Introduction to Jet Finding and Jetography (2)

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2011 IPMU-YITP School and Workshop
on Monte Carlo Tools for LHC

Yukawa Institute for Theoretical Physics, Kyoto University, Japan
September 2011

A full set of IRC-safe jet algorithms

Generalise inclusive-type sequential recombination with

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

	Alg. name	Comment	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Hierarchical in rel. k_t	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple R at once $\leftrightarrow$ QCD angular ordering	$N \ln N$
$p = -1$	anti-k_t Cacciari, GPS, Soyez '08 $\sim$ reverse-k_t Delsart	Hierarchy meaningless, jets like CMS cone (IC-PR)	$N^{3/2}$
SC-SM	SISCone GPS Soyez '07 + Tevatron run II '00	Replaces JetClu, ATLAS MidPoint (xC-SM) cones	$N^2 \ln N$ exp.

Compromise between having a limited set of algs.
and a good range of complementary properties

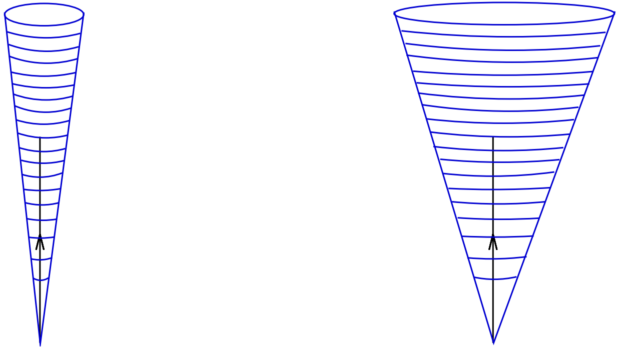
Towards an understanding of jets

How a jet is and isn't like a parton — quantitatively

And how this relationship is affected by the jet radius

Small v. large jet radius (R) $\equiv$ HSBC

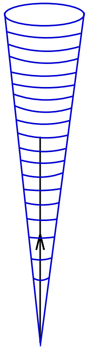
Small jet radius **Large jet radius**



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

Small v. large jet radius (R) ≡ HSBC

Small jet radius **Large jet radius**



single pa

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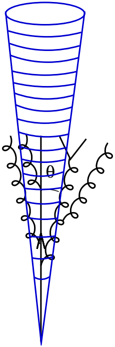
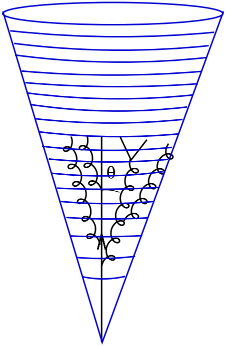


Large jet radius



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

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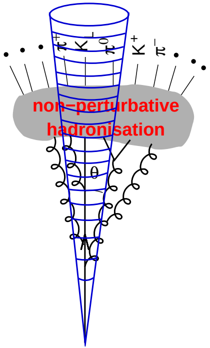
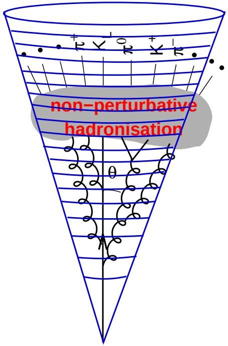
Small jet radius



Large jet radius

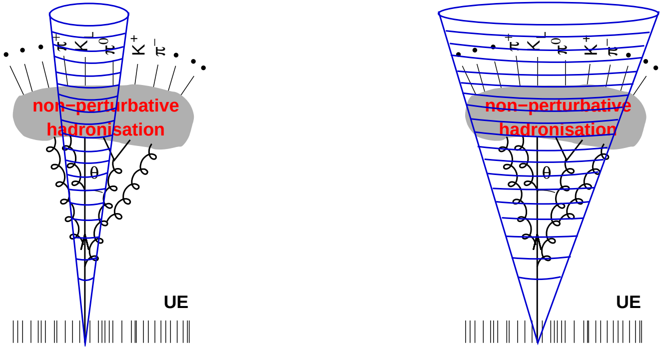


non-perturbative fragmentation: **large jet radius better**

(it captures more)

Small v. large jet radius (R) $\equiv$ HSBC

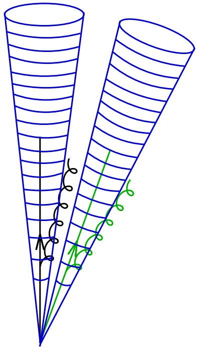
Small jet radius **Large jet radius**



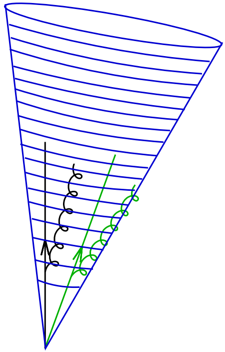
underlying ev. & pileup "noise": **small jet radius better**
(it captures less)

Small v. large jet radius (R) $\equiv$ HSBC

Small jet radius



Large jet radius



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

Parton p_t v. jet p_t

3 physical effects:

1. Gluon radiation from the parton
2. Hadronisation
3. Underlying Event

One important consideration:

Whether the parton is a quark or a gluon
[quarks radiate with colour factor $C_F = 4/3$
gluons radiate with colour factor $C_A = 3$]

Jet p_t v. parton p_t: perturbatively?

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

Jet p_t v. parton p_t: hadronisation?

Hadronisation: the "parton-shower" → hadrons transition

Method:

- "infrared finite α_s" — à la Dokshitzer & Webber '95
- **prediction** based on e^+e^- event shape data
- could have been deduced from old work — Korchemsky & Sterman '95, Seymour '97

Main result

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

cf. Dasgupta, Magnea & GPS '07

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

Underlying Event (UE)

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

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

Modern Monte Carlo tunes tell you ($\sqrt{s} = 7$ TeV):

$$\Delta p_t \simeq \mathbf{8\ GeV} \times \frac{R^2}{2} \simeq 1.2 \text{ GeV} \times (\pi R^2)$$

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?

cf. Cacciari, GPS & Soyez '08

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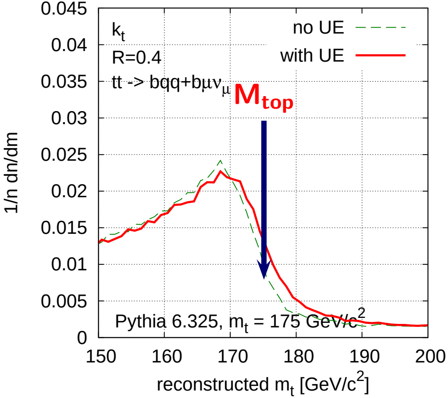
A qualitative example: top reconstruction

Robustness: M_{top} varies with R?



Game: measure top mass to 1 GeV

example for Tevatron

$m_t = 175$ GeV

- Small R: lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant
- Large R: hadronisation and PT radiation leave mass at ~ 175 GeV, UE adds $2-4$ GeV.

Is the final top mass (after W, jet-energy-scale and Monte Carlo unfolding) independent of R used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects

cf. Seymour & Tevlin '06

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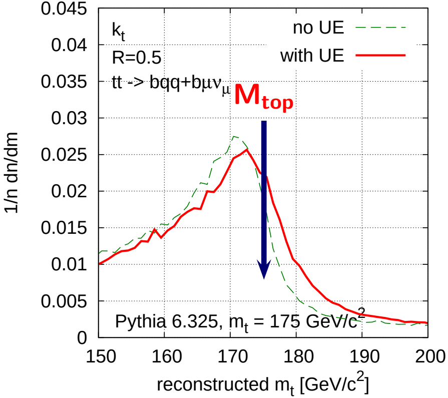

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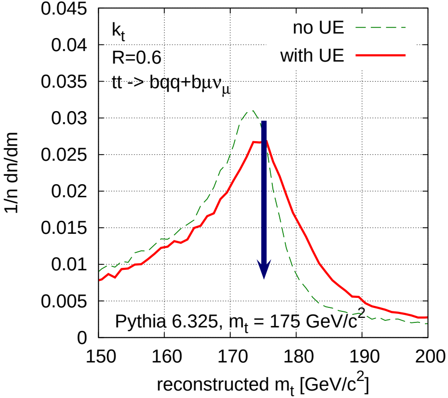

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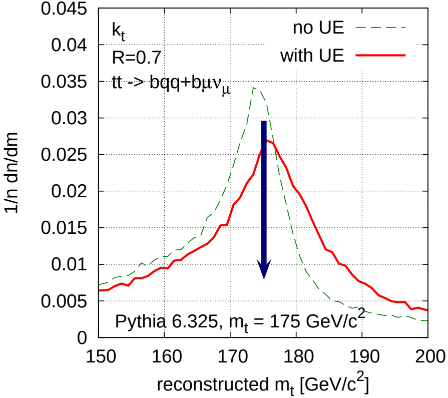

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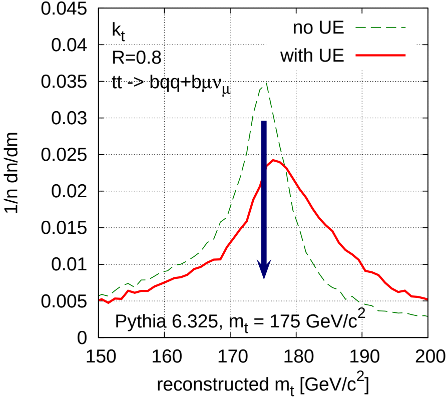

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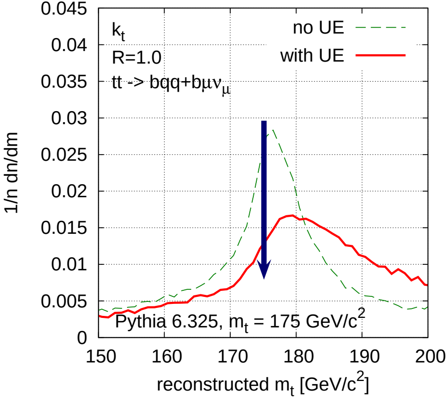

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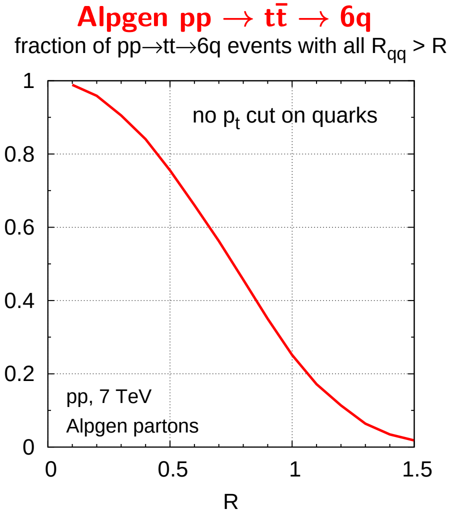
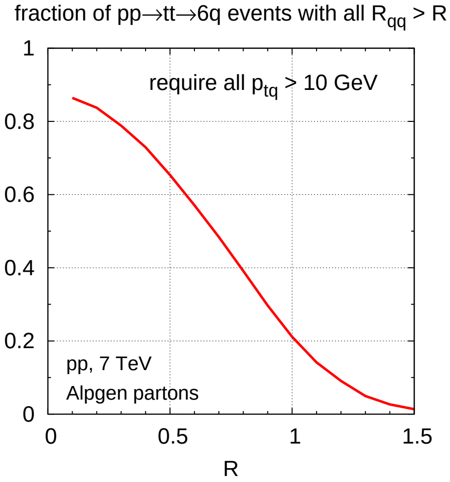
6 partons v. 6 jets?



6 partons v. 6 jets?

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



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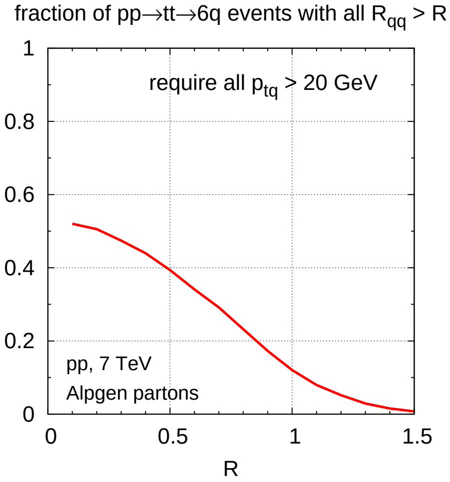

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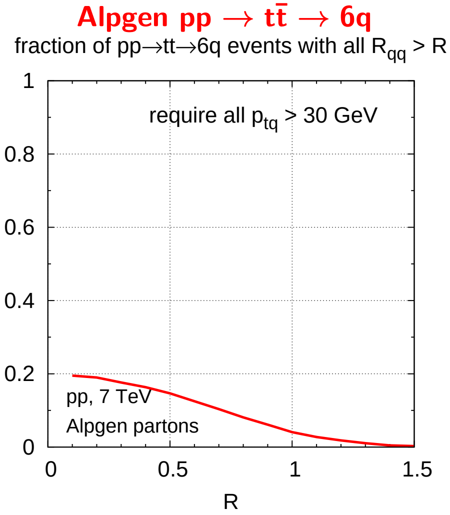

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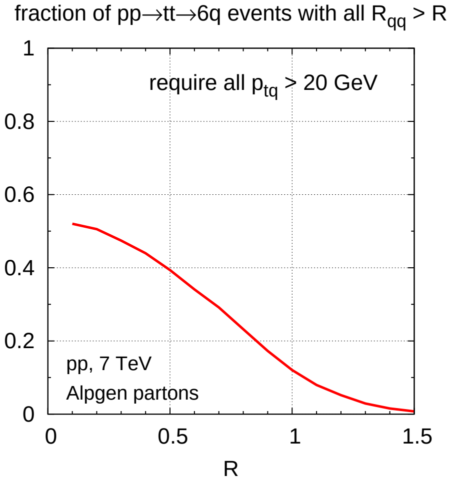
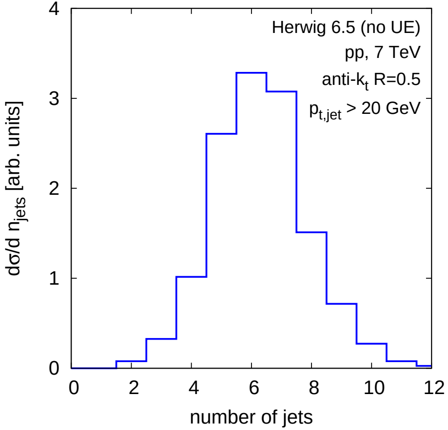


Herwig pp → $t\bar{t}$ → hadrons

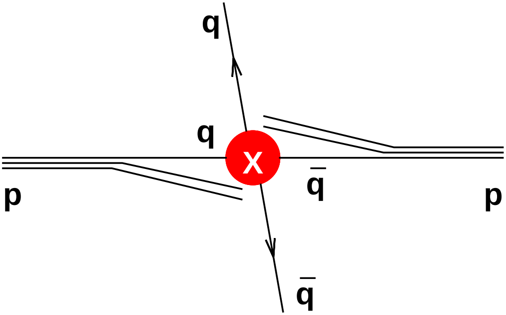
Distribution of number of jets



Using our understanding to help discover a dijet resonance, $q\bar{q} \to X \to q\bar{q}$.

