Jets at Hadron Colliders (3)

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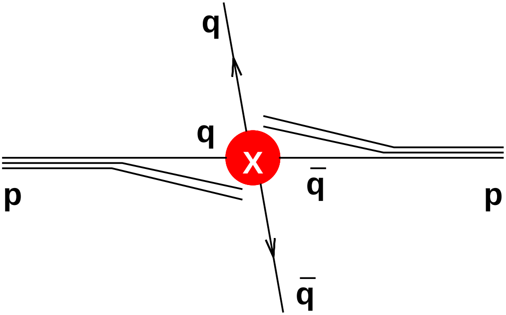
Using our understanding to help discover a dijet resonance, $q\bar{q} \to X \to q\bar{q}$.

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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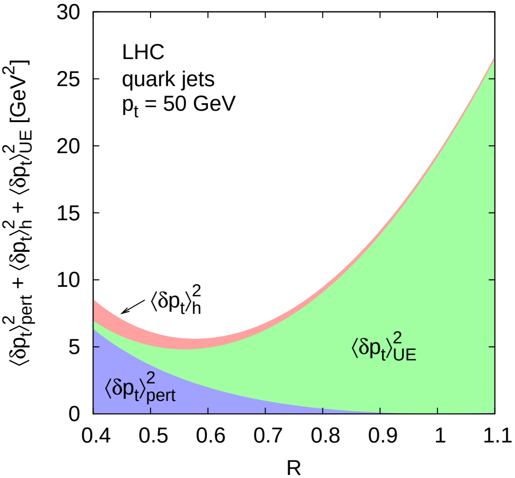
50 GeV quark jet



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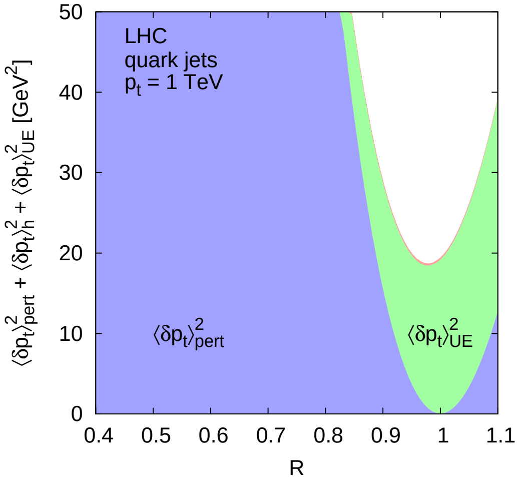
1 TeV quark jet



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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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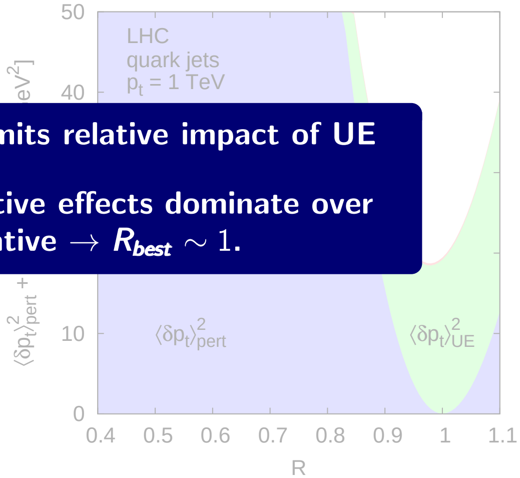

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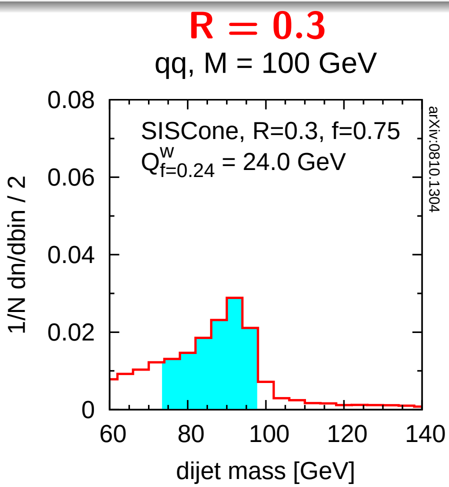
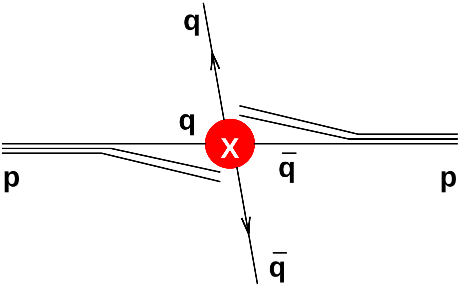
Dijet mass: scan over *R* [Pythia 6.4]



Resonance X → dijets



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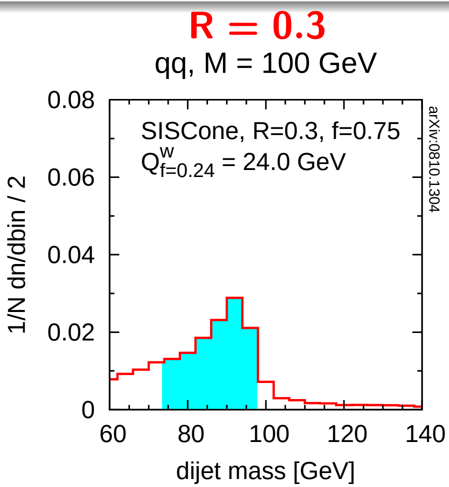
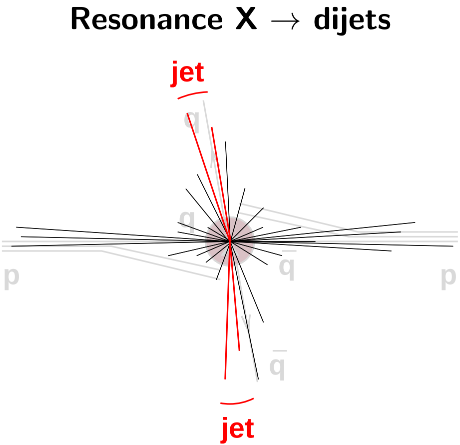
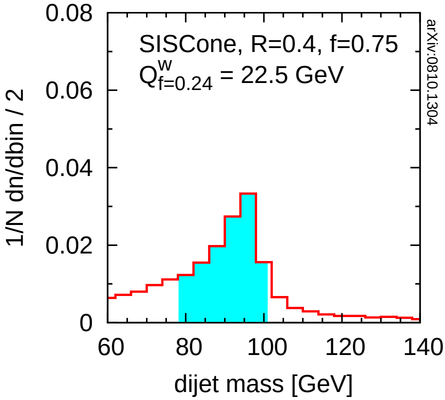




Dijet mass: scan over R [Pythia 6.4]

$R = 0.4$

qq, M = 100 GeV



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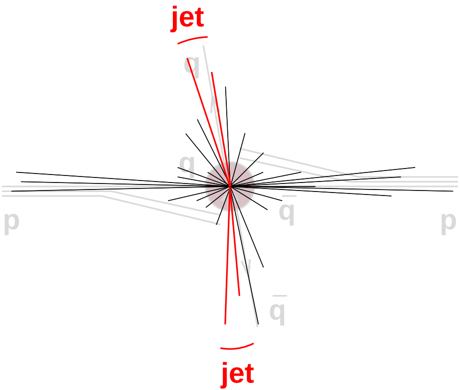
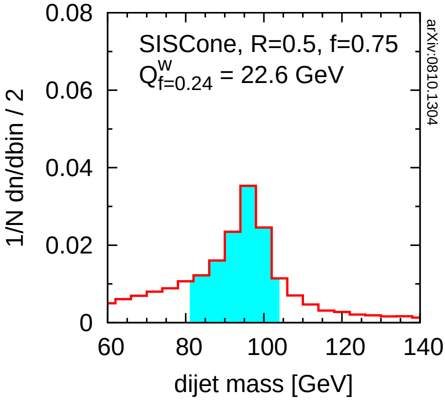


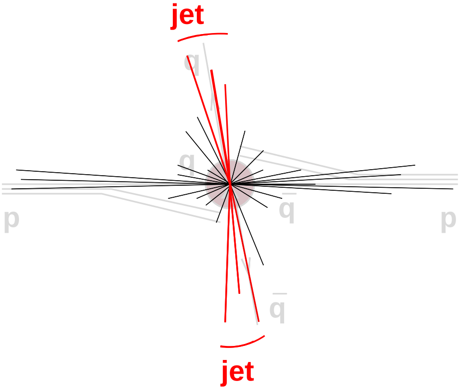
Dijet mass: scan over *R* [Pythia 6.4]

R = 0.5

qq, M = 100 GeV

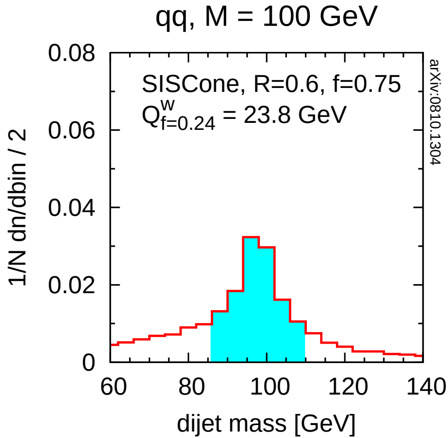


Resonance X → dijets

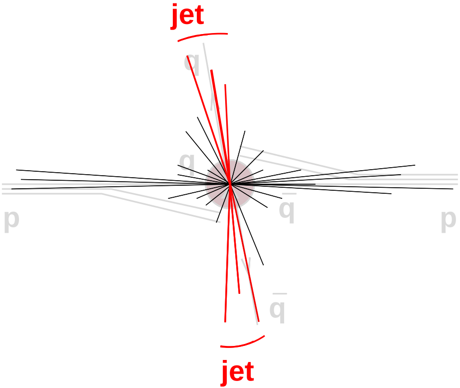


Dijet mass: scan over *R* [Pythia 6.4]

R = 0.6

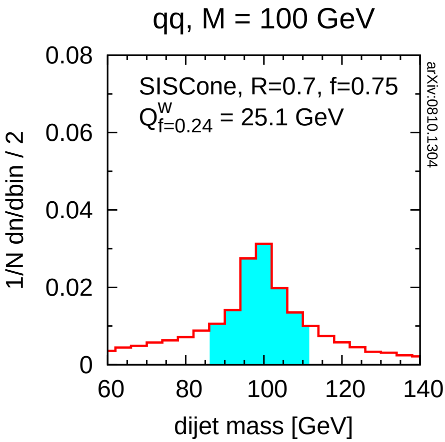


Resonance X → dijets



Dijet mass: scan over R [Pythia 6.4]

R = 0.7



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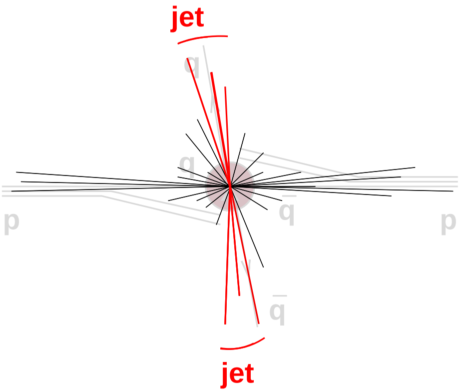
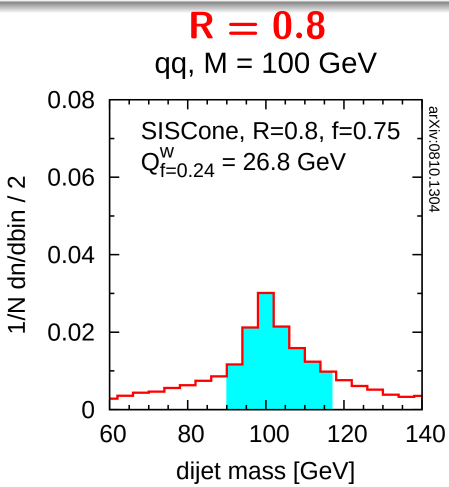
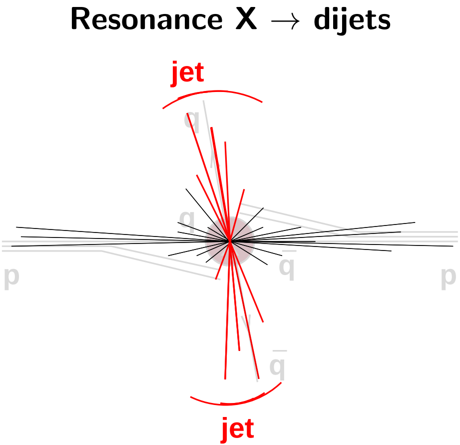


Dijet mass: scan over *R* [Pythia 6.4]

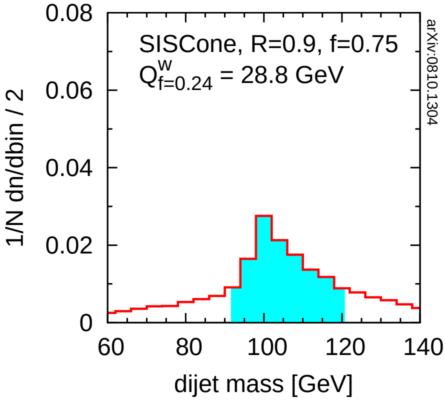




Dijet mass: scan over *R* [Pythia 6.4]

R = 0.9

qq, M = 100 GeV



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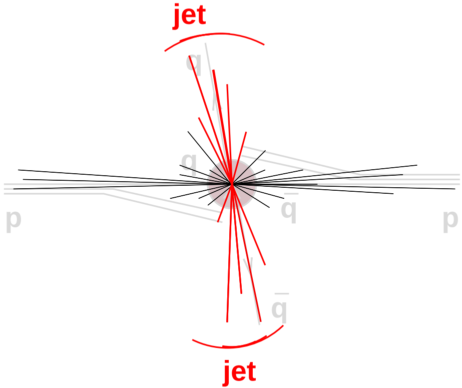
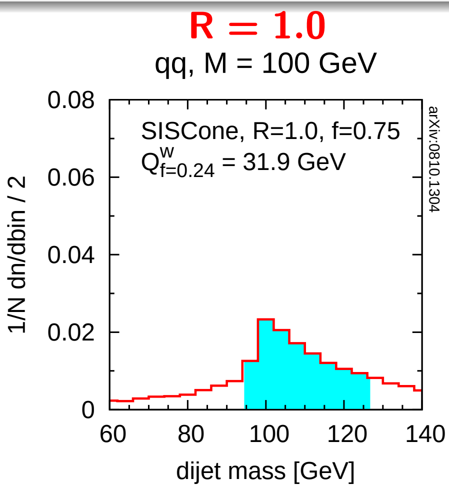
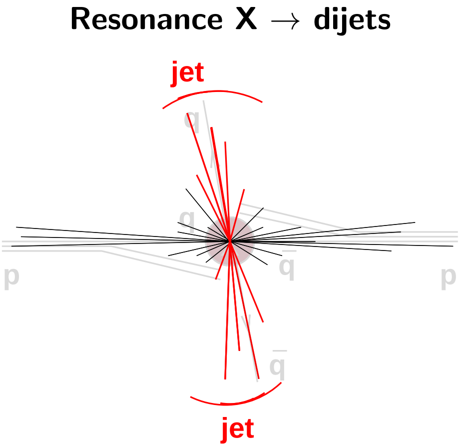


