Towards Jetography

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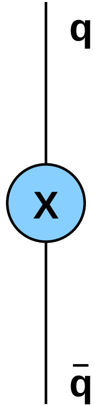
LPTHE, CNRS and UPMC (Univ. Paris 6)

DESY Theory Seminar
18 November 2008

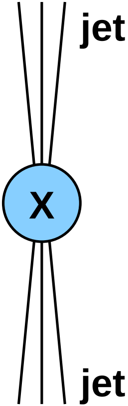
Based on papers with
Jon Butterworth, Matteo Cacciari, Mrinal Dasgupta, Adam Davison,
Lorenzo Magnea, Juan Rojo, Mathieu Rubin & Gregory Soyez

Jets & LHC



We never see quarks or gluons, only jets

Jets & LHC



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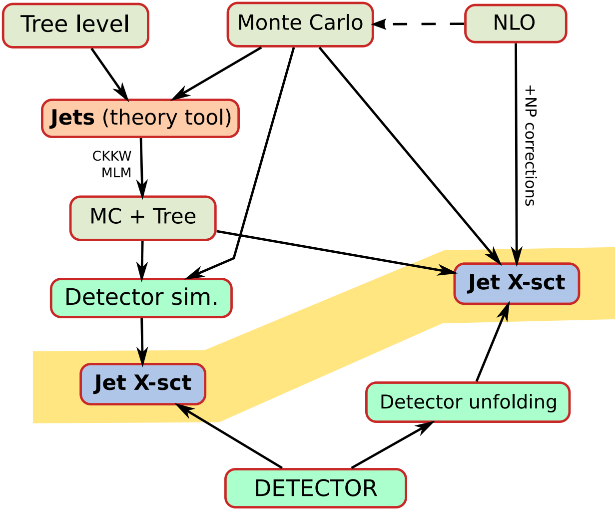
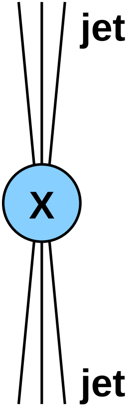
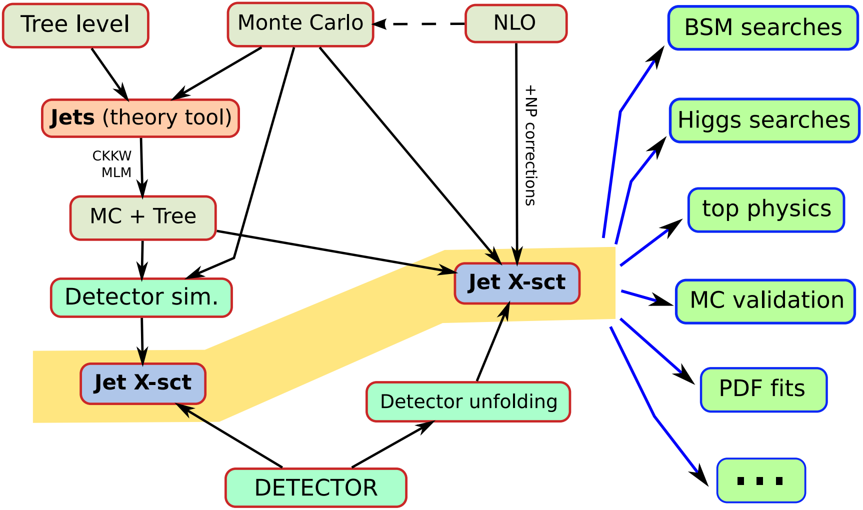




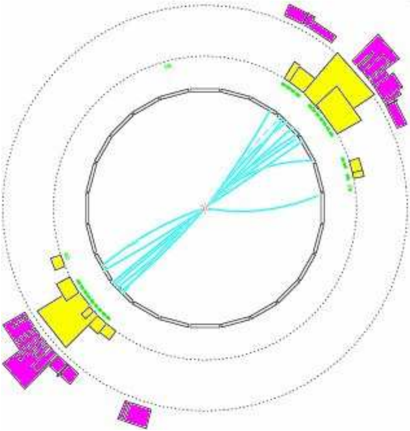
Jets are commong language of experiment and theory

Jets & LHC



And the input to nearly all hadronic analyses

Seeing v. defining jets



Jets are what we see.
Clearly(?) 2 of them.

2 partons?
$E_{parton} = M_z/2$?

How many jets do you see?
Do you really want to ask yourself this question for 10^8 events?

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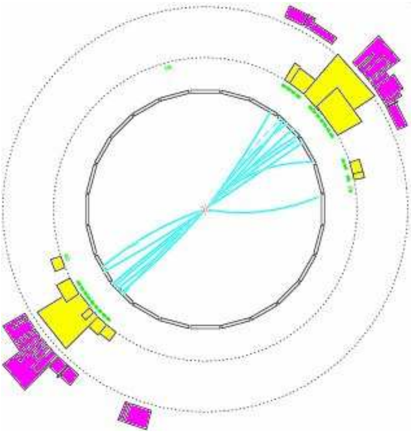

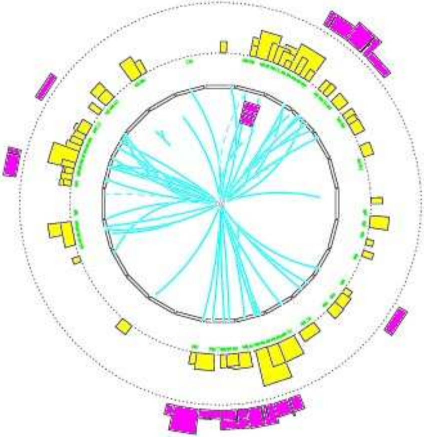

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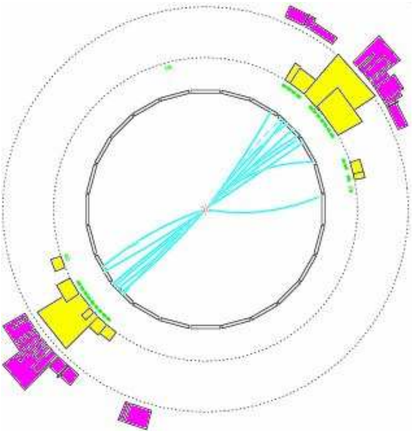

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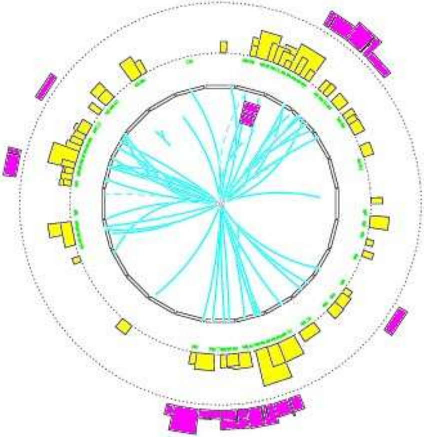

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Les Houches 2007 proceedings, arXiv:0803.0678

jet definition

jet algorithm

$\{p_i\} \longrightarrow \{j_k\}$

particles,
4-momenta,
calorimeter towers, ...

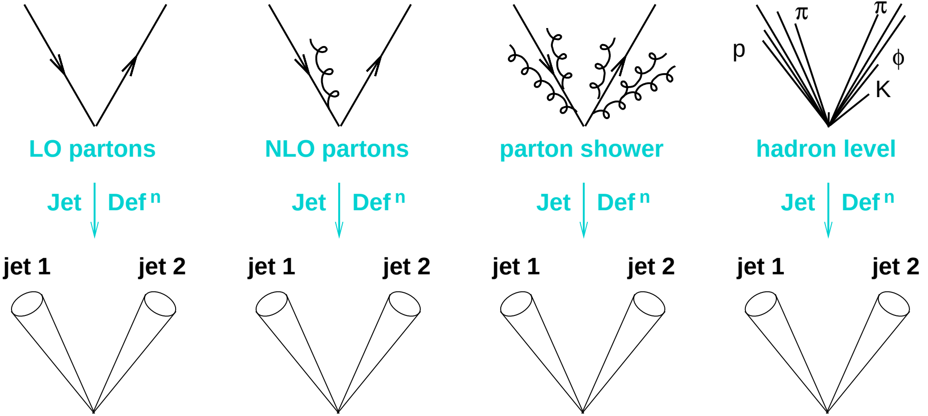
jets

+ parameters (usually at least the radius R)

+ recombination scheme

Reminder: running a jet definition gives a well defined physical observable, which we can measure and, hopefully, calculate

Jets as projections



Projection to jets should be resilient to QCD effects

Which jet definition(s) for LHC?

Can we address this question scientifically?

Jetography

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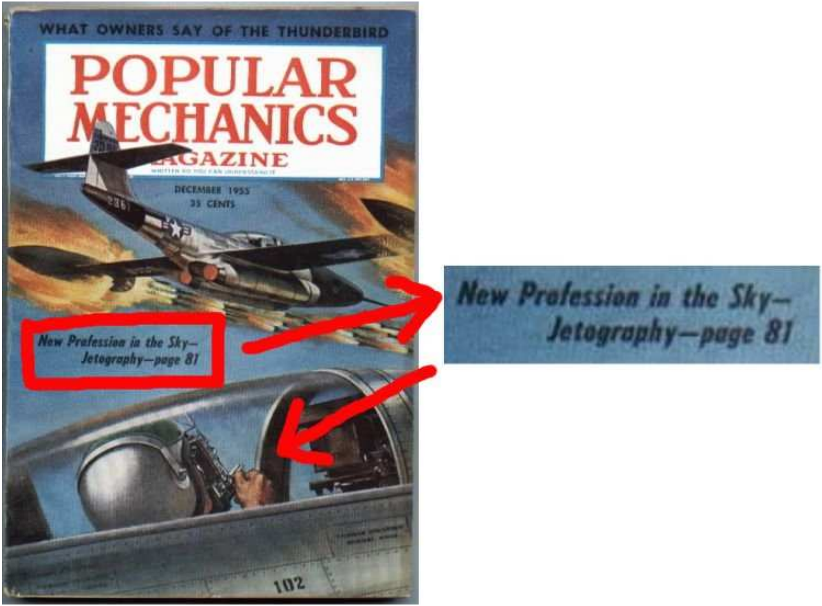

Question #1:
What's wrong with what we have?

HERA, Tevatron v. LHC

HERA:

- jets from 5 – 100 GeV
- very quiet environment

use single jet-def:
k_t with $R = 1$

Tevatron:

- jets from 50 – 500 GeV
- some noise: 2 – 10 GeV/unit rapidity
- multi-jet important (e.g. $t\bar{t} \to 6$ jets)

use two jet-defs: cone with $R = 0.4$, $R = 0.7$

LHC:

- jets from 50 – 5000 GeV [that's why it's being built]
- lots of noise: 10 – 100 GeV/unit rapidity [high-lumi pileup]
- multi-jet still important (e.g. $t\bar{t} \to 6$ jets)

2 orders of magnitude in jet energy + 1 order of magnitude in noise
"Fixed-focus" jet finding just won't be good enough at LHC

Just as fixed-focus cameras aren't adequate for professional photography

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Question #2: what jet algorithms are out there?

sequential recombination (k_t)
& cone type

Sequential recombination (k_t alg)

Sequential recombination algorithms:

- introduce distance d_{ij} between pairs of particles
- combine closest pair into one
- repeat

k_t algorithm: Catani et al '91–93
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- $d_{ij} = \min(k_{ti}^2, k_{tj}^2)(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)/R^2$
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One parameter, R, sets the angular reach for the jets

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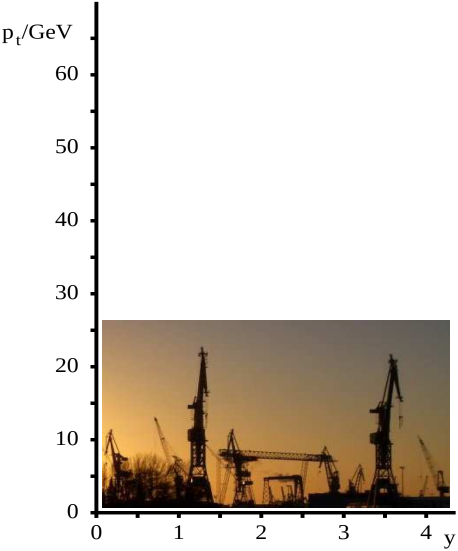

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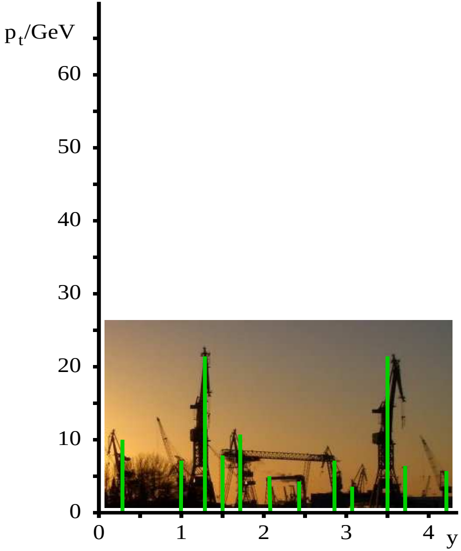

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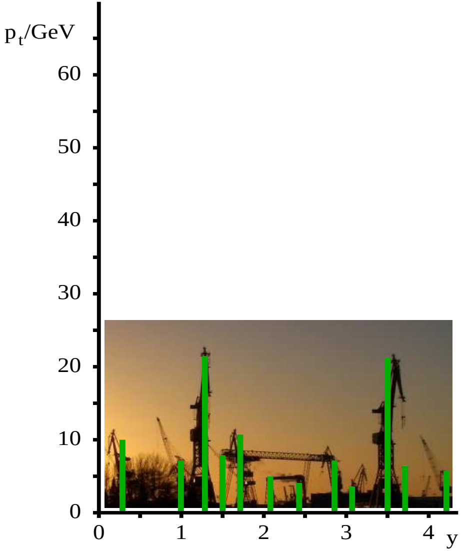

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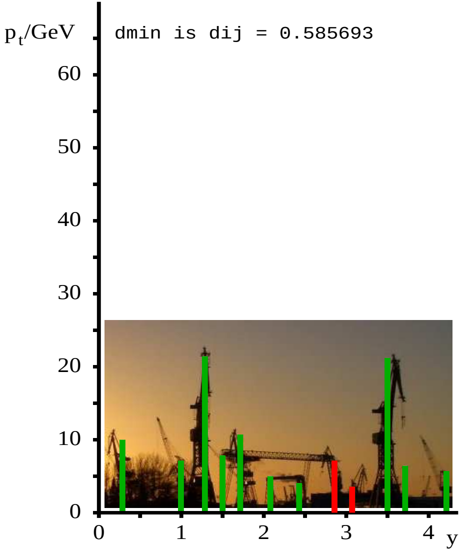