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

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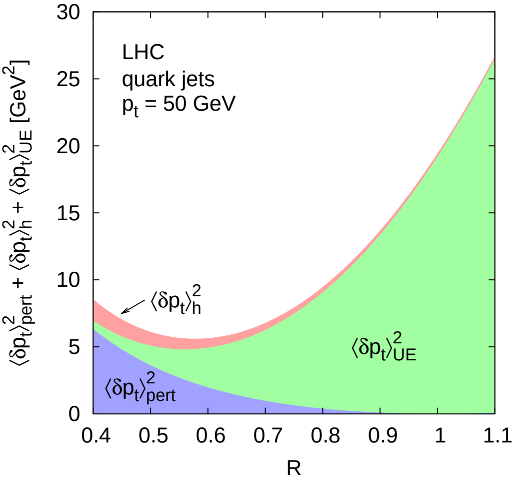
50 GeV quark jet



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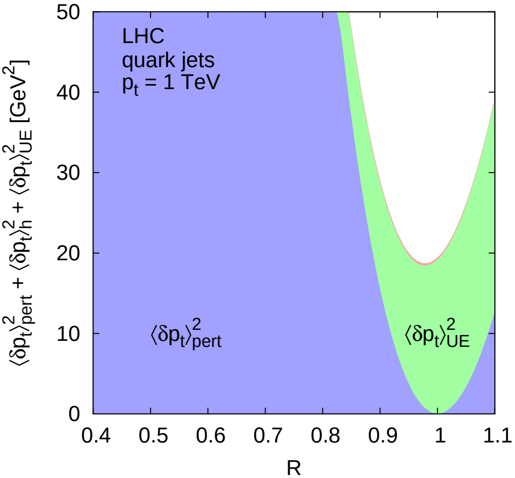
1 TeV quark jet



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What R is best for an isolated jet?

PT radiation:

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Hadr

$q:$

At low p_t, small R limits relative impact of UE

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

Underlying event:

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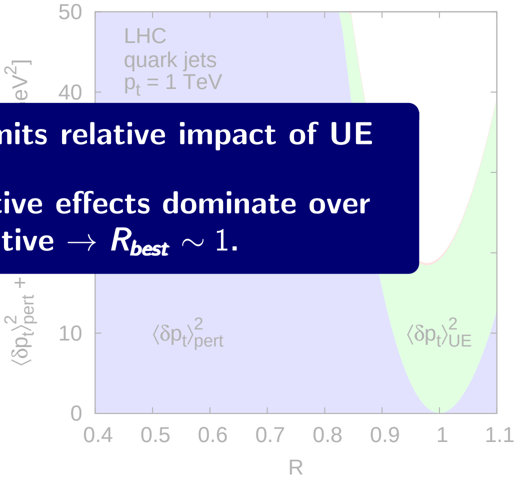

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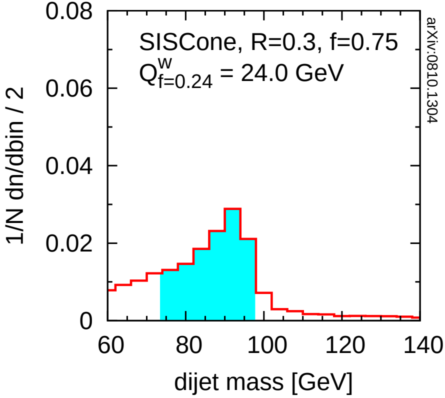
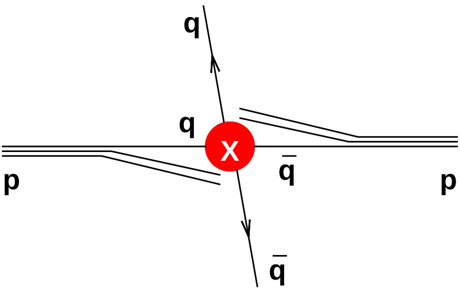
Dijet mass: scan over R [Pythia 6.4]

R = 0.3

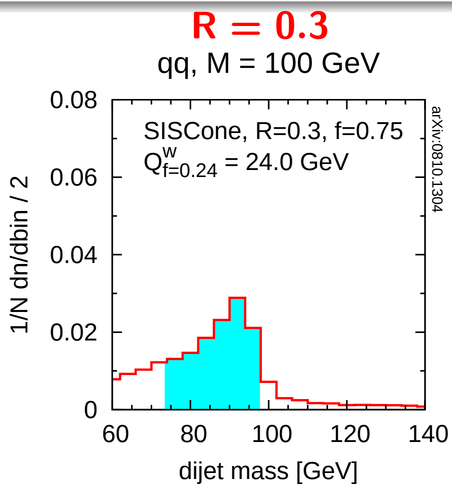
qq, M = 100 GeV

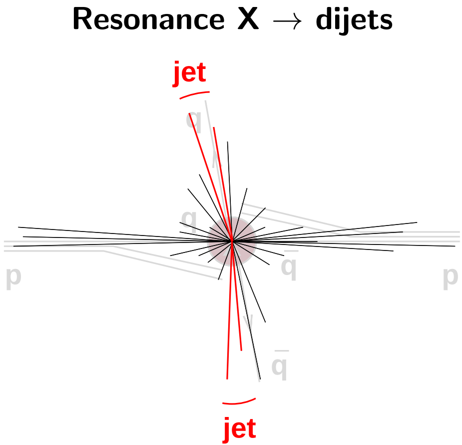


Resonance X → dijets



Dijet mass: scan over *R* [Pythia 6.4]





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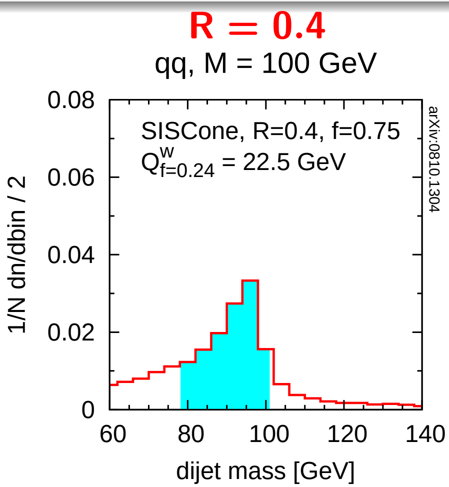

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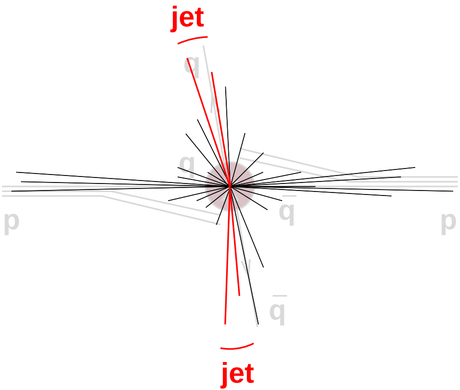
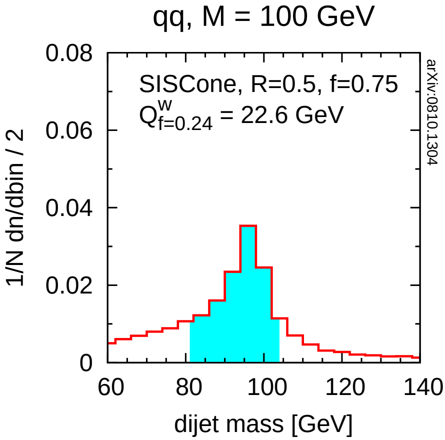


Dijet mass: scan over *R* [Pythia 6.4]

R = 0.5



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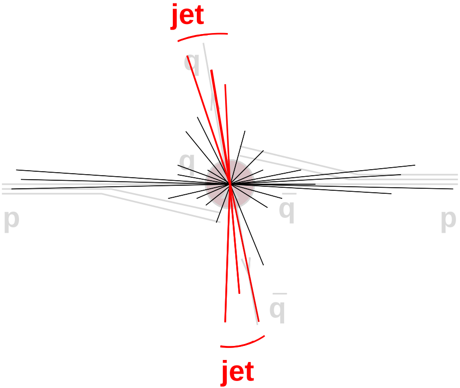
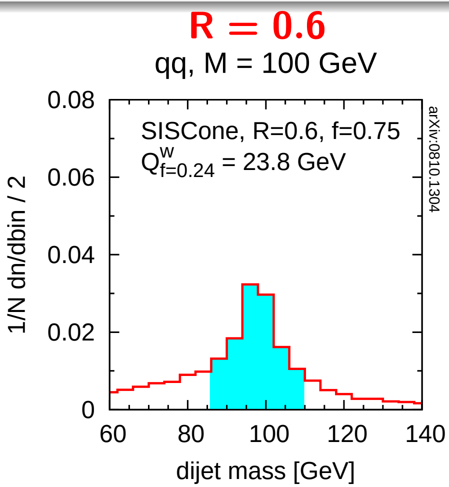
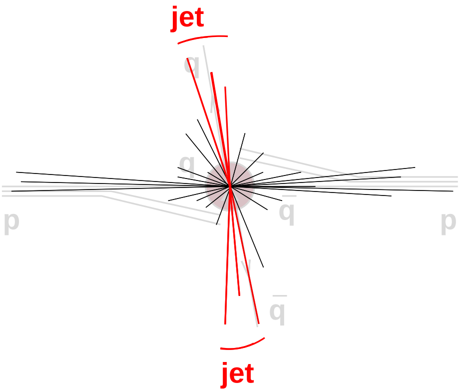


Dijet mass: scan over R [Pythia 6.4]



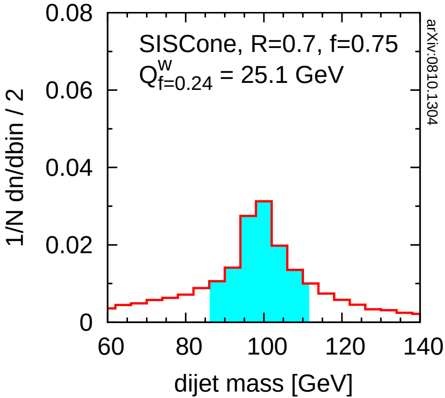
Resonance X → dijets



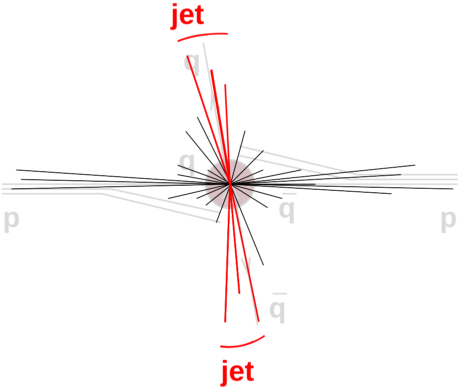
Dijet mass: scan over *R* [Pythia 6.4]

R = 0.7

qq, M = 100 GeV



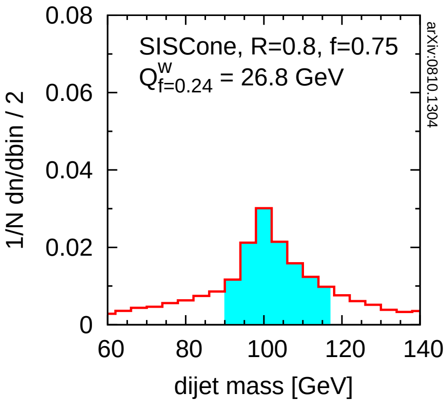
Resonance X → dijets



Dijet mass: scan over *R* [Pythia 6.4]

R = 0.8

qq, M = 100 GeV



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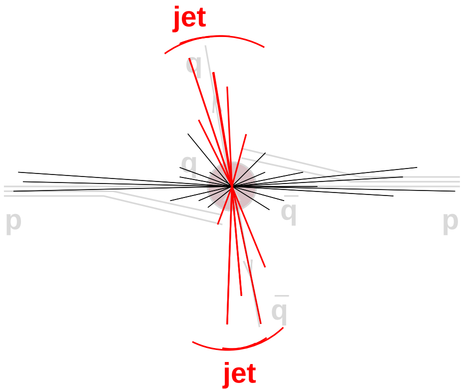

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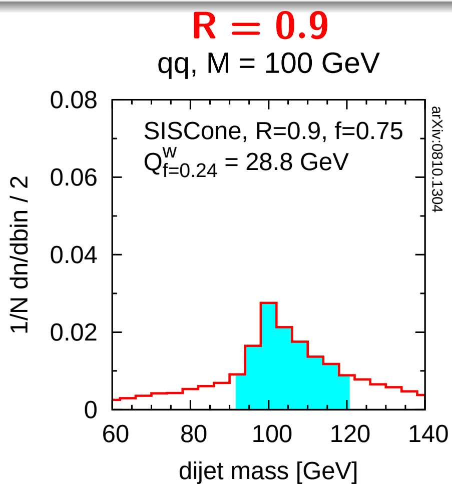
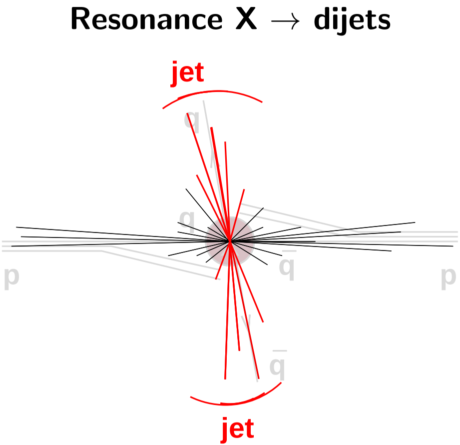
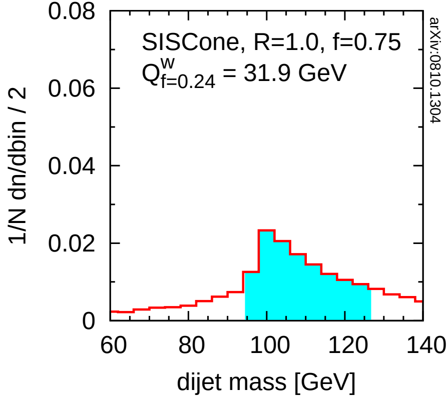




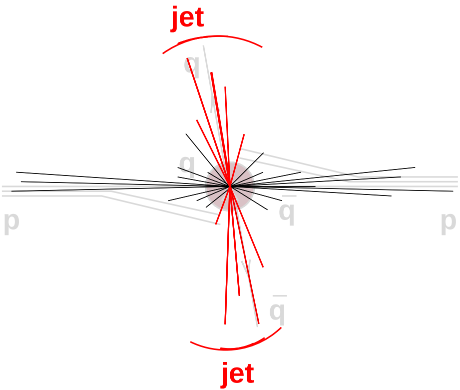
Dijet mass: scan over *R* [Pythia 6.4]

R = 1.0

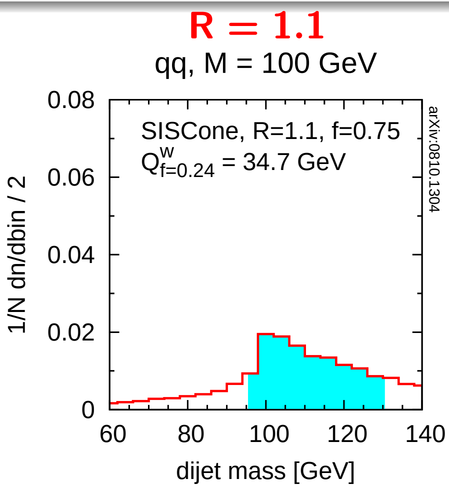
qq, M = 100 GeV

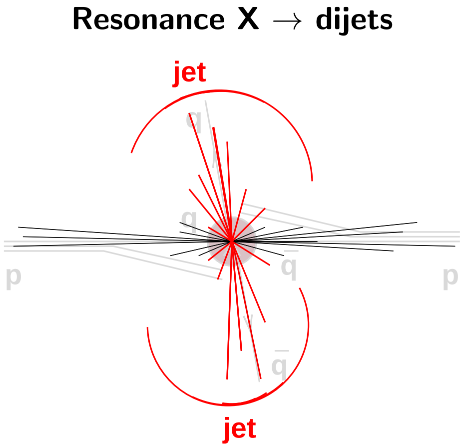


Resonance X → dijets

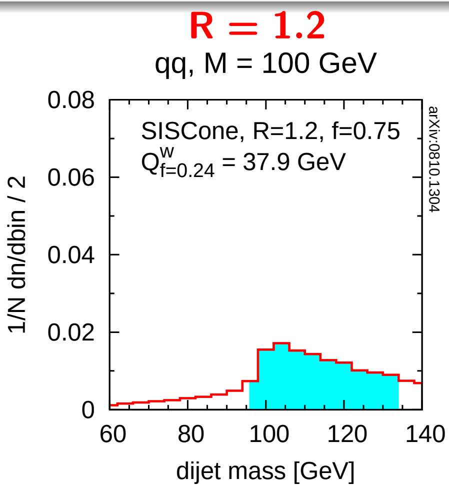


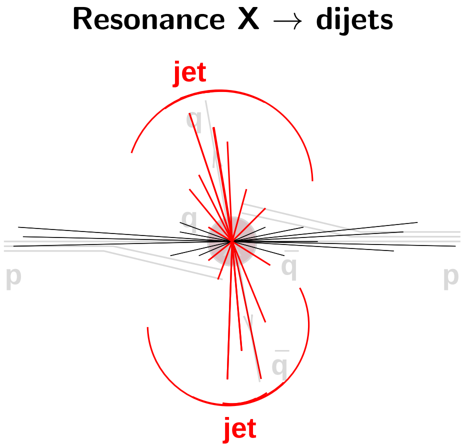
Dijet mass: scan over *R* [Pythia 6.4]





