Basic matter about the "Jet"

-- by collecting information from materials

Mainly, slides are taken from :

Reference 1 : Katharina Muller "Jet reconstruction"

Reference 2 : Matteo Cacciari "Jets"

Some review papers such as:

"JETS AND QCD: A historical review of the discovery of the quark and gluon jets and its impact on QCD", A. Ali and G. Kramer , arXiv:1012.2288v2

"Review of jet reconstruction lgorithms", Ryan Atkin , Journal of Physics: Conference Series 645 (2015) 012008

06/29/2018

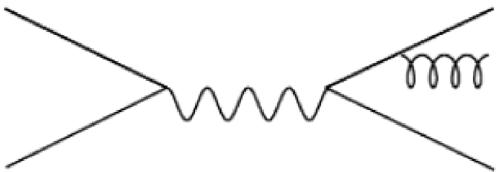
What is “Jet” ?

What are jets?

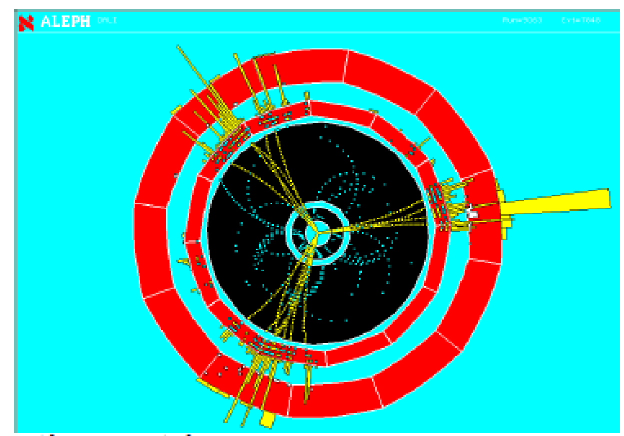
Jets for non- particle physicists

Jets for theorists

- jets of partons: gluons, quarks



ALEPH: e+e- → 3 jets

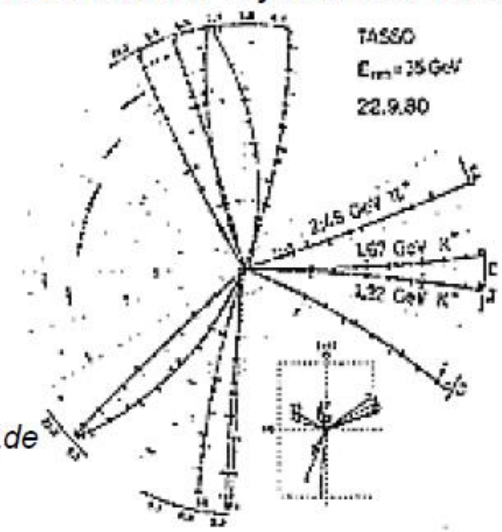


Jets for experimentalists

- bunch of particles generated by hadronization of a common source: quark, gluon fragmentation → the particles in this bunch have correlated kinematic properties
- observables in the detector: protons, neutrons, pions, photons, electrons, muons, plus other particles with lifetime > 10 ps
- non-interacting particles do not generate a signal – mostly neutrinos

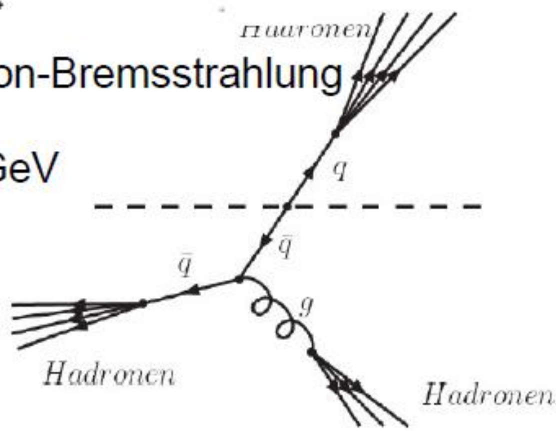
TASSO: discovery of the gluon

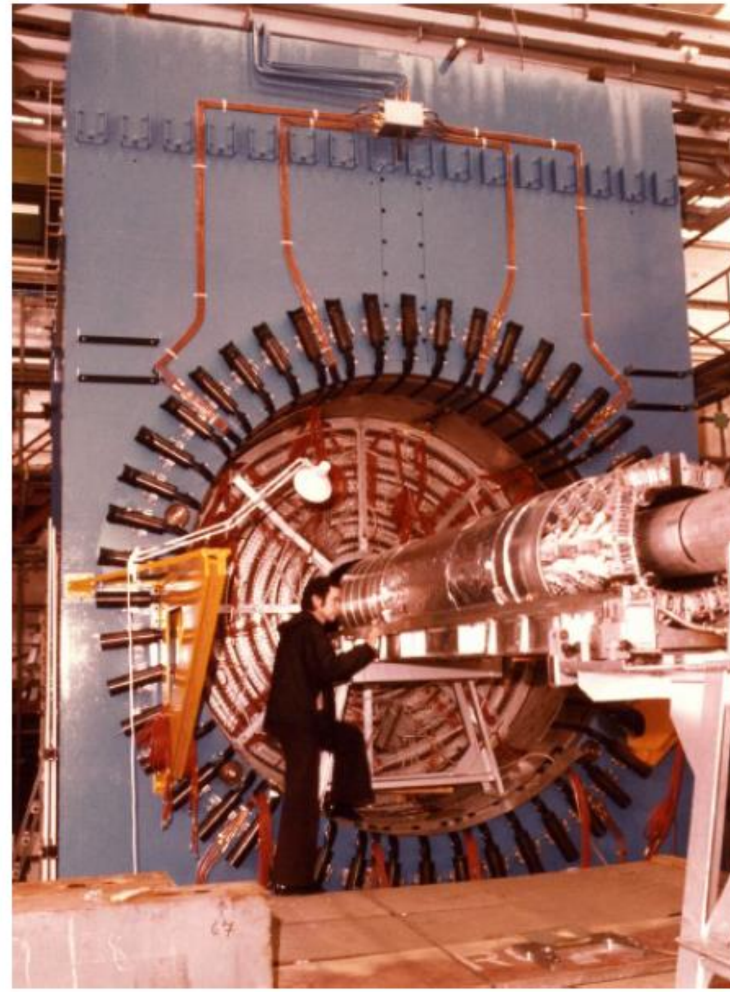
1979 observation: 3-jet event measured as TASSO



