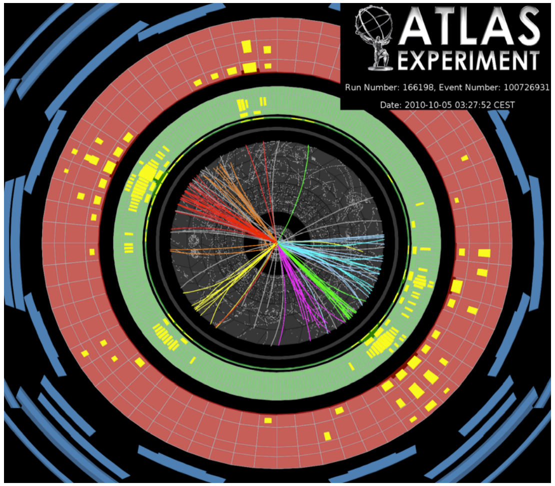
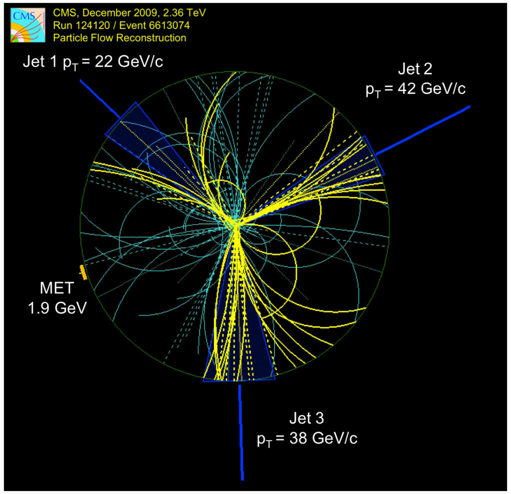
Experimental Aspects of Jets at the LHC





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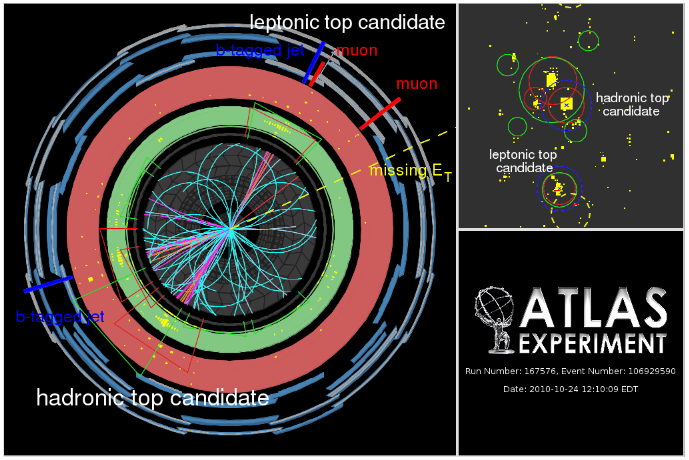
BOOST 2012, Valencia, Spain
23-Jul-2012

Outline

- **Jet reconstruction and calibration at ATLAS and CMS**
  - Detectors
  - Challenges
  - Calibration techniques
  - Performance and issues
- **Jet energy scale**
  - Strategy and methods
  - Uncertainty determination
- **Pile-up**
  - Challenges
  - Pile-up corrections, issues, and performance
  - Advanced methods and issues at very high luminosity
- **Jet substructure**
  - Mass scale and uncertainty
  - Use of tracks
- **What we learned**

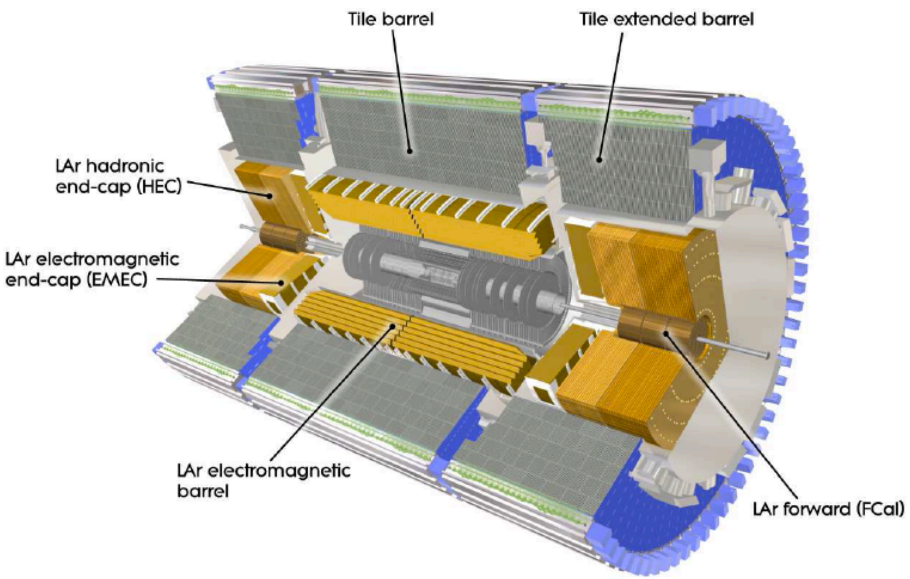
Jets at the LHC

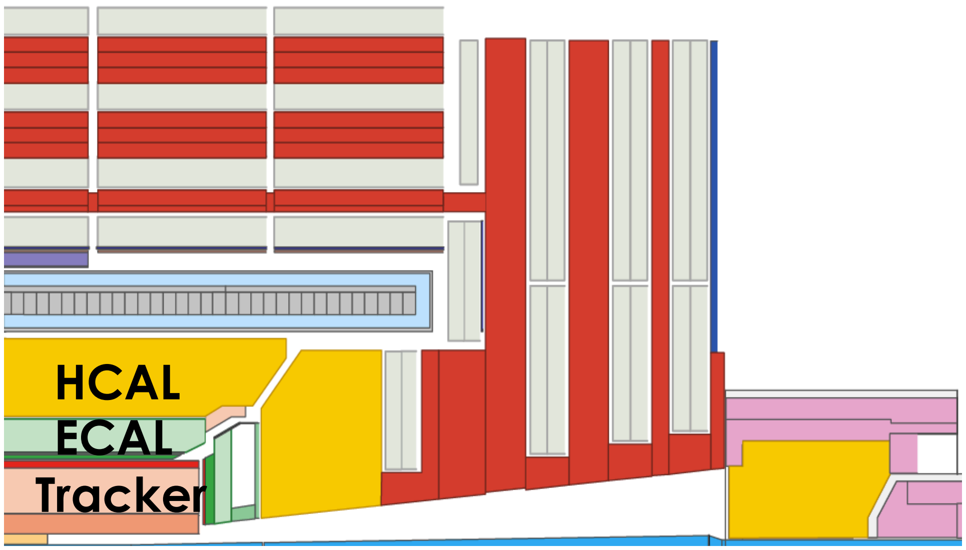


- **Jets are key elements in a very broad range physics signatures at the LHC**
  - Almost all physics analyses at the LHC utilize jets
- **A new energy regime and new tools for the analysis of hadronic final states from the theory community:**
  - New Jet algorithms (anti-k_t, large-R jets)
  - Jet substructure and jet-by-jet tagging techniques
  - Unprecedented high luminosity environment
    - New techniques for pile-up subtraction and suppression
- **Excellent detectors capabilities**
  - Calorimeter granularity and tracking
    - Enable sophisticated clustering algorithms and calibration
    - Combine information from sub-detectors (tracker + calorimeter + muon)
  - Excellent detector simulation
    - Development of complex calibration schemes based on Monte Carlo
  - Large statistics calibration samples (Z/γ + jets)
- **Strong connection between theory and experiment:**
  - early adoption of new ideas:
    - FastJet, anti-k_t algorithm adopted before data-taking

LHC Detectors

ATLAS and CMS (I)





Tracking detector within 2T magnetic field

Excellent hadronic calorimeter resolution

Fine longitudinal segmentation

- 3 to 7 layers

Long integration time:

- ~20 bunch crossings

Tracking and calorimeters inside **strong 3.8 T superconducting magnet**

- Reduced inactive material in front of calorimeters
- **Greater separation between particle showers**
- Low p_T charged particles not reaching calorimeter and increased out-of-cone

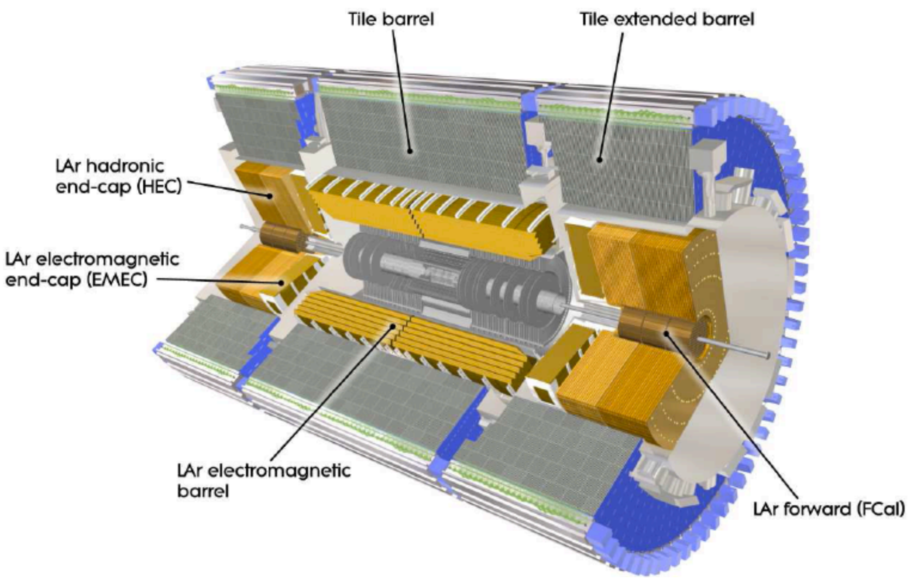
High transverse granularity and high resolution crystal ECAL

Fast integration time (~2 bunch crossings)

