

# Towards Jetography

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Based on work with

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Lorenzo Magnea, Juan Rojo, Mathieu Rubin & Gregory Soyez

CERN Theory Institute

SM and BSM physics at the LHC

August 2009

quark



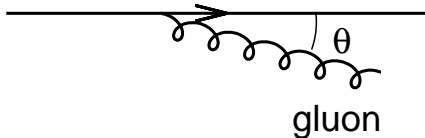
Gluon emission:

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

At low scales:

$$\alpha_s \rightarrow 1$$

quark

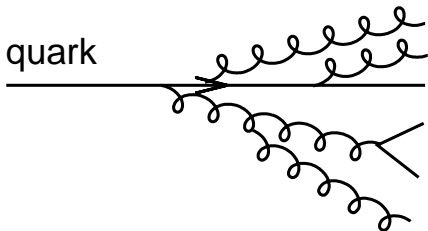


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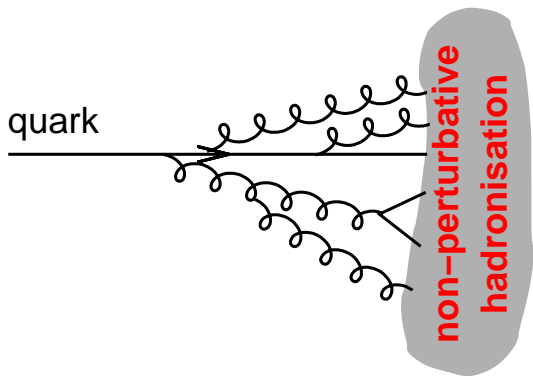


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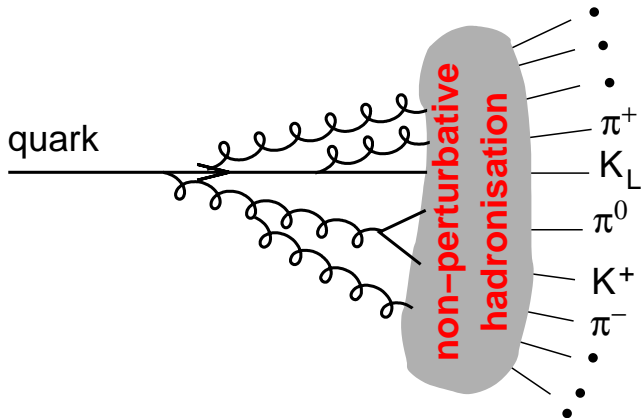


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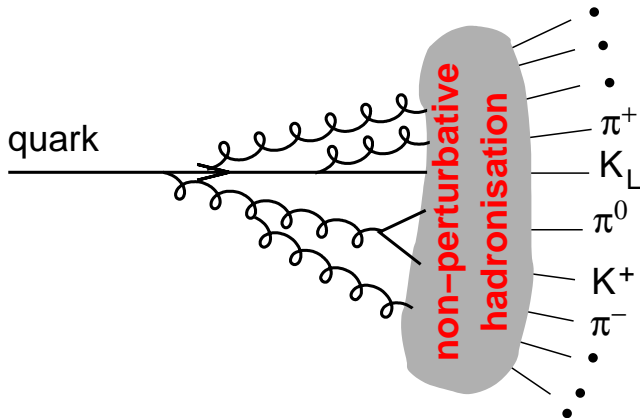


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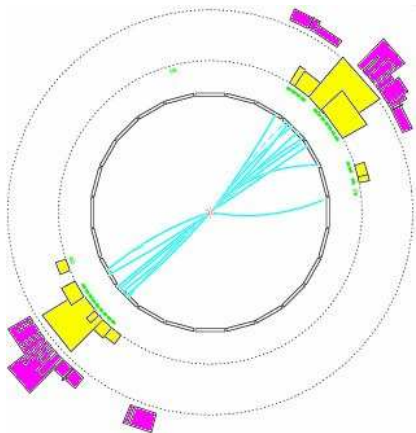
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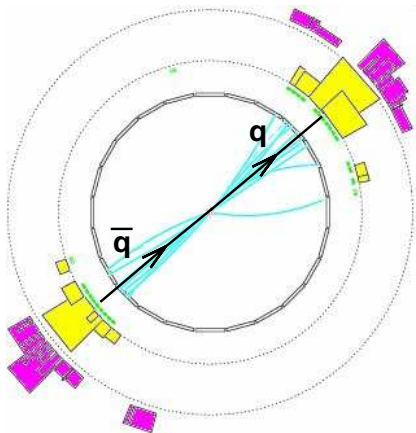
**This is a jet**



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

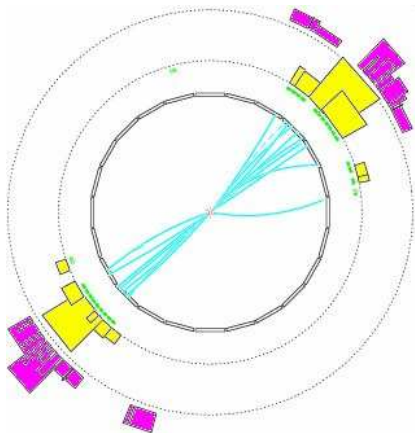
How many jets do you see?  
Do you really want to ask yourself  
this question for  $10^9$  events?



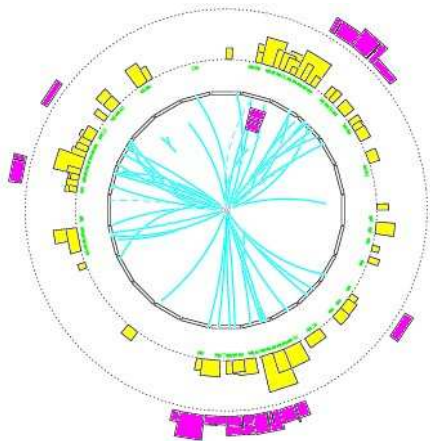


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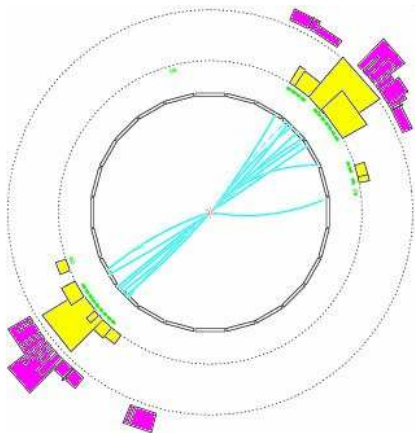
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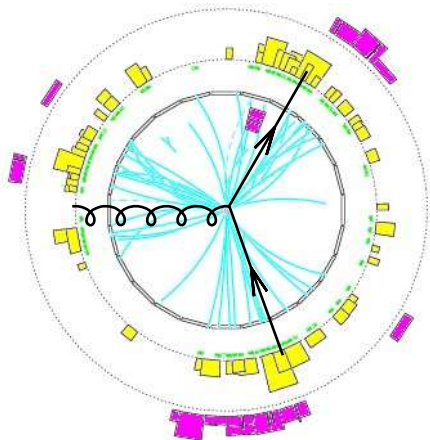
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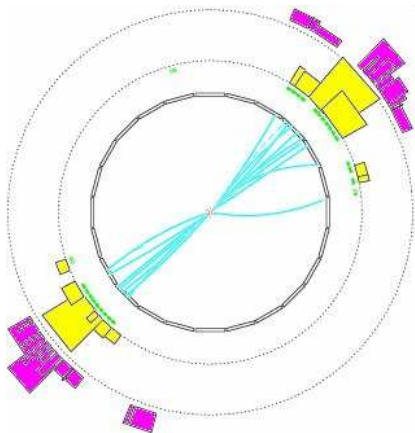
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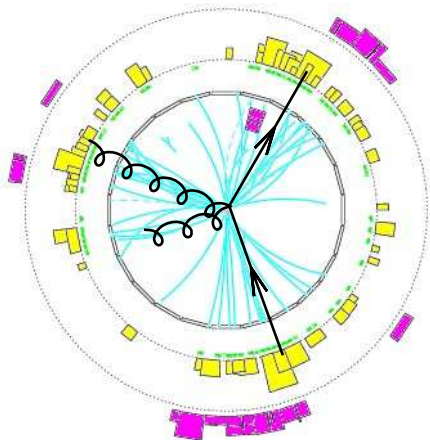
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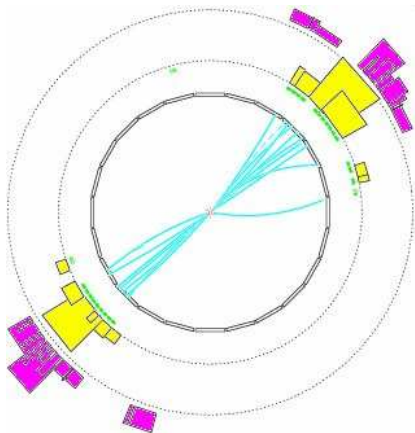
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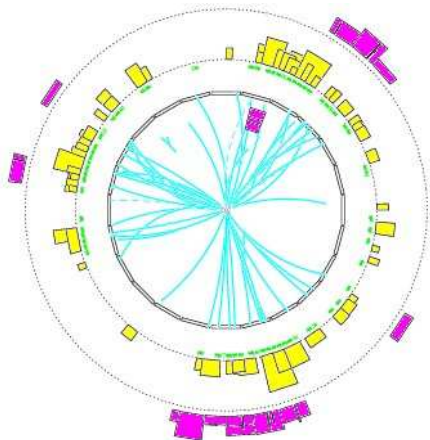
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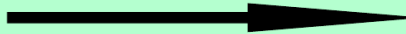
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## jet definition

 $\{P_i\}$ 

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

jet algorithm

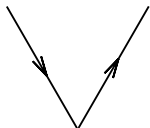
 $\{j_k\}$ 

jets

+ parameters (usually at least the radius  $R$ )

+ recombination scheme

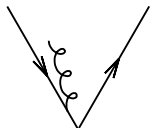
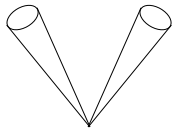
Reminder: running a jet definition gives a well defined physical observable,  
which we can measure and, hopefully, calculate



LO partons

Jet ↓ Def<sup>n</sup>

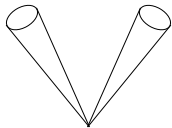
jet 1      jet 2



NLO partons

Jet ↓ Def<sup>n</sup>

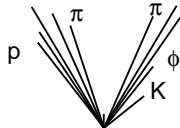
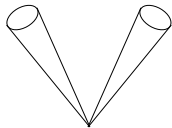
jet 1      jet 2



parton shower

Jet ↓ Def<sup>n</sup>

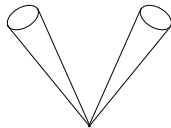
jet 1      jet 2



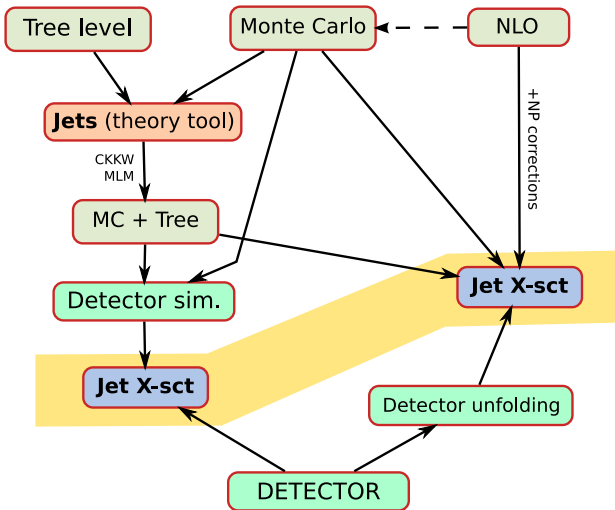
hadron level

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jet 1      jet 2

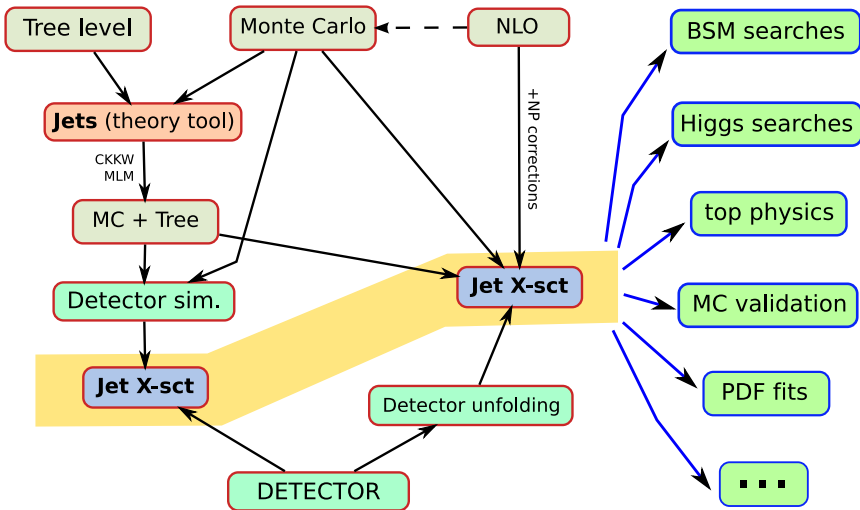


**Projection to jets should be resilient to QCD effects**



Jet (definitions) provide central link between expt., “theory” and theory  
And jets are an input to almost all analyses





Jet (definitions) provide central link between expt., “theory” and theory  
**And jets are an input to almost all analyses**

- ▶ 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

## $k_t$ 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)**

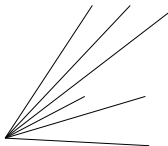


- variables
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### NB: hadron collider variables

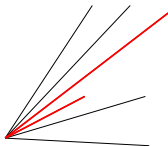
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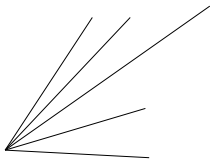
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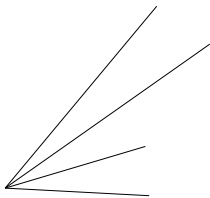
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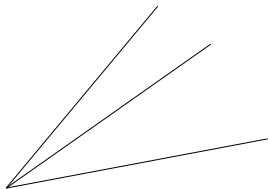
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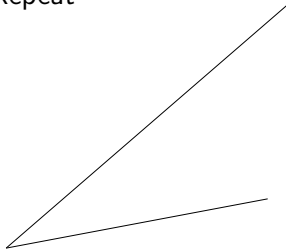
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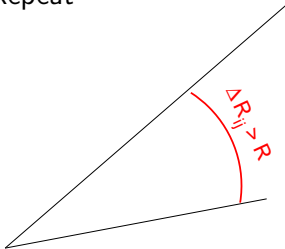
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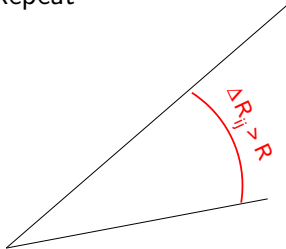
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NB:  $d_{ij}$  distance  $\leftrightarrow$  QCD branching probability  $\sim \alpha_s \frac{dk_{tj}^2 dR_{ij}^2}{d_{ij}}$

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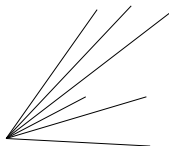
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  - ≡ cone pointing in same direction as the momentum of its contents
  - Found by iterating from some initial seed directions
- ▶ Resolve cases of overlapping stable cones