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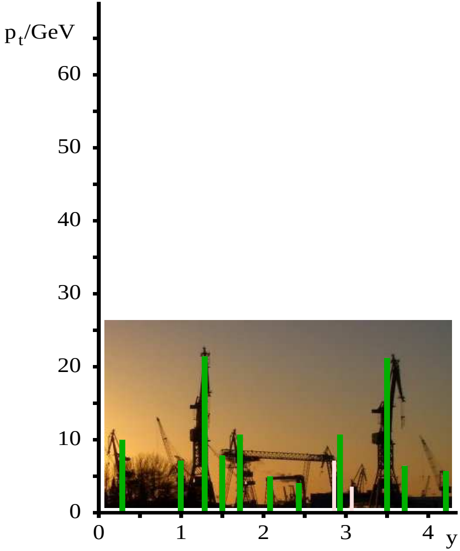

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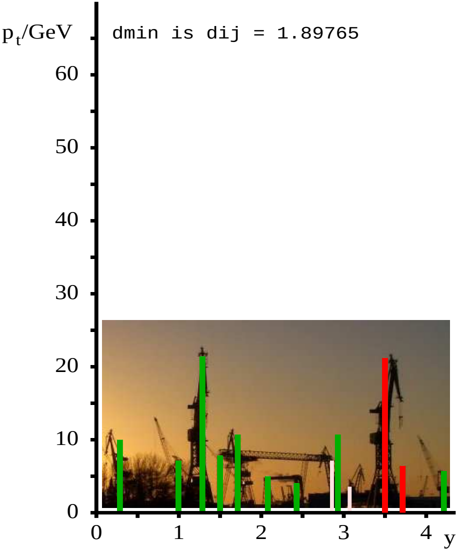

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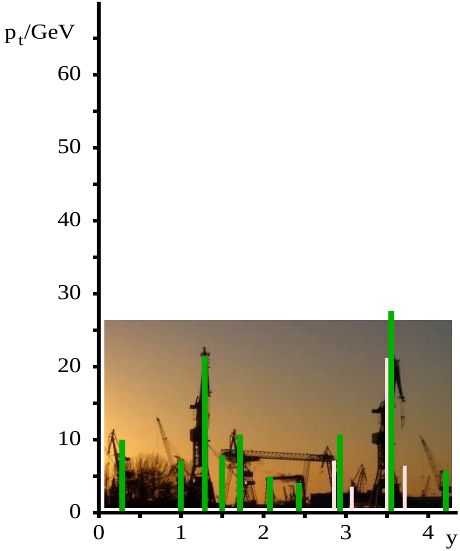

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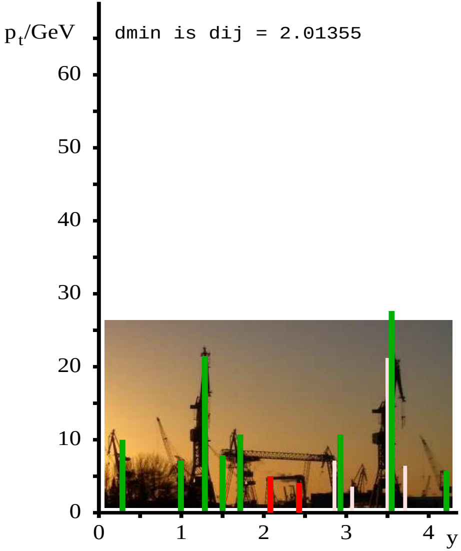

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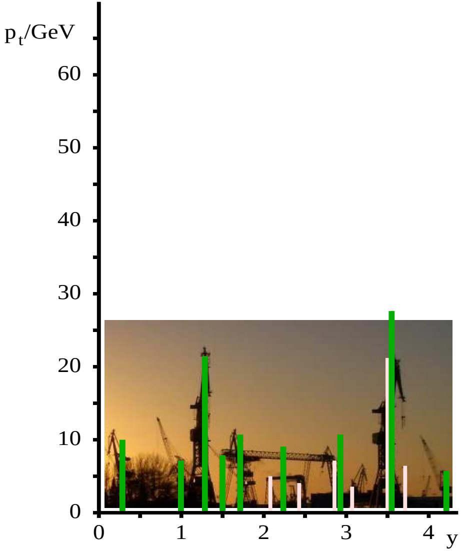

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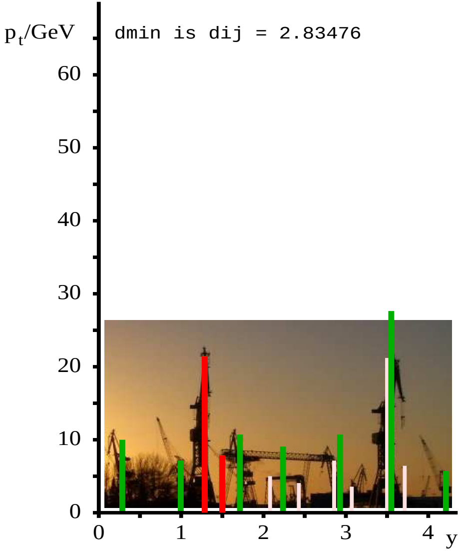

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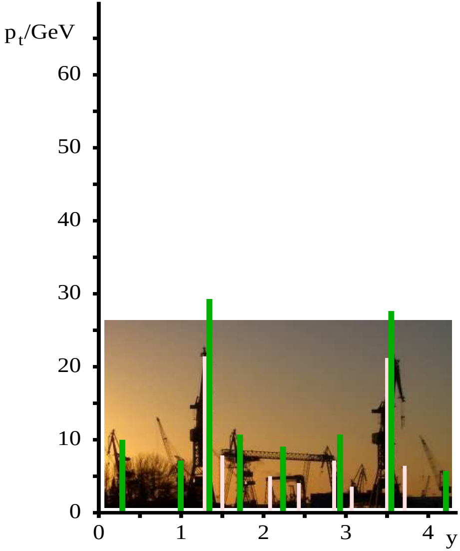

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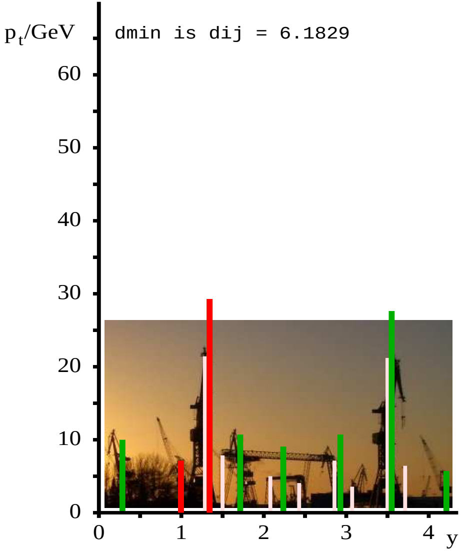

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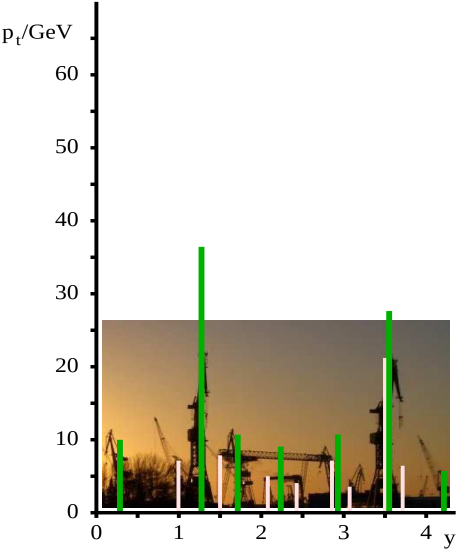

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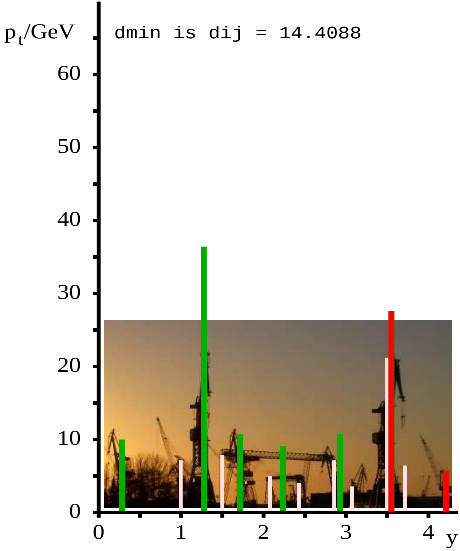

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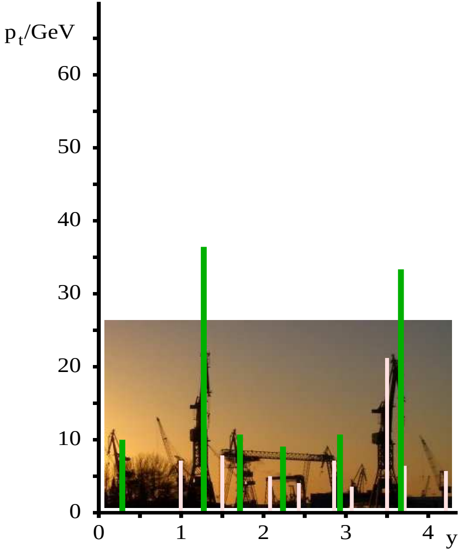

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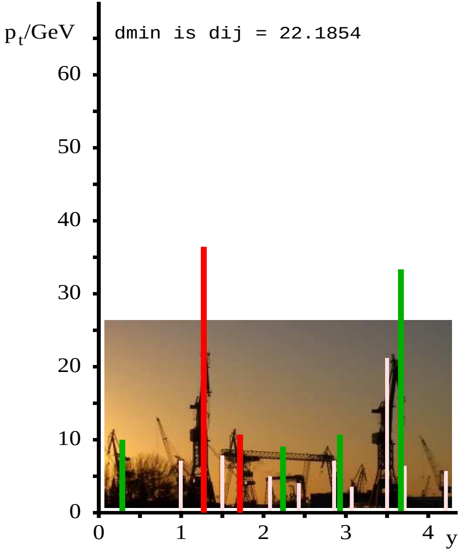

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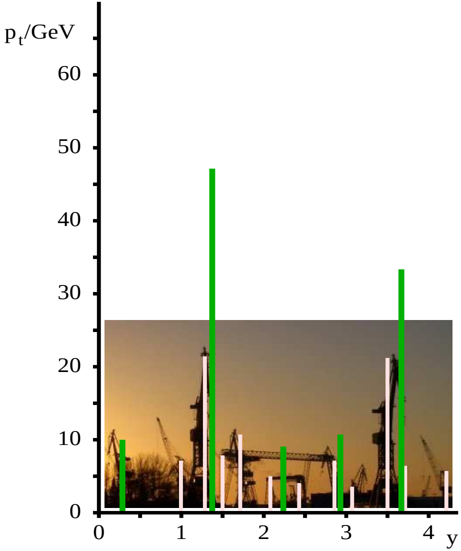

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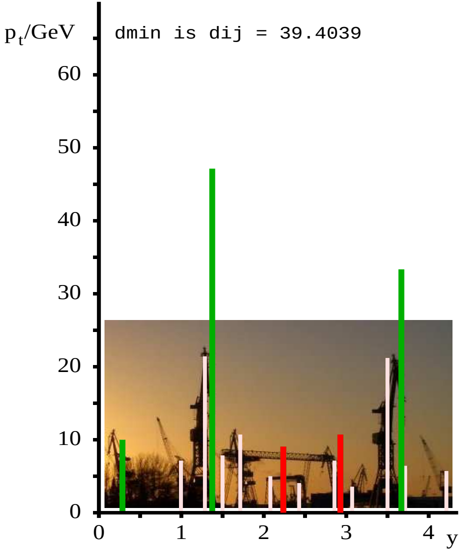

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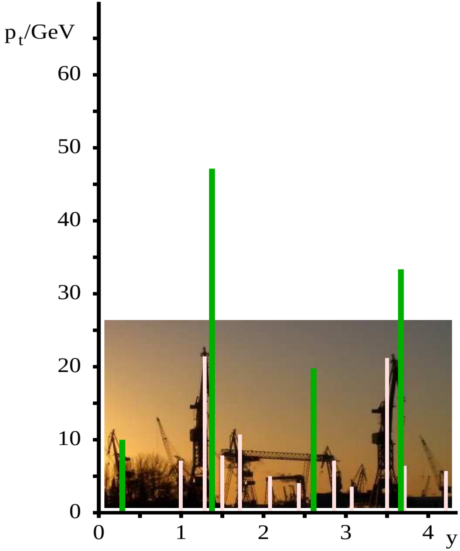

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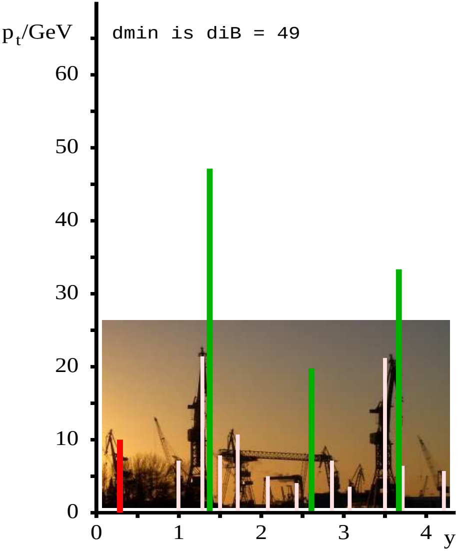

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- $d_{ij} = \min(k_{ti}^2, k_{tj}^2)(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)/R^2$
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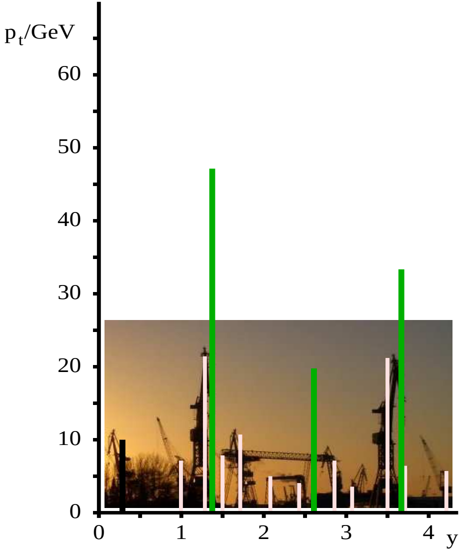

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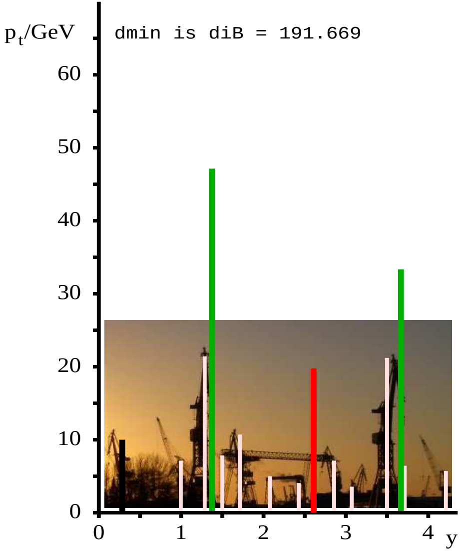

