Jet physics at the LHC
an introduction

UoL intercollegiate postgraudate course

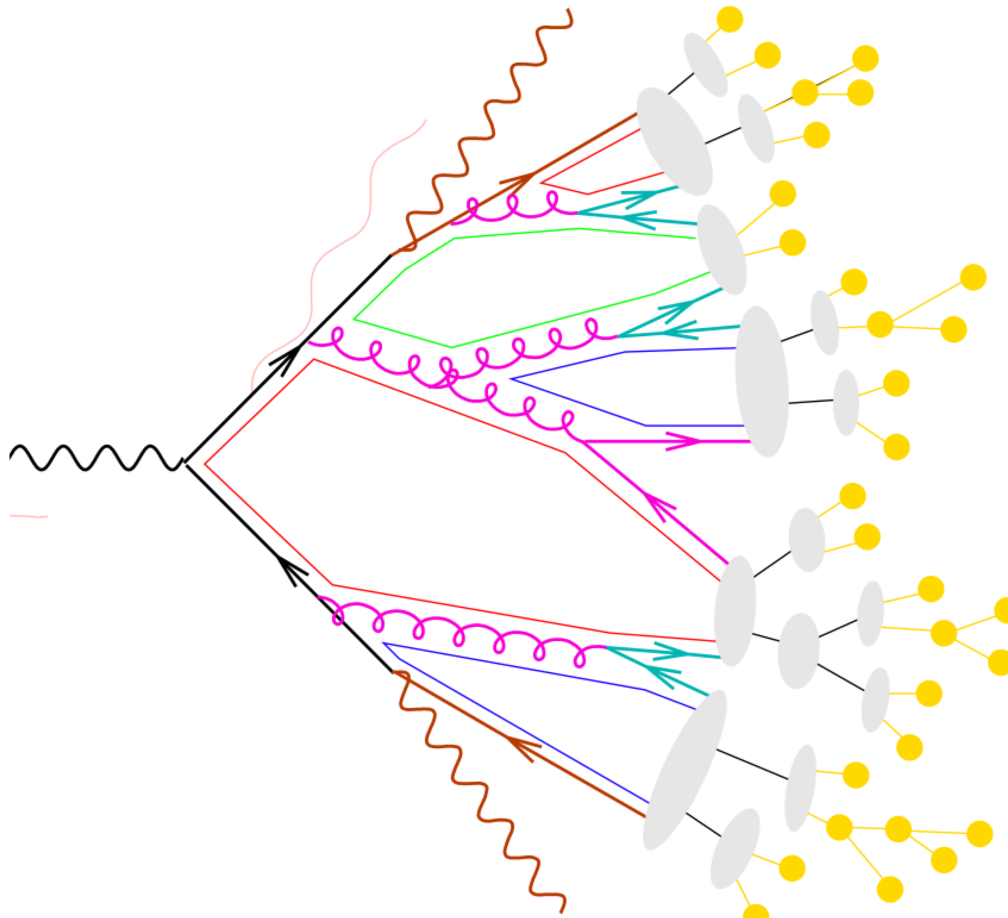
Amal Vaidya

Why do we need jets?

Consequence of QCD

- Quarks and gluons are produced at high energies (perturbative QCD)
- Will radiate more partons as they propagate
- At lower energies they will form colourless hadrons

parton (or something decaying to partons)



Mainly pions, with additional hadrons, photons and neutrinos

Reconstructing a jet gives us a proxy for the kinematics of the parent particle (and more!)

Why do we need jets?

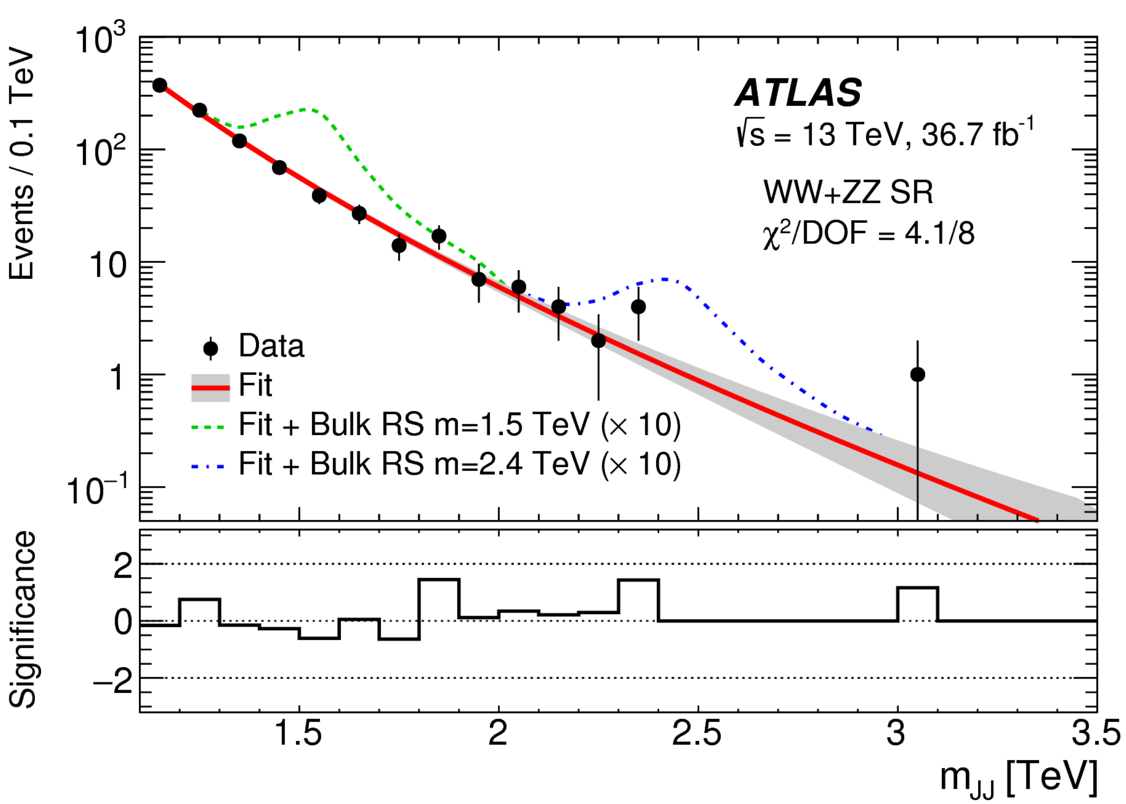
Even though they are less well defined than leptons or muons they are essential for understanding LHC physics

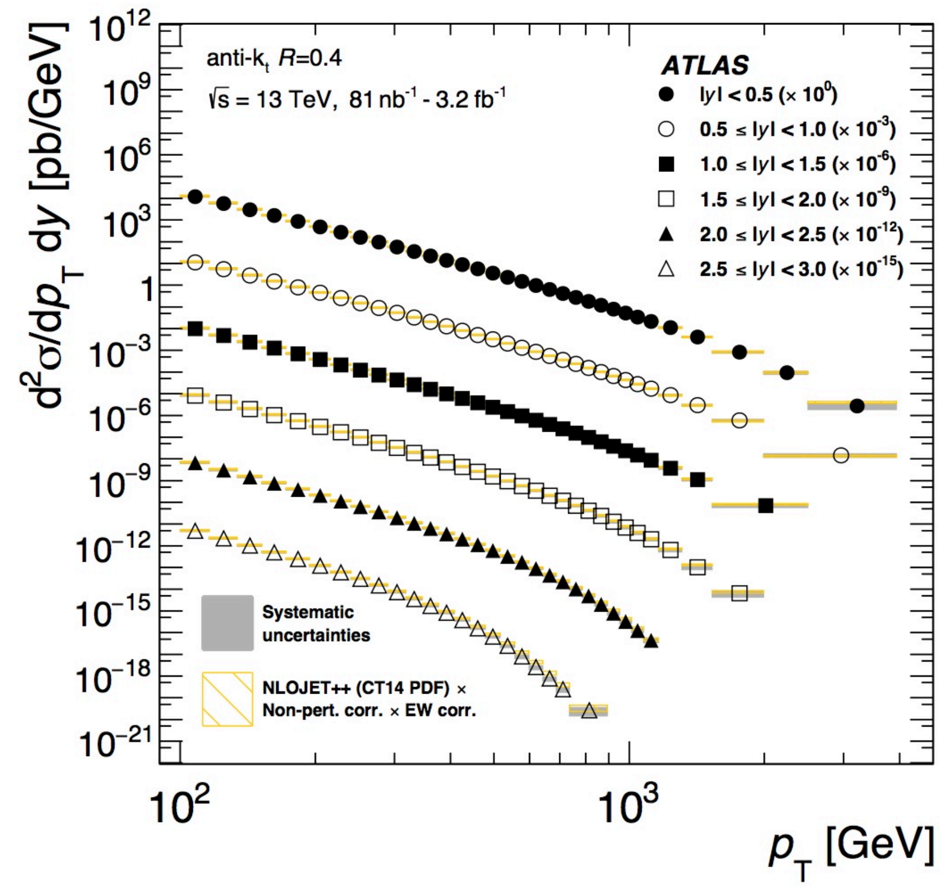
Standard Model physics:

- Many standard model processes produce jets, are sensitive to **α** strong
- Multijet cross section measurements test QCD
- Hadronic decays of heavy particles

New physics searches:

- Many searches looking for final states with jets, or in regions of phase space with high jet multiplicities



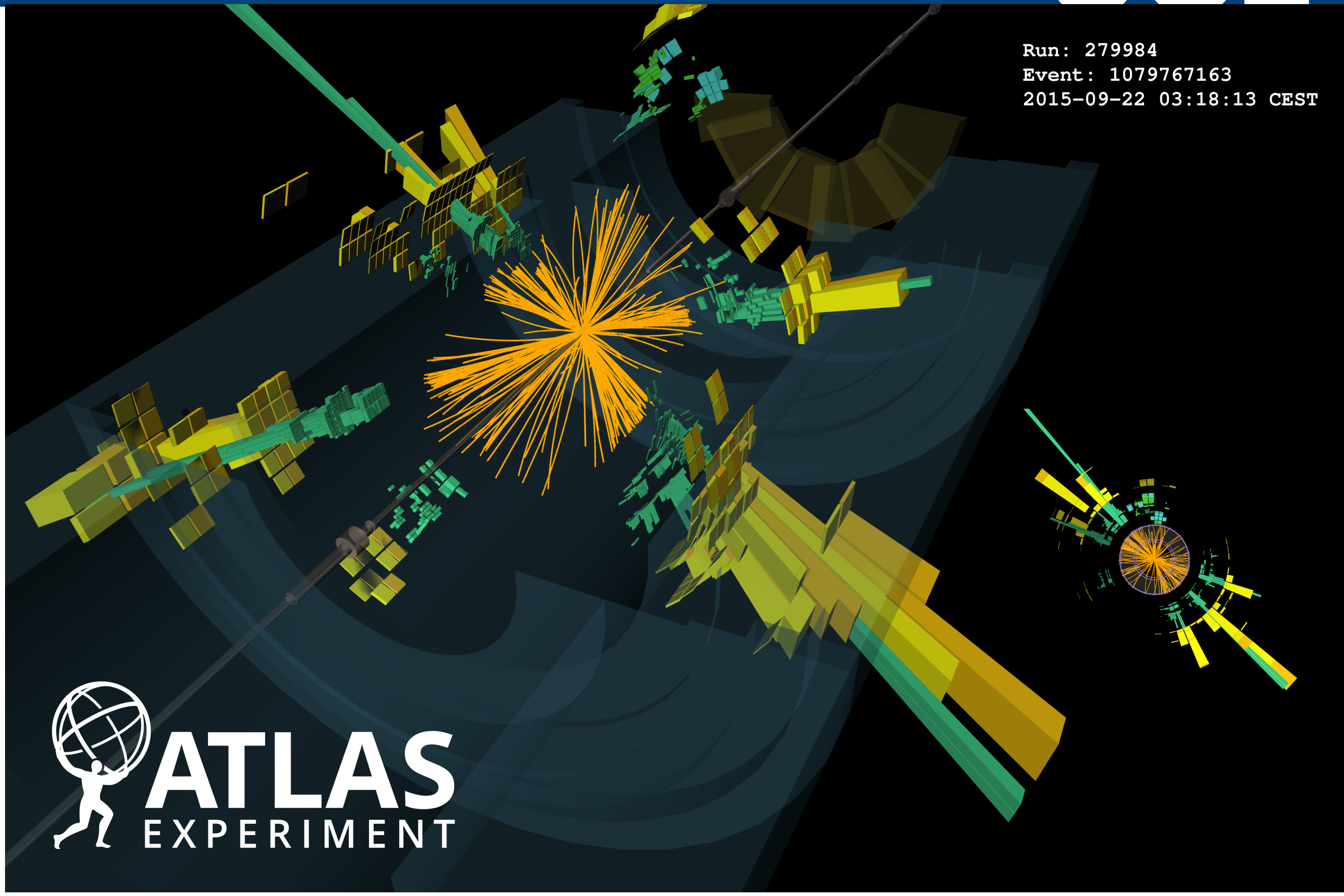


What is a jet?

Different kinds of jets

Truth/Particle level:
The constituents of the jet are final state (visible) particles

detector level:
Can be constructed from a number of detector objects
- calorimeter clusters
- charged tracks
- some combination thereof (particle flow)



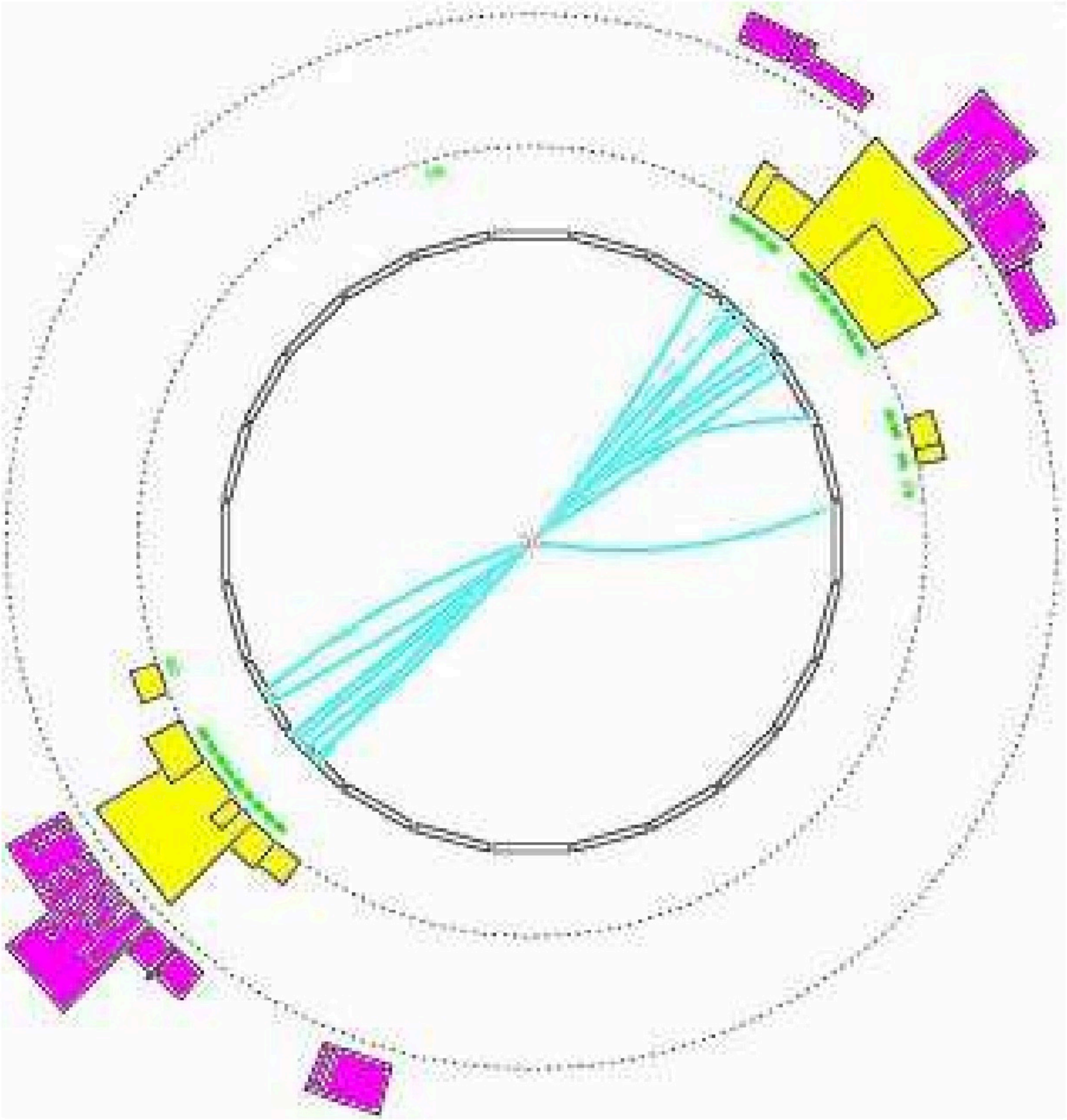
Jet have typical kinematics and a number of other properties:
- Cone size
- Jet finding algorithm
- Substructure
- Charge fraction
- Active area….

But first, how do we define what is and isn't a jet?

Jet finding

You have your constituents, now find jets! How many are there….

in this event?