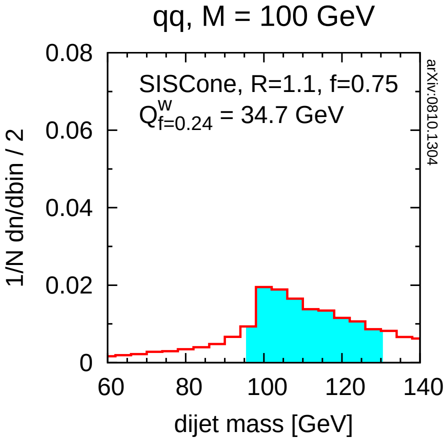
Dijet mass: scan over *R* [Pythia 6.4]





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

R = 1.1



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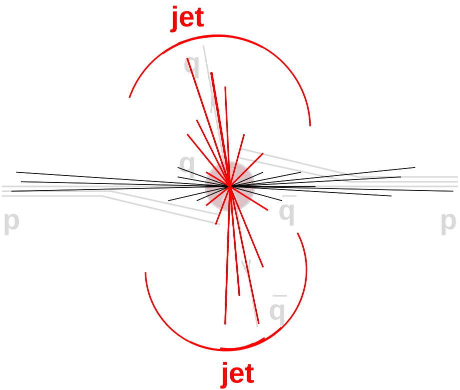

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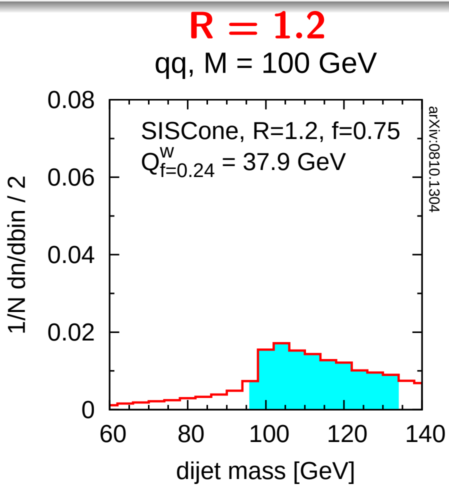
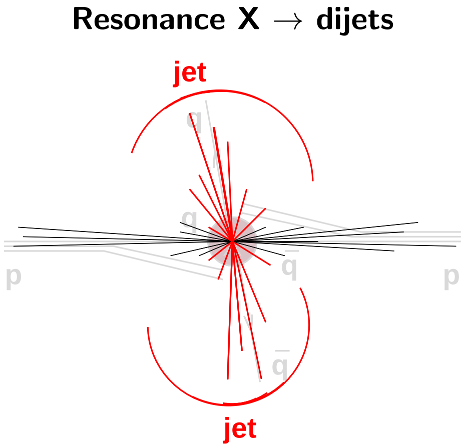
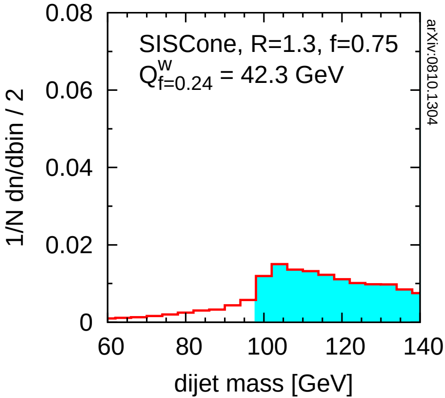




Dijet mass: scan over *R* [Pythia 6.4]

R = 1.3

qq, M = 100 GeV



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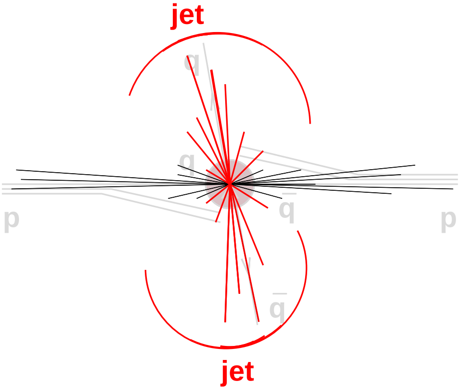
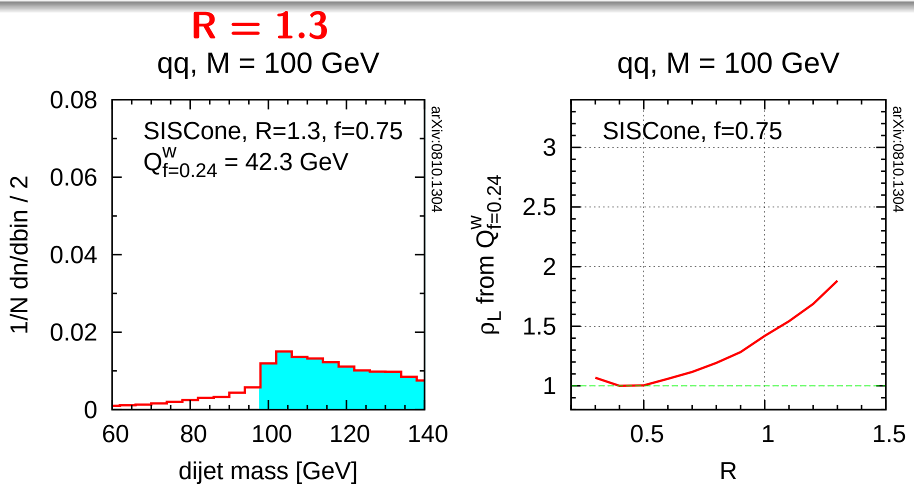


Dijet mass: scan over R [Pythia 6.4]

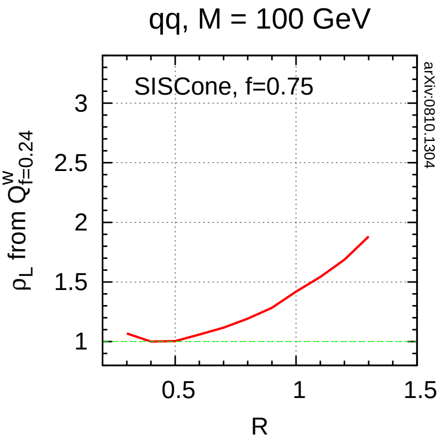


After scanning, summarise "quality" v. *R*. Minimum ≡ BEST

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, just like crude analytical prediction

NB: current analytics too crude

BUT: so far, LHC's plans involve running with fixed smallish R values

ATLAS: $R = 0.4$ & 0.6

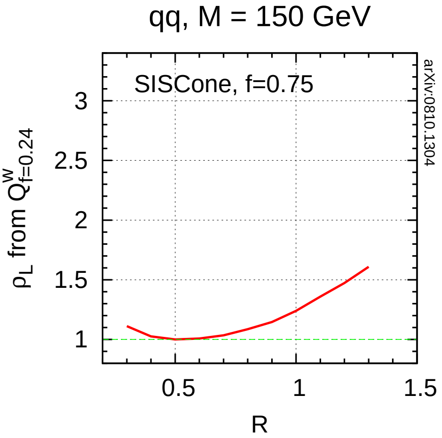
CMS: $R = 0.5$ & 0.7

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

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

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

m_{qq} = 150 GeV



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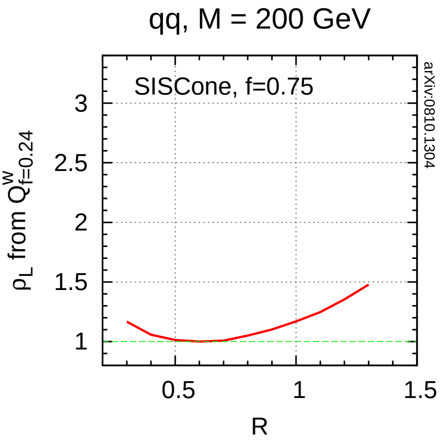
Scan through $q\bar{q}$ mass values

$m_{qq} = 200$ GeV



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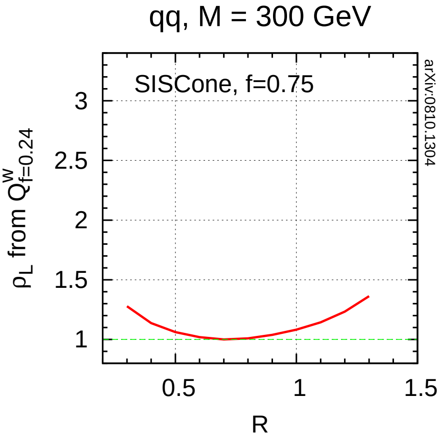
Scan through $q\bar{q}$ mass values

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



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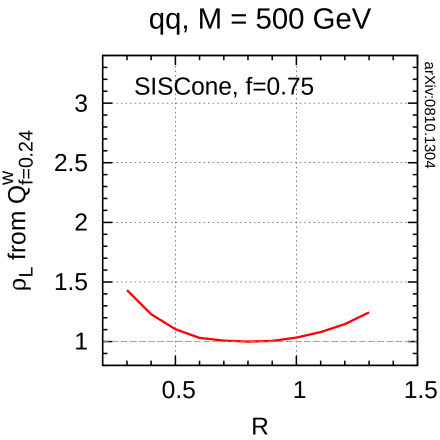
Scan through $q\bar{q}$ mass values

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



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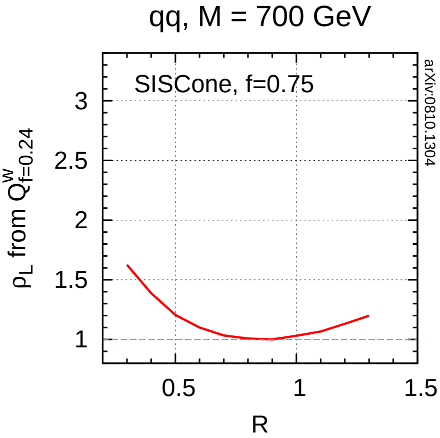
Scan through $q\bar{q}$ mass values

$m_{qq} = 700$ GeV



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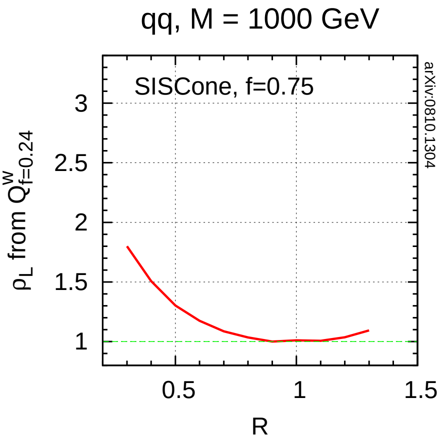
Scan through $q\bar{q}$ mass values

$\mathbf{m_{qq} = 1000\ GeV}$



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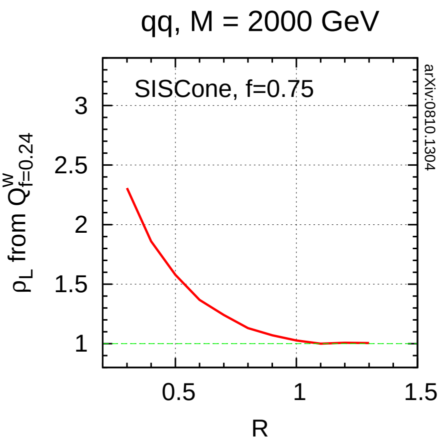
Scan through $q\bar{q}$ mass values

m_{qq} = 2000 GeV



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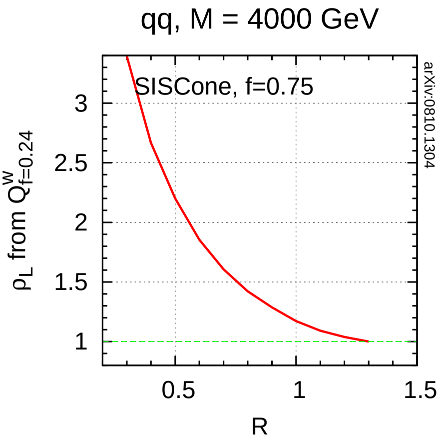
Scan through $q\bar{q}$ mass values

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



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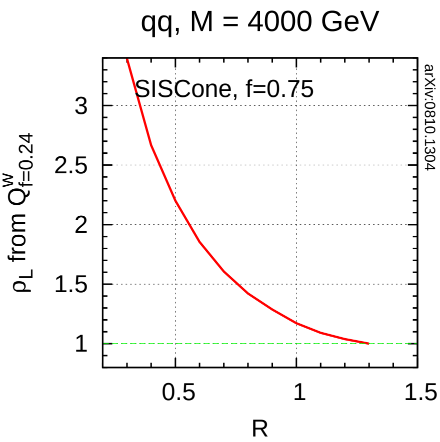

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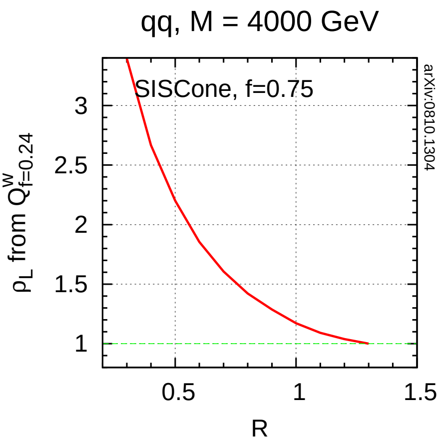

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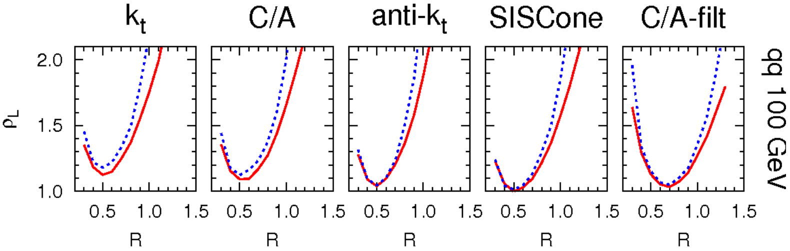
Cacciari, Rojo, GPS & Soyez '08

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

quality: 5 algorithms, 3 processes



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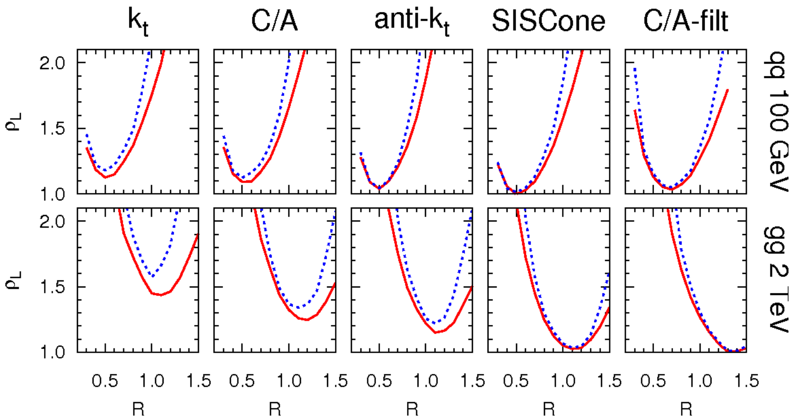