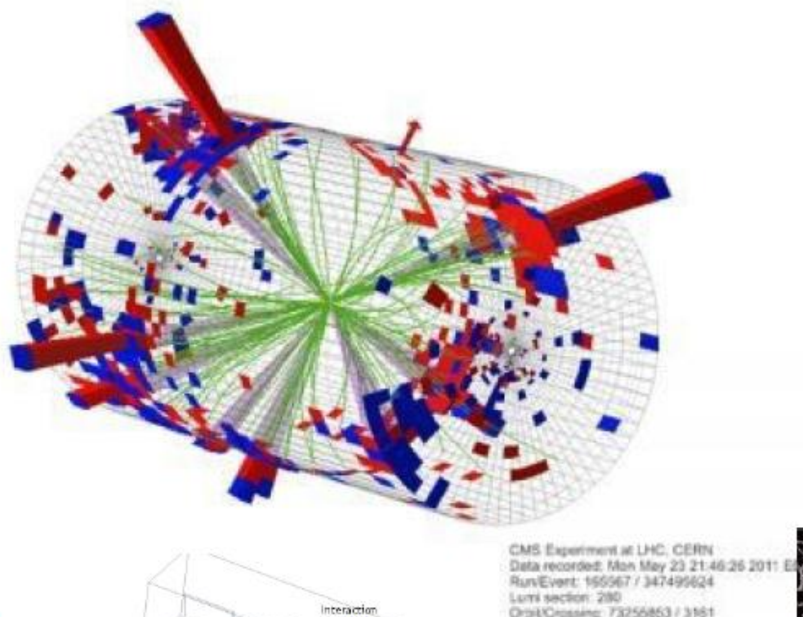
www.desy.de

Interpretation: Gluon-Bremsstrahlung
e+e- → q qbar g
cms energy 27.4 GeV



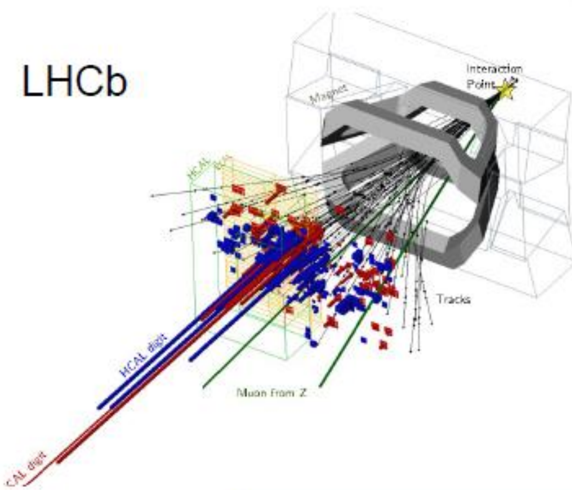


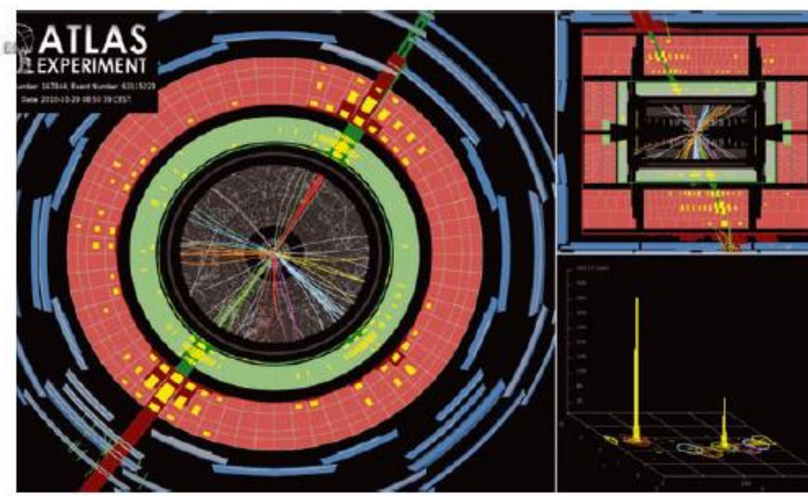
Jets at LHC



Jets:
collimated, energetic bunches of particles

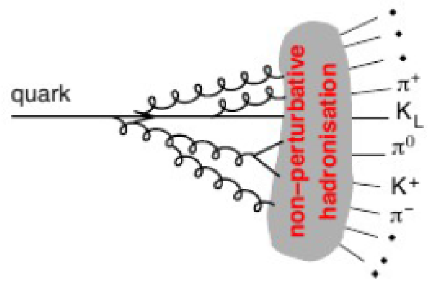
LHCb



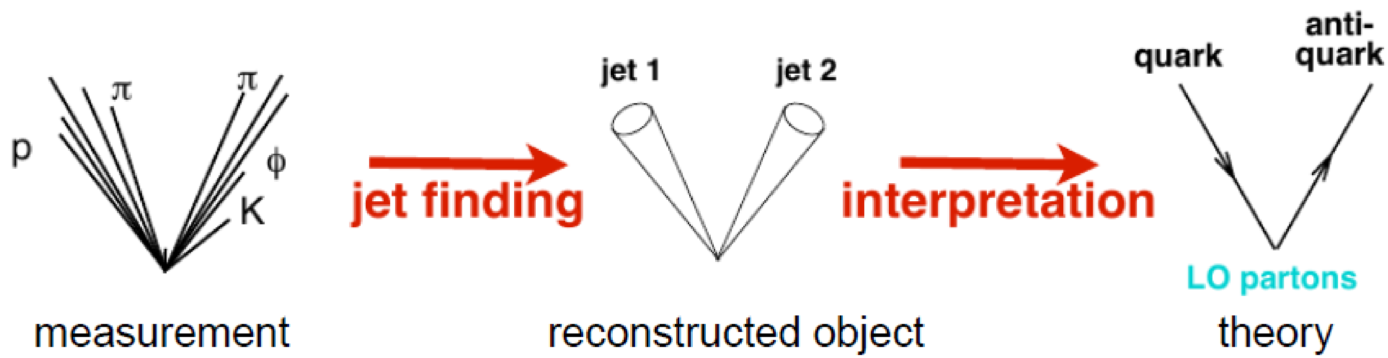


Key aspects

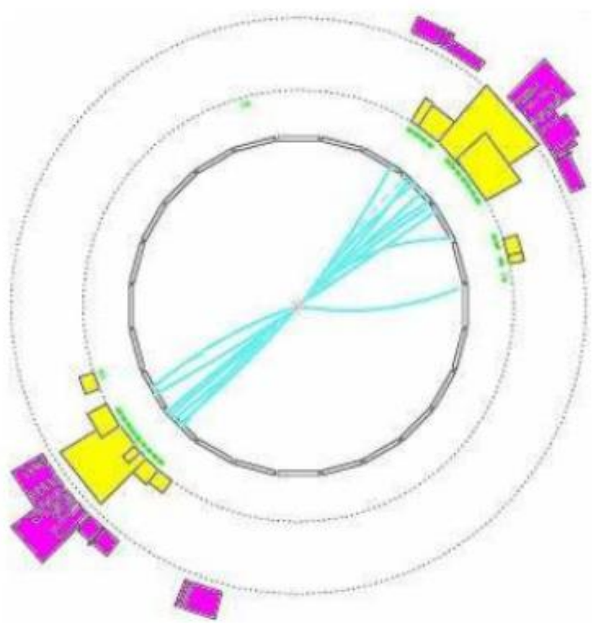
Jets get their structure through fragmentation and hadronisation