**Top-down jets:  
cone algorithms  
(energy flow conserved by QCD)**

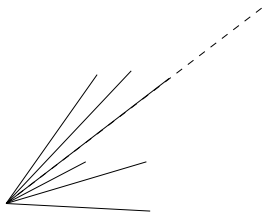
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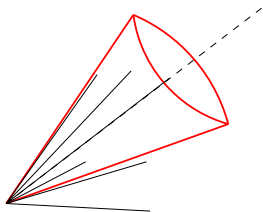
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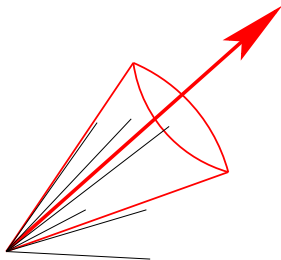
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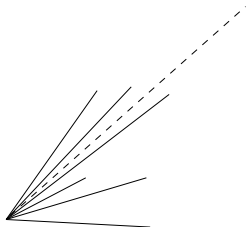
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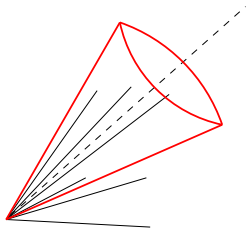
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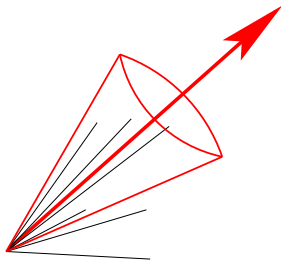
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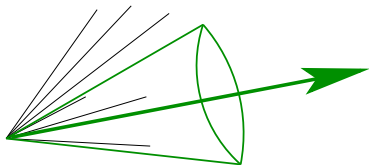
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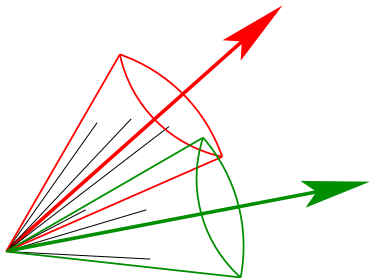
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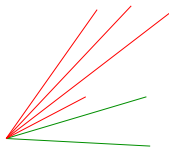
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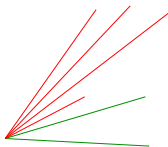


## Tevatron & ATLAS cone algs have two main steps:

- ▶ Find some/all stable cones
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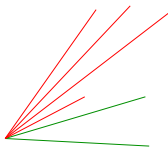


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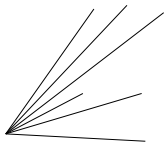
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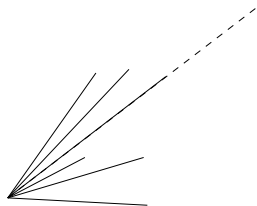


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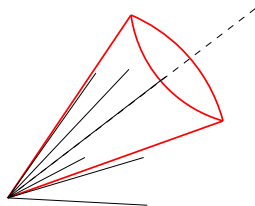


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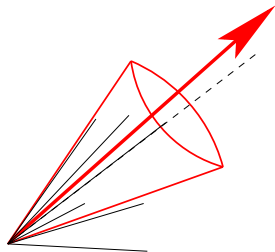


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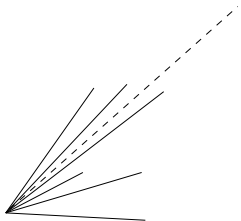
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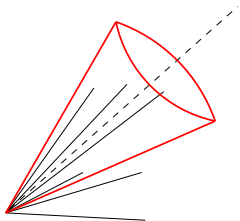
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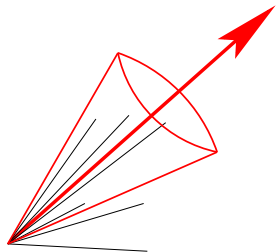
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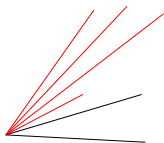
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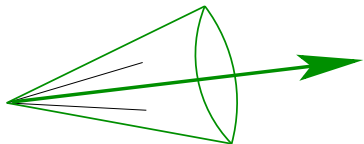
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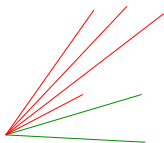
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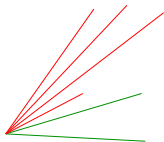
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## **Iterative Cone with Progressive Removal (IC-PR)**

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

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



# Readying jet “technology” for the LHC era

[a.k.a. satisfying Snowmass]

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;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.



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**Property 1  $\Leftrightarrow$  speed.** (+other aspects)

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

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

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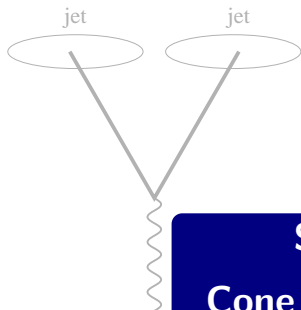
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**Property 4  $\equiv$  Infrared and Collinear (IRC) Safety.** It helps ensure:

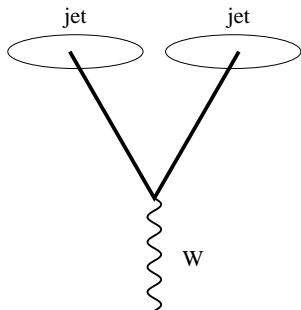
- ▶ Soft (low-energy) emissions & collinear splittings don't change jets
- ▶ Each order of perturbation theory is smaller than previous (at high  $p_t$ )

**Wasn't satisfied by the cone algorithms**



**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	$\mathcal{O}(1)$	$-\infty$	$0$



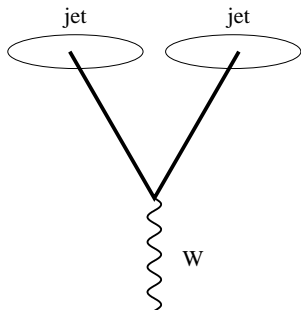
1-jet  $\alpha_s^2 \alpha_{EW}$   
 2-jet  $\mathcal{O}(1)$

$\alpha_s^3 \alpha_{EW}$   
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With these (& most) cone algorithms, perturbative infinities fail to cancel at some order  $\equiv$  IR unsafety

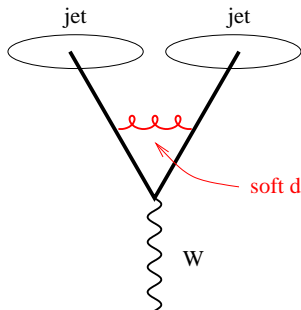
# JetClu (& Atlas Cone) in $Wjj$ @ NLO



$$\alpha_s^2 \alpha_{EW}$$

1-jet

2-jet  $\mathcal{O}(1)$



$$\alpha_s^3 \alpha_{EW}$$

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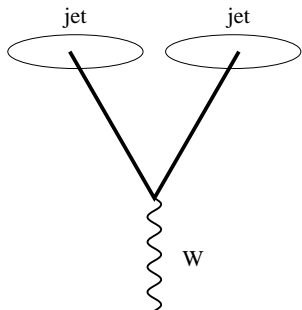
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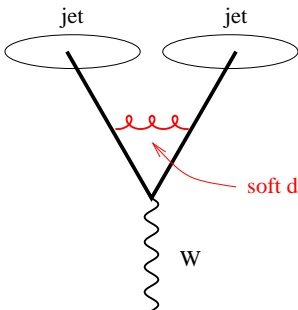
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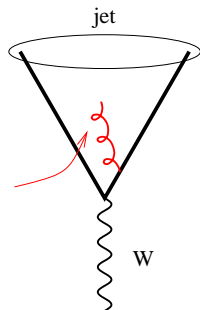
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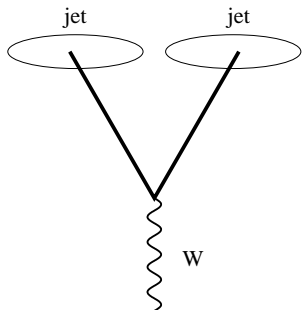
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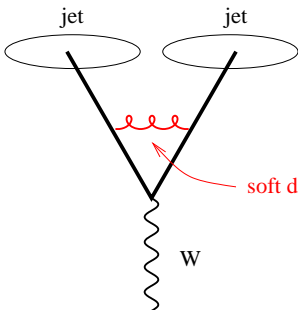
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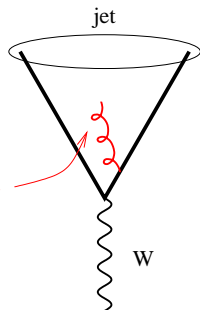
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Real life does not have infinities, but pert. infinity leaves a real-life trace

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

Among consequences of IR unsafety:

	<i>Last meaningful order</i>			Known at
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC <sub>mp</sub> -SM]	CMS it. cone [IC-PR]	
Inclusive jets	LO	NLO	NLO	NLO (→ NNLO)
W/Z + 1 jet	LO	NLO	NLO	NLO
3 jets	<b>none</b>	LO	LO	NLO [nlojet++]
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NB: 50,000,000\$/£/CHF/€ investment in NLO

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

And LHC will rely on QCD for background double-checks  
 extraction of cross sections, extraction of parameters



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How do we solve  
cone IR safety  
problems?

Fix stable-cone finding



**SISCone**

GPS & Soyez '07

Same family as Tev. Run II alg

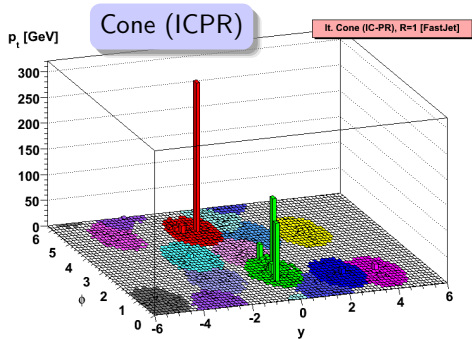
Invent "cone-like" alg.



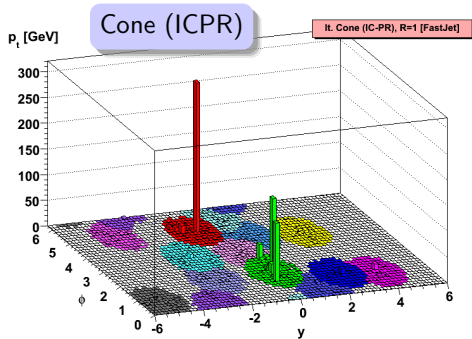
**anti-kt**

Cacciari, GPS & Soyez '08

# Essential characteristic of cones?



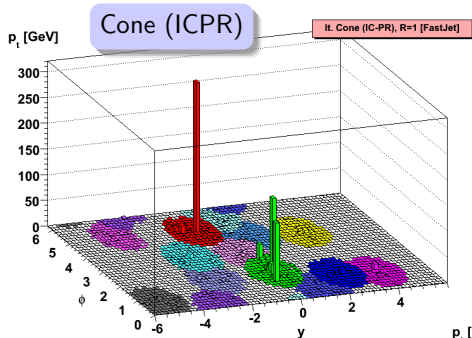
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(Some) cone algorithms give **circular** jets in  $y - \phi$  plane

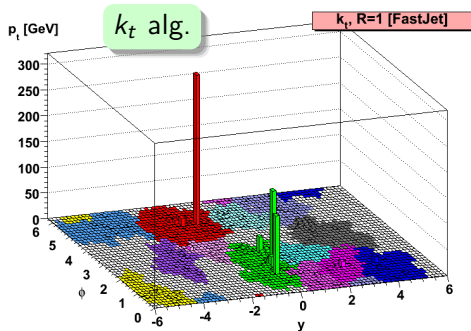
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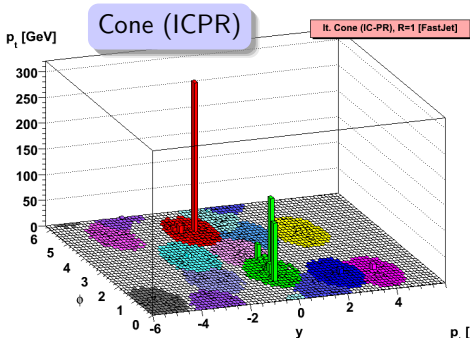


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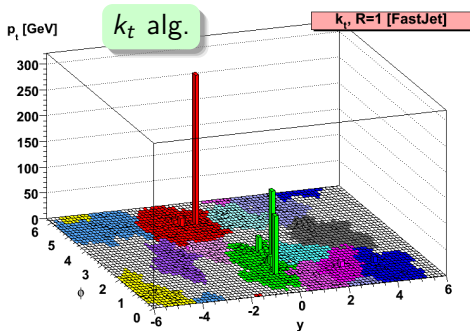
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$k_t$  jets are **irregular**

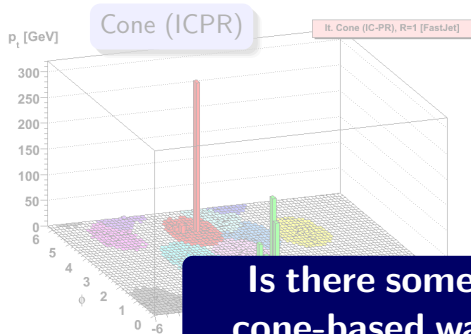
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**Regularly held against  $k_t$**



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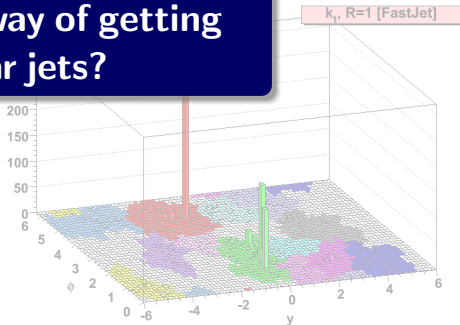
**Is there some other, non cone-based way of getting circular jets?**

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Soft stuff clusters with nearest neighbour

$$k_t: d_{ij} = \min(k_{ti}^2, k_{tj}^2) \Delta R_{ij}^2 \longrightarrow \text{anti-}k_t: d_{ij} = \frac{\Delta R_{ij}^2}{\max(k_{ti}^2, k_{tj}^2)}$$

Hard stuff clusters with nearest neighbour  
Privilege collinear divergence over soft divergence  
Cacciari, GPS & Soyez '08

