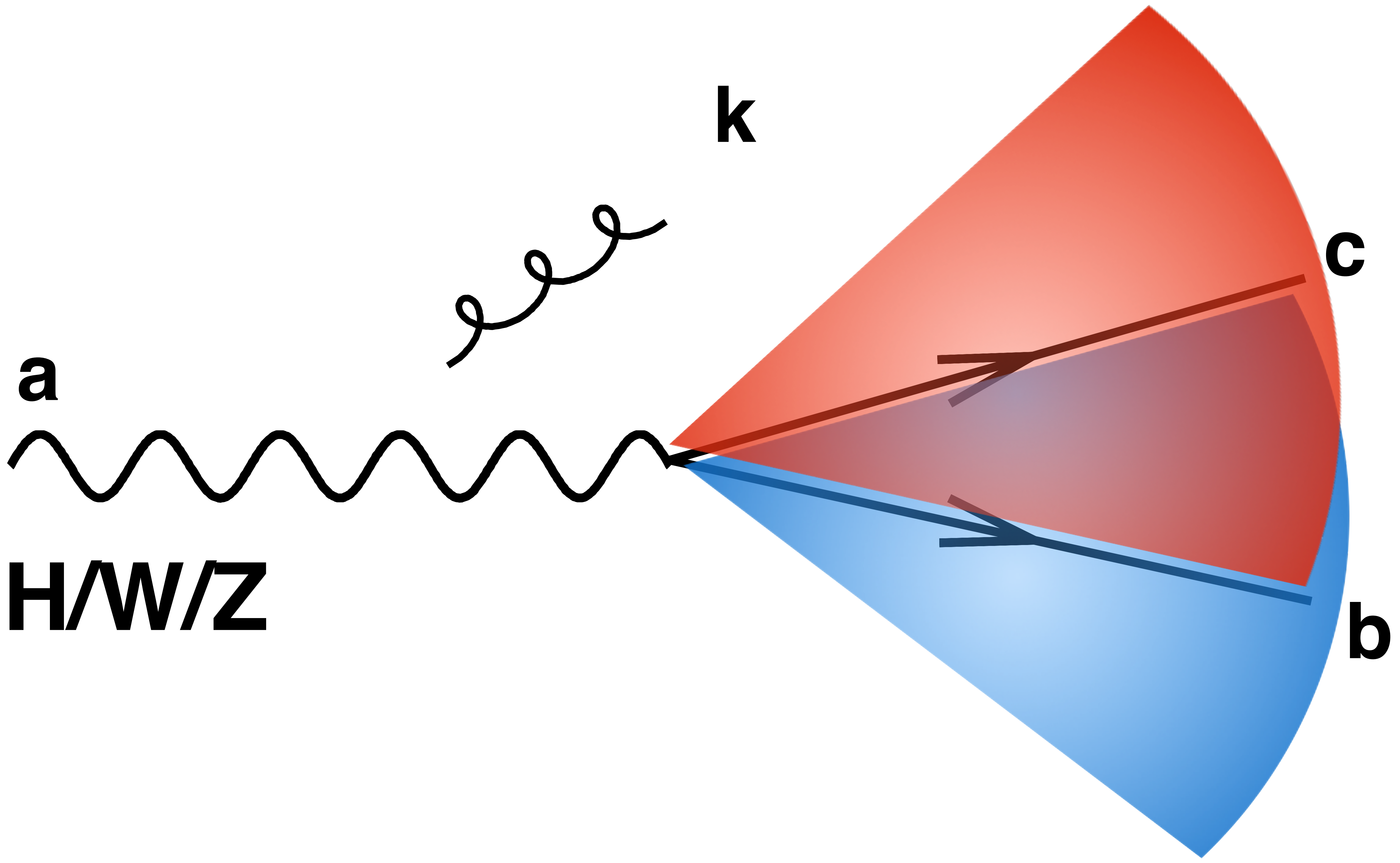
$$0 \times \frac{d\theta_{ak}^2}{\theta_{ak}^2} \Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2} \Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_F \frac{d\theta_{ck}^2}{\theta_{ck}^2} \Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation

radiation from a **colour-singlet** multi-parton system

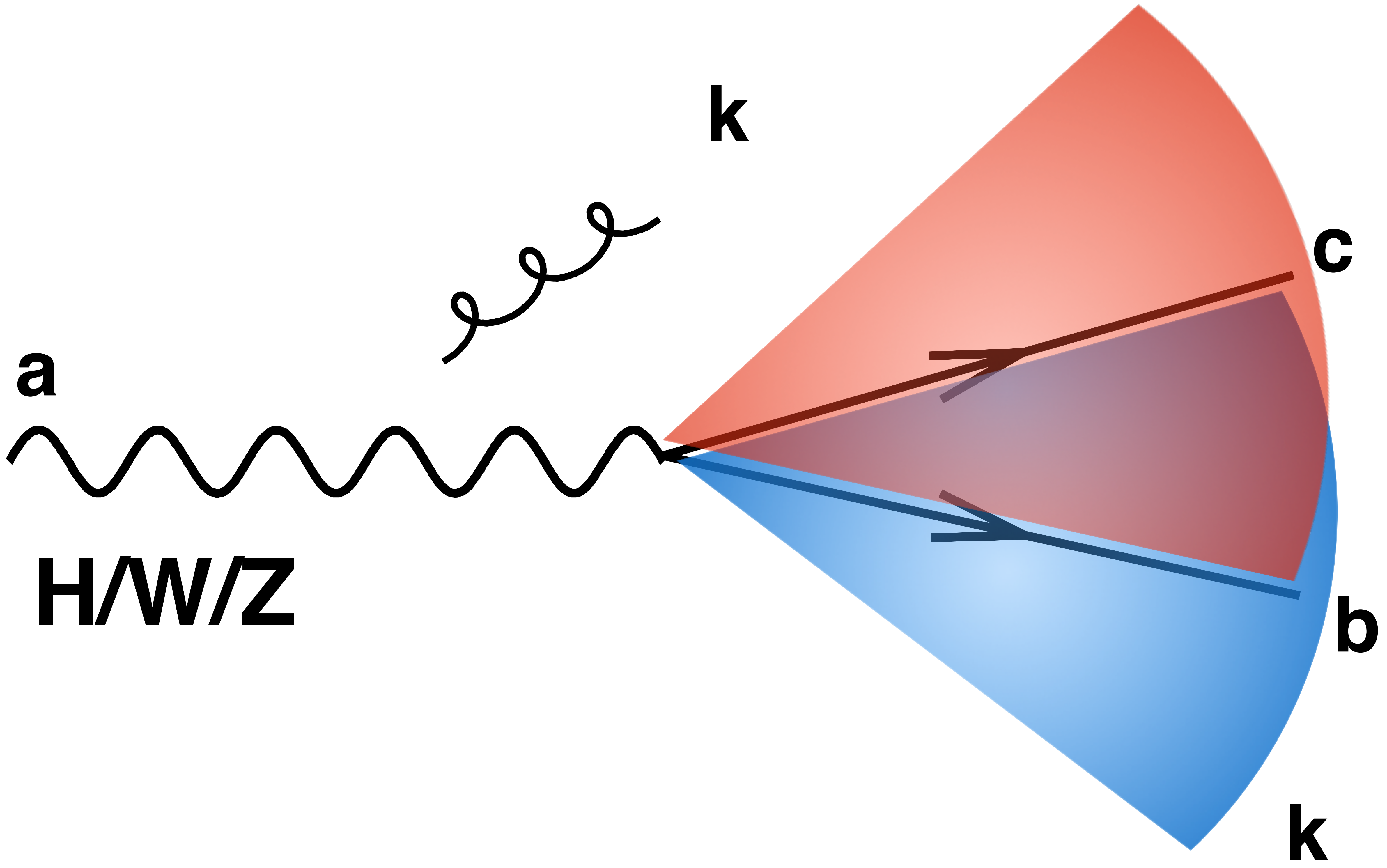


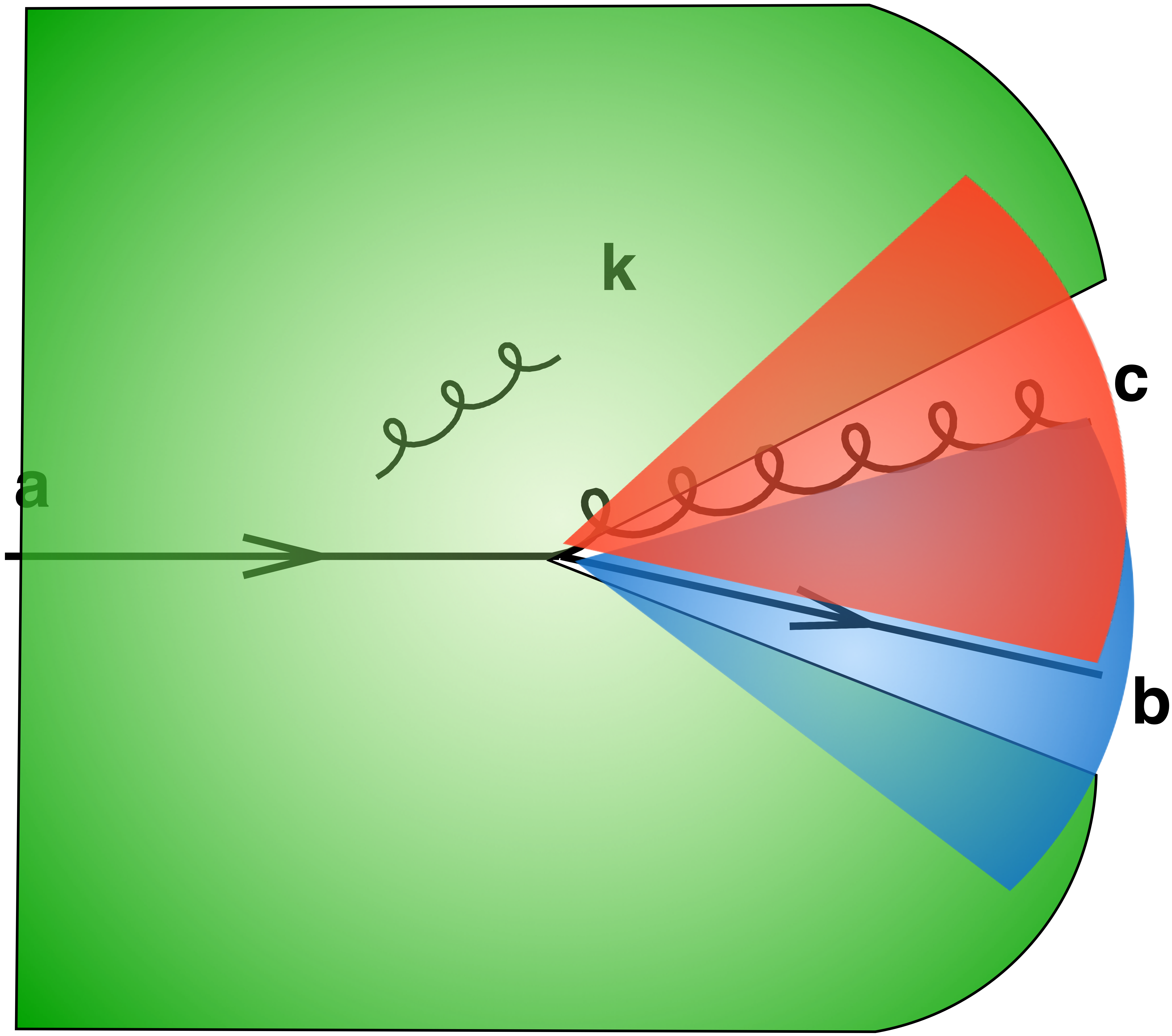
$$0 \times \frac{d\theta_{ak}^2}{\theta_{ak}^2}\Theta(\theta_{ak} \gtrsim \theta_{bc})$$

$$C_F \frac{d\theta_{bk}^2}{\theta_{bk}^2}\Theta(\theta_{bk} \lesssim \theta_{bc})$$

$$C_F \frac{d\theta_{ck}^2}{\theta_{ck}^2}\Theta(\theta_{ck} \lesssim \theta_{bc})$$

angular ordering approximation





signal (H/W/Z → $q\bar{q}$)

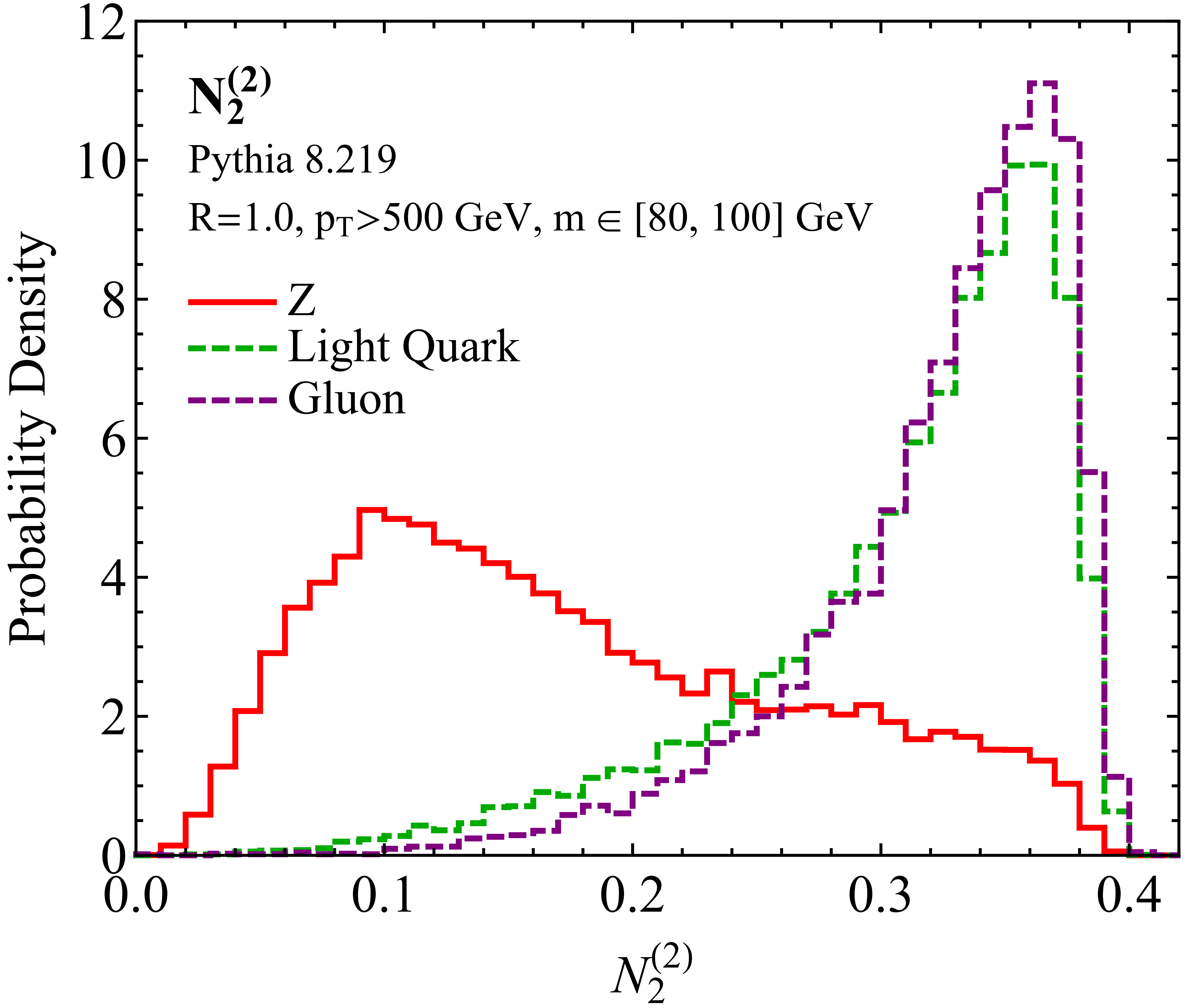
background (q → qg)

observables sensitive to radiation pattern

$$ {}_2e_3^{(\beta)} = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \min\left\{\theta_{ij}^{\beta}\theta_{ik}^{\beta}\,,\theta_{ij}^{\beta}\theta_{jk}^{\beta}\,,\theta_{ik}^{\beta}\theta_{jk}^{\beta}\right\} $$

$$ {}_1e_2^{(\beta)} \equiv e_2^{(\beta)} = \sum_{1\le i<j\le n_J} z_i z_j\, \theta_{ij}^{\beta}\,, $$

$$ N_2 = \frac{{}_2e_3^{(\beta)}}{({}_1e_2^{(\beta)})^2}\,, $$



Moult, Necib & Thaler
arXiv:1609.07483

Decorrelate radiation taggers from jet mass

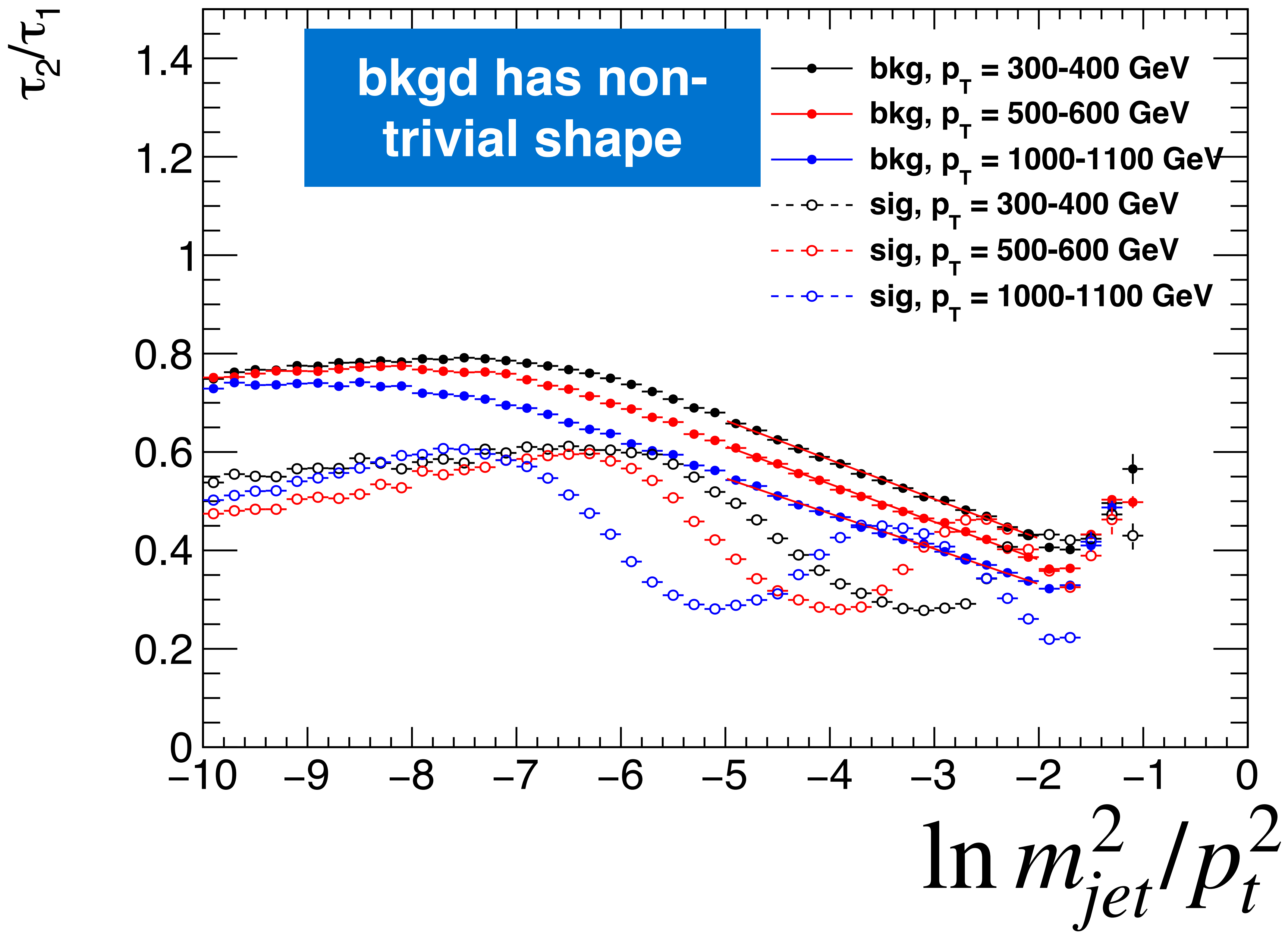
Original radiation tagger

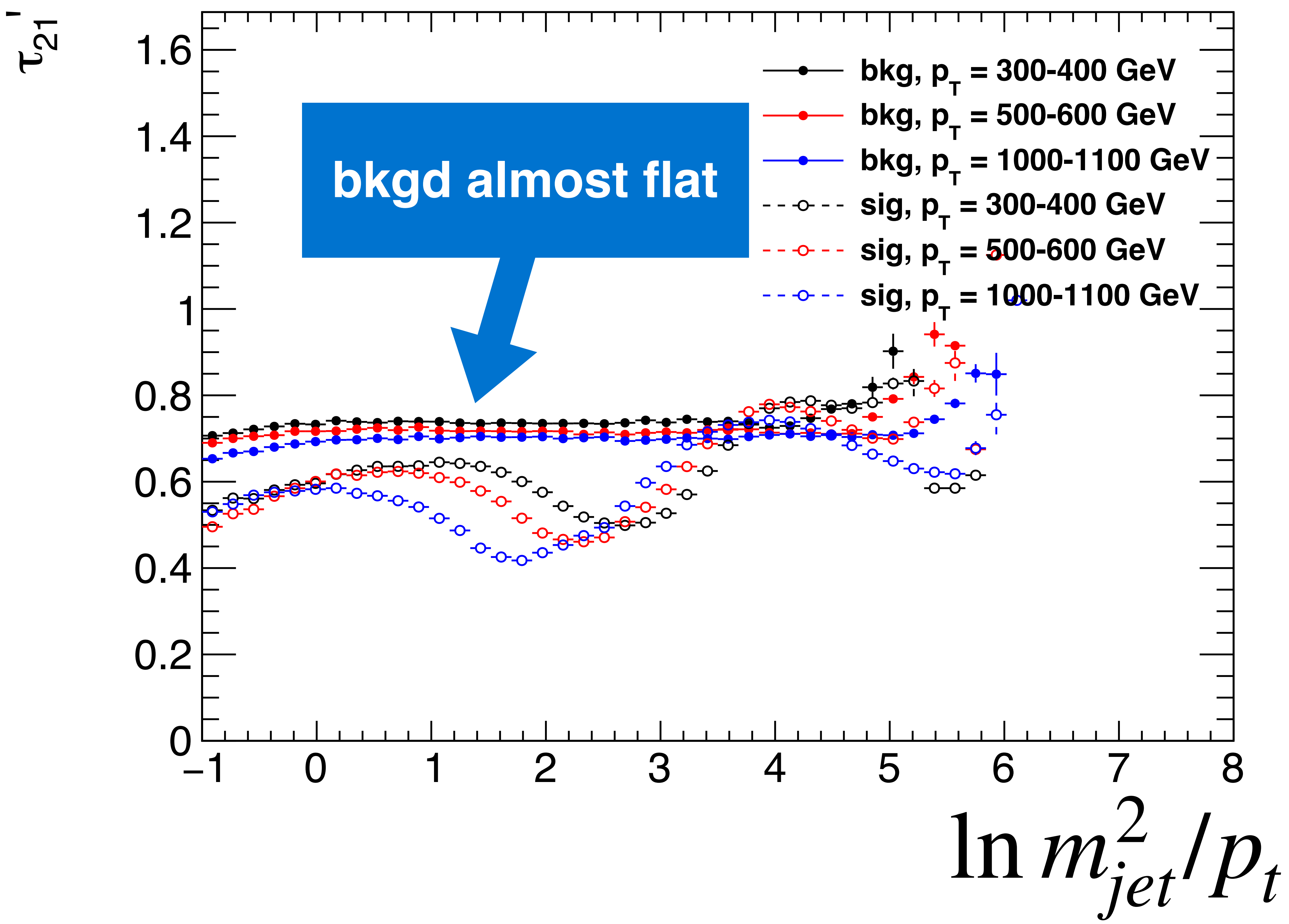
$$\tau_{21} \equiv \tau_2/\tau_1$$

(plot shows avg v. jet mass)

Decorrelated radiation tagger

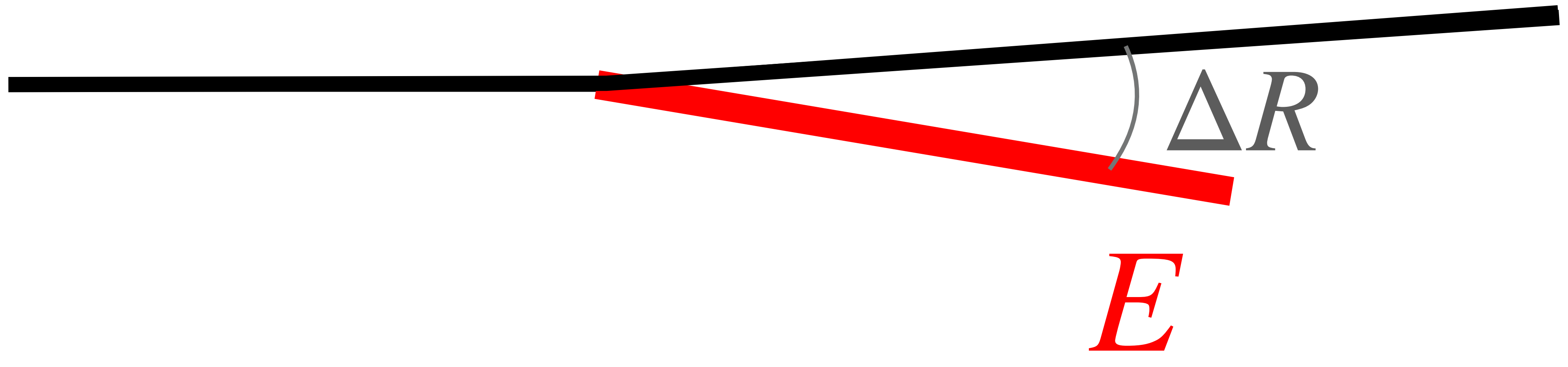
$$\tau'_{21} \equiv \tau_2/\tau_1 - \text{const} \times \ln m_{jet}^2/p_t$$





Dolen, Harris, Marzani, Rappoccio, Tran, arXiv:1603.00027

Phase space: two key variables (+ azimuth)



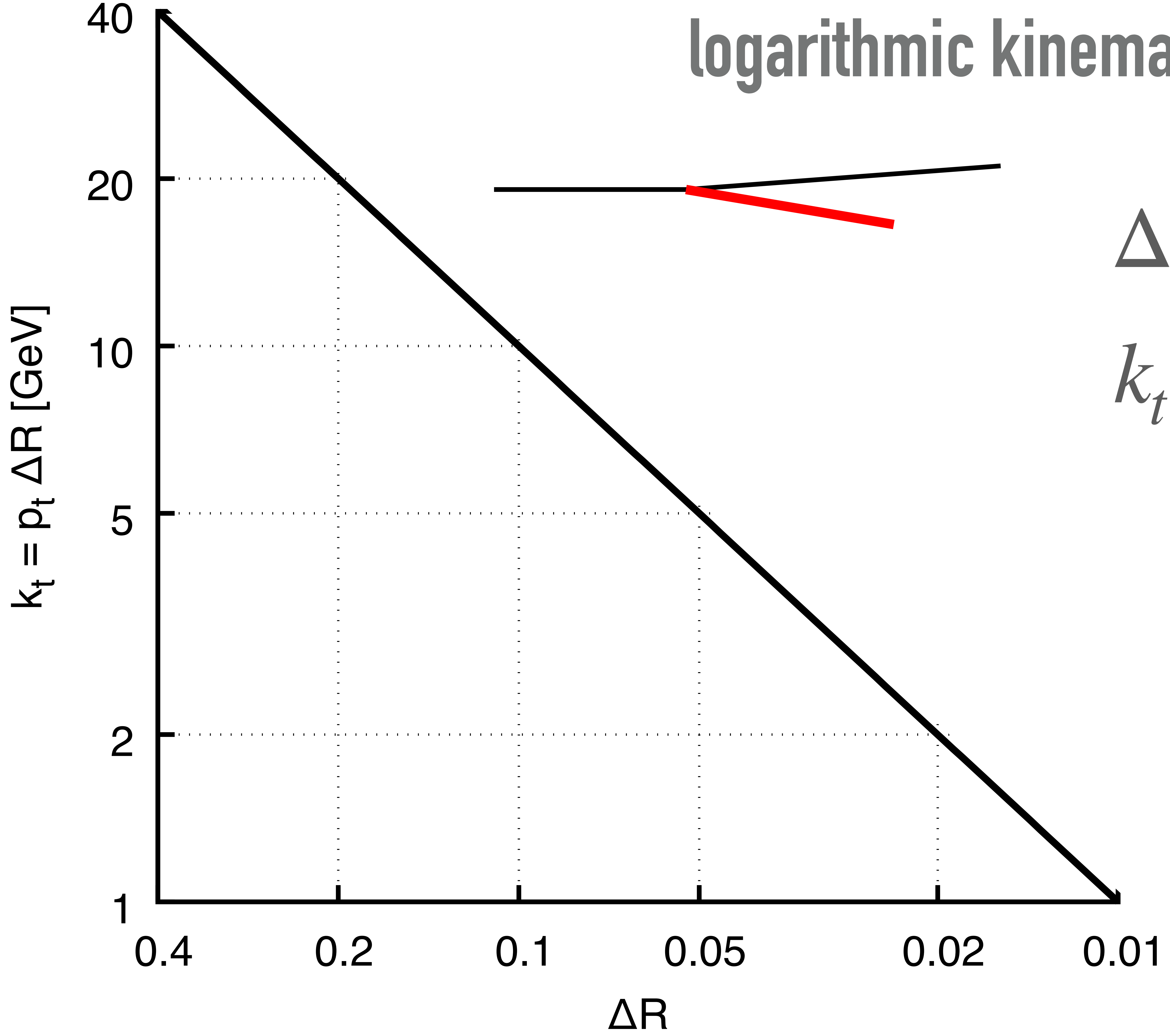
$$\Delta R \,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