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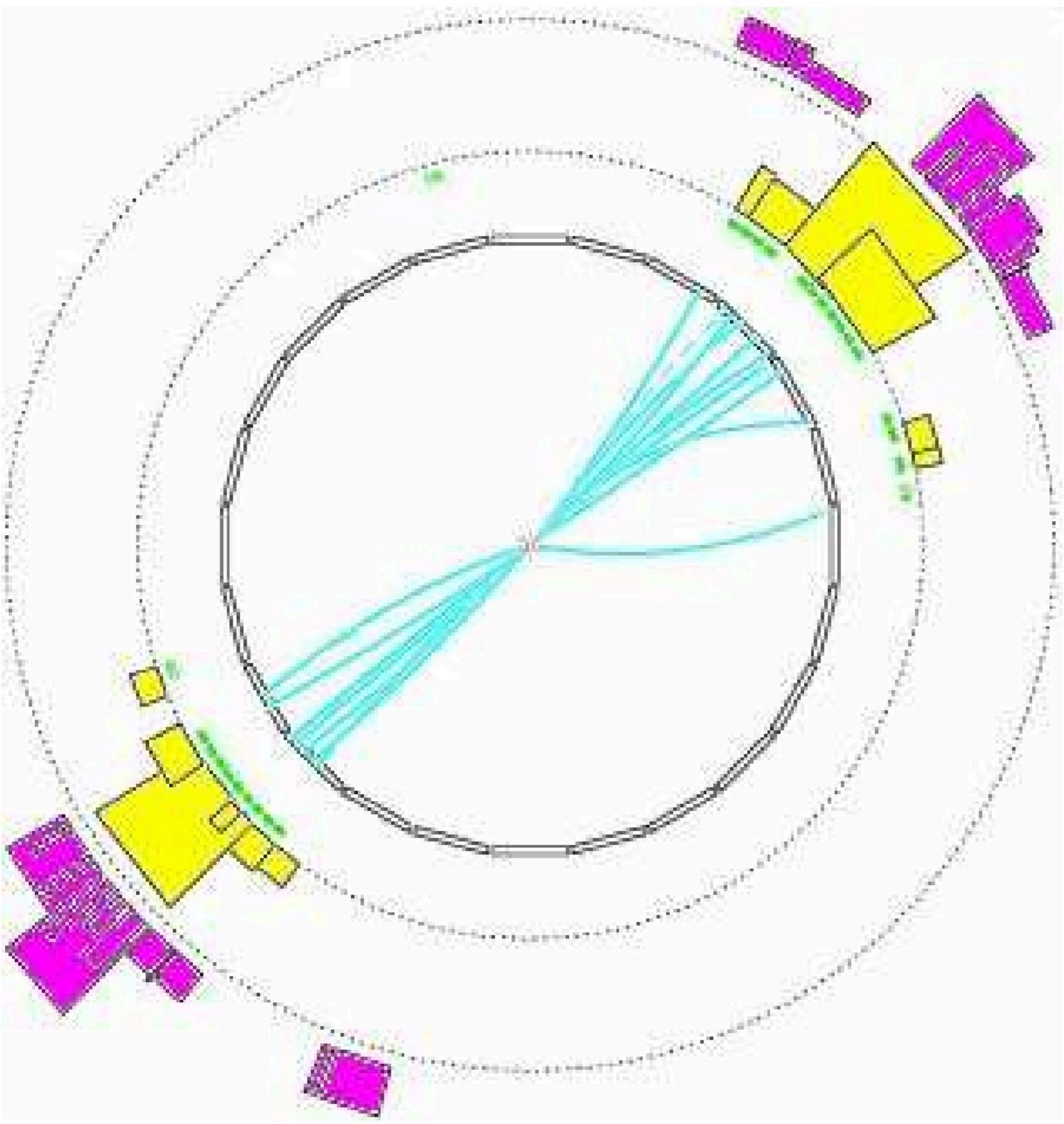
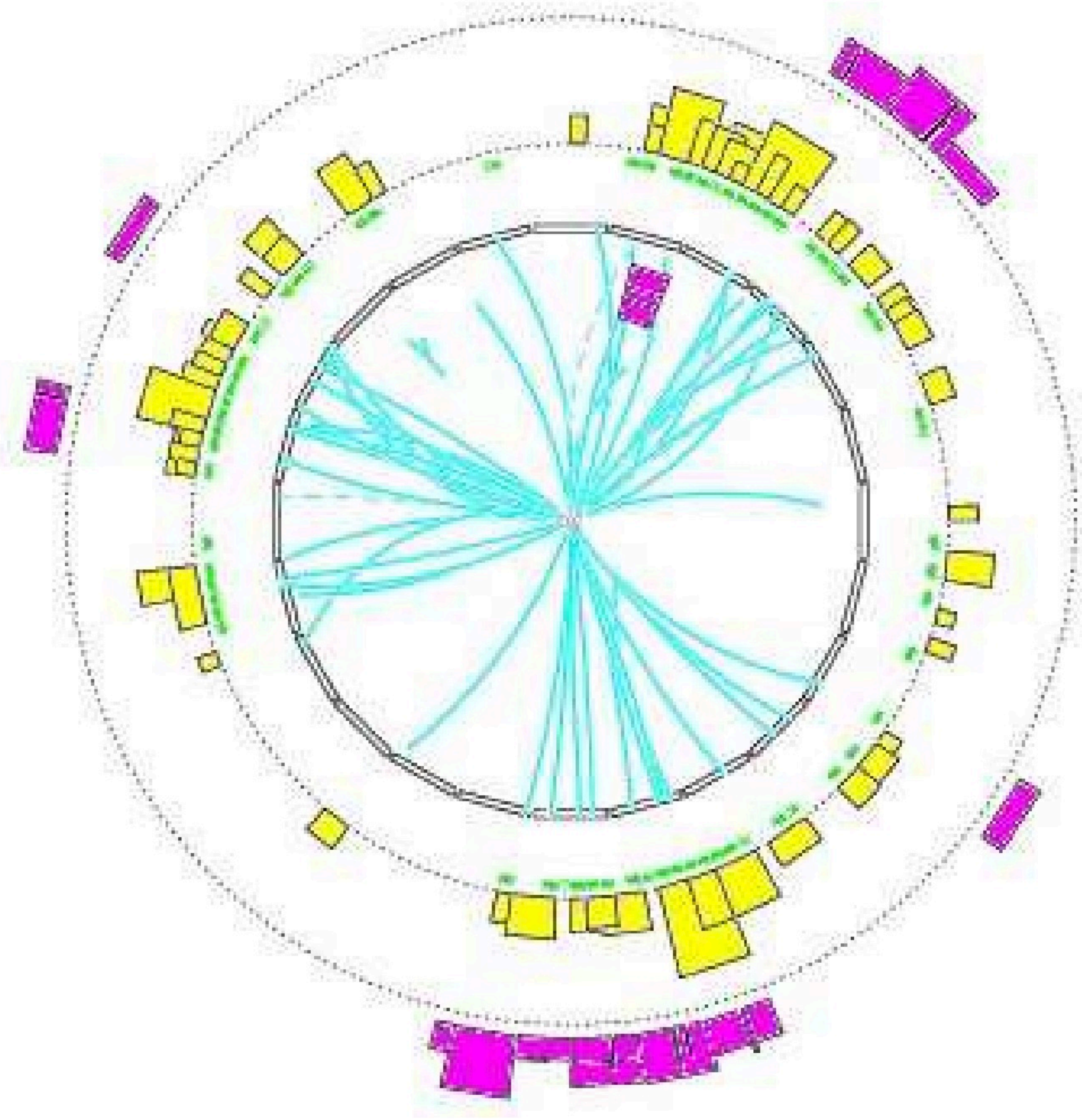
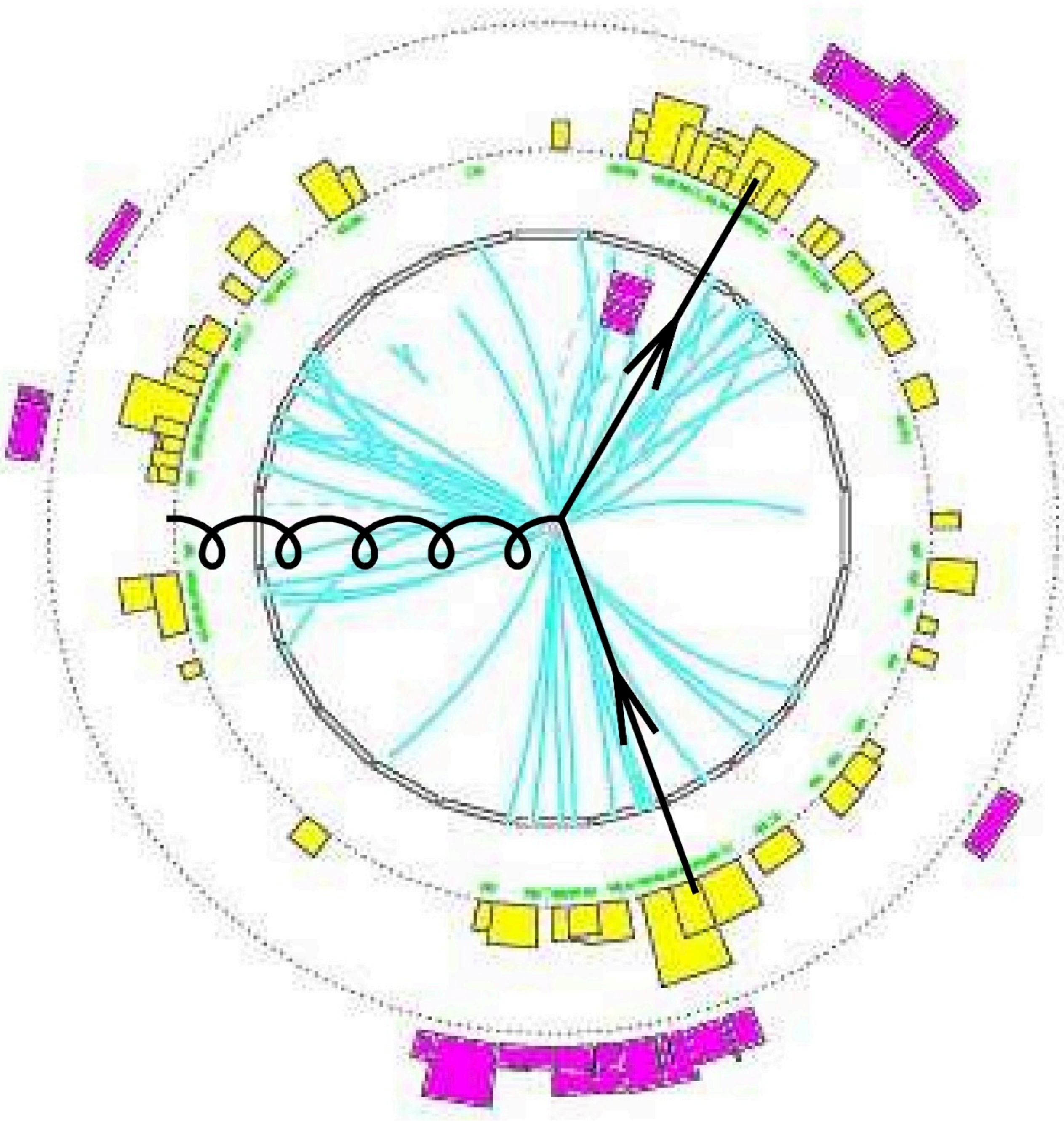


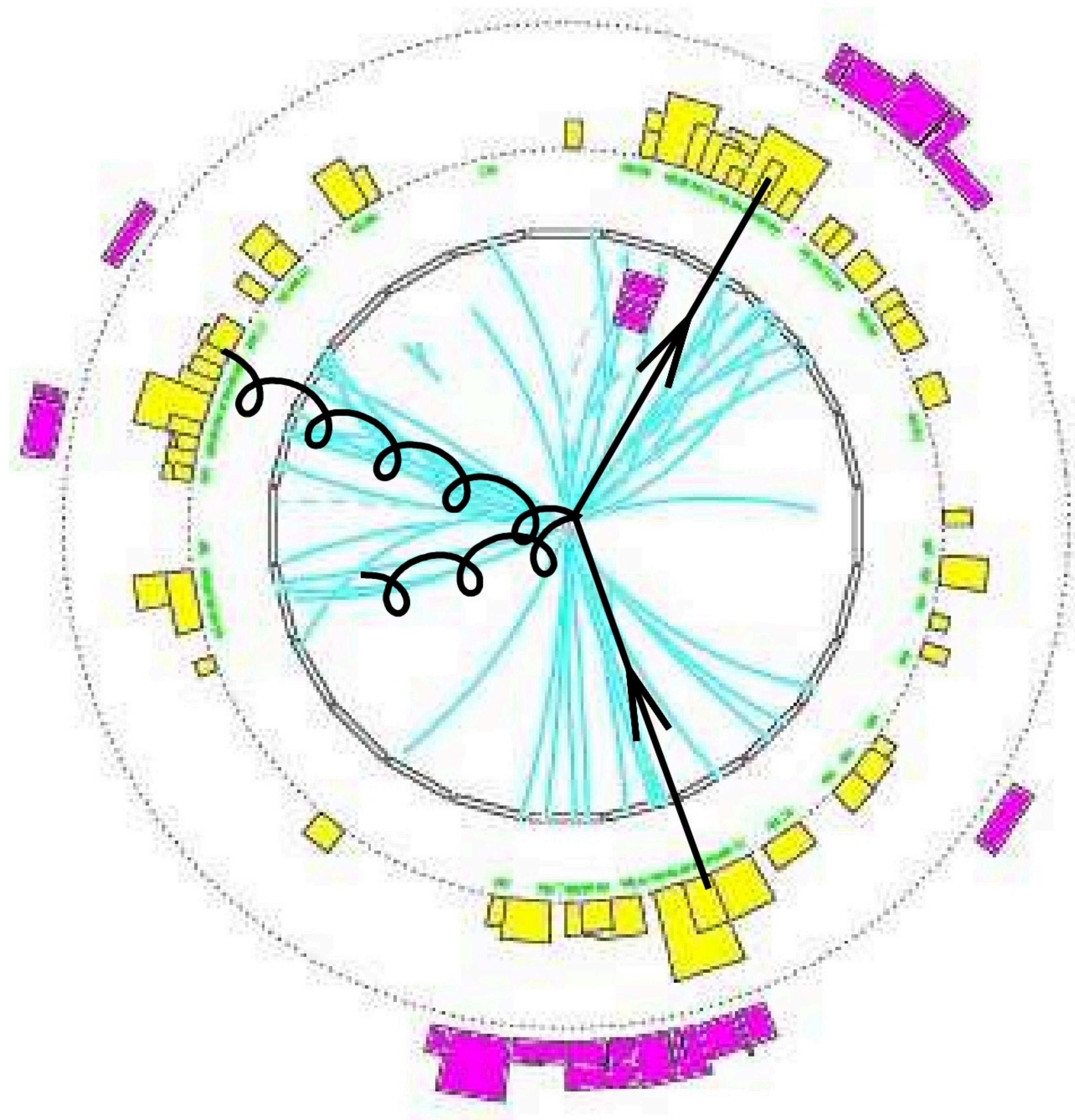
and this one?



Jet finding

We need a robust, unambiguous definition of a jet





Jet Algorithms

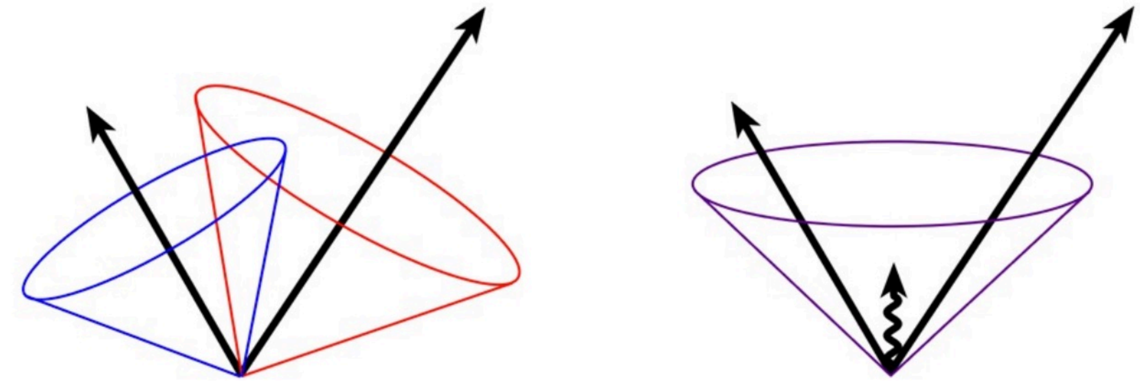
What properties should a good jet finding algorithm have?

parton and jet correspondence

- find all physically interesting jets from high energy partons

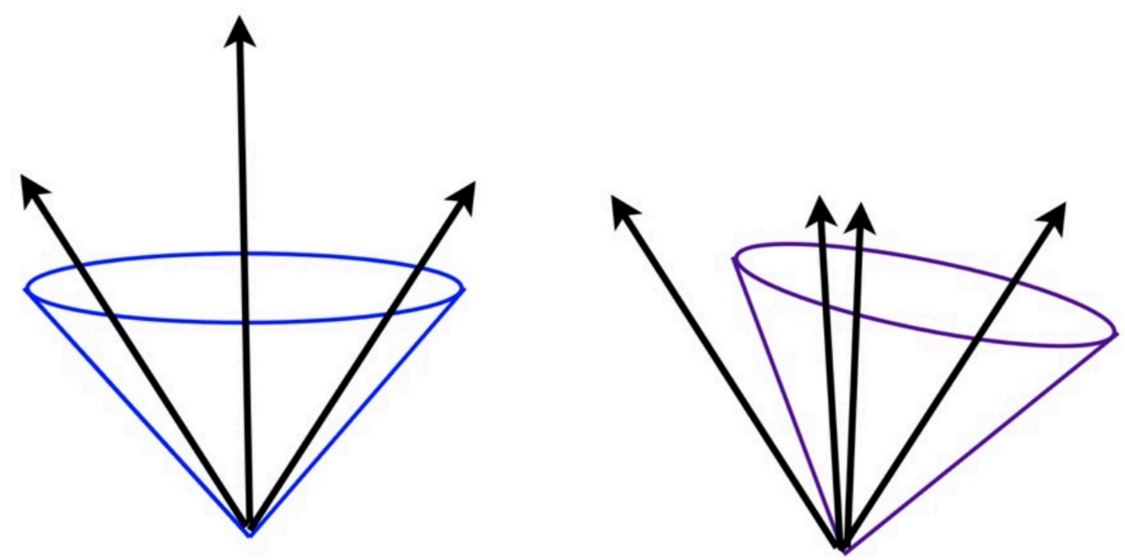
Infrared safety

- soft radiation should not effect jet configuration
- Only observables that are IR safe can be calculated in pQCD



collinear safety

- Collinear splittings should not bias jet finding



Other things to consider

- should be independent of detector technology (works at particle level)
- computationally fast
- Easy to calibrate and stable in noisy, pileup filled detector environments