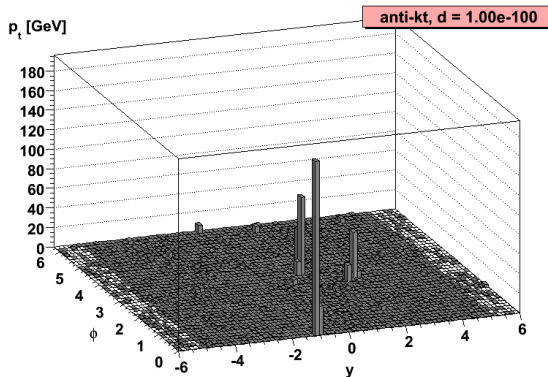
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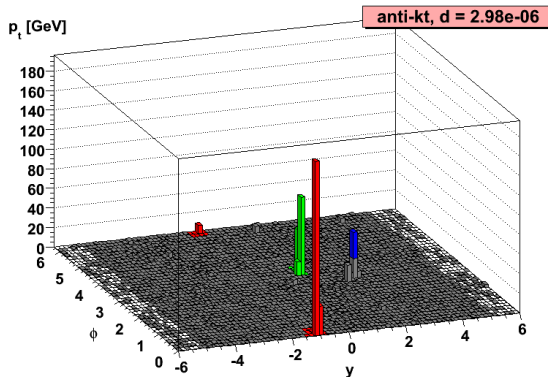
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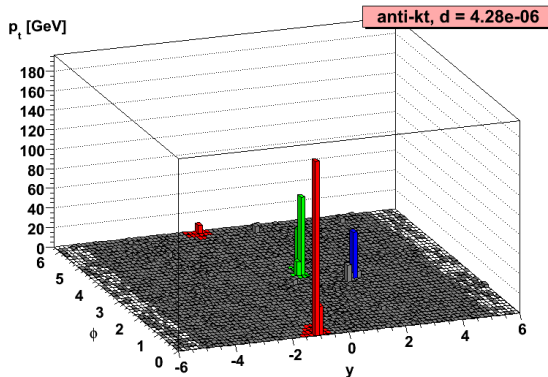
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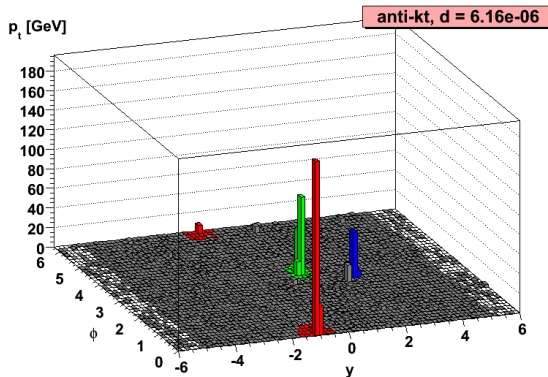
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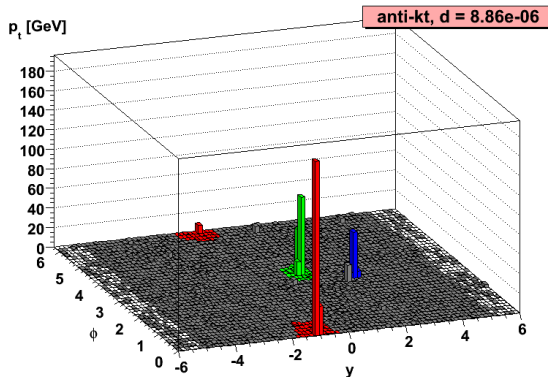
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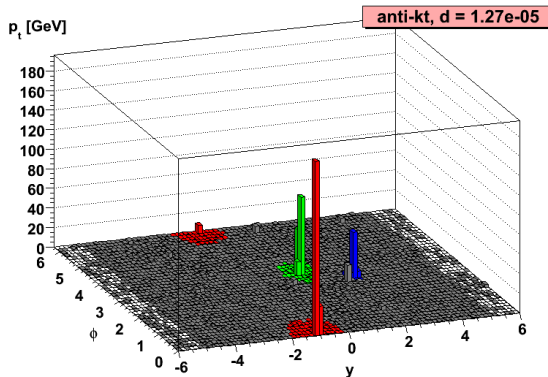
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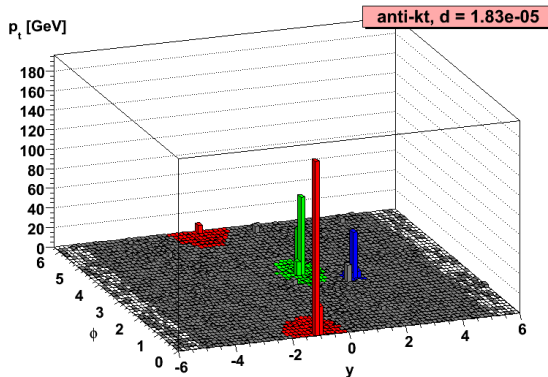
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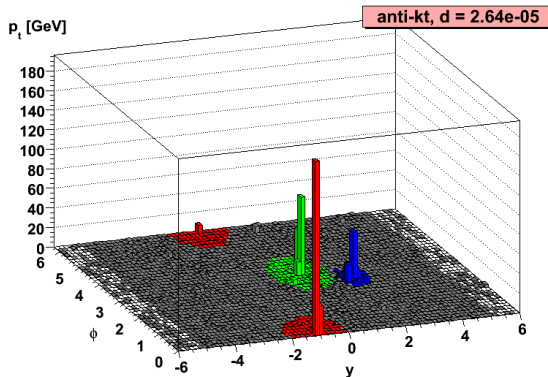
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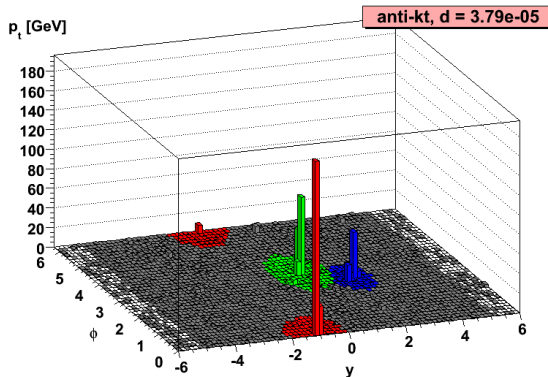
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Privilege collinear divergence over soft divergence

Cacciari, GPS & Soyez '08



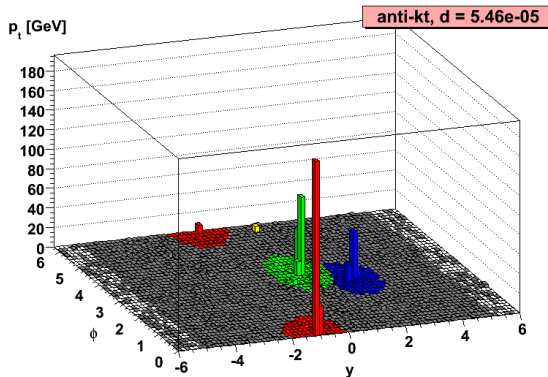
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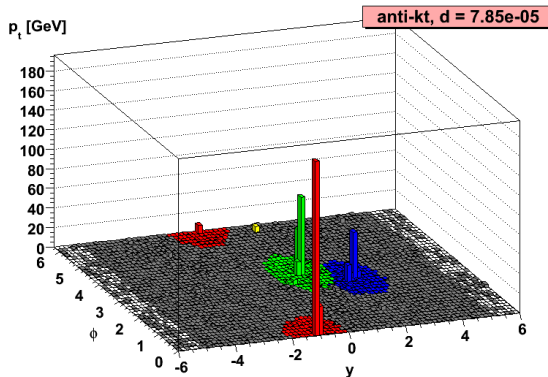
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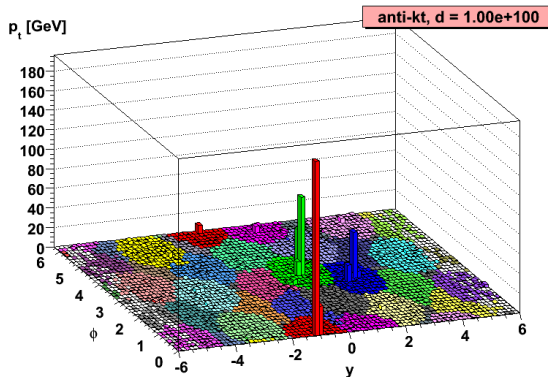
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Hard stuff clusters with nearest neighbour

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Cacciari, GPS & Soyez '08



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

Generalise inclusive-type sequential recombination with

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

	Alg. name	Comment	time
$p = 1$	$k_t$ CDOSTW '91-93; ES '93	Hierarchical in rel. $k_t$	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple $R$ at once ↔ QCD angular ordering	$N \ln N$
$p = -1$	anti- $k_t$ Cacciari, GPS, Soyez '08 ~ 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)

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



Which jet definition(s) for LHC?

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

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Can we address this question scientifically?

**Jetography**

## **Jet definitions differ mainly in:**

$$\text{alg} + R$$

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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## 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

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

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

**Hadronisation: the “parton-shower”  $\rightarrow$  hadrons transition**Method:

- ▶ “infrared finite  $\alpha_s$ ” à la Dokshitzer & Webber '95
- ▶ **prediction** based on  $e^+e^-$  event shape data
- ▶ could have been deduced from old work Korchensky & Sterman '95  
Seymour '97

Main result

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

cf. Dasgupta, Magnea & GPS '07  
coefficient holds for anti- $k_t$ ; see Dasgupta & Delenda '09 for  $k_t$  alg.

“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

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## Jet algorithm properties: summary

	$k_t$	Cam/Aachen	anti- $k_t$	SISCone
reach	$R$	$R$	$R$	$(1 + \frac{p_{t2}}{p_{t1}})R$
$\Delta p_{t,PT} \simeq \frac{\alpha_s C_i}{\pi} \times$	$\ln R$	$\ln R$	$\ln R$	$\ln 1.35R$
$\Delta p_{t,hadr} \simeq -\frac{0.4 \text{ GeV} C_i}{R} \times$	0.7	?	1	?
area = $\pi R^2 \times$	$0.81 \pm 0.28$	$0.81 \pm 0.26$	1	0.25
$+ \pi R^2 \frac{C_i}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} \times$	$0.52 \pm 0.41$	$0.08 \pm 0.19$	0	$0.12 \pm 0.07$

**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:

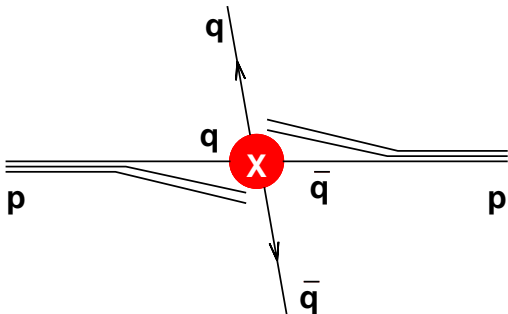
$$q : \langle \Delta p_t \rangle \simeq \frac{\alpha_s C_F}{\pi} p_t \ln R$$

## Hadronisation:

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

## Underlying event:

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



## 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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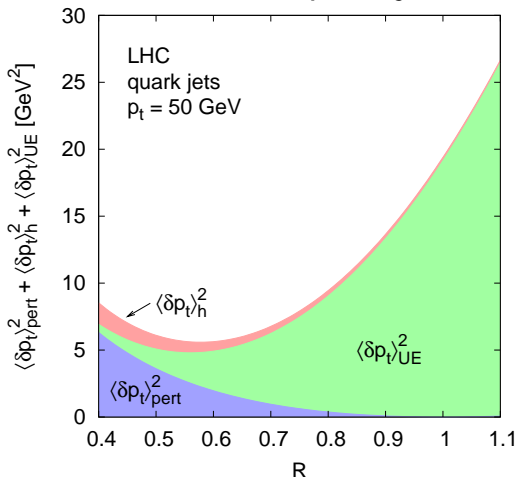
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## 50 GeV quark jet



in small- $R$  limit (!)

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# What $R$ is best for an isolated jet?

## PT radiation:

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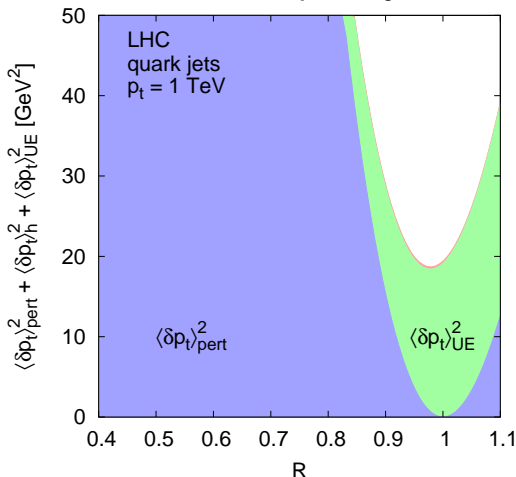
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## Minimise fluctuations in $p_t$

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## 1 TeV quark jet



in small- $R$  limit (!)

cf. Dasgupta, Magnea & GPS '07

# What $R$ is best for an isolated jet?

## PT radiation:

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

## Hadronisation:

$q :$

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

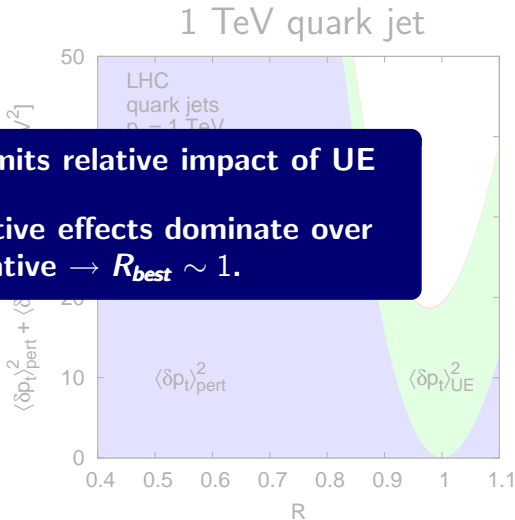
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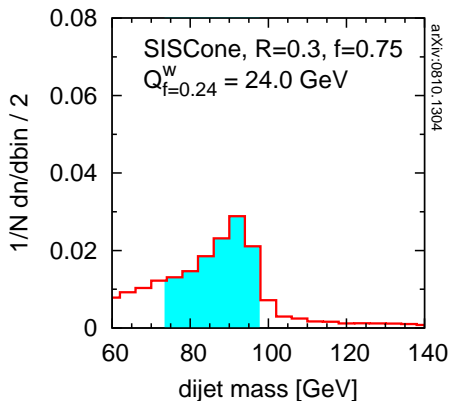
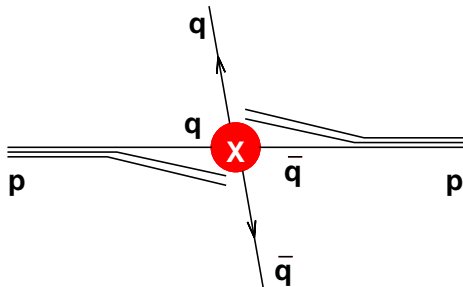
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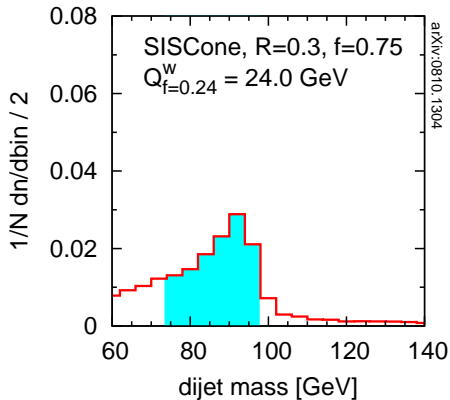
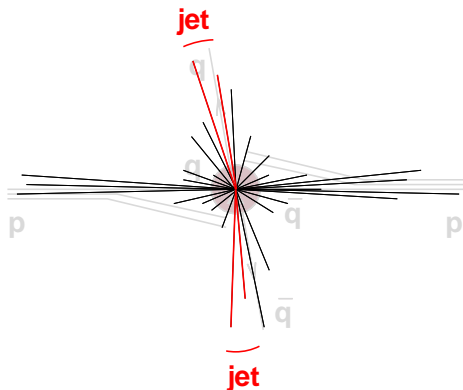
$$\langle \Delta p_t^2 \rangle \simeq \langle \Delta p_t \rangle^2$$

