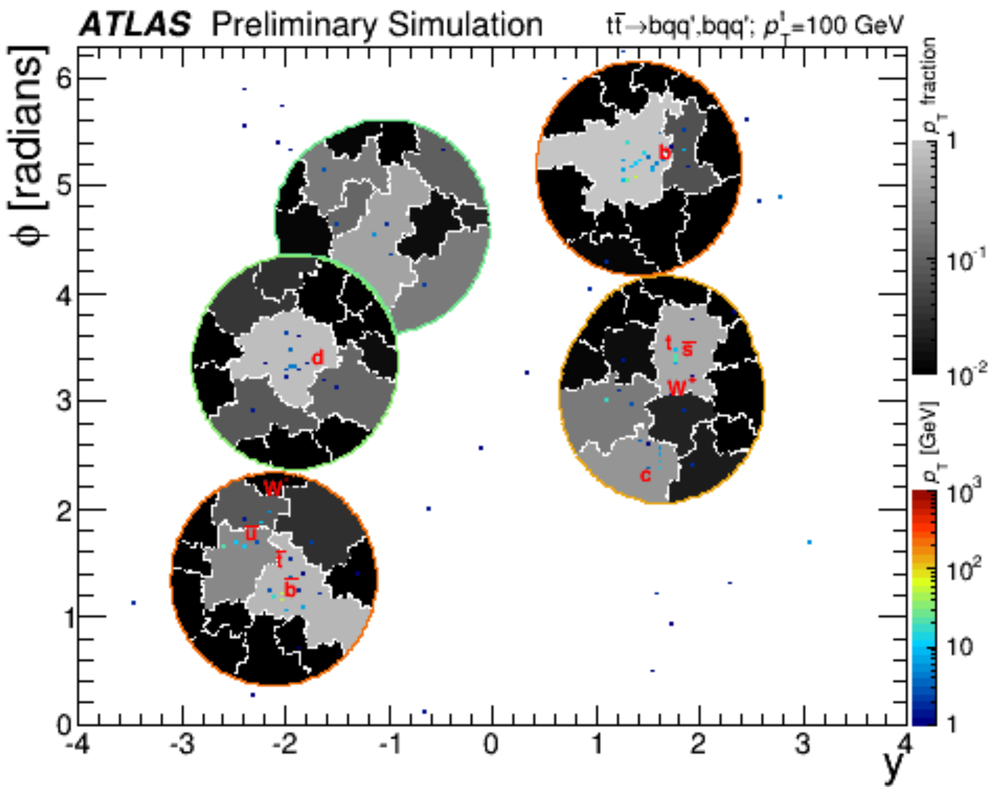
Summary of Jet Substructure Studies in ATLAS



- Introduction
- Inputs to substructure variables
- Substructure calibration and systematic uncertainties
- Current uses and future experimental developments
- Conclusions

David López Mateos, Harvard University, for the ATLAS Collaboration,
BOOST 2014, August 19th, 2014

Introduction

- A wealth of substructure techniques have been proposed and studied in this workshop in its last 5 editions

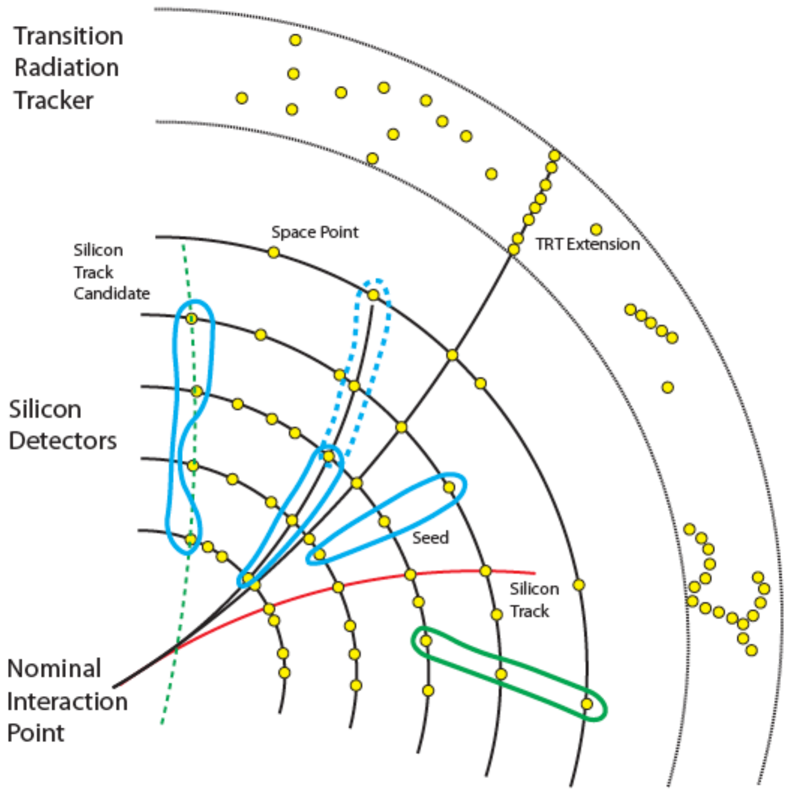
- ATLAS is implementing and studying, at the detector level, many of these techniques

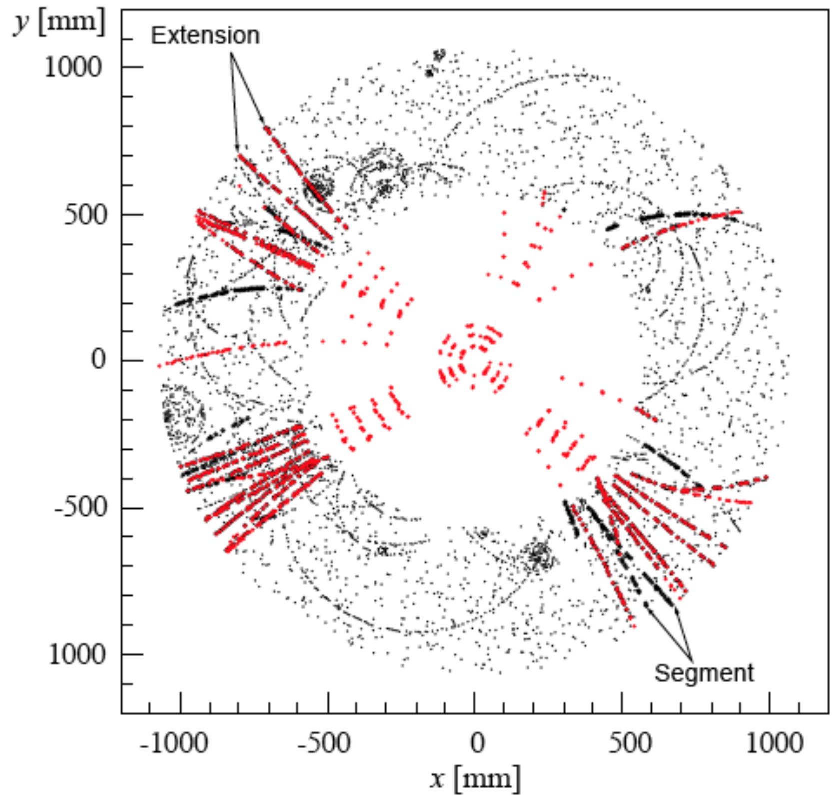
- At the same time, understanding the precision with which our detector allows us to learn about these techniques is crucial

- This can be done through a combination of the understanding of our low-level objects and the use of standard candles (but extrapolations beyond the kinematic regime of those candles are not trivial and result in larger uncertainties)

⇒ Try to summarize in this talk how substructure techniques are studied in ATLAS, and how systematic uncertainties are established (with an eye on improvements for Run 2)

Inputs to Jet Substructure: Tracks

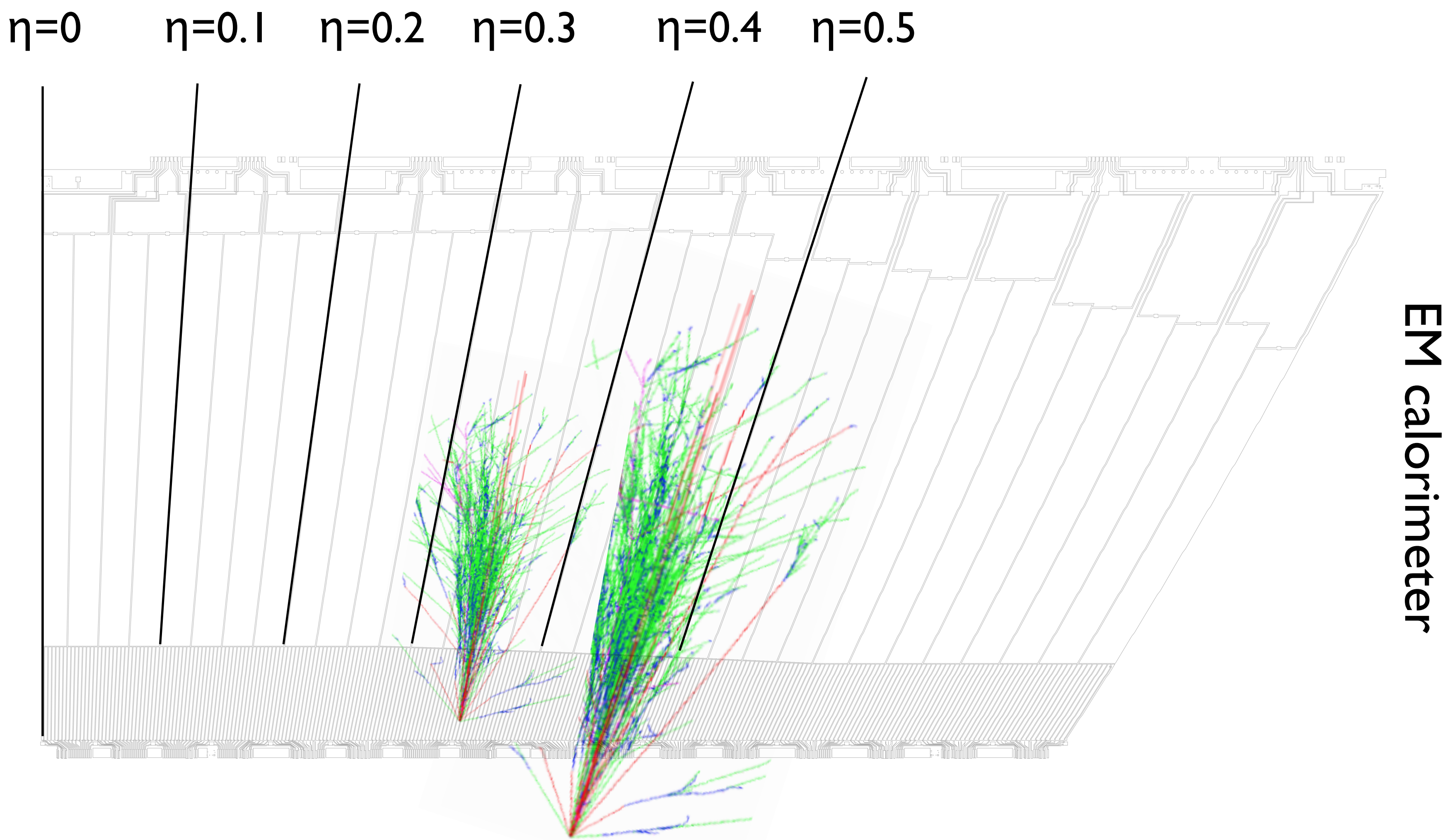




[*] ATL-SOFT-PUB-2007-007

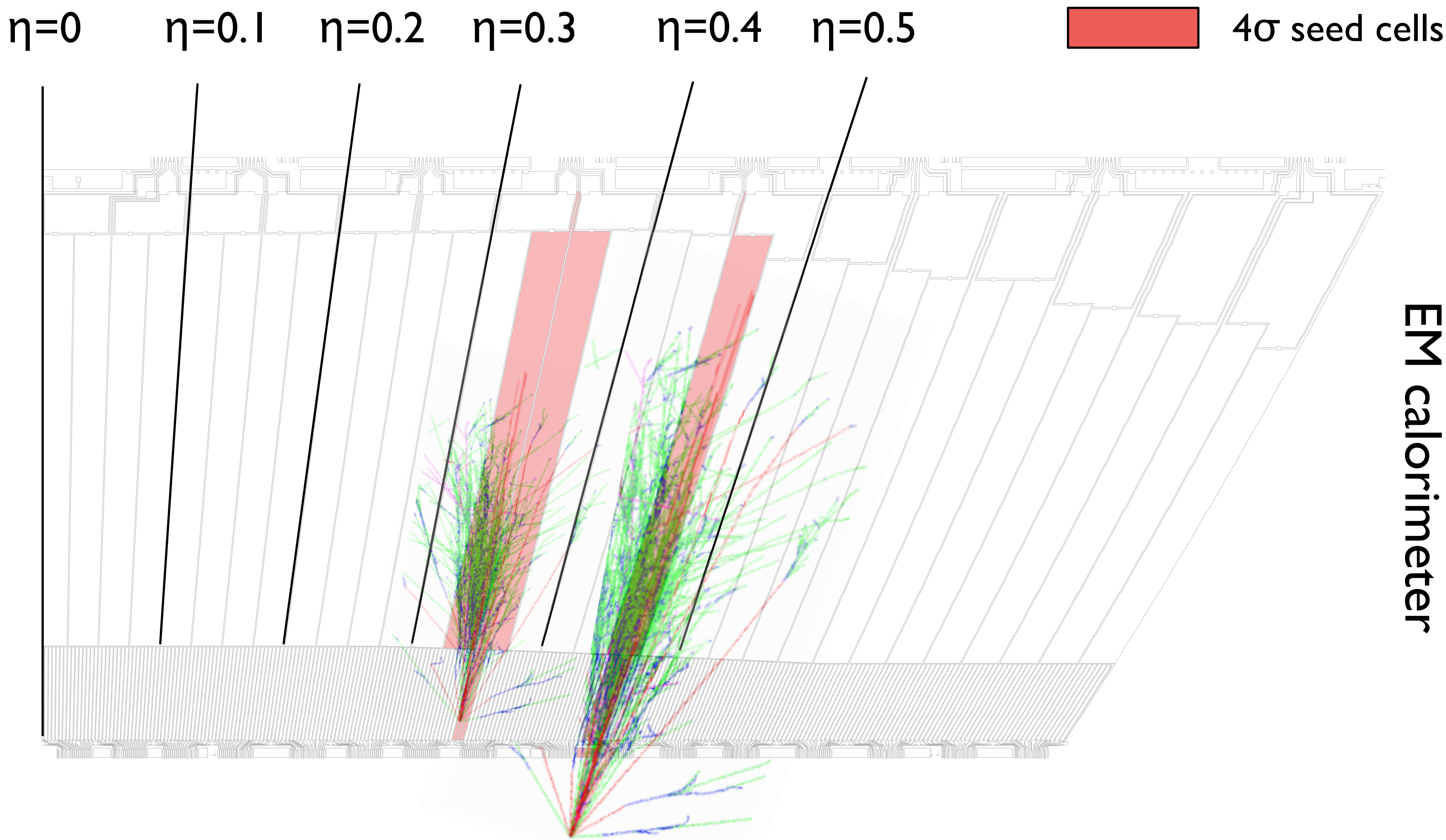
- Tracking using three different sub detector technologies: inside-out tracking combined with outside-in tracking
- Can go as low as $p_T \approx 100$ MeV, but typically for jets use $p_T > 500$ MeV or 1 GeV, $|\eta| < 2.5$
- Tracking challenging in jets of $p_T \gtrsim 500$ GeV (efficiency starts dropping)