Jet Algorithms

Cone algorithms (no one uses these anymore)

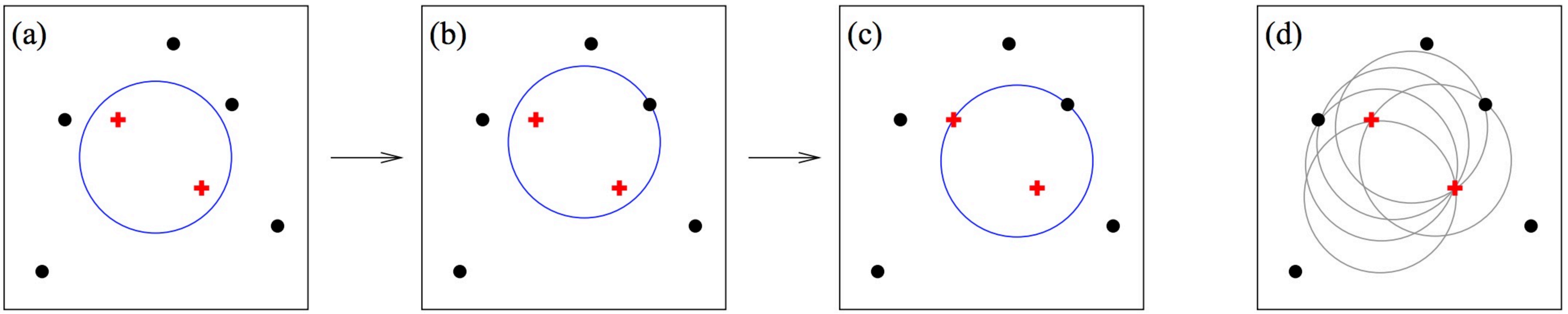
Iterative cone
- select the most energetic particle as a seed
- all constituents within cone of radius R are considered part of the jet
- jet axis re-calculated, if it's stable, w.r.t seed axis. STABLE CONE

Not IR safe

SIScone (seedless infrared-safe cone) algorithm

scales as $N^2 \ln(N)$:(

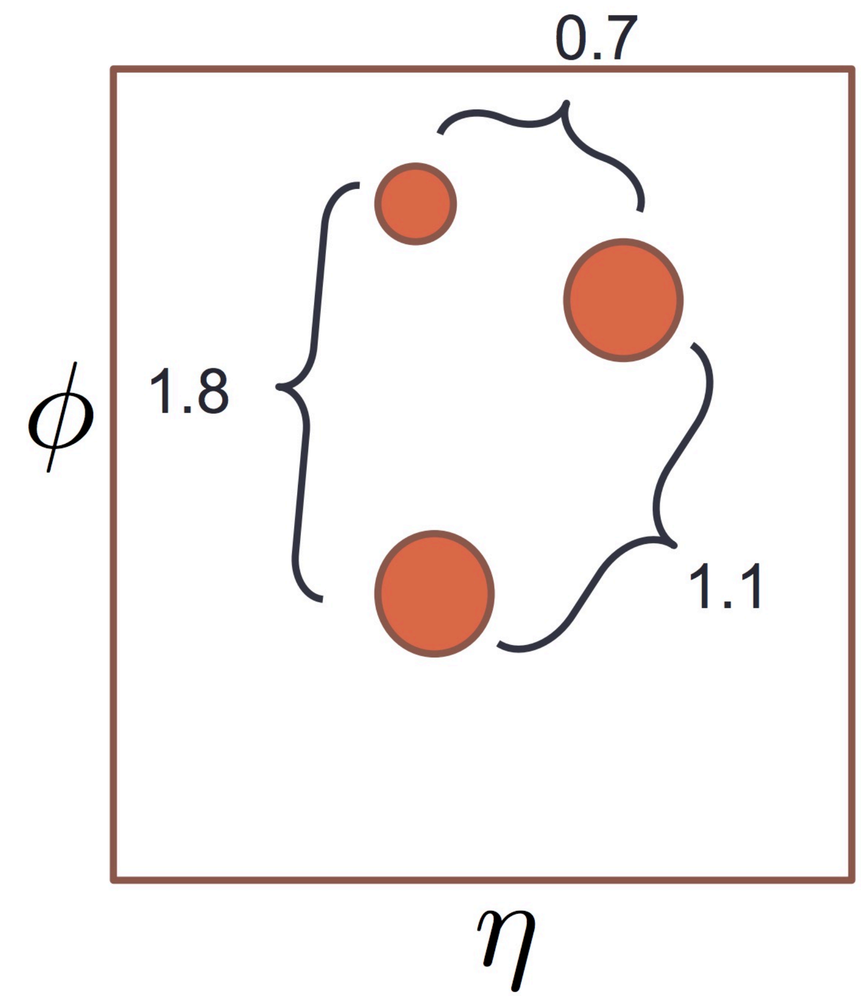
- find all stable cones as above as "protojets"
- remove constituents from those cones and repeat until new no cones are found
- merge overlapping protojets into final jets

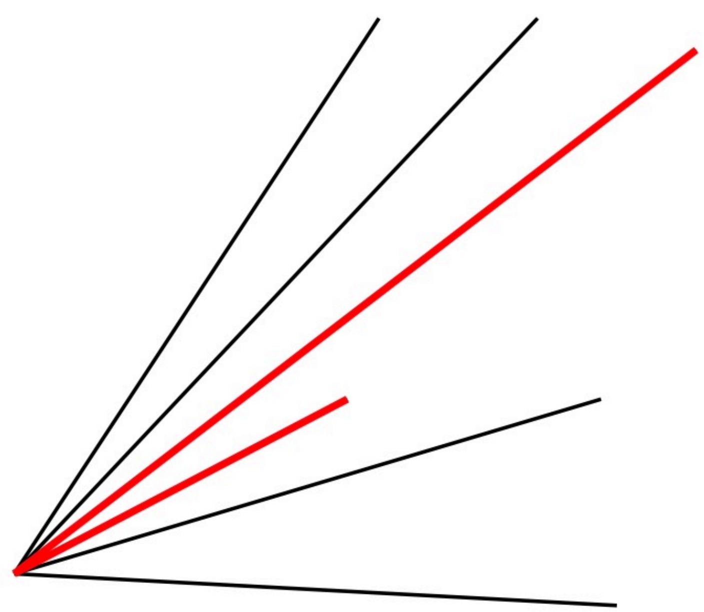


Sequential Recombination (clustering) algorithms

Can intuitively think of clustering algorithms as working their way back through the parton branching

Define a distance measure based on the constituent angular separation and their energy/pT and combine particles which are “closest”





Jet Algorithms

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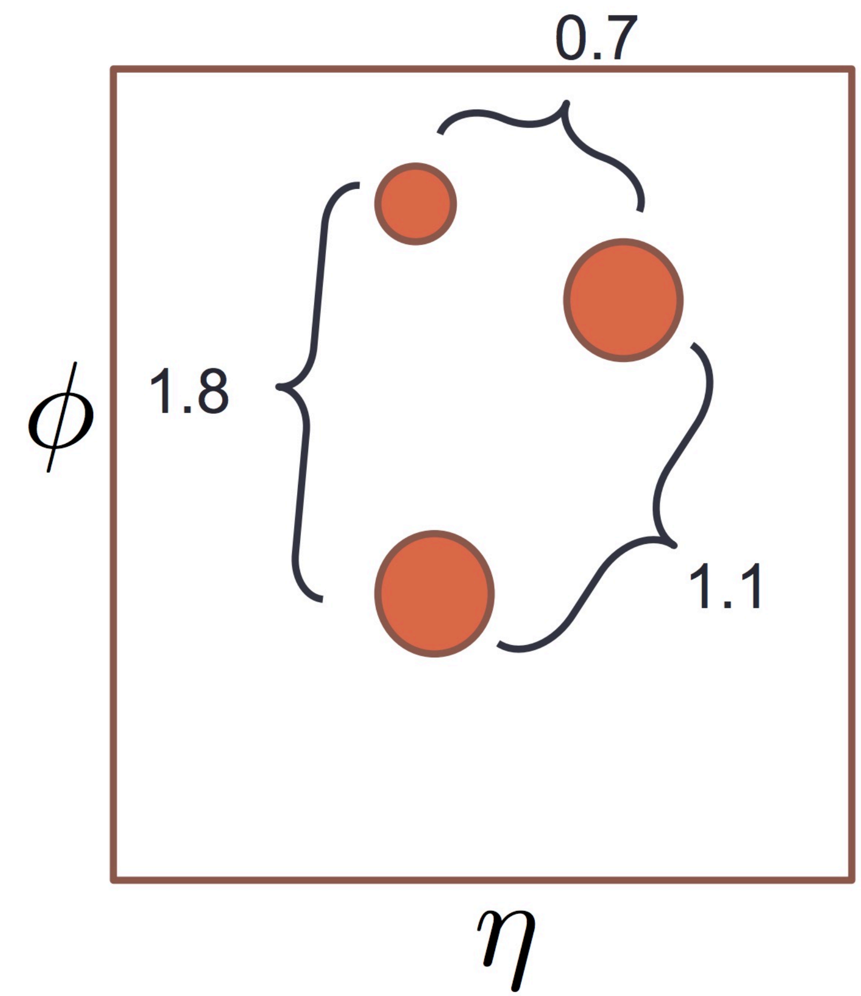
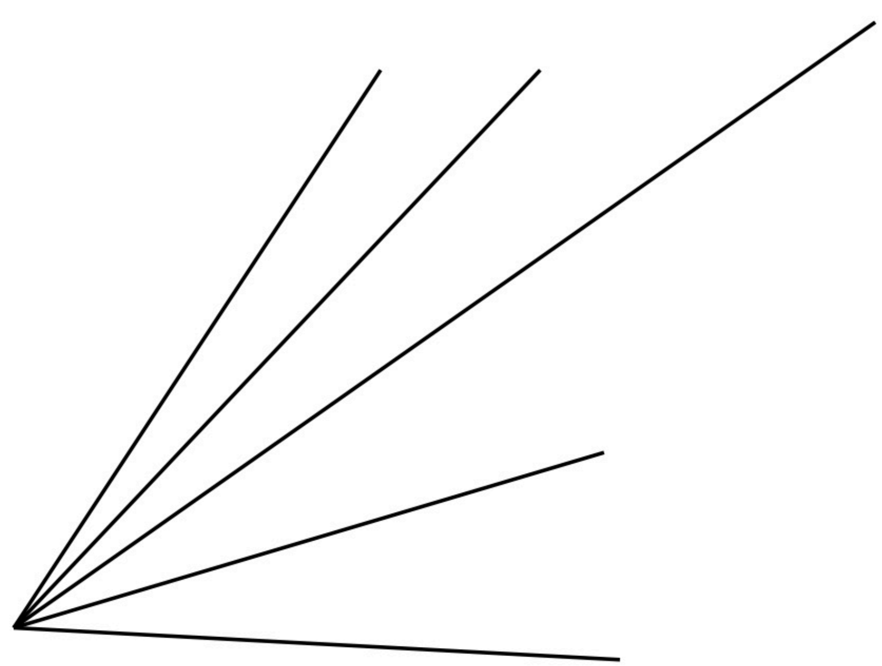
Can intuitively think of clustering algorithms as working their way back through the parton splittings

Define a distance measure based on the constituent angular separation and their energy/pT and combined particles which are closest





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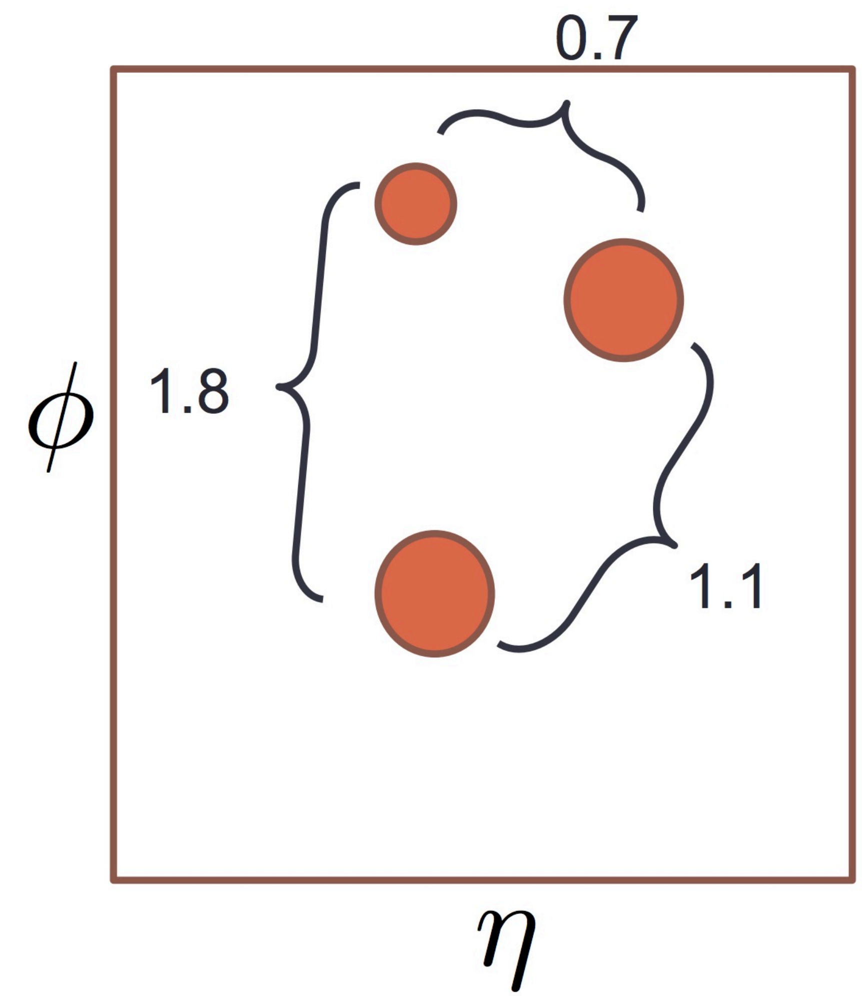

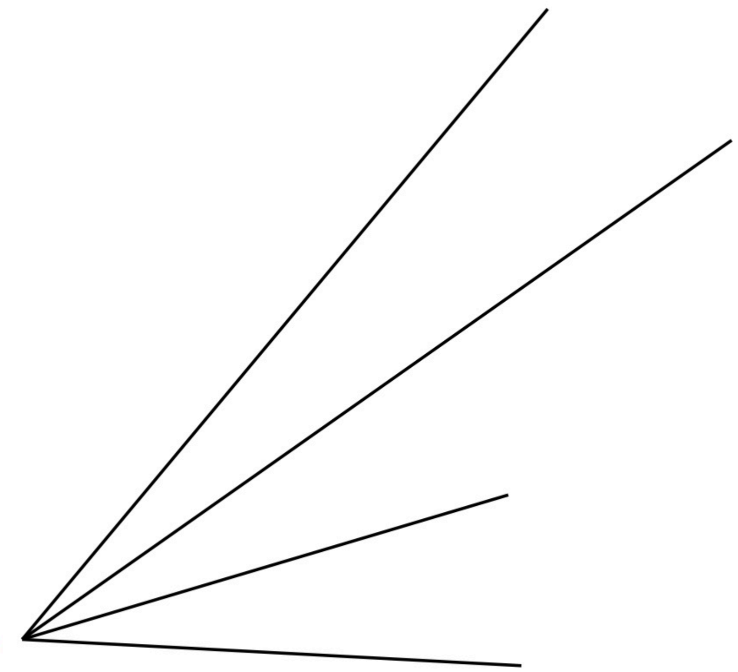

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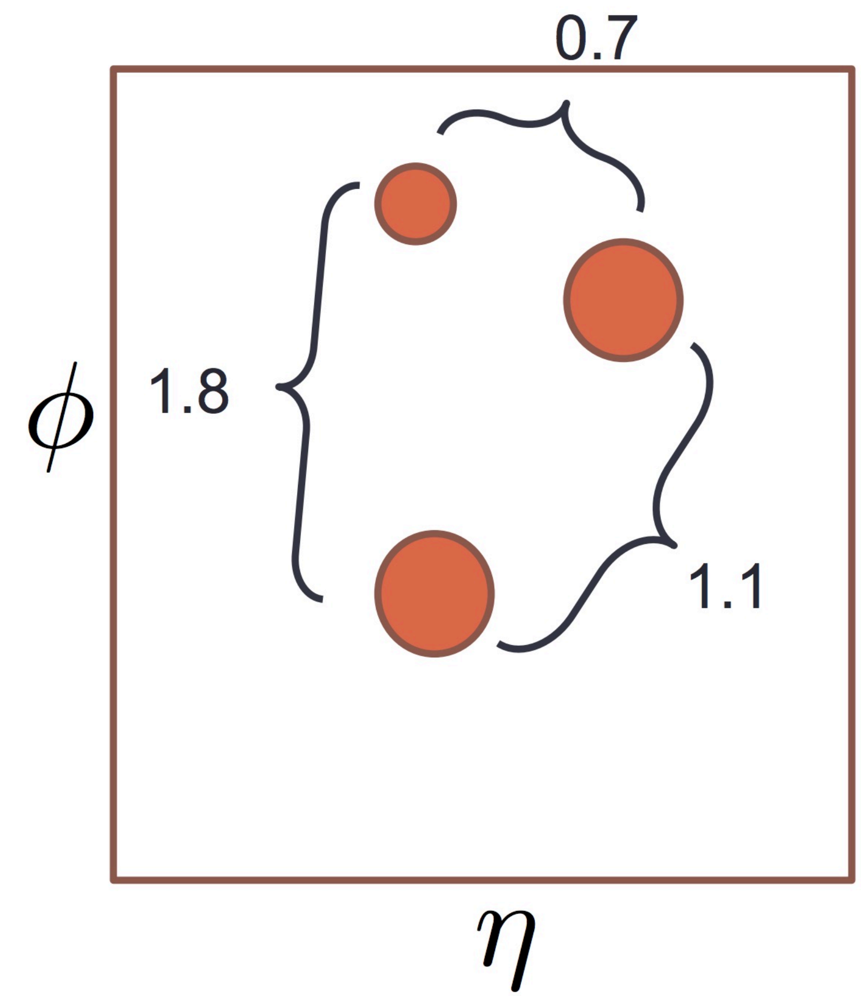

