

# New jet methods (and precision measurements)

Gavin Salam

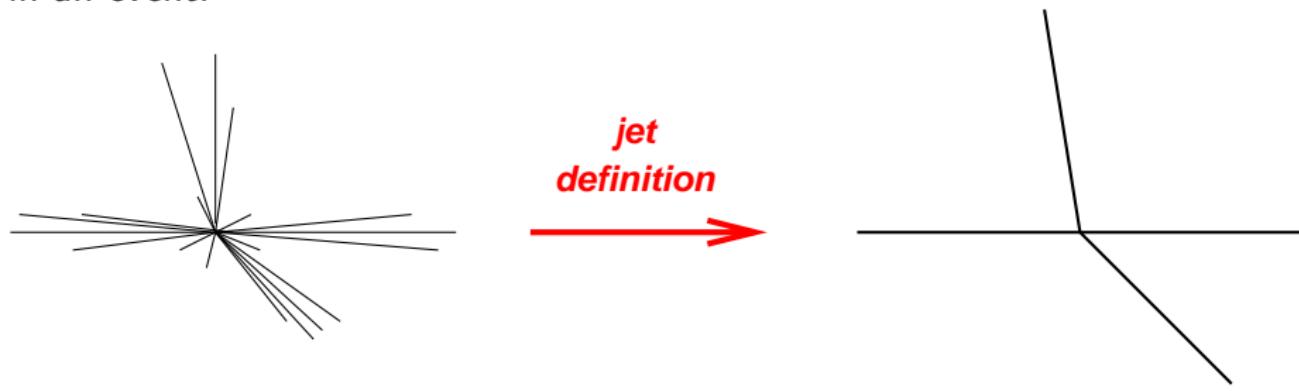
Based on work with Matteo Cacciari, Mrinal Dasgupta,  
Lorenzo Magnea, Juan Rojo, Sebastian Sapeta, Gregory Soyez

CERN, Princeton & LPTHE/CNRS (Paris)

Challenges for Precision Physics at the LHC

LPNHE, UPMC, Paris  
15 December 2010

A jet definition is a systematic procedure that **projects away the multiparticle dynamics**, so as to leave a simple picture of what happened in an event:



Jets are *as close as we can get to a physical single hard quark or gluon*: with good definitions their properties (multiplicity, energies, [flavour]) are

- ▶ finite at any order of perturbation theory
- ▶ insensitive to the parton → hadron transition

**NB: finiteness  $\longleftrightarrow$  set of jets depends on jet def.**

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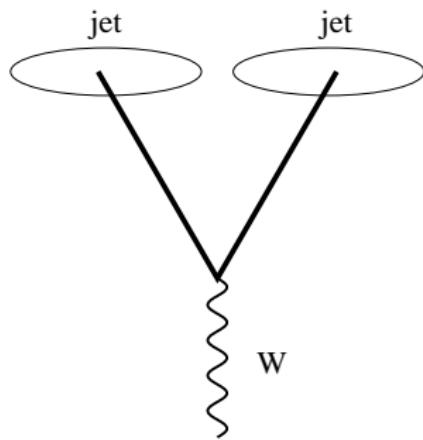


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## Infrared and collinear safety



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

1-jet

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

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

$-\infty$

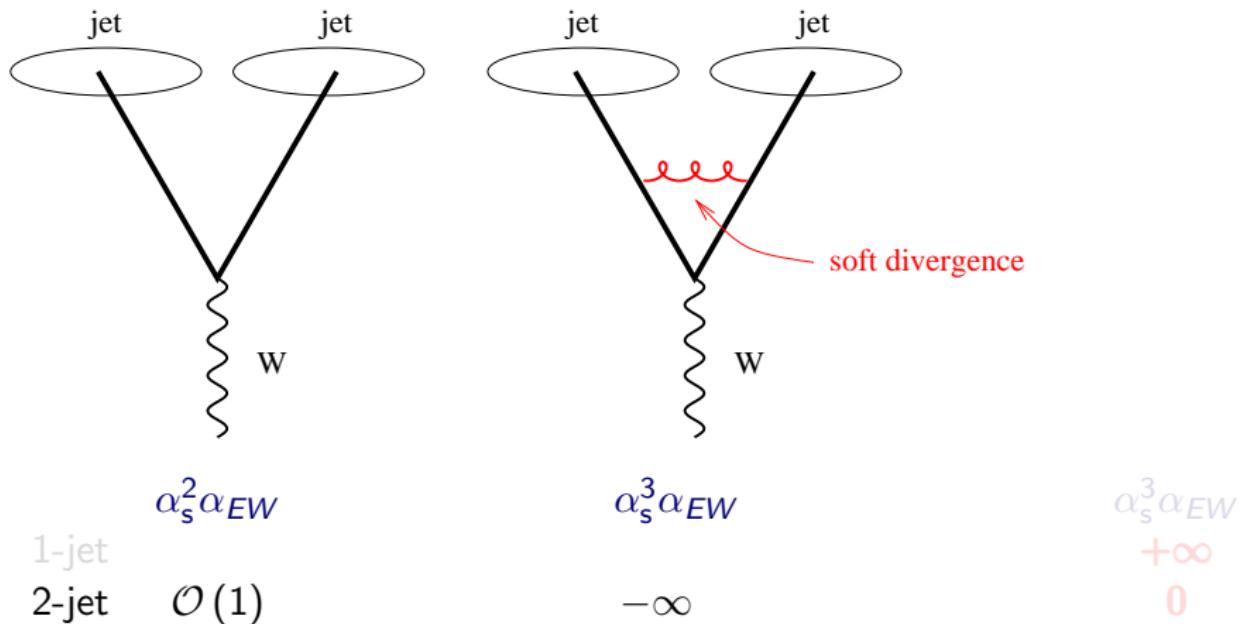
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$+\infty$

0

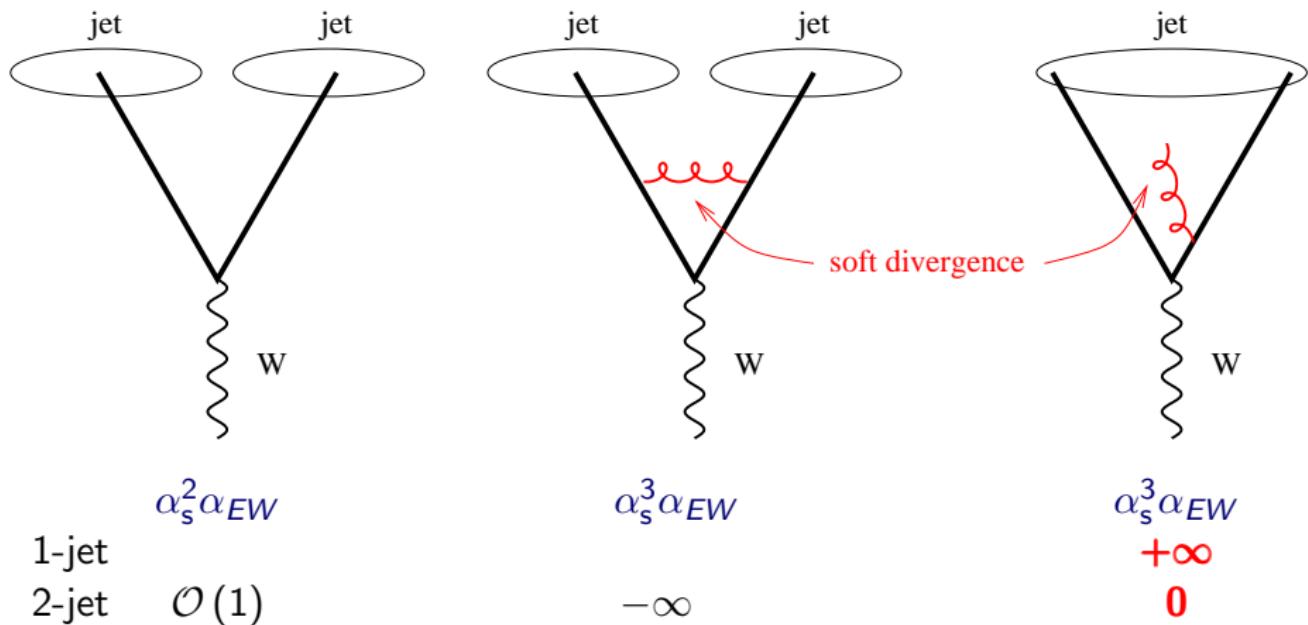
With these (& most) cone algorithms, perturbative infinities fail to cancel at some order  $\equiv$  IR unsafety

## JetClu (&amp; Atlas Cone) in Wjj @ NLO



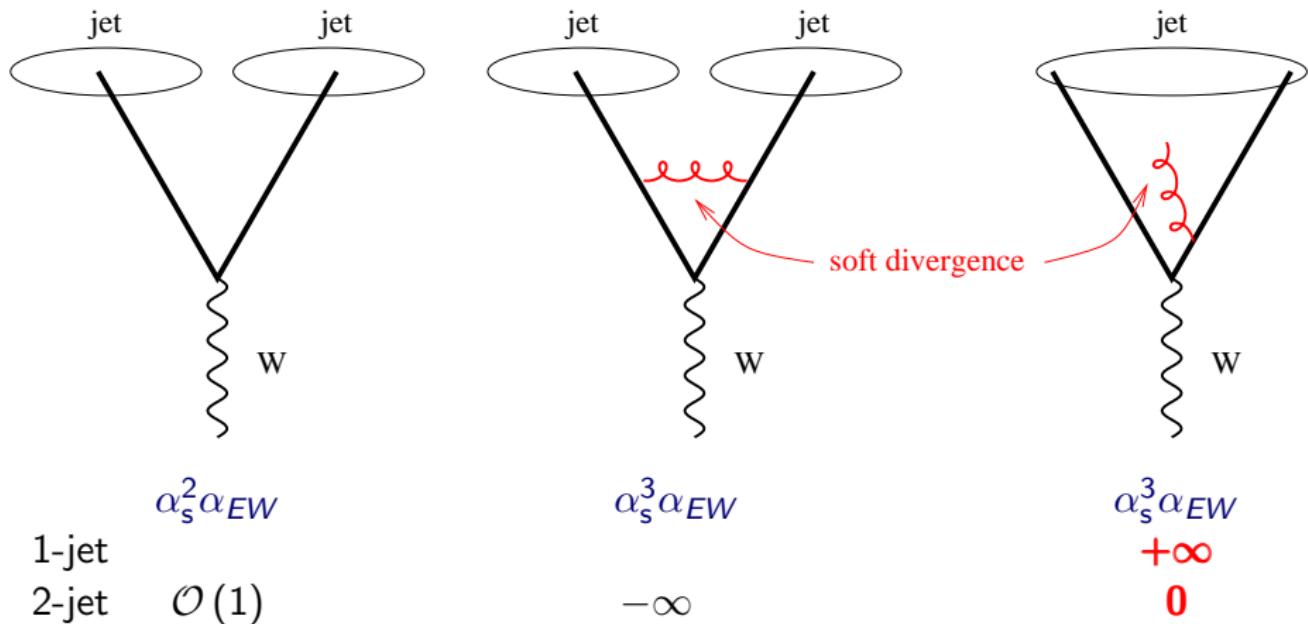
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Real life does not have infinities, but pert. infinity leaves a real-life trace

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

Among consequences of IR unsafety:

|                              | <i>Last meaningful order</i>  |                                    |                         | Known at                  |
|------------------------------|-------------------------------|------------------------------------|-------------------------|---------------------------|
|                              | JetClu, ATLAS<br>cone [IC-SM] | MidPoint<br>[IC <sub>mp</sub> -SM] | CMS it. cone<br>[IC-PR] |                           |
| Inclusive jets               | LO                            | NLO                                | NLO                     | NLO ( $\rightarrow$ NNLO) |
| $W/Z + 1$ jet                | LO                            | NLO                                | NLO                     | NLO                       |
| 3 jets                       | none                          | LO                                 | LO                      | NLO [nlojet++]            |
| $W/Z + 2$ jets               | none                          | LO                                 | LO                      | NLO [MCFM]                |
| $m_{\text{jet}}$ in $2j + X$ | none                          | none                               | none                    | NLO [Blackhat/Rocket/...] |

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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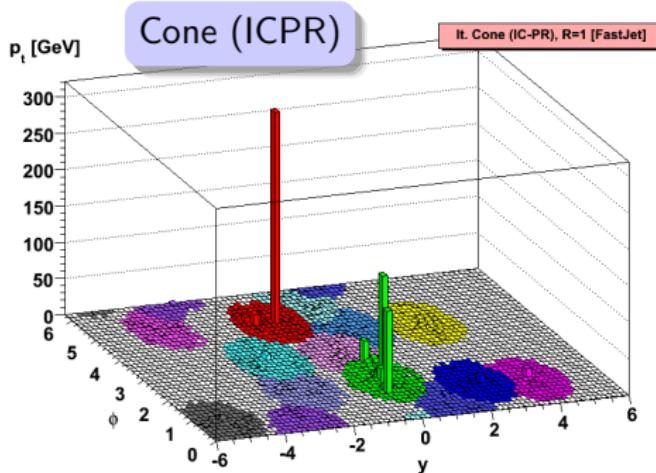
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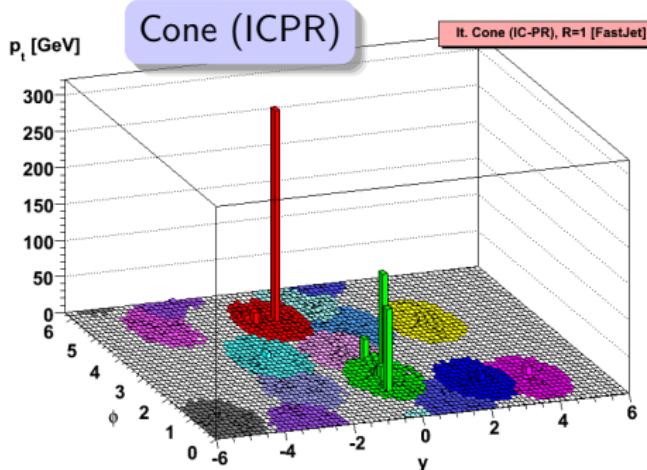
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# Essential characteristic of cones?



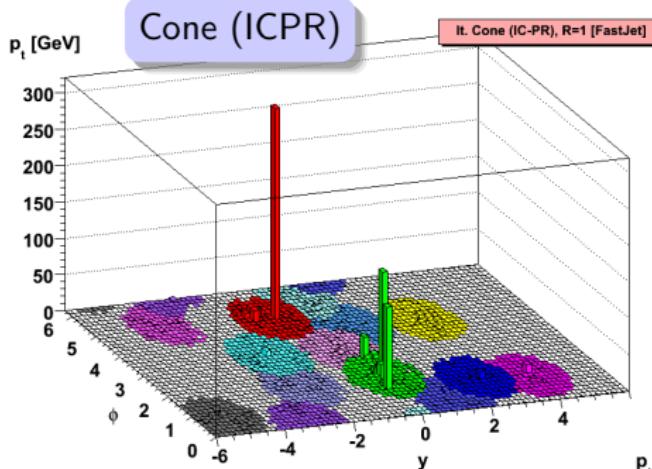
# Essential characteristic of cones?