- no out-of-time pile-up

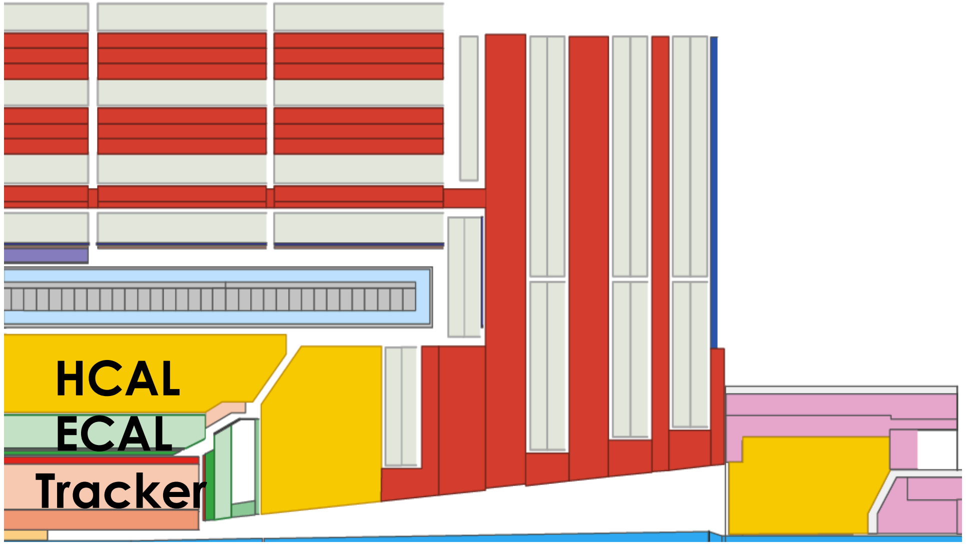
No longitudinal segmentation in ECAL/HCAL

ATLAS and CMS (II)



- Calorimeter transverse granularity($\eta \times \phi$):
  - EM: (0.025 x 0.025)
  - HAD: (0.1x0.1) – (0.2x0.2)
- Resolution (stochastic term)
  - EM ~ 10%/√E
  - HAD ~ 60%/√E

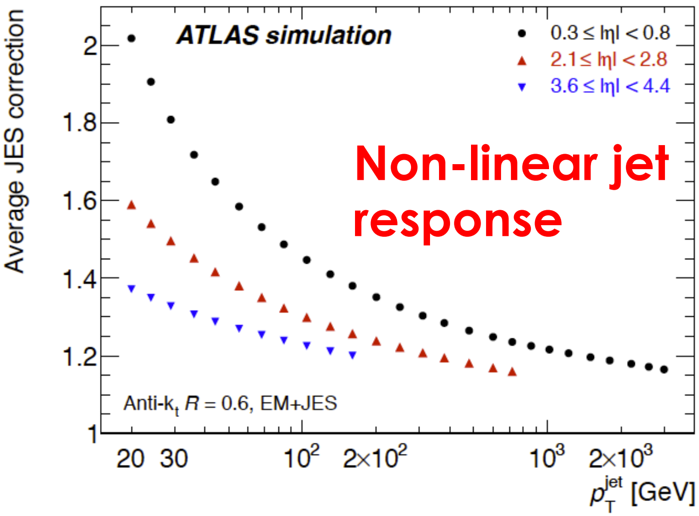
e/h>1

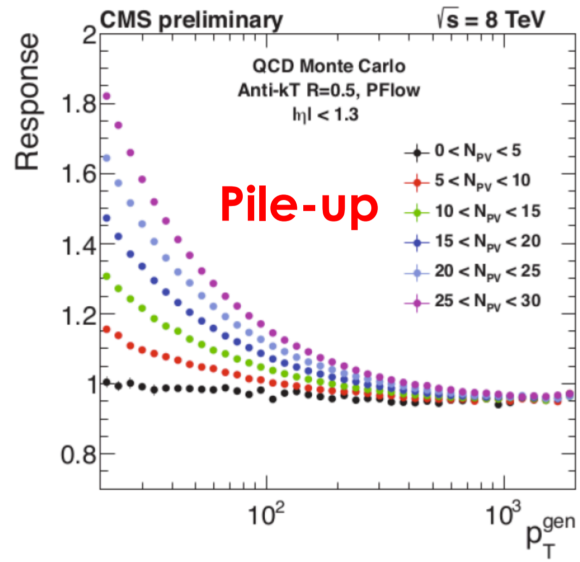


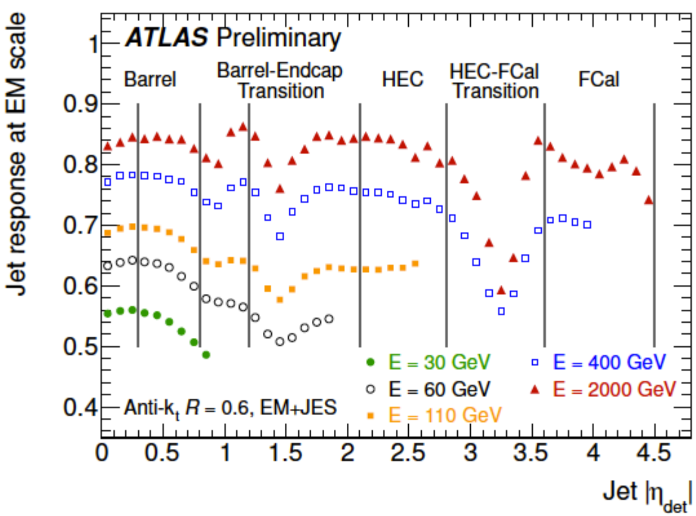
- Calorimeter transverse granularity($\eta \times \phi$):
  - ECAL: (0.0174 x 0.0174)
  - HCAL: (0.087x0.087) --5 times coarser
- Resolution (stochastic term)
  - ECAL ~ 3%/√E
  - HCAL ~ 120%/√E

e/h>1

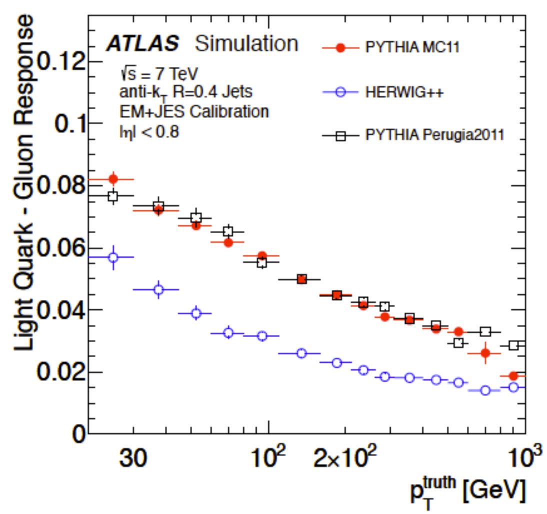
Challenges for jet reconstruction







Eta-dependent response



Flavor dependence

- **Non-compensating calorimeters (e/h>1):**
  - Non-linear response
  - Flavor dependence
  - Energy resolution
- **Pile-up:**
  - Luminosity-dependent jet performance
  - Increased fluctuations (noise term of the jet energy resolution)
- **ATLAS/CMS:** different approaches exploiting different detector capabilities
  - **Distinguish EM/HAD depositions**

Jet reconstruction at CMS

CMS Jet Types

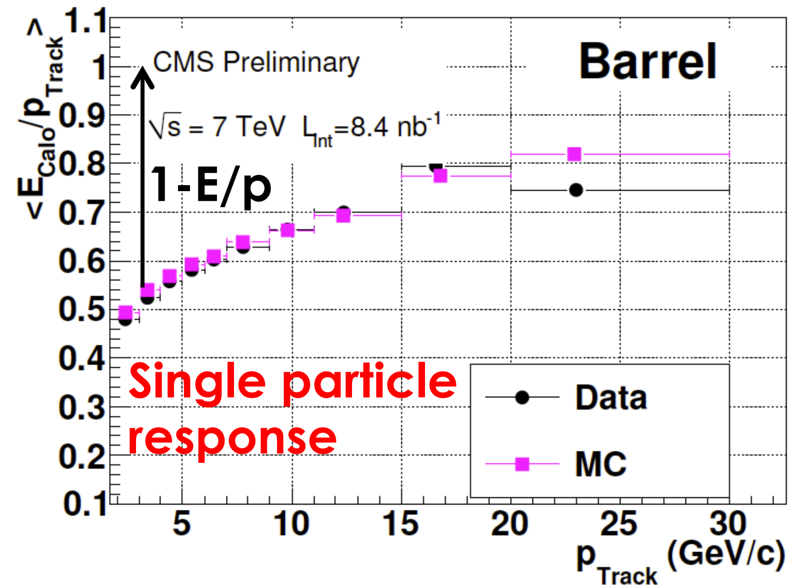
Exploit high resolution and <u>transverse</u> granularity of ECAL, tracking, and high B

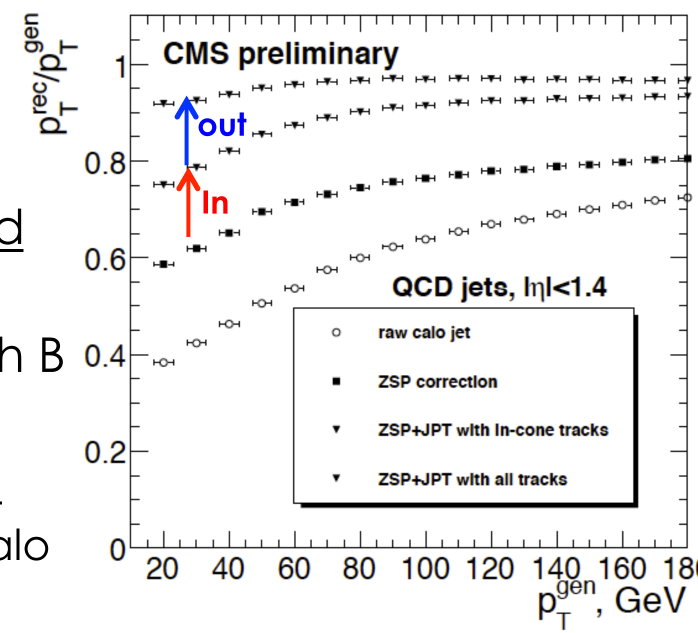
- **Calorimeter jets:**
  - Projective towers of 5x5 ECAL cells and 1 HCAL cell
  - No EM/HAD weighting
  - Simple p_T-Eta dependent jet energy scale correction:
    - Large correction (Jet energy scale (JES) uncertainties)
    - Does not improve energy resolution
    - Poor angular resolution (does not utilize fine ECAL segmentation)
- **Jet Plus Track (JPT)**
  - Improve calorimeter jets by accounting for the effect of e/h from charged particle tracks jet-by-jet (no track-cluster matching required)
    - Advanced JES correction using track p and single particle response (E/p)
    - Account for out-of-cone tracks *jet-by-jet*
- **Particle Flow (PF):**
  - Attempt to reconstruct individual *particles* fully exploiting calorimeter granularity and tracking (Global event reconstruction)
  - Relies on ECAL and tracking to measure ~90% of the jet energy precisely
  - Effective at low/medium jet p_T, where track resolution is better than calorimeter