Dijet mass: scan over *R* [Pythia 6.4]

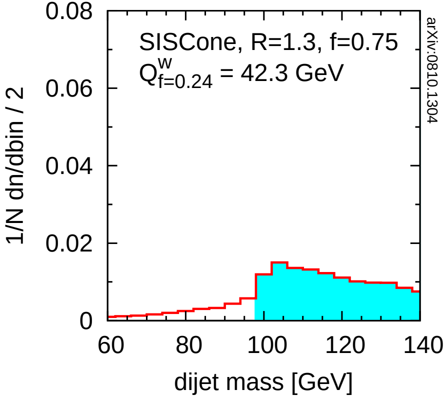




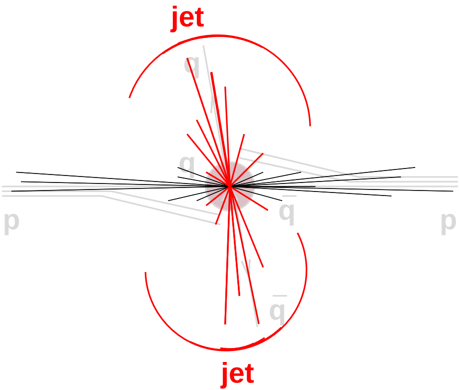
Dijet mass: scan over *R* [Pythia 6.4]

R = 1.3

qq, M = 100 GeV

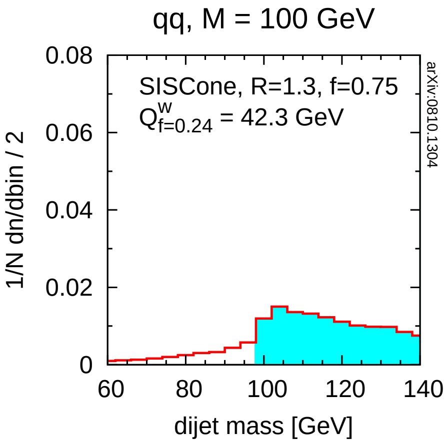


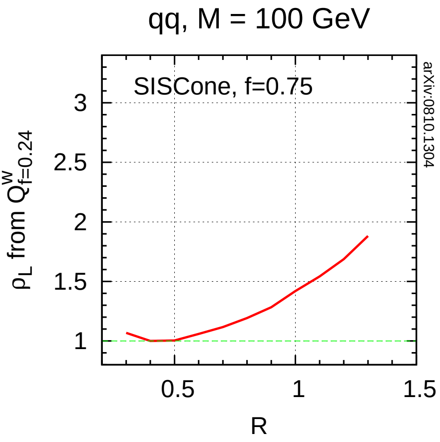
Resonance X → dijets



Dijet mass: scan over R [Pythia 6.4]

R = 1.3



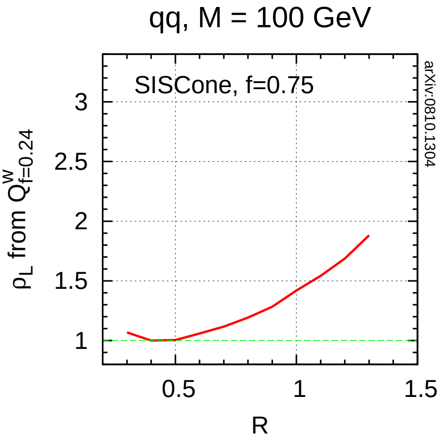


After scanning, summarise "quality" v. R. Minimum $\equiv$ BEST

picture not so different from crude analytical estimate

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

m_{qq} = 100 GeV



Best R is at minimum of curve

- Best R depends strongly on mass of system
- Increases with mass

can reproduce this anayltically Soyez '10

Message received by CMS: they combine all $R = 0.5$ jets ($p_t >$ 10 GeV) within $\Delta R = 1.1$ of two hardest to improve resolution.

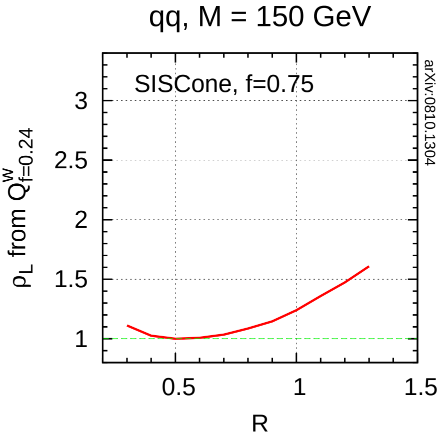
ATLAS '11 still just use $R = 0.6$

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

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

$\mathbf{m_{qq} = 150\ GeV}$



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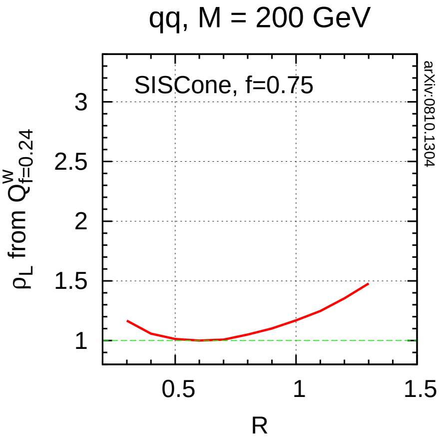
Scan through $q\bar{q}$ mass values

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



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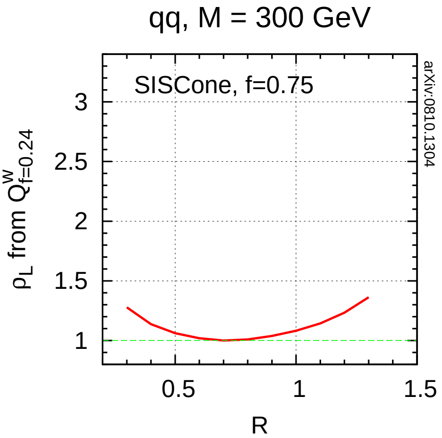
Other related work: Krohn, Thaler & Wang '09

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

$m_{qq} = 300$ GeV



Best R is at minimum of curve

- Best R depends strongly on mass of system
- Increases with mass

can reproduce this anayltically

Soyez '10

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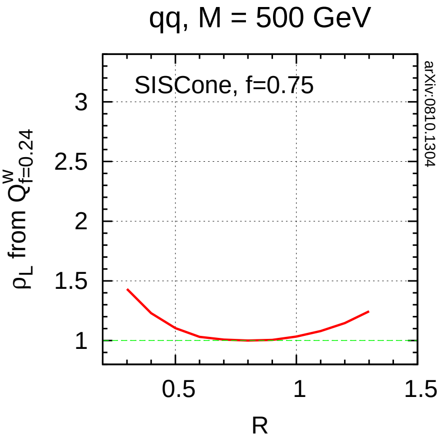
Other related work: Krohn, Thaler & Wang '09

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

$m_{qq} = 500$ GeV



Best R is at minimum of curve

- Best R depends strongly on mass of system
- Increases with mass

can reproduce this anayltically

Soyez '10

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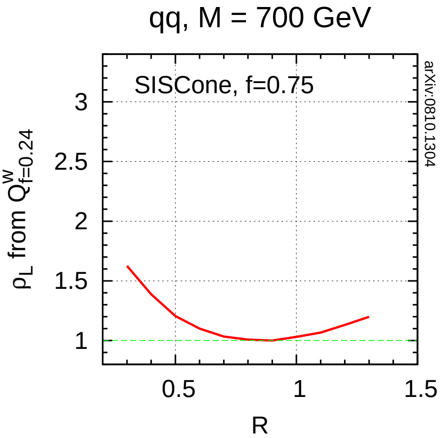
Other related work: Krohn, Thaler & Wang '09

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

$m_{qq} = 700$ GeV



Best R is at minimum of curve

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- Increases with mass

can reproduce this anayltically
Soyez '10

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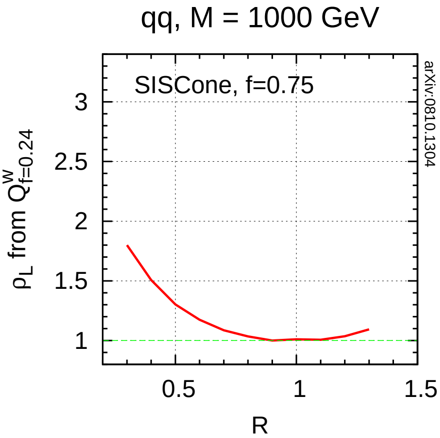
Other related work: Krohn, Thaler & Wang '09

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

m_{qq} = 1000 GeV



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- Increases with mass

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Soyez '10

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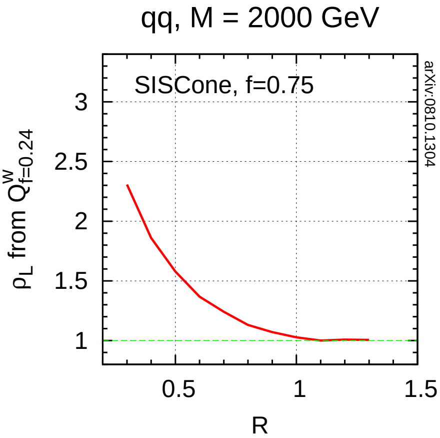
Scan through $q\bar{q}$ mass values

$m_{qq} = 2000$ GeV



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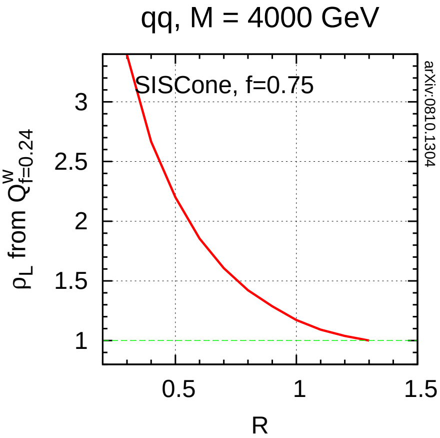
Other related work: Krohn, Thaler & Wang '09

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

m_{qq} = 4000 GeV



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Soyez '10

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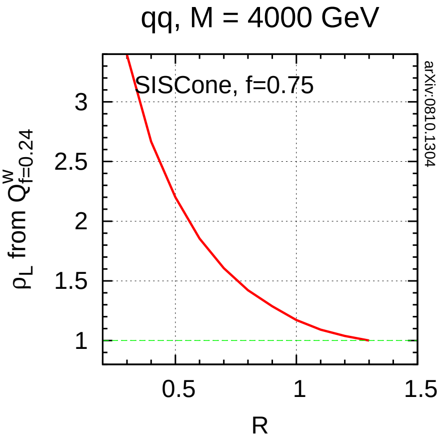
Other related work: Krohn, Thaler & Wang '09

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

m_{qq} = 4000 GeV



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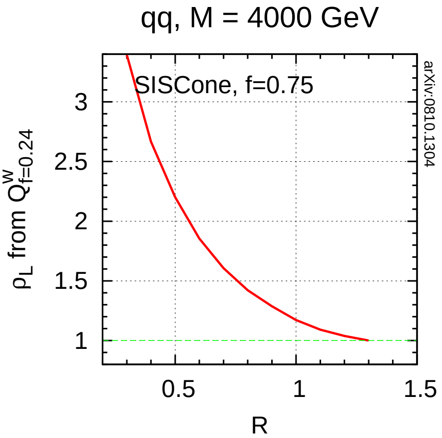
Scan through $q\bar{q}$ mass values

$m_{qq} = 4000$ GeV



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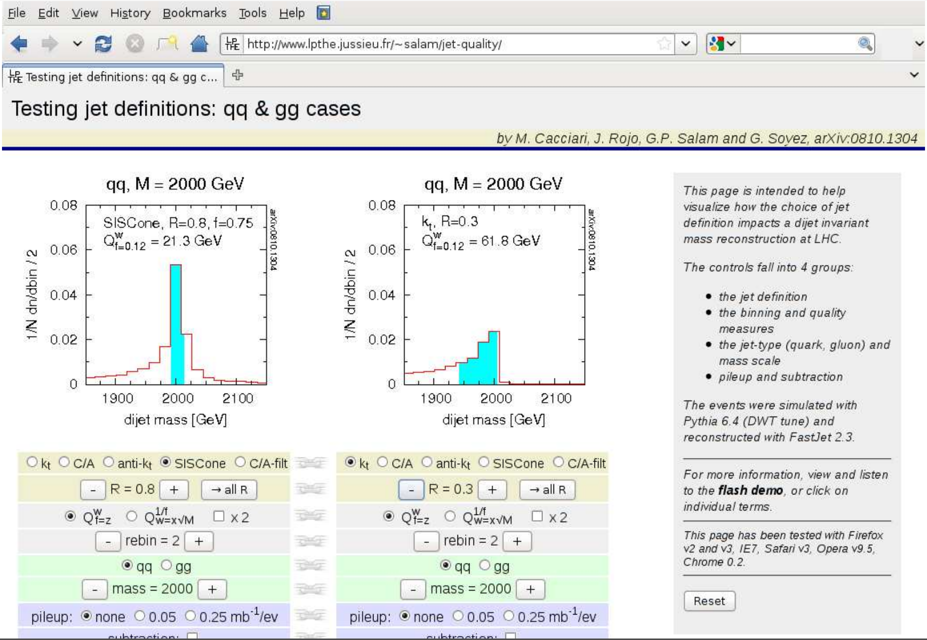

File Edit View History Bookmarks Tools Help
http://www.lpthe.jussieu.fr/~salam/jet-quality/
Testing jet definitions: qq & gg c...
Testing jet definitions: qq & gg cases
by M. Cacciari, J. Rojo, G.P. Salam and G. Soyez, arXiv:0810.1304
qq, M = 2000 GeV
SISCone, R=0.8, f=0.75
Q^W_{f=0.12} = 21.3 GeV
qq, M = 2000 GeV
k_t, R=0.3
Q^W_{f=0.12} = 61.8 GeV
1/N dn/dbin / 2
dijet mass [GeV]
arXiv:0810.1304
kt C/A anti-kt SISCone C/A-filt
R = 0.8 → all R
R = 0.3 → all R
x 2
rebin = 2
qq gg
mass = 2000
pileup: none 0.05 0.25 mb^-1/ev
This page is intended to help visualize how the choice of jet definition impacts a dijet invariant mass reconstruction at LHC.
The controls fall into 4 groups:
the jet definition
the binning and quality measures
the jet-type (quark, gluon) and mass scale
pileup and subtraction
The events were simulated with Pythia 6.4 (DWT tune) and reconstructed with FastJet 2.3.
For more information, view and listen to the flash demo, or click on individual terms.
This page has been tested with Firefox v2 and v3, IE7, Safari v3, Opera v9.5, Chrome 0.2.
Reset