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

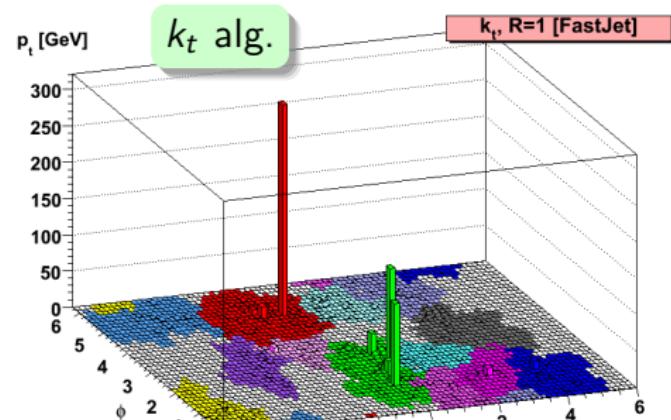
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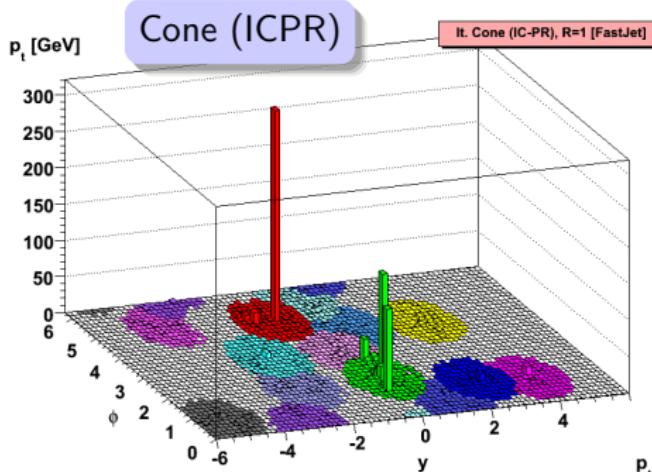


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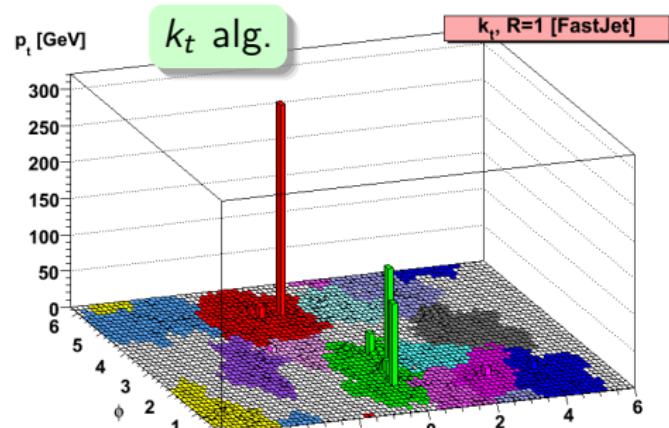
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$k_t$  jets are **irregular**

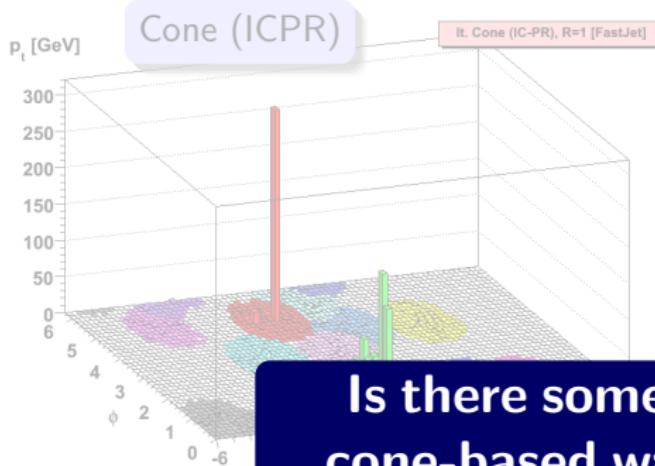
Because soft junk clusters together first:

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

**Regularly held against  $k_t$**



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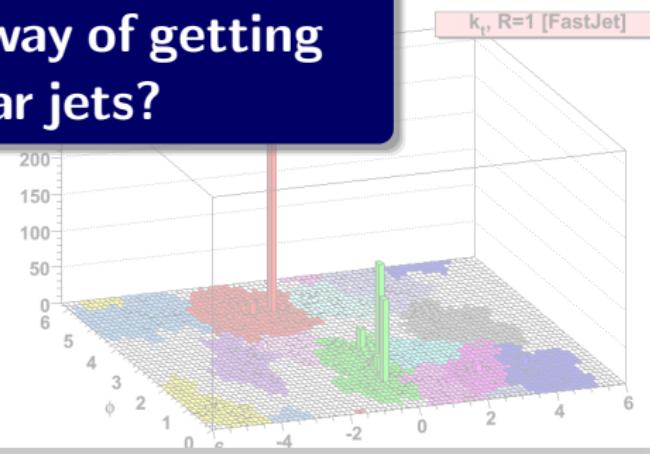
**Is there some other, non cone-based way of getting circular jets?**

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# A 3-year old general-purpose jet algorithm

**anti- $k_t$ :**

repeatedly recombine pair  
of objects with smallest

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Hard stuff clusters with nearest neighbour

Cacciari, GPS & Soyez '08

[included in FastJet]

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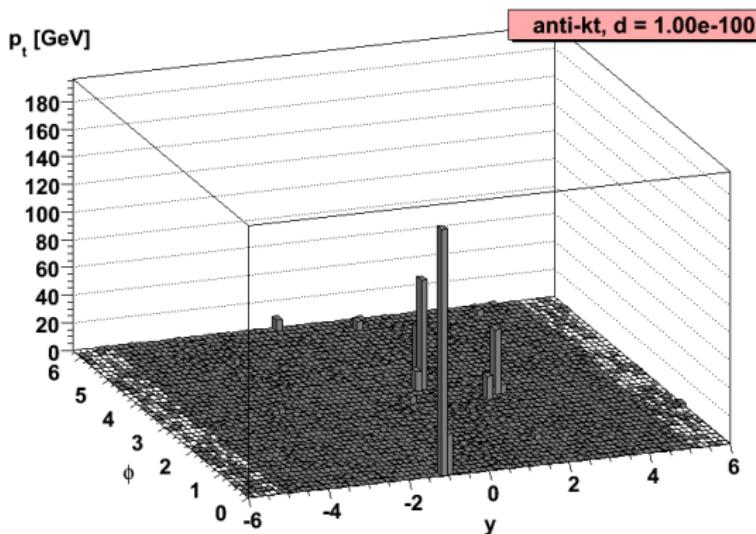
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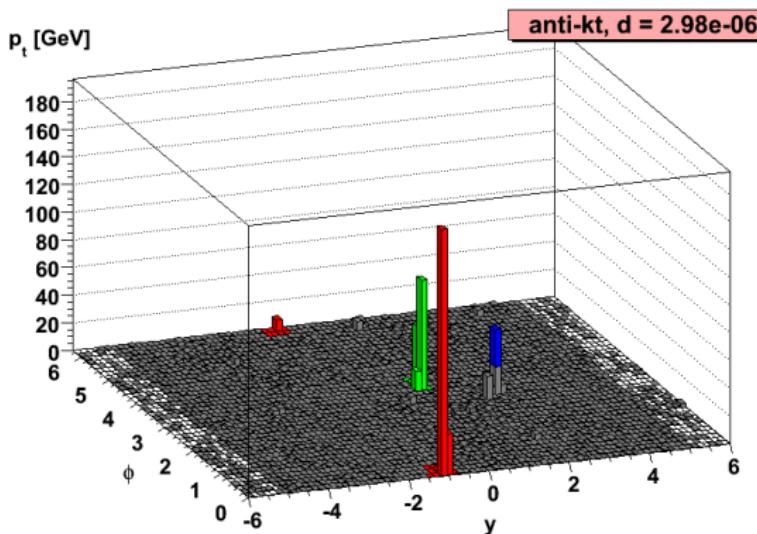
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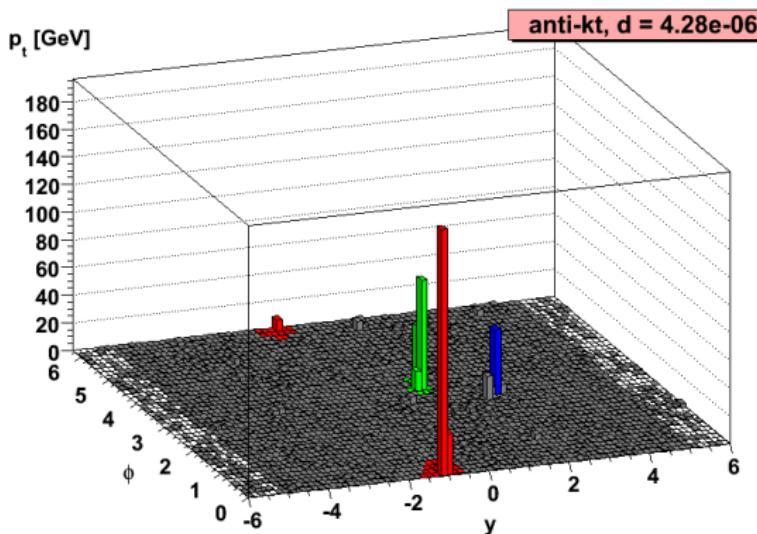
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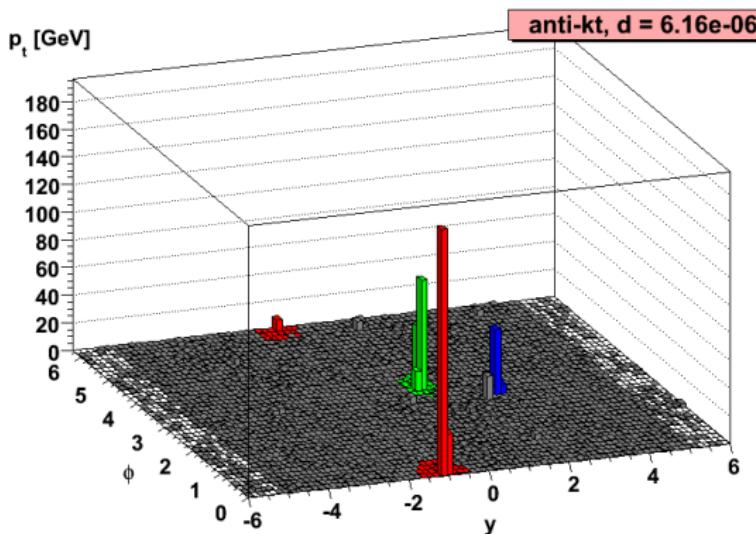
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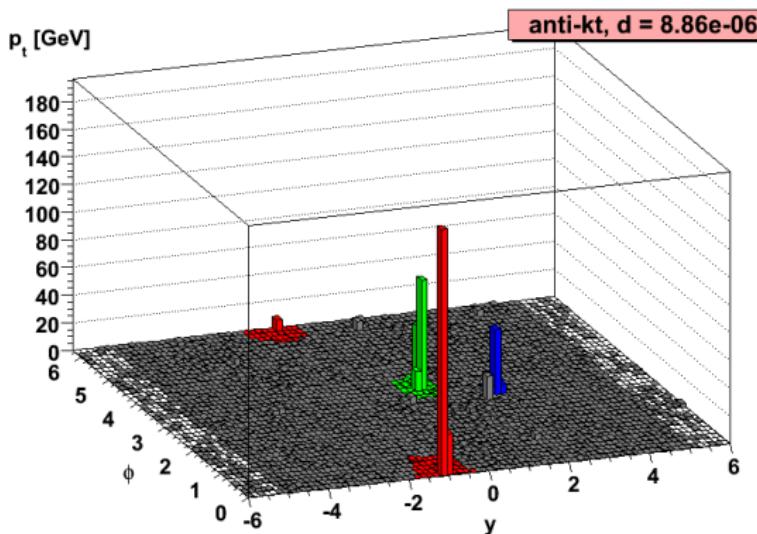
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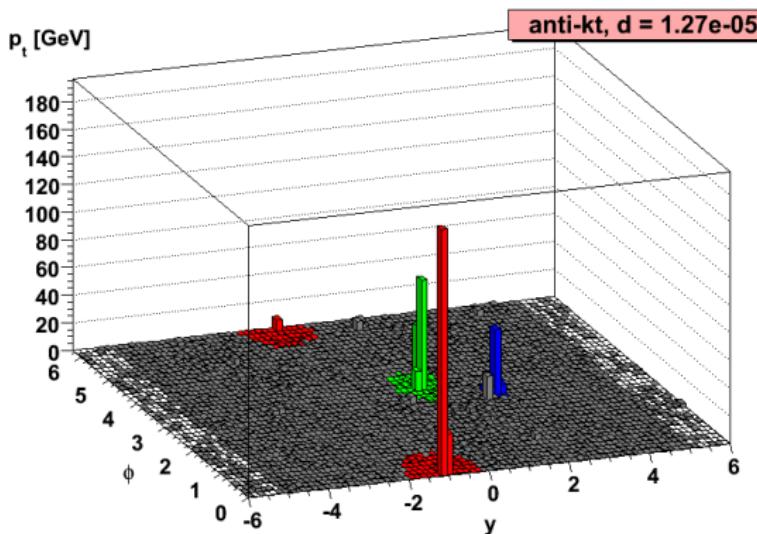
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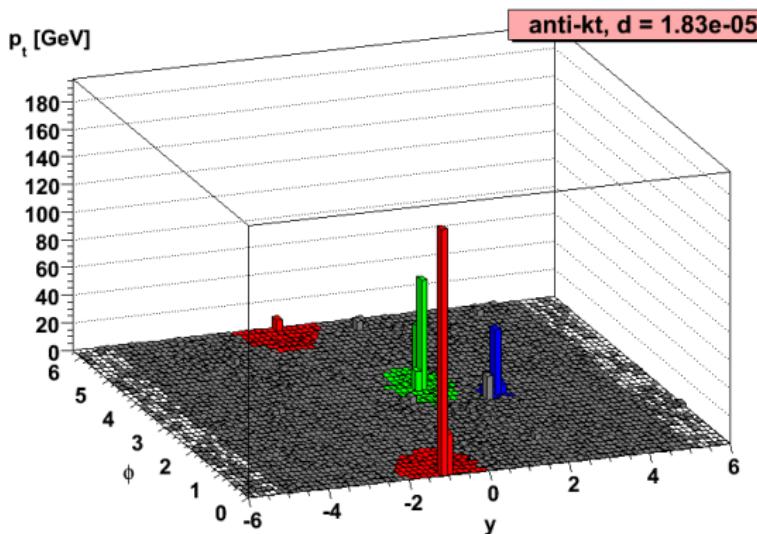
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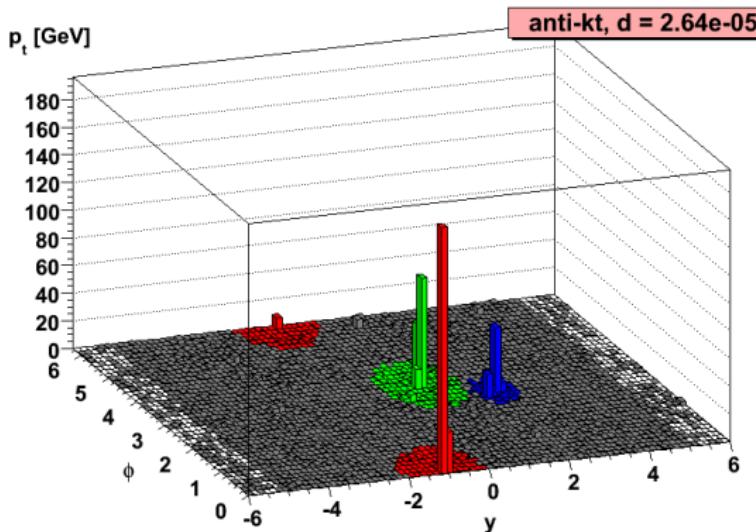
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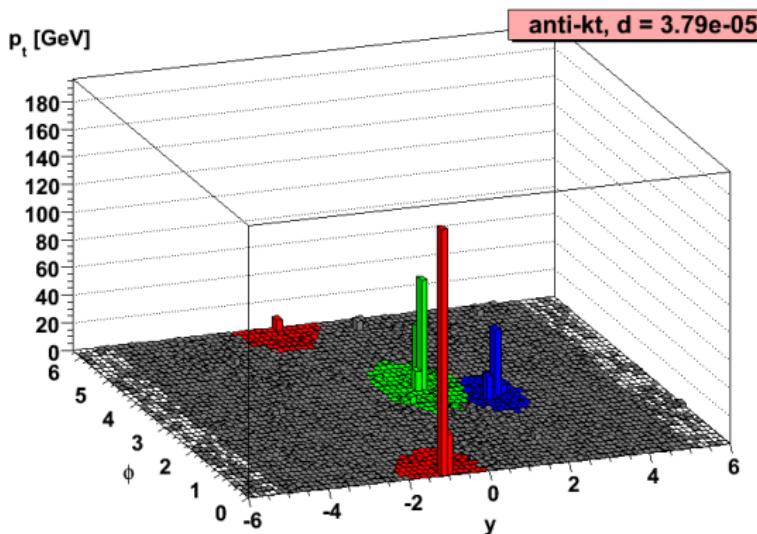
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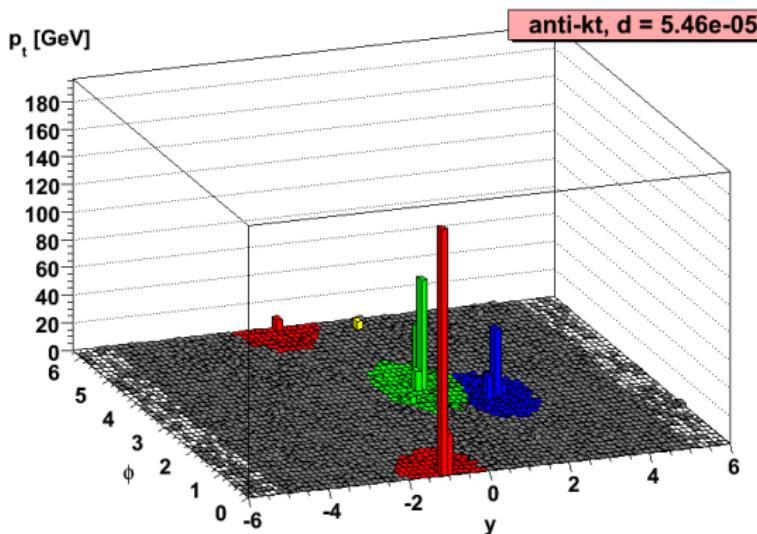
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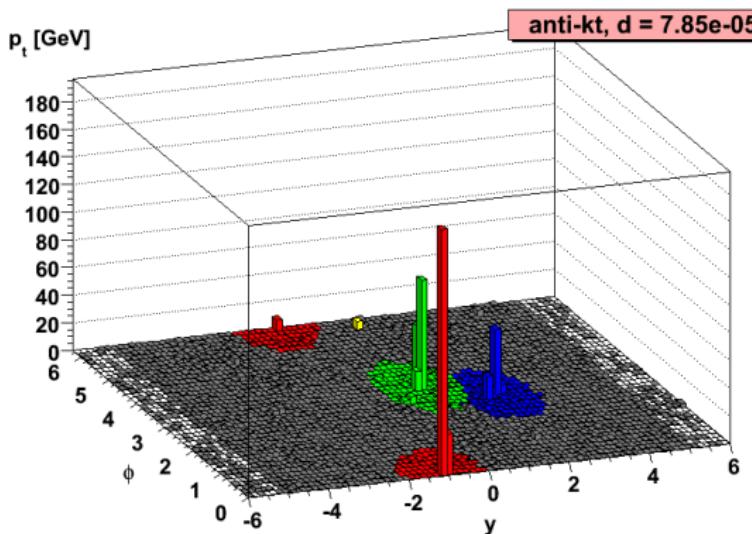
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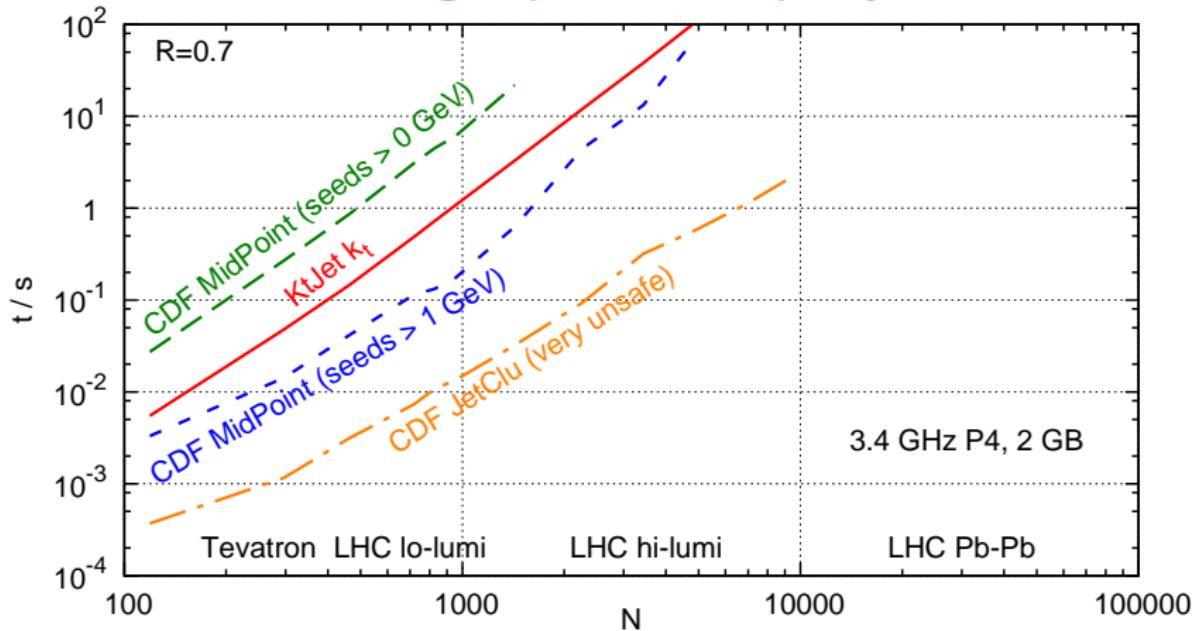
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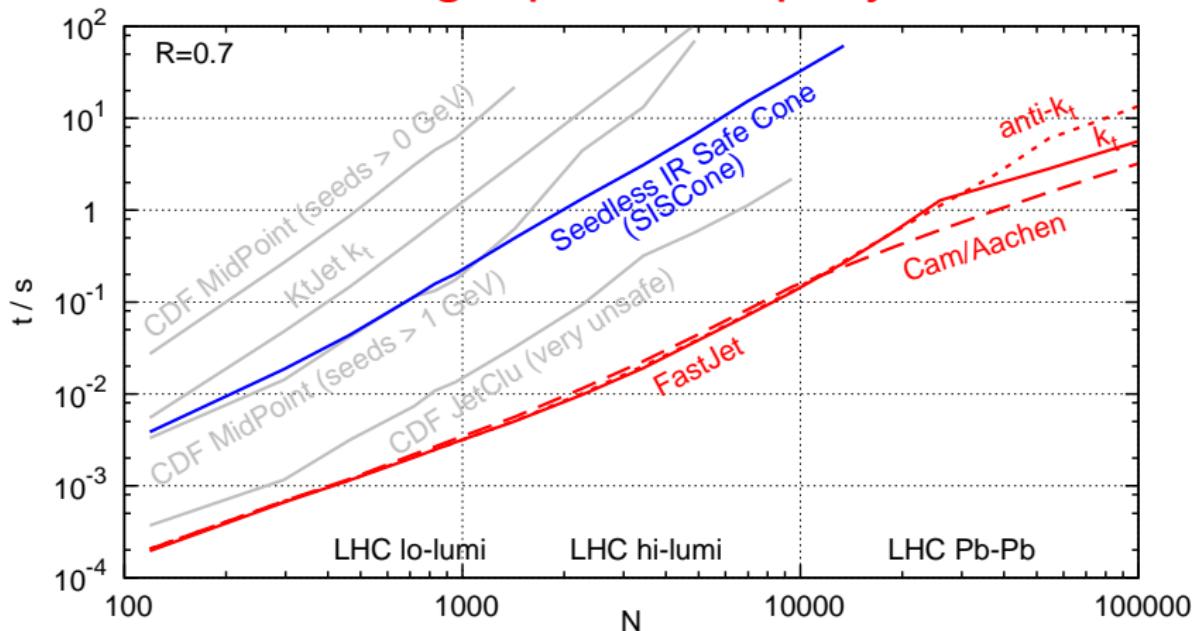
anti- $k_t$  gives  
cone-like jets  
without using cones