Jet Plus Track

- **Start with calorimeter jets**
- Correct for the non-linear and low calorimeter response of pions, jet-by-jet
- Correct for out-of-cone tracks

$$E_{JPT} = E_{CALO} + \sum_{in-cone} p_{trk} - \left\langle E_{trk}^{calo} \right\rangle + \sum_{out-of-cone} p_{trk} - \sum_{out>in} \left\langle E_{trk}^{calo} \right\rangle$$

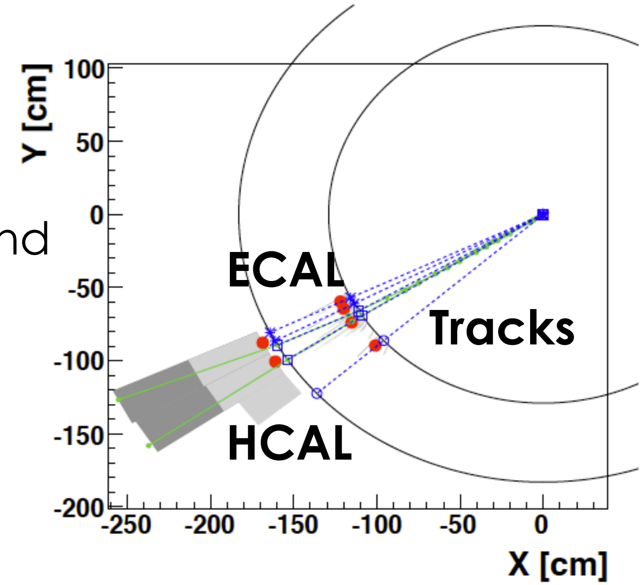




- **No cluster-track matching required**
- Reduces fluctuations (significant jet energy and angular resolution improvement)
- Significant out-of-cone contribution due to high B
- **Works best in highly non-compensating calorimeters**: correction proportional to (1-E/p)
  - Not as effective in ATLAS (E/p~1 after cell and calo cluster weighting / lower magnetic field)

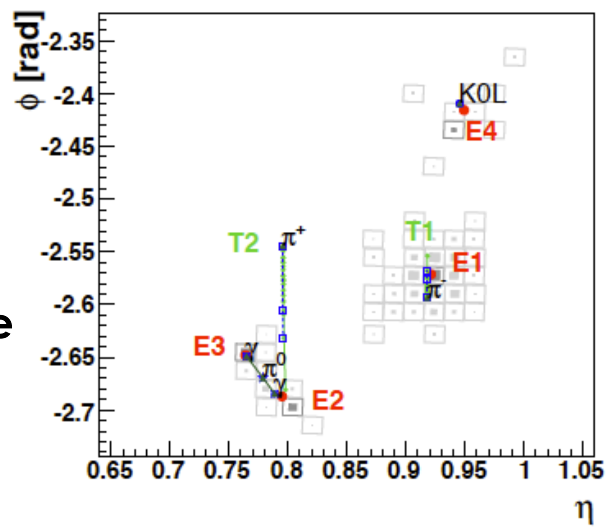
Particle Flow

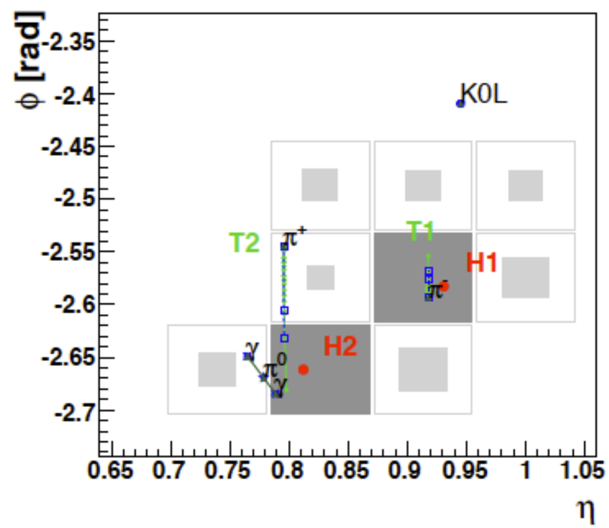
- **Reconstruct individually each particle combining tracking and calorimeter information:**
  - Relies on high granularity and resolution of ECAL and **high magnetic field** to separate individual showers
  - Connect "PF elements" and remove double counting



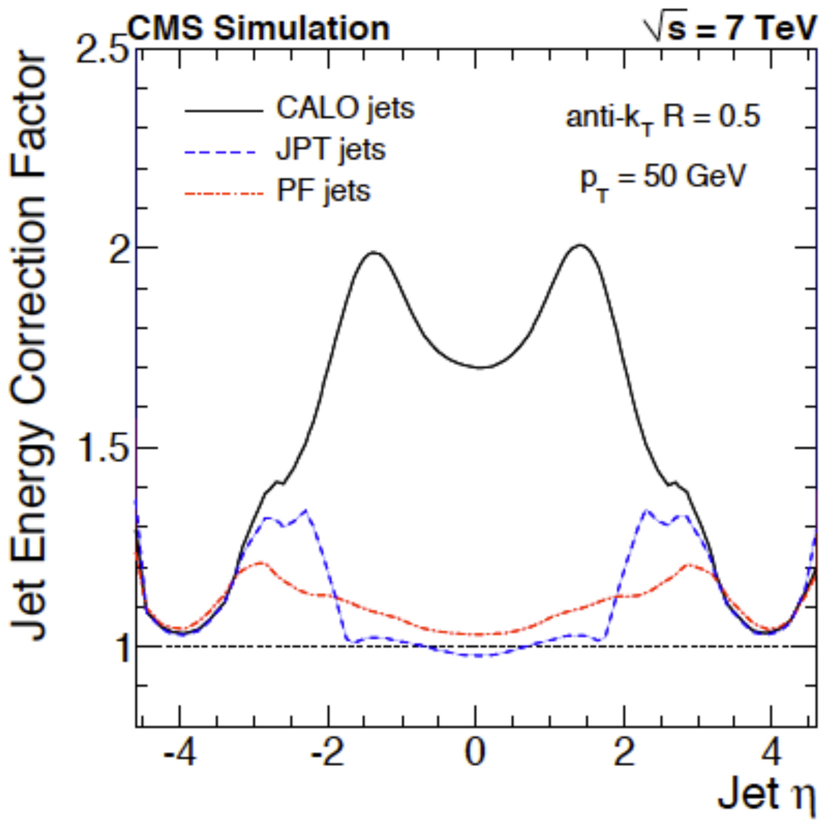
65% charged hadrons → Tracker
25% photons → ECAL
10% neutral hadrons → HCAL

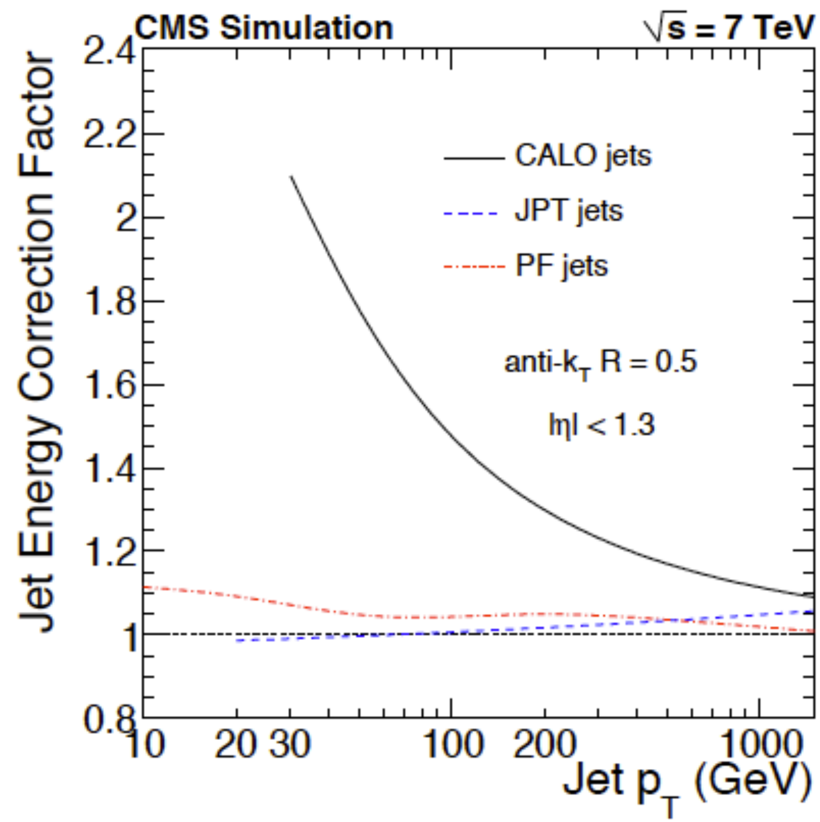
- Improved energy and angular resolution and uncertainties
- Individual "particles" used as input to jet finding:
  - **Ideal for jet substructure**
- Limited by "confusion" term (ability to separate overlapping showers)
- At high p_T limited by calorimeter resolution