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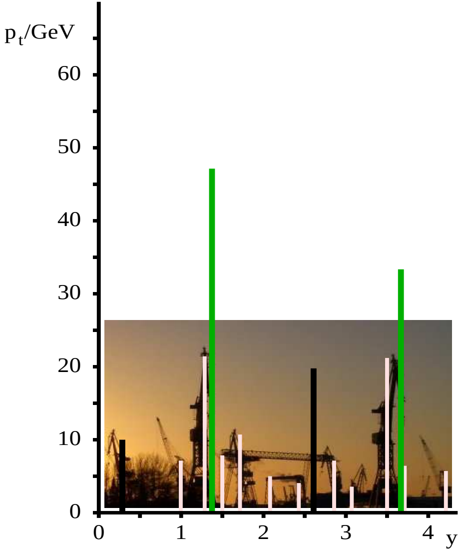

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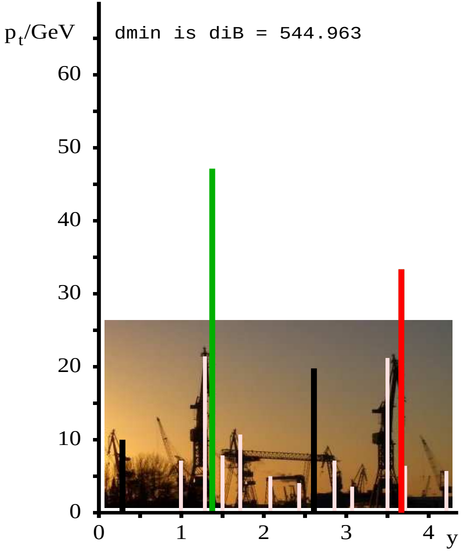

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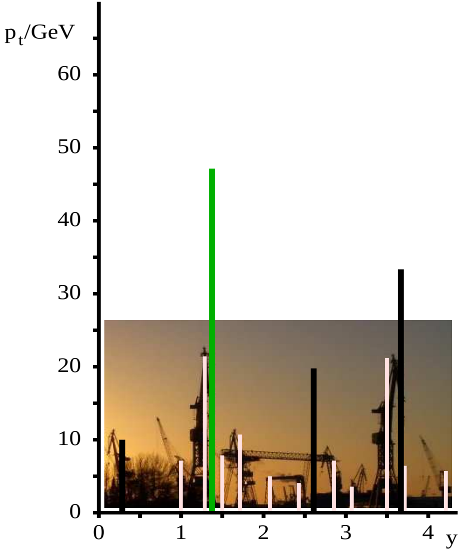

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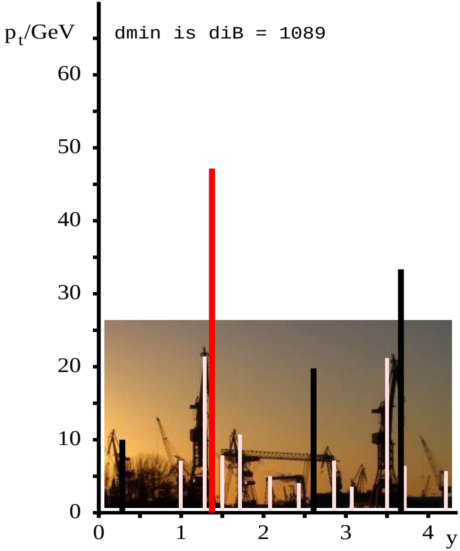

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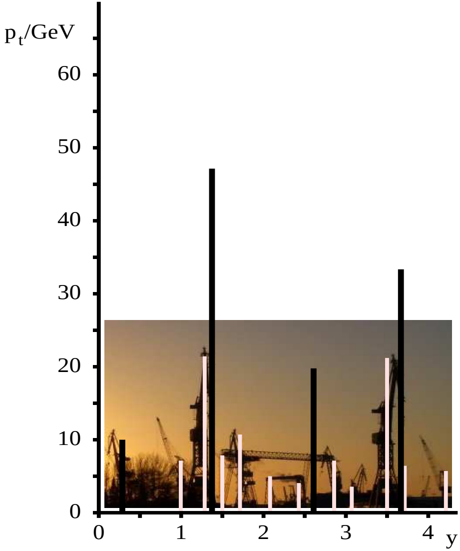

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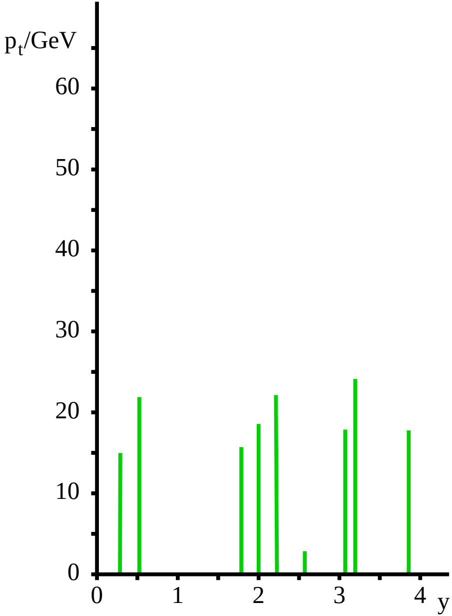

Aim to identify *all* stable cones, independently of any seeds

Procedure in 1 dimension (y):

- find all distinct enclosures of radius R by repeatedly sliding a cone sideways until edge touches a particle
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In 2 dimensions (y,ϕ) can design analogous procedure **SISCone**

GPS & Soyez '07

This gives an IRC safe cone alg.

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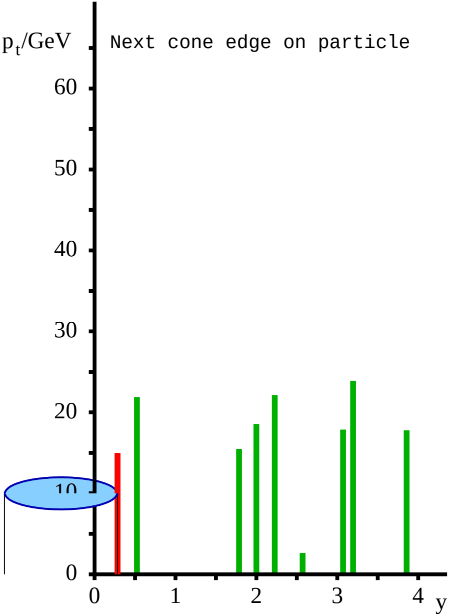

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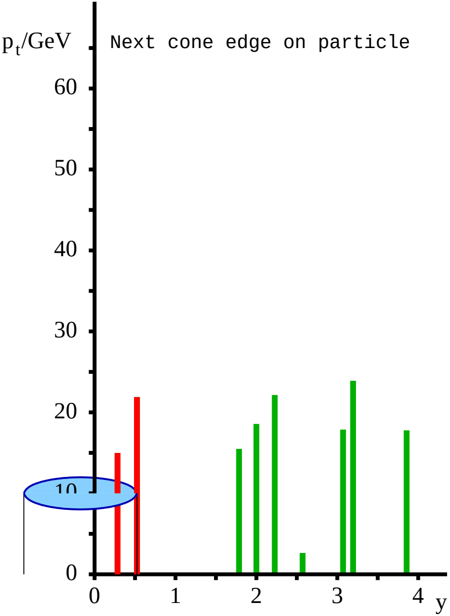

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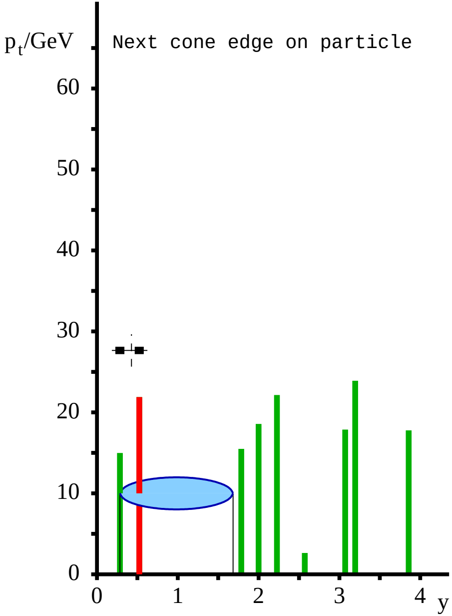

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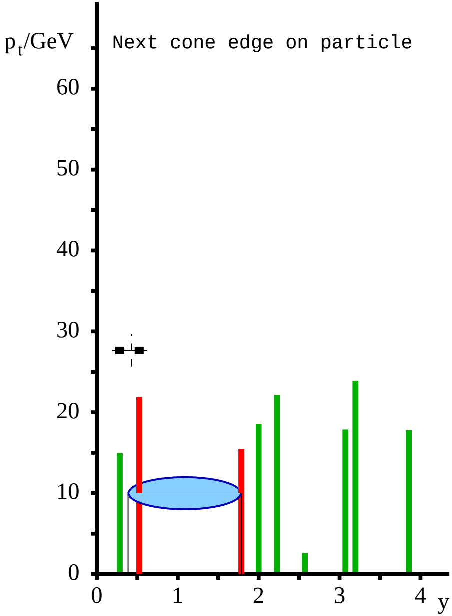

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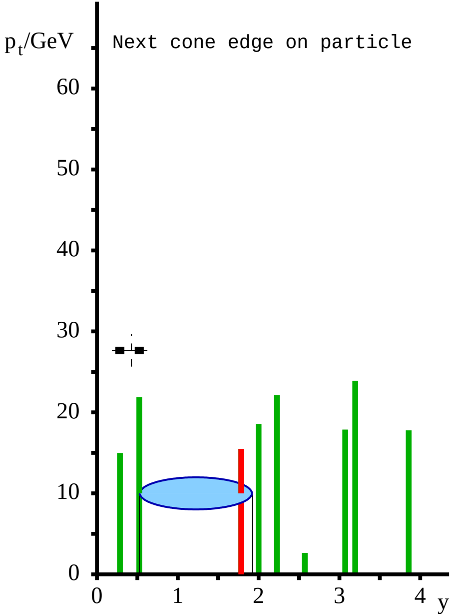

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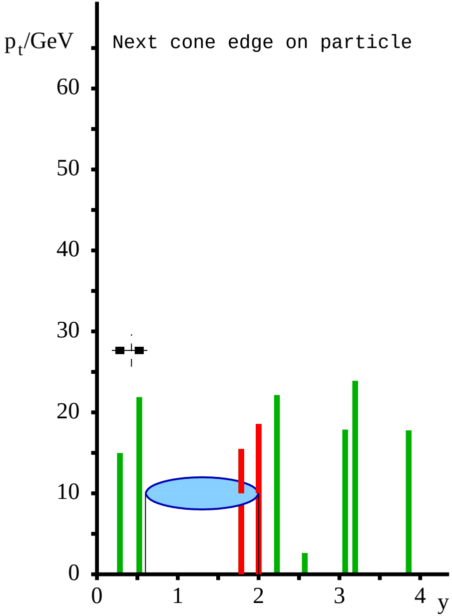

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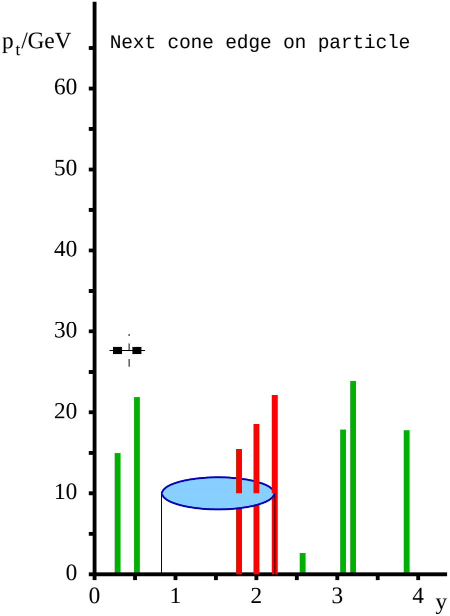

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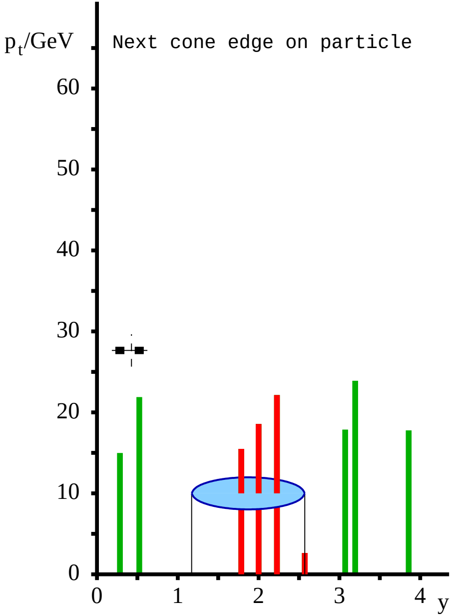

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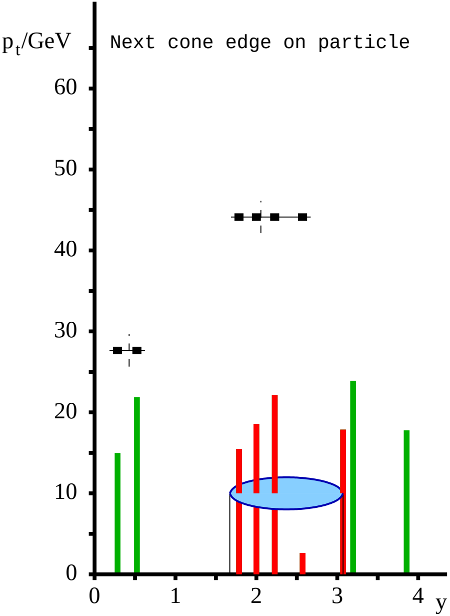

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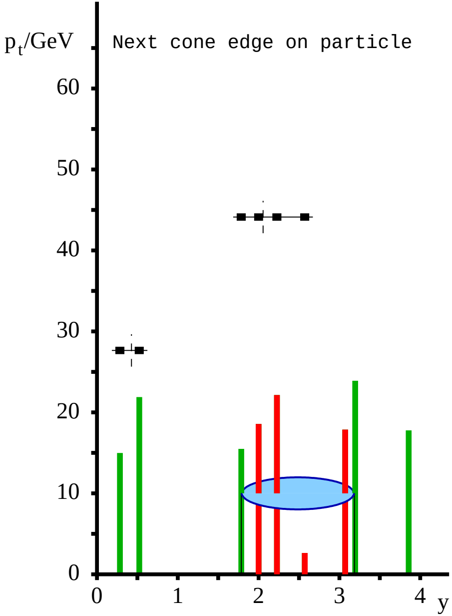

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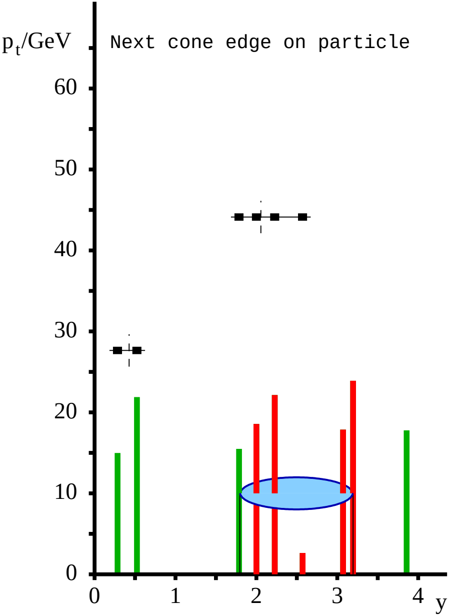