And is infrared & collinear safe

## Timing v. particle multiplicity 2005



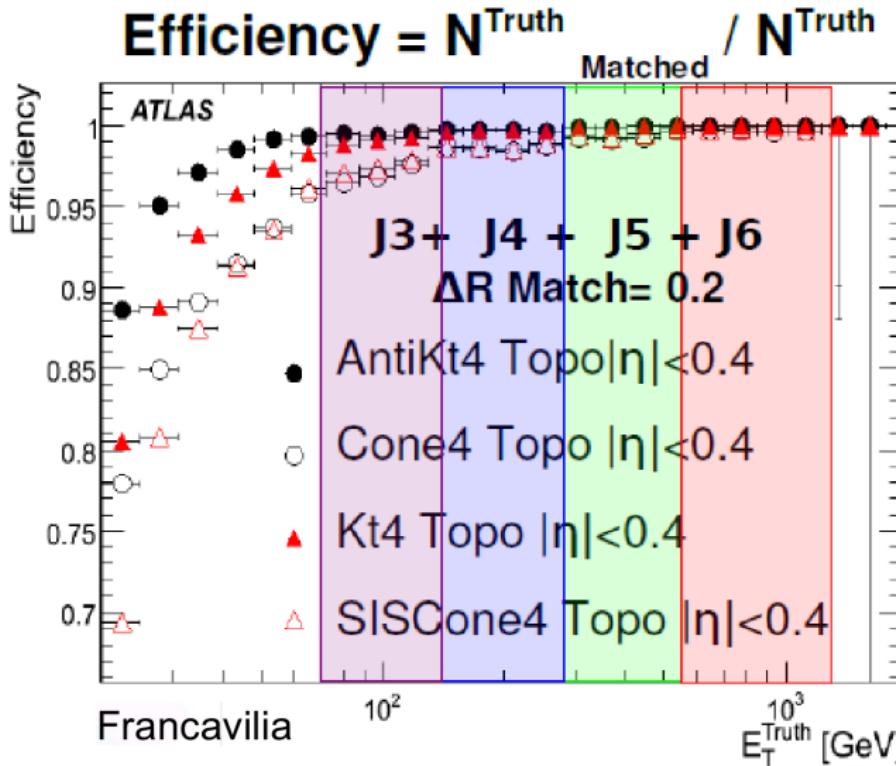
## Timing v. particle multiplicity 2008



in critical region of  $N \sim 2000 - 4000$

1000 times faster than previous attempts with similar jet algorithms

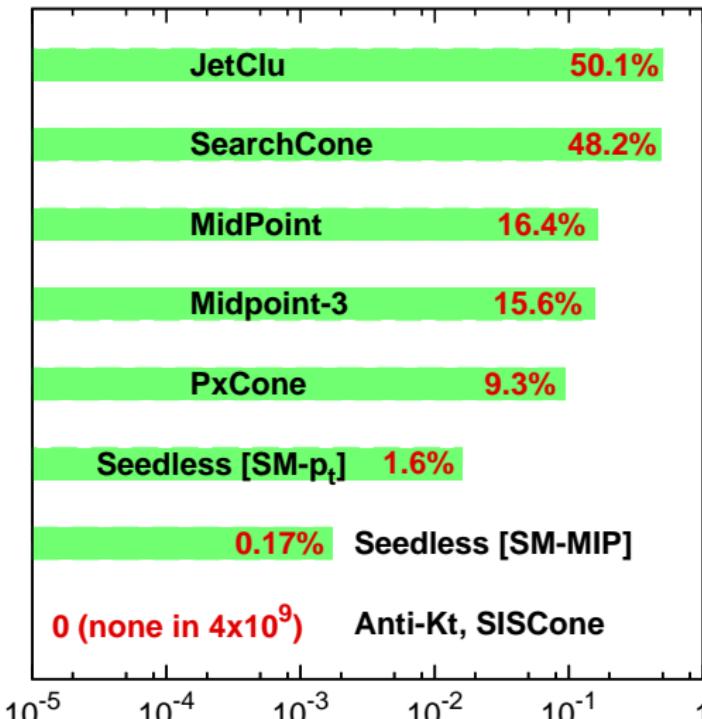
## Experimental sensitivity to noise



As good as, or better than all previous experimentally-favoured algorithms.

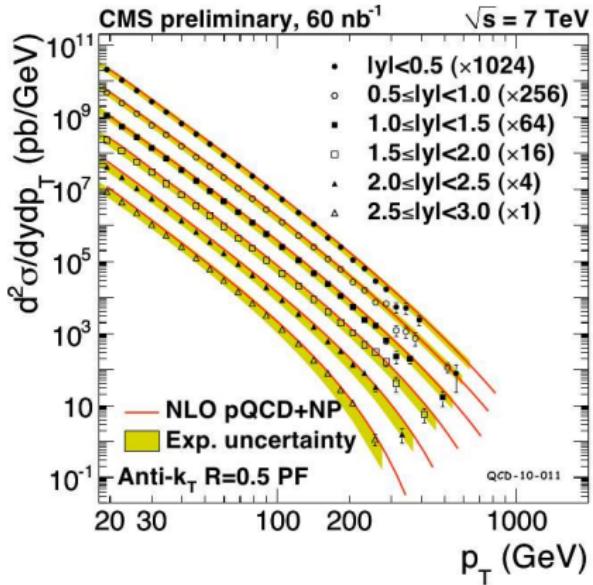
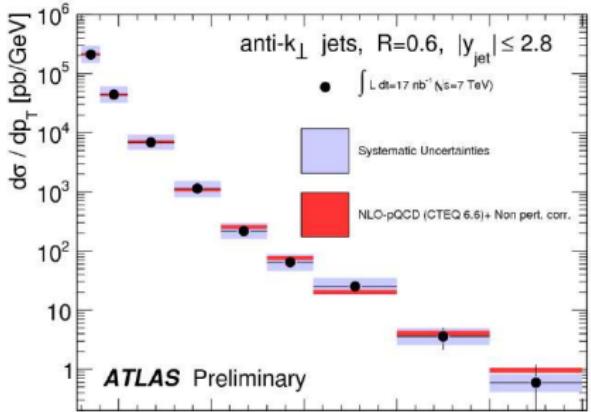
Essentially because anti- $k_t$  has linear response to soft particles.

### Coefficient of “infinity”

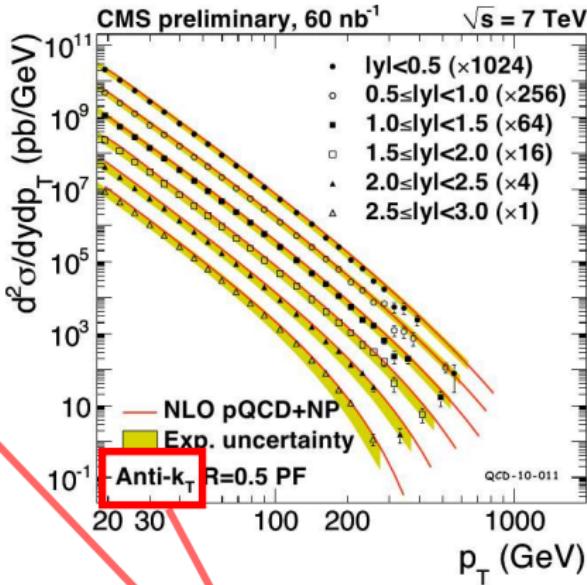
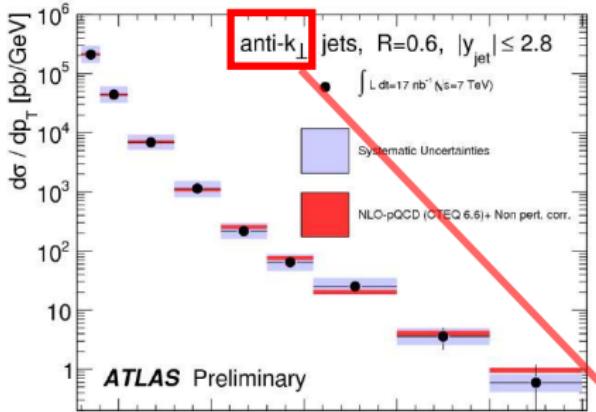


Safe for perturbative QCD predictions:

No “leakage” of infinities to higher orders

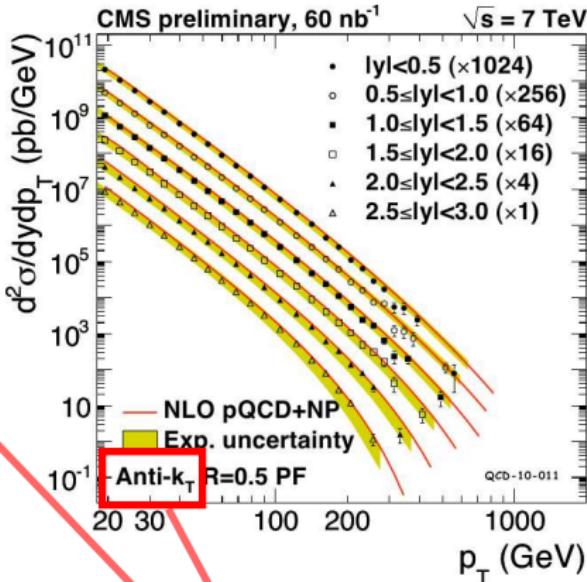
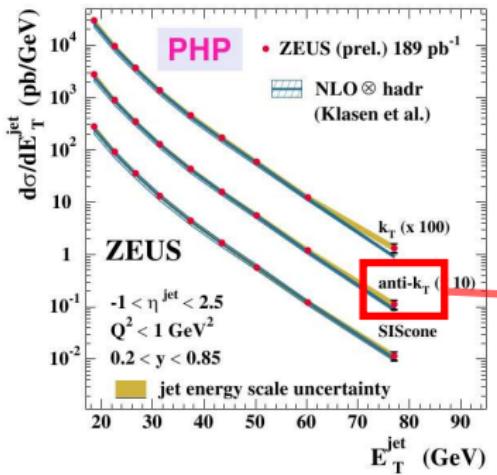
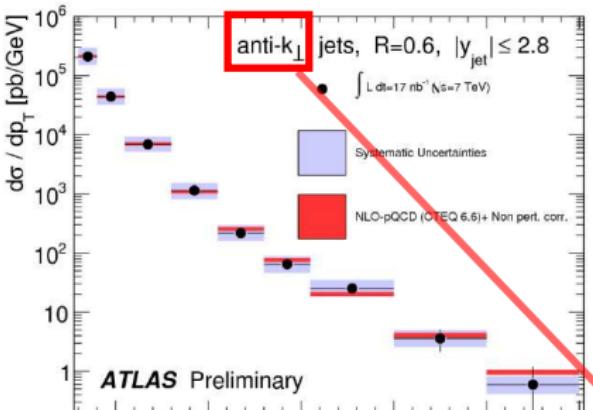