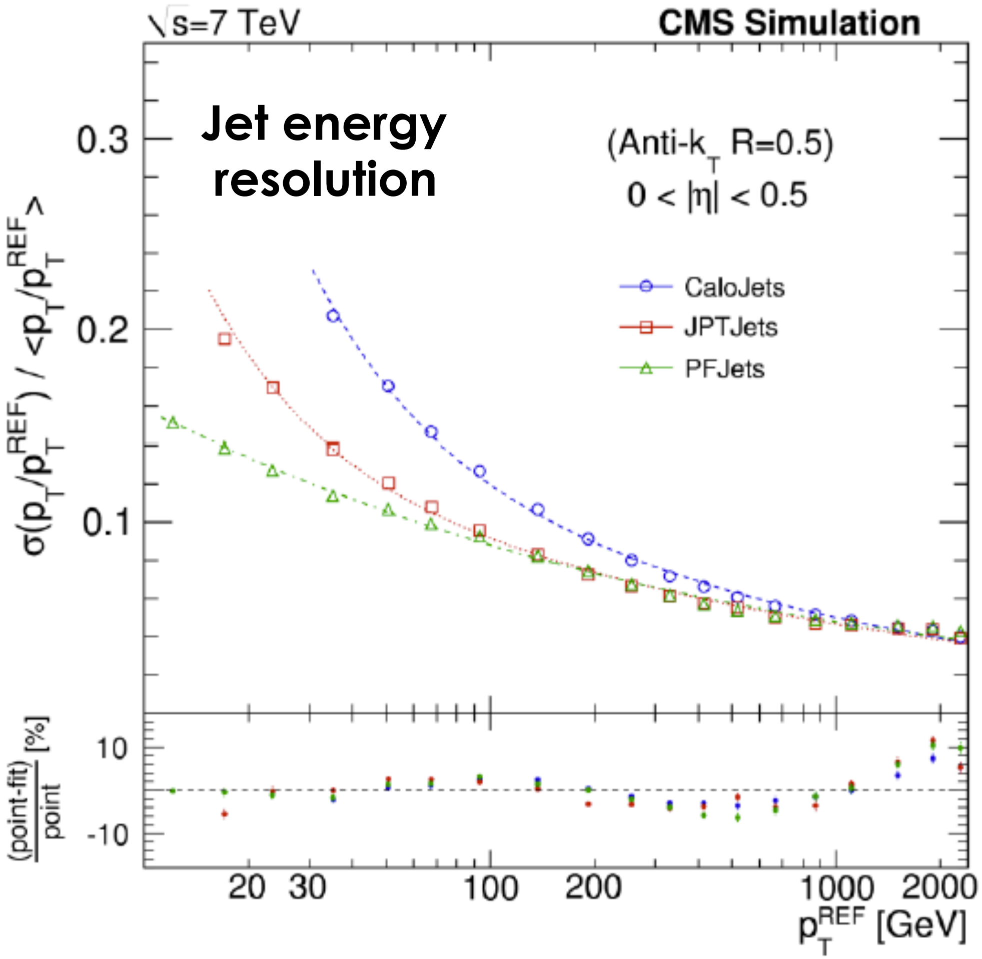
Performance of CMS jets (I)

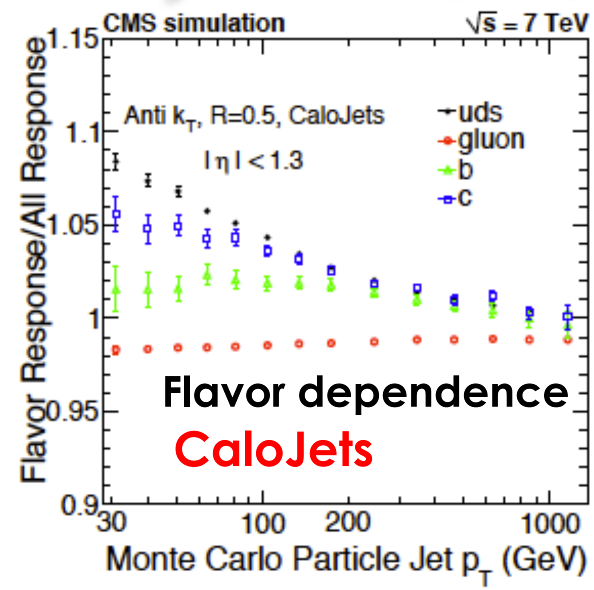


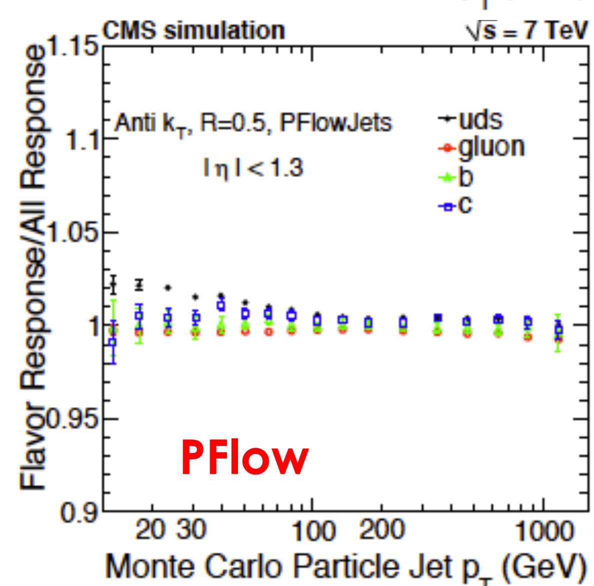


- Significant improvement in the linearity of the jet response
  - Small jet energy scale correction required after JPT/PFlow

Performance of CMS jets (II)







- Large performance improvement up to p_T~300GeV (**stochastic term**)
- JPT comparable to PFlow for p_T>60GeV
- PFlow very effective at very low p_T (<30GeV)

Jet reconstruction at ATLAS

Jet Schemes in ATLAS

Exploit high resolution HAD calorimeter and fine longitudinal segmentation

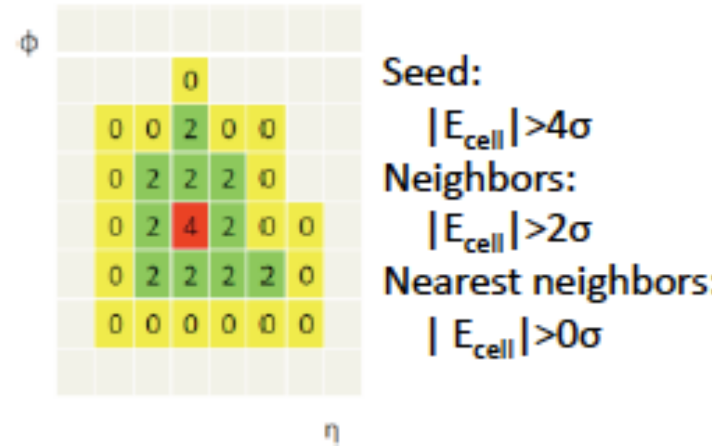
- 3-dimensional topological clustering
  - Optimized to follow shower development in calorimeter / noise suppression
  - Define inputs to jet finding
- EM (Electromagnetic-scale jets)
  - Add EM/HAD energy components of clusters
  - Large p_T-Eta dependent jet energy scale correction
- LCW (Local cluster weighting jets)
  - Cell/cluster weighting using local properties
  - Distinguish EM/HAD depositions
  - Small residual p_T-Eta dependent jet energy scale correction

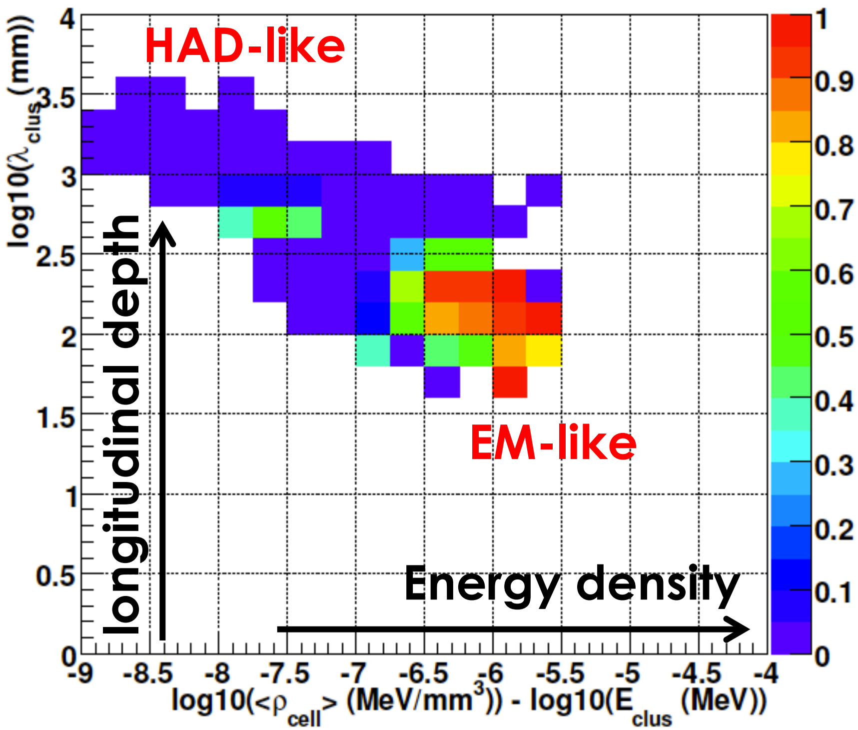
Calorimeter Jets

- **Tracks:**
  - **post-calibration jet-by-jet corrections:**
    - Reduce fluctuations using global information about jet fragmentation
  - **Validation tool:**
    - Set the jet energy scale, insitu, from calorimeter-independent track-jets

