Towards Jetography

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Based on work with

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C. N. Yang Institute for Theoretical Physics
Stony Brook
9 February 2010

Startup (again) for LHC

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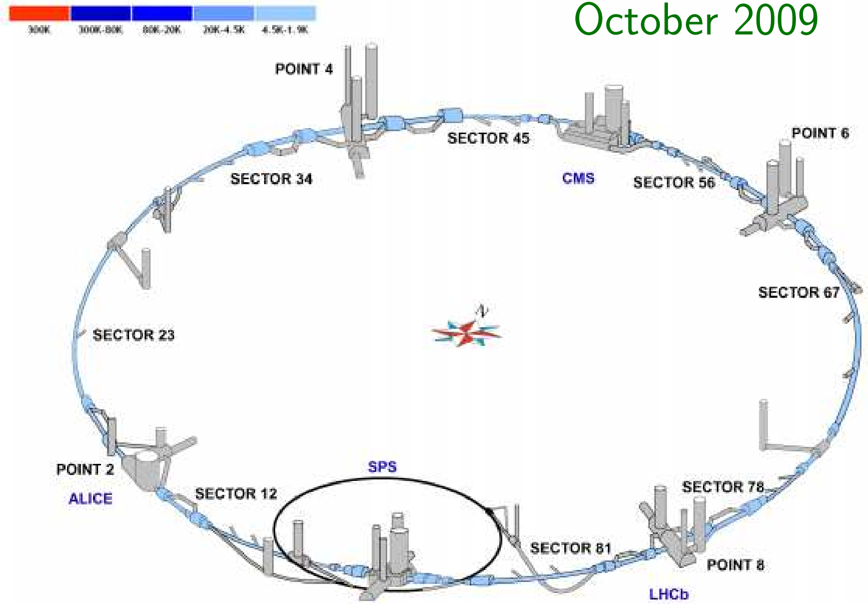
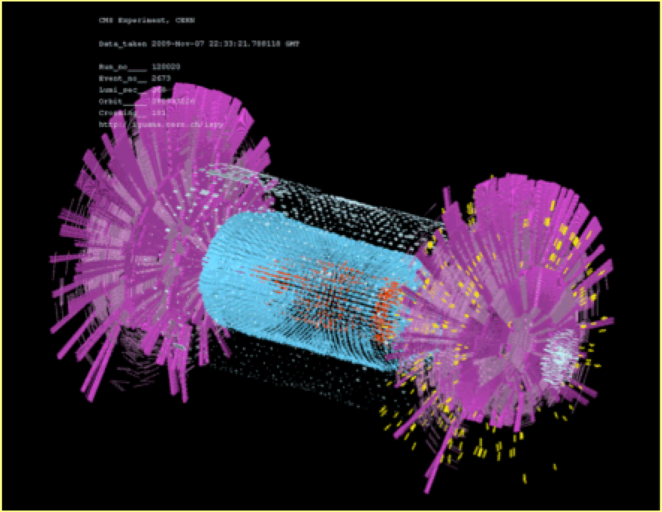
October 2009



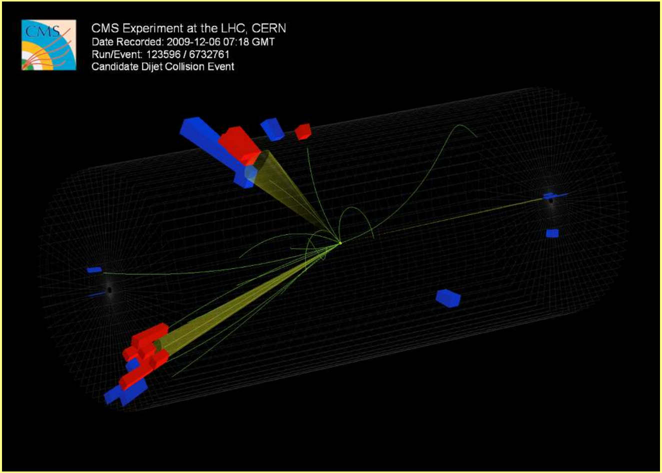
Startup (again) for LHC

7 November: first beam (picture: CMS)



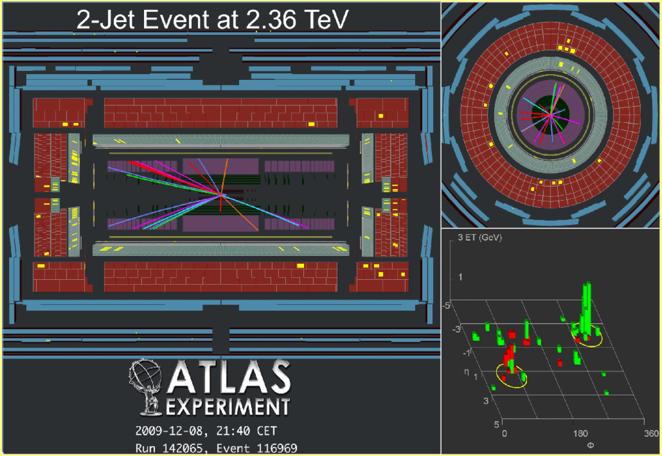
Startup (again) for LHC

December: 10^6 collisions at $\sqrt{s} = 900$ GeV

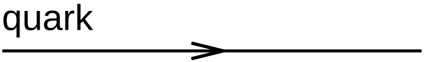


Startup (again) for LHC

December: collisions at $\sqrt{s} = 2360$ GeV



Parton fragmentation



Gluon emission:

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

At low scales:

$$\alpha_s \to 1$$

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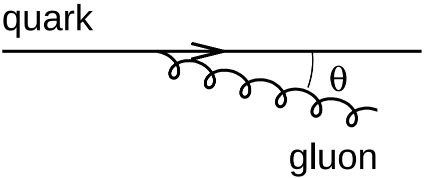

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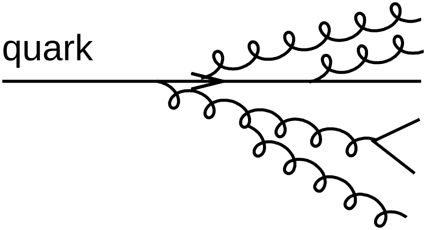

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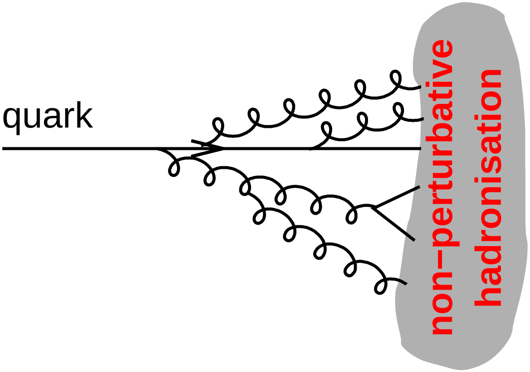

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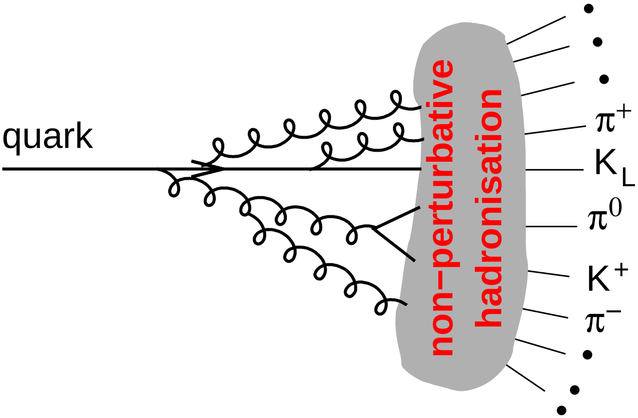

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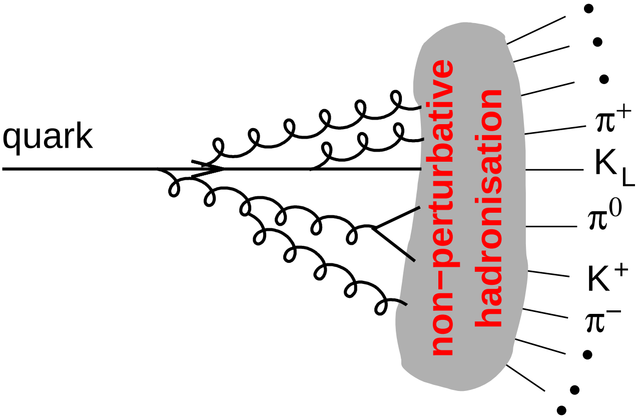

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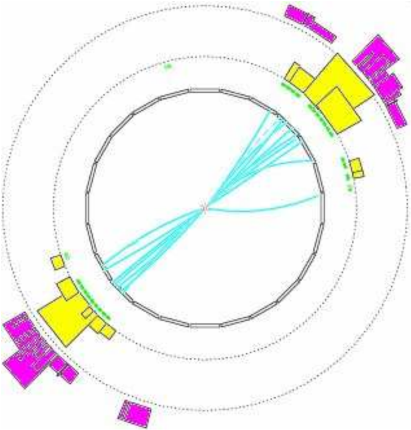
This is a jet

Seeing v. defining jets



Jets are what we see.
Clearly(?) 2 jets here

How many jets do you see?
Do you really want to ask yourself this question for 10^9 events?

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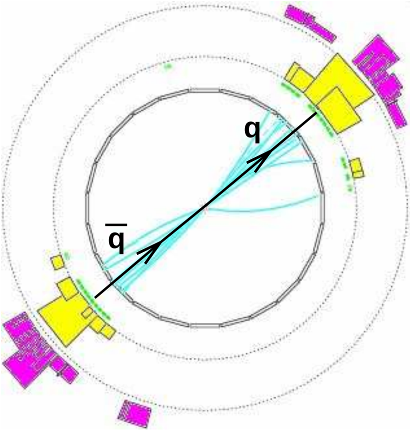

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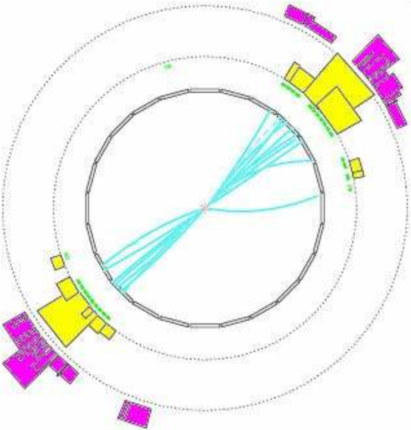

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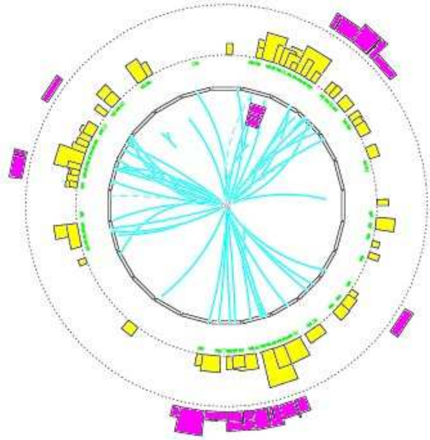

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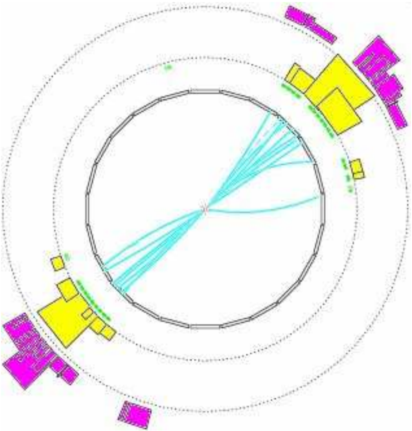

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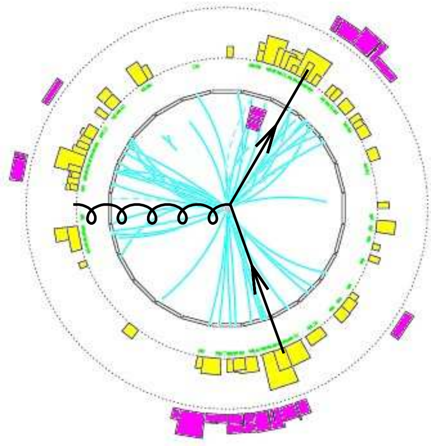

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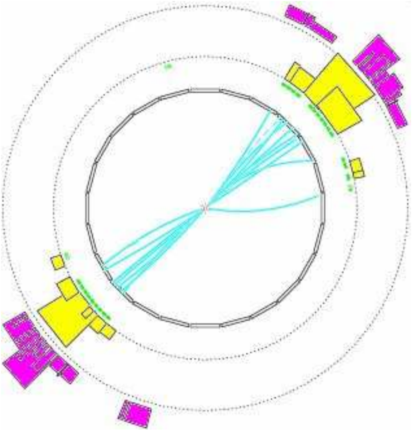

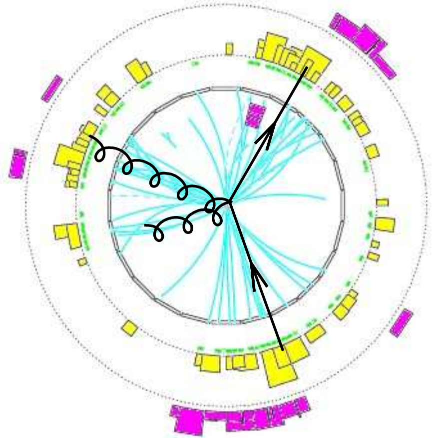

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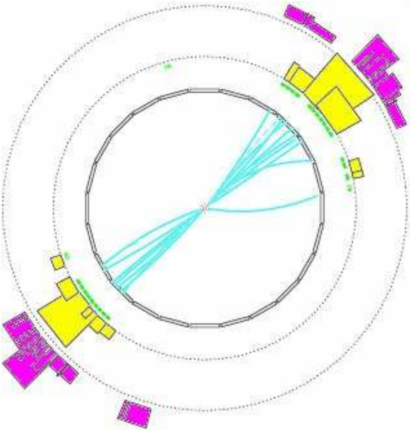

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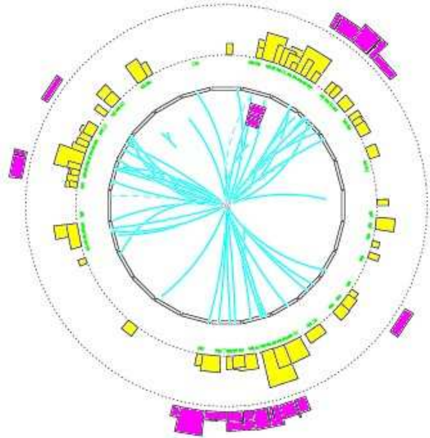

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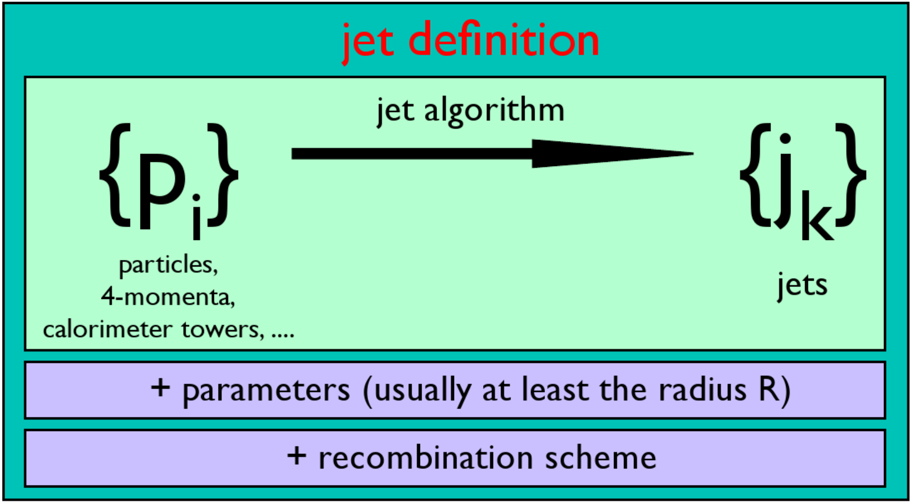
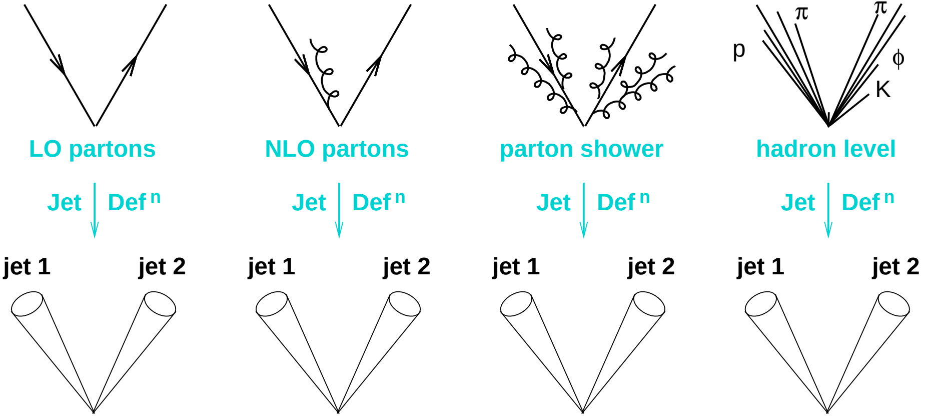
Les Houches 2007 proceedings, arXiv:0803.0678