ATLAS and CMS have shown all jet results with an infrared and collinear safe jet finder, **anti- $k_t$** ;



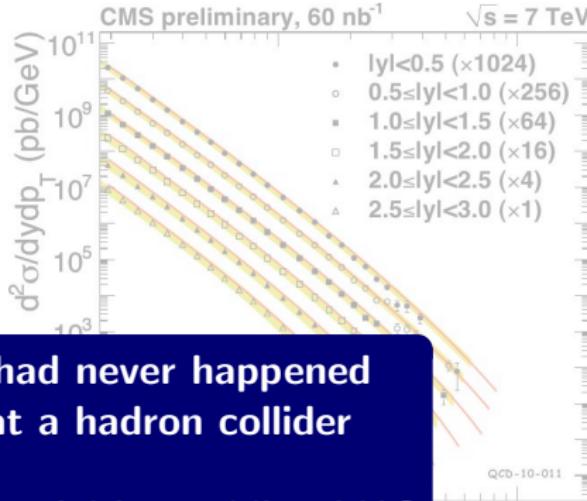
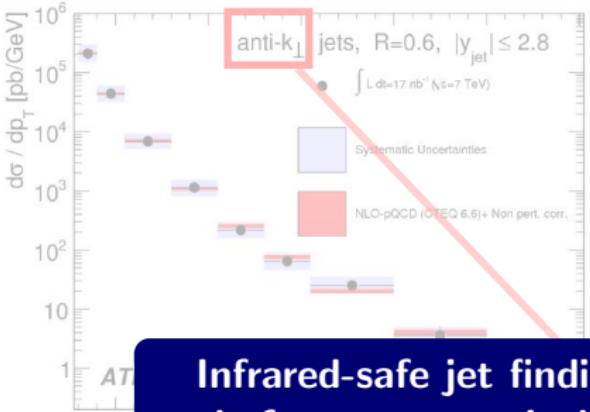
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soft junk doesn't change hard jets  
NLO calculations are finite



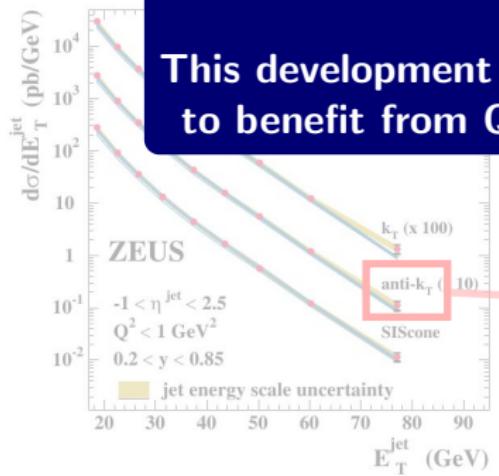
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Infrared-safe jet finding had never happened before, systematically, at a hadron collider

This development will be crucial in enabling LHC to benefit from QCD's progress in recent years



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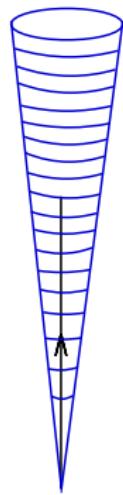
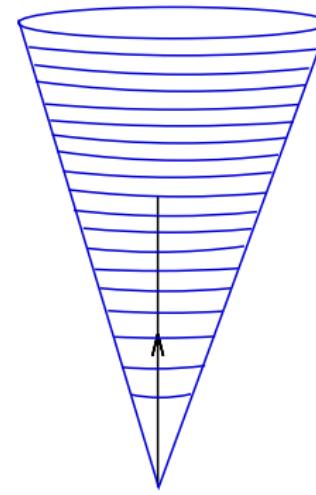
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Major activity in past 3 years geared towards understanding use of jets for discovery physics.

Of the lessons we've learnt, which ones carry over to precision physics?

## Lesson 1: be flexible

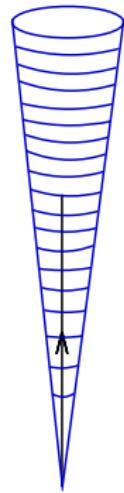
This can benefit precision studies and searches

**Small jet radius****Large jet radius**

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

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

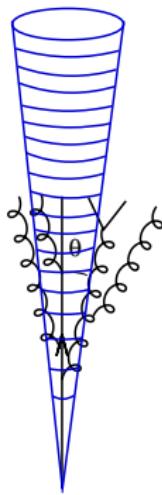
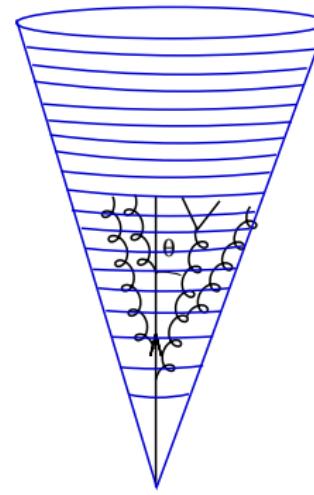
**Small jet radius**



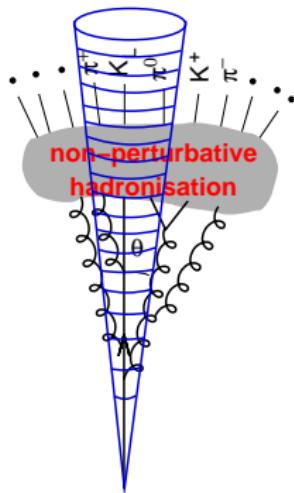
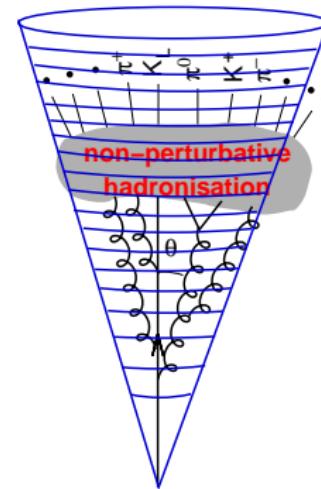
**Large jet radius**



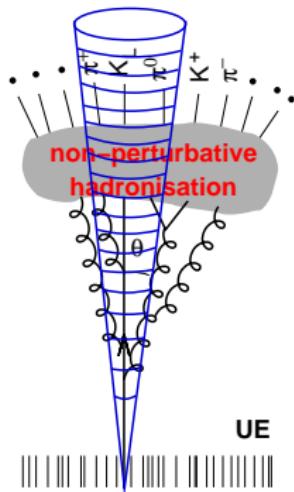
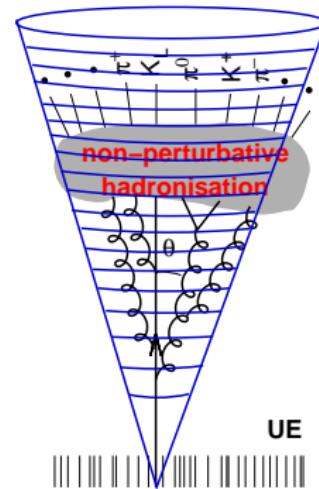
single part

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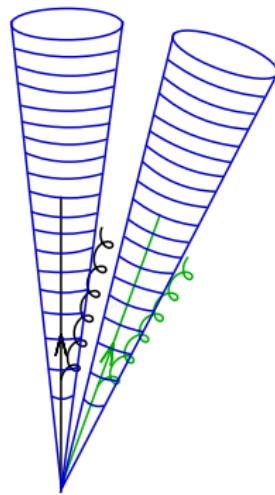
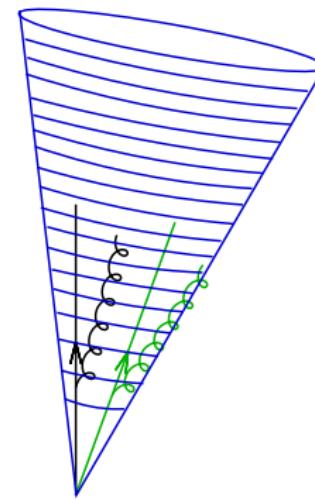
perturbative fragmentation: **large jet radius better**  
(it captures more)

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

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

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

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

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

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

Parton  $p_t \rightarrow$  jet  $p_t$

Ill-defined: MC “parton”

### PT radiation:

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

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

### Hadronisation:

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

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

### Underlying event:

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

Dasgupta, Magnea & GPS '07

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III-defined: MC "parton"

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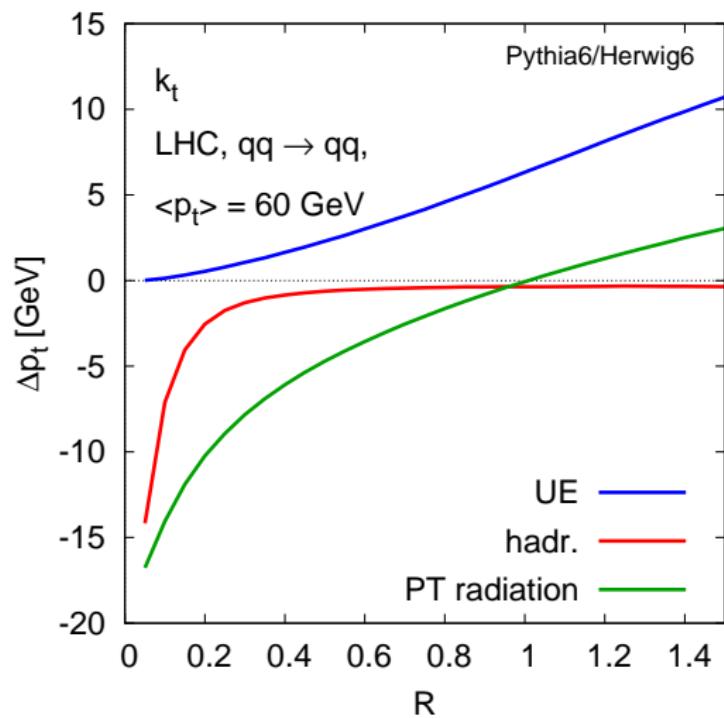
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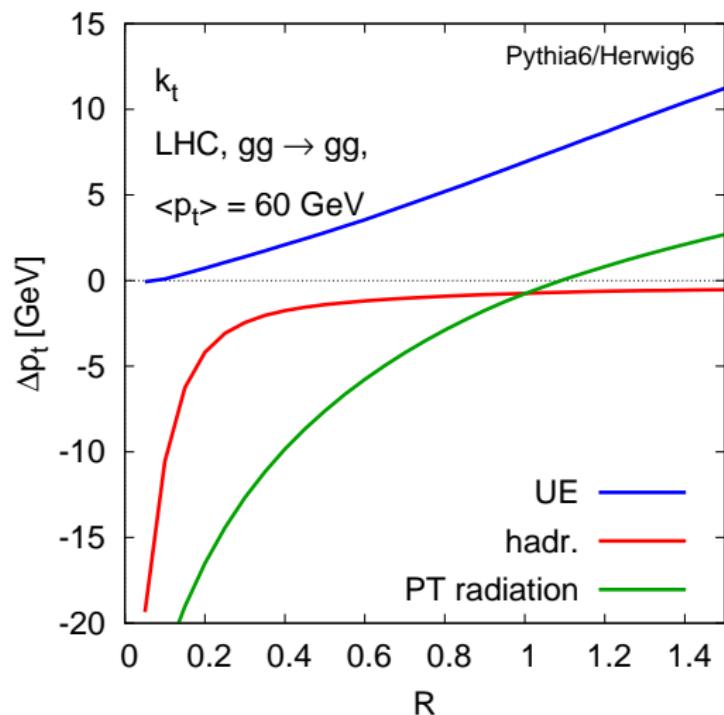
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Dasgupta, Magnea & GPS '07