η is (pseudo)rapidity ***within the jet***

$$k_t = p_t \Delta R$$

p_t (or $p_\perp$) is transverse momentum ***within the jet***

jet with $R = 0.4$, $p_t = 200$ GeV



logarithmic kinematic plane whose two variables are

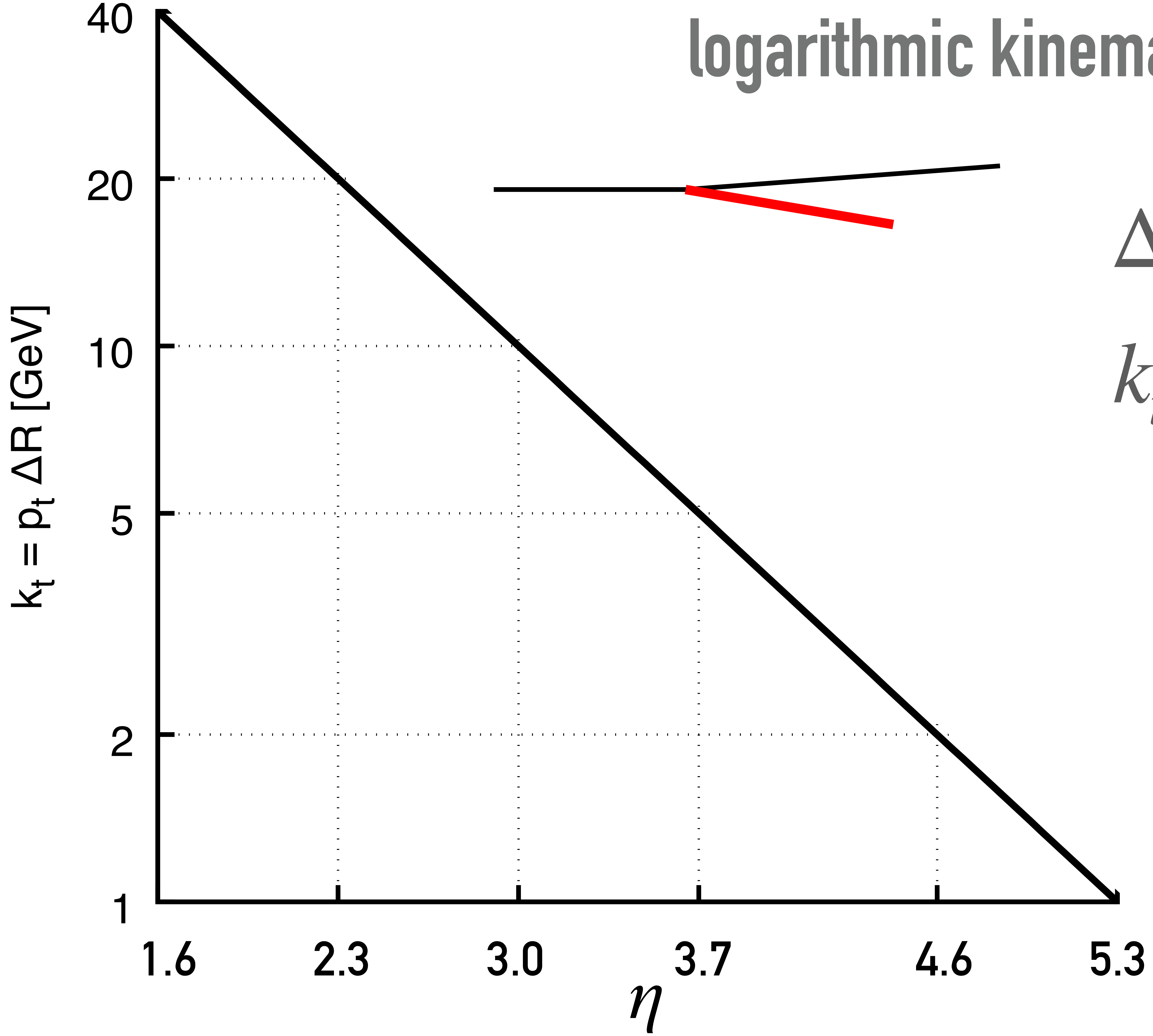
$$\Delta R \,(or\ \eta = -\ln \tan \frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



logarithmic kinematic plane whose two variables are

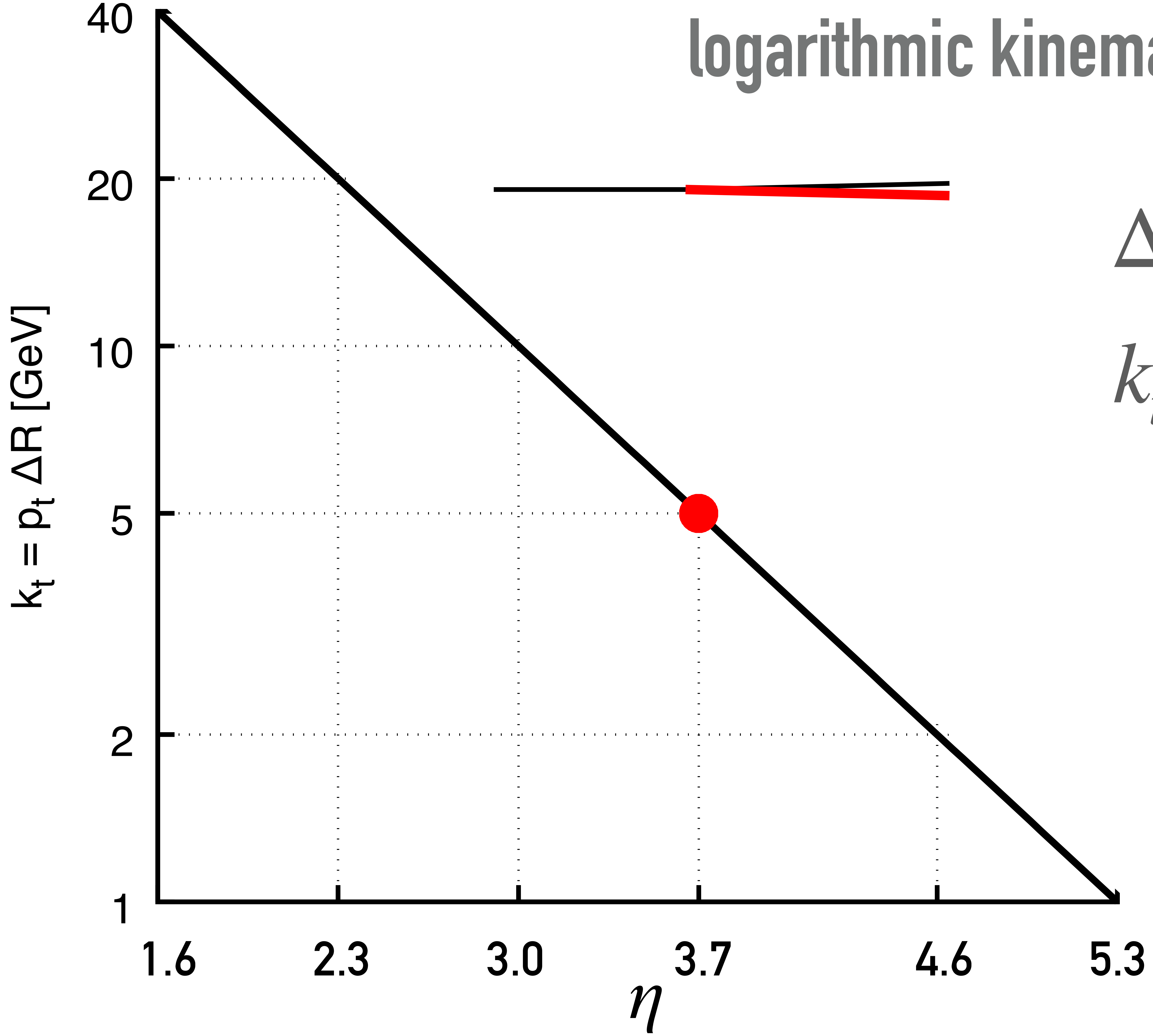
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



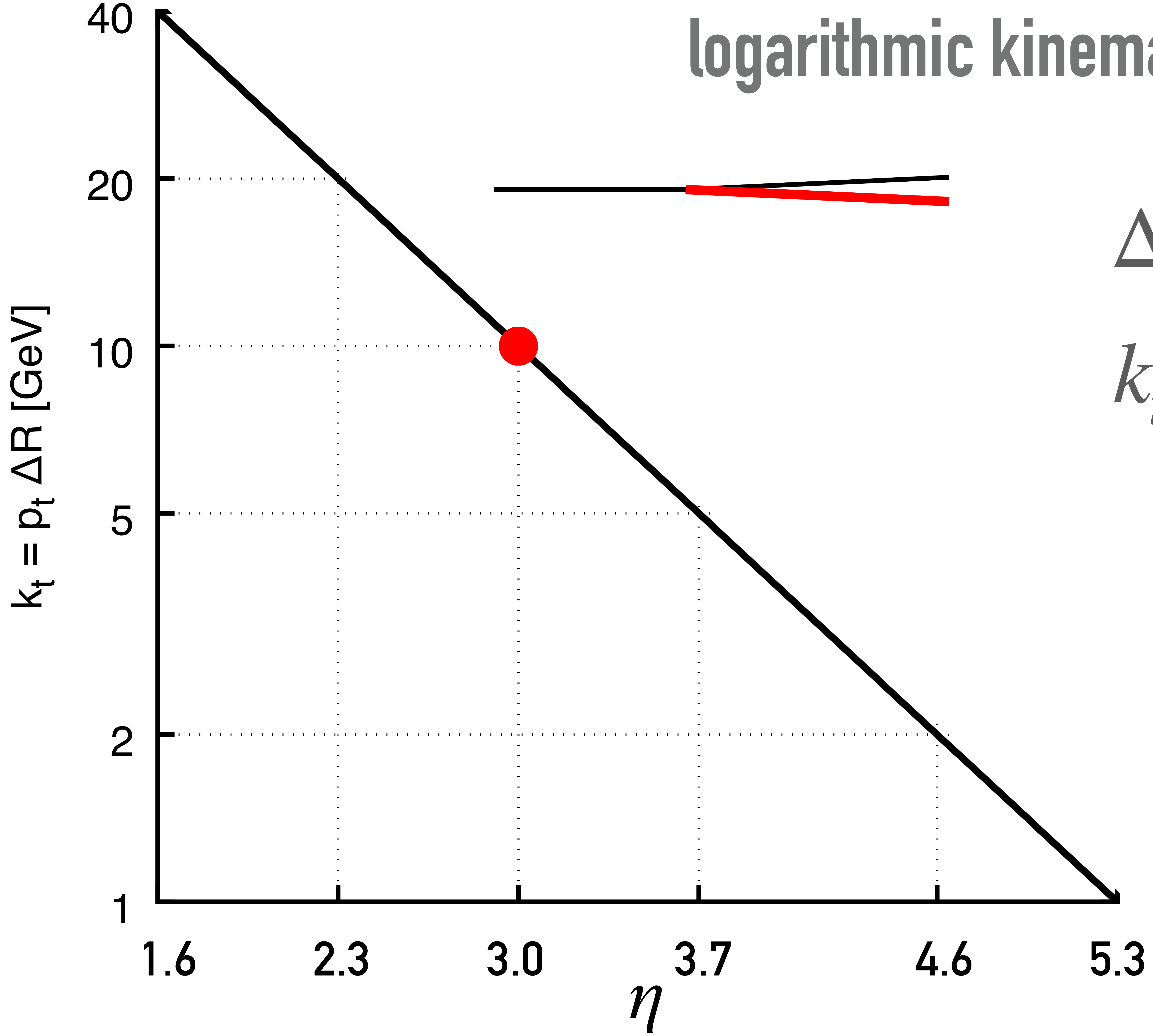
logarithmic kinematic plane whose two variables are

$$\Delta R\ (or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane



logarithmic kinematic plane whose two variables are

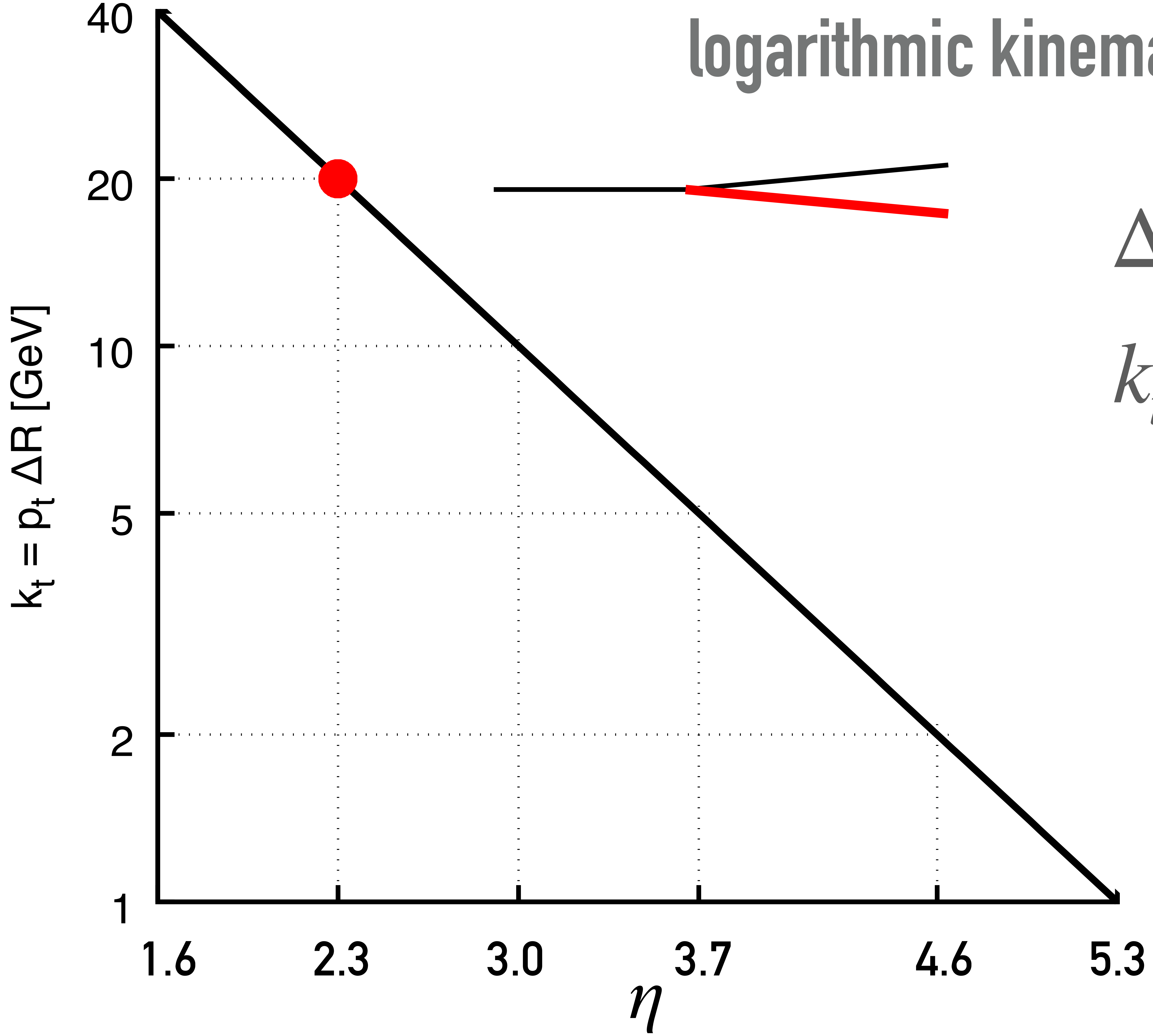
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



logarithmic kinematic plane whose two variables are

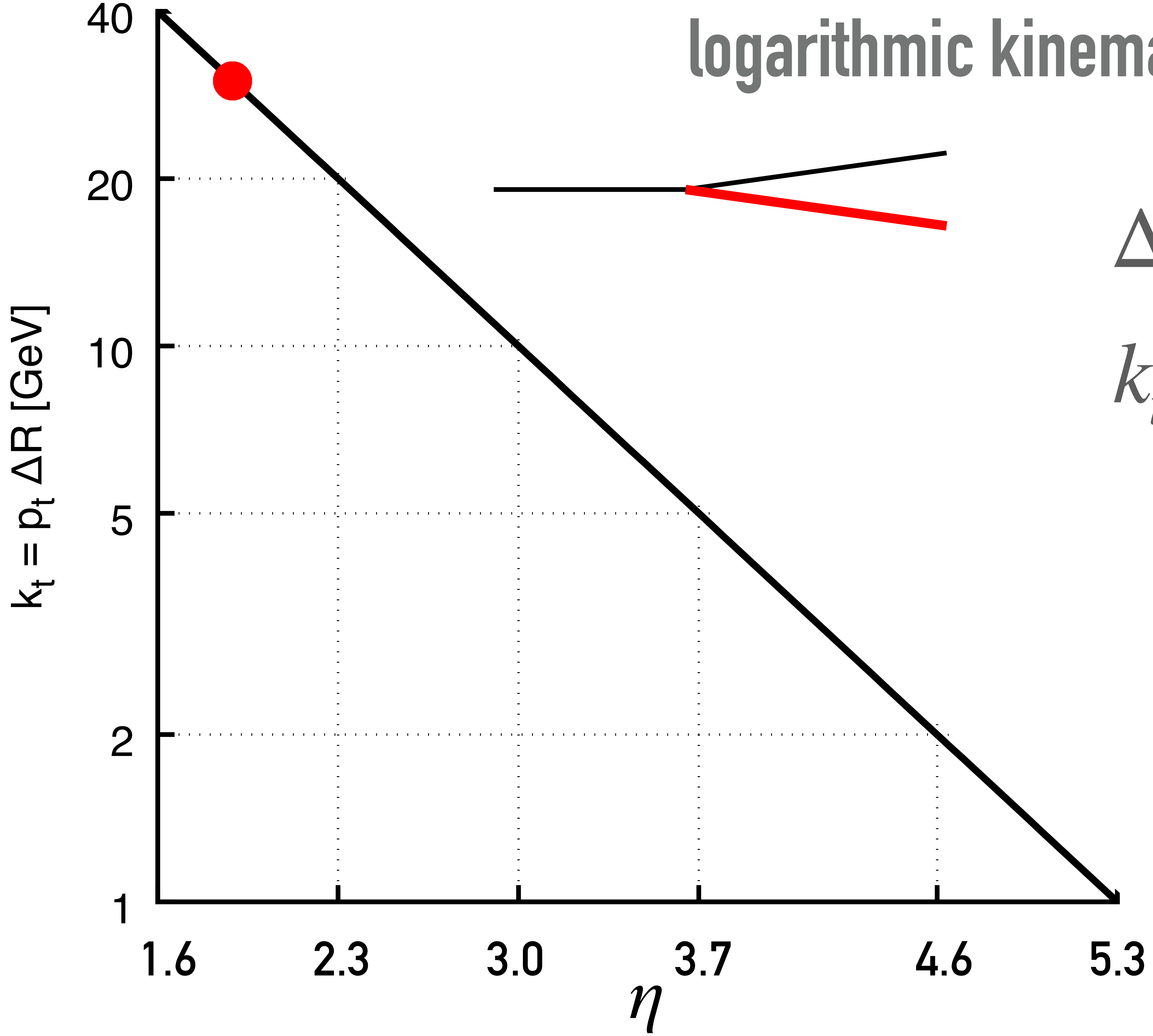
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



logarithmic kinematic plane whose two variables are

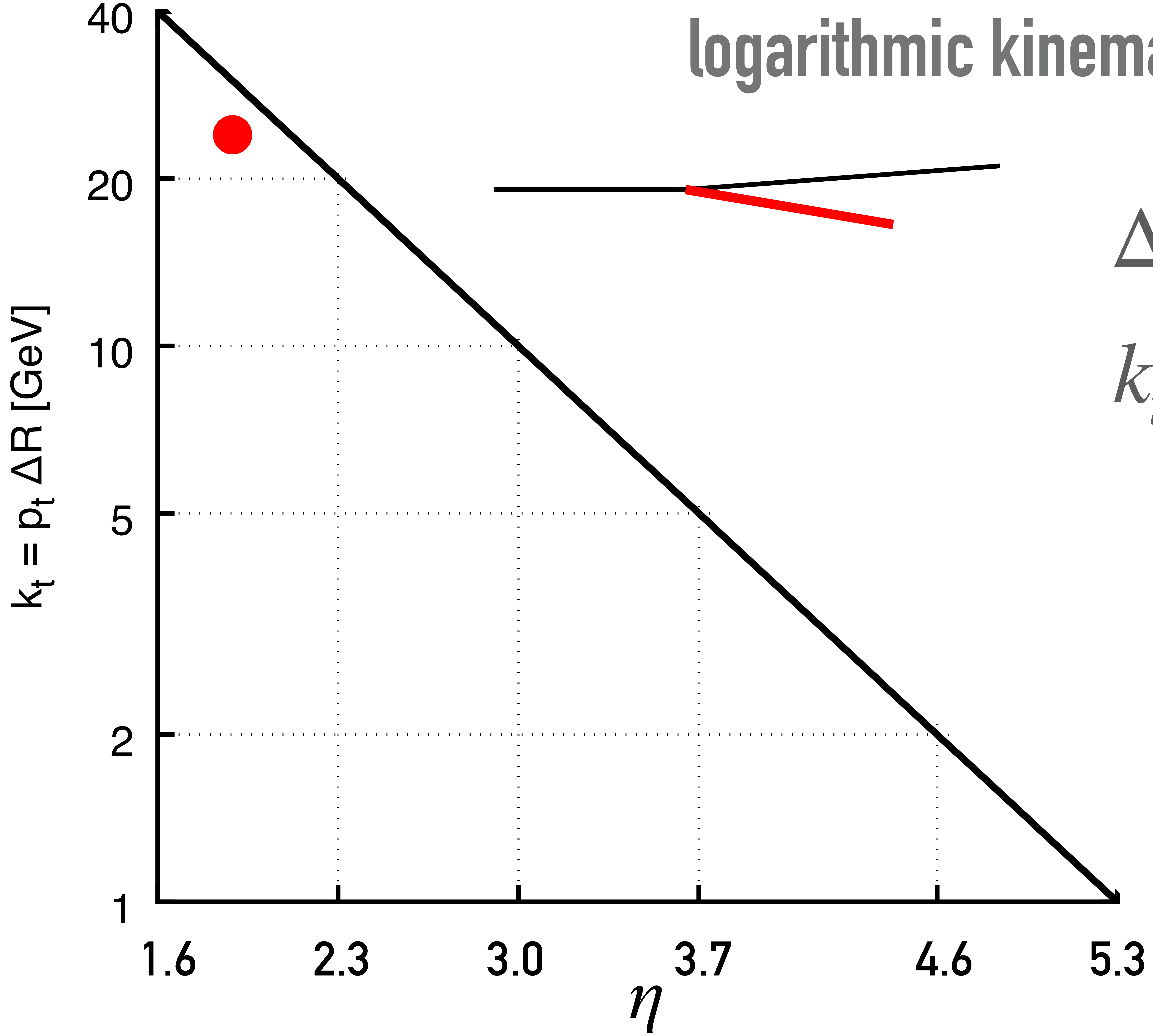
$$\Delta R \,(or\ \eta = -\ln \tan \frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with R= 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

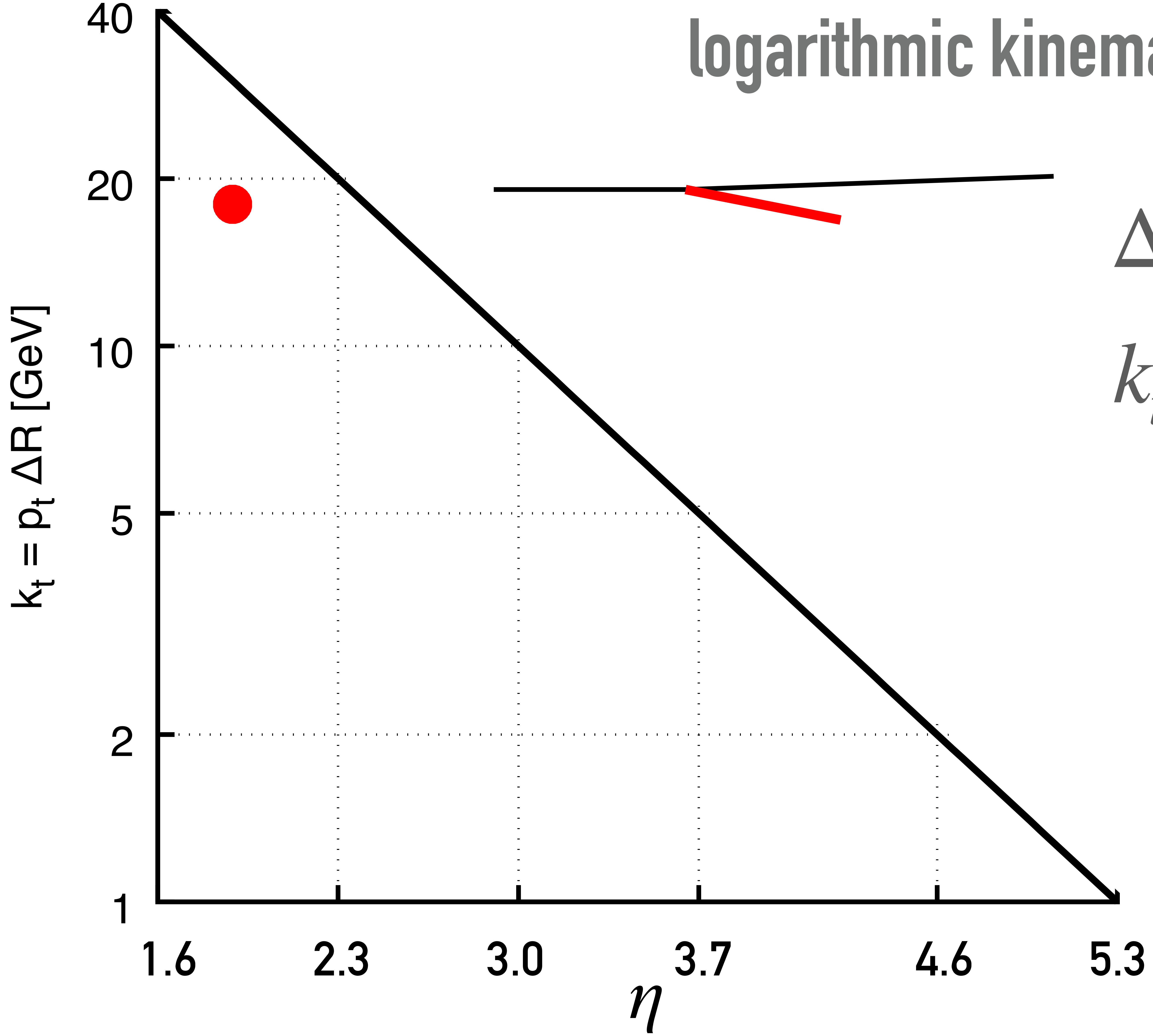
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with R= 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

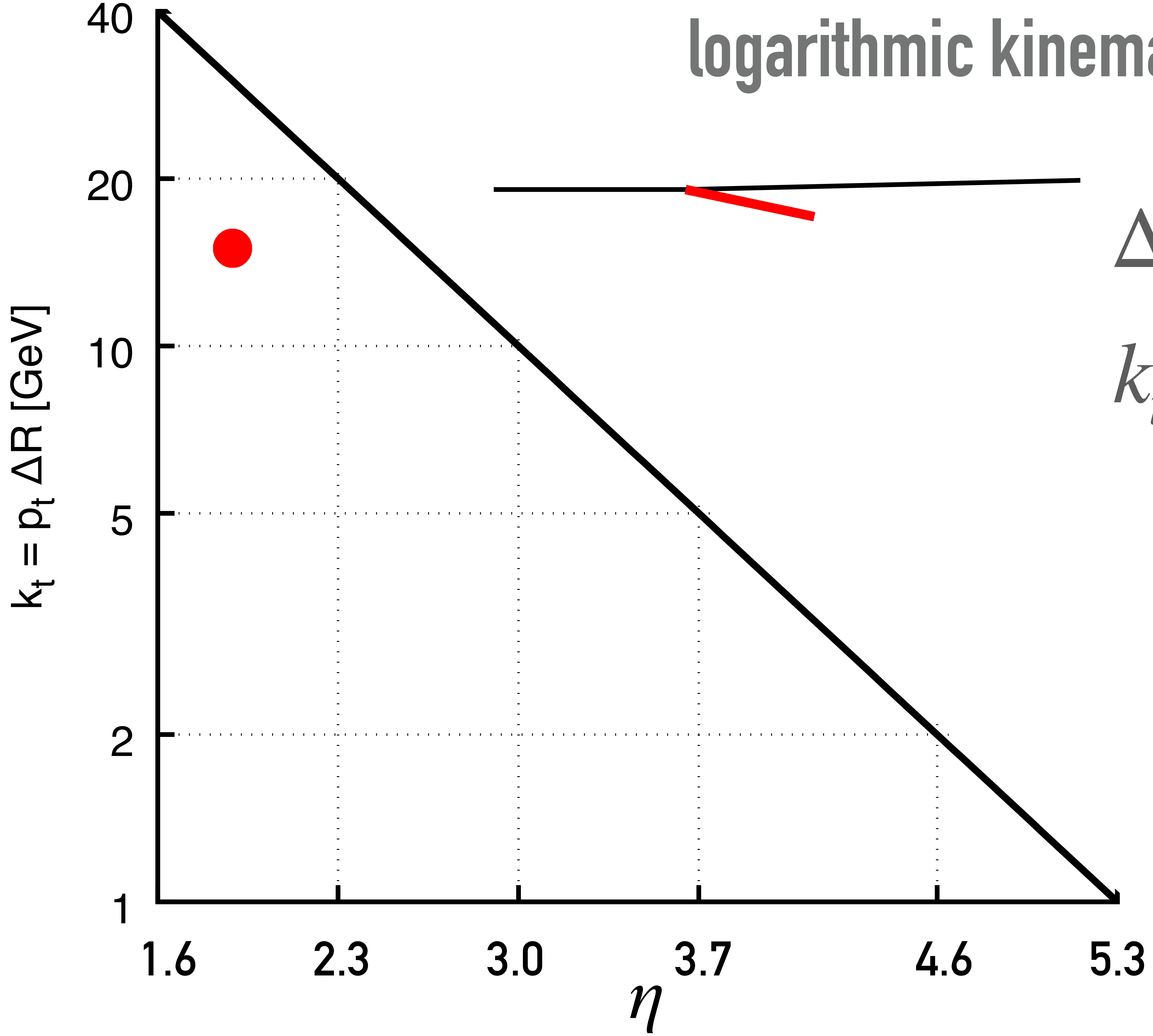
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by
B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



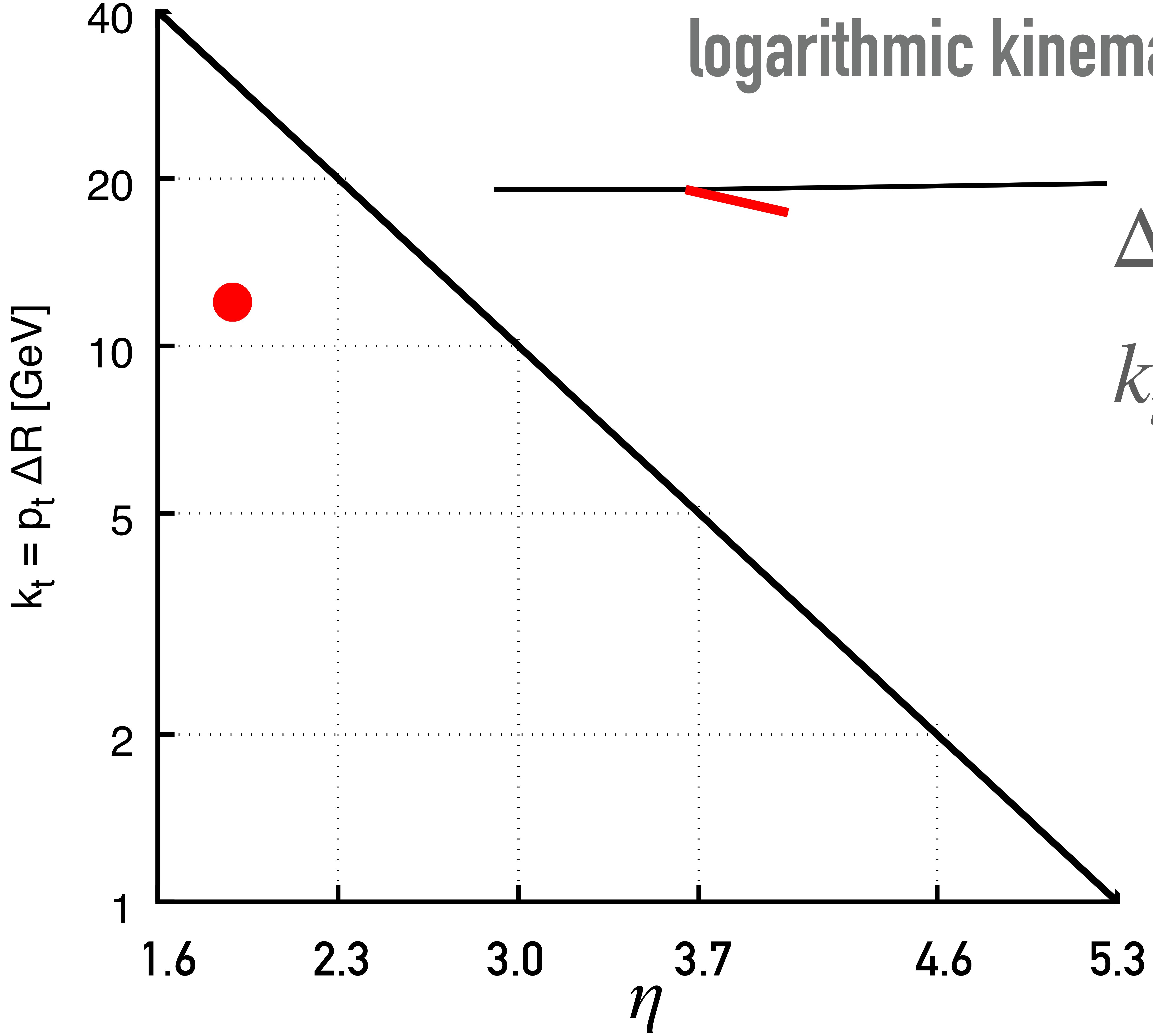
logarithmic kinematic plane whose two variables are