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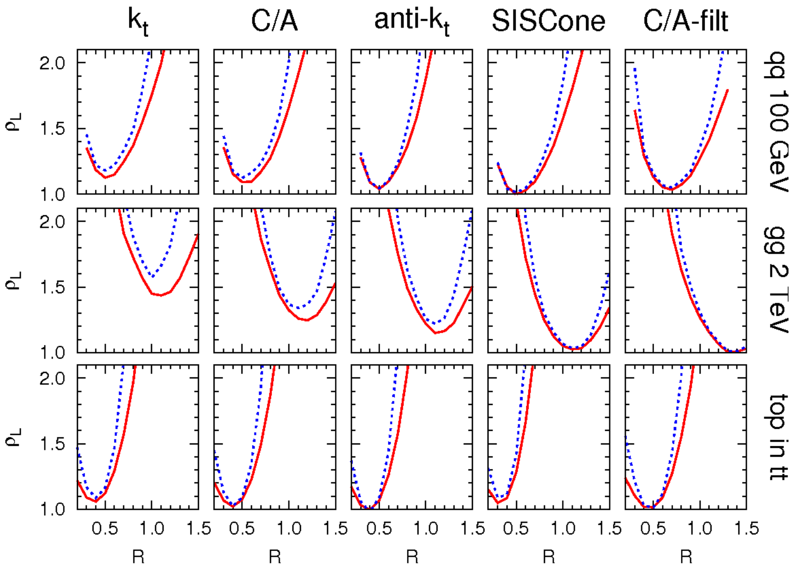

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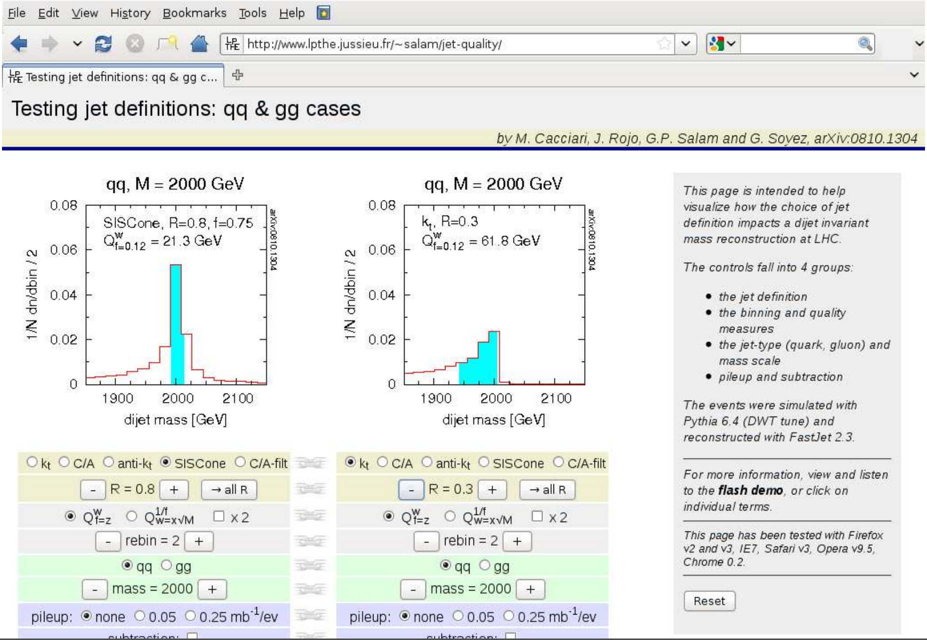


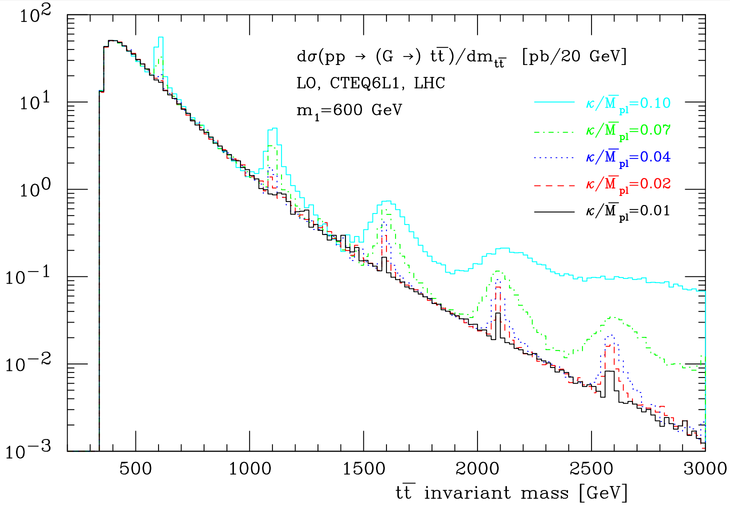
Fat jets

boosted massive hadronically decaying objects

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

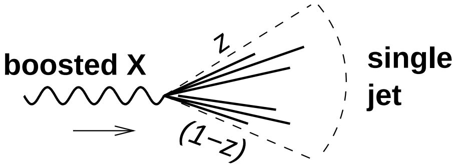


RS KK resonances $\to t\bar{t}$, from Frederix & Maltoni, 0712.2355

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



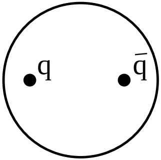
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Rules of thumb:

$m = 100$ GeV, $p_t = 500$ GeV

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

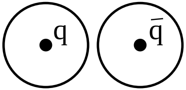
Boosted ID strategies



Select on the jet mass with one large (cone) jet

Can be subject to large bkgds

[high-p_t jets have significant masses]

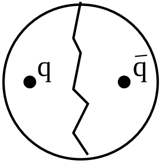


Choose a small jet size (R) so as to resolve two jets

Easier to reject background

if you actually see substructure

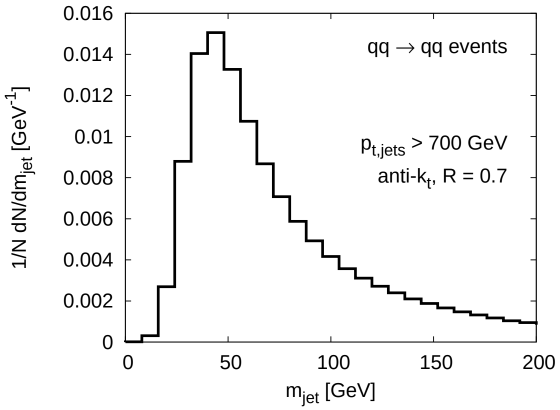
[NB: must manually put in "right" radius]



Take a large jet and split it in two

Let jet algorithm establish correct division

Jet masses



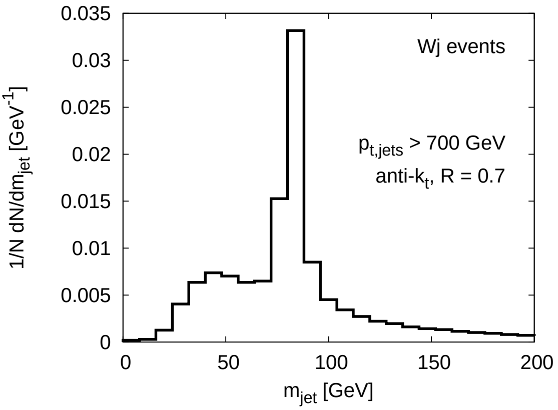
Look at jet mass distribution for two leading jets in

- $qq \to qq$ 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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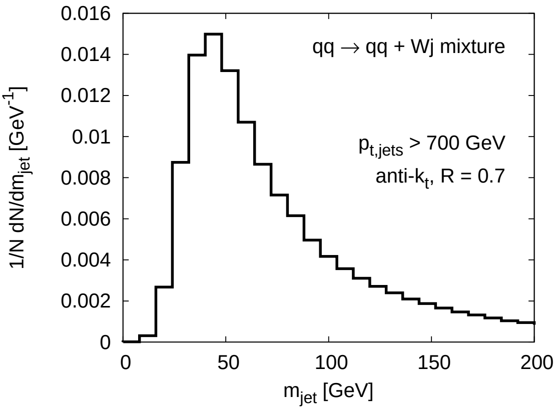

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- $pp \to W +$ jet events
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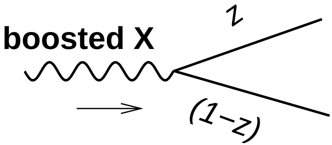
In roughly sensible proportions

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

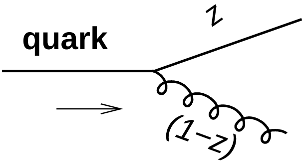
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

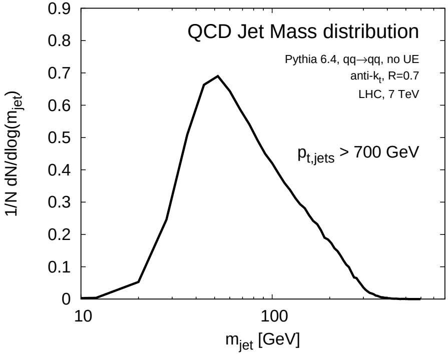
$$P(z) \propto \frac{1+z^2}{1-z}$$

$1/(1-z)$ 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

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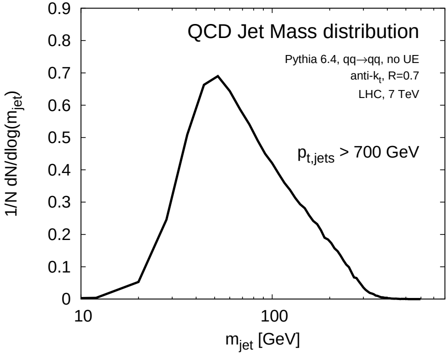

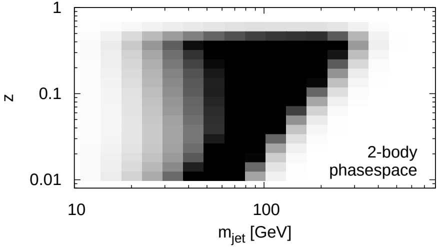

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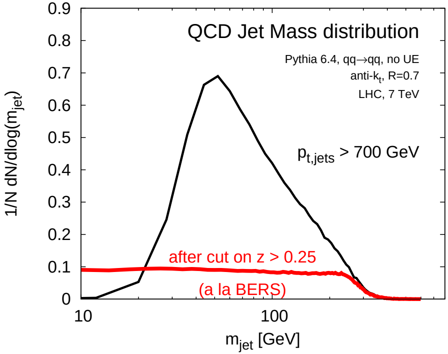

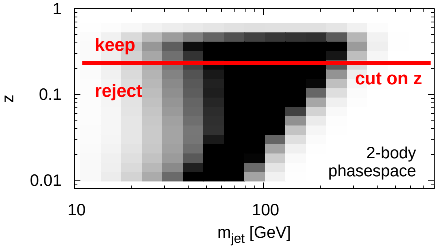

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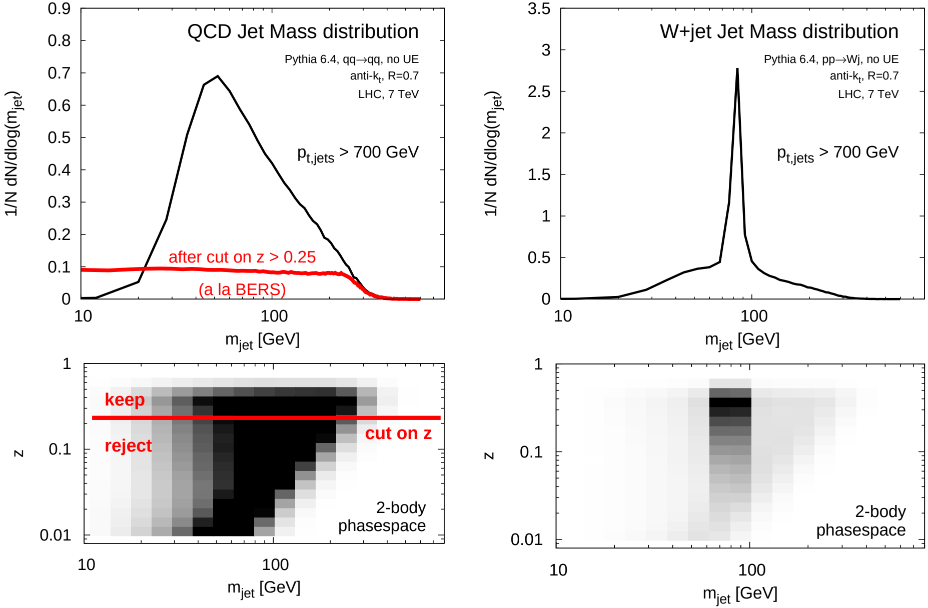
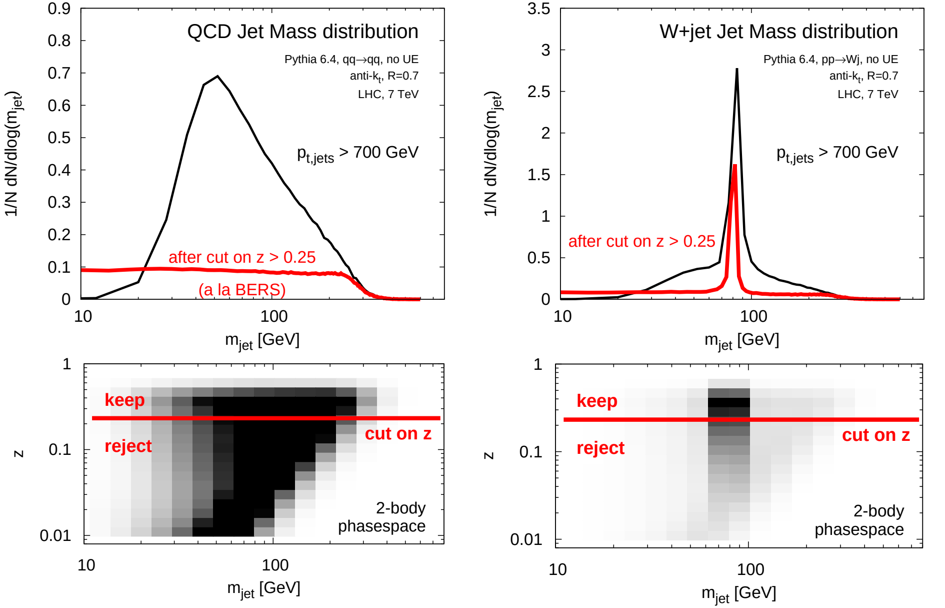
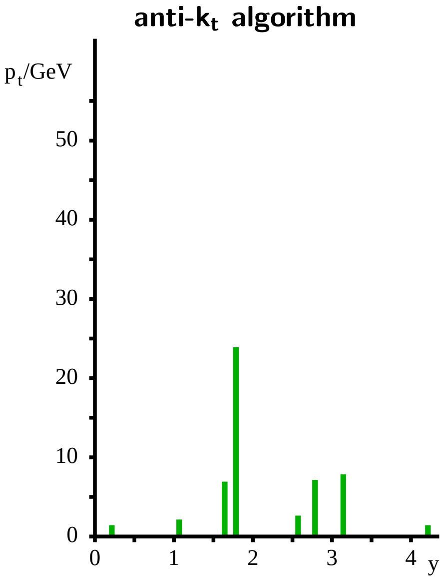