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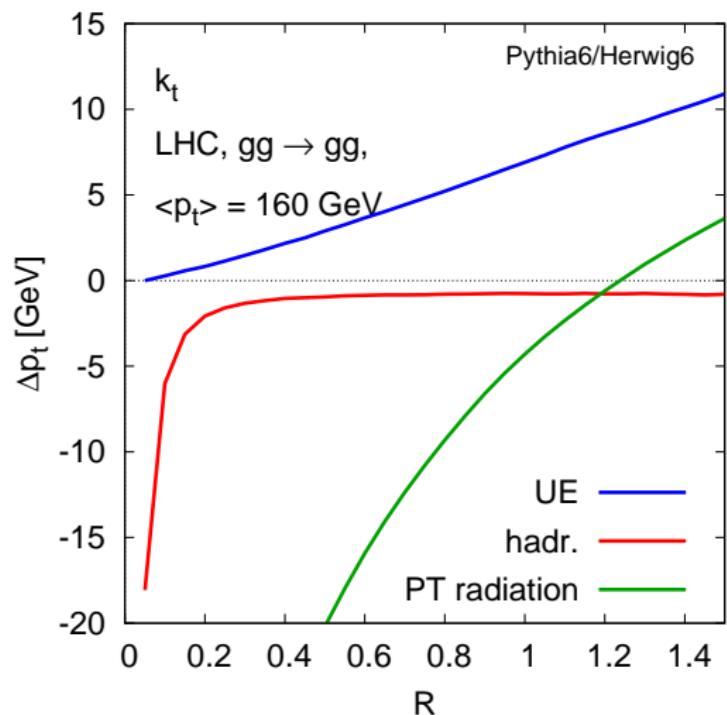
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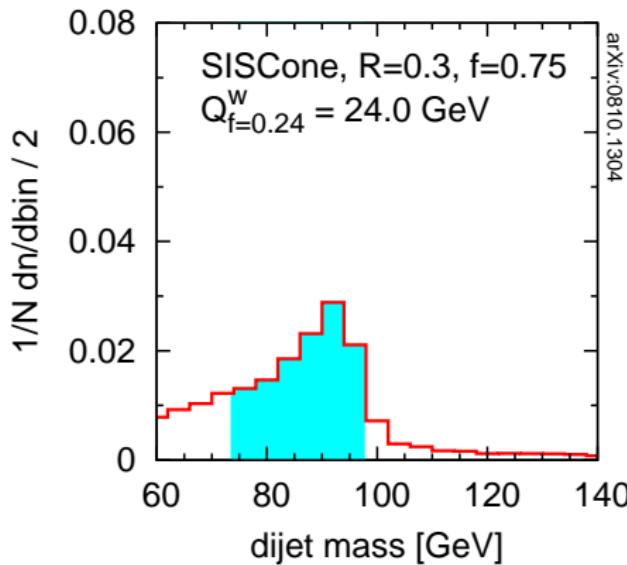
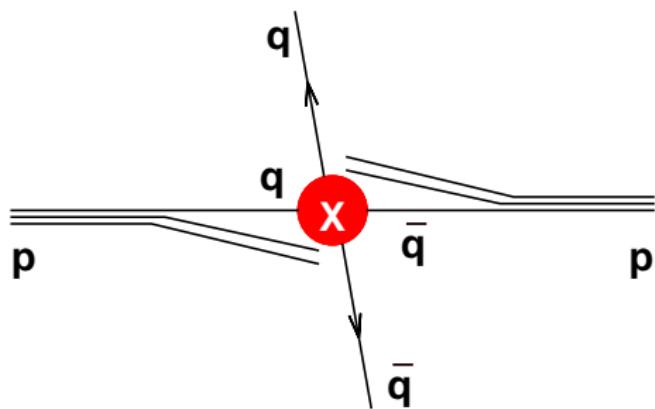
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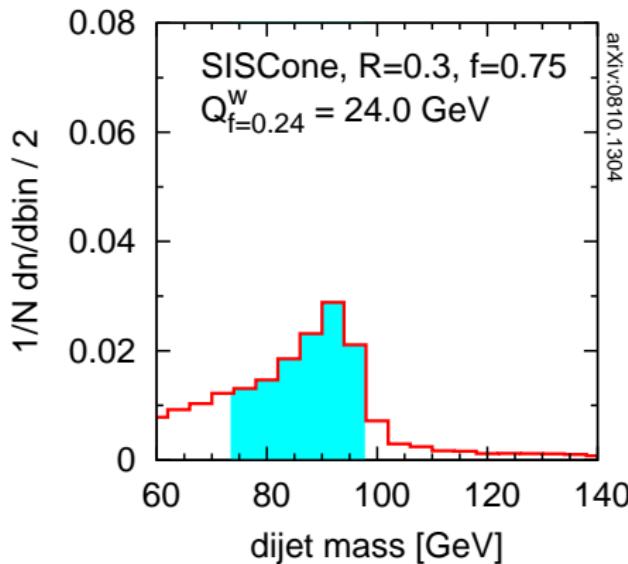
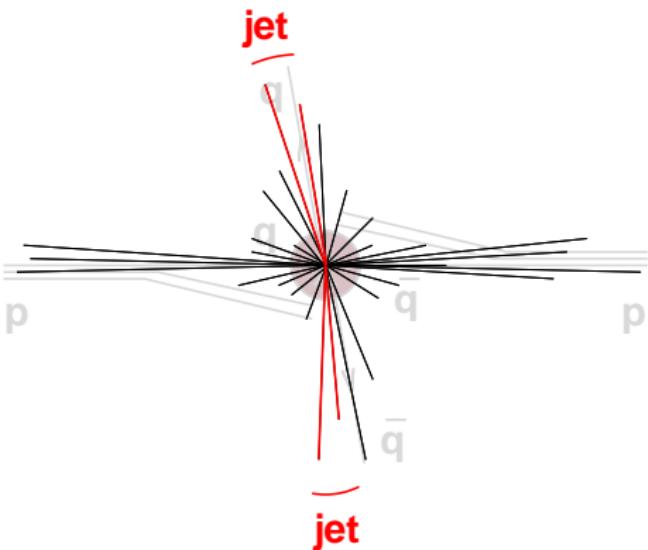
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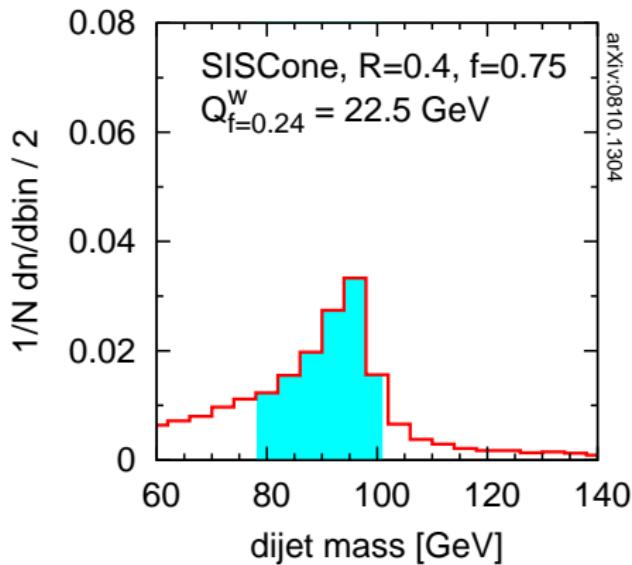
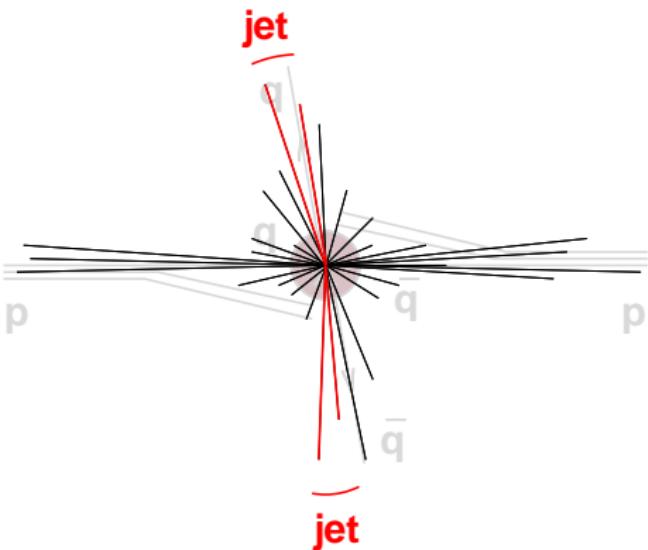
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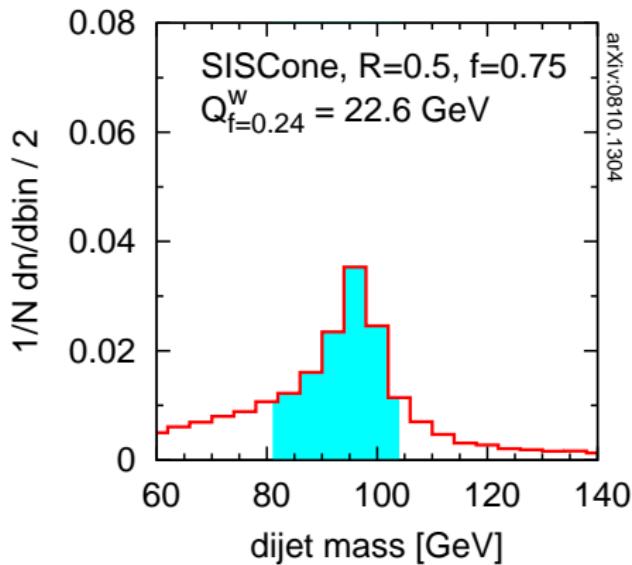
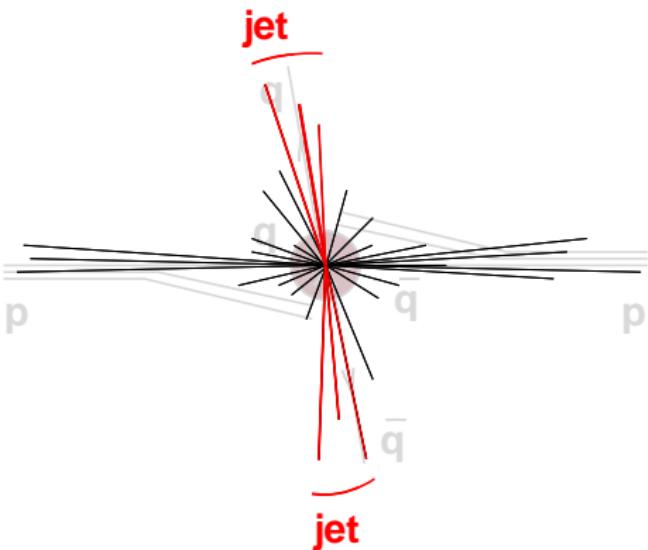


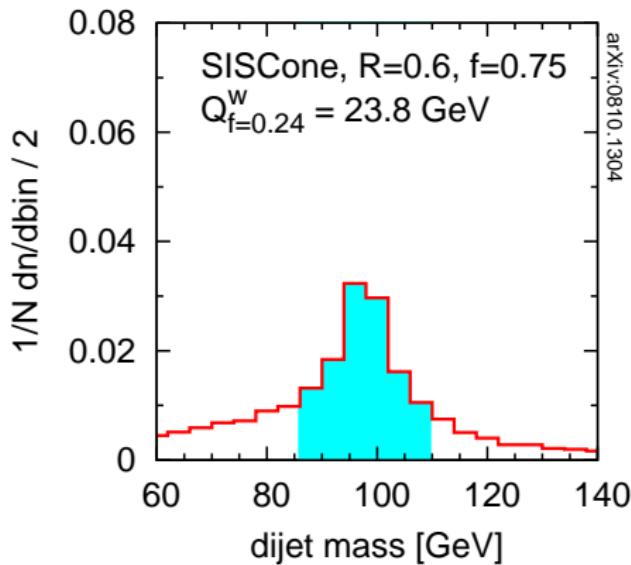
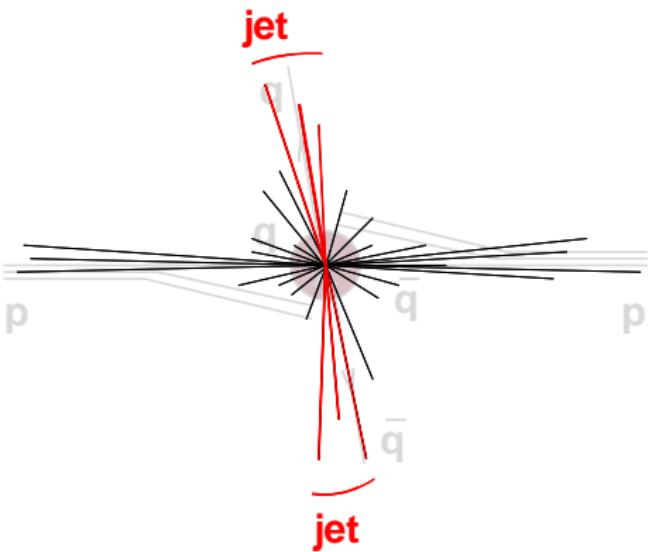
Dasgupta, Magnea & GPS '07

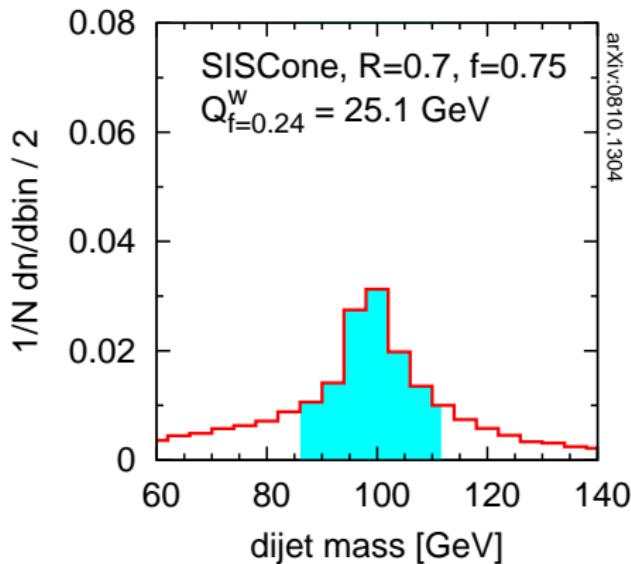
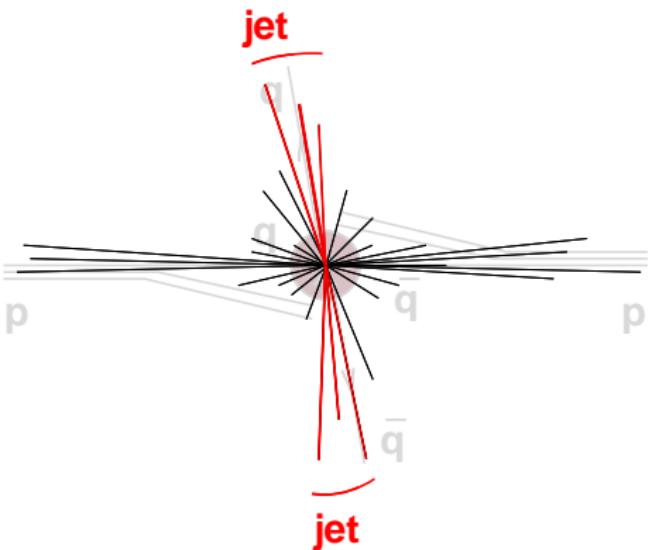
Dijet mass: scan over  $R$  [Pythia 6.4] **$R = 0.3$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

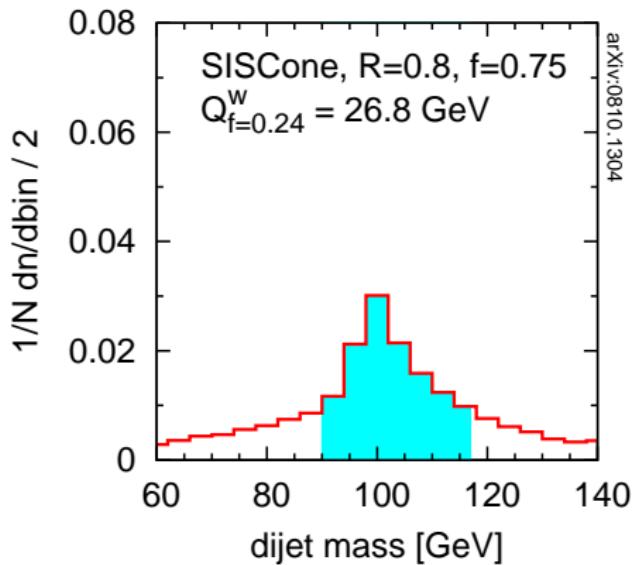
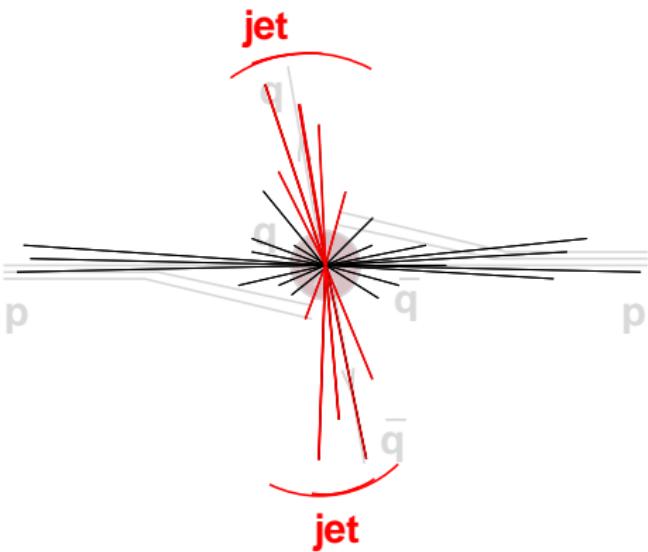
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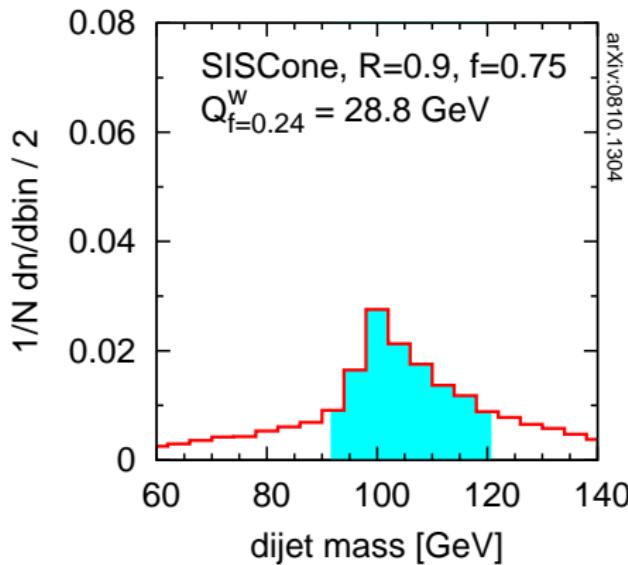
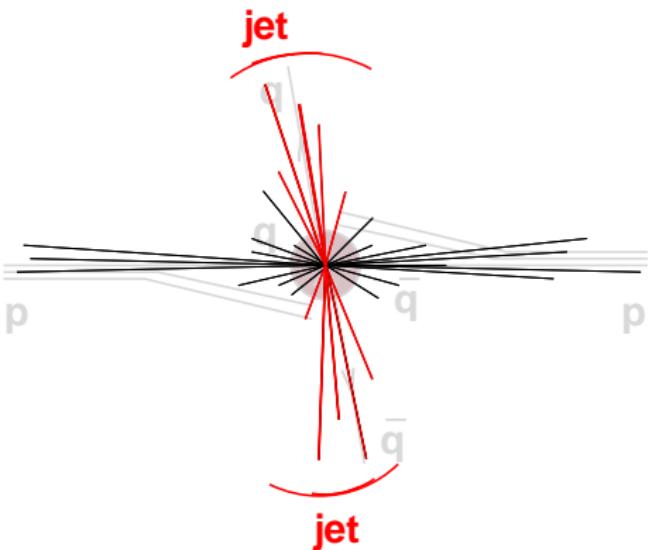
**$R = 0.4$** qq,  $M = 100$  GeV**Resonance  $X \rightarrow$  dijets**