$$\Delta R \,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane



logarithmic kinematic plane whose two variables are

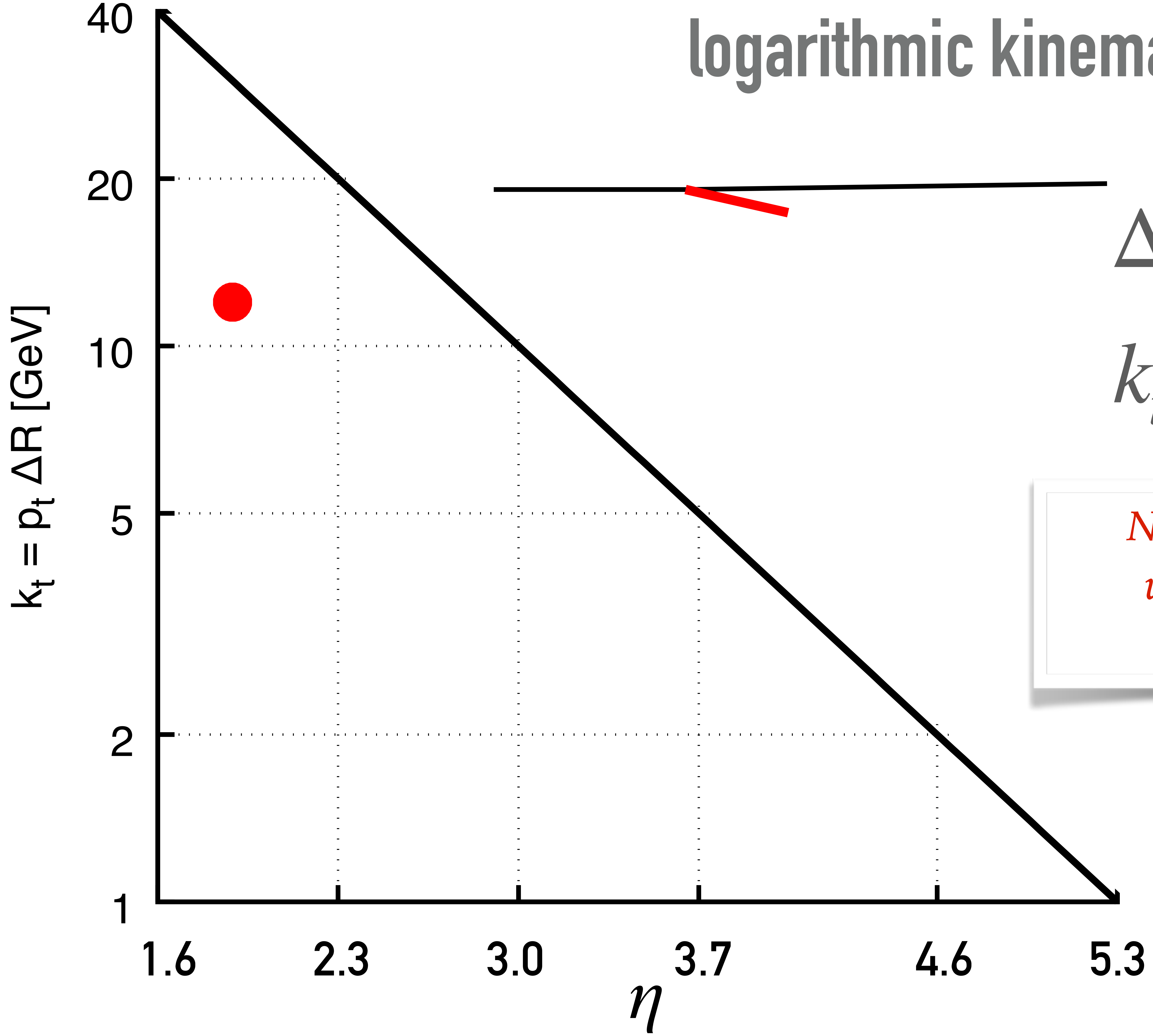
$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

$$k_t = p_t \Delta R$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



logarithmic kinematic plane whose two variables are

$$\Delta R\,(or\ \eta = -\ln\tan\frac{\Delta R}{2})$$

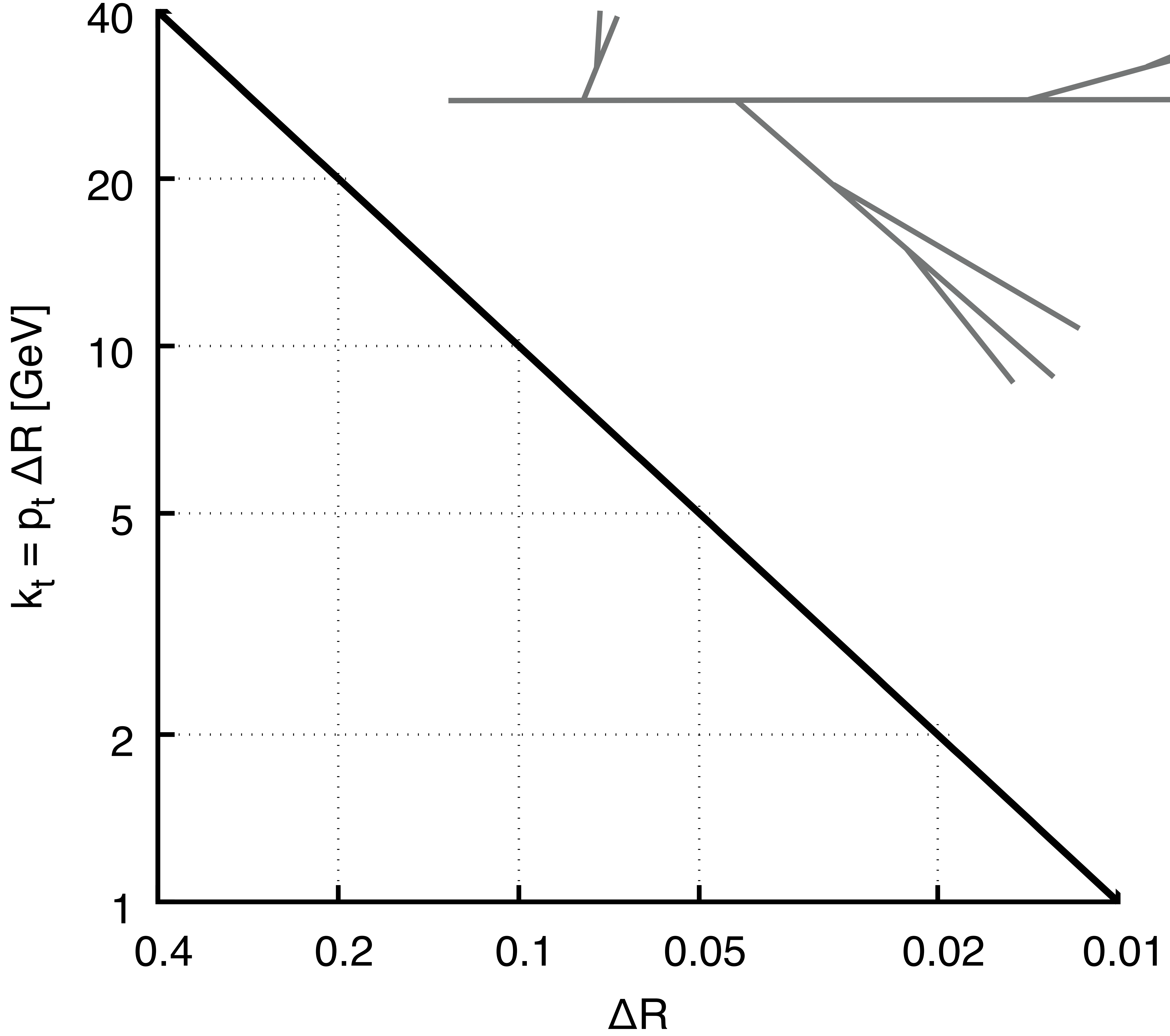
$$k_t = p_t \Delta R$$

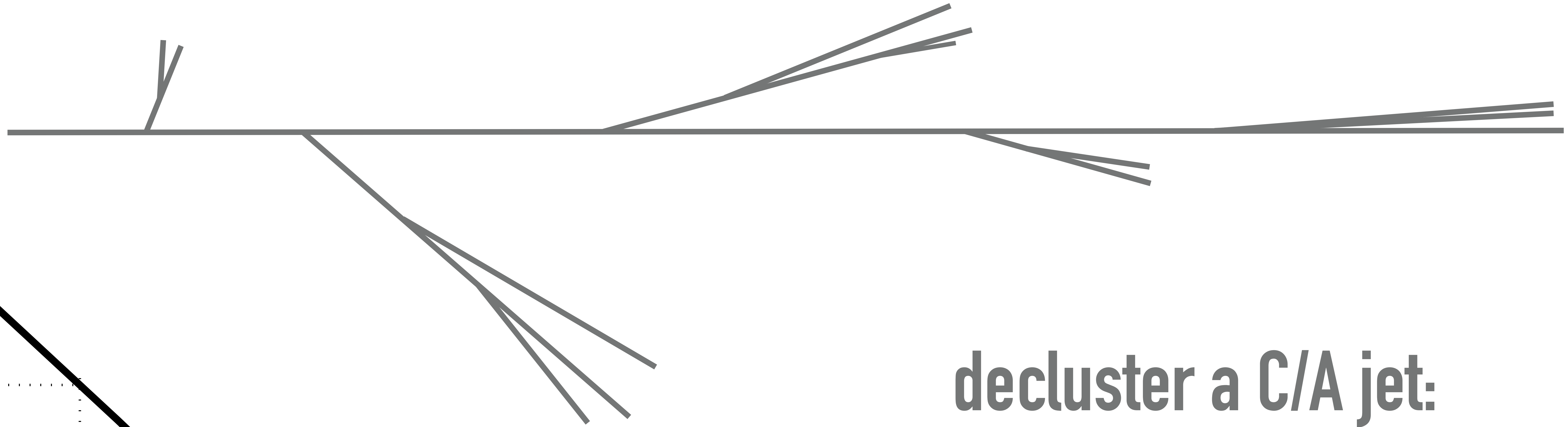
NB: Lund plane can be constructed event-by-event using Cambridge/Aachen jet clustering sequence,
cf. Dreyer, GPS & Soyez '18

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV



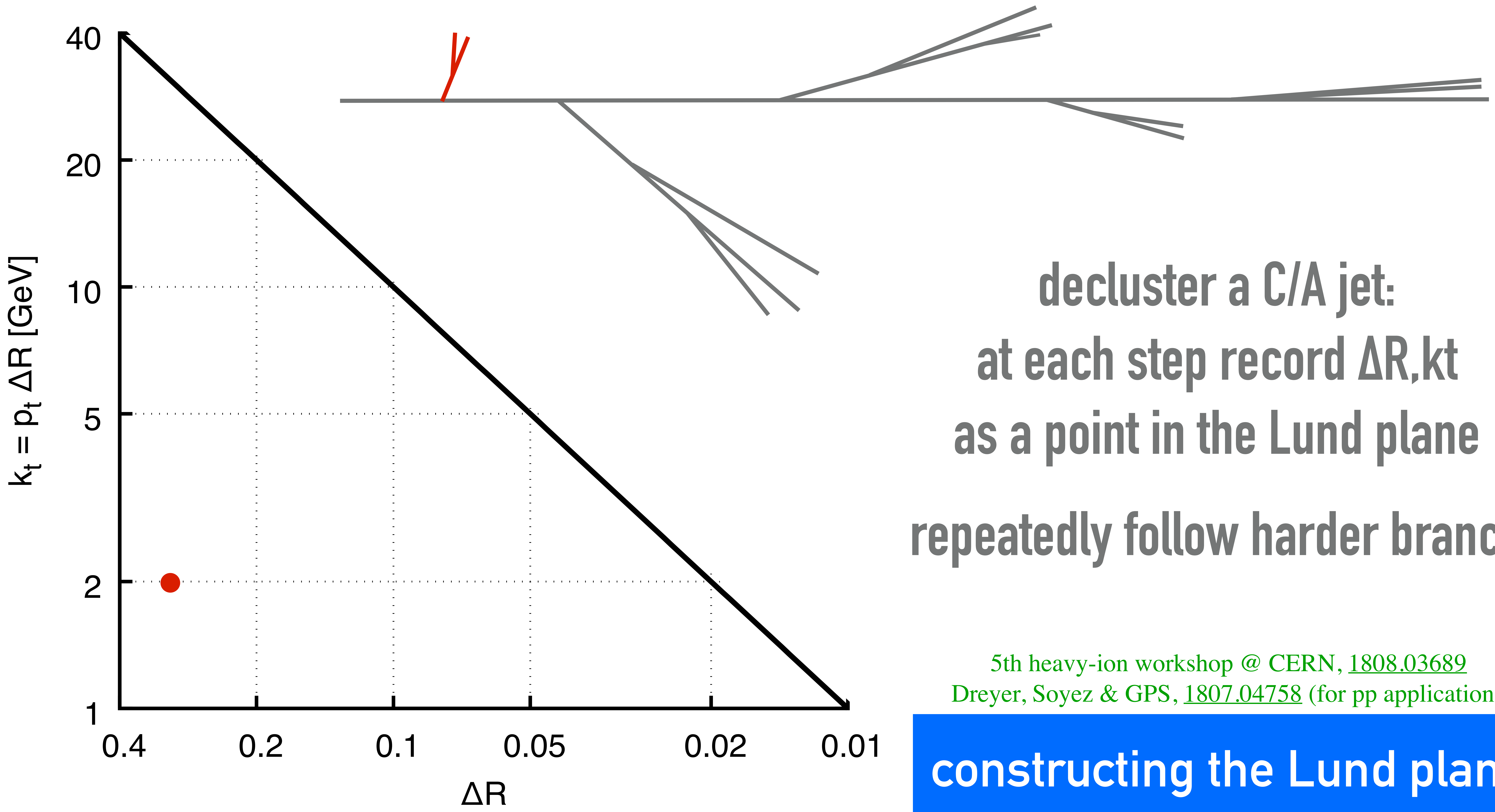


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane

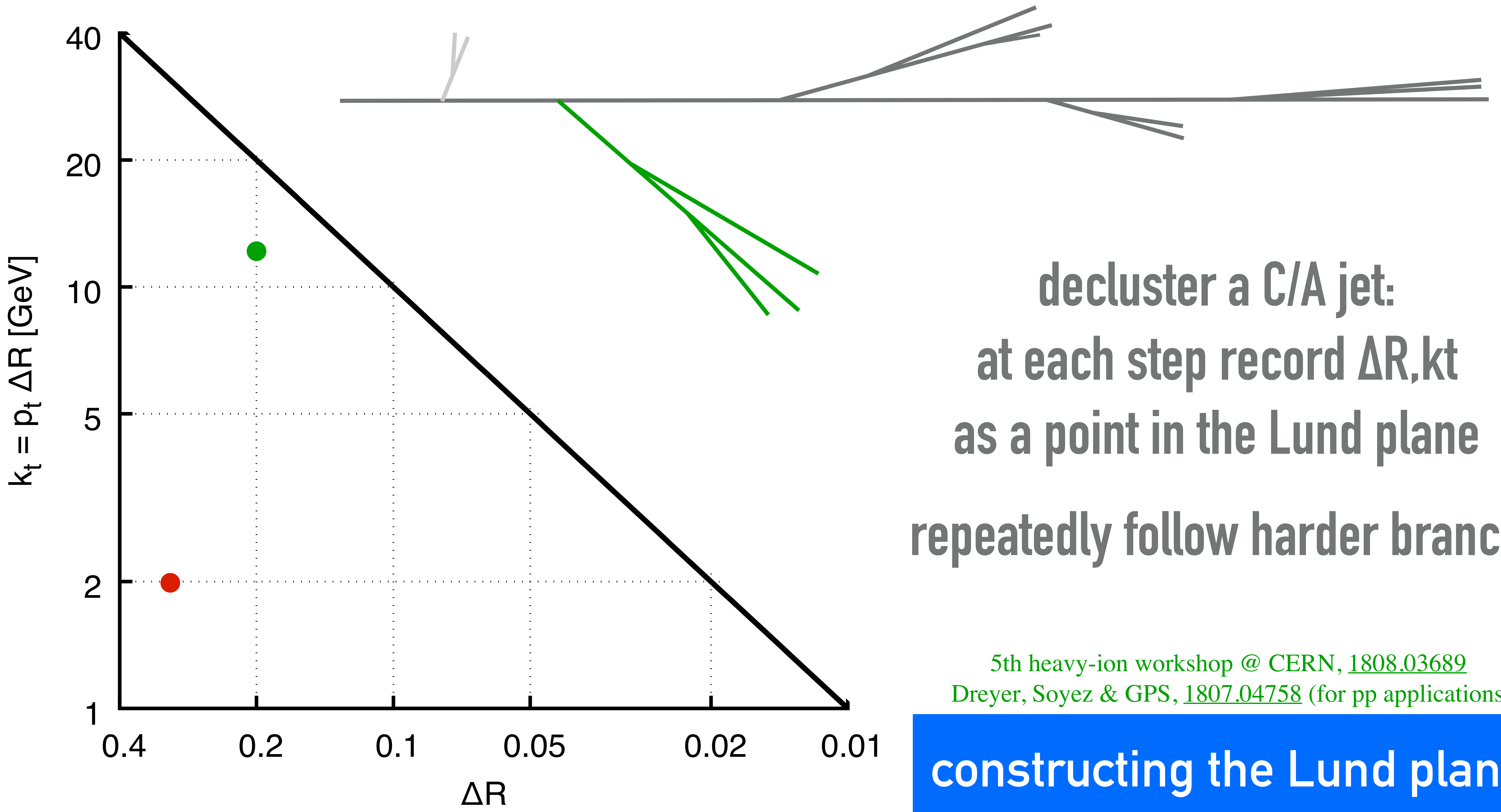


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane

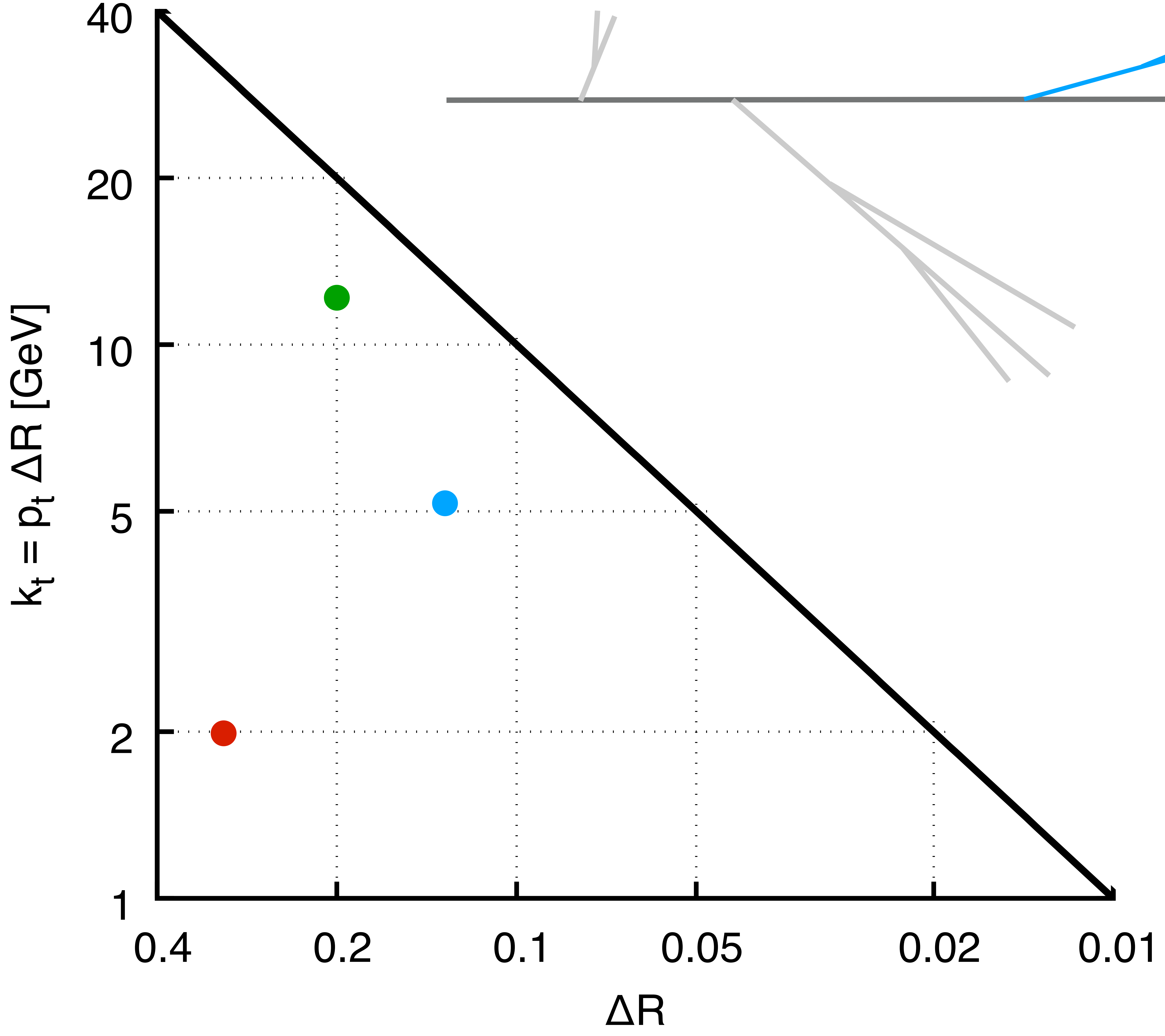


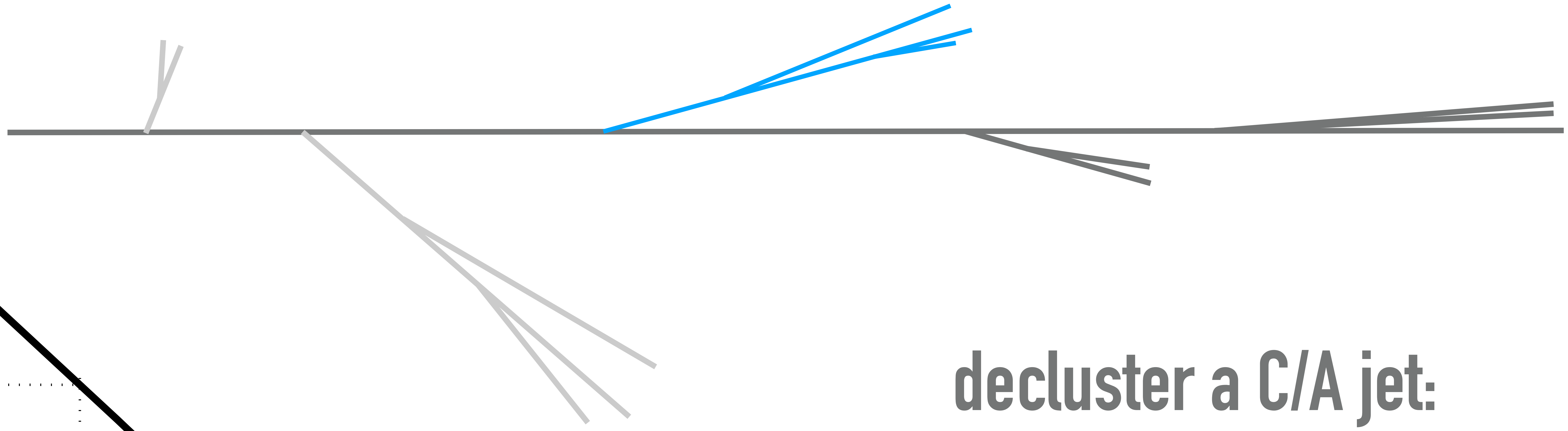
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane



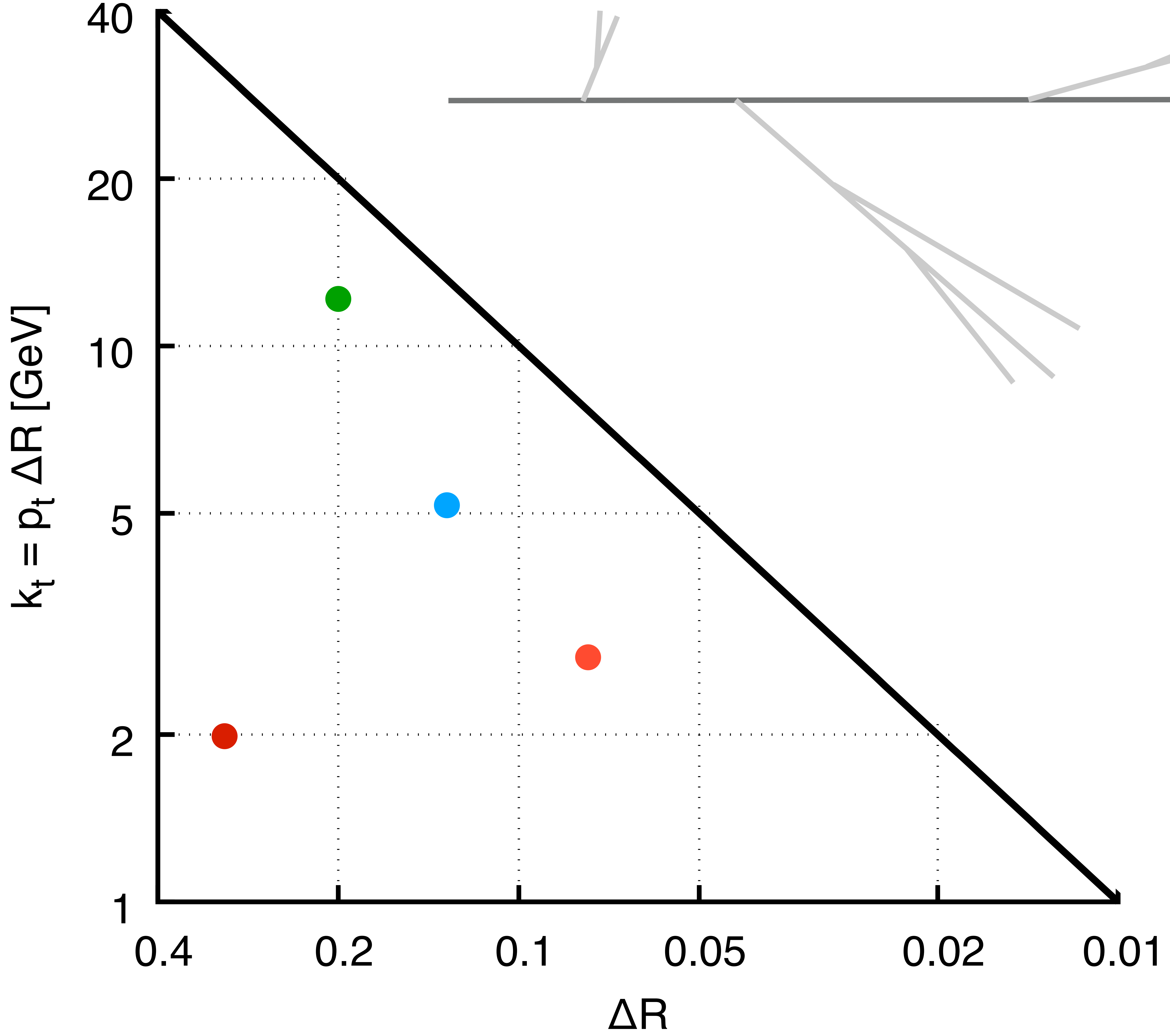


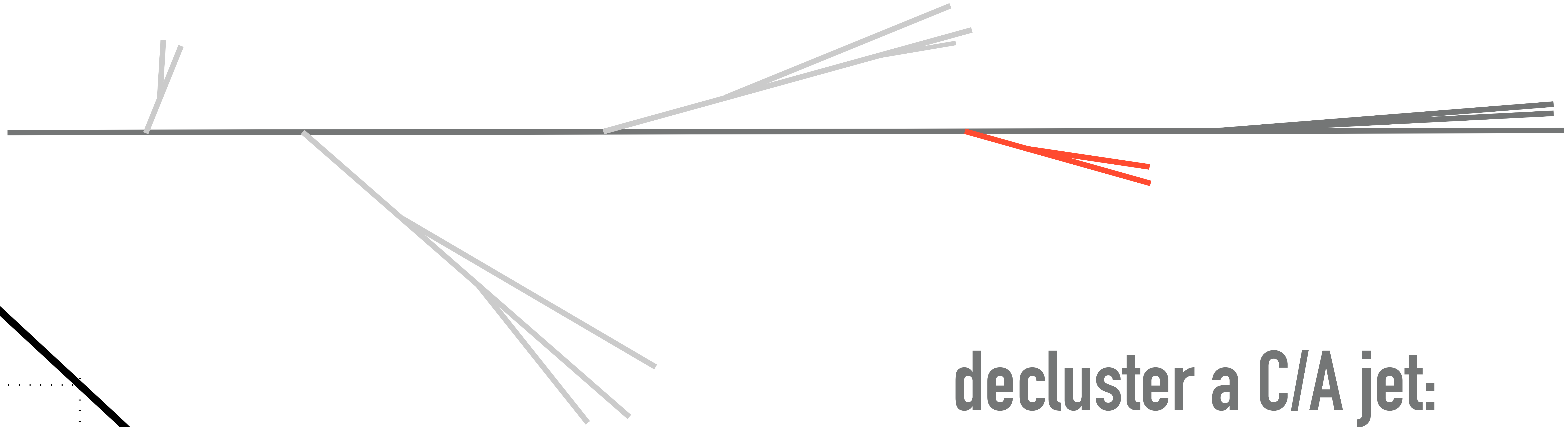
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane



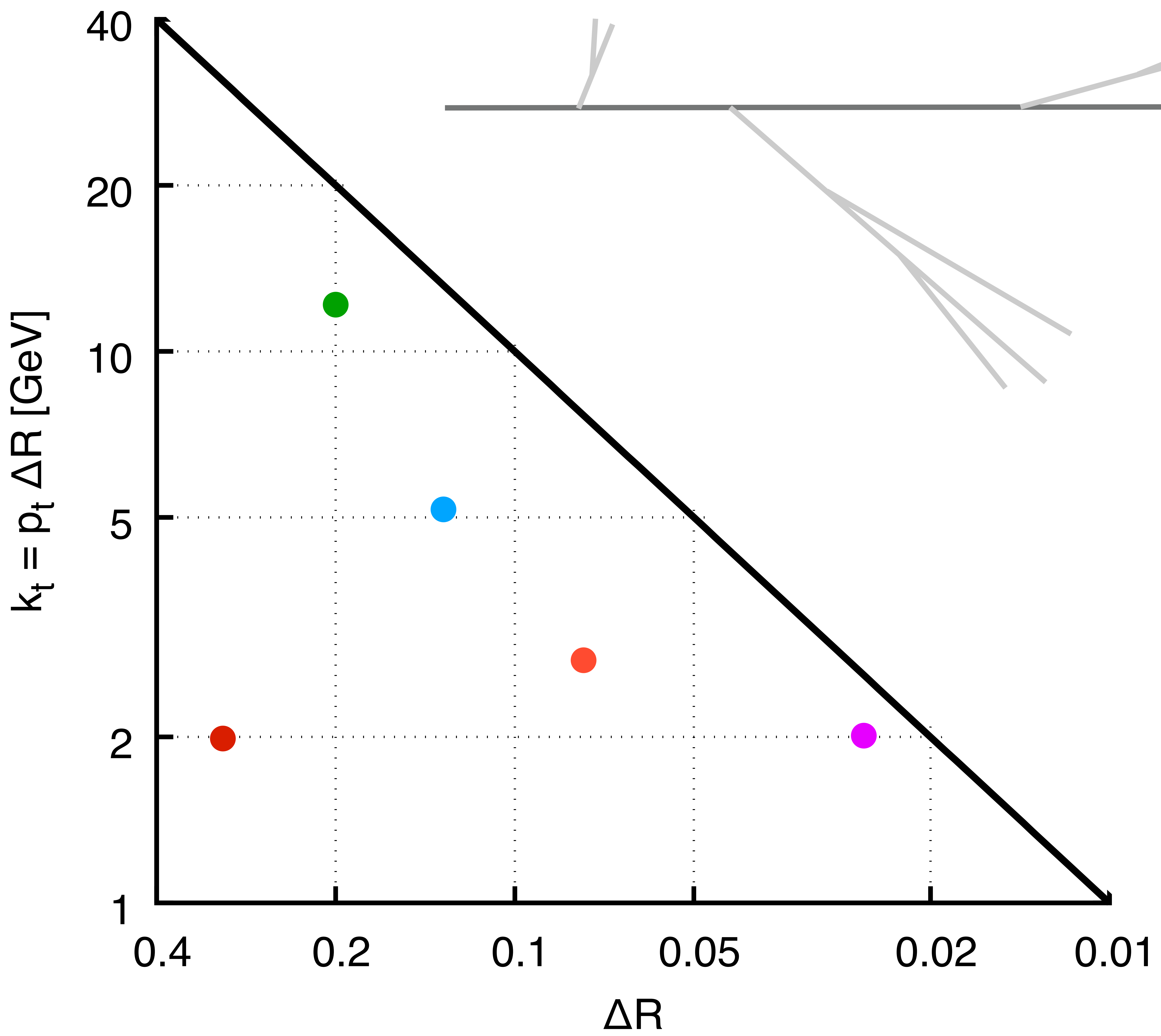


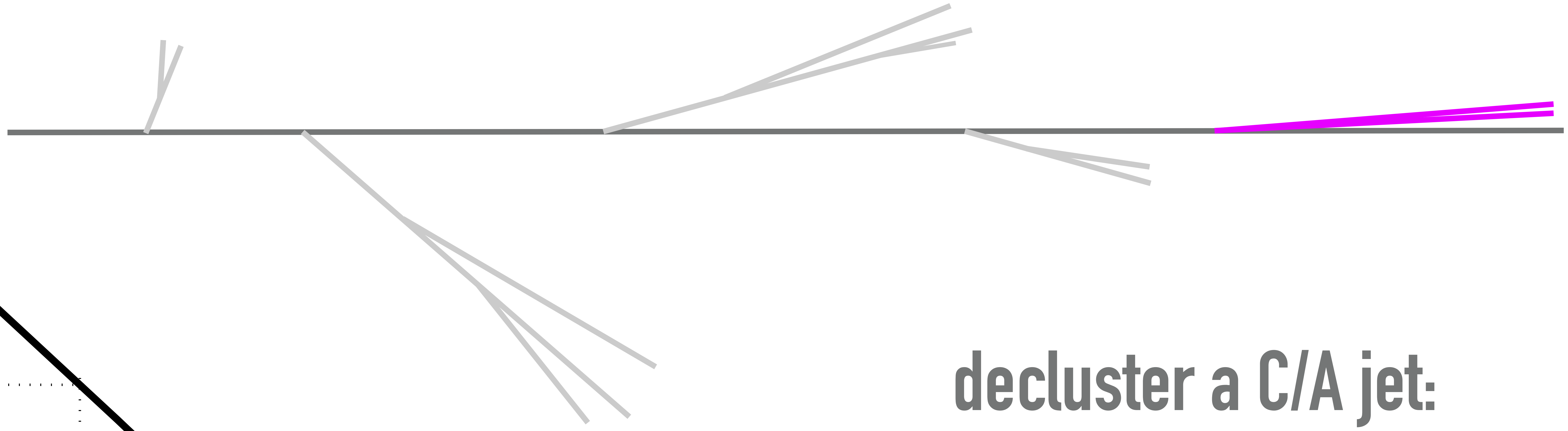
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane



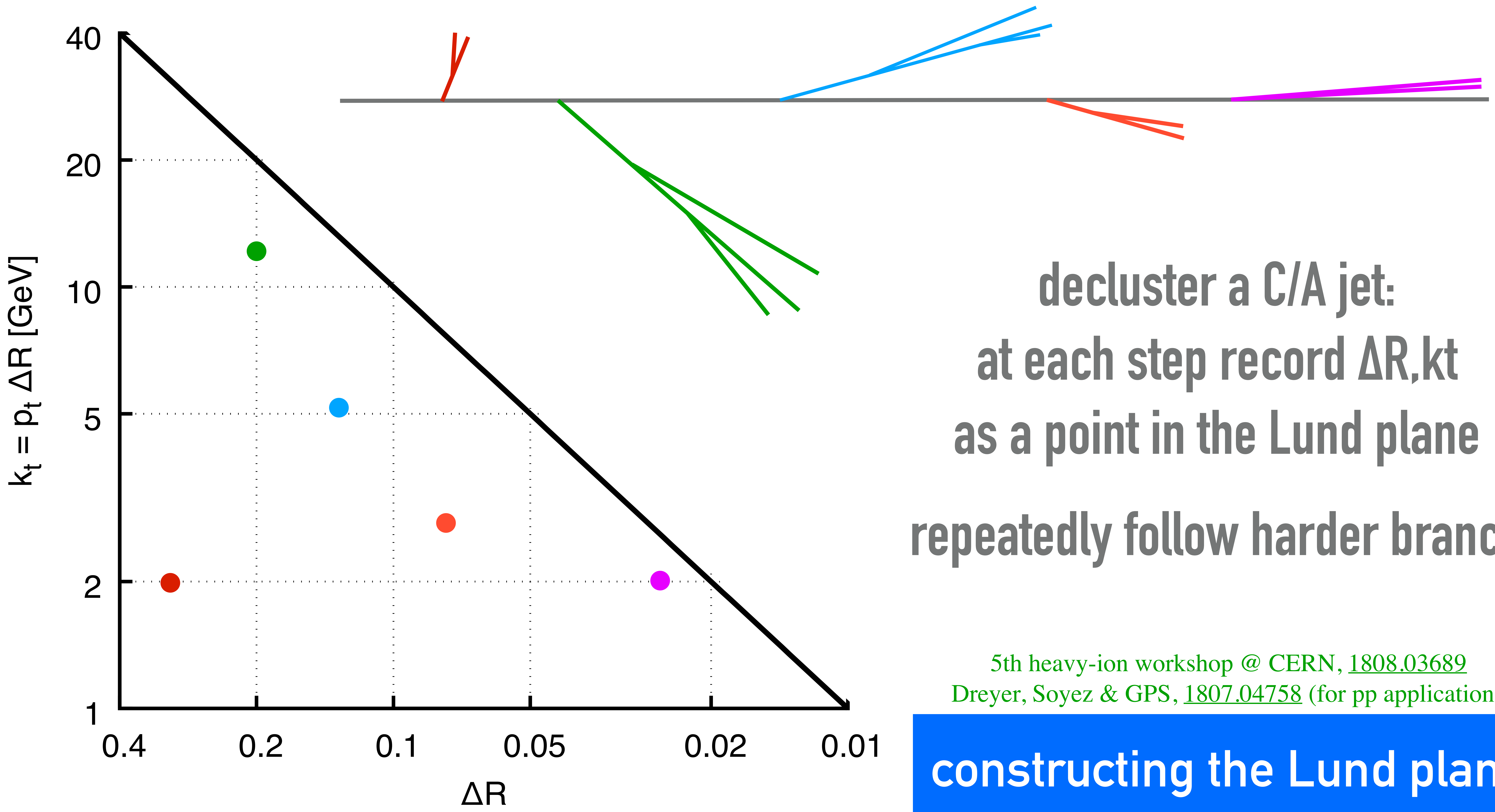


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane

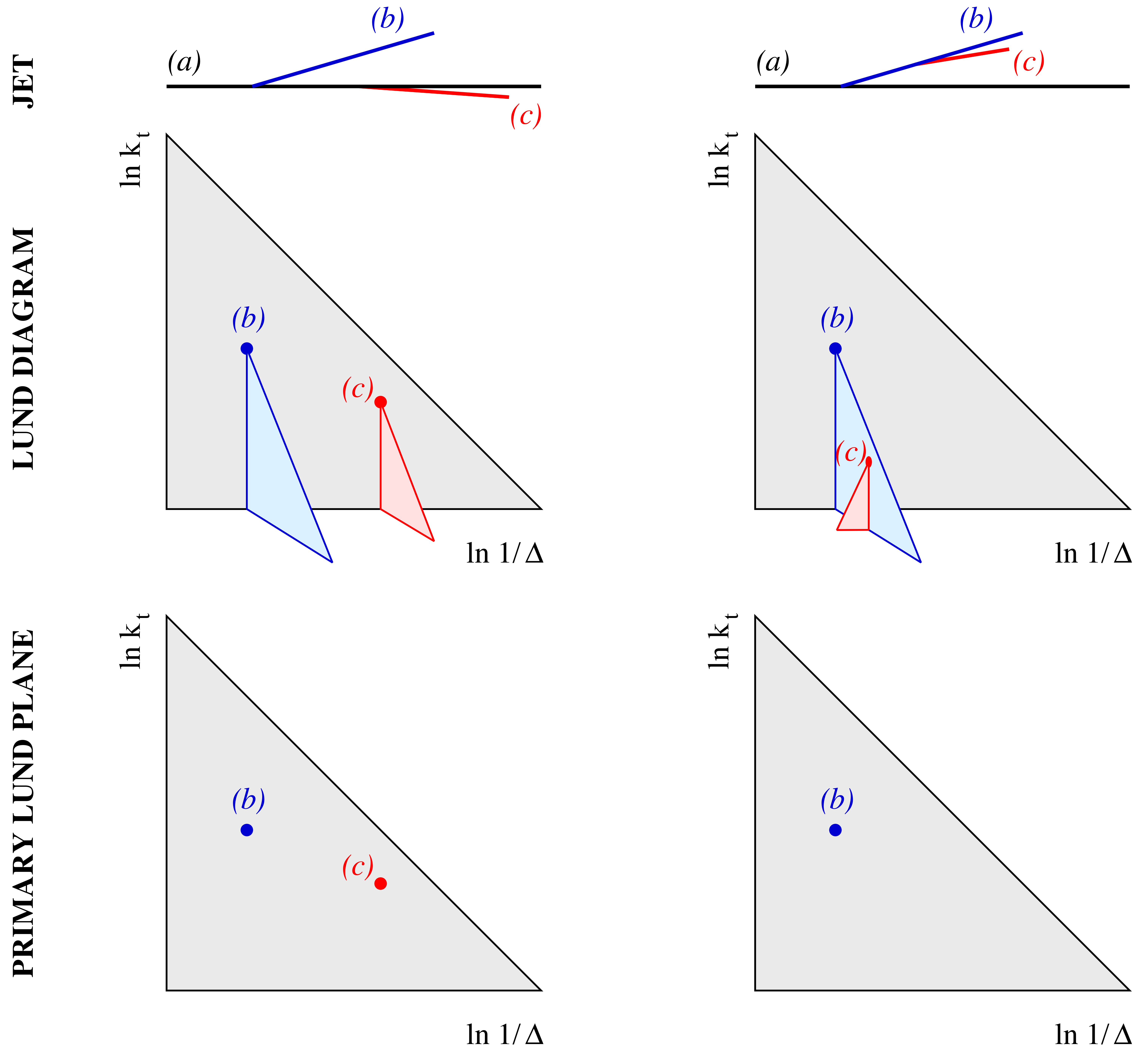


decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane


JET
LUND DIAGRAM
PRIMARY LUND PLANE
(a)
(b)
(c)
ln k_t
ln 1/Δ
(a)
(b)
(c)
ln k_t
ln 1/Δ
(b)
(c)
ln k_t
ln 1/Δ
(b)
(c)
ln k_t
ln 1/Δ
(b)
ln k_t
ln 1/Δ

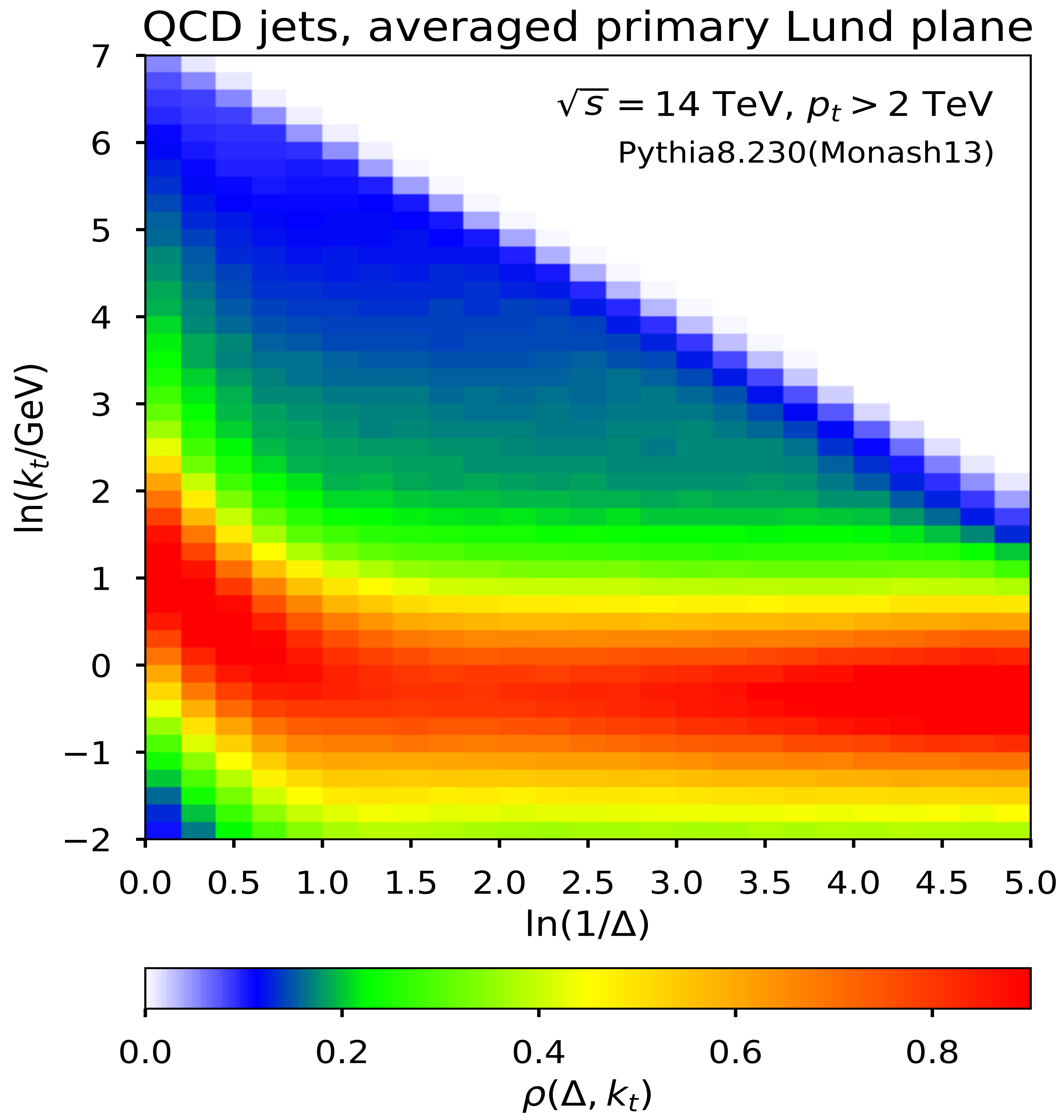
jet with $R = 0.4$, $p_t = 200$ GeV

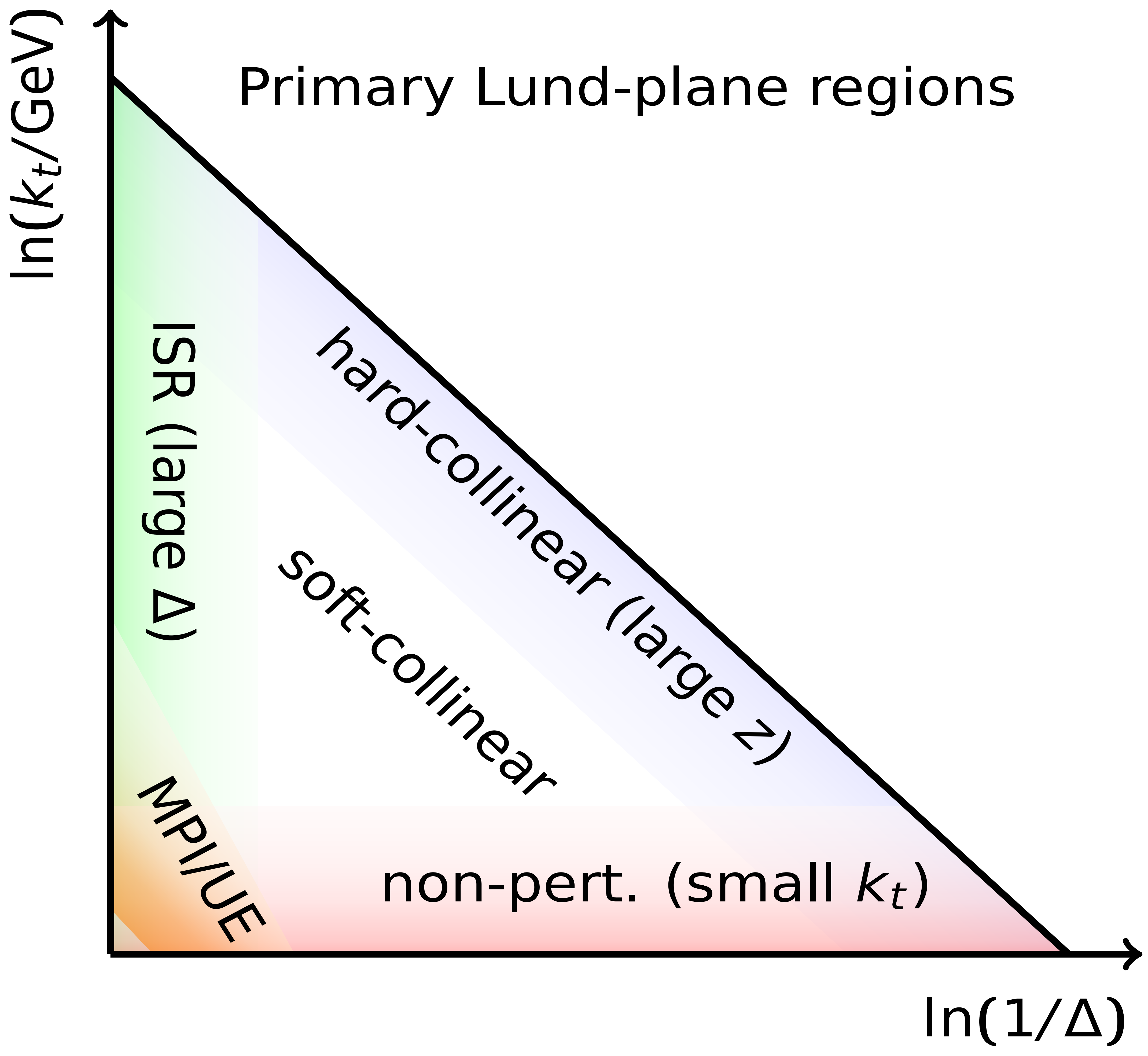
average over many jets:

Lund plane density

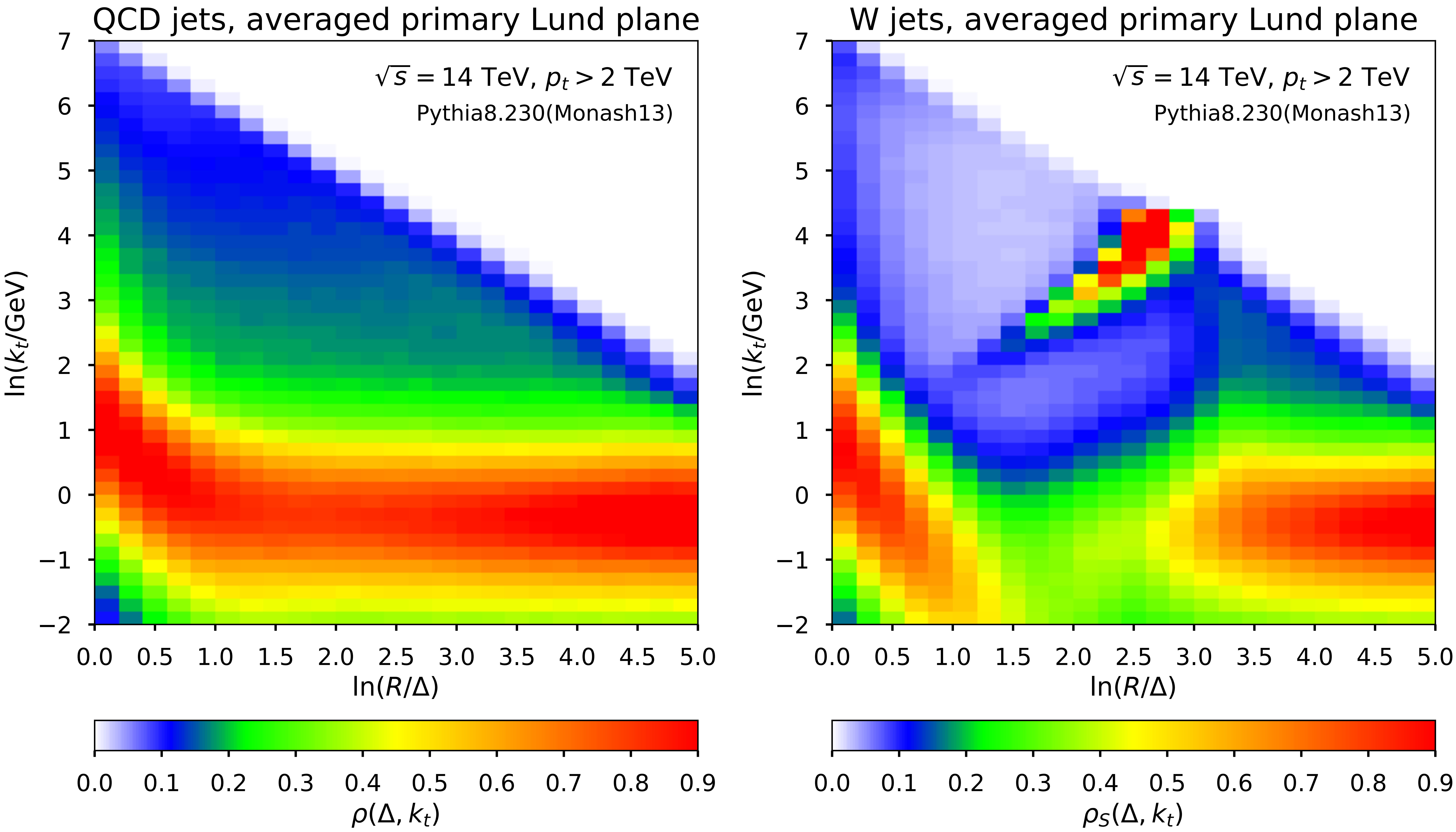
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)
& 5th heavy-ion workshop @ CERN, 1808.03689

constructing the Lund plane

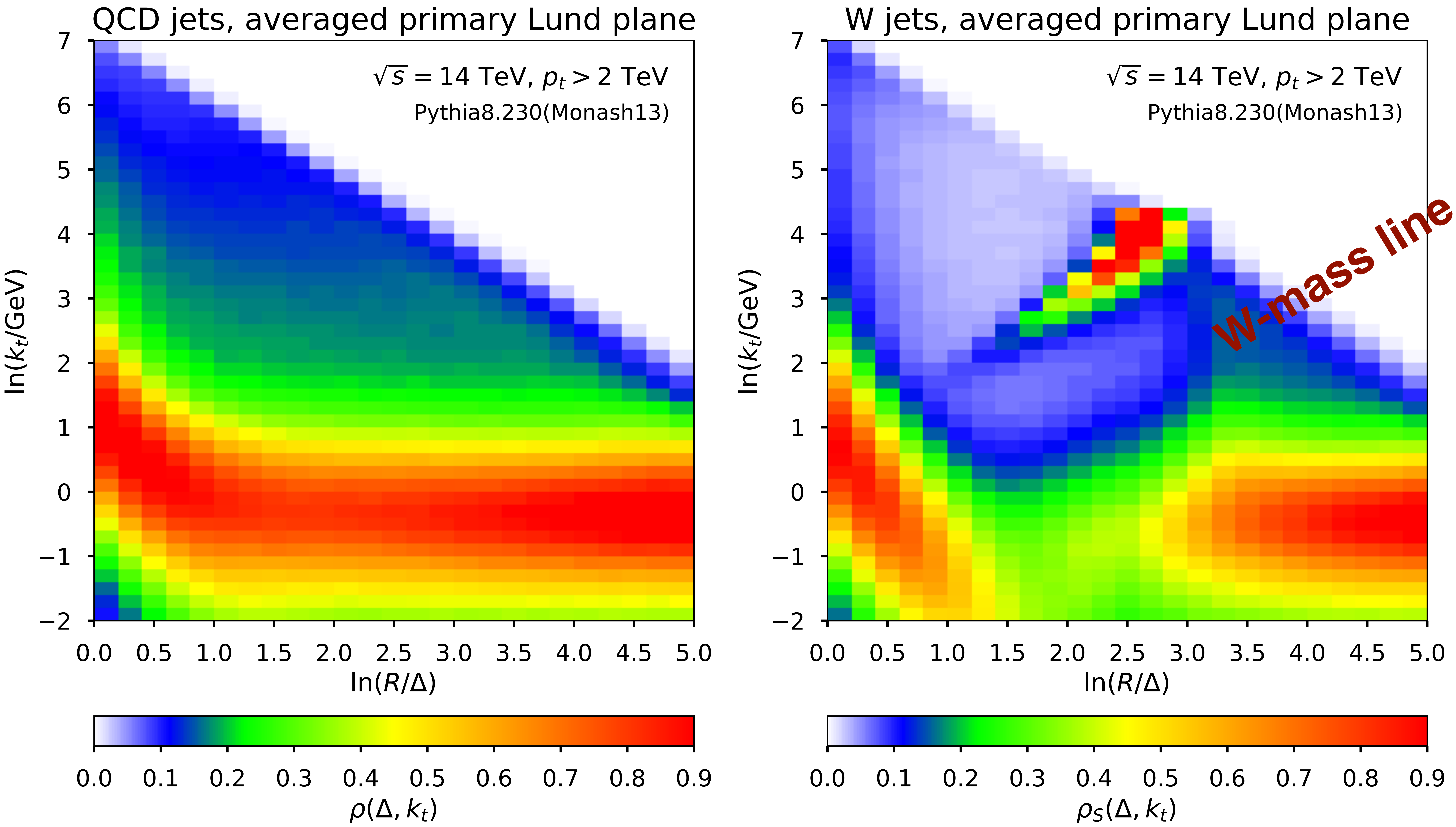

QCD jets, averaged primary Lund plane
$\sqrt{s} = 14$ TeV, $p_t > 2$ TeV
Pythia8.230(Monash13)
$\ln(k_t/\mathrm{GeV})$
7
6
5
4
3
2
1
0
−1
−2
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
$\ln(1/\Delta)$
0.0 0.2 0.4 0.6 0.8
$\rho(\Delta, k_t)$


Primary Lund-plane regions
$\ln(k_t/\mathrm{GeV})$
$\ln(1/\Delta)$
ISR (large Δ)
hard-collinear (large z)
soft-collinear
MPI/UE
non-pert. (small k_t)

intrajet energy flow for QCD jets & W jets

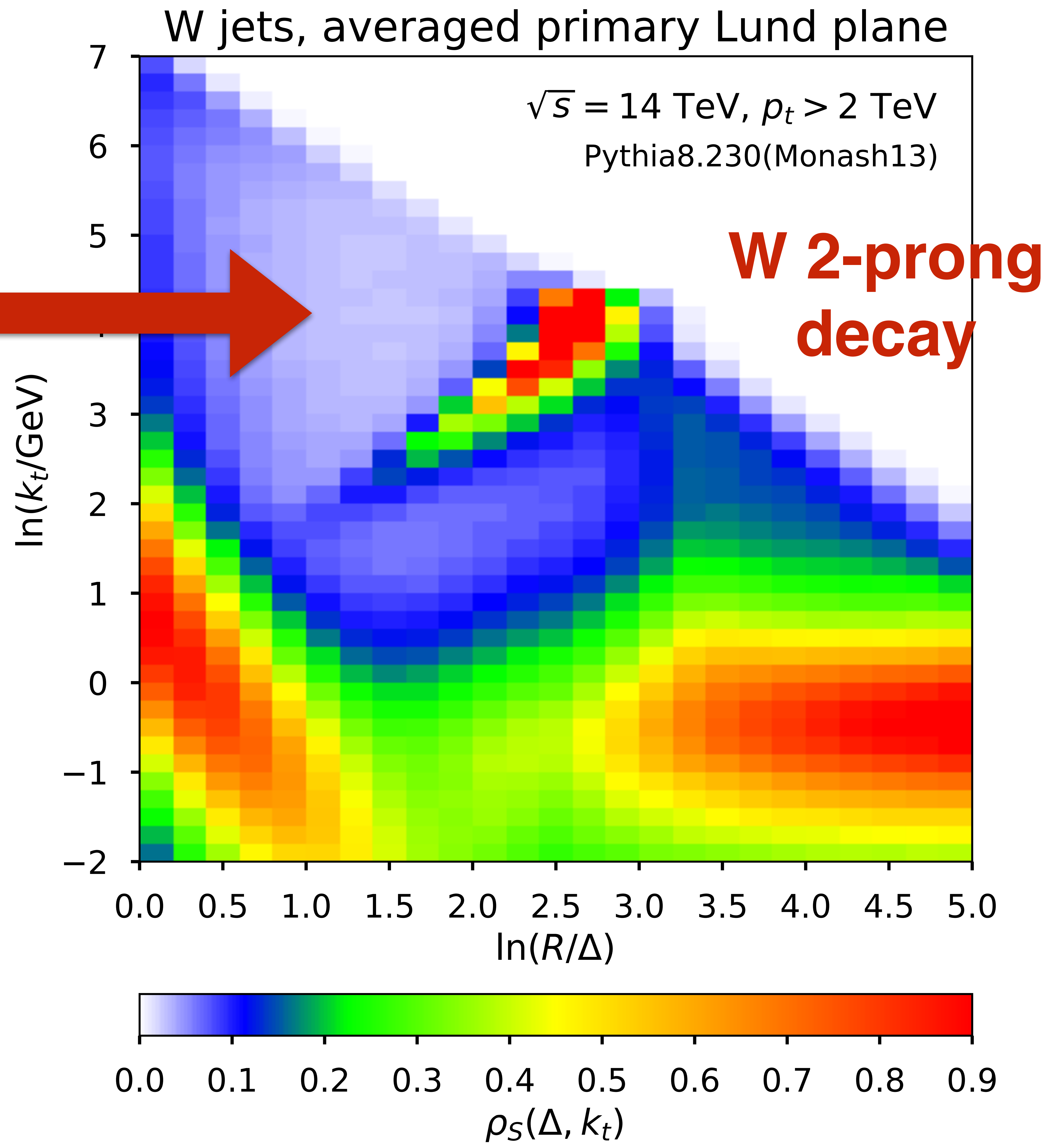


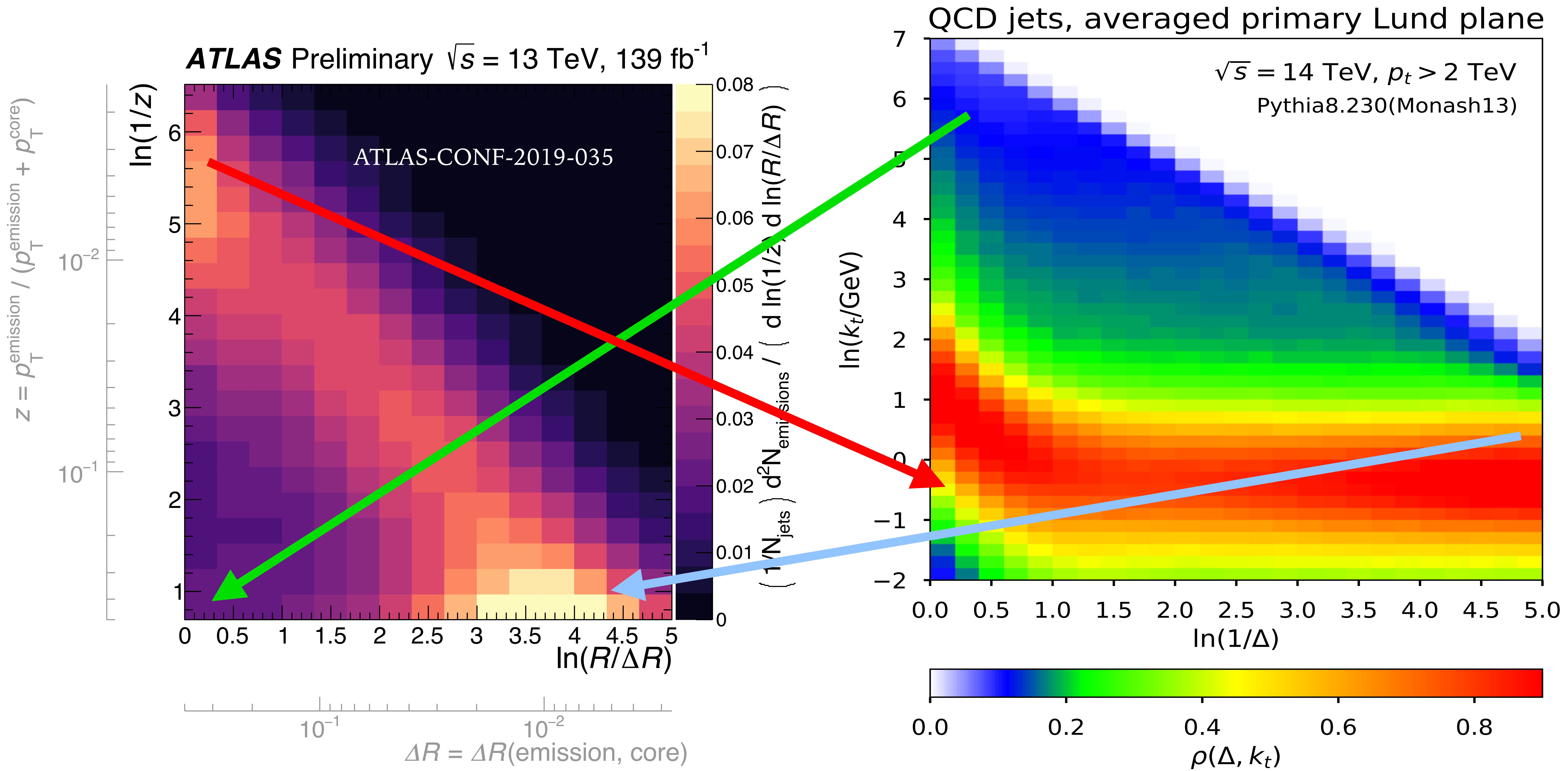
intrajet energy flow for QCD jets & W jets