Inside the jet mass



Identifying jet substructure: try out anti-k_t



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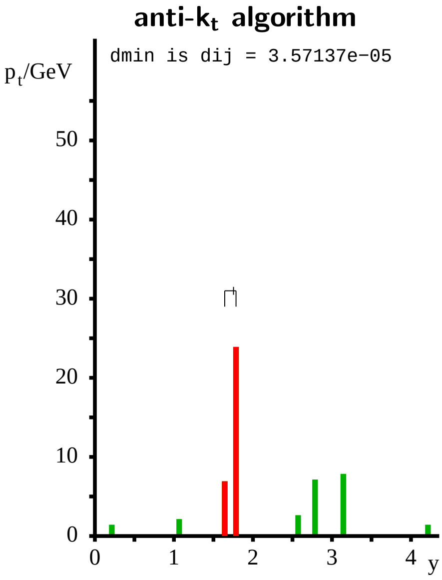

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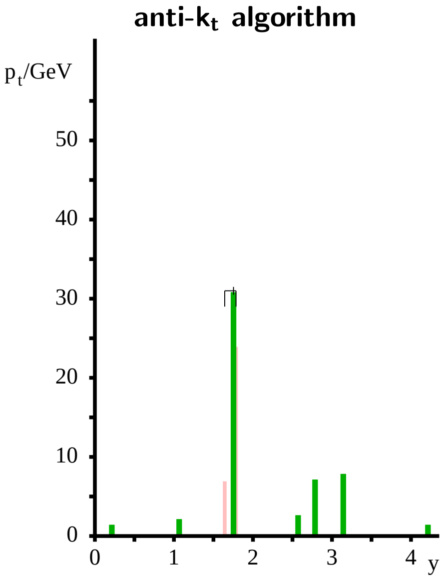

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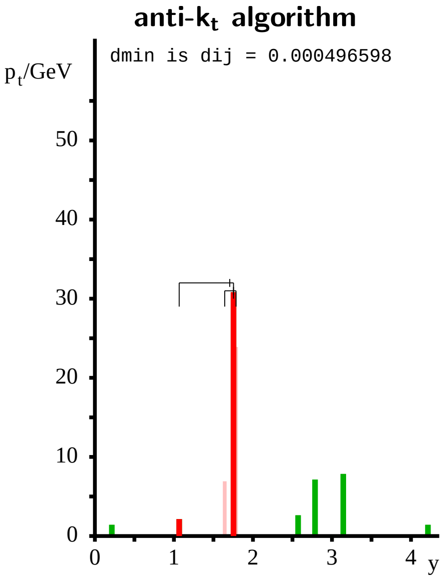

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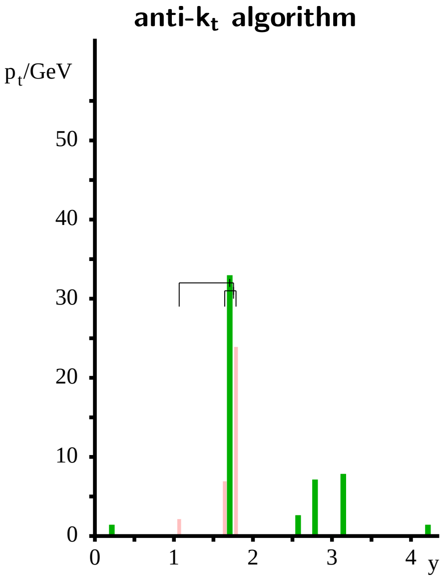

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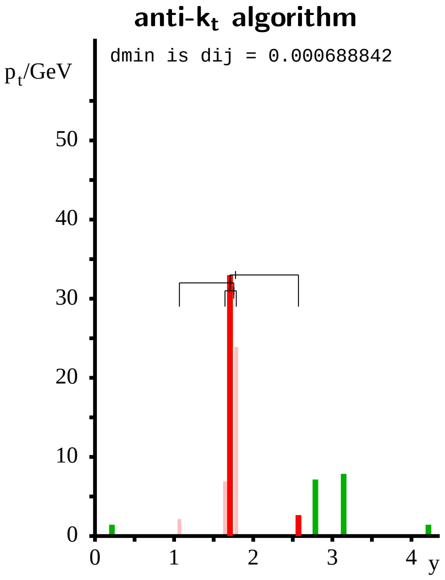

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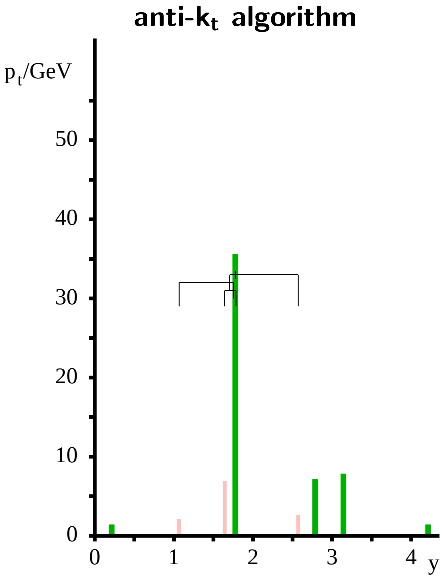

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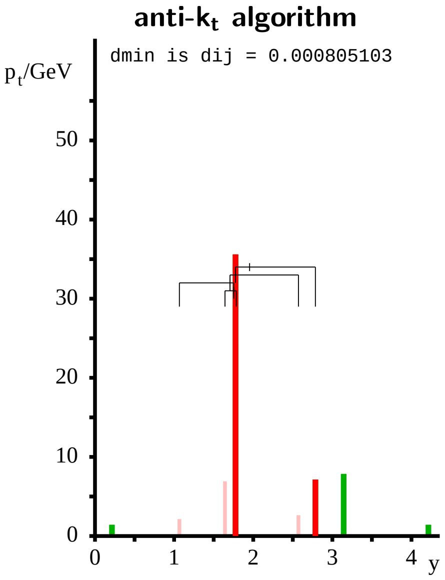

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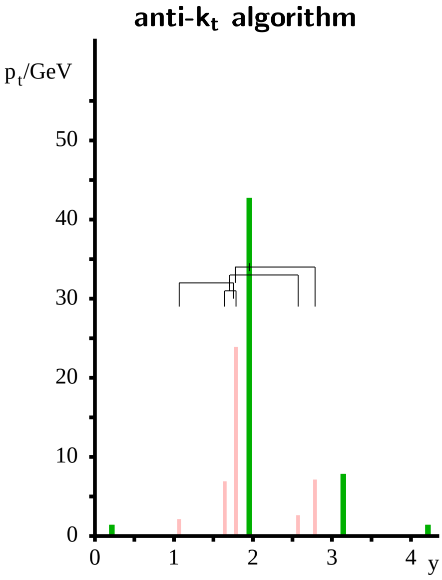

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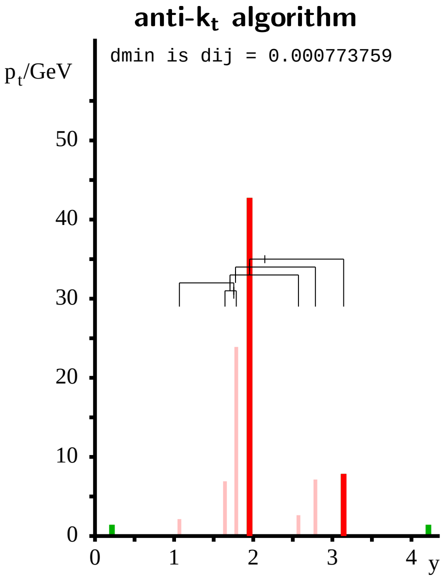

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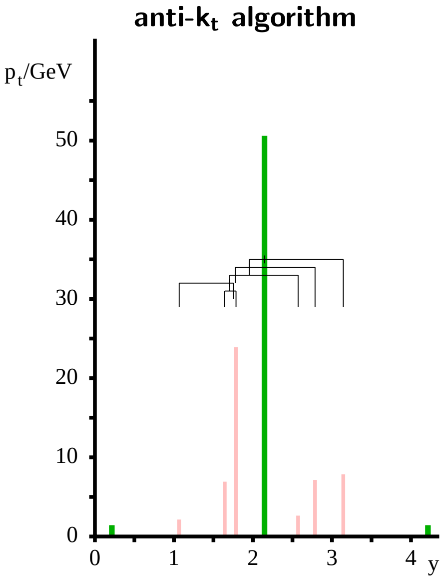

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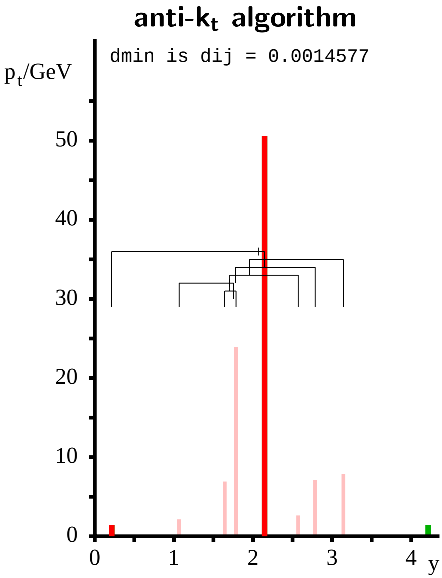

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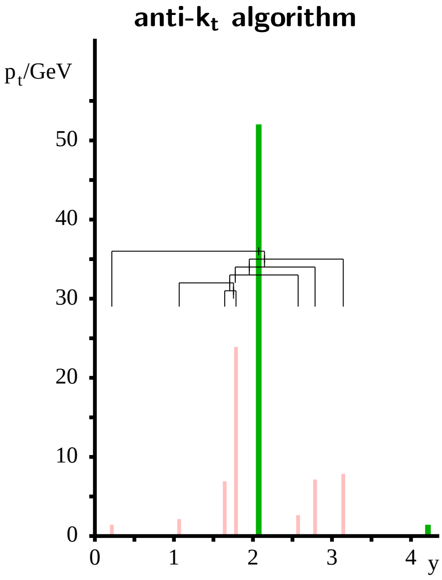

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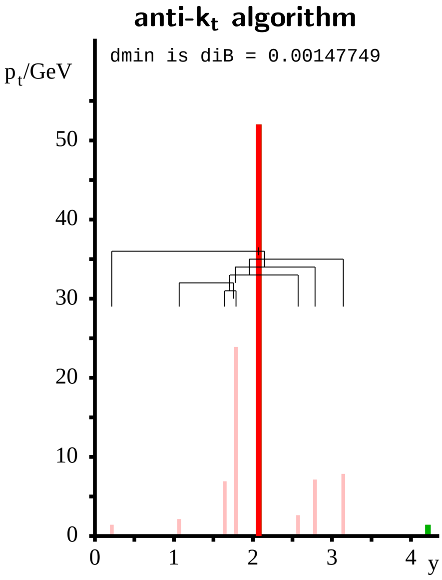

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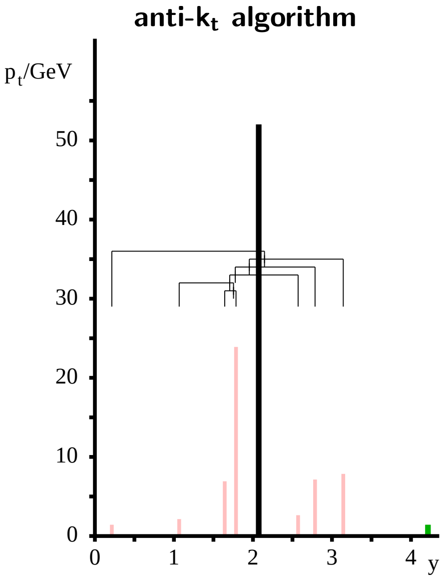

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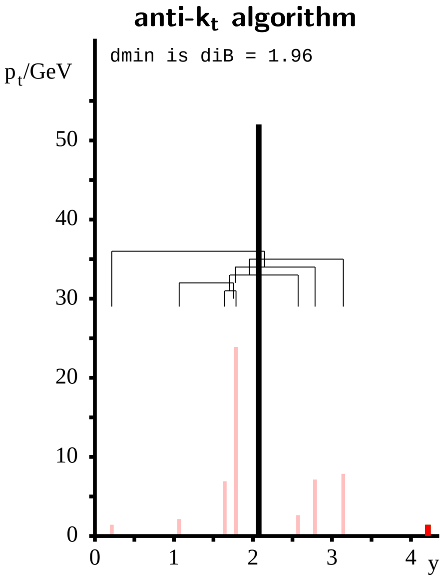

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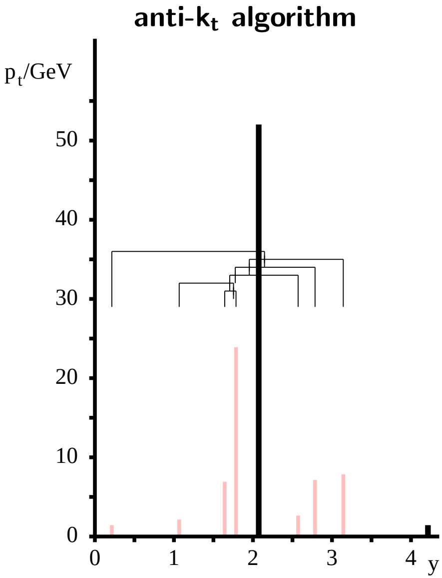

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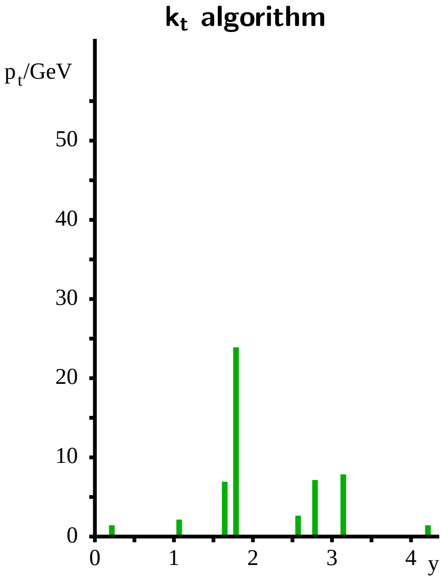

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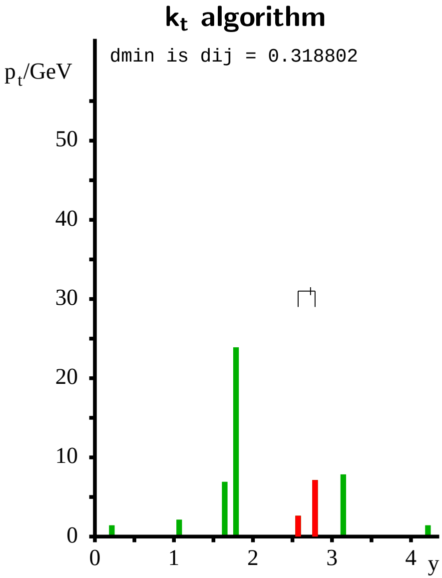