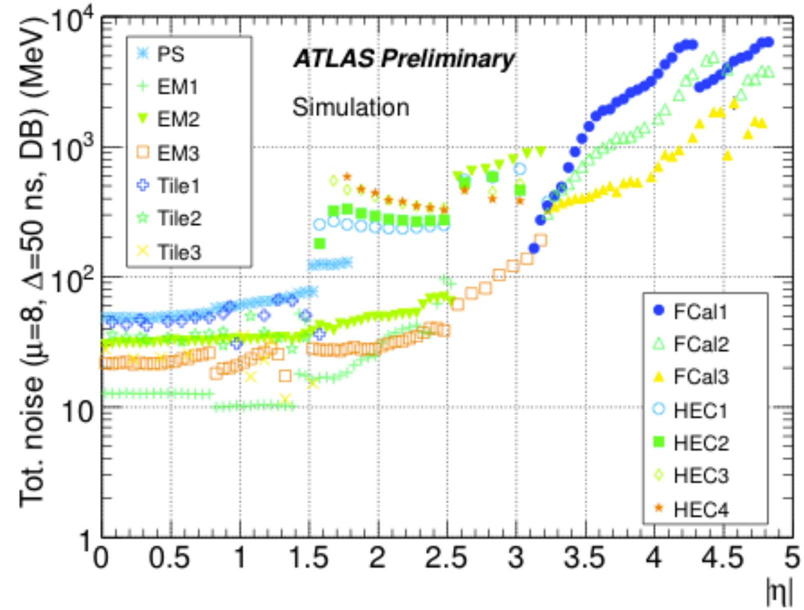
Topological clusters

- Follow shower development
- Pille-up + electronic noise suppression
- EM/HAD local calibration to correct for calorimeter non-compensation, energy losses in dead material, and out-of-cluster energy
    - Derived from single pion simulation

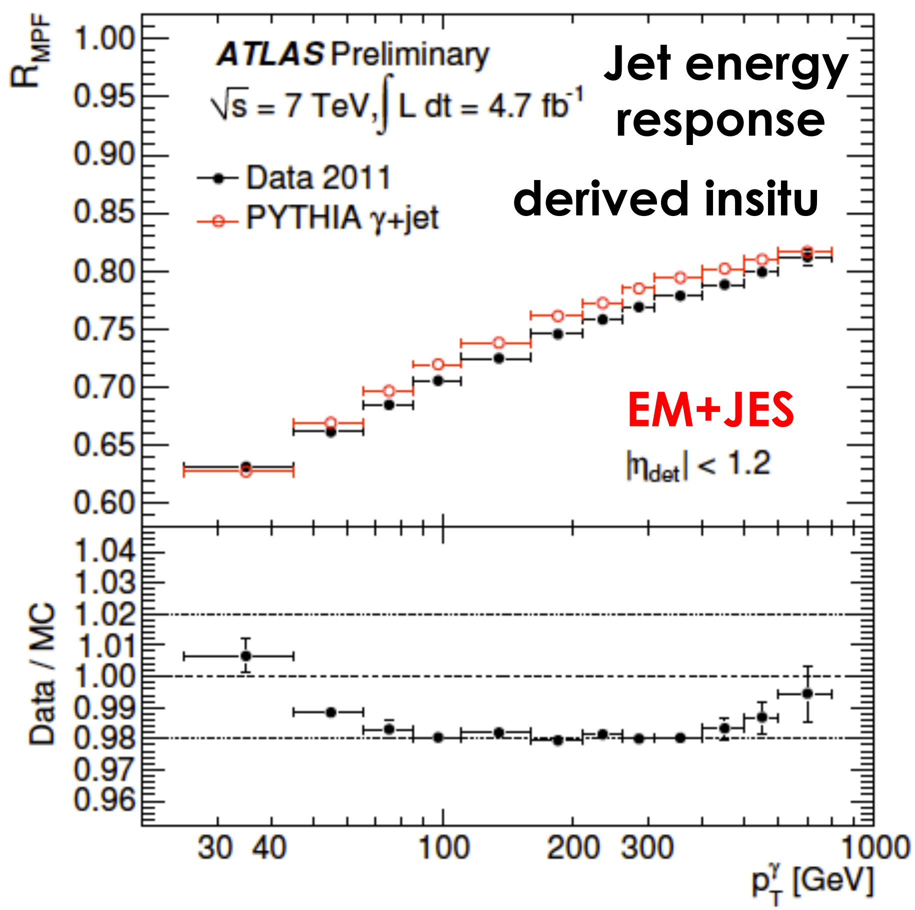


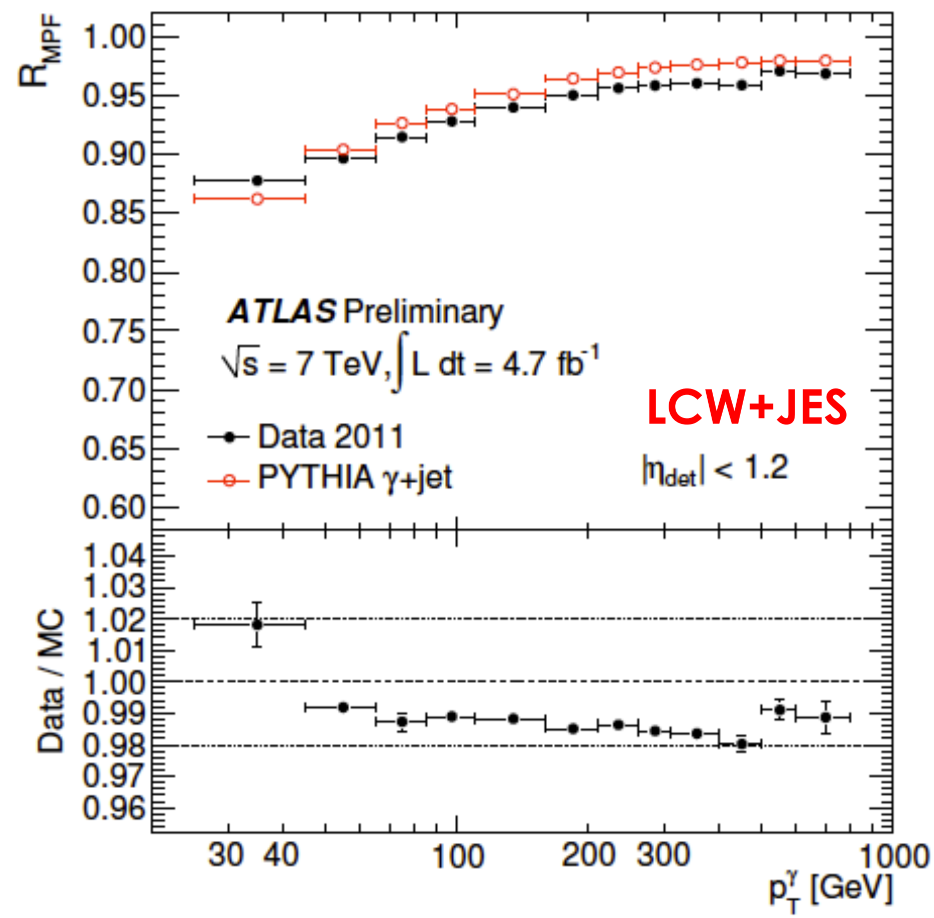


Cluster thresholds account for pile-up noise



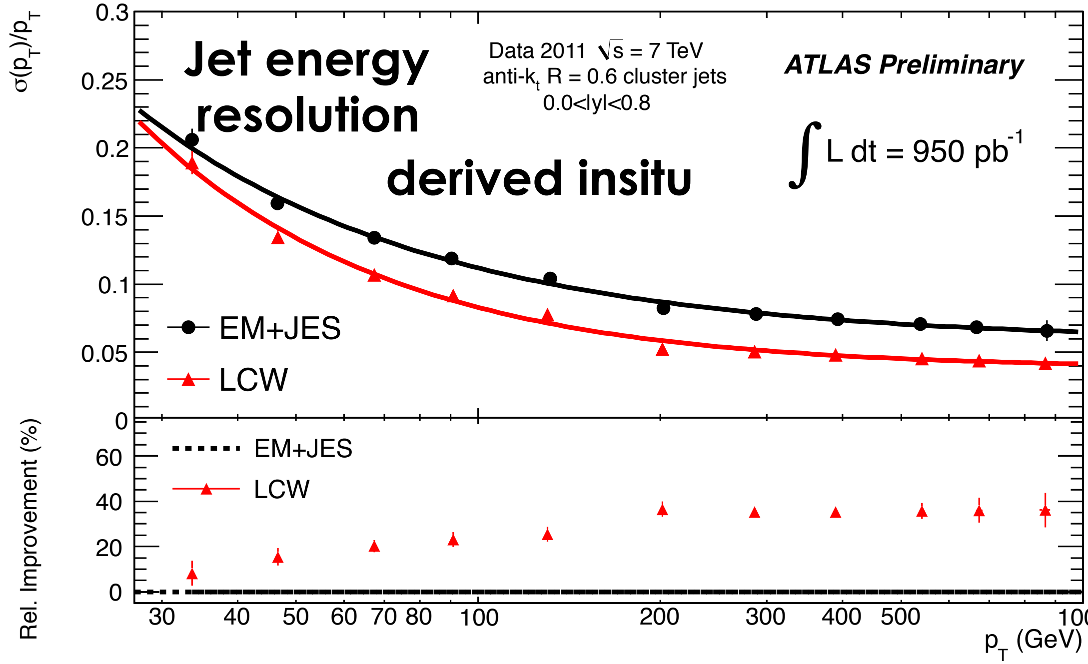
Calorimeter Jet Performance (I)