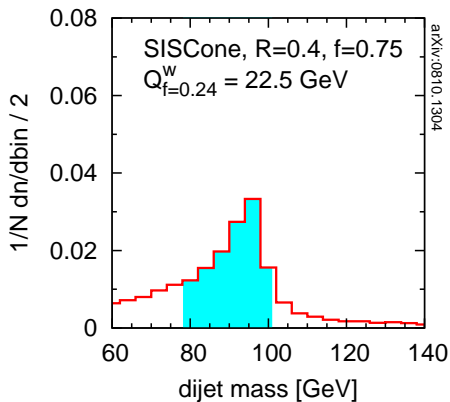
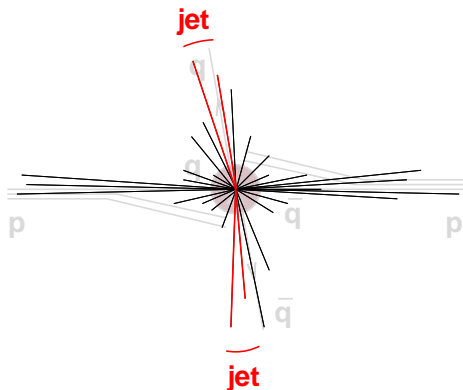


in small- $R$  limit (!)  
 cf. Dasgupta, Magnea & GPS '07

$R = 0.3$  $qq, M = 100 \text{ GeV}$ Resonance  $X \rightarrow$  dijets

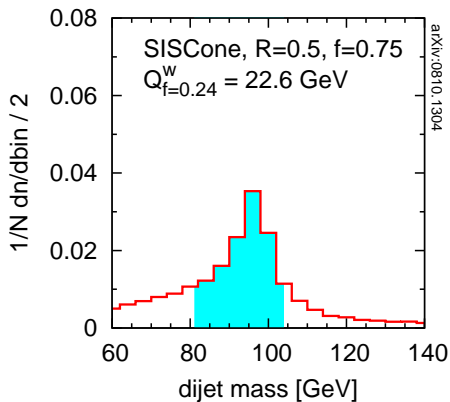


Dijet mass: scan over  $R$  [Pythia 6.4] $R = 0.3$ qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

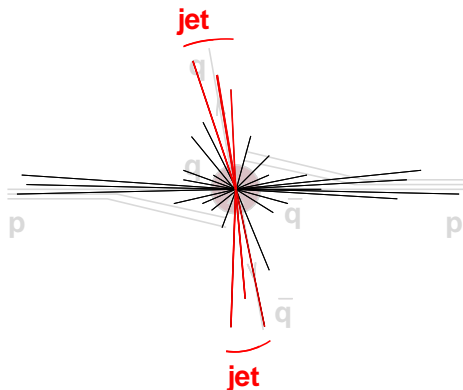
$R = 0.4$ qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

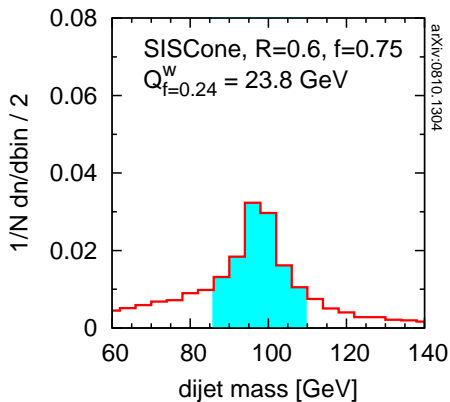
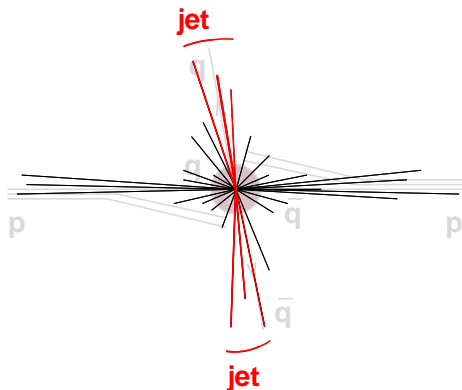
**$R = 0.5$**

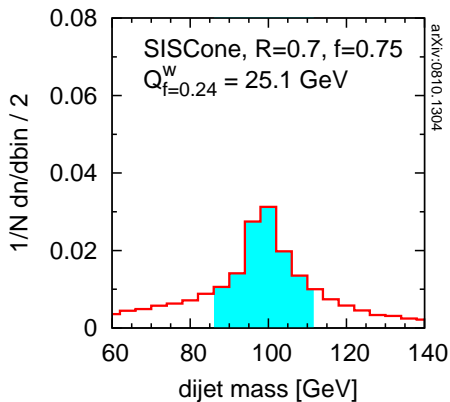
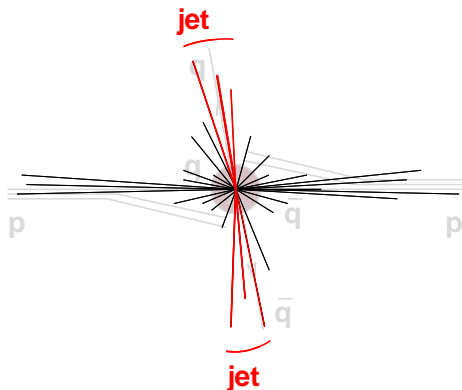
$qq, M = 100 \text{ GeV}$

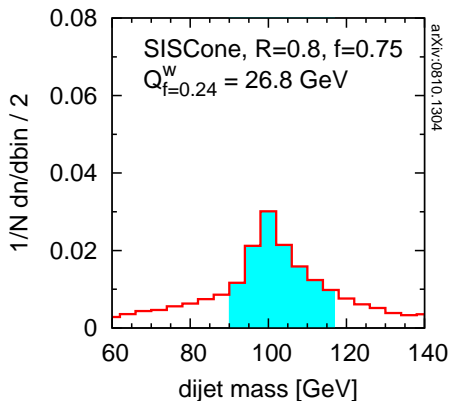
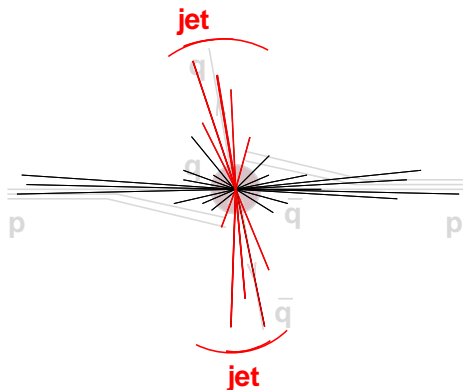


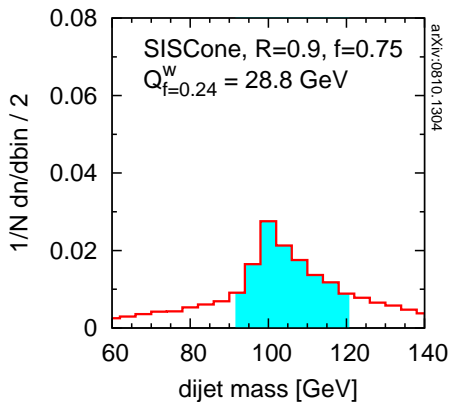
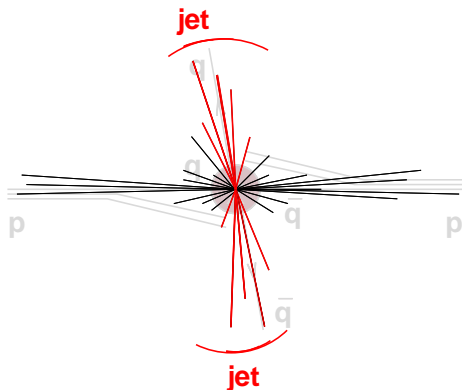
**Resonance X  $\rightarrow$  dijets**

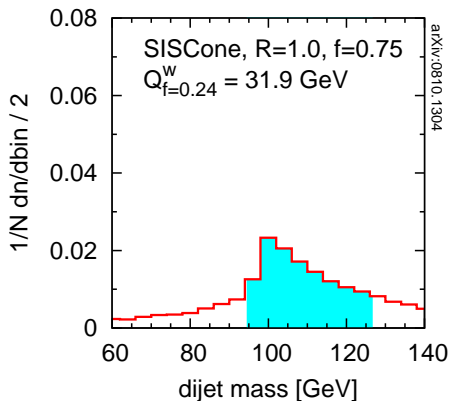
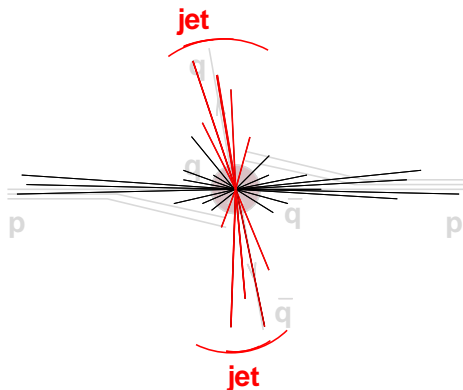


**$R = 0.6$** qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

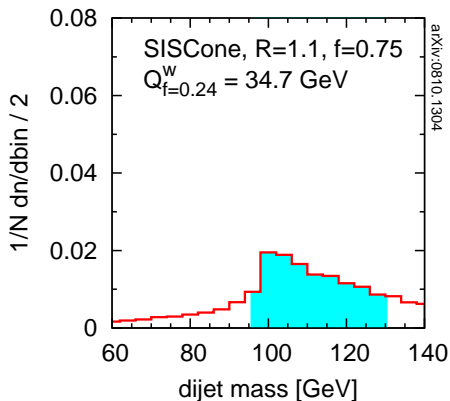
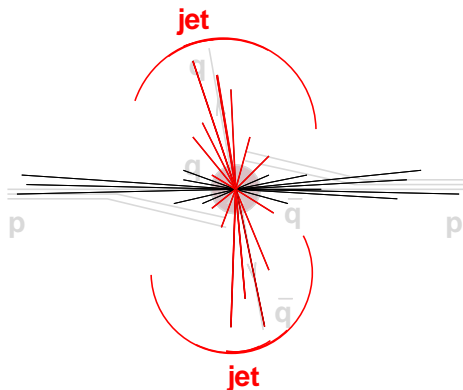
$R = 0.7$ qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

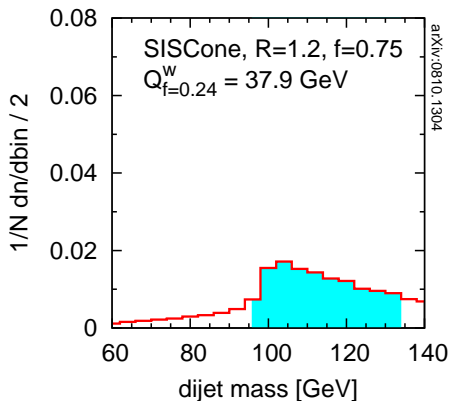
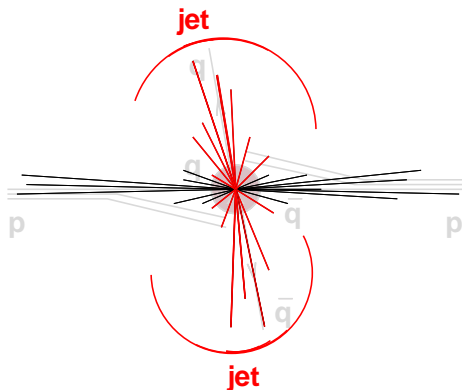
**$R = 0.8$** qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

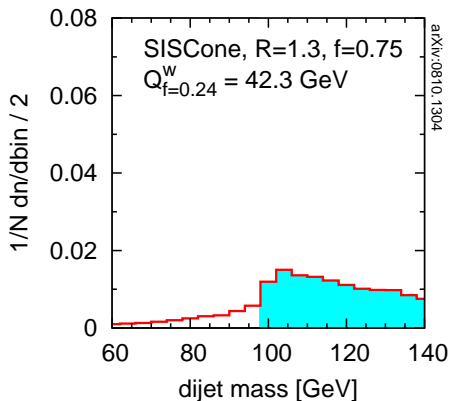
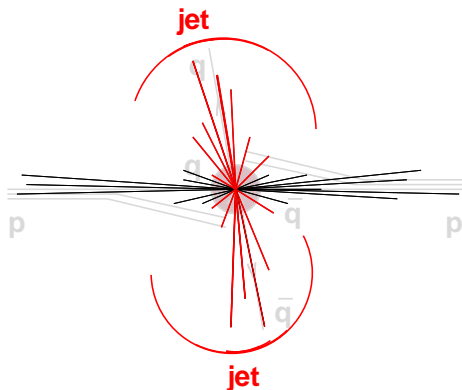
$R = 0.9$ qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

$R = 1.0$  $qq, M = 100 \text{ GeV}$ Resonance X  $\rightarrow$  dijets



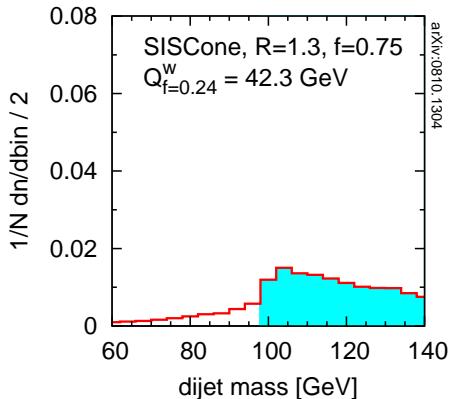
Dijet mass: scan over  $R$  [Pythia 6.4] $R = 1.1$  $qq, M = 100 \text{ GeV}$ Resonance X  $\rightarrow$  dijets

Dijet mass: scan over  $R$  [Pythia 6.4] $R = 1.2$  $qq, M = 100 \text{ GeV}$ Resonance X  $\rightarrow$  dijets

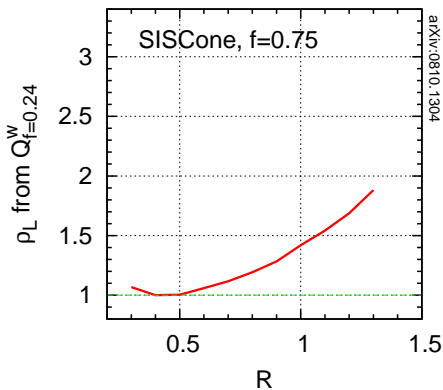
$R = 1.3$ qq,  $M = 100$  GeVResonance X  $\rightarrow$  dijets

**$R = 1.3$**

qq,  $M = 100$  GeV



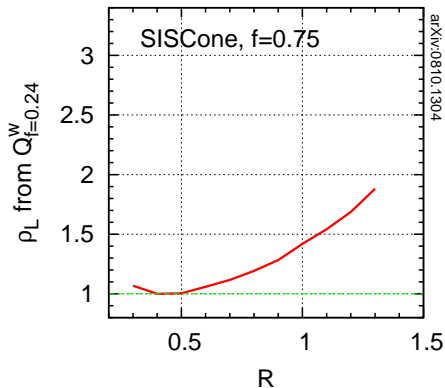
qq,  $M = 100$  GeV



**After scanning, summarise “quality” v.  $R$ . Minimum  $\equiv$  BEST**  
picture not so different from crude analytical estimate

$m_{qq} = 100 \text{ GeV}$

$qq, M = 100 \text{ GeV}$



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

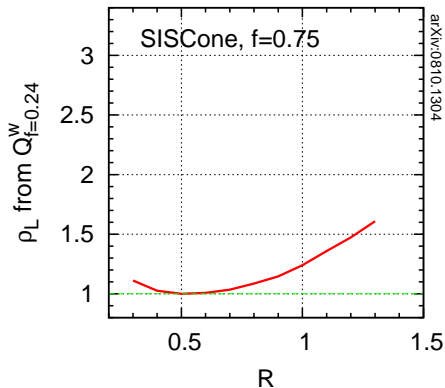
e.g. CMS arXiv:0807.4961

NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $g\bar{g}$  resonances from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08