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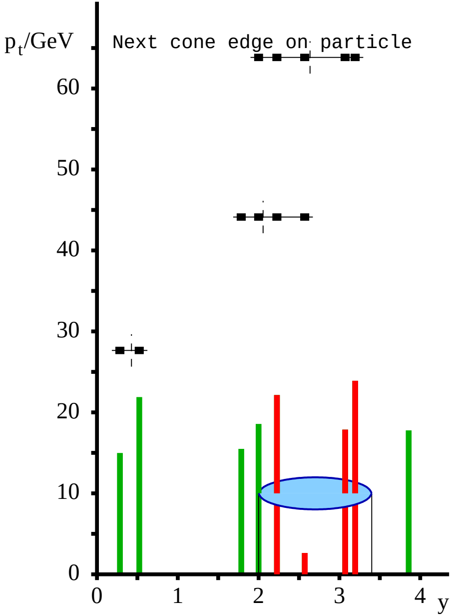

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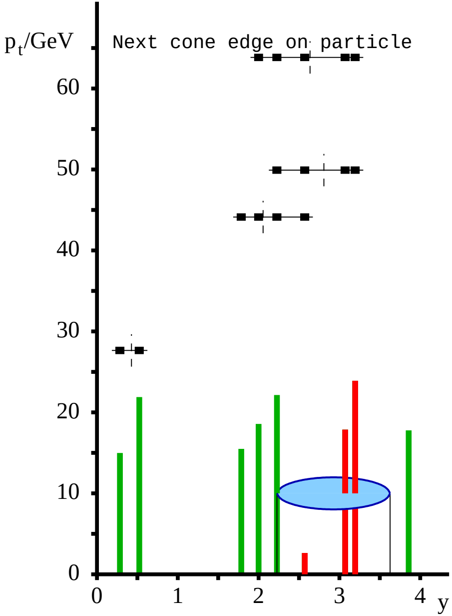

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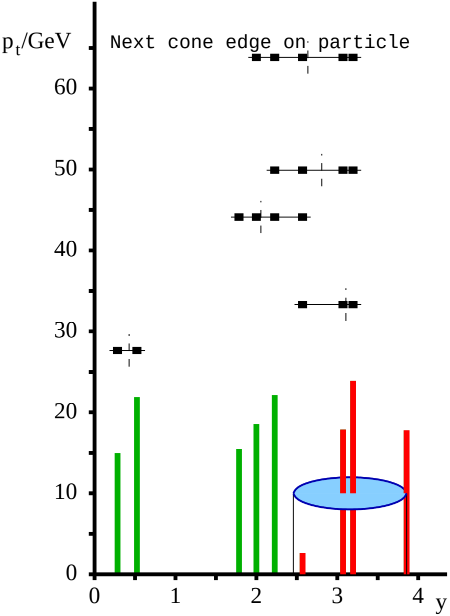

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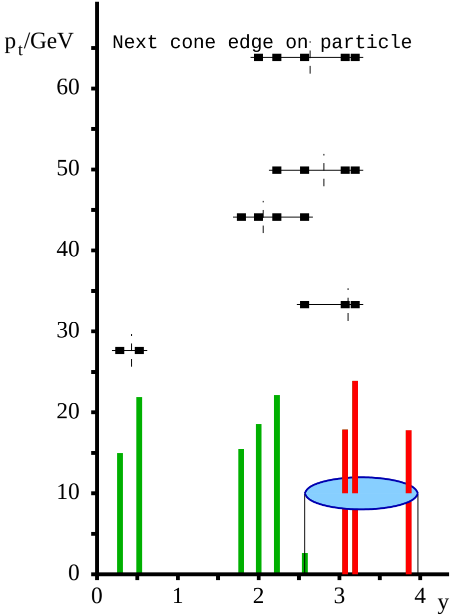

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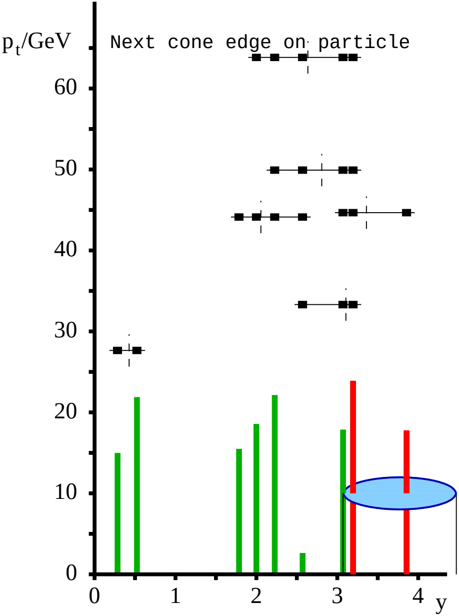

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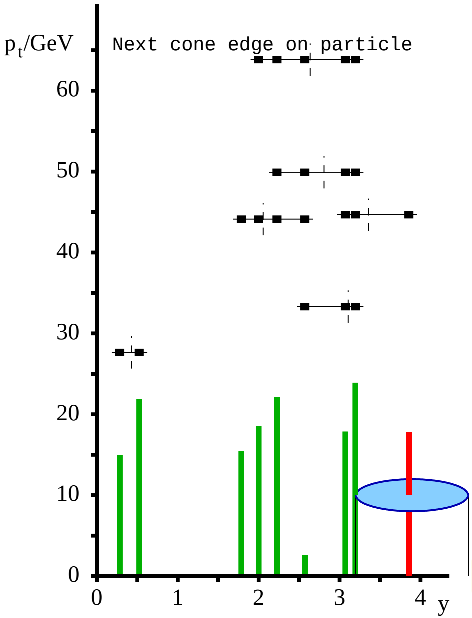

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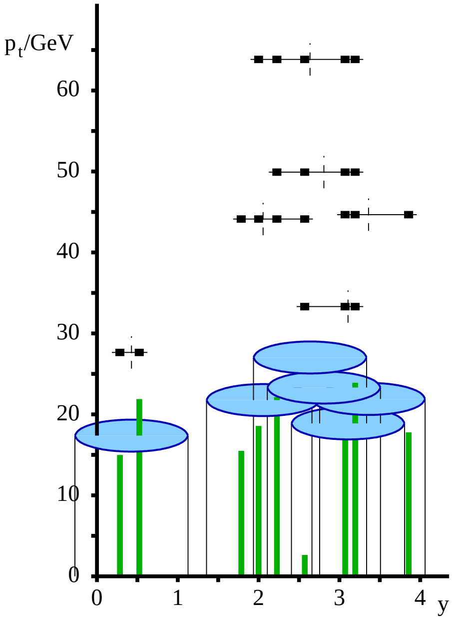

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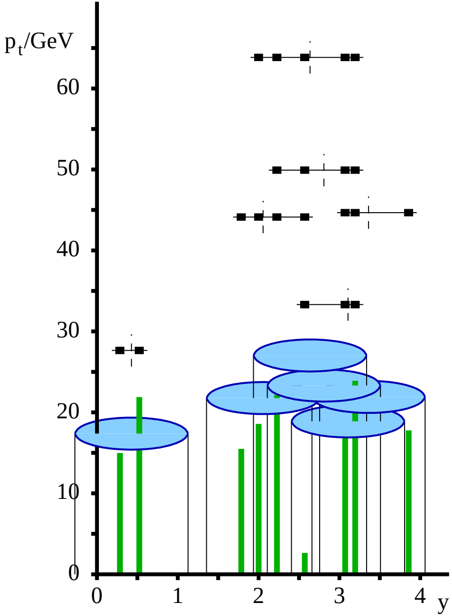

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A full set of IRC-safe jet algorithms

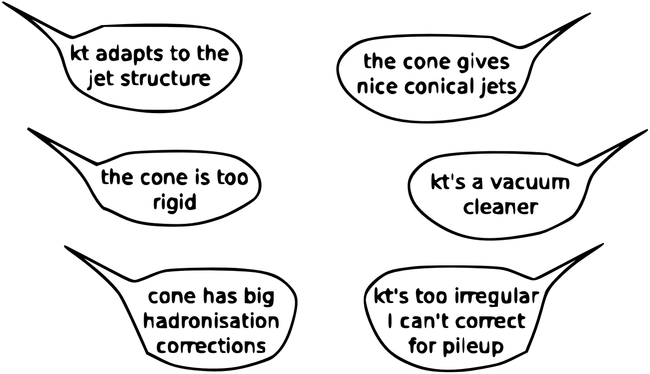
Generalise inclusive-type sequential recombination with

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

	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.

All these algorithms coded in (efficient) C++ at
http://fastjet.fr/ (Cacciari, GPS & Soyez '05-08)

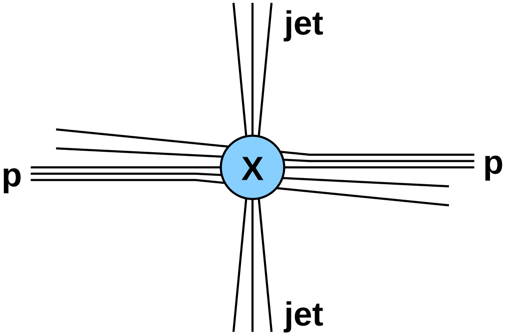
Jet Folklore



Past jet discussions often polarised, driven by unquantified statements

Question #3: what do we mean by a "better" jet definition?

Jet quality?



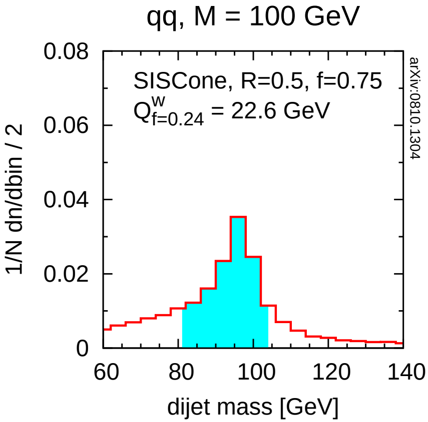
Quality = suited to whatever you use the jets for

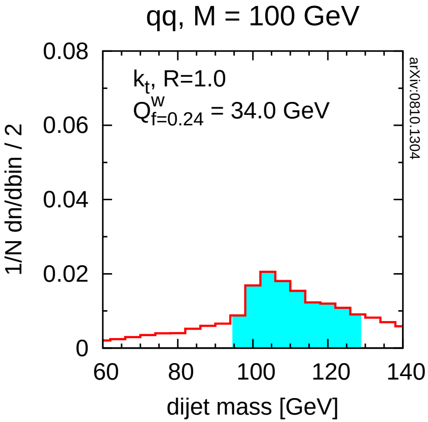
Simplest application: reconstruct dijet invariant mass peak for some new particle.

e.g. $pp \to X \to qq \to 2$ jets

Good jet algorithm $\to$ better invariant mass peak.

Not (yet) an HSBC advert





SISCone $R = 0.5$

BETTER

k_t, $R = 1.0$

WORSE

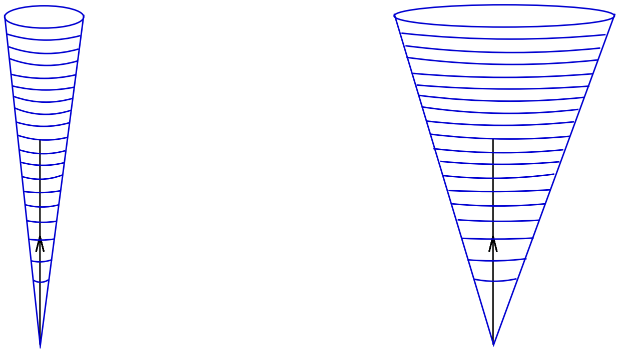
Question #4a:

What physics governs quality of jet definition?

[R-dependence]

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

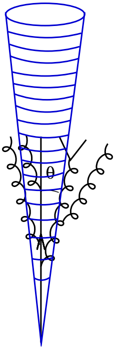
Small jet radius **Large jet radius**



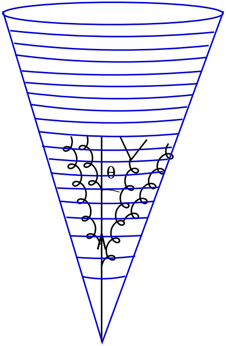
single parton @ LO: **jet radius irrelevant**

Small v. large jet radius (R) ≡ HSBC

Small jet radius



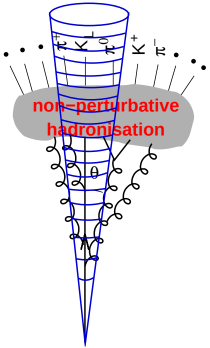
Large jet radius



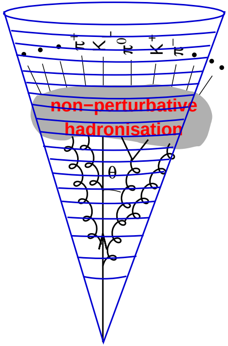
perturbative fragmentation: **large jet radius better**
(it captures more)

Small v. large jet radius (R) ≡ HSBC

Small jet radius

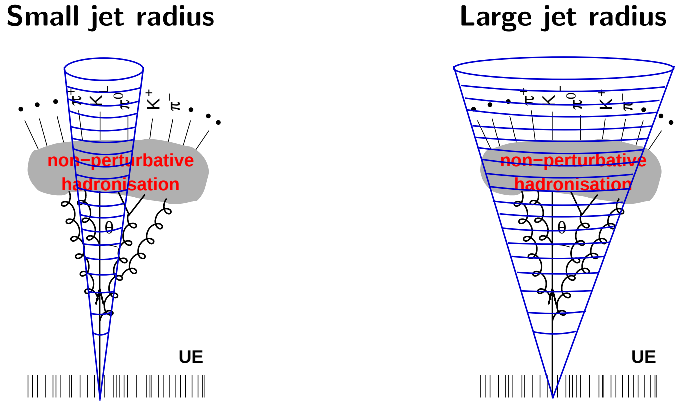


Large jet radius



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

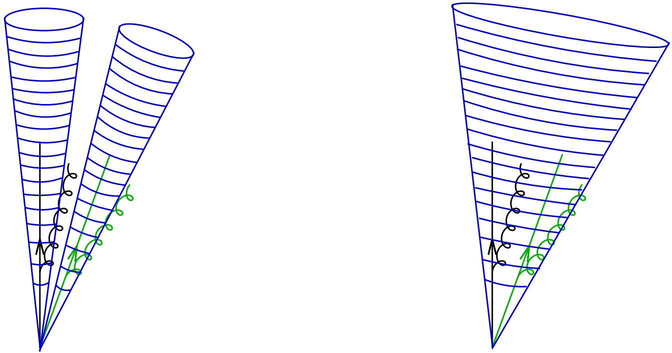
Small v. large jet radius (R) ≡ HSBC



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)