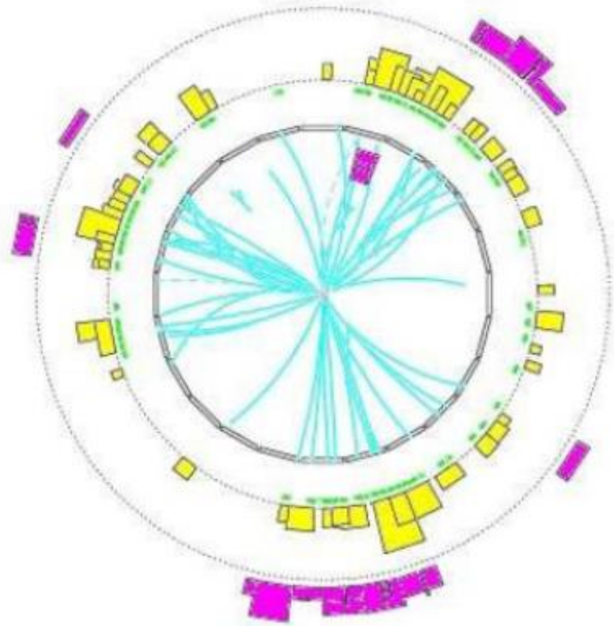


How do we reconstruct jets – correlation to underlying physics



Seeing jets



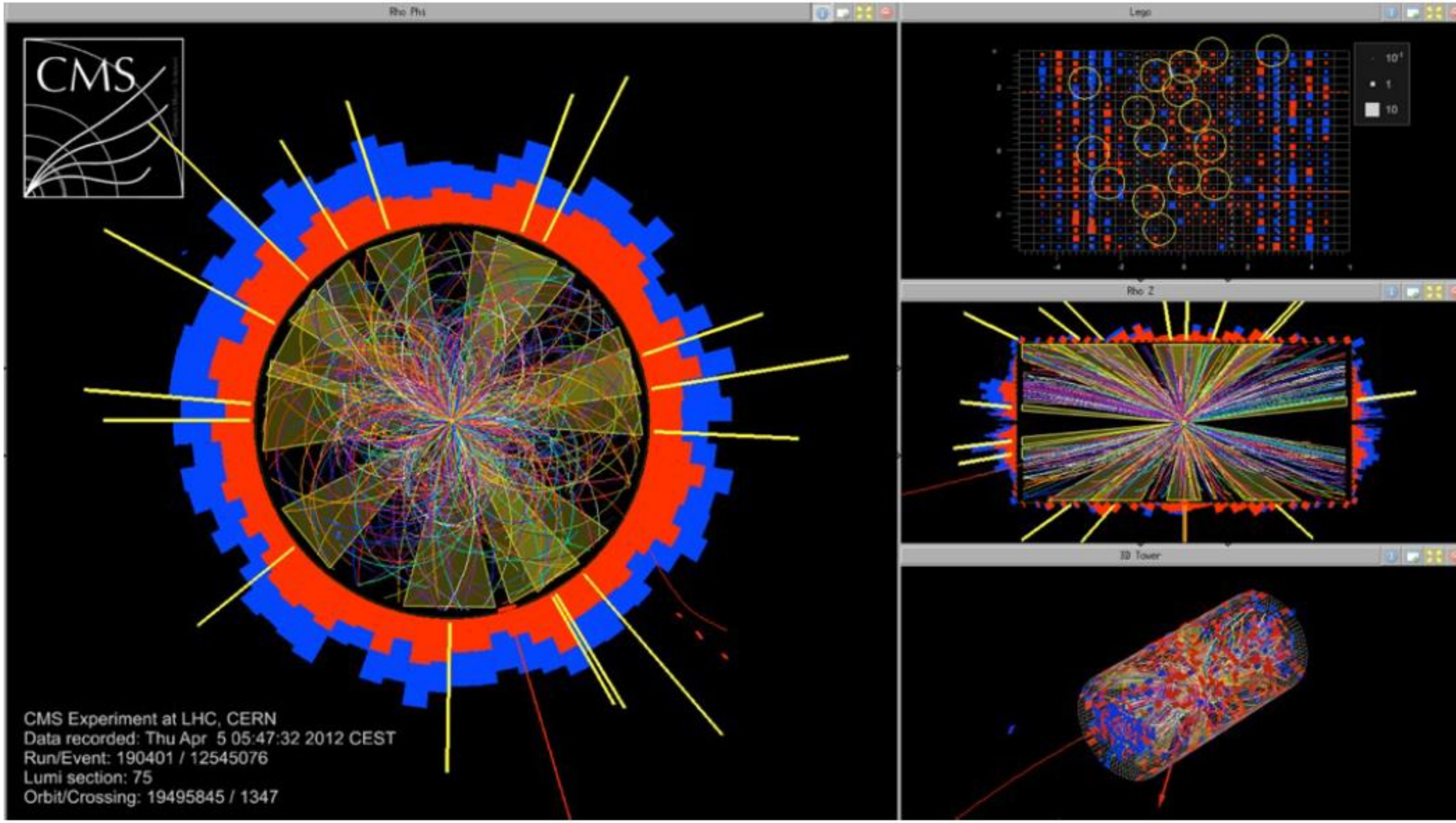


Clearly two jets

How many jets?

need to define clever algorithms to use the jet information

how many jets??

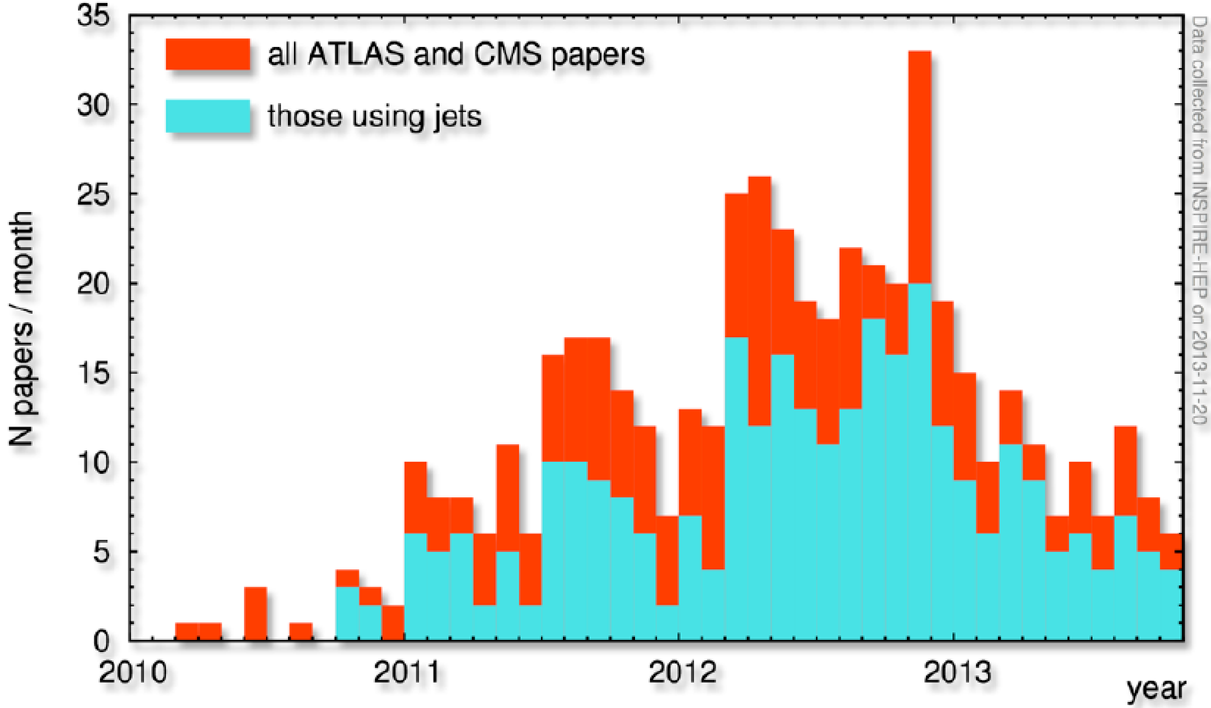


Jet reconstruction

The pervasiveness of jets

- ATLAS and CMS have each published **400+** papers since 2010
  - More than **half** of these papers make use of **jets**
  - **60%** of the **searches** papers makes use of **jets**

Plot by G. Salam

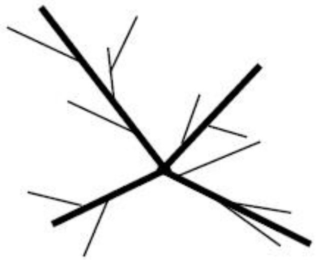


(Source: INSPIRE. Results may vary when employing different search keywords)

Why are jets so important?

Taming reality

Multileg + PS



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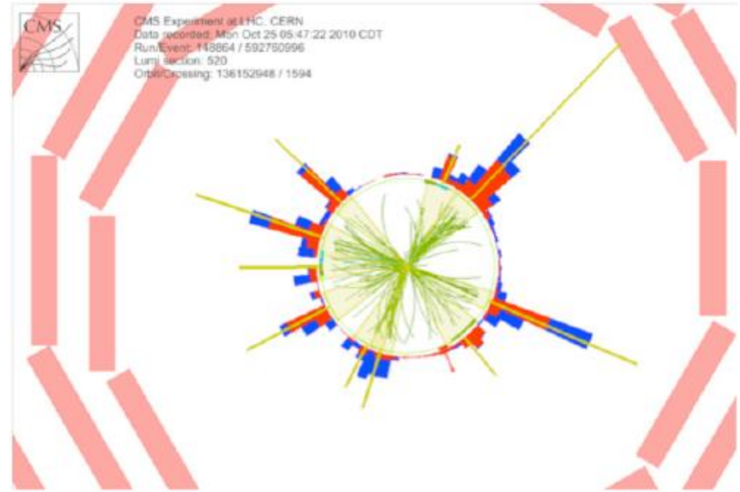


QCD predictions

Real data

Jets

One purpose of a 'jet clustering' algorithm is to **reduce the complexity** of the final state, simplifying many hadrons to **simpler objects** that one can hope to **calculate**

Jet clustering algorithm

A **jet algorithm** maps the momenta of the final state particles into the momenta of a certain number of jets:

$$\{p_i\} \xrightarrow{\text{jet algorithm}} \{j_k\}$$

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

jets

Most algorithms contain a resolution parameter, **R**, which controls the extension of the jet

Two main classes of jet algorithms

- **Sequential recombination algorithms**

  Bottom-up approach: combine particles starting from **closest ones**

  How? Choose a **distance measure**, iterate recombination until few objects left, call them jets

  Works because of mapping closeness ⇔ QCD divergence

  Examples: Jade, k_t, Cambridge/Aachen, anti-k_t, …..

