Jets: where from, where to?

Gavin P. Salam
LPTHE, UPMC Paris 6 & CNRS

London workshop on standard-model discoveries with early LHC data
UCL, London, 31 March 2009

Based on work with
M. Cacciari, M. Dasgupta, L. Magnea, J. Rojo & G. Soyez

Les Houches 2007 proceedings, arXiv:0803.0678

jet definition

jet algorithm

$\{p_i\}$ → $\{j_k\}$

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

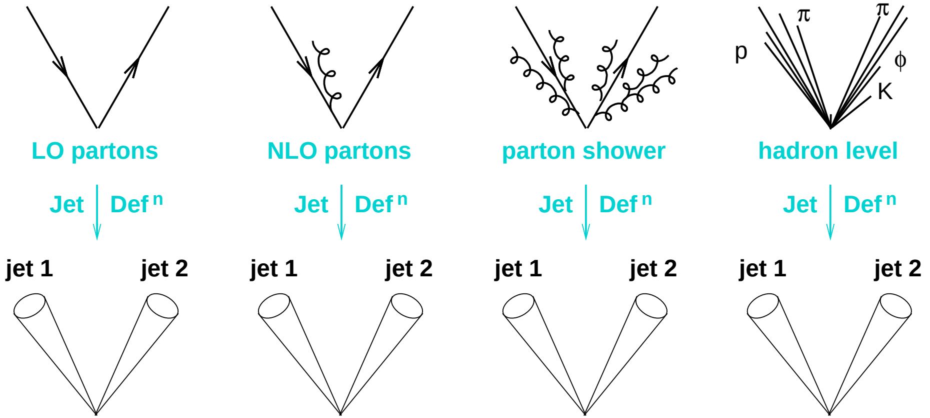
jets

+ parameters (usually at least the radius R)

+ recombination scheme

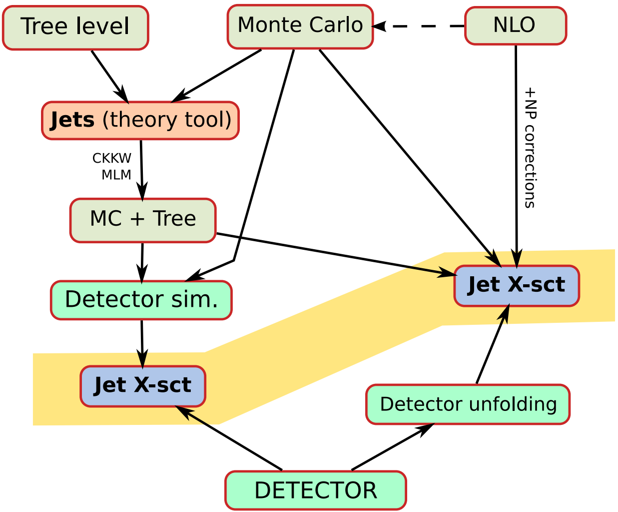
Reminder: running a jet definition gives a well defined physical observable, which we can measure and, hopefully, calculate

Jets as projections



Projection to jets provides "universal" view of event

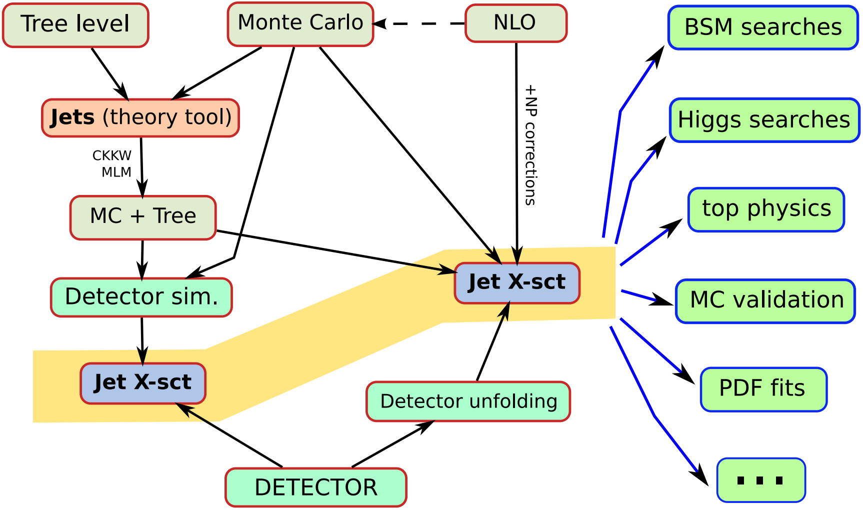
QCD jets flowchart



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

QCD jets flowchart



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And jets are an input to almost all analyses

What tools do we have?

"The" cone algorithm

CDF JetClu

CDF MidPoint

CDF MidPoint with searchcones

DØ Run II Cone (midpoint)

ATLAS Iterative Cone

CMS Iterative Cone

PxCone

PyCell/CellJet/GetJet

"The" cone algorithm

Each "cone" involves

- different code
- different physics

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Each “cone” is essentially

- infrared unsafe
- collinear unsafe
- or some detector-influenced mixture of the two

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"The" cone algorithm

Each "cone" involves

- different code
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Each "cone" is essentially

- infrared unsafe
- collinear unsafe
- or some detector-influenced mixture of the two

Maybe half the cones are incompletely documented

This is complex

It's theoretically unsatisfactory (IR unsafety is inconsistent with perturbative calculations, even at LO)

[and NLO calculations have seen $\sim$ $50 million investment]

	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC_{mp}-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO
$W/Z + 1$ jet	LO	NLO	NLO	NLO
3 jets	**none**	LO	LO	NLO [nlojet++]
$W/Z + 2$ jets	**none**	LO	LO	NLO [MCFM]
m_{jet} in $2j + X$	**none**	**none**	**none**	LO $\rightarrow$ NLO

This is complex

It's theoretically unsatisfactory (IR unsafety is inconsistent with perturbative calculations, even at LO)

[and NLO calculations have seen ∼ $50 million investment]

But change has tended to be slow and hard-going

E.g.: midpoint cone was proposed for Tevatron Run II:

- it was (only) a "patch" for earlier algorithm's IR safety issues
- its adoption was only partial at Tevatron
- Most of LHC's physics studies ignored it

Cones: what to use?

“xC-SM”

CDF JetClu

CDF MidPoint

DØ Run II Cone (midpoint)

ATLAS Iterative Cone

$\longrightarrow$ **SISCone**

find all stable cones

run split–merge on overlaps

[GPS & Soyez ’07]

“xC-PR”

CMS Iterative Cone

PyCell/CellJet/GetJet

$\longrightarrow$ **anti-$\mathbf{k_t}$**

cluster min $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2$

if $d_{iB} = k_{ti}^{-2}$ smallest, $i \longrightarrow$ jet

[Cacciari, GPS & Soyez ’08]

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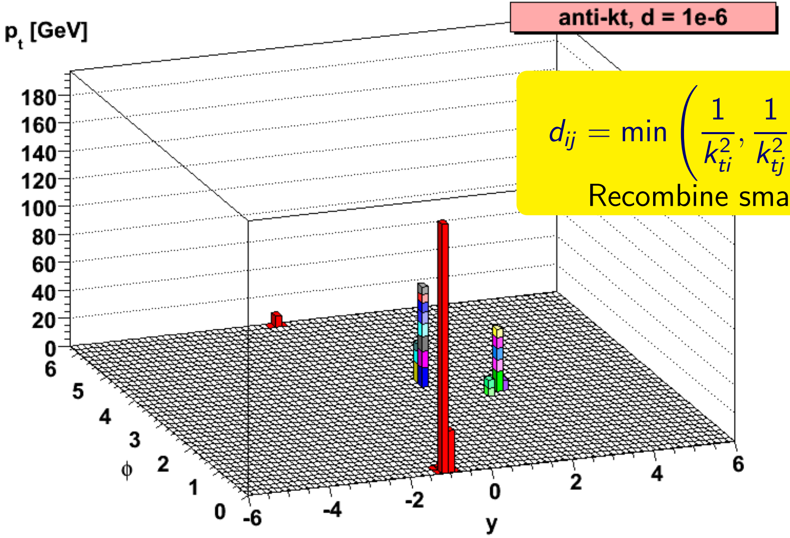
[Cacciari, GPS & Soyez '08]

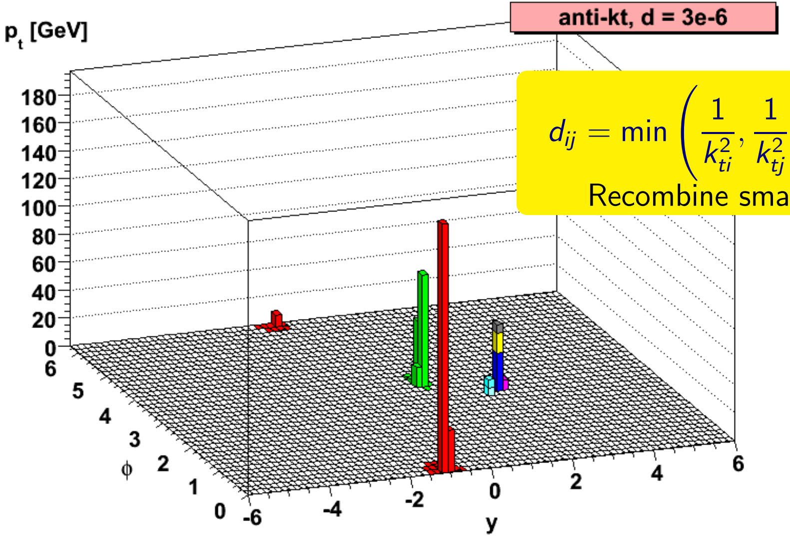
Build up of jets with anti-k_t



$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right) \Delta R_{ij}^2$$

Recombine smallest

Build up of jets with anti-k_t



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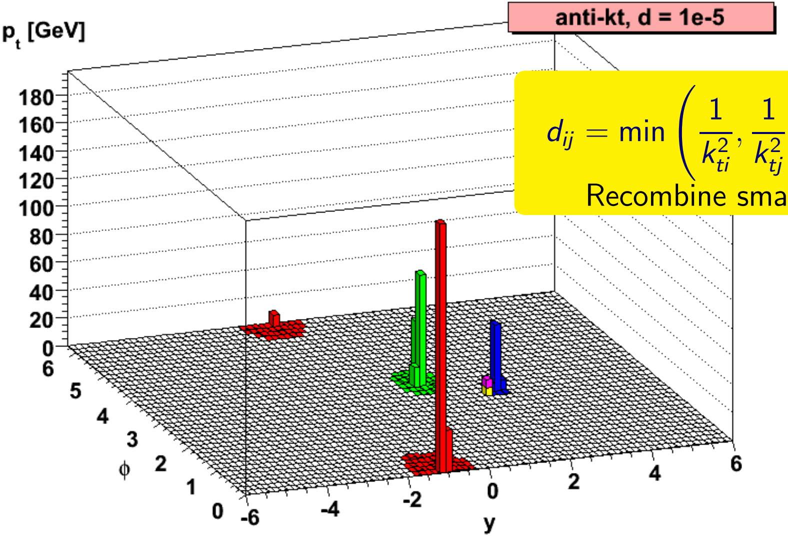

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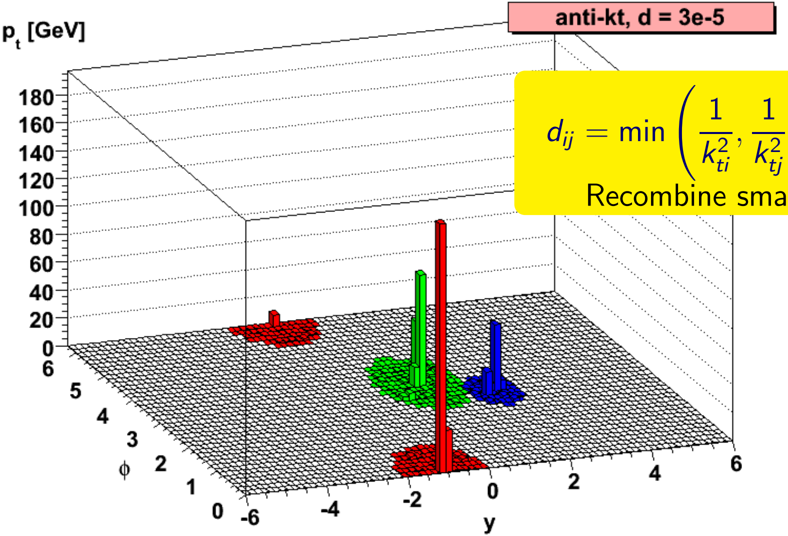

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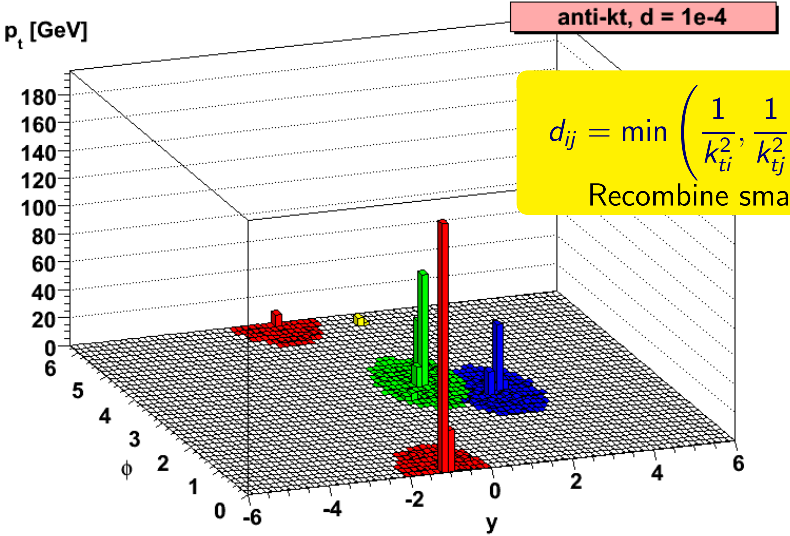

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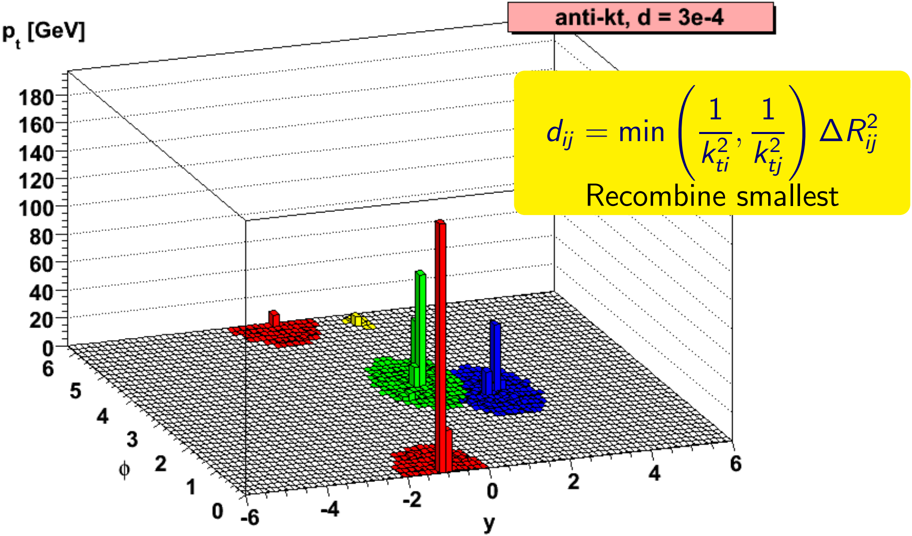