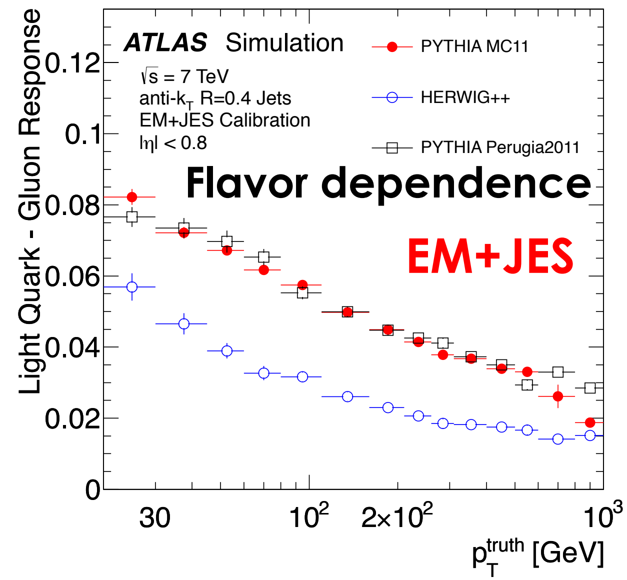


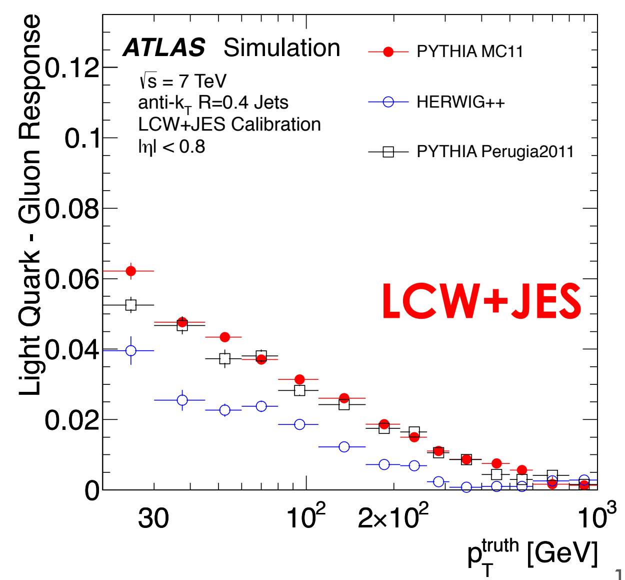


- Significantly improved linearity after local cluster weighting

Calorimeter Jet Performance (II)

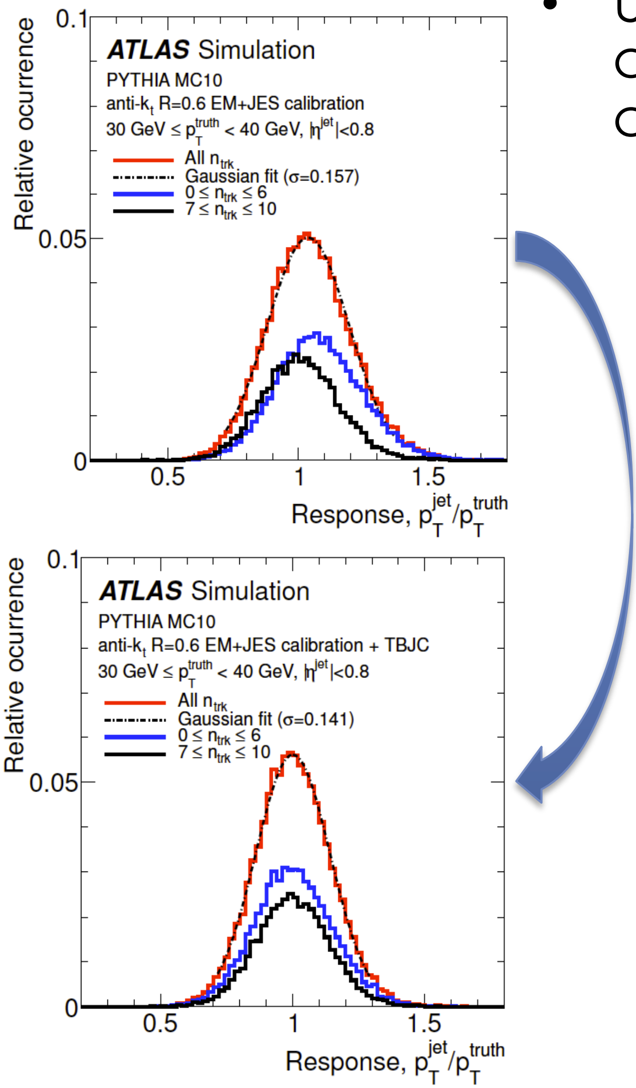




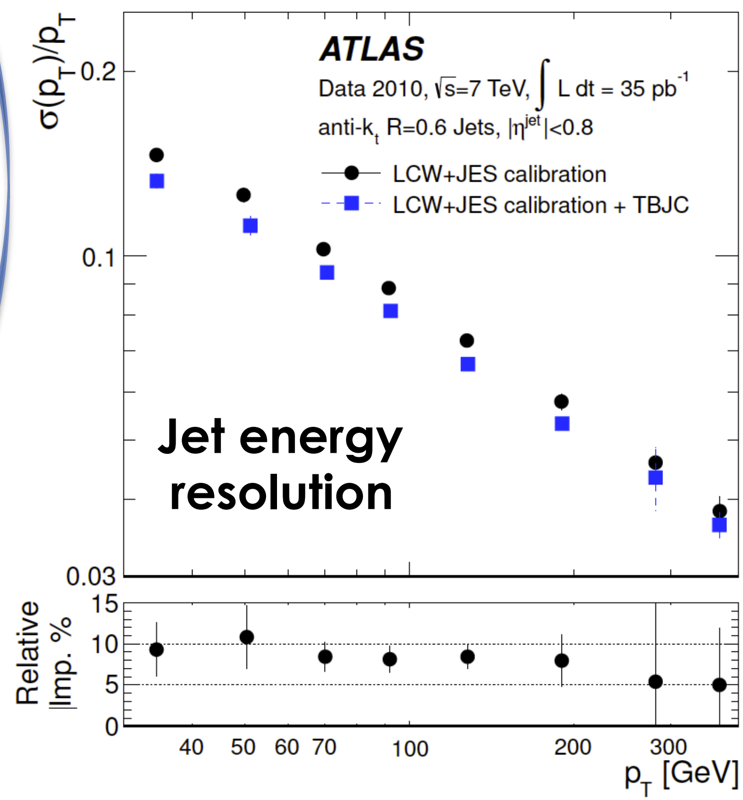


- Significantly improved energy resolution
    - **Stochastic <u>and constant</u>** term (35%)
- Reduced flavor dependence

Tracking input to jets



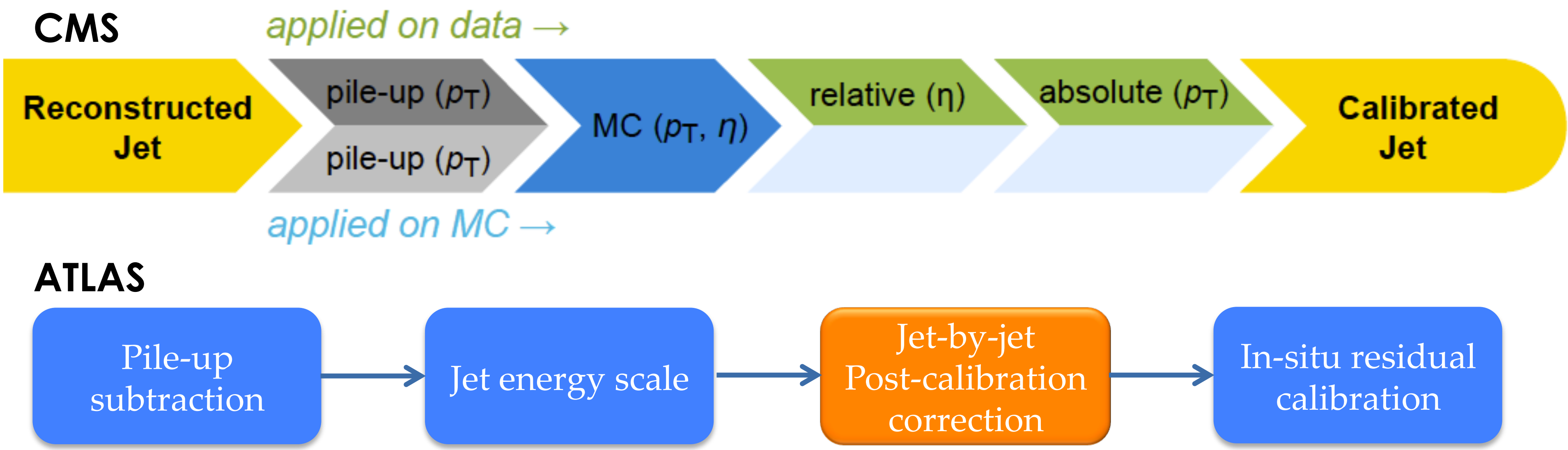
- Use <u>tracks and jet properties</u> to refine the jet calibration ***after*** the JES (post-calibration corrections)
  - Improved jet <u>energy **(stochastic term)** and angle resolution</u>
  - Reduced flavor dependence of the jet response



