29th Nov. ‘17

Jet Grooming

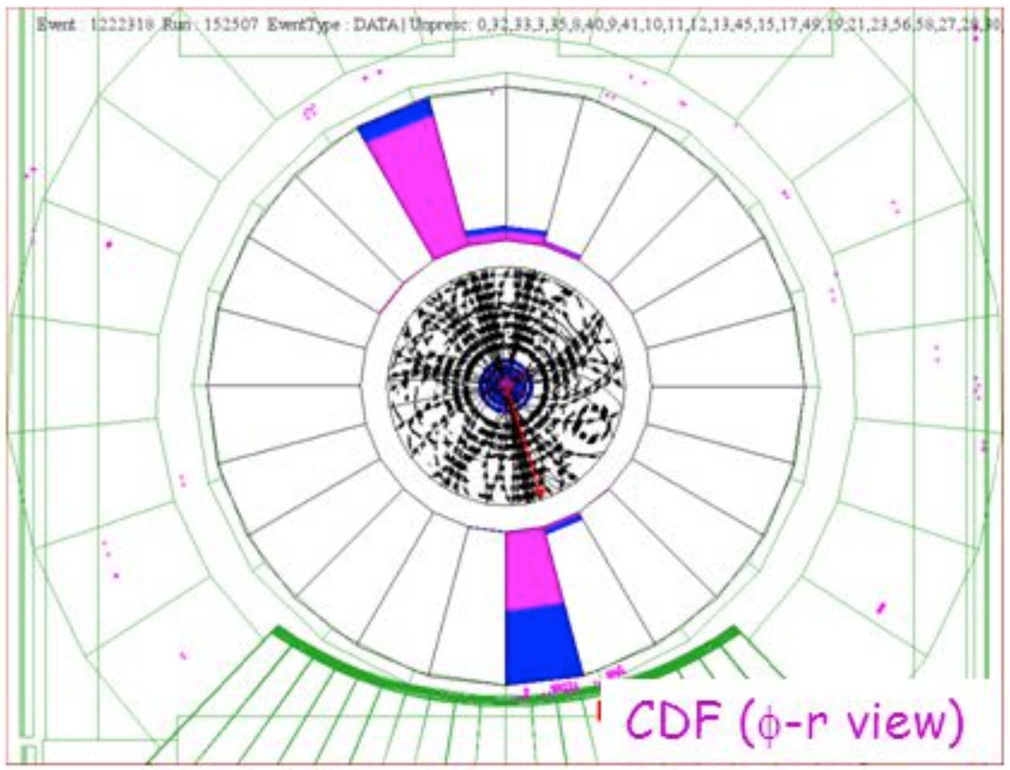
290E seminar

Jet structure grooming in ATLAS, techniques old and new

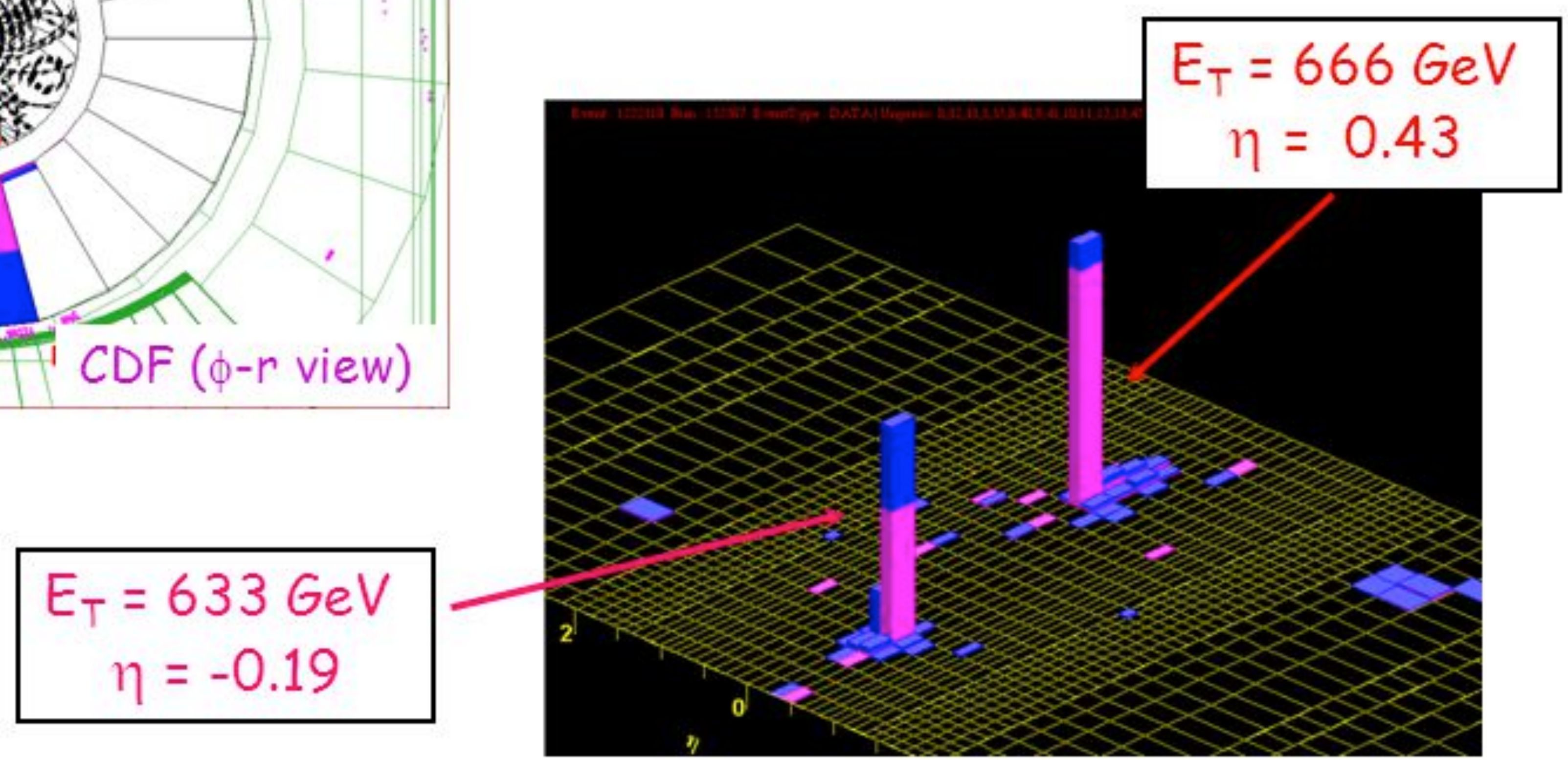
Rebecca Carney

CDF calorimeter

$$\Delta\eta \times \Delta\phi = 0.1 \times 15^\circ = 0.1 \times \left(\frac{\pi}{12}\right) \quad (|\eta| < 1)$$



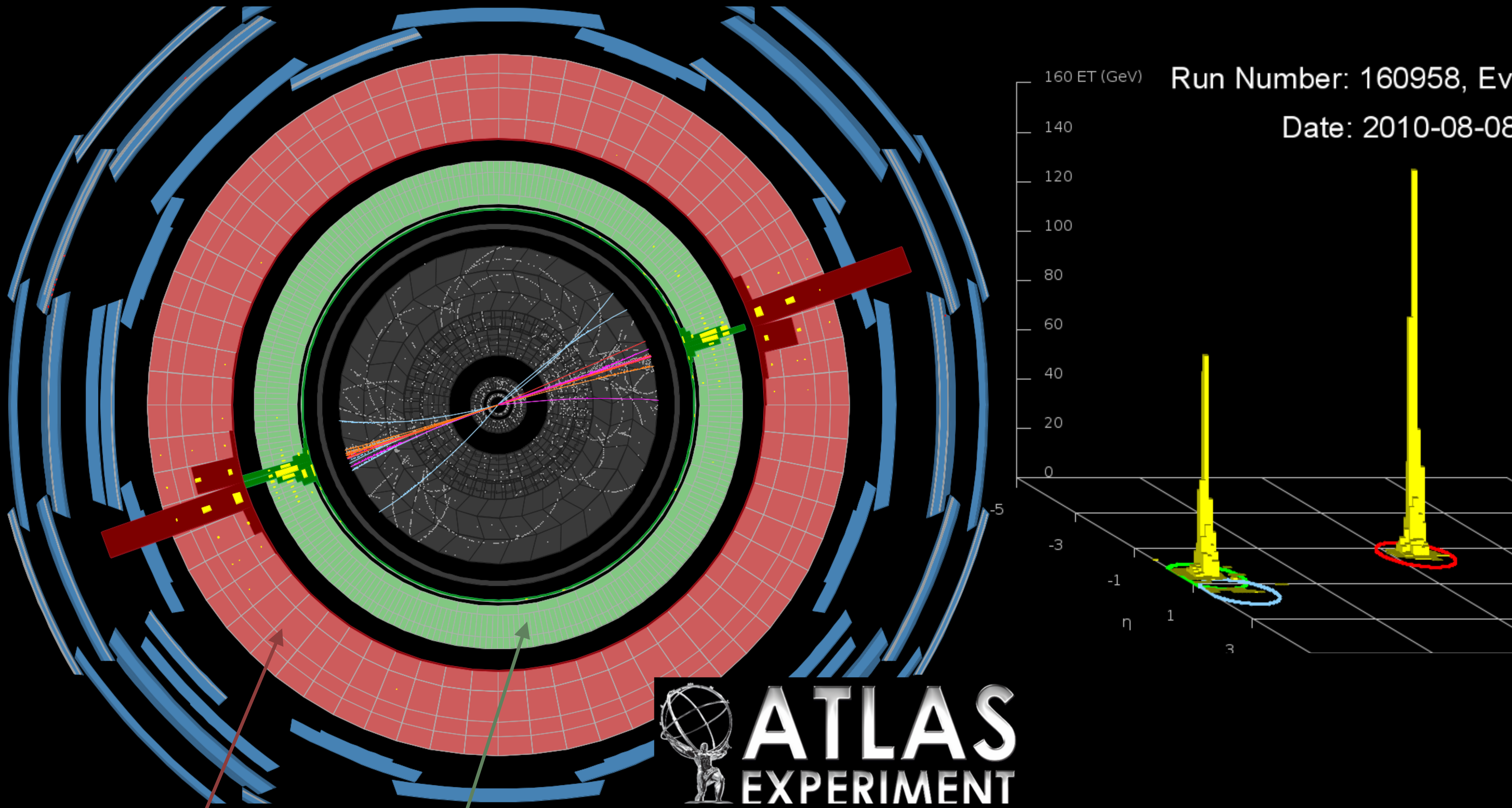
Dijet Mass = 1364 GeV
(probing distance ~10^{-19} m)



ATLAS calorimeter segmentation

Greater segmentation and granularity means more structure

$$\Delta\eta \times \Delta\phi = 0.1 \times 15^\circ = 0.1 \times \left(\frac{\pi}{12}\right) \; (|\eta| < 1)$$



$$\Delta\eta \times \Delta\phi = 0.025 \times 1.4^\circ = 0.025 \times \left(\frac{\pi}{128}\right) \; (|\eta| < 1)$$

$$\Delta\eta \times \Delta\phi = 0.025 \times 5.625^\circ = 0.025 \times \left(\frac{\pi}{32}\right) \; (|\eta| < 1)$$

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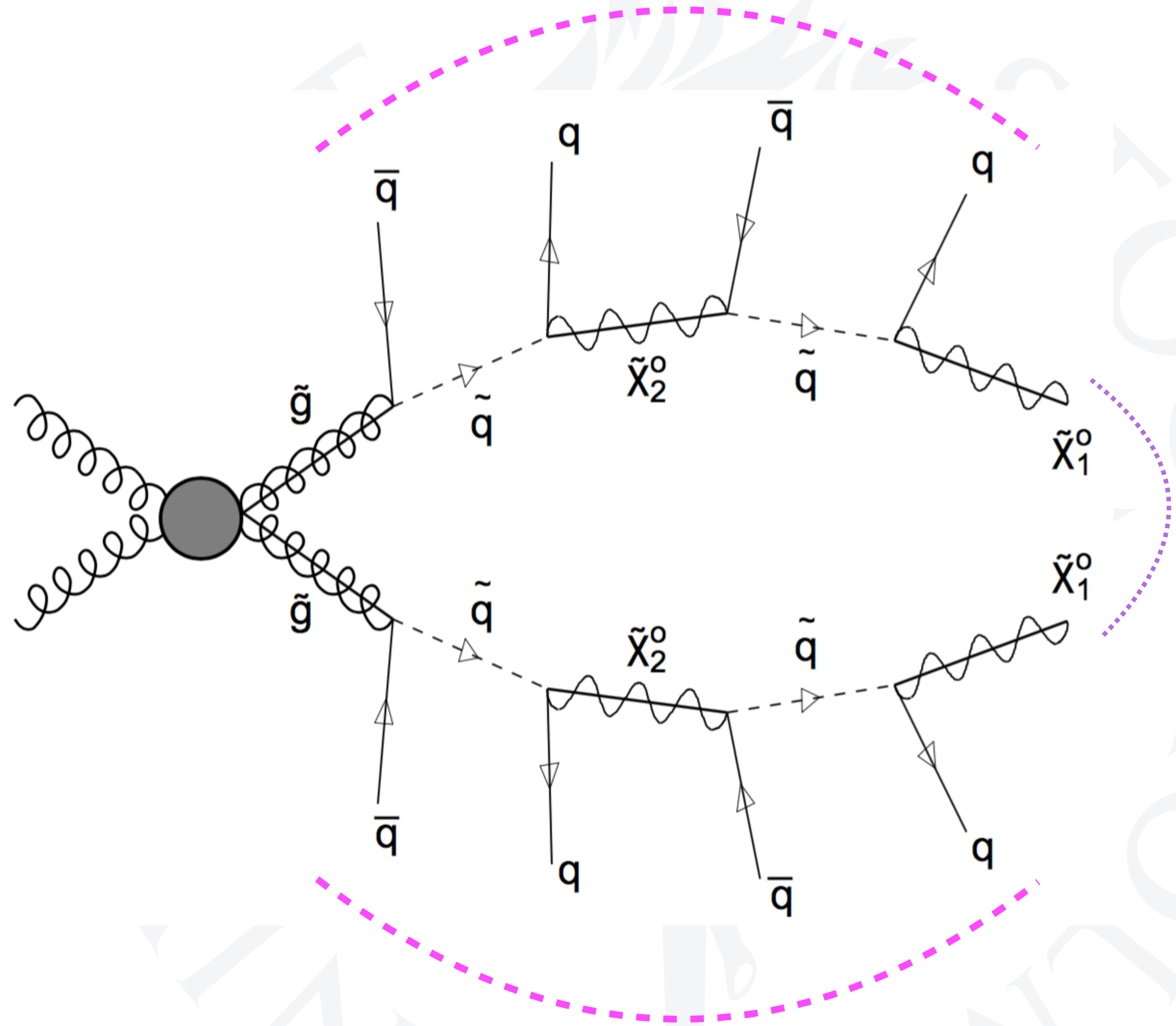
Quark or gluon jet?

4 jets



Neutral stable SUSY particles (MET)

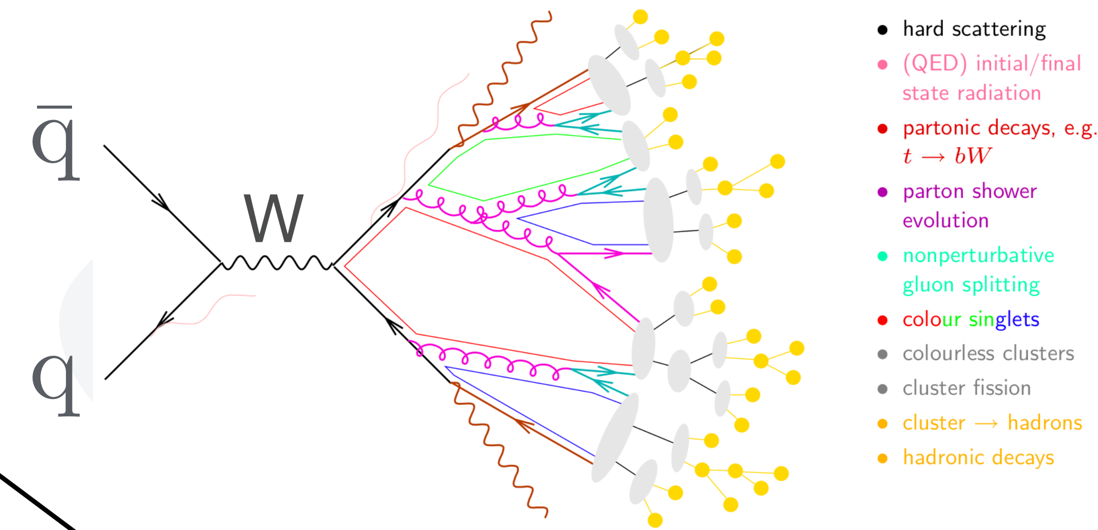
4 jets

This amount of quark-jets is extremely unlikely in background processes, so quark-gluon discrimination is a useful selection tool!

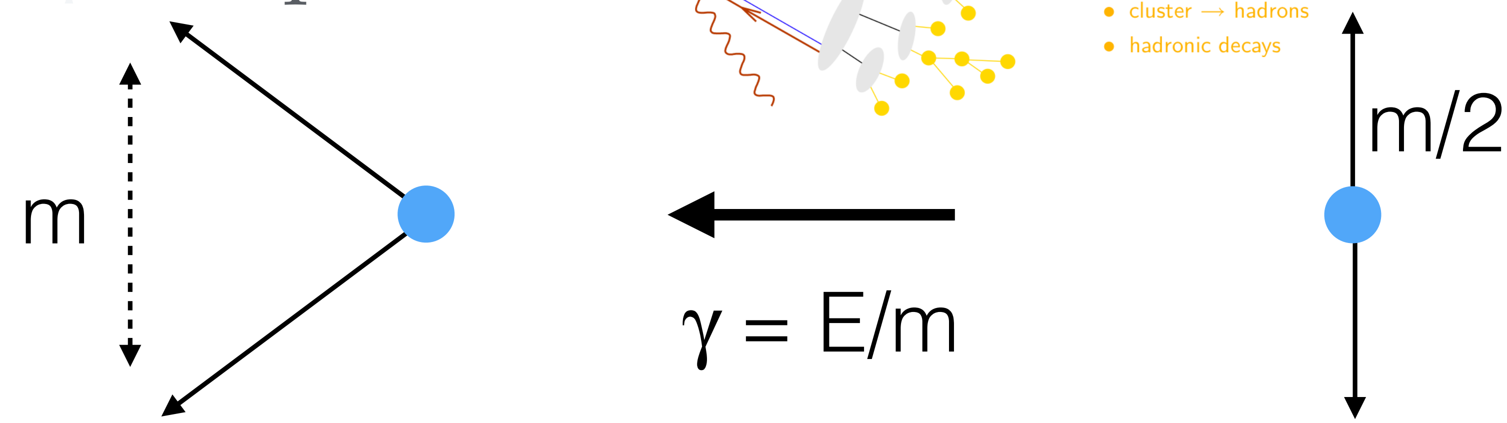
Boosted dijet resonances

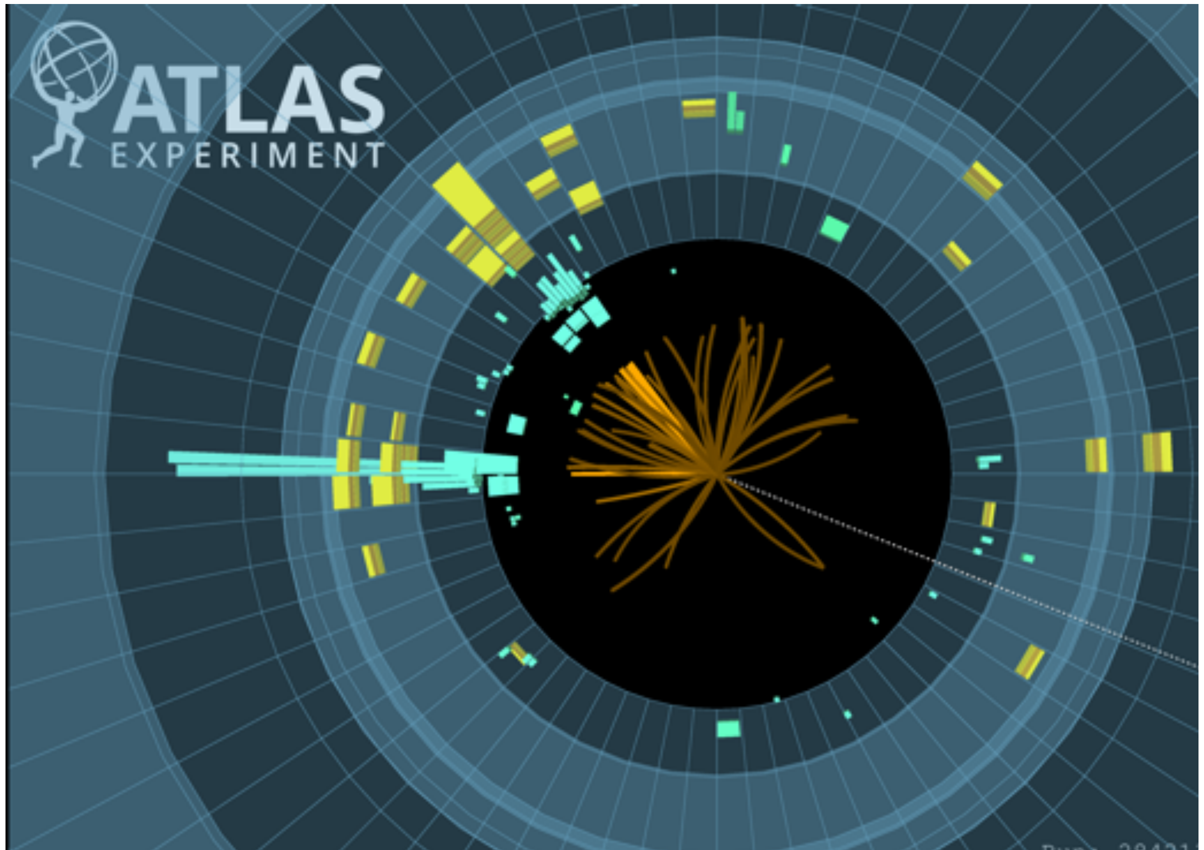
Some uses for jet substructure

Heavy particles decaying produce boosted 'fat' jets.