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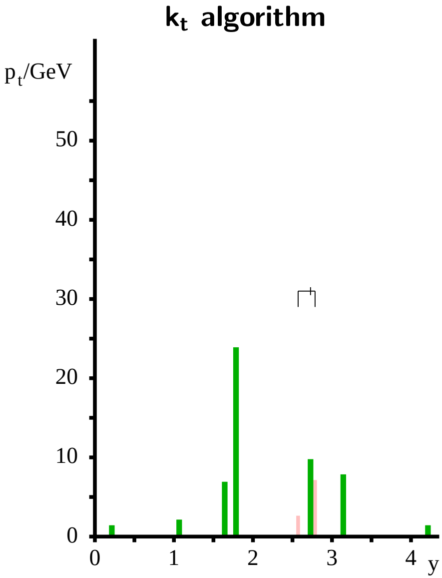

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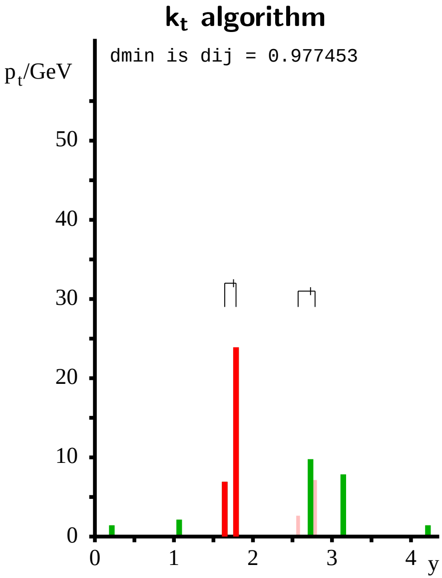

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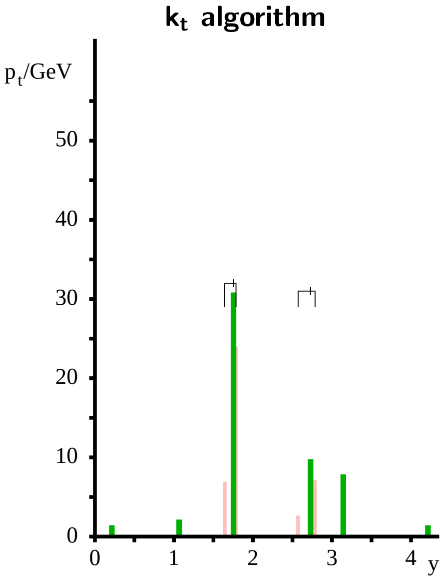

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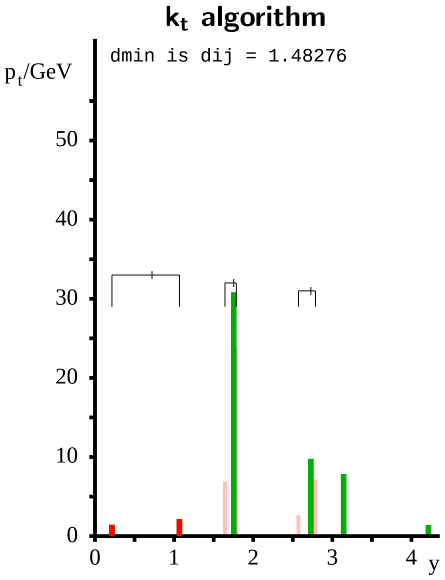

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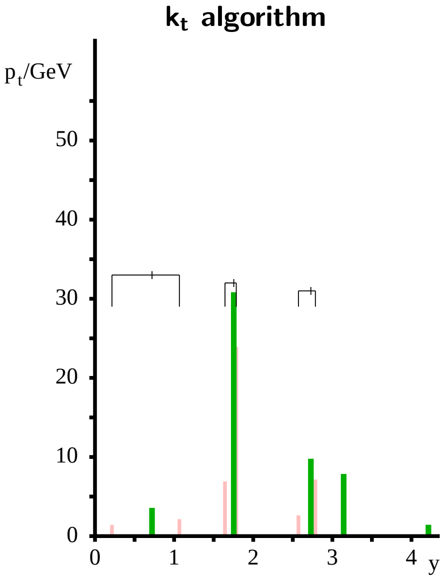

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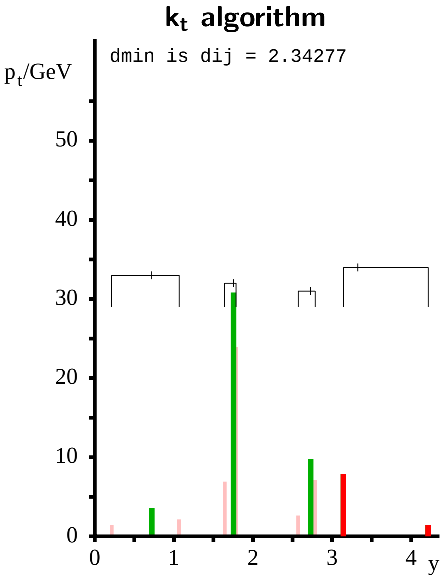

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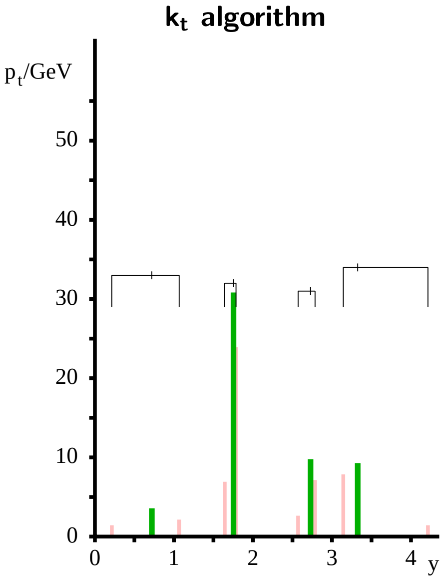

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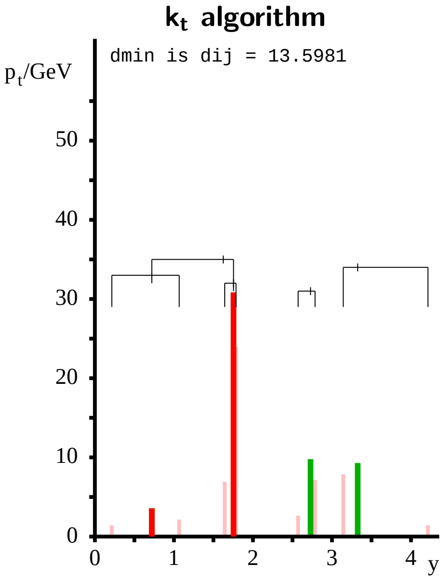

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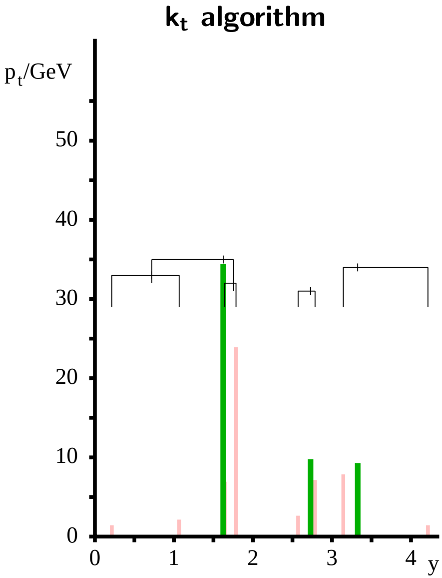

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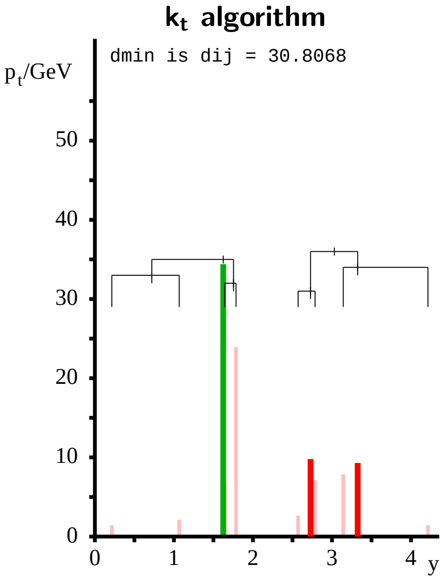

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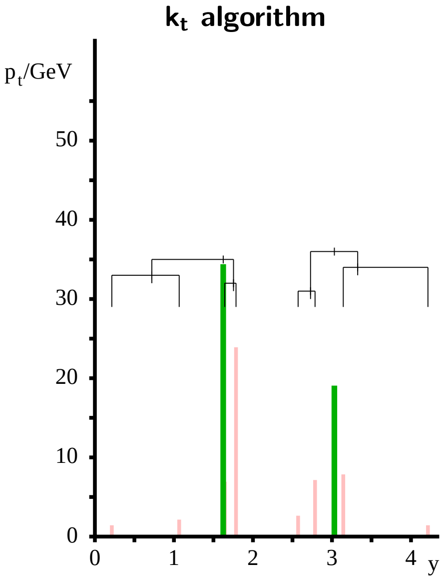

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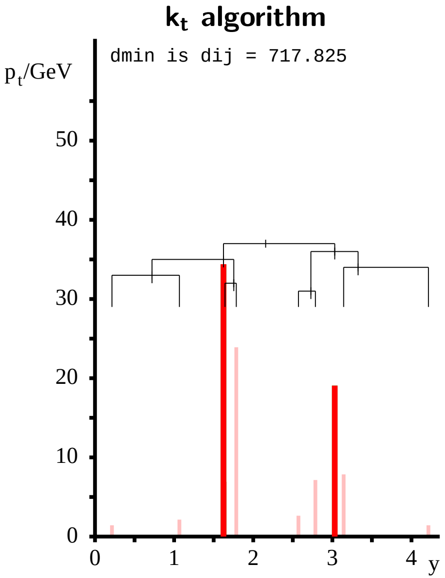

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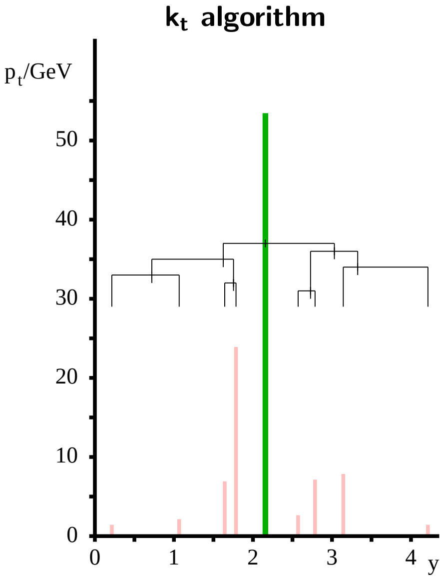

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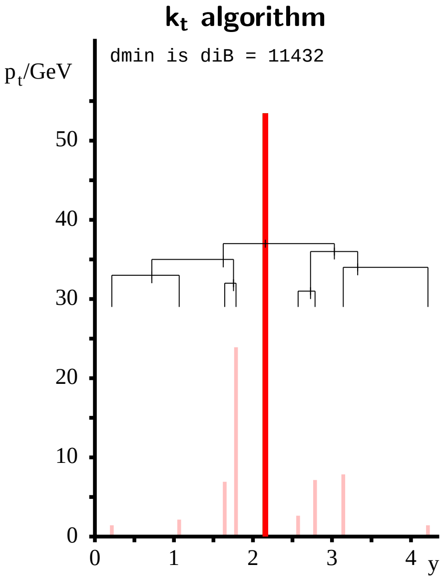

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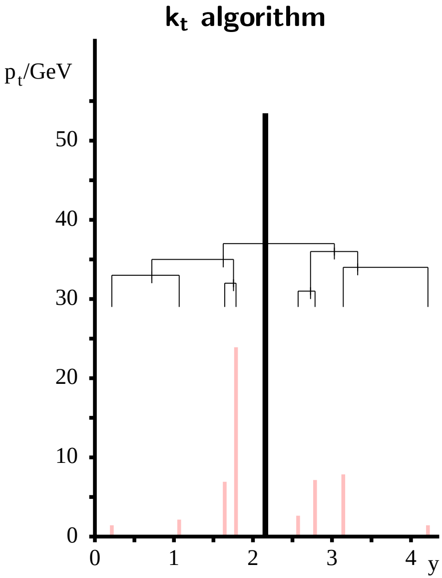

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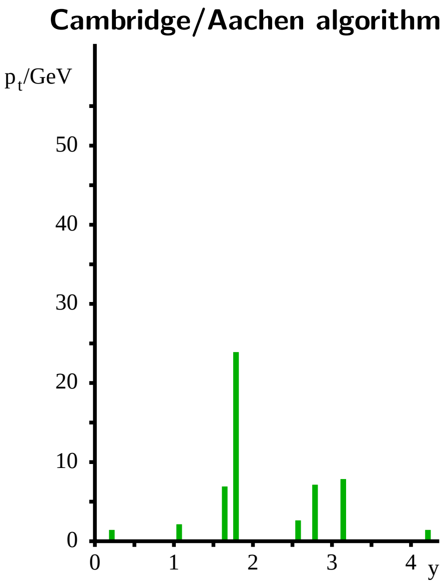
Its last step is to merge two hard pieces. Easily undone to identify underlying kinematics

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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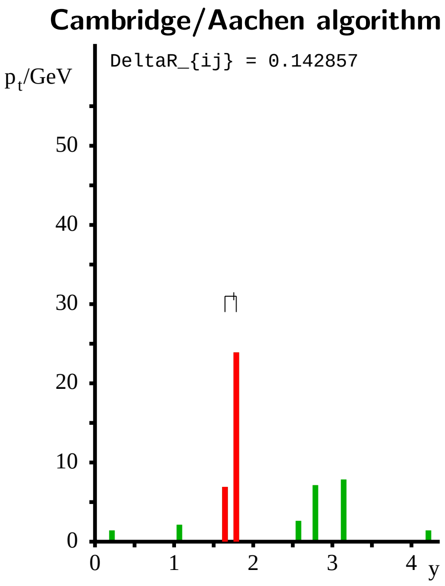

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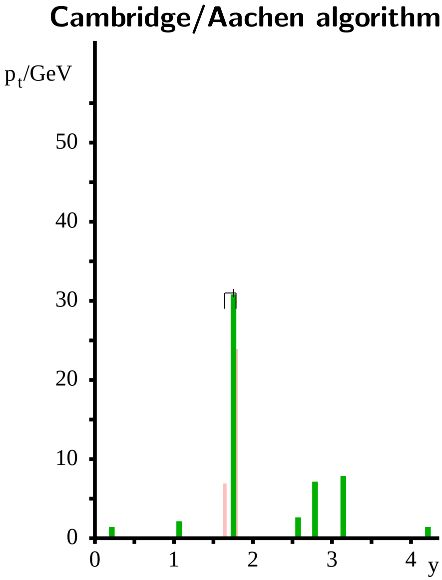