- Track multiplicity
- Track width
- No 1-to-1 track-cluster matching required

Jet Energy Scale

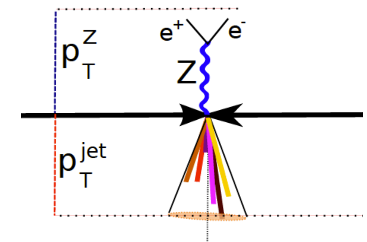
Jet energy scale strategy

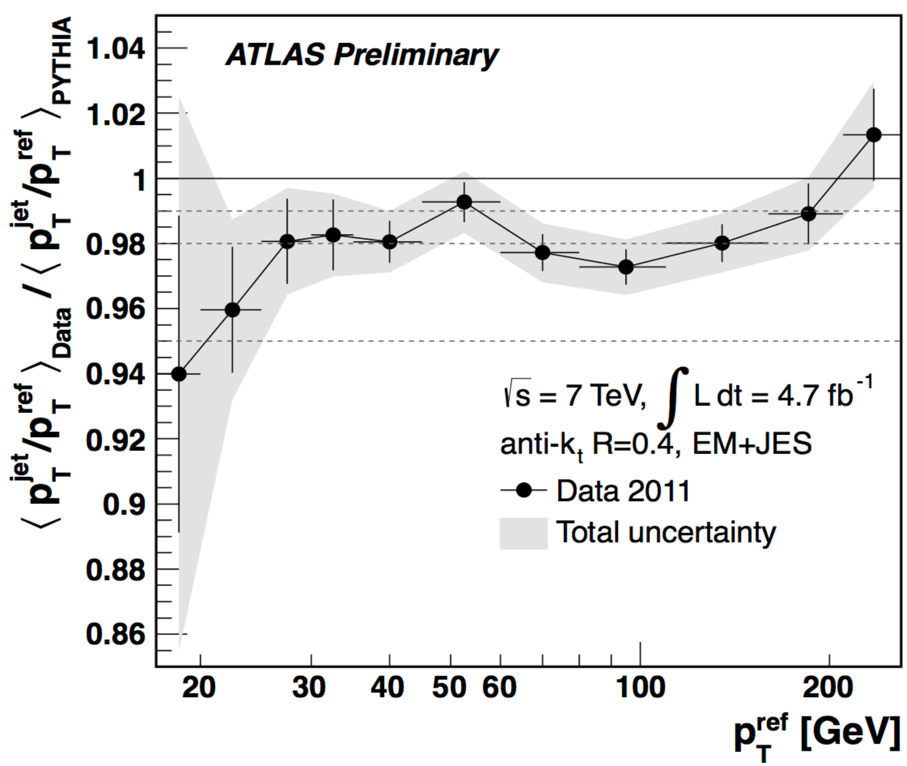


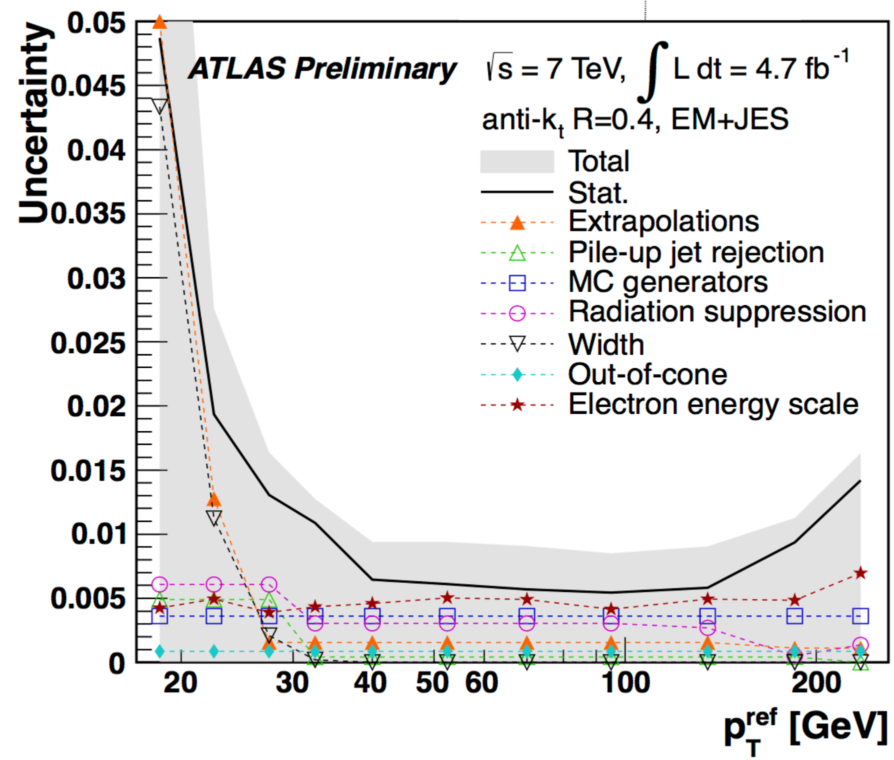
- **Correct reconstructed jet energy to particle level**
  - Pile-up, non-compensation, inactive material, shower leakage
  - Derived from simulation, jet algorithm dependent
  - Factorized approach
- **Residual insitu data/MC correction** (only applied to jets in data)
  - Allows significant reduction of jet energy scale systematic uncertainties
  - More sensitive to physics effects and modeling (radiation, backgrounds)

Insitu jet energy scale: Z+jets

- Use large 2011/2012 datasets to improve the precision of the jet energy scale and to adjust the jet calibration using insitu techniques
- Z+jet balance probes the jet response at low p_T (low background, and low p_T thresholds)
- **Total uncertainty 1% to 2% for jet p_T > 30 GeV**

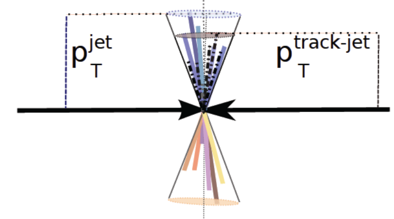




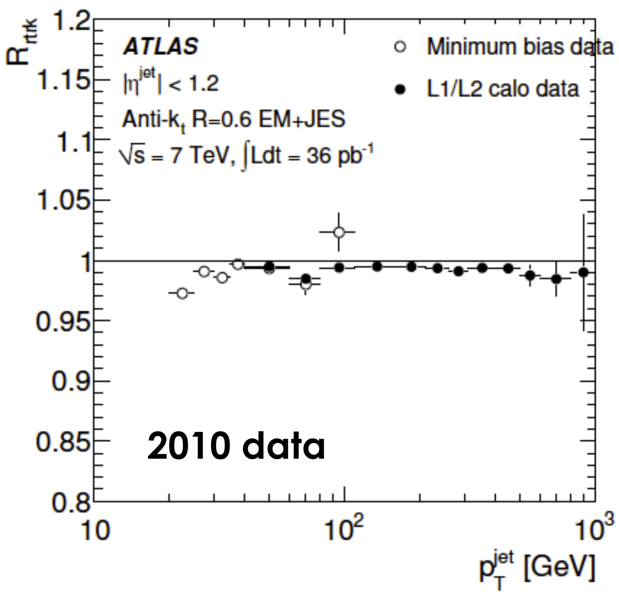


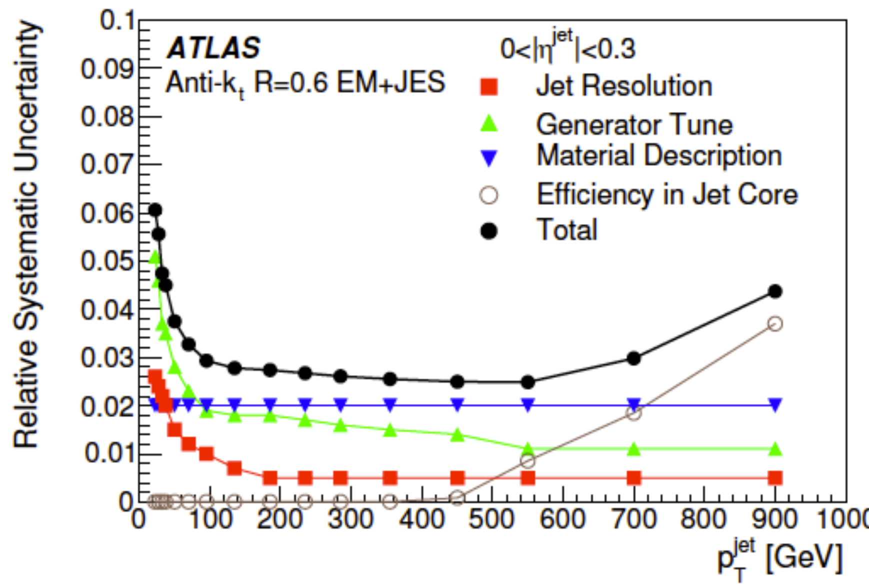
Jet energy scale from tracks

- **Probe the calorimeter jet energy scale using track-jets**
  - Independent of calorimeter jets: only possible for calorimeter-based jets (ATLAS)
  - Track and calorimeter jet uncertainties are uncorrelated
    - Separate detector from physics effects
  - Robust against pile-up (z-vertex information from tracker)



- **Can be used to calibrate jet mass and jet substructure observables**
  - Dominant uncertainties from knowledge of tracking efficiency inside jets, inner detector material description in the simulation, and variations from generator tunes



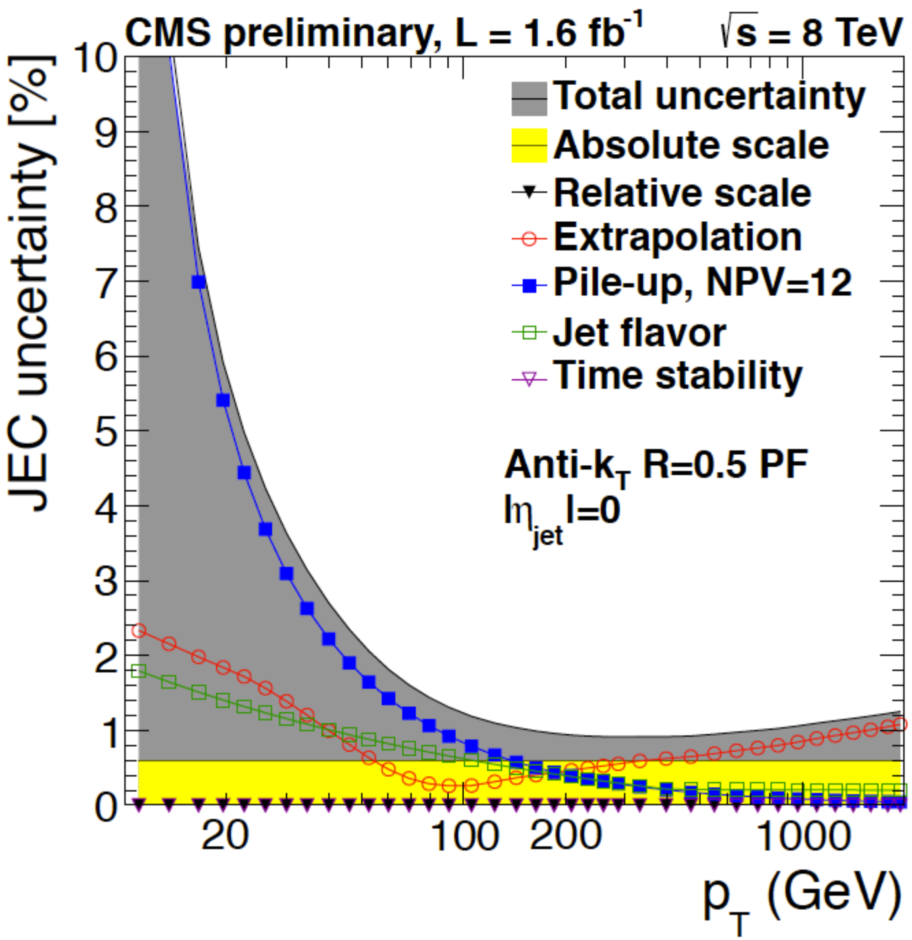


$$r_{track-jet}^{p_T} = \frac{p_T^{calo-jet}}{p_T^{track-jet}}$$

$$R^{p_T} = \frac{r_{track-jet}^{p_T,data}}{r_{track-jet}^{p_T,MC}}$$

Jet energy scale uncertainty

- Absolute response and eta-intercalibration derived insitu from Z/ γ +jet, and di-jet events (difference between data and simulation)
- Additional physics sample dependent uncertainties (jet flavor, pile-up, close-by jets)