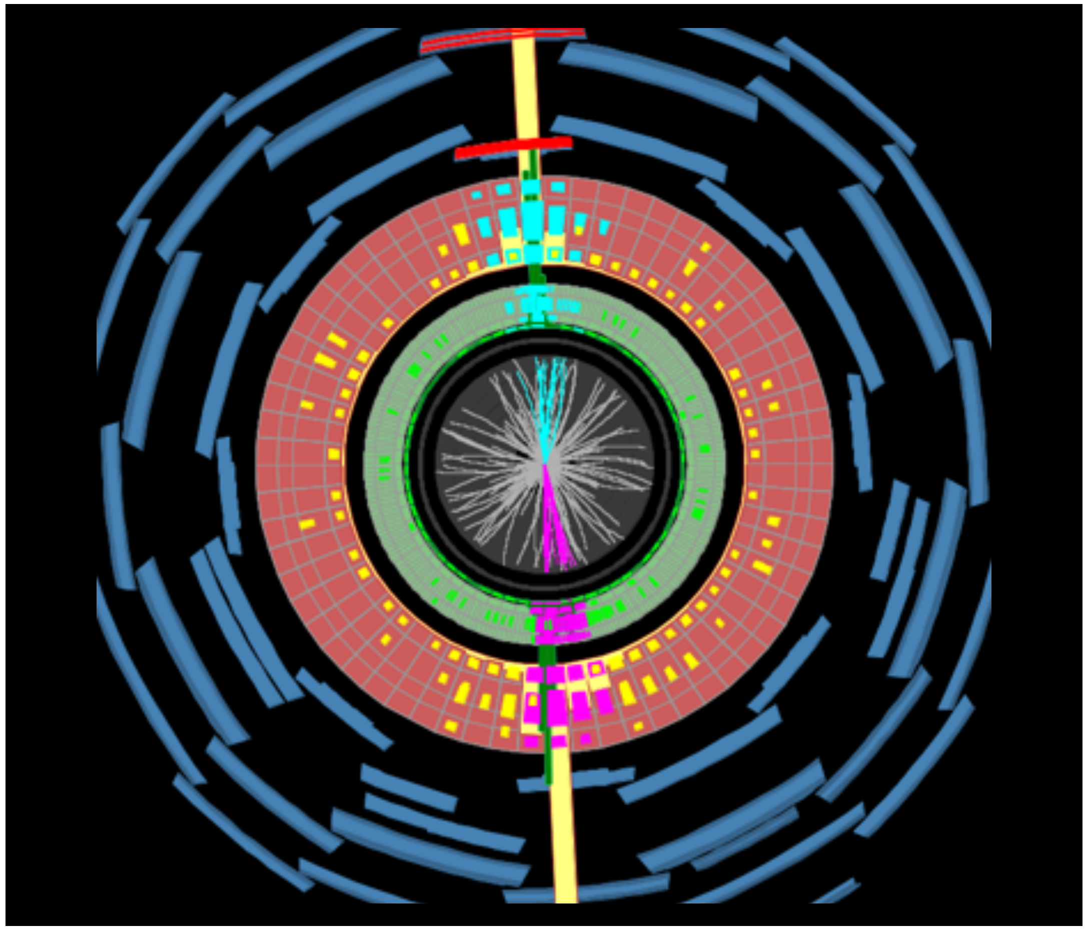


$\phi \sim 1/\gamma = m/E$





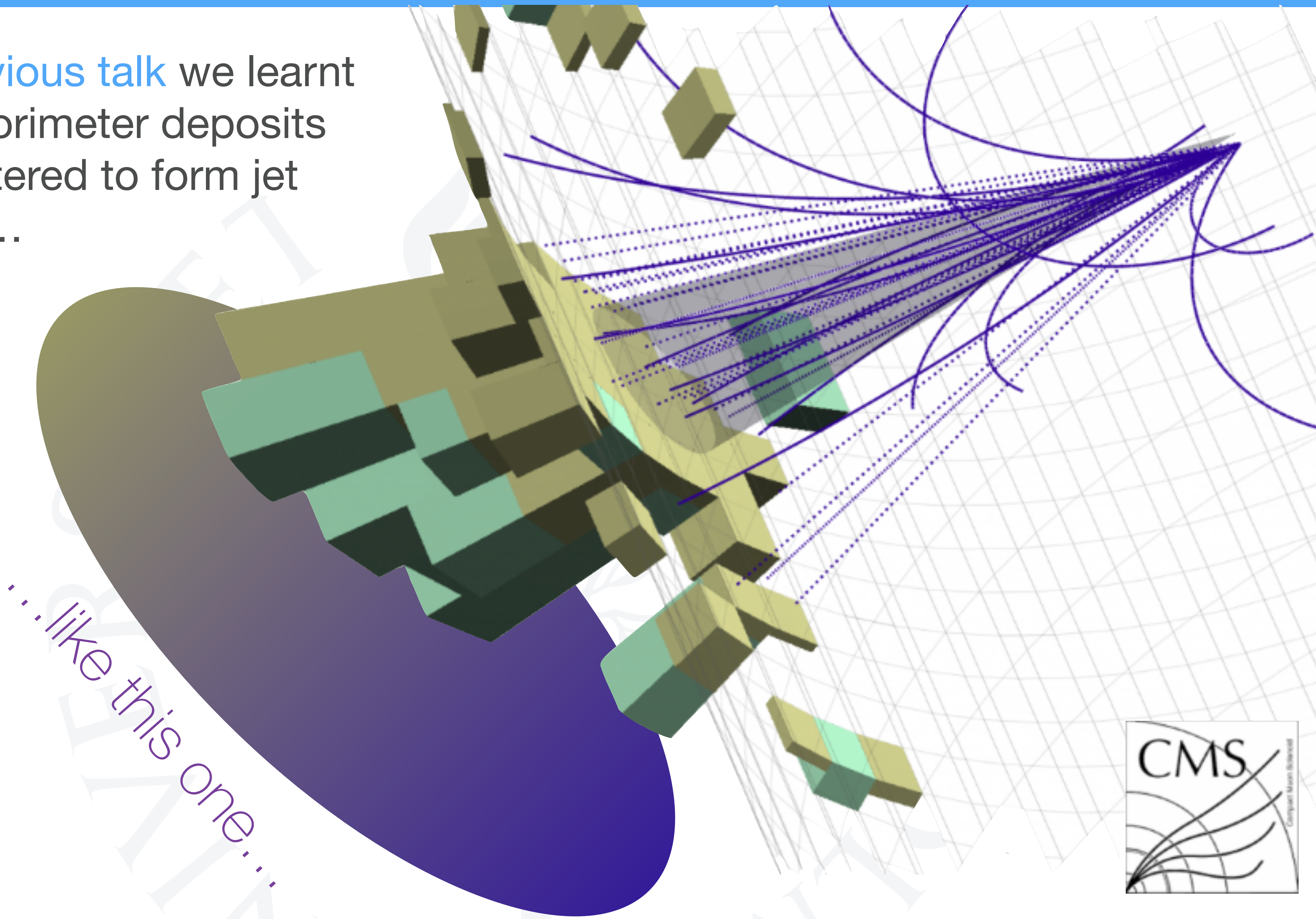
Ben Nachman - CERN 2017



From jets to substructure

Recover structure from jet object

In a previous talk we learnt how calorimeter deposits are clustered to form jet objects…



… and in this talk we'll discuss how jet structure is recovered.

Jet Grooming

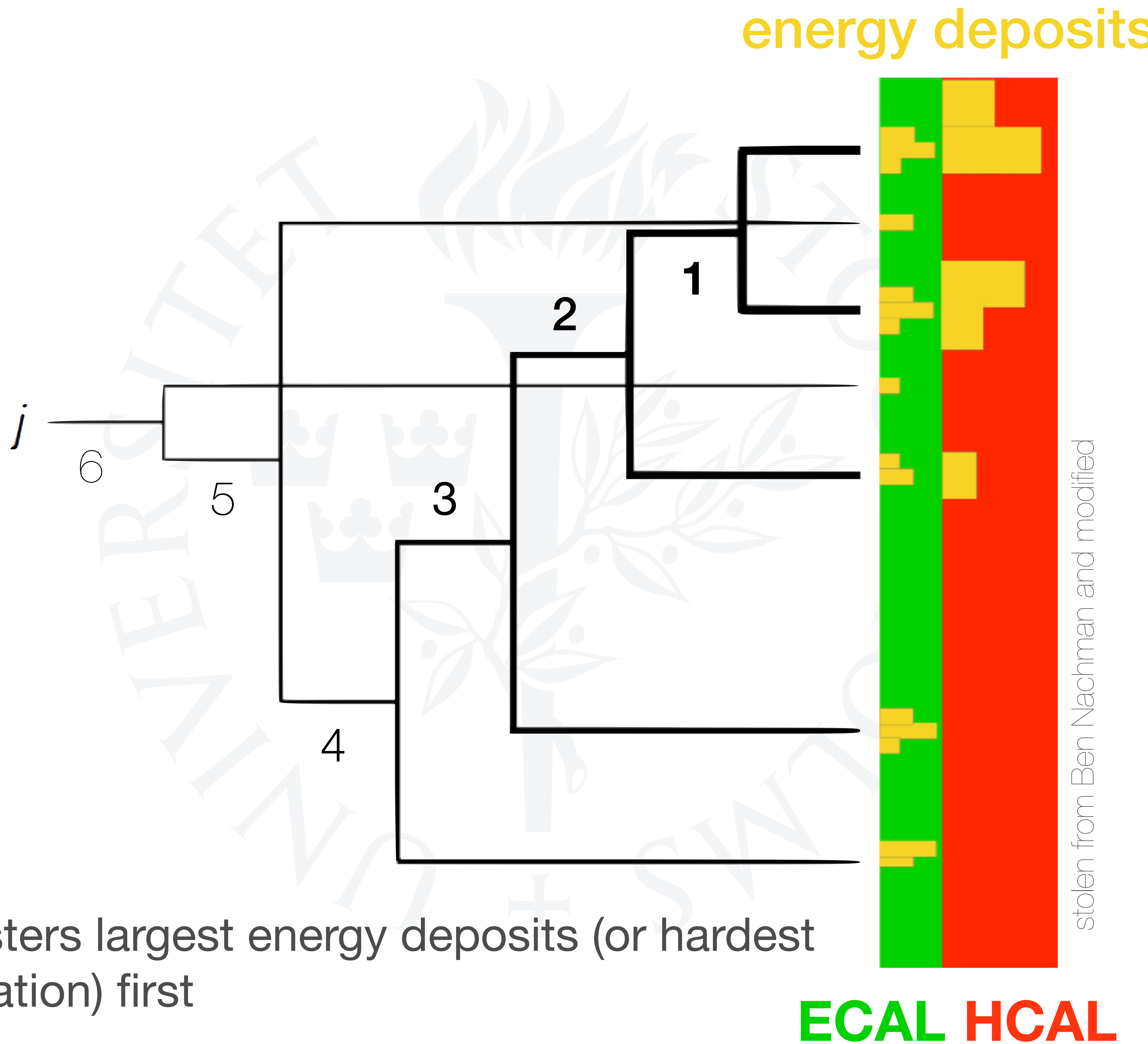
Jet grooming algorithms: an example

The effect of jet grooming

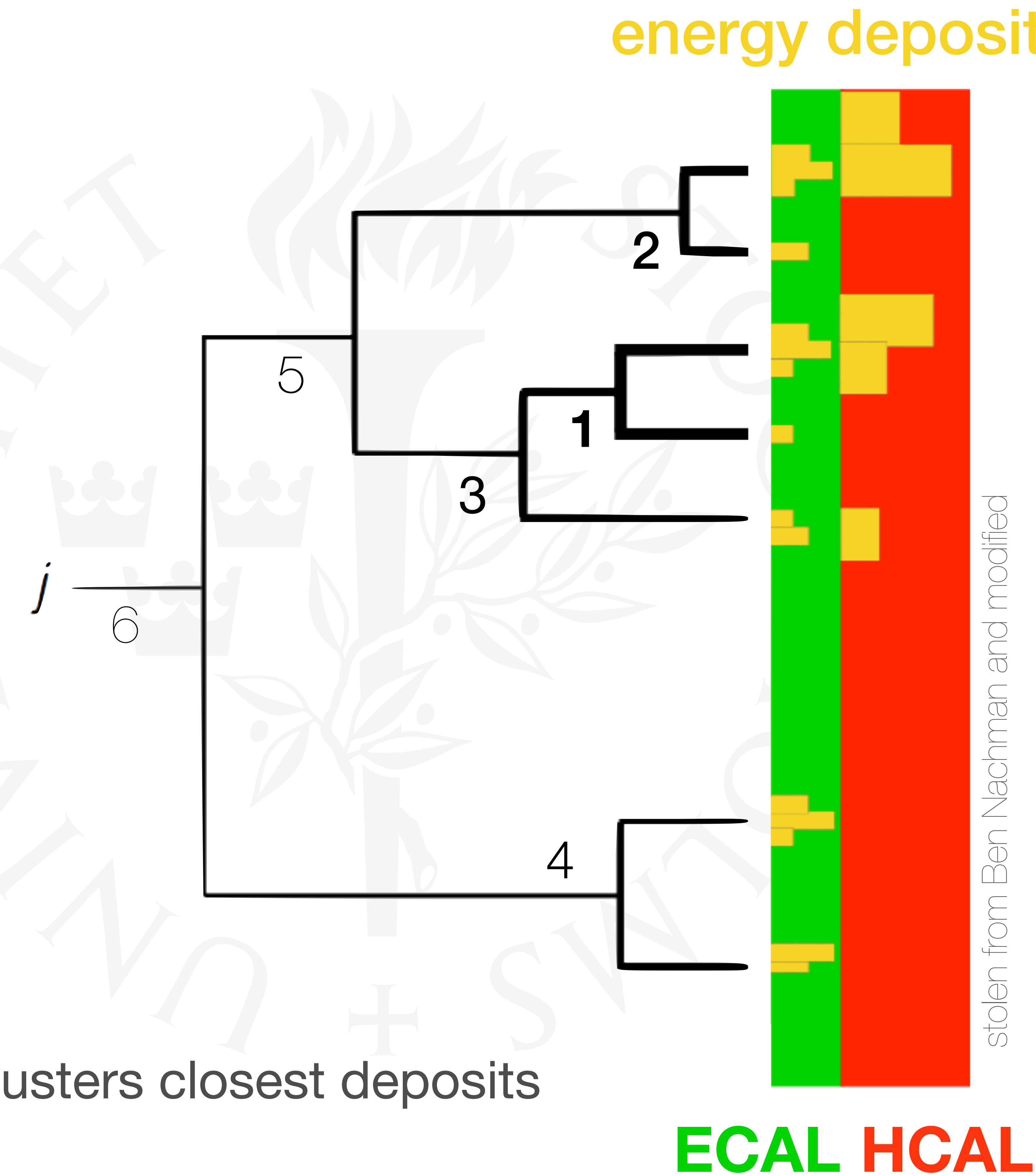
Computational development and future work

Mass-drop filtering

Reminder: Anti-kT clustering



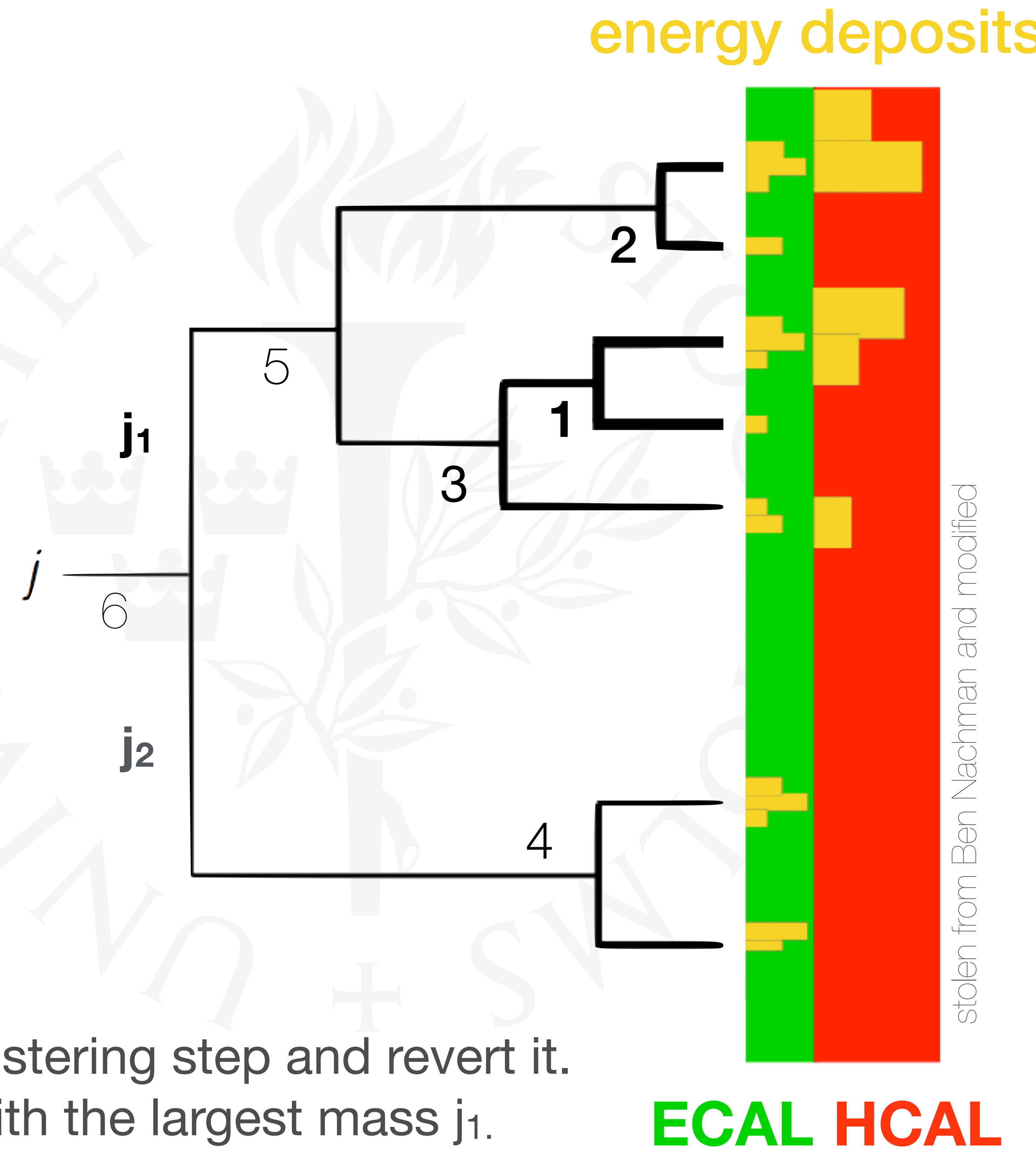
Clusters largest energy deposits (or hardest radiation) first



Whilst C/A clusters closest deposits first

Mass-drop filtering

Step 1: Split last step



Go to last clustering step and revert it.
Call the jet with the largest mass j_1.