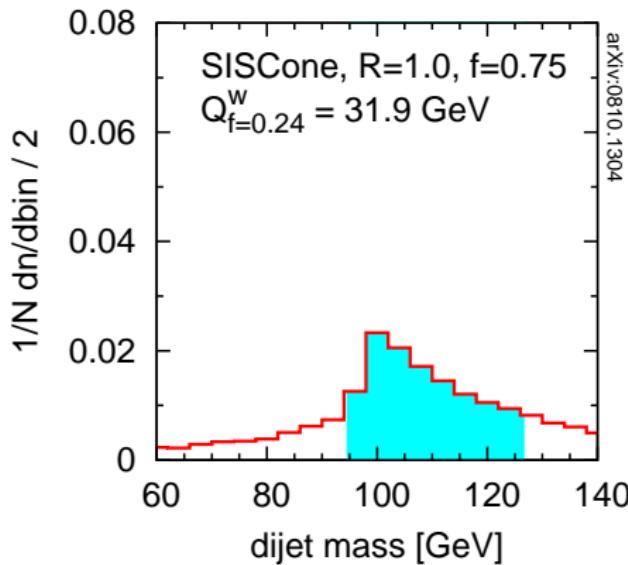
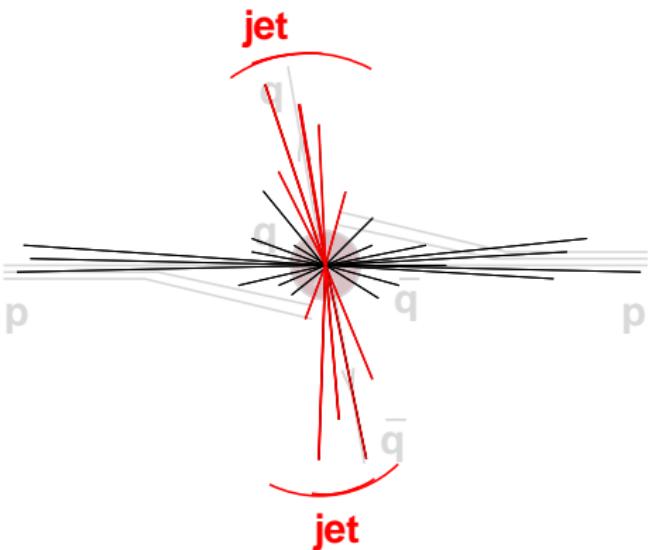
**$R = 0.5$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

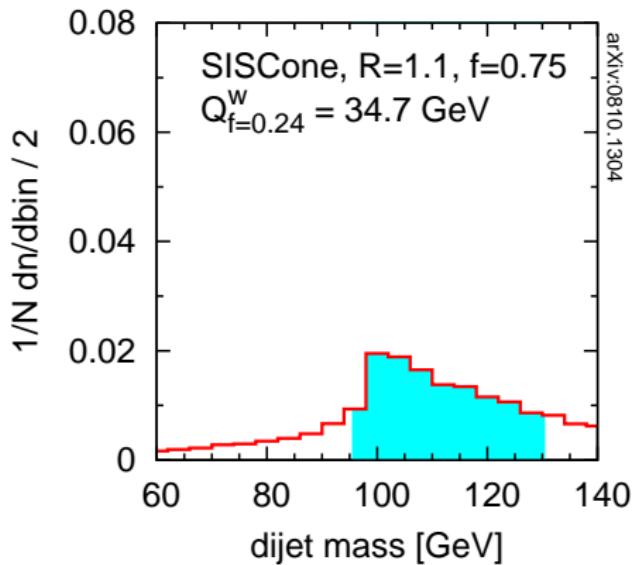
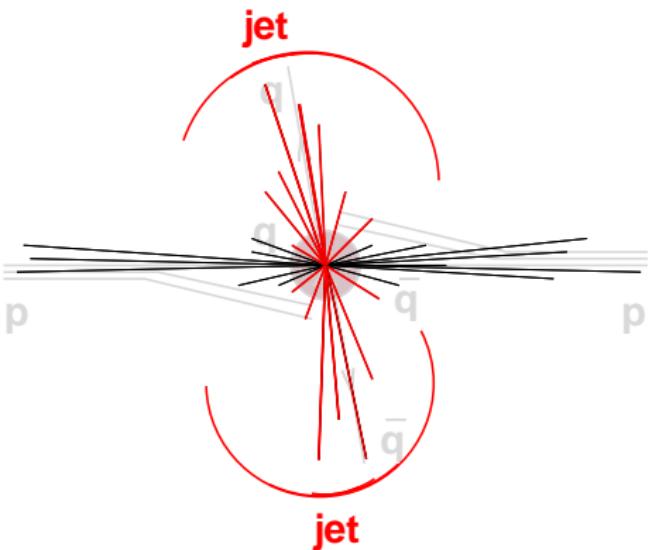
**$R = 0.6$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

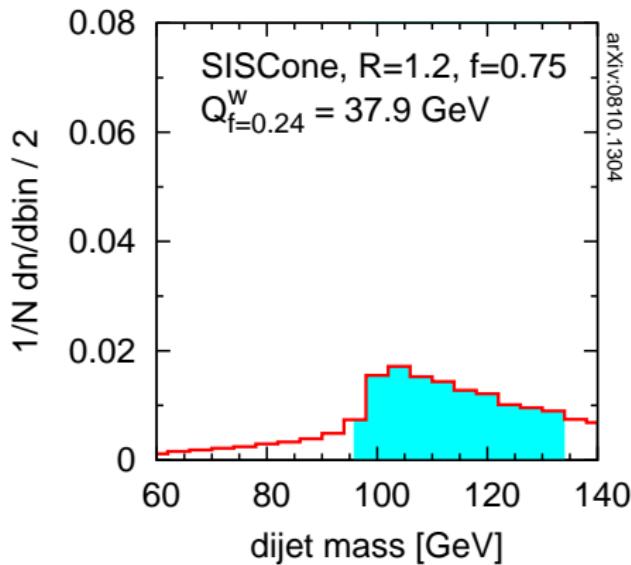
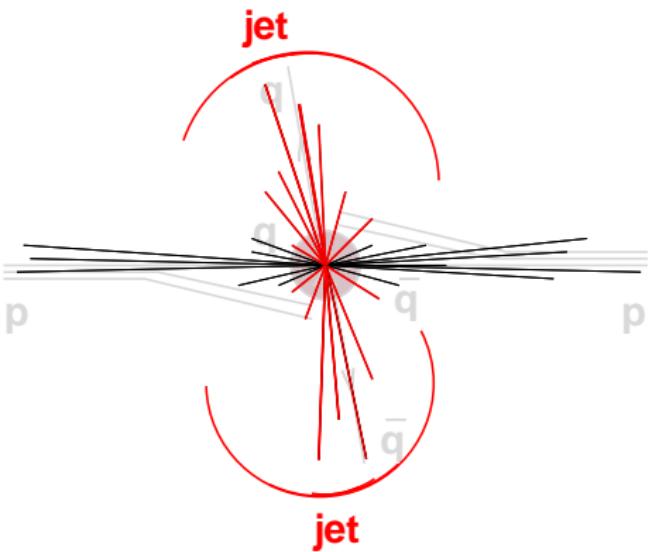
Dijet mass: scan over  $R$  [Pythia 6.4] **$R = 0.7$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

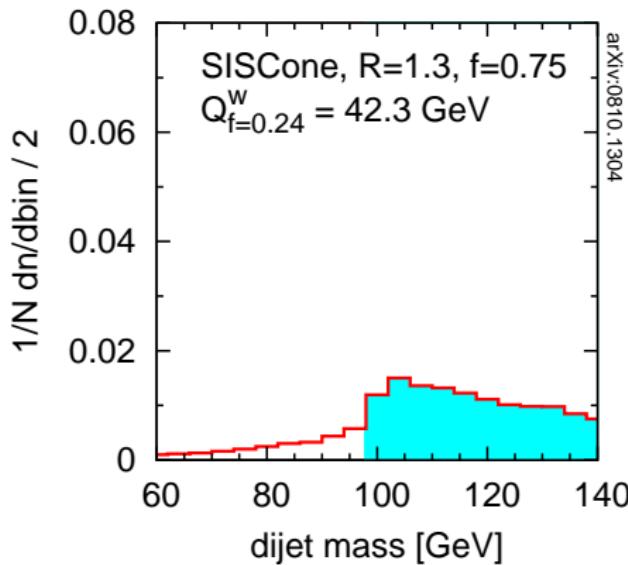
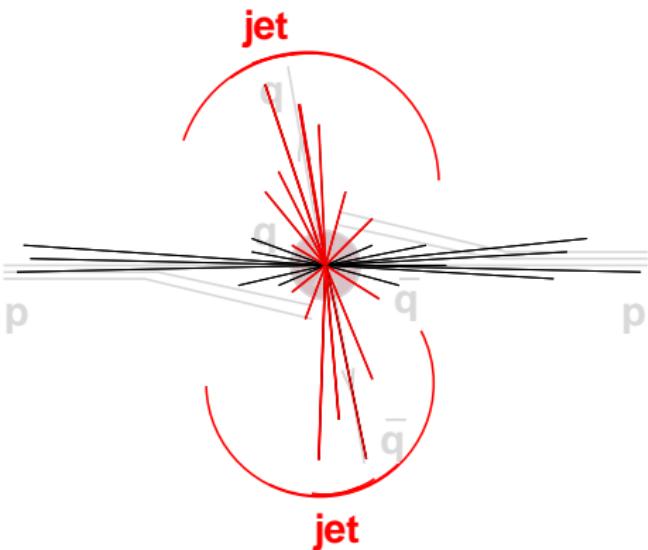
Dijet mass: scan over  $R$  [Pythia 6.4] **$R = 0.8$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

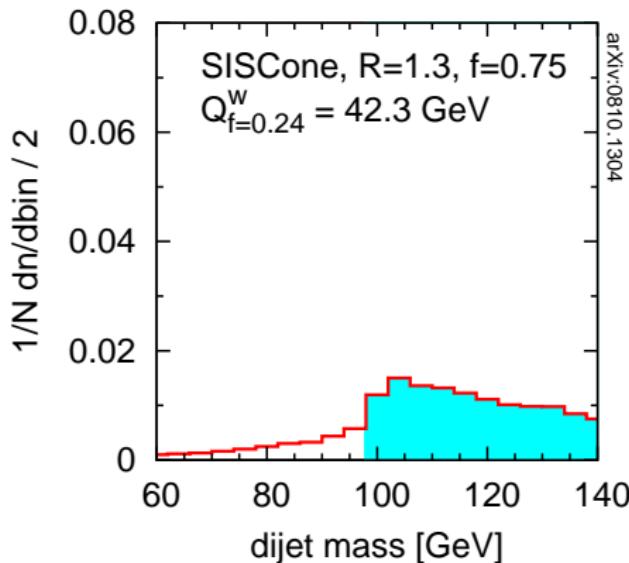
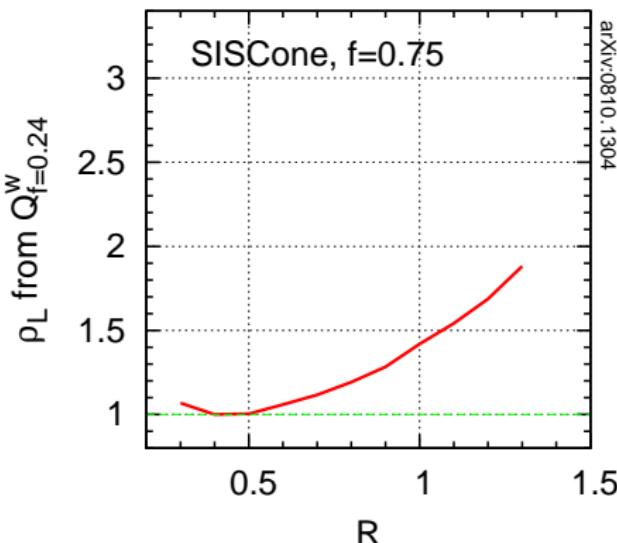
Dijet mass: scan over  $R$  [Pythia 6.4] **$R = 0.9$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

Dijet mass: scan over  $R$  [Pythia 6.4] **$R = 1.0$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

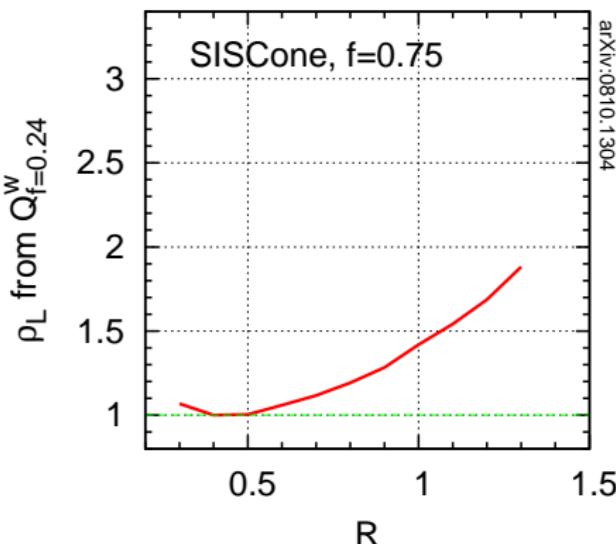
**$R = 1.1$** qq,  $M = 100$  GeVResonance  $X \rightarrow$  dijets

**$R = 1.2$** qq,  $M = 100$  GeV**Resonance  $X \rightarrow$  dijets**

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

**$R = 1.3$** qq,  $M = 100$  GeVqq,  $M = 100$  GeV

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

Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 100 \text{ GeV}$**  $q\bar{q}, M = 100 \text{ GeV}$ Best  $R$  is at minimum of curve

- Best  $R$  depends strongly on mass of system
- Increases with mass
- can reproduce this analytically  
Soyez '10

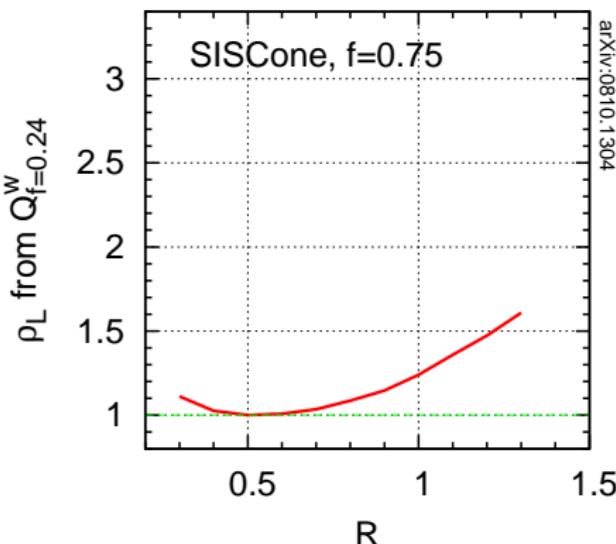
BUT: so far, LHC has used smallish  $R$  values

e.g. ATLAS '10, CMS '10

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

Cacciari, Rojo, GPS &amp; Soyez '08

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

Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 150 \text{ GeV}$**  $q\bar{q}, M = 150 \text{ GeV}$ Best  $R$  is at minimum of curve

- Best  $R$  depends strongly on mass of system
- Increases with mass
- can reproduce this analytically  
Soyez '10

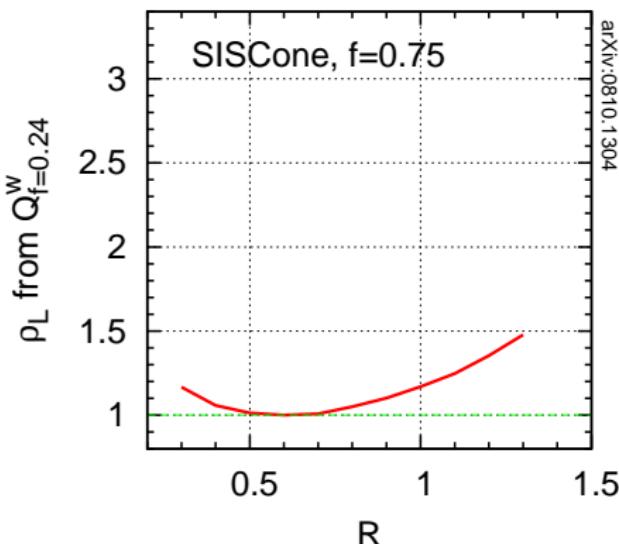
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Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 200 \text{ GeV}$**  $q\bar{q}, M = 200 \text{ GeV}$ Best  $R$  is at minimum of curve

- Best  $R$  depends strongly on mass of system
- Increases with mass  
can reproduce this analytically  
Soyez '10

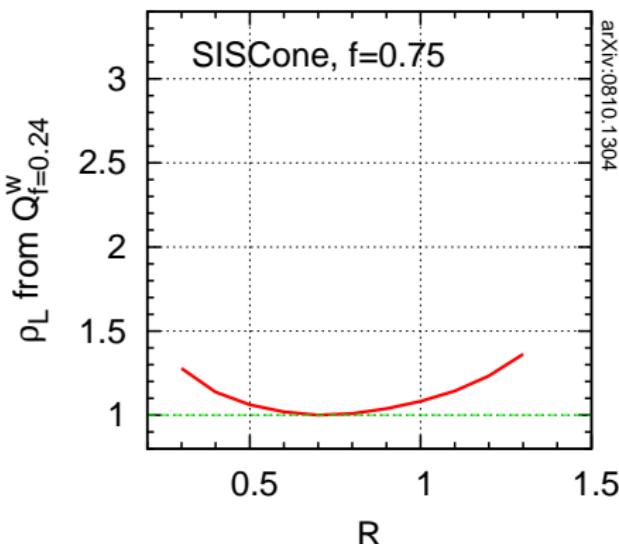
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Cacciari, Rojo, GPS &amp; Soyez '08