Inputs to Jet Substructure: Clusters



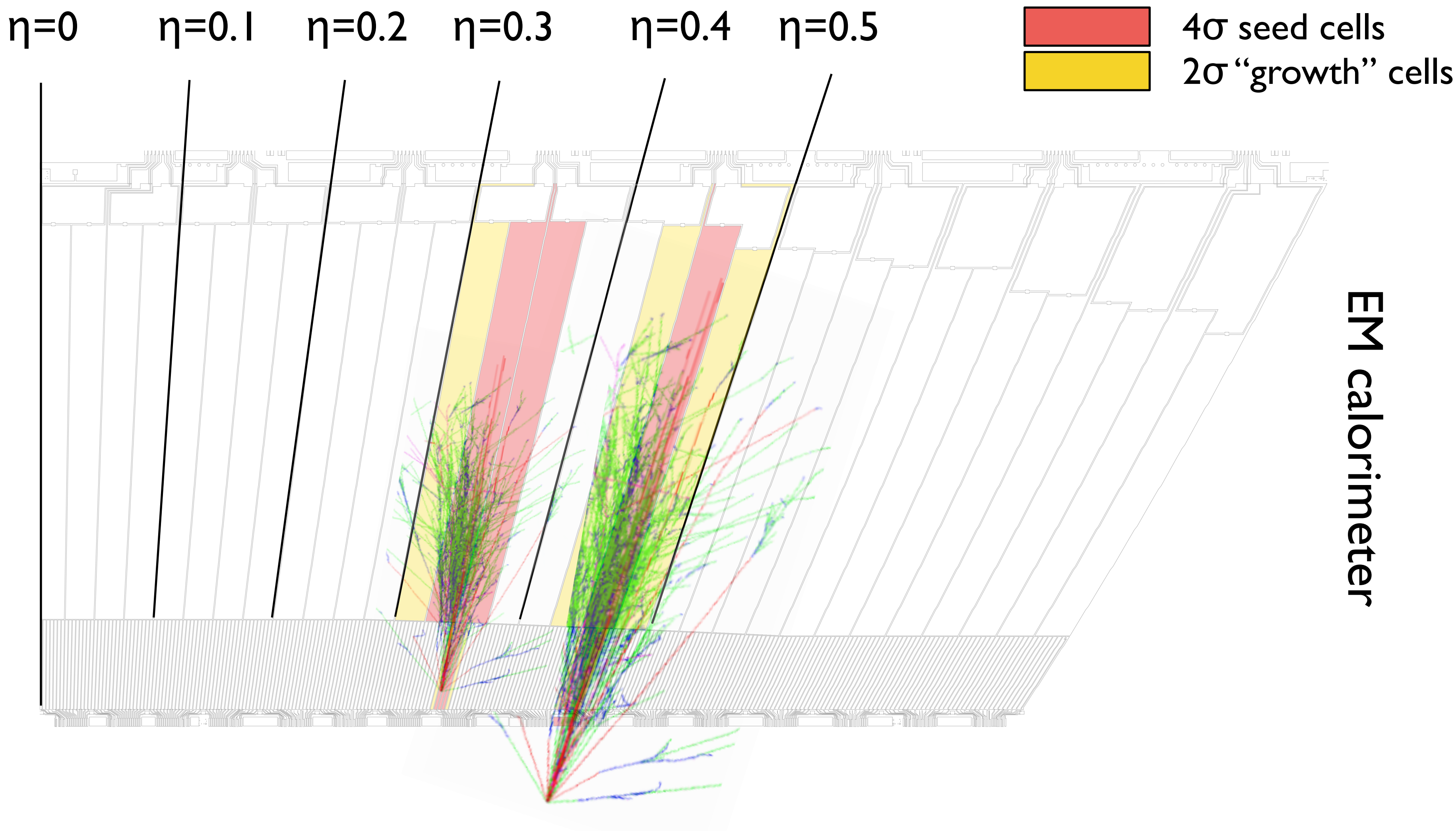
- Clusters are built starting from the fine readout granularity of the ATLAS calorimeter (above the EM calorimeter in the central region)

Inputs to Jet Substructure: Clusters



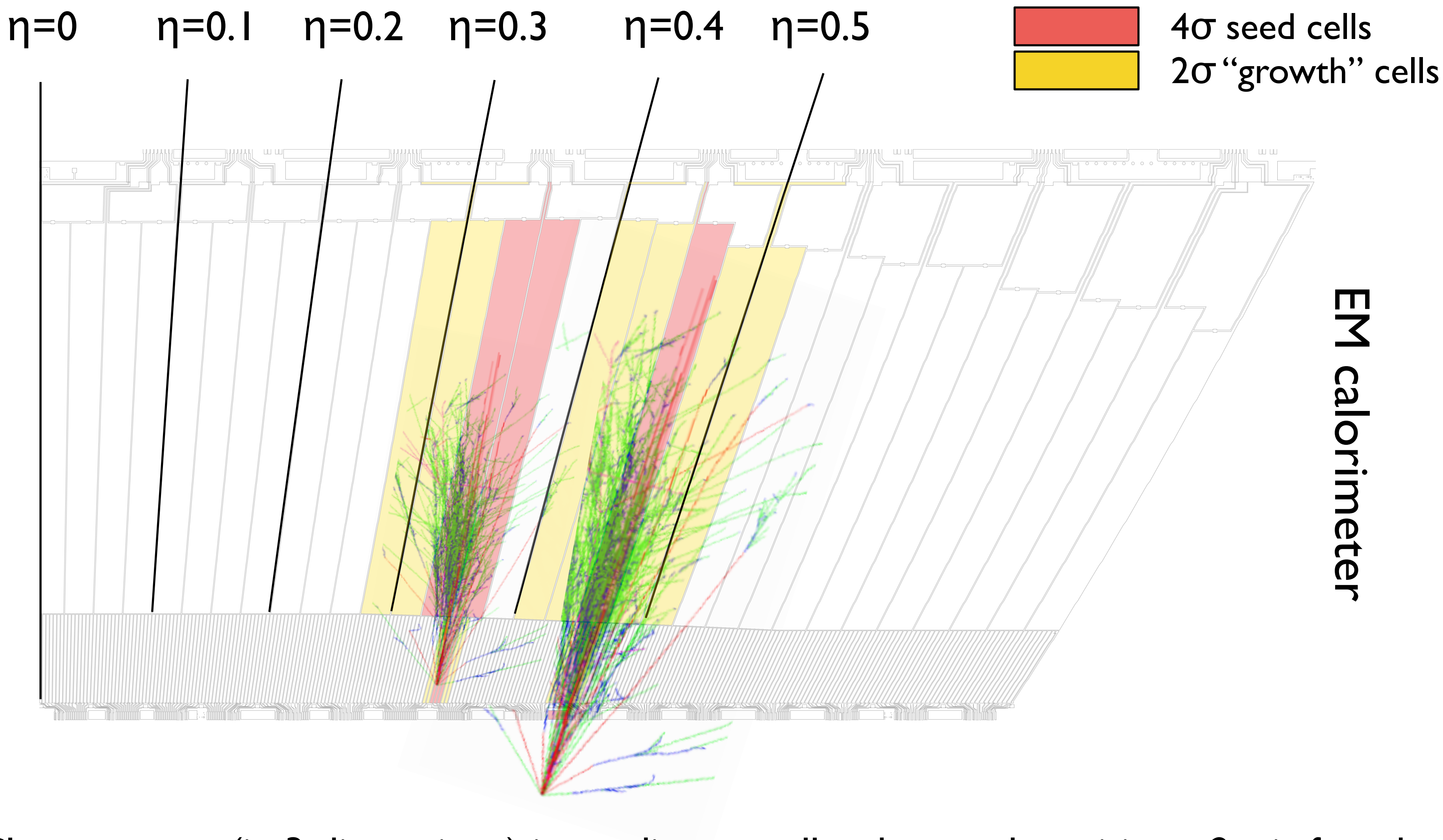
- Seeds are taken from cells that are above 4 standard deviations of the noise
- Noise includes electronic noise and average energy readings from pile-up
- Each cell has its value of noise stored in a database and that value is validated in data

Inputs to Jet Substructure: Clusters



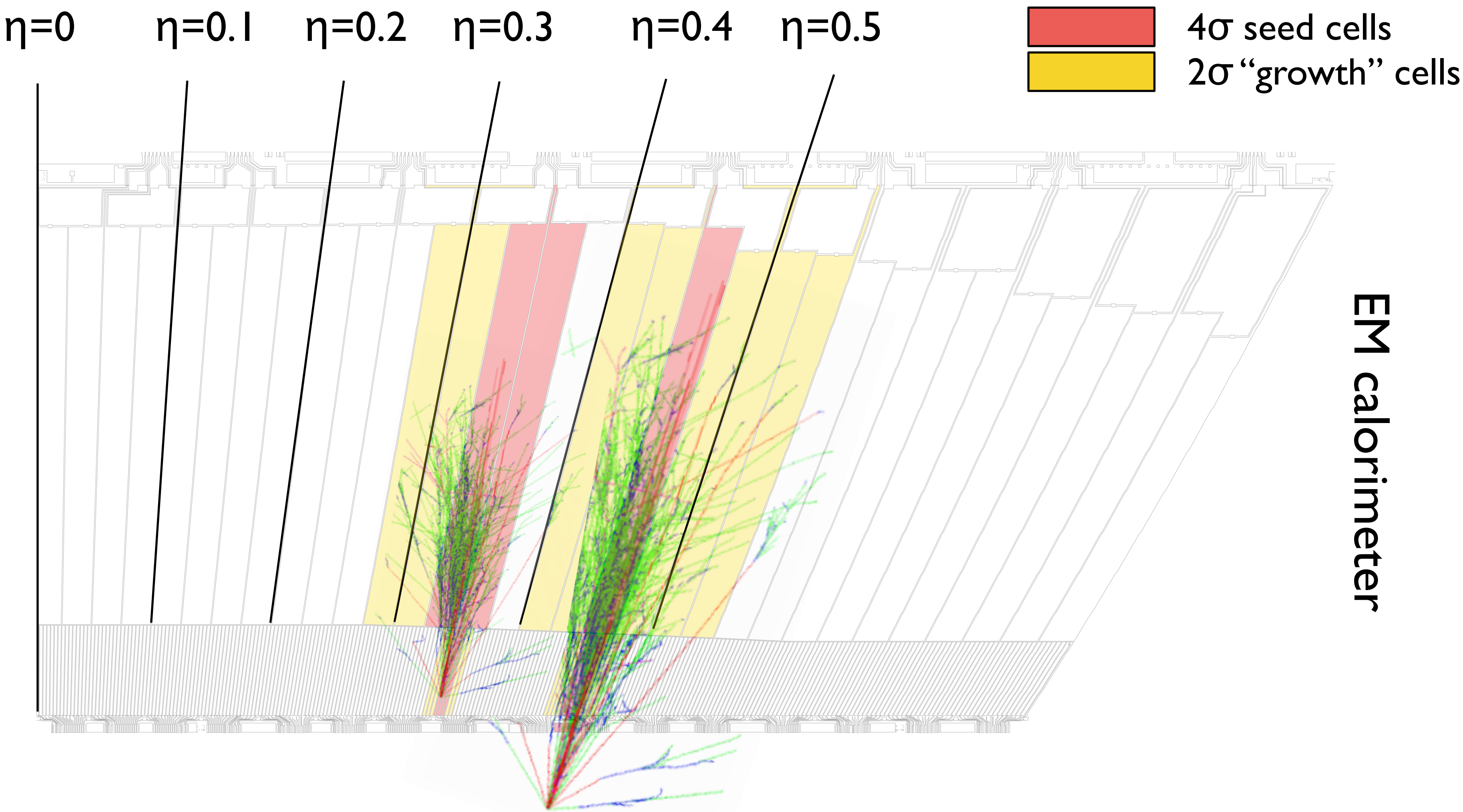
- Cluster grows (in 3 dimensions) into adjacent cells where a deposition >2σ is found

Inputs to Jet Substructure: Clusters



- Cluster grows (in 3 dimensions) into adjacent cells where a deposition >2σ is found
- Growth continues while adjacent cells with >2σ are found