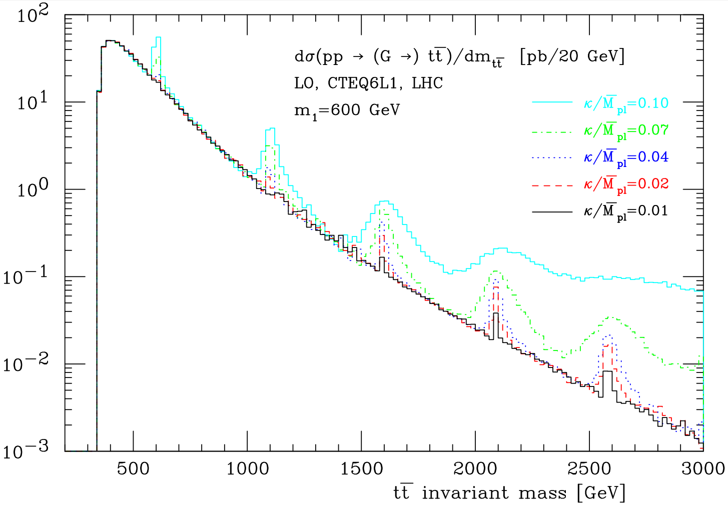
Fat jets

boosted massive hadronically decaying objects

E.g. when a known particle, W, Z or a top $\rightarrow$ a single jet
or a new particle, Higgs, gluino, neutralino $\rightarrow$ a single jet

This will be common for electroweak-scale objects at LHC:
$m_W, m_t \ll 14$ TeV

E.g. $X \to t\bar{t}$ resonances of varying difficulty

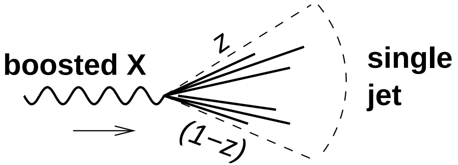


RS KK resonances $\to t\bar{t}$, from Frederix & Maltoni, 0712.2355

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

Boosted massive particles, e.g.: EW bosons

Hadronically decaying EW boson at high p_t $\neq$ two jets

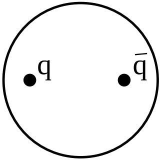


$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

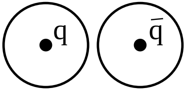
Rules of thumb: $m = 100$ GeV, $p_t = 500$ GeV

- $R < \dfrac{2m}{p_t}$: always resolve **two** jets $R < 0.4$
- $R \gtrsim \dfrac{3m}{p_t}$: resolve **one** jet in ~75% of cases ($\frac{1}{8} < z < \frac{7}{8}$) $R \gtrsim 0.6$

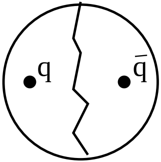
Boosted ID strategies



Select on the jet mass with one large (cone) jet
Can be subject to large bkgds
[high-p_t jets have significant masses]

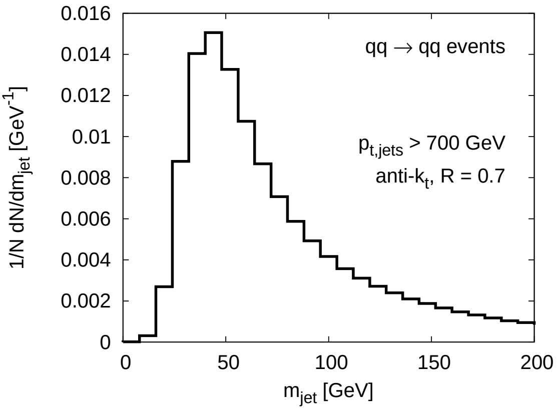


Choose a small jet size (R) so as to resolve two jets
Easier to reject background
if you actually see substructure
[NB: must manually put in "right" radius]



Take a large jet and split it in two
Let jet algorithm establish correct division

Jet masses



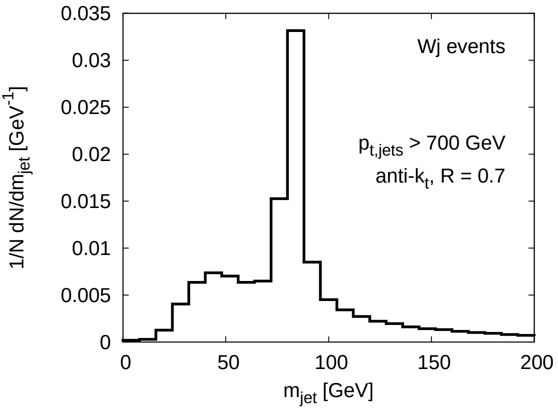
Look at jet mass distribution for two leading jets in

- $qq \to qq$ events
- $pp \to W +$ jet events
- a mixture of the two

In roughly sensible proportions

Jet mass gives clear sign of massive particles inside the jet;

Jet masses



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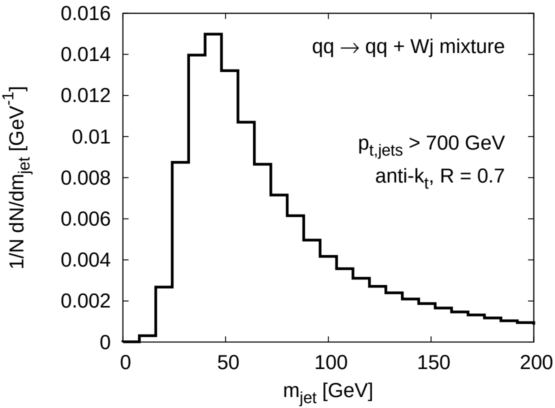


Look at jet mass distribution for two leading jets in

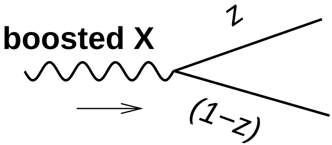
- $qq \to qq$ events
- $pp \to W +$ jet events
- a mixture of the two

In roughly sensible proportions

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

QCD principle: soft divergence

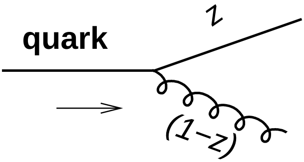
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

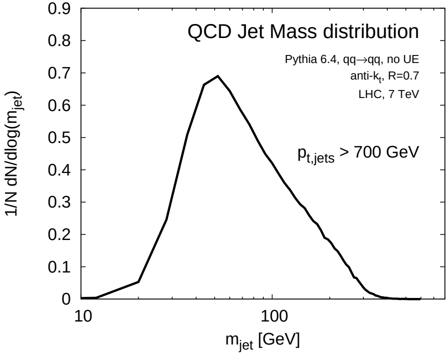
$$P(z) \propto \frac{1+z^2}{1-z}$$

$1/(1-z)$ divergence enhances background

Remove divergence in bkdg with cut on z
Can choose cut analytically so as to maximise $S/\sqrt{B}$

Originally: cut on (related) k_t-distance
Butterworth, Cox & Forshaw '02

Inside the jet mass



QCD jet mass distribution has the approximate

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

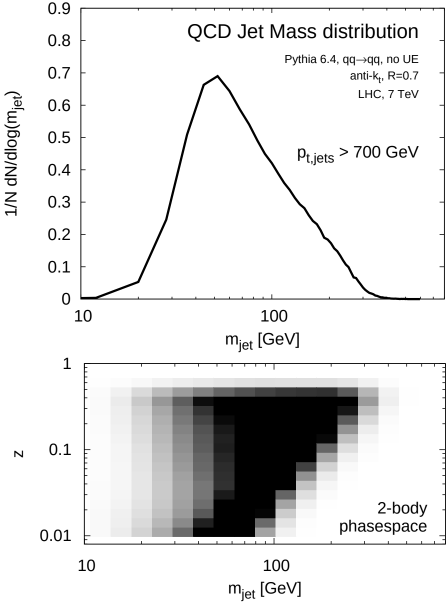
Work from '80s and '90s
+ Almeida et al '08

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



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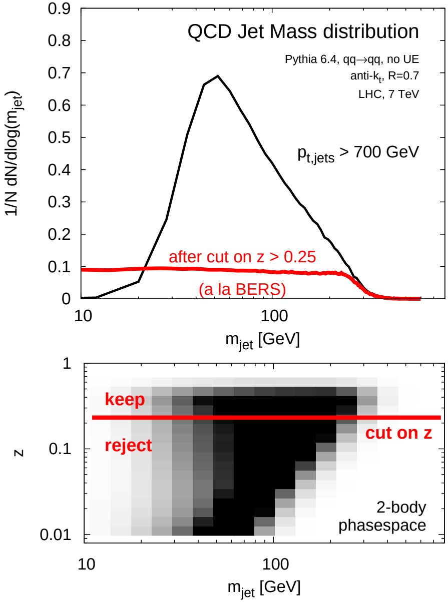

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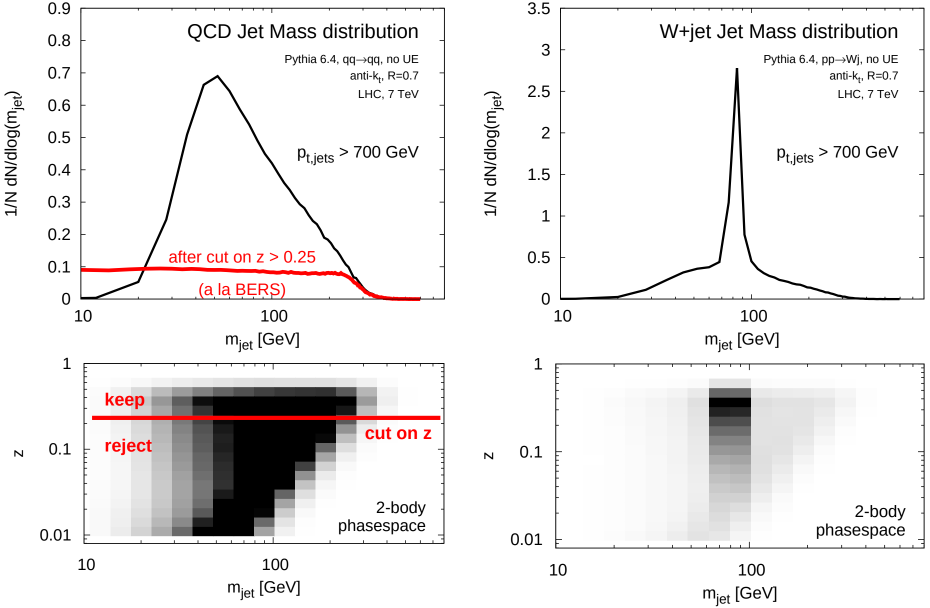
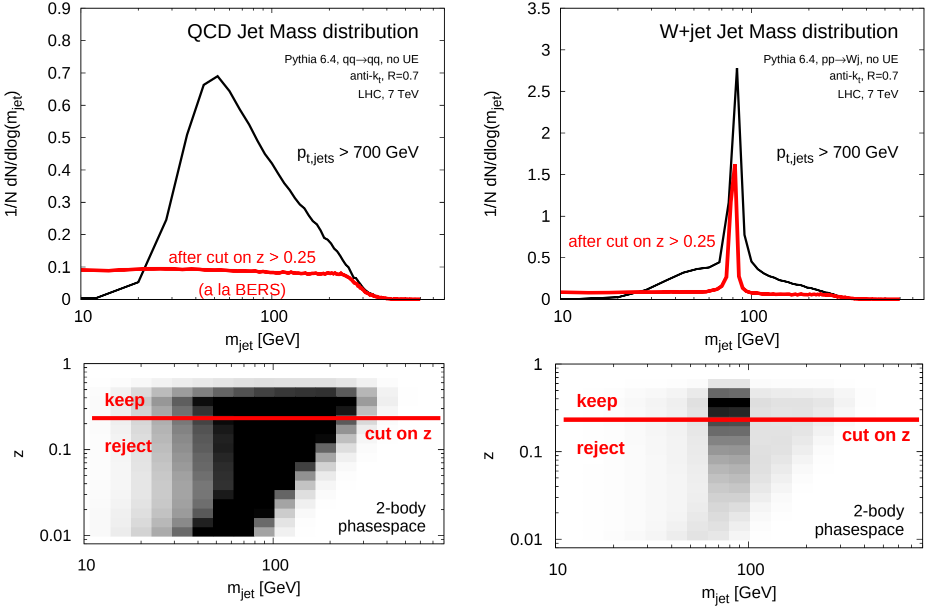
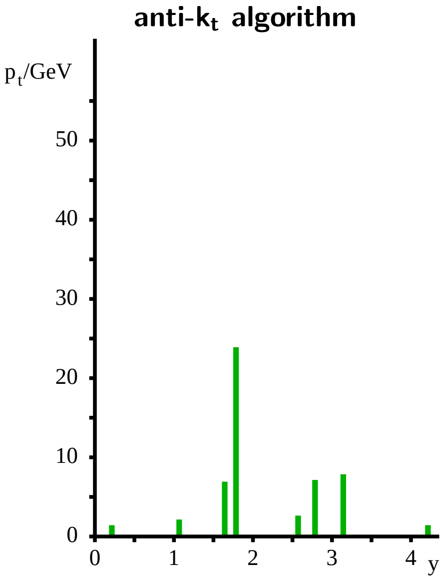
Inside the jet mass



Inside the jet mass



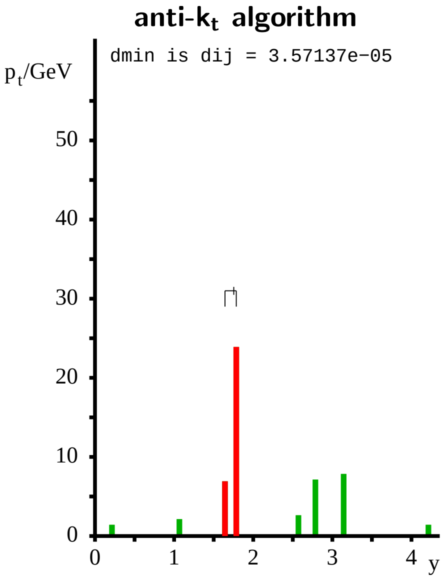
Identifying jet substructure: try out anti-k_t



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 jet (e.g. z).