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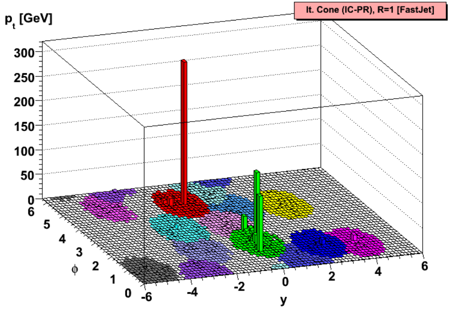
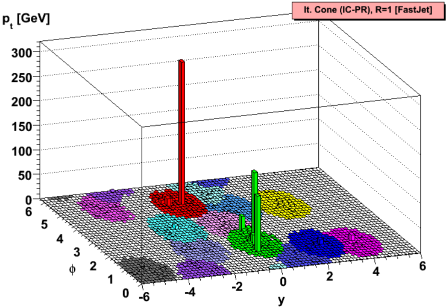


- ICPR has circular jets
  But collinear unsafe
- So does anti-k_t
  safe from theory point of view
- Cones with split-merge (SISCone) **shrink** to remove soft junk



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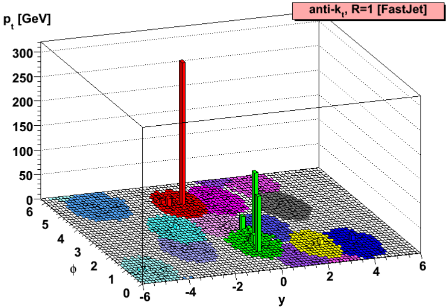

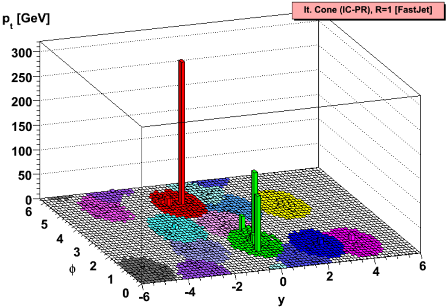

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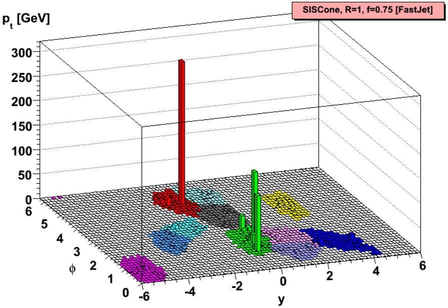

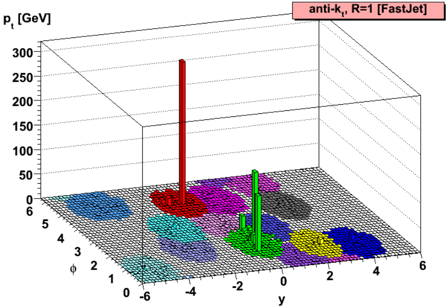

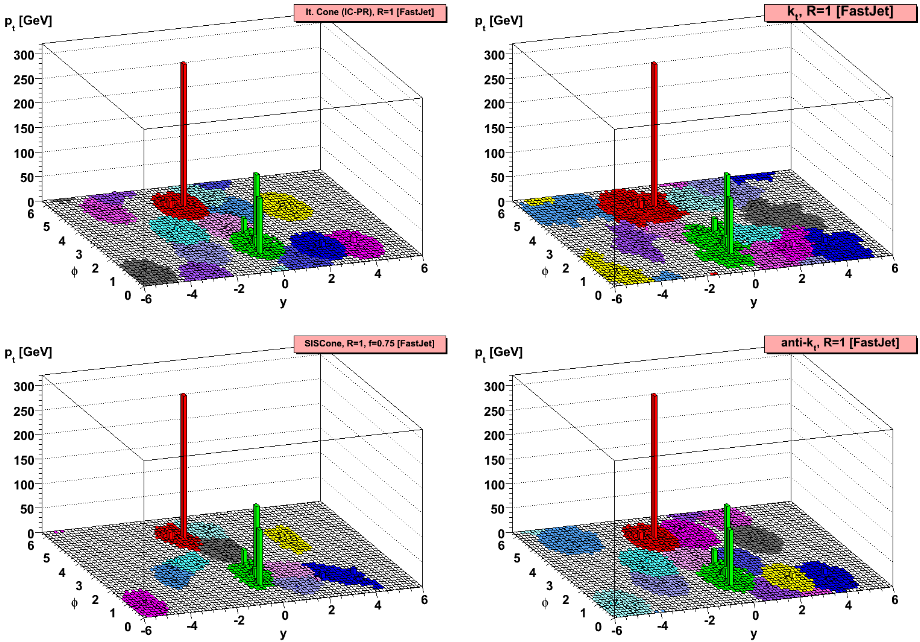

It. Cone (IC-PR), R=1 [FastJet]
kt, R=1 [FastJet]
SISCone, R=1, f=0.75 [FastJet]
anti-kt, R=1 [FastJet]
pt [GeV]
φ
y

Sequential recombination algs

The k_t algorithm

Find smallest $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and recombine;
If $d_{iB} = k_{ti}^2$ is smallest, call i a jet.

The Cambridge/Aachen algorithm

Repeatedly recombine objects with smallest ΔR_{ij}^2, until all $\Delta R_{ij} > R$

Both involve a tradeoff:

✓ useful information from clustering hierarchy

✗ irregularity of the jets

My favourite: Cam/Aachen

(it's more easily twisted to fit your needs)

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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)

FastJet 2.3.x also contains

CDF JetClu (legacy)
CDF MidPoint cone (legacy)
PxCone (legacy)

FastJet 2.4 will add (in next few weeks)

DØ Run II cone (legacy)
ATLAS Iterative cone (legacy)
CMS Iterative cone (legacy)
Trackjet (legacy)

A whole range of e^+e^- algorithms

Tools to help you build your own seq. rec. algorithms

[NB: many algs available also in SpartyJet]

FastJet 2.3.x also contains

CDF JetClu (legacy)
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FastJet's inclusion of many legacy cones is not an endorsement of them.

They are to be deprecated for any new physics analysis.

TrackJet (legacy)

A whole range of e^+e^- algorithms

Tools to help you build your own seq. rec. algorithms

[NB: many algs available also in SpartyJet]

Can we understand our tools?

Jet def^n differences

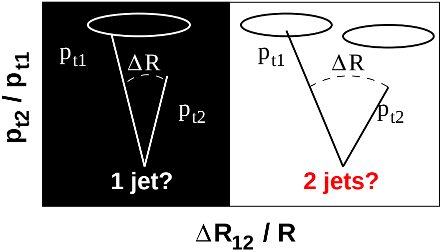
Jet definitions differ mainly in:

1. How close two particles must be to end up in same jet
[discussed in the '90s, e.g. Ellis & Soper]

2. How much perturbative radiation is lost from a jet
[indirectly discussed in the '90s (analytic NLO for inclusive jets)]

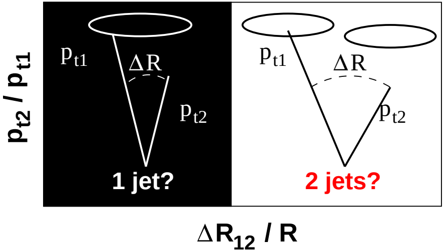
3. How much non-perturbative contamination (hadronisation, UE, pileup) a jet receives
[partially discussed in '90s — Korchemsky & Sterman '95, Seymour '97]

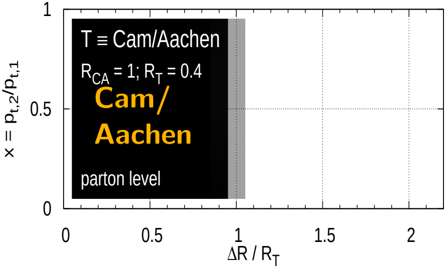
the *reach* of jet algorithms



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

the *reach* of jet algorithms





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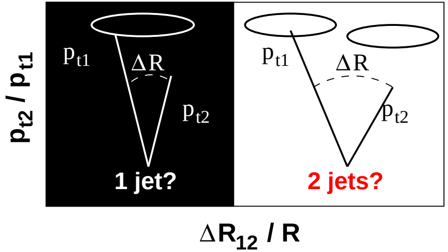

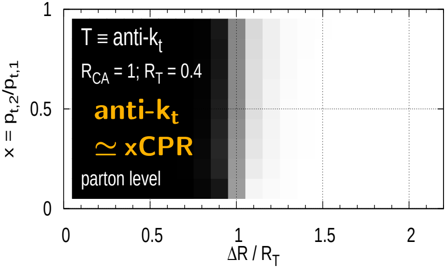

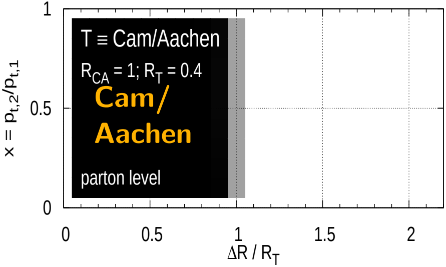

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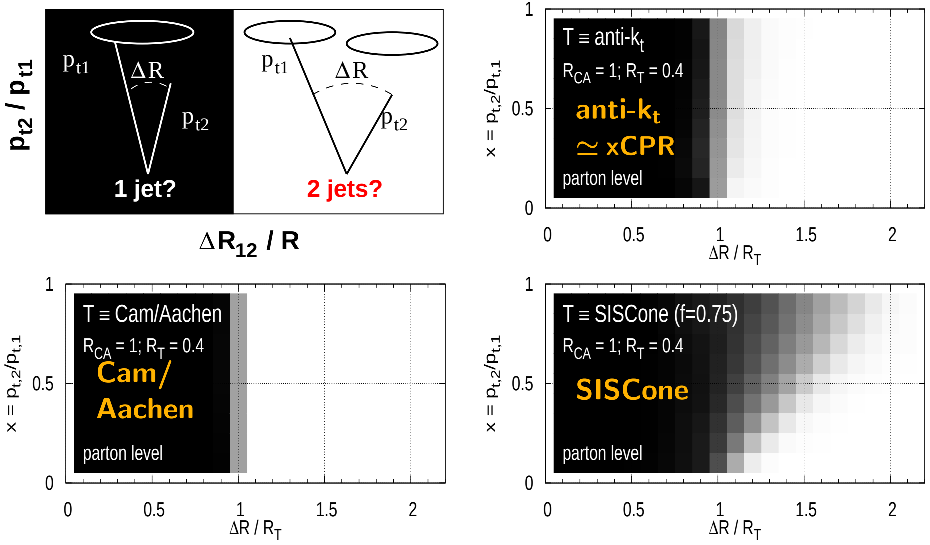

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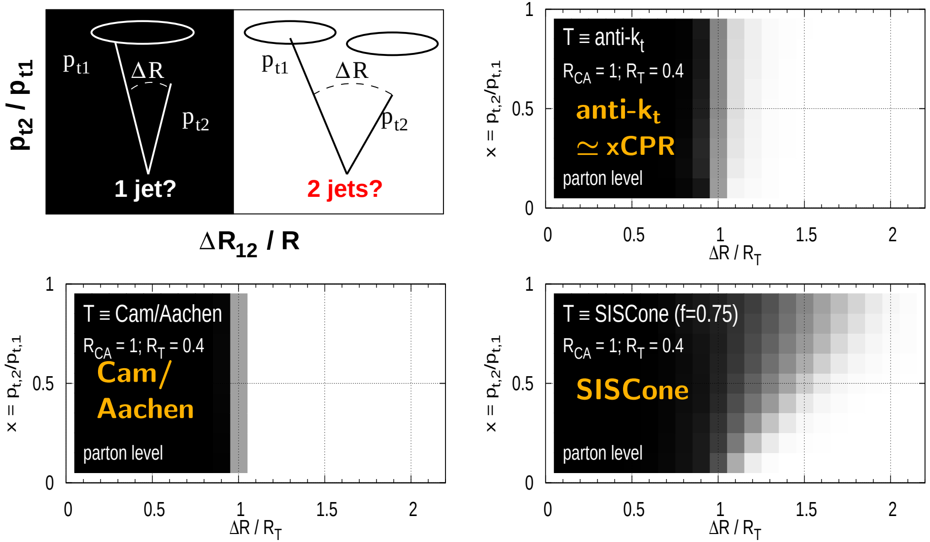


SISCone (xC-SM) reaches further for hard radiation than other algs

Jet p_t v. parton p_t: perturbatively?

The question's dangerous: a "parton" is an ambiguous concept

Three limits can help you:

- Threshold limit — e.g. de Florian & Vogelsang '07
- Parton from color-neutral object decay (Z')
- Small-R (radius) limit for jet

One simple result

$$\frac{\langle p_{t,jet} - p_{t,parton} \rangle}{p_t} = \frac{\alpha_s}{\pi} \ln R \times \begin{cases} 1.01 C_F & \textit{quarks} \\ 0.94 C_A + 0.07 n_f & \textit{gluons} \end{cases} + \mathcal{O}(\alpha_s)$$

only $\mathcal{O}(\alpha_s)$ depends on algorithm & process
cf. Dasgupta, Magnea & GPS '07

Jet p_t v. parton p_t: hadronisation?

Hadronisation: the "parton-shower" $\longrightarrow$ hadrons transition

Method:

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

Main result

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

cf. Dasgupta, Magnea & GPS '07

coefficient holds for anti-k_t; see Mrinal's talk for k_t alg.

Underlying Event (UE)

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

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

DWT Pythia tune or ATLAS Jimmy tune tell you:

$$\Delta p_t \simeq \mathbf{10 - 15 \text{ GeV}} \times \frac{R^2}{2}$$

This big coefficient motivates special effort to understand interplay between jet algorithm and UE: "jet areas"

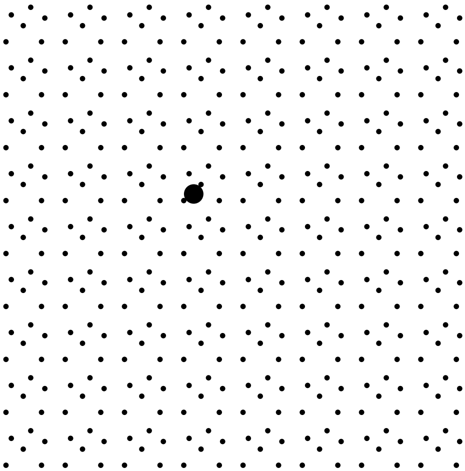
How does coefficient depend on algorithm?