- **Cone algorithms**

  Top-down approach: find coarse regions of energy flow.

  How? Find **stable cones** (i.e. their axis coincides with sum of momenta of particles in it)

  Works because QCD only modifies energy flow on small scales

  Examples: JetClu, MidPoint, ATLAS cone, CMS cone, SISCone…..

A little history

- Cone-type jets were introduced first in QCD in the 1970s (Sterman-Weinberg '77)
- In the 1980s cone-type jets were adapted for use in hadron colliders (SppS, Tevatron...) → iterative cone algorithms
- LEP was a golden era for jets: new algorithms and many relevant calculations during the 1990s
  - Introduction of the 'theory-friendly' k_t algorithm
    - sequential recombination type algorithm, IRC safe
    - it allows for all order resummation of jet rates
  - Several accurate calculations in perturbative QCD of jet properties: rates, jet mass, thrust, ...

e^+e^- k_t (Durham) algorithm

[Catani, Dokshitzer, Olsson, Turnock, Webber '91]

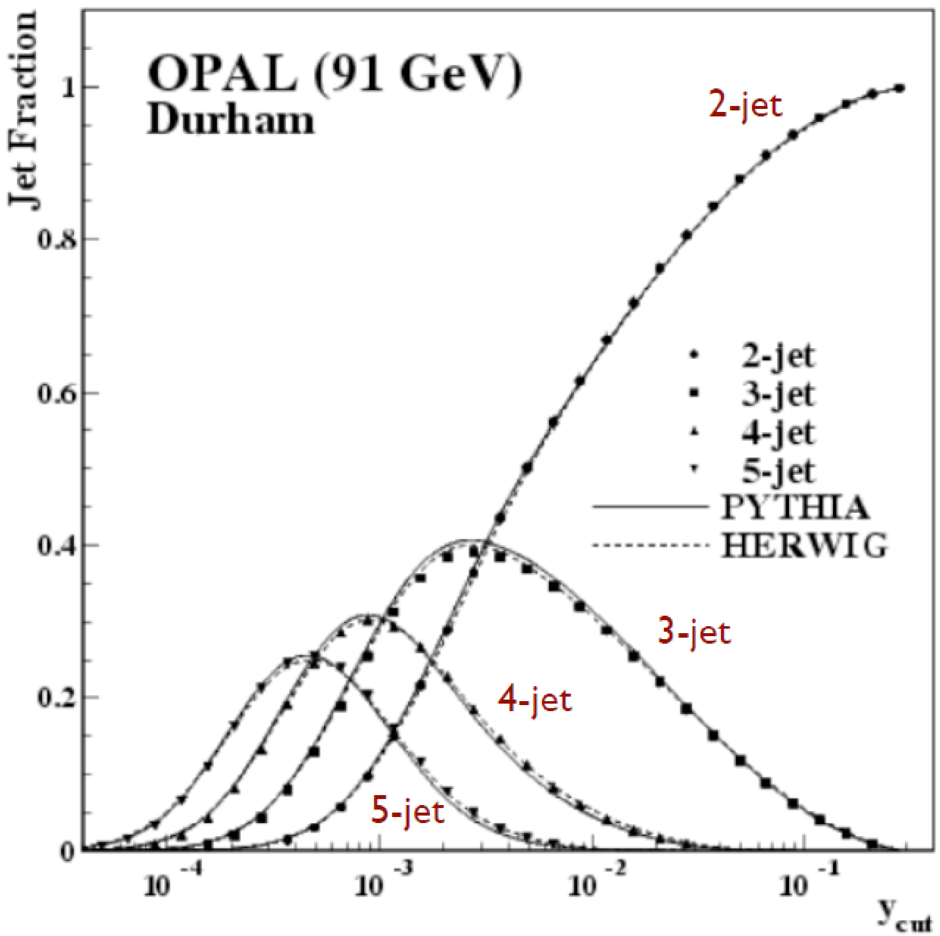
Distance:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

In the collinear limit, the numerator reduces to the **relative transverse momentum** (squared) of the two particles, hence the name of the algorithm

- Find the minimum y_{min} of all y_{ij}
- If y_{min} is below some jet resolution threshold y_{cut}, recombine i and j into a single new particle ('pseudojet'), and repeat
- If no $y_{min} < y_{cut}$ are left, all remaining particles are jets

e^+e^- k_t (Durham) algorithm in action



Characterise events in terms of number of jets (as a function of y_{cut})

Resummed calculations for distributions of y_{cut} doable with the k_t algorithm

e^+e^- k_t (Durham) algorithm v. QCD

k_t is a sequential recombination type algorithm

One key feature of the k_t algorithm is its relation to the structure of QCD divergences:

$$\frac{dP_{k\to ij}}{dE_i d\theta_{ij}} \sim \frac{\alpha_s}{\min(E_i, E_j)\theta_{ij}}$$

The y_{ij} distance is the inverse of the emission probability

- The k_t algorithm roughly inverts the QCD branching sequence (the pair which is recombined first is the one with the largest probability to have branched)
- The history of successive clusterings has physical meaning

The k_t algorithm and its siblings

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = k_{ti}^{2p}$$

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

p = 0 Cambridge/Aachen algorithm

Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001
M.Wobisch and T.Wengler, hep-ph/9907280

p = -1 **anti-k_t algorithm**

MC, G. Salam and G. Soyez, arXiv:0802.1189

NB: in anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

Quite ironically, a sequential recombination algorithm is the 'perfect' cone algorithm