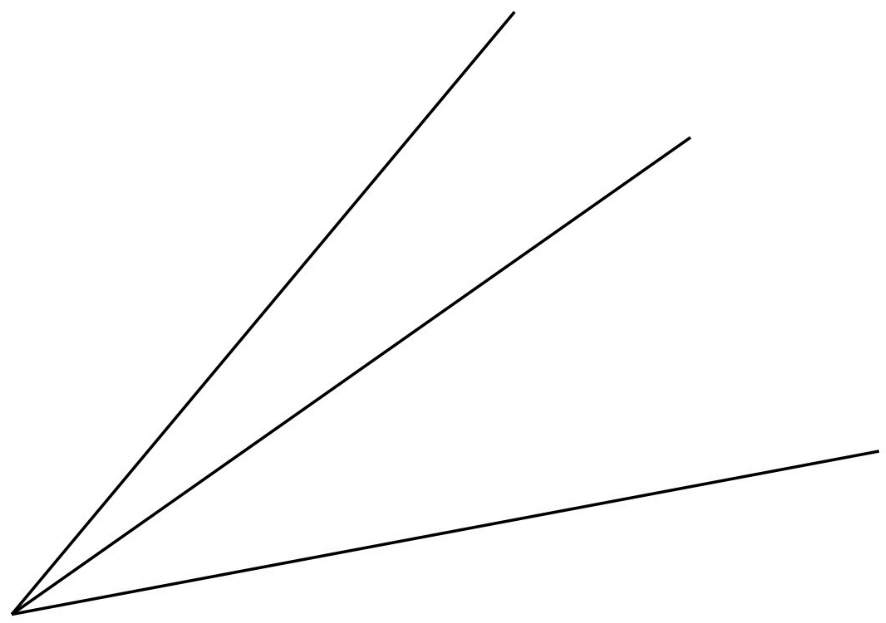

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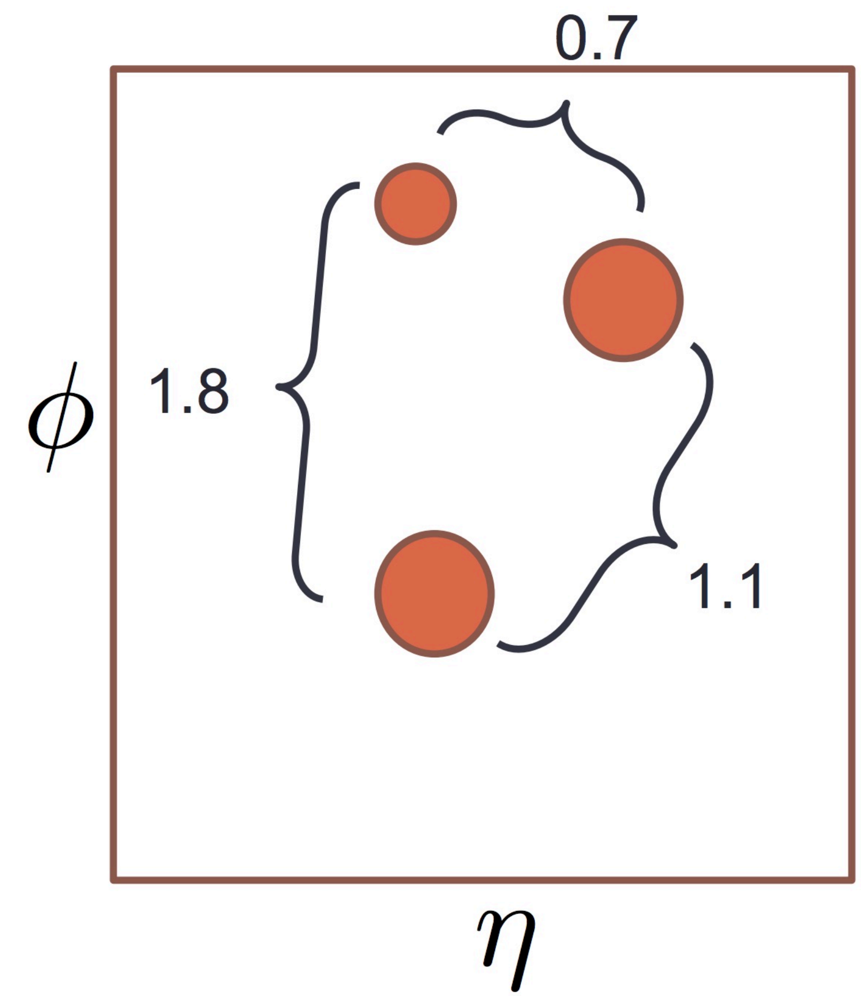

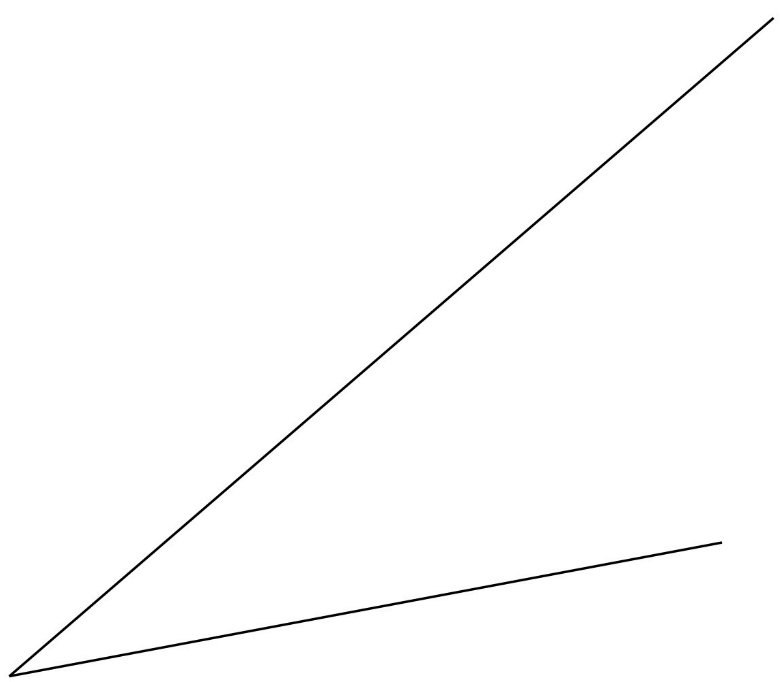

Jet Algorithms

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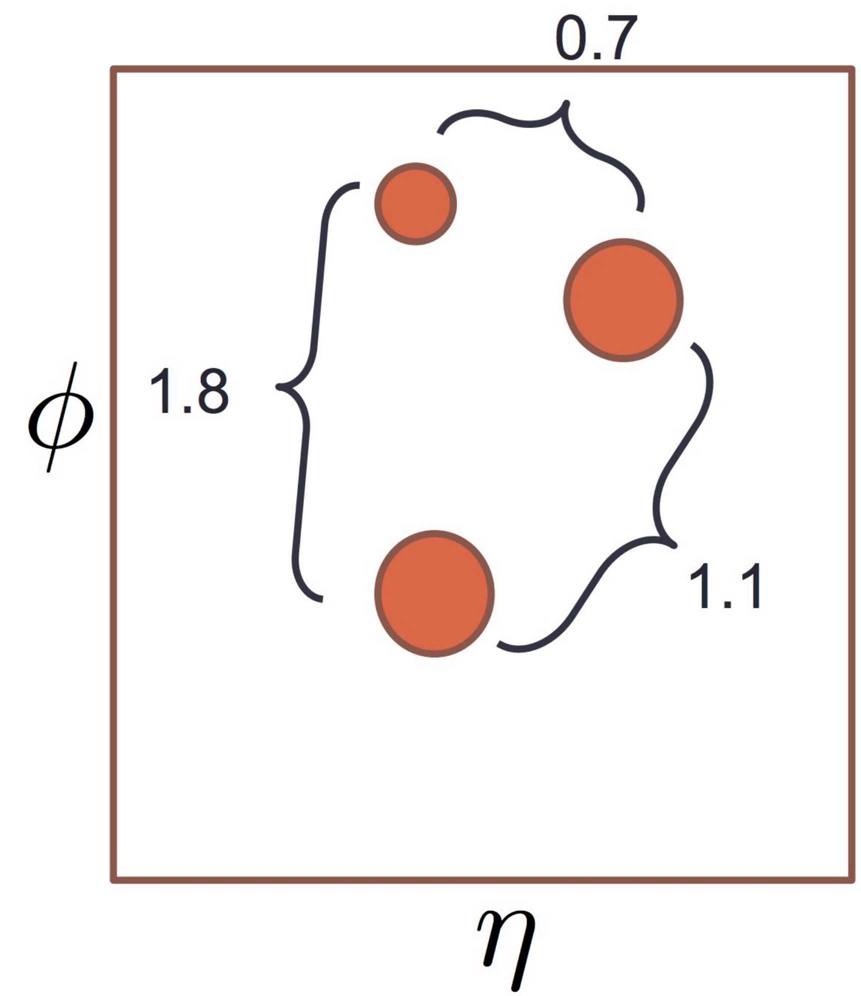
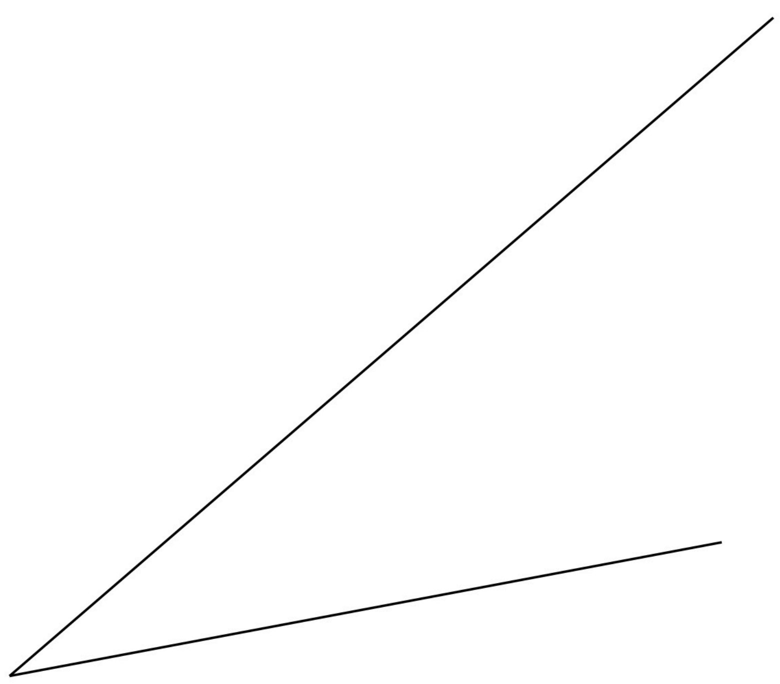




The JADE algorithm was the first clustering algorithm.

IR and collinear safe

Could sometimes cluster soft, back to back particles together…

Jet Algorithms

Modern ("second generation") Jet clustering algorithms

3 jet algorithms are currently used for various purposes at both ATLAS and CMS (AFAIK!)

All can be defined using a set of generalised distance parameters

constituent pT **angular separation**

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

Radius parameter **"Beam distance"**

indices *i* and *j* run over all candidate jet constituents

p = 1 : k_t algorithm
p = 0 : Cambridge/Aachen algorithm
p = -1: anti-k_t algorithm

Cluster as follows

- work out all of the d_{ij} and d_{iB}
- Find the minimum of the d_{ij} and d_{iB}
- If it is a d_{ij} the combine *i* and *j*, if not, *i* is considered a final state jet and removed
- repeat until now particles are left

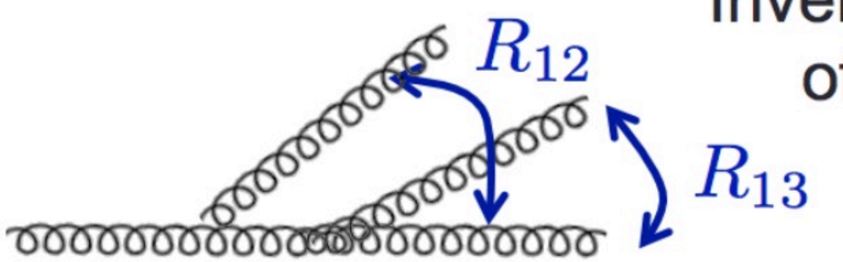
Jet Algorithms

(Shameless slide theft)

Cambride/Aachen algorithm

$$d_{ij} = \left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters closest radiation first



Inversion of **Herwig shower**

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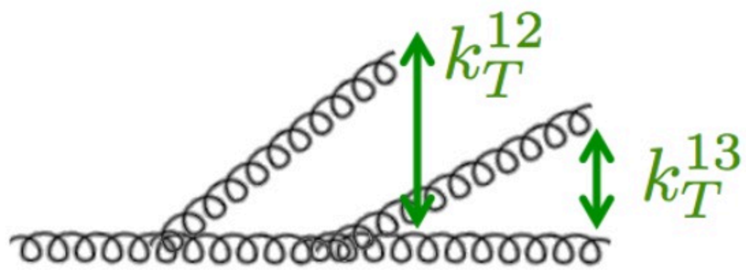
k_T algorithm

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{R_{ij}}{R_0}\right)^2$$

- clusters hard collinear radiation first



Inversion of **Pythia shower**

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anti k_T algorithm

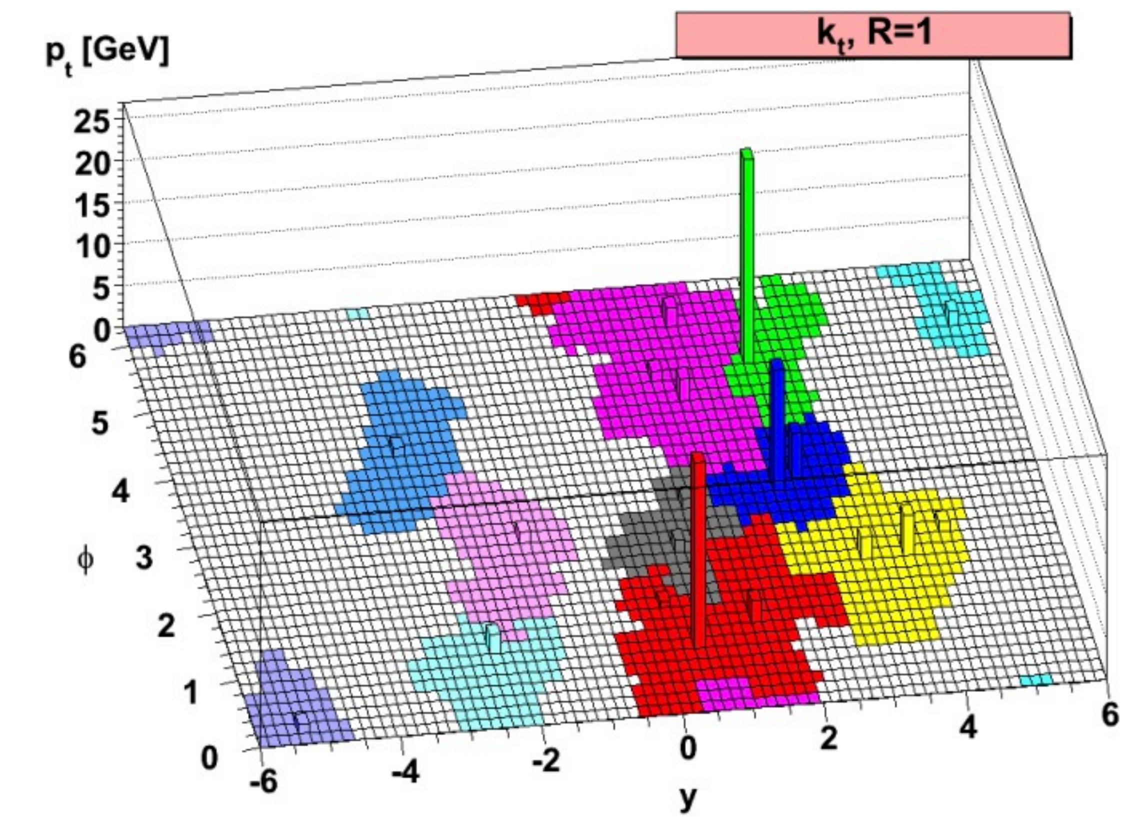
$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{R_{ij}}{R_0}\right)^2$$

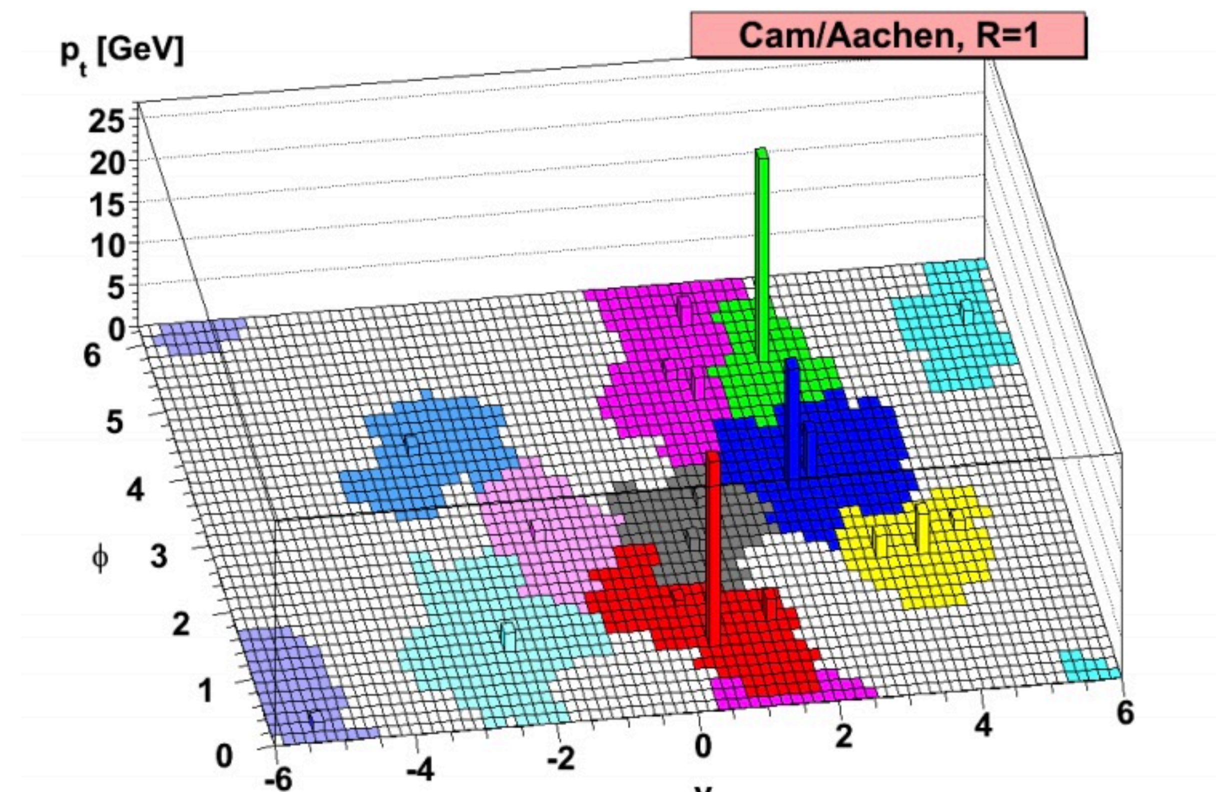
- Clusters farthest first
- No inverse parton-shower interpretation