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

cf. Cacciari, GPS & Soyez '08

E.g. SISCone jet area

1. One hard particle, many soft



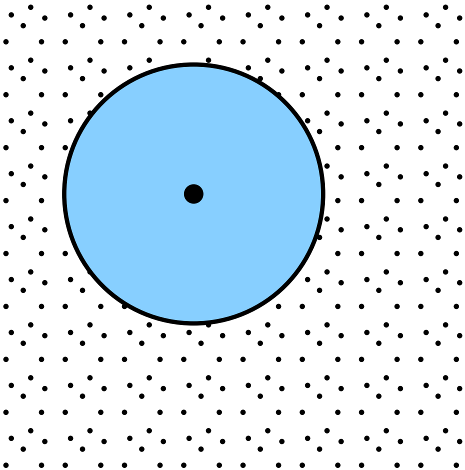
SISCone, any R, $f \gtrsim 0.391$

Jet area =
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

2. One hard stable cone



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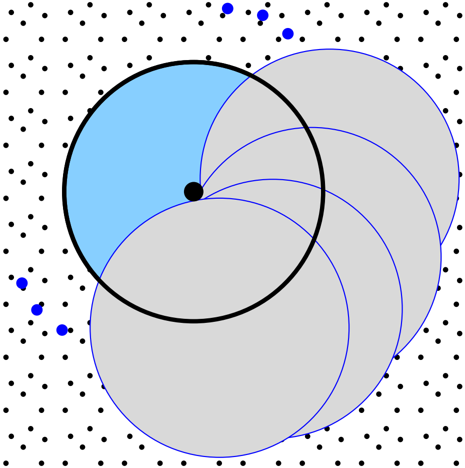
E.g. SISCone jet area

3. Overlapping "soft" stable cones



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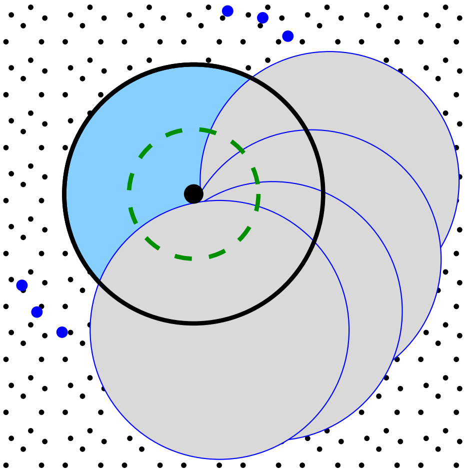
E.g. SISCone jet area

4. "Split" the overlapping parts



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Jet area =
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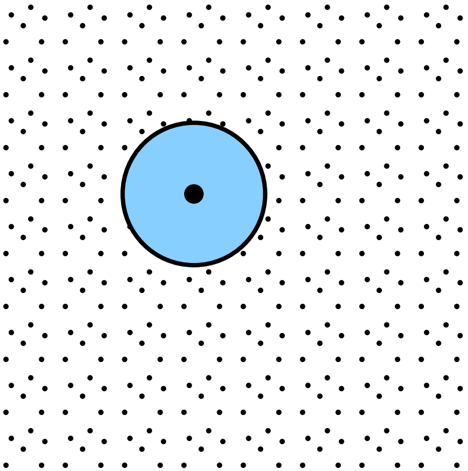
Depends on details of an algorithm's clustering dynamics.

E.g. SISCone jet area

5. Final hard jet (reduced area)



SISCone, any R, $f \gtrsim 0.391$

Jet area =
Measure of jet's susceptibility to uniform soft radiation

Depends on details of an algorithm's clustering dynamics.

SISCone's area (1 hard particle)
$$= \mathbf{\frac{1}{4}}\,\pi R^2$$

Jet algorithm properties: summary

	k_t	Cam/Aachen	anti-k_t	SISCone
reach	R	R	R	$(1 + \frac{p_{t2}}{p_{t2}})R$
$\Delta p_{t,PT} \simeq \frac{\alpha_s C_i}{\pi} \times$	$\ln R$	$\ln R$	$\ln R$	$\ln 1.35R$
$\Delta p_{t,hadr} \simeq -\frac{0.4 \text{ GeV} C_i}{R} \times$	0.7	?	1	?
area $= \pi R^2 \times$	0.81 ± 0.28	0.81 ± 0.26	1	0.25
$+\pi R^2 \frac{C_i}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(R p_t)} \times$	0.52 ± 0.41	0.08 ± 0.19	0	0.12 ± 0.07

In words:

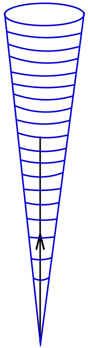
- k_t: area fluctuates a lot, depends on p_t (bad for UE)
- Cam/Aachen: area fluctuates somewhat, depends less on p_t
- anti-k_t: area is constant (circular jets)
- SISCone: reaches far for hard radiation (good for resolution, bad for multijets), area is smaller (good for UE)

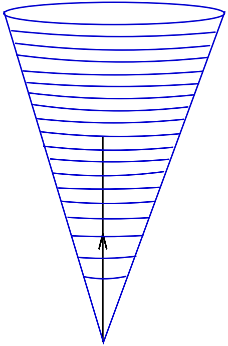
Using our understanding

(concentrate on R-dependence)

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

Small jet radius **Large jet radius**

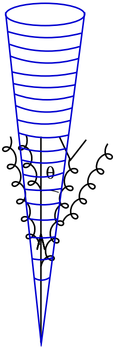




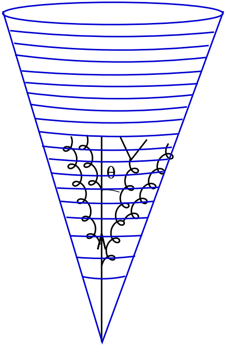
single parton @ LO: **jet radius irrelevant**

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

Small jet radius



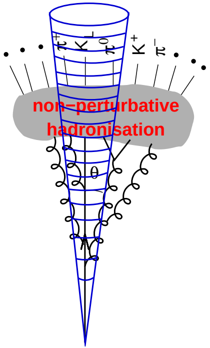
Large jet radius



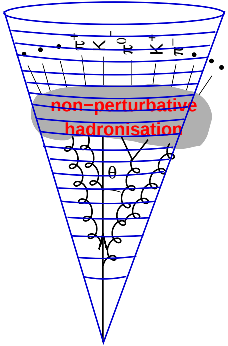
perturbative fragmentation: **large jet radius better**
(it captures more)

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

Small jet radius



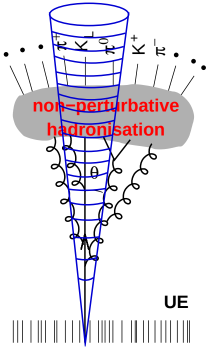
Large jet radius



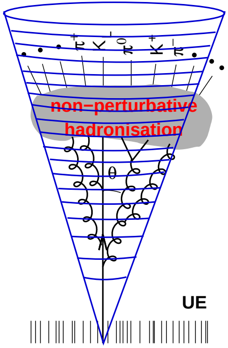
non-perturbative fragmentation: **large jet radius better**
(it captures more)

Small v. large jet radius (R) ≡ HSBC

Small jet radius



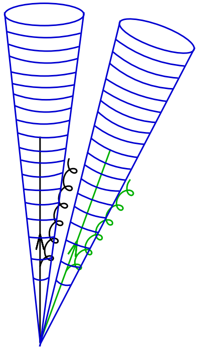
Large jet radius



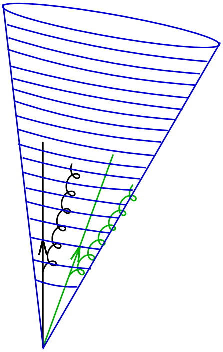
underlying ev. & pileup "noise": **small jet radius better**
(it captures less)

Small v. large jet radius (R) ≡ HSBC

Small jet radius



Large jet radius



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

What R is best for an isolated jet?

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:

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

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 (?!)

cf. Dasgupta, Magnea & GPS '07

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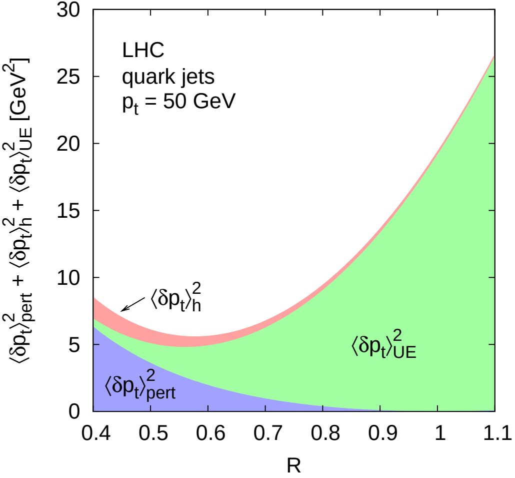
50 GeV quark jet



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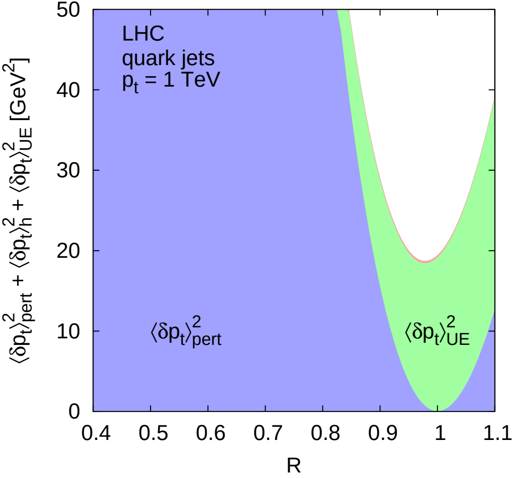
1 TeV quark jet



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What R is best for an isolated jet?

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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 $\rightarrow R_{best} \sim 1$.

Underlying event:

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

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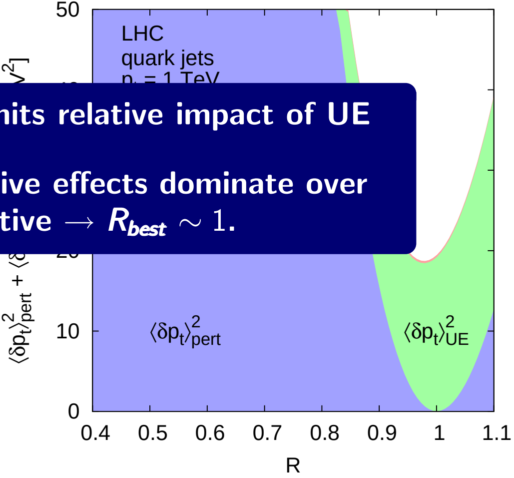
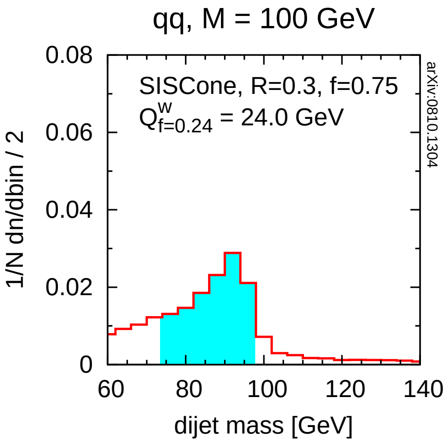


in small-R limit (?!)

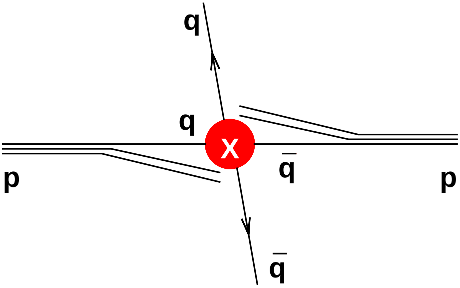
cf. Dasgupta, Magnea & GPS '07

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

R = 0.3



Resonance X → dijets



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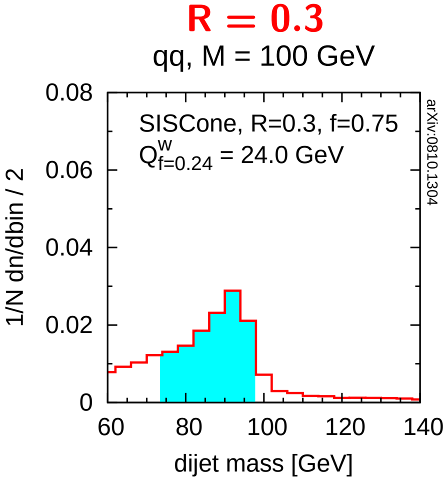

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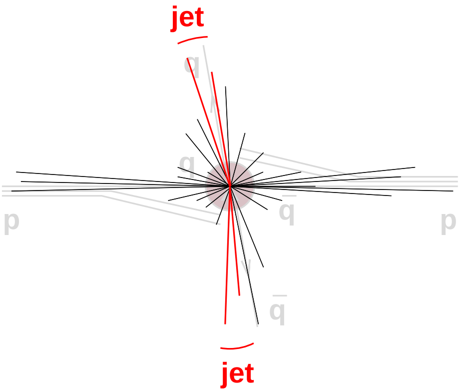

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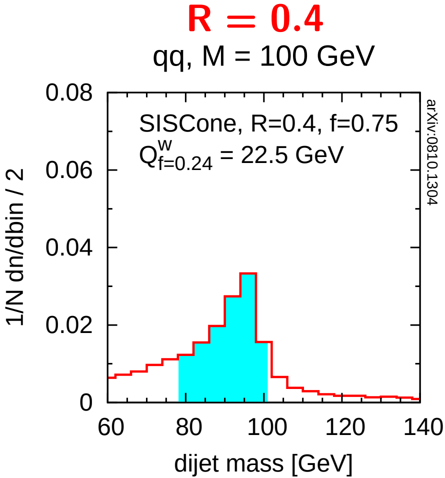

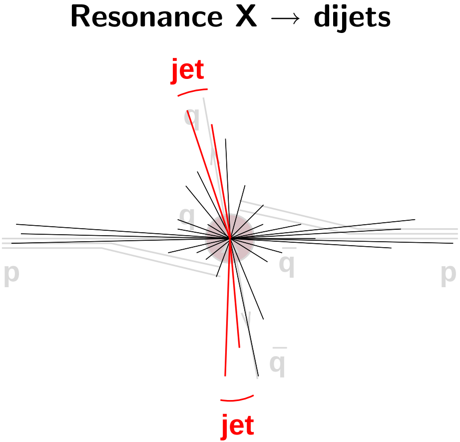

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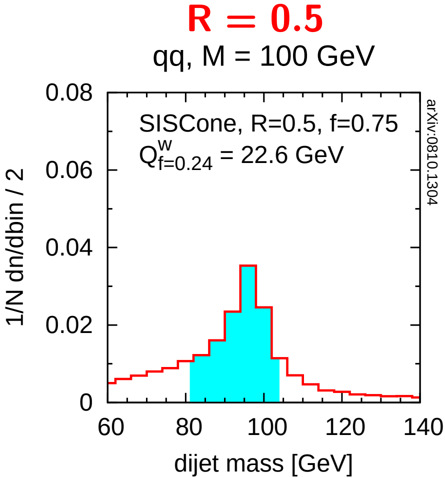
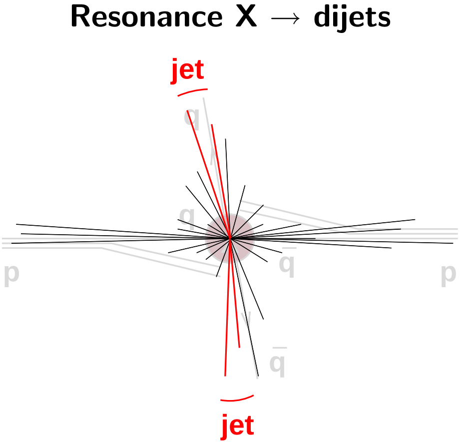
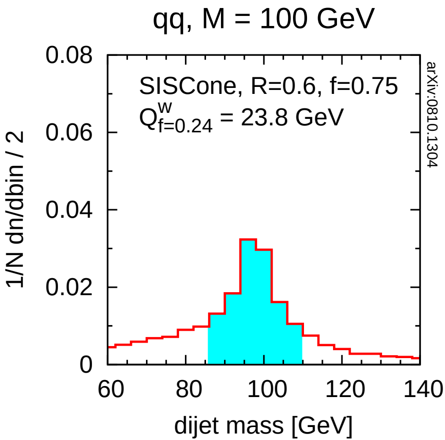


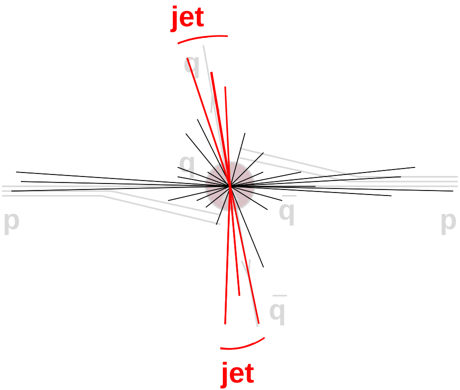


Dijet mass: scan over *R* [Pythia 6.4]