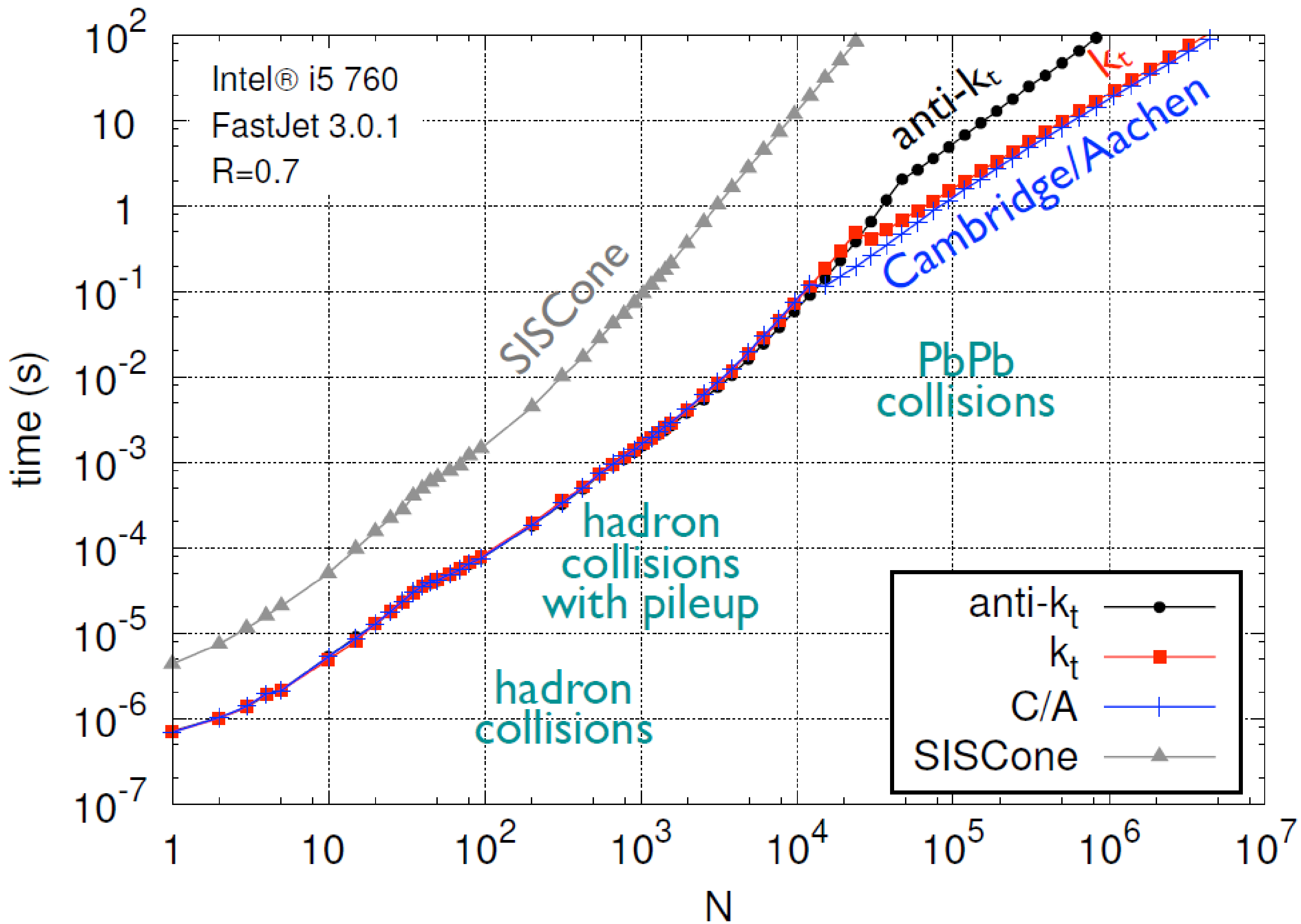
Comparison of (some) jet algorithm

-- A little bit detail for this S.P.

-- But it seems it is just first step for "jet community"

FastJet speed

Time needed to cluster an event with N particles



Hard jets and background

How are the hard jets modified by the background?

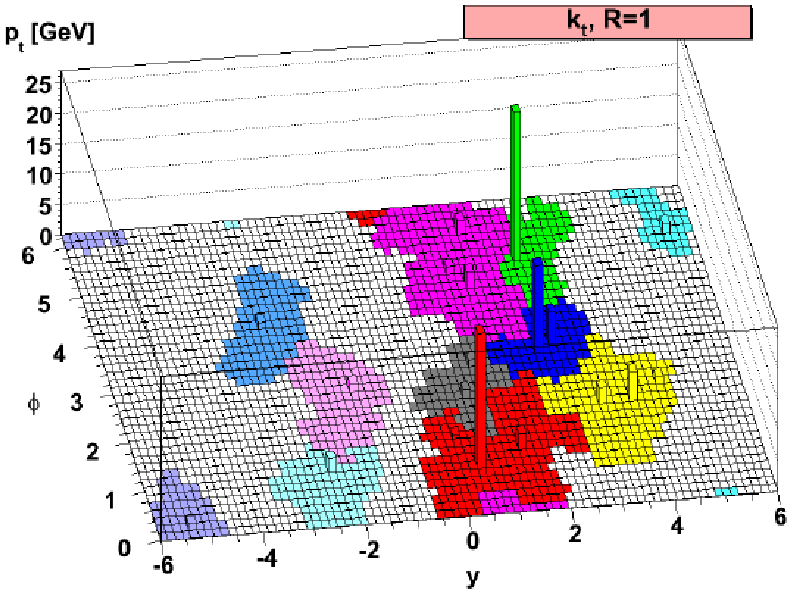
Susceptibility (how much bkgd gets picked up)	**Jet areas**
Resiliency (how much the original jet changes)	**Backreaction**

Jet areas

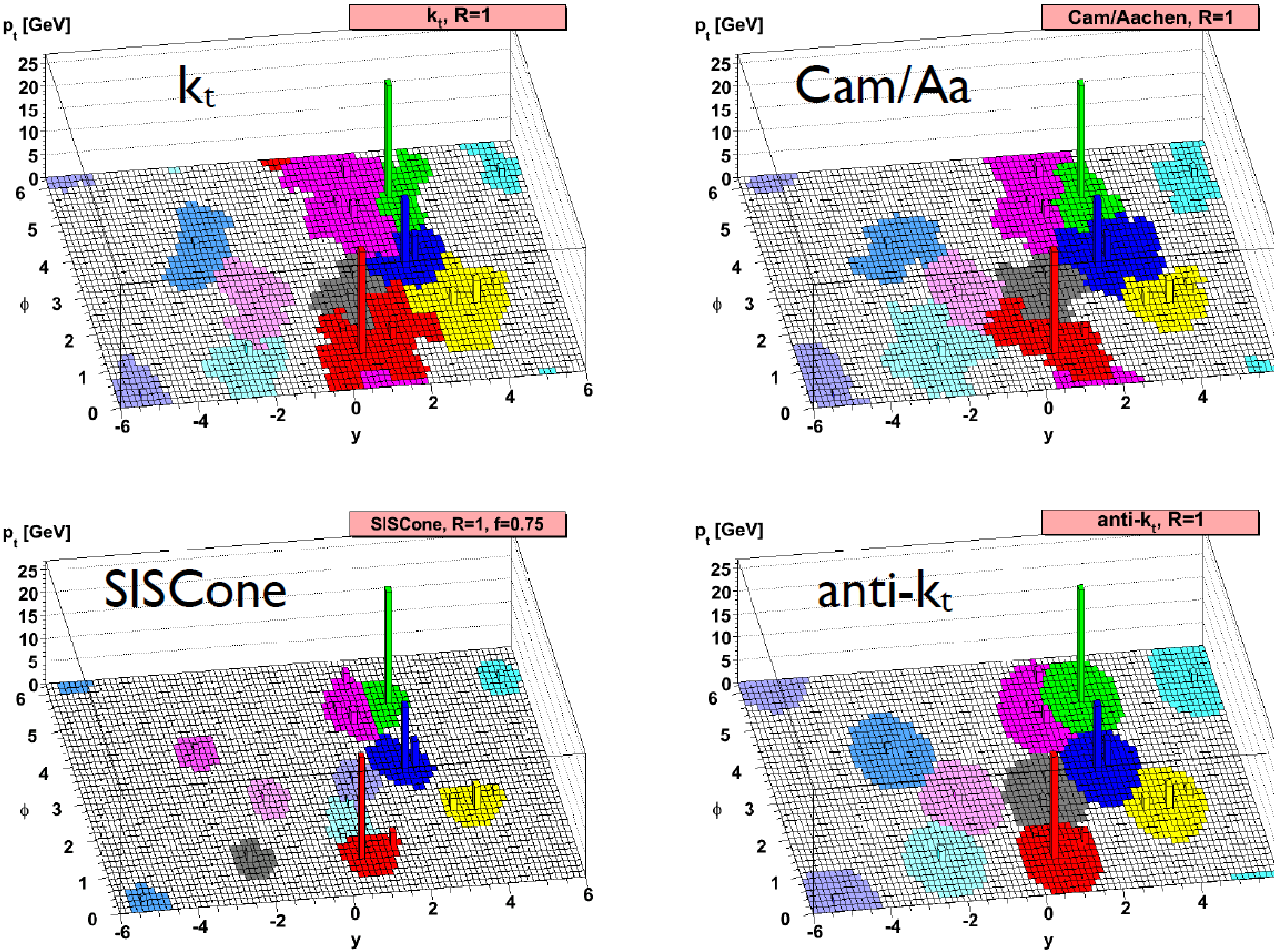
A jet's area is **defined** as the extent of the region where infinitesimally soft particles get clustered into the jet

More in details, a jet's **active area** is the extent of the region where a distribution of infinitesimally soft particles, that can also cluster among themselves, is clustered into the jet