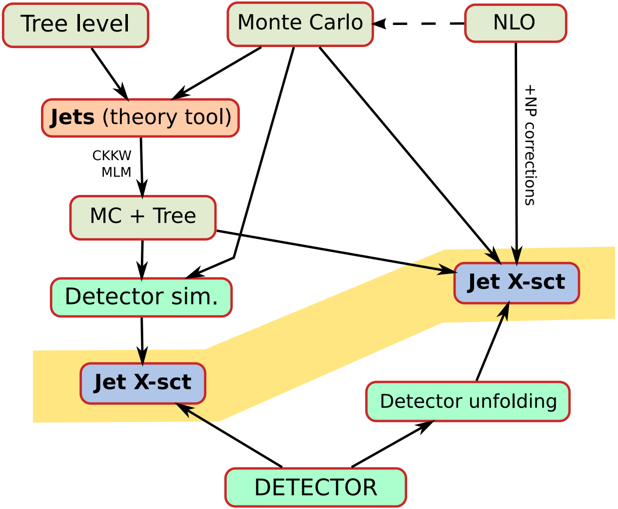
Reminder: running a jet definition gives a well defined physical observable, which we can measure and, hopefully, calculate

Jets as projections



Projection to jets should be resilient to QCD effects

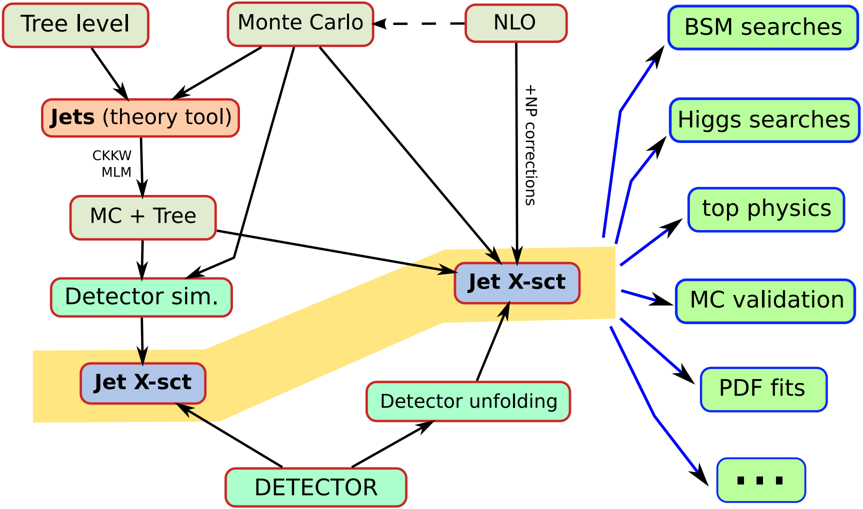
QCD jets flowchart



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

And jets are an input to almost all analyses

QCD jets flowchart



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

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Talk Structure

- The different kinds of jet algorithm
- The historical problems with them ("Snowmass criteria") and some of the solutions
  Speed, infrared safety
- Understanding the physics of jet algorithms
  the momentum of a jet v. the momentum of a "parton"
- Doing better physics *with* jets
  Dijet mass reconstruction
  Low-mass Higgs-boson search

What jet algorithms are out there?

2 broad classes:

1. sequential recombination

"bottom up", e.g. k_t, preferred by many theorists

2. cone type

"top down", preferred by many experimenters

Sequential recombination algorithms

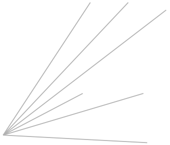
k_t algorithm — Catani, Dokshitzer, Olsson, Seymour, Turnock, Webber '91–'93; Ellis, Soper '93

- 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
- Repeat

Bottom-up jets:

Sequential recombination

(attempt to invert QCD branching)



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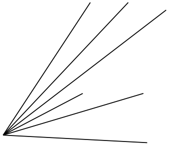

NB: hadron collider variables

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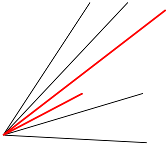

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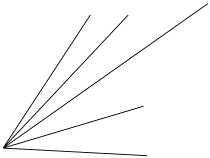

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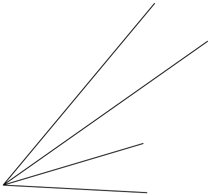

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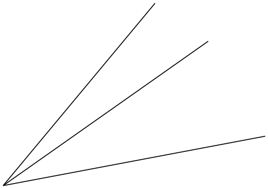

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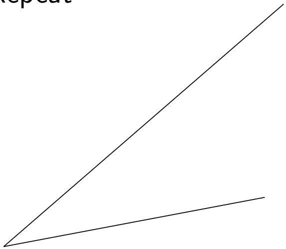

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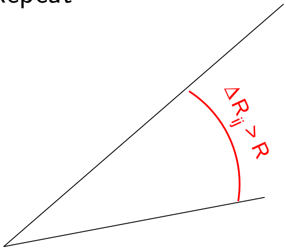

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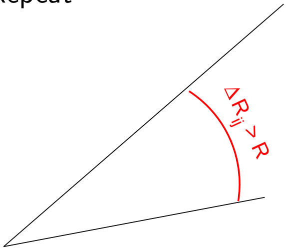

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NB: d_{ij} distance $\leftrightarrow$ QCD branching probability $\sim \alpha_s \frac{dk_{tj}^2 dR_{ij}^2}{d_{ij}}$

Cones with Split Merge (SM)

Tevatron & ATLAS cone algs have two main steps:

- Find some/all stable cones

  ≡ cone pointing in same direction as the momentum of its contents

  Found by iterating from some initial seed directions

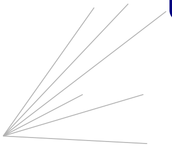
- Resolve cases of overlapping stable cones

  merge procedure

Top-down jets:

cone algorithms

(energy flow conserved by QCD)



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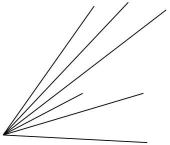

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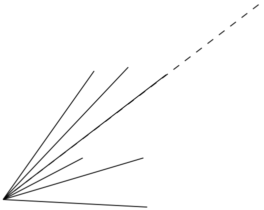

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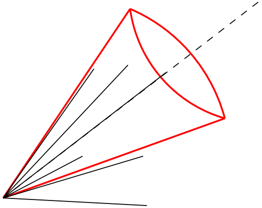

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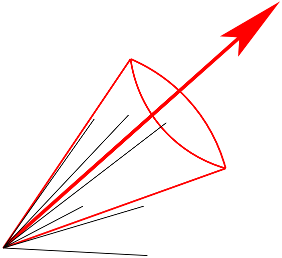

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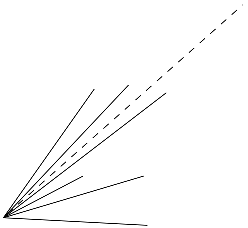

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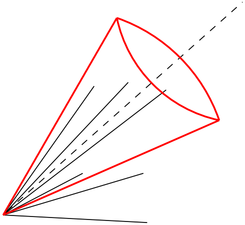

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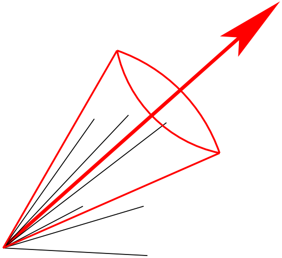

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Tevatron & ATLAS cone algs have two main steps:

- Find some/all stable cones

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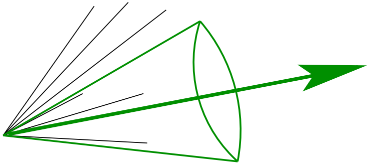

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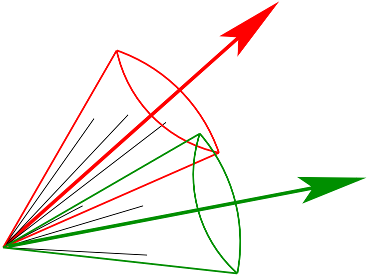

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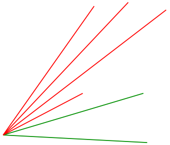

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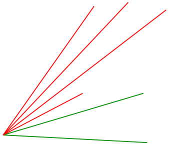

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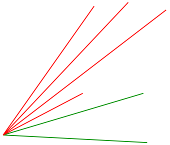

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Readying jet "technology" for the LHC era

[a.k.a. satisfying Snowmass]

Snowmass accords

Snowmass Accord (1990):

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
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Property 1 ⇔ speed. (+other aspects)

- LHC events may have up to $N = 4000$ particles (at high-lumi)
- Sequential recombination algs. (k_t) slow, $\sim N^3 \to 60s$ for $N = 4000$, not practical for $\mathcal{O}\left(10^9\right)$ events

Can be reduced to N ln N (60 s → 20 ms) **Cacciari & GPS '05 + CGAL**

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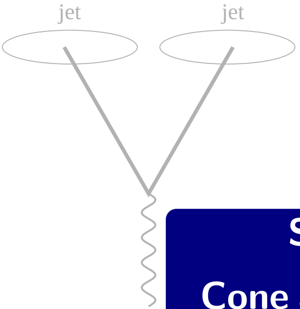
Property 4 ≡ Infrared and Collinear (IRC) Safety. It helps ensure:

- Soft (low-energy) emissions & collinear splittings don't change jets
- Each order of perturbation theory is smaller than previous (at high p_t)

Wasn't satisfied by the cone algorithms

JetClu (& Atlas Cone) in Wjj @ NLO



Snowmass issue #4

Cone algorithms and IR safety

	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	

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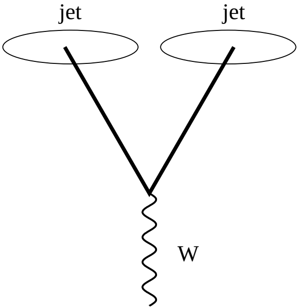

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With these (& most) cone algorithms, perturbative infinities fail to cancel at some order ≡ **IR unsafety**

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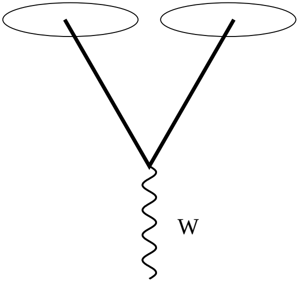

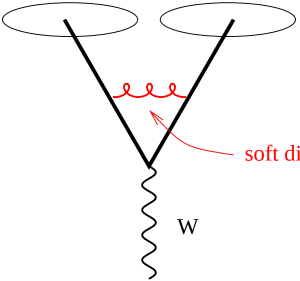

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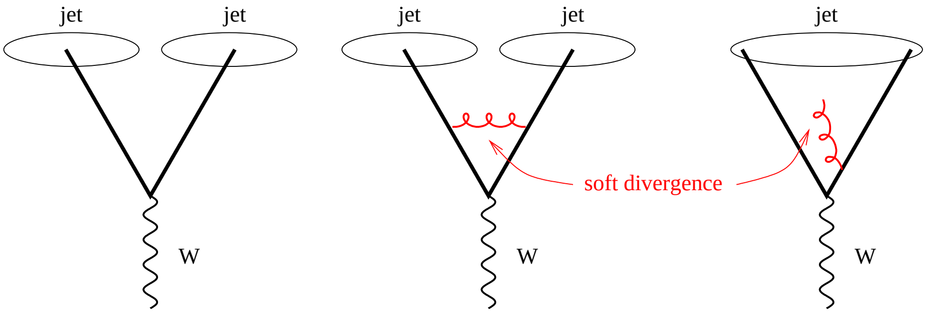

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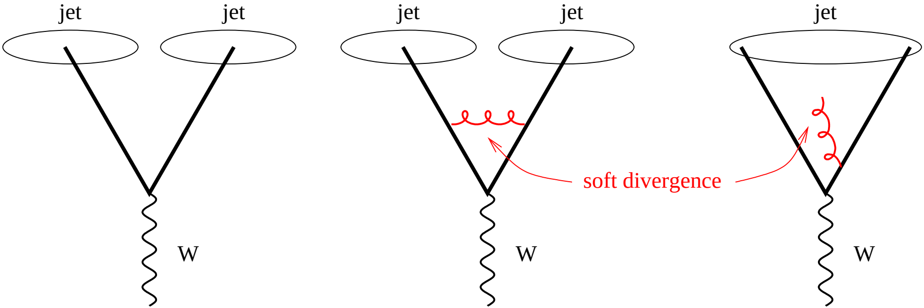

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IRC safety & real-life

Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \to \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \to \alpha_s^2 + \underbrace{\alpha_s^3 + \alpha_s^3}_{\text{BOTH WASTED}}$$

Among consequences of IR unsafety:

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Inclusive jets	LO	NLO	NLO	NLO ($\to$ NNLO)
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NB: 50,000,000\$/£/CHF/€ investment in NLO

Multi-jet contexts much more sensitive: **ubiquitous at LHC**

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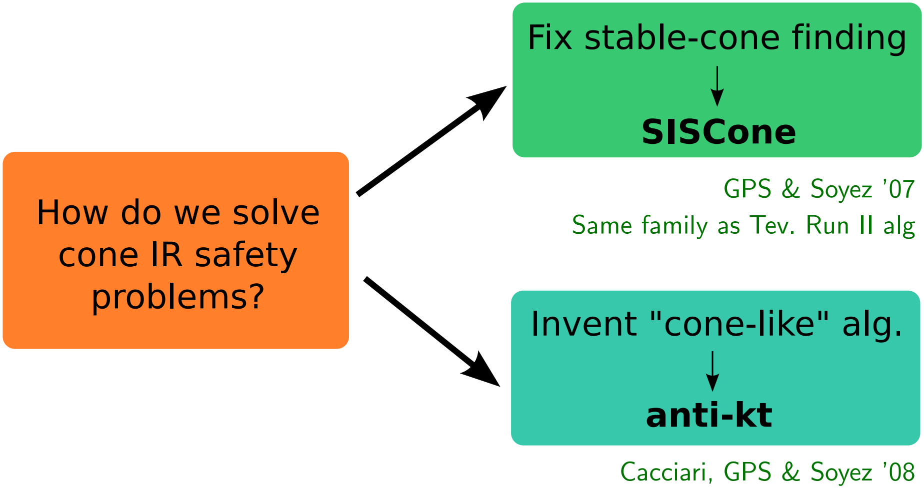
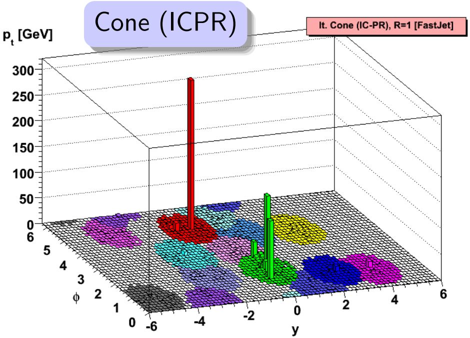
Two directions



Essential characteristic of cones?



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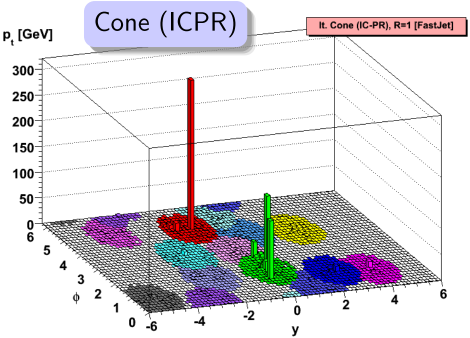

(Some) cone algorithms give **circular** jets in $y - \phi$ plane

Much appreciated by experiments e.g. for acceptance corrections

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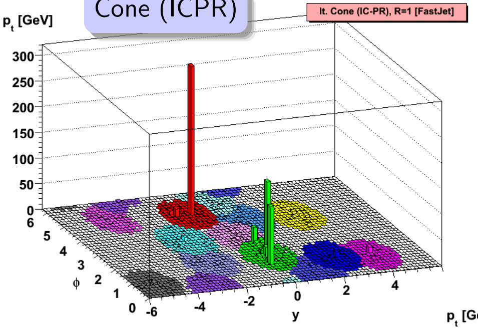
Cone (ICPR)



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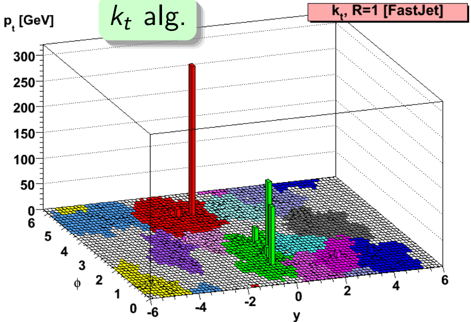

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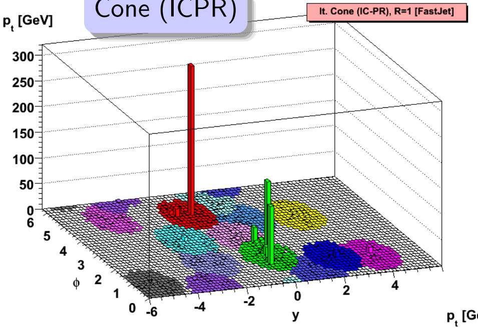

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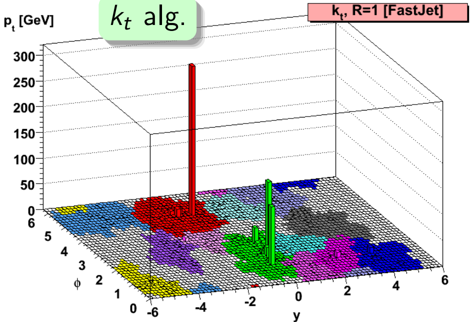

k_t jets are **irregular**

Because soft junk clusters together first:

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

Regularly held against k_t

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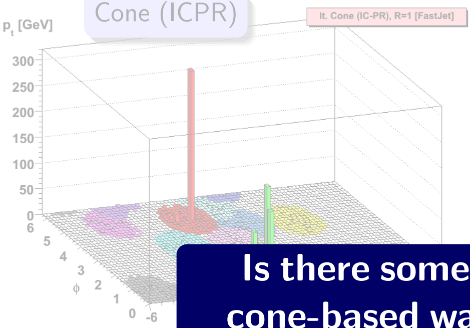

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Is there some other, non cone-based way of getting circular jets?