R = 0.6

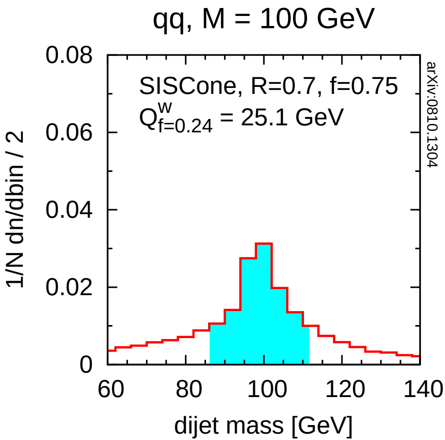


Resonance X → dijets

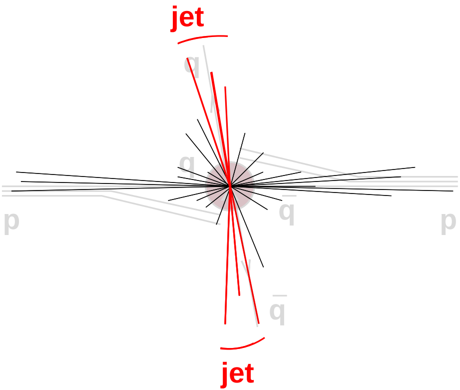


Dijet mass: scan over *R* [Pythia 6.4]

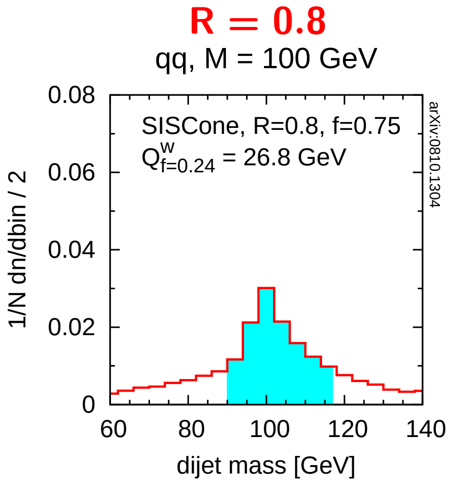
R = 0.7



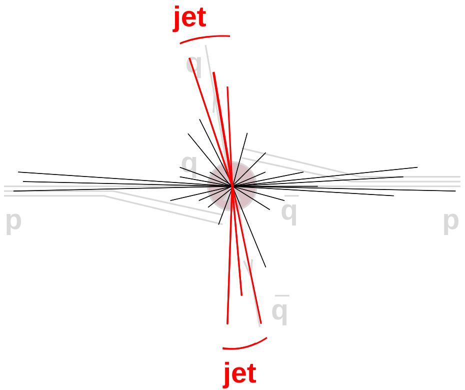
Resonance X → dijets



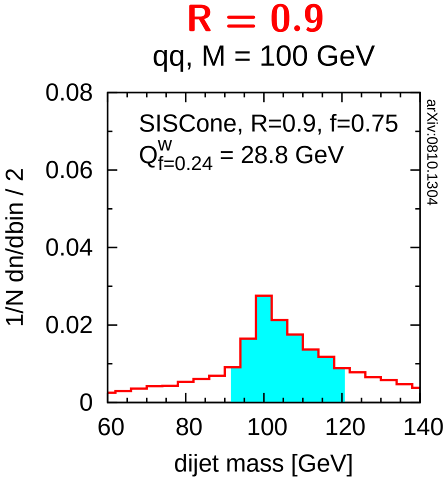
Dijet mass: scan over *R* [Pythia 6.4]

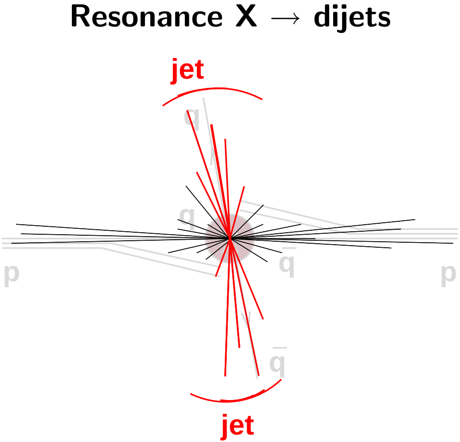


Resonance X → dijets

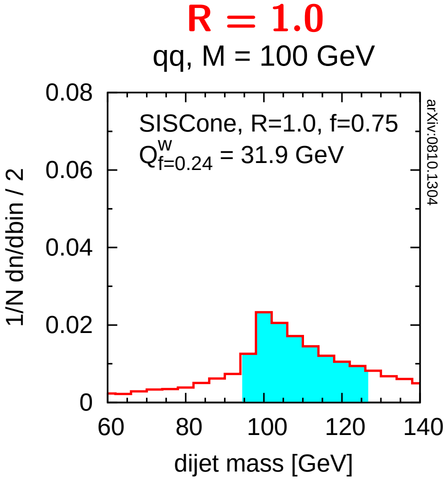


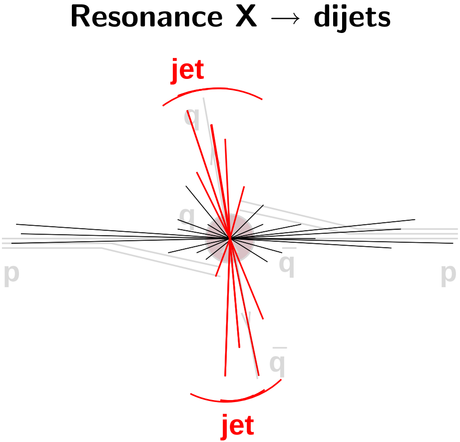
Dijet mass: scan over R [Pythia 6.4]





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





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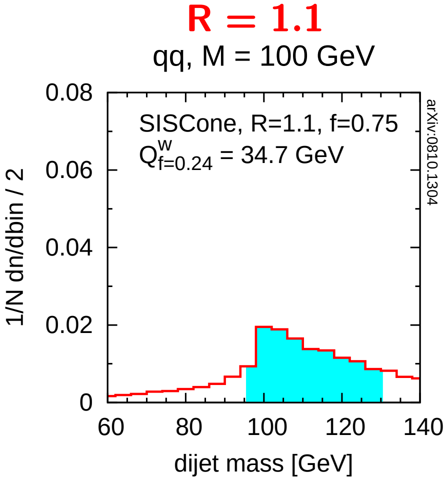

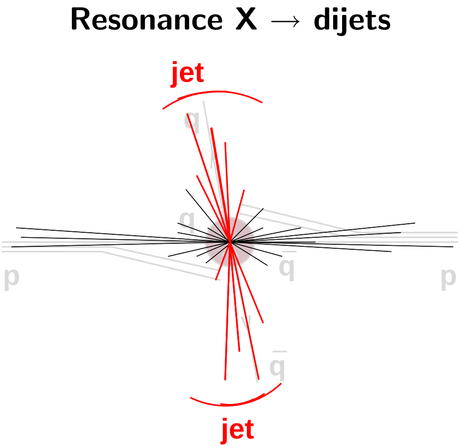

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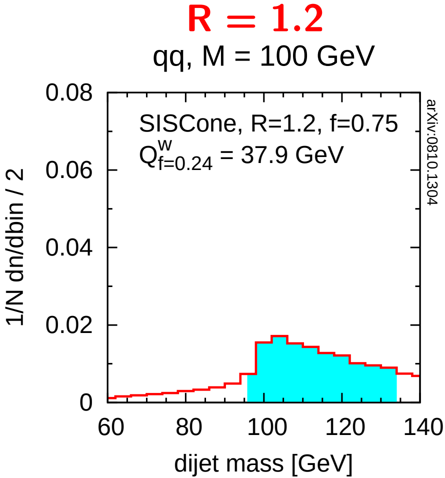

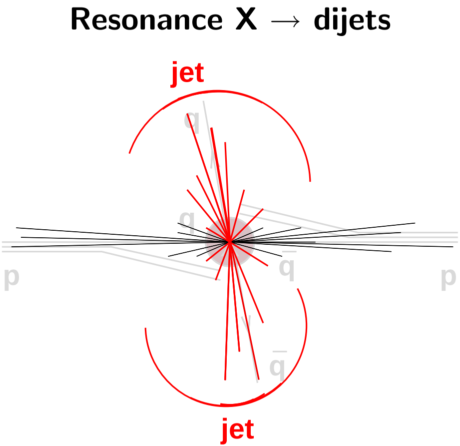

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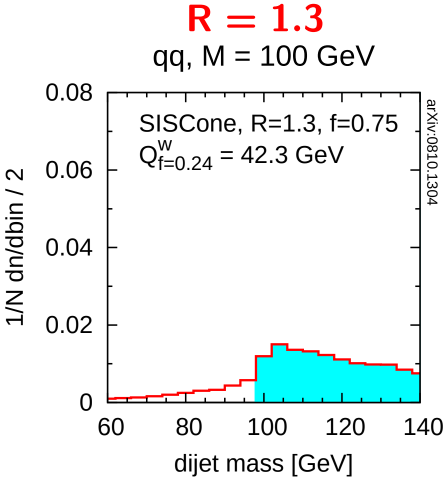

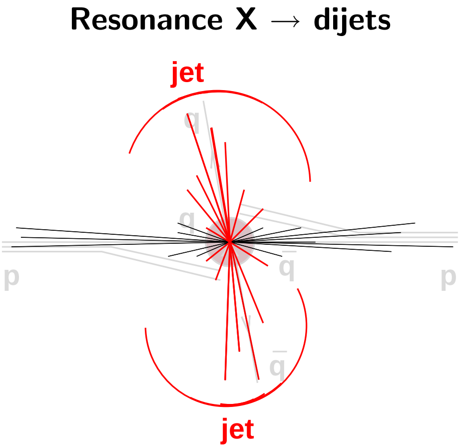

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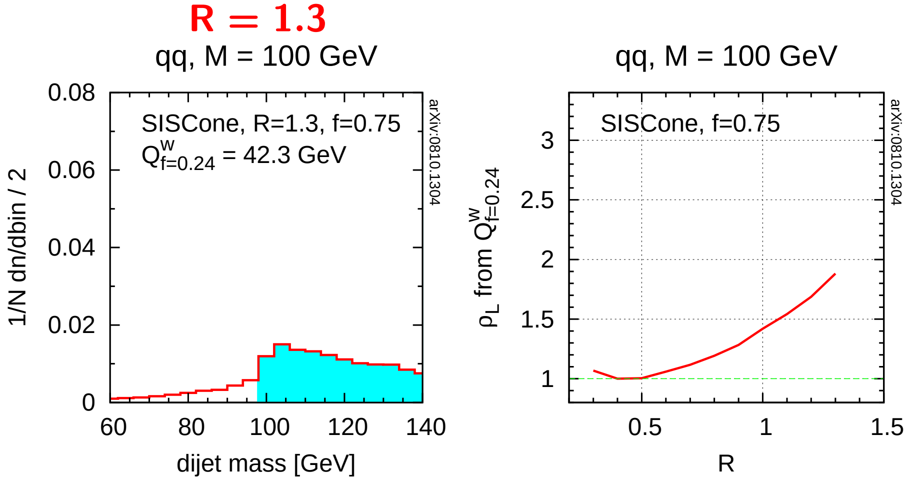
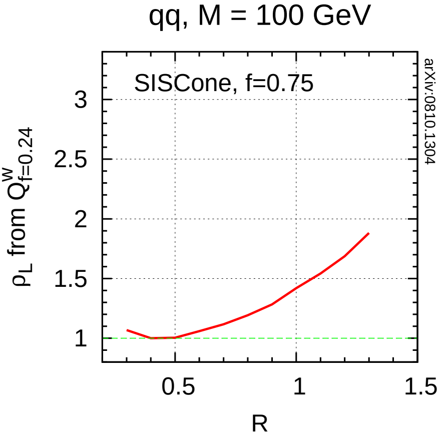


After scanning, summarise "quality" v. *R*. Minimum ≡ BEST

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

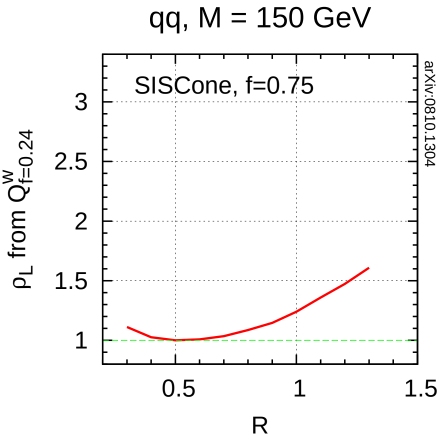
BUT: so far, LHC's plans involve running with fixed smallish R values

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 $q\bar{q}$ mass values

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



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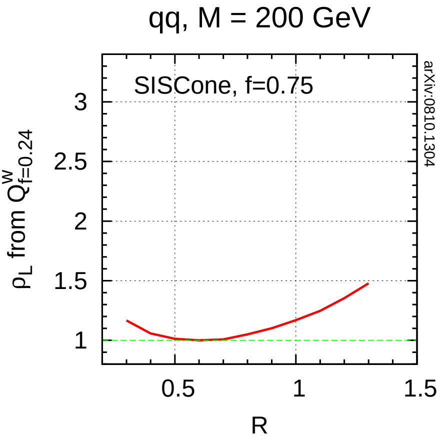
Scan through $q\bar{q}$ mass values

m_{qq} = 200 GeV



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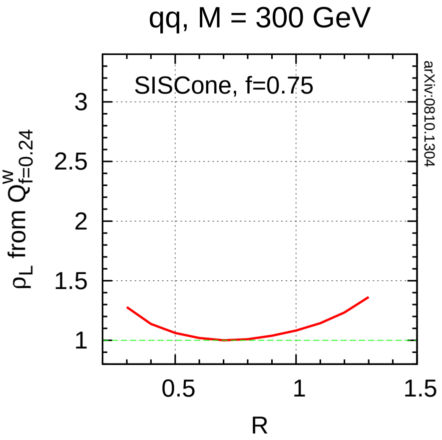
Scan through $q\bar{q}$ mass values

$m_{qq} = 300$ GeV



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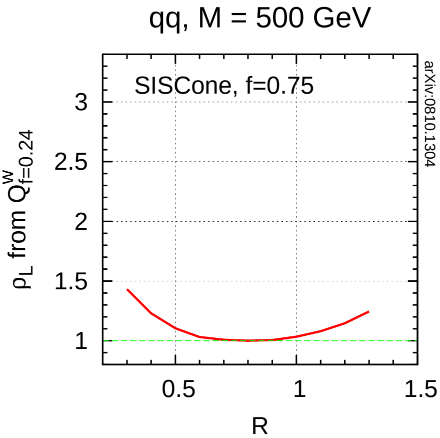
Scan through $q\bar{q}$ mass values

$m_{qq} = 500$ GeV



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e.g. CMS arXiv:0807.4961

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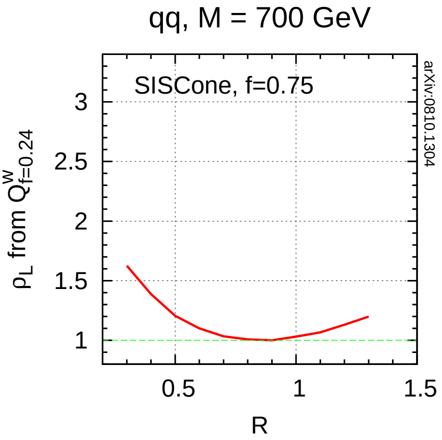
Scan through $q\bar{q}$ mass values