A jet's active area measures a jet's sensitivity to contamination from soft particles like underlying event and pileup



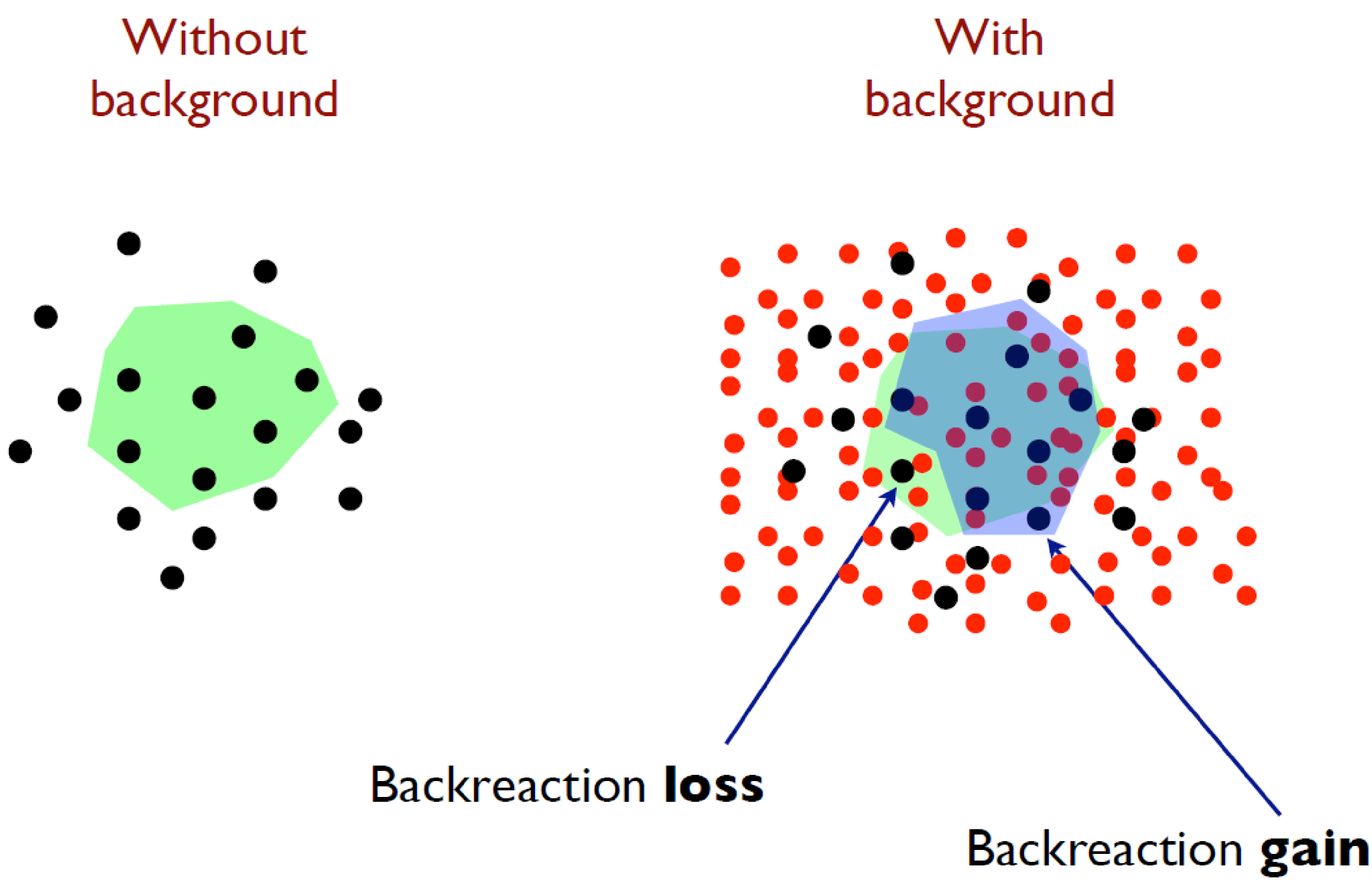
Jets do not necessarily have cone-shaped profiles



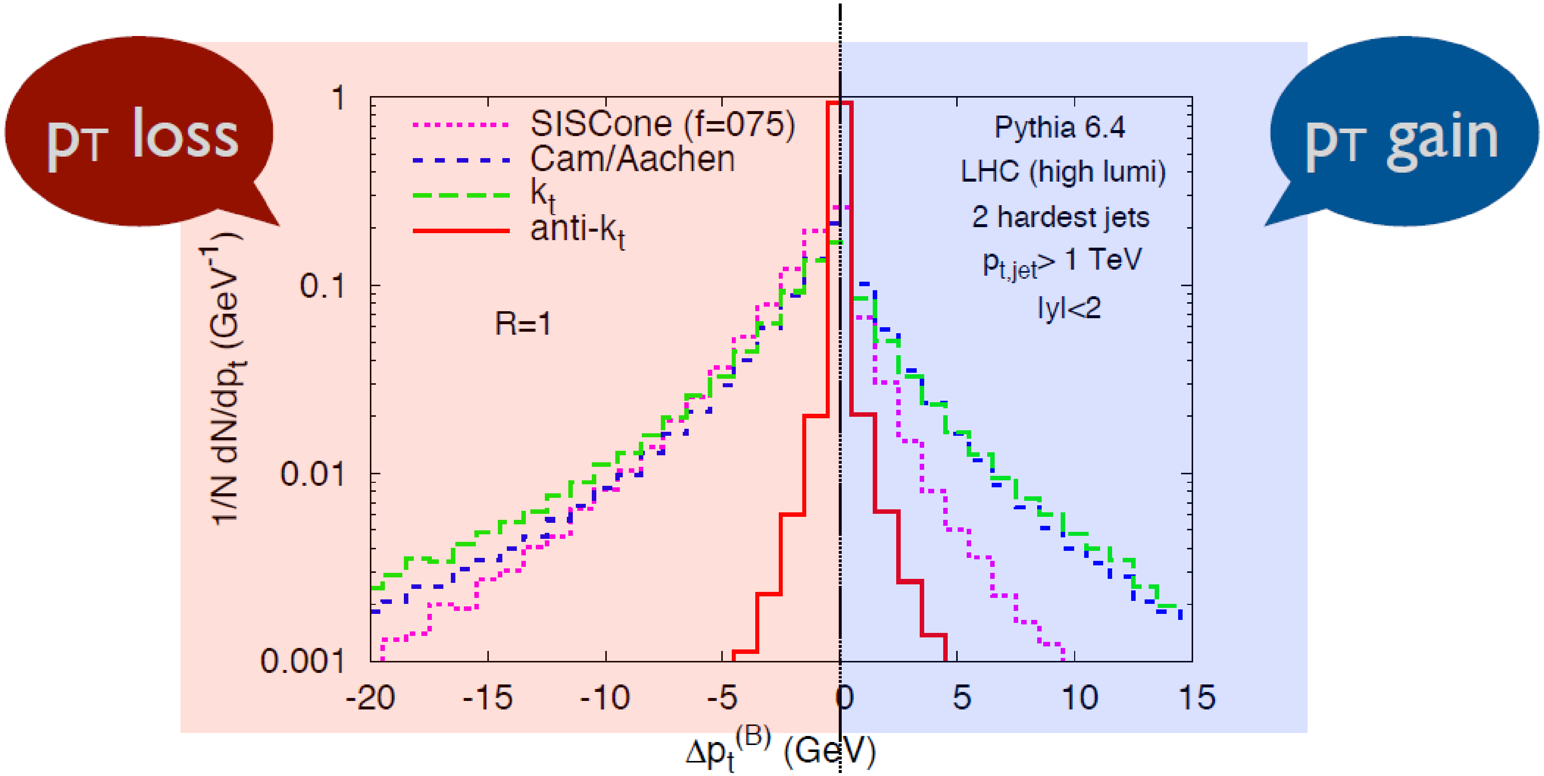
kt, R=1
kt
pt [GeV]
0 5 10 15 20 25
φ
0 1 2 3 4 5 6
y
-6 -4 -2 0 2 4 6
Cam/Aachen, R=1
Cam/Aa
pt [GeV]
0 5 10 15 20 25
φ
0 1 2 3 4 5 6
y
-6 -4 -2 0 2 4 6
SISCone, R=1, f=0.75
SISCone
pt [GeV]
0 5 10 15 20 25
φ
0 1 2 3 4 5 6
y
-6 -4 -2 0 2 4 6
anti-kt, R=1
anti-kt
pt [GeV]
0 5 10 15 20 25
φ
0 1 2 3 4 5 6
y
-6 -4 -2 0 2 4 6