Identifying jet substructure: try out anti-k_t



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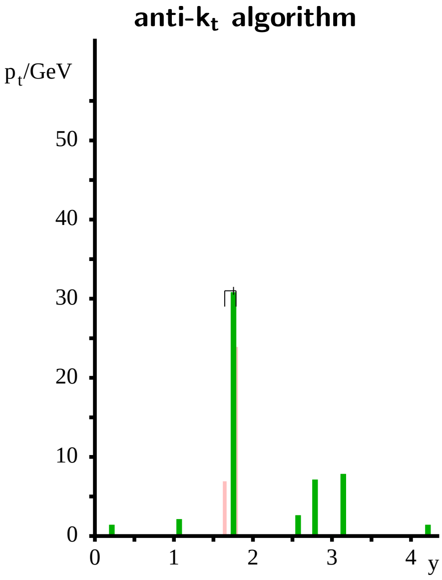

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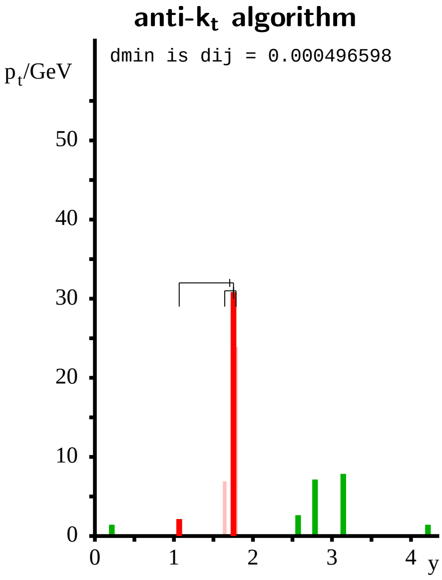

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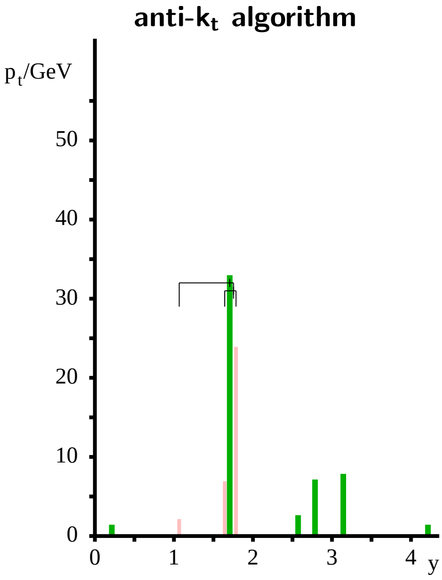

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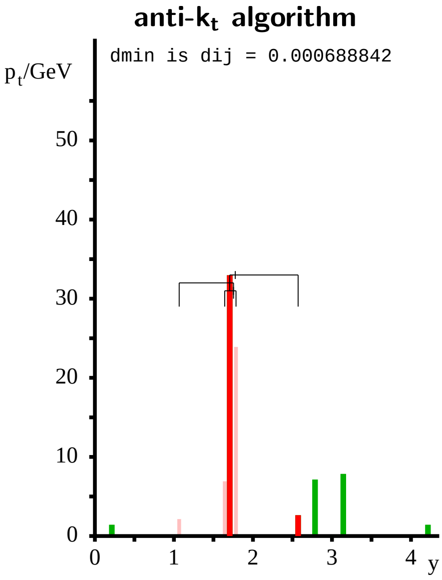

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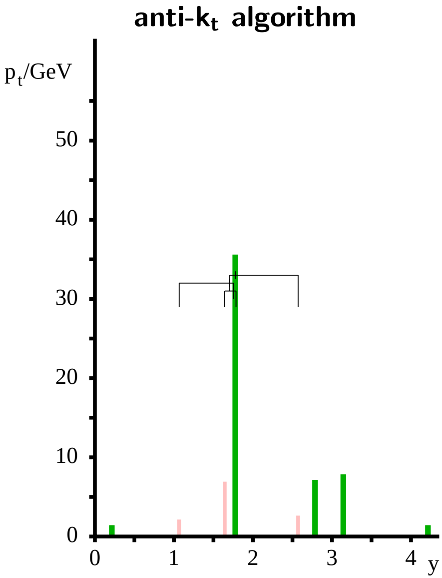

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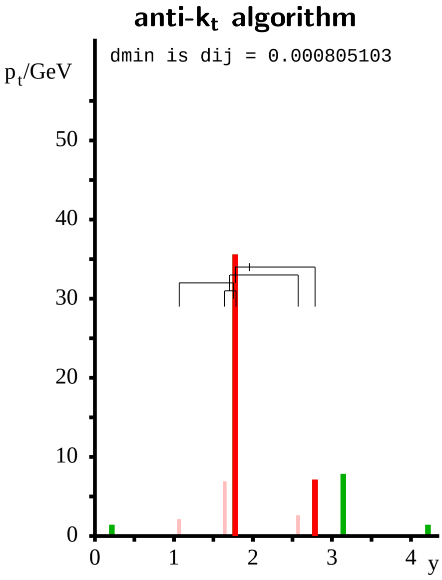

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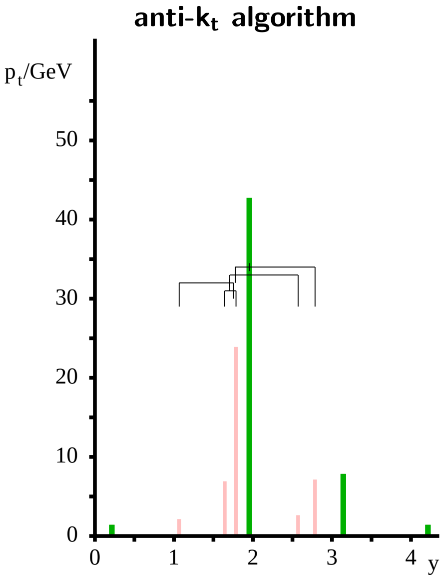

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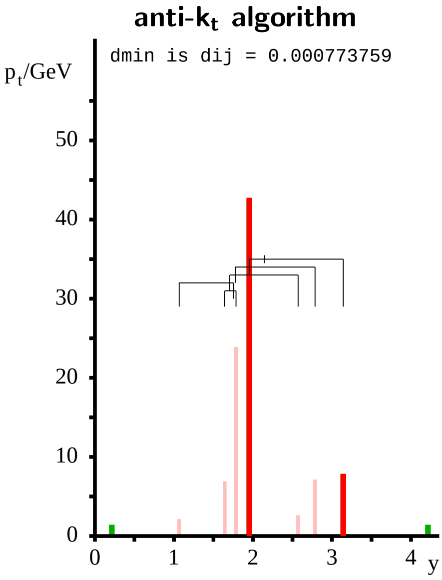

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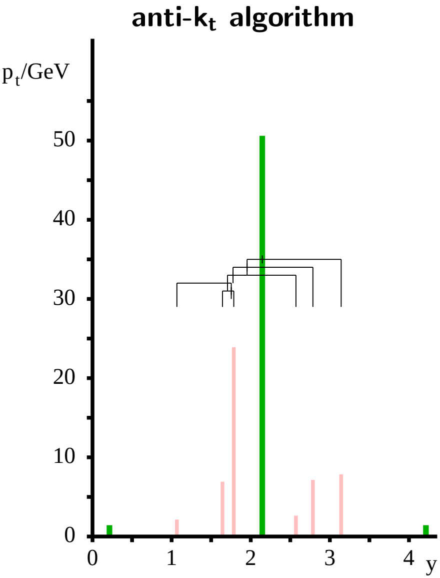

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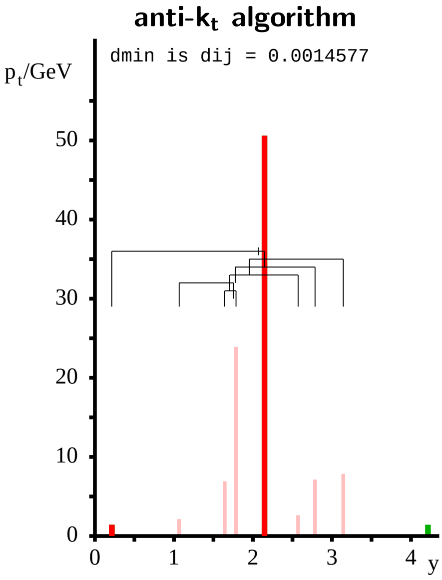

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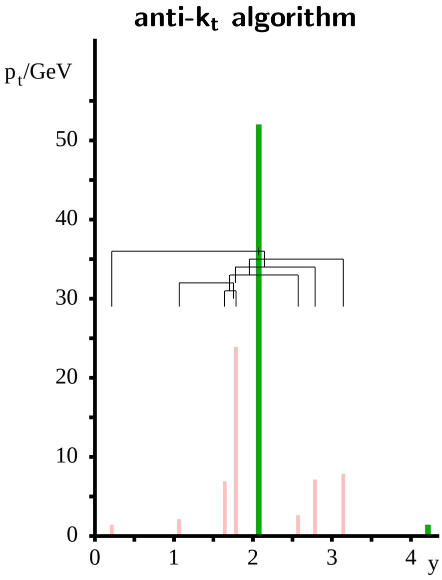

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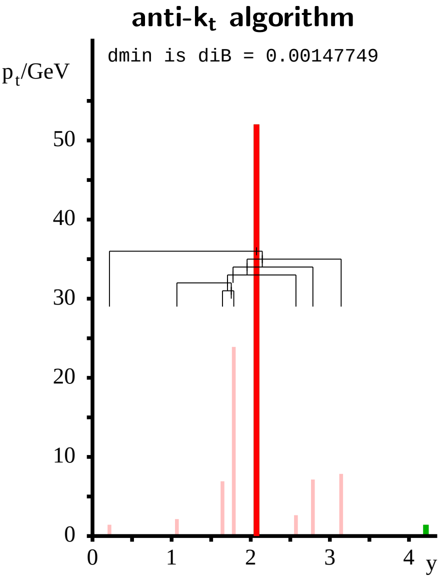

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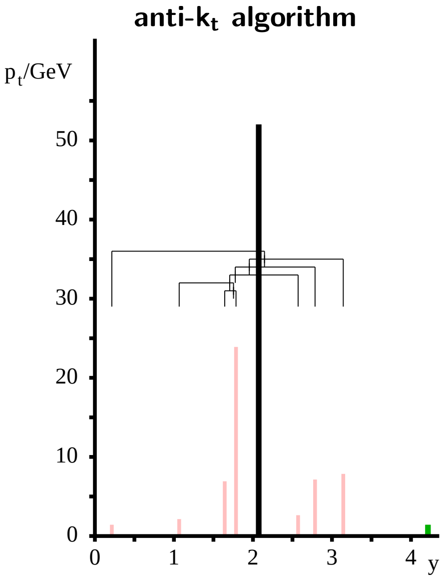

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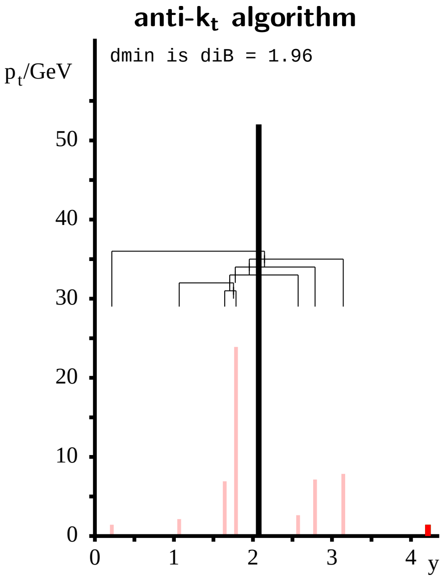

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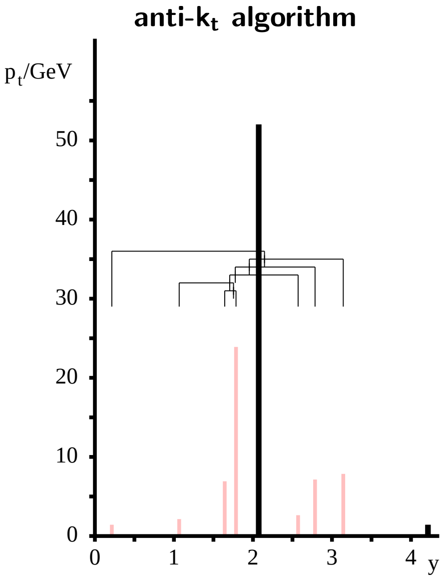

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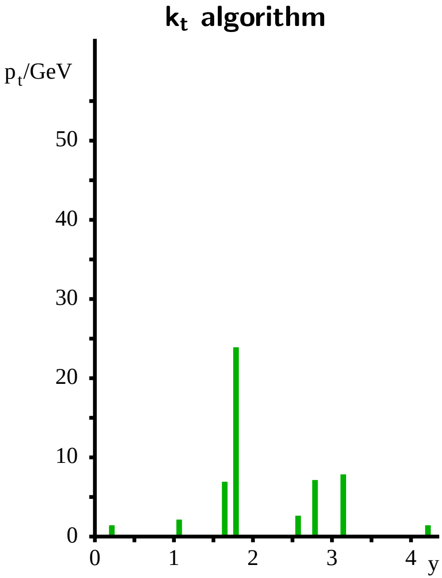

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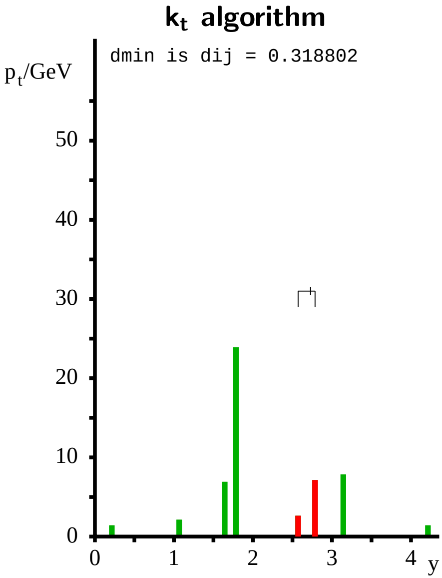

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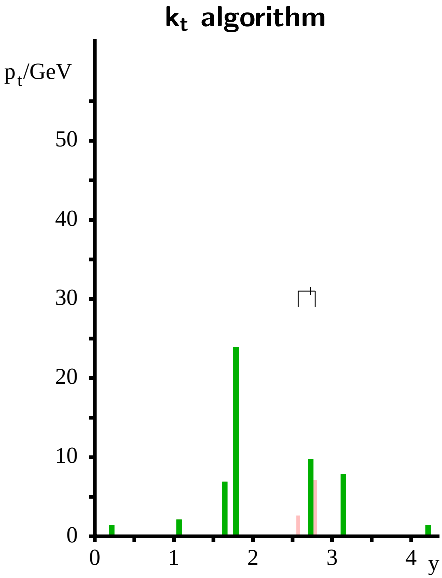

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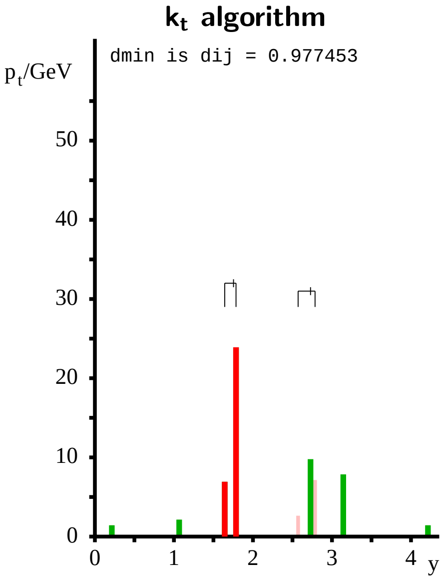

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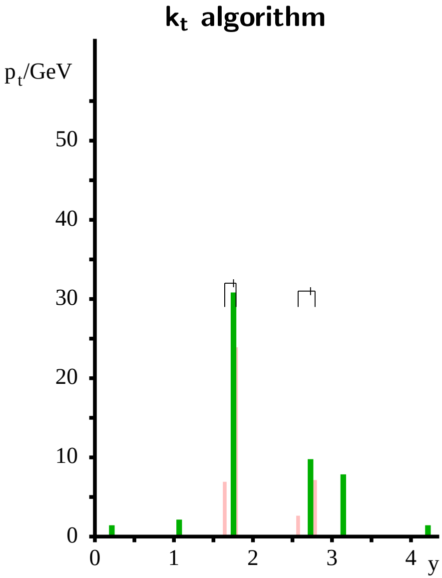

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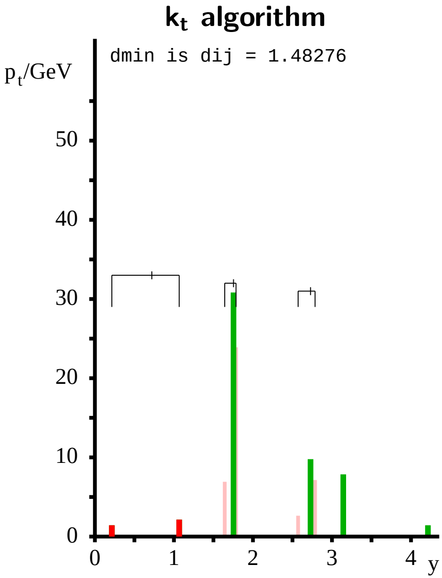

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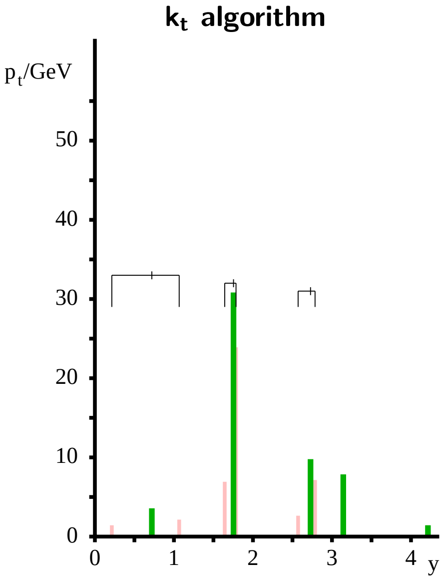