- Produces round jets
- Almost exclusively used by ATLAS and CMS

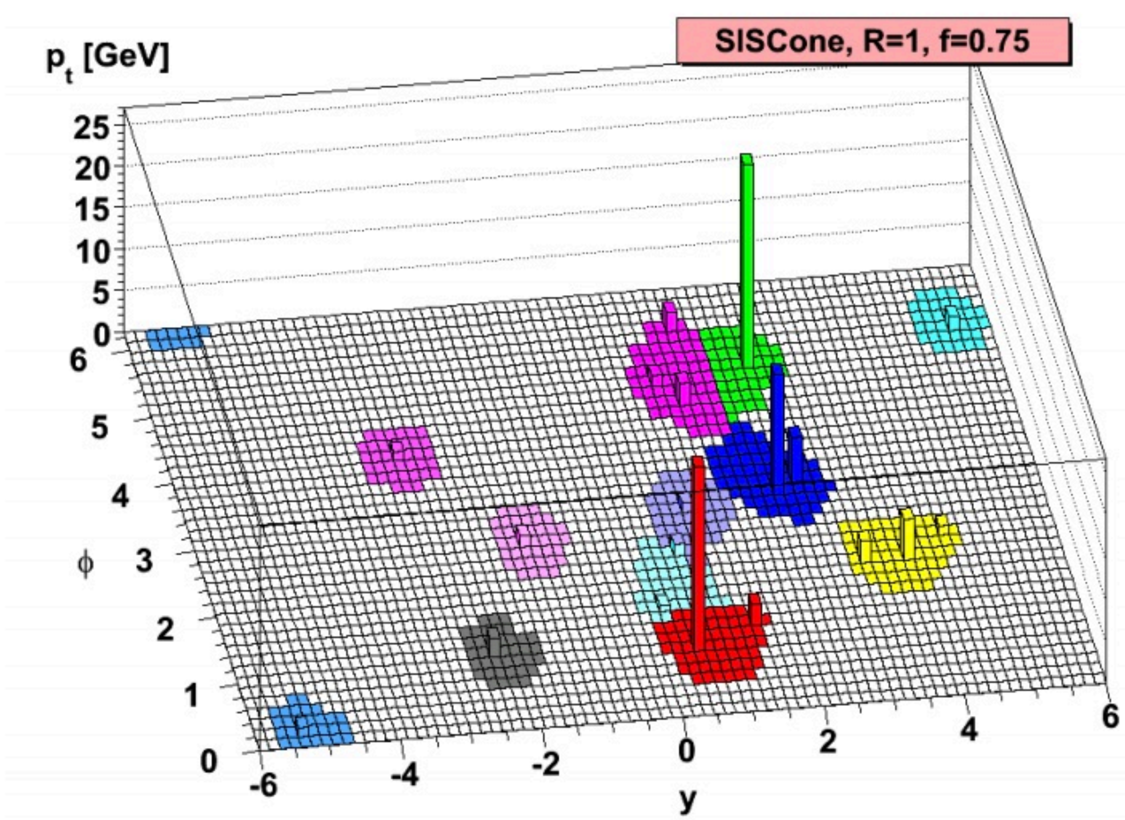
Other have their niche uses too (later)

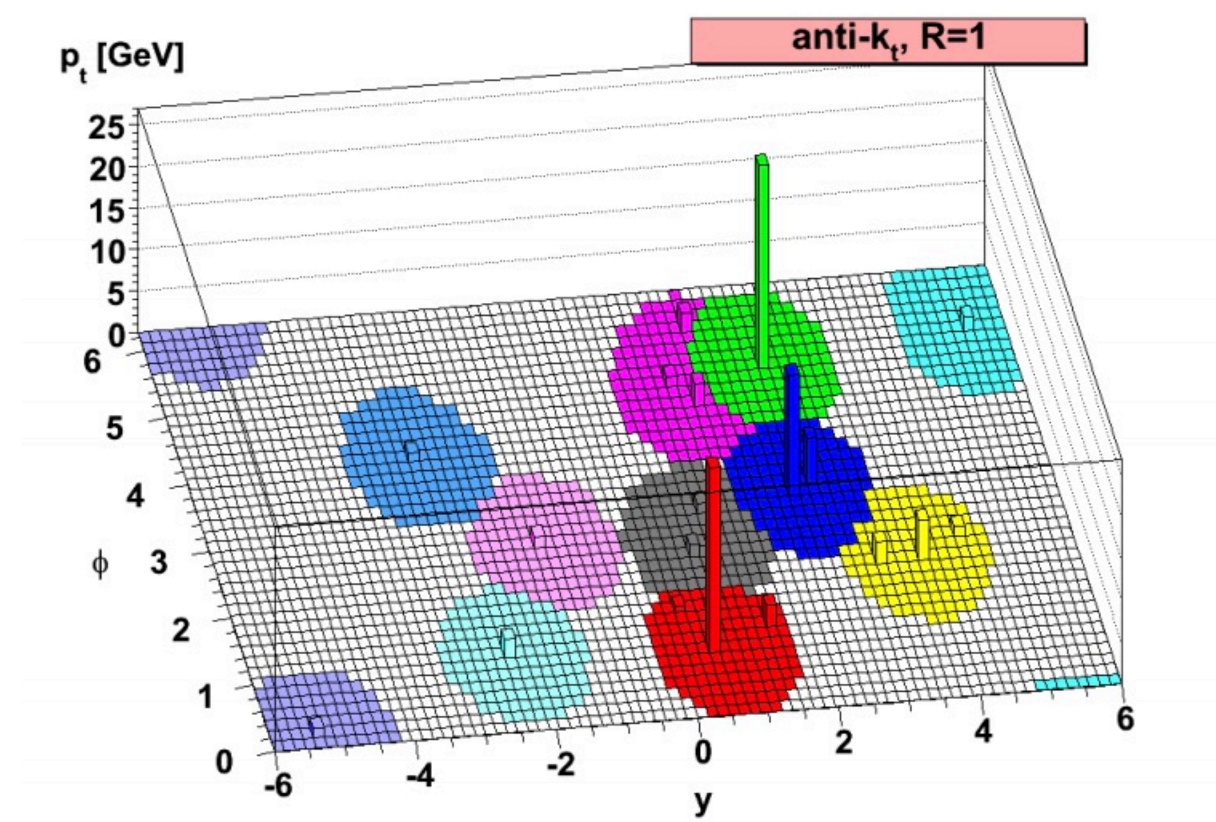
Jet Algorithms





Jet active and passive area stable

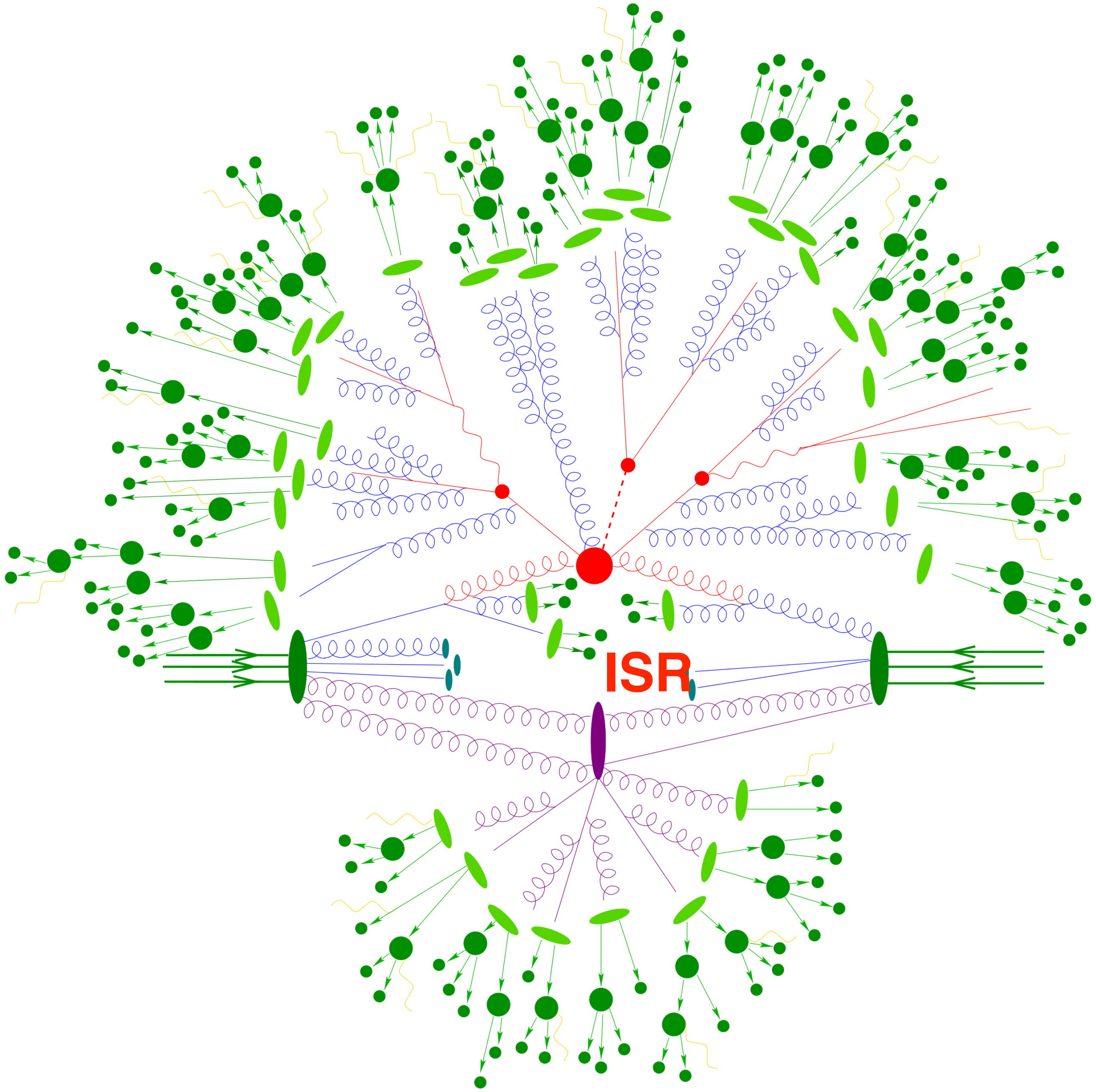




experimental Challenges

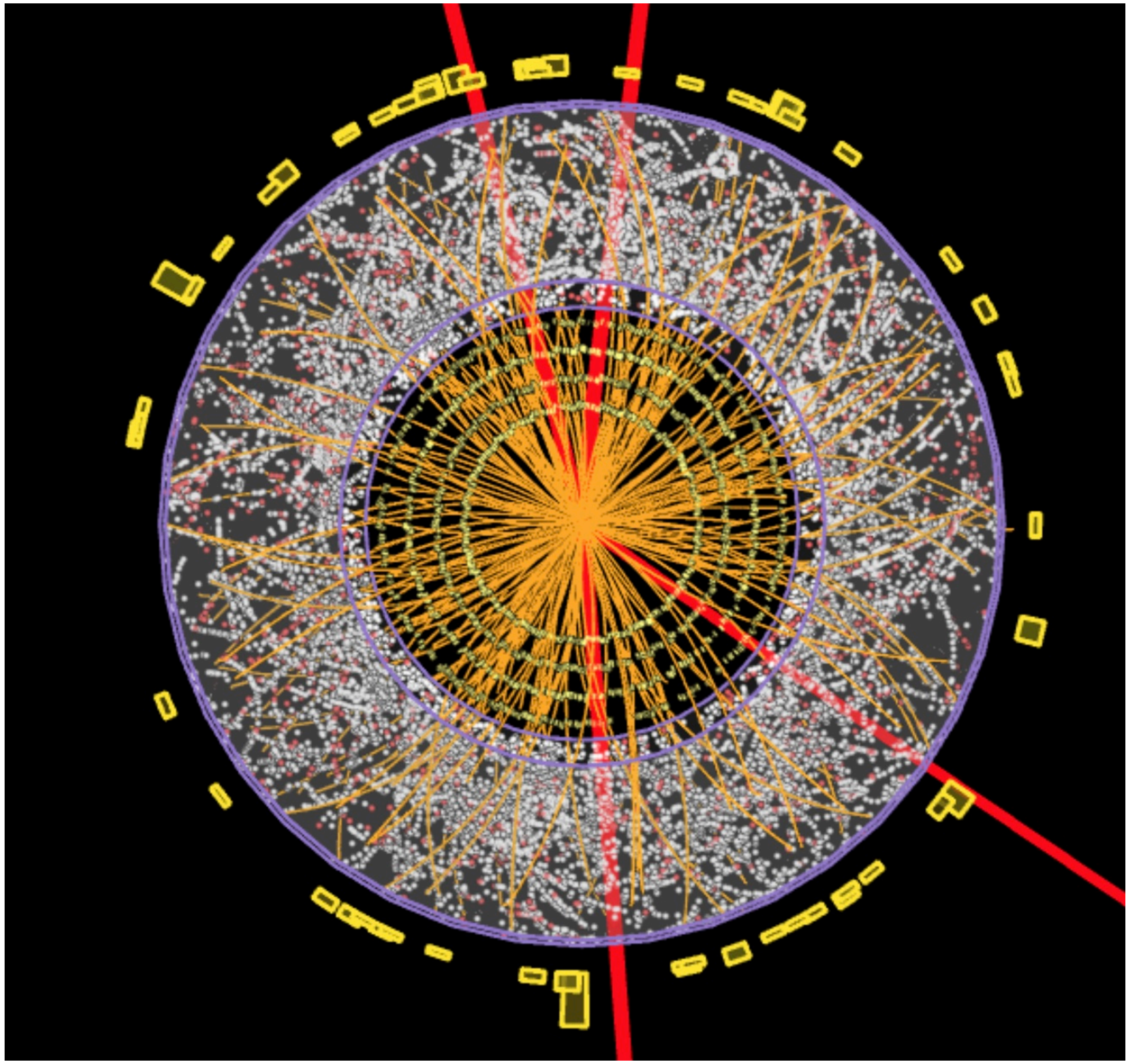
We (vaguely) know what jets are and how to find them

Events are complicated and additional pileup makes things worse



underlying event

pileup



Jet calibration

Why do we meed to calibrate jets?