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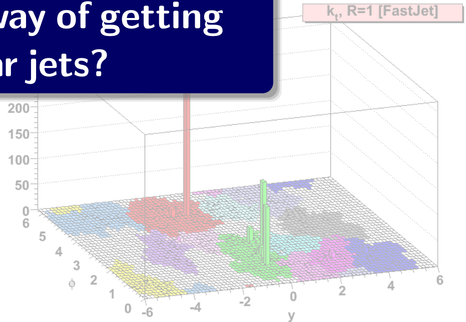

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Privilege collinear divergence over soft divergence

Cacciari, GPS & Soyez '08

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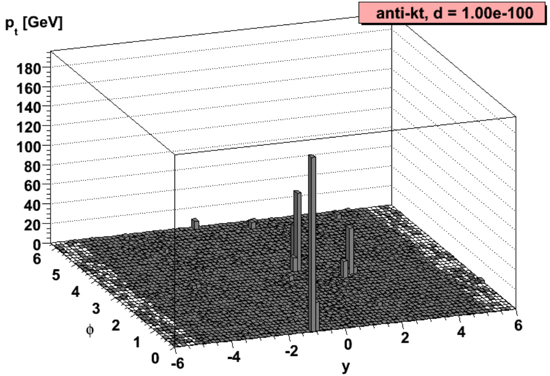

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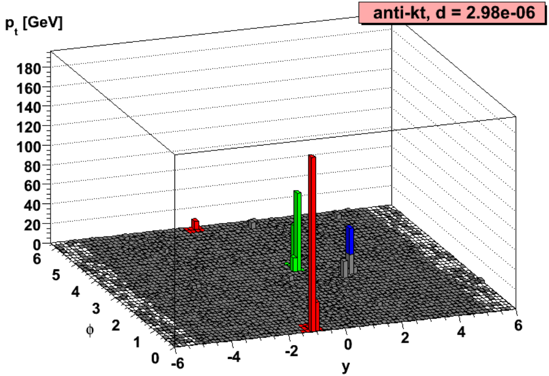

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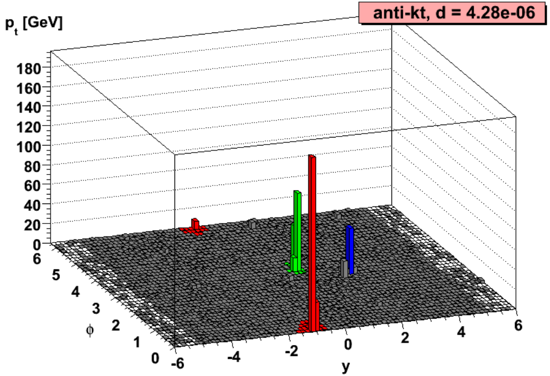

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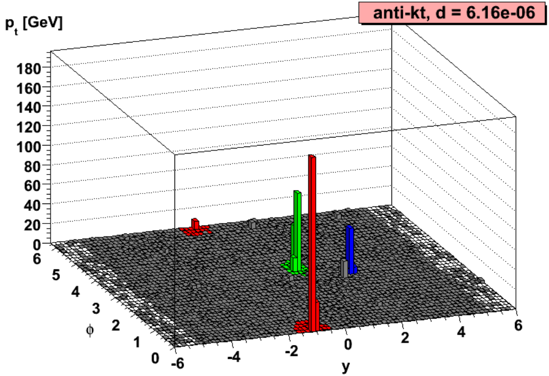

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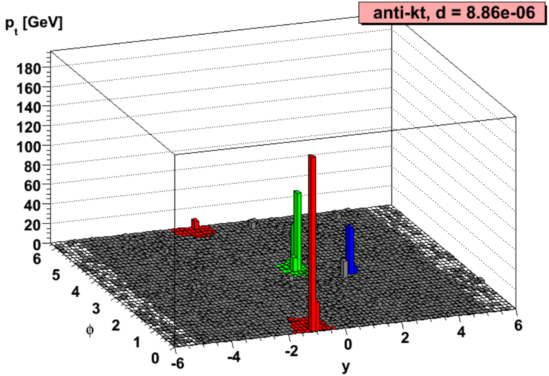

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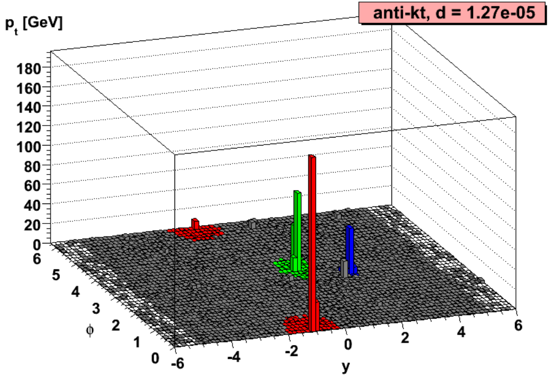

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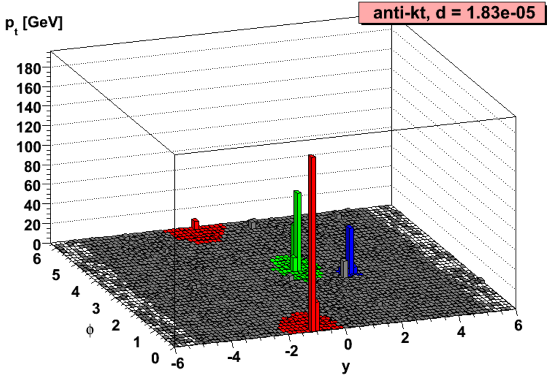

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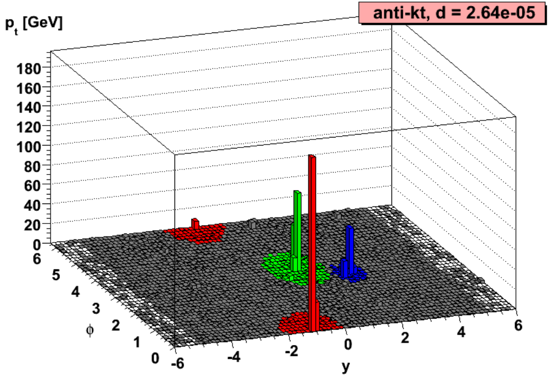

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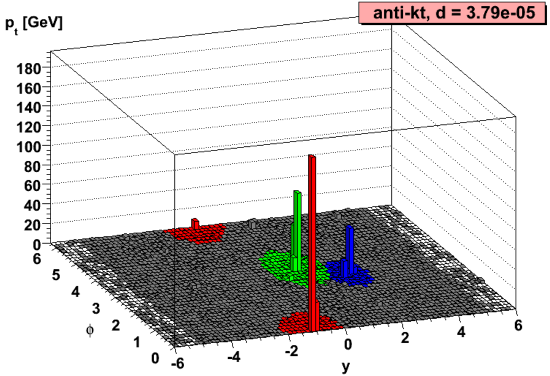

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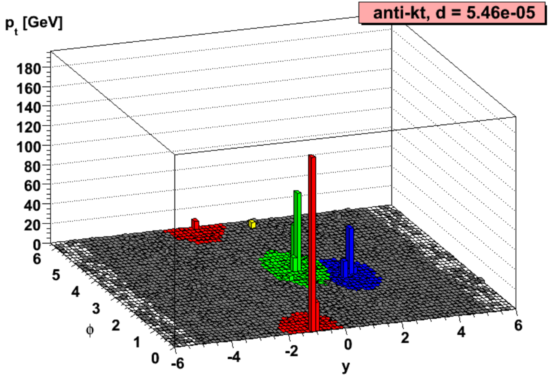

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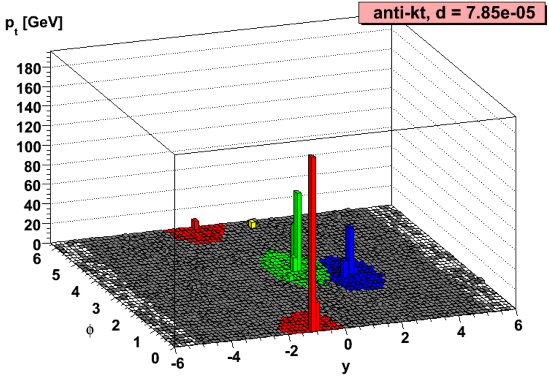

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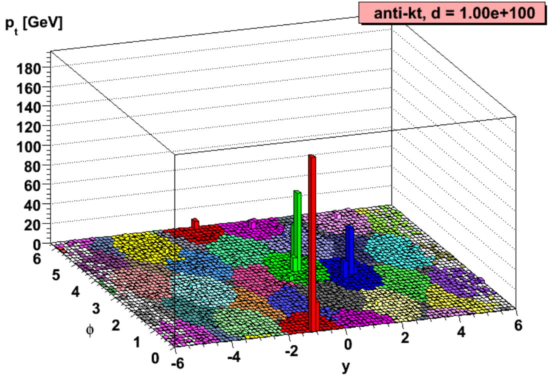
Hard stuff clusters with nearest neighbour

Privilege collinear divergence over soft divergence

Cacciari, GPS & Soyez '08



anti-k_t gives cone-like jets without using stable cones

A full set of IRC-safe jet algorithms

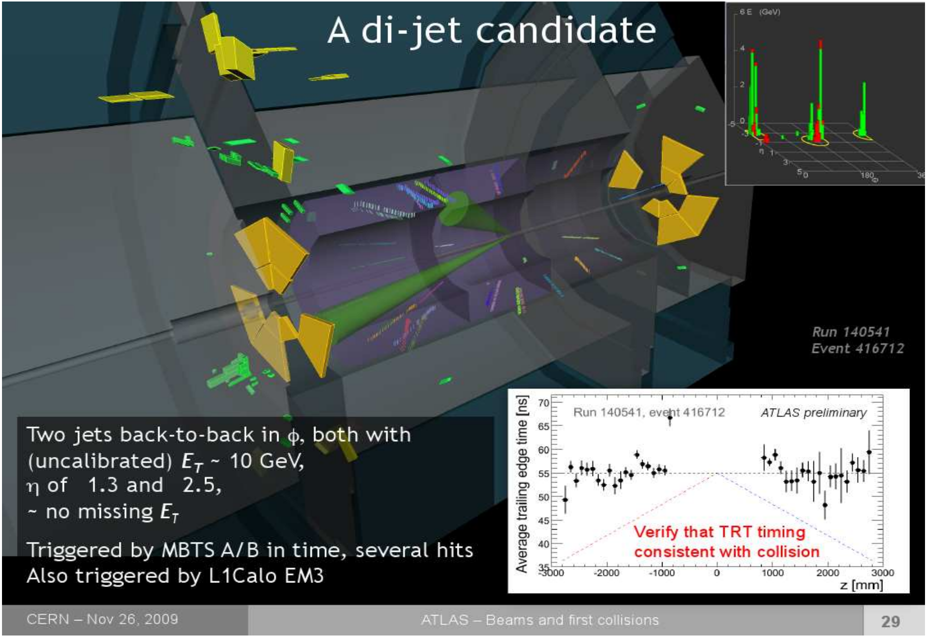
Generalise inclusive-type sequential recombination with

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

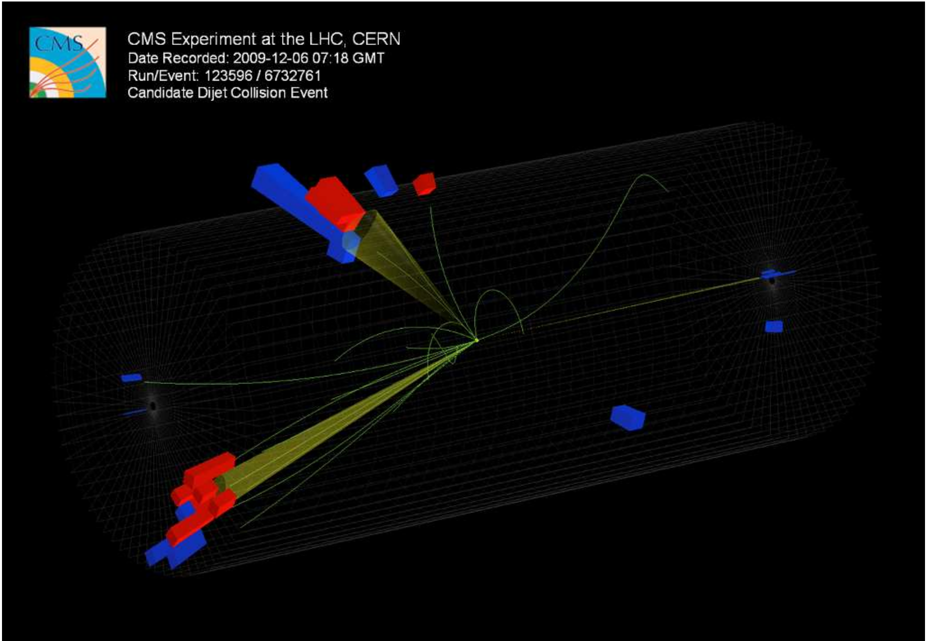
	Alg. name	Comment	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Hierarchical in rel. k_t	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple R at once $\leftrightarrow$ QCD angular ordering	$N \ln N$
$p = -1$	anti-k_t Cacciari, GPS, 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 [& much more] coded in (efficient) C++ at
`http://fastjet.fr/` (Cacciari, GPS & Soyez '05-'09)

ATLAS: first dijet event, with anti-k_t



CMS: first dijet event, with anti-k_t



Snowmass is solved
But it was a problem from the 1990s

What are the problems we *should* be trying to solve for LHC?

Which jet definition(s) for LHC?

Choice of algorithm (k_t, SISCone, ...)

Choice of parameters (R, ...)

Can we address this question scientifically?

Jetography

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Jetography

Jet def^n differences

Jet definitions differ mainly in:

$\underbrace{\text{Jet definitions}}_{\text{alg} + R}$

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]

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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" → 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 Dasgupta & Delenda '09 for k_t alg.

Underlying Event (UE)

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

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

DWT Pythia tune or ATLAS Jimmy tune tell you:

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

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

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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
$+\pi R^2 \frac{C_i}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} \times$	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)

Can we benefit from this understanding in our use of jets?

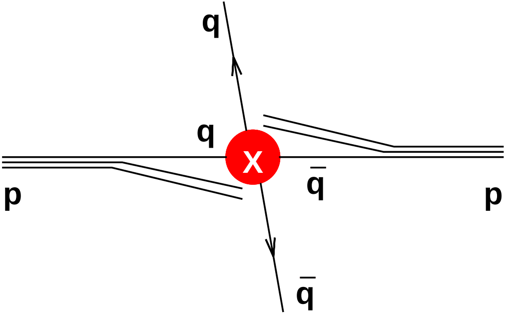
Jet momentum significantly affected by R

So what R should we choose?

Examine this in context of reconstruction of dijet resonance

What R is best for an isolated jet?

E.g. to reconstruct $m_X \sim (p_{tq} + p_{t\bar{q}})$



PT radiation:

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

Hadronisation:

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

Underlying event:

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

Minimise fluctuations in p_t

Use crude approximation:

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

in small-R limit (?!)

cf. Dasgupta, Magnea & GPS '07

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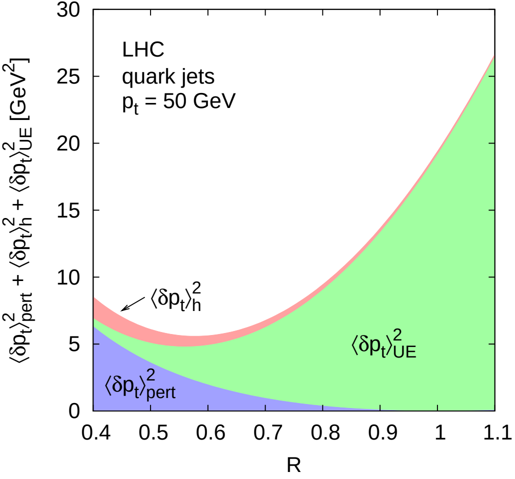
50 GeV quark jet



in small-R limit (?!)
cf. Dasgupta, Magnea & GPS '07

What R is best for an isolated jet?

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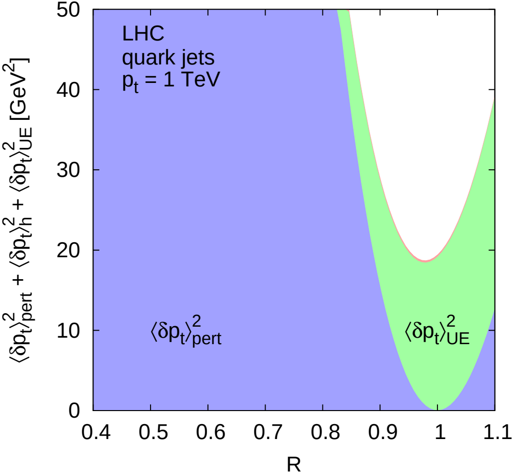
1 TeV quark jet



in small-R limit (?!)

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What R is best for an isolated jet?