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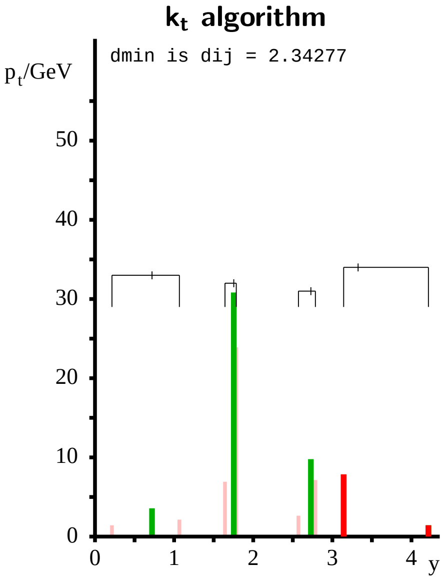

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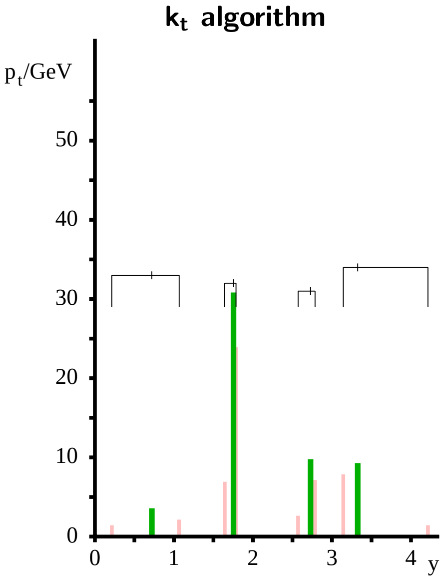

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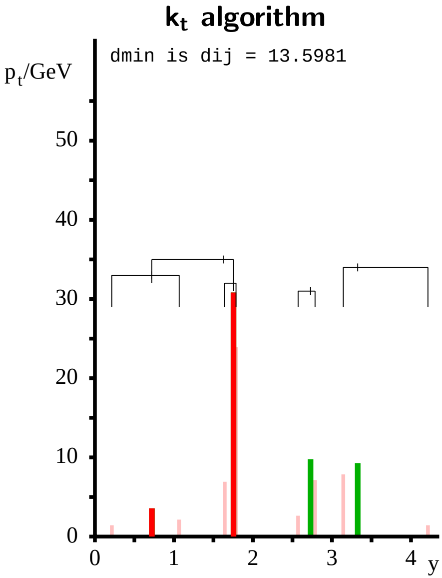

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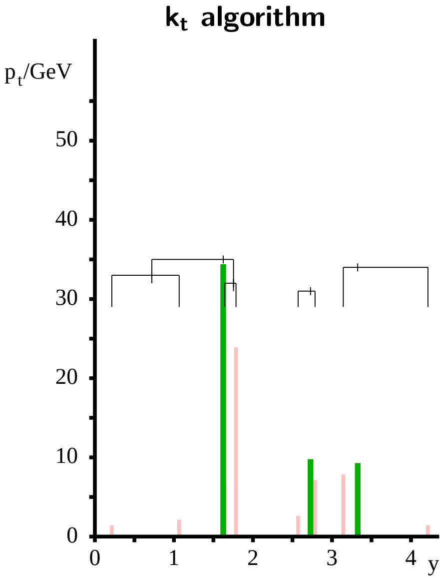

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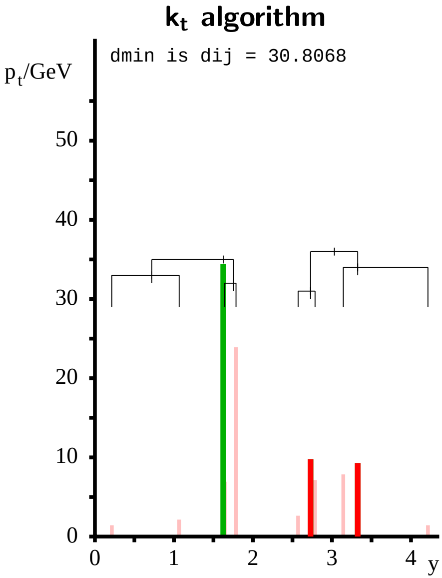

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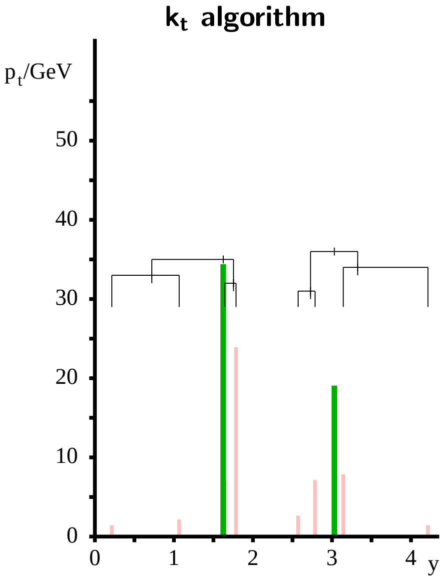

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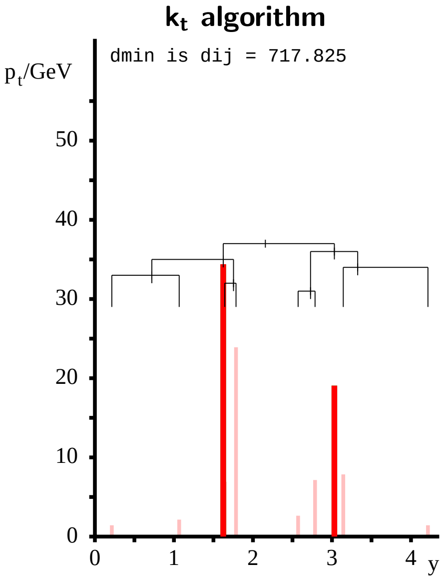

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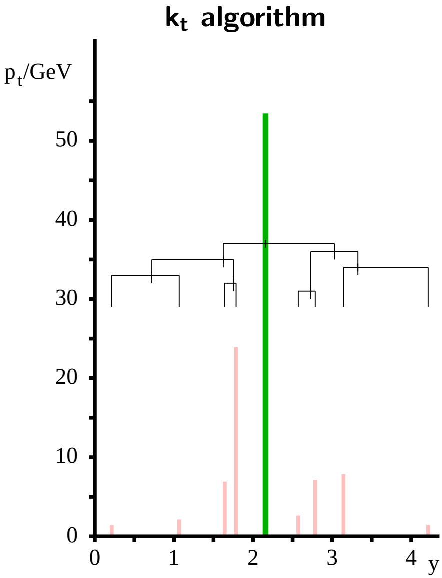

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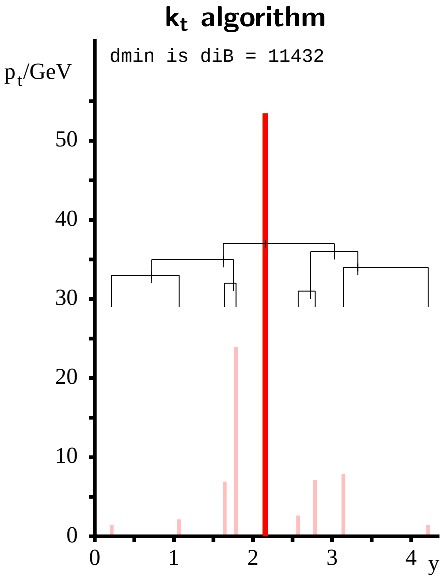

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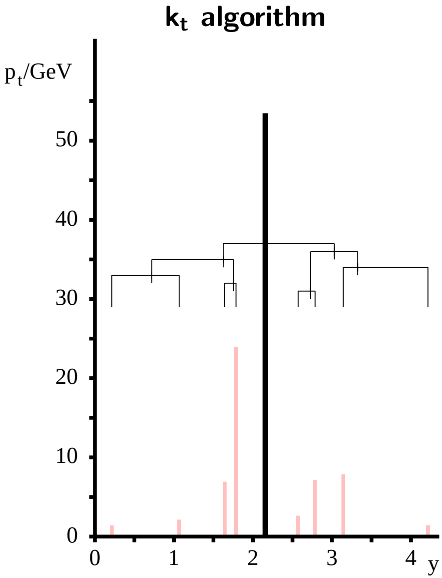

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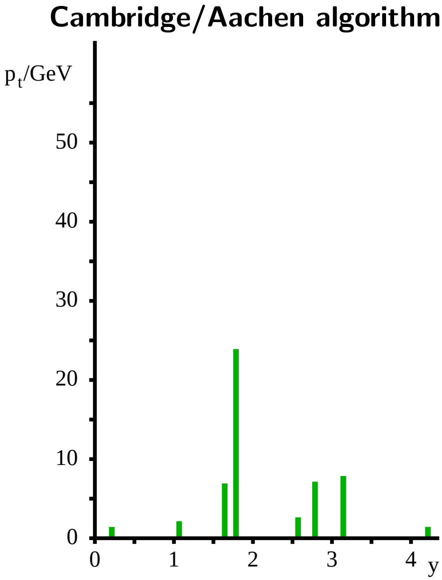
This meant it was the first algorithm to be used for jet substructure.

Seymour '93

Butterworth, Cox & Forshaw '02

Identifying jet substructure: Cam/Aachen



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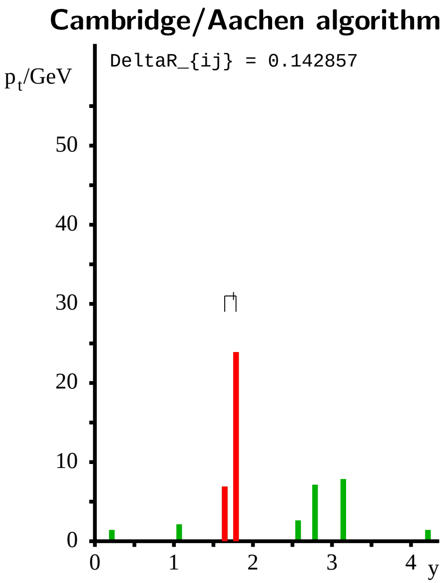

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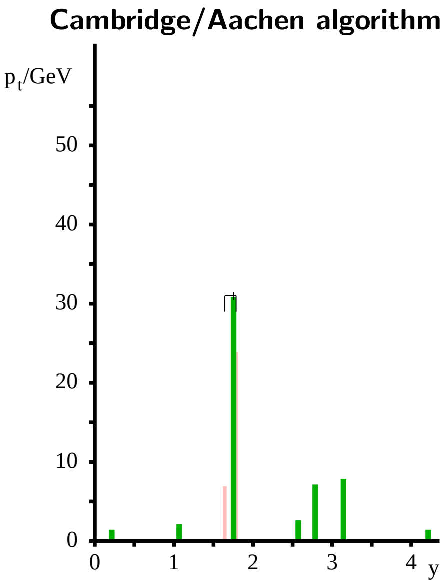

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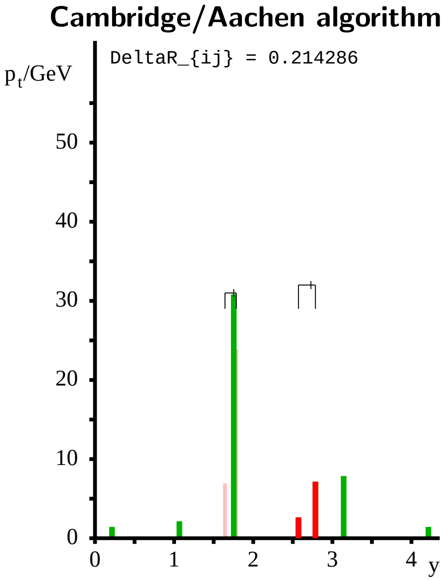

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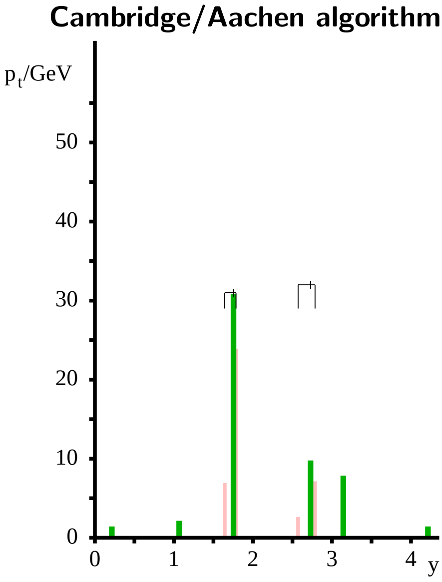

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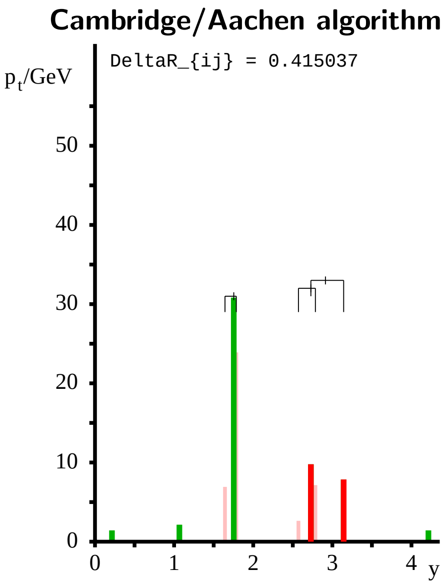

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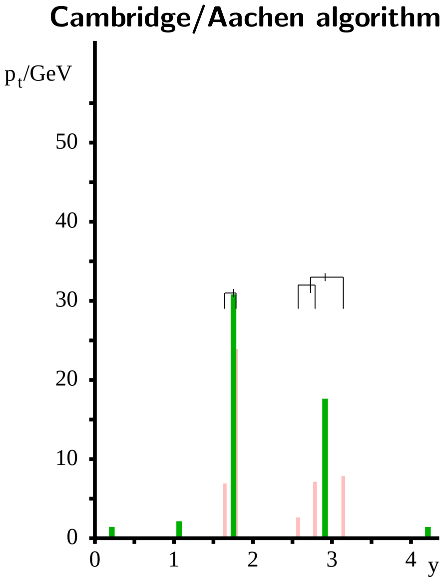

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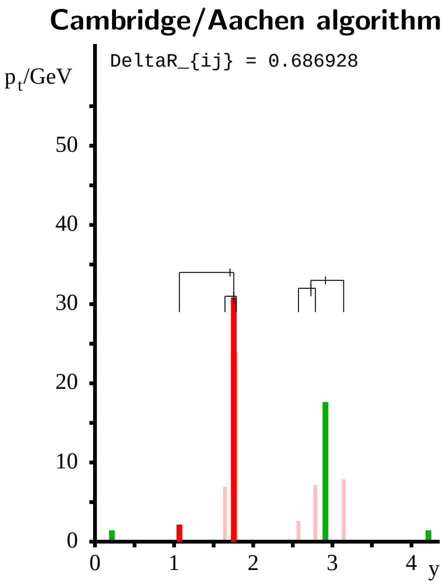

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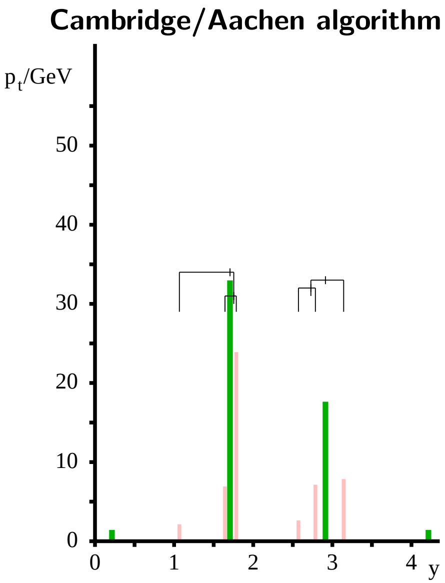

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C/A identifies two hard blobs with limited soft contamination