Inputs to Jet Substructure: Clusters



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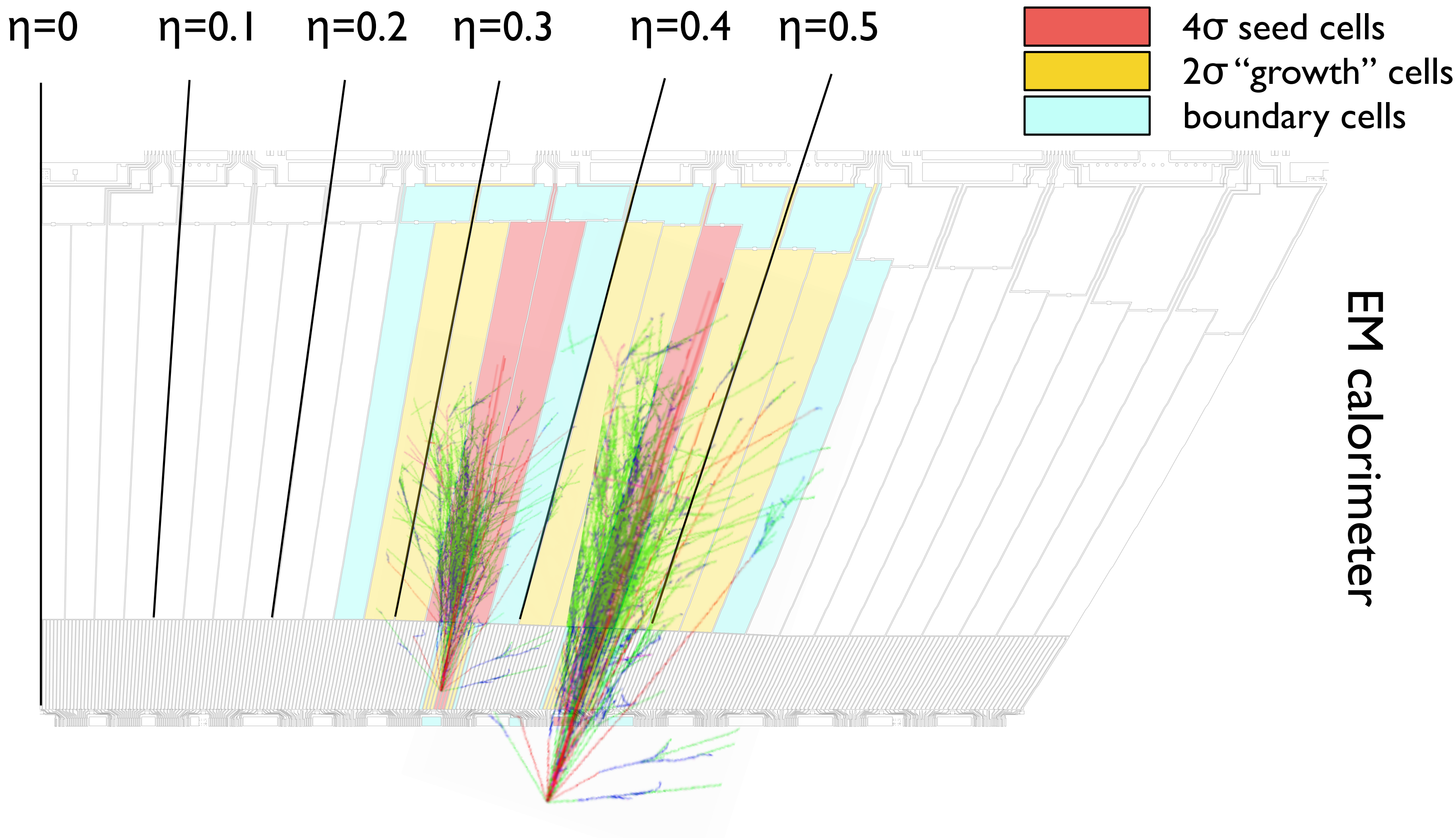
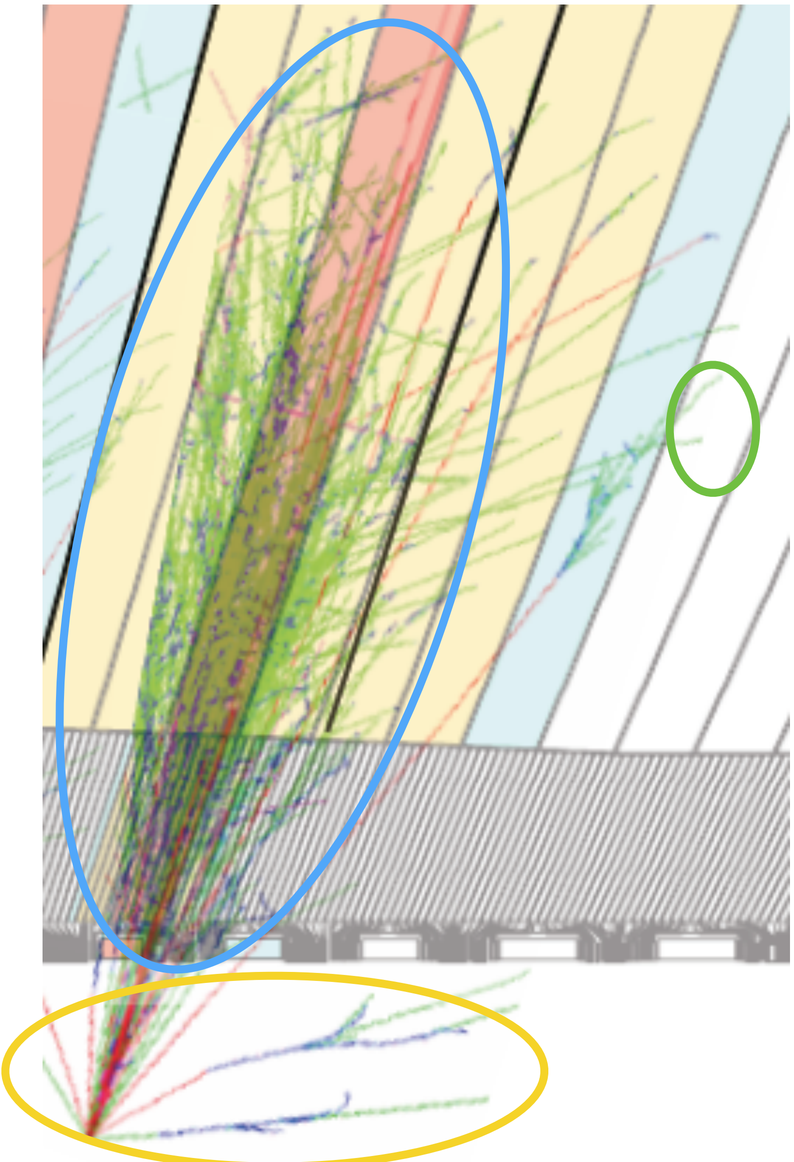
- Growth continues while adjacent cells with >2σ are found

Inputs to Jet Substructure: Clusters

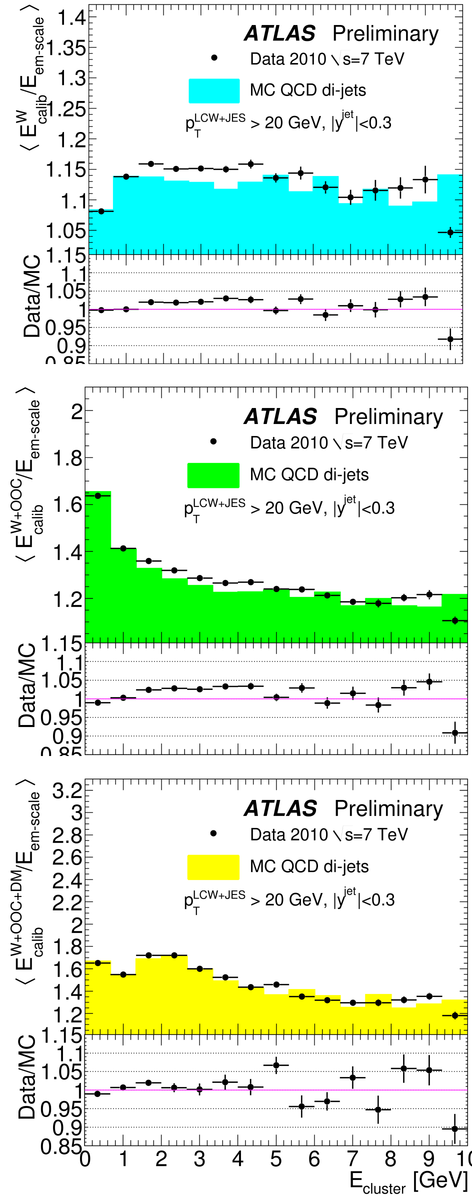


- Once growth is no longer possible, an additional set of boundary cells is added (irrespective of their energy)

Calibration of Clusters

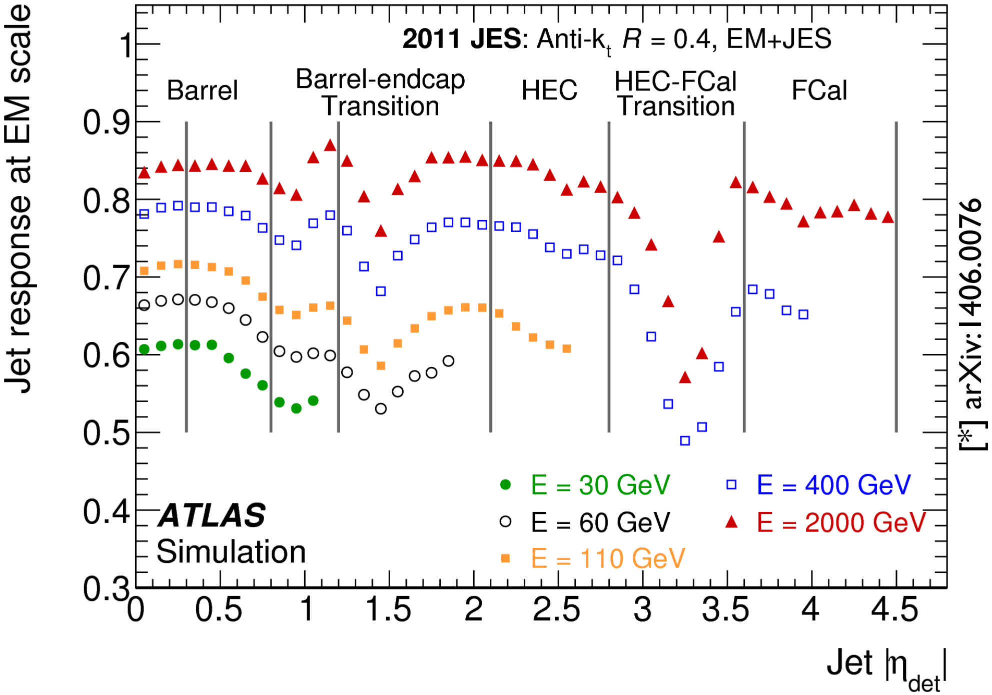


- Weights for non-compensation
  - Cluster energy
  - Cluster depth
  - Cell energy density
- Weights for energy out of the cluster
  - Cluster depth
  - Cluster isolation
- Weights for energy in dead material
  - Cluster energy
  - Energy deposited in each layer
  - Cluster depth

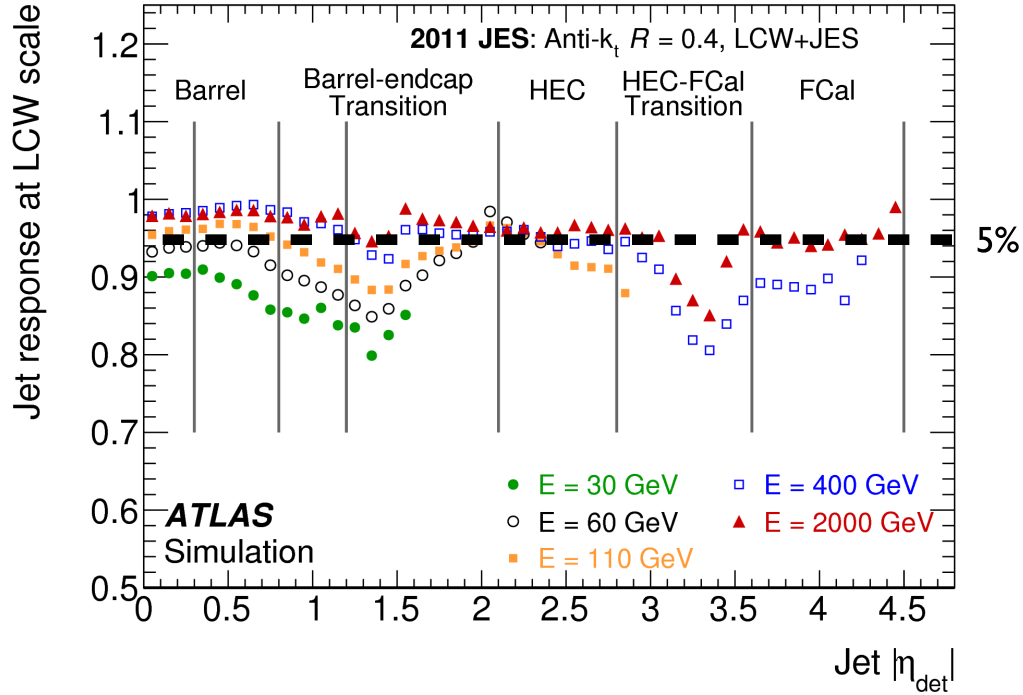


Calibration of Clusters: Effects on Jets

Jets using uncalibrated clusters



Jets using calibrated clusters



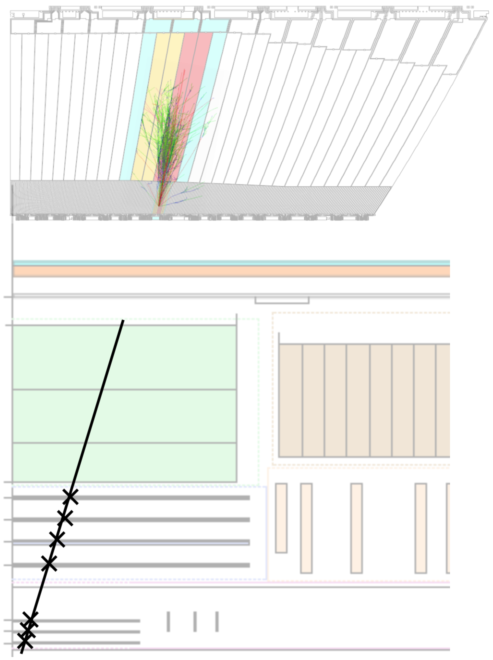
- Using calibrated clusters, jet calibration factors are less than 5% for $p_T \gtrsim 100$ GeV