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

$qq, M = 150 \text{ GeV}$



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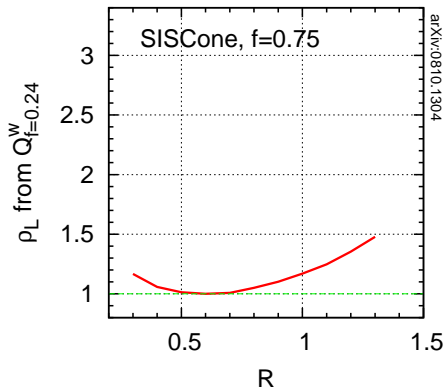
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NB: 100,000 plots for various jet algorithms, narrow  $qq$  and  $gg$  resonances from <http://quality.fastjet.fr> Cacciari, Rojo, GPS & Soyez '08

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

$qq, M = 200 \text{ GeV}$



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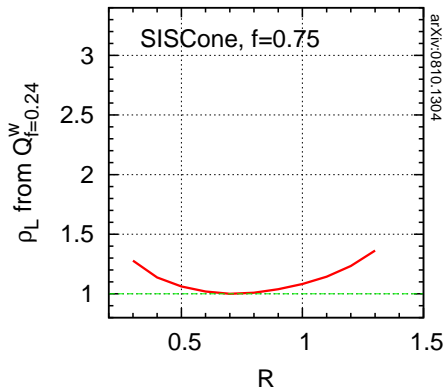
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NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $g\bar{g}$  resonances from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08

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

$$qq, M = 300 \text{ GeV}$$



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

e.g. CMS arXiv:0807.4961

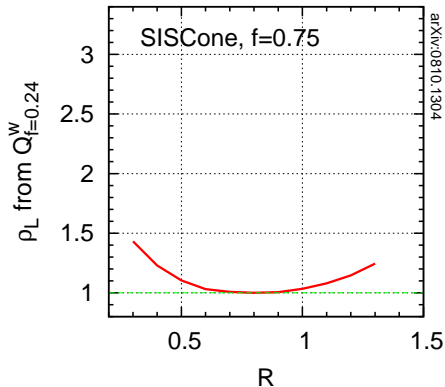
NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $g\bar{g}$  resonances from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08



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

$$qq, M = 500 \text{ GeV}$$



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

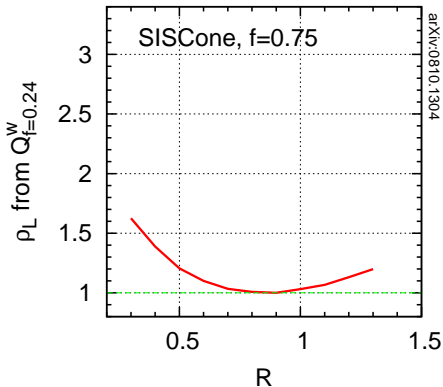
e.g. CMS arXiv:0807.4961

NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $g\bar{g}$  resonances from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08

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

$$qq, M = 700 \text{ GeV}$$



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

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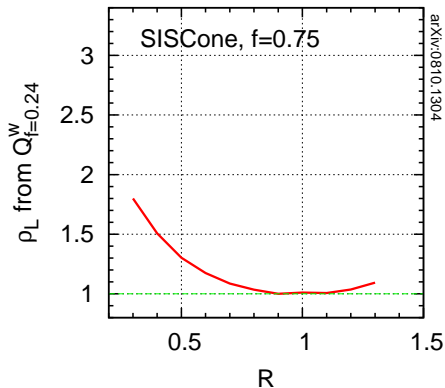
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NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $g\bar{g}$  resonances from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08

$m_{q\bar{q}} = 1000 \text{ GeV}$

$q\bar{q}, M = 1000 \text{ GeV}$



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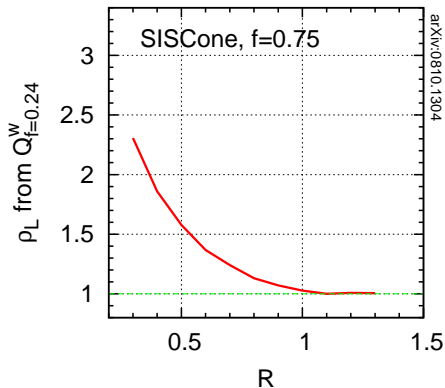
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$m_{q\bar{q}} = 2000 \text{ GeV}$

$q\bar{q}, M = 2000 \text{ GeV}$



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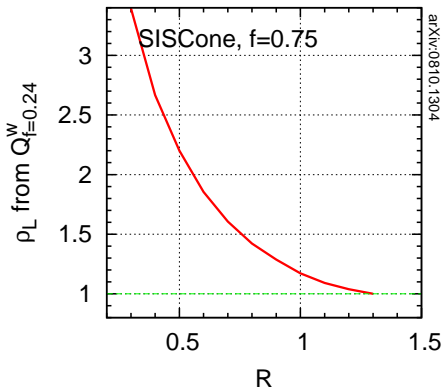
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$m_{q\bar{q}} = 4000 \text{ GeV}$

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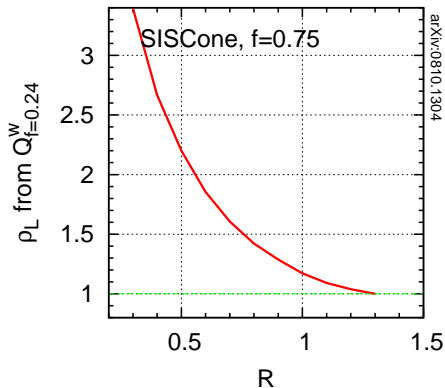
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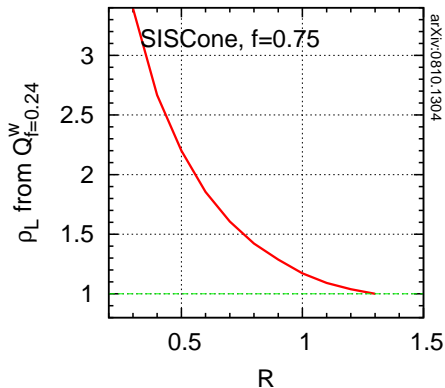
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Cacciari, Rojo, GPS & Soyez '08

File Edit View History Bookmarks Tools Help

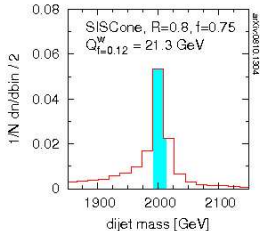
http://www.lpthe.jussieu.fr/~salam/jet-quality/

Testing jet definitions: qq &amp; gg c...

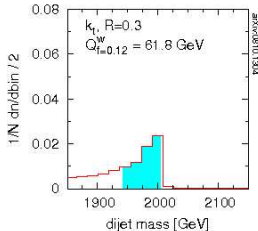
## Testing jet definitions: qq &amp; gg cases

by M. Cacciari, J. Rojo, G.P. Salam and G. Soyez, arXiv:0810.1304

qq, M = 2000 GeV



qq, M = 2000 GeV


  $k_t$   C/A  anti- $k_t$   SIScone  C/A-filt

 R = 0.8  
  $Q_{f=z}^W$    $Q_{f=x\sqrt{M}}^W$   x 2

 rebin = 2 
 qq  gg

 mass = 2000 

 pileup:  none  0.05  0.25  $\text{mb}^{-1}/\text{ev}$ 

 subtraction: 
  $k_t$   C/A  anti- $k_t$   SIScone  C/A-filt

 R = 0.3  
  $Q_{f=z}^W$    $Q_{f=x\sqrt{M}}^W$   x 2

 rebin = 2 
 qq  gg

 mass = 2000 

 pileup:  none  0.05  0.25  $\text{mb}^{-1}/\text{ev}$ 

 subtraction: 

This page is intended to help visualize how the choice of jet definition impacts a dijet invariant mass reconstruction at LHC.

The controls fall into 4 groups:

- the jet definition
- the binning and quality measures
- the jet-type (quark, gluon) and mass scale
- pileup and subtraction

The events were simulated with Pythia 6.4 (DWT tune) and reconstructed with FastJet 2.3.

For more information, view and listen to the **flash demo**, or click on individual terms.

This page has been tested with Firefox v2 and v3, IE7, Safari v3, Opera v9.5, Chrome 0.2.



The dijet mass is a classic jets analysis.

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

We can and should make use of this

Illustrated in next slides, for low-mass Higgs search.

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

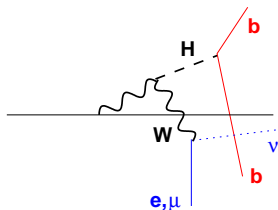
Studied e.g. in ATLAS TDR

Difficulties, e.g.

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

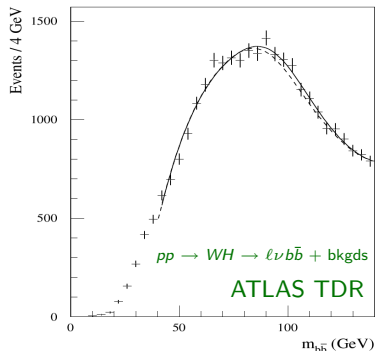
## Try a long shot?

- ▶ 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?



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

Studied e.g. in ATLAS TDR

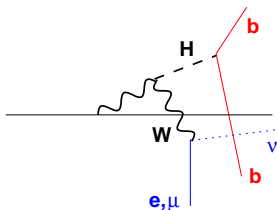


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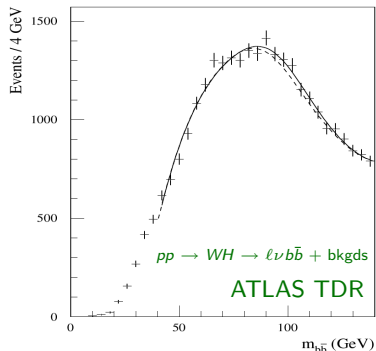
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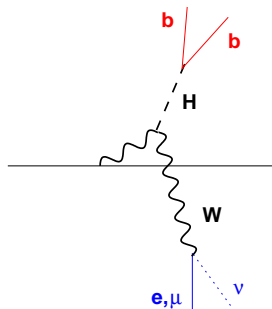


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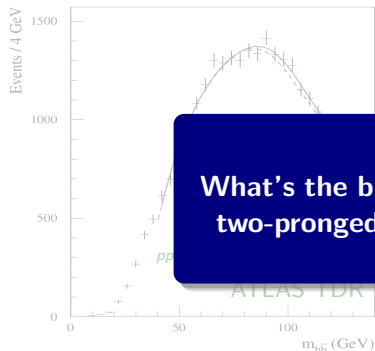
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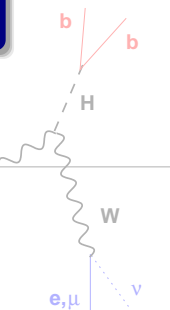
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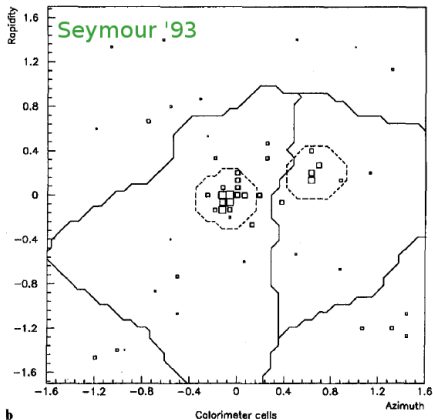
Difficulties, e.g.

- ▶  $gg \rightarrow t\bar{t}$  has  $\ell\nu b\bar{b}$  with same intrinsic partonic

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

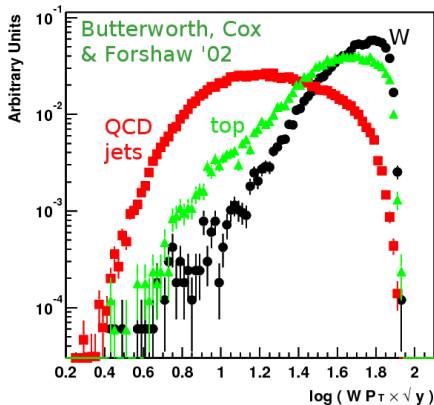


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**Fig. 2.** A hadronic  $W$  decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission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

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

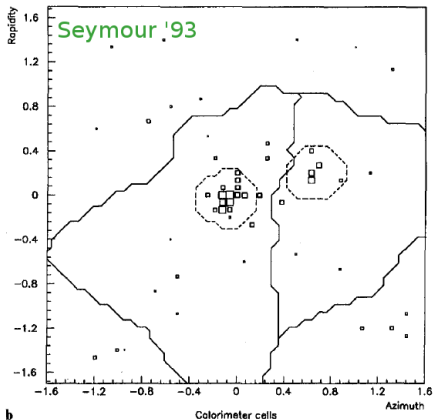


Use  $k_t$  alg.'s distance measure (rel. trans. mom.) to cut out QCD bkgd:

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

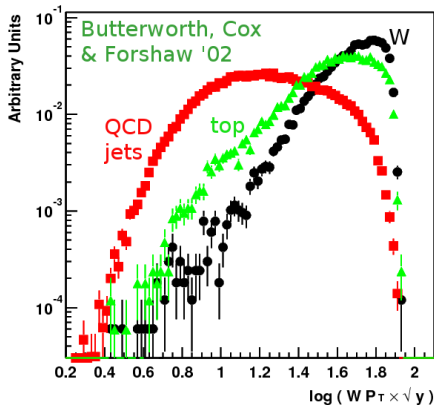
Y-splitter

only partially correlated with mass



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## 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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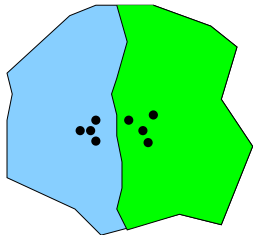
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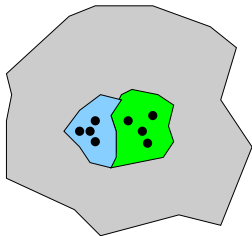
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$k_t$  algorithm



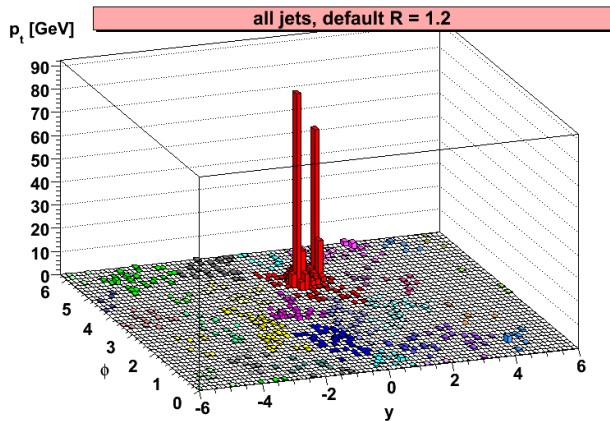
Cam/Aachen algorithm



Allows you to “dial” the correct  $R$  to keep perturbative radiation, but throw out UE