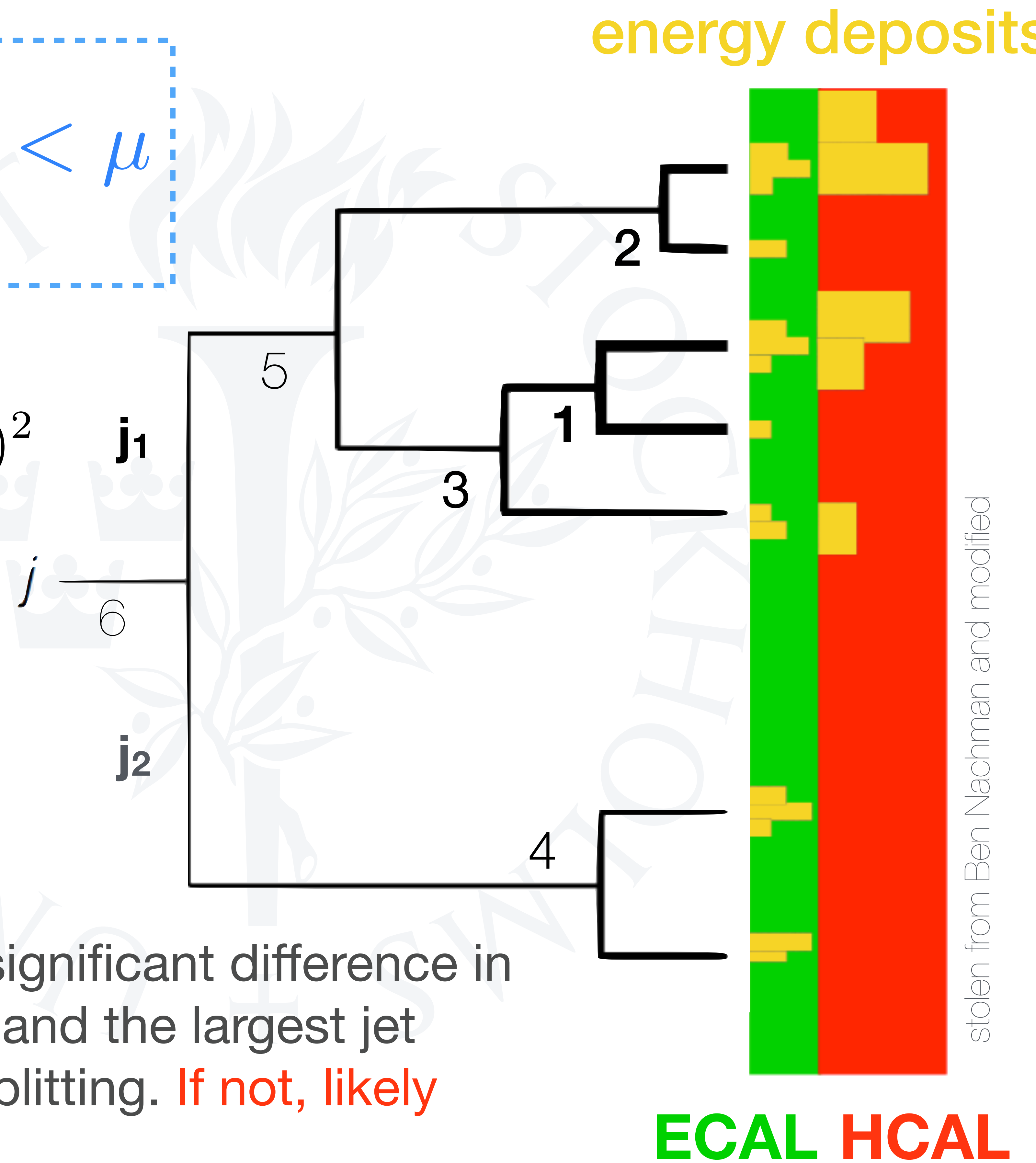
Mass-drop filtering

Step 2: significant difference after splitting

$$\frac{m_{j_1}}{m_{j_{total}}} < \mu$$

$$m^2_{j_{total}} = p^2_{total}$$
$$= (p_1 + p_2)^2$$
$$\neq p_1^2 + p_2^2$$
$$m_{j_{total}} > m_{j_1} + m_{j_2}$$

So it's not obvious what value mu should take. One third? Two thirds?



There must be a significant difference in the total jet mass and the largest jet mass, following splitting. If not, likely soft radiation.

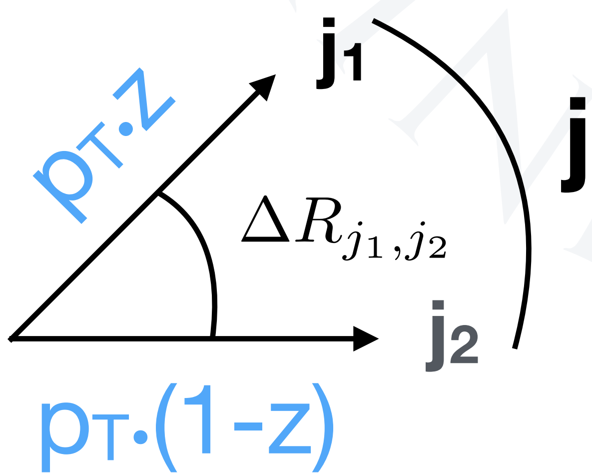
Step 3: is the splitting symmetric?

Established: a significant mass difference when jet split

Not established: how symmetric is the split?

$$\frac{\min\left[\left(p_{\mathrm{T}}^{j_1}\right)^2, \left(p_{\mathrm{T}}^{j_2}\right)^2\right]}{m_j^2} \cdot \Delta R^2_{j_1, j_2} > y_{cut}$$

Not immediately obvious why this formula enforces the condition…



$$m_j^2 \approx z(1-z) \cdot p_T^2 \cdot \Delta R^2_{j_1, j_2}$$

$$\therefore \Delta R_{j_1, j_2} \approx \frac{m}{p_T \sqrt{z(1-z)}}$$

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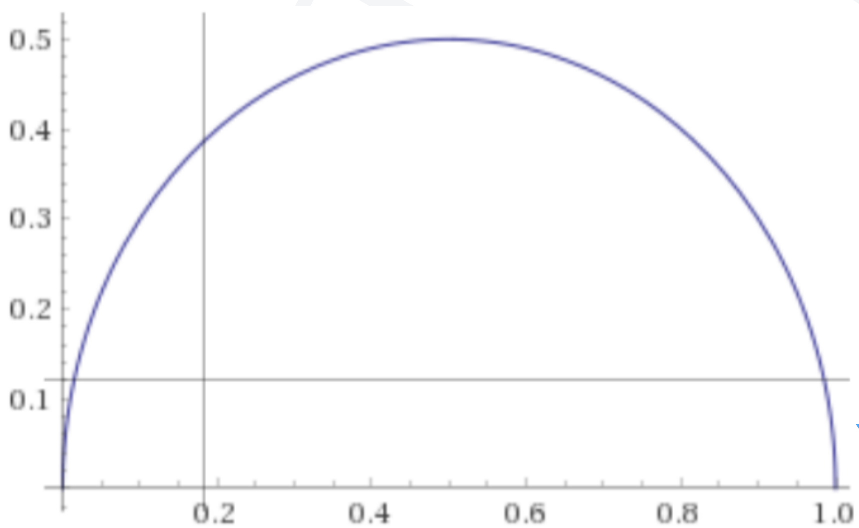
Mass-drop filtering

Step 3b: understanding the mass-drop

$$\min\left[\left(p_{\mathrm{T}}^{j_1}\right)^2, \left(p_{\mathrm{T}}^{j_1}\right)^2\right] > y_{cut} \cdot \frac{m_j^2}{\Delta R^2_{j_1,j_2}}$$

$$> y_{cut} \cdot \frac{m_j^2 \cdot p_{\mathrm{T}}^2 \cdot z(1-z)}{m_j^2}$$

$$> y_{cut} \cdot p_{\mathrm{T}}^2 \cdot z(1-z)$$



$$\therefore p_{\mathrm{T}_{\mathrm{subjet}}}^{\mathrm{min}} > \sqrt{y_{cut}} \cdot p_{\mathrm{T}}\sqrt{z(1-z)}$$

This requirement says that even the jet with the smallest pT must be at least y_{cut} of the fractional total pT, where that fraction depends on the mass splitting.

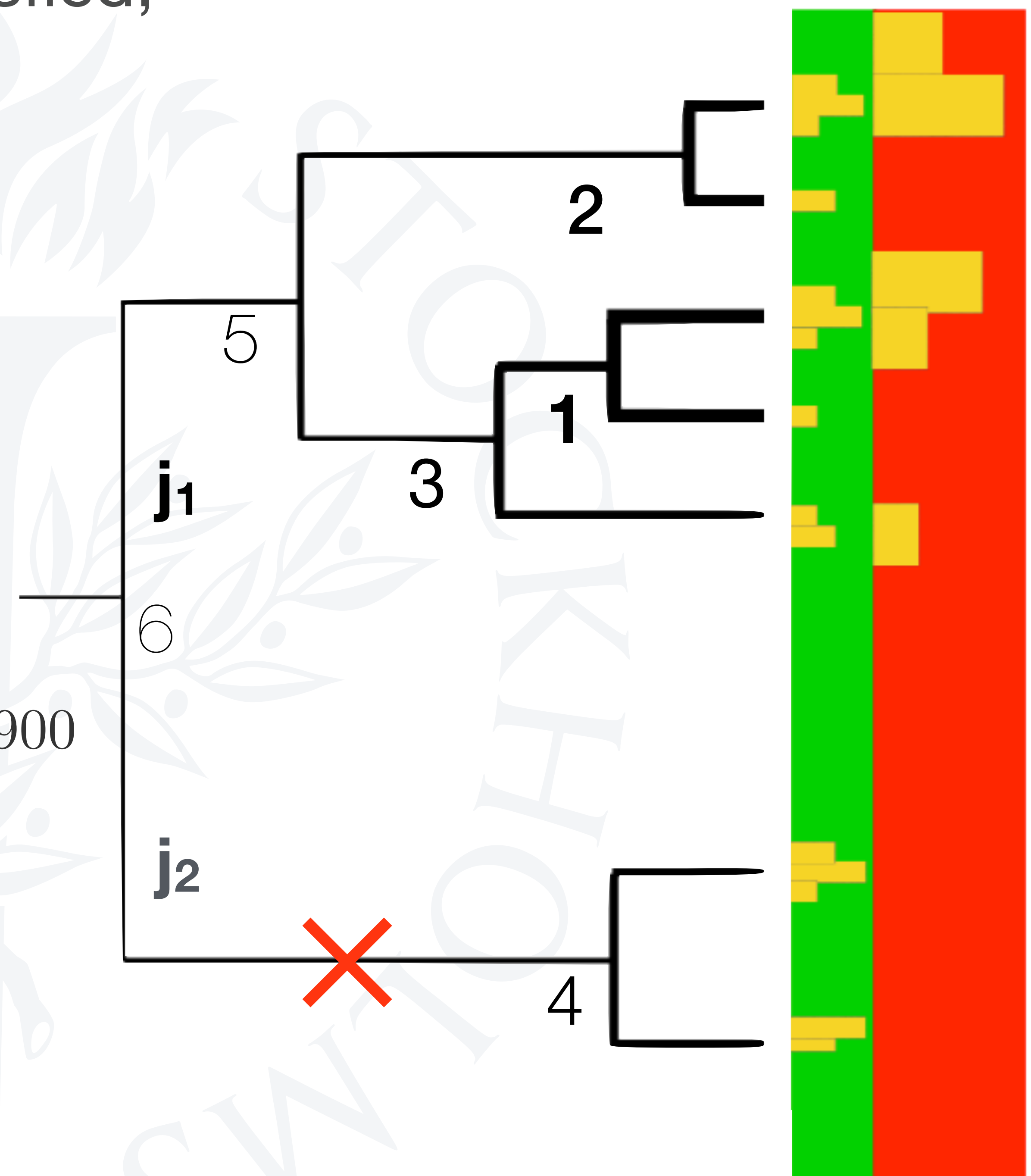
Step 3: is the splitting symmetric?

So, if this condition is not satisfied, remove the smaller pT jet.

e.g. an 80 GeV W boson decaying to hadrons.
- W has pT 200 GeV.
- ΔR = 0.8
- y = 9%

$$\min\left[\left(p_{\mathrm{T}}^{j_1}\right)^2, \left(p_{\mathrm{T}}^{j_1}\right)^2\right] > y_{cut} \cdot \frac{m_j^2}{\Delta R^2_{j_1,j_2}}$$
$$> 0.09 \cdot \frac{80^2}{0.8^2} = 900$$
$$\therefore p_{\mathrm{T}_{\mathrm{subjet}}}^{\mathrm{min}} > 30 \ [\mathrm{GeV}]$$

Which corresponds to a subset fraction of ~ 30/200 = 15% of total jet pT.



$$p_{\mathrm{T}_{\mathrm{subjet}}}^{\mathrm{min}} > \sqrt{y_{cut}} \cdot p_{\mathrm{T}} \sqrt{z(1-z)}$$

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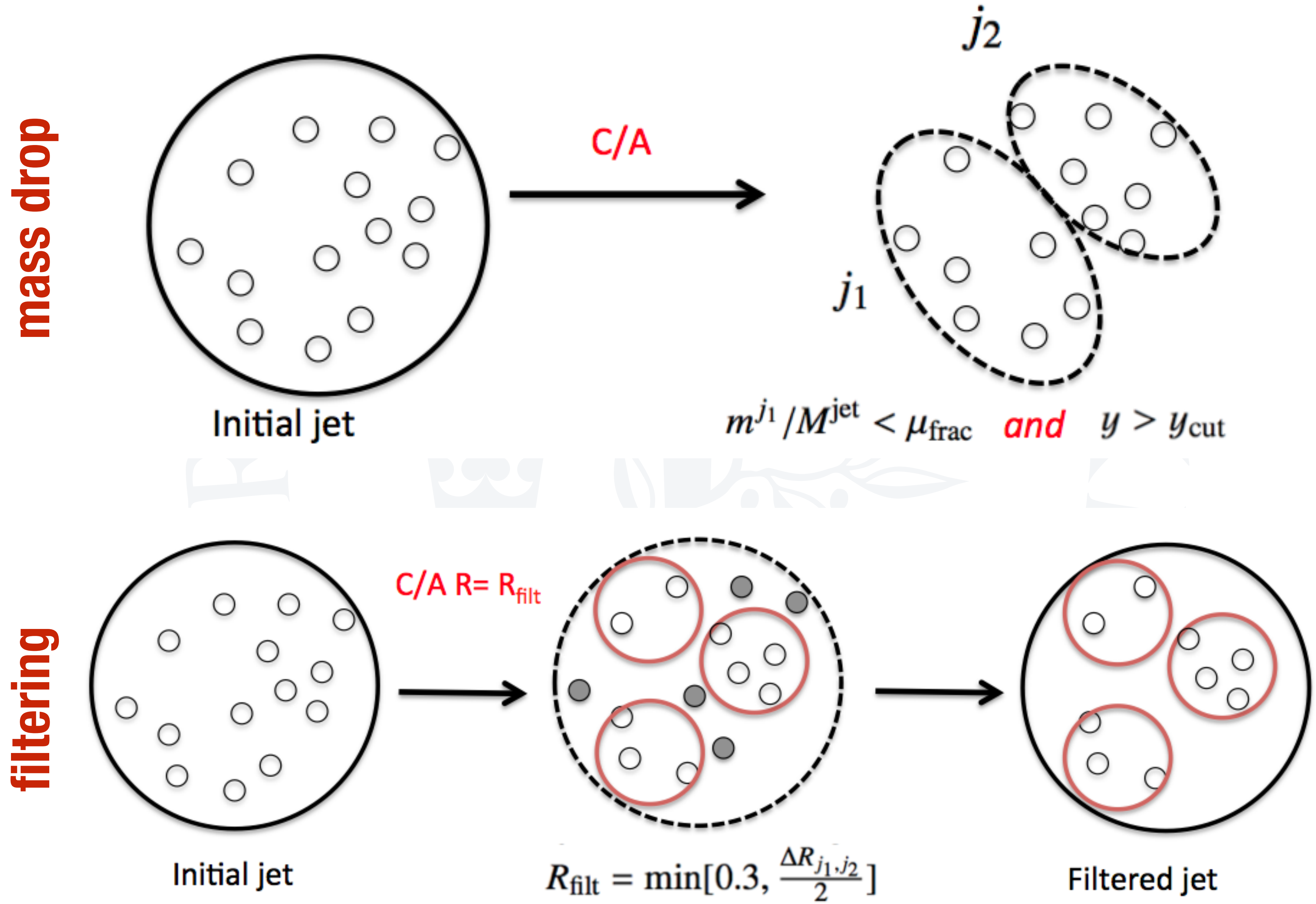
Mass-drop **filtering**

Step 4: filtering

Even if every deposit makes it through the mass-drop cut…

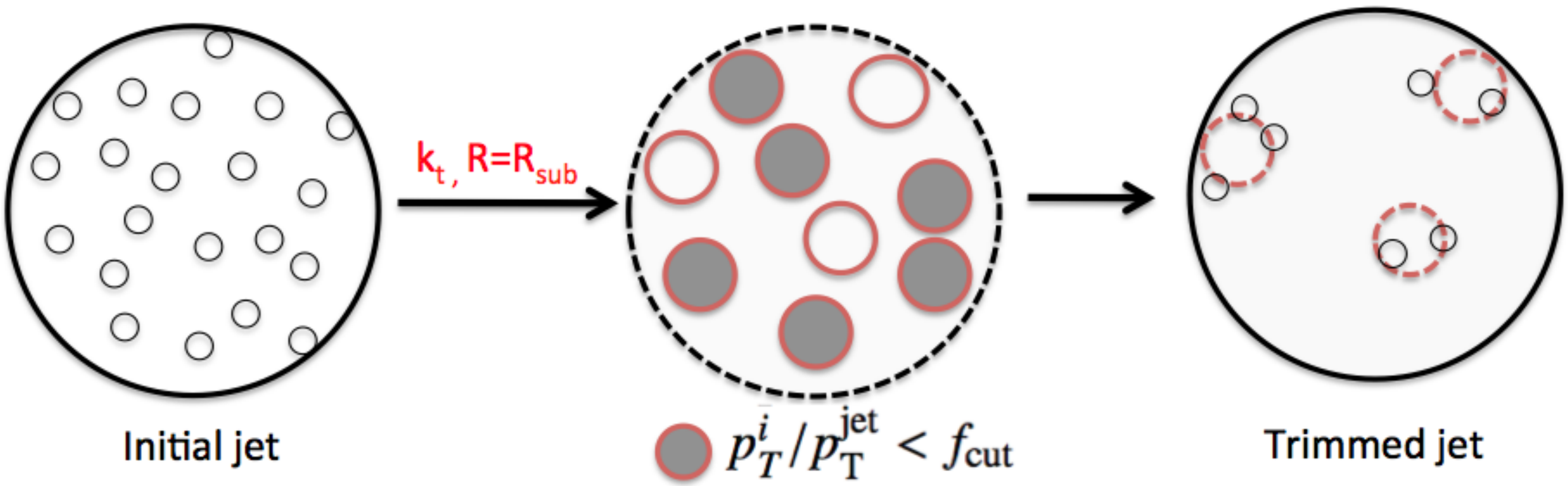


constituents of j_1 and j_2 are reclustered using the C/A algorithm with radius parameter $R_{\rm filt}$

… it might not make it through filtering

Subjet algorithms: a few more

Jet trimming



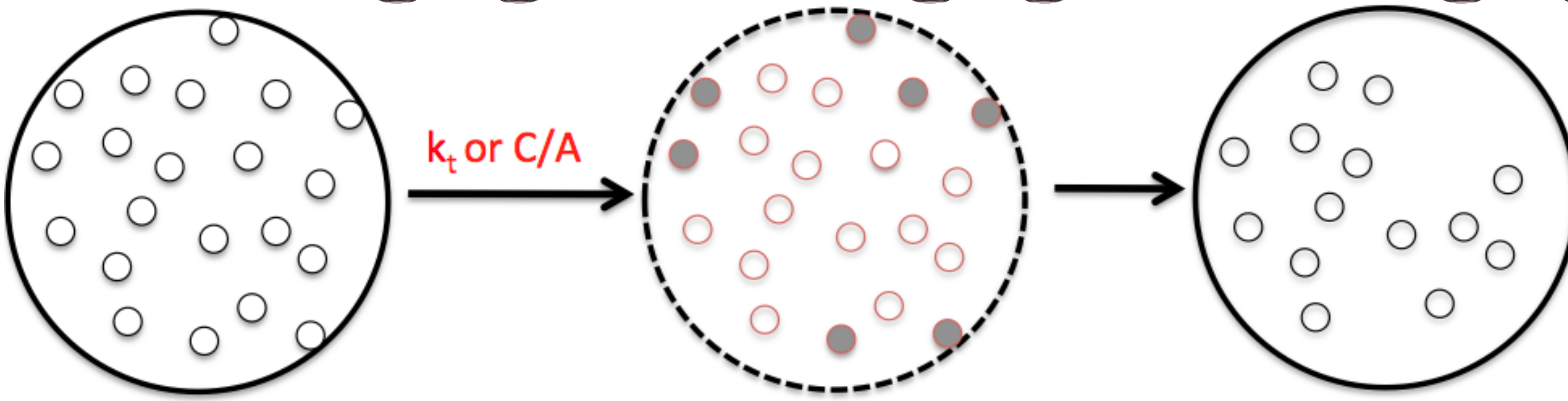
Pile-up contamination is mostly soft:

- create subjets with radius R_{sub}
- If subjet has fractional pT < threshold, remove it.