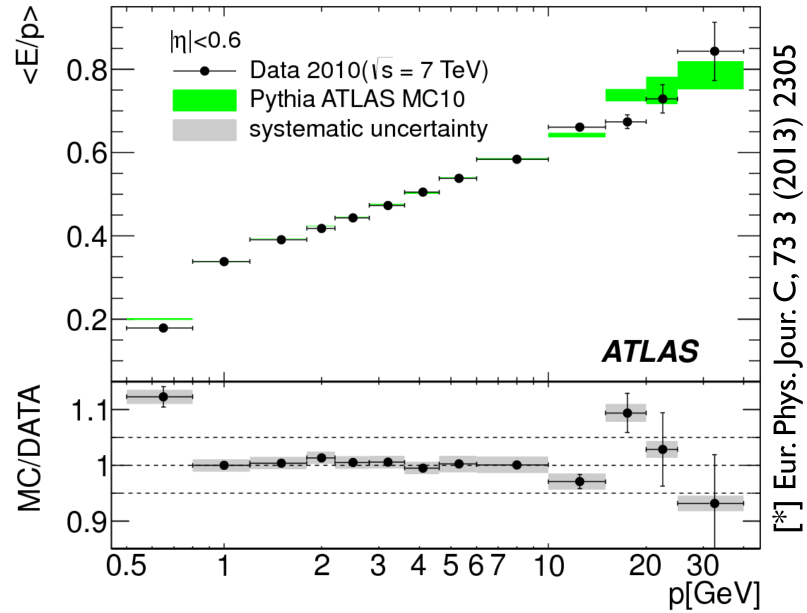
⇒ Jet substructure analyses use calibrated (LCW) jets and clusters

Clustering in data: Scale results

E measurement

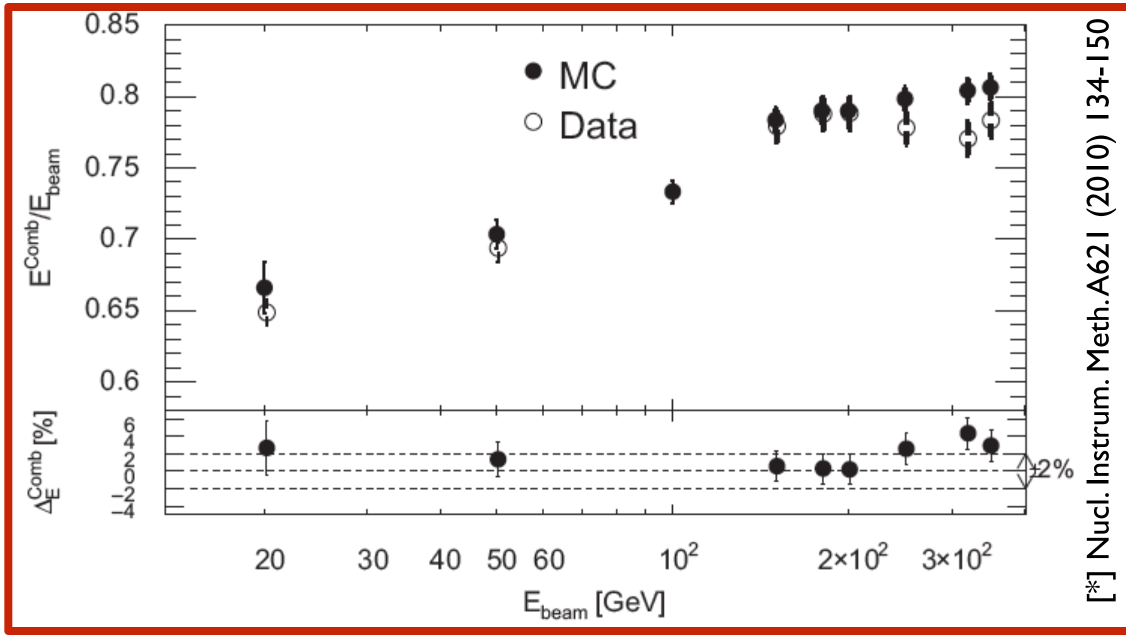
p measurement

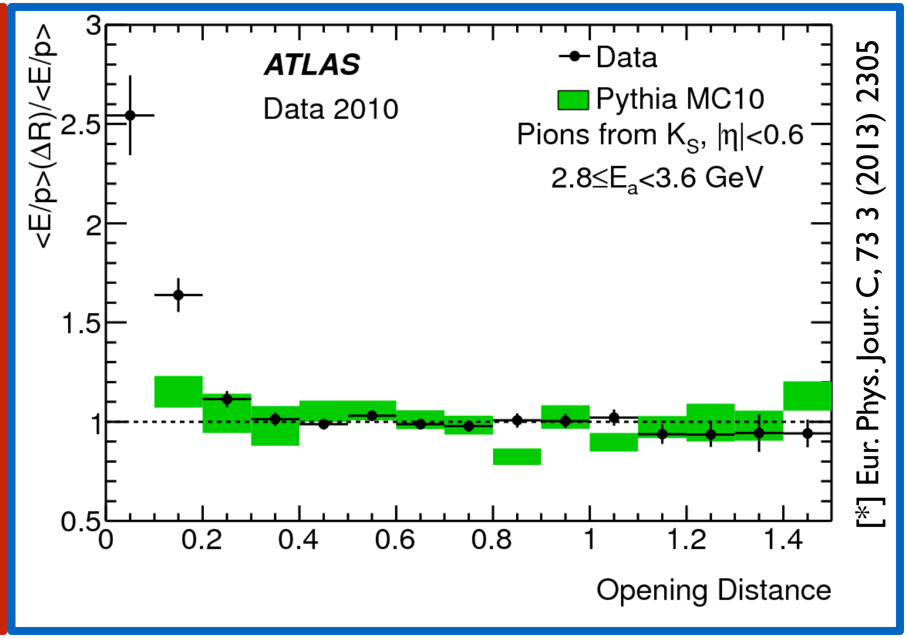




- Good handle into scale of clusters via isolated hadron response measurements
- Compare momentum measurement in ID with cluster measurement (neutral subtraction not completely trivial)
- Angular resolution of isolated clusters similarly well behaved

Clustering in data: Jet environment



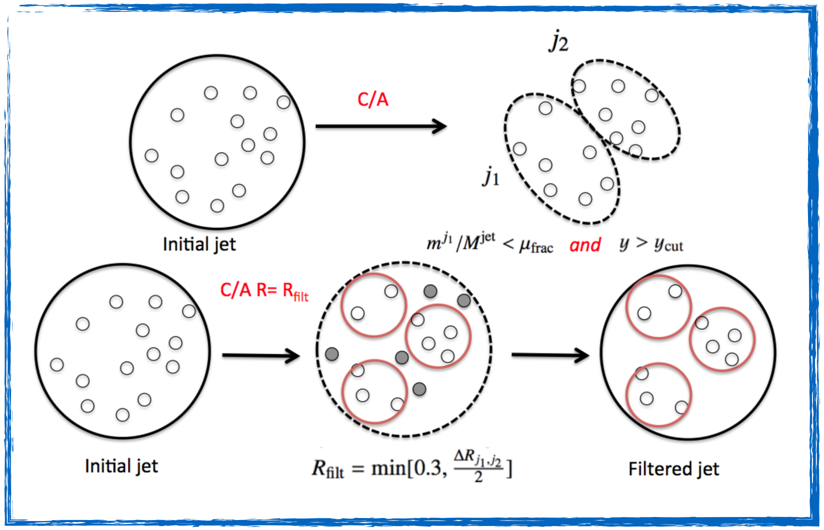


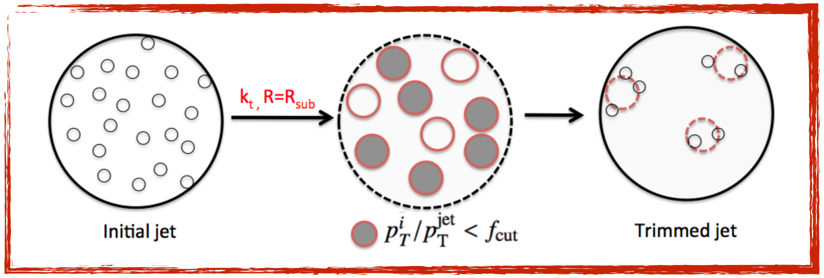
- Regime accessible with 2010 (or 2012) data is not the most relevant for substructure
- High energy only reachable using test beam data (ATLAS uses this to set uncertainties for very high-p_T jets, where no significant statistics are available)
- Some insight into jet environment obtained using $K_S \rightarrow \pi\pi$ decays

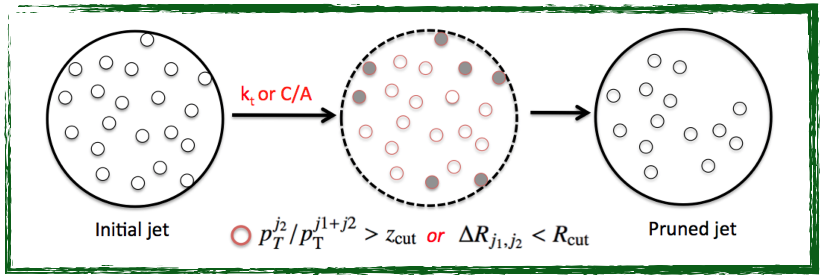
⇒Need additional handles to understand systematic uncertainties on complex substructure variables

Substructure Techniques: Grooming

- Split-filtering, trimming and pruning studied in detail with 2011 and 2012 data







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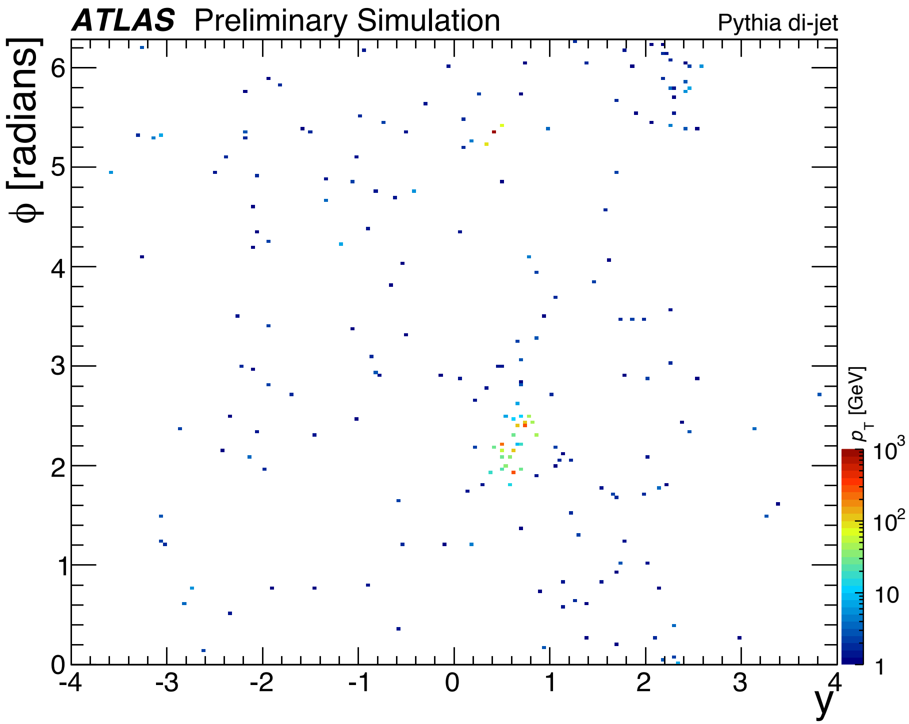
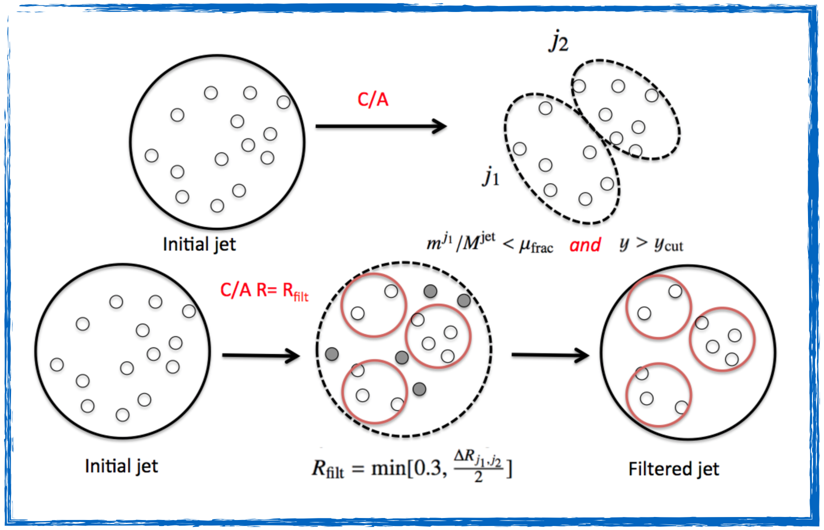
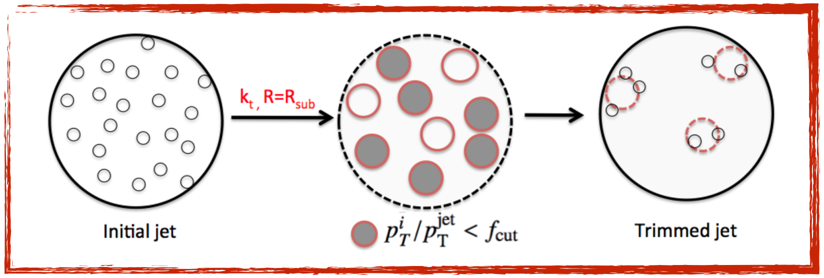
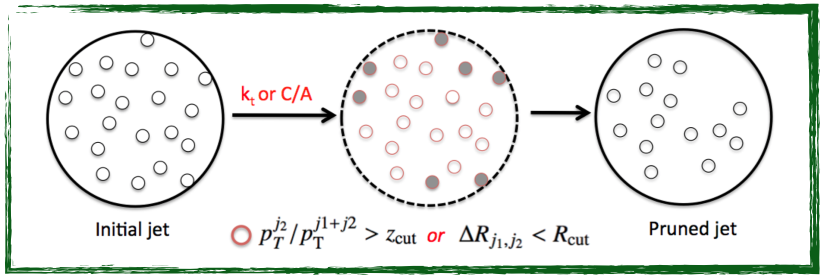