4-way tension in many measurements:

Prefer small R	prefer large R
resolve many jets (e.g. $t\bar{t}$)	minimize QCD radiation loss
limit UE & pileup	limit hadronisation

Jets v. R

Parton $p_t \longrightarrow$ jet p_t

Ill-defined: MC "parton"

PT radiation:

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

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

Hadronisation:

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

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

Underlying event:

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

Dasgupta, Magnea & GPS '07

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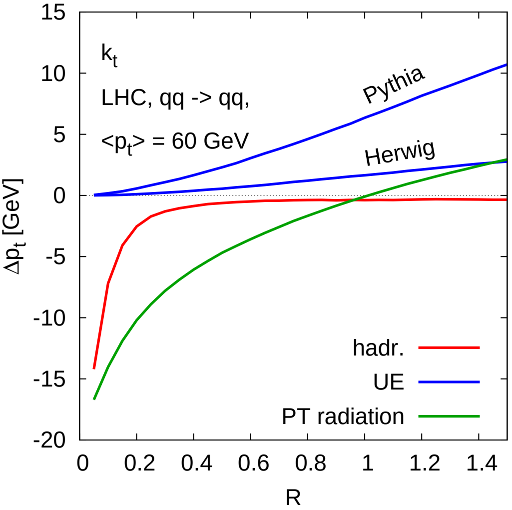

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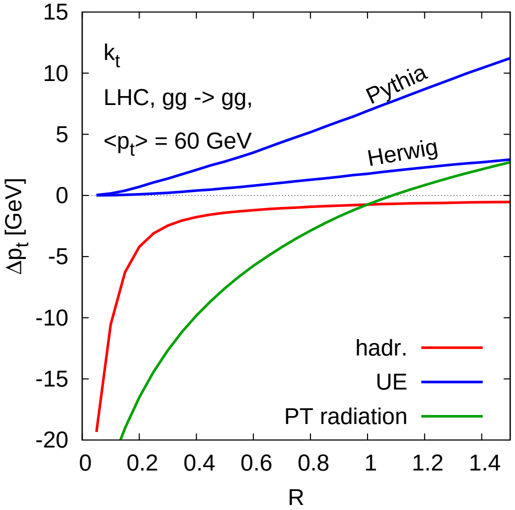

Dasgupta, Magnea & GPS '07

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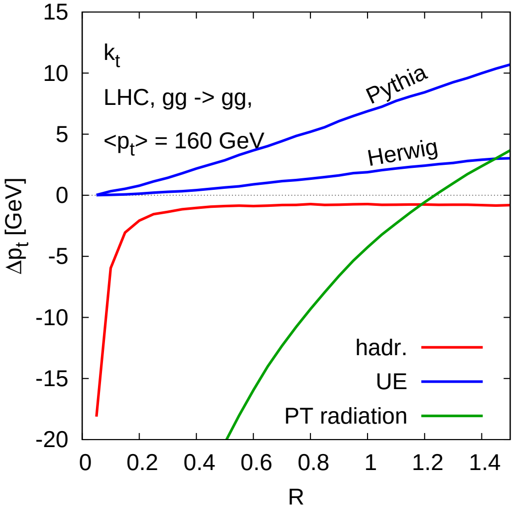

Dasgupta, Magnea & GPS '07

Quality ⇔ p_t dispersion

Best jet quality ⇔ least dispersion between "parton" p_t and jet p_t.

NB: "parton" not well-defined

Simplifying assumption:

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

$\langle \Delta p_t \rangle^2$ from perturbatve, hadronisation and UE effects

- low-p_t jet → prefer small R
  UE matters a lot
- high-p_t jet → prefer large R
  pert matters most

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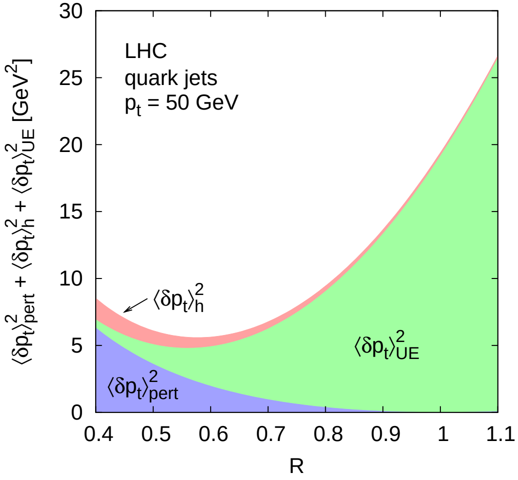

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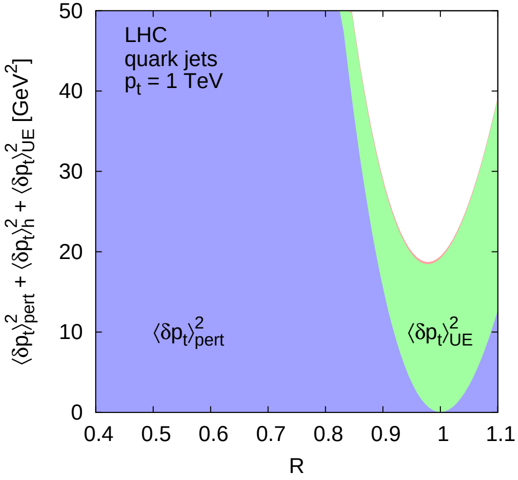
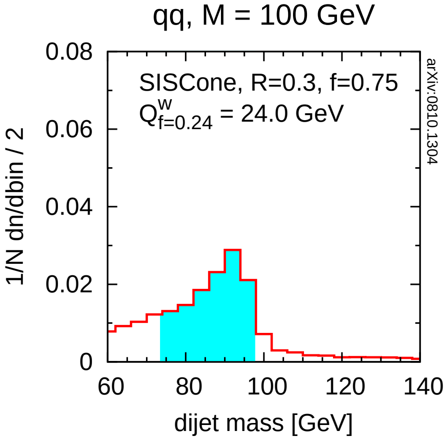


Does this match what one sees in Monte Carlo simulation?

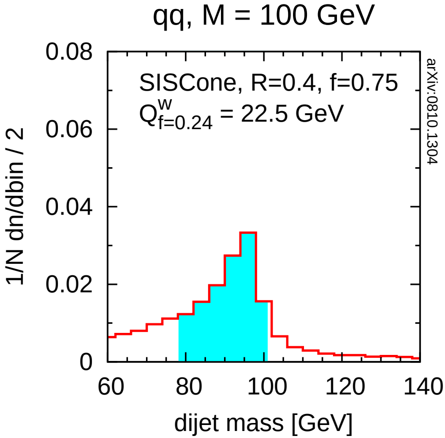
Scan through R values, Pythia (6.4)

R = 0.3

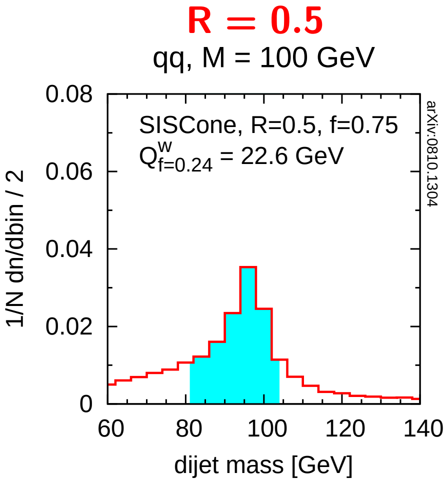


Scan through *R* values, Pythia (6.4)

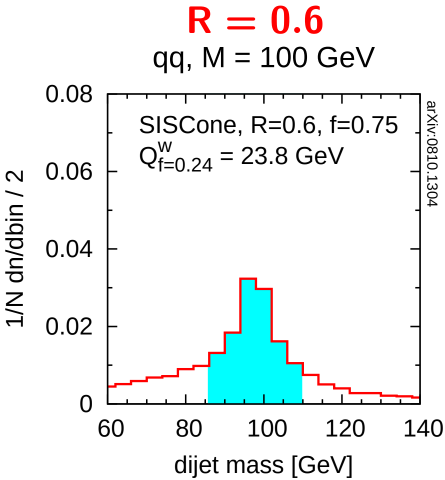
R = 0.4



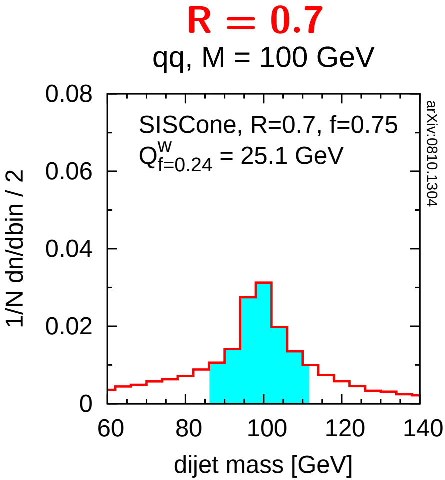
Scan through R values, Pythia (6.4)



Scan through R values, Pythia (6.4)



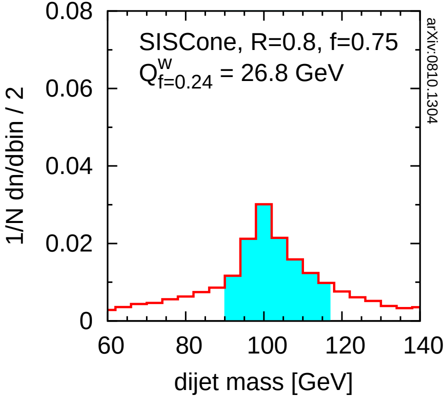
Scan through *R* values, Pythia (6.4)



Scan through R values, Pythia (6.4)

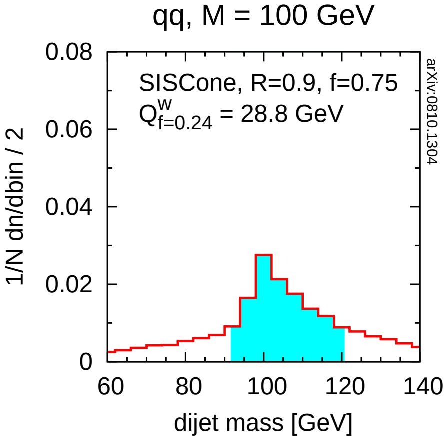
R = 0.8

qq, M = 100 GeV



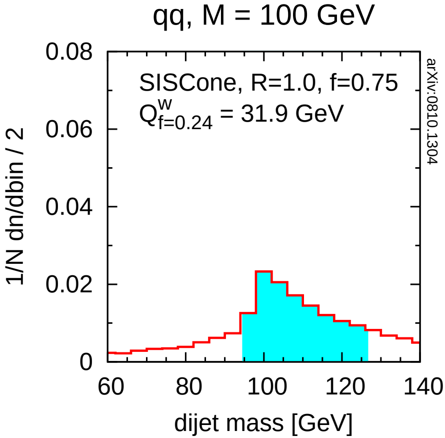
Scan through *R* values, Pythia (6.4)

R = 0.9



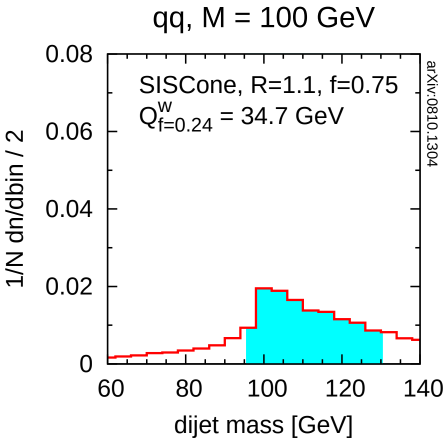
Scan through R values, Pythia (6.4)

R = 1.0



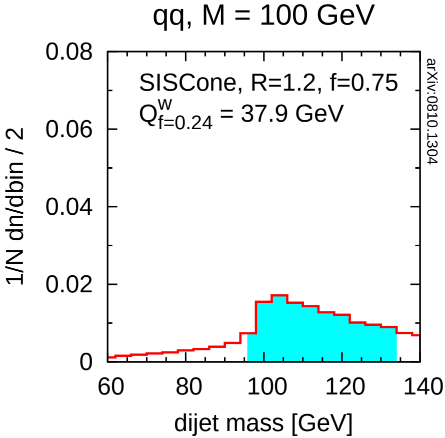
Scan through *R* values, Pythia (6.4)

R = 1.1



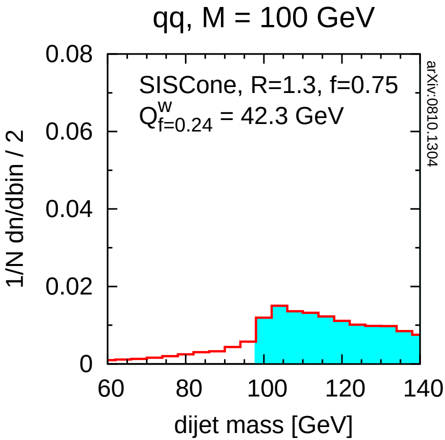
Scan through R values, Pythia (6.4)

$R = 1.2$



Scan through R values, Pythia (6.4)

R = 1.3



Scan through R values, Pythia (6.4)

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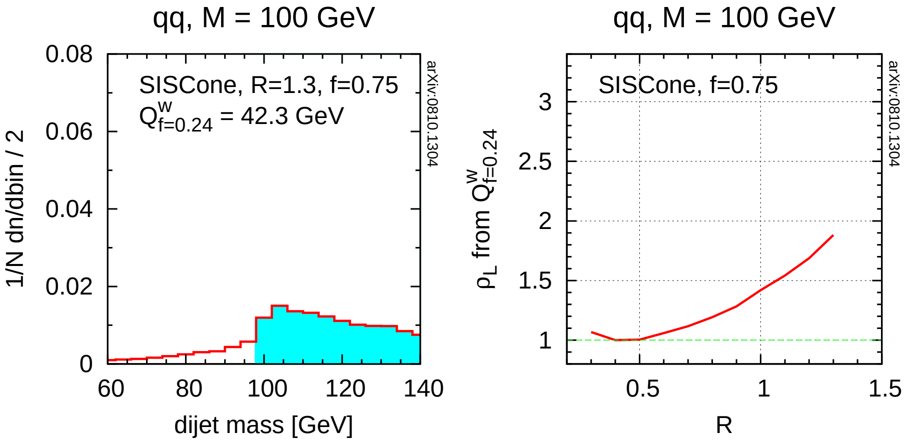
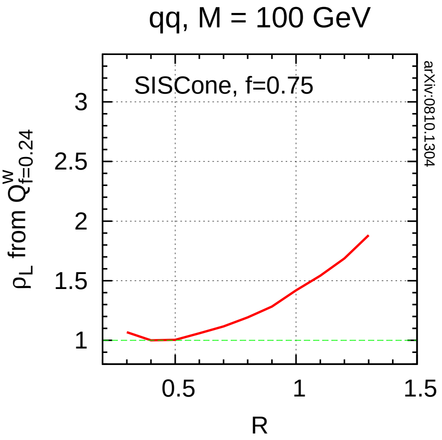