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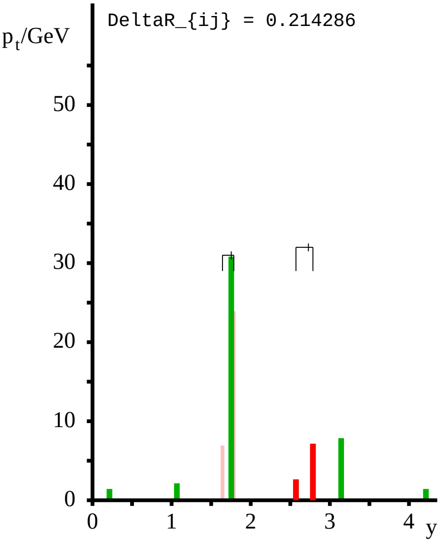

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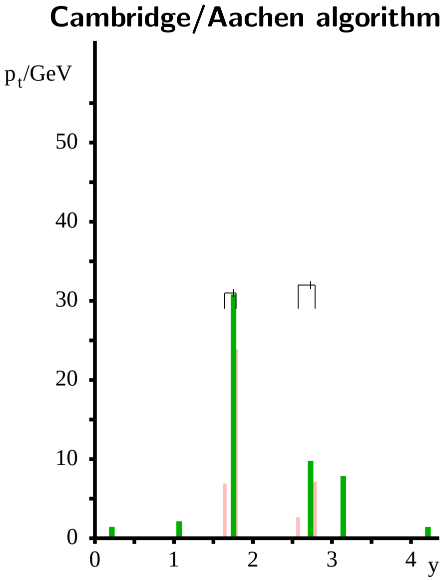

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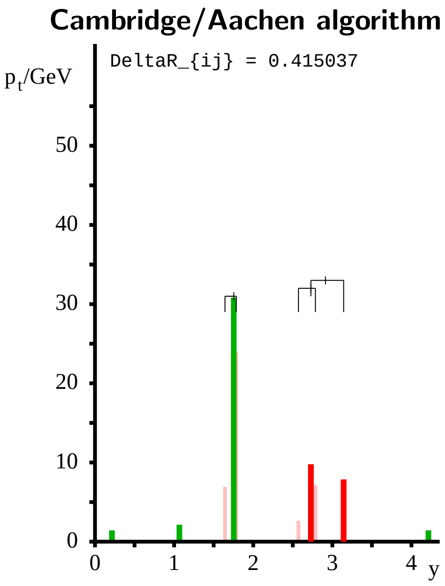

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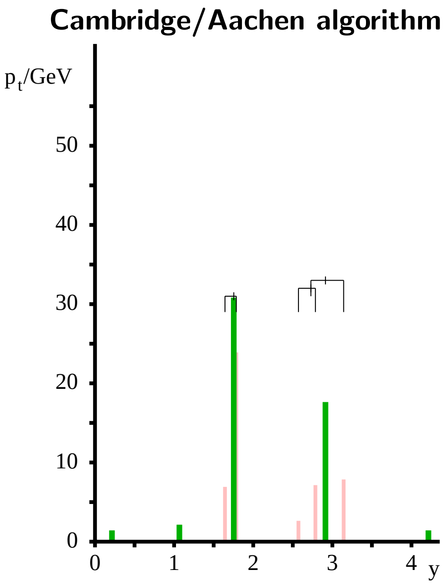

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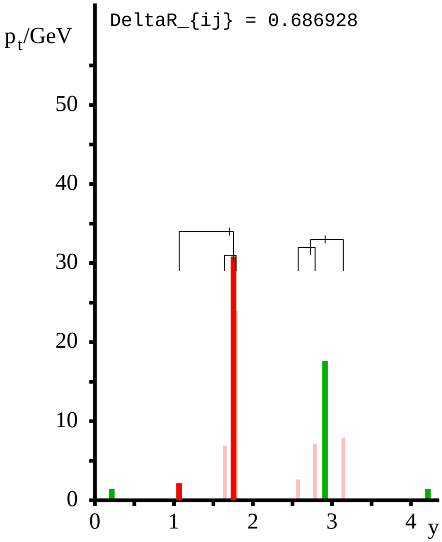

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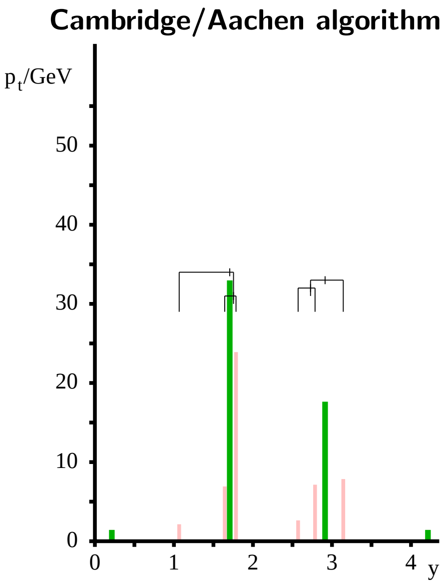

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C/A identifies two hard blobs with limited soft contamination

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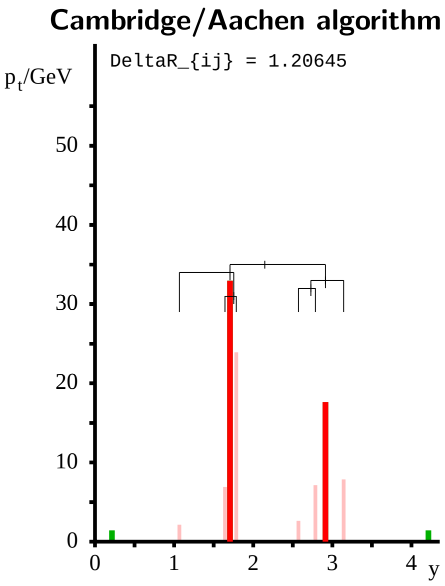

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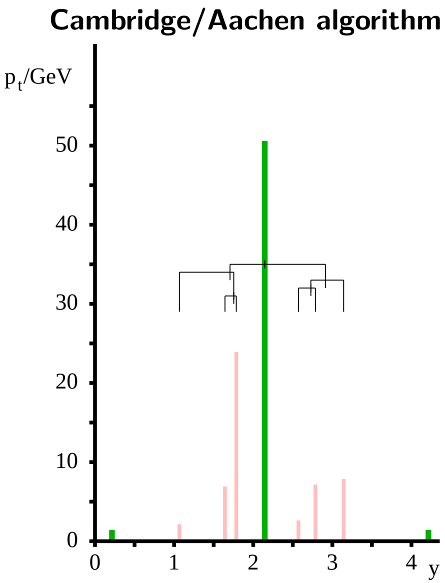

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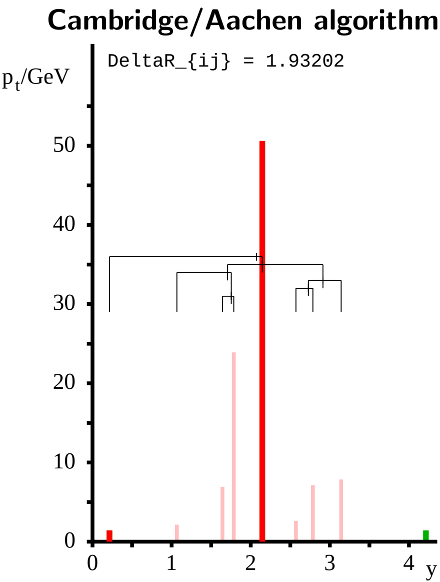

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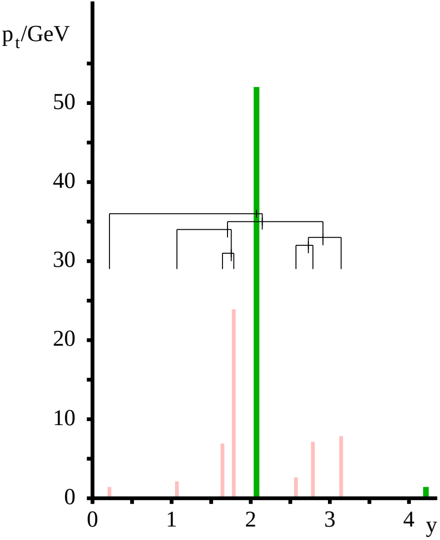

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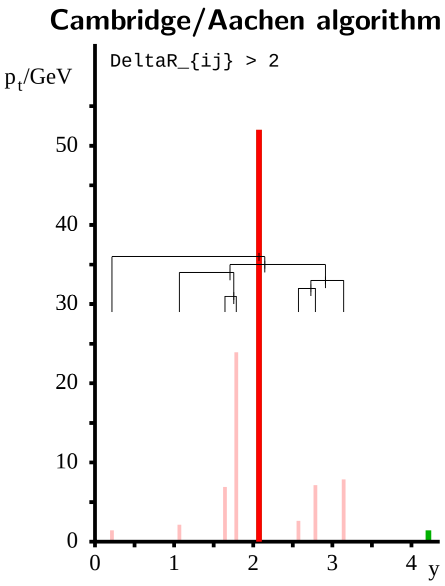

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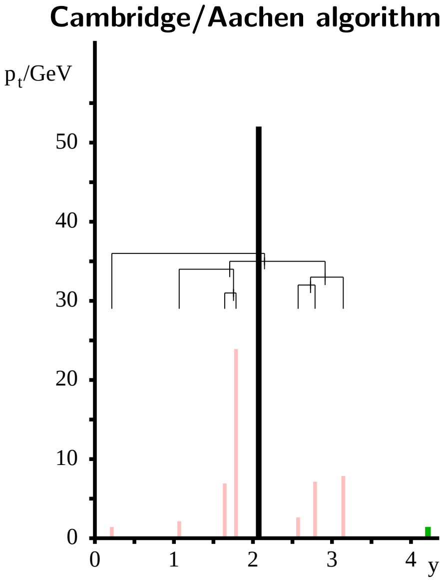

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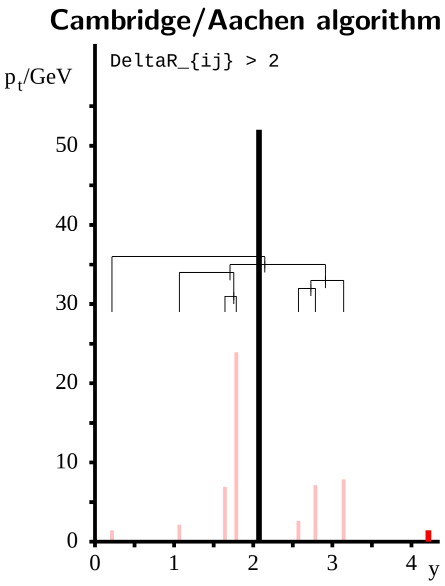

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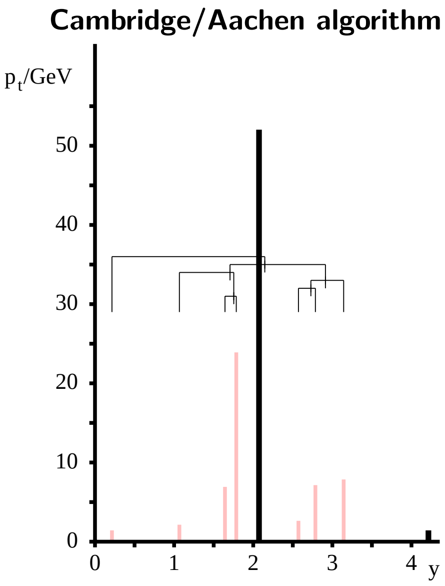

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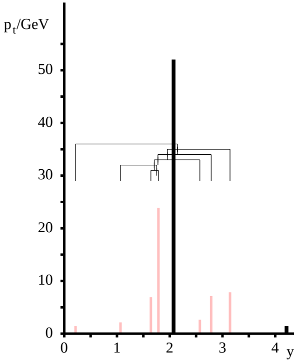
The interesting substructure is buried inside the clustering sequence — it's less contamined by soft junk, but needs to be pulled out with special techniques

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

anti-k_t algorithm



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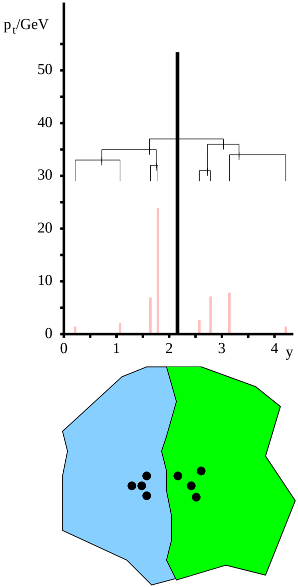

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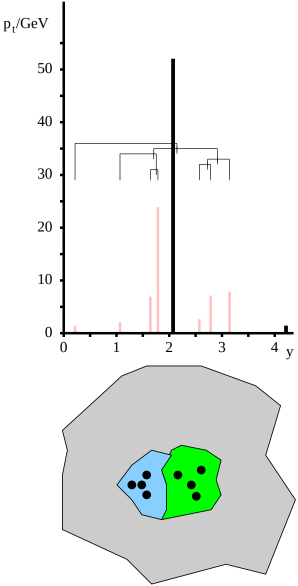
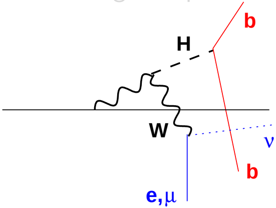


$H \to b\bar{b}$ (main light-Higgs decay) v. hard to see

Best hope is $pp \to W^{\pm}H$, $W^{\pm} \to \ell^{\pm}\nu$, $H \to b\bar{b}$.

Difficulties, e.g.

- $gg \to t\bar{t}$ has $\ell\nu b\bar{b}$ with **same intrinsic mass scale**, but much higher partonic luminosity
- Wjj background has cut-induced peak
- Need exquisite control of bkgd shape



Conclusion (ATLAS TDR):

"The extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]"

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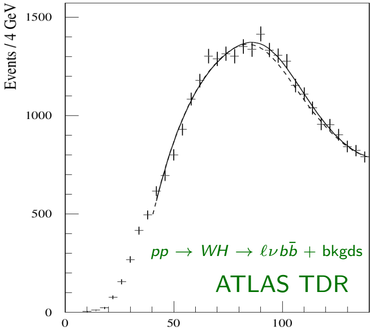

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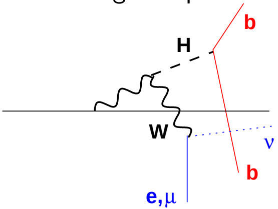

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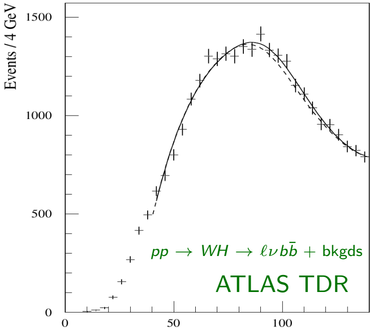

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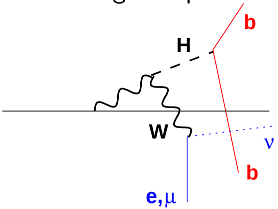

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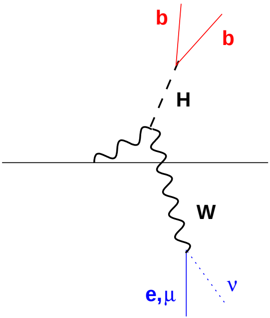
Study subset of WH/ZH with high p_t

Take advantage of the fact that $\sqrt{s} \gg M_H, m_t, \ldots$



Go to high p_t:

✓ Higgs and W/Z more likely to be central

✓ high-p_t $Z \to \nu\bar{\nu}$ becomes visible

✓ Fairly collimated decays: high-p_t $\ell^{\pm}, \nu, b$

Good detector acceptance

✓ Backgrounds lose cut-induced scale

✓ $t\bar{t}$ kinematics cannot simulate bkgd

Gain clarity and S/B

✗ Cross section will drop dramatically

By a factor of 20 for $p_{tH} > 200$ GeV

Will the benefits outweigh this?