Trimming in action







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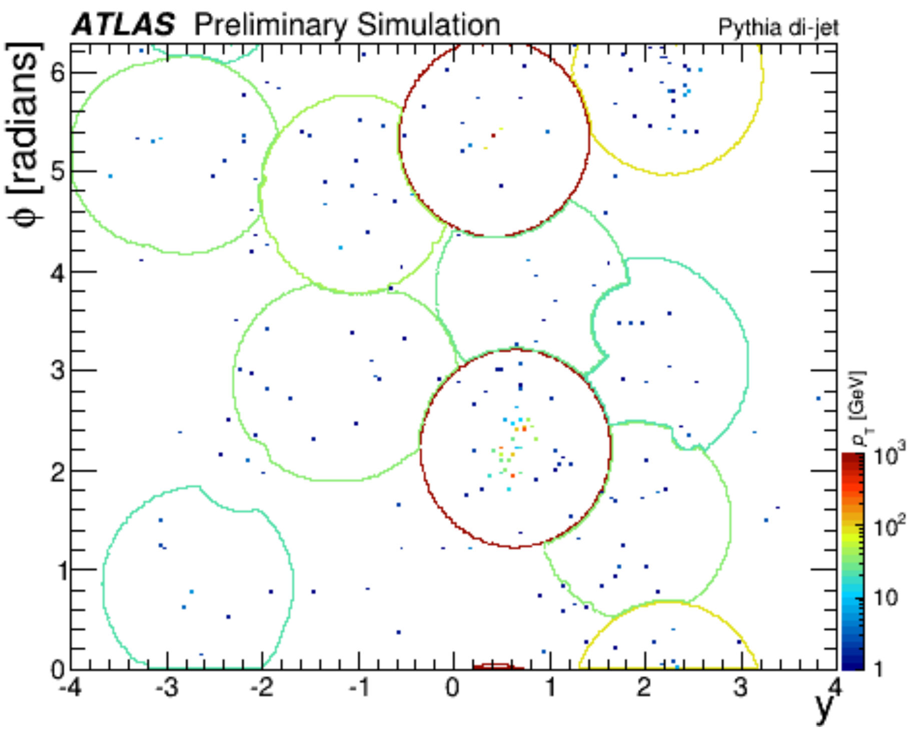
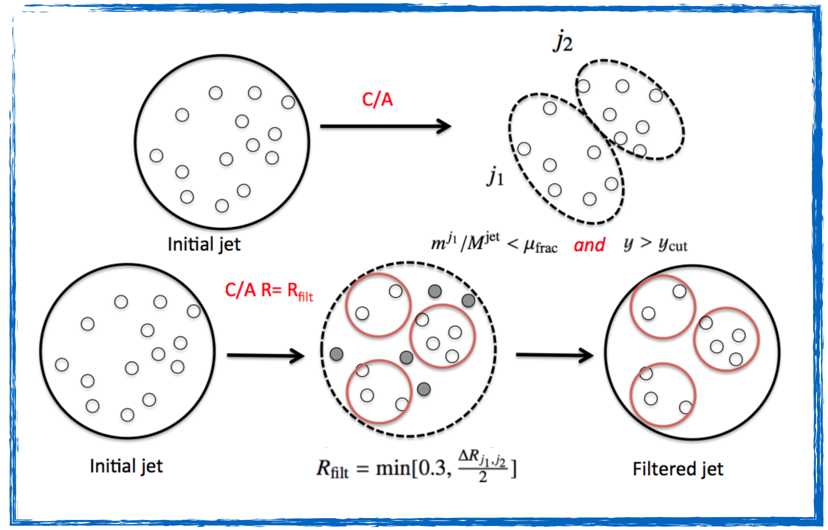
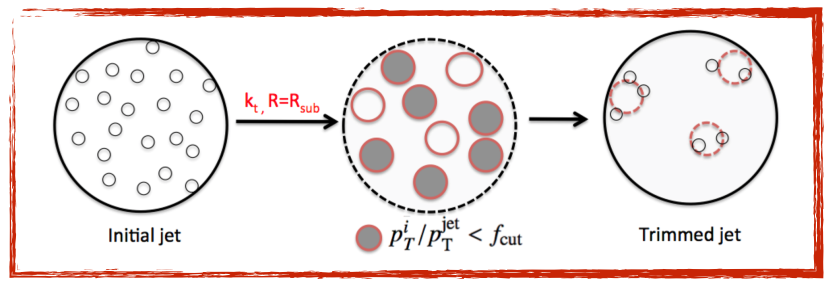
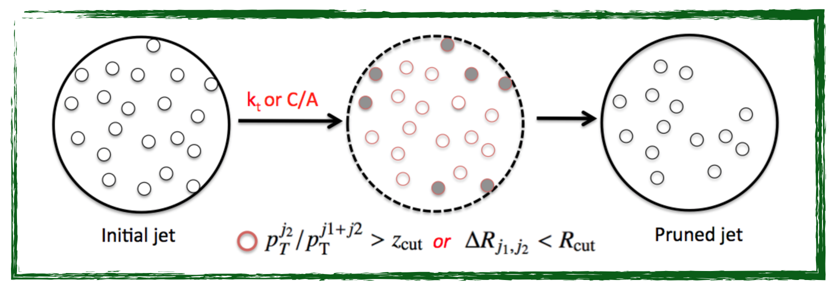


anti-k_t R=1.0 jets

Trimming in action







Substructure Techniques: Grooming

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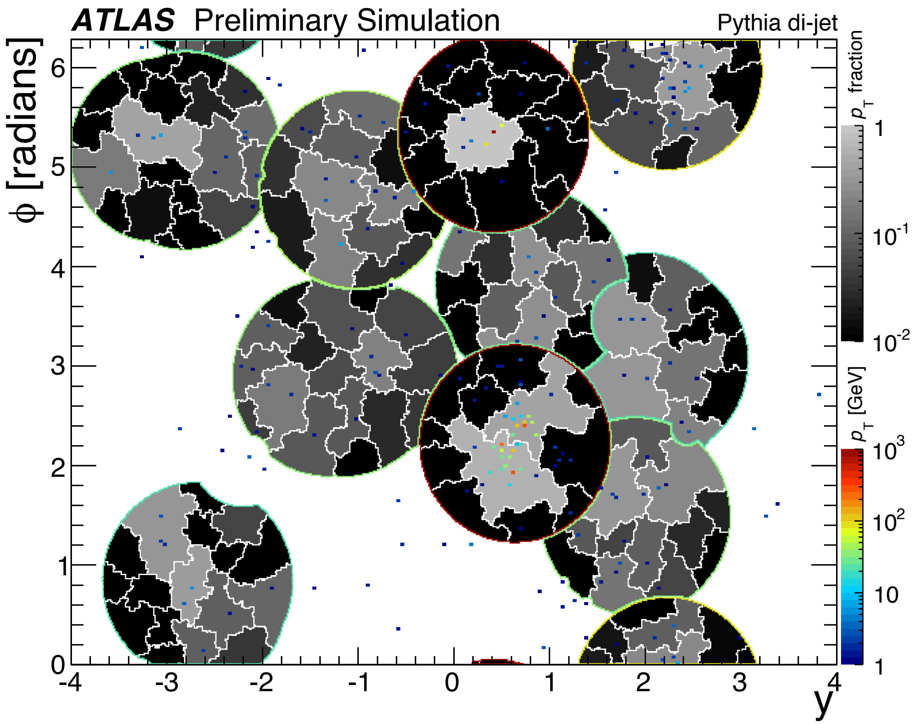
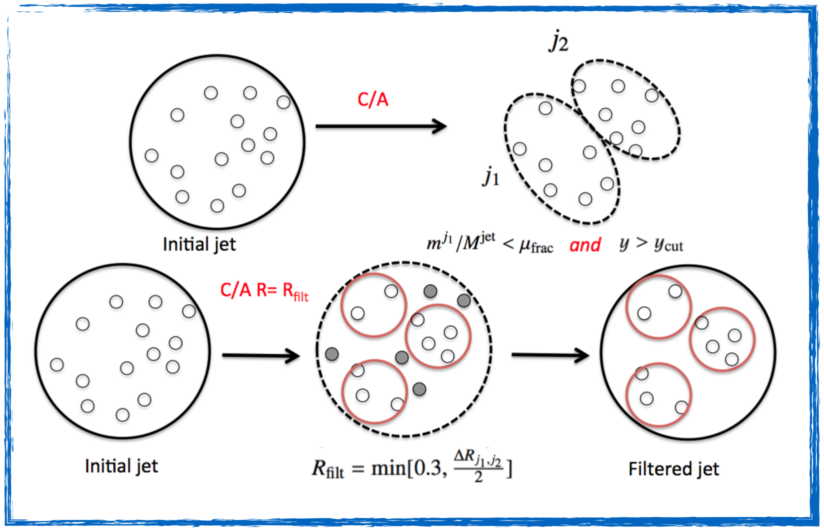
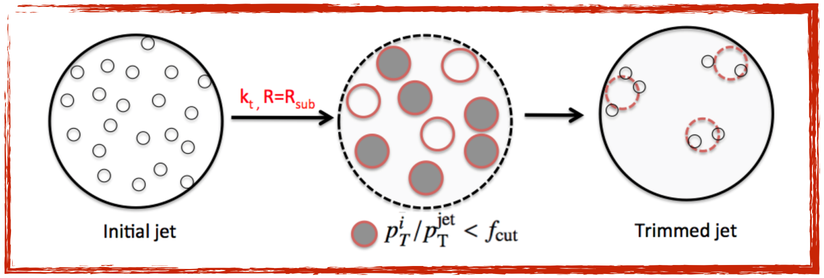
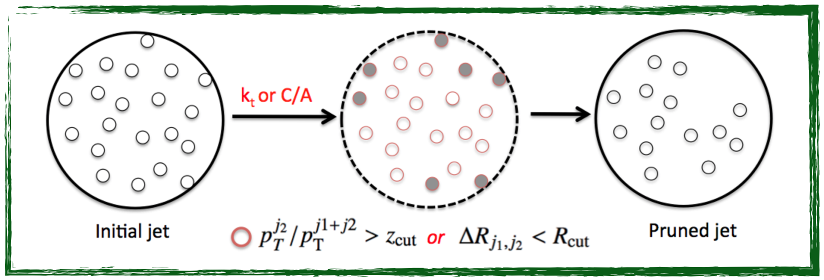


anti-k_t R=1.0 jets
k_t R=0.3 subjets

Trimming in action







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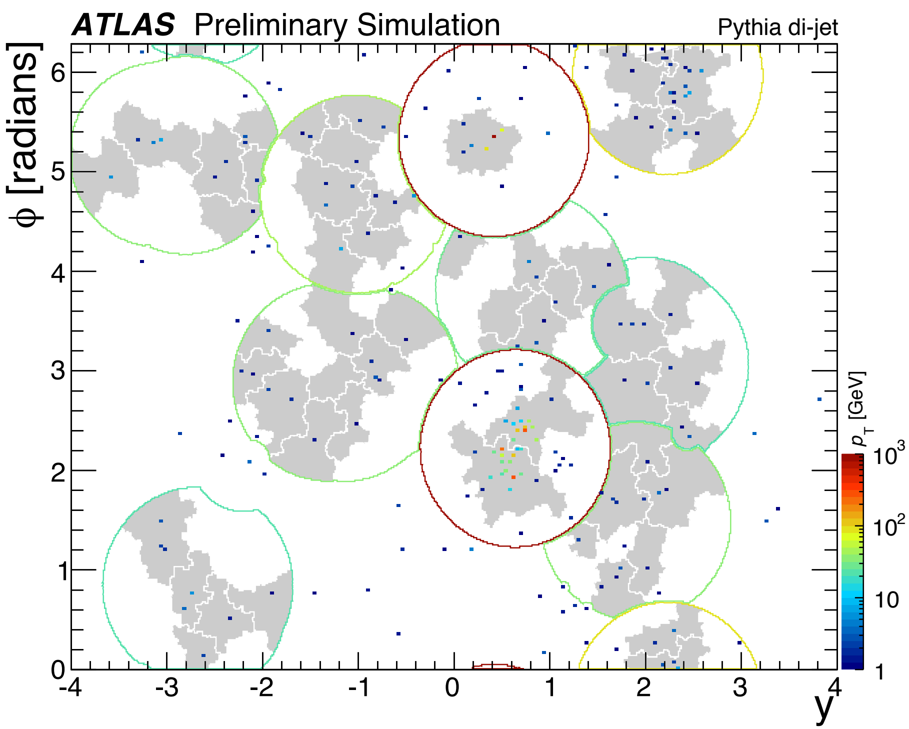
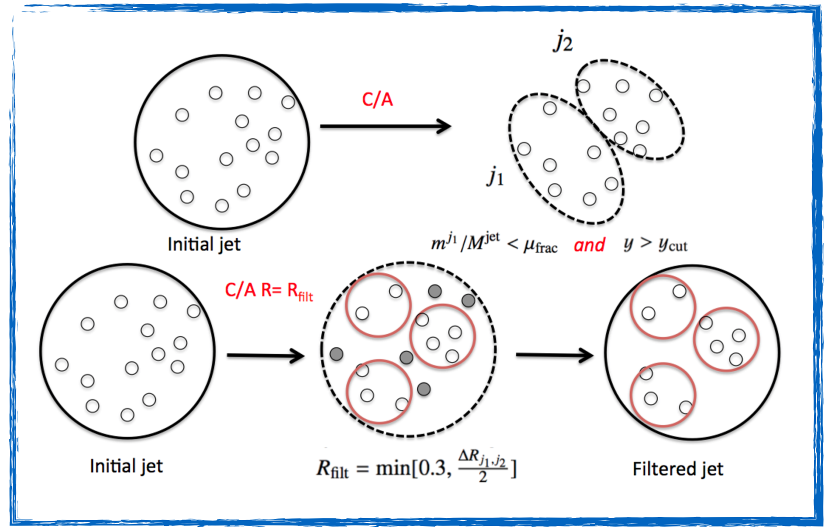
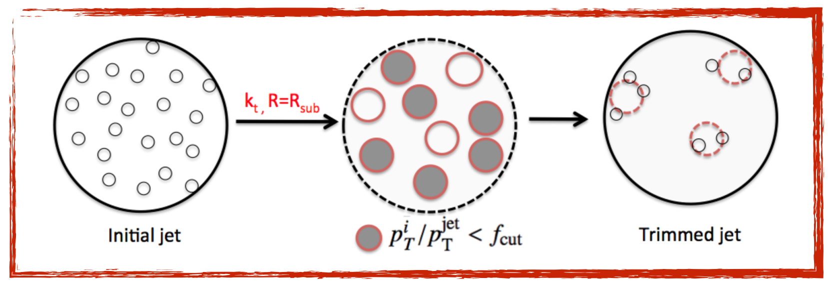
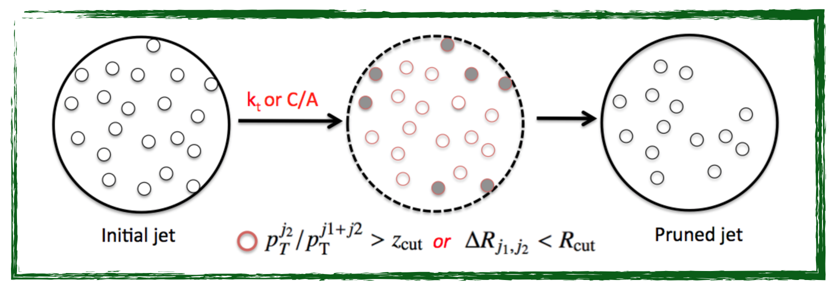