Light quark or gluon jets: 30-50% mass loss

Boosted decay products: <10% mass loss

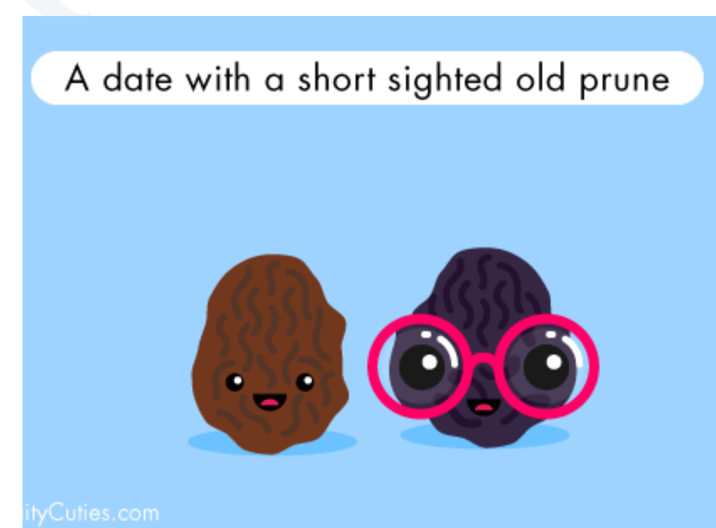
Subjet algorithms: a few more



Initial jet $\quad$ ○ $p_T^{j2}/p_T^{j1+j2} > z_{\rm cut}$ or $\Delta R_{j_1,j_2} < R_{\rm cut}$ $\quad$ Pruned jet

Pile-up contamination is mostly soft:

- recluster deposits with C/A or kT (soft first)
- at each recluster, the pT must increase by some amount
  OR
  new cluster must be within a given radius
- else: j2 discarded, continue



Also removes small pT deposits

Applies wide-angle veto

Jet grooming algorithms: an example

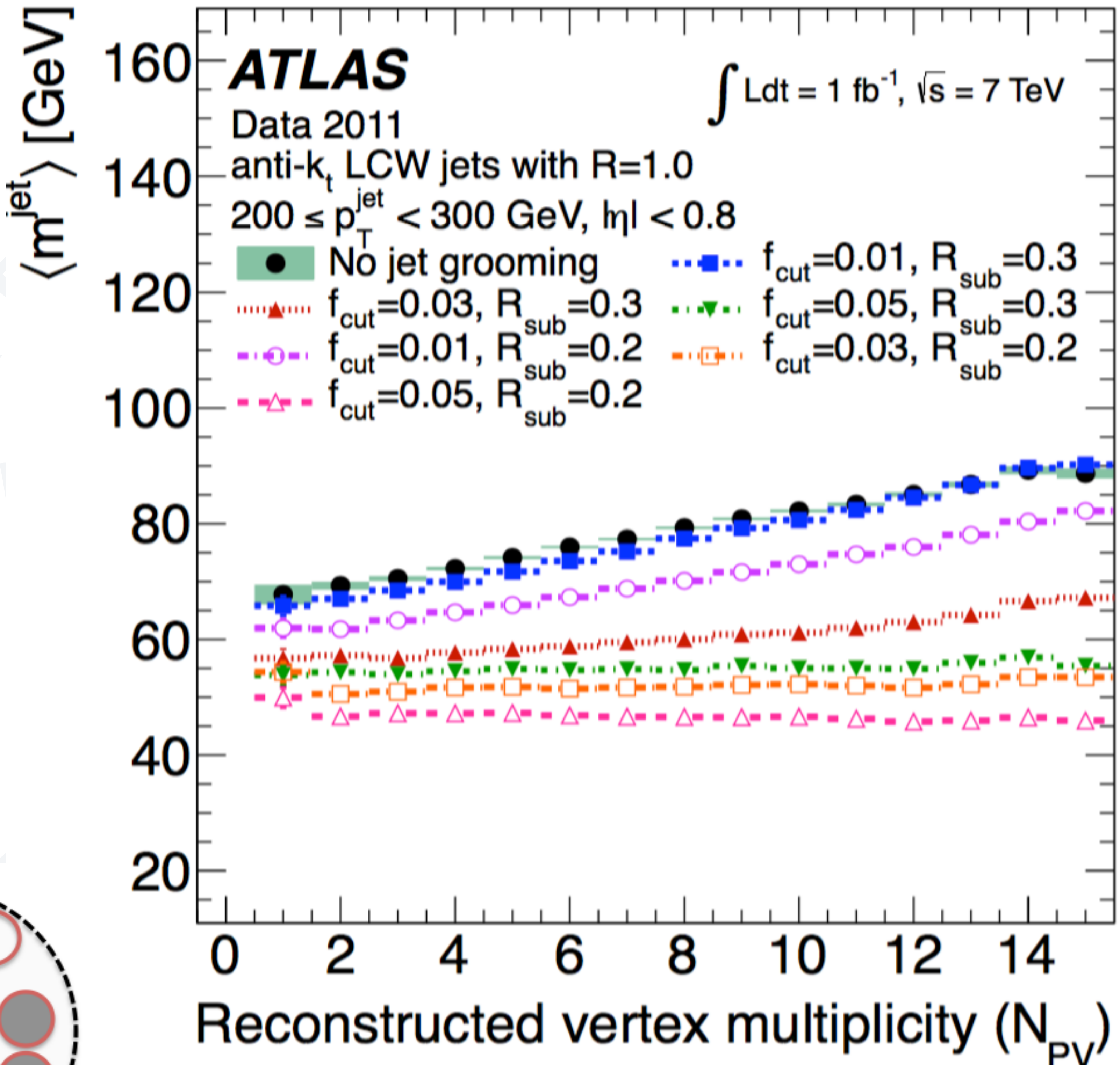
The effect of jet grooming

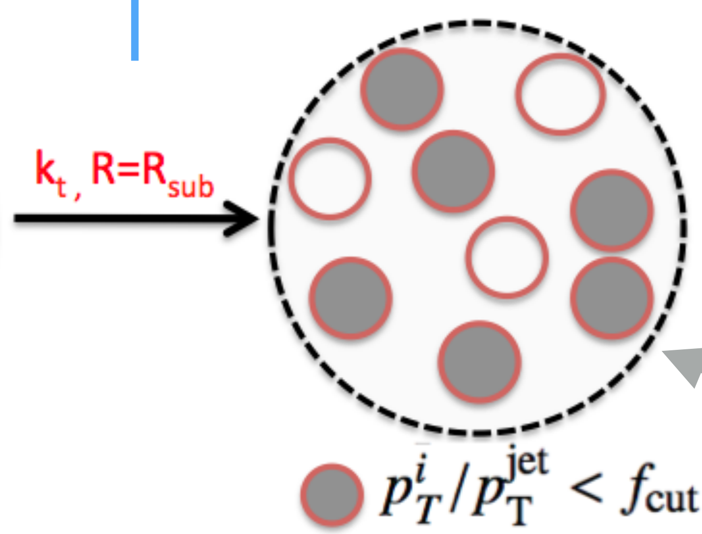
Computational development and future work

Subjet algorithms: effects

Does grooming help with PU discrimination? (a) Trimming

Trimming



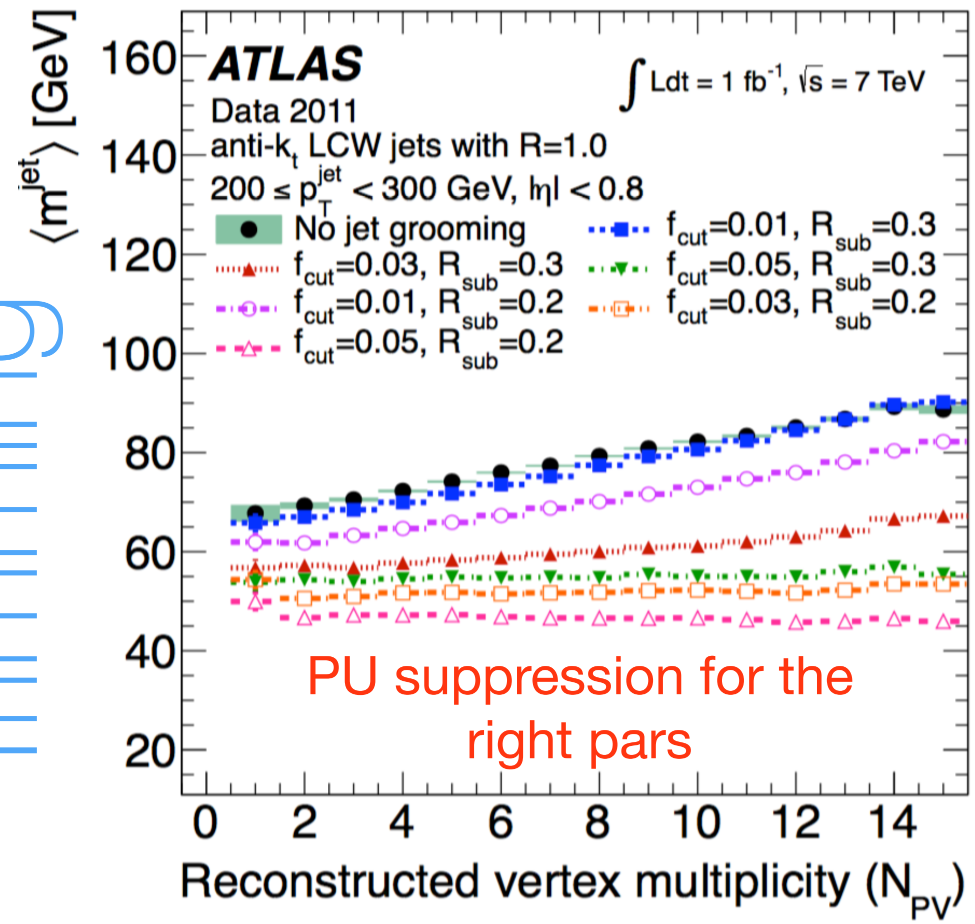


Remember me?

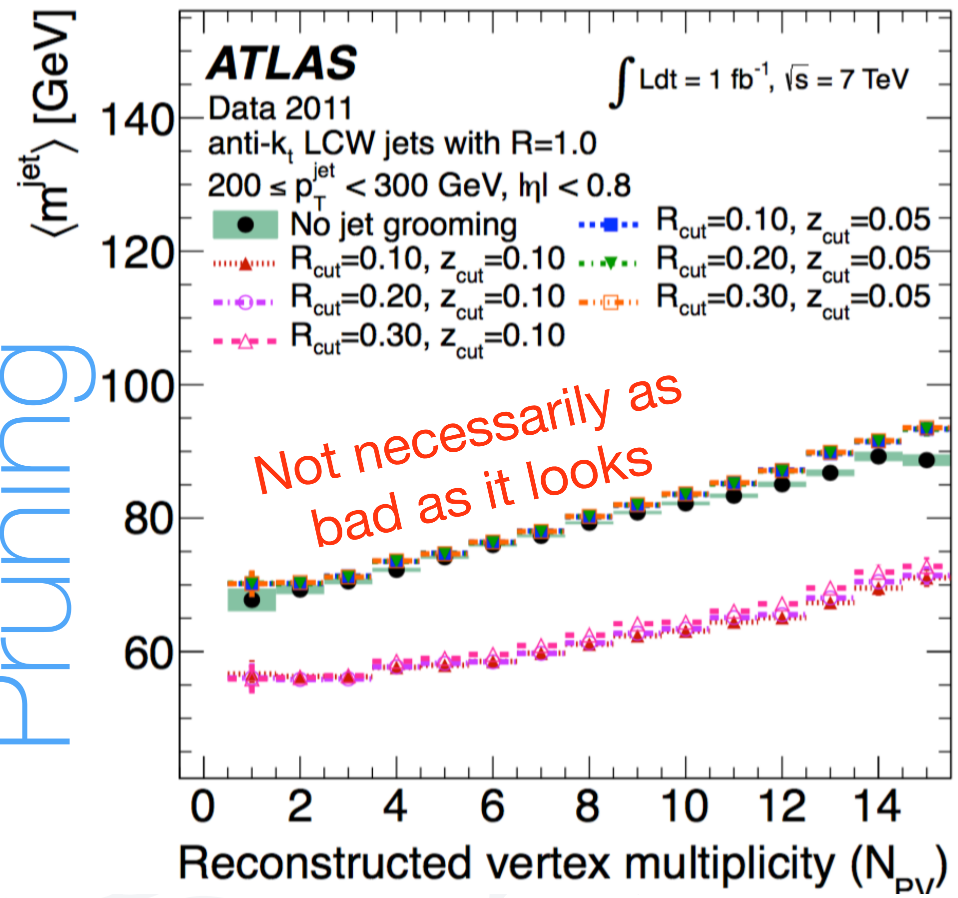
Subjet algorithms: comparison

Does grooming help with PU discrimination?

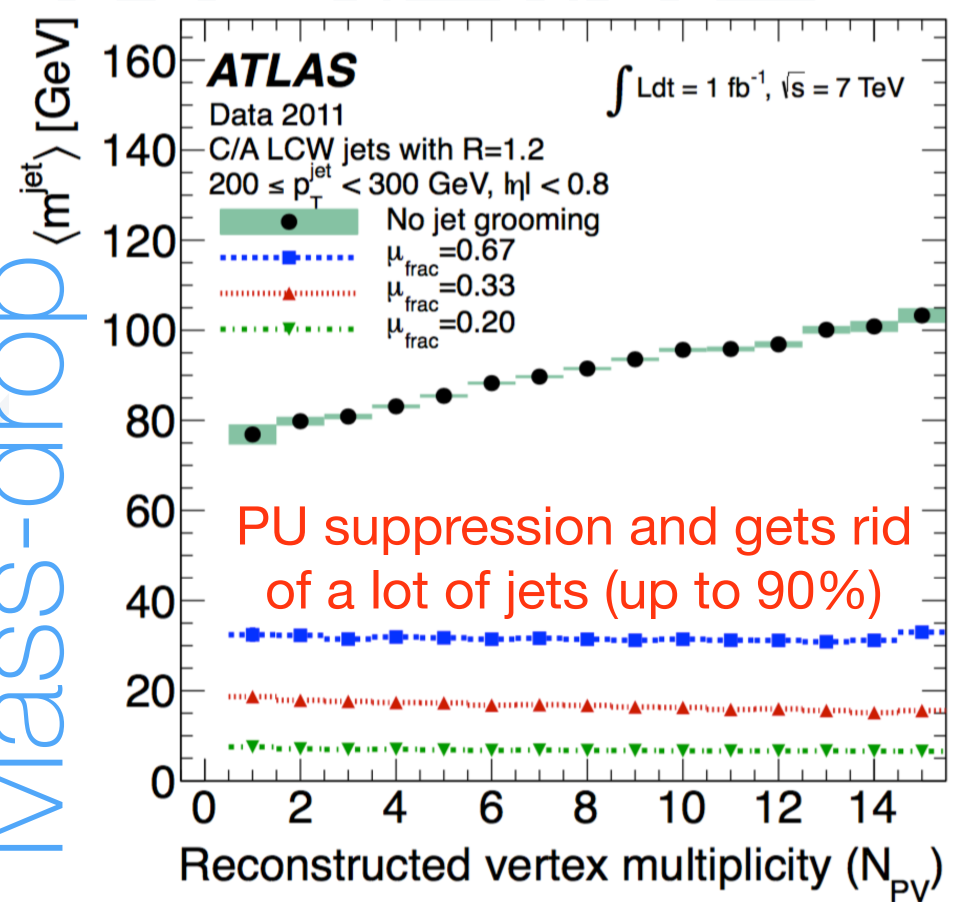
Trimming



Pruning



Mass-drop



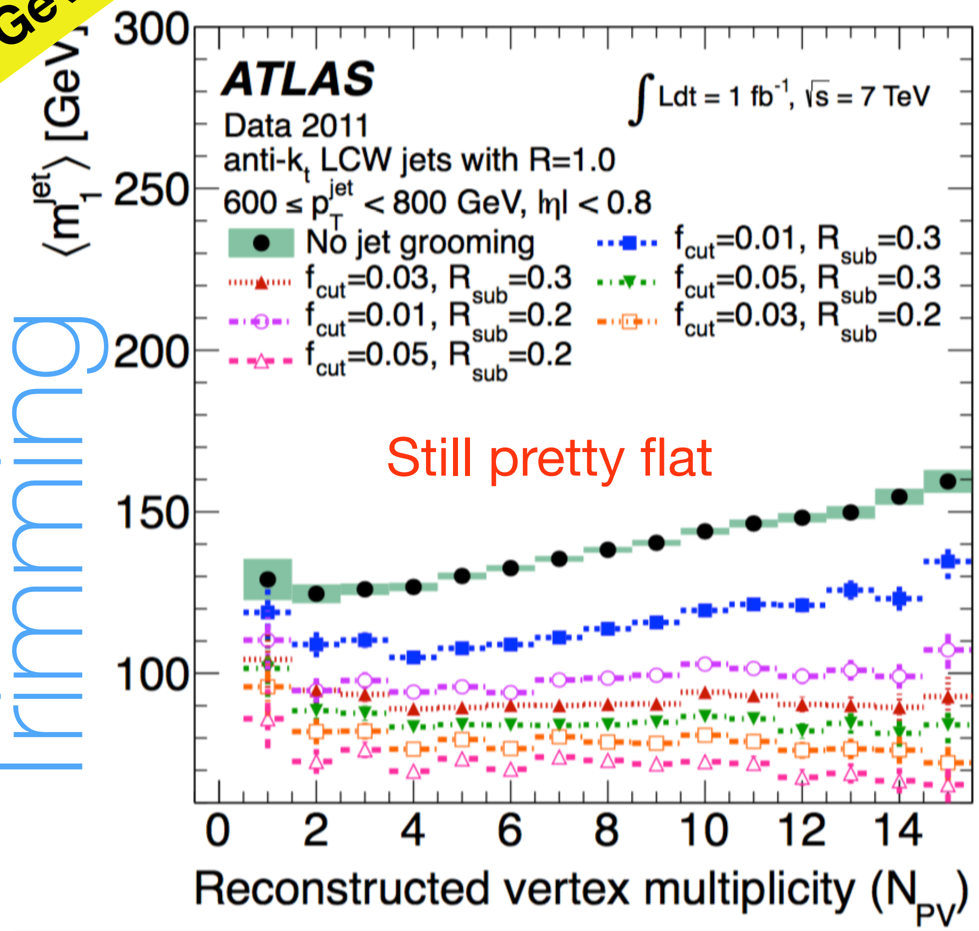
- mass range: threshold for hadronic, boosted object measurements