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Hadr

$q:$

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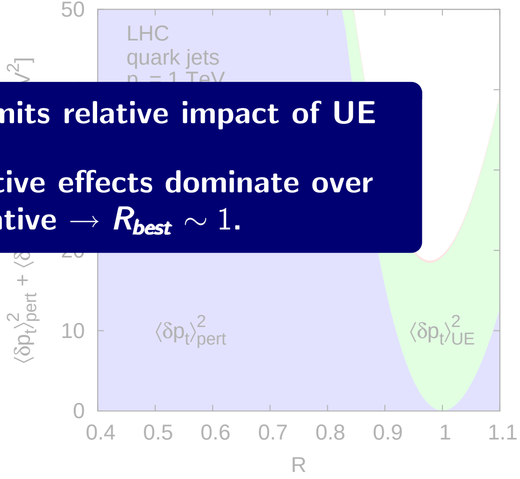


At low p_t, small R limits relative impact of UE

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

Minimise fluctuations in p_t

Use crude approximation:

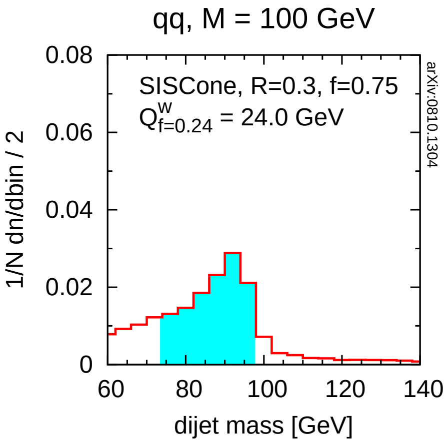
$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

in small-R limit (?!)

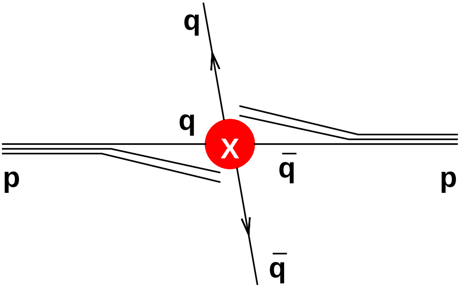
cf. Dasgupta, Magnea & GPS '07

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

R = 0.3



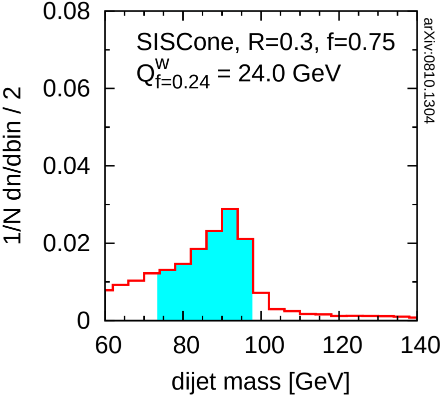
Resonance X → dijets



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

R = 0.3

qq, M = 100 GeV



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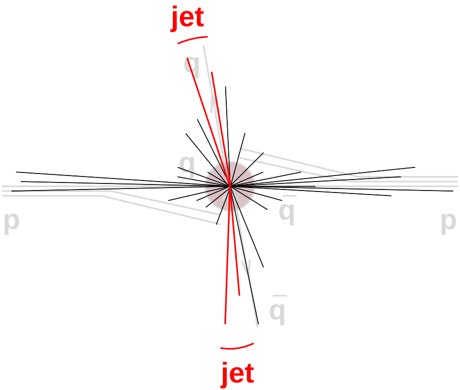
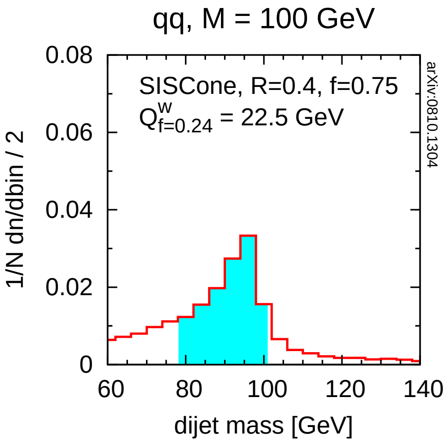


Dijet mass: scan over *R* [Pythia 6.4]

R = 0.4



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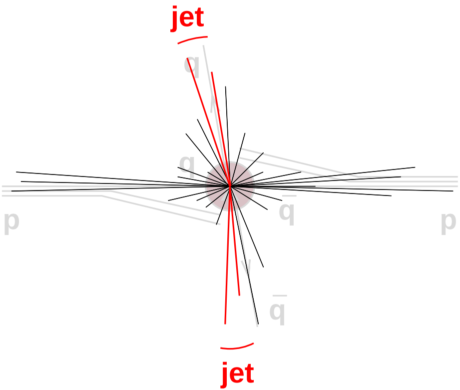

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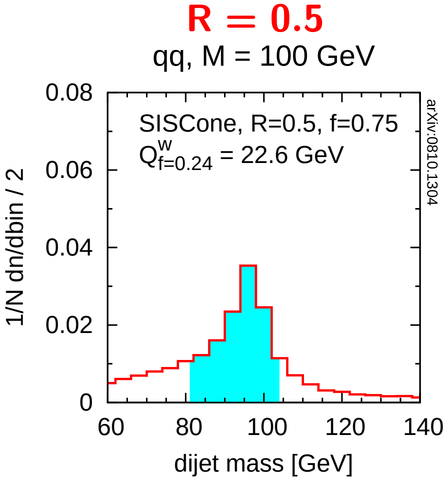

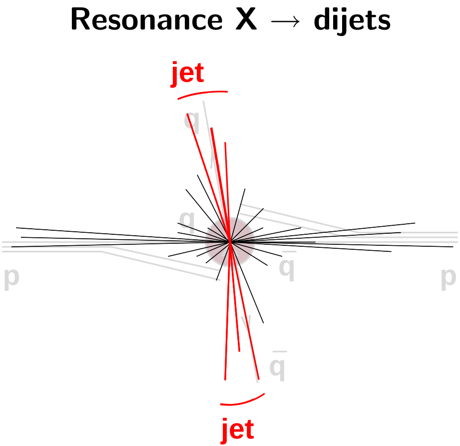

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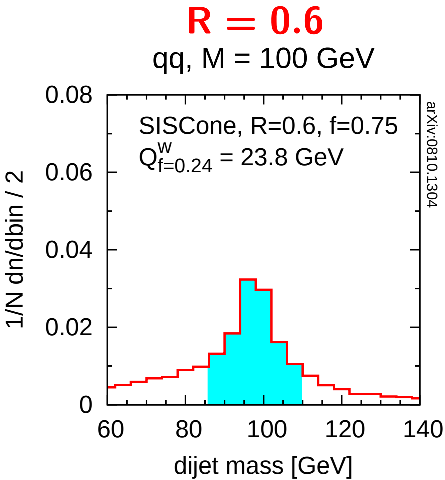

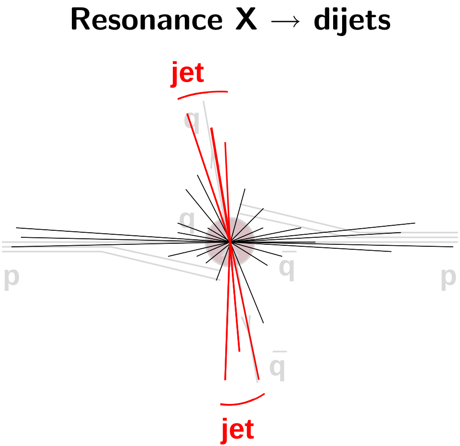

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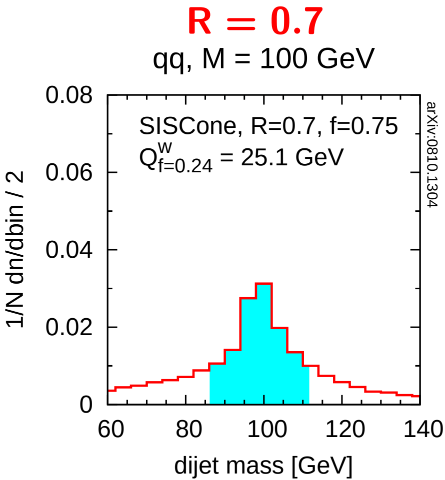

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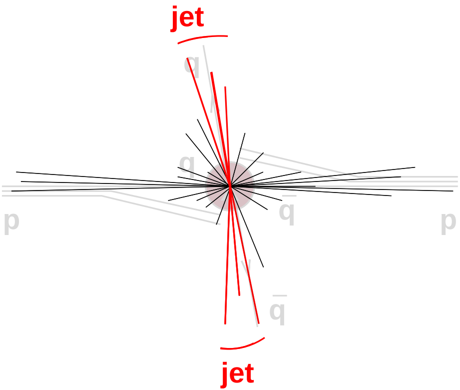

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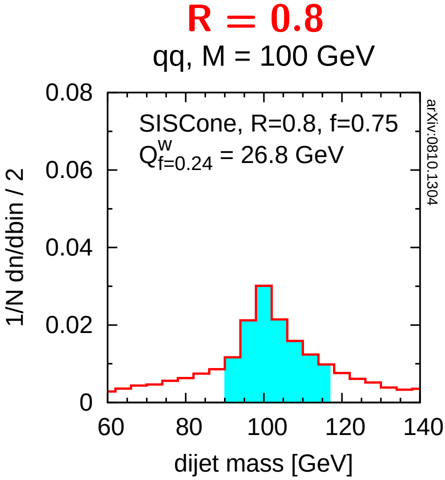

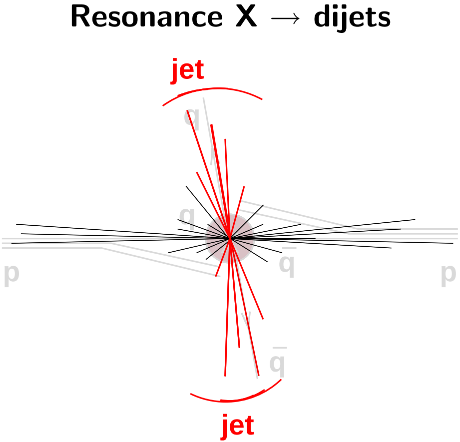

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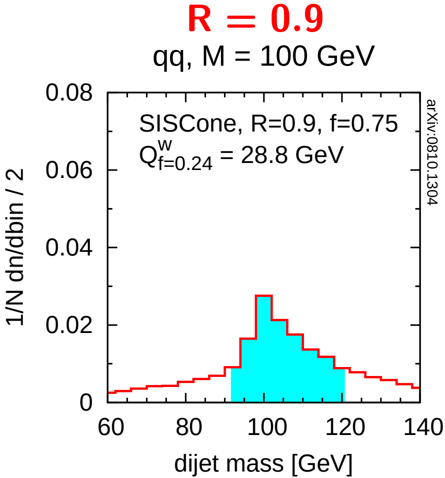

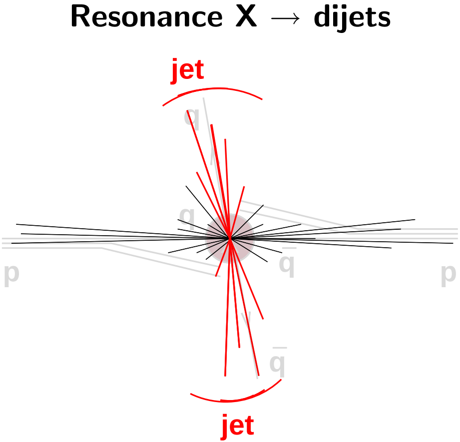

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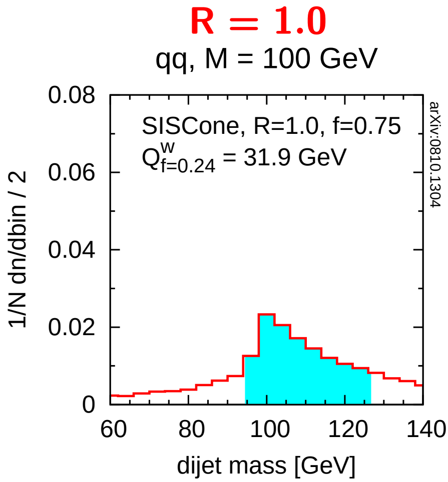
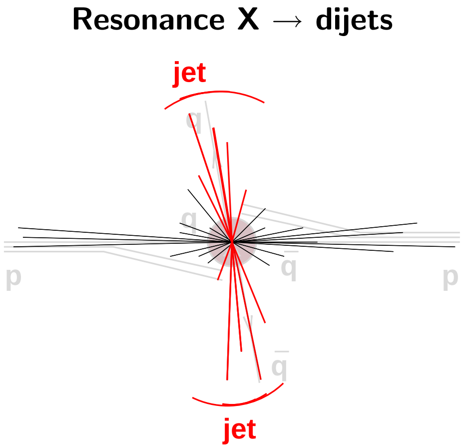
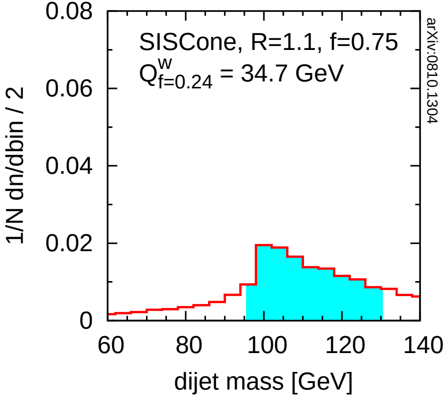




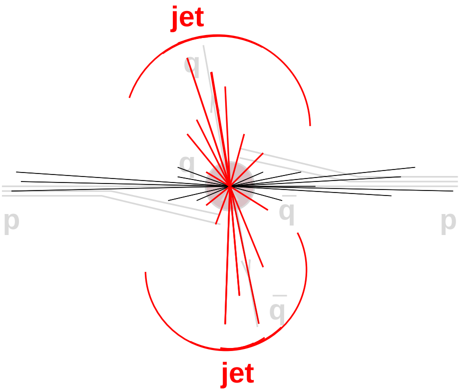
Dijet mass: scan over *R* [Pythia 6.4]

R = 1.1

qq, M = 100 GeV

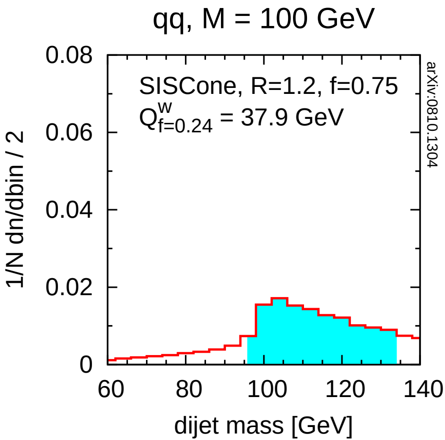


Resonance X → dijets

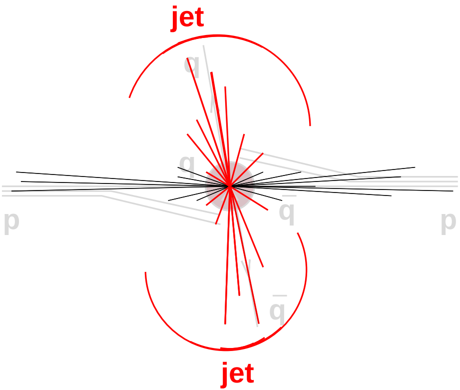


Dijet mass: scan over *R* [Pythia 6.4]

R = 1.2

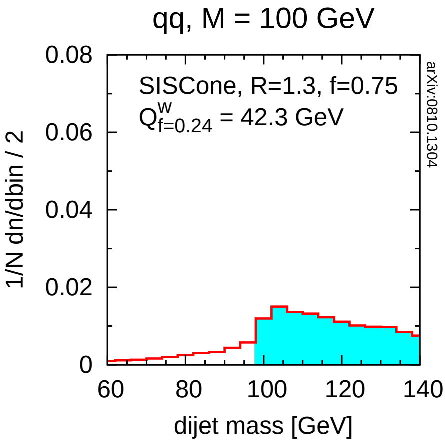


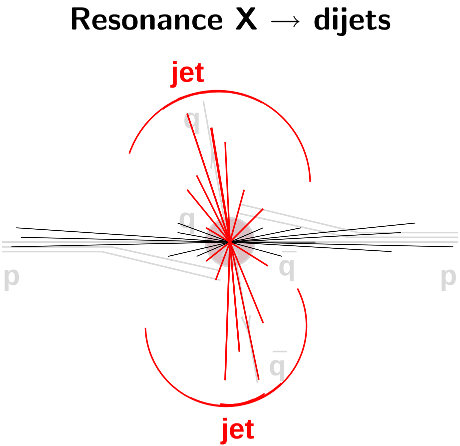
Resonance X → dijets



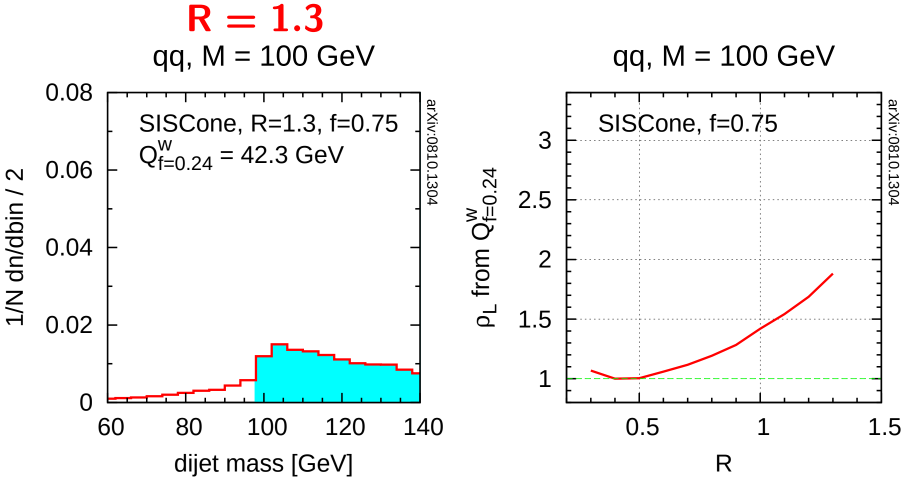
Dijet mass: scan over *R* [Pythia 6.4]