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Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 300 \text{ GeV}$**  $q\bar{q}, M = 300 \text{ GeV}$ Best  $R$  is at minimum of curve

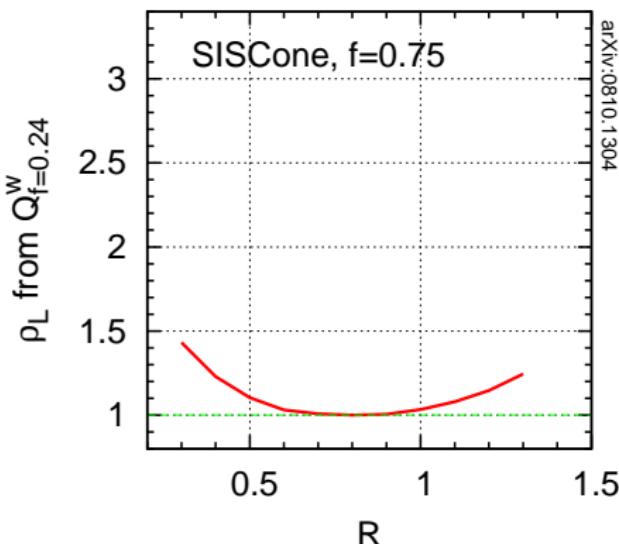
- Best  $R$  depends strongly on mass of system
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can reproduce this analytically  
Soyez '10

BUT: so far, LHC has used smallish  $R$  values

e.g. ATLAS '10, CMS '10

NB: 100,000 plots for various jet algorithms, narrow  $q\bar{q}$  and  $gg$  resonances  
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Cacciari, Rojo, GPS & Soyez '08  
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Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 500 \text{ GeV}$**  $q\bar{q}, M = 500 \text{ GeV}$ Best  $R$  is at minimum of curve

- Best  $R$  depends strongly on mass of system
- Increases with mass  
can reproduce this analytically  
Soyez '10

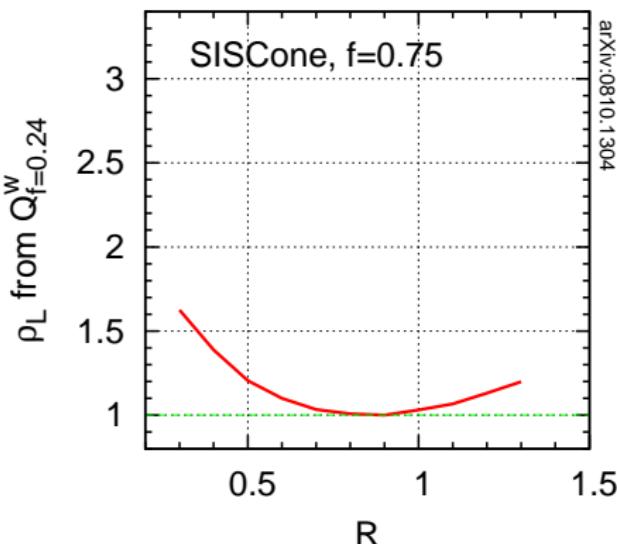
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Cacciari, Rojo, GPS &amp; Soyez '08

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

Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 700 \text{ GeV}$**  **$q\bar{q}, M = 700 \text{ GeV}$** Best  $R$  is at minimum of curve

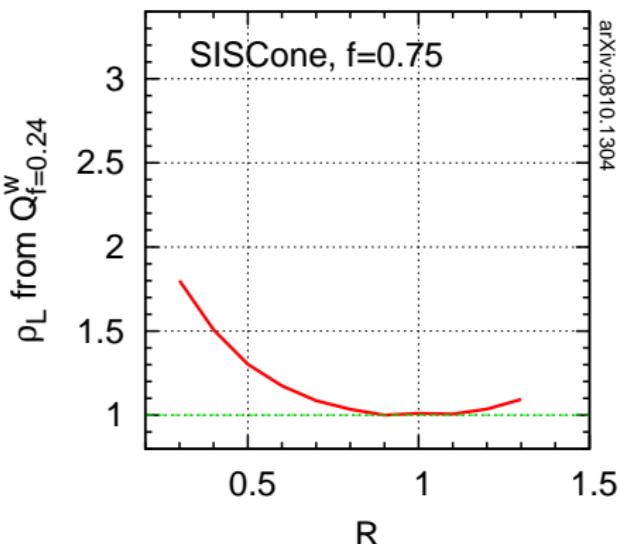
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 from <http://quality.fastjet.fr>

Cacciari, Rojo, GPS & Soyez '08  
 Other related work: Krohn, Thaler & Wang '09

Scan through  $q\bar{q}$  mass values **$m_{qq} = 1000 \text{ GeV}$**  $qq, M = 1000 \text{ GeV}$ Best  $R$  is at minimum of curve

- ▶ Best  $R$  depends strongly on mass of system
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can reproduce this analytically  
Soyez '10

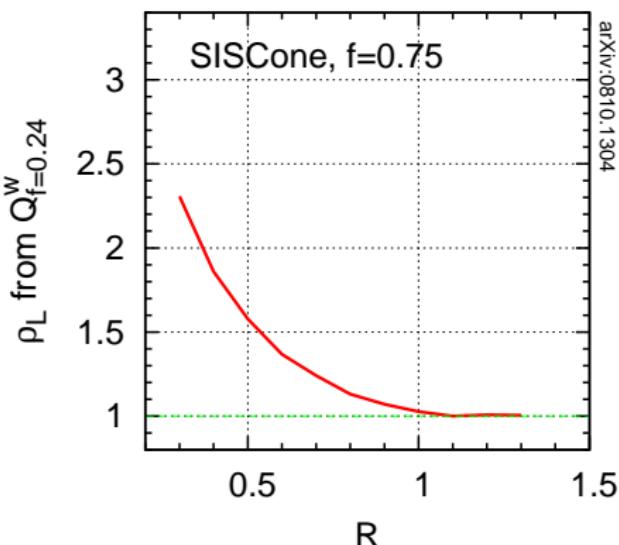
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Other related work: Krohn, Thaler &amp; Wang '09

Scan through  $q\bar{q}$  mass values **$m_{q\bar{q}} = 2000 \text{ GeV}$**  **$q\bar{q}, M = 2000 \text{ GeV}$** Best  $R$  is at minimum of curve

- ▶ Best  $R$  depends strongly on mass of system
  - ▶ Increases with mass
- can reproduce this analytically  
Soyez '10

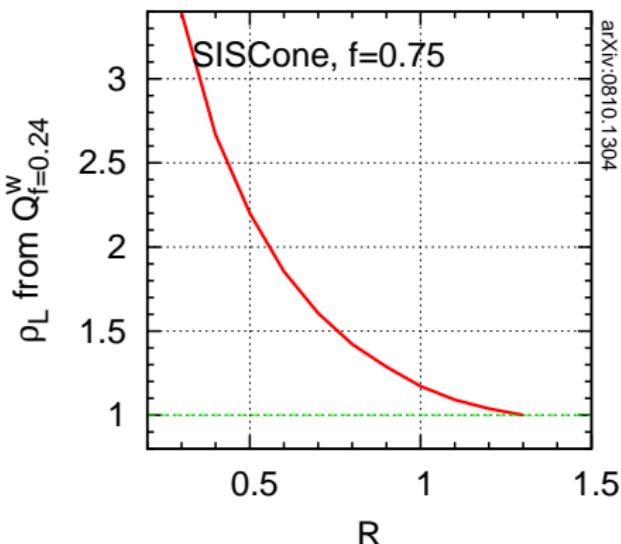
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Cacciari, Rojo, GPS & Soyez '08

Other related work: Krohn, Thaler & Wang '09

Scan through  $q\bar{q}$  mass values $m_{qq} = 4000 \text{ GeV}$  $qq, M = 4000 \text{ GeV}$ Best  $R$  is at minimum of curve

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Soyez '10

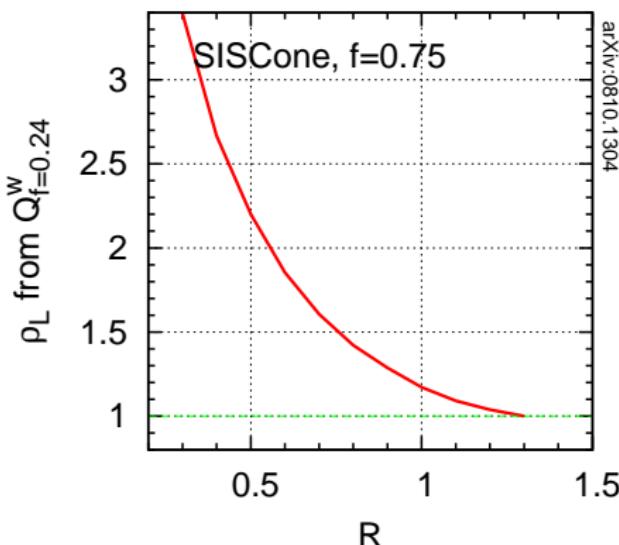
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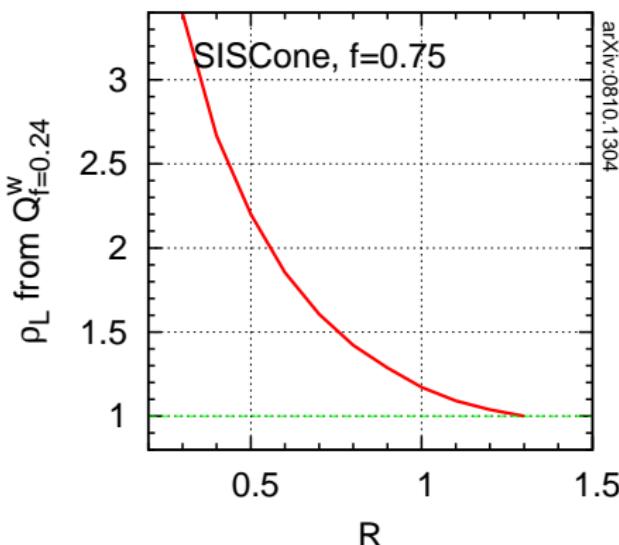
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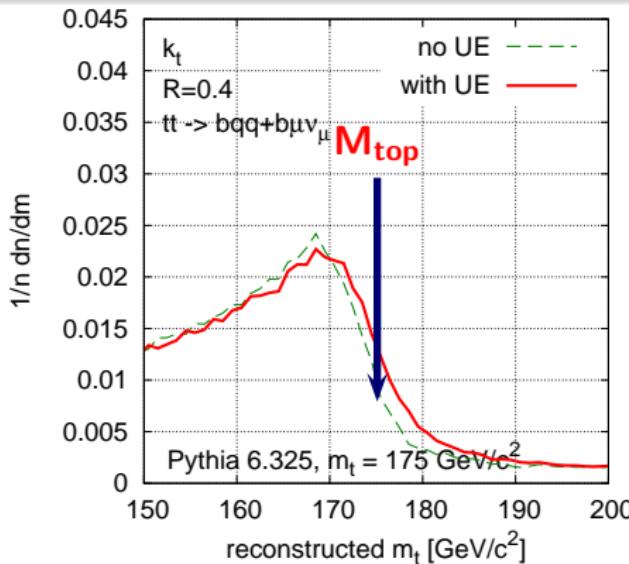
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Cacciari, Rojo, GPS & Soyez '08

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How does this carry over for precision physics?

# Robustness: $M_{top}$ varies with $R$ ?



Game: measure top mass to 1 GeV

example for Tevatron

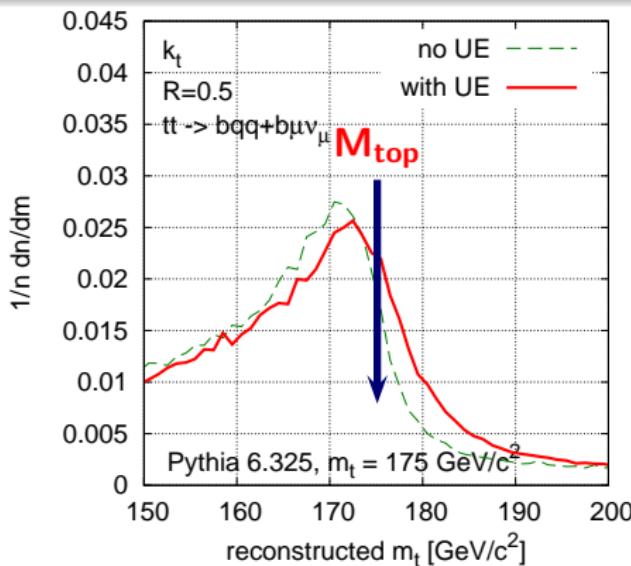
$$m_t = 175 \text{ GeV}$$

- ▶ Small  $R$ : lose 6 GeV to PT radiation and hadronisation, UE and pileup irrelevant
- ▶ Large  $R$ : hadronisation and PT radiation leave mass at  $\sim 175$  GeV, UE adds 2 – 4 GeV.

Is the final top mass (after  $W$  jet-energy-scale and Monte Carlo unfolding) independent of  $R$  used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects  
cf. Seymour & Teylin '06

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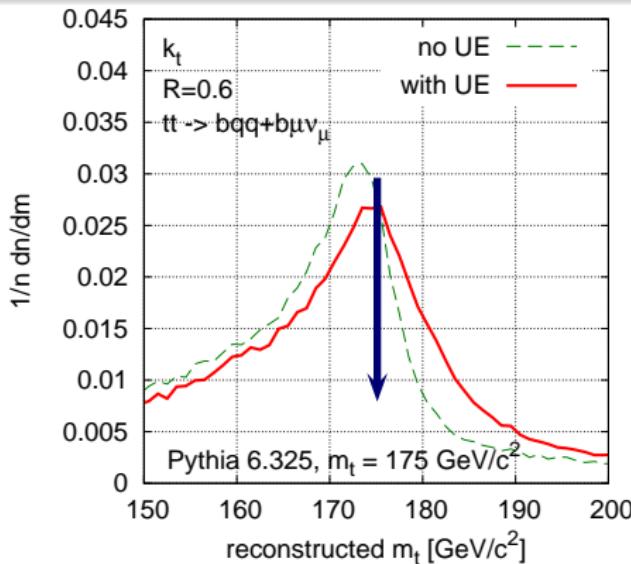
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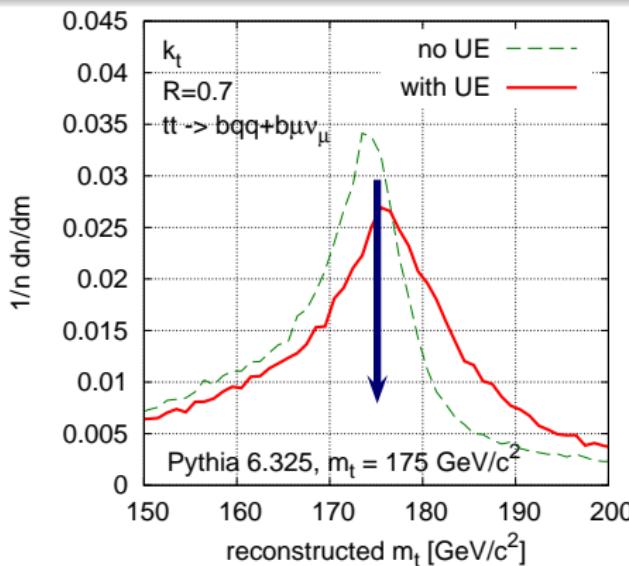
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Is the final top mass (after  $W$  jet-energy-scale and Monte Carlo unfolding) independent of  $R$  used to measure jets?