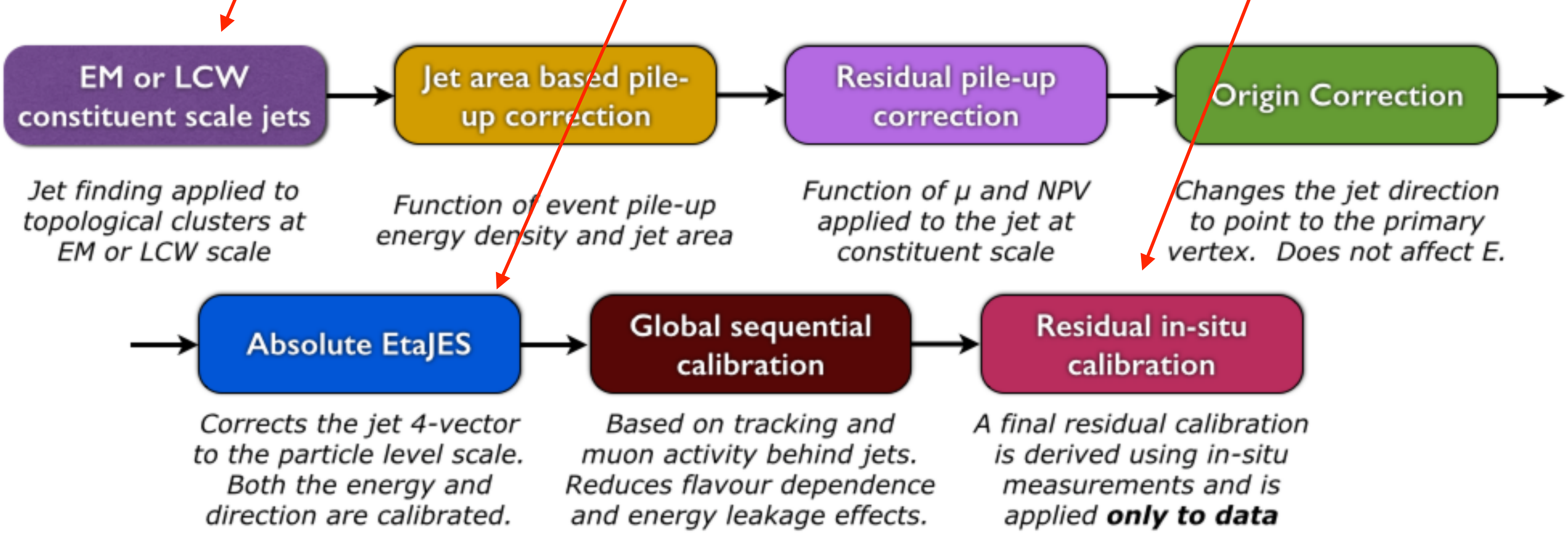
- Non-compensating calorimeter response, need to correct for it
- Pileup contributions to jets
- Finite resolution of calorimeter

Topoclustering has inherent noise suppression

Dedicated analyses for this part

Numerical inversion

ATLAS jet calibration chain. (FatJets have additional mass calibrations)



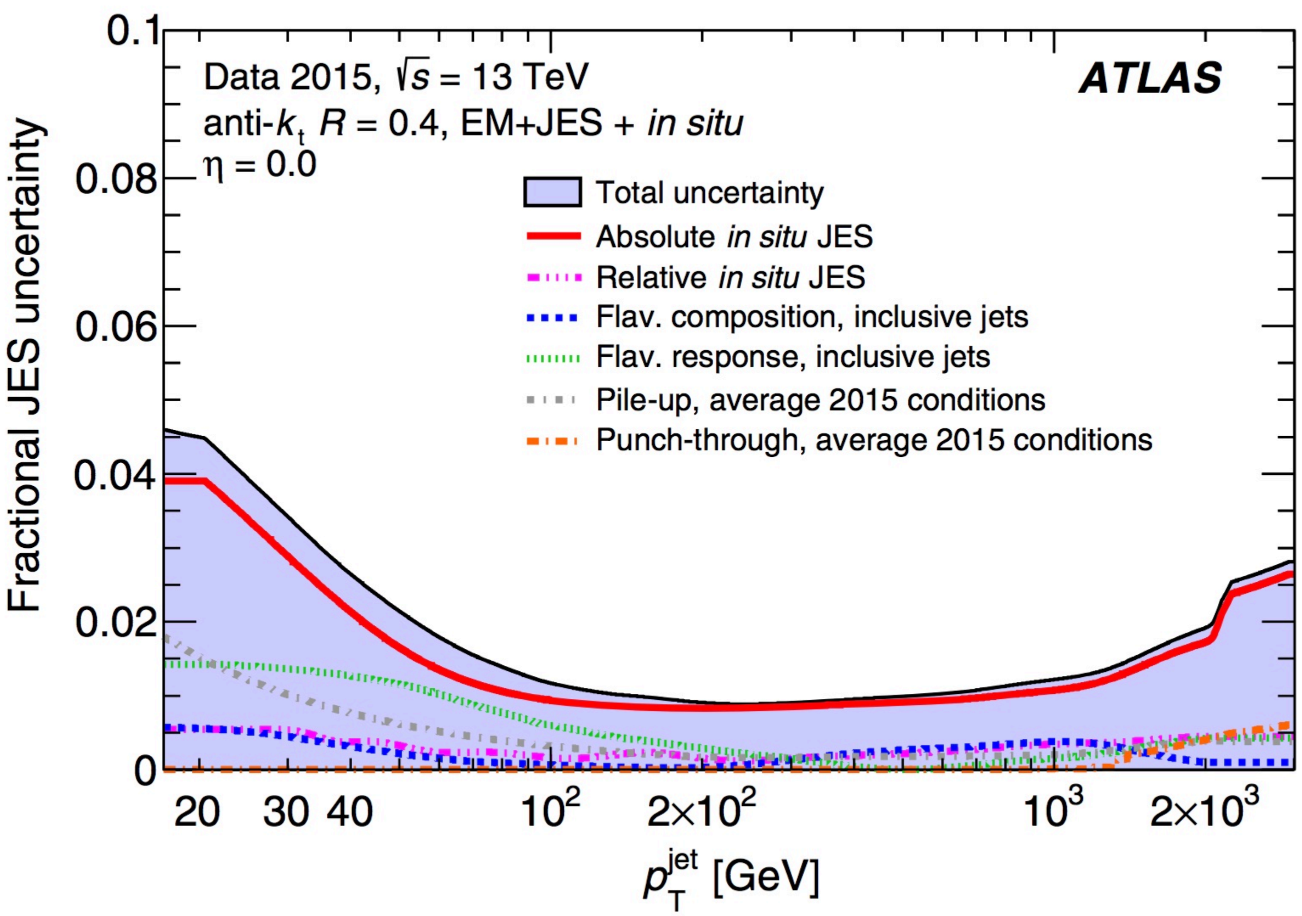
Uncertainties and quality cuts

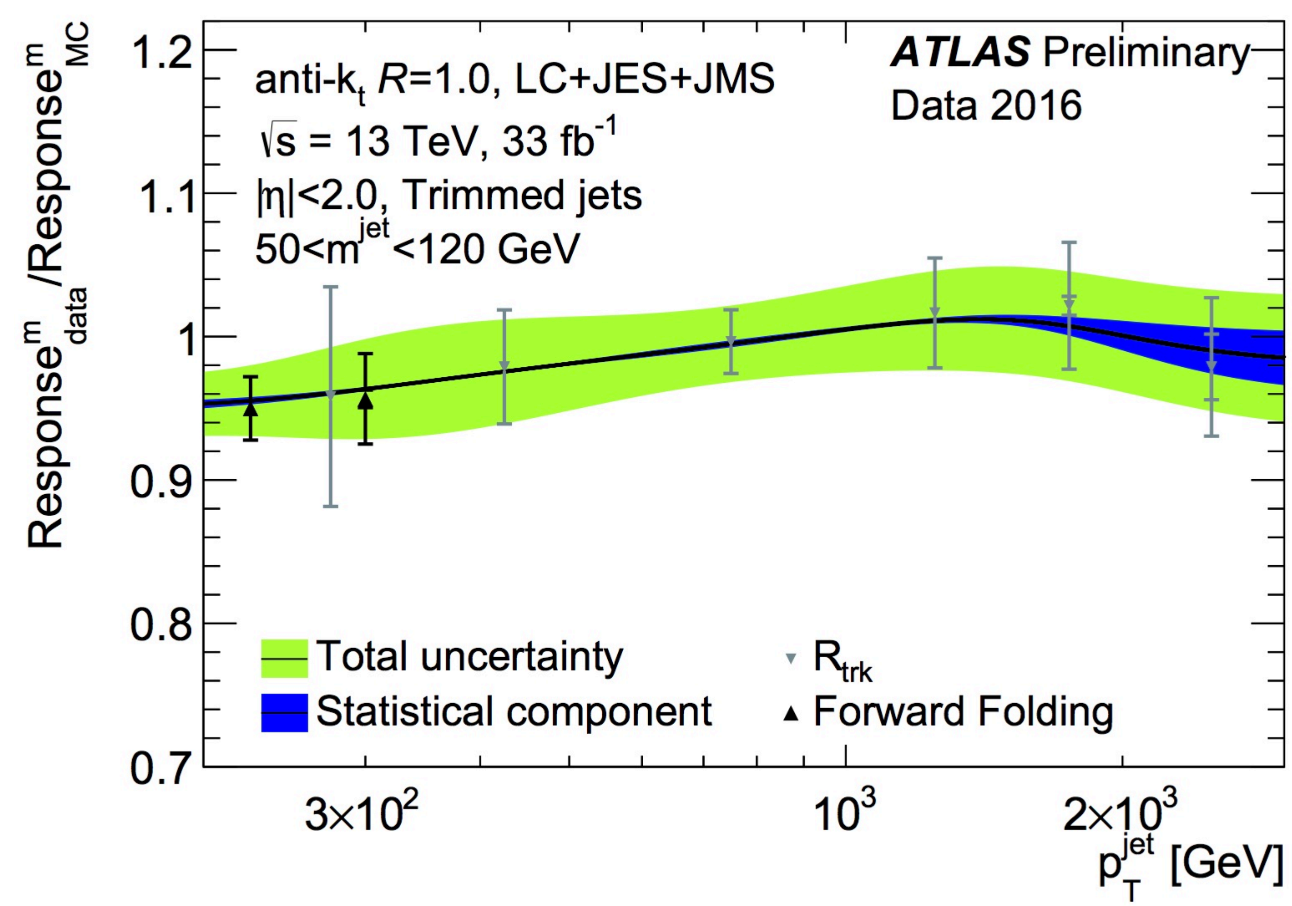
Additional quality cuts

- Veto jets based on energy distribution in different calorimeter layers (EM frac etc)
- JVT cut: assess whether a jet is pileup based on the proportion of PV tracks it has

What does this all get us?

- Small uncertainties of the kinematics of jets
- Well understood jet kinematics

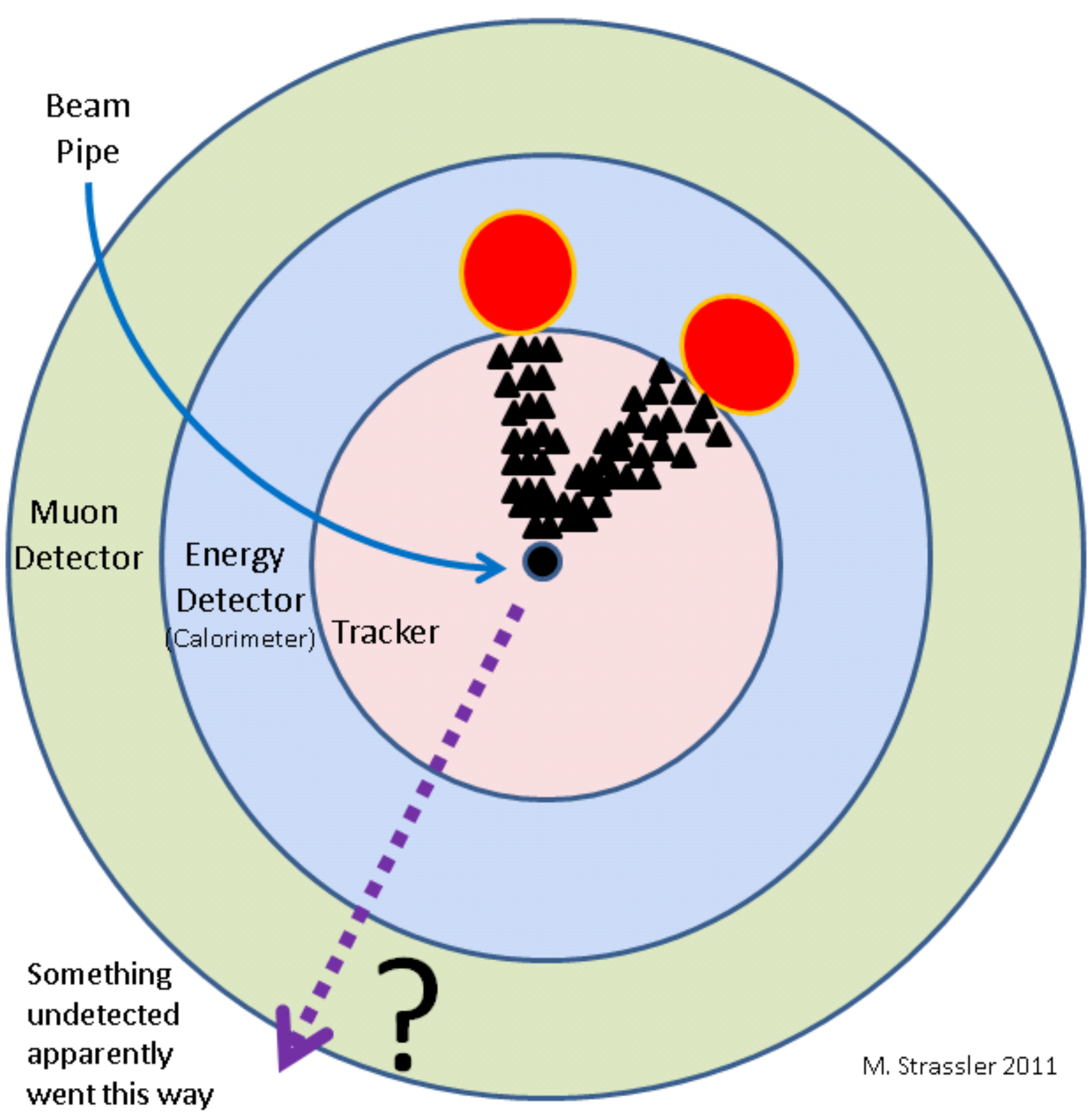




Measuring the invisibles: missing energy

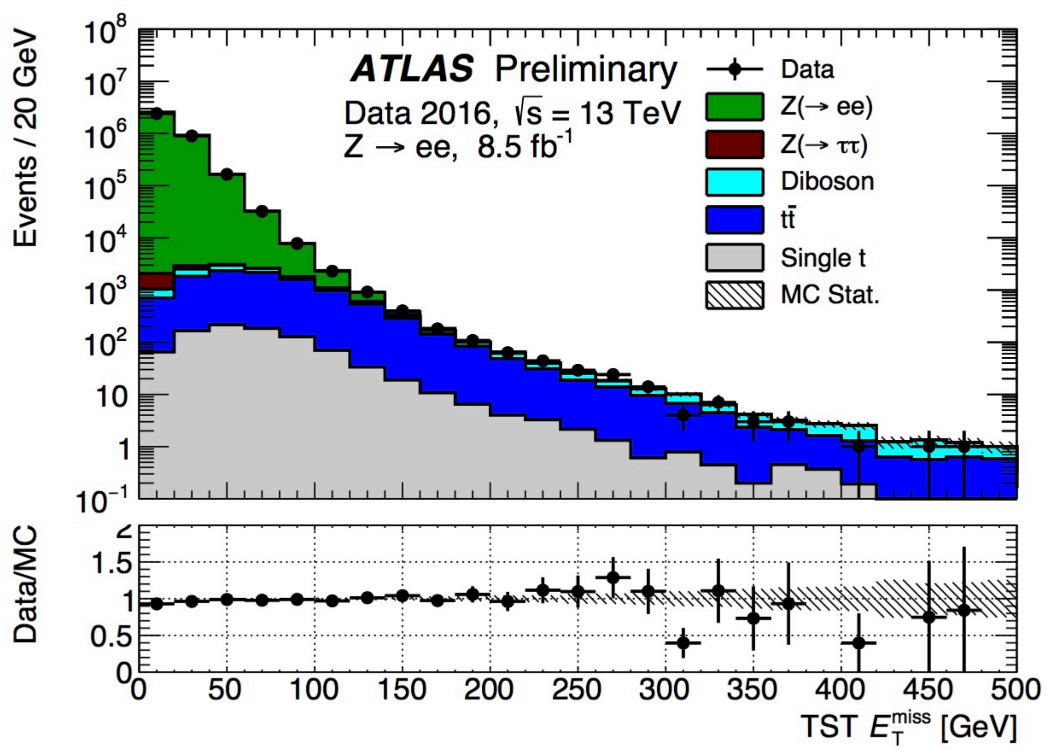
Neutrinos and potential BSM signatures cannot be reconstructed by detectors

Infer their presence by measuring the missing transverse energy of all final state objects in an event



The removal of pileup jets is crucial to measuring the missing energy correctly

- ten to use information from primary vertex tracks of identify hard scatter and PU jets
- In the forward regions can use correlations between central and forwards jets

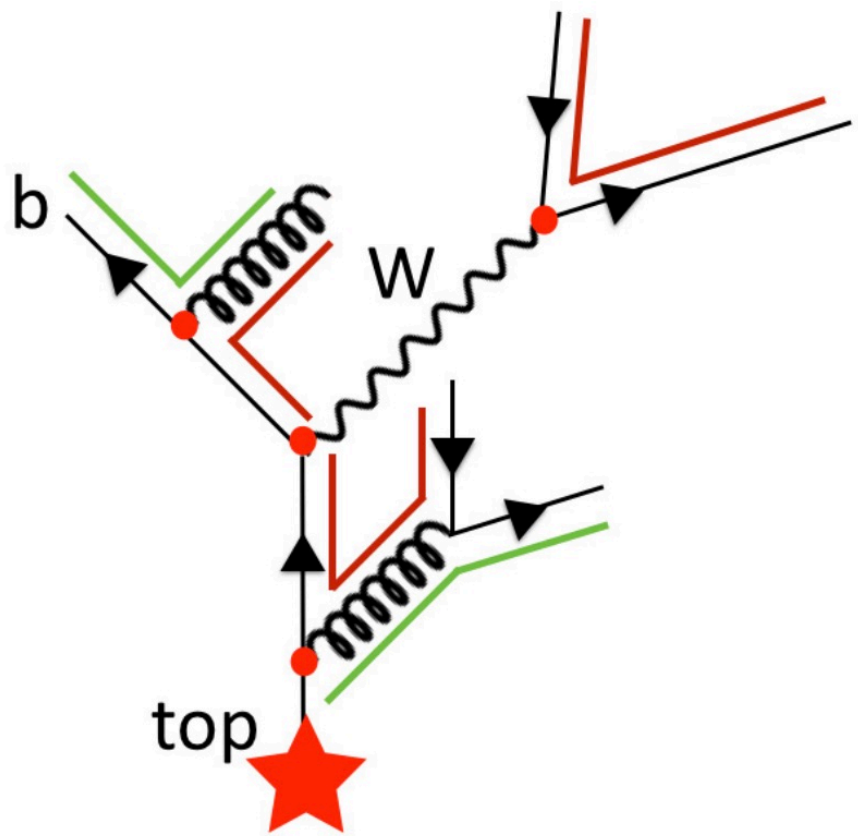


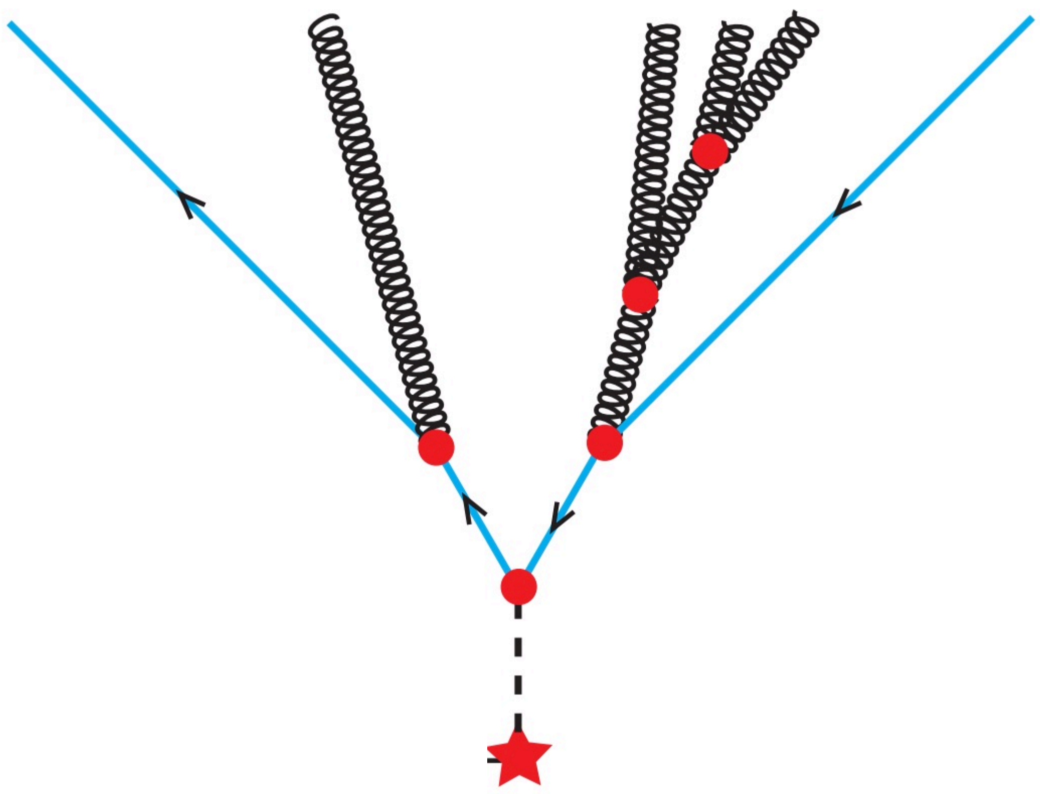
All done, right? Nope

So far, we have had a crash course in jet reconstruction and calibration

In the last decade or so, much work has been done on the classification of jets using jet substructure: the distribution of energy within jets