After scanning, summarise "quality" v. R. Minimum $\equiv$ BEST

picture not so different from crude analytical estimate

Scan through *qq* 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

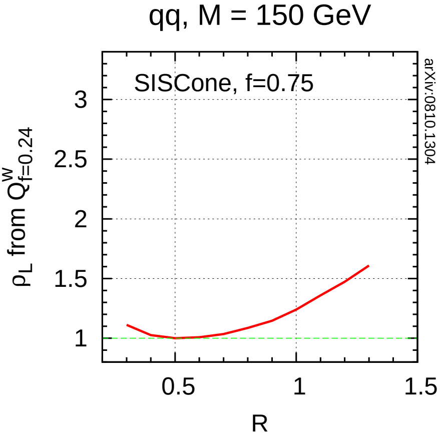
BUT: so far, LHC's plans involve running with fixed smallish *R* values

e.g. CMS arXiv:0807.4961

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

Scan through *qq* mass values

m_{qq} = 150 GeV



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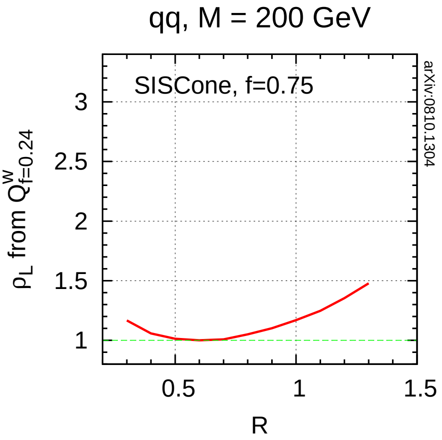
Scan through *qq* mass values

m_{qq} = 200 GeV



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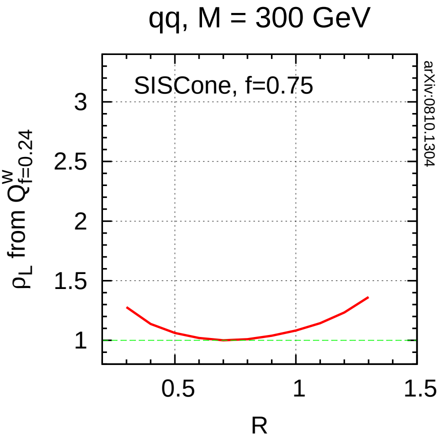
Scan through *qq* mass values

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



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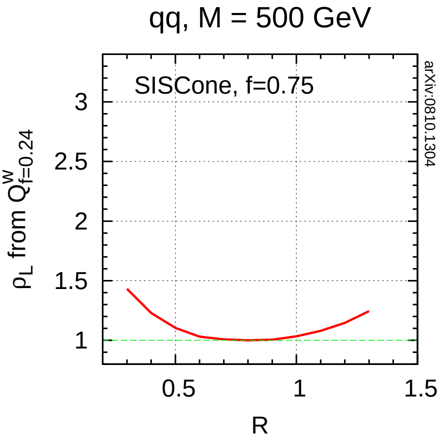
Scan through *qq* mass values

m_{qq} = 500 GeV



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e.g. CMS arXiv:0807.4961

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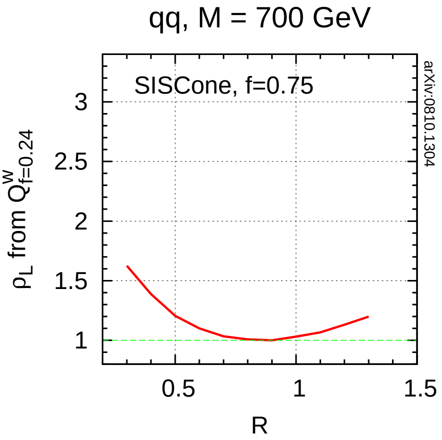
Cacciari, Rojo, GPS & Soyez '08

Scan through *qq* mass values

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



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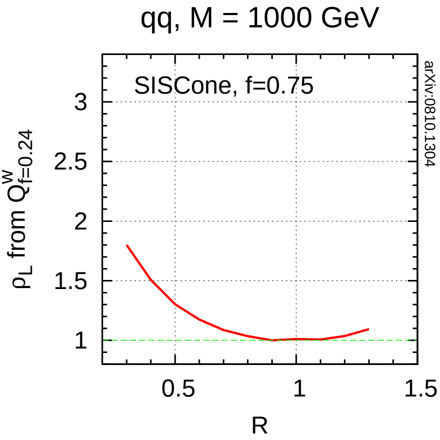
NB: 100,000 plots for various jet algorithms, narrow *qq* and *gg* resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

Scan through *qq* mass values

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



Best R is at minimum of curve

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

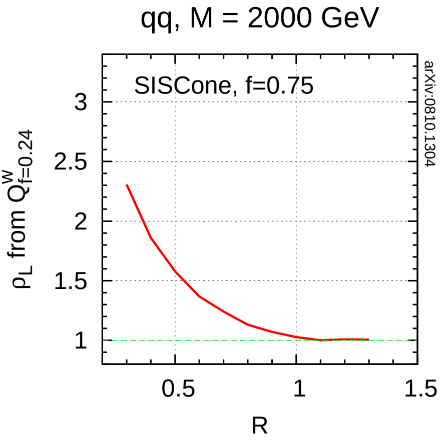
BUT: so far, LHC's plans involve running with fixed smallish R values

e.g. CMS arXiv:0807.4961

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

Scan through *qq* mass values

$m_{qq} = 2000$ GeV



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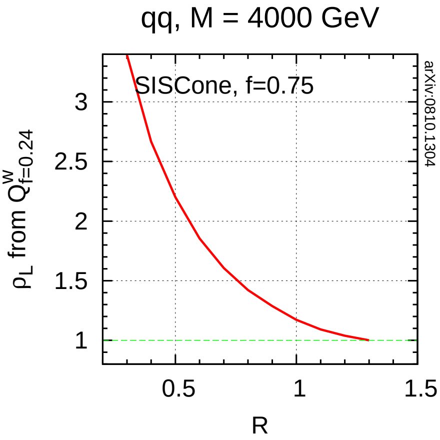
NB: 100,000 plots for various jet algorithms, narrow *qq* and *gg* resonances from `http://quality.fastjet.fr`

Cacciari, Rojo, GPS & Soyez '08

Scan through *qq* mass values

m_{qq} = 4000 GeV



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

Cacciari, Rojo, GPS & Soyez '08

Scan through qq mass values

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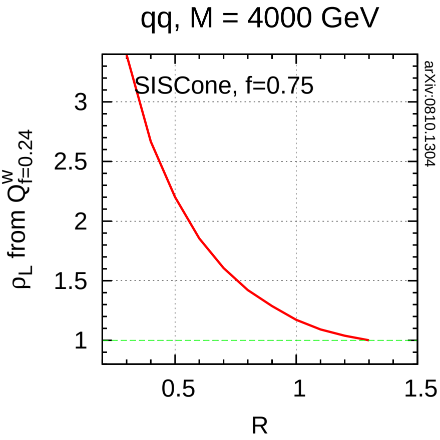

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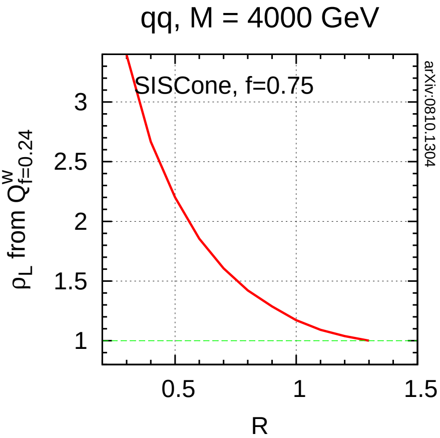

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Cacciari, Rojo, GPS & Soyez '08

What conclusions?

1) 'Best' jet definition depends strongly on context

2) Key element is interplay between

- Loss of perturbative radiation from partons
- "Noise" contamination from underlying event (and pileup)

3) We've not discussed choice of jet algorithm

- But it's relevant too

Relates to "jet areas"
= analytic study of UE contamination
also being looked at by H1

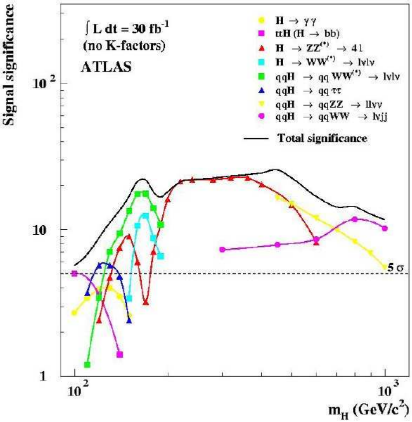
Question #5:
Can we apply understanding somewhere new?

An example: light Higgs search

As example, a Higgs-boson search illustrates two things:

- Using LHC scale hierarchy $\sqrt{s} \gg M_{EW}$ to our advantage
- Using QCD to help us extract cleaner signals

taken from Butterworth, Davison, Rubin & GPS '08



Low-mass Higgs search @ LHC: complex because dominant decay channel, $H \to bb$, often swamped by backgrounds.

Various production processes

- $gg \to H\ (\to \gamma\gamma)$ — feasible
- $WW \to H \to \dots$ — feasible
- $gg \to t\bar{t}H$ — v. hard
- $q\bar{q} \to WH, ZH$

  small; but gives access to WH and ZH couplings

  Currently considered impossible

WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$.

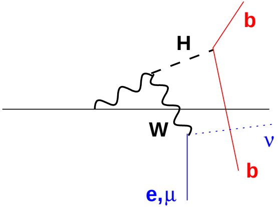
Studied e.g. in ATLAS TDR

- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

Difficulties, e.g.

- Poor acceptance ($\sim 12\%$)

  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape



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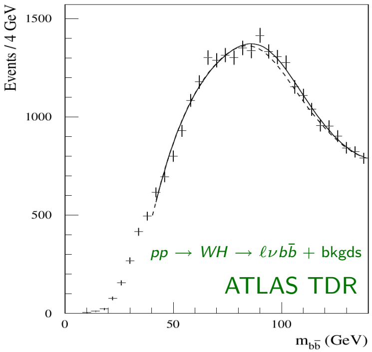

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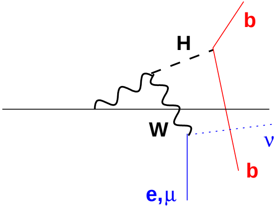

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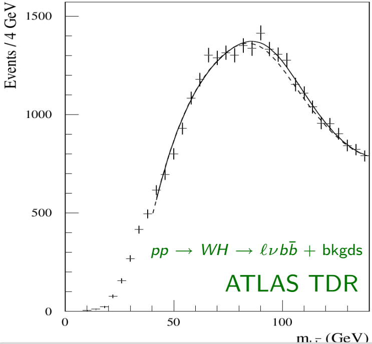

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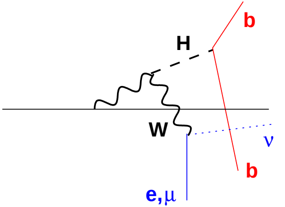
- small S/B
- Need exquisite control of bkgd shape

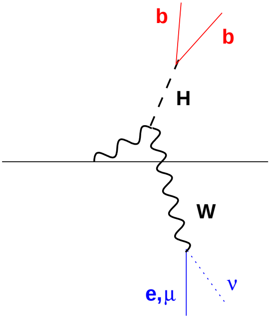
Conclusion (ATLAS TDR):

"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 [...]"



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

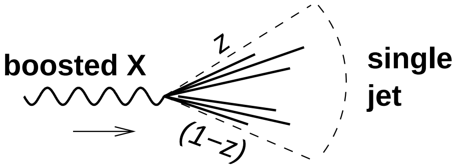
✗ Cross section will drop dramatically

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

Will the benefits outweigh this?

Boosted EW bosons

Hadronically decaying Higgs boson at high p_t = single massive jet?



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

discussion of this & related problems: Seymour '93; Butterworth, Cox & Forshaw '02; Butterworth, Ellis & Raklev '07; Skiba & Tucker-Smith '07; Holdom '07; Baur '07; Agashe et al. '07; Lillie, Randall & Wang '07; Contino & Servant '08; Brooijmans '08; Thaler & Wang '08; Kaplan et al '08; Almeida et al '08; [. . .]

What does QCD tell us about how to deal with this?

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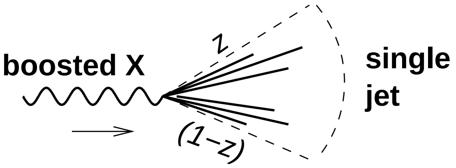

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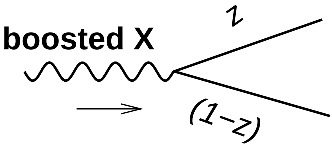
What does QCD tell us about how to deal with this?

QCD principle: soft divergence

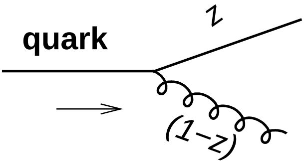
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

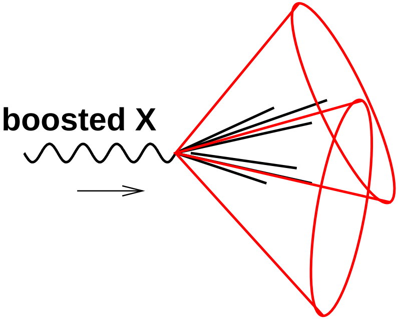
$$P(z) \propto \frac{1+z^2}{1-z}$$

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

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

Originally: ad-hoc cut on (related) k_t-distance
Seymour '93; Butterworth, Cox & Forshaw '02

QCD principle: angular ordering



Given a color-singlet $q\bar{q}$ pair of opening angle R_{bb}:

Nearly all the radiation from the pair is contained in two cones of opening angle R_{bb}, one centred on each quark.

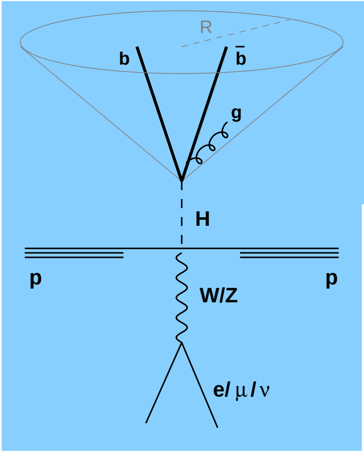
Standard result also in QED

Use this to capture just the radiation from the $q\bar{q} \Rightarrow$ good mass resol^n

Searching for high-p_t HW/HZ?

High-p_t light Higgs decays to $b\bar{b}$ inside a single jet. Can this be seen?

Butterworth, Davison, Rubin & GPS '08



Cluster with Cambridge/Aachen

1. Find a high-p_t massive jet J
2. Undo last stage of clustering ($\equiv$ reduce R)
3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged $\to$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

Then on the Higgs-candidate: *filter* away UE/pileup by reducing $R \to R_{filt}$, take *three hardest subjets* (keep LO gluon rad^n) + require b-tags on two hardest.