$m_{qq} = 700$ GeV



Best R is at minimum of curve

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- Increases with mass, just like crude analytical prediction

NB: current analytics too crude

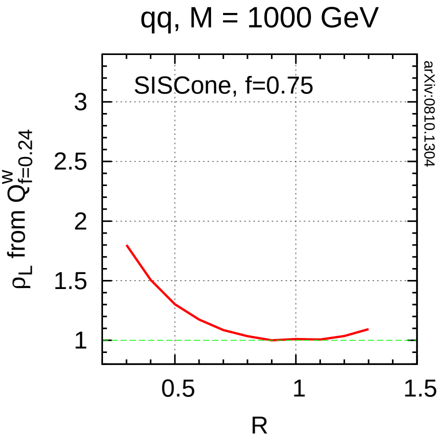
BUT: so far, LHC's plans involve running with fixed smallish R values

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 $q\bar{q}$ mass values

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



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NB: current analytics too crude

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

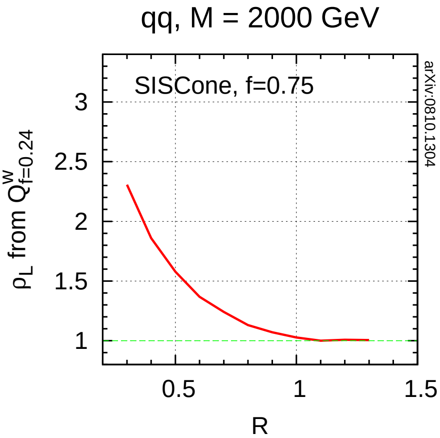
e.g. CMS arXiv:0807.4961

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 $q\bar{q}$ mass values

$\mathbf{m_{qq} = 2000\ GeV}$



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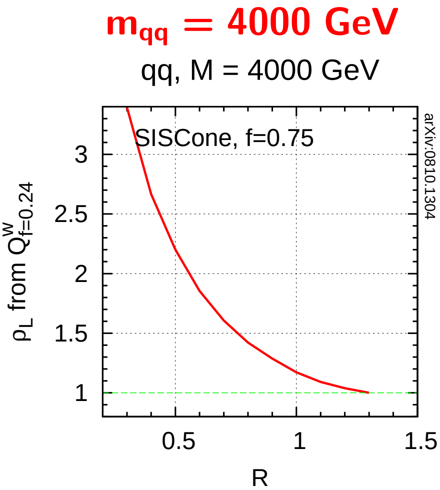
Scan through $q\bar{q}$ mass values



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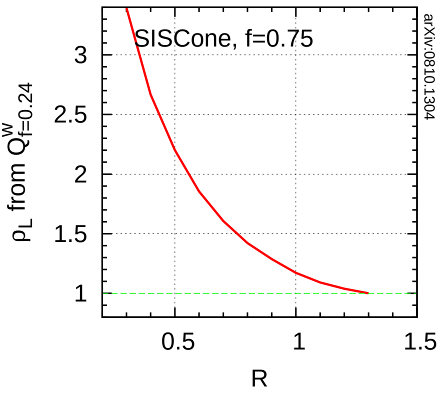
e.g. CMS arXiv:0807.4961

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 $q\bar{q}$ mass values

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



Best R is at minimum of curve

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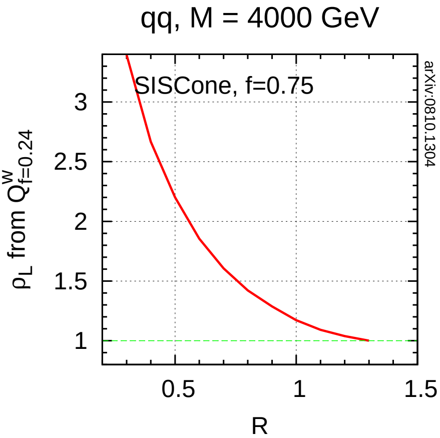
e.g. CMS arXiv:0807.4961

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 $q\bar{q}$ mass values

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



Best R is at minimum of curve

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NB: current analytics too crude

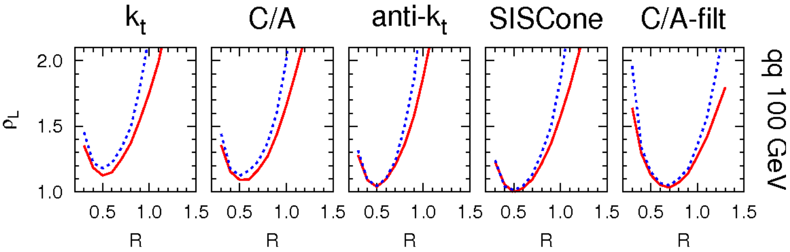
BUT: so far, LHC's plans involve running with fixed smallish *R* values

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

quality: 5 algorithms, 3 processes



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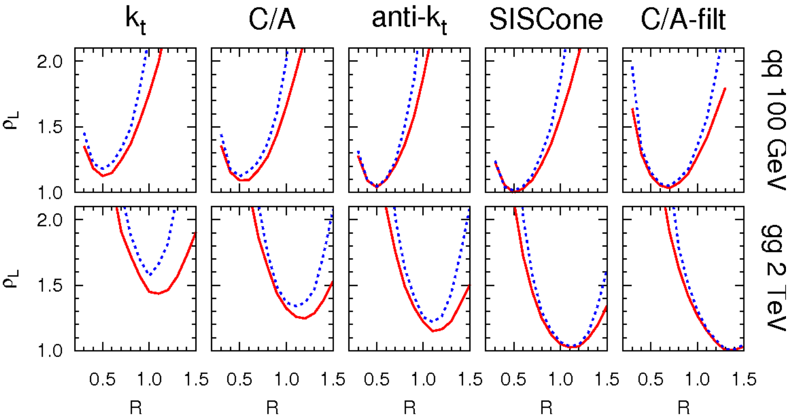

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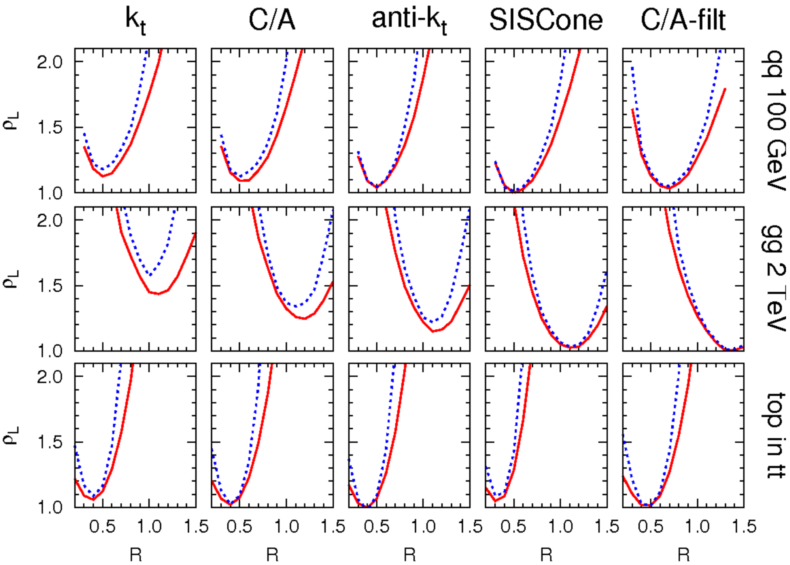
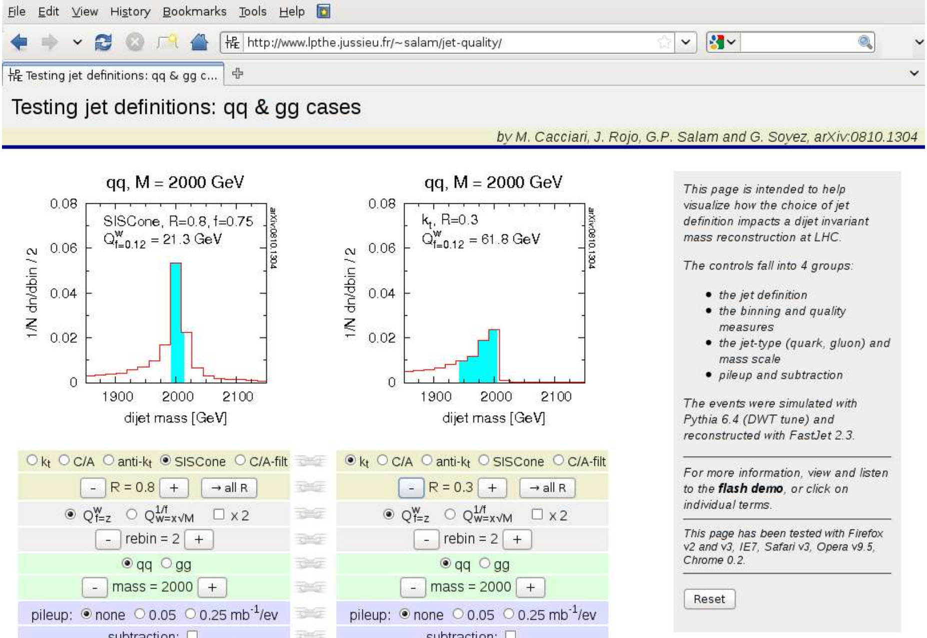


http://quality.fastjet.fr/



These studies show that:

Choice of jet definition matters

(it's worth a factor of $1.5 - 2$ in lumi)

There is no single best jet definition

LHC will span two orders of magnitude in p_t

(experiments should build in flexibility)

There is logic to the pattern we see

(it fits in with crude analytical calculations)

Towards *jetography*

These studies motivate a more systematic approach:

More realistic analytical calculations

e.g. using known differences between algorithms

Consideration of backgrounds

Consideration of multi-jet signals

(relation to boosted W/Z/H/top (subjet) ID methods)

Design of more "optimal" jet algorithms

(R alone may not give enough freedom — cf. "filtering")

Towards *jetography*

These studies motivate a more systematic approach:

More realistic analytical calculations

e.g. using known differences between algorithms

Consideration of backgrounds

Consideration of multi-jet signals

(relation to boosted W/Z/H/top (subjet) ID methods)

Design of more "optimal" jet algorithms

(R alone may not give enough freedom — cf. "filtering")

→ **Jetography:** "auto-focus" for jets

To conclude

Past experience (CDF/JetClu) suggests that if an IRC unsafe legacy algorithm remains available within an experiment, the majority of analyses will use it.

Maybe not the pure QCD analyses

But all the others

There are no longer any good reasons to prefer IRC unsafe algorithms.

As a *community*, let us try and make sure LHC does the right job.

So we get full value form perturbative QCD

And so that we can move on to more useful questions

EXTRAS

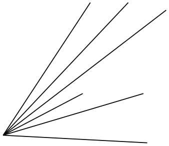
Cone basics I: IC-SM

Many cone algs have two main steps:

- Find some/all stable cones

  ≡ cone pointing in same direction as the momentum of its contents
- Resolve cases of overlapping stable cones

  By running a 'split–merge' procedure [Blazey et al. '00 (Run II jet physics)]



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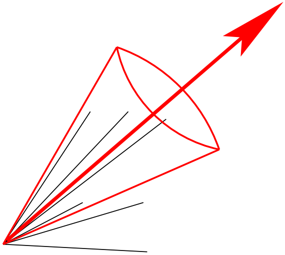

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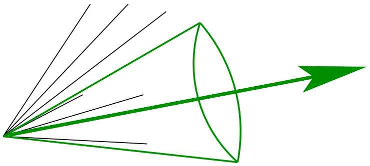

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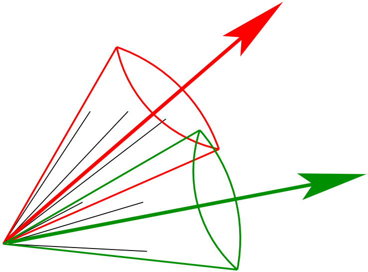

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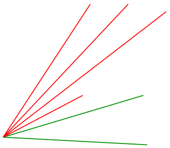

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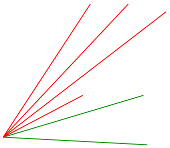
Qu: How do you find the stable cones?



Until recently used iterative methods:

- use each particle as a starting direction for cone; use sum of contents as new starting direction; repeat.

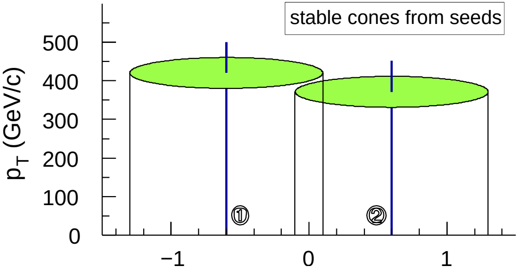
Iterative Cone with Split Merge (IC-SM)

e.g. Tevatron cones (JetClu, midpoint)

ATLAS cone

Seeded IC-SM: infrared issue

Use of seeds is *dangerous*



Extra soft particle adds new seed → changes final jet configuration.

This is **IR unsafe**.

Kilgore & Giele '97

Partial fix: add extra seeds at midpoints of all pairs, triplets, . . . of stable cones.

Adopted for Tevatron Run II

But only **postpones** the problem by one order . . .

Analogy: if you rely on Minuit to find minima of a function, in complex cases, results depend crucially on starting points

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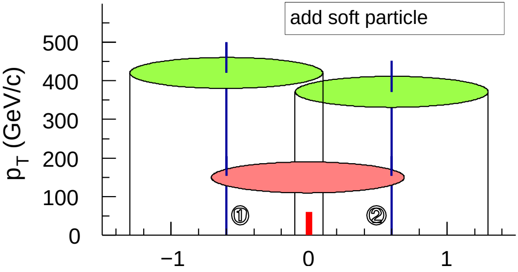

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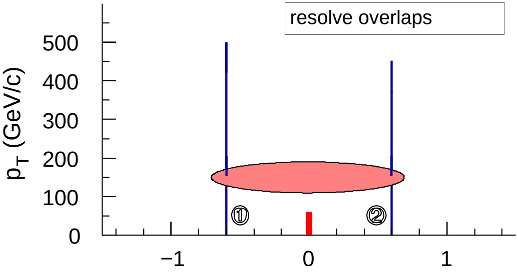

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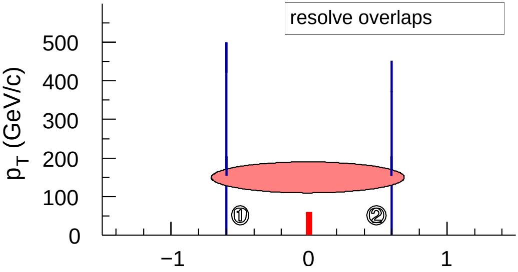

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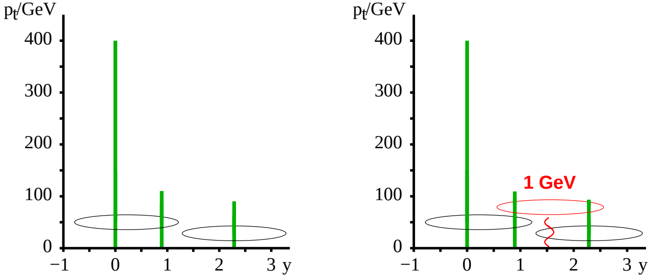
Midpoint IR problem



Stable cones with midpoint:	{1,2} & {3}	{1,2} & {2,3} & {3}
Jets with midpoint ($f = 0.5$)	{1,2} & {3}	{1,2,3}

Midpoint cone alg. misses some stable cones; extra soft particle → extra starting point → extra stable cone found