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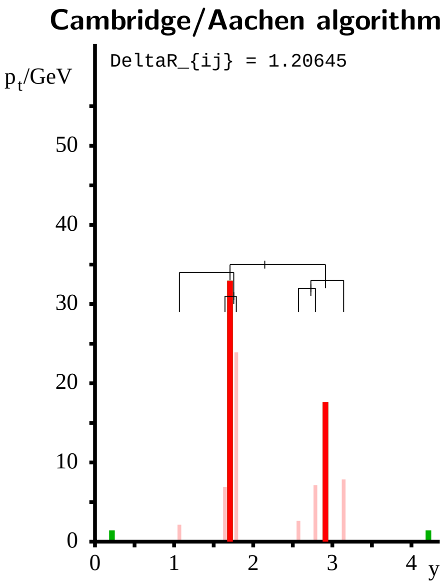

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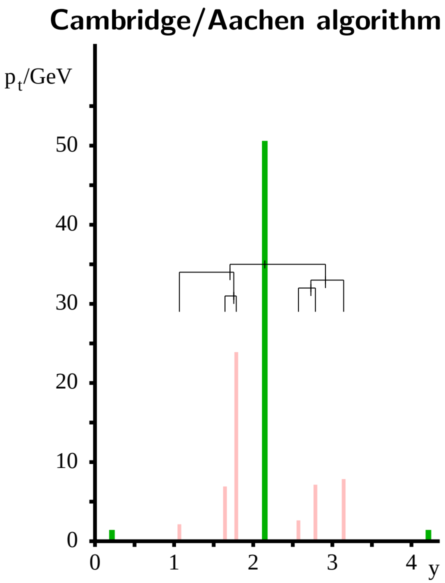

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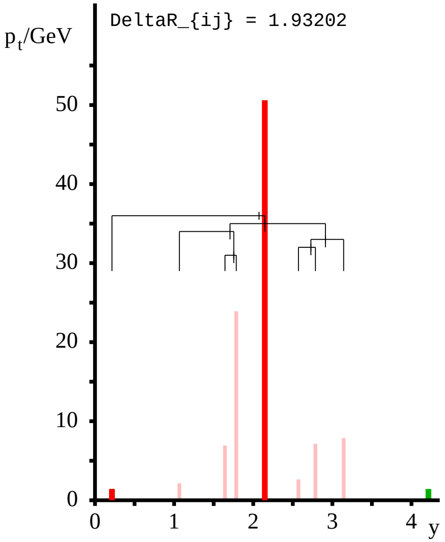
Cambridge/Aachen algorithm



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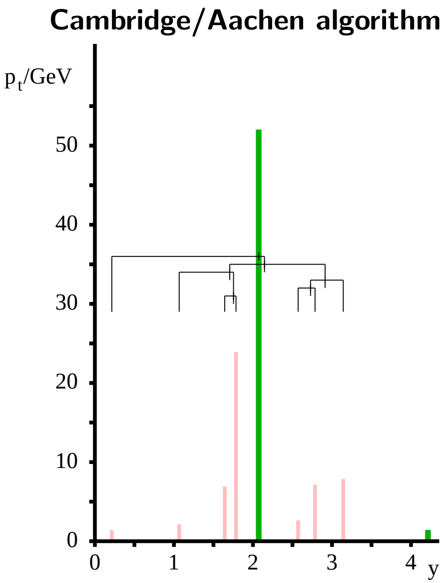

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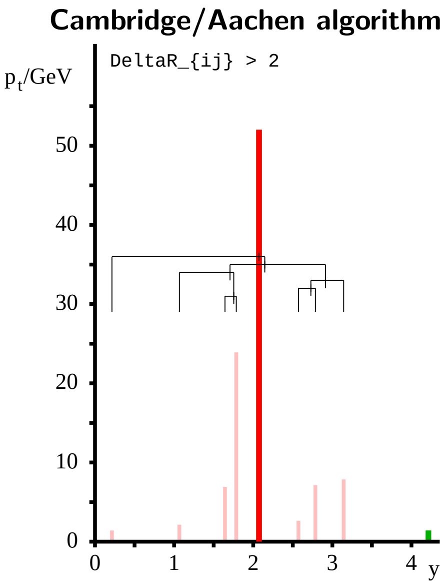

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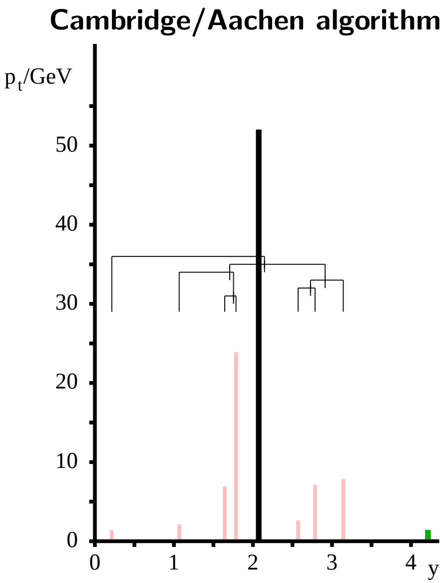

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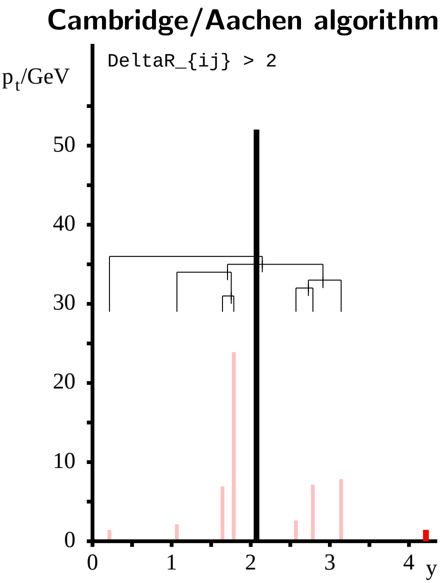

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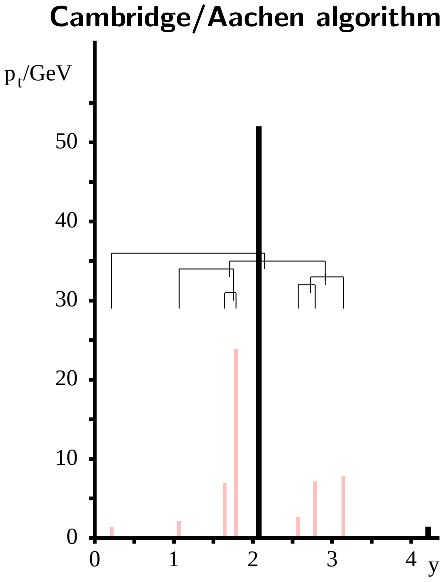

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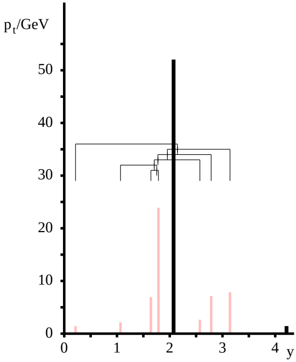
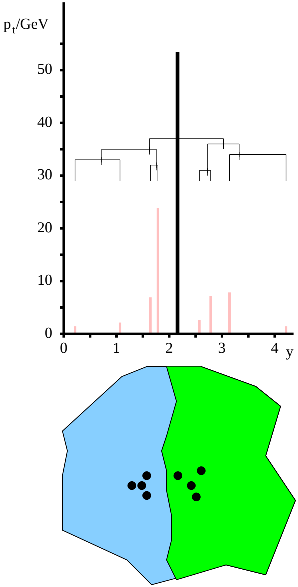
The interesting substructure is buried inside the clustering sequence — it's less contamined by soft junk, but needs to be pulled out with special techniques

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

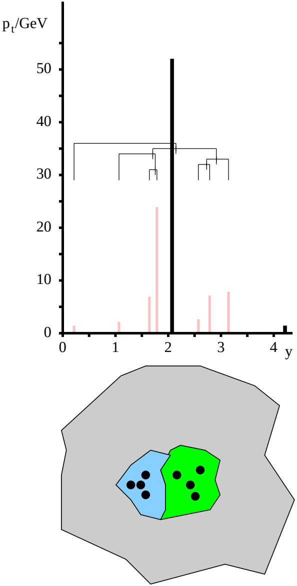
anti-k_t algorithm



k_t algorithm

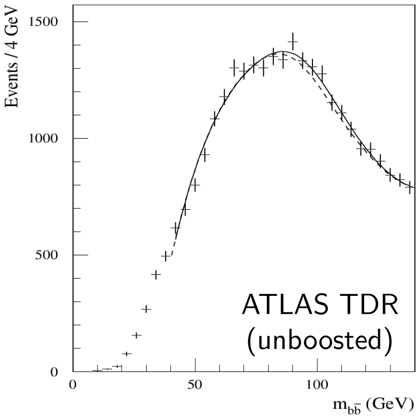


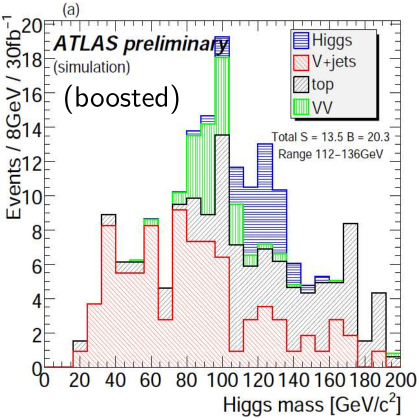
Cambridge/Aachen



Example improvement from boosted regime

Search for main decay of light Higgs boson in W/Z+H, $H \to b\bar{b}$





restricting search to $p_{tH} > 200$ GeV

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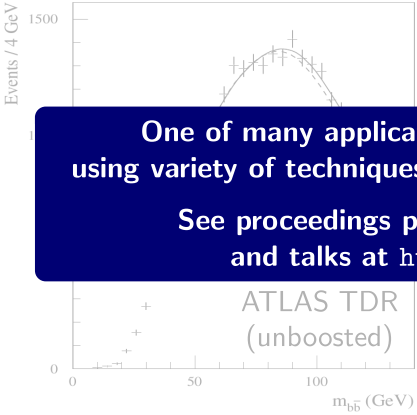
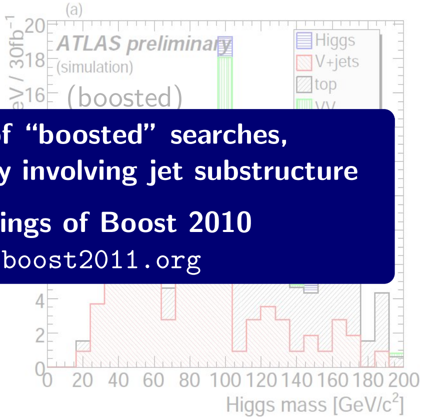




One of many applications of "boosted" searches, using variety of techniques, many involving jet substructure

See proceedings proceedings of Boost 2010 and talks at `http://boost2011.org`

restricting search to $p_{tH} > 200$ GeV
using the method from Butterworth, Davison, Rubin & GPS '08

Closing

Conclusions

LHC events will cover 2 orders of magnitude in jet p_t

Flexibility in the choice of jet definitions has potential to bring significant gains

[there is no unique best definition;
anti-k_t with $R = 0.5$ or 0.6 will sometimes be far from optimal]

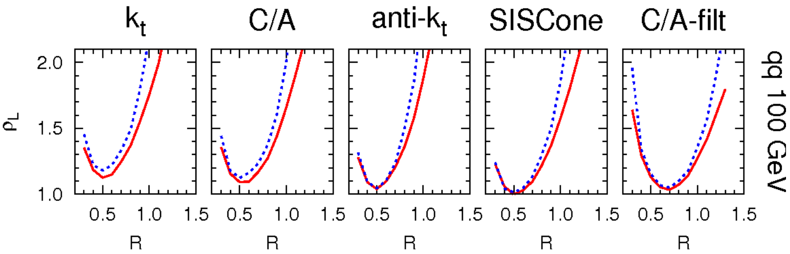
EW-scale particles are "light" relative to the TeV scale

Using the full power of jet algorithms & their substructure helps pull out signals that might otherwise be missed

[currently a very active research field]

EXTRAS

quality: 5 algorithms, 3 processes



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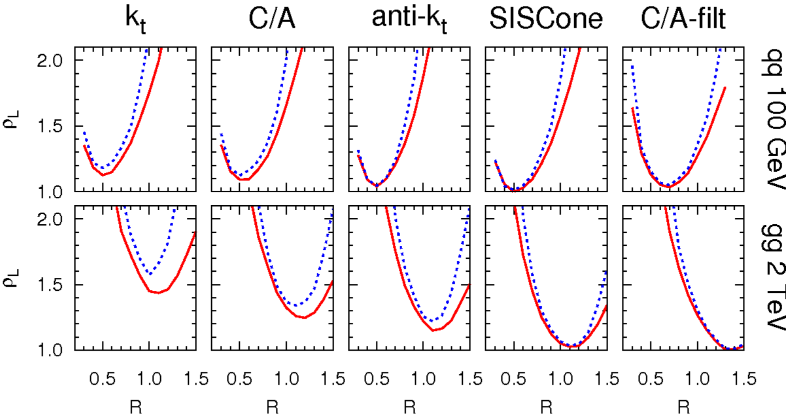

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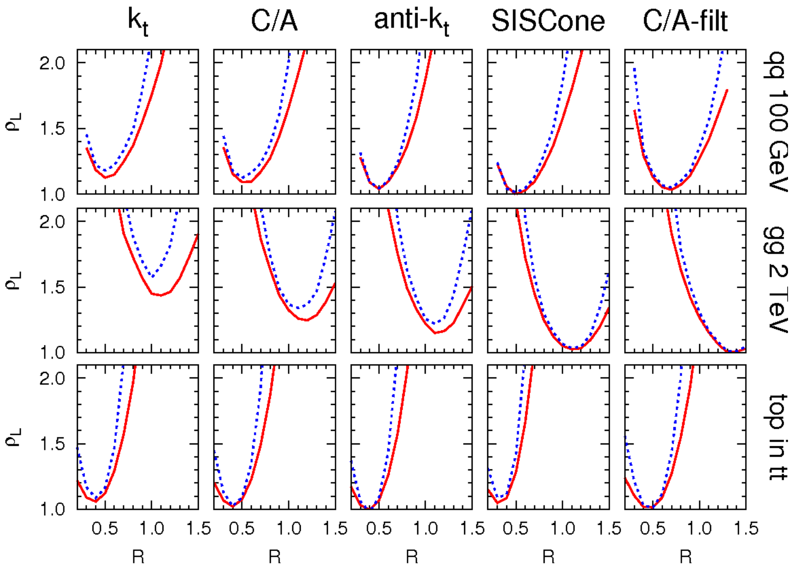


Other work → improving the methods

- Using matrix-element methods for the substructure

  Done analytically
  Soper & Spannowsky '11
  Most "physically interesting"

- Using jet shapes. E.g. subjettiness: break a jet into subjets $1, 2, \ldots N$

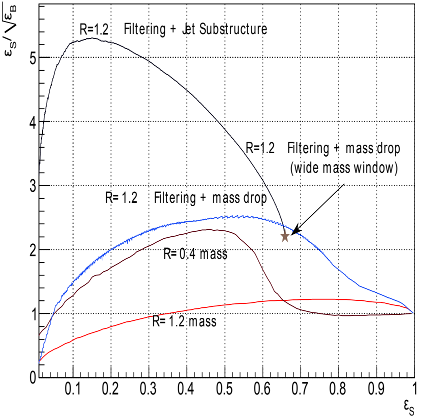
$$S_N = \frac{1}{p_t} \sum_i p_{ti} \min(\delta R_{i1}, \ldots \delta R_{iN})$$

J-H Kim '10; Thaler & Van Tilburg '10

- Using boosted decision trees

Cui, Han & Schwartz '10; seems powerful

Cui et al BDT v. BRDS



Biggest improvements are to be had at moderate signal efficiencies

Conclusion from Boost 2010 comparison study of top taggers
The method to be adopted depends on the signal efficiency you want

Pileup

high p_t → requires high lumi → high pileup

28/03/2011 LHC 8:30 meeting

2011 Records

3.5 TeV

Items in red are records set in the past week

Peak Stable Luminosity Delivered	2.49×10^{32}	Fill 1645	11/03/22, 17:12
Maximum Peak Events per Bunch Crossing	13.08	Fill 1644	11/03/22, 02:20
Maximum Average Events per Bunch Crossing	8.93	Fill 1644	11/03/22, 02:20

$\gtrsim 10$ events per bunch crossing

$\mathcal{O}(10 \text{ GeV})$ of extra p_t per jet, with large fluctuations

Subtracting noise from jets

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

Cacciari, GPS & Soyez '08

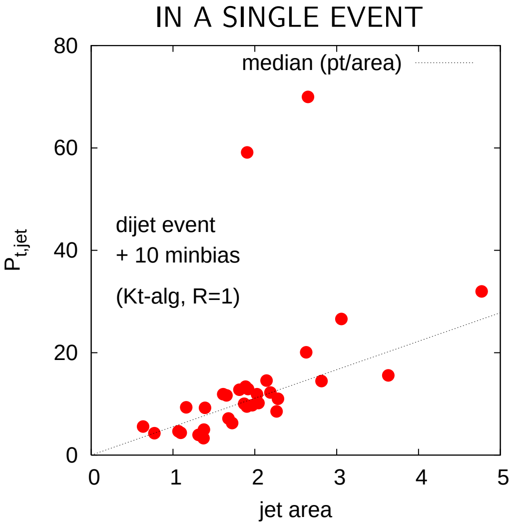
$$A_{jet} = \text{jet area}$$

$$\rho = p_t \text{ per unit area from pileup}$$
(or "background")

This procedure is intended to be common to pp ($\rho \sim 1-2$ GeV), pp with pileup ($\rho \sim 2-15$ GeV) and Heavy-Ion collisions ($\rho \sim 100-300$ GeV)

As proposed so far: jet-by-jet area determination, event-by-event ρ determination

Event-by-event ρ (background) estimation



Most jets in event are "background"

Their p_t is correlated with their area.