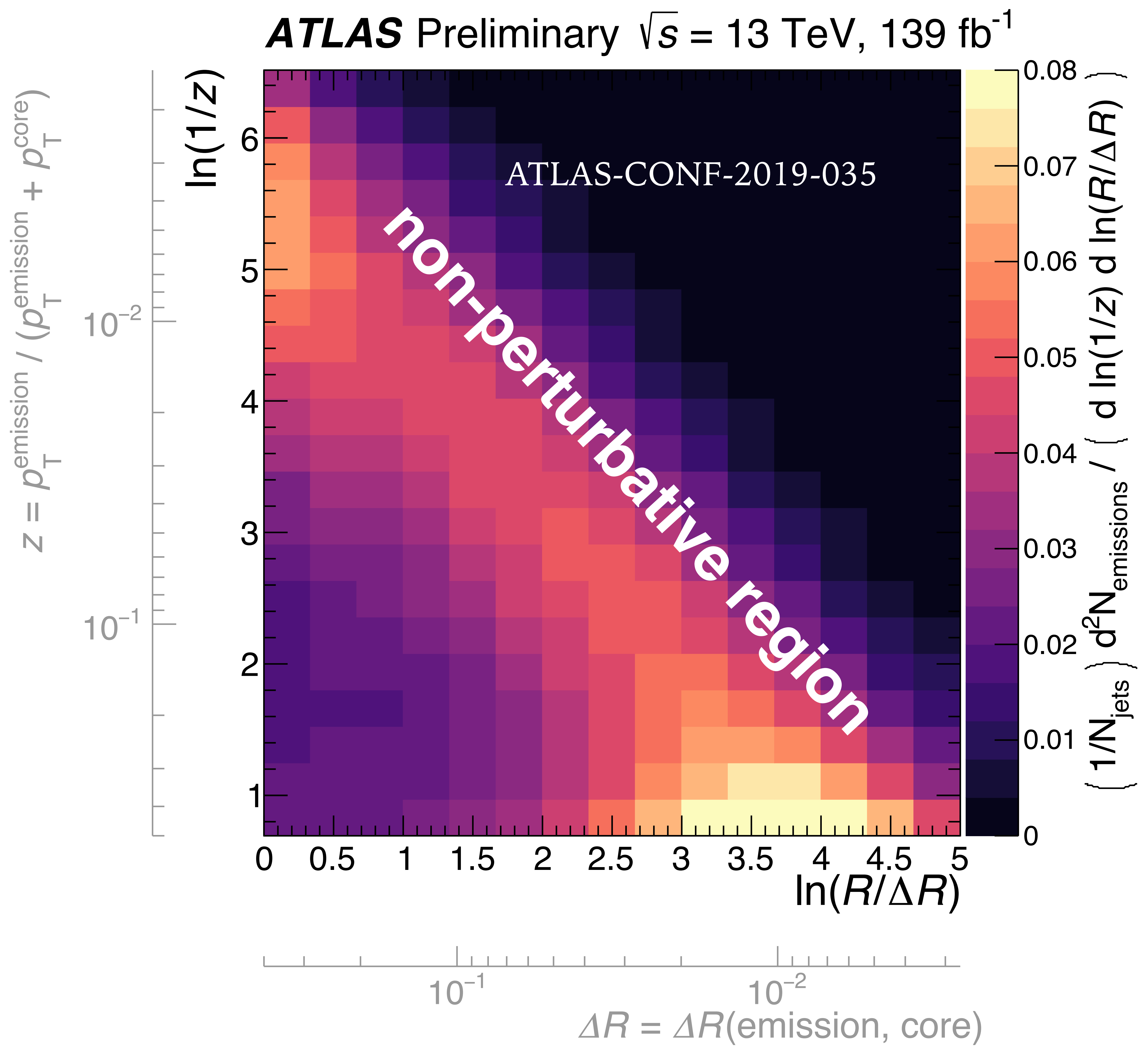
intrajet energy flow for QCD jets & W jets

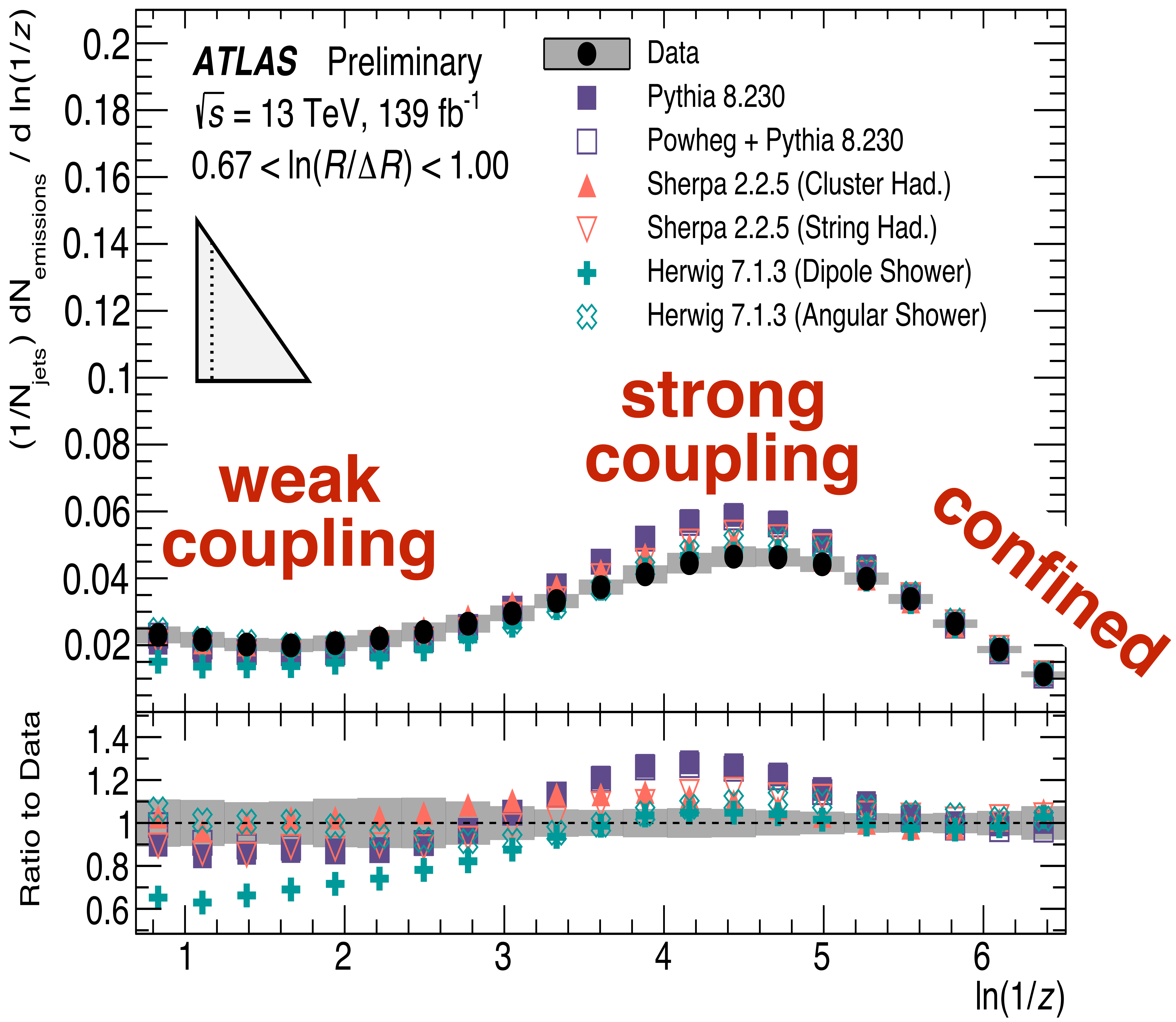
reduced emission (W colour singlet)



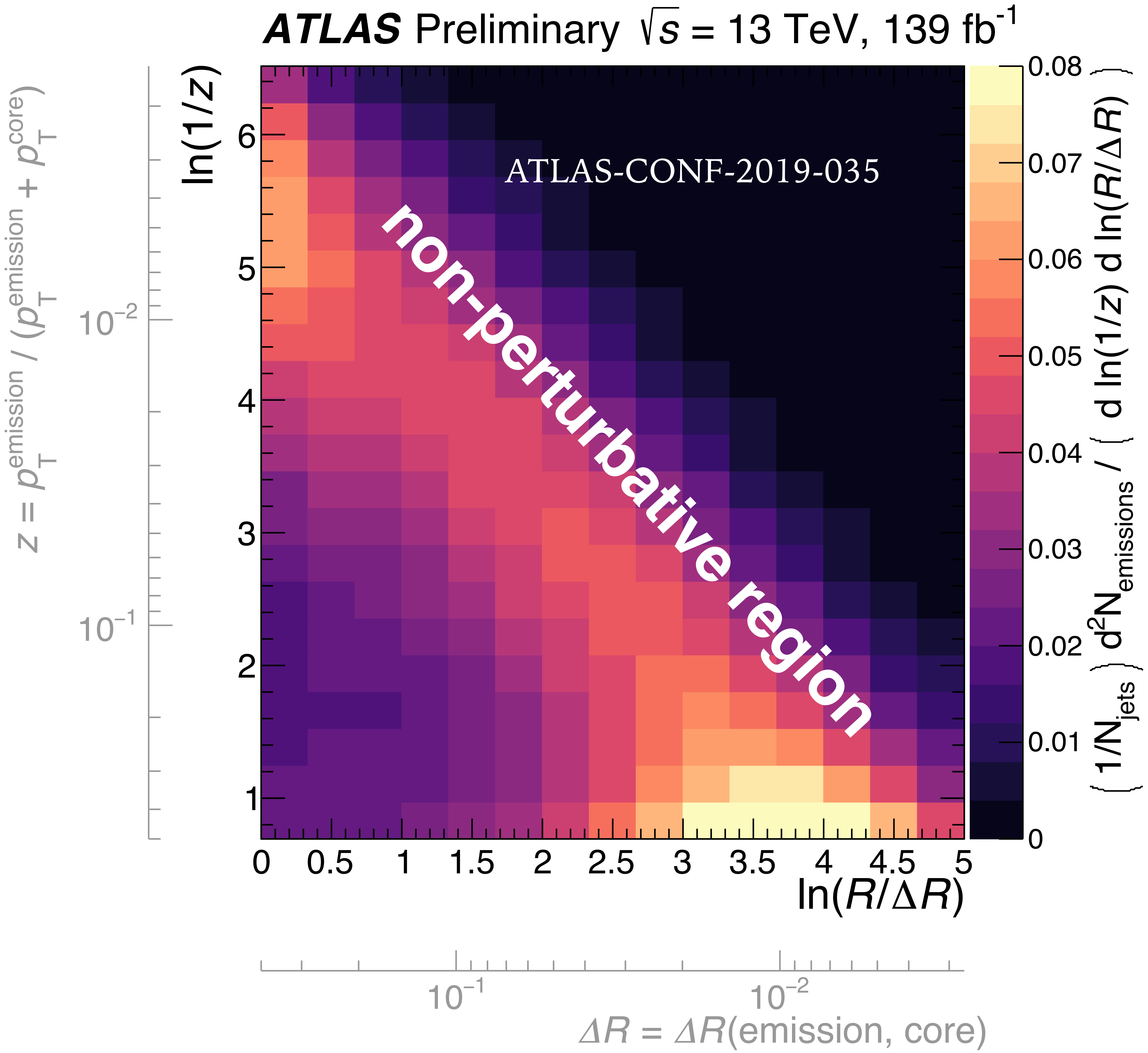


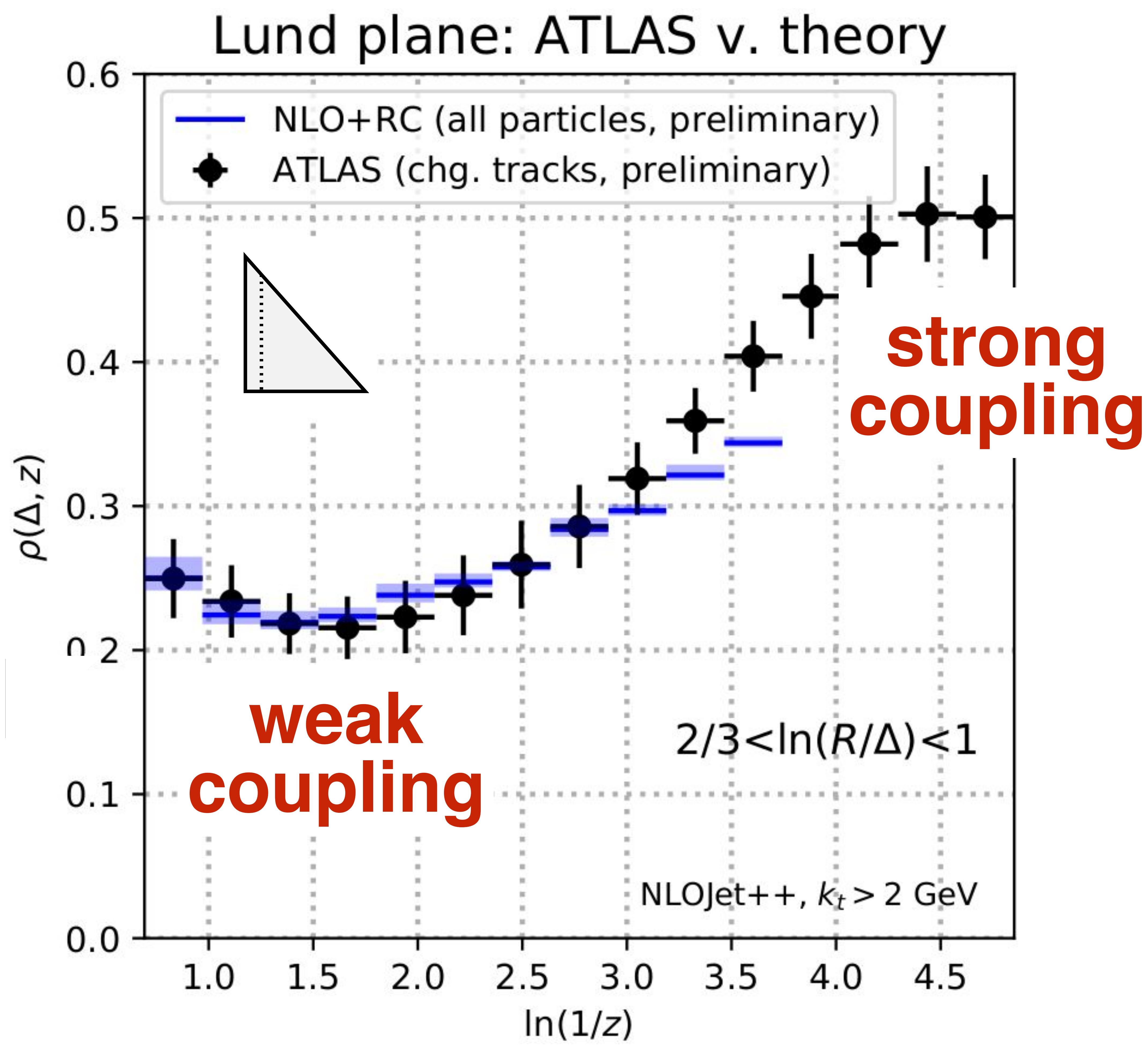
ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
ATLAS-CONF-2019-035
ln(1/z)
ln(R/ΔR)
z = $p_T^{emission}$ / ($p_T^{emission}$ + p_T^{core})
ΔR = ΔR(emission, core)
(1/N$_{jets}$) d^{2}N$_{emissions}$ / (d ln(1/z) d ln(R/ΔR))
QCD jets, averaged primary Lund plane
$\sqrt{s}$ = 14 TeV, p_t > 2 TeV
Pythia8.230(Monash13)
ln(k_t/GeV)
ln(1/Δ)
ρ(Δ, k_t)





MC deviates up to 40% wrt data



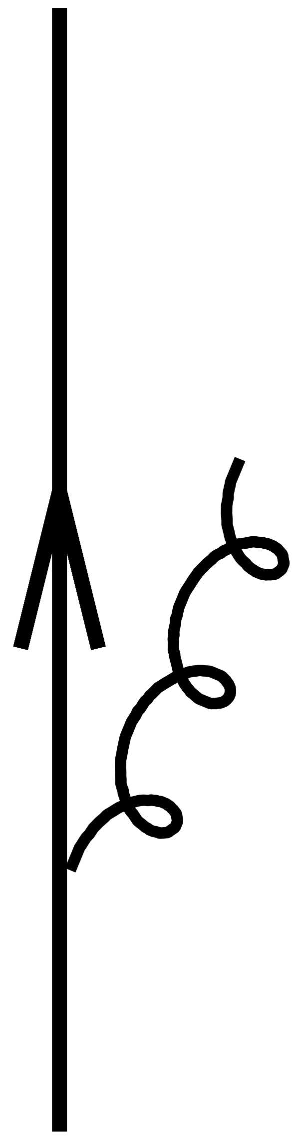


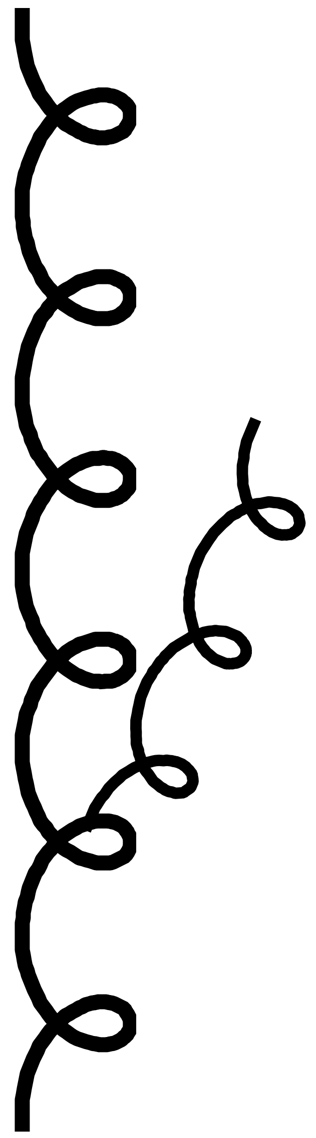
Dreyer & Soyez prelim @Boost 2019

quark/gluon tagging

relies entirely on radiation pattern

Intensity of gluon radiation from a quark or gluon





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

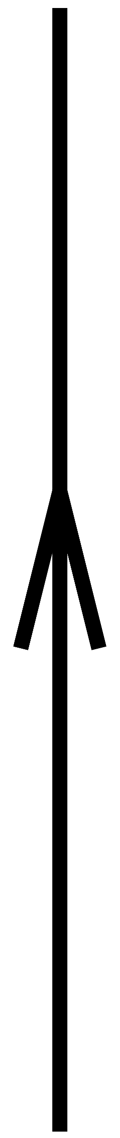
$$C_F = \frac{4}{3}$$

$$\frac{\boxed{C_A}\alpha_s}{\pi}\frac{dE}{E}\frac{d\theta^2}{\theta^2}$$

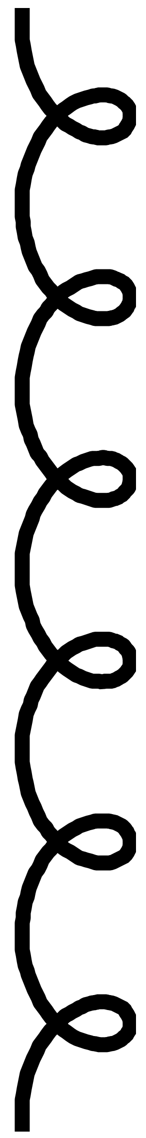
$$C_A = 3$$

Only observable difference between quark and gluon-induced jets is in the amount of radiation that they emit

quark v. gluon-induced jet is ambiguous

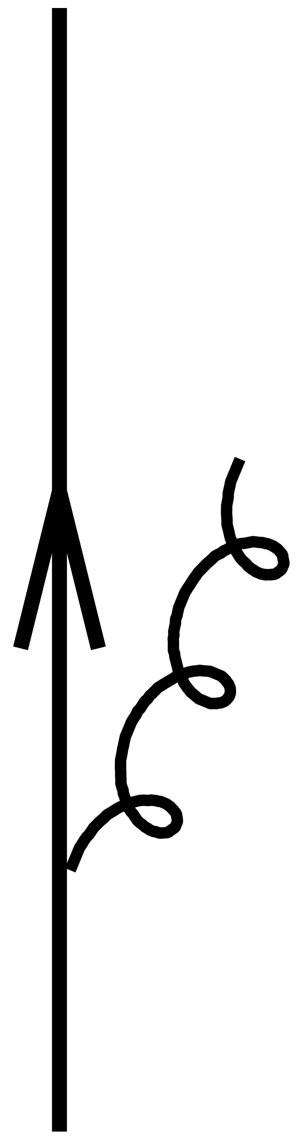


quark-induced
jet

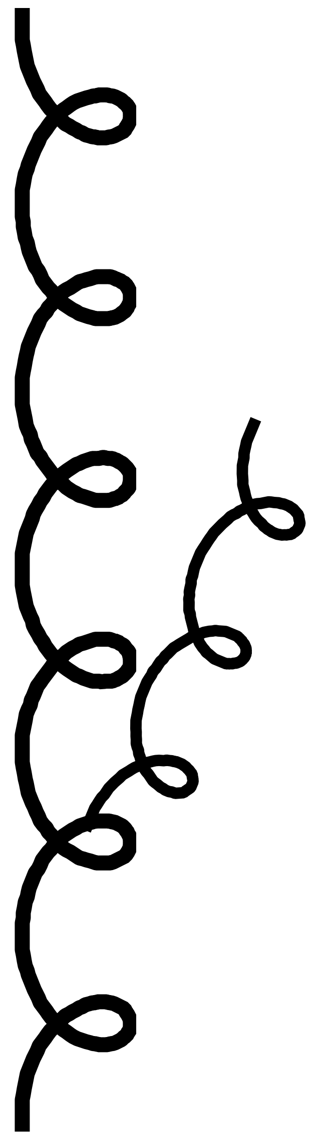


gluon-induced
jet

quark v. gluon-induced jet is ambiguous

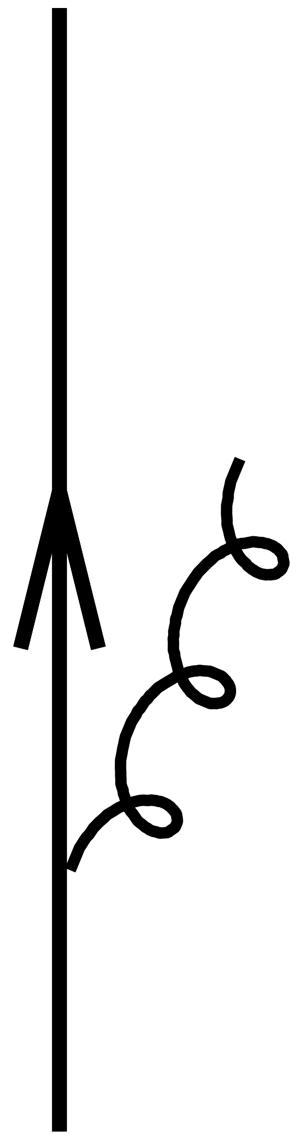


quark-induced
jet

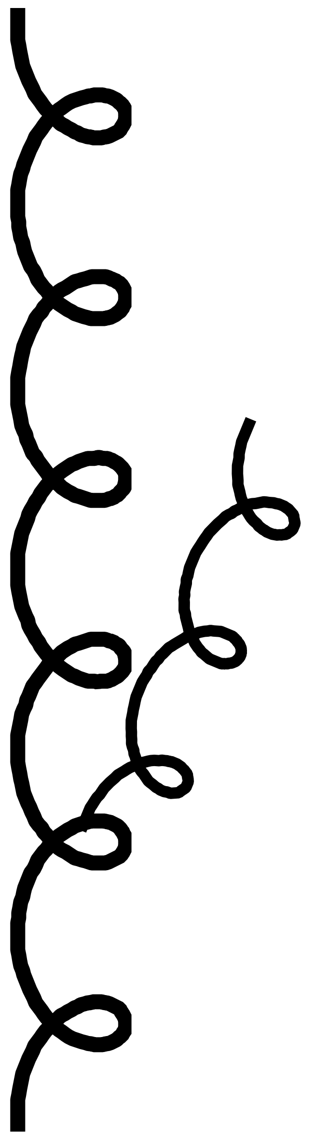


gluon-induced
jet

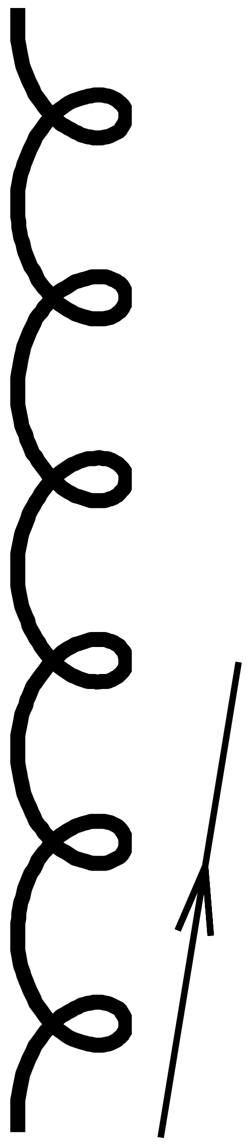
quark v. gluon-induced jet is ambiguous



quark-induced jet



gluon-induced jet



quark-induced jet that radiated hard gluon?

or gluon jet with a random quark that flew in?

occurs for fraction α_s of jets

Pythia dijet and Z+jet sub-process fractions

dijet sample p_t > 250 GeV

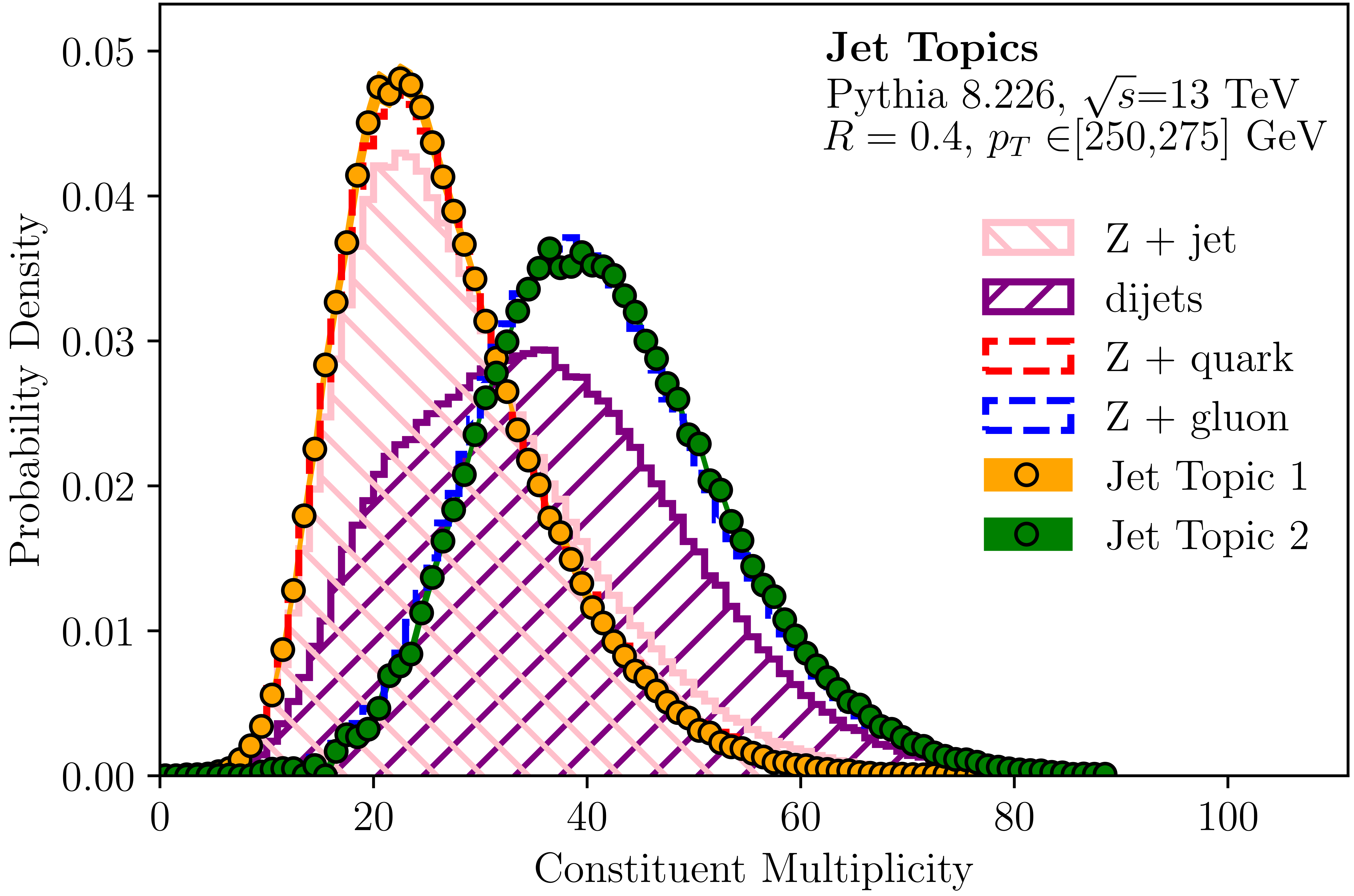
```
==============================================================================
I                                  I                            I            I
I            Subprocess            I      Number of points      I    Sigma   I
I                                  I                            I            I
I----------------------------------I----------------------------I    (mb)    I
I                                  I                            I            I
I N:o Type                         I    Generated         Tried I            I
I                                  I                            I            I
==============================================================================
I                                  I                            I            I
I   0 All included subprocesses    I         1000          6578 I  2.256D-05 I
I  11 f + f' -> f + f' (QCD)       I          139           828 I  3.000D-06 I
I  12 f + fbar -> f' + fbar'       I            6             9 I  6.865D-08 I
I  13 f + fbar -> g + g            I            1             4 I  5.411D-08 I
I  28 f + g -> f + g               I          553          4209 I  1.193D-05 I
I  53 g + g -> f + fbar            I           12            47 I  2.856D-07 I
I  68 g + g -> g + g               I          289          1481 I  7.228D-06 I
I                                  I                            I            I
==============================================================================
```

Z+jet sample p_t > 250 GeV

```
==============================================================================
I                                  I                            I            I
I            Subprocess            I      Number of points      I    Sigma   I
I                                  I                            I            I
I----------------------------------I----------------------------I    (mb)    I
I                                  I                            I            I
I N:o Type                         I    Generated         Tried I            I
I                                  I                            I            I
==============================================================================
I                                  I                            I            I
I   0 All included subprocesses    I         1000          4111 I  2.589D-08 I
I  15 f + fbar -> g + Z0           I          151           546 I  3.971D-09 I
I  30 f + g -> f + Z0              I          849          3565 I  2.192D-08 I
I                                  I                            I            I
==============================================================================
```

57% gluon jets

85% quark jets



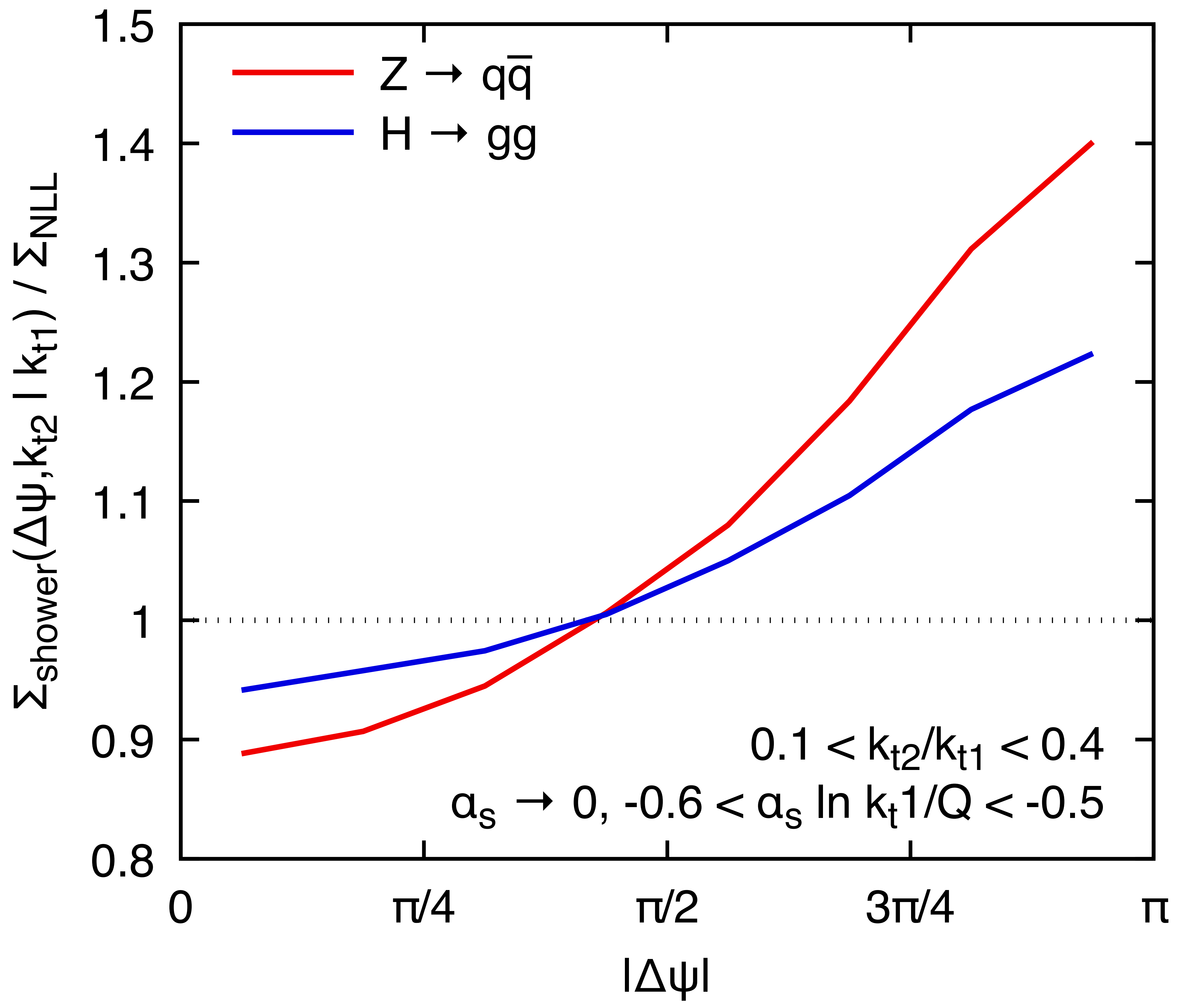
particle multiplicity N distribution has region at low N (high N) populated only by quarks (gluons) [mutual irreducibility]