MIDPOINT IS INFRARED UNSAFE

Or collinear unsafe with seed threshold

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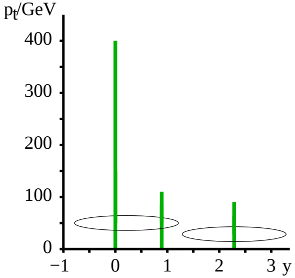

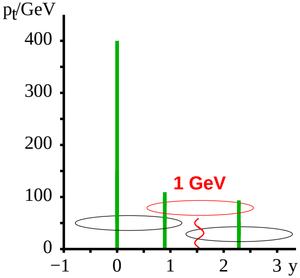

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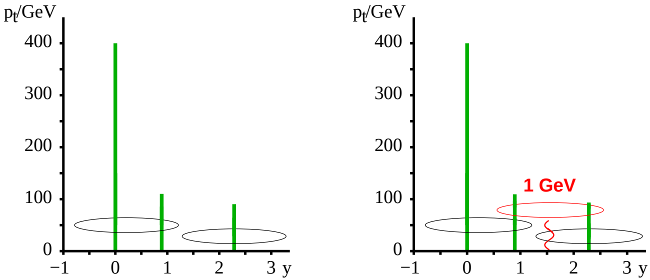

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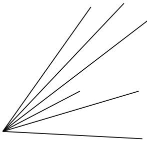
Iterative Cone [with progressive removal]

Procedure:

- Find one stable cone — By iterating from hardest seed particle
- Call it a jet; remove its particles from the event; repeat



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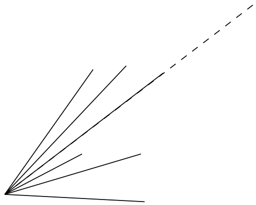

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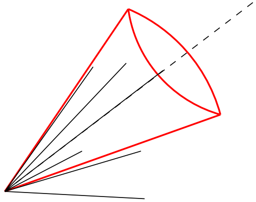

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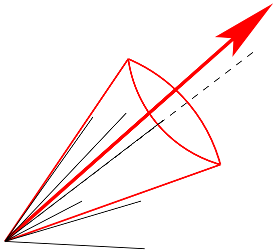

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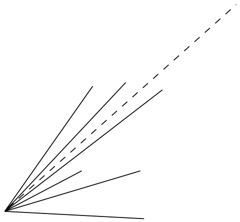

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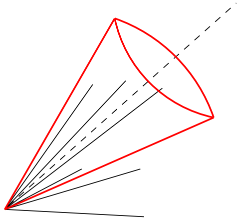

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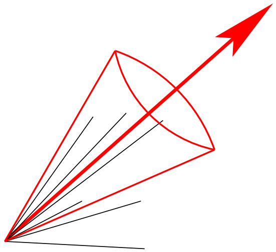

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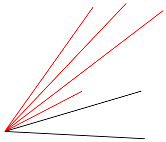

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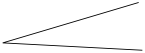

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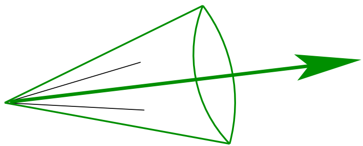

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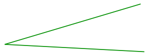

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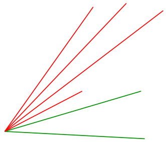

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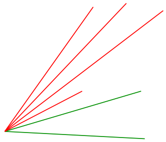
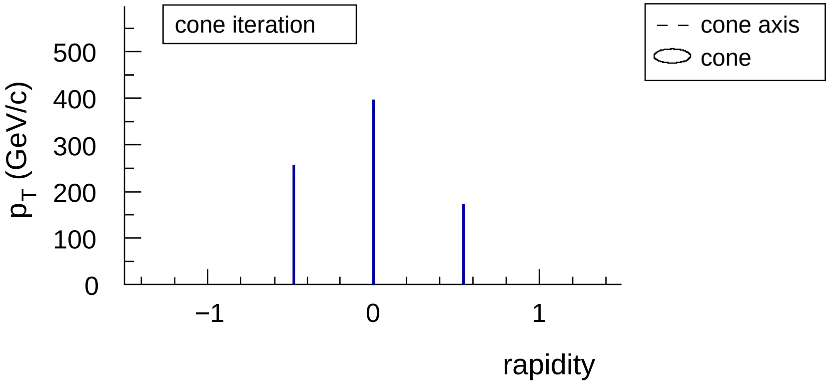


Iterative Cone with Progressive Removal (IC-PR)

e.g. CMS it. cone, [Pythia Cone, GetJet], . . .

- NB: not same type of algorithm as Atlas Cone, MidPoint, SISCone

ICPR iteration issue



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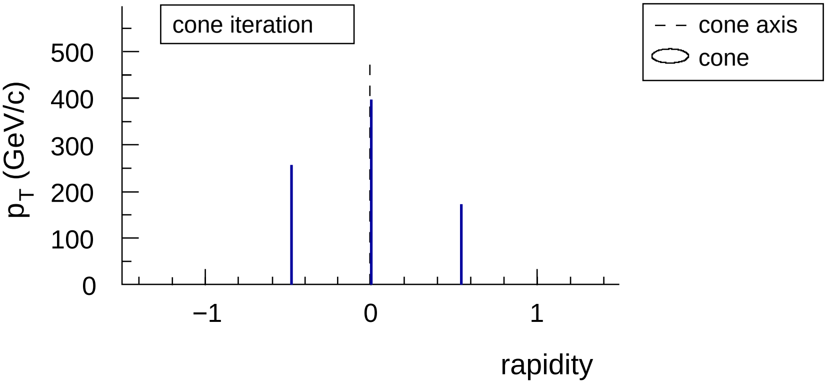

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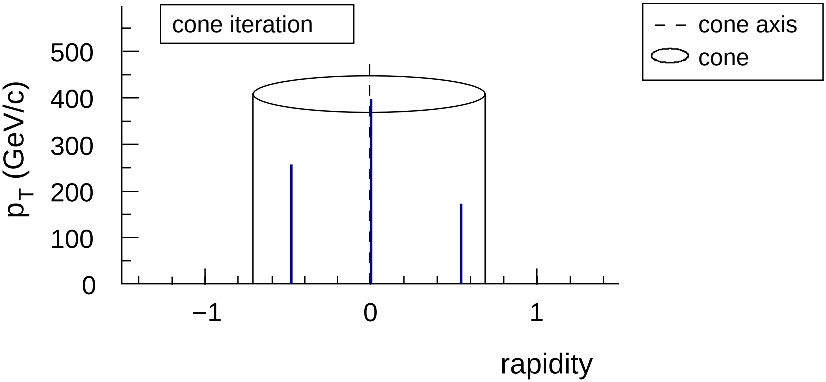

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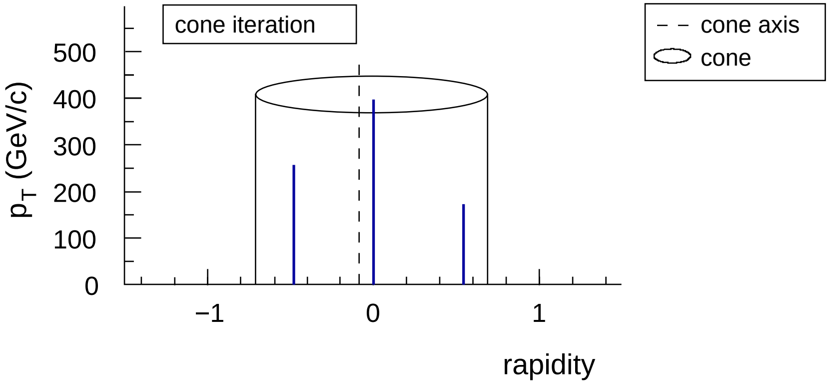

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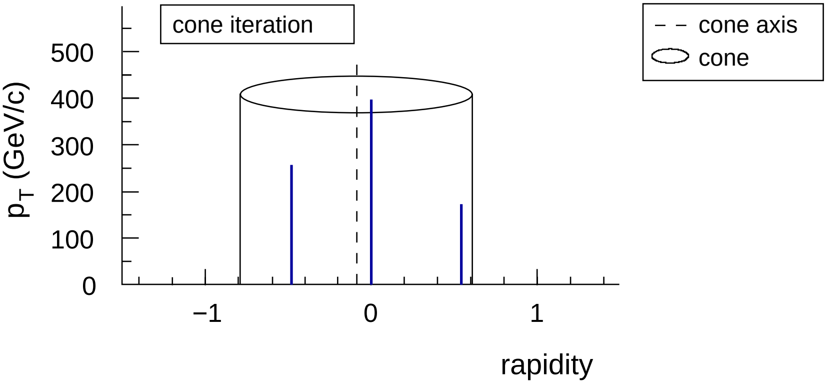

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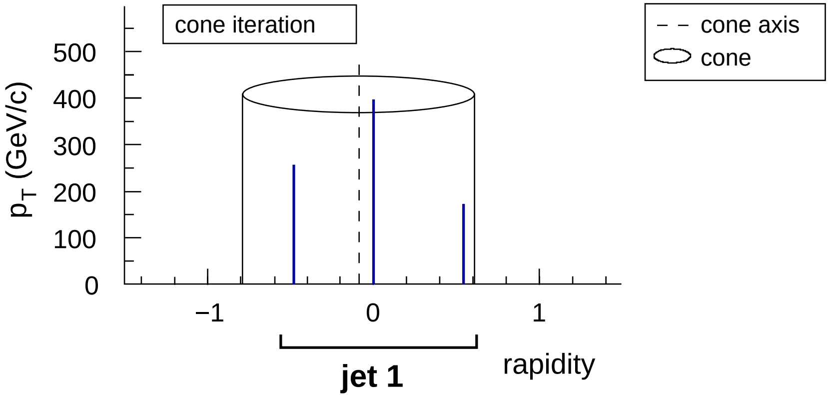

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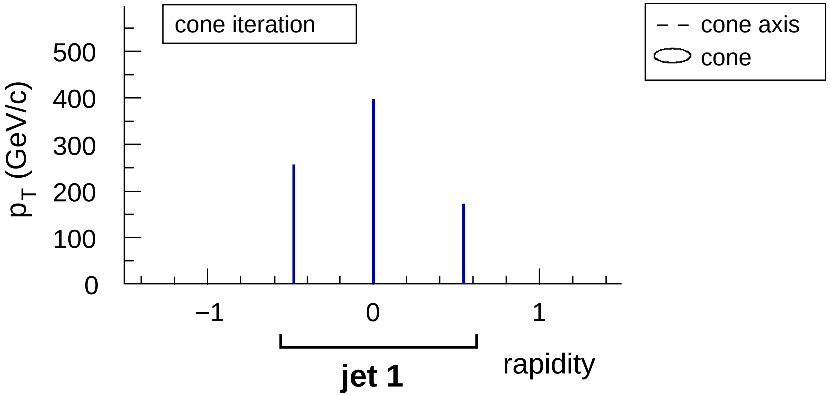

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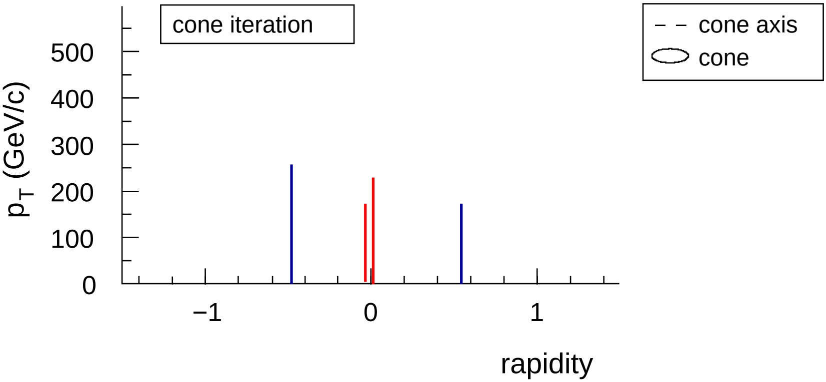

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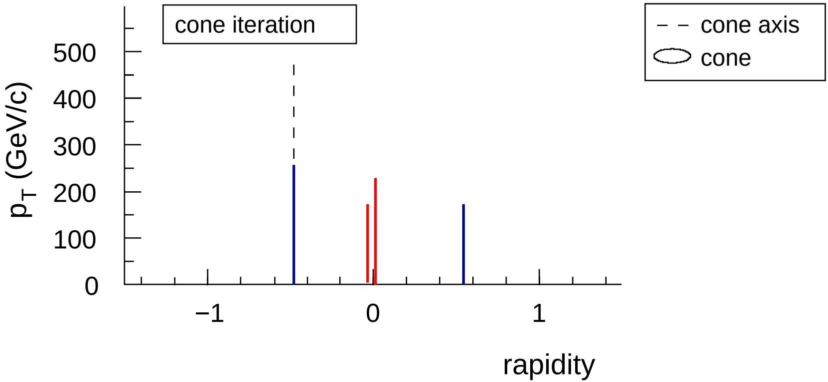

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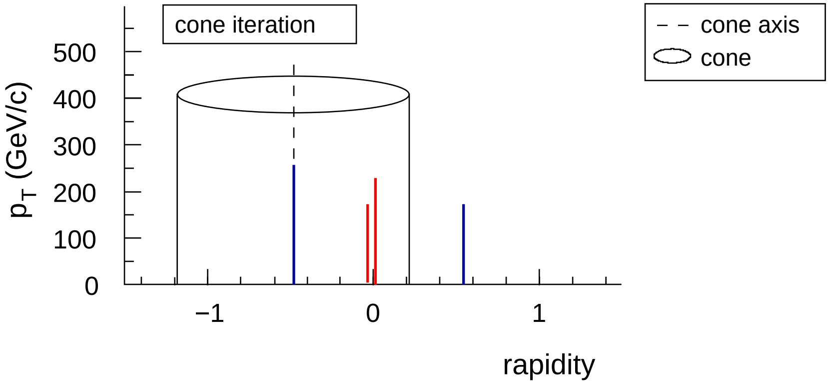

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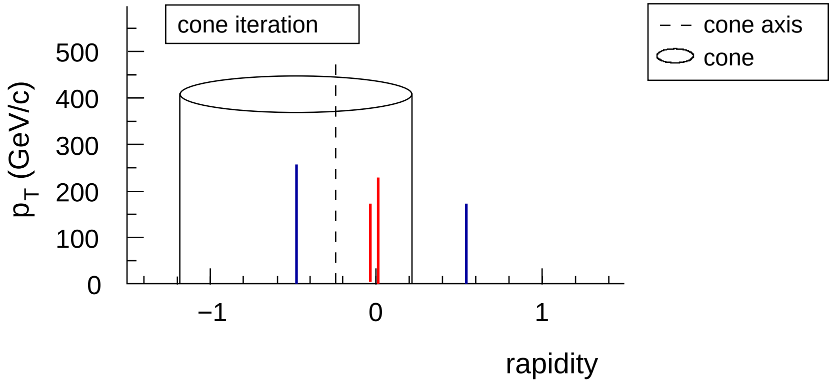

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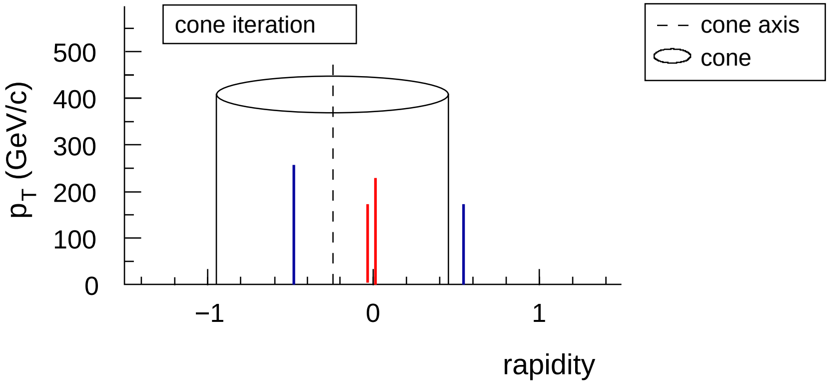