Flexibility in jet finding gives powerful cross-check of systematic effects  
cf. Seymour & Tevlin '06

# Robustness: $M_{top}$ varies with $R$ ?



Game: measure top mass to 1 GeV

example for Tevatron

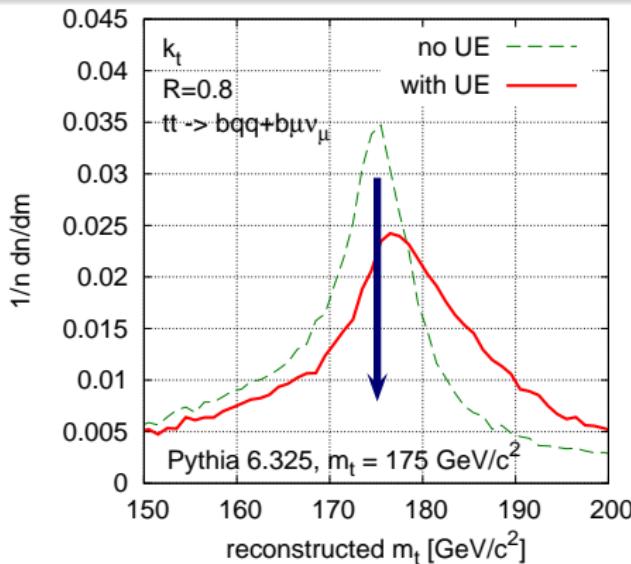
$$m_t = 175 \text{ GeV}$$

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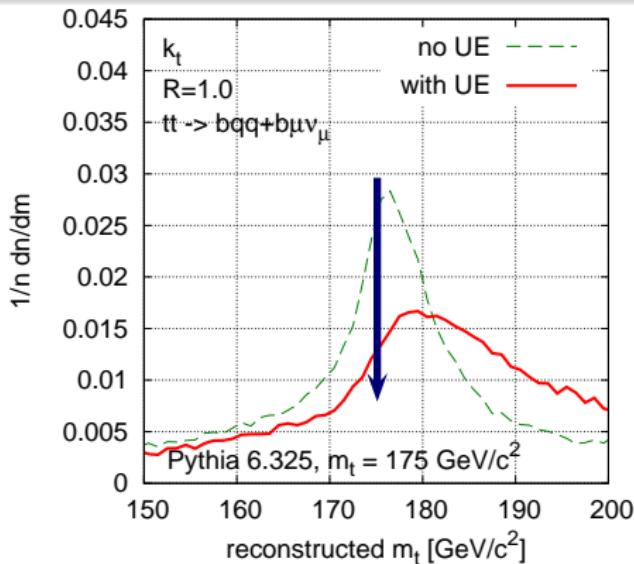
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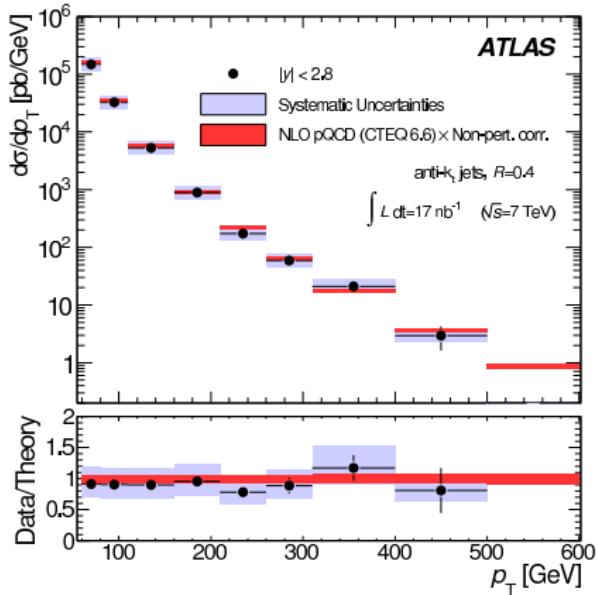
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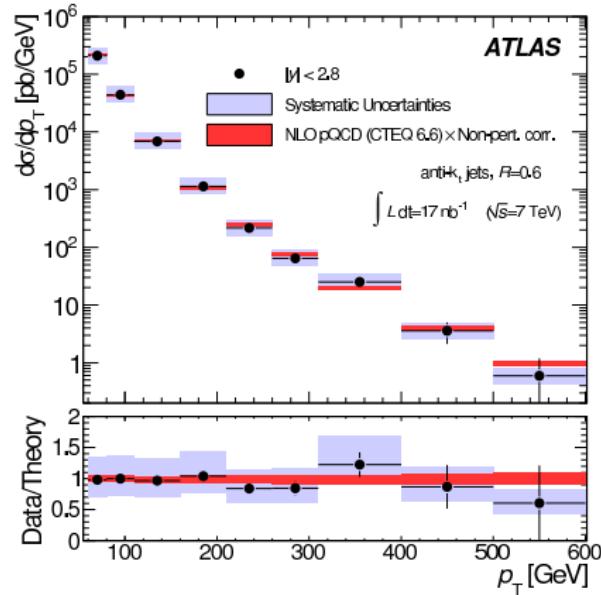
Flexibility in jet finding gives powerful cross-check of systematic effects  
cf. Seymour & Tevlin '06

# Example of use of different $R$ values (ATLAS)

$R = 0.4$



$R = 0.6$



## Inclusive jet spectrum:

robustness under change of  $R$  is important check of theory/data agreement

## Lesson 2:

Control pileup (PU) and the underlying event (UE)

UE:  $\sim 10$  GeV per unit rapidity

PU: up to  $\mathcal{O}(100)$  GeV per unit rapidity

iev 0 (irepeat 24): number of particles = 1428

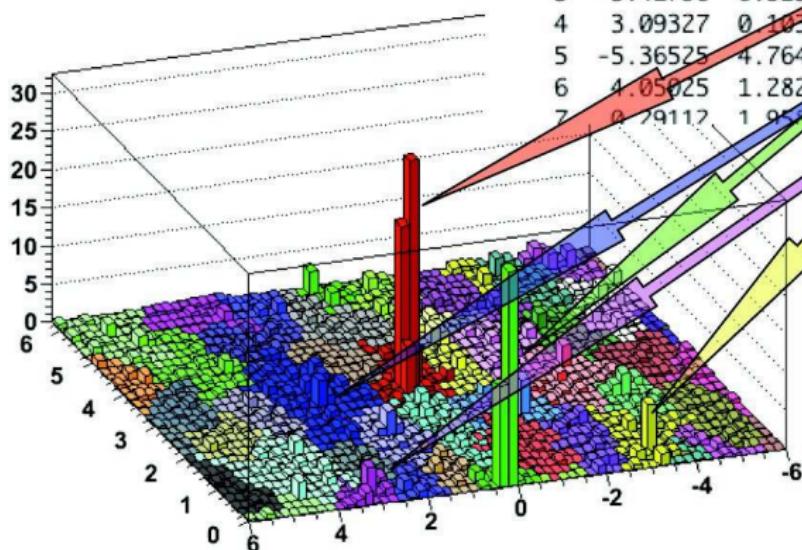
strategy used = NlnN

number of particles = 9051

Total area: 76.0265

Expected area: 76.0265

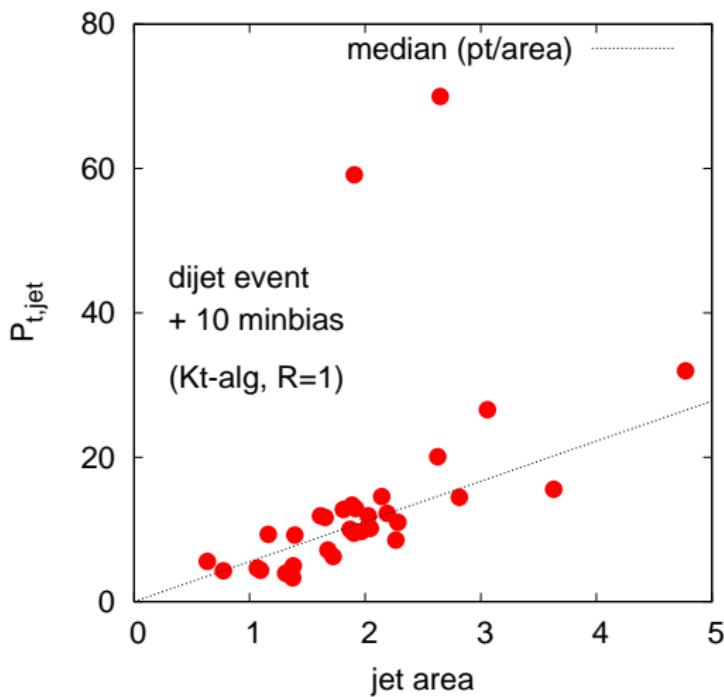
| ijet | eta      | phi     | Pt     | area  | +- | err   |
|------|----------|---------|--------|-------|----|-------|
| 0    | 0.15050  | 3.24498 | 69.970 | 2.625 | +- | 0.020 |
| 1    | 0.18579  | 0.13150 | 59.133 | 1.896 | +- | 0.020 |
| 2    | 2.33840  | 3.23960 | 31.976 | 4.749 | +- | 0.028 |
| 3    | -3.41796 | 0.52394 | 26.535 | 3.084 | +- | 0.021 |
| 4    | 3.09327  | 0.10350 | 22.072 | 2.688 | +- | 0.023 |
| 5    | -5.36525 | 4.76491 | 19.582 | 2.780 | +- | 0.012 |
| 6    | 4.05025  | 1.28279 | 15.861 | 3.592 | +- | 0.028 |
| 7    | 0.29112  | 1.95145 | 11.566 | 2.114 | +- | 0.018 |



Approximate linear relation  
between Pt and area for  
minimum bias jets.

Can be used on an event-by-  
event basis to correct the hard  
jets

# Estimating $\rho \equiv$ background noise level



Most jets in event are “background”

Their  $p_t$  is correlated with their area.

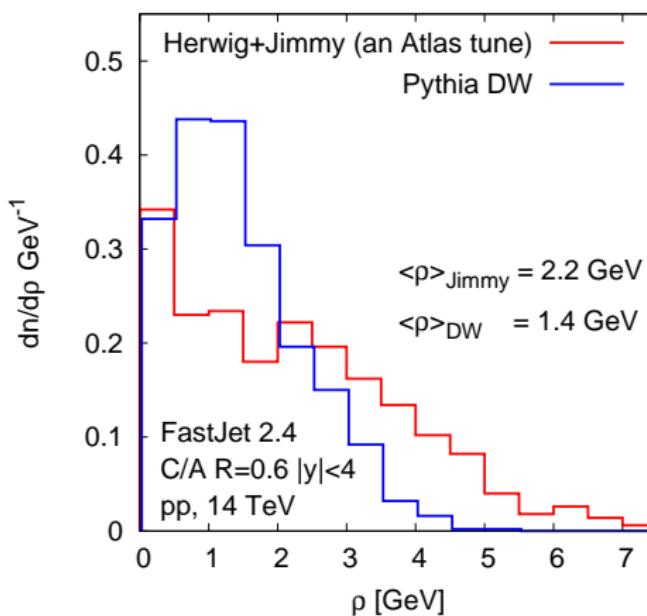
**Estimate  $\rho$ :**

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

Median limits bias  
from hard jets  
Cacciari & GPS '07

# Probability dist. of $\rho$ , the UE $p_t$ density

E.g. take dijet events with  $p_t > 50$  GeV, extract  $\rho$  from the median procedure. Look at **distribution** of  $\rho$  across events:



Cacciari, GPS & Sapeta '09

Result for  $\rho$  consistent in topological and jet-based methods;

But also get event-by-event dist.

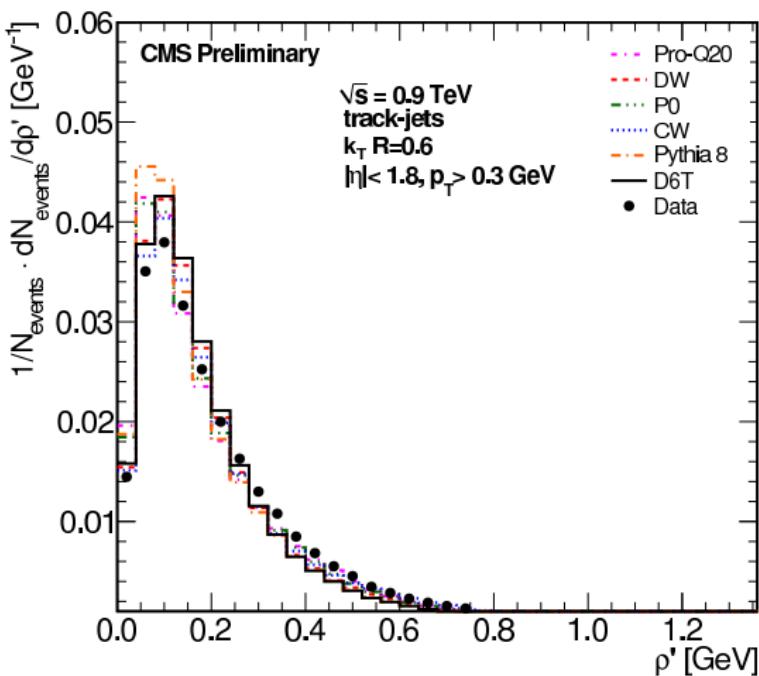
Jet-based method works in complex events too (e.g.  $t\bar{t}$ )

E.g. select quiet events  
for clean studies

# Median/area measurement of UE by CMS

First measurement of fluctuations in the underlying event based on variant of this method.

Applied to track-jets (to reduce calorimeter systematics).



CMS preliminary  
from  $\sqrt{s} = 900 \text{ GeV}$  data

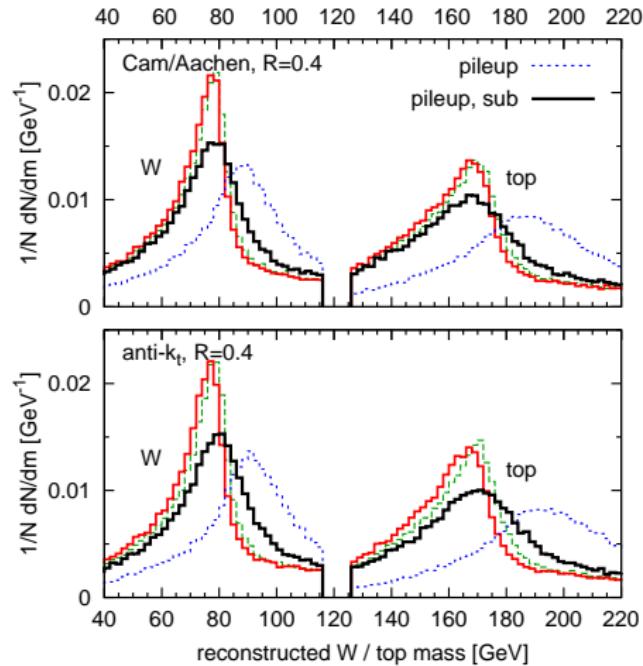
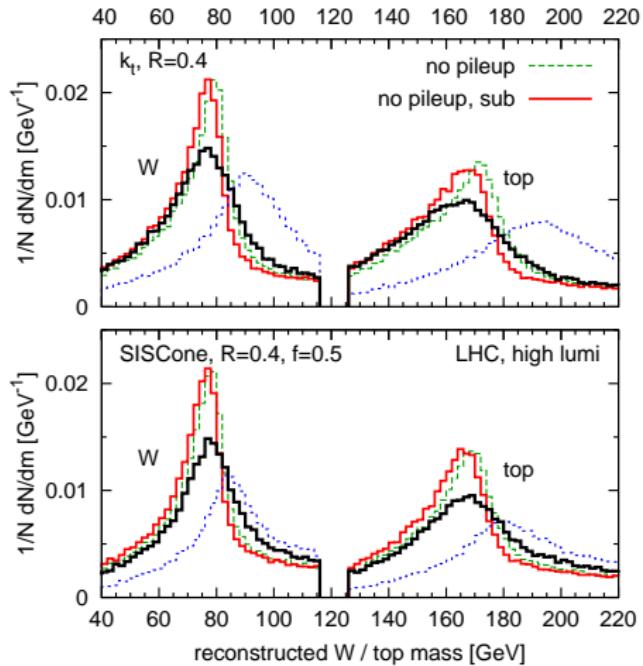
$$p_{t,jet}^{\text{subtracted}} = p_{t,jet} - \rho \times A_{jet}$$

$A_{jet}$  = jet area

$\rho = p_t$  per unit area from underlying event  
(or “background”)

This procedure is intended to be common to pp, pp with pileup (multiple simultaneous minbias) and HIC

# Pileup subtraction applied to $t\bar{t}$ events



## How does this matter for $W$ , $Z$ measurements?

- ▶ Precision  $W$  (and  $Z$ ) relies to some extent on understanding of lepton isolation.
- ▶ Lepton isolation relies on understanding of energy flow in the event.

Methods developed for pileup subtraction open door to **event-by-event** isolation criteria.

**Most jet work so far hasn't been directly related to precision W,Z**

**But recent progress may still have benefits for W/Z studies**

- ▶ Adoption of infrared-safe anti- $k_t$  algorithm
- ▶ Flexibility of jet finding, important for discovery, can also be useful for precision studies
- ▶ Event-by-event measurement of UE/pileup (e.g. for isolation)

**Other areas of recent jet progress not covered here include**

- ▶ Looking for boosted W, Z, H, top, new-physics, etc.
- ▶ Designing jet algorithms that are insensitive to UE/pileup in the first place