That information, together with two samples with different (but unknown) q/g fractions, is enough to operationally define q/g fractions in each sample

Metodiev & Thaler, arXiv:1802.00008 ,
Komiske, Metodiev & Thaler, arXiv:1809.01140

beware, parton showers are not perfect

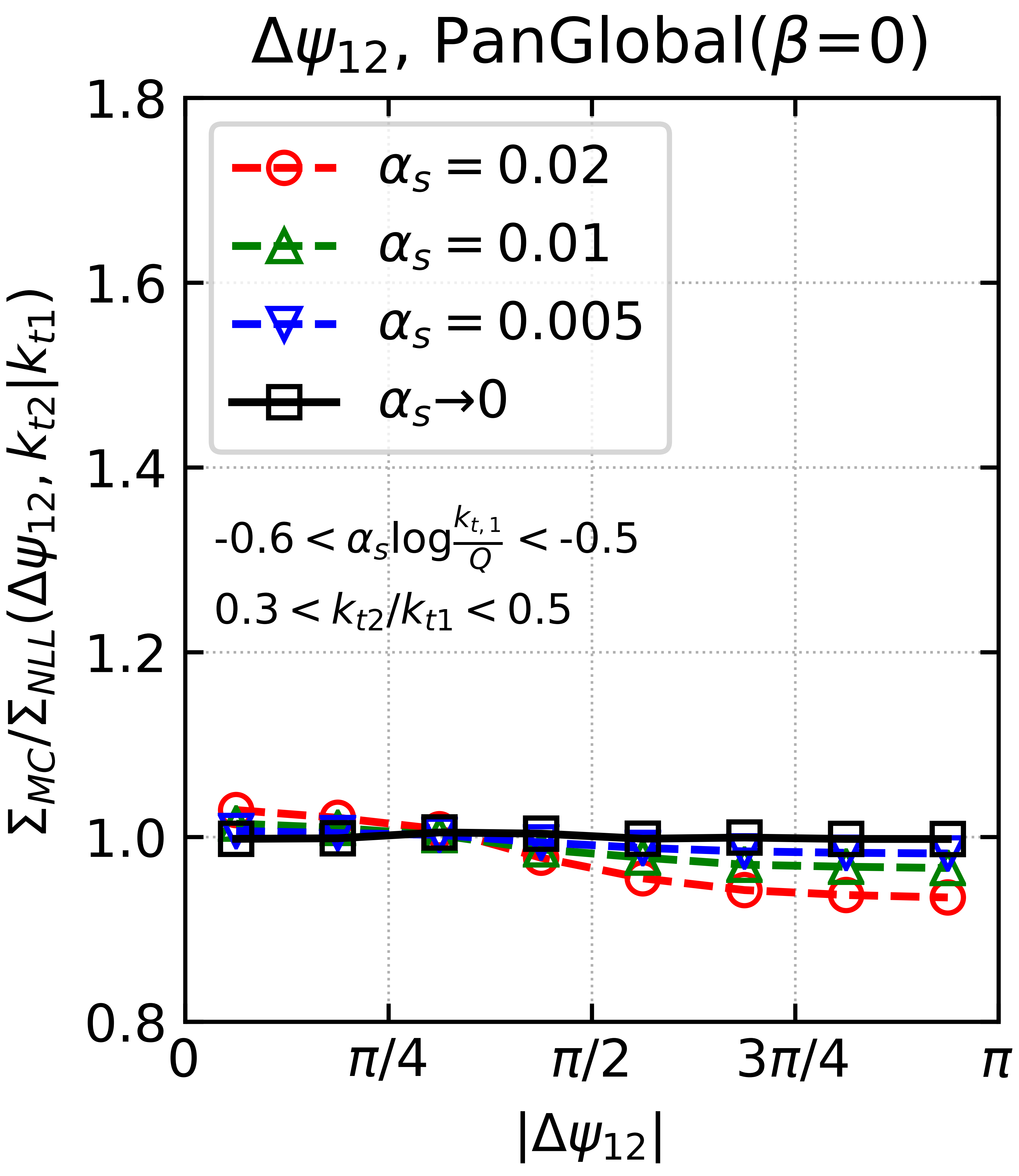
dipole shower (Dire v1) ratio to NLL



common dipole showers display quark/gluon differences (e.g. in some azimuthal observables) that shouldn't be there

especially relevant for machine learning

Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, arXiv:2002.11114



common dipole showers display quark/gluon differences (e.g. in some azimuthal observables) that shouldn't be there

time has come to develop new generation of parton showers with quantifiable accuracy

especially relevant for machine learning

Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, arXiv:2002.11114

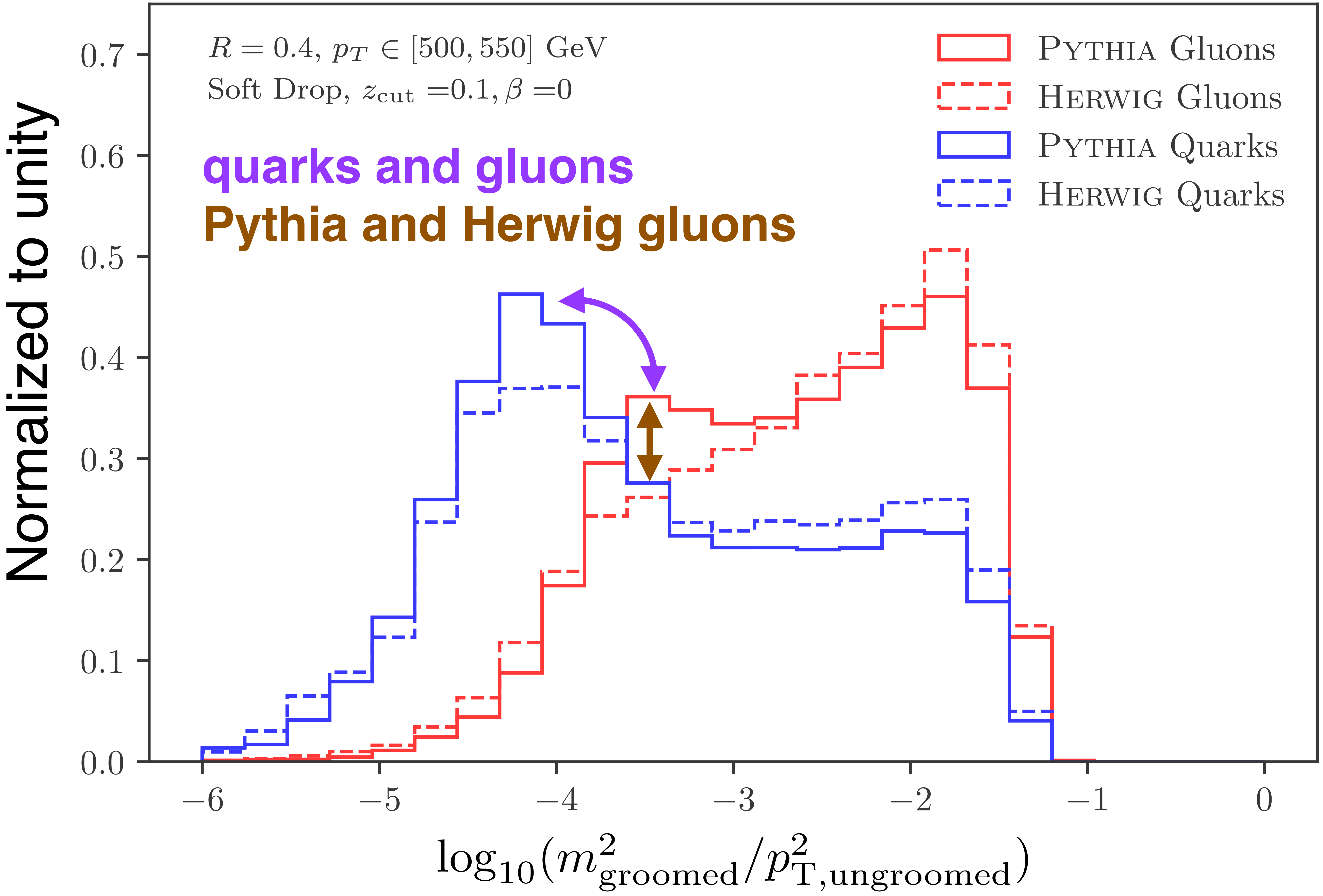
- **SoftDrop:** for extracting underlying hard jet substructure (e.g. 2-prong structure). Uses key idea of C/A declustering, gives distributions with well-understood characteristics (e.g. only collinear single logarithms in resummation)

- **Subjettiness / energy-energy-correlations / energy-flow polynomials / Lund Plane structure:** all try to measure the additional radiation flow around the core n-prong structure of a jet (e.g. 2-prong for Higgs decay)

- **Top performance ultimately comes from machine learning**, but we should still aim to understand the information we are using, whether data or MC driven, and questions such as assigning meaning to the categories we use (e.g. quark v gluon-induced jets)

- **SoftDrop:** uses key idea of C/A declustering, gives distributions with well-understood characteristics (e.g. only collinear single logarithms in resummation)
- **Subjettiness / energy-energy-correlations / energy-flow polynomials / Lund Plane structure:** all try to measure the energy flow around the core n-prong structure of a jet (e.g. 2-prong for Higgs decay)
- **Machine learning:** jet substructure is one of the most dynamic playgrounds for ML, with large gains to be had in pulling out all info from jets

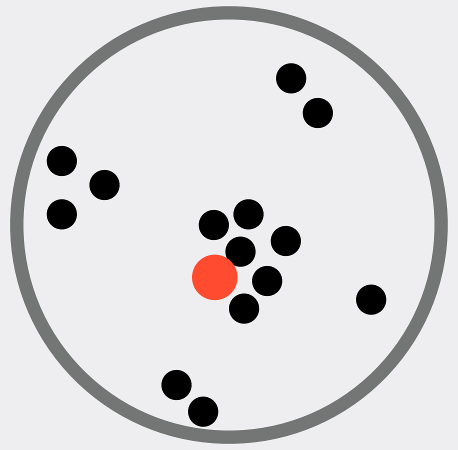
EXTRAS



- comment on differences
- but at some level they are most prominent at non-perturbative level (which is around -4.3)

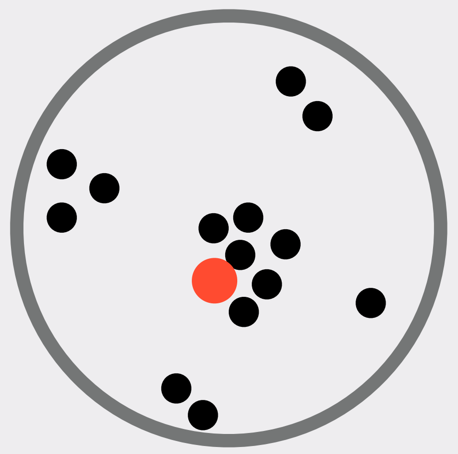
fragmentation function

$$D(z) = \left\langle \sum_{i\in\text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



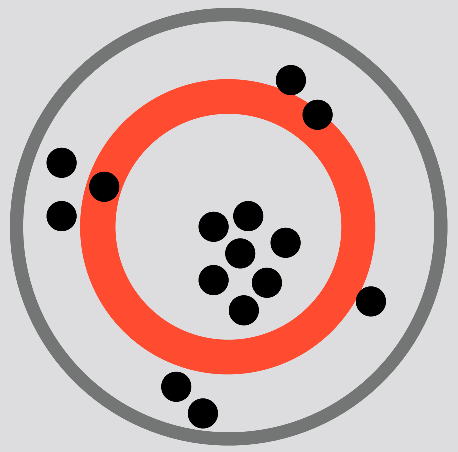
fragmentation function

$$D(z) = \left\langle \sum_{i\in\text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



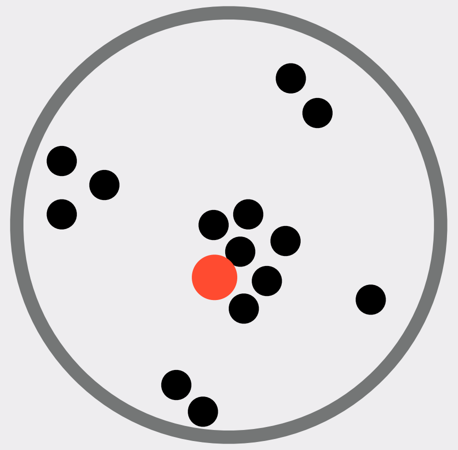
differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ}\in[r,r+\delta r]}} p_\perp^{(k)} \,,$$



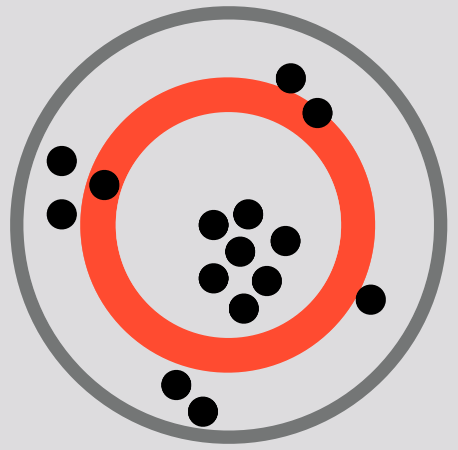
fragmentation function

$$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



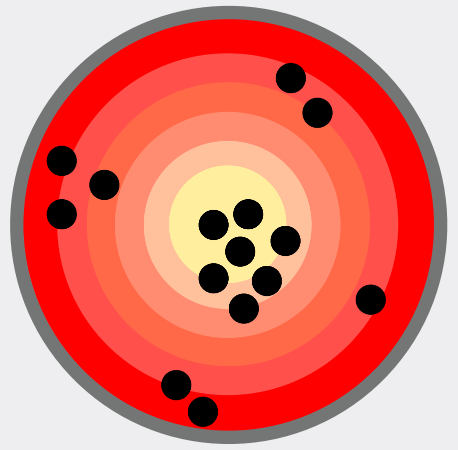
differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)} ,$$

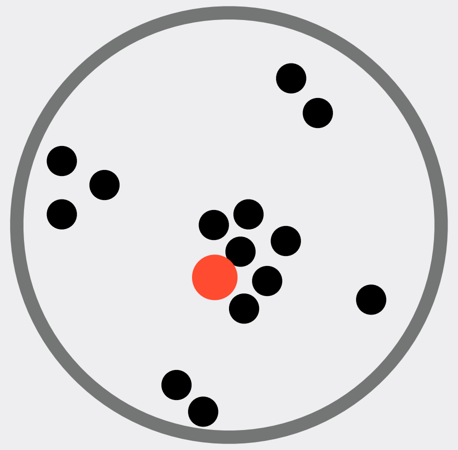
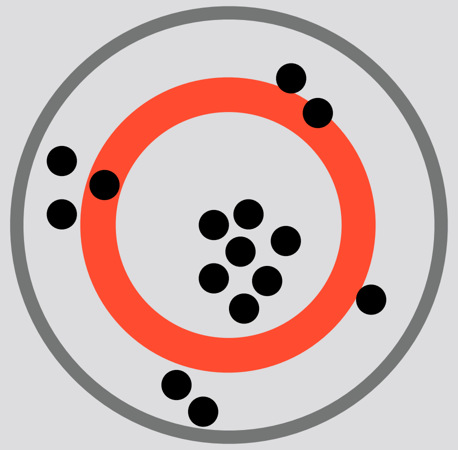
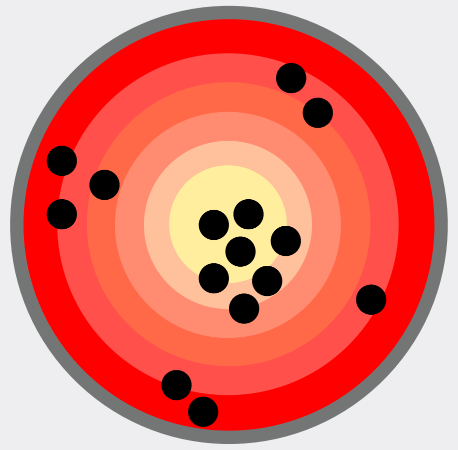
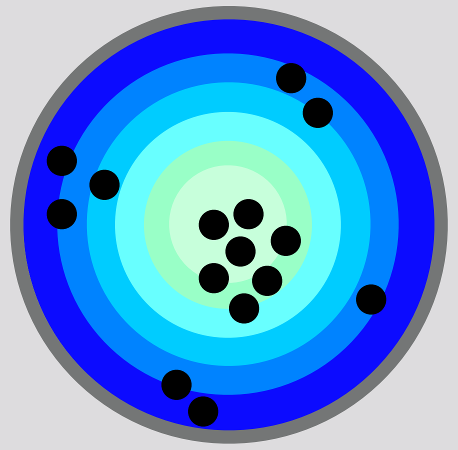


width≡ broadening

$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ} ,$$



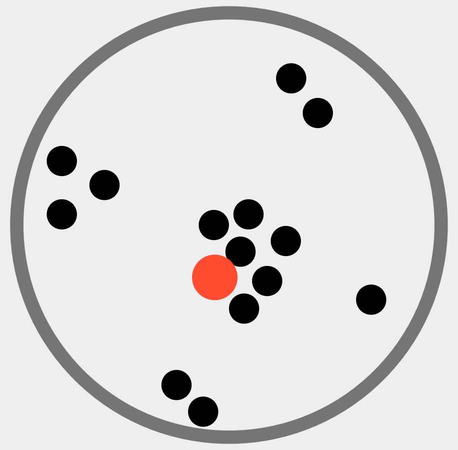
Jet structure observables

fragmentation function	$$D(z) = \left\langle \sum_{i\in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$	
differential jet shape	$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ}\in[r,r+\delta r]}} p_\perp^{(k)}\,,$$	
width≡ broadening	$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k\in J} p_\perp^{(k)} \Delta R_{kJ}\,,$$	
jet mass, groomed & ungroomed	$$m^2 = \left(\sum_{i\in(\text{sub})\text{jet}} p_i^\mu \right)^2$$	

Jet structure observables

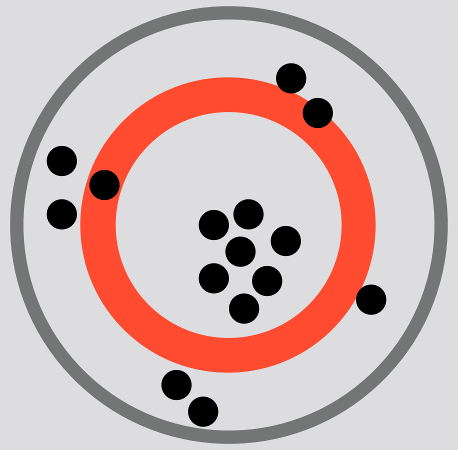
fragmentation function

$$D(z) = \left\langle \sum_{i\in\text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



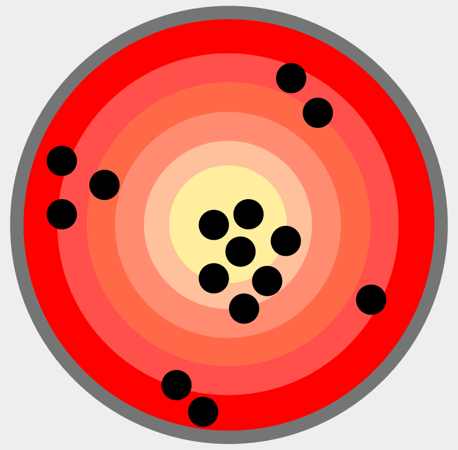
differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ}\in[r,r+\delta r]}} p_\perp^{(k)} \,,$$



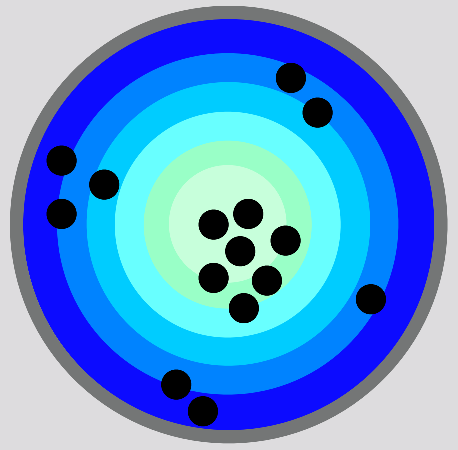
width≡ broadening

$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k\in J} p_\perp^{(k)} \Delta R_{kJ} \,,$$



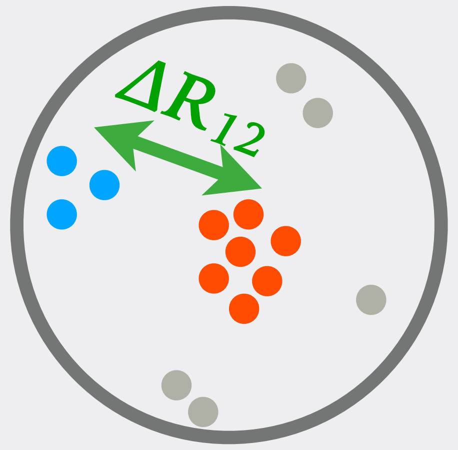
jet mass, groomed & ungroomed

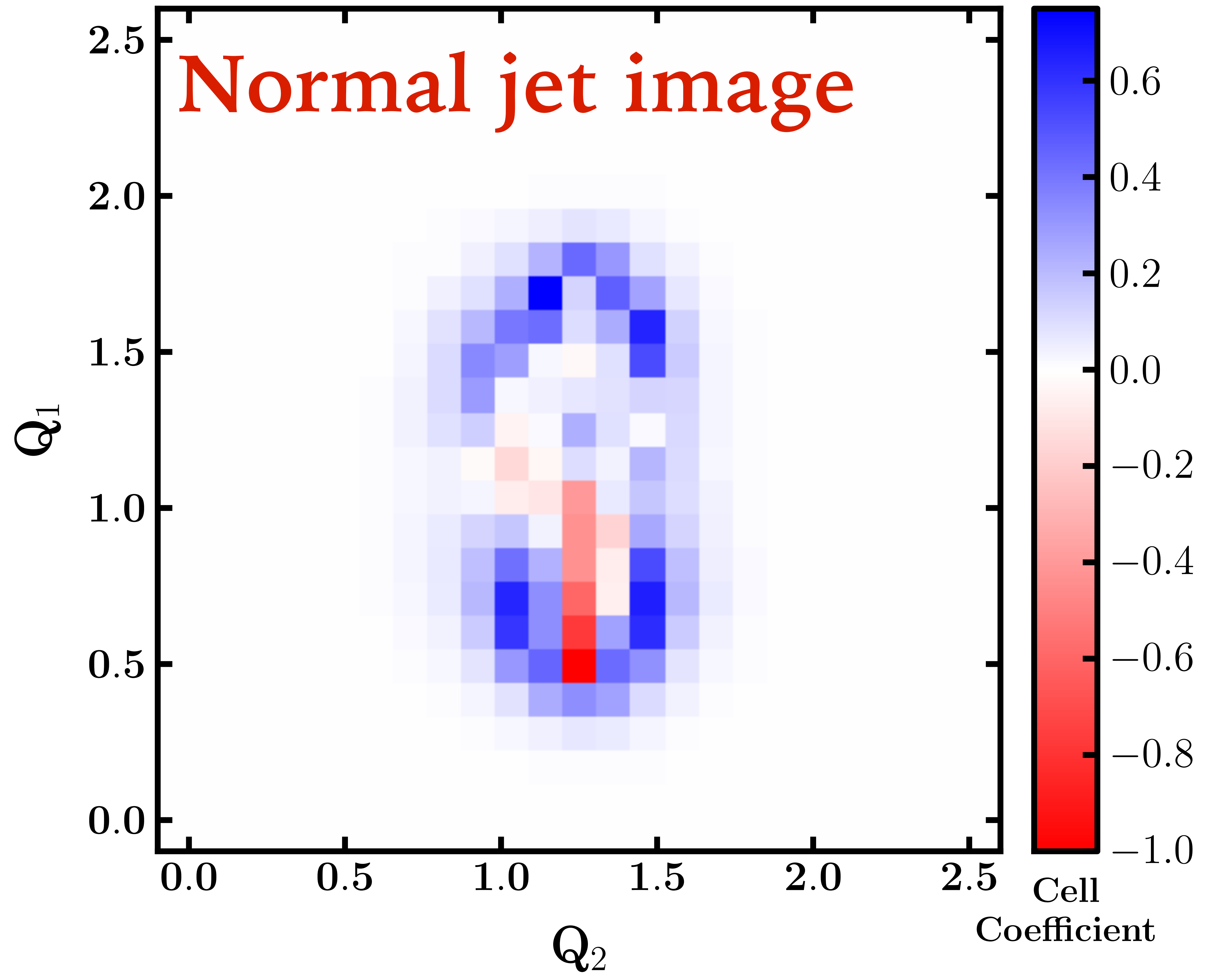
$$m^2 = \left(\sum_{i\in(\text{sub})\text{jet}} p_i^\mu \right)^2$$



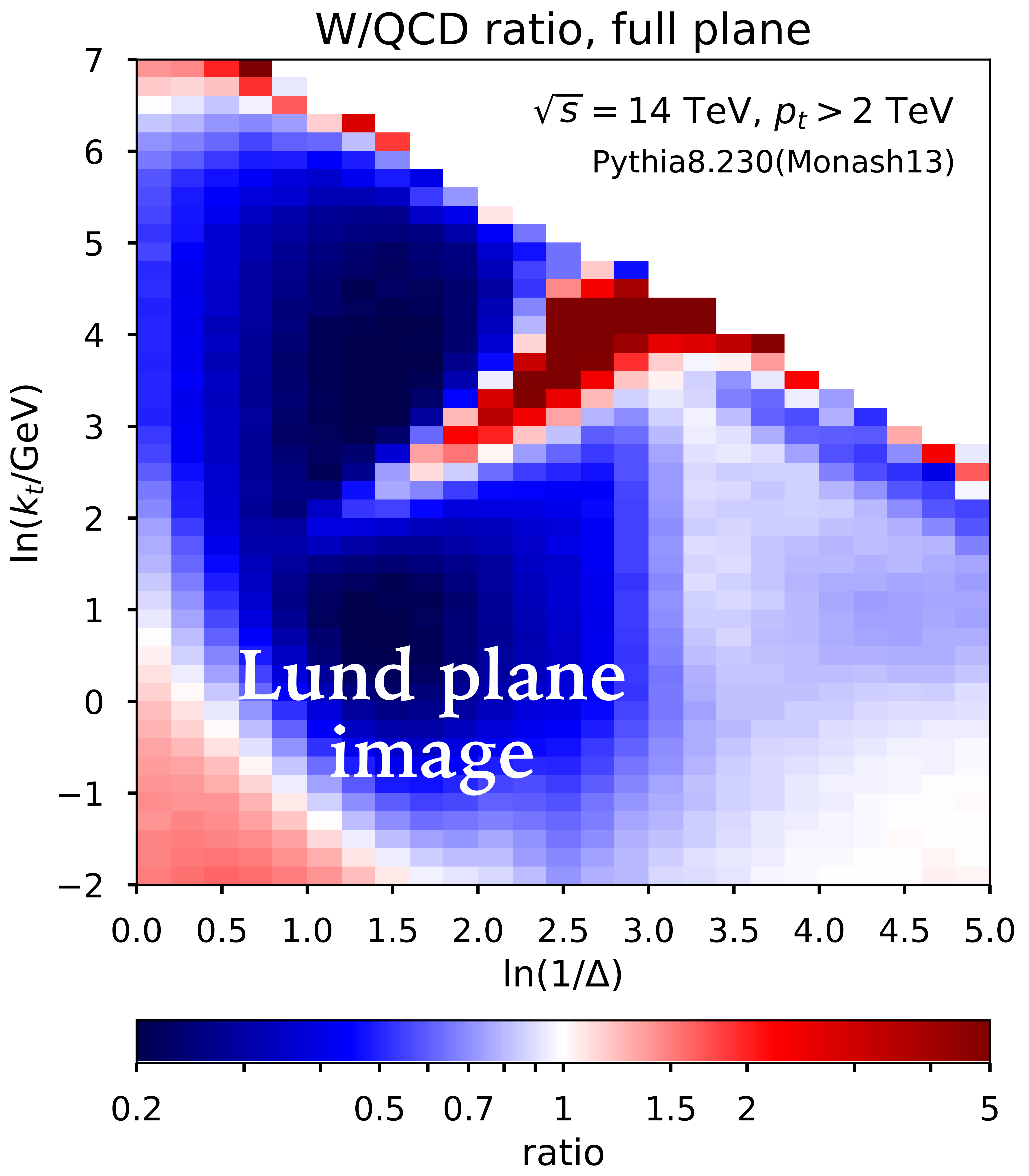
z_g, ΔR_{12}

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$$





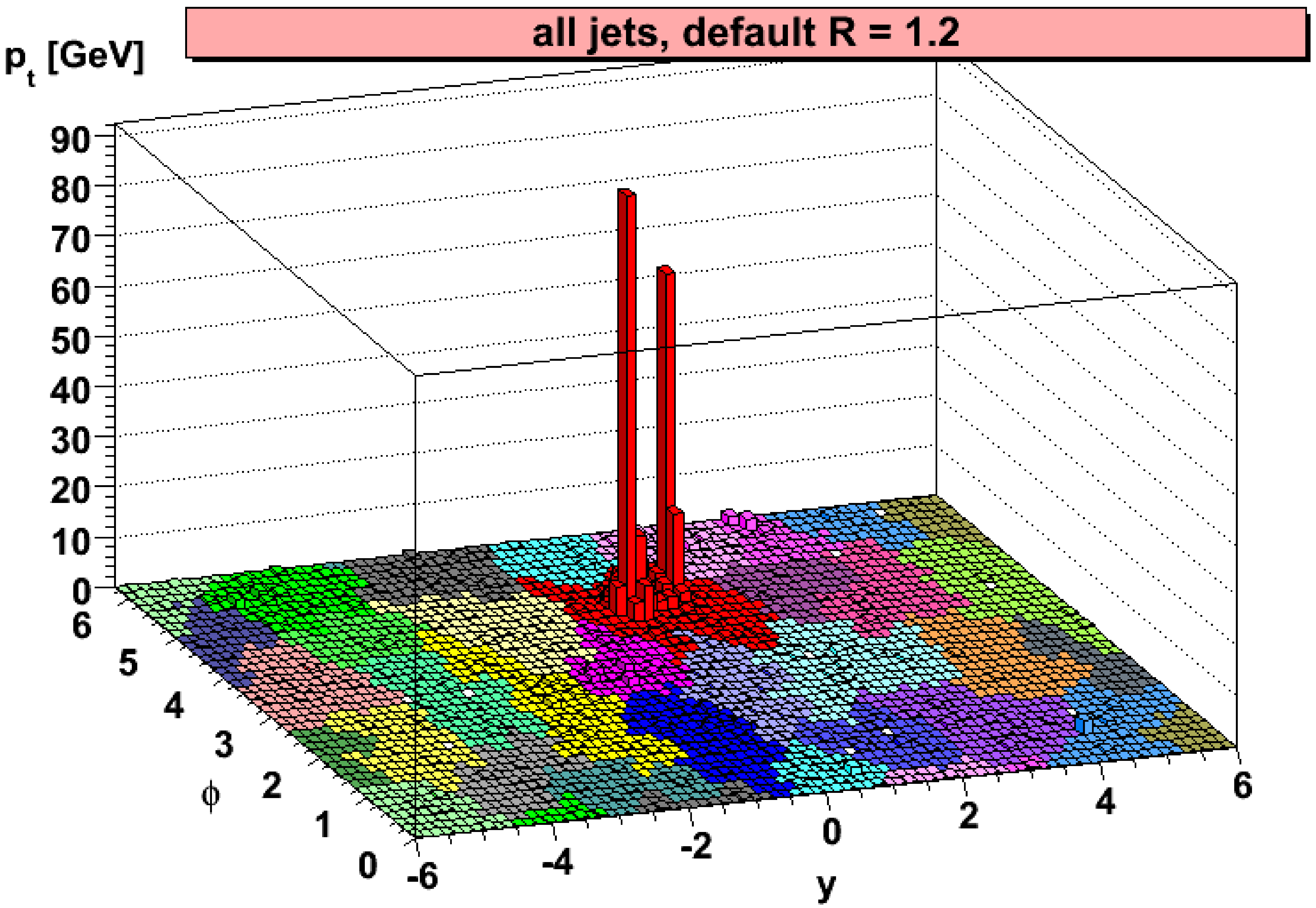
Cogan, Kagan, Strauss, Schwartzman, 1407.5674



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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