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

SIGNAL



Zbb BACKGROUND

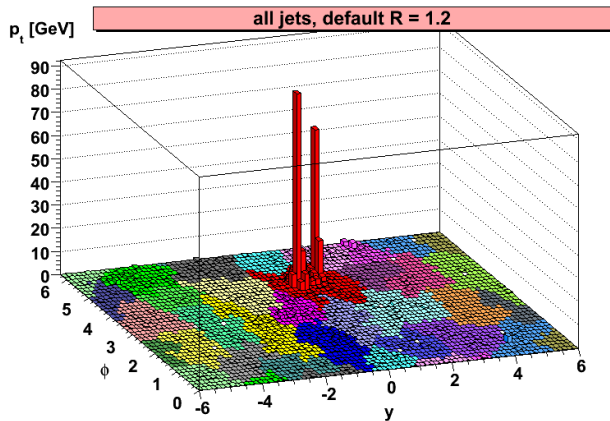
Cluster event, C/A, R=1.2

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

SIGNAL



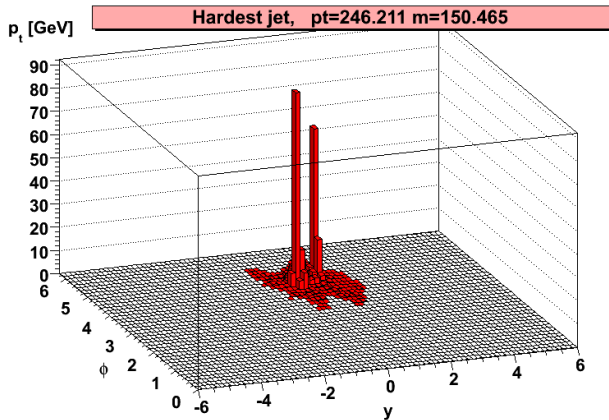
Zbb BACKGROUND

Fill it in,  $\rightarrow$  show jets more clearly

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

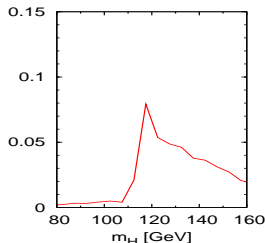


Consider hardest jet,  $m = 150$  GeV

Butterworth, Davison, Rubin & GPS '08

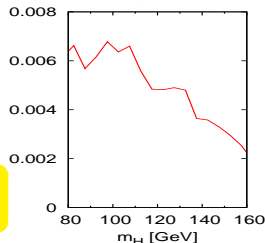
SIGNAL

$200 < p_{tZ} < 250$  GeV



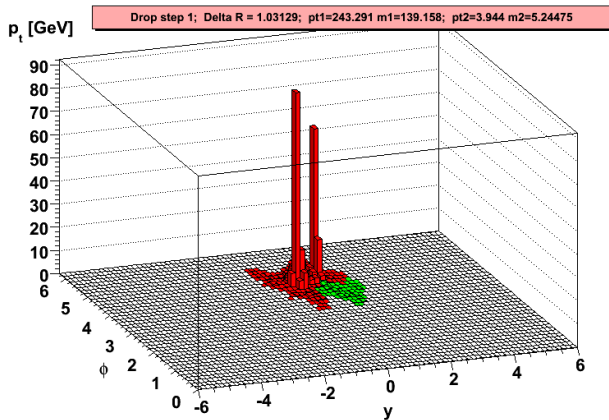
Zbb BACKGROUND

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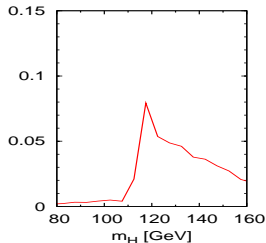


split:  $m = 150$  GeV,  $\frac{\max(m_1, m_2)}{m} = 0.92 \rightarrow$  repeat

Butterworth, Davison, Rubin & GPS '08

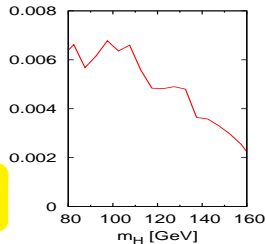
SIGNAL

$200 < p_{tZ} < 250$  GeV



Zbb BACKGROUND

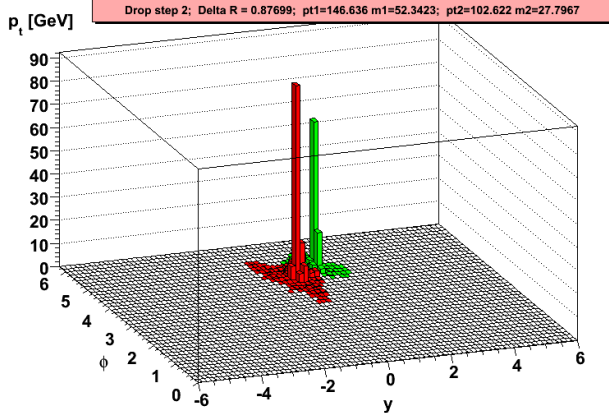
$200 < p_{tZ} < 250$  GeV



arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

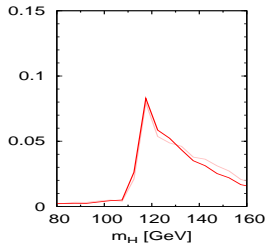


split:  $m = 139\text{ GeV}, \frac{\max(m_1, m_2)}{m} = 0.37 \rightarrow$  mass drop

Butterworth, Davison, Rubin & GPS '08

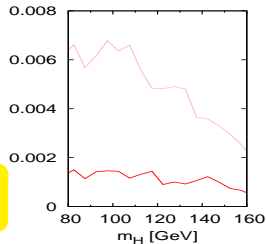
SIGNAL

$200 < p_{tZ} < 250\text{ GeV}$



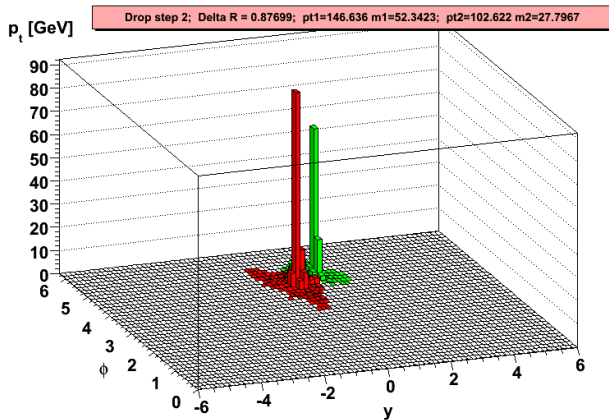
Zbb BACKGROUND

$200 < p_{tZ} < 250\text{ GeV}$



arbitrary norm.

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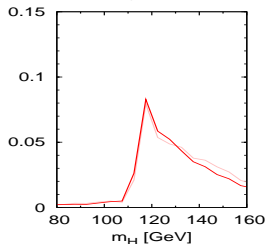


check:  $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \rightarrow \text{OK} + 2 b\text{-tags (anti-QCD)}$

Butterworth, Davison, Rubin & GPS '08

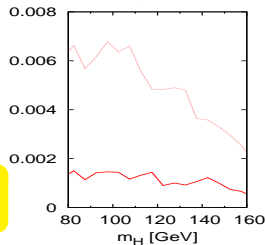
SIGNAL

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Zbb BACKGROUND

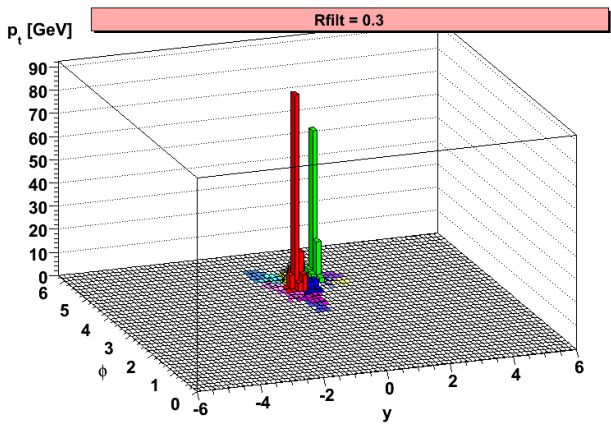
$200 < p_{tZ} < 250$  GeV



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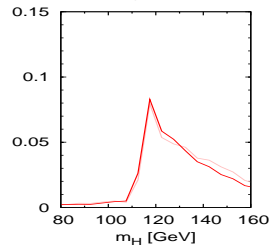


$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

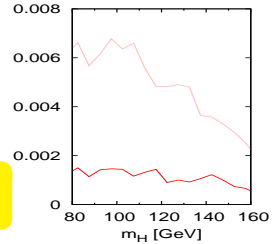
### SIGNAL

$200 < p_{tZ} < 250\text{ GeV}$



### Zbb BACKGROUND

$200 < p_{tZ} < 250\text{ GeV}$

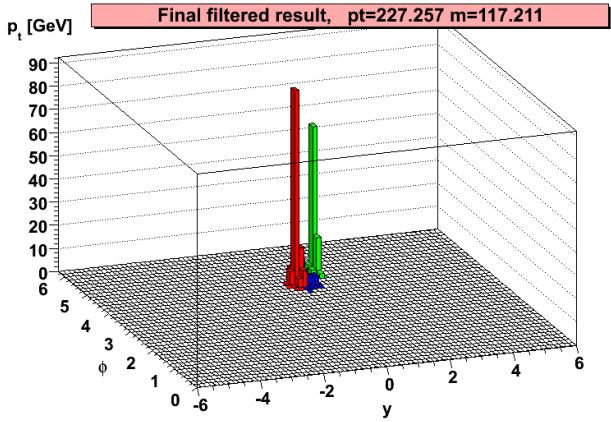


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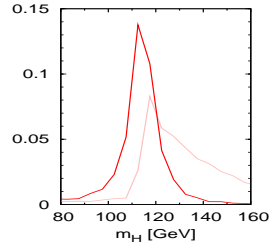


$R_{filt} = 0.3$ : take 3 hardest,  $m = 117\text{ GeV}$

Butterworth, Davison, Rubin & GPS '08

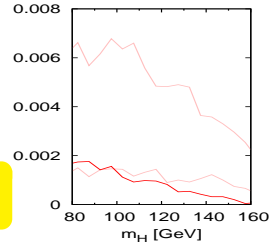
SIGNAL

$200 < p_{tZ} < 250\text{ GeV}$



Zbb BACKGROUND

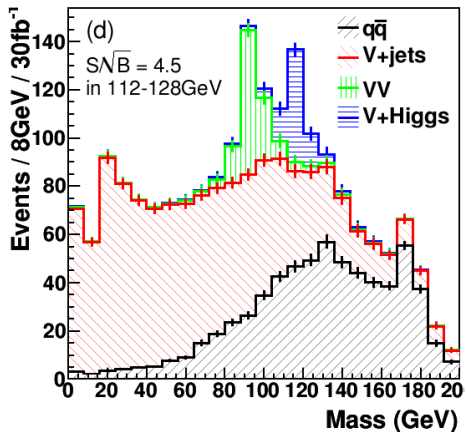
$200 < p_{tZ} < 250\text{ GeV}$



arbitrary norm.

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	$\sigma_S/\text{fb}$	$\sigma_B/\text{fb}$	$S/\sqrt{B \cdot \text{fb}}$
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

combine HZ and HW,  $p_t > 200$  GeV

- ▶ Take  $Z \rightarrow \ell^+ \ell^-$ ,  $Z \rightarrow \nu \bar{\nu}$ ,  
 $W \rightarrow \ell \nu$   $\ell = e, \mu$
- ▶  $p_{tV}, p_{tH} > 200$  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  $30 \text{ fb}^{-1}$  this looks like a competitive channel for light Higgs discovery. **A powerful method!**

Currently under study in the LHC experiments

High- $p_t$  top production often envisaged in New Physics processes.  
 $\sim$  high- $p_t$  EW boson, but: top has 3-body decay and is coloured.

6 papers on top tagging in '08-'09 (at least). All use the jet mass + something extra.

## Questions

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

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

	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 $k_t$ subjets, $d_{cut}$	45%	5%
Thaler & Wang '08	2,3 $k_t$ subjets, $z_{cut}$ + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut}$ + $\theta_h$	40%	1%
Almeida et al. '08	predict mass dist <sup>n</sup> , use jet-shape	–	–
Ellis et al '09	C/A pruning	–	–
ATLAS '09	3,4 $k_t$ subjets, $d_{cut}$ MC likelihood	90%	15%

# 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

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*:

$$\begin{aligned} \min_{i,j} d_{ij} &\equiv \min_{i,j} (\min\{k_{ti}^2, k_{tj}^2\} \Delta R_{ij}^2) \\ &= \min_{i,j} (k_{ti}^2 \Delta R_{ij}^2) \\ &= \min_i (k_{ti}^2 \min_j \Delta R_{ij}^2) \end{aligned}$$

*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  $\rightarrow$  need only calculate  $N$   $d_{ij}$ 's



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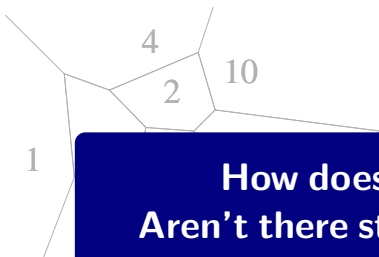
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Given a set of vertices on plane (1...10) a *Voronoi diagram* partitions plane into cells containing all points closest to each vertex.

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

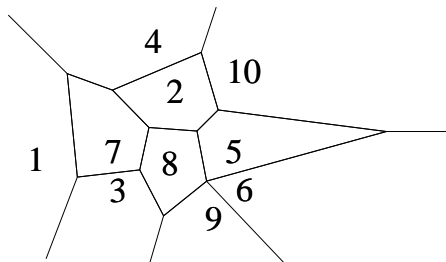
**Geometrical nearest neighbour finding is a classic problem in the field of Computational Geometry**

Devillers '99 [+ related work by other authors]  
 Convenient C++ package available: CGAL, <http://www.cgal.org>

With help of CGAL, clustering can be done in  $N \ln N$  time.