Resiliency: backreaction

"How (much) a jet changes when immersed in a background"



Resiliency: backreaction

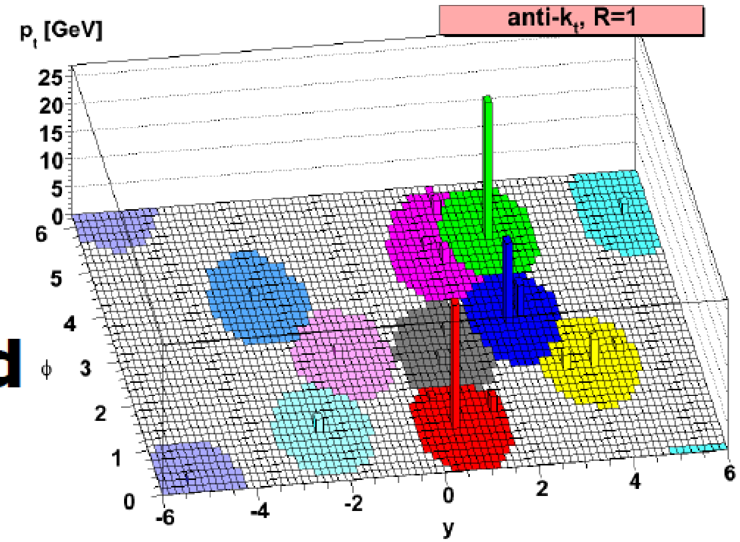


Anti-k_t jets are much more resilient to changes from background immersion

(NB. Backreaction is a minimal issue in pp background and at large pt.
Can be much more important in Heavy Ion collisions)

Anti-k_t jets and background

Anti-k_t jets **maximise resiliency**, and their regular shapes makes them **easier to correct for detector-related effects**



Default choice of all LHC collaborations

The IRC safe algorithms

	Speed	Regularity	UE/pileup contamination	Backreaction	Hierarchical substructure
k_t	☺ ☺ ☺	☂	☂☂	☁☁	
Cambridge /Aachen	☺ ☺ ☺	☂	☂	☁☁	
anti-k_t	☺ ☺ ☺	☺ ☺	☁/ ☺	☺ ☺	
SISCone	☺	☁	☺ ☺	☁	

Array of tools with different characteristics.
Pick the right one for the job

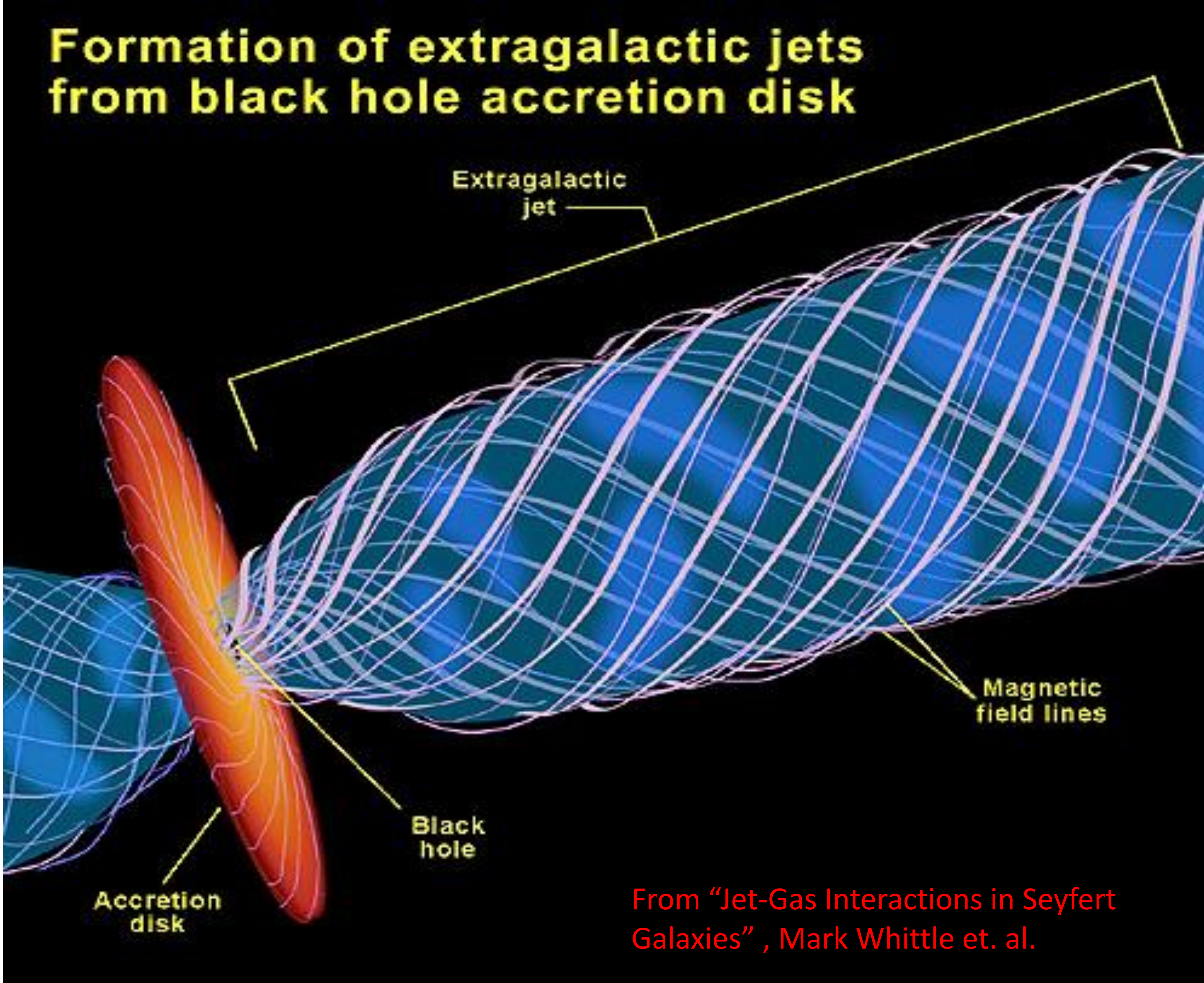
Short Summary

・ "Jet" has several "meanings" : parton "jets", hadron "jets", reconstructed "jets"