And how do we ID high-p_t hadronic Higgs decays?

Noise removal

UE adds $\Lambda \simeq 10 - 15$ GeV of noise per unit rapidity. For a jet of size R, effect on jet mass goes as

$$\langle \delta m^2 \rangle \simeq \Lambda p_t \frac{R^4}{4} \sim 4\Lambda \frac{m^4}{p_t^3}$$

Dasgupta, Magnea & GPS '07

Filtering, Pruning & Trimming are all intended to reduce this noise.
Viewing the jet on some smaller scale R_{sub}, throw out softest subjets:

- **Filtering**: break jet into subjets on angular scale R_{filt}, take n_{filt} hardest subjets — Butterworth, Davison, Rubin & GPS '08
- **Trimming**: break jet into subjets on angular scale R_{trim}, take all subjets with $p_{t,sub} > \epsilon_{trim} p_{t,jet}$ — Krohn, Thaler & Wang '09
- **Pruning**: as you build up the jet, if the two subjets about to be recombined have $\Delta R > R_{prune}$ and $\min(p_{t1}, p_{t2}) < \epsilon_{prune}(p_{t1} + p_{t2})$, discard the softer one. — Ellis, Vermilion & Walsh '09

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Dasgupta, Magnea & GPS '07

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These techniques matter most for moderate p_t objects

(And also for high-mass resonances $\to$ jets)

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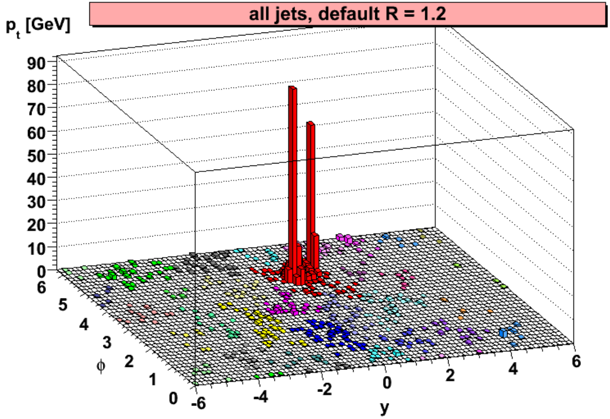
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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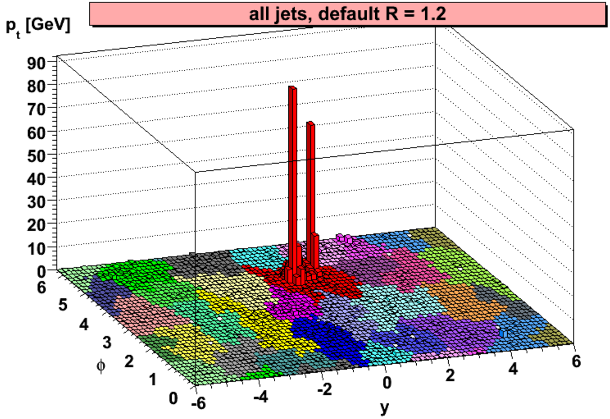

Zbb BACKGROUND

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

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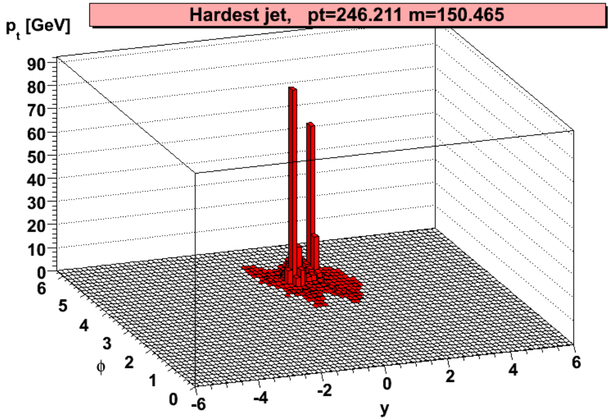

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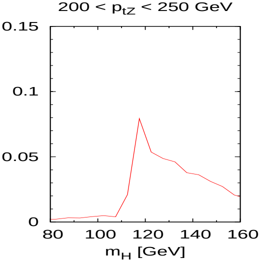

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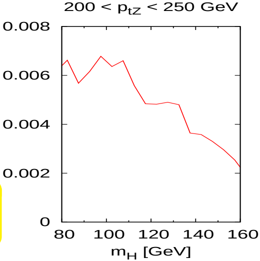

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

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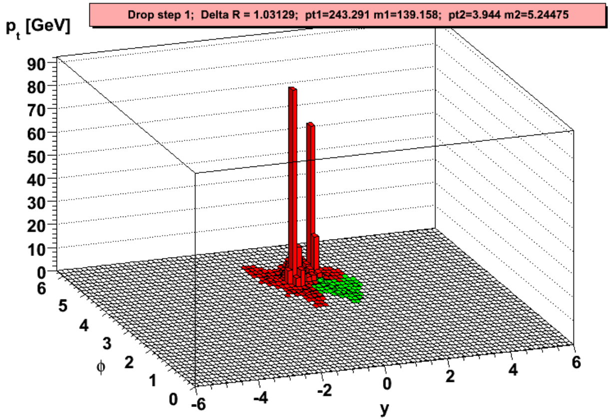
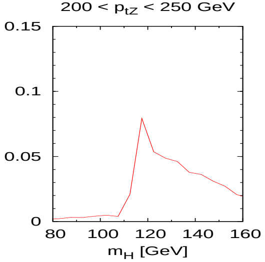


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

SIGNAL



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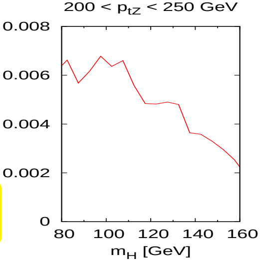

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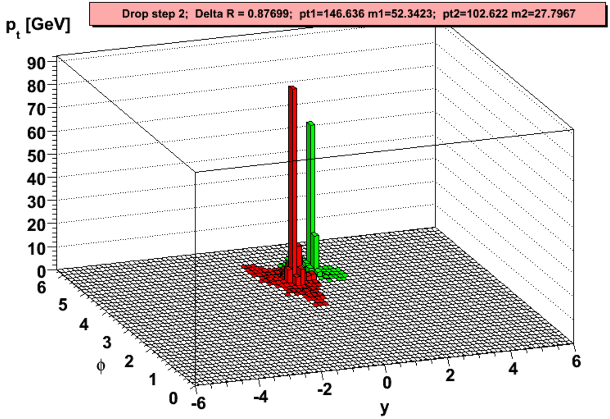
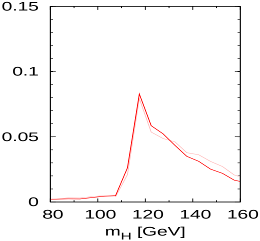


SIGNAL

$200 < p_{tZ} < 250$ GeV



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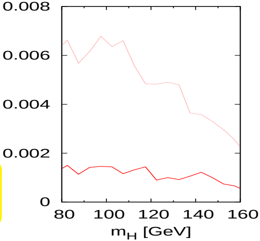

split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

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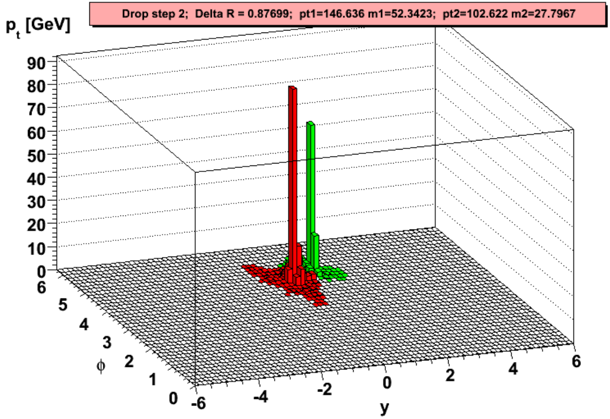

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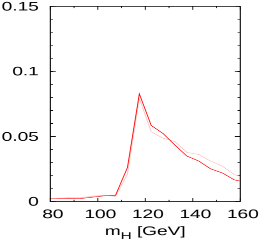

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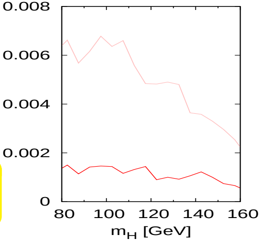

check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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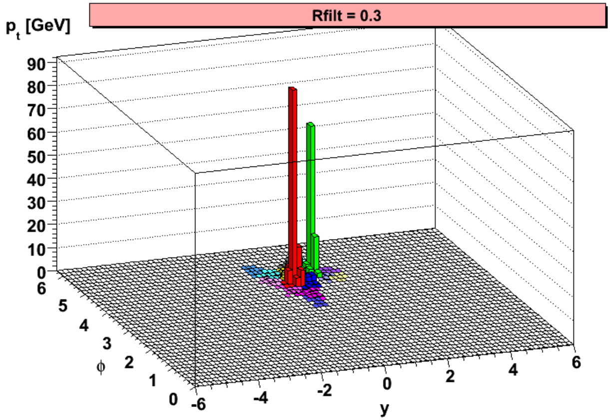
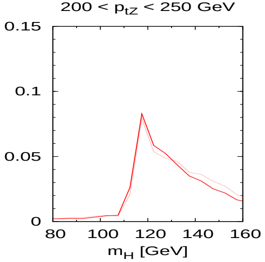
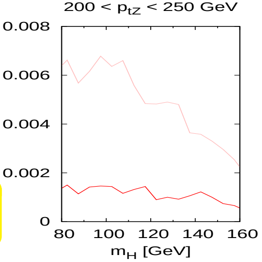
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

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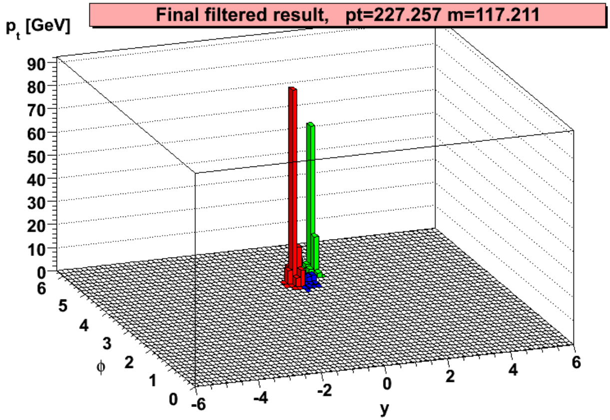

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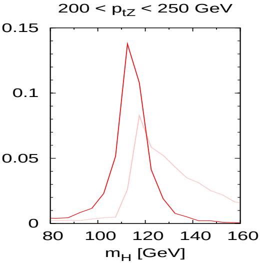

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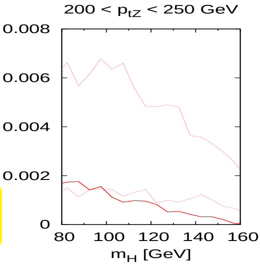
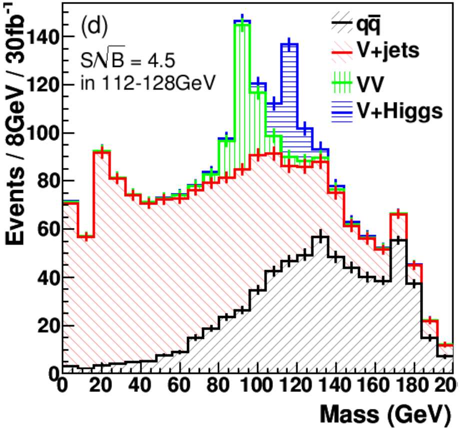


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

combine HZ and HW, $p_t > 200$ GeV



- Take $Z \to \ell^+\ell^-$, $Z \to \nu\bar{\nu}$, $W \to \ell\nu$ $\quad \ell = e, \mu$
- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_V|, |\eta_H| < 2.5$
- Assume real/fake b-tag rates of 0.6/0.02.
- Some extra cuts in HW channels to reject $t\bar{t}$.
- Assume $m_H = 115$ GeV.

At $\sim 5\sigma$ for 30 fb^{-1} this looks like a competitive channel for light Higgs discovery. **A powerful method!**

Currently under study in the LHC experiments

ATLAS combined results

Likelihood-based analysis of all three channels together gives signal significance of

3.7σ for 30 fb^{-1} (14 TeV)

To be compared with 4.2σ in hadron-level analysis for $m_H = 120$ GeV

K-factors not included: don't affect significance (~ 1.5 for VH, $2 - 2.5$ for Vbb)

With 5% (20%) background uncertainty, ATLAS result becomes 3.5σ (2.8σ)

Comparison to other channels at ATLAS ($m_H = 120$, 30 fb^{-1}):

$gg \to H \to \gamma\gamma$	$WW \to H \to \tau\tau$	$gg \to H \to ZZ^*$
4.2σ	4.9σ	2.6σ

Extracted from 0901.0512

Tagging boosted top-quarks

Many papers on top tagging in '08-'11: jet mass + something extra.

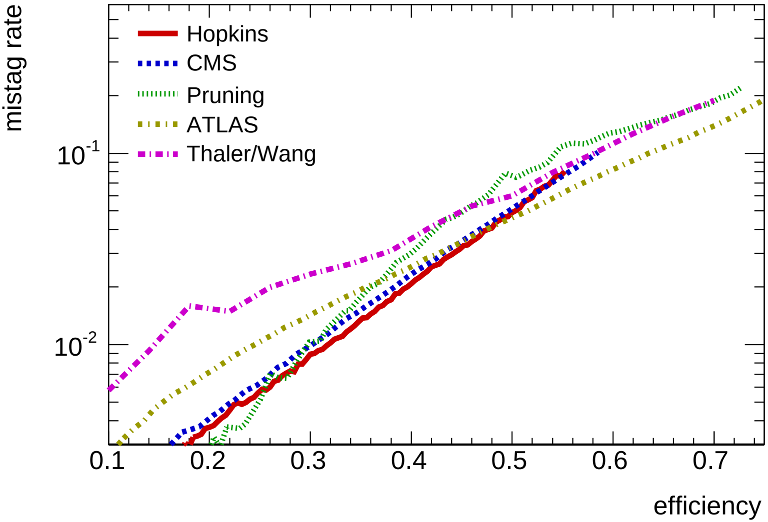
Questions

- What efficiency for tagging top?
- What rate of fake tags for normal jets?