R = 1.3





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

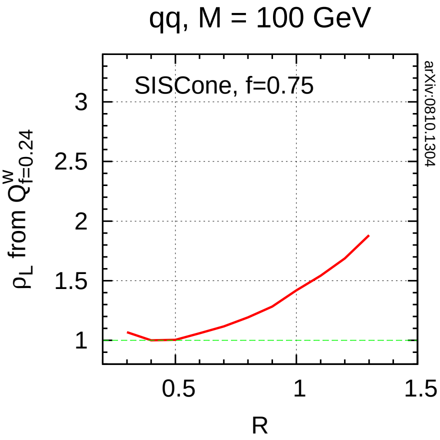


After scanning, summarise "quality" v. *R*. Minimum ≡ BEST

picture not so different from crude analytical estimate

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

$\mathbf{m_{qq} = 100}$ 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

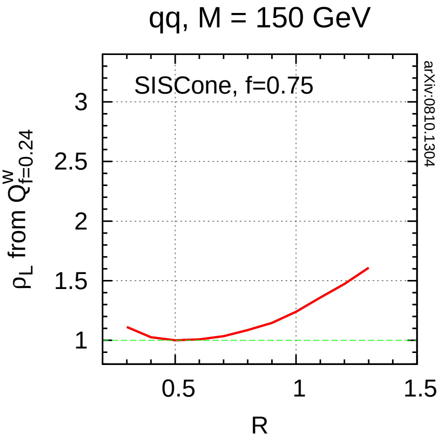
BUT: so far, LHC's plans involve running with fixed smallish *R* values

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

m_{qq} = 150 GeV



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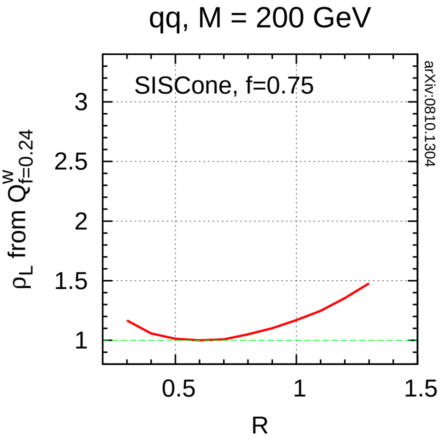
Scan through $q\bar{q}$ mass values

$m_{qq} = 200$ GeV



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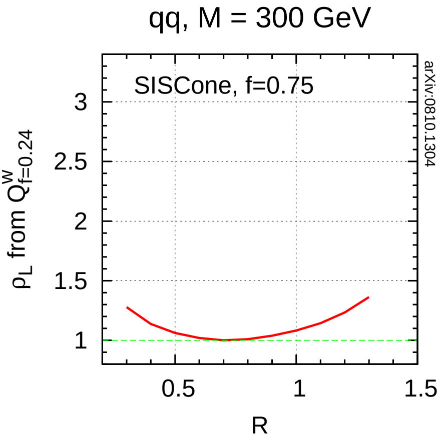
NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

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

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



Best R is at minimum of curve

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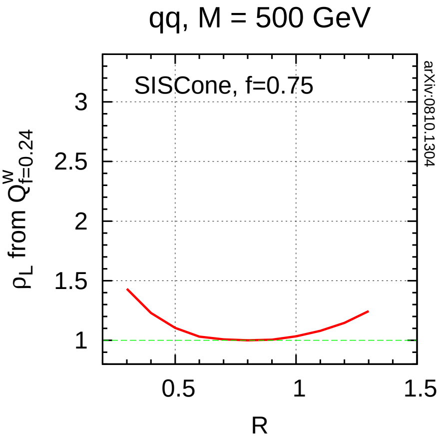
e.g. CMS arXiv:0807.4961

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

$m_{qq} = 500$ GeV



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

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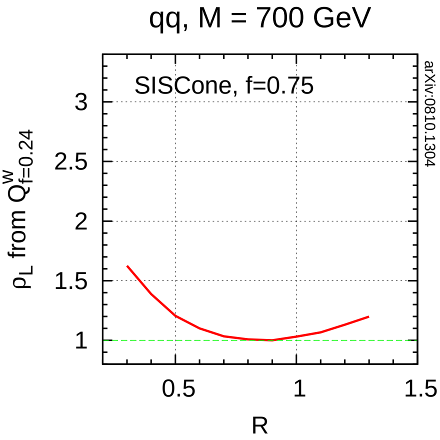
NB: 100,000 plots for various jet algorithms, narrow qq and gg resonances from `http://quality.fastjet.fr` Cacciari, Rojo, GPS & Soyez '08

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

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



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

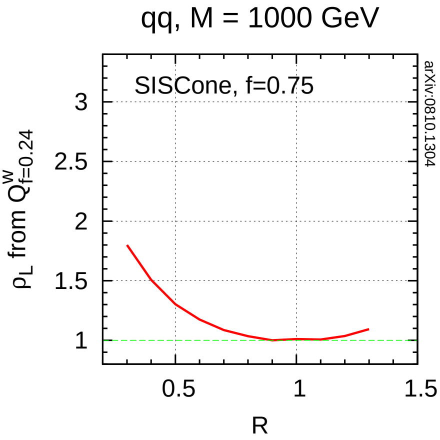
e.g. CMS arXiv:0807.4961

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

$m_{qq} = 1000$ GeV



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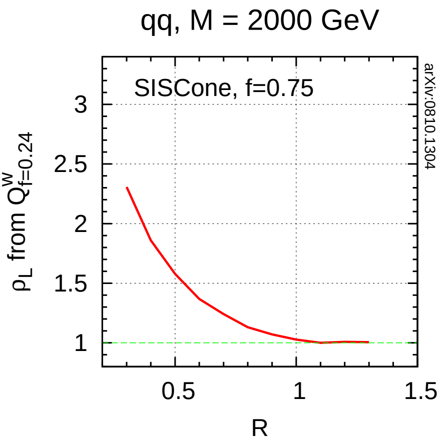
Cacciari, Rojo, GPS & Soyez '08

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

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



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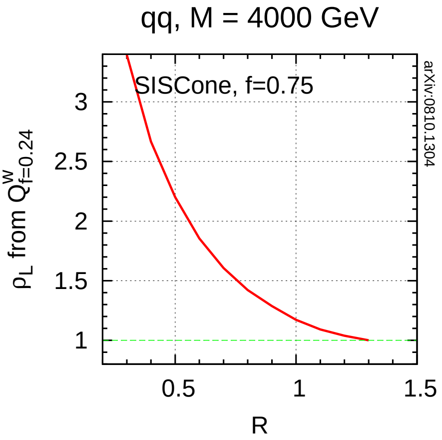
Scan through $q\bar{q}$ mass values

m_{qq} = 4000 GeV



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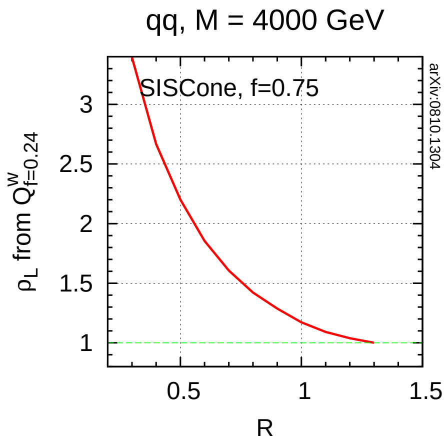

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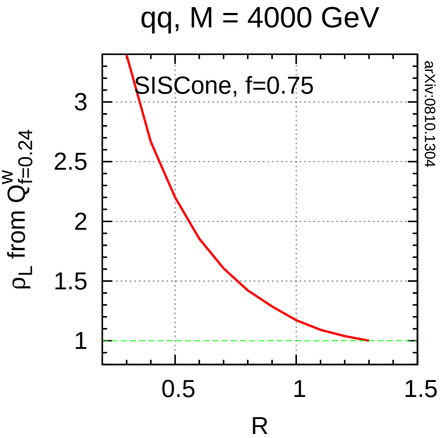

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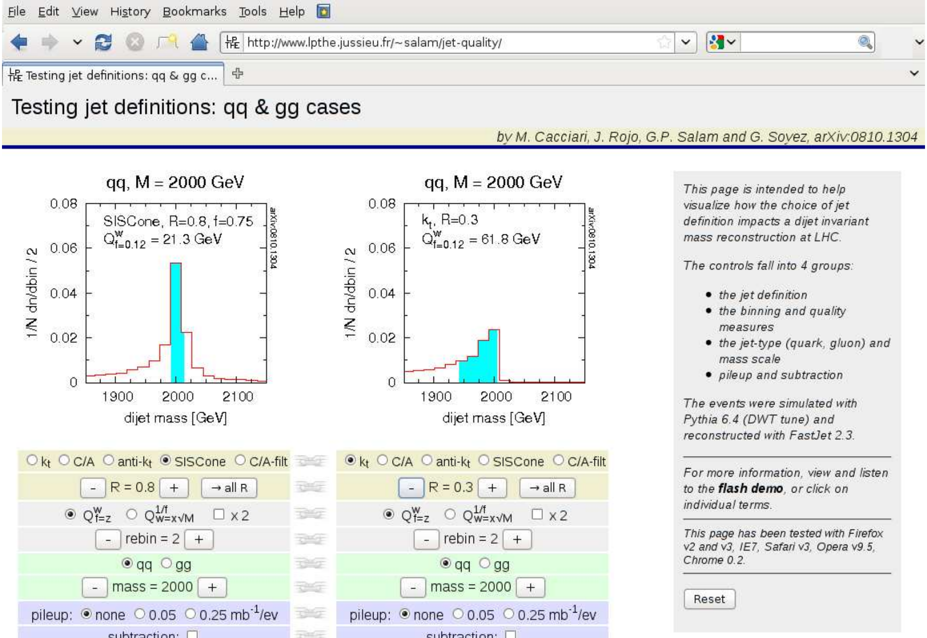


The dijet mass is a classic jets analysis.

But LHC also opens up characteristically new kinematic regions, because $\sqrt{s} \gg m_{EW}$.

We can and should make use of this

Illustrated in next slides, for Higgs search with $m_H = 115$ GeV, $H \to b\bar{b}$

E.g.: WH/ZH search channel @ LHC

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

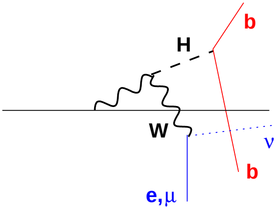
Studied e.g. in ATLAS TDR

Difficulties, e.g.

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

Try a long shot?

- Go to high p_t ($p_{tH}, p_{tV} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?



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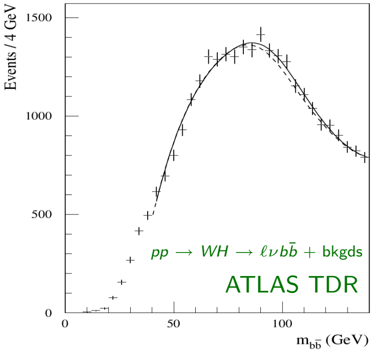

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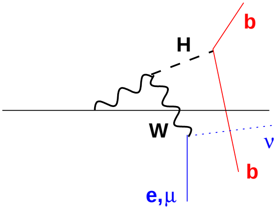

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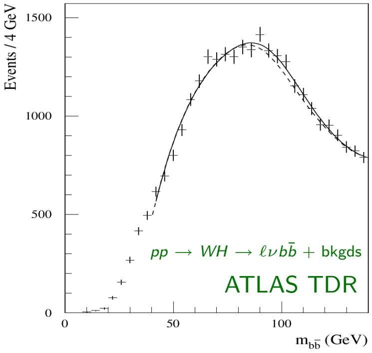

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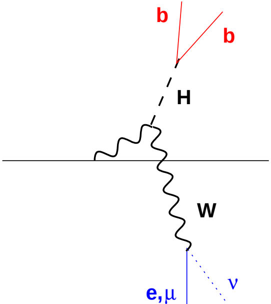

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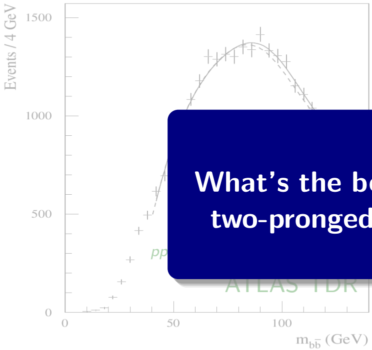


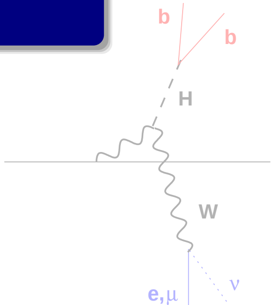
Difficulties, e.g.

- $gg \to t\bar{t}$ has $\ell\nu b\bar{b}$ with **same intrinsic**
  er partonic

  kgd shape

Question:

What's the best strategy to identify the two-pronged structure of the boosted Higgs decay?



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Past methods

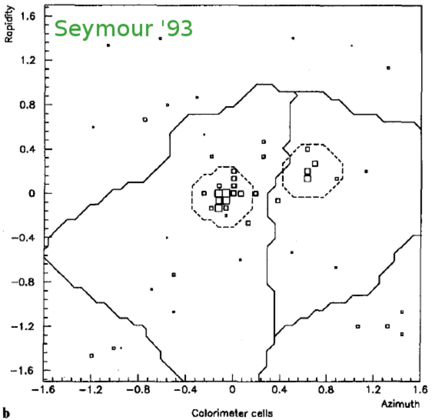
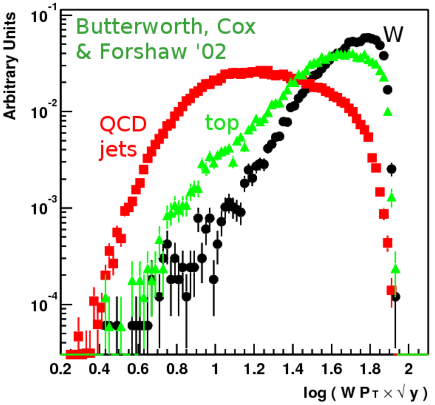


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

Use k_t jet-algorithm's hierarchy to split the jets



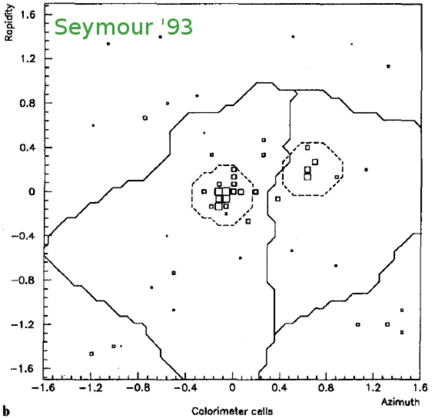
Use k_t alg.'s distance measure (rel. trans. mom.) to cut out QCD bkgd:

$$d_{ij}^{k_t} = \min(p_{ti}^2, p_{tj}^2)\Delta R_{ij}^2$$

Y-splitter

only partially correlated with mass

Past methods



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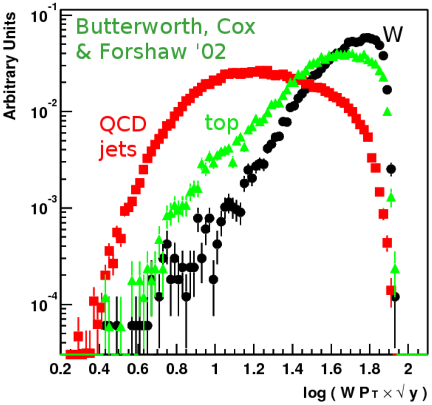

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Our tool

The Cambridge/Aachen jet alg.