anti-k_t R=1.0 jets
k_t R=0.3 subjets
f_{cut}=0.05

Trimming in action







Substructure Techniques: Grooming

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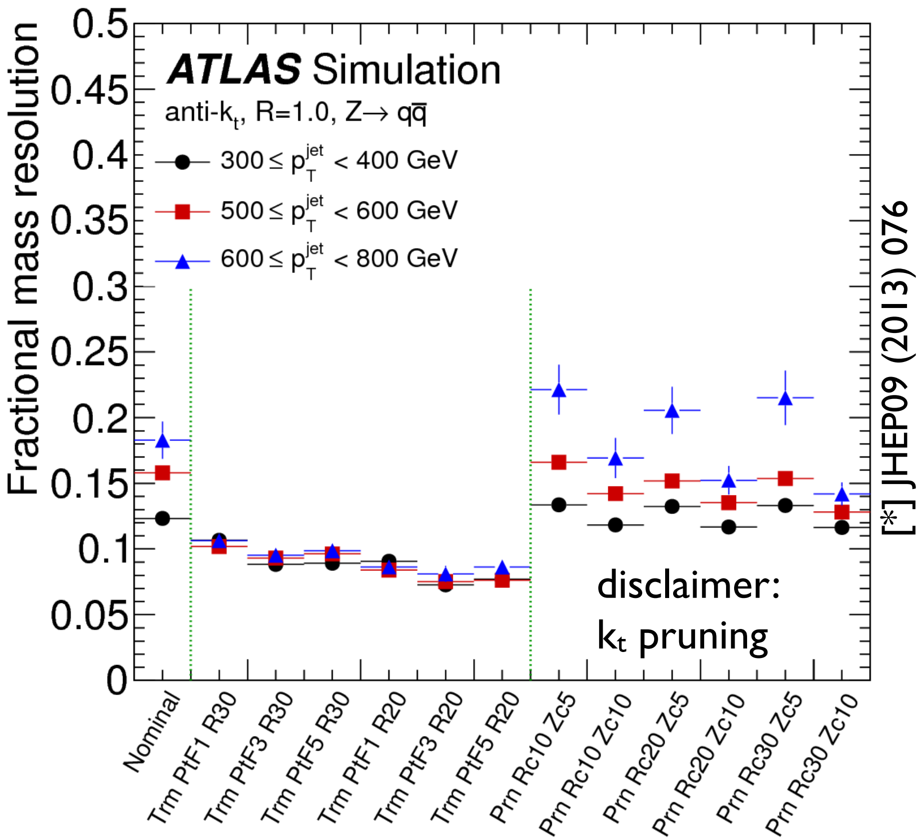
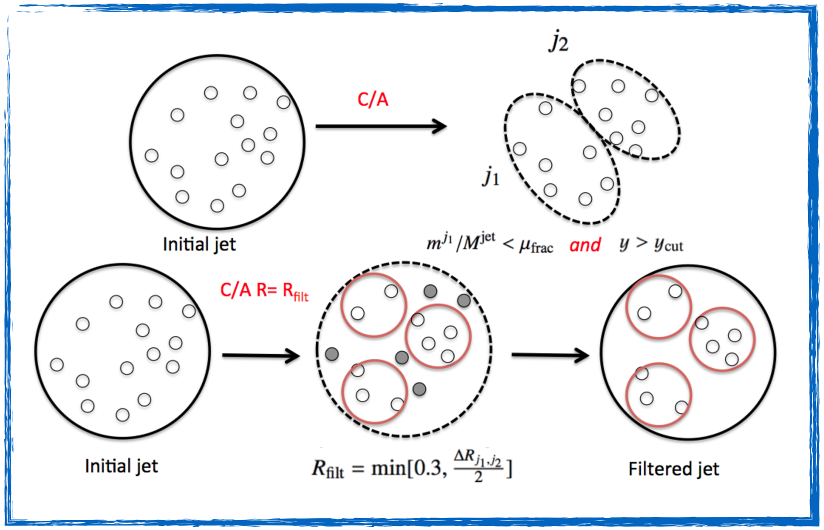
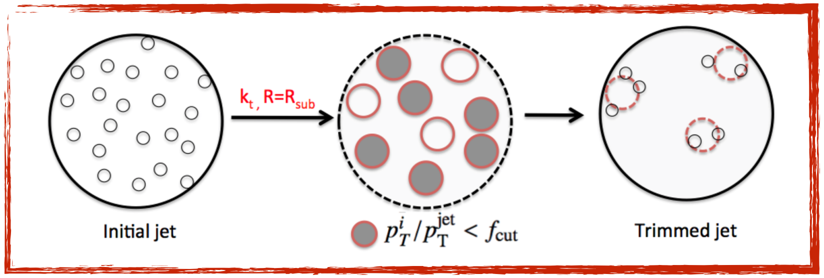
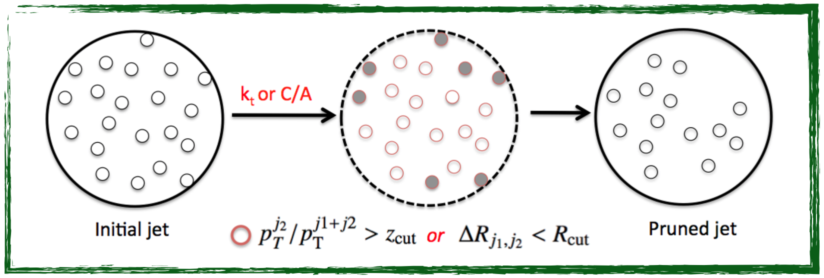








- Grooming parameter optimization studied in detail in 2011

Ghost Pile-up Subtraction

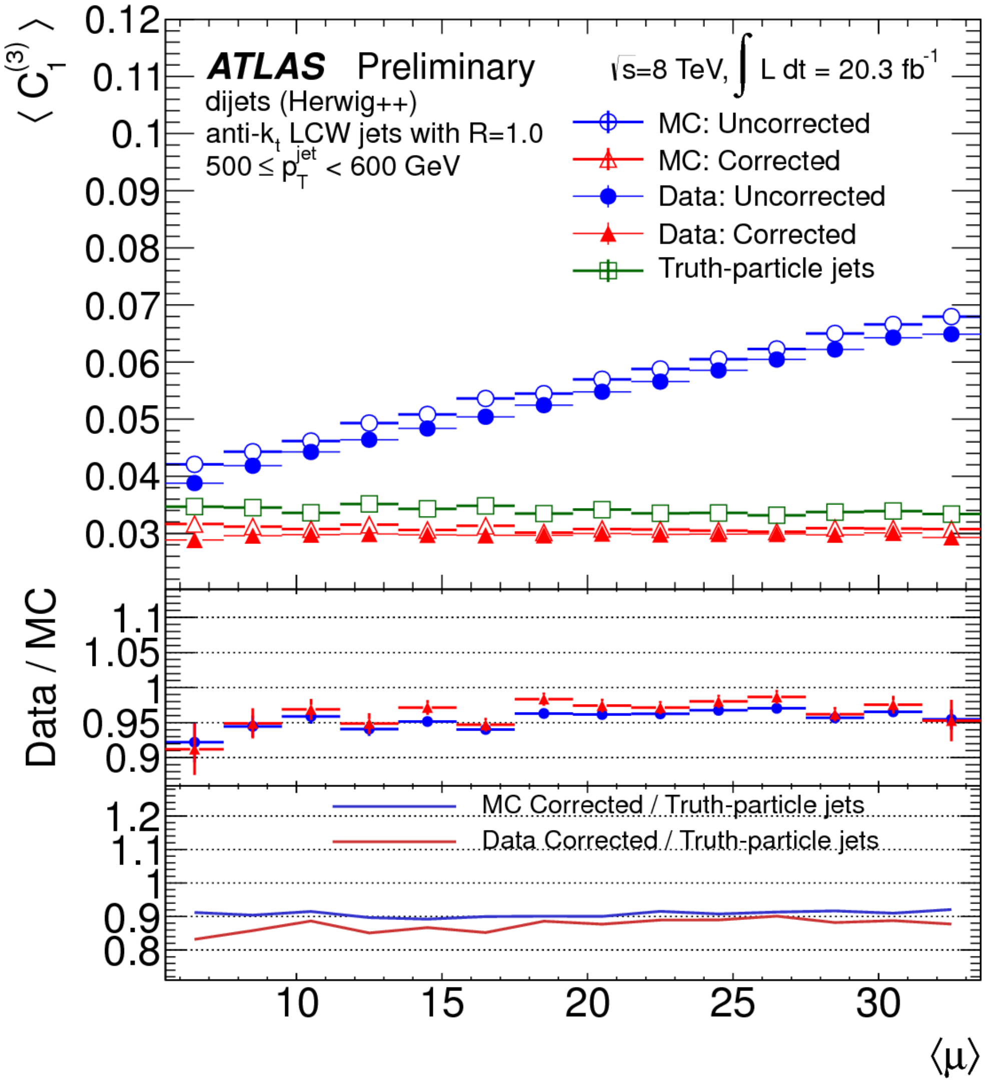
- Subtract the equivalent ghost pile-up contribution in building substructure variables:

$$\vec{g_t} = -\rho \vec{A_g}$$

- This can be done analytically, or through a Taylor expansion

- Pile-up dependence can be significantly reduced for many substructure variables

- At high luminosity we need to combine this technique and grooming (see Ariel's talk)



[*] ATLAS-CONF-2013-085

Substructure Variables

- Jet mass
- Jet charge

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see Danilo Ferreira's talk

- k_t splitting scales
- N-subjetiness
- Volatiliy
- Planar flow

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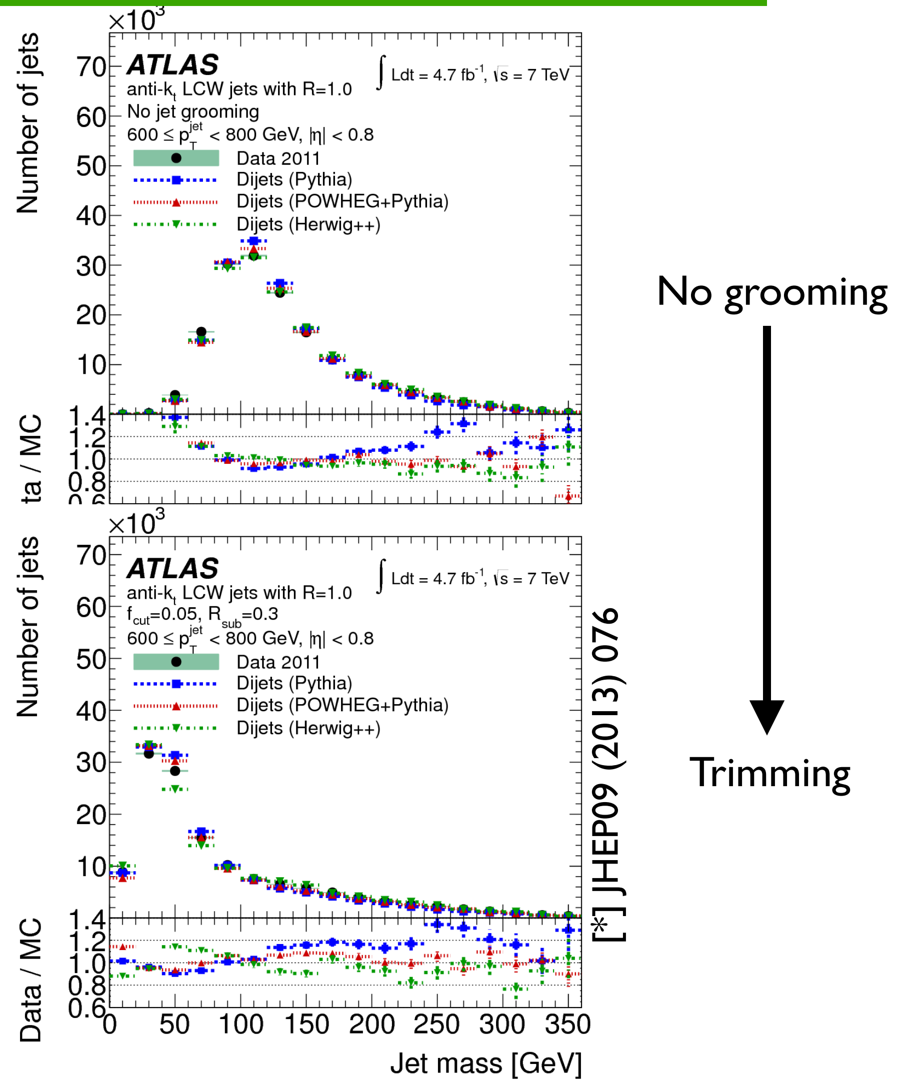
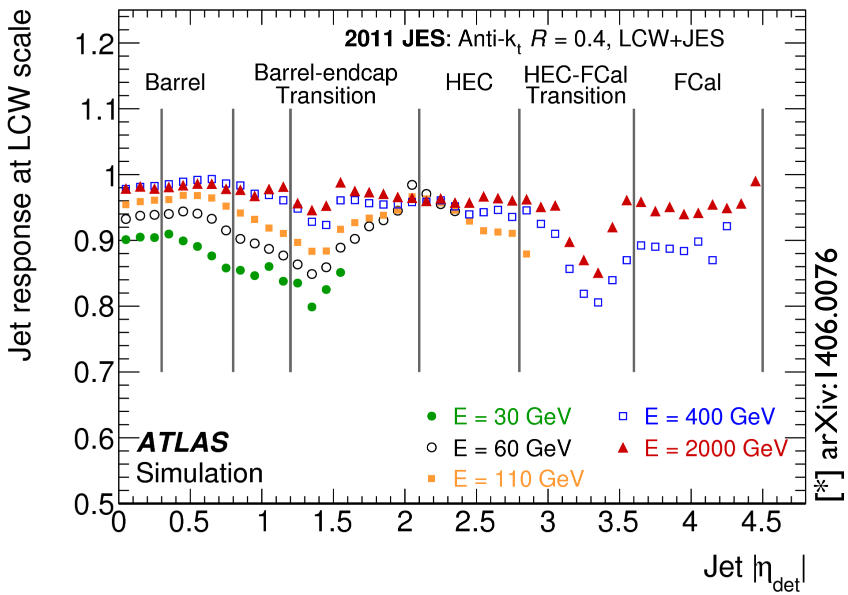
see Max Swiatlowski's talk