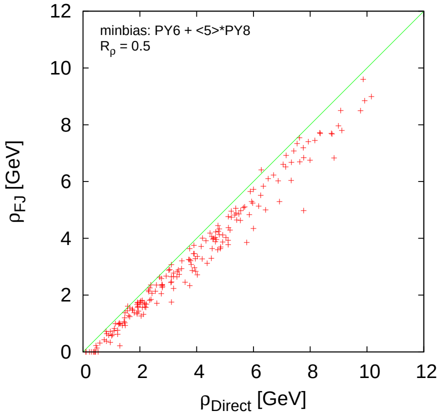
Estimate ρ:

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

Median limits bias from hard jets
Cacciari & GPS '07

Comparing pileup estimation methods

Compare FastJet median ρ to Monte Carlo truth (ρ_{Direct})



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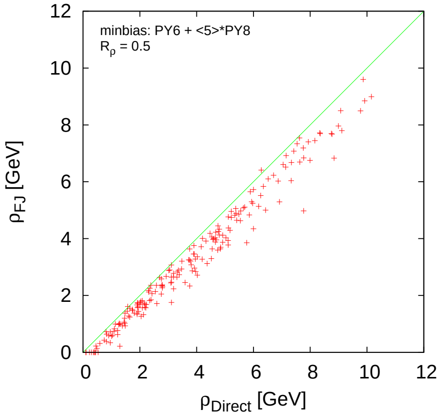
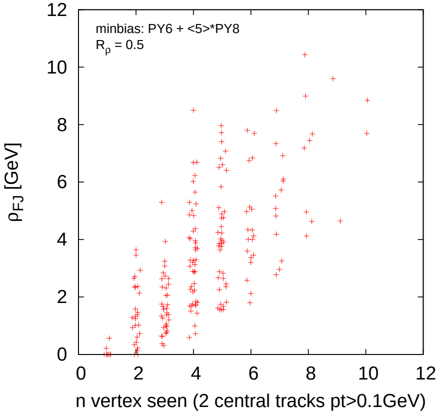


Works much better than counting primary vertices



A non-trivial issue: rapidity dependence

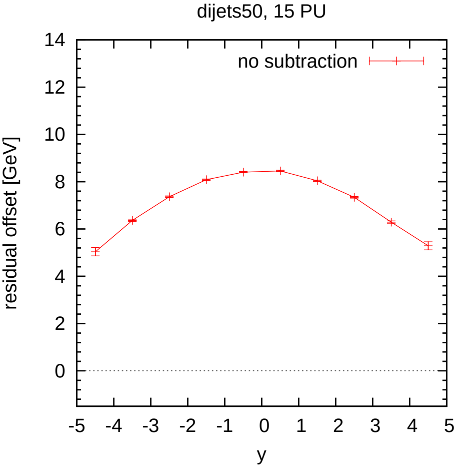
The original method assumed rapidity dependence was small

- In some sense it is, $\lesssim 1.5$ GeV
- Measure ρ globally, and include a rapidity-dependent rescaling

$$p_t^{sub} = p_t - f(y)\rho A$$

determine $f(y)$ from min-bias

- Measure ρ "locally" in strips of $|\Delta y| < 1.5$



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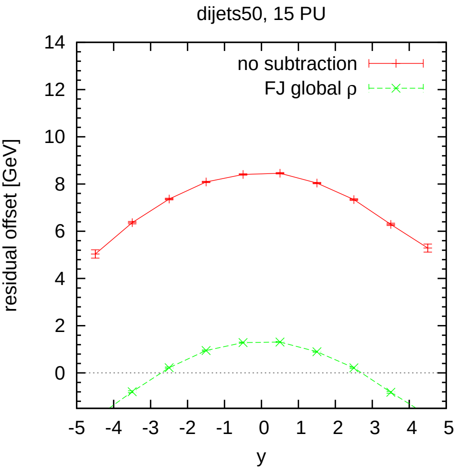

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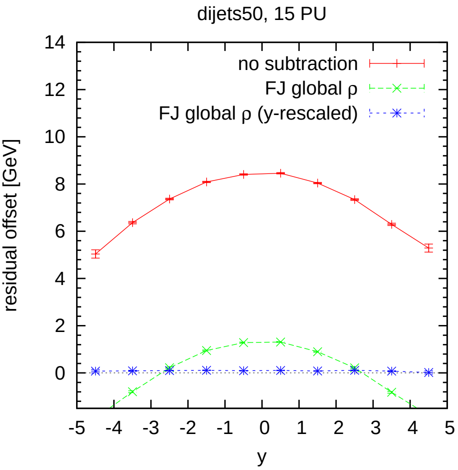

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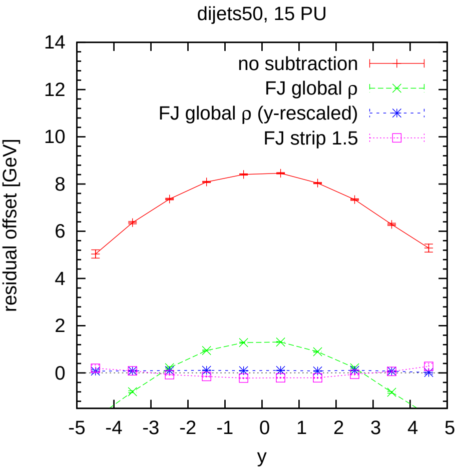

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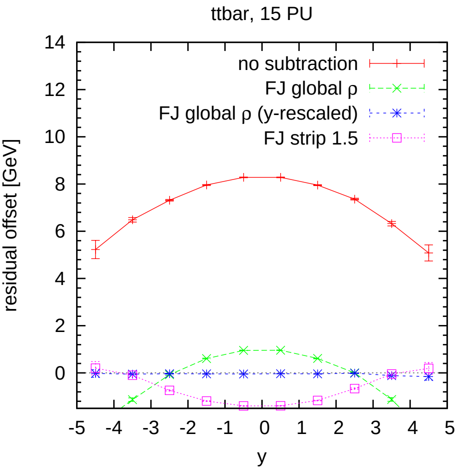

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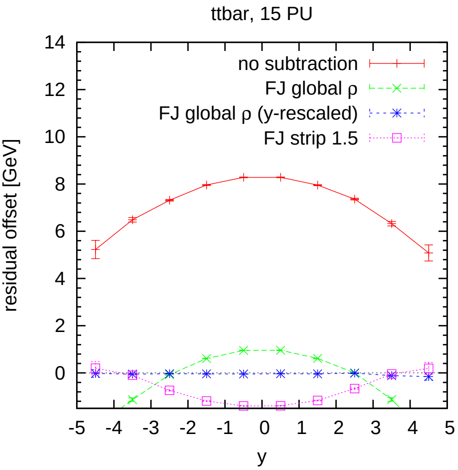

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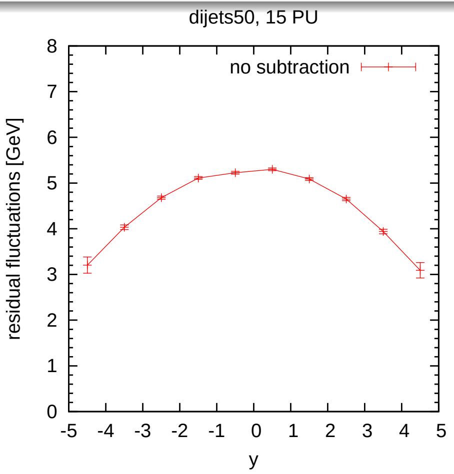
Hints from charged tracks

Dispersion of offset gives another measure of the subtraction "quality"

- several GeV without subtraction
- only partially reduced with FJ subtraction
- alternative: use PF to remove PU charged tracks in each jet
  if PU is in-time
  - scaling PU charged track in the jet to correct also for neutrals
  - or supplementing with FJ subtraction for the neutrals



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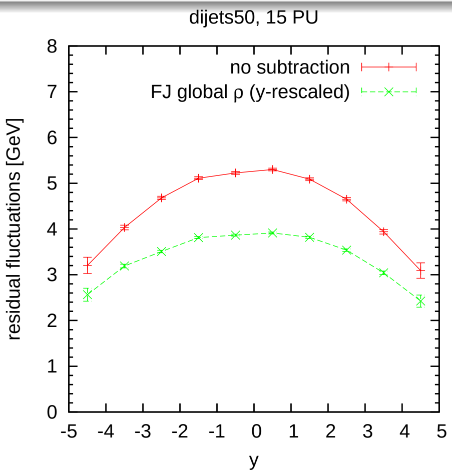

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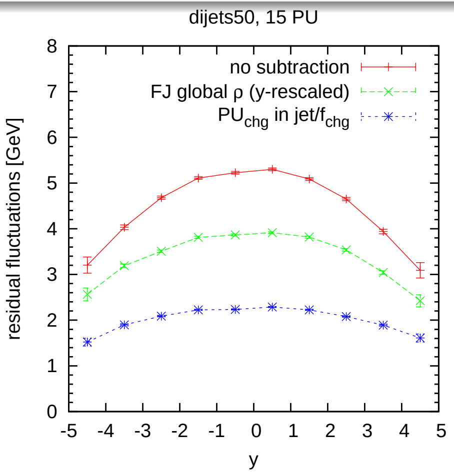

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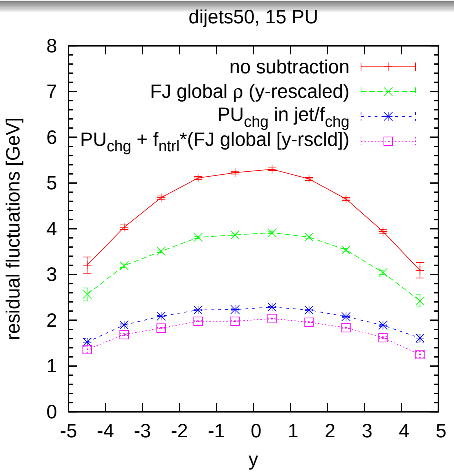

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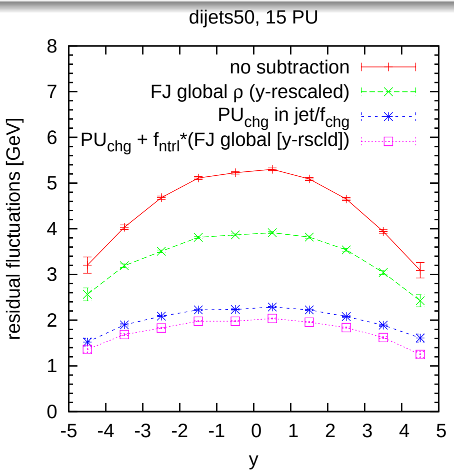

Direct knowledge of PU from tracks can be beneficial

Detector impact harder to judge

Jet masses etc.?

Fat-jet studies need more than just the jet p_t. E.g. **jet mass**

There are methods to limit PU sensitivity of jet masses.

Filtering: Butterworth et al '08
Pruning: Ellis et al '09
Trimming: Thaler et al '09

4-vector subtraction can also help

$$p_\mu^{(sub)} = p_\mu - f(y)\rho A_\mu$$

"Automatically" corrects mass
as long as hadron masses set to zero

Many more things can be corrected for PU beyond jet p_t
Tests are still in v. early stages / drawing board

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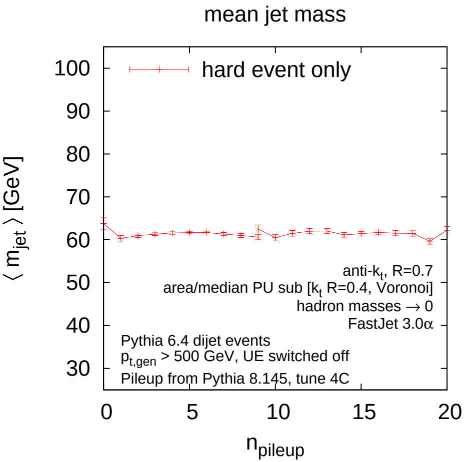

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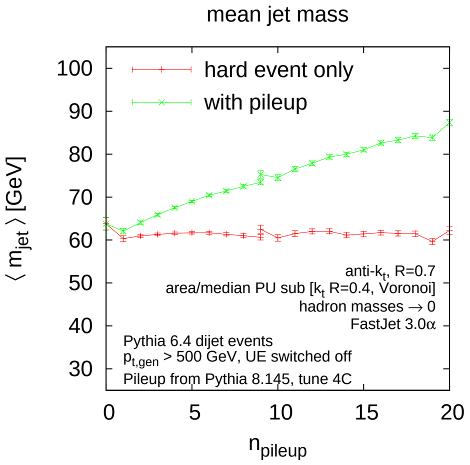

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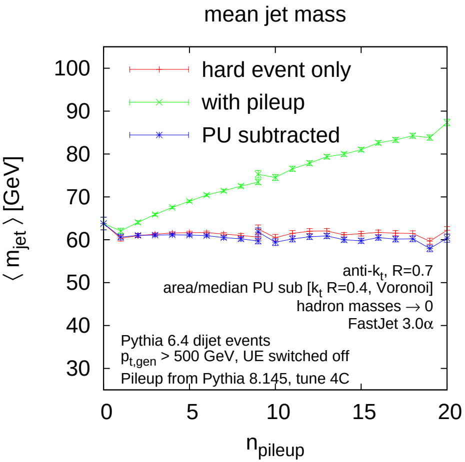

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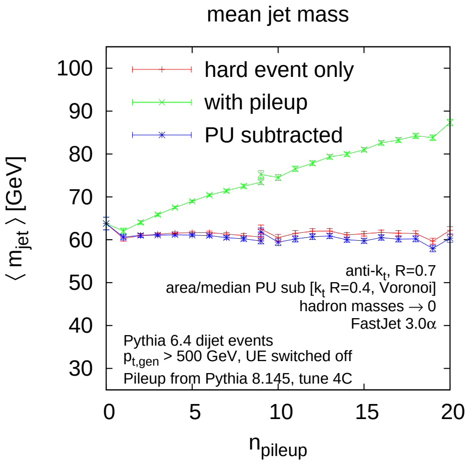

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