Dokshitzer et al '97
Wengler & Wobisch '98

Work out $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$ between all pairs of objects i, j;
Recombine the closest pair;
Repeat until all objects separated by $\Delta R_{ij} > R$. [in FastJet]

Gives "hierarchical" view of the event; work through it backwards to analyse jet

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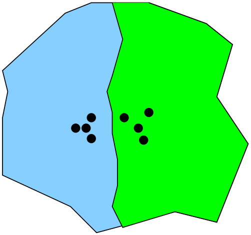
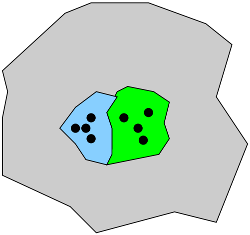
k_t algorithm



Cam/Aachen algorithm

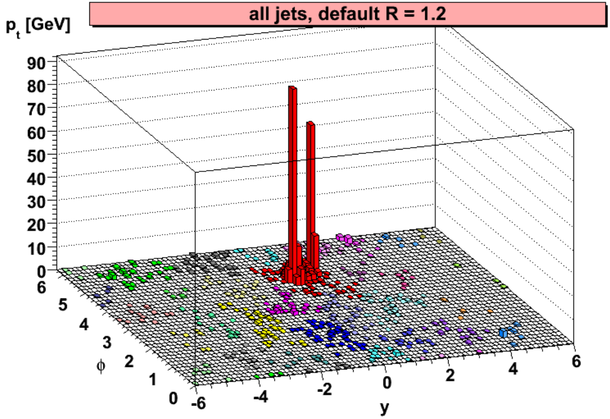


Allows you to "dial" the correct R to keep perturbative radiation, but throw out UE

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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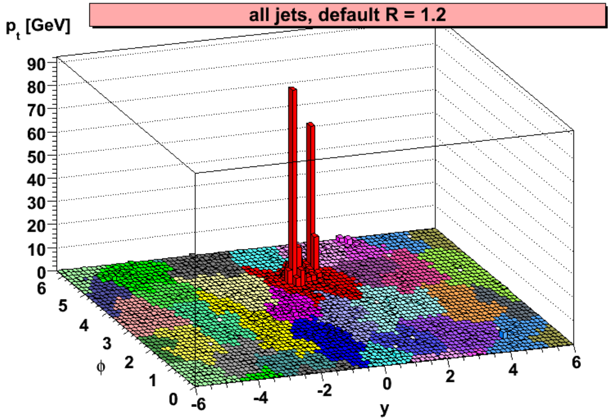

Zbb BACKGROUND

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

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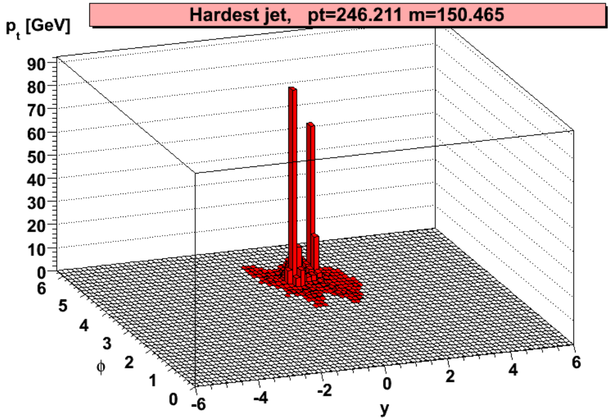

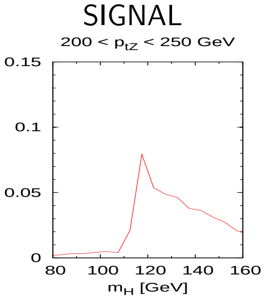

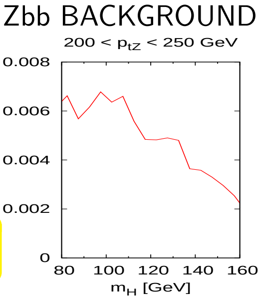

Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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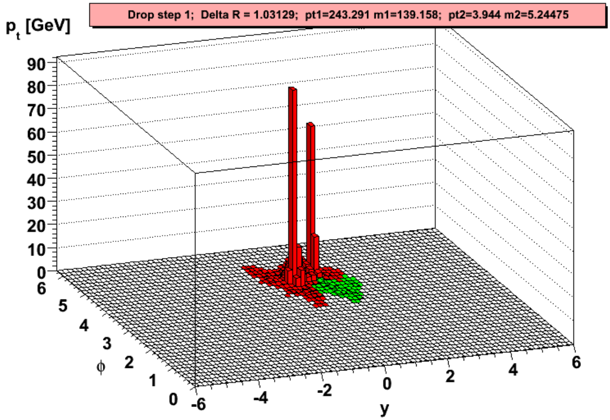

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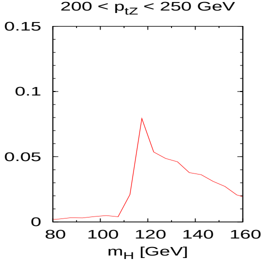

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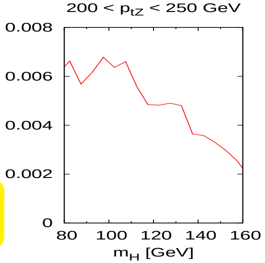

split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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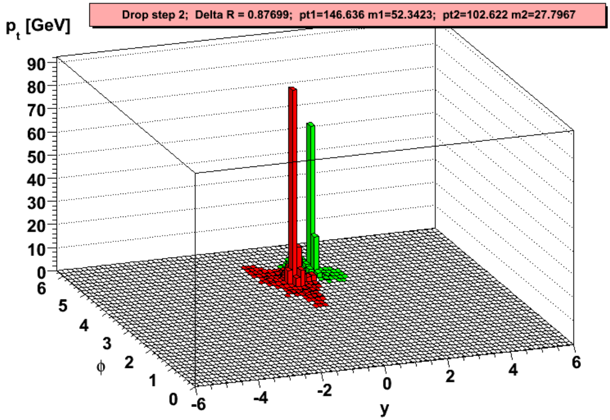

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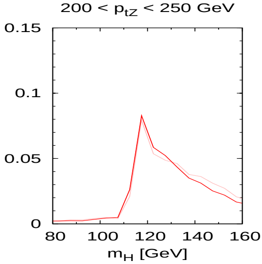

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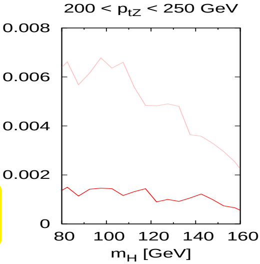


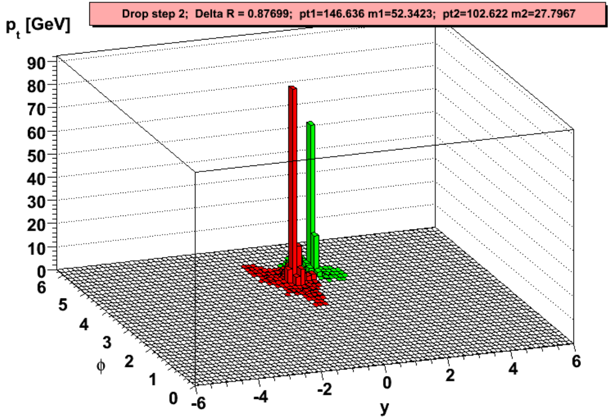
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \rightarrow$ mass drop

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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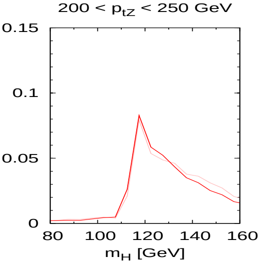

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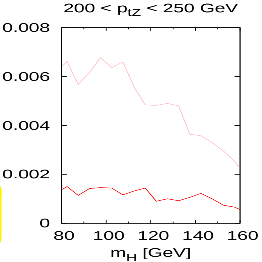

check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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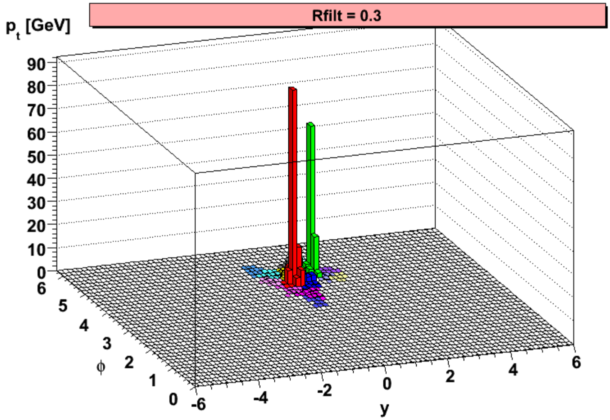

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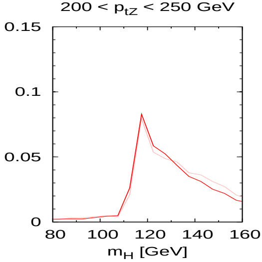

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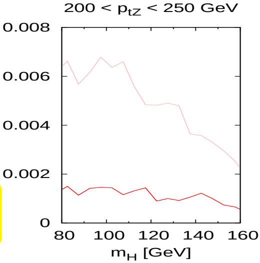

$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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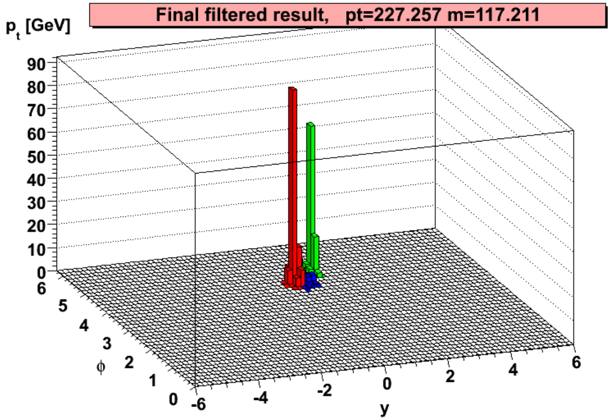
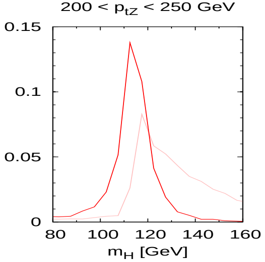
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



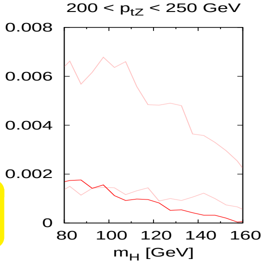
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

Butterworth, Davison, Rubin & GPS '08

SIGNAL

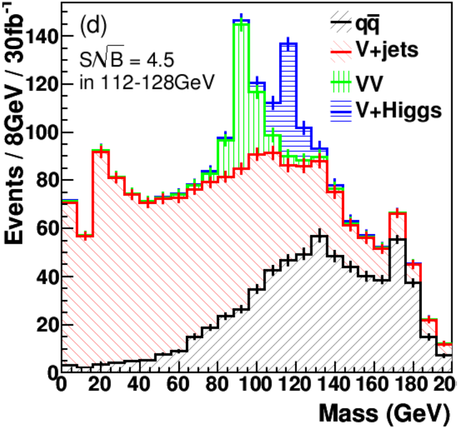


Zbb BACKGROUND



arbitrary norm.

combine HZ and HW, $p_t > 200$ GeV



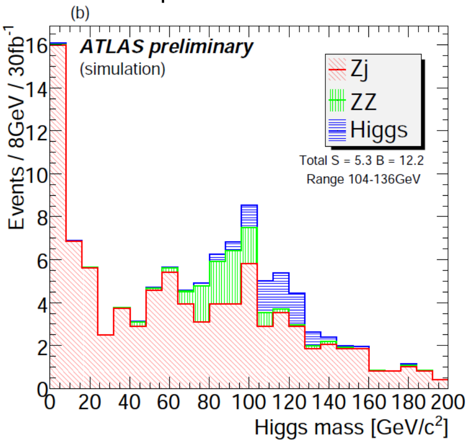
- Take $Z \to \ell^+\ell^-$, $Z \to \nu\bar{\nu}$, $W \to \ell\nu$ $\quad \ell = e, \mu$
- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_V|, |\eta_H| < 2.5$
- Assume real/fake b-tag rates of 0.6/0.02.
- Some extra cuts in HW channels to reject $t\bar{t}$.
- Assume $m_H = 115$ GeV.

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

Currently under study in the LHC experiments

ATLAS results

Leptonic channel



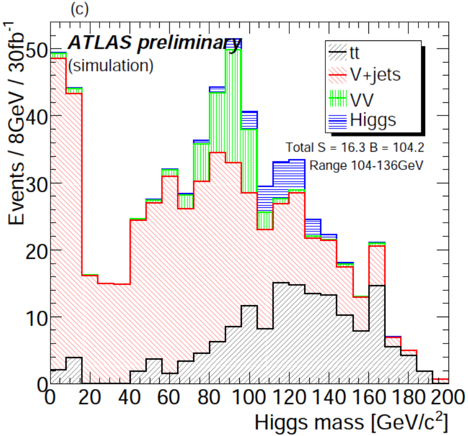
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 2.1σ

Expected given larger mass window

ATLAS results

Missing E_T channel



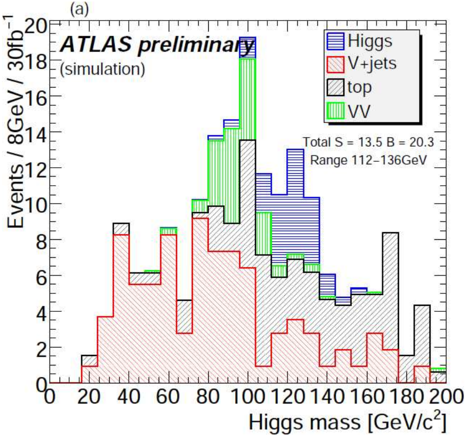
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 3σ

Suffers: some events redistributed to semi-leptonic channel

ATLAS results

Semi-leptonic channel



What changes compared to particle-level analysis?

$\sim 3\sigma$ as compared to 3σ

Benefits: some events redistributed from missing E_T channel

ATLAS combined results

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

3.7σ for 30 fb^{-1}

To be compared with 4.2σ in hadron-level analysis for $m_H = 120$ GeV
K-factors not included: don't affect significance (~ 1.5 for VH, $2 - 2.5$ for Vbb)
With 5% (20%) background uncertainty, ATLAS result becomes 3.5σ (2.8σ)

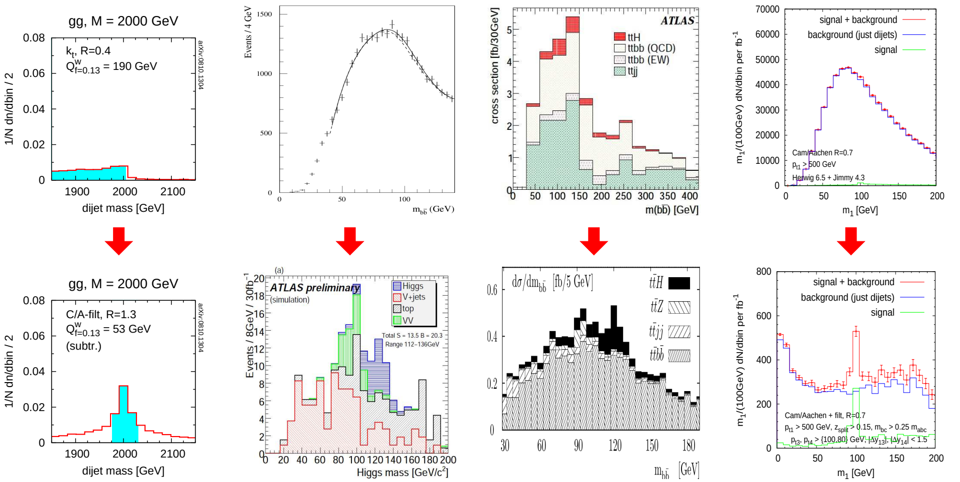
Comparison to other channels at ATLAS ($m_H = 120$, 30 fb^{-1}):

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

Extracted from 0901.0512

The potential of better jet finding

$X \to gg$ | $VH, H \to b\bar{b}$ | $ttH, H \to b\bar{b}$ | RPV $\tilde{\chi}_1^0 \to qqq$



1) Cacciari, Rojo, GPS & Soyez '08; 2) Butterworth, Davison, Rubin & GPS '08;
3) Plehn, GPS & Spannowsky '09; 4) Butterworth, Ellis, Raklev & GPS '09.

Conclusions

Conclusions

- There are no longer any valid reasons for using jet algorithms that are incompatible with the Snowmass criteria.

LHC experiments are adopting the new tools

Individual analyses need to follow suit

- It's time to move forwards with the question of how best to use jets in searches

- Examples here show two things:
  - Good jet-finding brings significant gains
  - There's room for serious QCD theory input into optimising jet use

Not the *only* way of doing things

But brings more insight than trial & error MC

This opens the road towards *Jetography*, QCD-based autofocus for jets

EXTRAS

k_t and geometry

There are $N(N-1)/2$ distances d_{ij} — surely we have to calculate them all in order to find smallest?

k_t distance measure is partly *geometrical:*

$$\min_{i,j} d_{ij} \equiv \min_{i,j}(\min\{k_{ti}^2, k_{tj}^2\}\Delta R_{ij}^2)$$
$$= \min_{i,j}(k_{ti}^2 \Delta R_{ij}^2)$$
$$= \min_{i}(k_{ti}^2 \min_{j} \Delta R_{ij}^2)$$

In words: for each i look only at the k_t distance to its 2D geometrical nearest neighbour (GNN).

k_t distance need only be calculated between GNNs

Each point has 1 GNN → need only calculate N d_{ij}'s

Cacciari & GPS, '05

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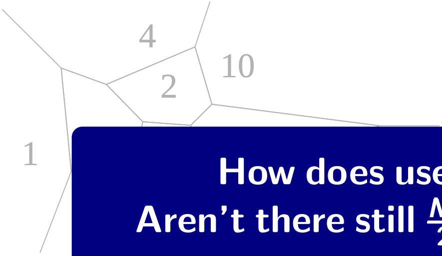
2d nearest-neighbours



Given a set of vertices on plane (1...10) a *Voronoi diagram* partitions plane into cells containing all points closest to each vertex

i '1908

x is al-

it is 3)

How does use of GNN help?
Aren't there still $\frac{N^2}{2}$ ΔR_{ij}^2 to check. . . ?

Geometrical nearest neighbour finding is a classic problem in the field of Computational Geometry

Const... une '88

Upda...

Devillers '99 [+ related work by other authors]

Convenient C++ package available: CGAL, http://www.cgal.org

with help of CGAL, k_t clustering can be done in N ln N time
Coded in the FastJet package (v1), Cacciari & GPS '06

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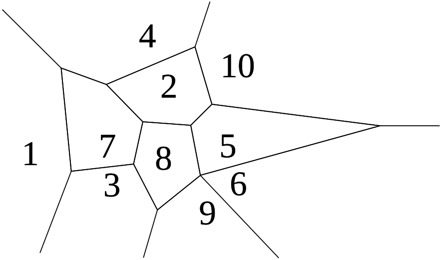

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Dirichlet '1850, Voronoi '1908

A vertex's nearest other vertex is always in an adjacent cell.