Heavy objects (top/W/Z/Higgs) decay to hadrons and form jets. These jets have different internal structures to typical quark/gluon jets (for b-tagging, see Andy's talk)

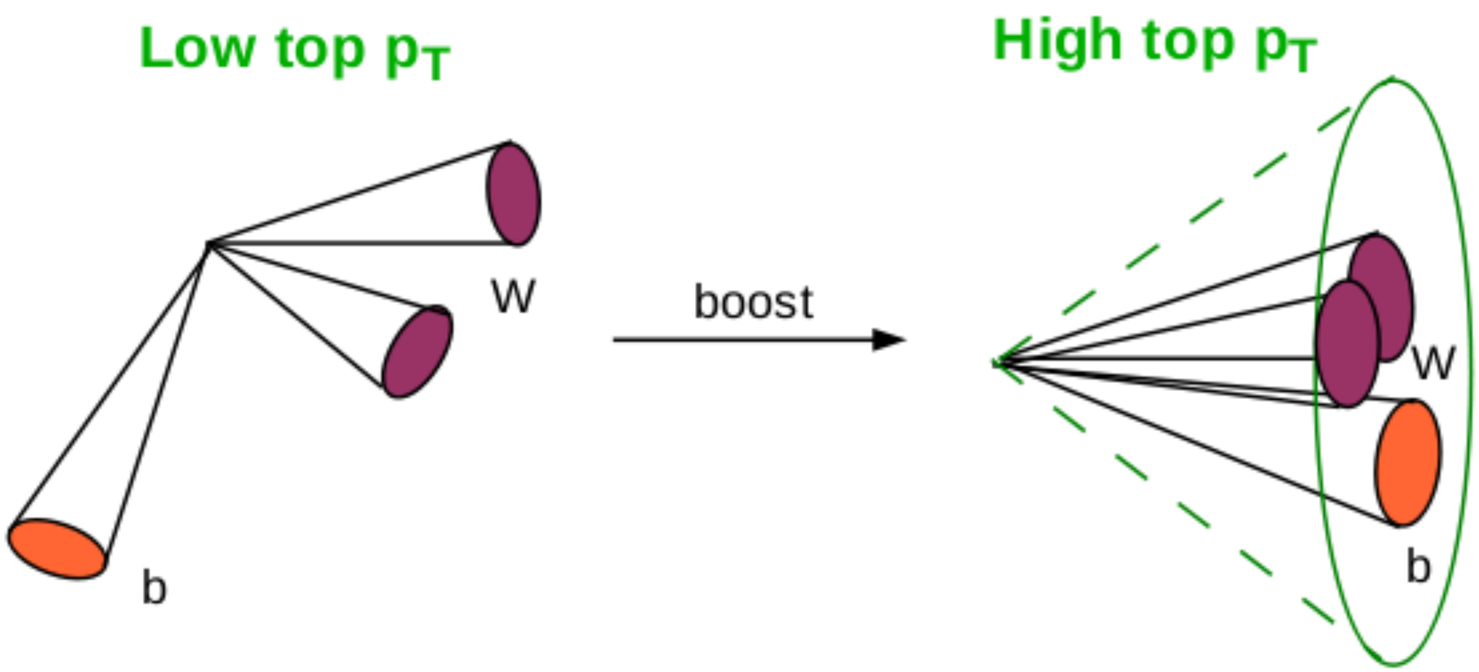




Quark and gluon jets also differ due to the different colour charge carried

Boosted jets and substructure

How do we reconstruct heavy, hadronically decaying particles?



At high pT can typically reconstruct a heavy object within an R=1.0 jet

Rule of thumb: angular separation of decay products of a massive particle in a 1 to 2 decay is

$$R = \frac{2m}{p_T}$$

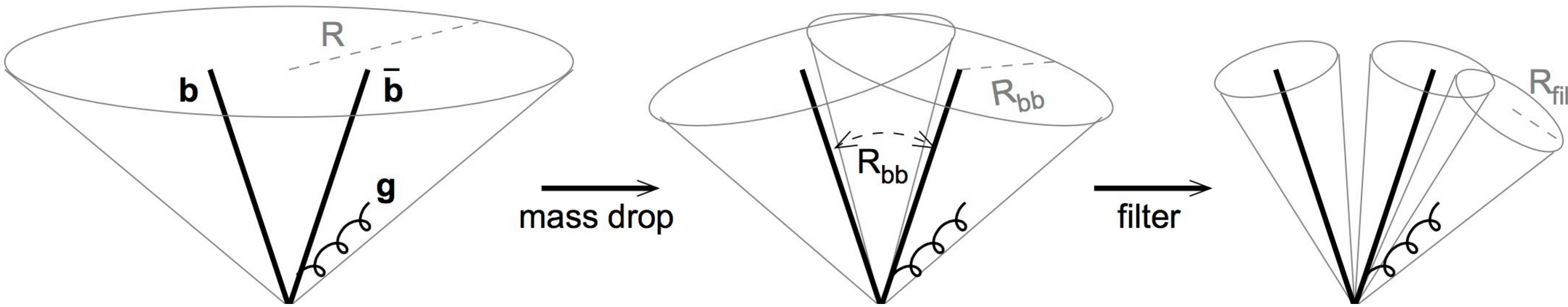
Jets from quarks and gluons typically have a single, hard core

Other challenges

- Have to deal with pileup, now at a constituent level rather than a jet level
- Finite resolution of the calorimeter: angular separation of constituents matters more

Substructure origins

BDRS tagger: Higgs tagging with split filtering



$$\mu = \frac{m_{j1}}{m_j}$$

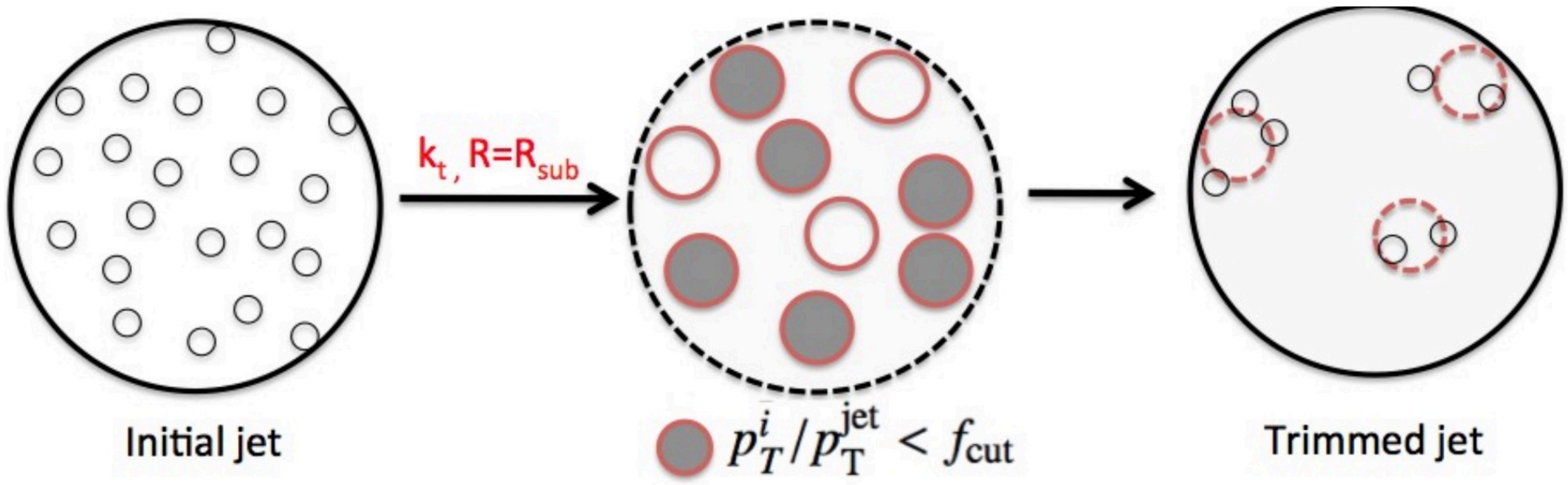
$$y = \frac{\min(p_{T1}, p_{T2}) \cdot (\Delta R_{12})^2}{m_{jet}^2}$$

- Cluster jet with C/A algorithm
- Undo the clustering history and at each step evaluate mass drop and subjet asymmetry
- If mass drop is small and asymmetry large, discard the subheading jet and repeat

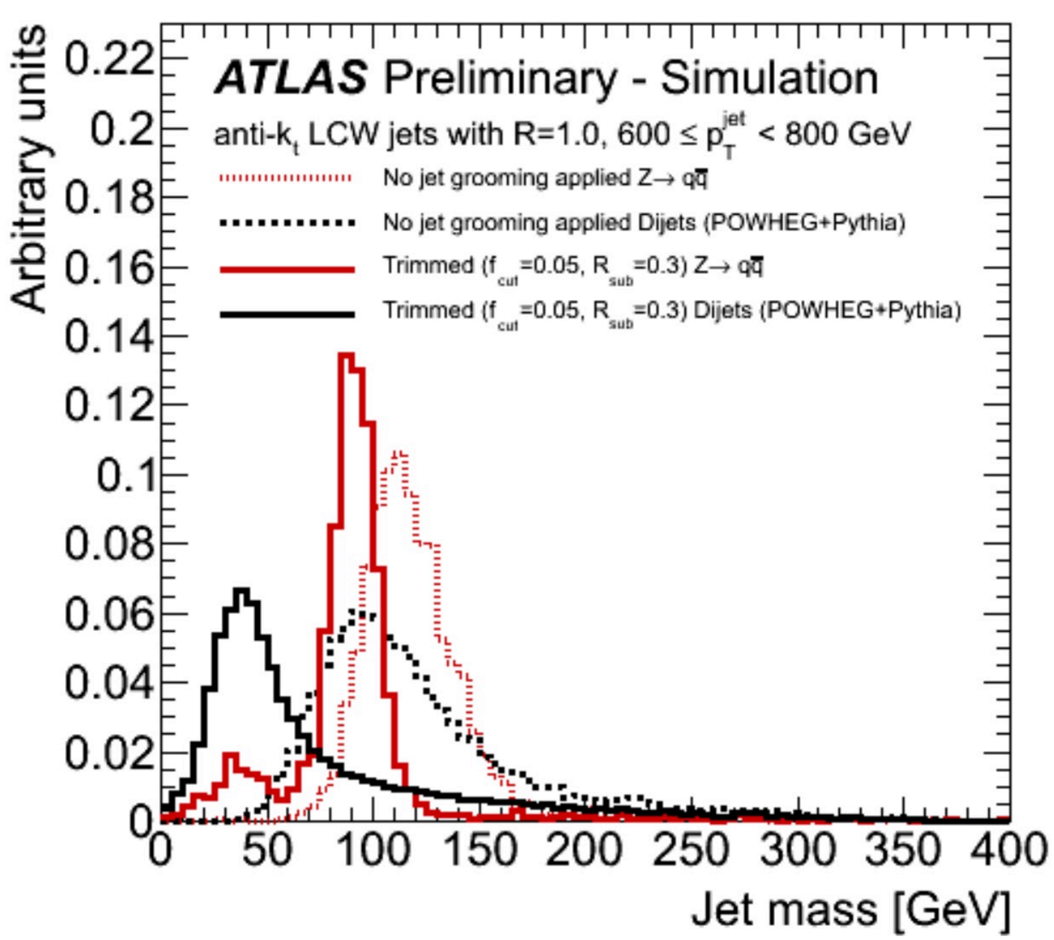
This will pick out the "hard splitting" and help identify the mass peak
Showed that more could be learnt about the physics of a jet by looking inside

Jet Grooming

The trimming algorithm



anti-kt R=1.0, (before/after trimming)



- JSS variables are smeared by soft radiation from ISR, pileup sources
- Grooming attempts to remove this while preserving substructure information
- Can be too aggressive

Trimming is currently used by ATLAS

softdrop is likey to replace it, and has interesting theoretical properties

Evaluating the substructure of jets

subjet independant “pronginess”

How many subjets does it look like this jet has?

Observable	Variable	Used For	Reference
Jet mass	m^{comb}	top,W	**[ATLAS-CONF-2016-035]**
Energy Correlation Ratios	ECF_1, ECF_2, ECF_3 C_2,D_2	top,W	**[ECF, D2]**
N-subjettiness	τ_1,τ_2,τ_3 τ_{21},τ_{32}	top,W	**[Thaler:2010tr, tau2]**
Center of Mass Observables	Fox Wolfram (R_2^{FW})	W	**[foxwolfram]**
Splitting Measures	Z_{CUT} $\sqrt{d_{12}}$,$\sqrt{d_{23}}$	W top,W	**[zcut12Qw]** **[splitingScale]**

ECFS and D2

$$E_{CF0}(\beta) = 1,$$

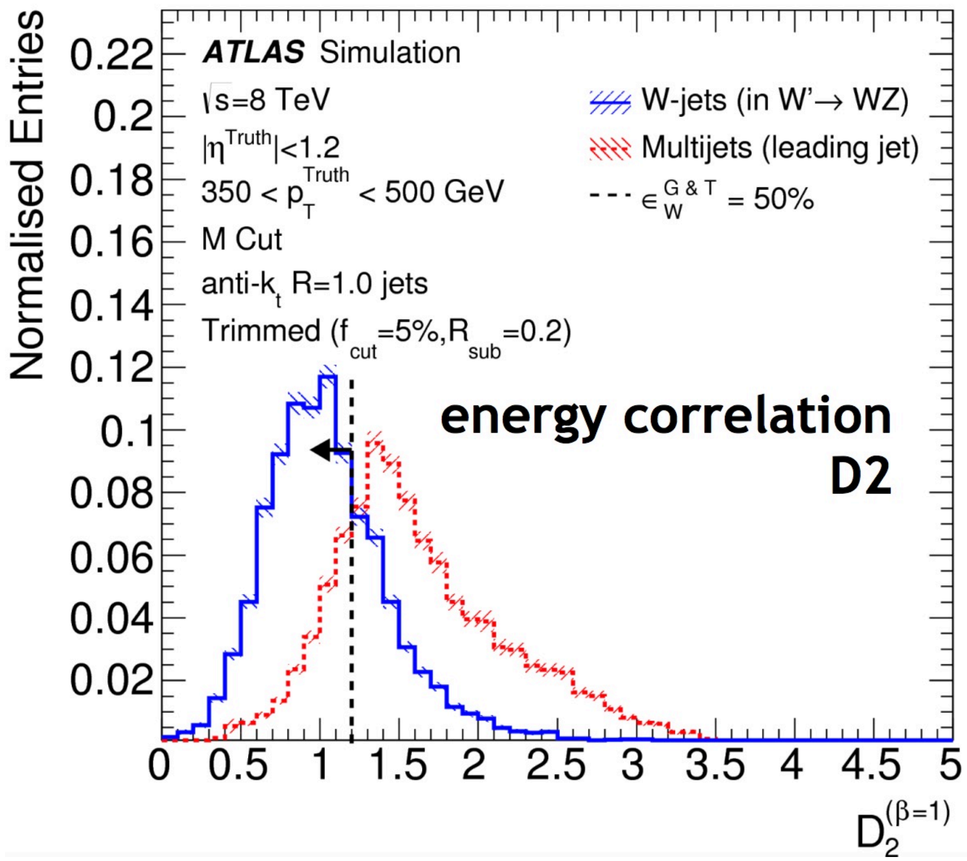
$$E_{CF1}(\beta) = \sum_{i\in J} p_{T_i},$$

$$E_{CF2}(\beta) = \sum_{i<j\in J} p_{T_i} p_{T_j} \left(\Delta R_{ij}\right)^{\beta},$$

$$E_{CF3}(\beta) = \sum_{i<j<k\in J} p_{T_i} p_{T_j} p_{T_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta}$$