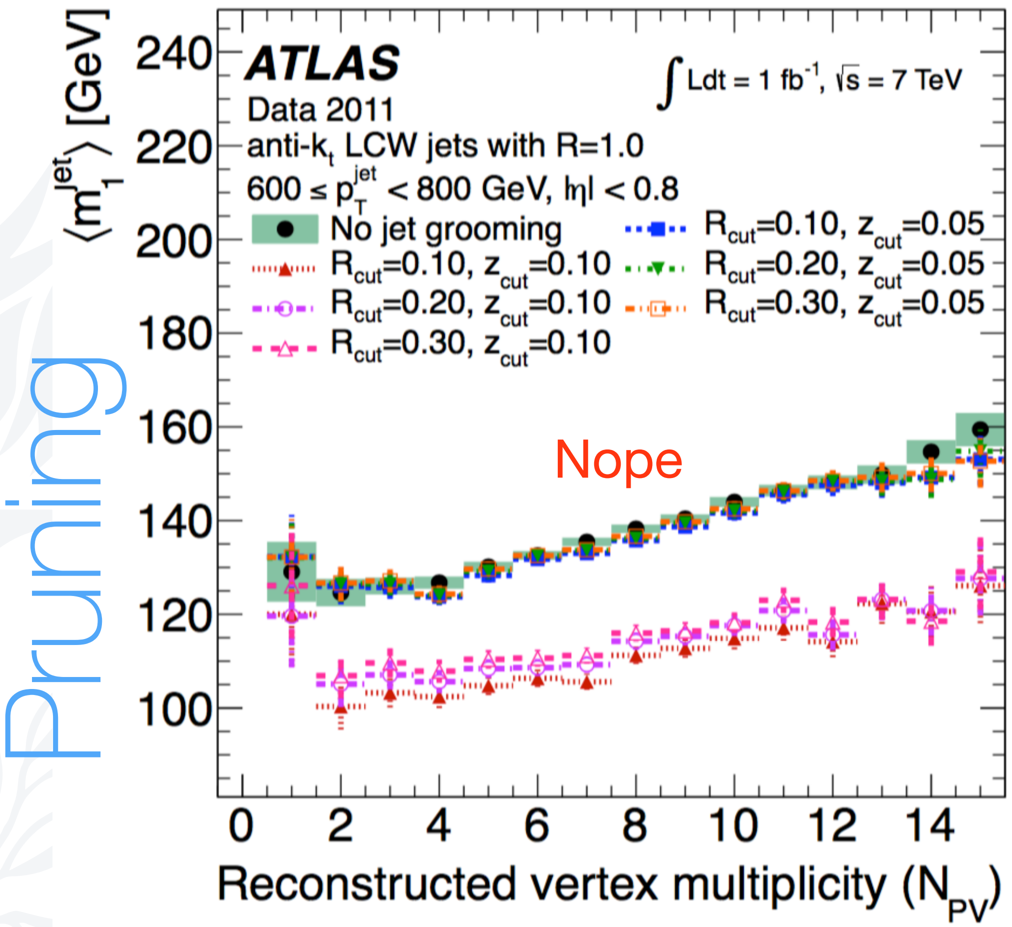
rcarney@lbl.gov

Subjet algorithms: comparison

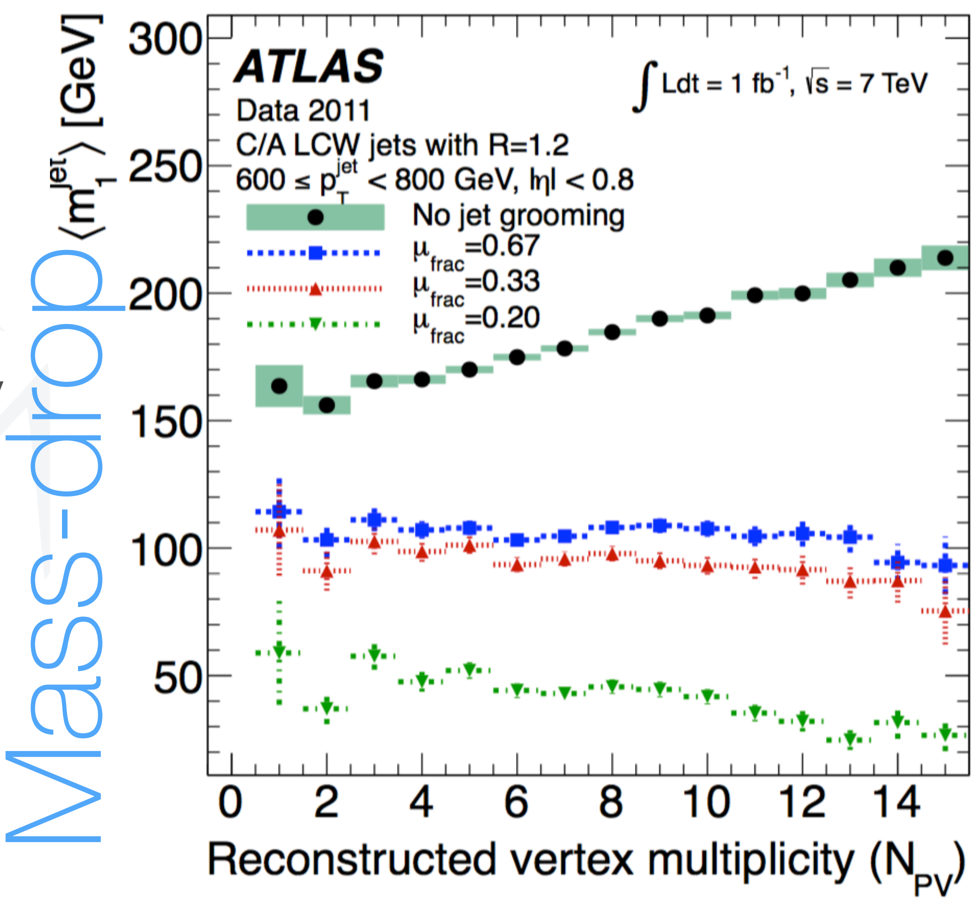
600 GeV < $p_T$jet < 800 GeV

Higher mass range





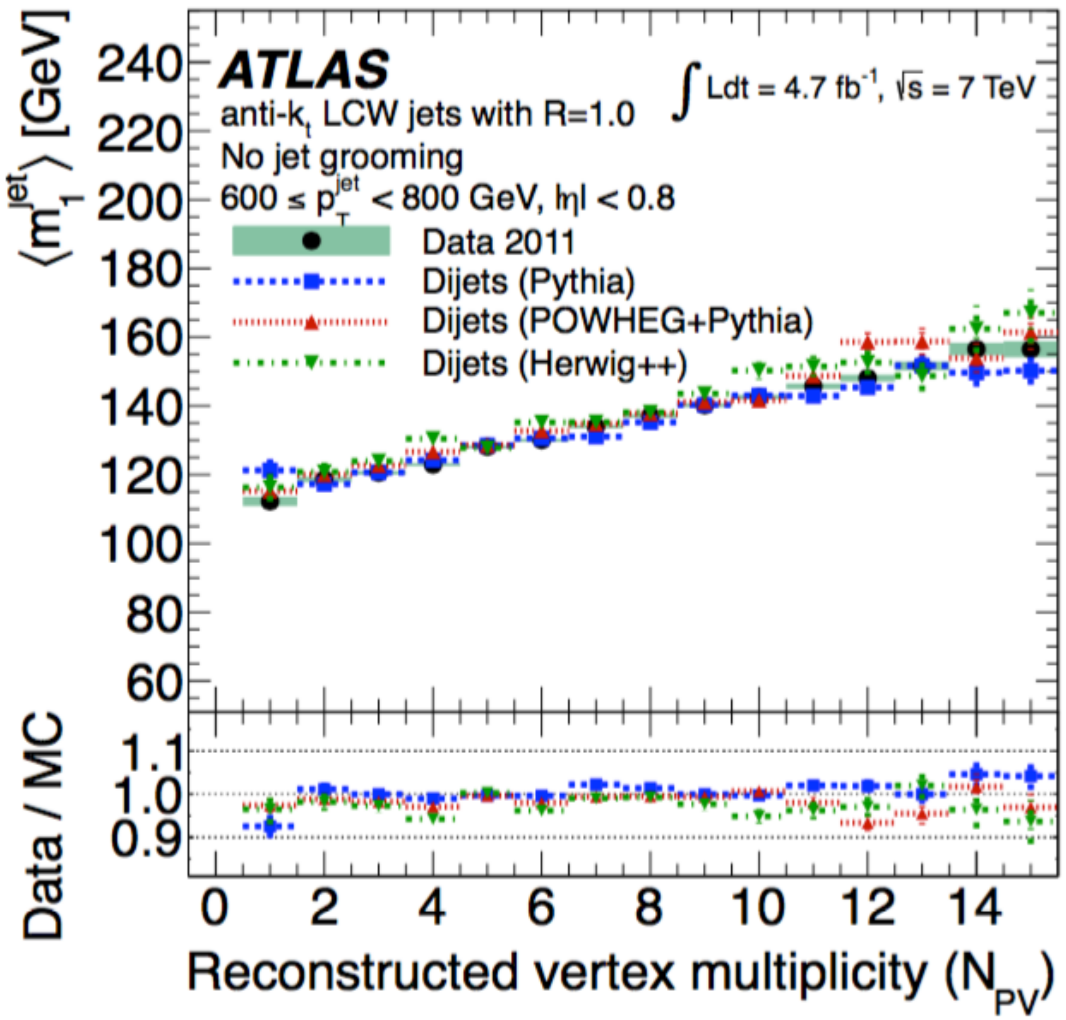
- mass range: 100% of top quark decay products merged within R=1.0



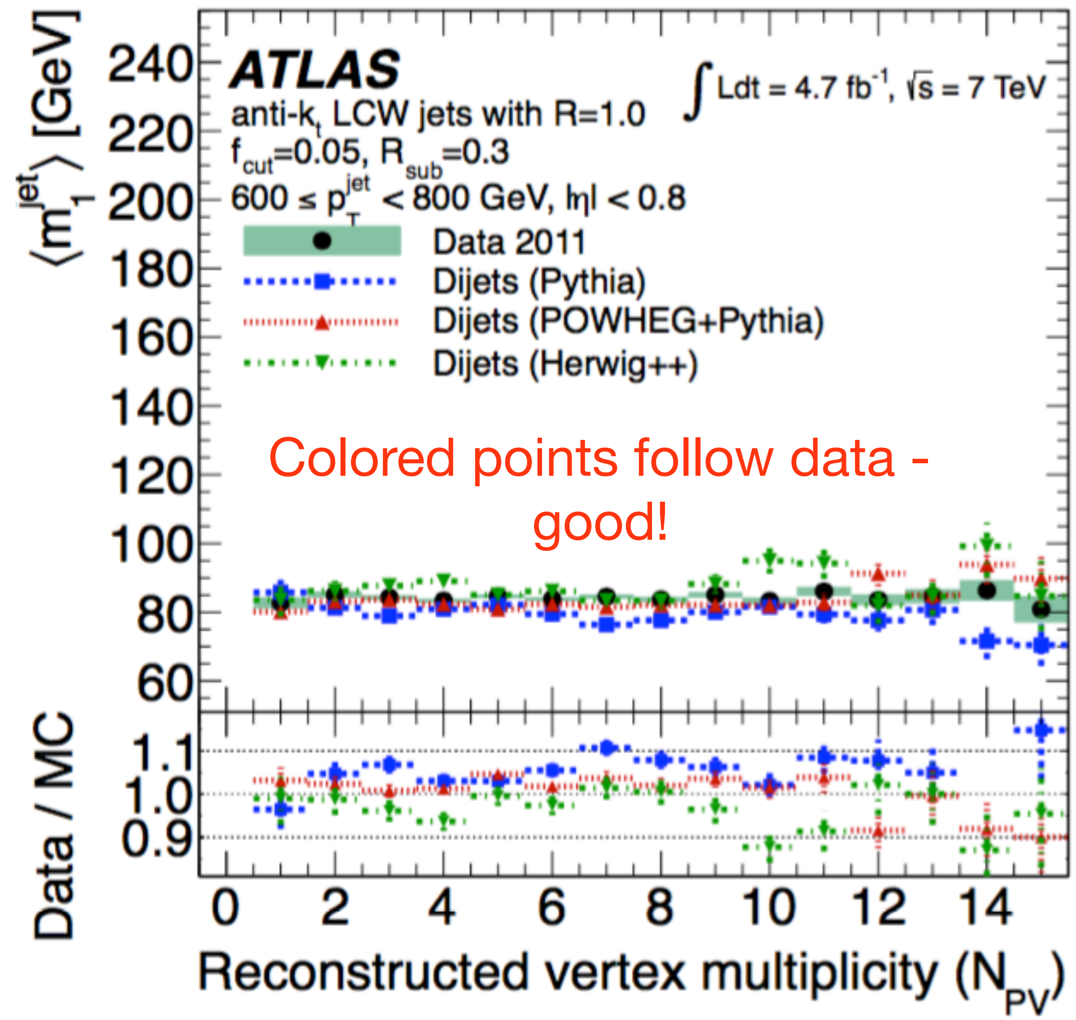
Mass-drop filtering reduced sensitivity at high PU due to filtering process. (Applying a harsher constraint but at a greater rate than trimming)

Subjet algorithms: MC & data

Effects of grooming on MC and data



(a) anti-k_t, $R = 1.0$: Ungroomed



(b) anti-k_t, $R = 1.0$: Trimmed

Impact of pile-up is very well modeled, with the slope of the dependence of $m^{jet}1$ on N_{PV} in data agreeing within 3% with the POWHEG+PYTHIA 1 T prediction for both the ungroomed and trimmed jets.

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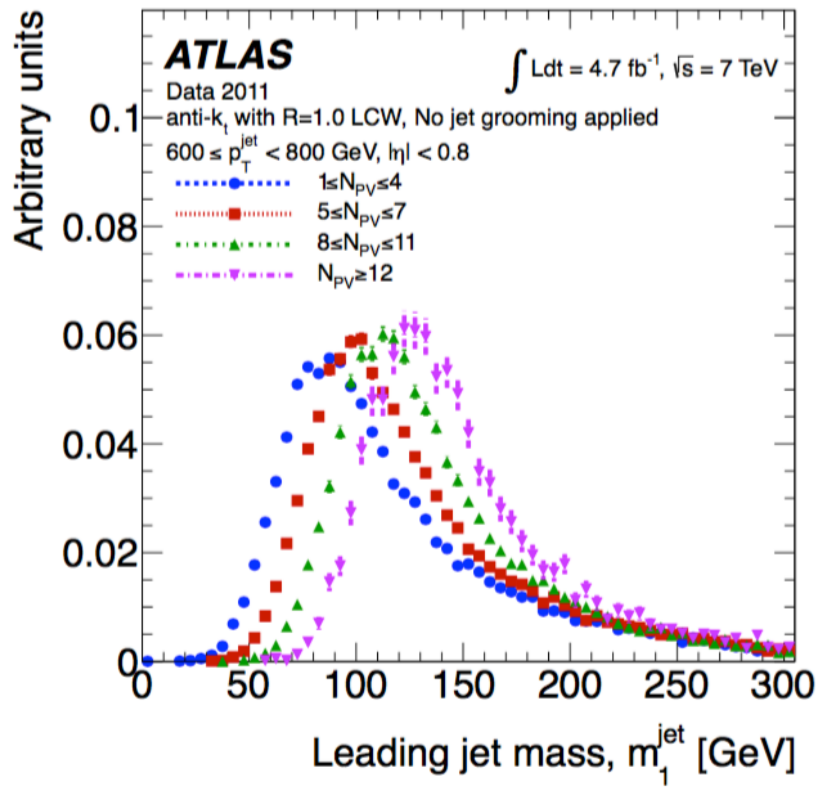
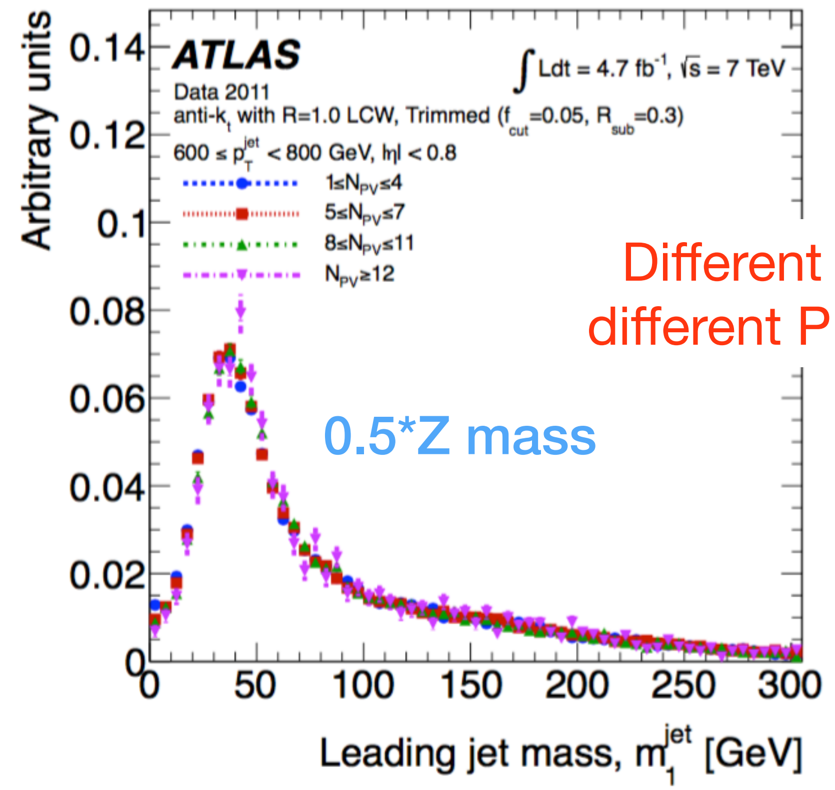
Subjet algorithms: mass peaks

Mass peaks after grooming

Data



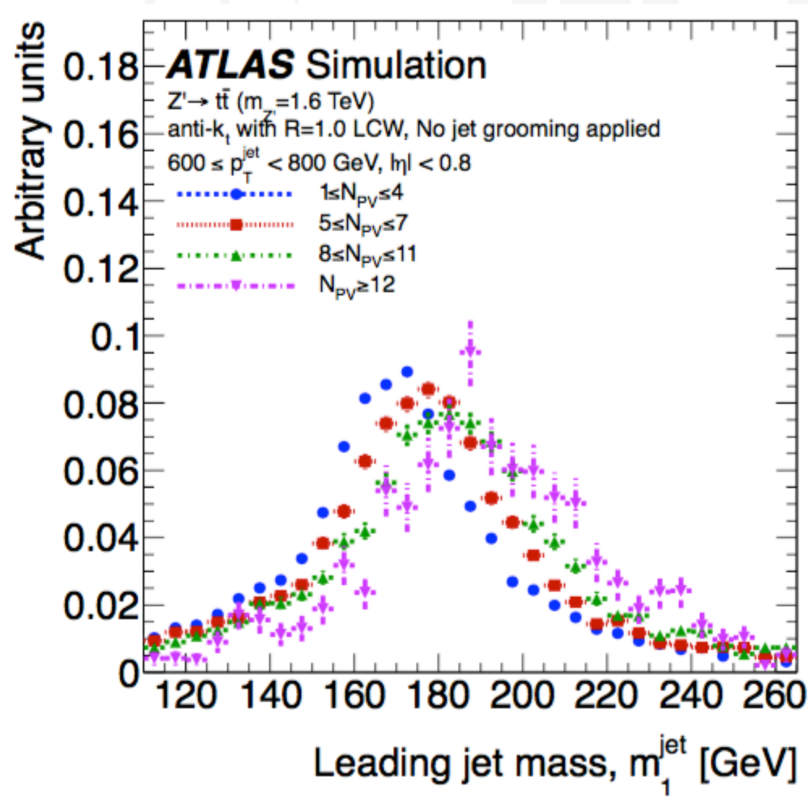
(a) Data: anti-k_t, $R = 1.0$: Ungroomed