E.g. GNN of point 7 must be among 1,4,2,8,3 (it is 3)

Construction of Voronoi diagram for N points: $N \ln N$ time — Fortune '88

Update of 1 point in Voronoi diagram: expected $\ln N$ time

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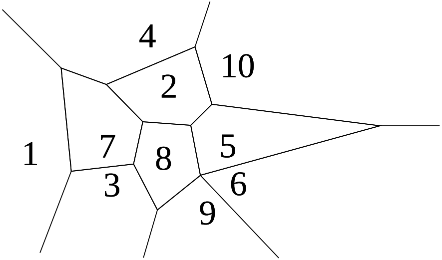

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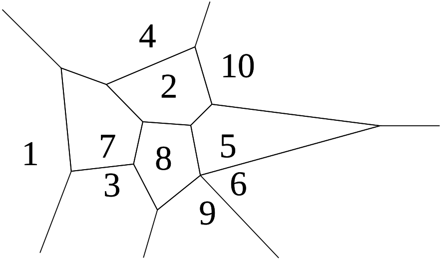

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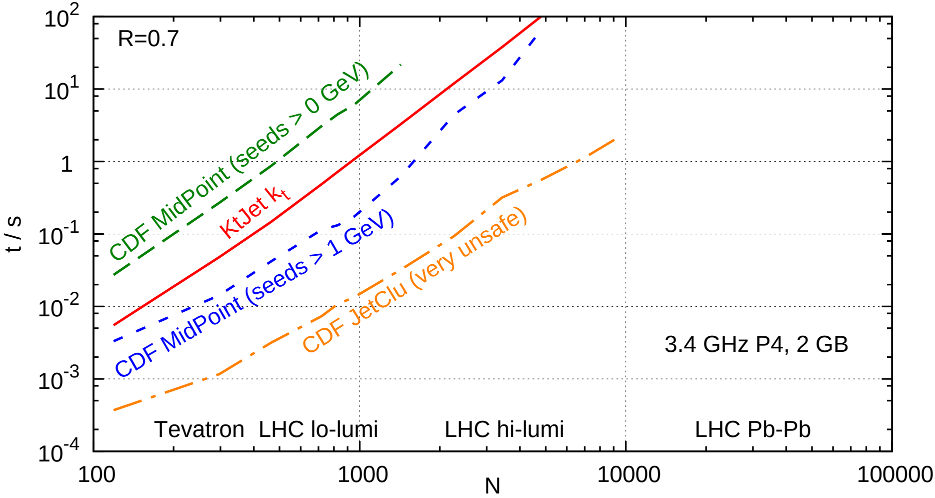
Speeds in 2005



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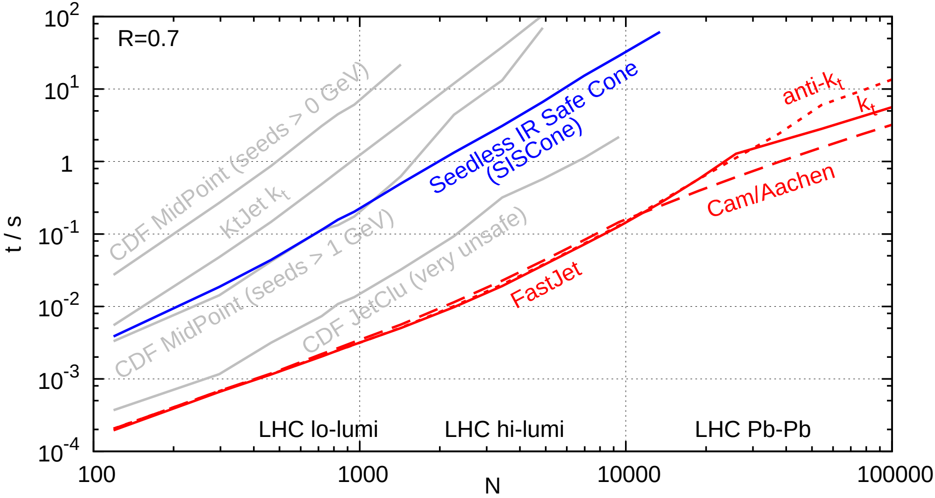
http://fastjet.fr/

Speeds in 2009



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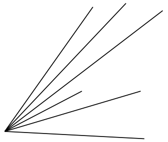
Iterative Cone [with progressive removal]

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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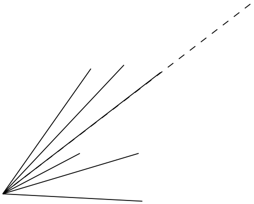

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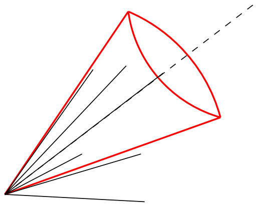

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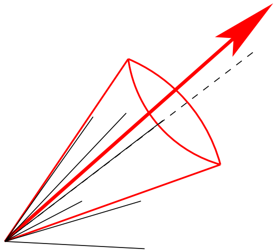

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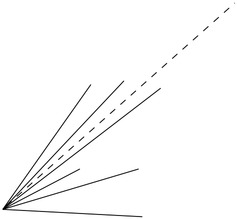

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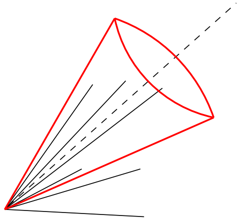

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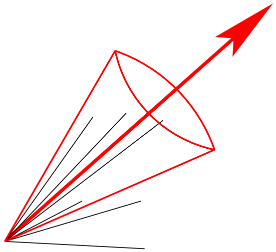

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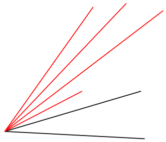

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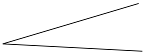

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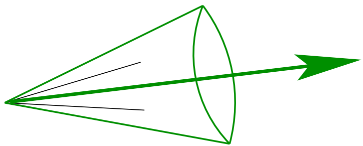

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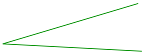

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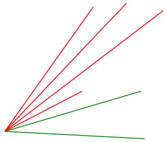

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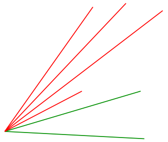
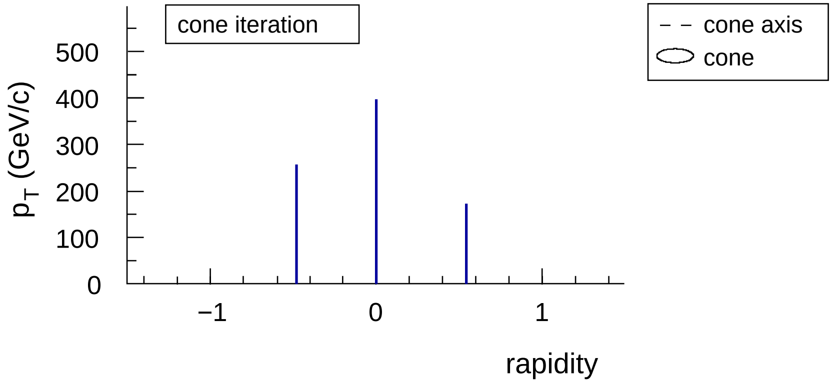


Iterative Cone with Progressive Removal (IC-PR)

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

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

ICPR iteration issue



Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give ∞

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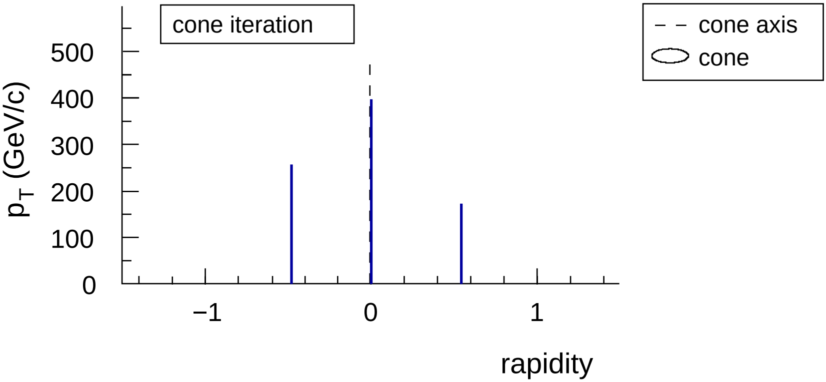

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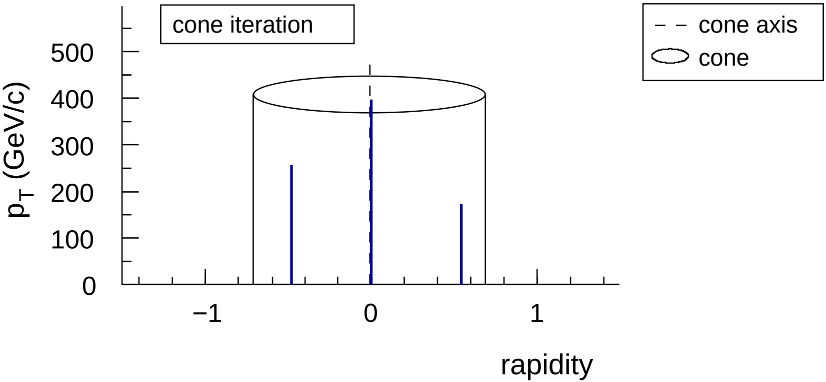

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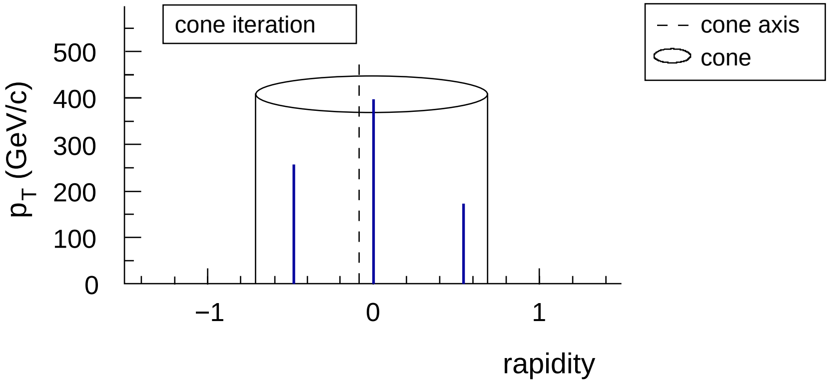

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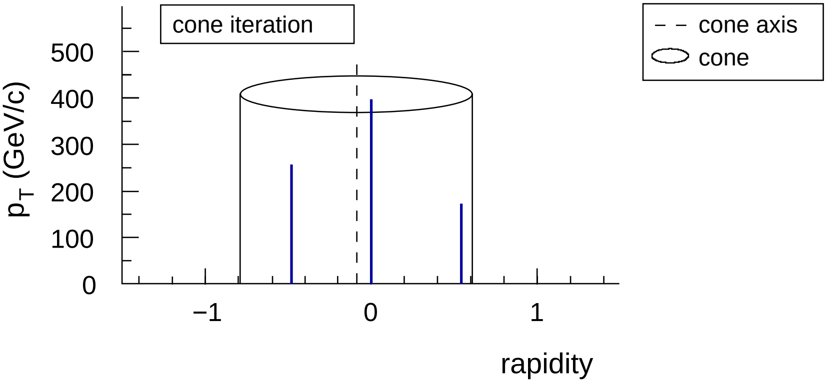

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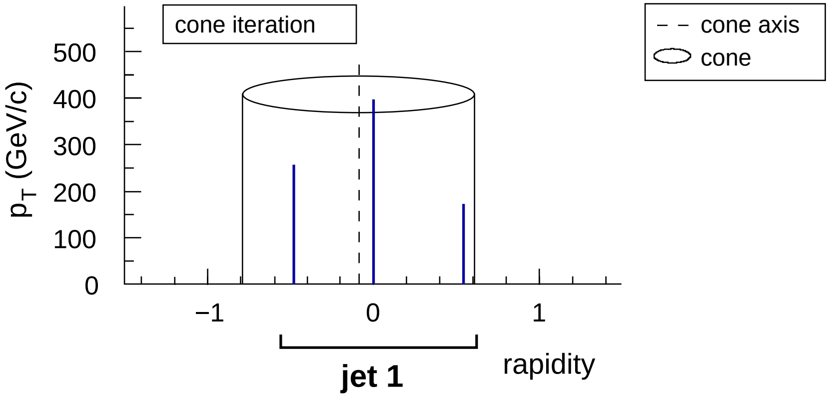

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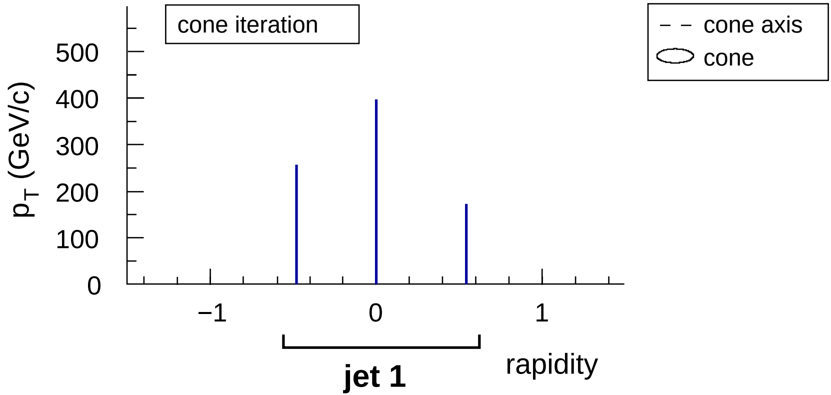

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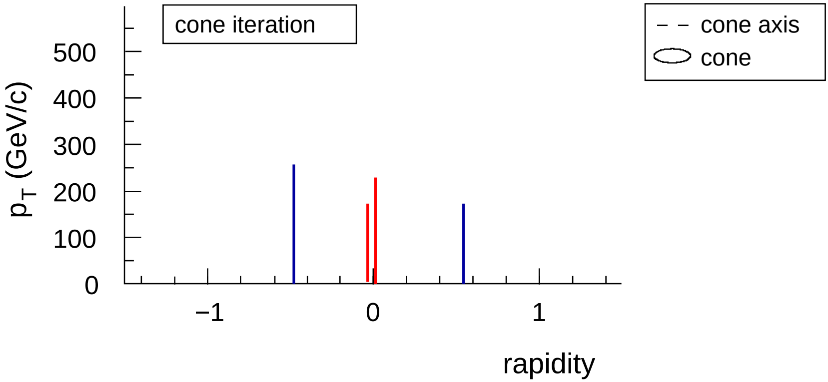

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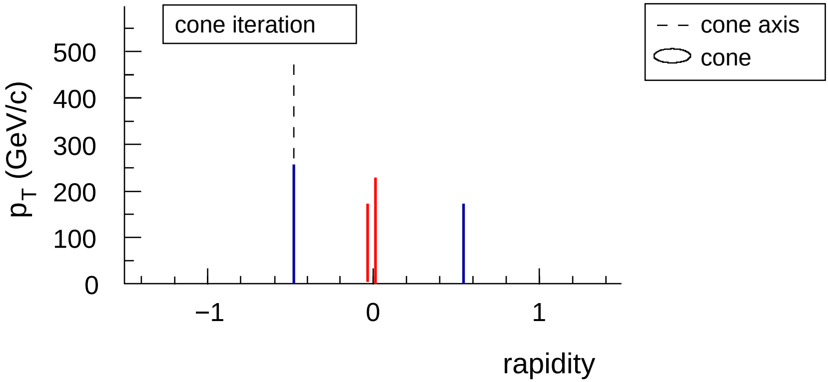

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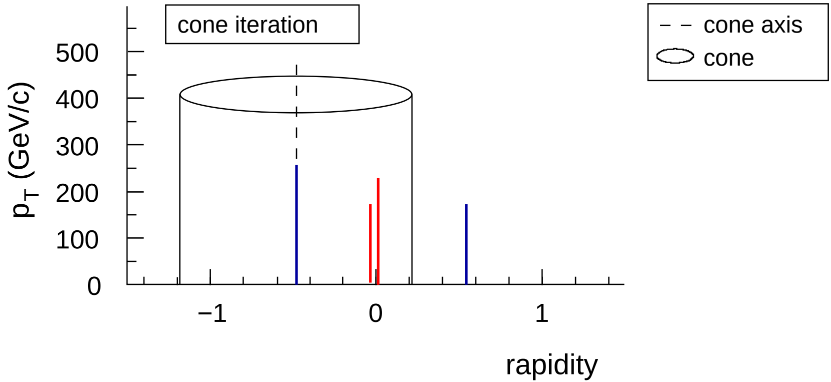

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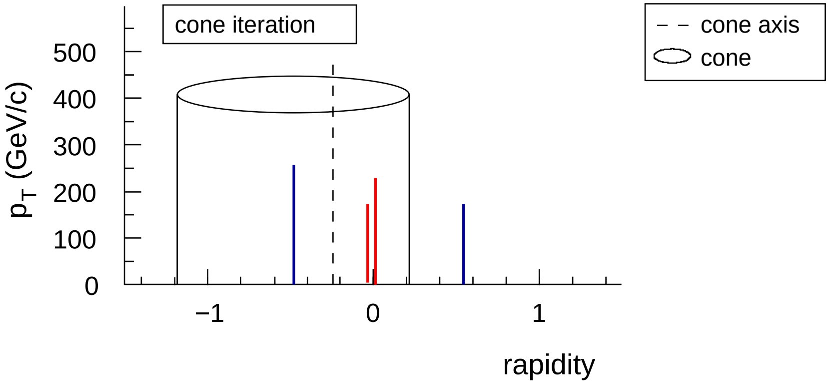

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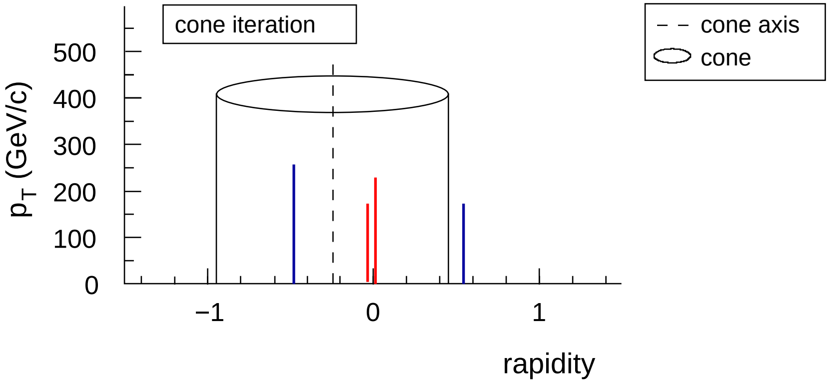