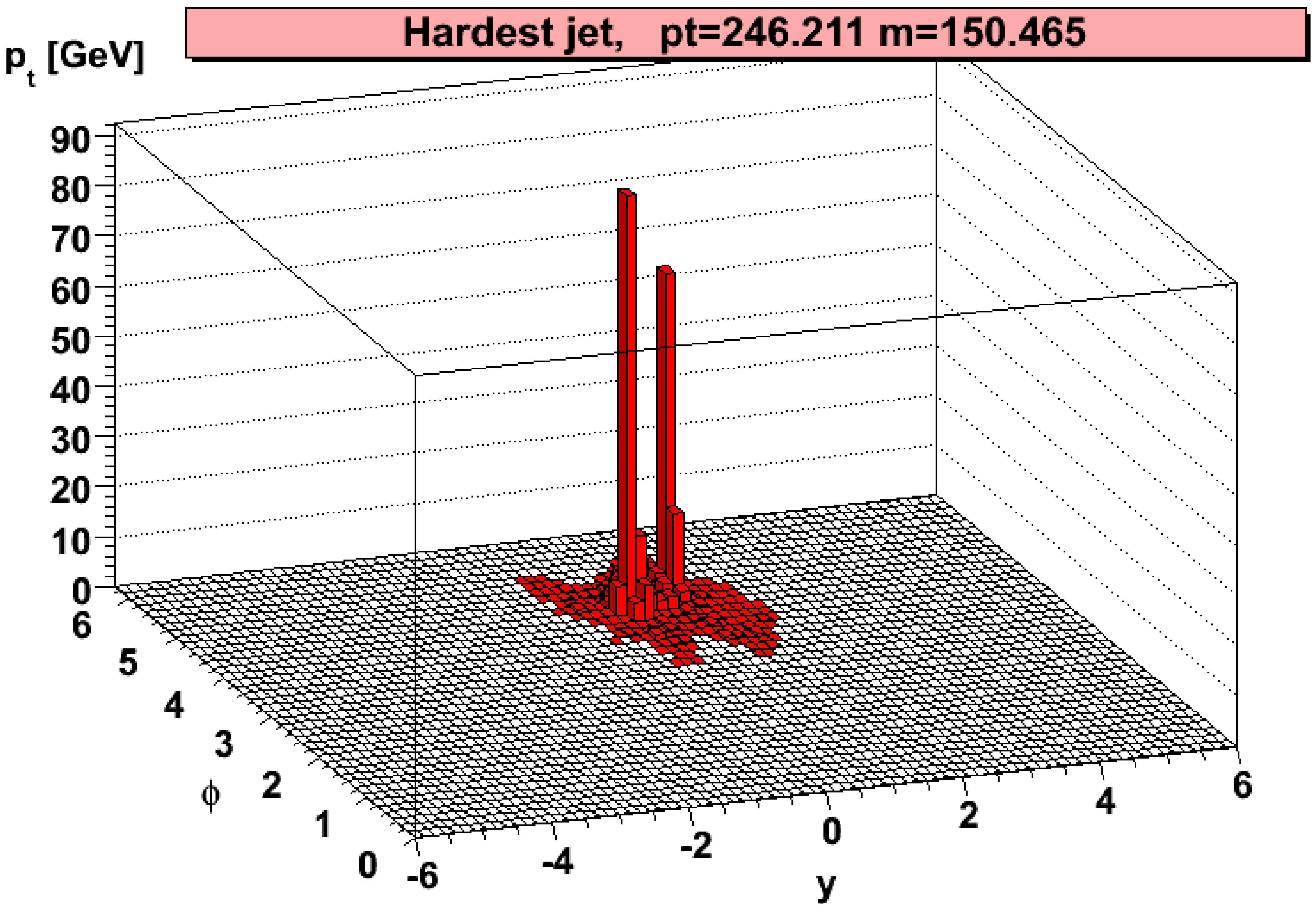
Fill it in, → show jets more clearly

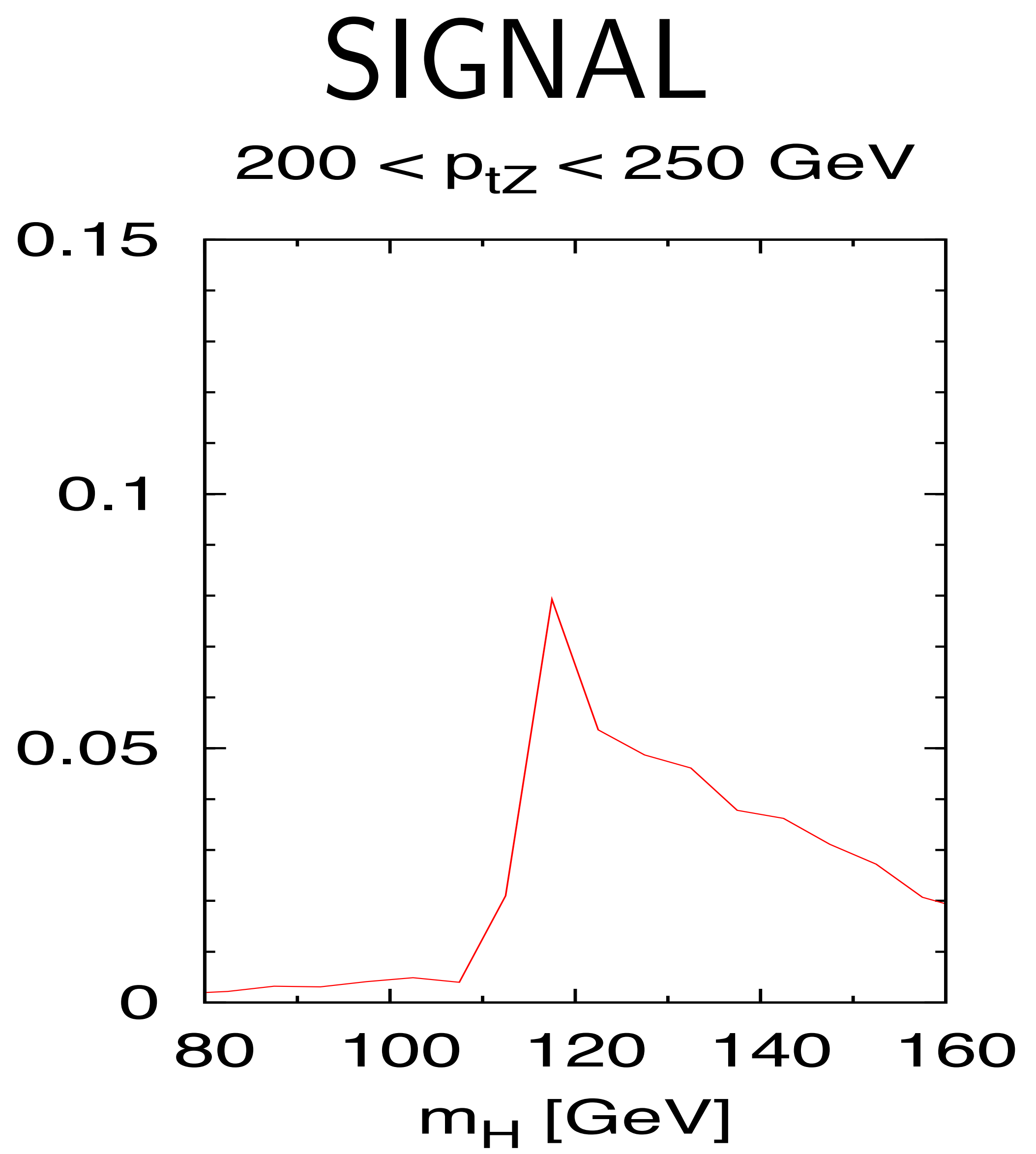
Butterworth, Davison, Rubin & GPS '08

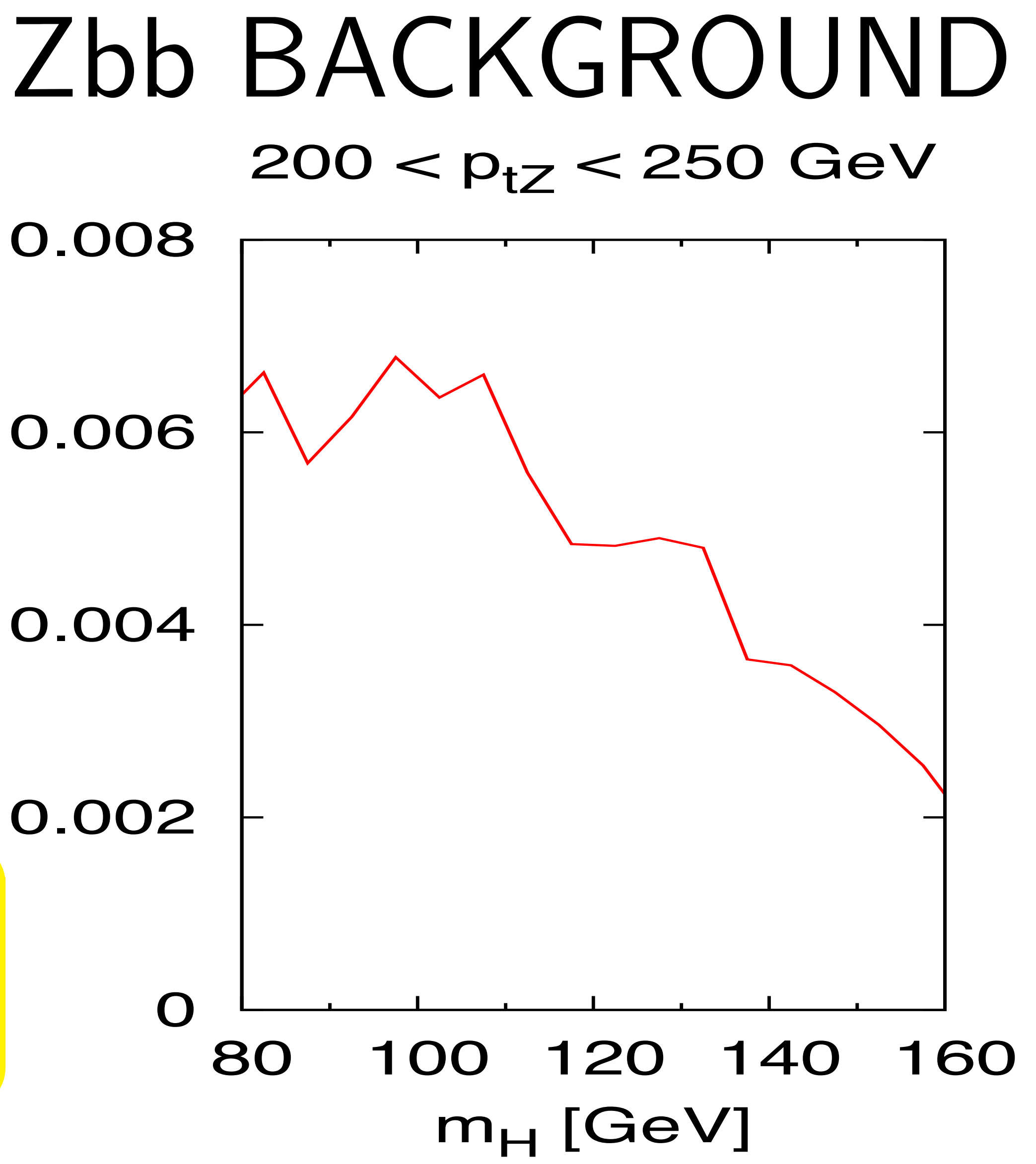
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







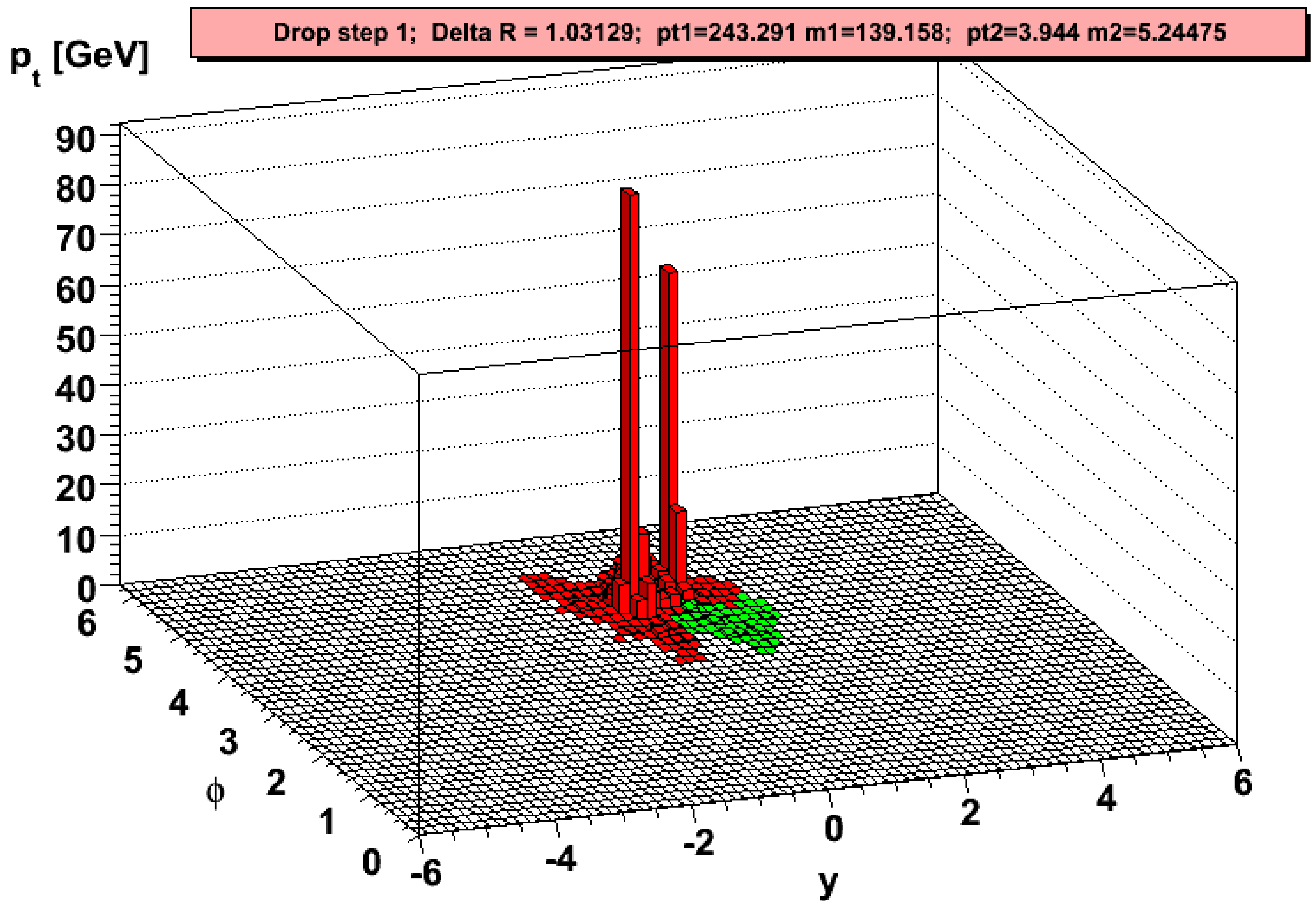
Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

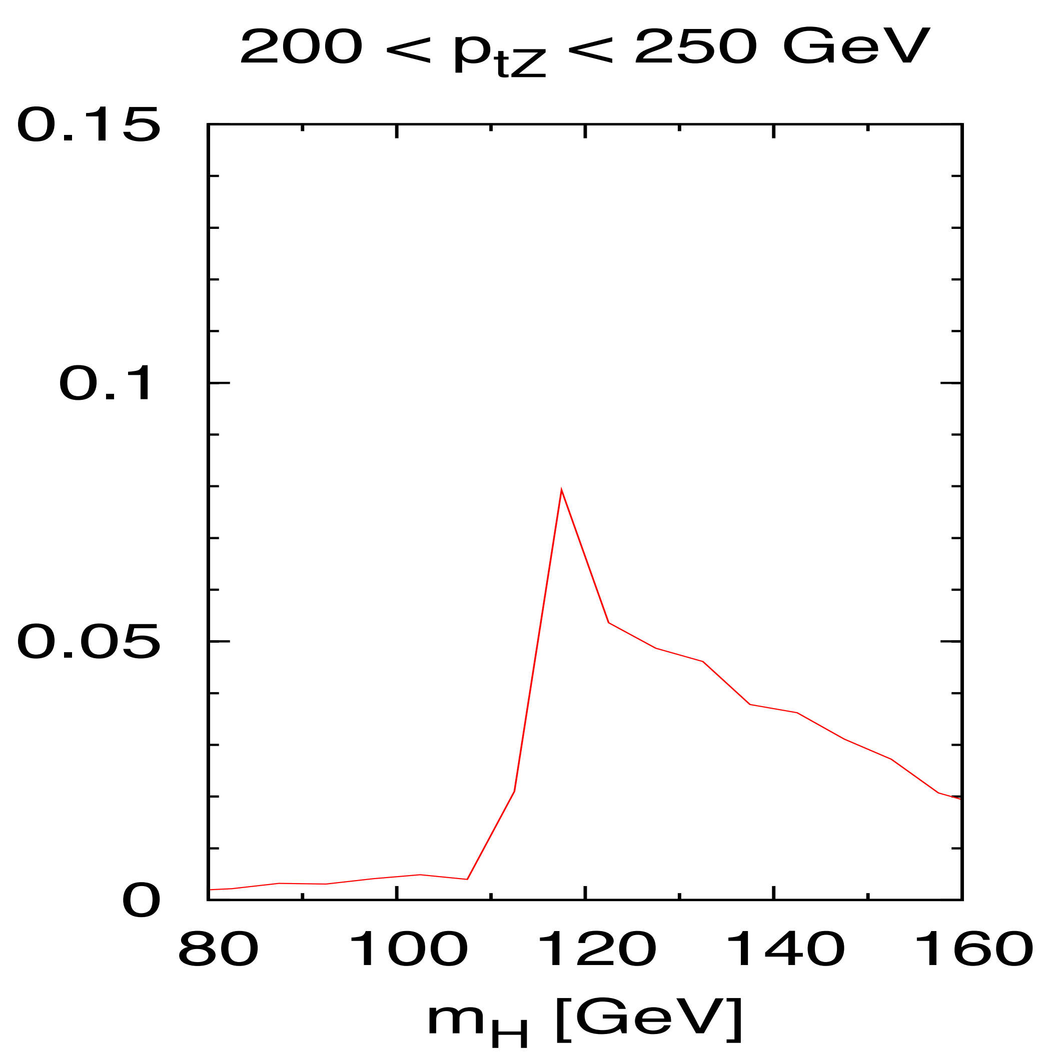
arbitrary norm.

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

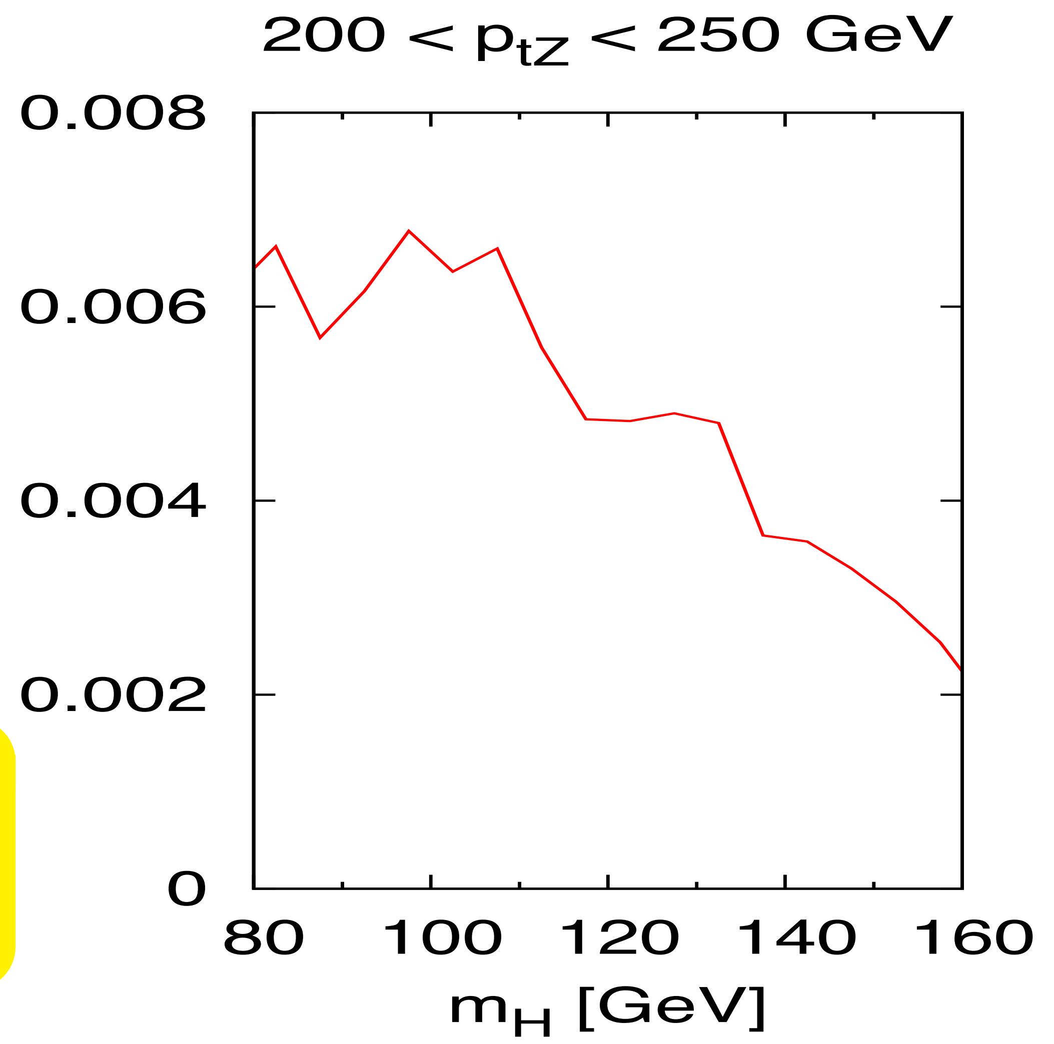
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



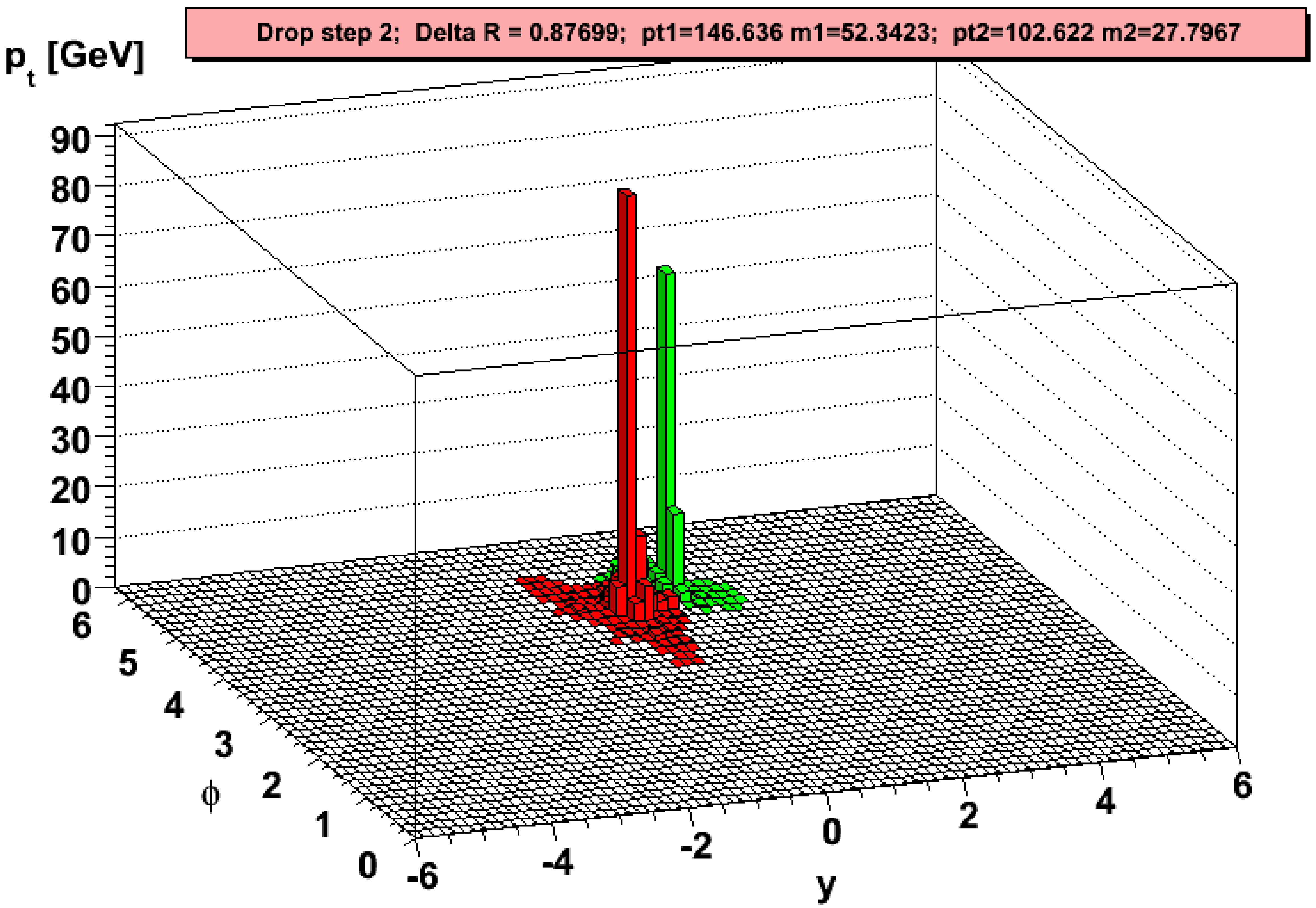
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

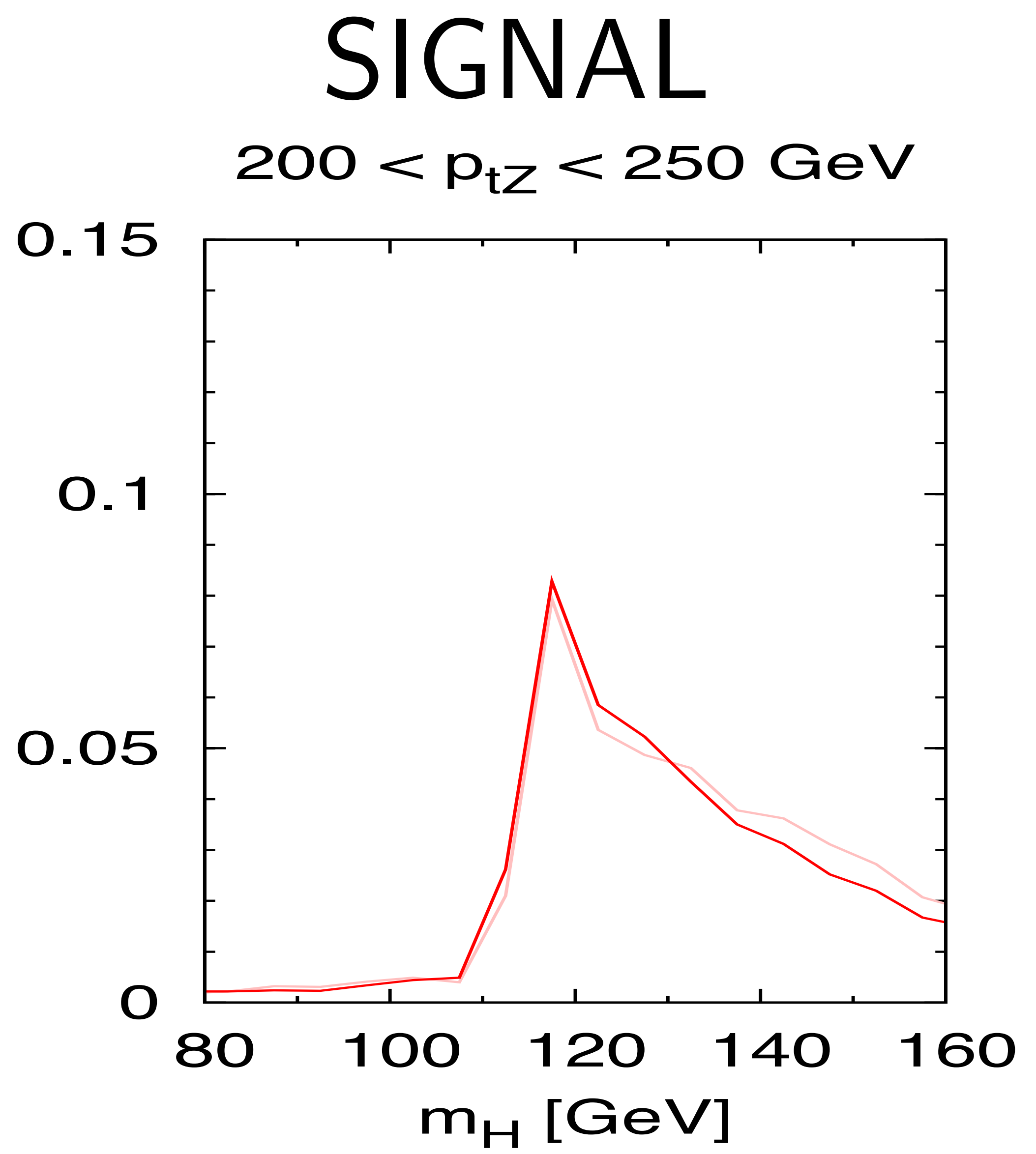
Butterworth, Davison, Rubin & GPS '08

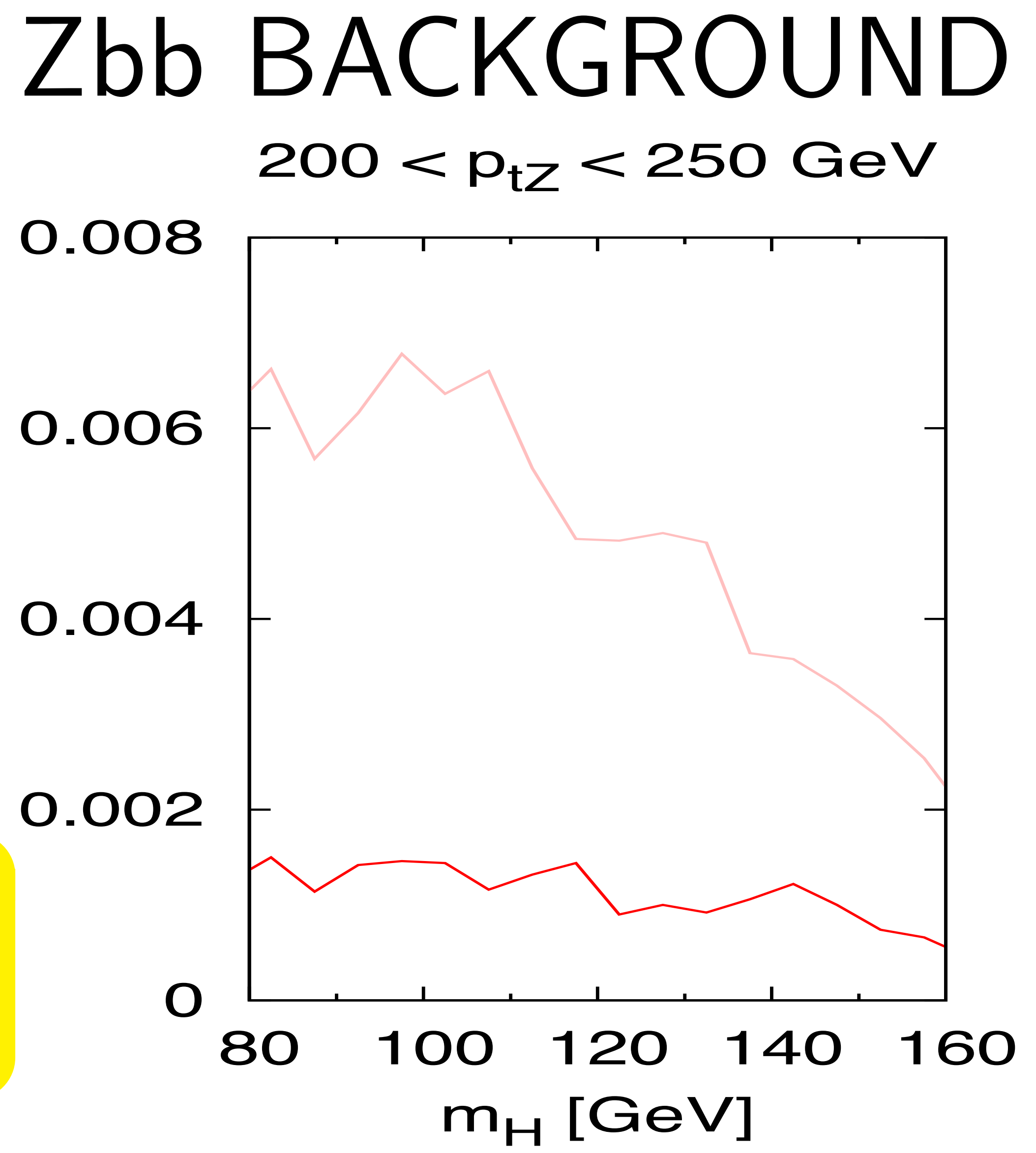
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