- Jet pull
- Track multiplicities
- Angularities (and EEC angularities)

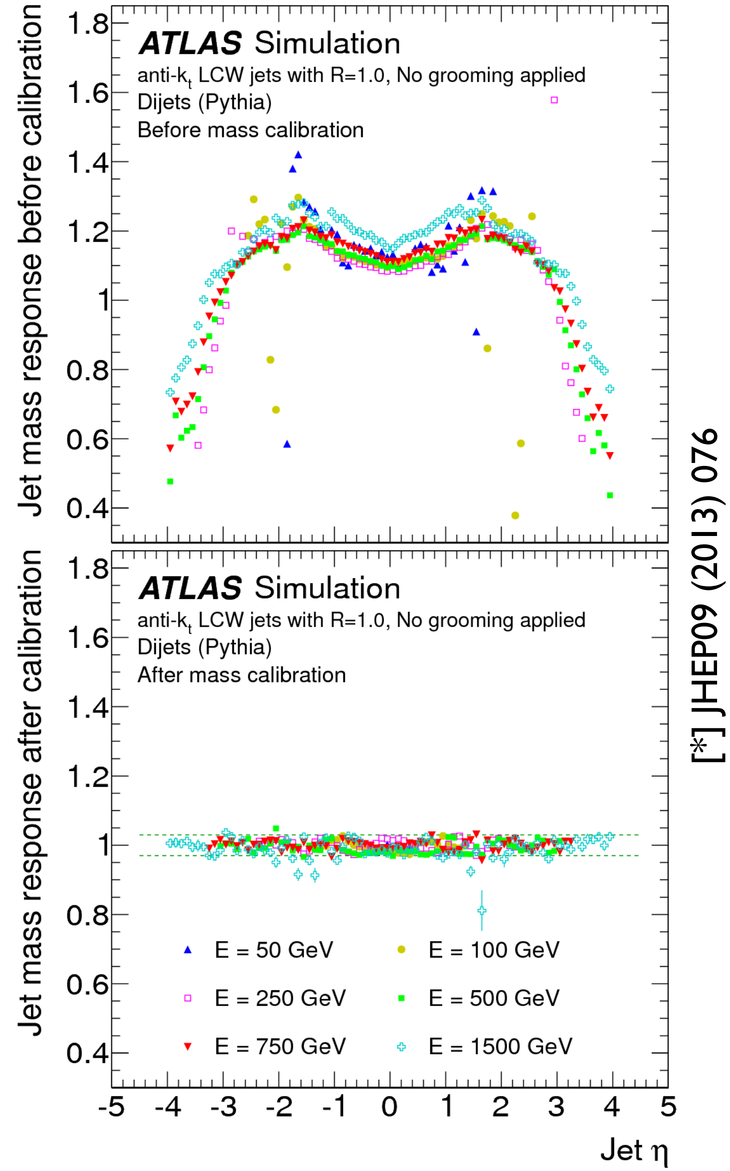


⇒Wealth of variables studied with different taggers as motivation, but they also teach us about QCD and MC implementations, and often used with groomers

Jet Energy/Mass Calibration

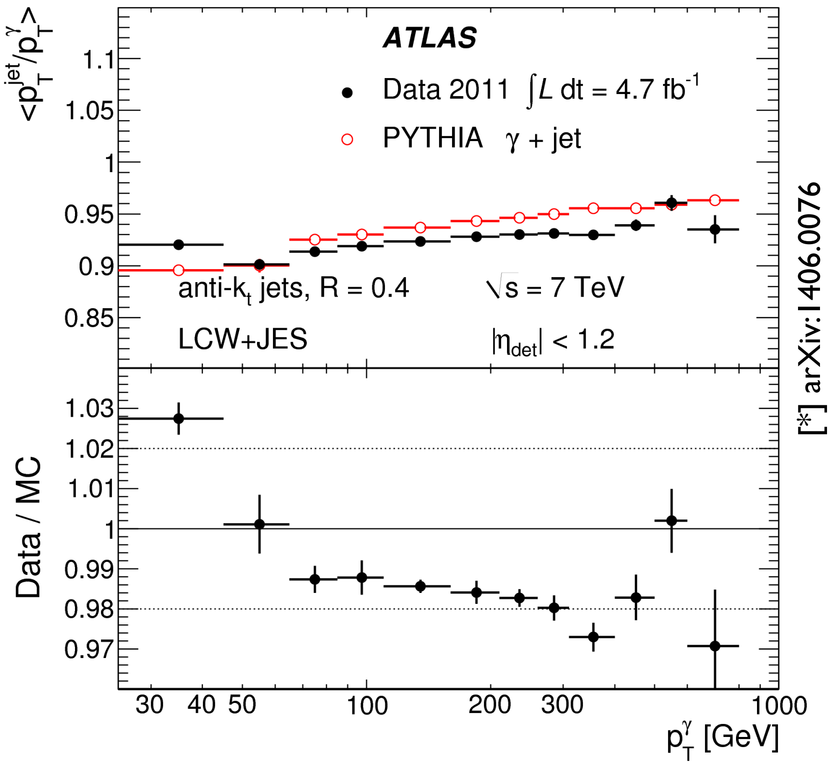


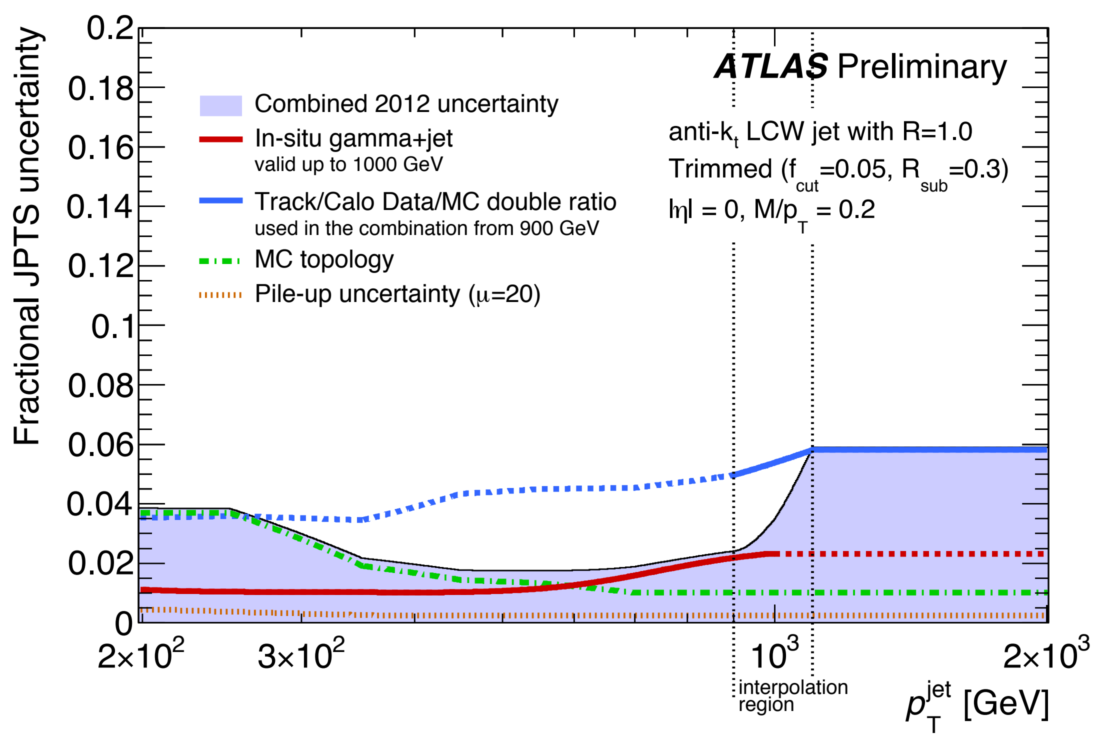
Same technique



- Calibrated energy doesn't mean calibrated mass (same goes for systematics)
- Calibration improves resolution and teaches us many things about detector response
- Generic mass calibration trickier at low masses, easier for EW jets

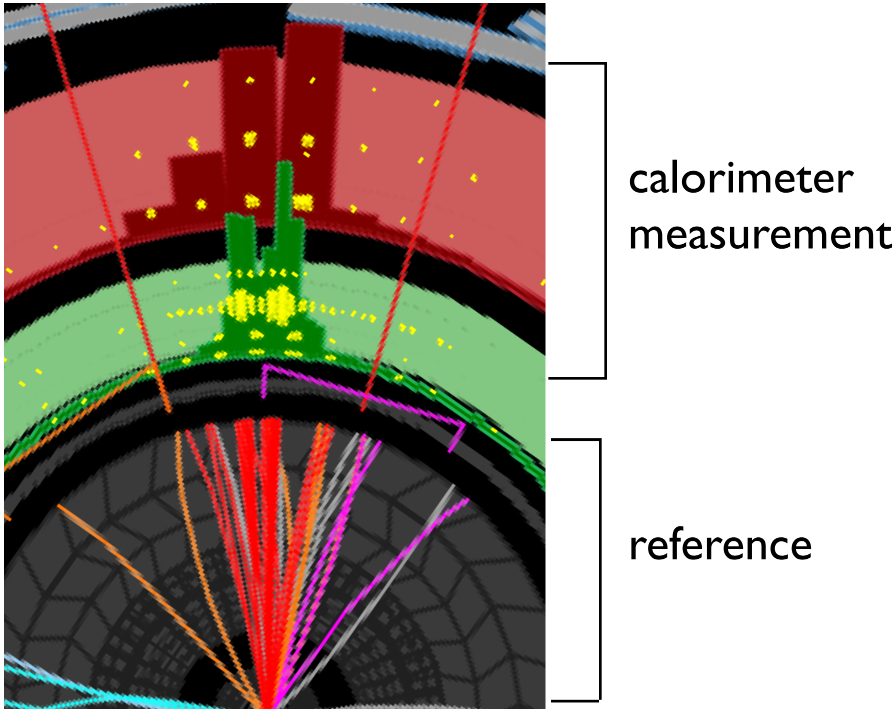
In-situ Energy Scale Systematics

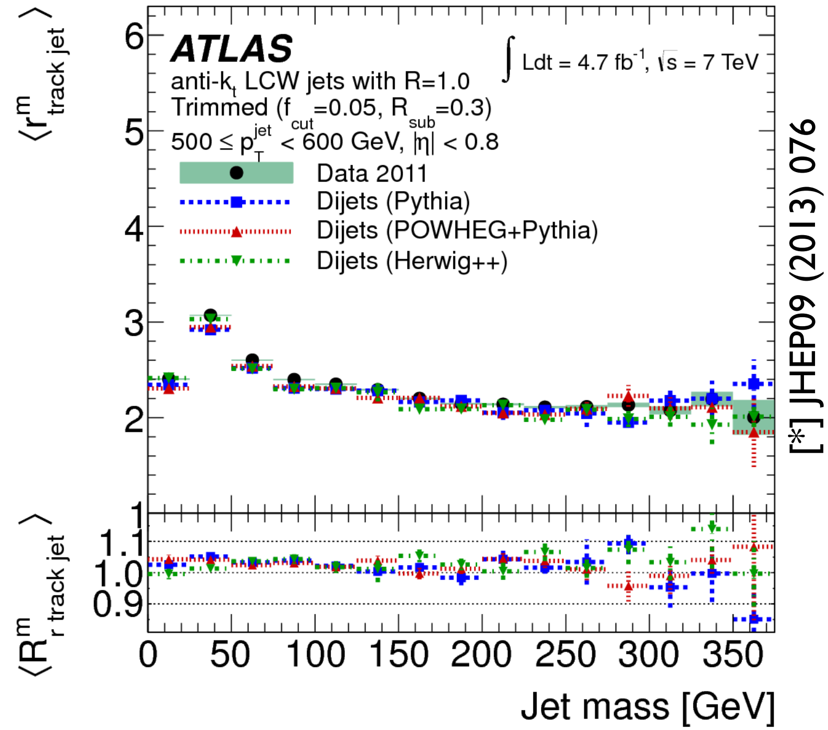




- To set uncertainties on p_T measurement, we need a reference object affected by independent effects (and preferably "well measured")
- Photons, Z-bosons, etc… are such objects in events where they balance jets
- You test in one sample, but apply to others with different topologies (quark/gluon, EW, top jets…), so some additional systematics needed