Coded in the FastJet package (v1), Cacciari & GPS '05

## 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

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

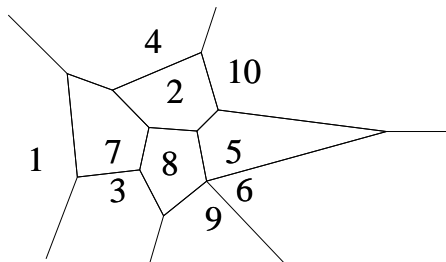
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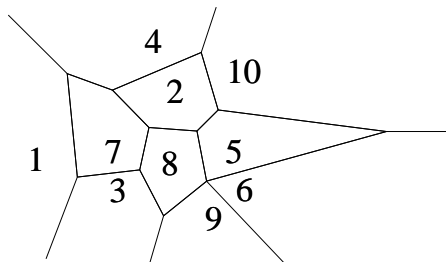
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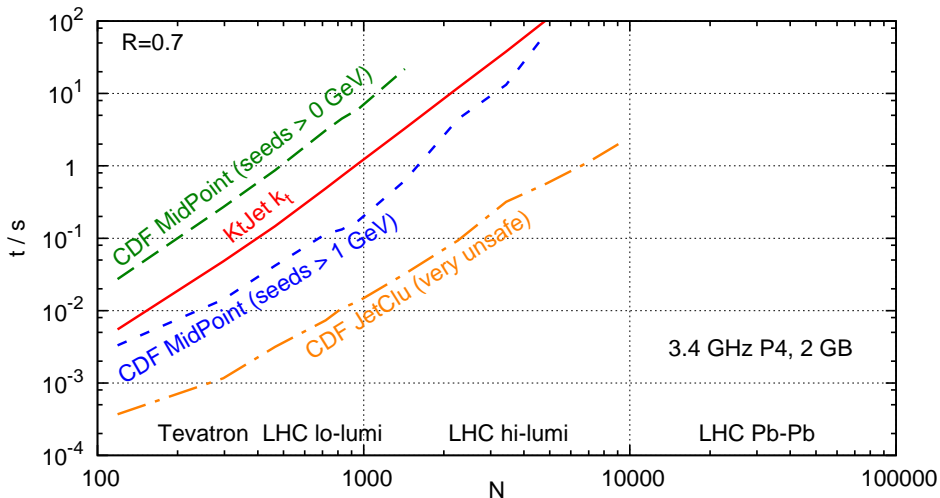
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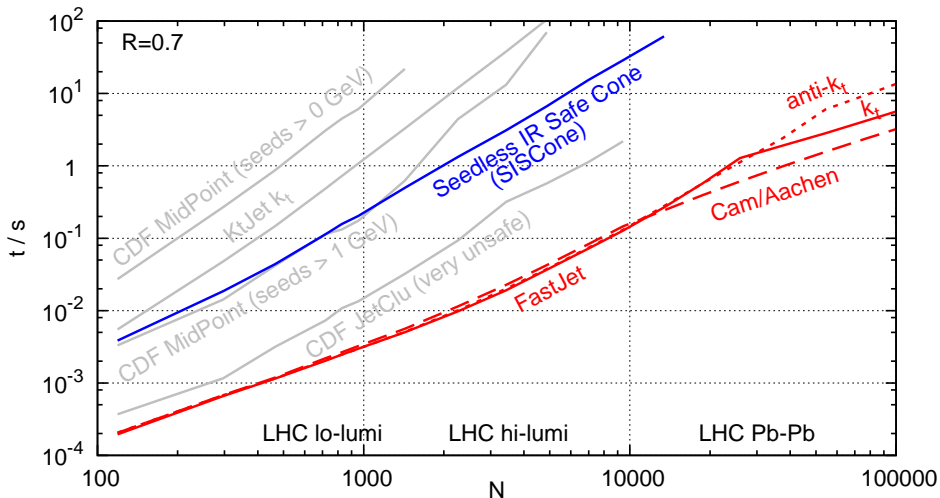
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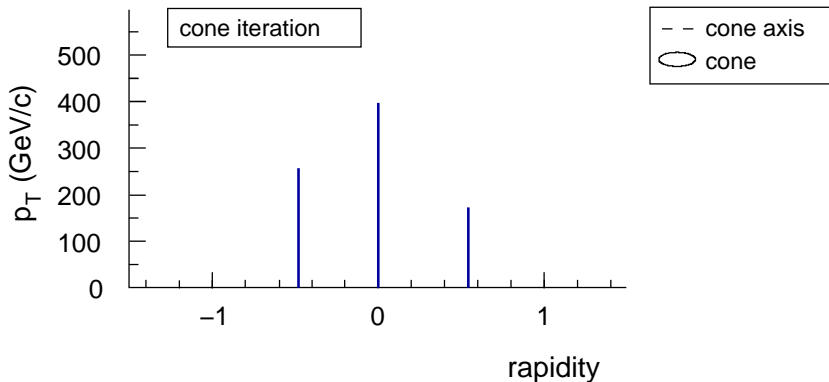
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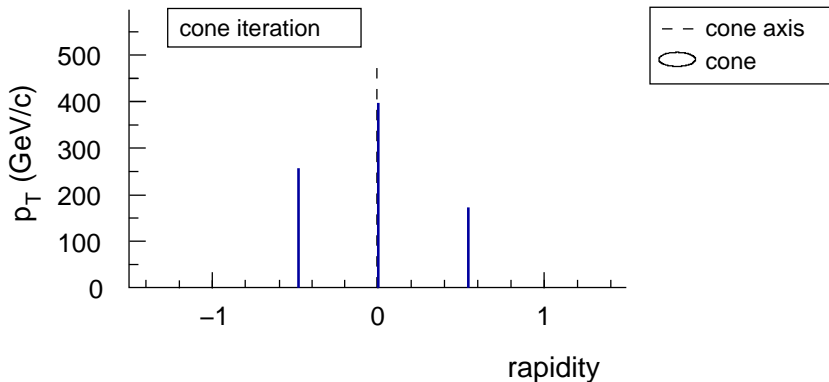


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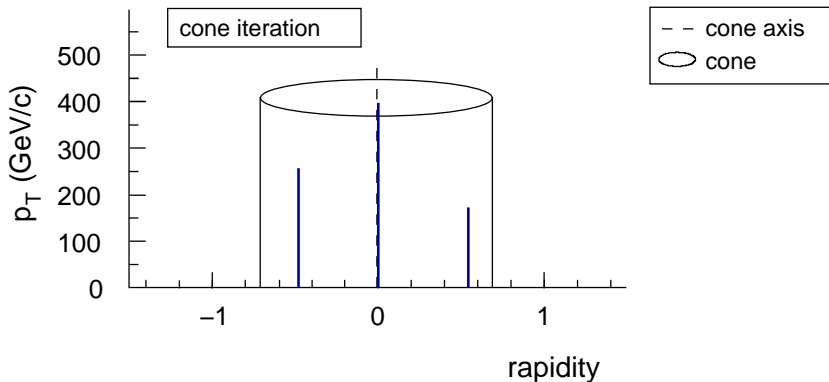
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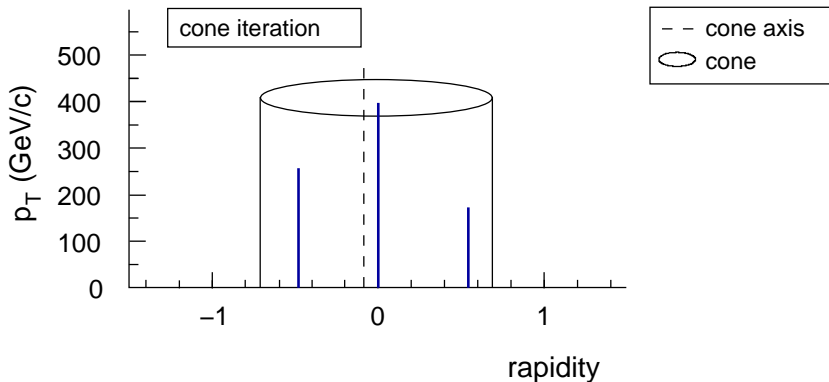
Collinear splitting can modify the hard jets: ICPR algorithms are  
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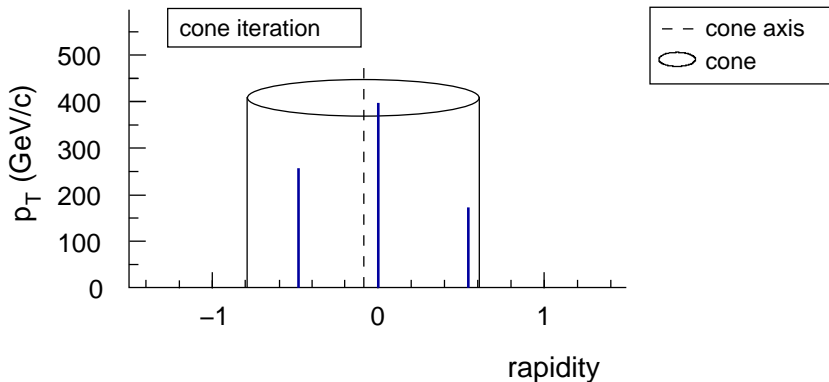
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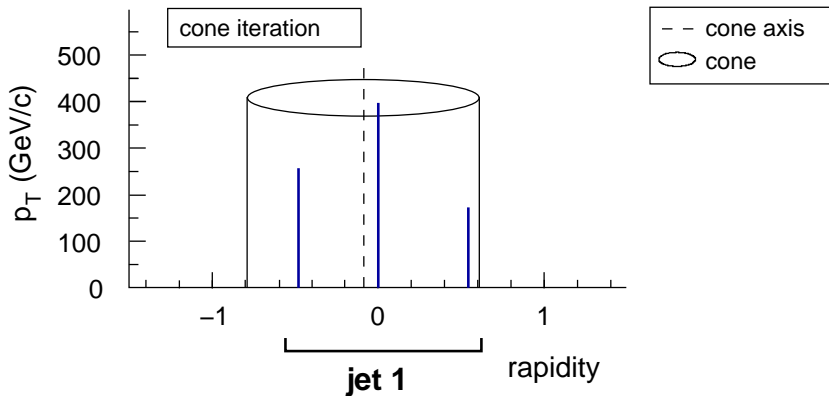
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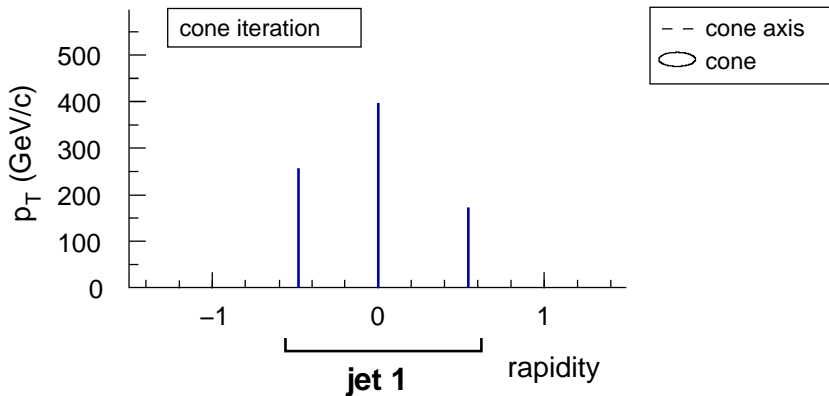


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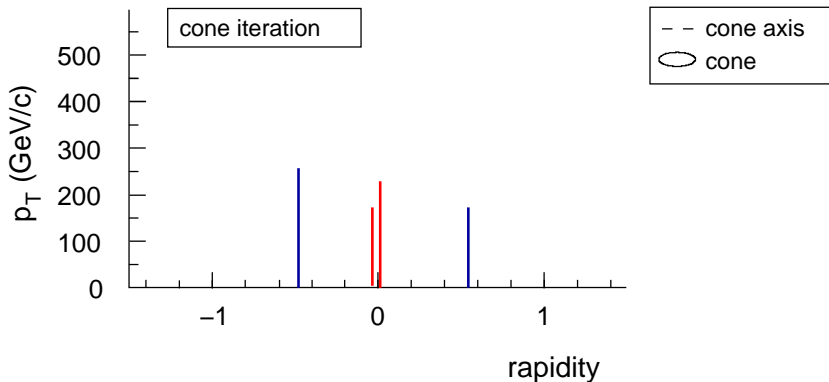


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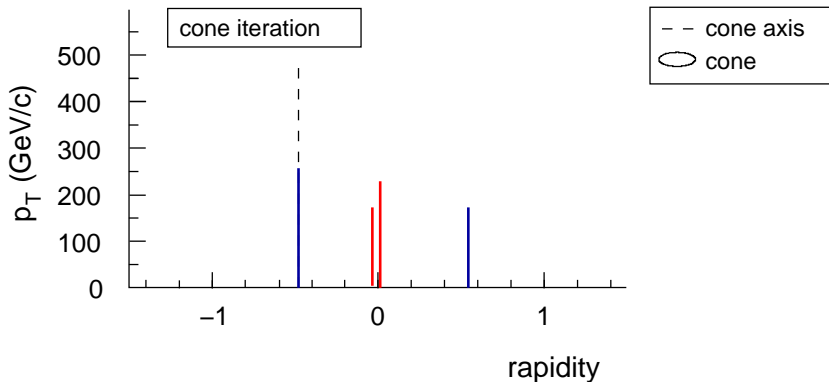




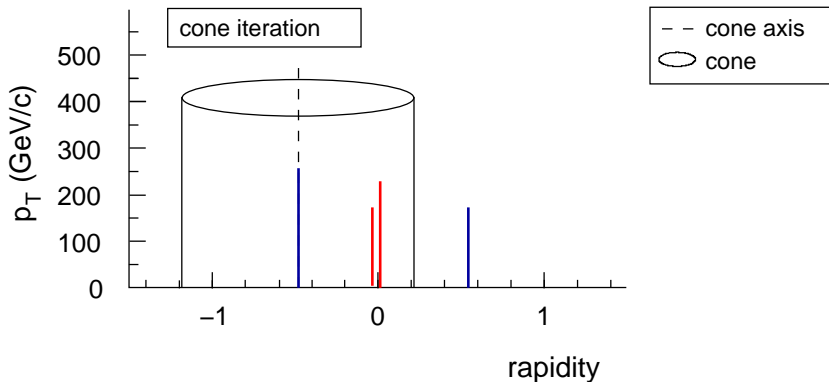
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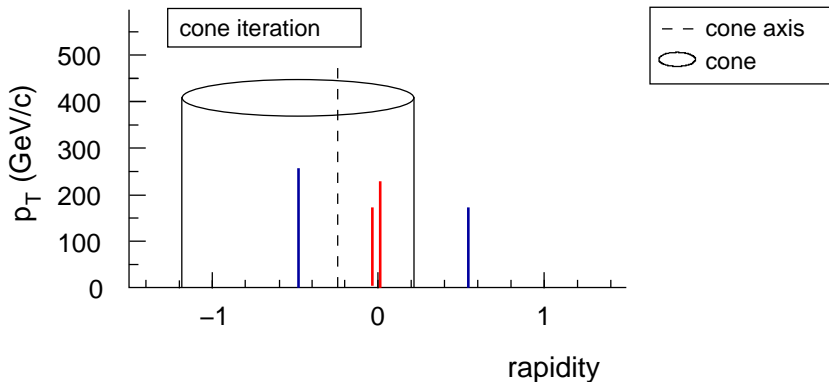
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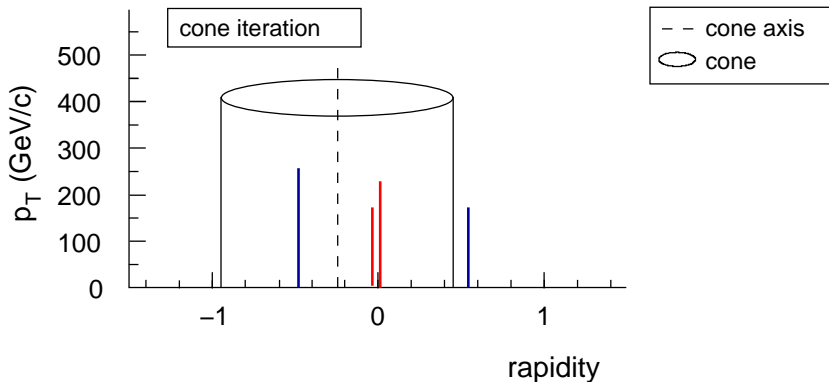
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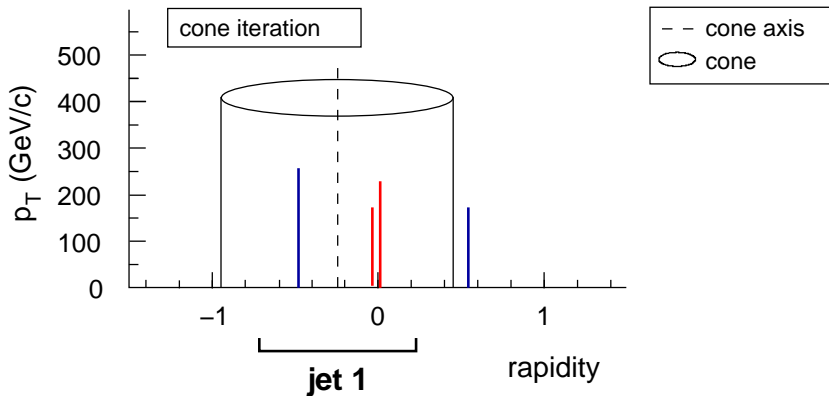
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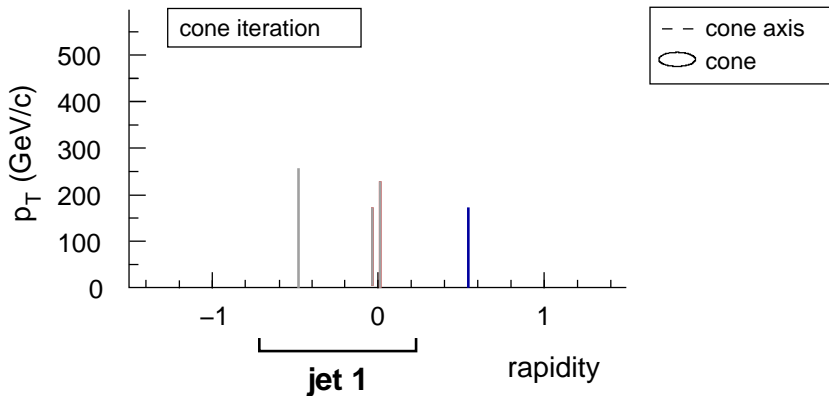
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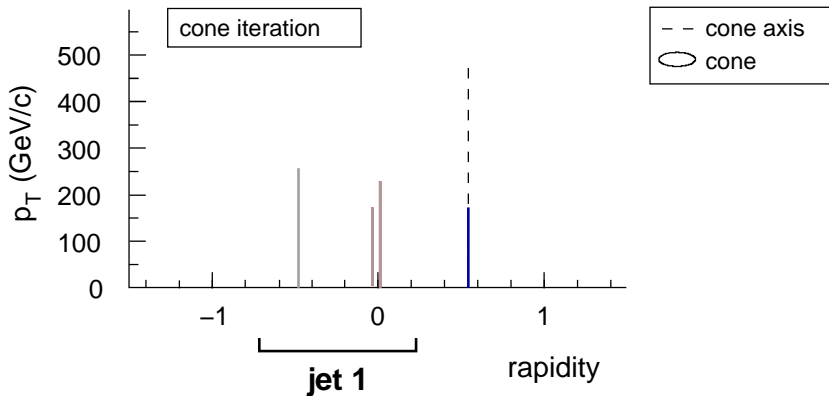