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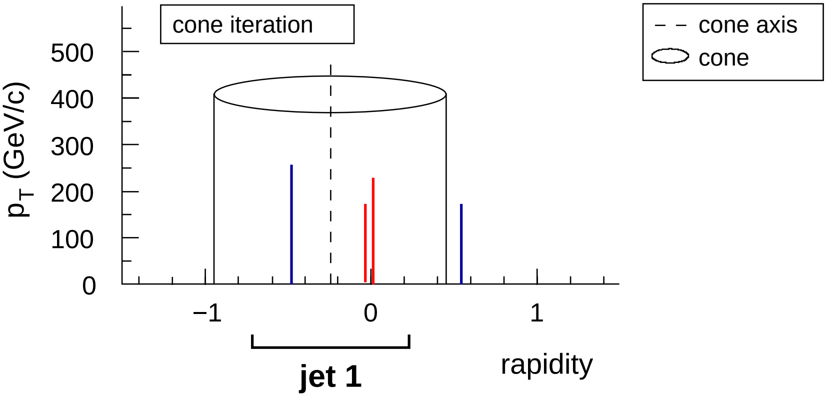

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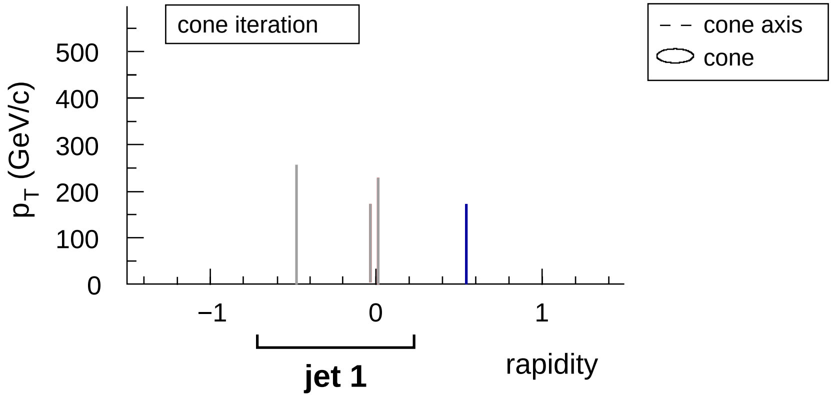

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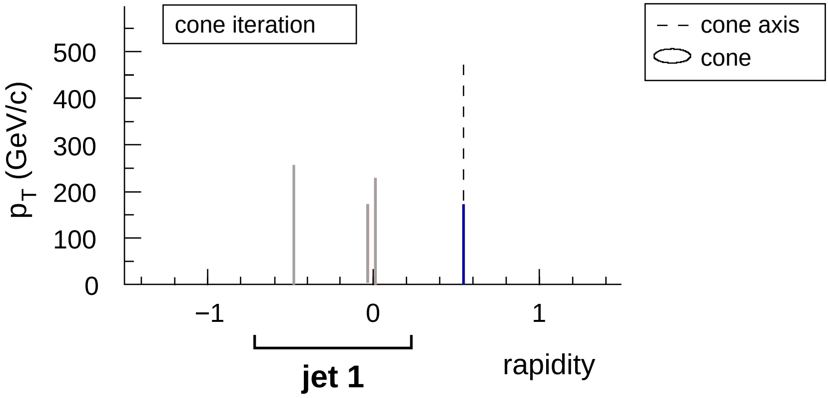

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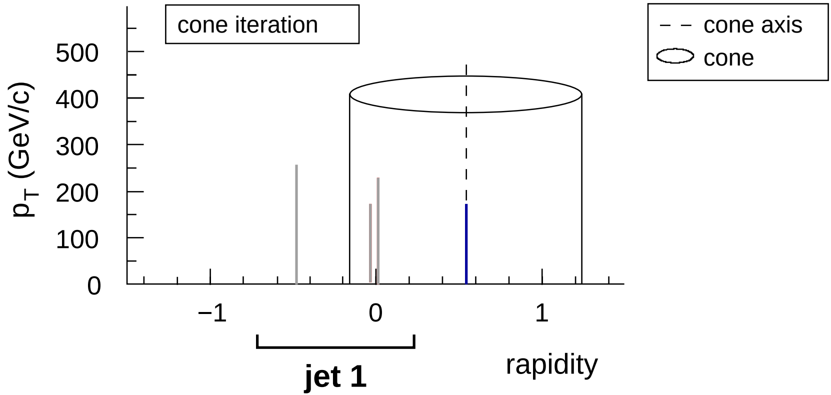

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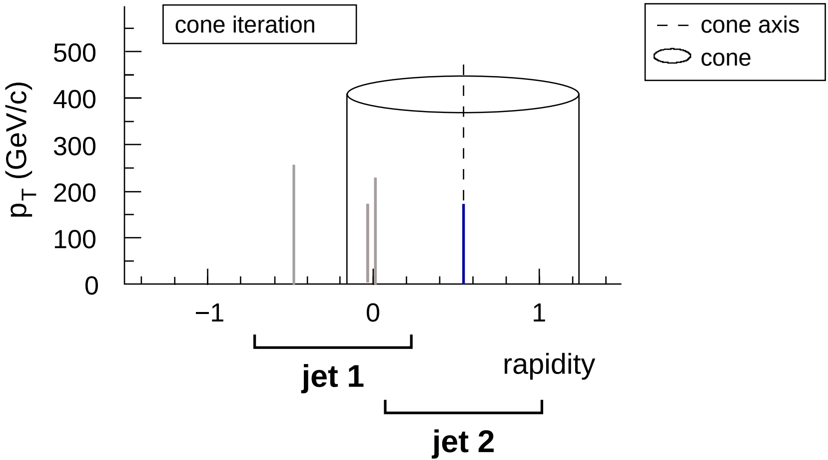

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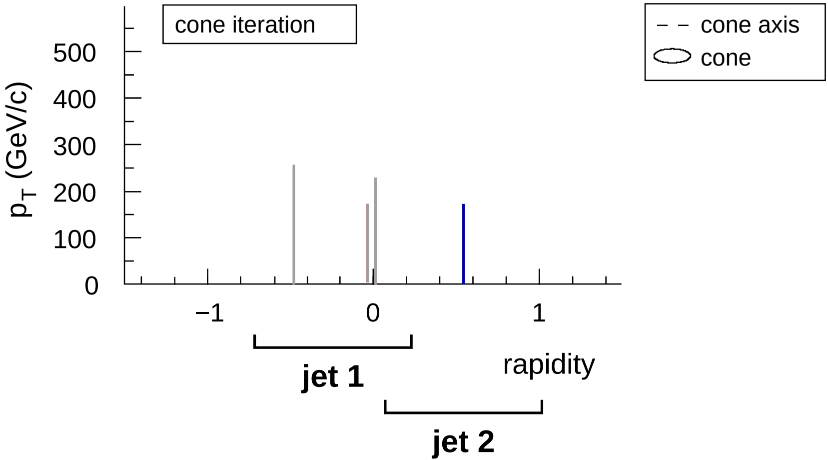

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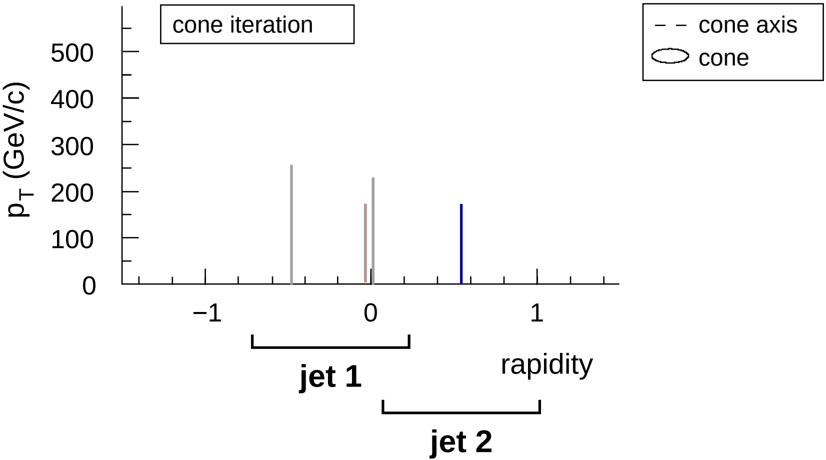

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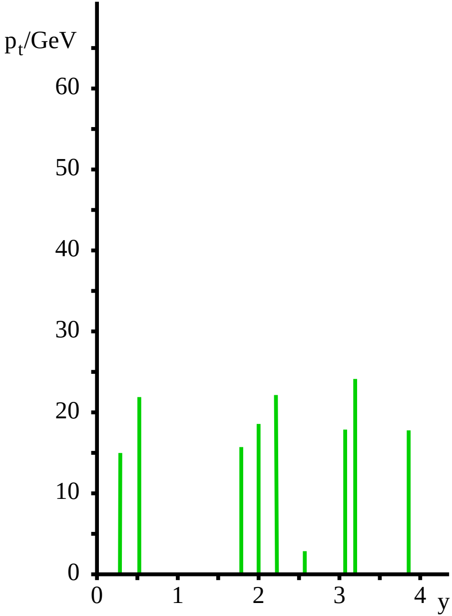
Seedless [Infrared Safe] cones (SC-SM)



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
- check each for stability
- then run usual split–merge

In 2 dimensions (y,ϕ) can design analogous procedure **SISCone**

GPS & Soyez '07

This gives an IRC safe cone alg.

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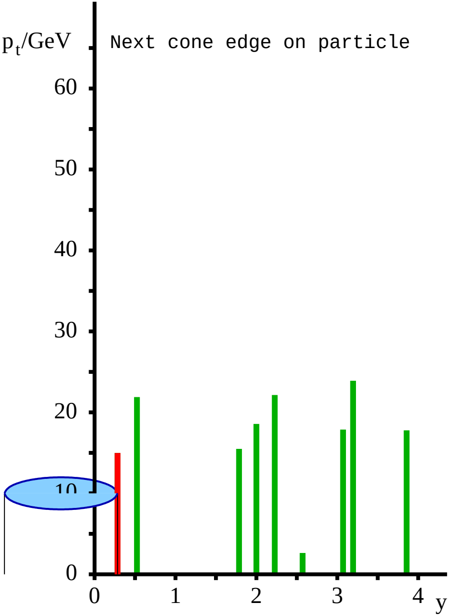

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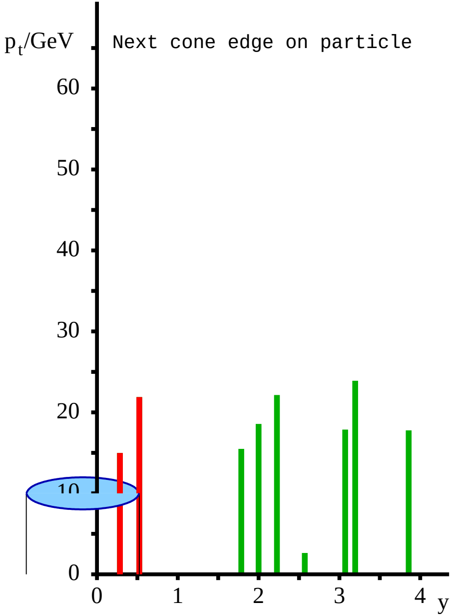

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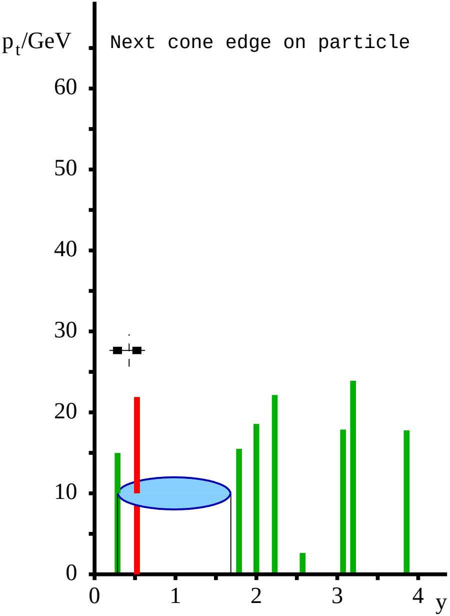

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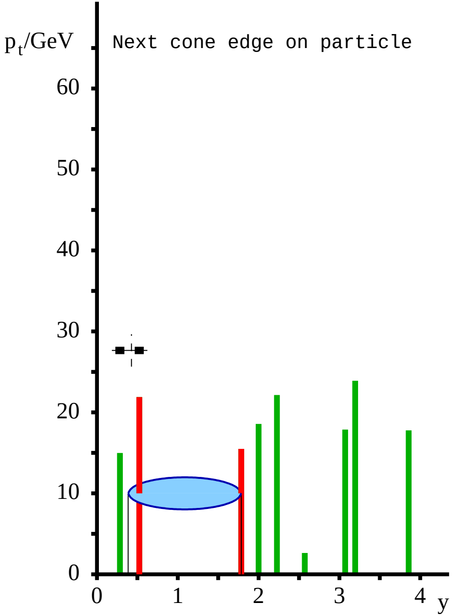

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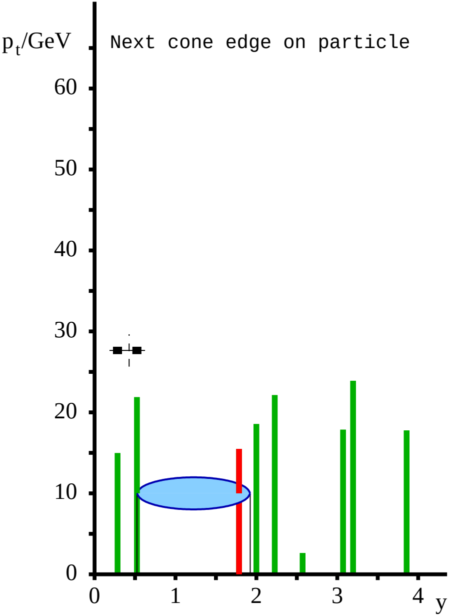

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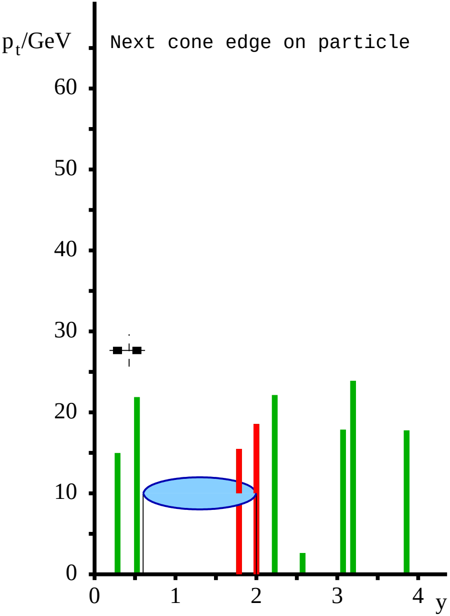