Rough results for top quark with $p_t \sim 1$ TeV

	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang '08	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Chekanov & P. '10	Jet shapes	60%	10%
Almeida et al. '08–'10	Template + shapes	13%	0.02%
Thaler & v Tilburg '10	Subjettiness	40%	2%
Plehn et al. '09–'10	C/A MD, θ_h/Dalitz [busy evs, $p_t \sim 300$]	35%	2%

Comparison of top taggers



Boost 2010 conference proceedings

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

[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

Other work → improving the methods

- Using matrix-element methods for the substructure — Done analytically
  Soper & Spannowsky '11
  Most "physically interesting"

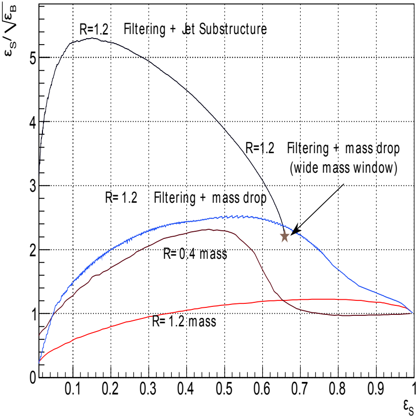
- Using jet shapes. E.g. subjettiness: break a jet into subjets $1, 2, \ldots N$

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

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

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

Cacciari, GPS & Soyez '08

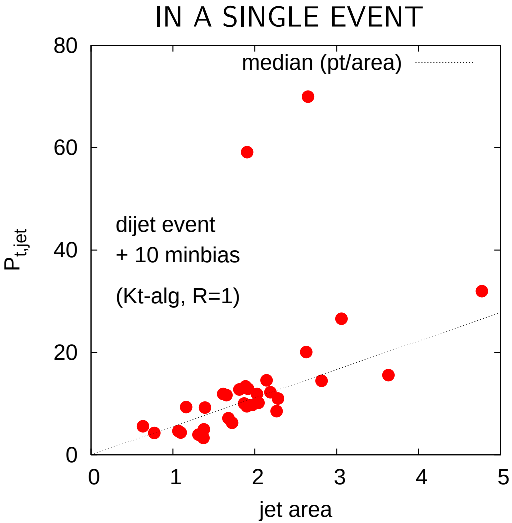
$$A_{jet} = \text{jet area}$$

$$\rho = p_t \text{ per unit area from pileup}$$
(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.

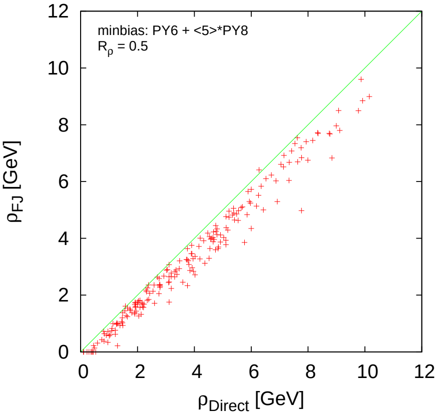
Estimate ρ:

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

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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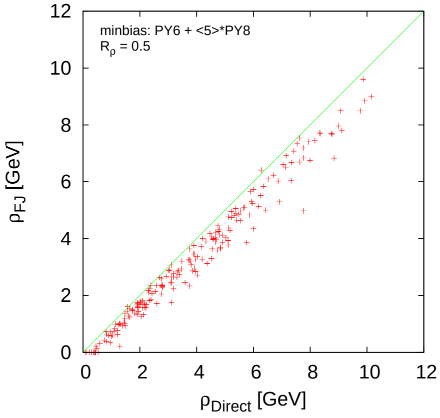
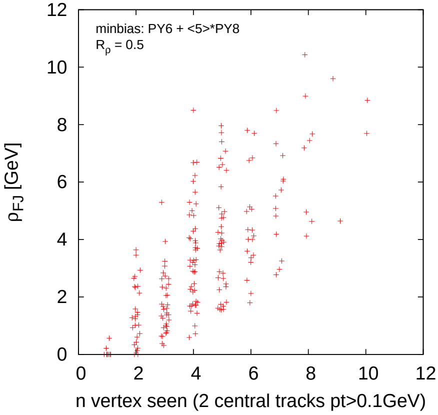


Works much better than counting primary vertices



A non-trivial issue: rapidity dependence

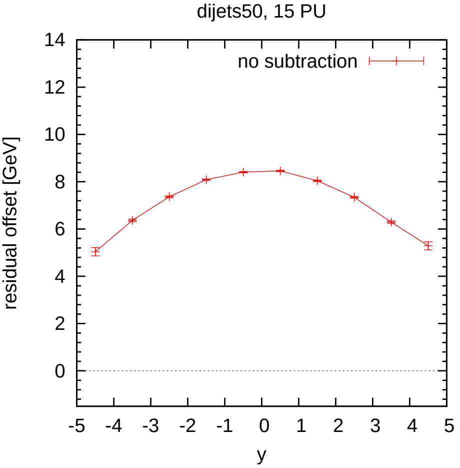
The original method assumed rapidity dependence was small

- 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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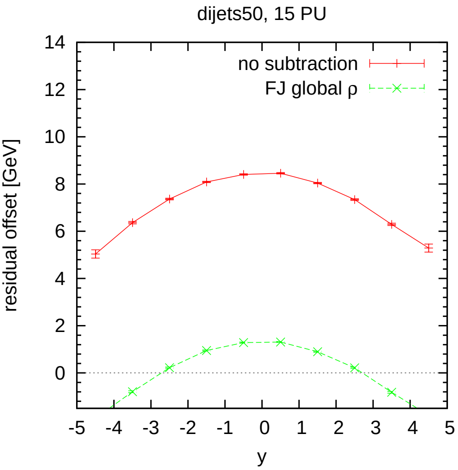

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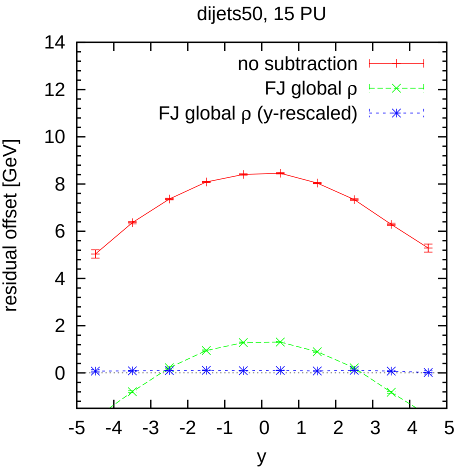

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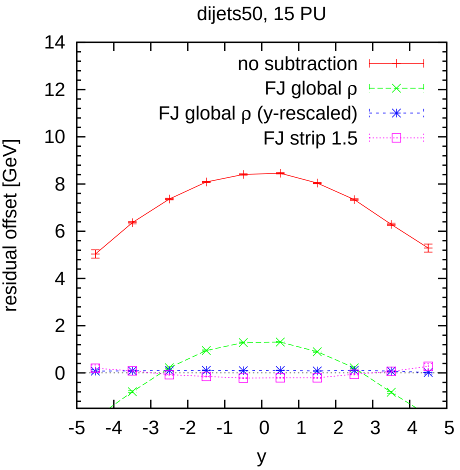

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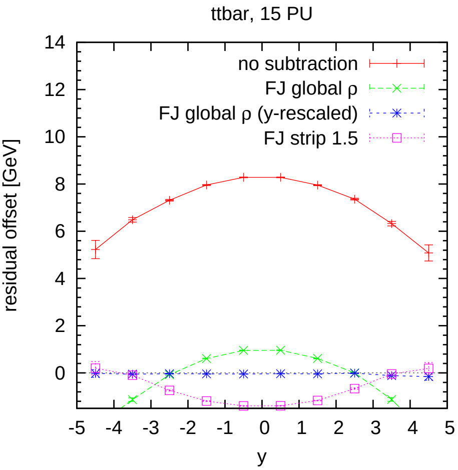

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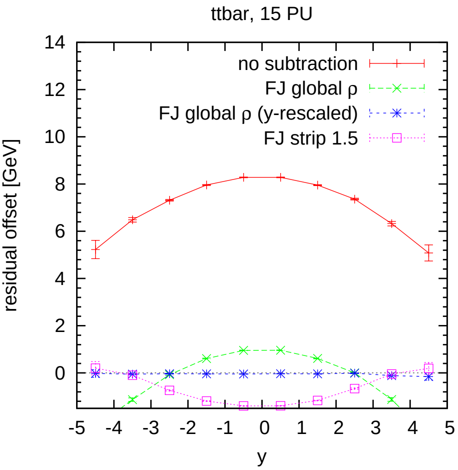

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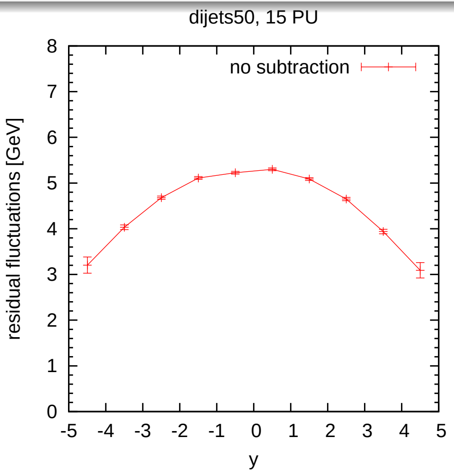
Hints from charged tracks

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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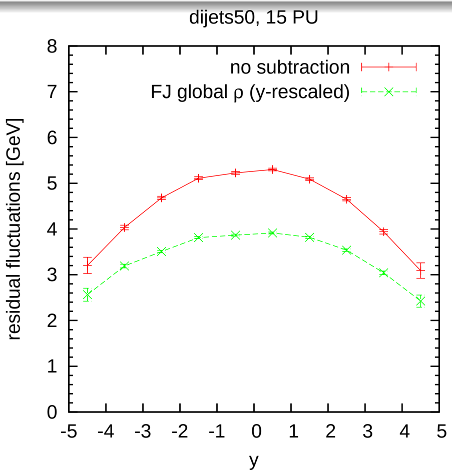

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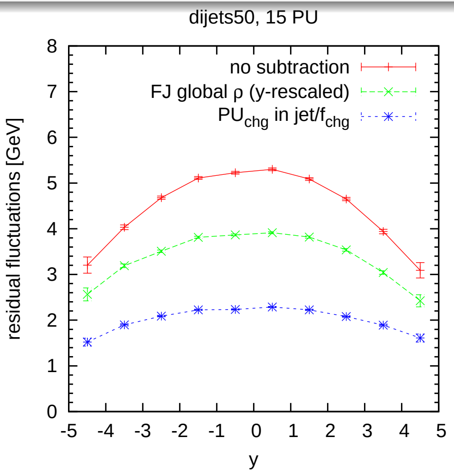

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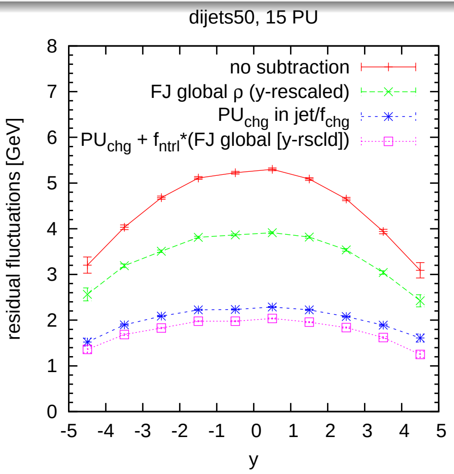

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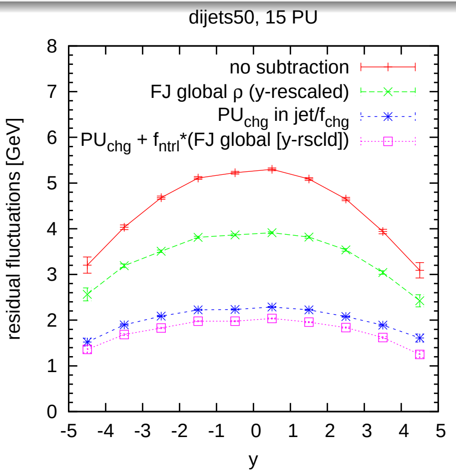

Direct knowledge of PU from tracks can be beneficial

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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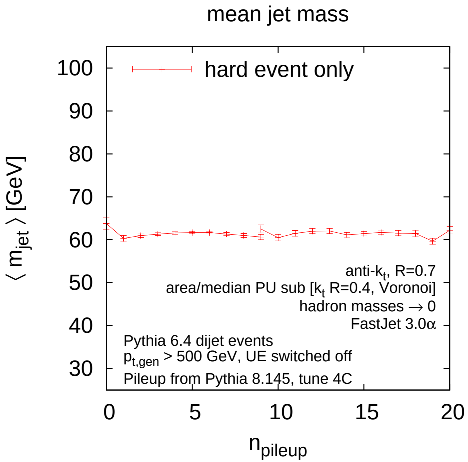

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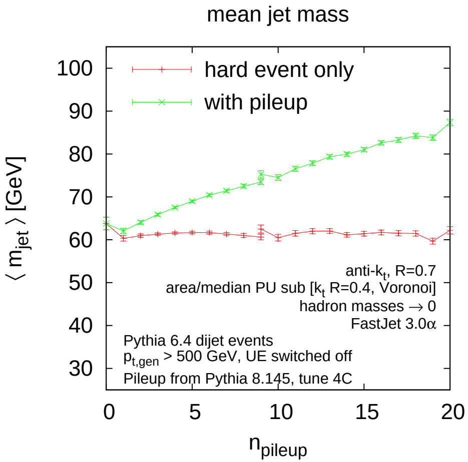

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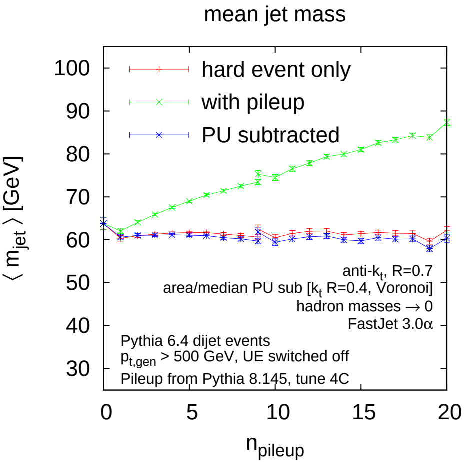

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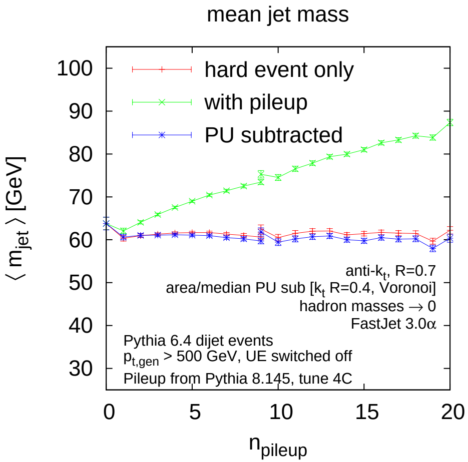

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