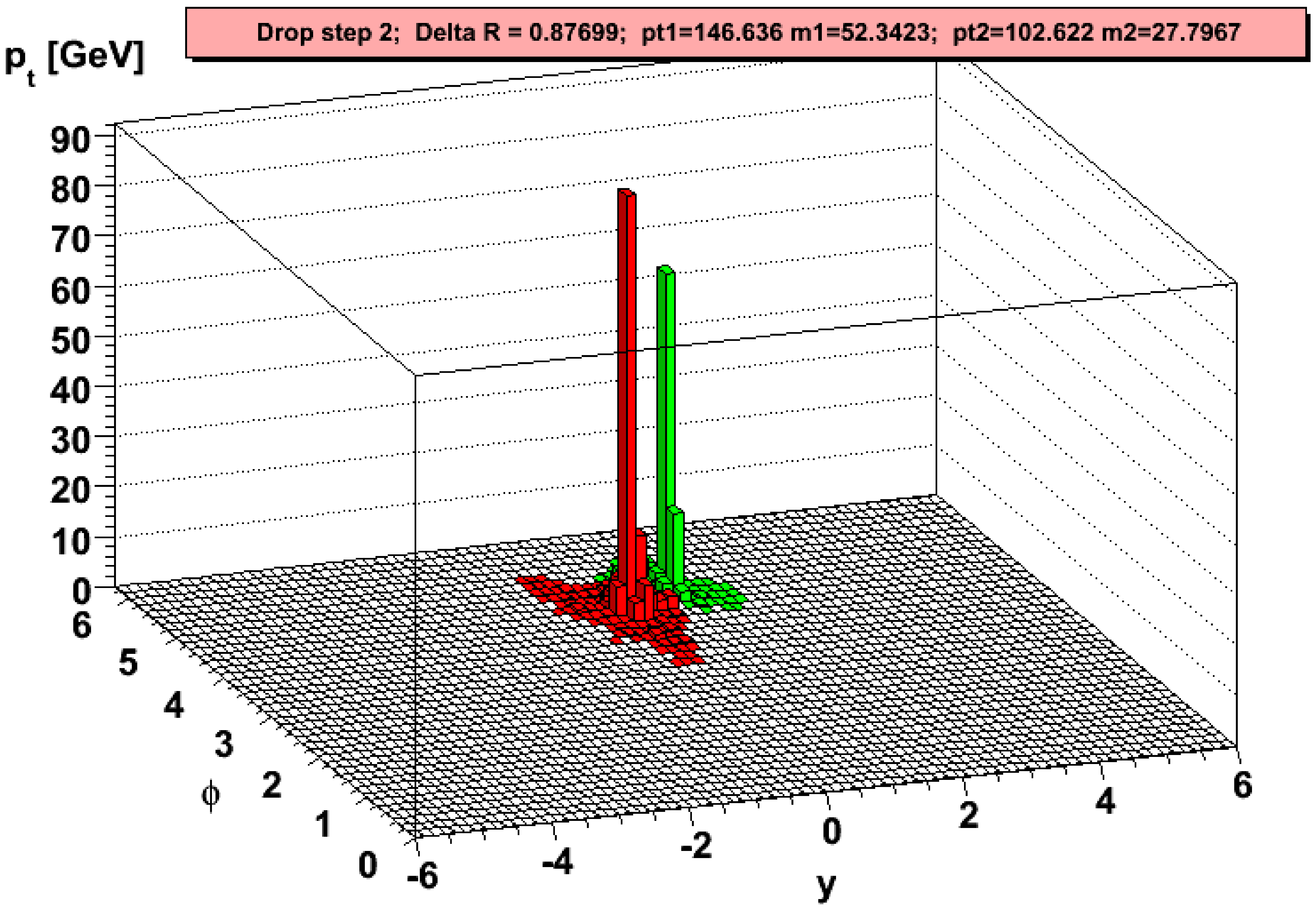
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

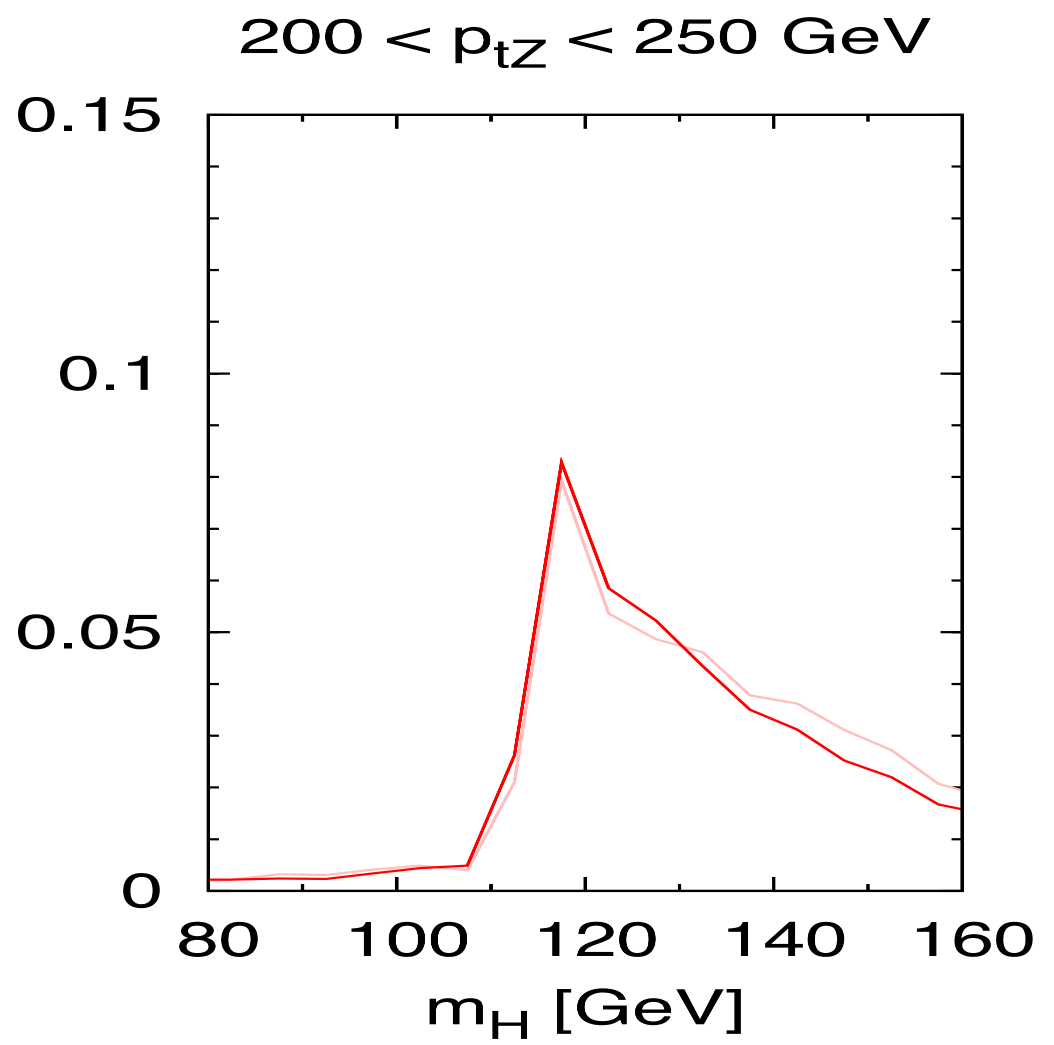
arbitrary norm.

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

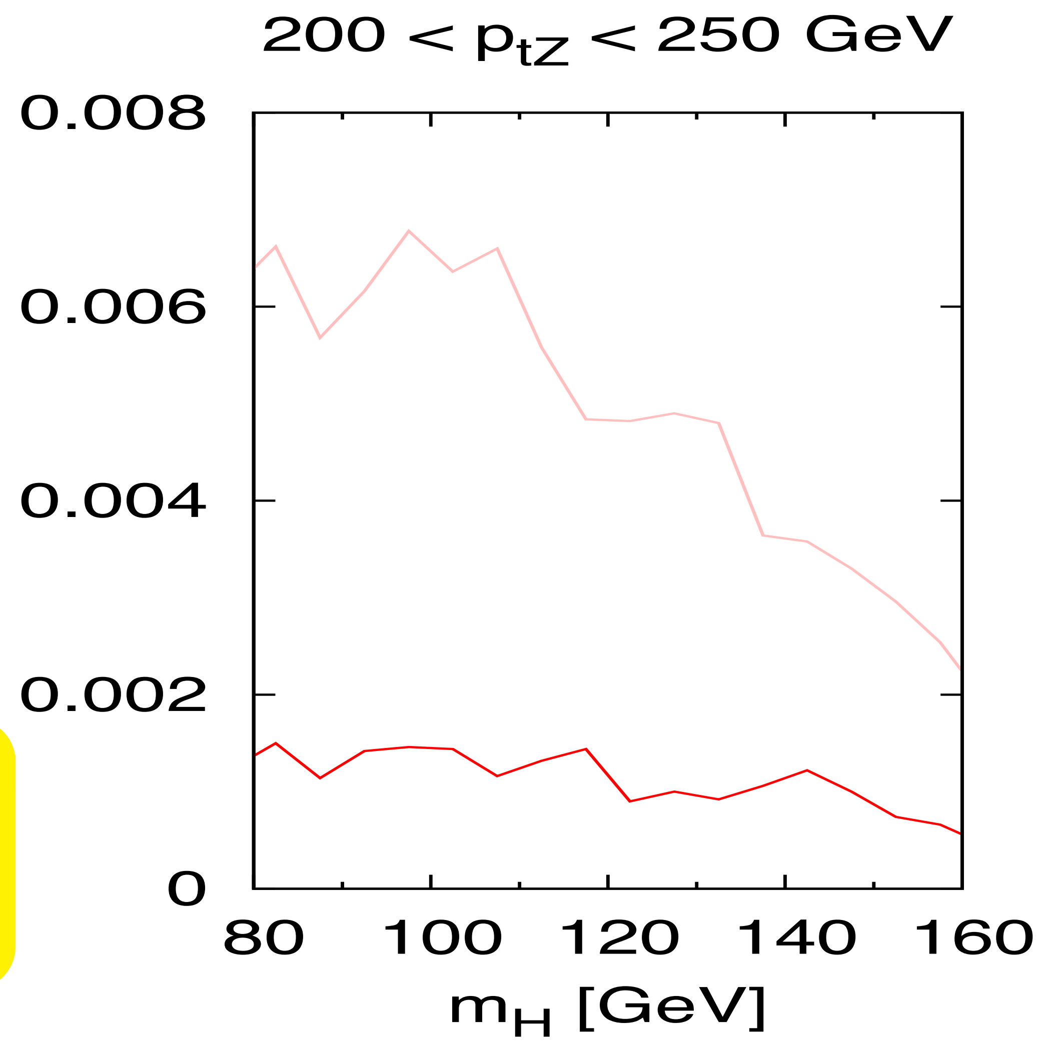
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



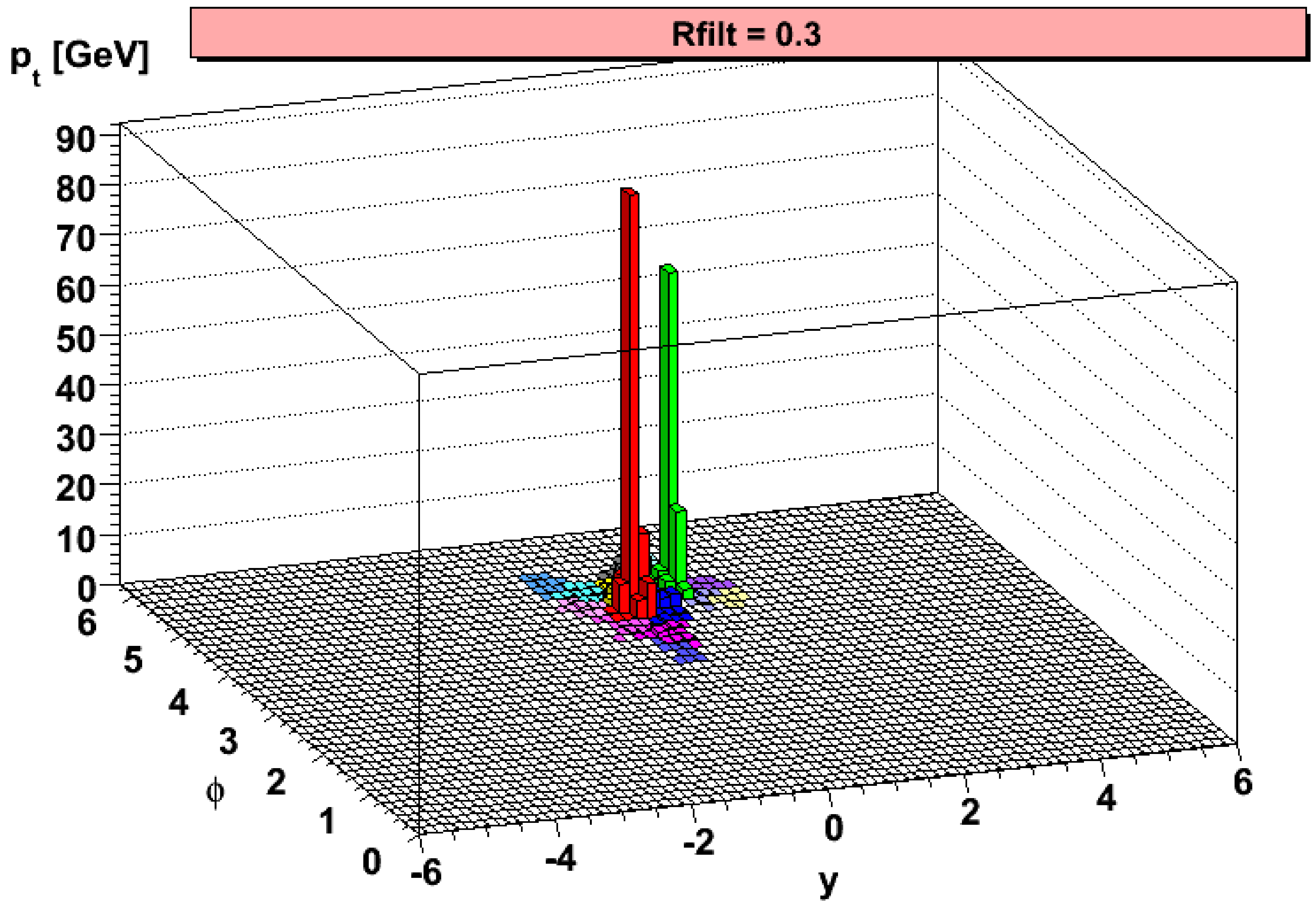
check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

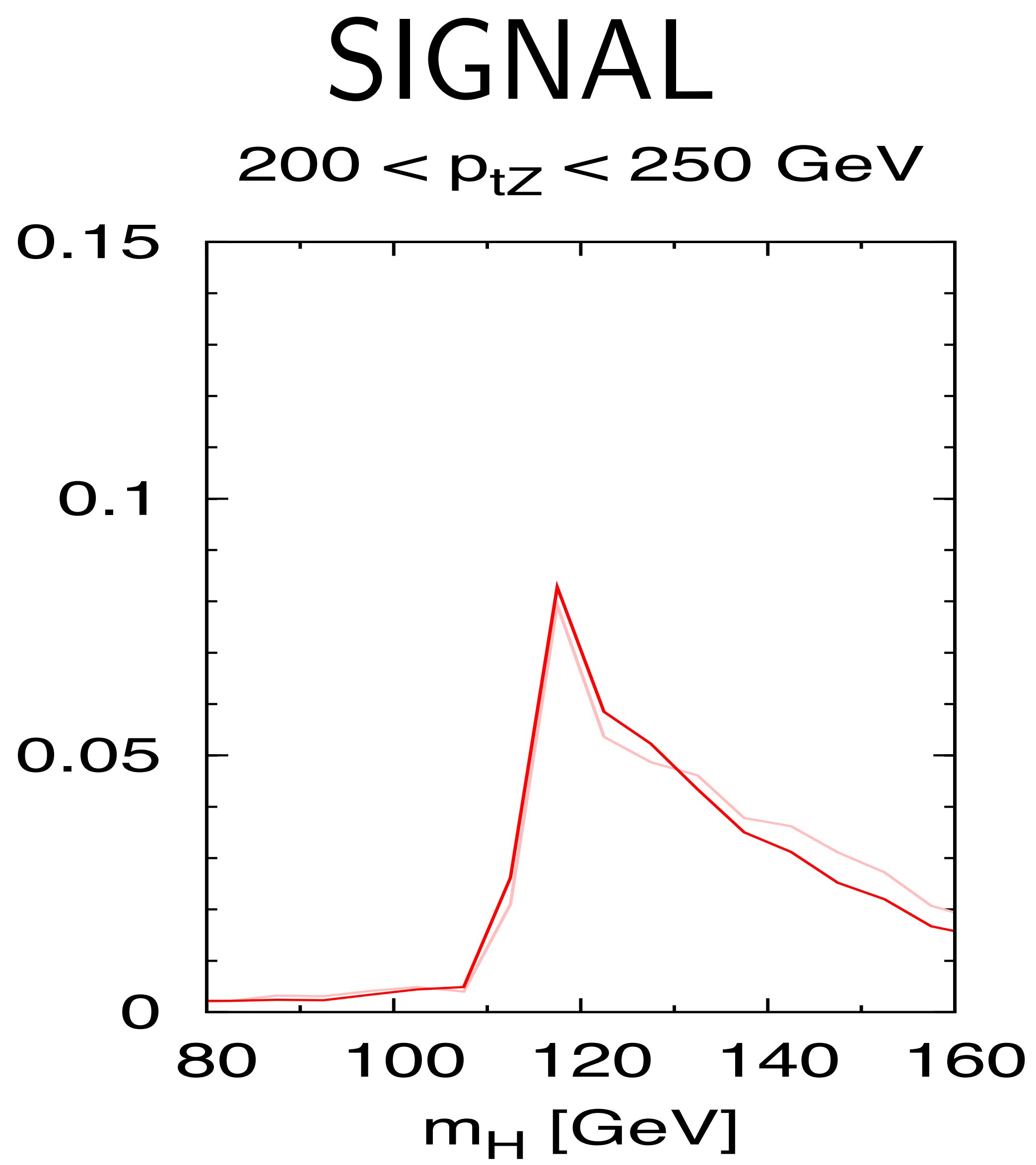
Butterworth, Davison, Rubin & GPS '08

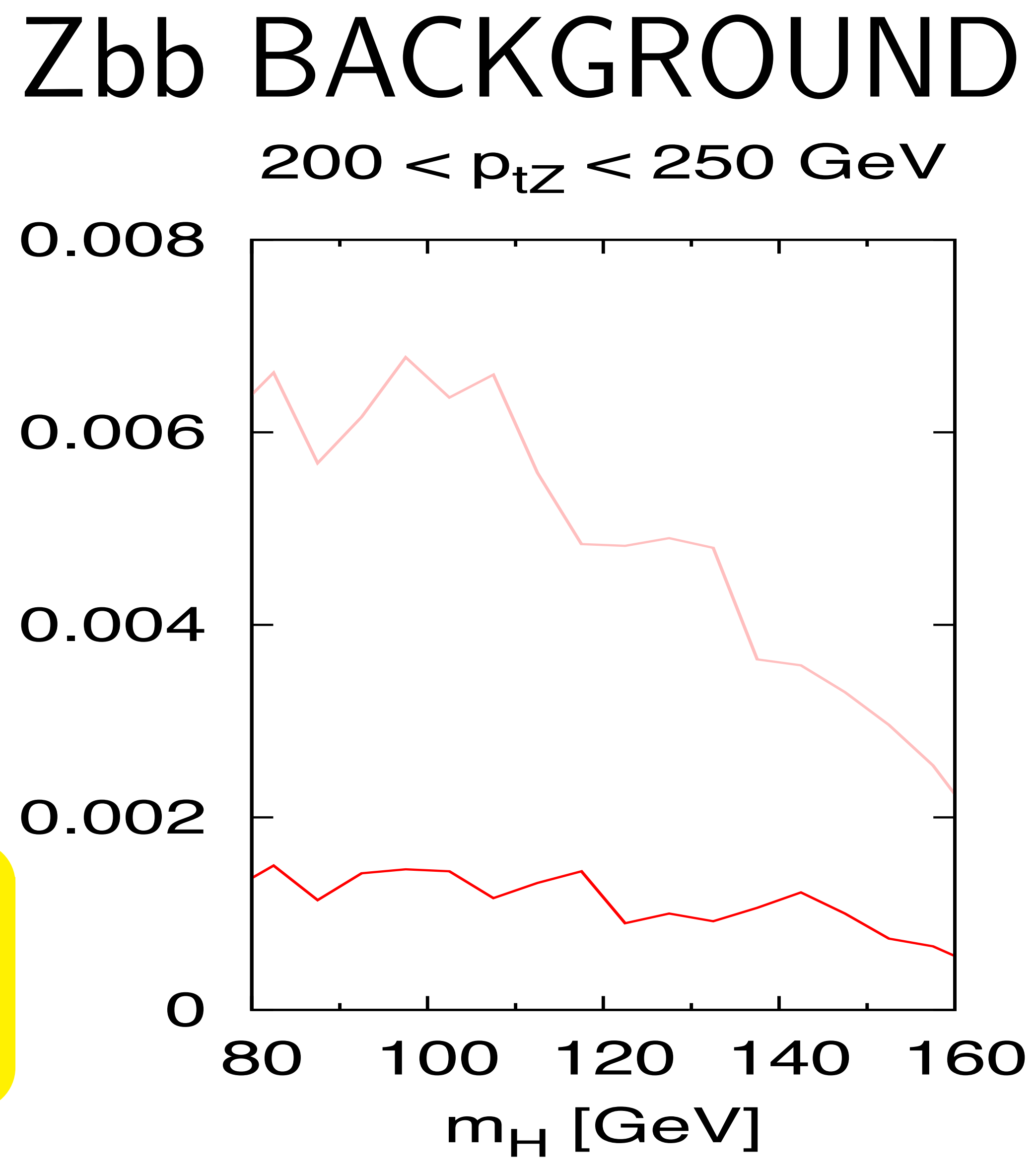
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







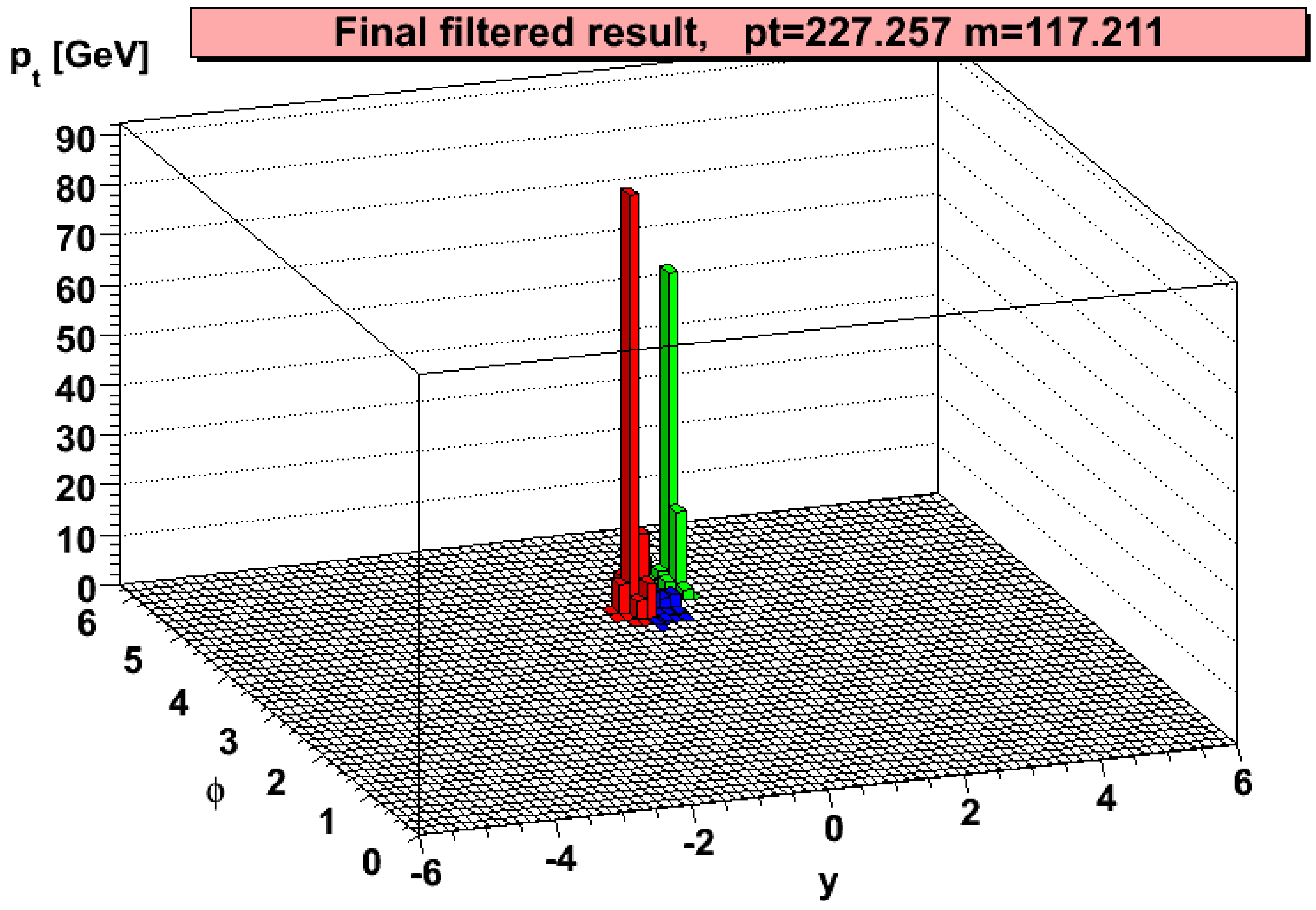
$R_{filt} = 0.3 \;\; [= \min(\Delta R/2, 0.3)]$

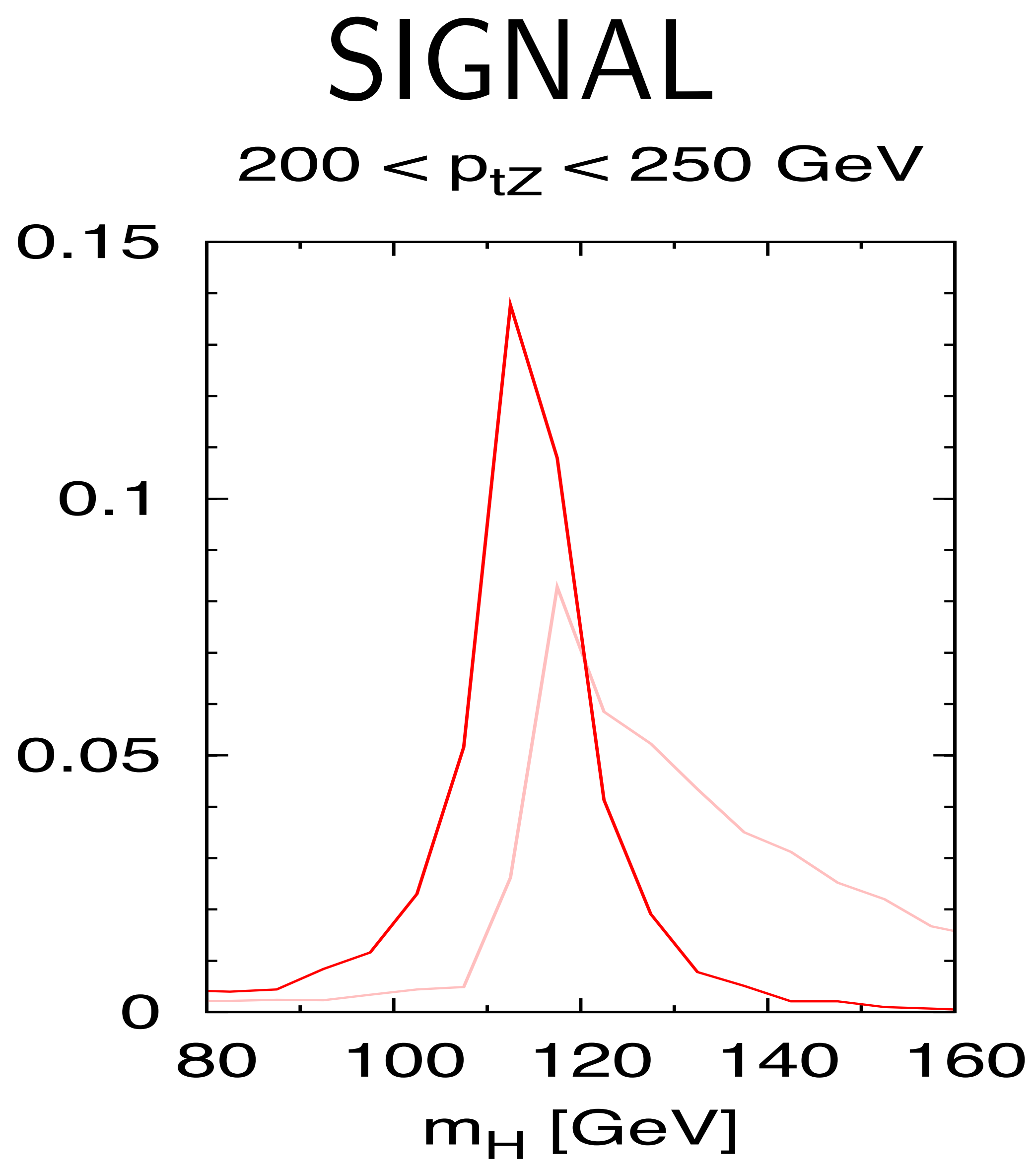
Butterworth, Davison, Rubin & GPS '08

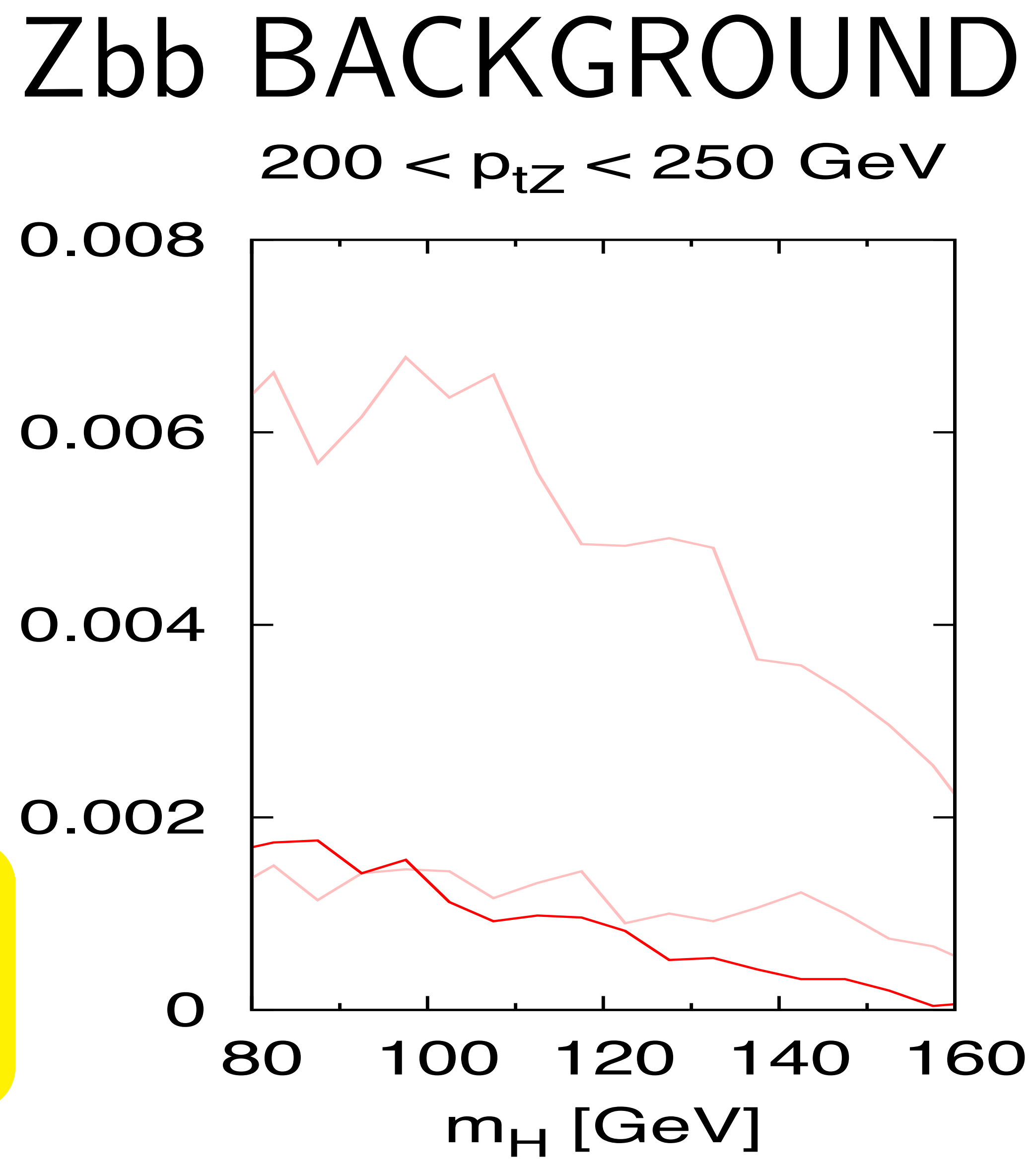
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







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

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.