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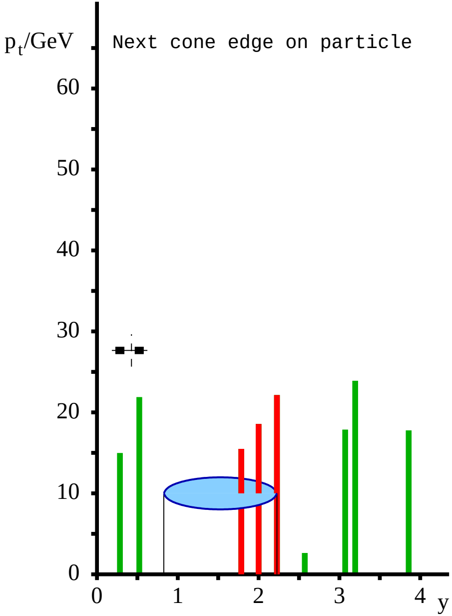

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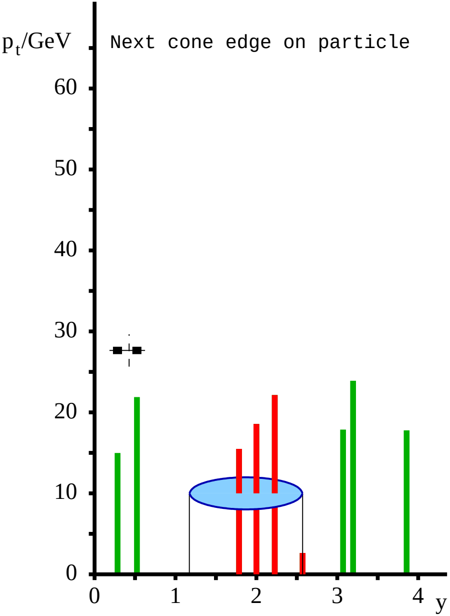

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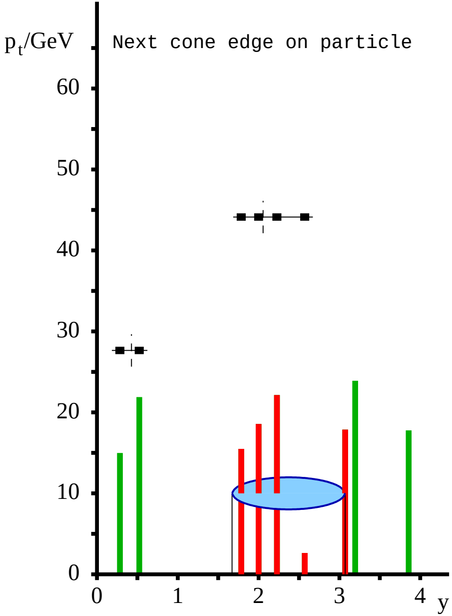

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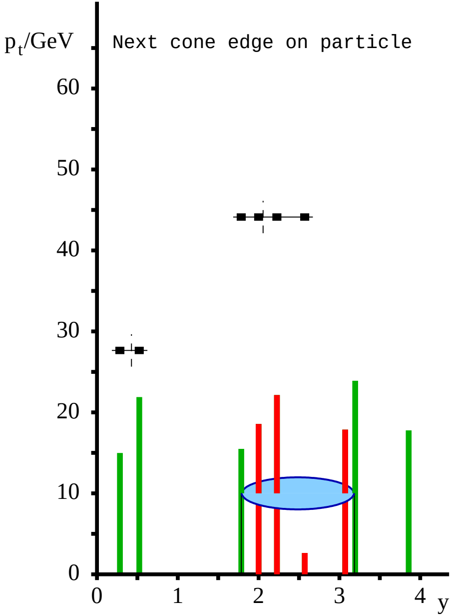

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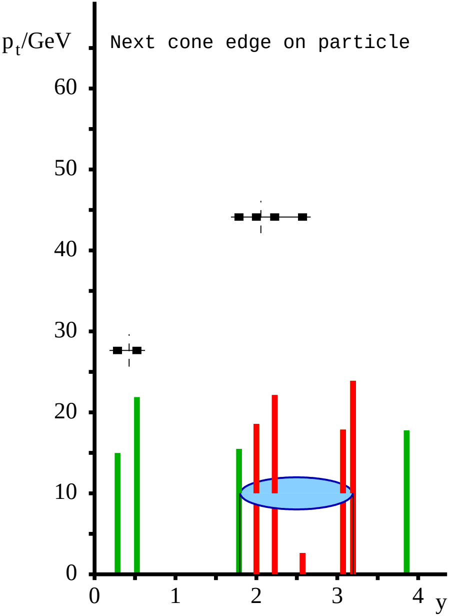

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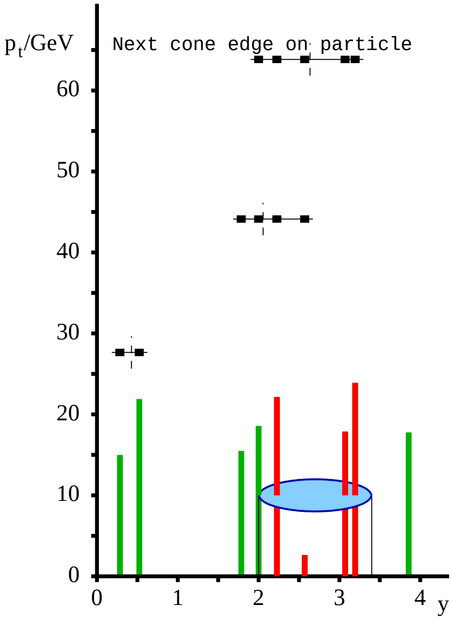

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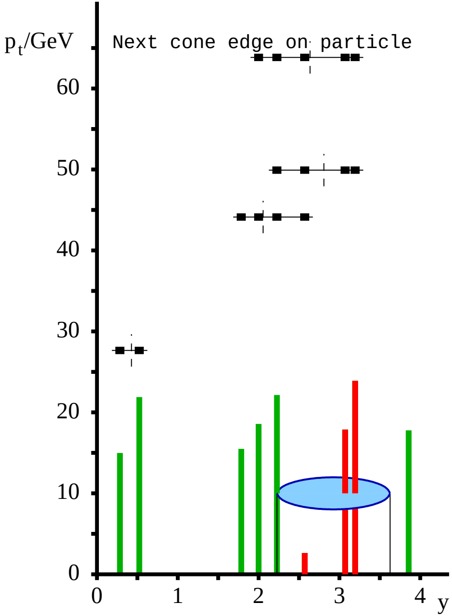

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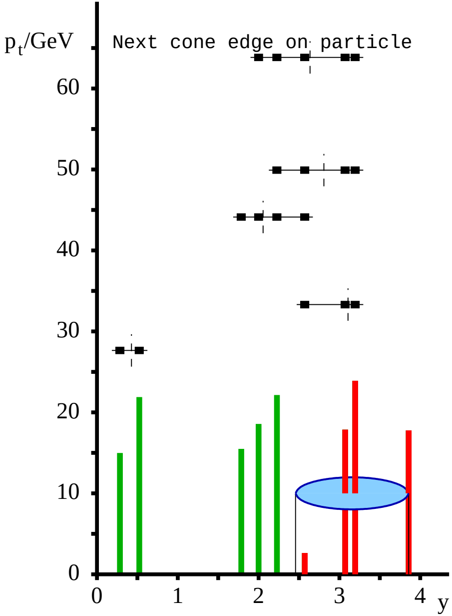

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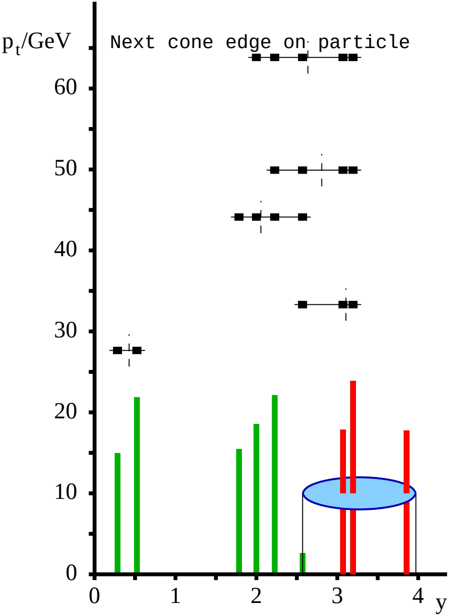

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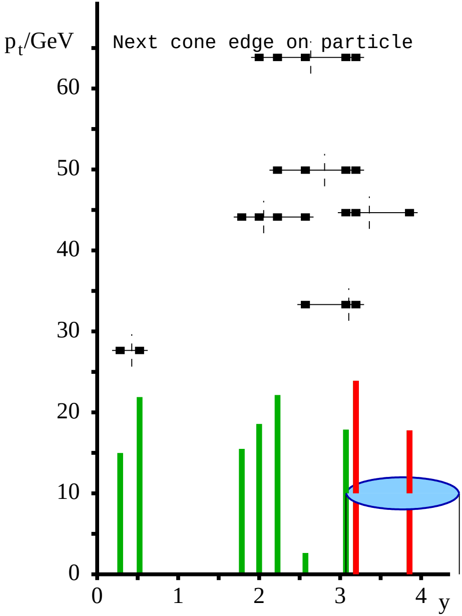

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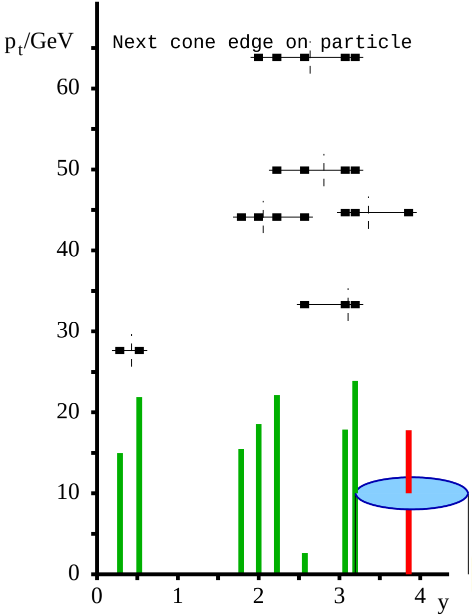

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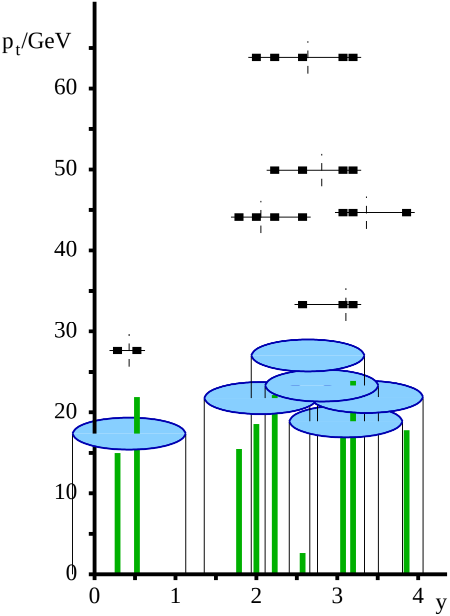

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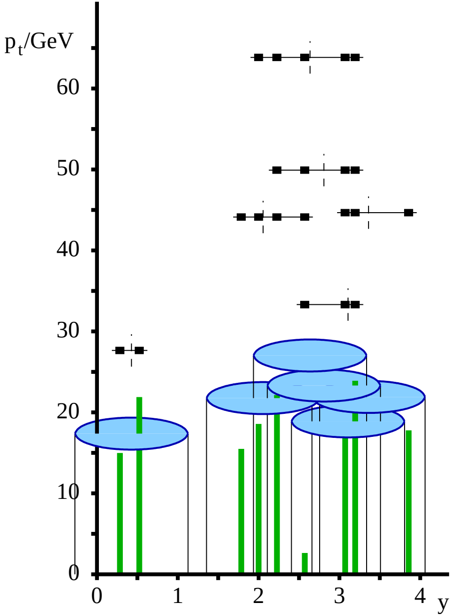

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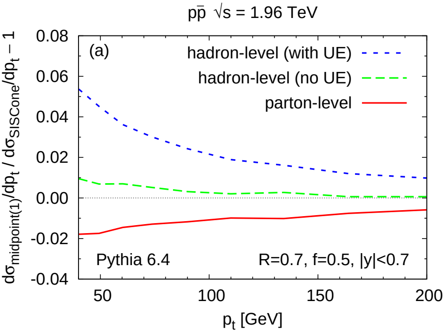
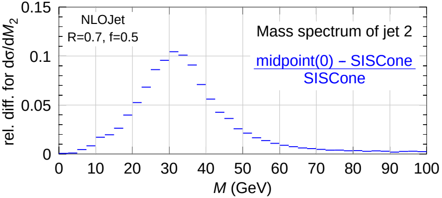
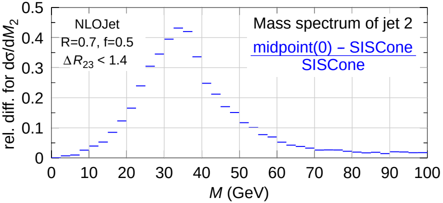
Magnitude of IR safety impact (midpoint)







Impact depends on context:
from a few % (inclusive)
to 50% (exclusive)

Does lack of IRC safety matter?

I do searches, not QCD. Why should I care about IRC safety?

- If you're looking for an invariant mass peak, it's not 100% crucial

IRC unsafety $\simeq$ R is ill-defined

A huge mass peak will stick out regardless

Well, actually my signal's a little more complex than that. . .

- If you're looking for an excess over background you need confidence in backgrounds E.g. some SUSY signals
  - Check W+1 jet, W+2-jets data against NLO in control region
  - Check W+n jets data against LO in control region
  - Extrapolate into measured region
- IRC unsafety means NLO senseless for simple topologies, *LO senseless for complex topologies*

Breaks consistency of whole

Wastes ∼ 50,000,000$/£/CHF/€

But I like my cone algorithm, it's fast, has good resolution, etc.

- Not an irrelevant point → has motivated significant work

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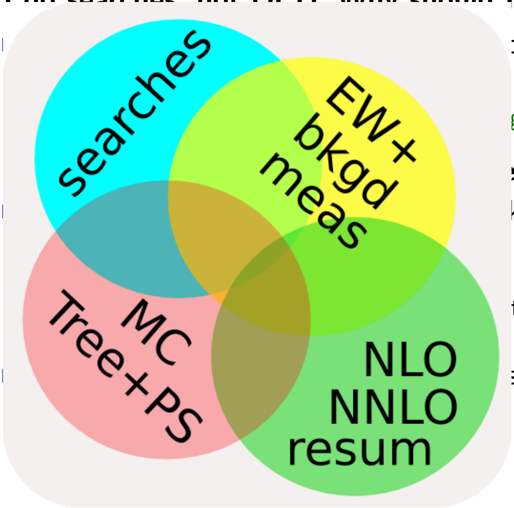

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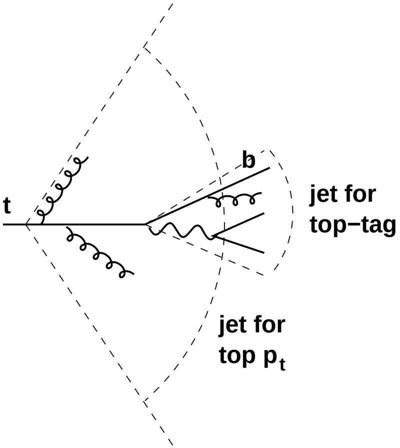
Using (coloured!) boosted top-quarks

If you want to use the tagged top (e.g. for $t\bar{t}$ invariant mass) QCD tells you:

the jet you use to tag a top quark $\neq$ the jet you use to get its p_t



Within inner cone $\sim \frac{2m_t}{p_t}$ (dead cone) you have the top-quark decay products, but no radiation from top

ideal for reconstructing top mass

Outside dead cone, you have radiation from top quark

essential for top p_t

Cacciari, Rojo, GPS & Soyez '09