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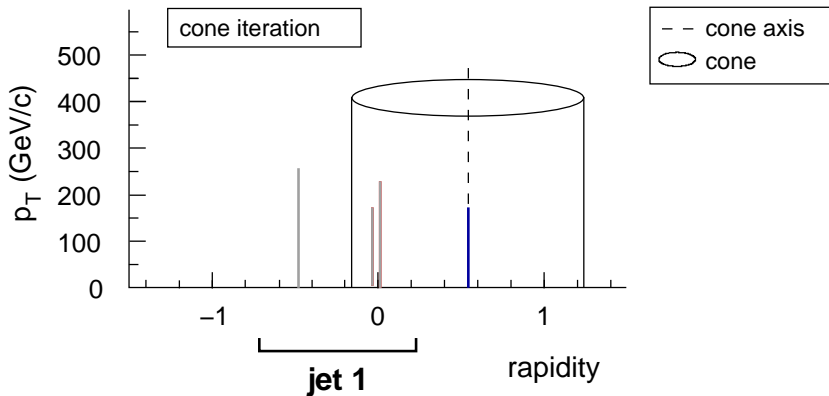


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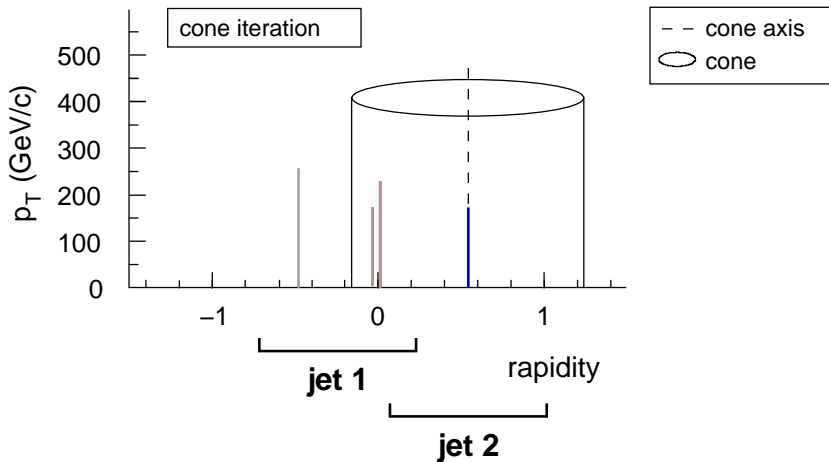




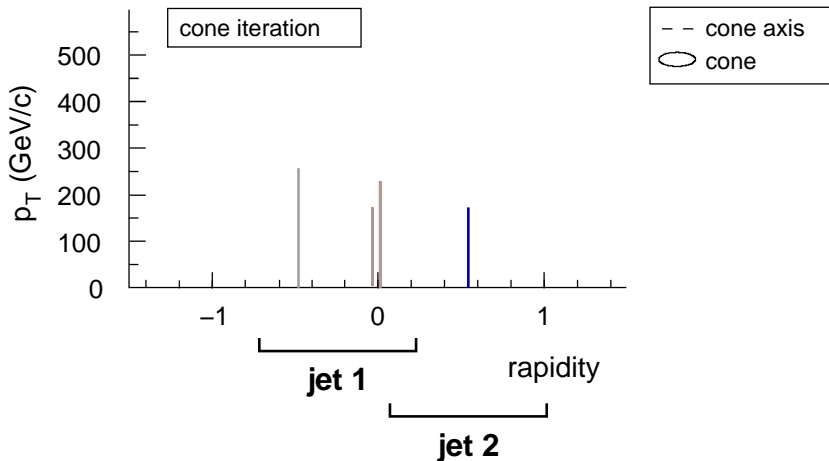
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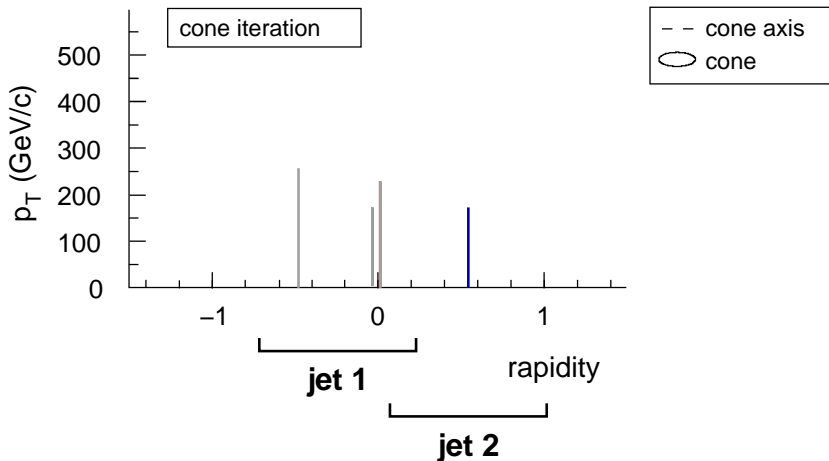
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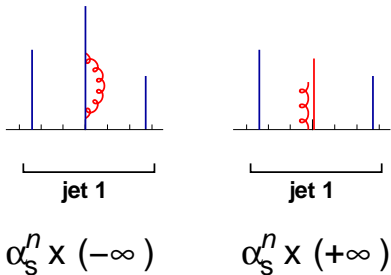


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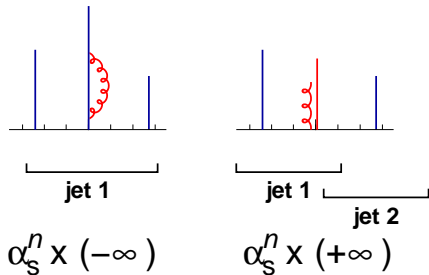
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## Collinear Safe



**Infinites cancel**

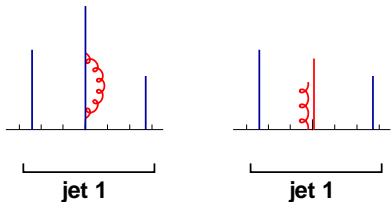
## Collinear Unsafe



**Infinites do not cancel**

Invalidates perturbation theory

## Collinear Safe

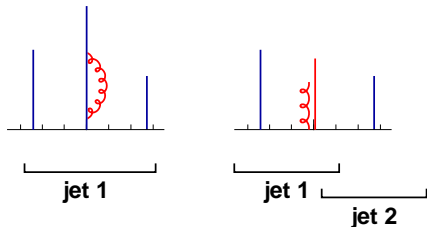


$$\alpha_S^n \times (-\infty)$$

$$\alpha_S^n \times (+\infty)$$

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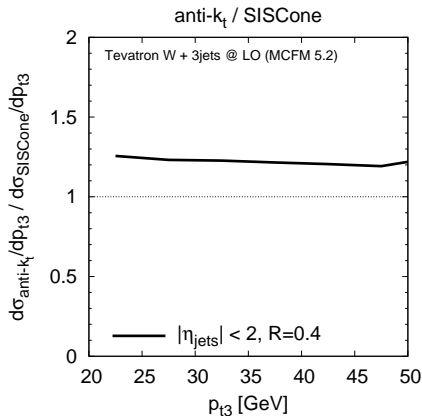
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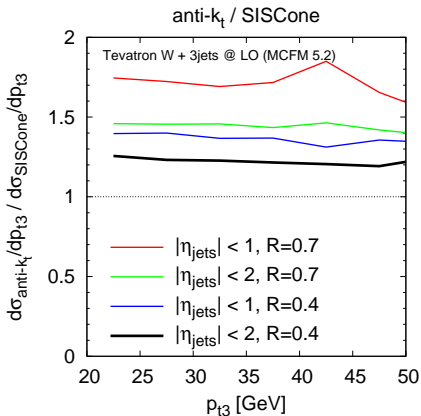
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**With other cuts and  $R$  choice,  
IRC systematic can be up to  
75%**

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



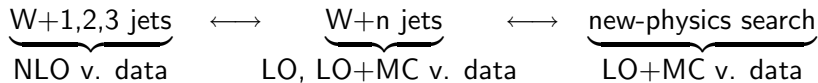
## I do searches, not QCD. Why should I care about IRC safety?

- ▶ Are you looking for a mass-peak?      ➔ you needn't care much
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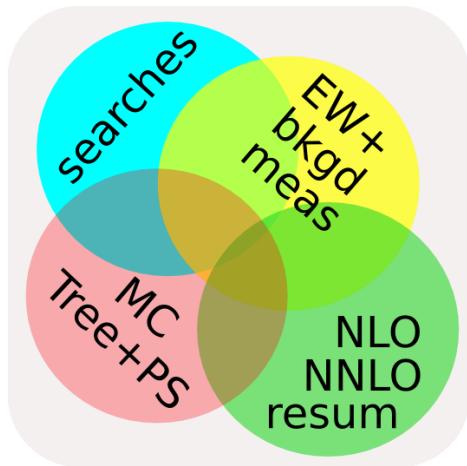
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 NLO v. data  
 IR safe alg.

↔

$W+n$  jets  
 LO, LO+MC v. data  
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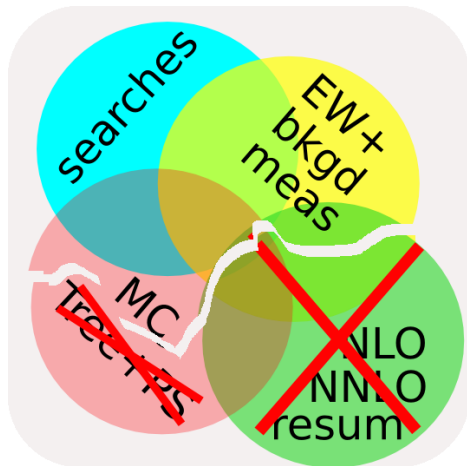
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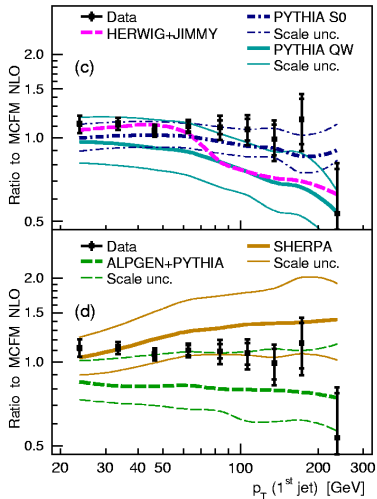
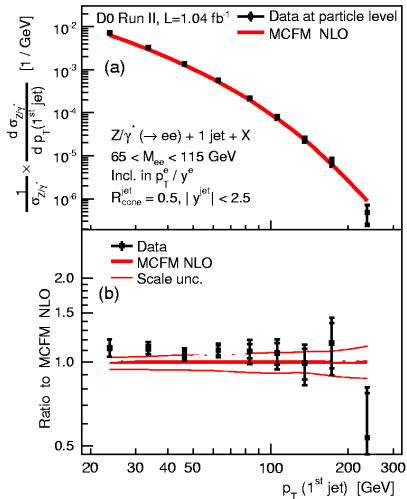
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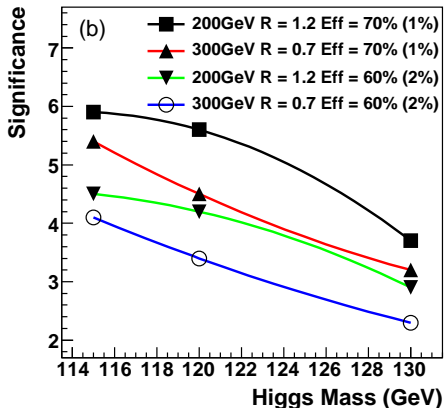
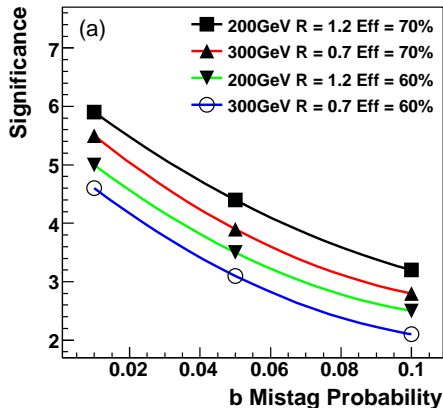
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## NLO

## LO+PS



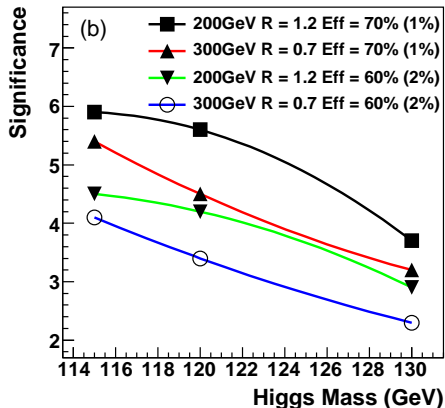
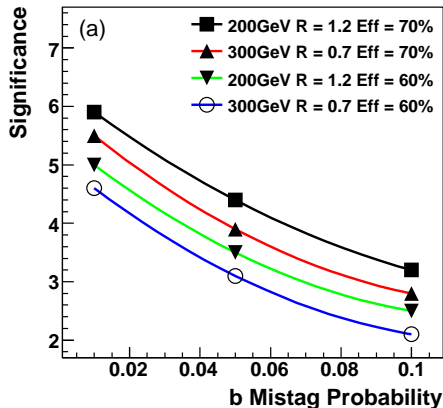


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In nearly all cases, looks feasible for extracting  $WH$ ,  $ZH$  couplings





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