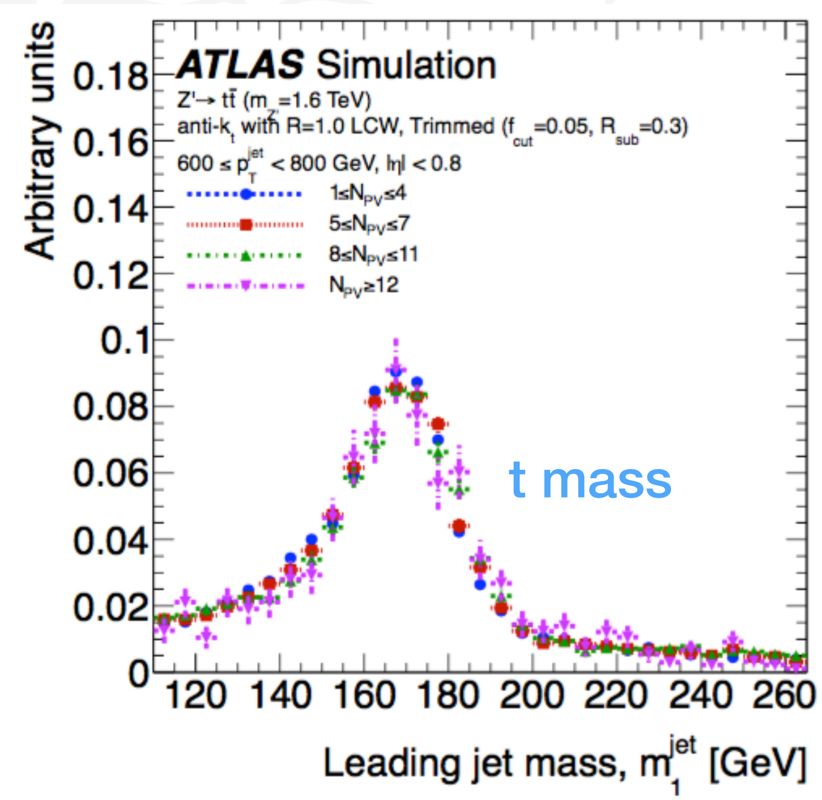
(b) Data: anti-k_t, $R = 1.0$: Trimmed

Different markers are different PU (PV) ranges

MC



(c) Z': anti-k_t, $R = 1.0$: Ungroomed



(d) Z': anti-k_t, $R = 1.0$: Trimmed

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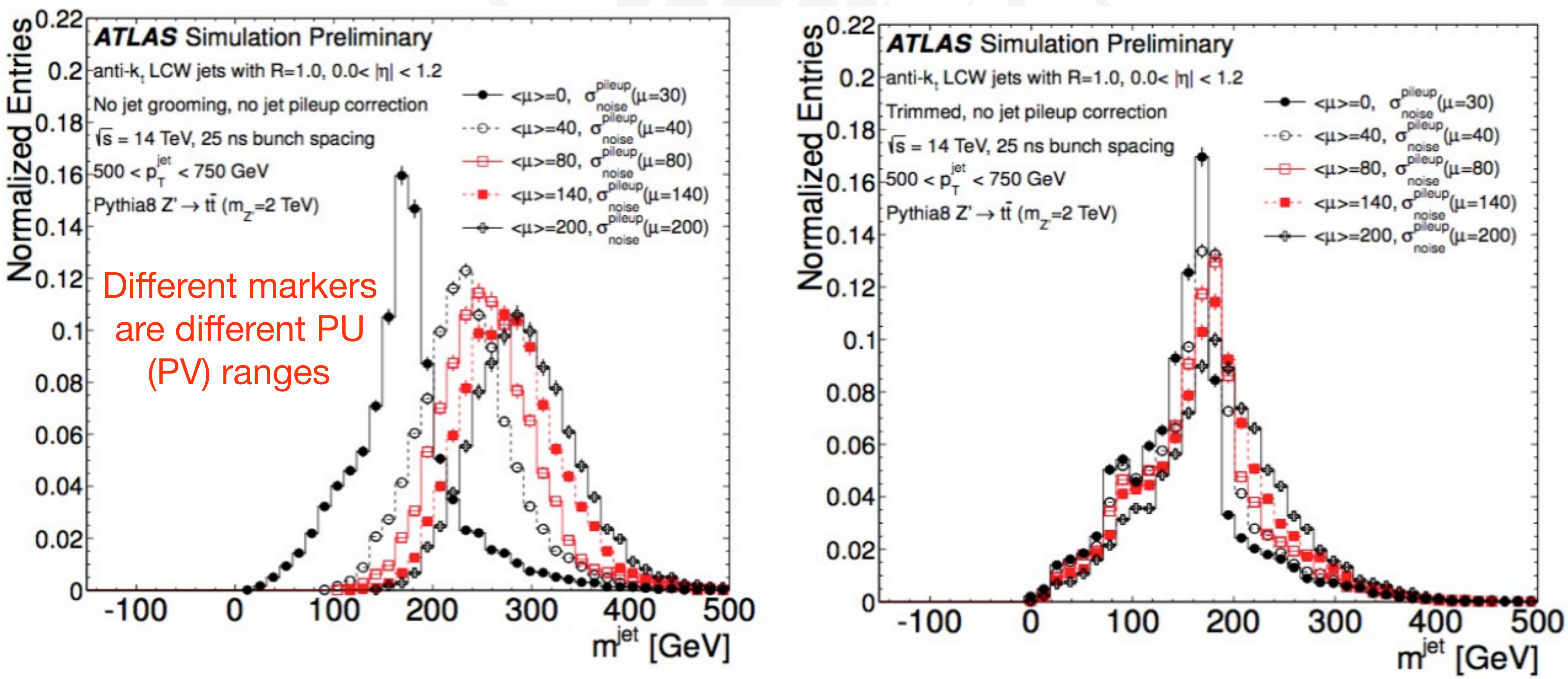
Subjet algorithms: v. high PU

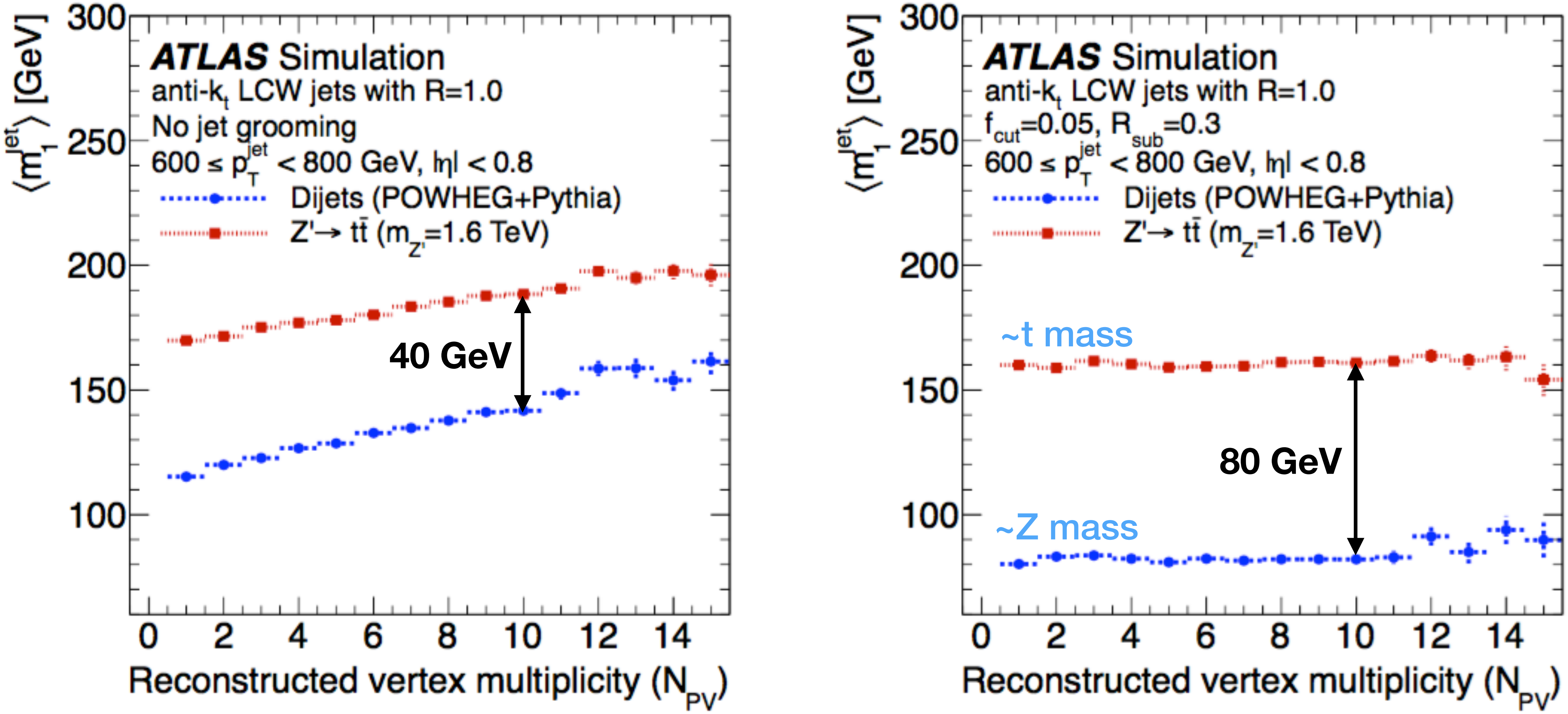
High pile-up, e.g. HL-LHC



NB: Without PU removal pre-processing.

Subjet algorithms: dijet and boosted

Flattened and greater discrimination!



(a) Ungroomed (b) Trimmed

Discrimination at PU=10 doubles!

Subjet algorithms: summary & pars

- Designed for H—>bbar, still favored for hadronic, 2-body decays.
- Resilient to pile-up at lower pT. Generally less efficient at retaining signal than trimming, although background suppression is good!

- Trimming exhibits better performance than pruning, with superior mass resolution and reduced dependence on pile-up.
- Is recommended for boosted top physics analyses, where a minimum pT requirement of 200 GeV is typical.
- Still most favored grooming algorithm for boosted decays.

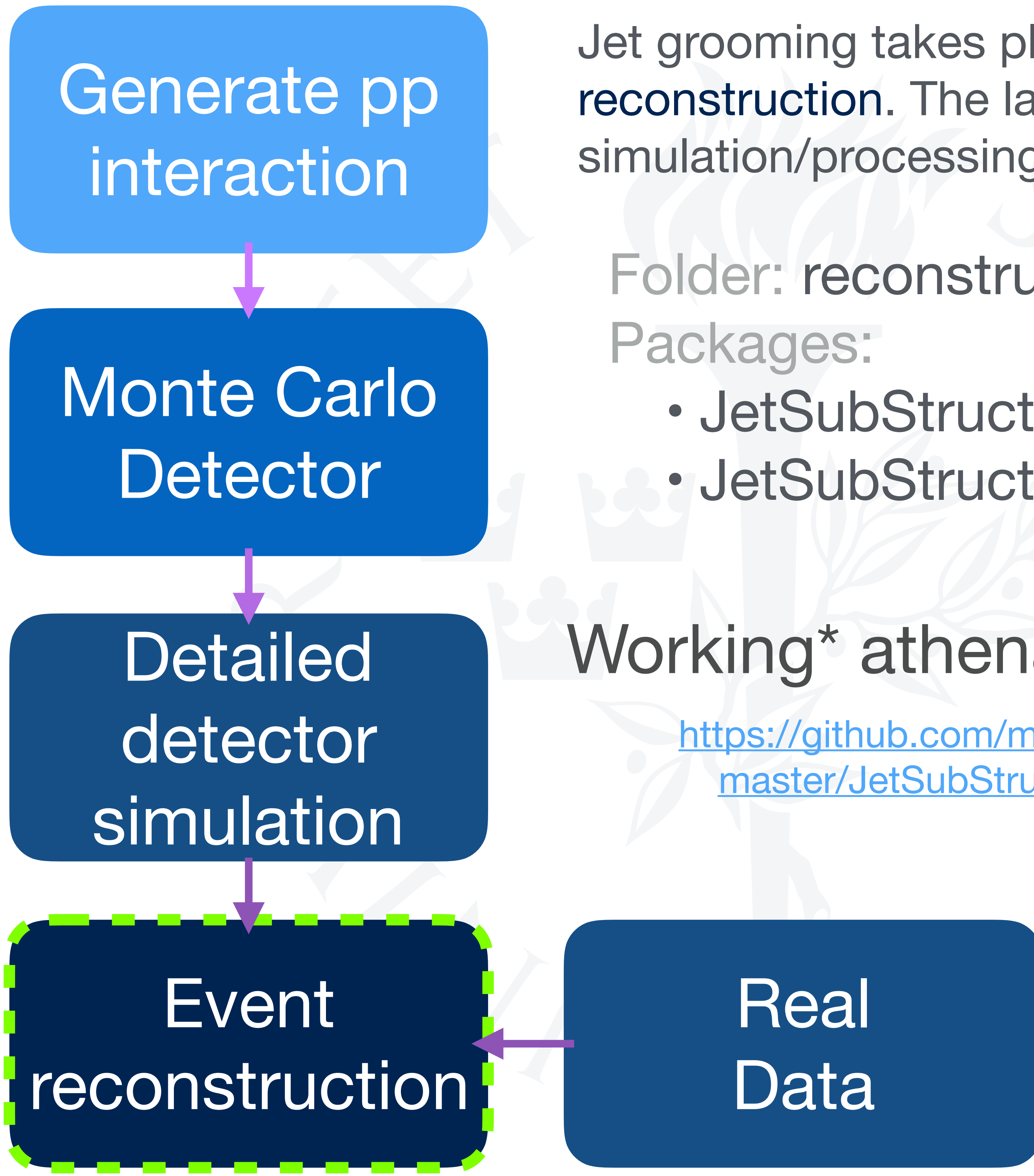
Jet finding algorithms used	Grooming algorithm	Configurations considered
C/A	Mass-Drop Filtering	$\mu_{\mathrm{frac}} = 0.20, 0.33, \mathbf{0.67}$
Anti-k_t and C/A	Trimming	$f_{\mathrm{cut}} = 0.01, \mathbf{0.03}, 0.05$ $R_{\mathrm{sub}} = \mathbf{0.2}, 0.3$
Anti-k_t and ~~C/A~~	Pruning	$R_{\mathrm{cut}} = 0.1, 0.2, 0.3$ $z_{\mathrm{cut}} = 0.05, 0.1$

Jet grooming algorithms: an example

The effect of jet grooming

Computational development and future work

Computing how is this implemented?



Jet grooming takes place during **reconstruction**. The last stage in the simulation/processing pipeline in Athena.

Folder: reconstruction/Jets/
Packages:

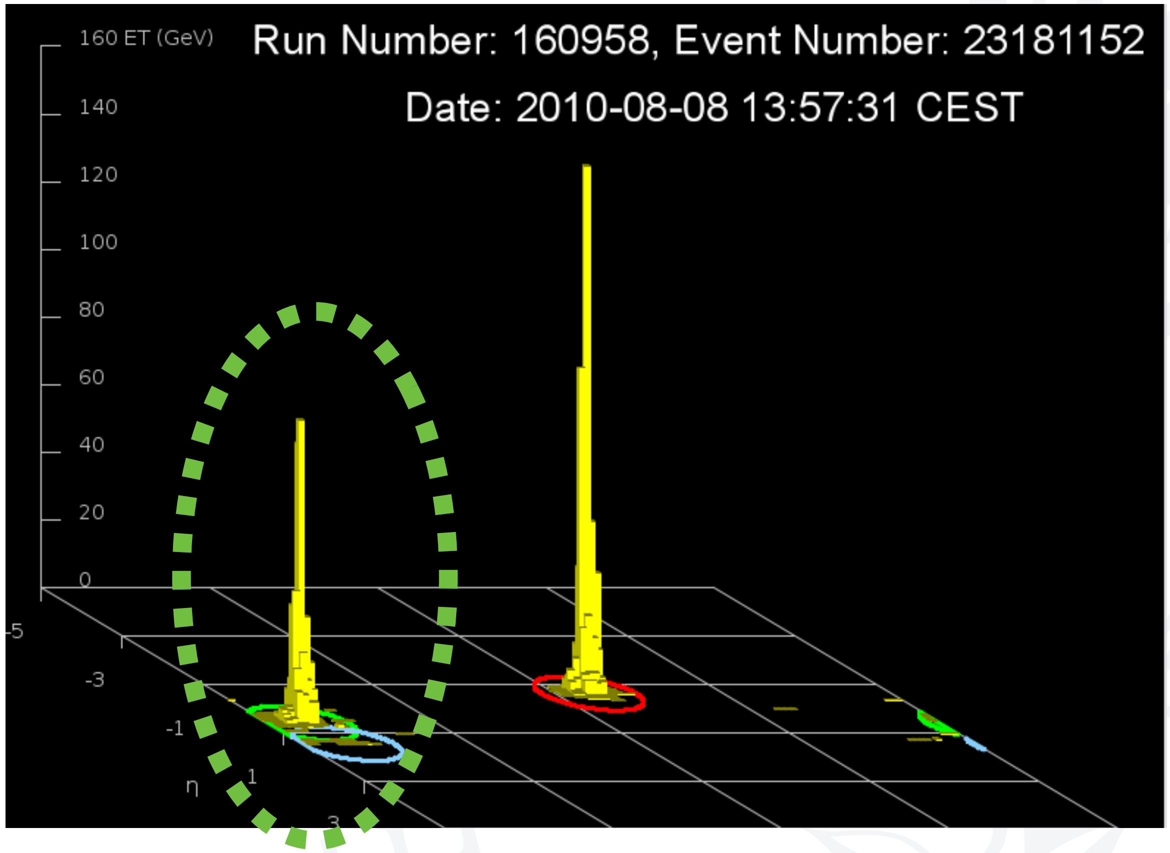
- JetSubStructureMomentTools
- JetSubStructureUtils

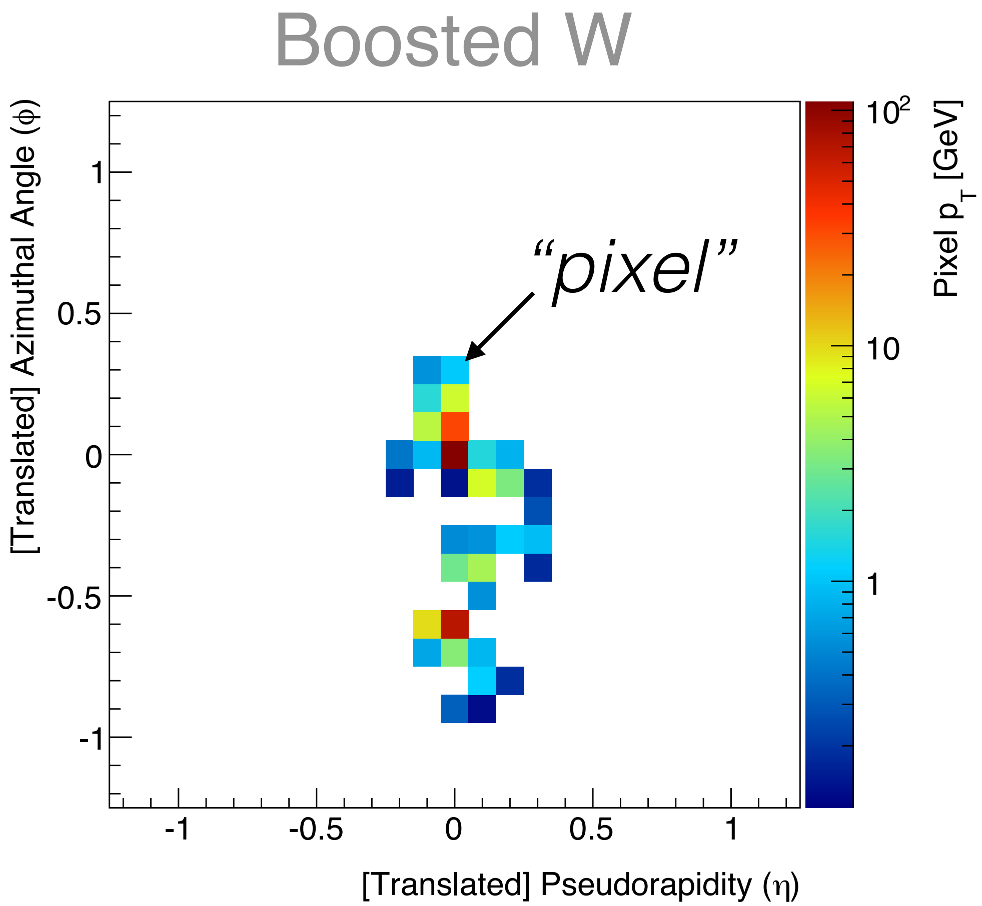
Working* athena example:

https://github.com/mileswu/JetSubstructureTools/blob/master/JetSubStructureMomentTools/share/run.py

(*from 2015. Packages haven't changed too much so might work with a little fiddling)

What about novel computing techniques?