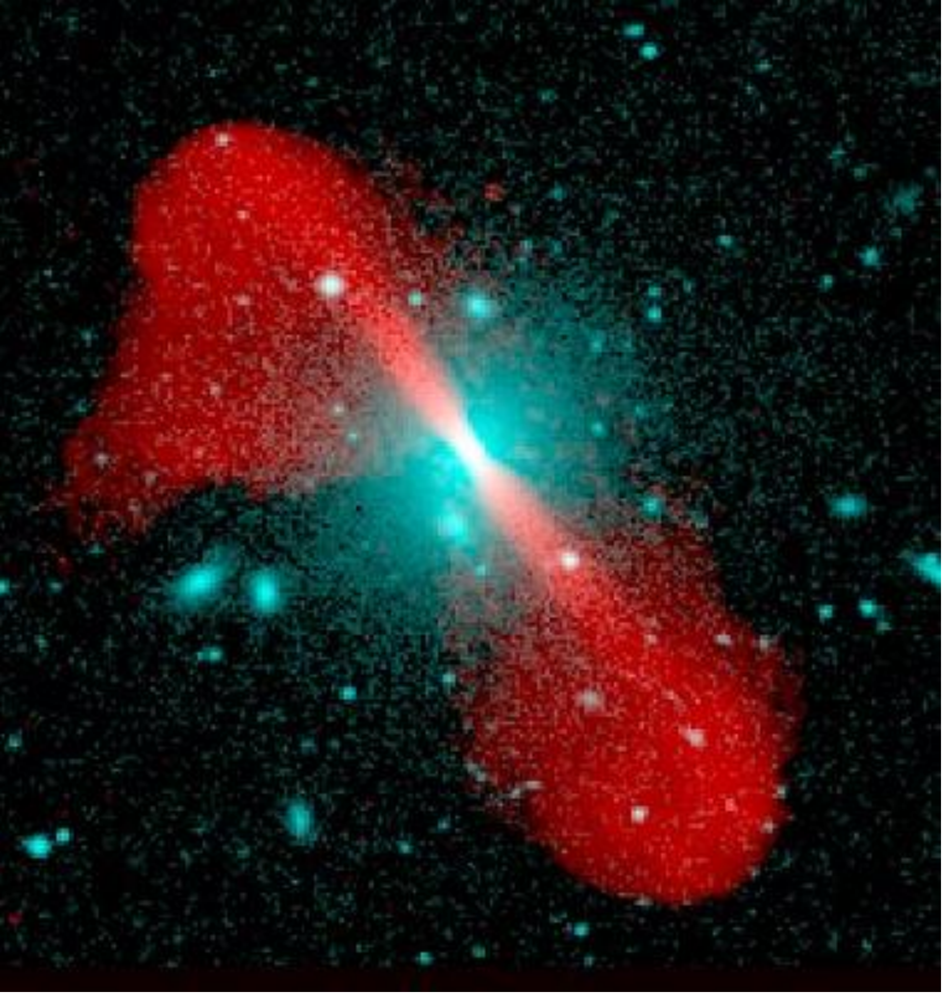
・ Jet algorithm is very hot topic from many aspects/properties.

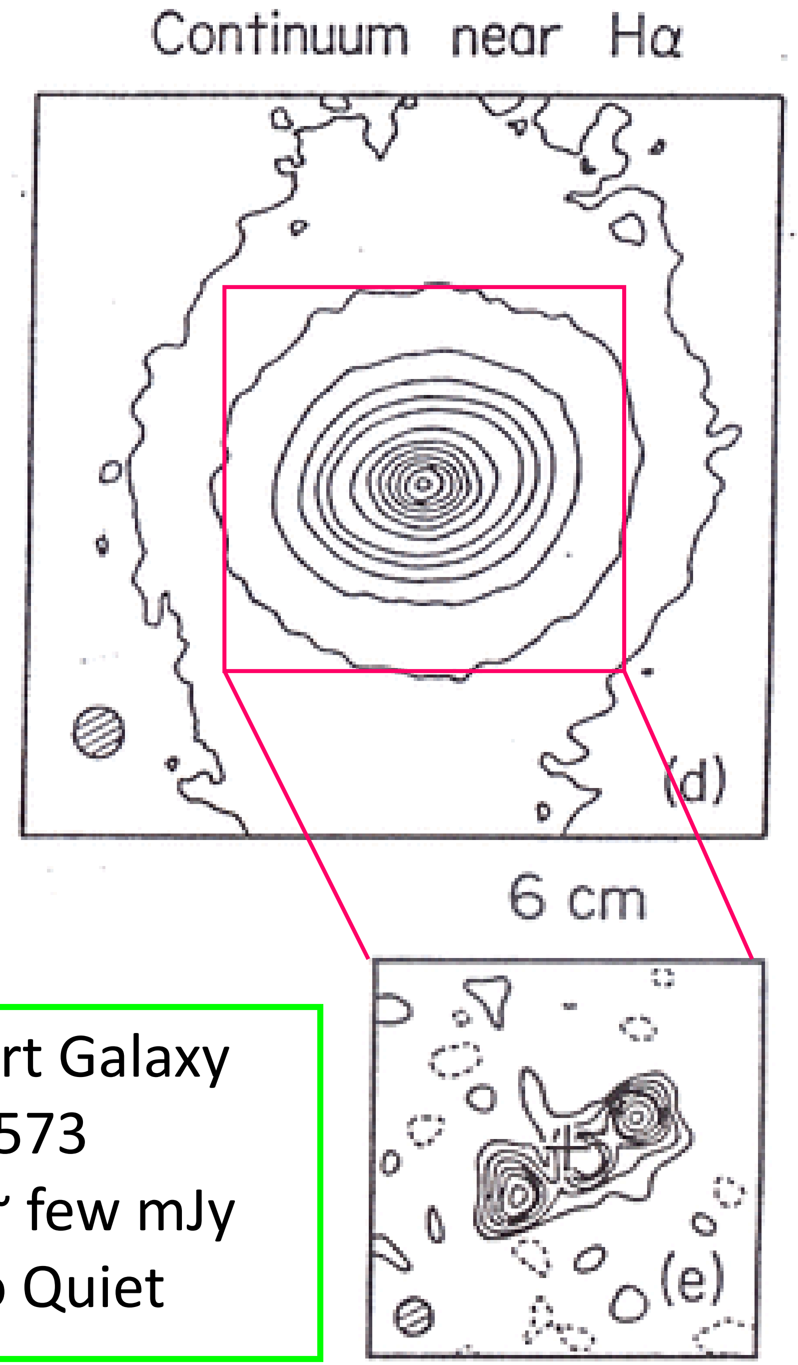
・ During the "CEPC-Physics and Software Workshop", I hear a comment that the result from different jet algorithm may differ for hadron collider (LHC) but not so much different for the lepton colliders (CEPC).

Back up



From “Jet-Gas Interactions in Seyfert Galaxies” , Mark Whittle et. al.



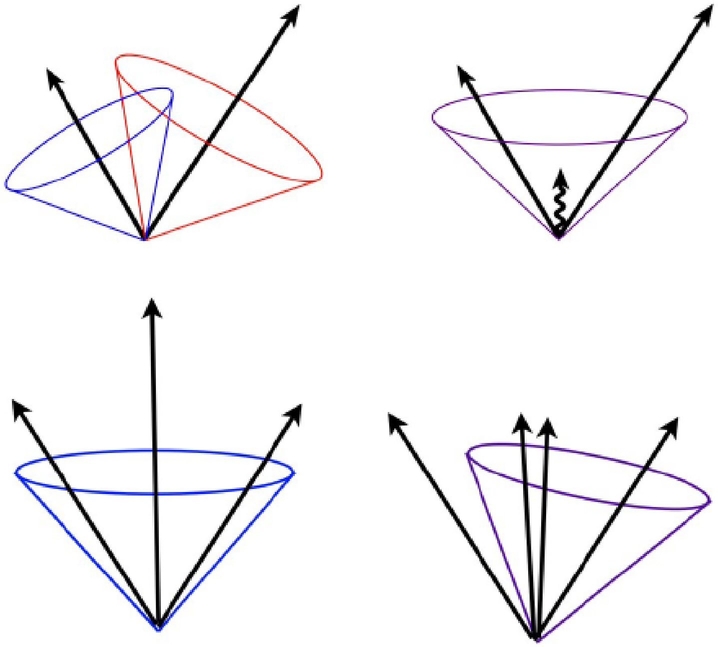


Radio Galaxy
3C 296
Flux ~ few Jy
Radio Loud

Seyfert Galaxy
Mkn 573
Flux ~ few mJy
Radio Quiet

Infrared and collinear safety

jet definition is ambiguous but
jets should be invariant with respect to certain modifications of the event:
infrared and collinear safe



infrared safe:
configuration must not change when adding a further soft particle

infrared unsafe:
after emission of soft gluon jets are merged: 2jets → 1 jet

collinear safe:
configuration does not change when substituting one particle with two collinear particles

examples: signal split into two towers
decay $\pi^0 \rightarrow \gamma\gamma$
collinear emission of a gluon
→ if jet energy and/or direction change algorithm is collinear unsafe