Systematic Uncertainties Using Tracking



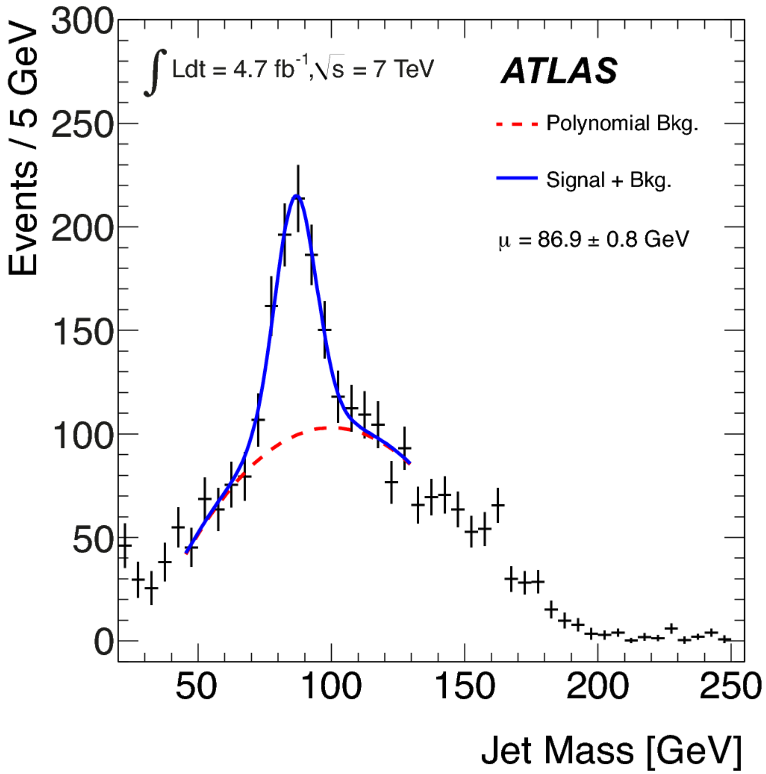


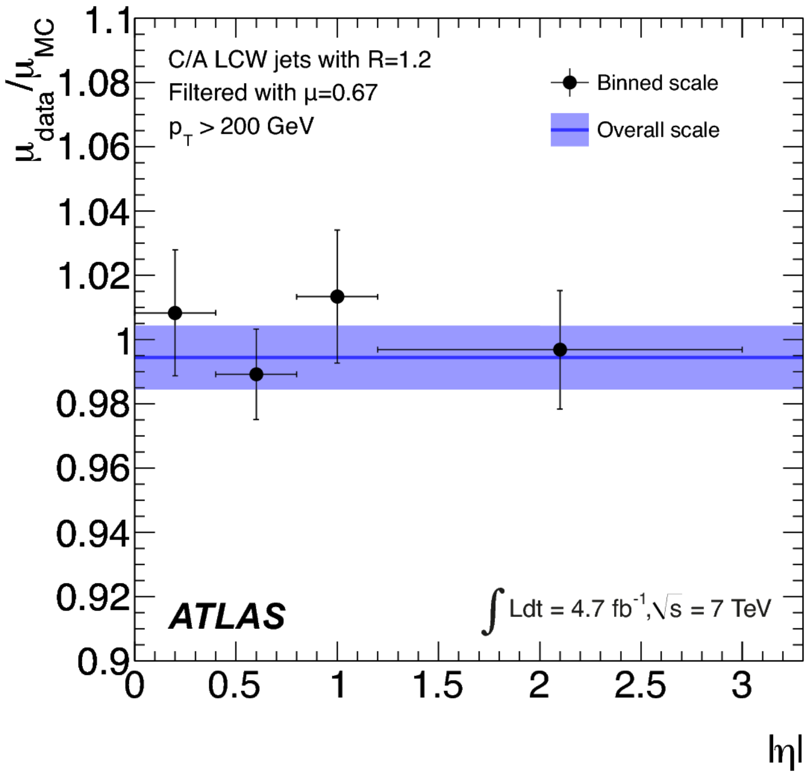
- Reference measurement is very precise, but of a quite different quantity than that of interest (large fragmentation systematics)

- Much more generic (do not exploit balance, can be applied to different topologies/ variables)

- Used in ATLAS for mass scale, splitting scales and N-subjetiness uncertainties

Other Techniques



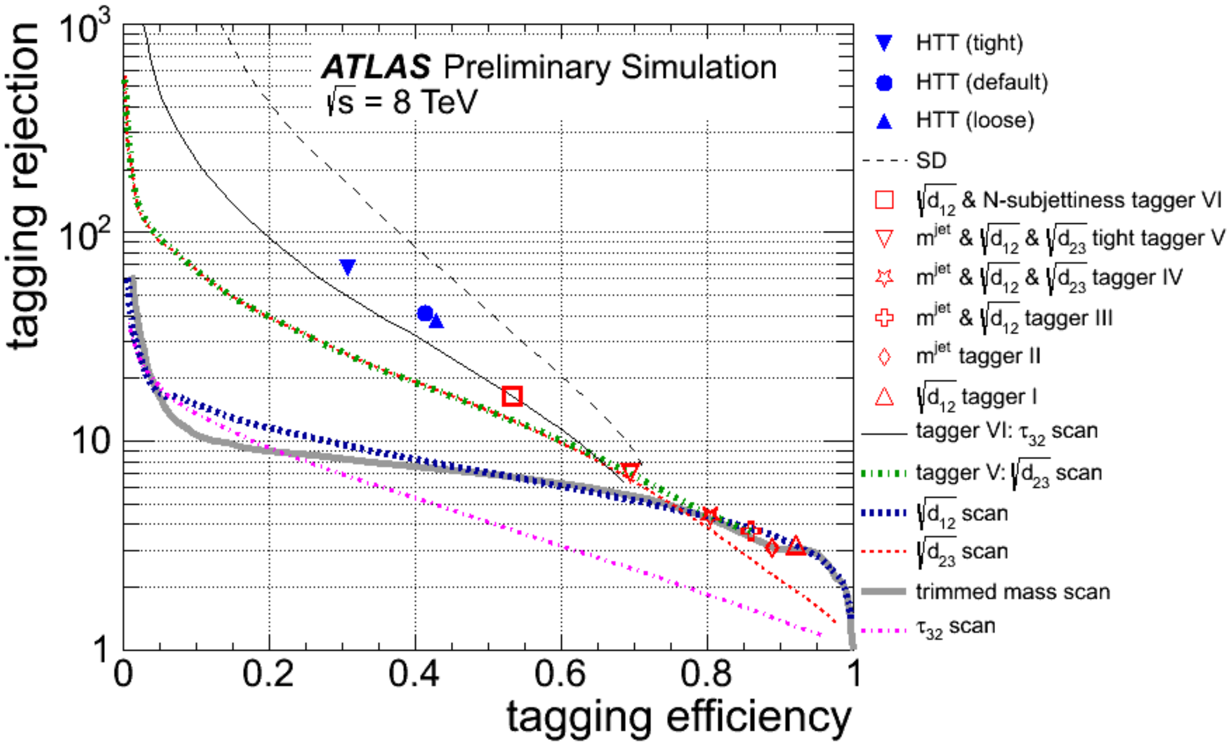


[*] JHEP09 (2013) 076

- Ws from tops can be used as a known-mass reference for EW jets
- Also for calibrating taggers in specific kinematic phase space
- Extrapolation to other regions of phase space requires understanding of tagging variables and use of MC simulation

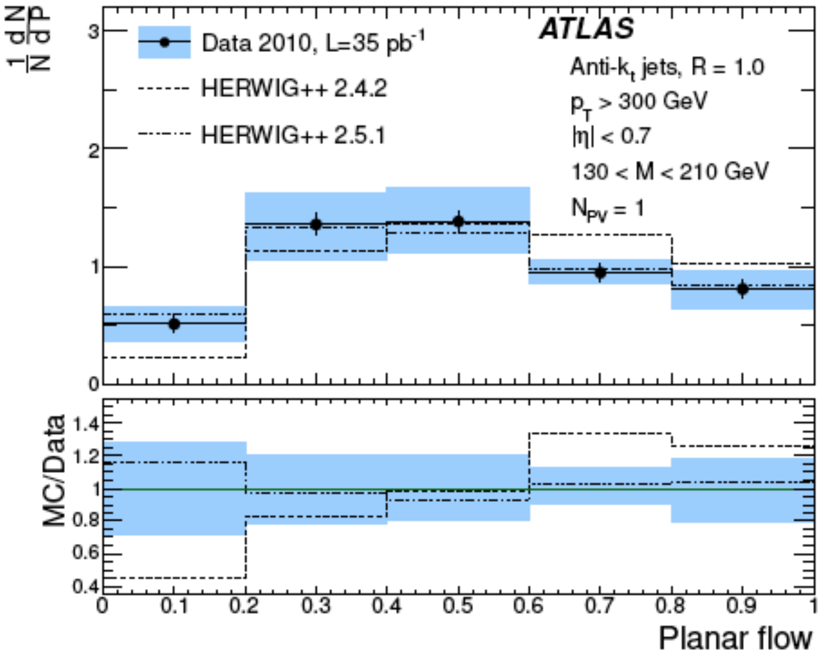
Substructure Variables in Tagging

- Variables can be directly used as taggers
- Systematic uncertainties on variables allows setting uncertainties on taggers
- Good understanding of correlations across the variables needed

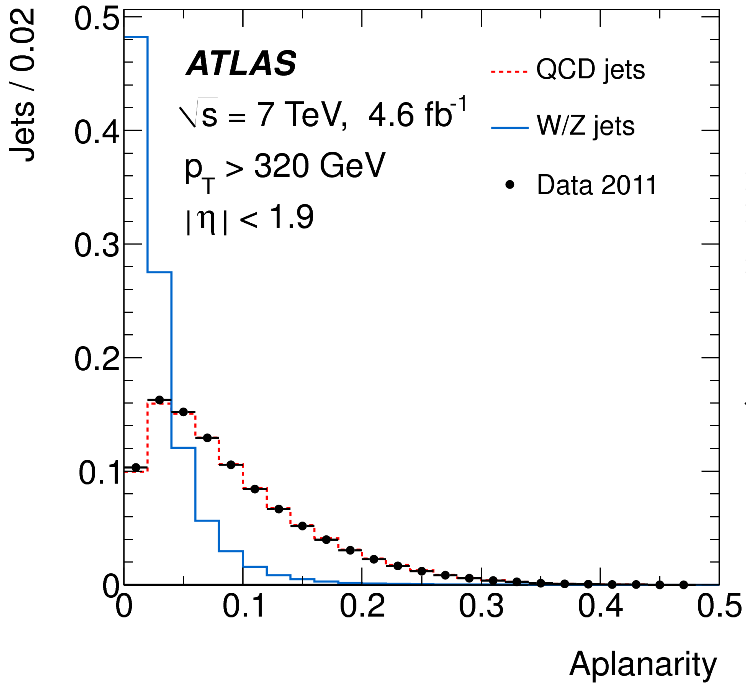


⇒Combination of r_{trk} techniques and direct efficiency measurements likely necessary for full systematics and correlations in more sophisticated taggers

Substructure Variables in Measurements



[*] Phys. Rev. D 86 (2012) 072006



[*] arXiv:1407.0800

- Few measurements on substructure variables, but helpful in tuning QCD showers

- Variables also used as part of measurements (e.g. to build custom discriminators for boosted cross section measurements)

⇒Detector-level plots come with only experimental uncertainties, but often enough for 10-20% idea of description/usefulness of the variable

Conclusions

- ATLAS jet substructure is studied mostly through calorimeter energy deposits

- Detailed studies of our understanding of hadronic showers creating those deposits exist, but hard to extrapolate to the environment relevant for boosted objects

- Other objects (Z, photons, W, tracks…) are used as references to understand behavior of the calorimeter; tracking has a lot of versatility, but hadronic Ws may allow for smaller systematics

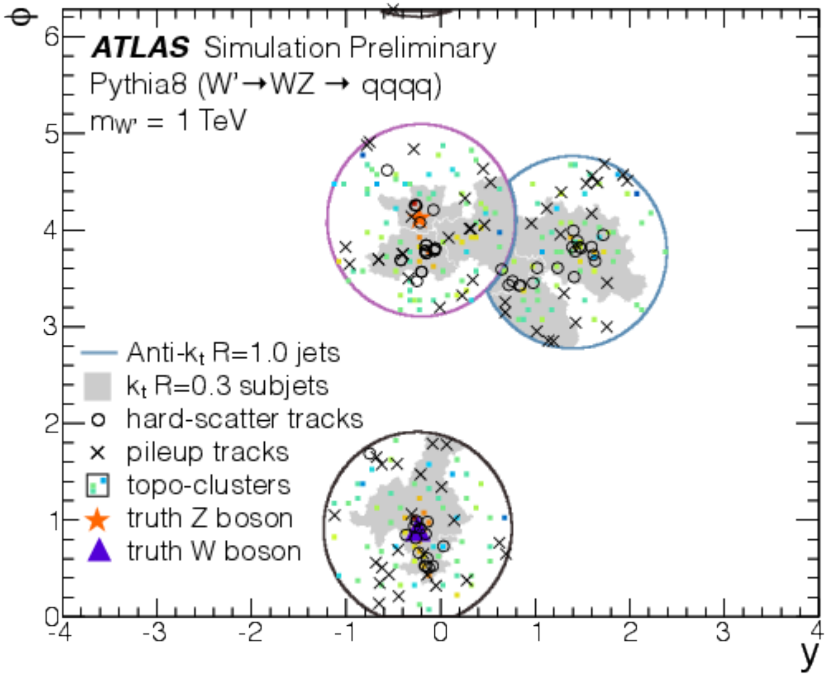
- Grooming is a necessary step for background rejection and reduction of pile-up sensitivity: optimizations using 2011 conditions exist and they are being redone for Run 2

- ATLAS has explored many substructure variables, as taggers directly, or for measurements

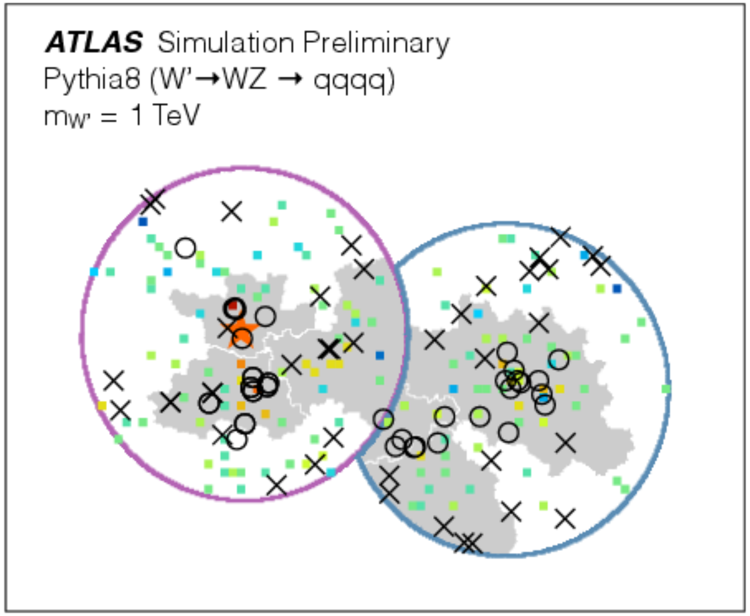
- Techniques for setting uncertainties on discriminators with the highest performance are still evolving; fully unfolded measurements only will happen with strong motivation from theoretical community

BACK-UP SLIDES

Substructure Techniques: Using Tracking



[*] ATLAS-CONF-2014-018



- Tracking can be used to help make decisions about which subjets to keep in the trimming process
- Mostly useful at very high luminosity (see Ariel's talk)