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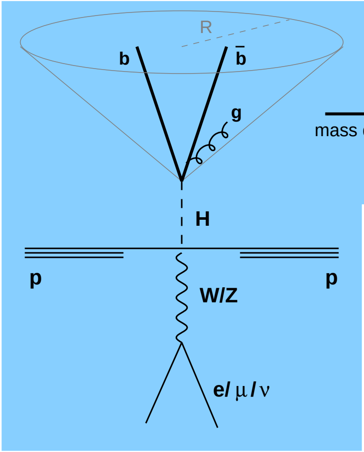

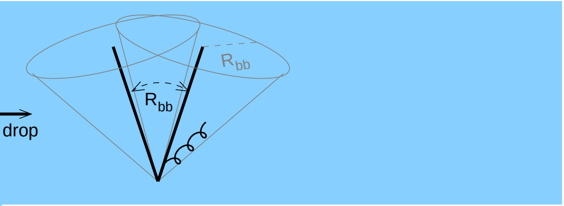

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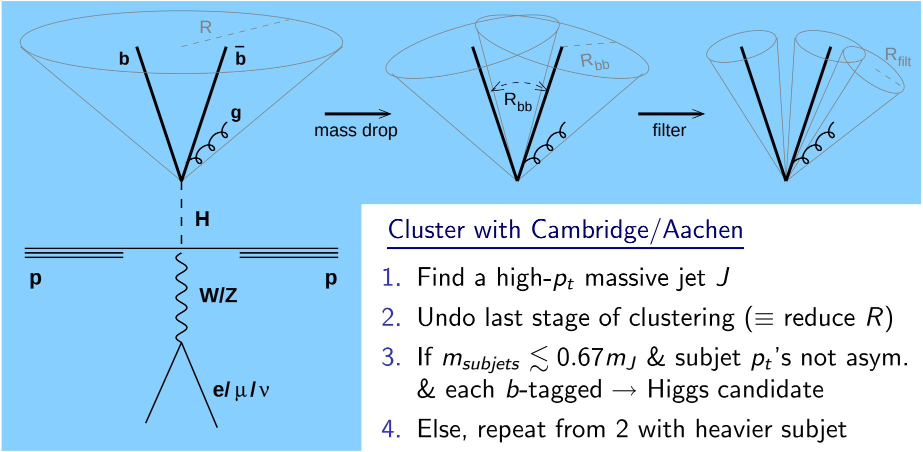

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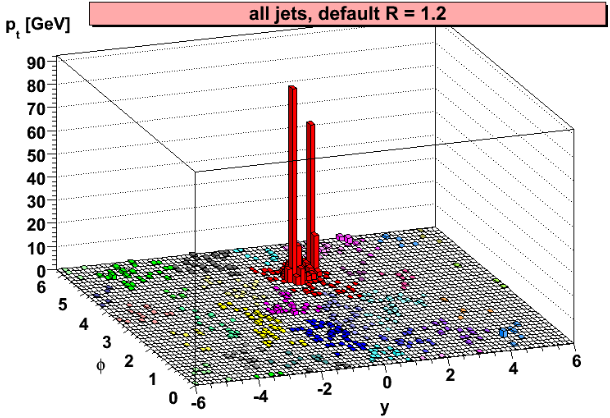
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

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

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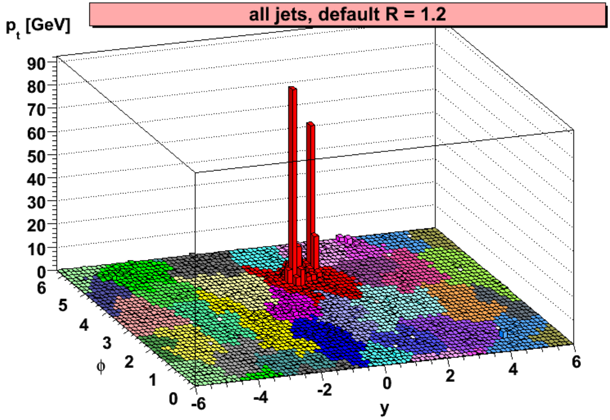

Zbb BACKGROUND

Fill it in, → show jets more clearly

arbitrary norm.

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

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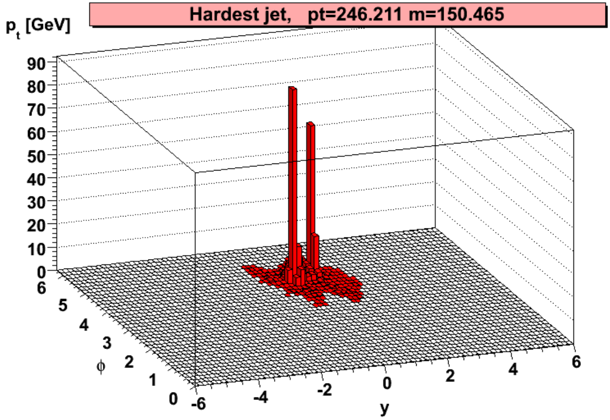
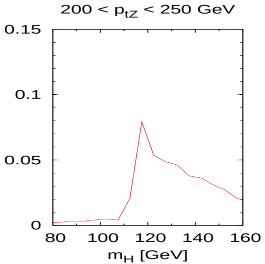
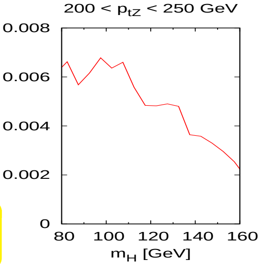


Consider hardest jet, $m = 150$ GeV

SIGNAL



Zbb BACKGROUND



arbitrary norm.

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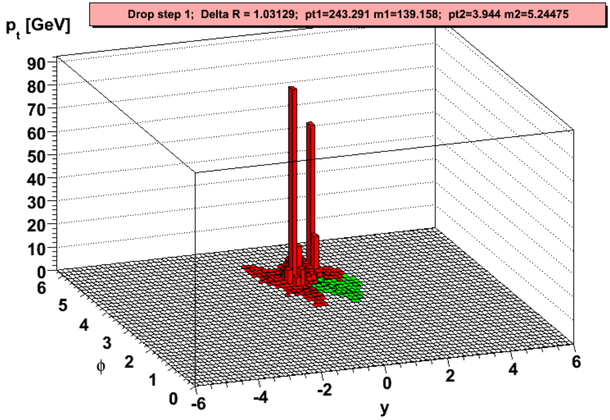
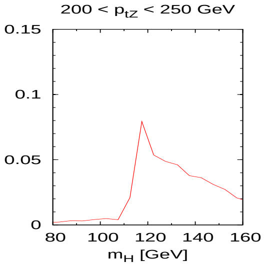
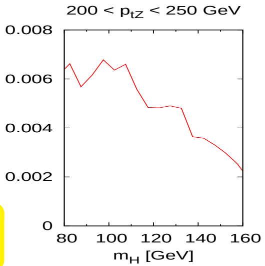


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \longrightarrow$ repeat

SIGNAL



Zbb BACKGROUND



arbitrary norm.

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

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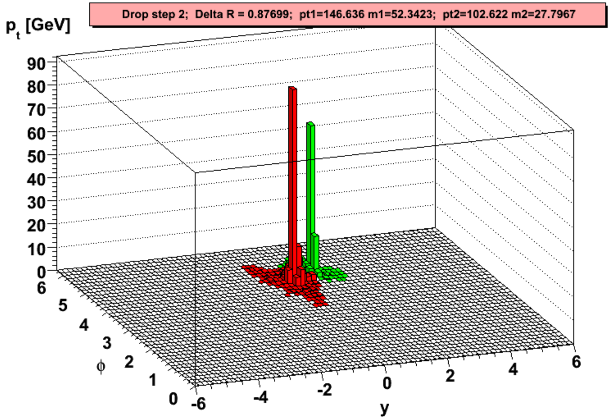
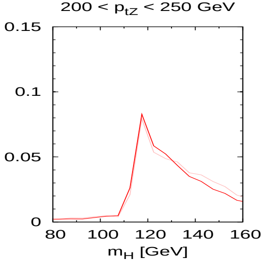
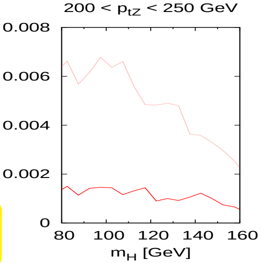


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

SIGNAL



Zbb BACKGROUND



arbitrary norm.

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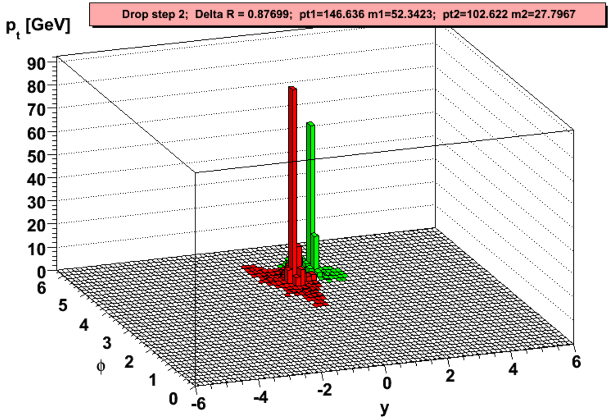

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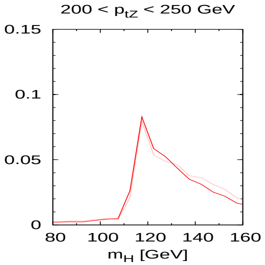

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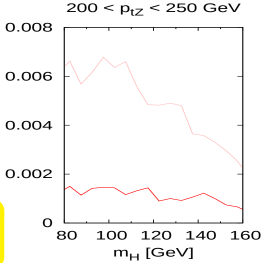

check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \rightarrow$ OK + 2 b-tags (anti-QCD)

arbitrary norm.

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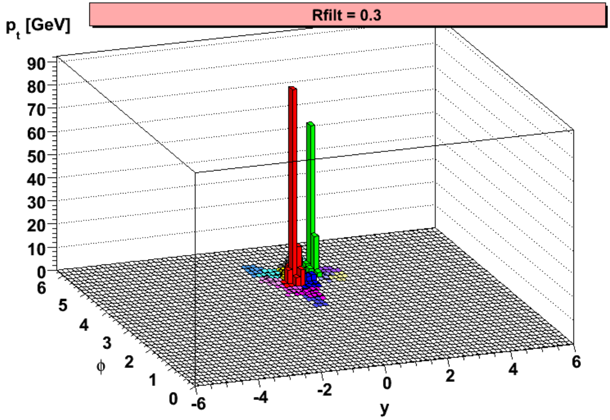

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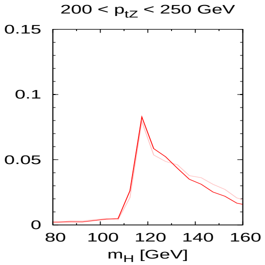

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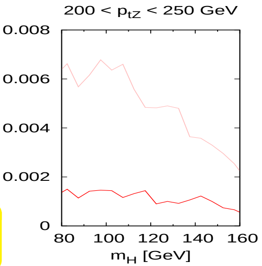

$R_{filt} = 0.3$

arbitrary norm.

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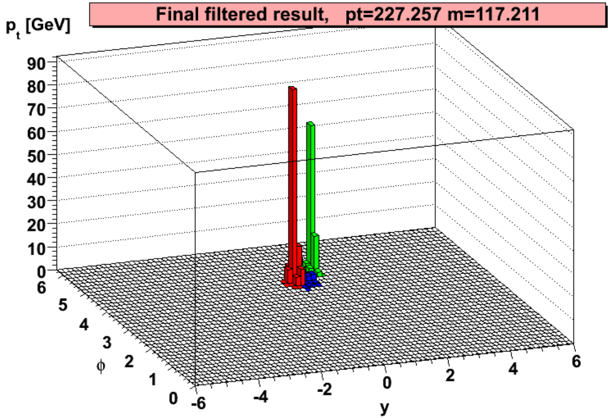

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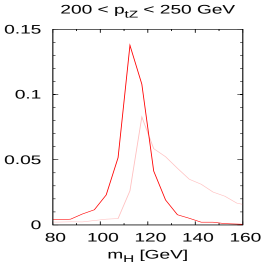
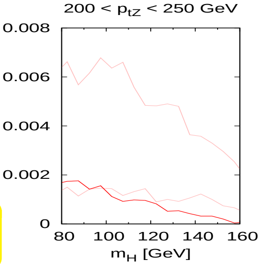


Zbb BACKGROUND

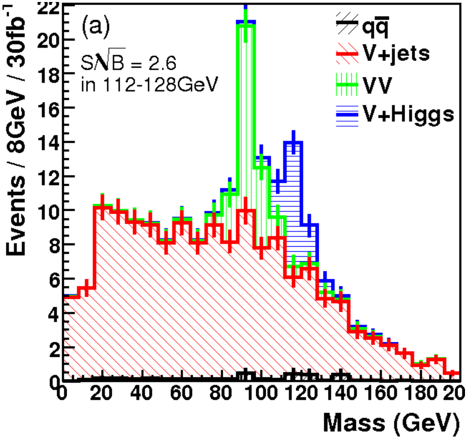


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

arbitrary norm.

combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



Common cuts

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra ℓ, b's with $|\eta| < 2.5$
- Real/fake b-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 16 GeV window

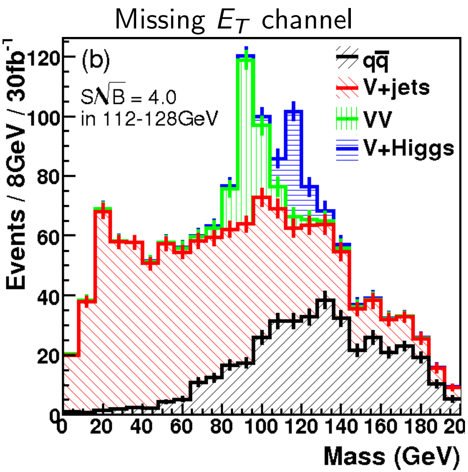
Leptonic channel

$Z \to \mu^+\mu^-, e^+e^-$

- $80 < m_{\ell^+\ell^-} < 100$ GeV

At 5.9σ for 30 fb^{-1} this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!

combine HZ and HW, $p_t > 200$ GeV



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Missing-E_t channel

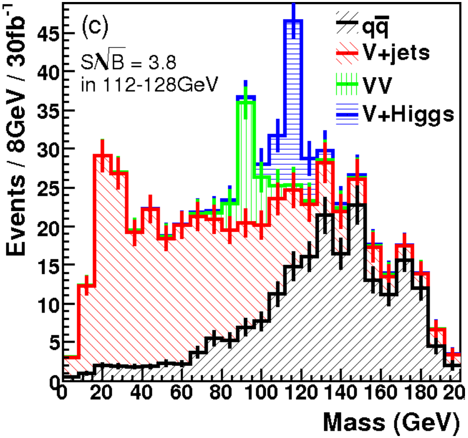
$Z \to \nu\bar{\nu}$, $W \to \nu[\ell]$

- $\not{E}_T > 200$ GeV

At 5.9σ for 30 fb^{-1} this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

combine HZ and HW, $p_t > 200$ GeV

Semi-leptonic channel



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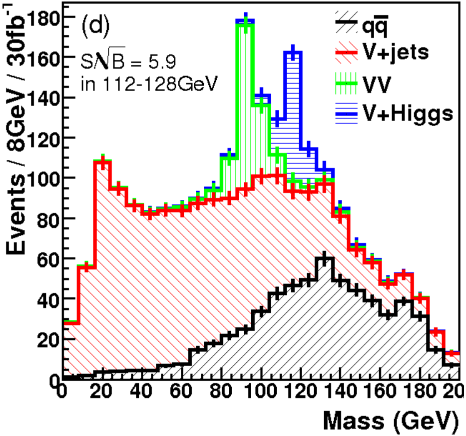
Semi-leptonic channel

$W \to \nu\ell$

- $\not{E}_T > 30$ GeV (& consistent W.)
- no extra jets $|\eta| < 3, p_t > 30$

At 5.9σ for 30 fb^{-1} this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

combine HZ and HW, $p_t > 200$ GeV



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3 channels combined

Note excellent VZ, $Z \to b\bar{b}$ peak for calibration

NB: $q\bar{q}$ is mostly $t\bar{t}$

At 5.9σ for 30 fb^{-1} this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

Not just about Higgs discovery

Higgs physics means establishing whether it has the expected SM couplings.