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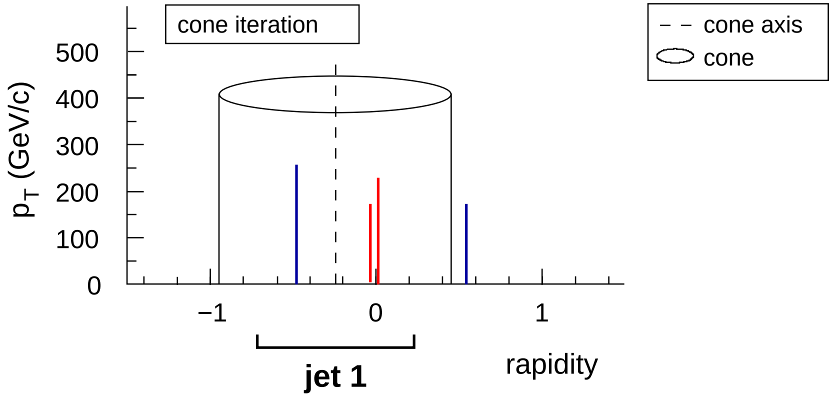

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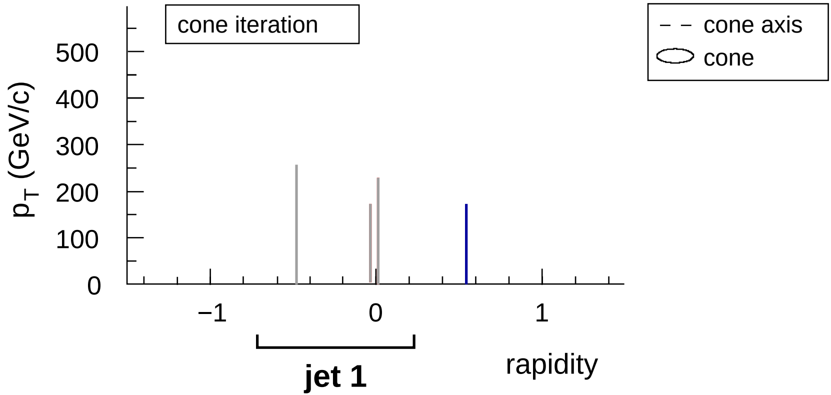

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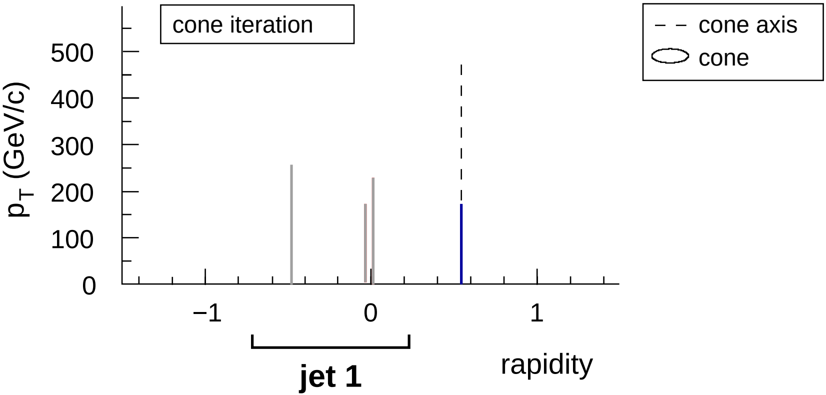

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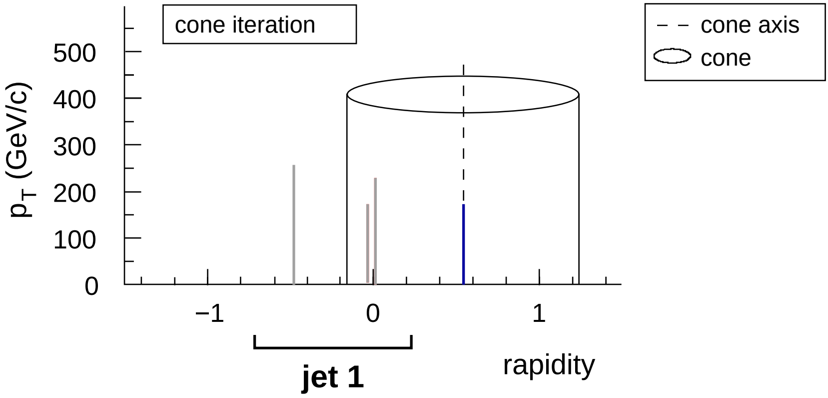

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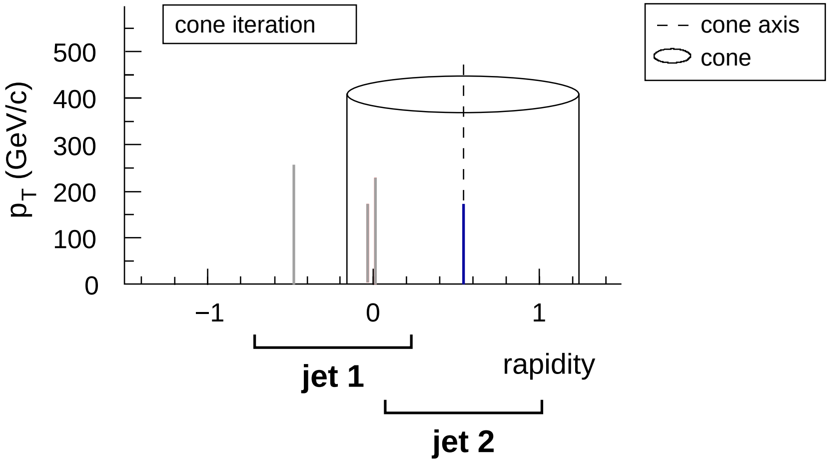

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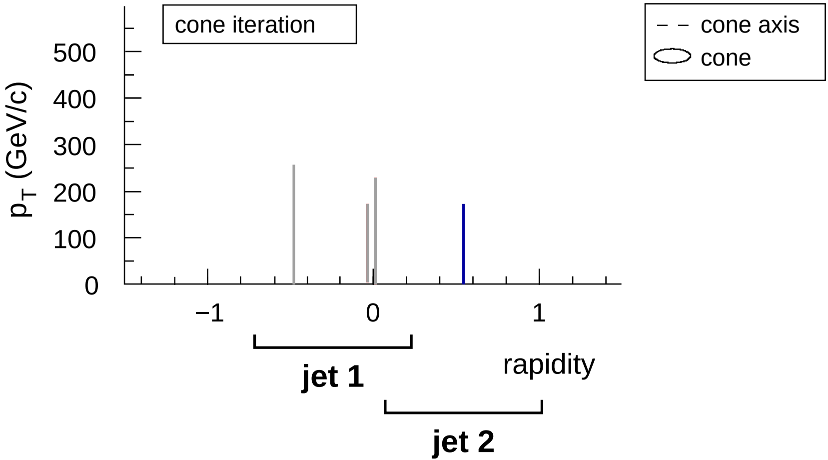

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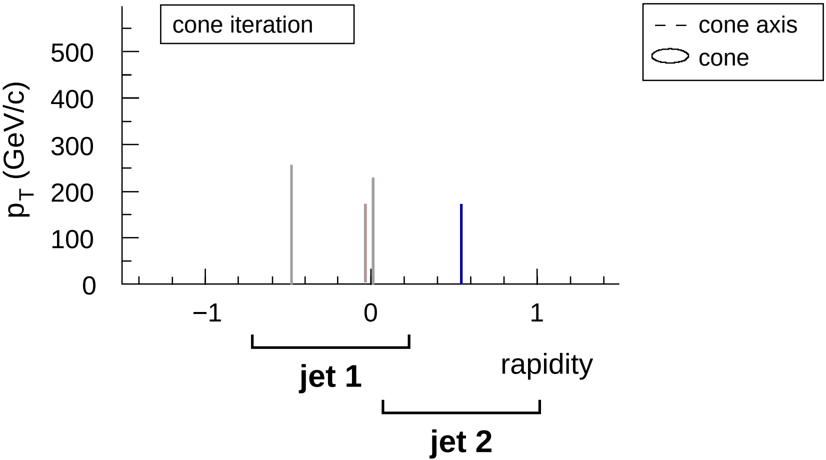

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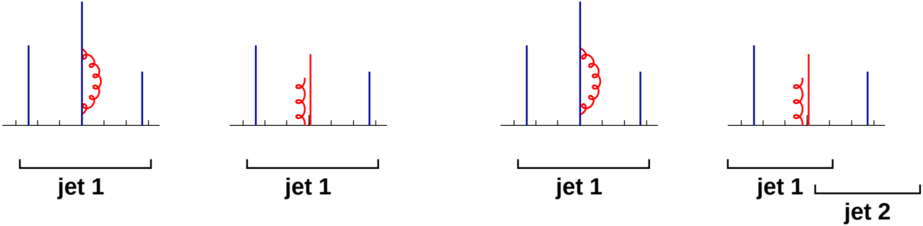
Consequences of collinear unsafety

Collinear Safe	**Collinear Unsafe**



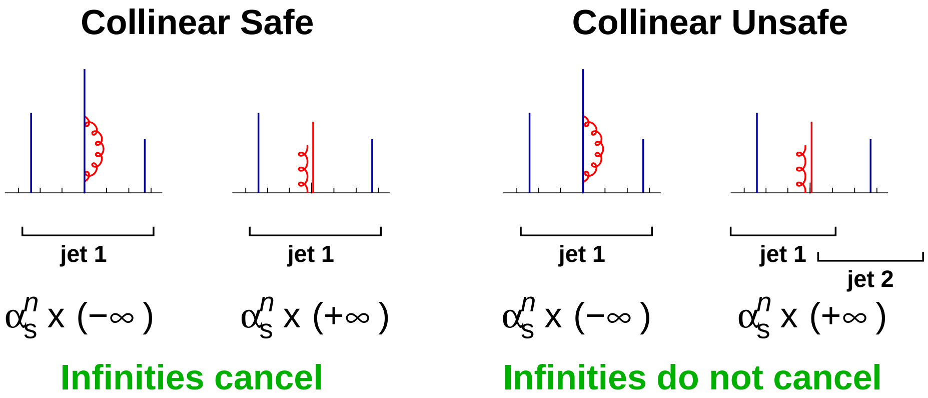
$\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$ $\alpha_s^n \times (-\infty)$ $\alpha_s^n \times (+\infty)$

Infinities cancel

Infinities do not cancel

Invalidates perturbation theory

Consequences of collinear unsafety



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Impact of IRC issues in W+3j

CDF have measured W+3jet X-section with JetClu (IR_{2+1} unsafe).

NLO calculation with JetClu would diverge [for zero seed threshold]

Strategy for theory: use 2 algs for theory prediction, SISCone & anti-k_t; difference between them is IRC unsafety "systematic".

With CDF cuts and R choice, difference is $\mathcal{O}(20\%)$

10% @ NLO: Ellis, Melnikov & Zanderighi '09

$\sim$ 20% exp. systematics

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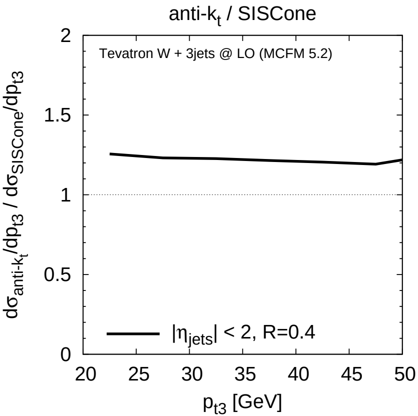

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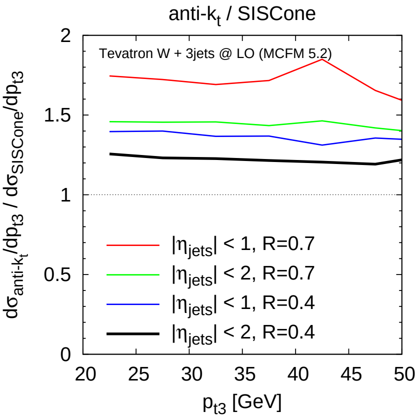
With other cuts and R choice, IRC systematic can be up to 75%

Future measurements deserve to be done with IRC safe algs...



Does lack of IRC safety matter?

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

- Are you looking for a mass-peak? ➥ you needn't care much
- Are you looking for an excess over bkgd? ➥ you need control samples, validated against QCD

W+1,2,3 jets	⟷	W+n jets	⟷	new-physics search
NLO v. data		LO, LO+MC v. data		LO+MC v. data

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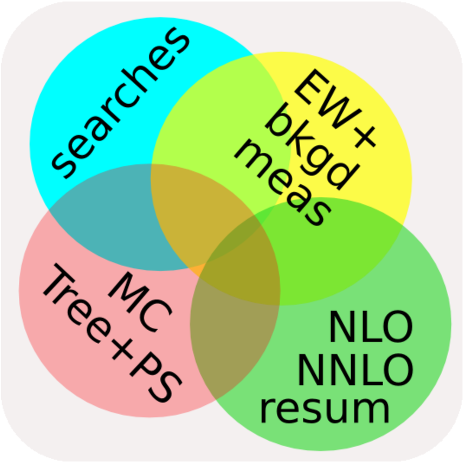

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IR safe alg. — IR safe alg. — IR safe alg.

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W+1,2,3 jets	$\longleftrightarrow$	W+n jets	$\not\longleftrightarrow$	new-physics search
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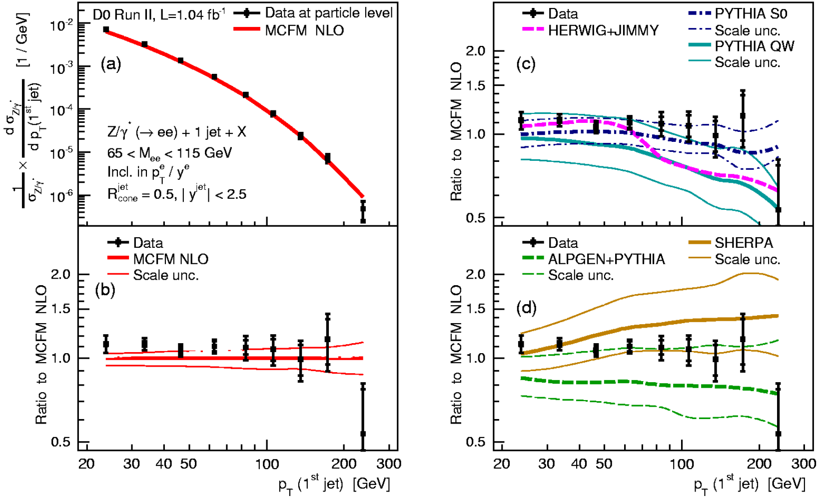
NLO v. LO+PS

NLO

LO+PS

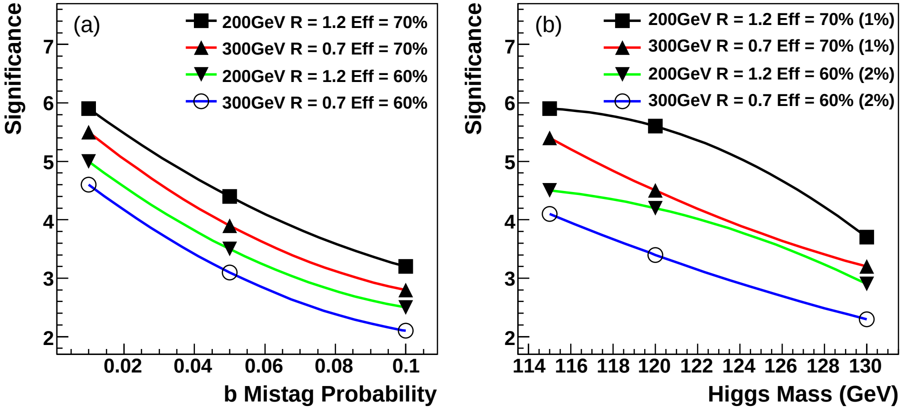


Jet-alg comparison

Cross section for signal and the Z+jets background in the leptonic Z channel for $200 < p_{TZ}/\,\text{GeV} < 600$ and $110 < m_J/\,\text{GeV} < 125$, with perfect b-tagging; shown for our jet definition (C/A MD-F), and other standard ones close to their optimal R values.

Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B \cdot \mathrm{fb}}$
C/A, $R = 1.2$, MD-F	0.57	0.51	0.80
k_t, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCone, $R = 0.8$	0.49	1.33	0.42
anti-k_t, $R = 0.8$	0.22	1.06	0.21

Impact of b-tagging, Higgs mass



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For it to be a significant discovery channel requires decent b-tagging, lowish mass Higgs [and good experimental resolution]

In nearly all cases, looks feasible for extracting WH, ZH couplings

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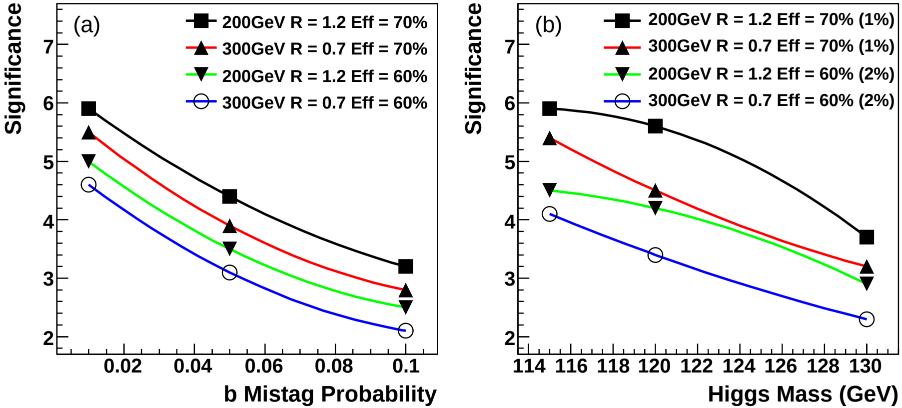

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