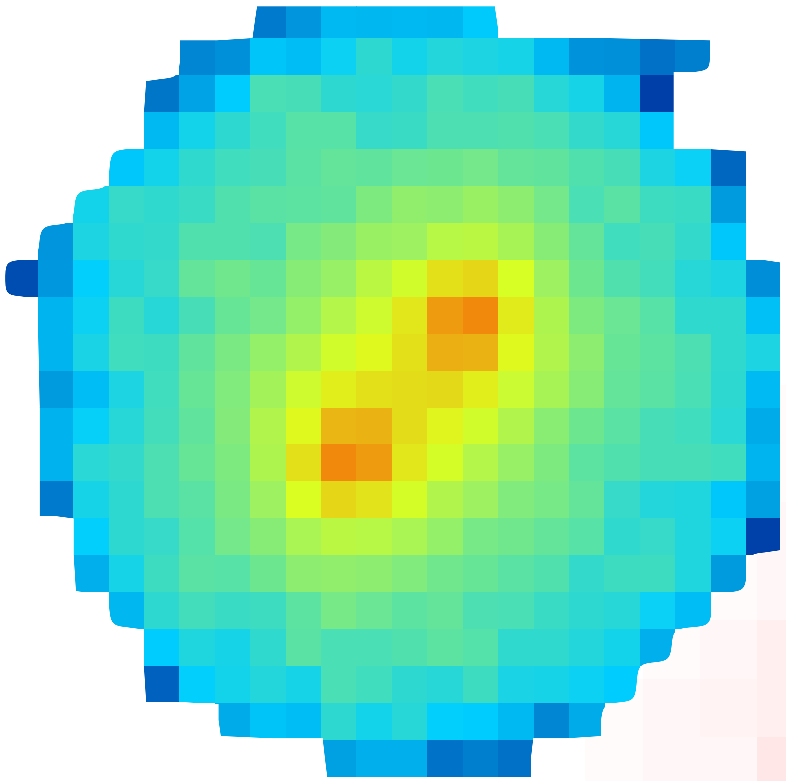


DCNN, [see previous talks in this seminar], more computationally viable options now than ever before.

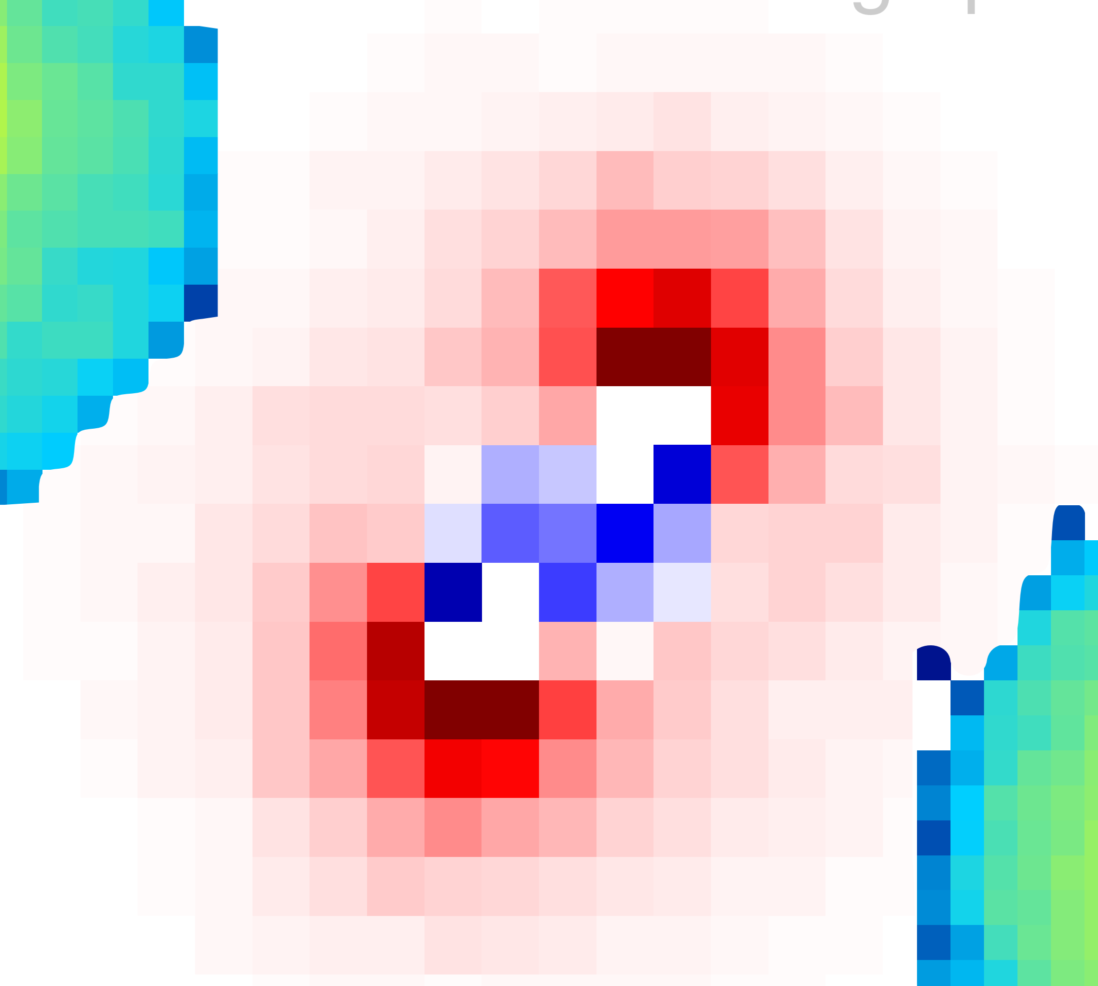
Why images?

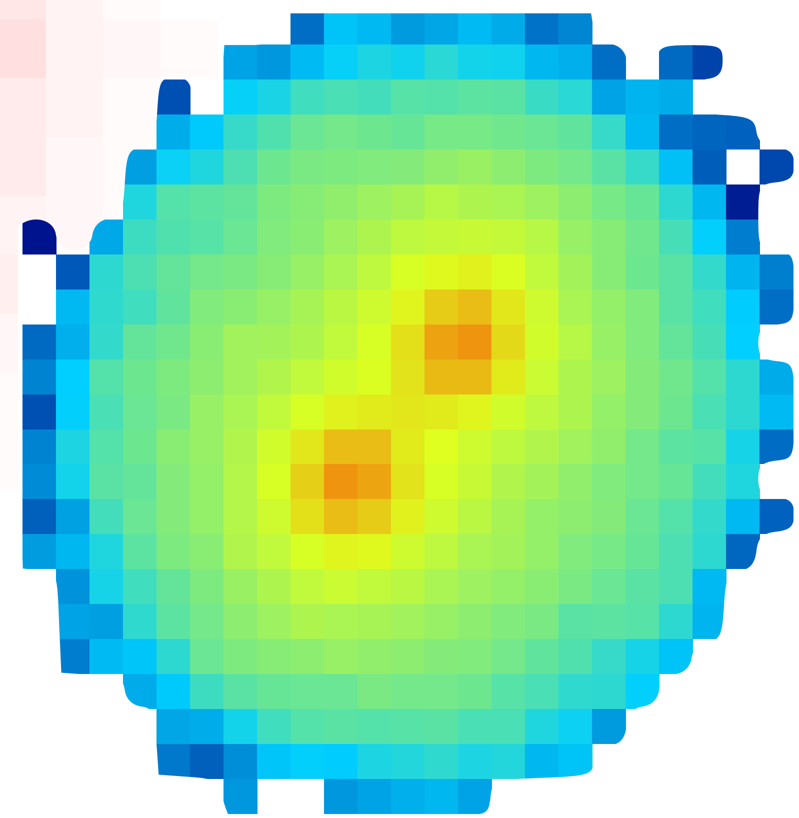
Can directly visualize physics

and we can benefit from the extensive image processing literature



W ⇢ $q\bar{q}$



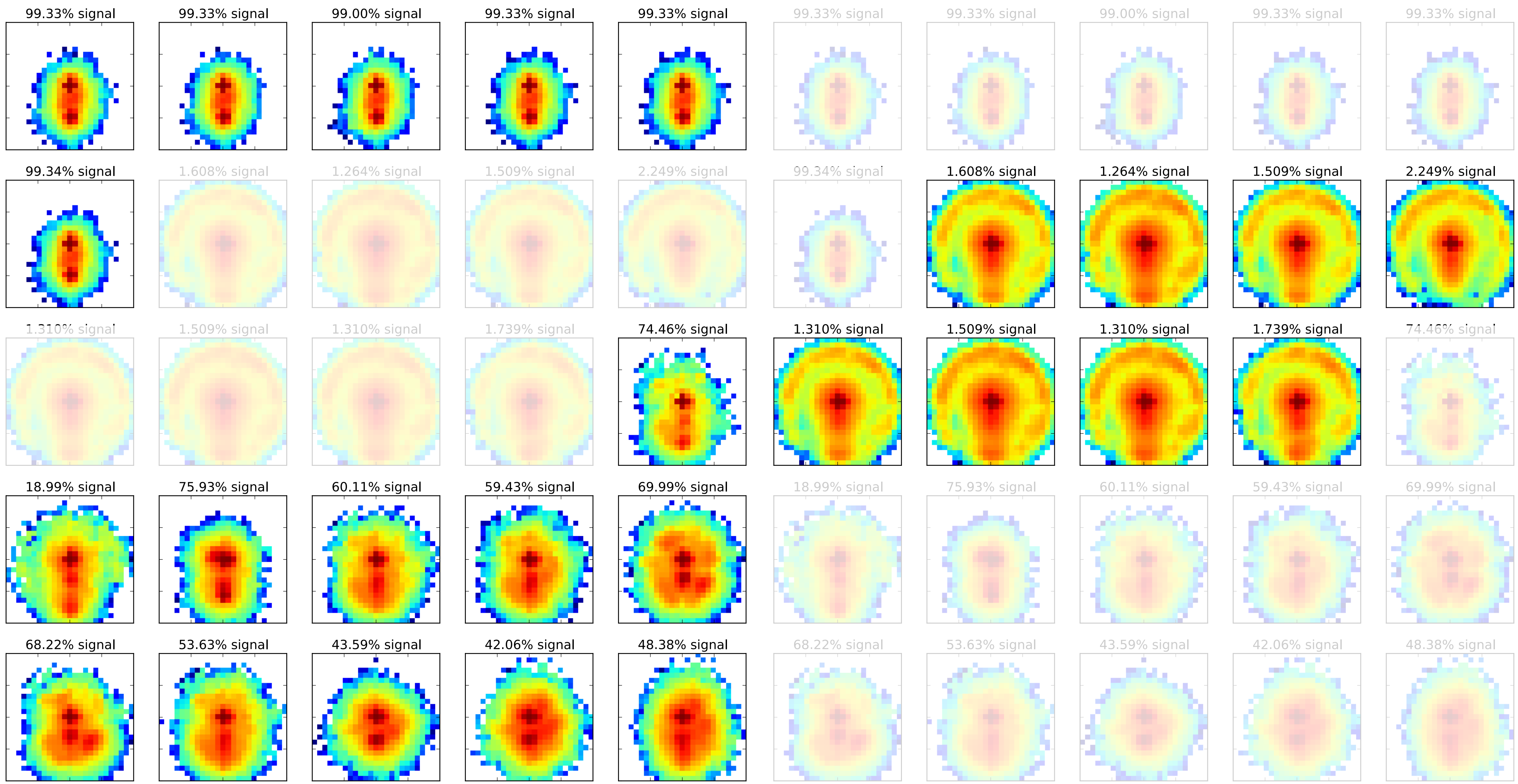


g ⇢ $q\bar{q}$

there is information encoded in the physical distance between pixels

Jet physics in DCNN: what does each filter learn?

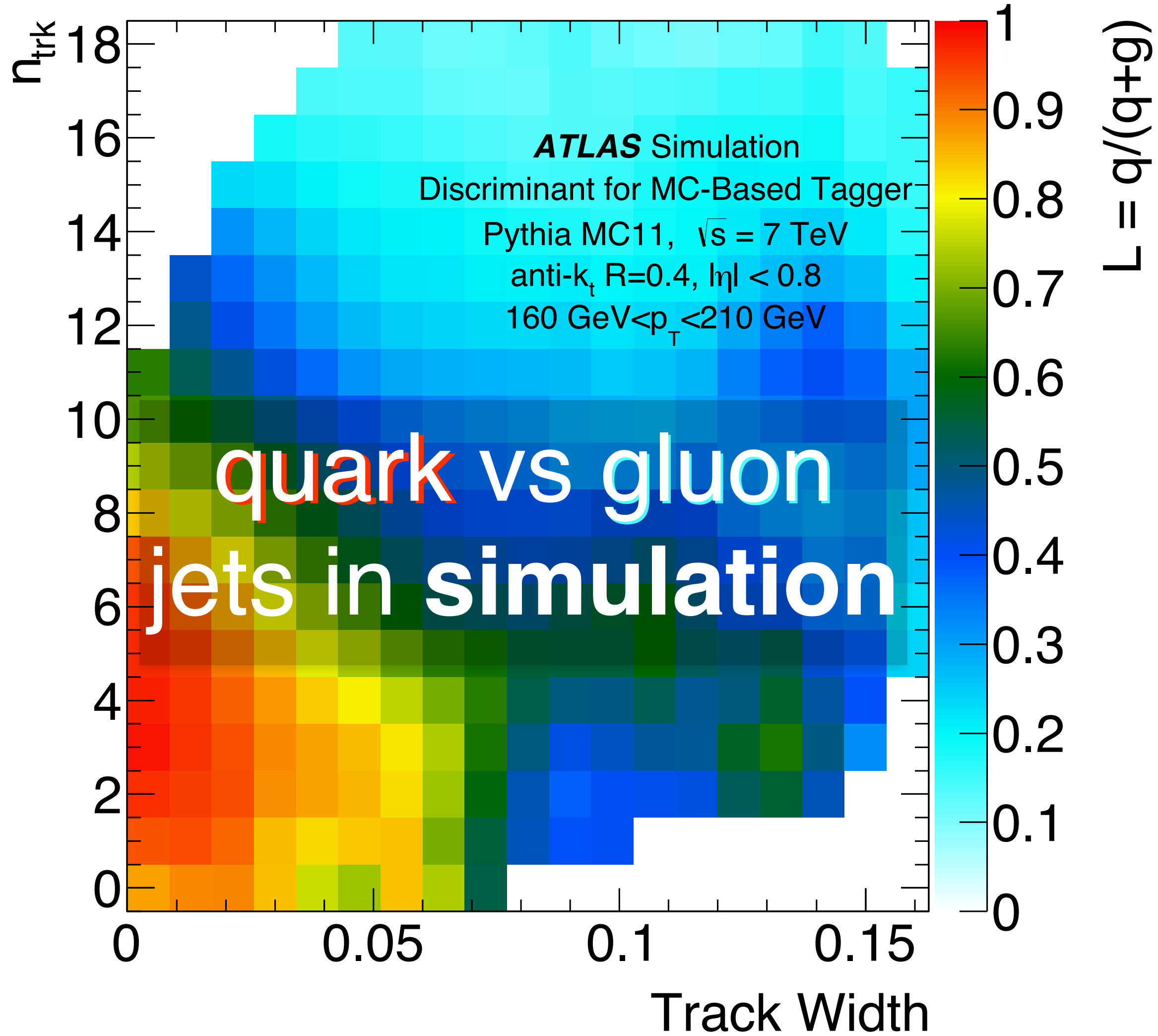
Some filters learnt subjets…

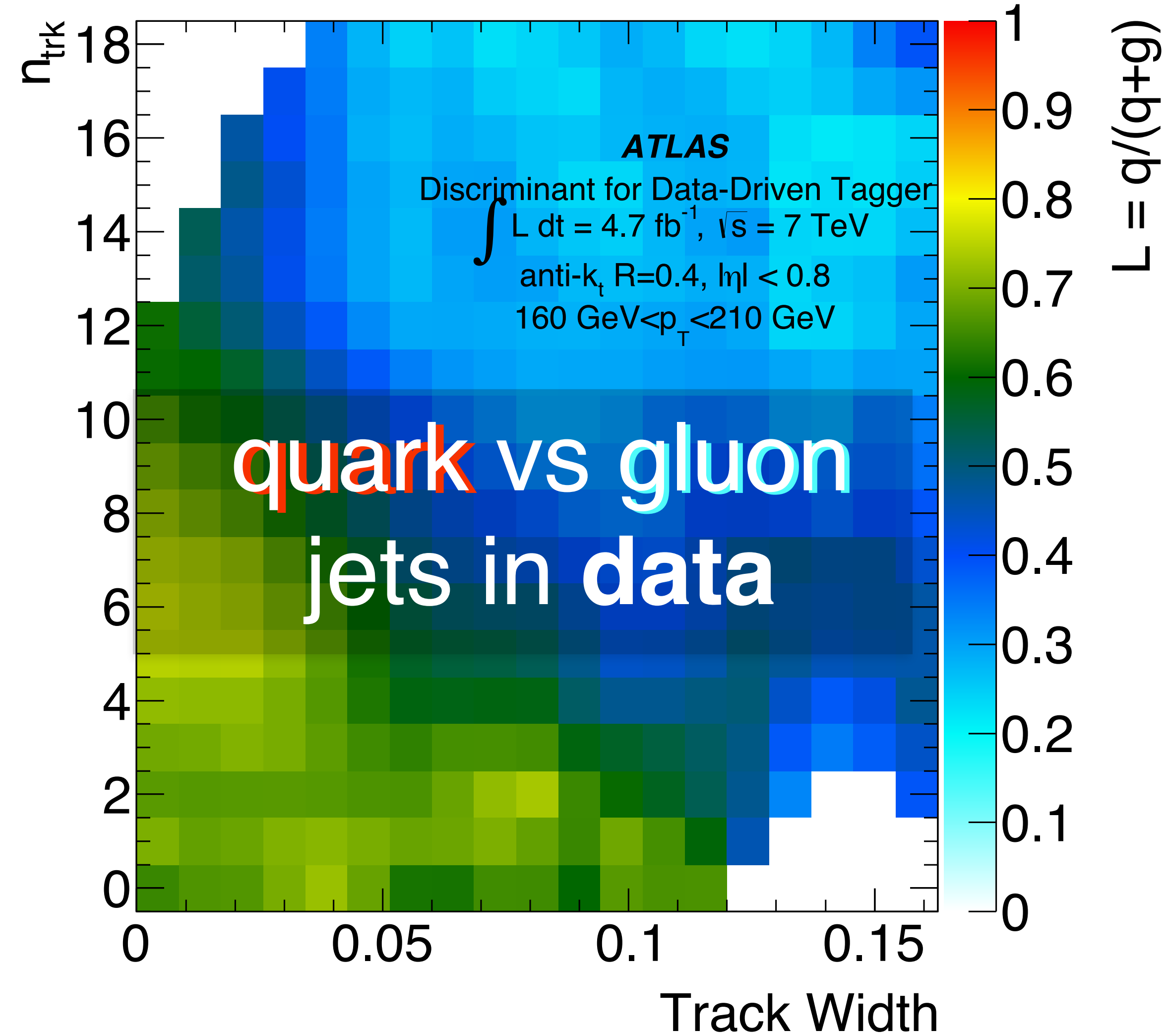


… some learnt about peripheral radiation.