Crucial part of that is seeing WH and ZH cleanly and separately from each other.

This channel seems to be the only good way of doing that for a light Higgs.

Alternative WW fusion: but mixes with ZZ fusion, gg fusion

Outlook

Outlook

- There seem to be clear benefits to be had from well-chosen jet-definitions
- No single jet-definition fits all physics tasks
- Unlike photography we don't yet have "autofocus, auto-exposure" jet finders
- But we're starting to understand the issues

Enough to qualitatively guide our choices

e.g. choice of R in dijet resonance searches

e.g. boosted EW bosons, cf. low-mass Higgs search

- What's the next goal? **Systematic, optimised jetography?**

Extras

Sequential recombination algorithms

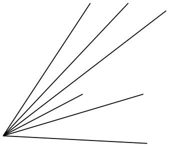
k_t algorithm

- Find smallest of all $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and $d_{iB} = k_i^2$
- Recombine i, j (if iB: $i \to$ jet)
- Repeat

'Trivial' computational issue:

- for N particles: N^2 d_{ij} searched through N times $= N^3$
- 4000 particles (or calo cells): 1 minute

NB: often study $10^7 - 10^8$ events



Advance #1: factorise momentum and geometry

Borrow methods & tools from Computational Geometry:

Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

Time reduced to $N\sqrt{n}$ or $N \ln N$: 25ms for N=4000. Cacciari & GPS '05

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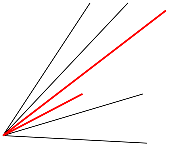

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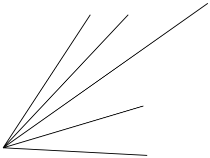

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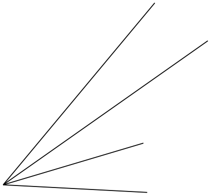

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Time reduced to Nn or $N \ln N$: 25ms for N=4000. Cacciari & GPS '05

Sequential recombination algorithms

k_t algorithm

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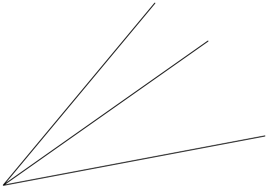

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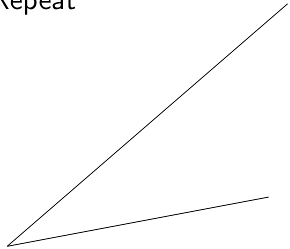

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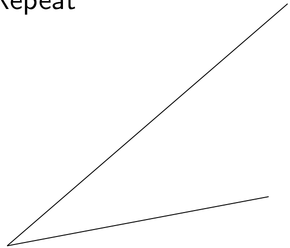

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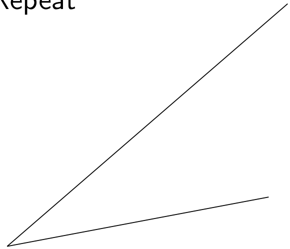

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Tevatron & ATLAS cone algs have two main steps:

- Find some/all stable cones

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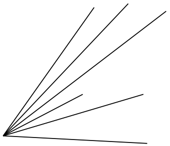
- Resolve cases of overlapping stable cones

  By running a 'split–merge' procedure



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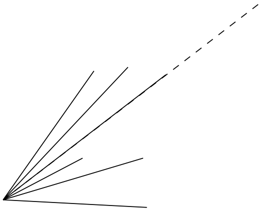

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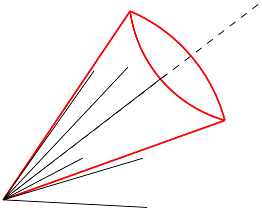

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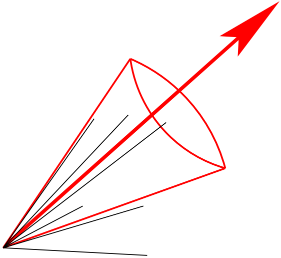

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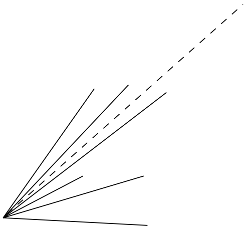

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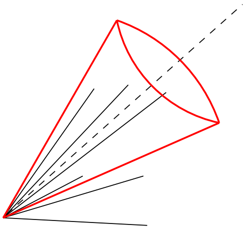

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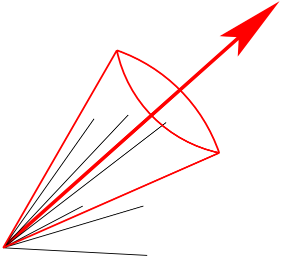

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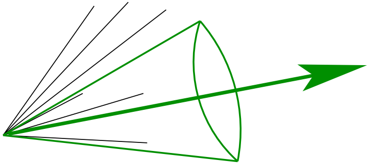

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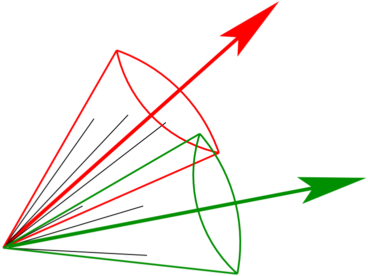

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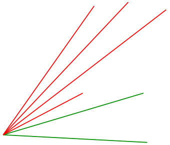

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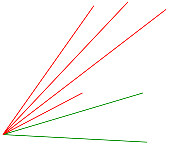

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- Iterate from 'midpoints' between cones from seeds   Midpoint cone, less IR unsafe, N^3
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  100 particles: 10^{17} **years**

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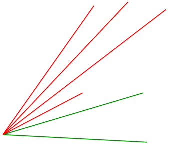

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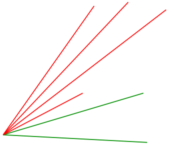

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Advance #2: IR safe seedless cone (SM) separate mom. and geometry

New comp. geometry techniques: 2D all distinct circular enclosures

Then for each check whether → stable cone

Time reduced from $N2^N$ to $\mathbf{N^2 \ln N}$: 6s for N=4000. GPS & Soyez '07

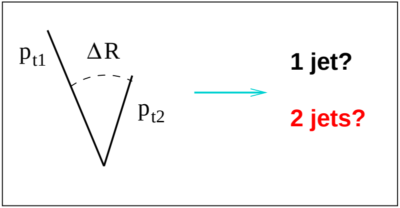
"SISCone"

Question #4b:

What physics governs quality of jet definition?

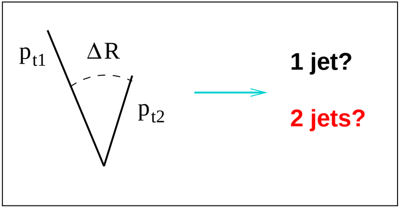
[jet algorithm dependence]

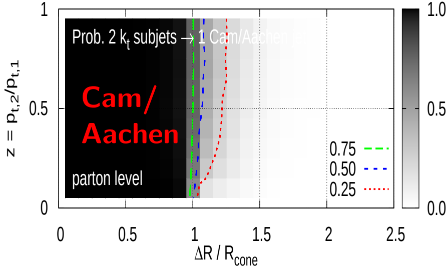
the *reach* of jet algorithms



SISCone (xC-SM) reaches further for hard radiation than other algs

the *reach* of jet algorithms





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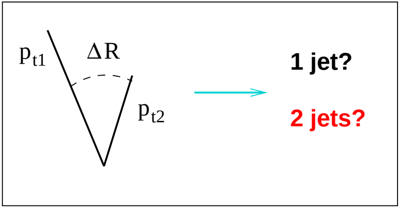

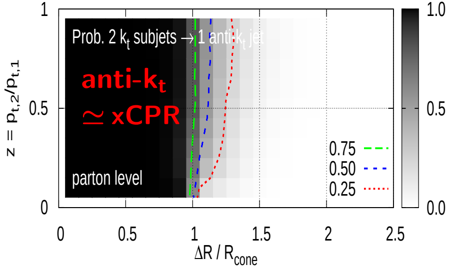

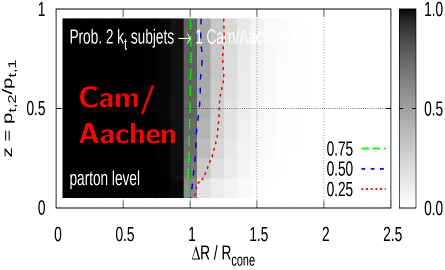

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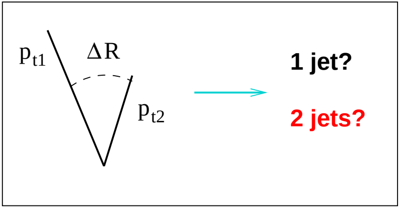

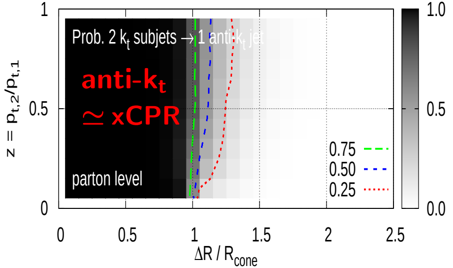

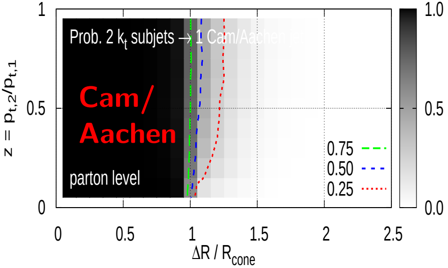

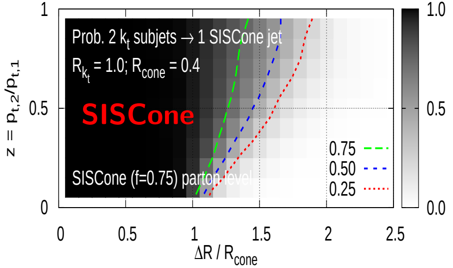

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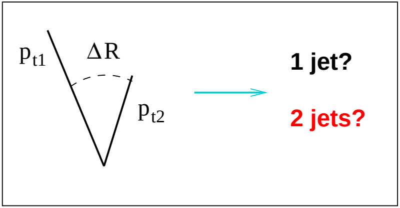

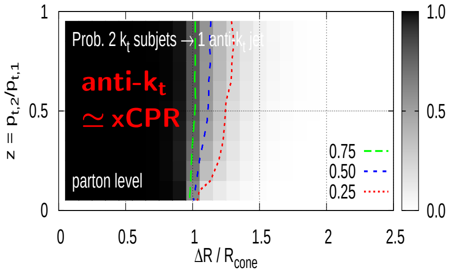

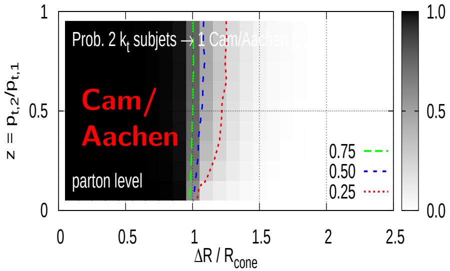

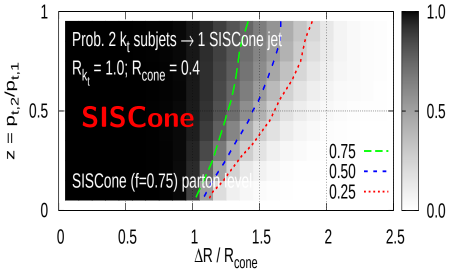

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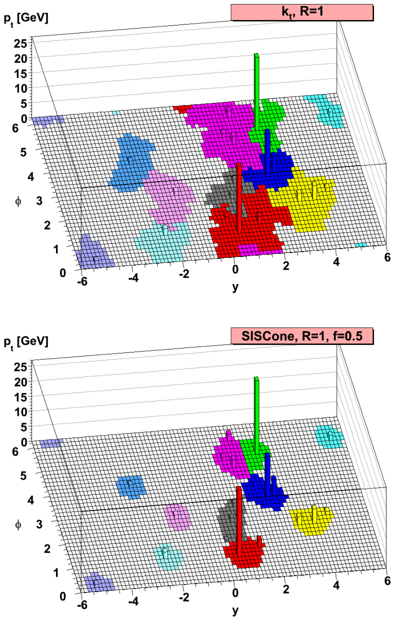
Jet contours – visualised



Jet areas

Can show that jet area goes as:

$$A = A_0 + D\frac{C_{F/A}}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} + \mathcal{O}\left(\alpha_s^2 \ln p_t^2\right)$$

Cacciari, GPS & Soyez '08

measurements in progress in H1

Passive area: suscept. to **point-like** radiation:

	$A_0/\pi R^2$	$D/\pi R^2$
k_t	1	0.56
Cam/Aachen	1	0.08
SISCone	1	−0.06

- Analytical calcs capture main MC features
- k_t has larger area than cone, neither is πR^2
- **SISCone has small areas**

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Active area: suscept. to **diffuse** radiation:

	$A_0/\pi R^2$	$D/\pi R^2$
k_t	$1 \to 0.81$	$0.56 \to 0.52$
Cam/Aachen	$1 \to 0.81$	$0.08 \to 0.08$
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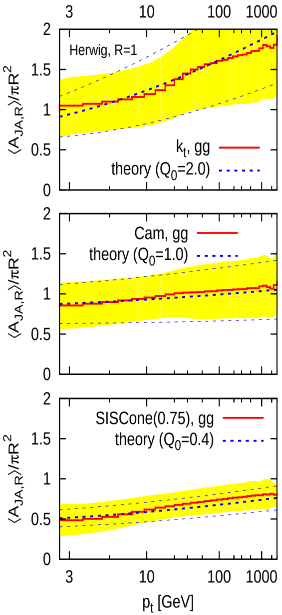

MISSING:
SISCone worked well because of small area and wider perturbative reach (NB latter good for dijets, bad for multijets)