$$C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2}$$

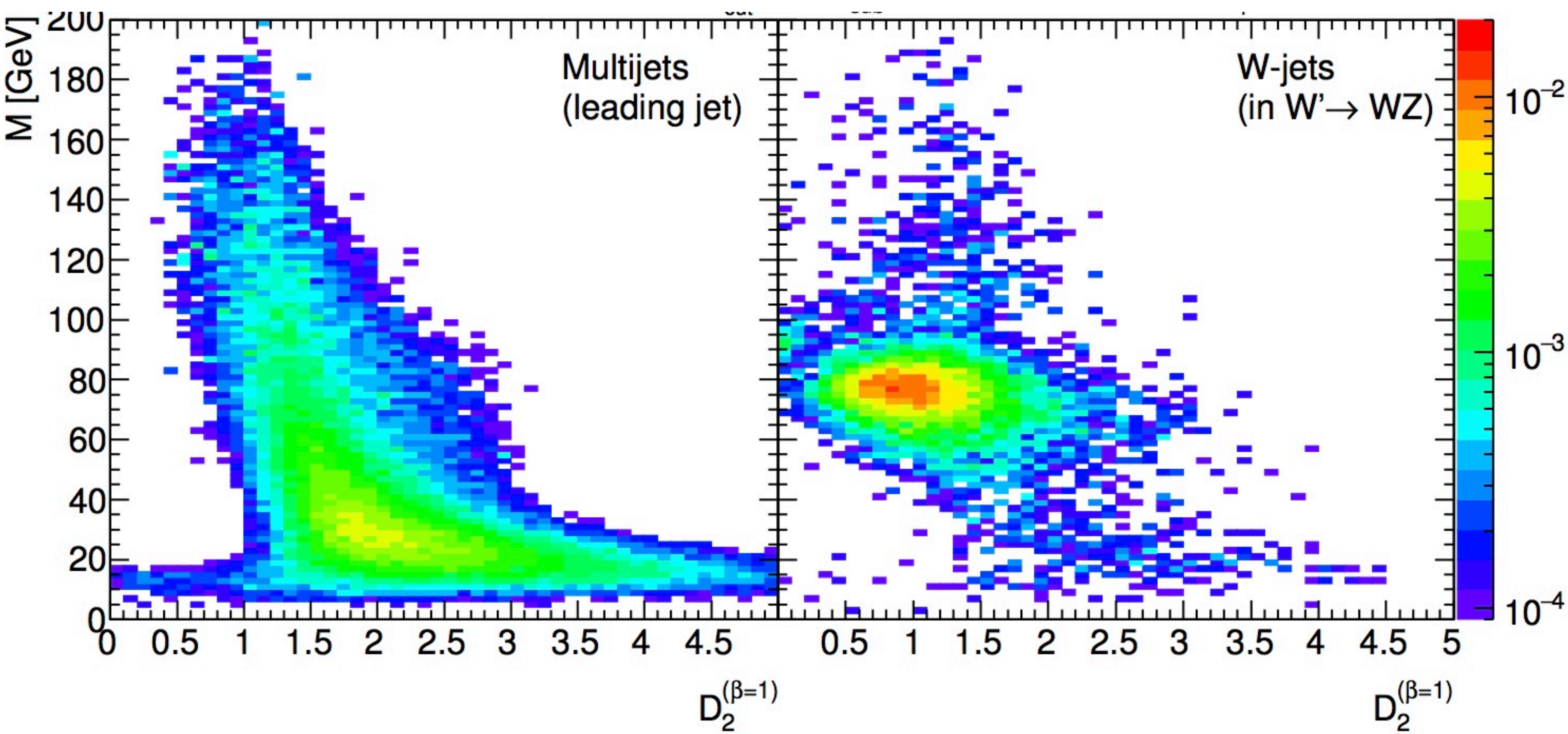
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$



Making a W tagger

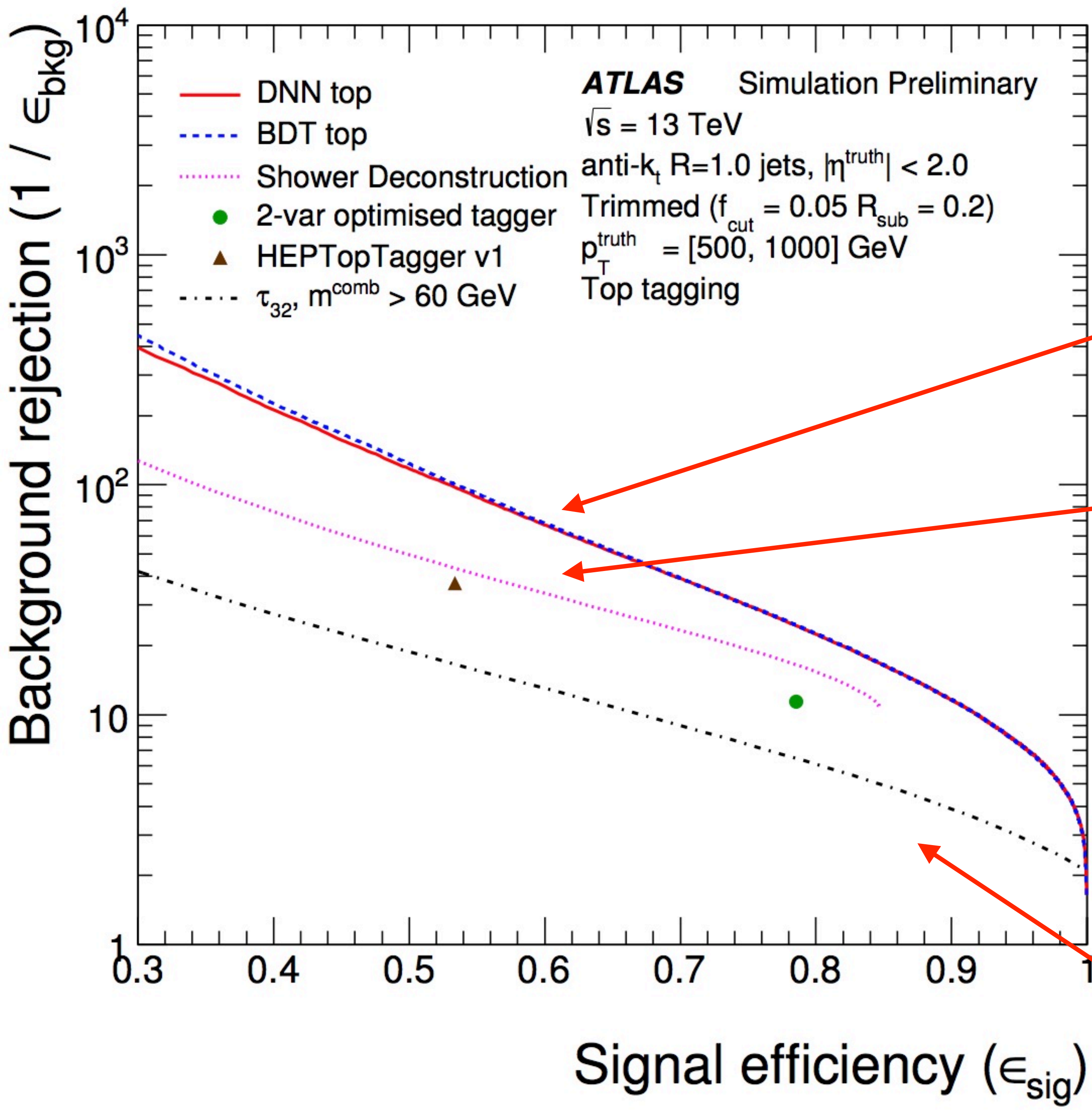
Compare different combinations of variables and cuts

Apply cuts optimise signal selection and background rejection



Advanced techniques

Many variables/topologies, becomes an interesting classification problem



Comparing different techniques on a level playing field

DNN/BDT trained on inputs of JSS variables

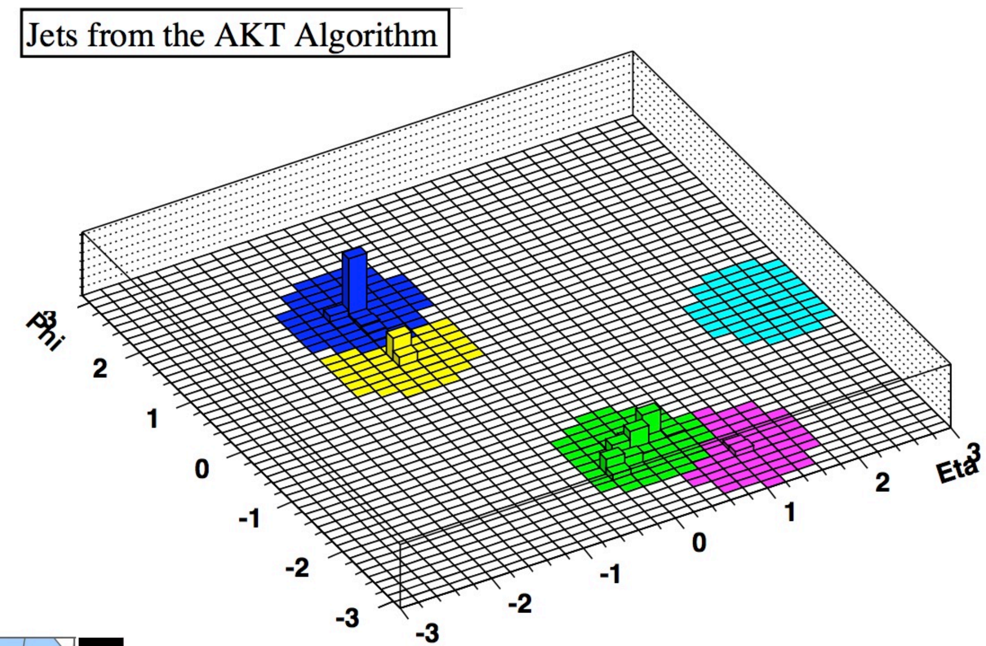
Theory motivated "smart taggers"

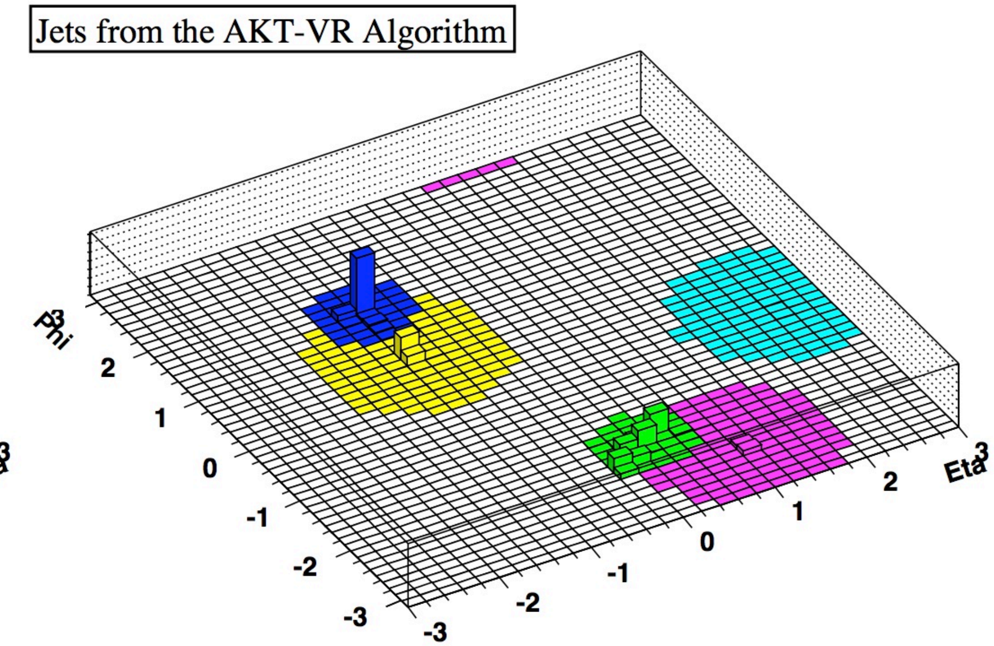
Plenty of ideas, a lot fo work is spent comparing which are best

Simple JSS variable cut

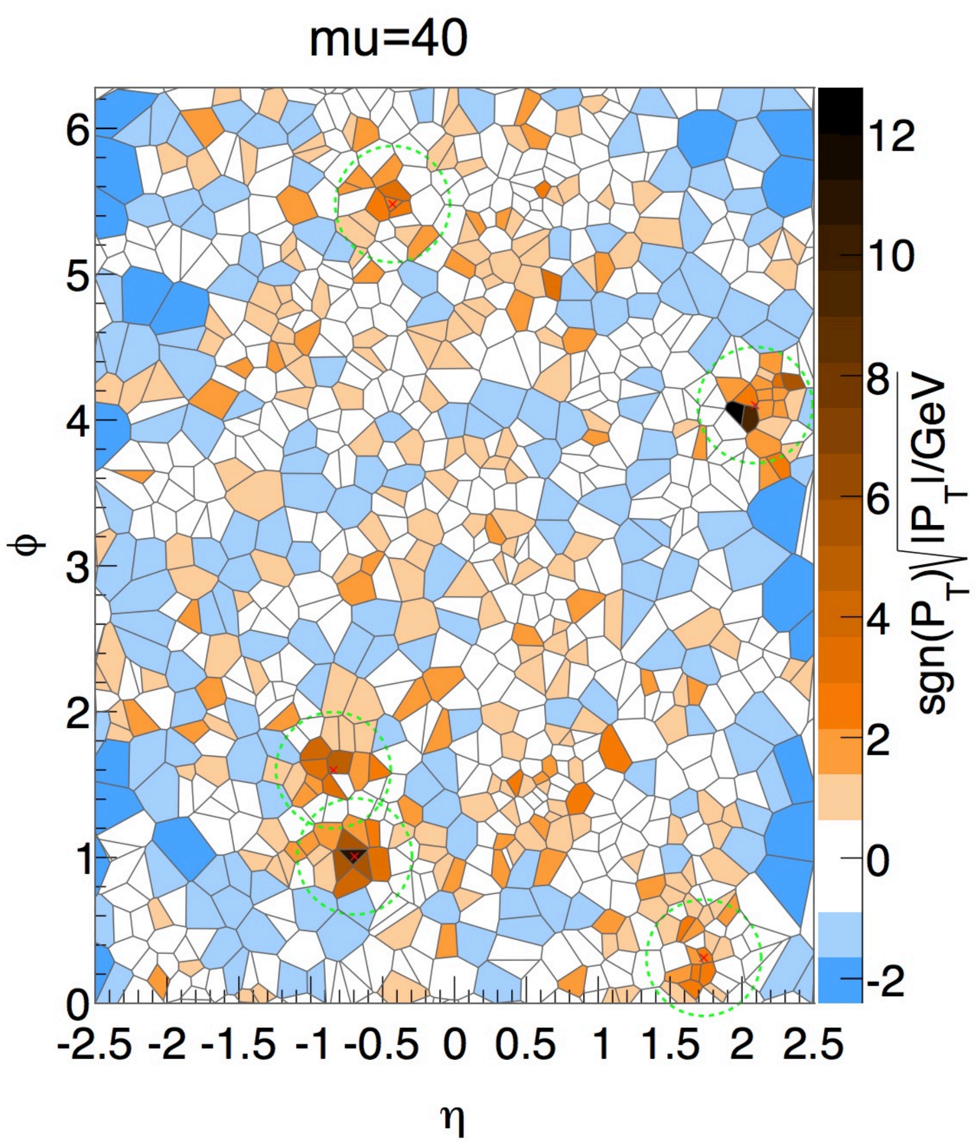
A few more things to watch out for

variable radius jets

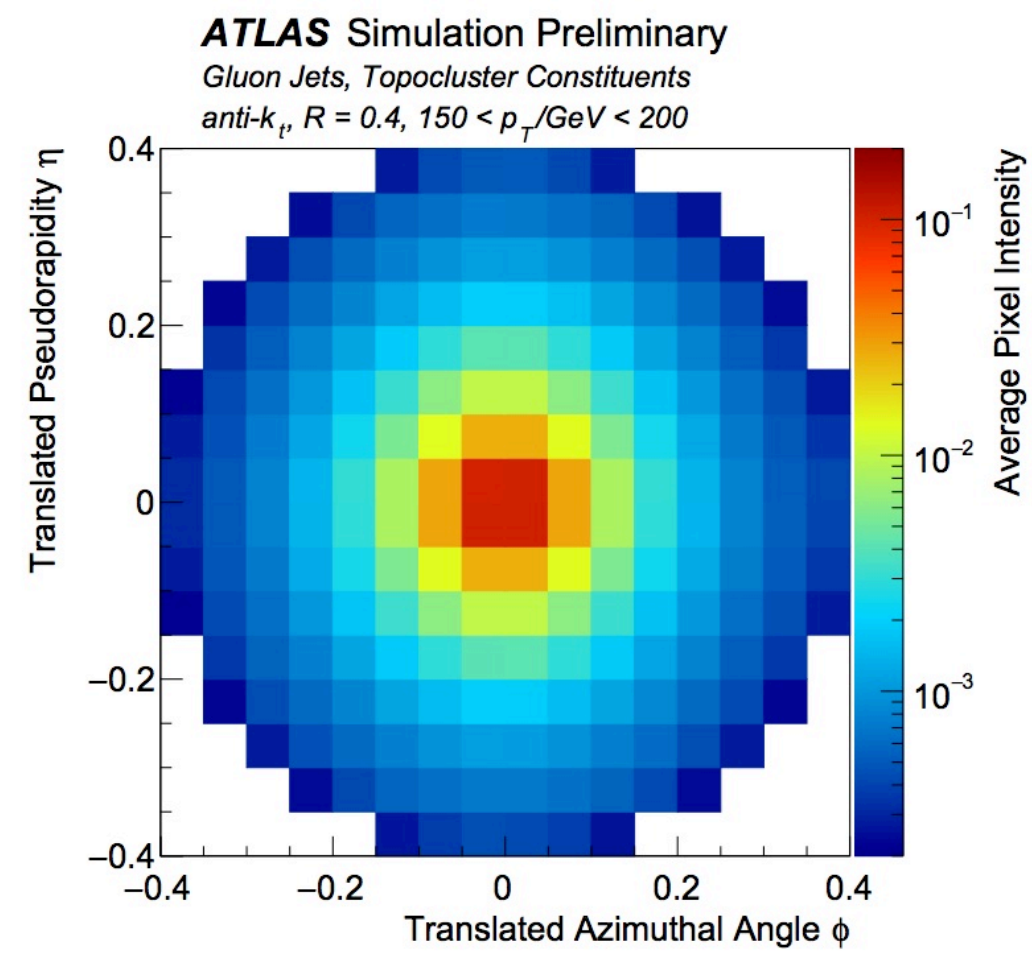




stochastic noise removal



Jet images and computer vision



Thanks for listening!

Any questions please ask!