Where next III: Learning directly from data

For supervised learning, we depend on labels
labels usually come from simulation



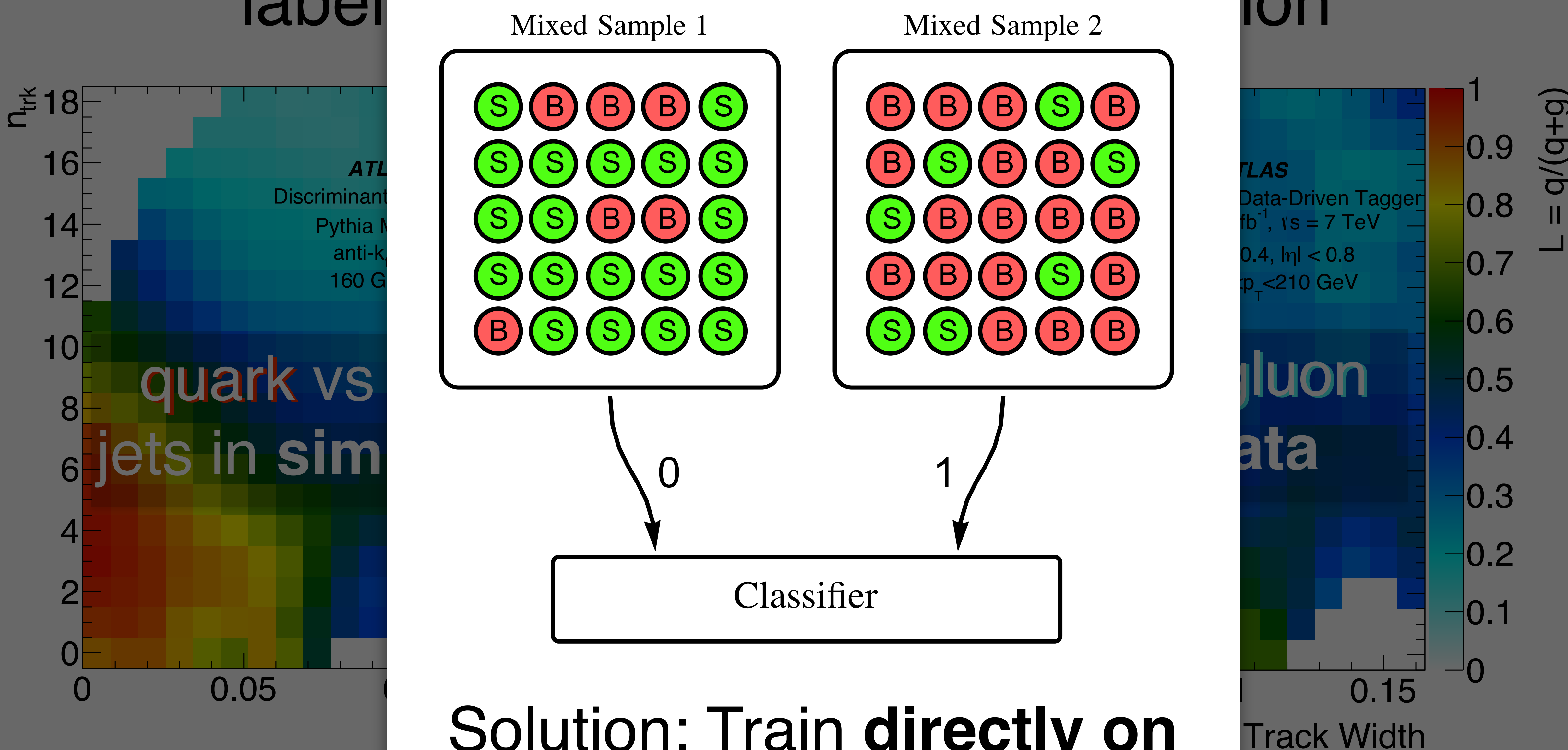


What if data and simulation are very different?
…your classifier will be sub-optimal

Where next III: Learning directly from data

For supervised learning, we depend on labels

label ... ion



Solution: Train **directly on data** using mixed samples

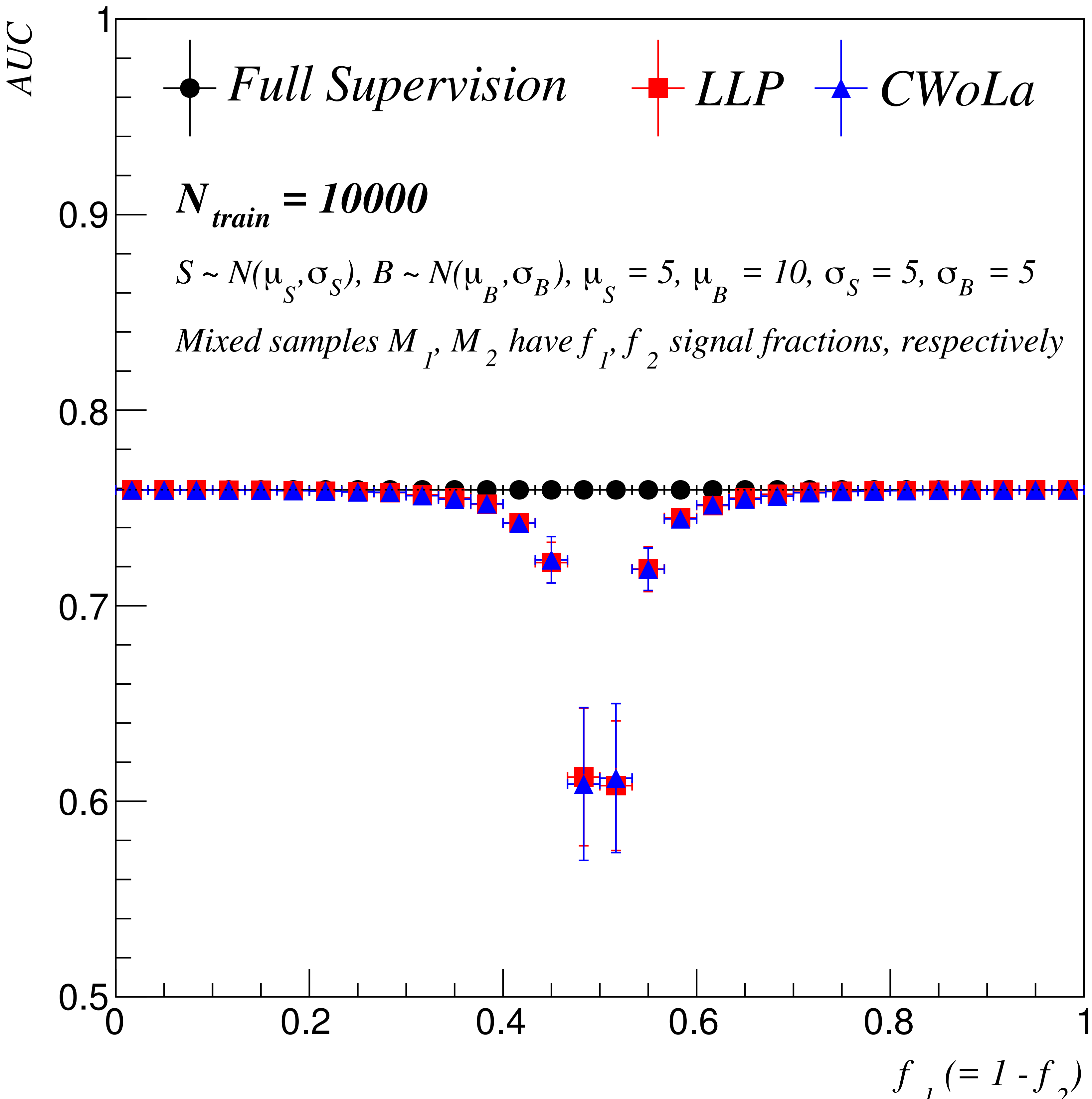
What if da ... ifferent?

your classifier will be sub-optimal

L. Dery et al., JHEP 05 (2017) 145

E. Metodiev et al., JHEP 10 (2017) 174

Learning when you know (almost) nothing



Nearly there slide

Jet grooming algorithms: an example

The effect of jet grooming

Computational development and **future work**

Optimise algorithm pars

Effort underway to re-optimize jet inputs and jet grooming for ATLAS Run 2 conditions

Using pile-up mitigation

- Particle flow
- Soft Killer
- Voronoi Subtraction

We've talked about grooming, but if you want to probe QCD, trimming is not necessarily your best choice! Optimise for the question you're trying to ask.

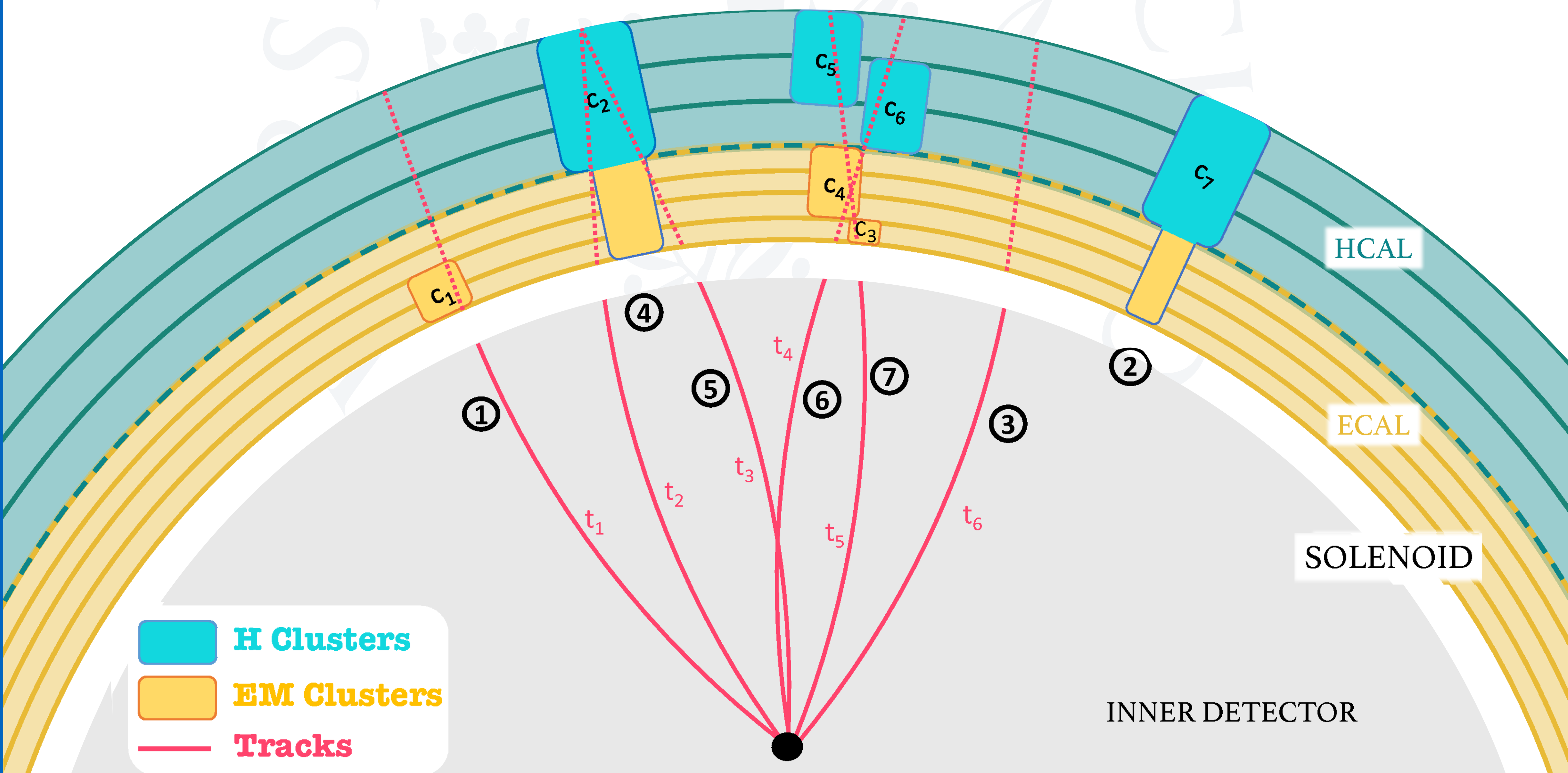
- Trimming
- Pruning
- Modified mass drop
- Soft Drop

Track Calo-Clusters

Build jet inputs from combined tracker and calo information
→ Mitigate calo angular resolution limitations to improve performance in highly-boosted regime: better high pT performance.

Already done as a linear combo, this method instead builds 4-vectors from each detector:

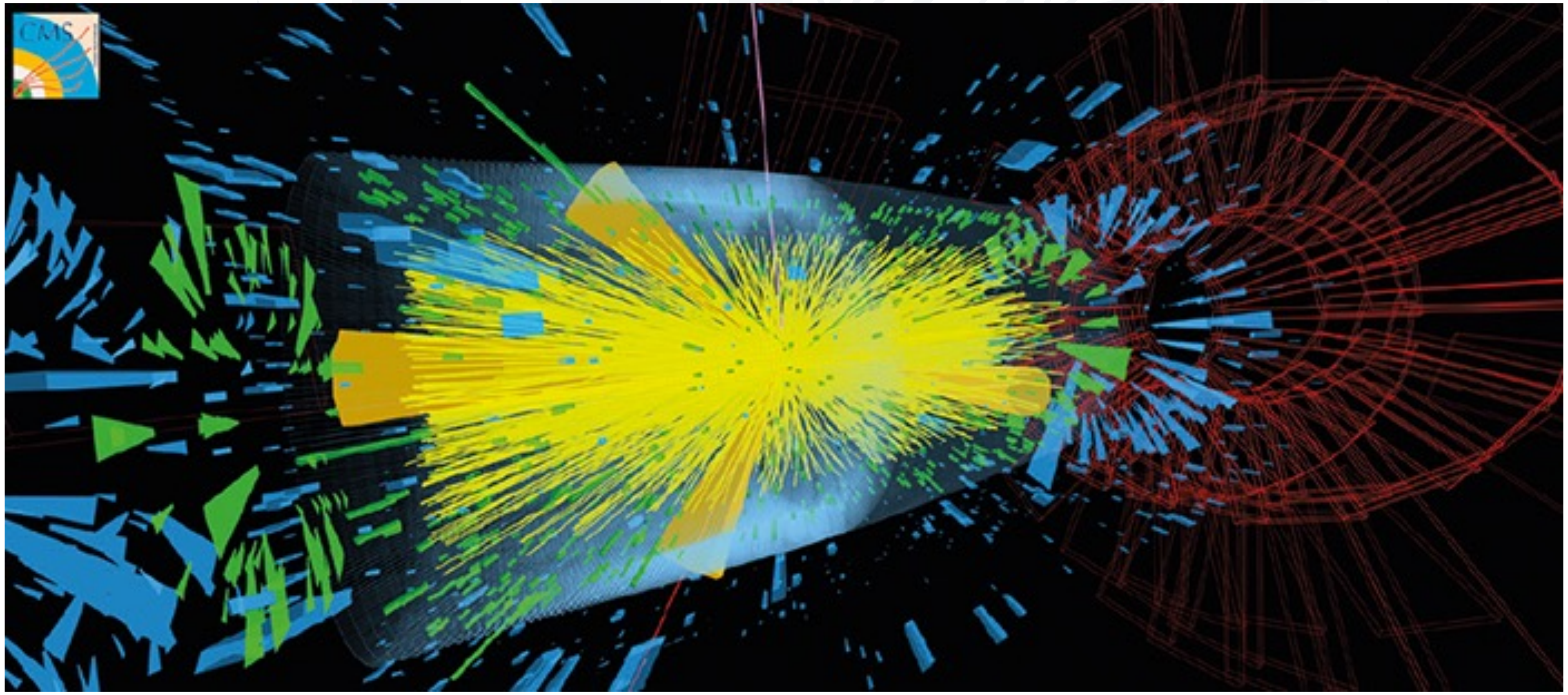
1. Correlates tracks and calo energy deposits
2. Passes correlated objects to jet builder



Penultimate slide

Like with CDS, we're now reaching the physical limits on the resolution the calorimeter can provide but there is still more we can squeeze out of the detector.

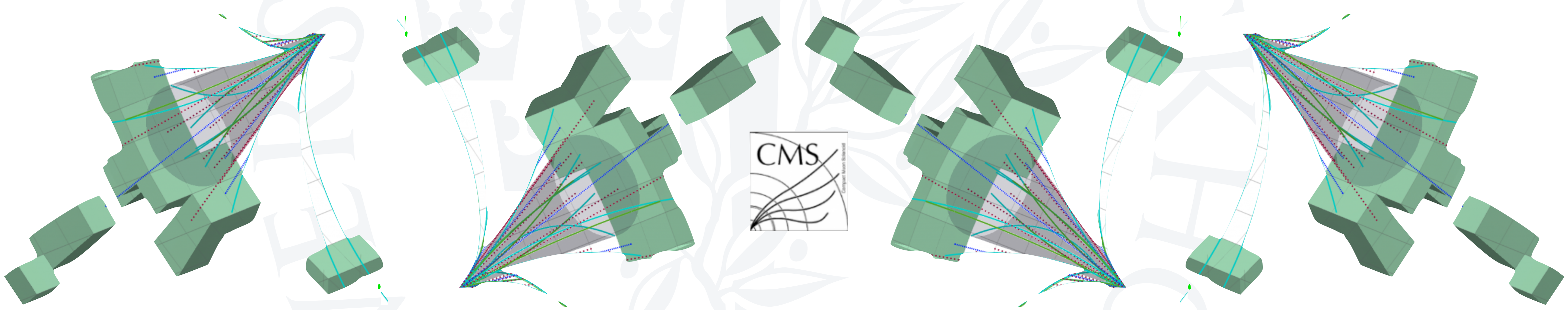
In the high-pileup, high energy runs in HL-LHC, pile-up mitigation and careful jet grooming will give us the best shot at reconstructing exciting physics!



Things I talked about and things I didn't have time to

Things I **talked** about

- Jet grooming algorithms: mass-drop filtering, trimming, & pruning
- Effects of jet grooming on pile-up mitigation, boosted decay and dijet discrimination
- Computing implementations and DCNN ML



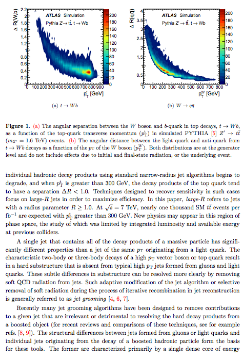
Things I **didn't** talk about

- Pile-up mitigation algorithms: PUPPI, SoftKiller, PUMML
- Jet grooming in the Quark-Gluon Plasma
- Improved algorithms: soft-drop (!)
- Other jet characteristics: tau_n, d12, colour-flow

References

Bibliography (1)

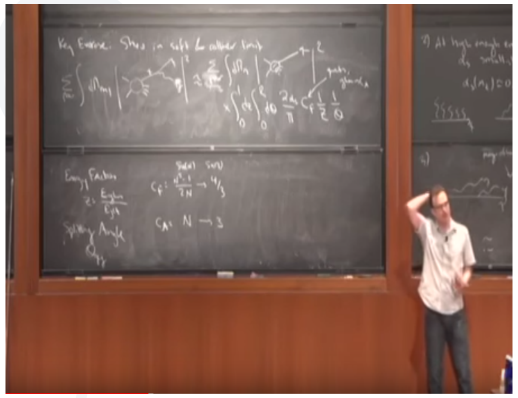
If you look at one reference…



Performance of jet substructure techniques for large-R jets in proton–proton collisions at ps = 7 TeV using the ATLAS detector - ATLAS Collab.
https://arxiv.org/abs/1306.4945

… also this conference…

BOOST 2017 talks (most of them)
https://indico.cern.ch/event/579660/



… and these lectures

Jet Substructure by Jesse Thaler
https://www.youtube.com/watch?v=o5VTjNyDxhU&t=1867s

Heavily borrowed from:

Performance of jet substructure techniques in early $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector (2015) - ATLAS Collab
https://cds.cern.ch/record/2041462

Advanced Machine Learning for Classification, Regression, and Generation in Jet Physics by Ben Nachman (2017)
https://indico.cern.ch/event/667334/

Boosted boson tagging in ATLAS Run-2 by Reina Camacho Toro (2015)
https://indico.cern.ch/event/522097/attachments/1275307/1910504/20160525_SLAC_JSSATLAS_Camacho_v0.pdf

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References

Bibliography (2)

Softdrop Mass Measurement by Ben Nachman (2017)
No public link available :(

Jet Grooming in ATLAS by Emily Thompson (2012)
https://cdsweb.cern.ch/record/1491166/files/ATL-PHYS-SLIDE-2012-691.pdf

Jet Measurement & Jet Substructure in ATLAS by Sanmay Ganguly (2017)
https://indico.fnal.gov/event/12423/session/10/contribution/53/material/slides/0.pdf

The Strong Interaction and LHC Phenomenology: Jet reconstruction and jet substructure by Juan Rojo (2014)
http://www2.physics.ox.ac.uk/sites/default/files/2014-03-31/qcdcourse_juanrojo_tt2014_lect8_pdf_18445.pdf

Large R jet reconstruction and calibration at 13 TeV with ATLAS by Joe Taenzer (2017)
https://indico.cern.ch/event/579660/contributions/2496135/attachments/1495415/2326534/BOOST17_largeR_reco_calib_ATLAS.pdf

Performance of boosted object and jet substructure techniques in Run 1 and 2 ATLAS data (2016) - ATLAS Collab.
https://cds.cern.ch/record/2229555?ln=en

Gluon and quark jet substructure (2013)
https://arxiv.org/abs/1211.7038v2

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