High p_T jet calibration:

- Monte Carlo extrapolation from single particle response and fragmentation properties
- **Insitu multi-jet balance**

Large pile-up uncertainty at low p_T

Pile-up

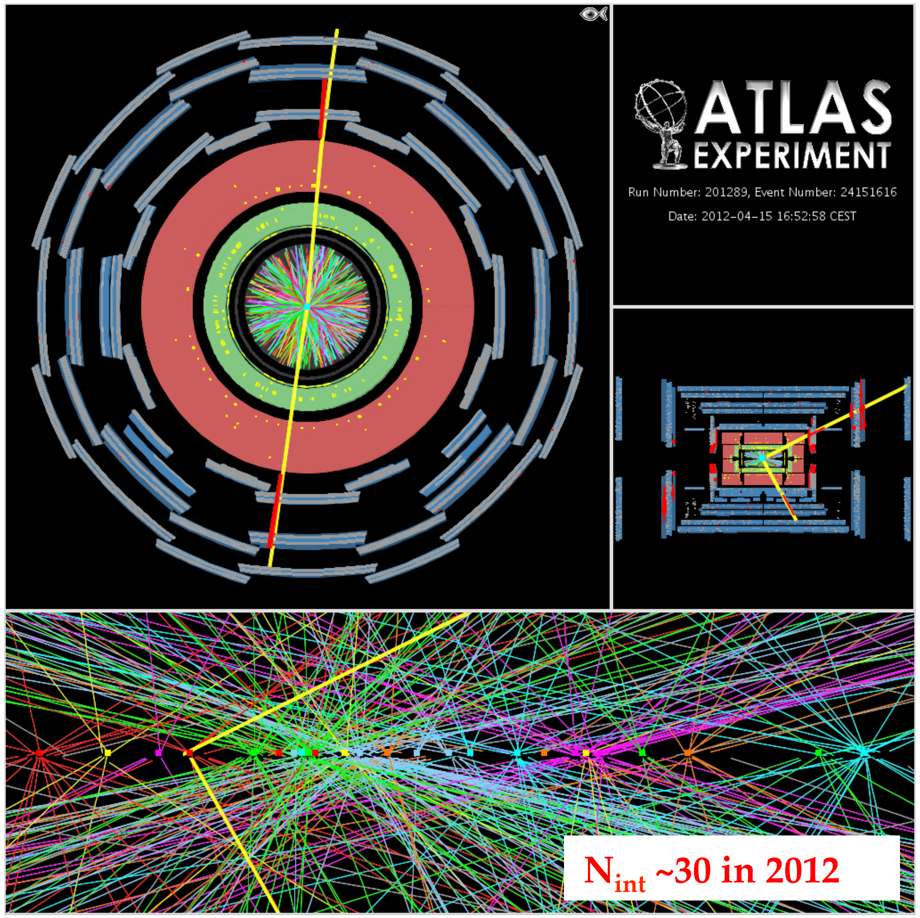
Pile-up

Pile-up is one of the main challenges for jets at the LHC:

- **Additional energy** (offset)
- **Pile-up fluctuations**:
  - o increase the noise term of the jet energy resolution (event-by-event global fluctuations)
  - o additional fake jets (local fluctuations)
- Large effect on jet mass and properties

Pile-up corrections are a key component of the jet calibration strategy at the LHC:

- Bring the jet response to N_{PV}=1 and make jet performance independent of varying pile-up conditions
- Reduce fluctuations (pile-up subtraction)
- Reject pile-up jets (pile-up suppression)

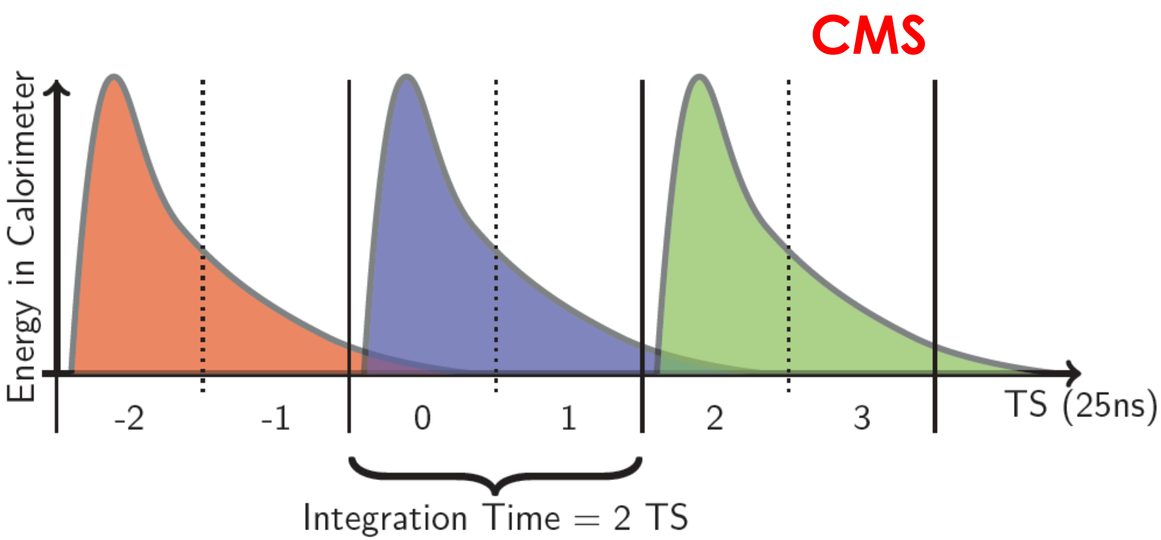


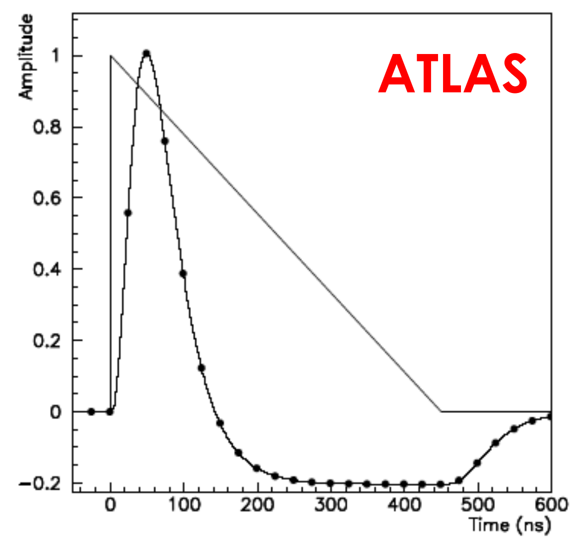
Expect much higher pile-up after the 2013 shutdown

See John Backus Mayes' talk

In-time and out-of-time pile-up

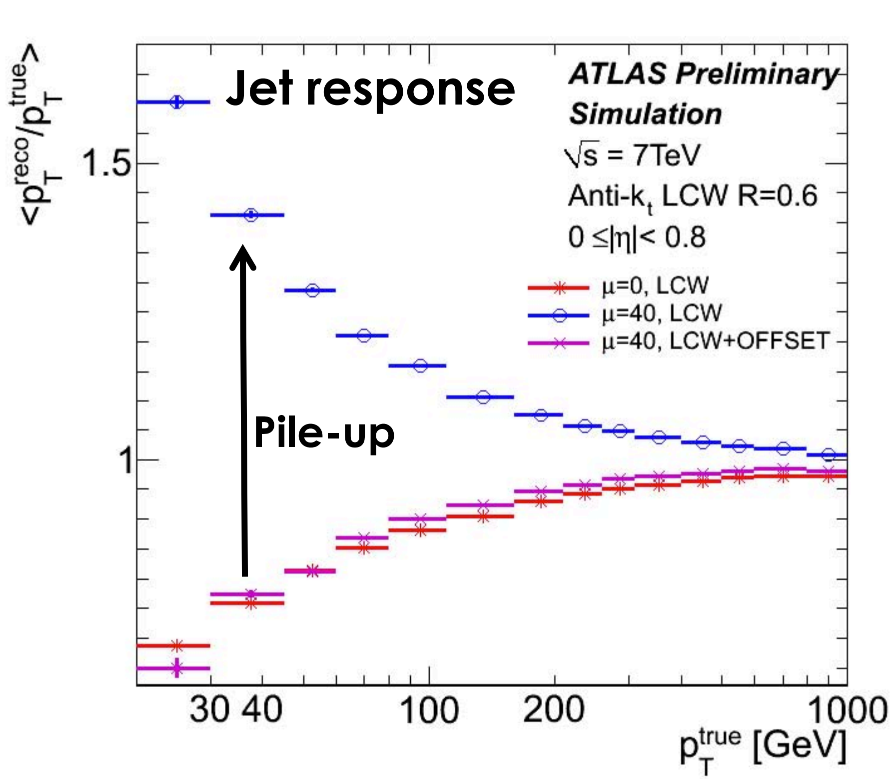
- ATLAS LAr calorimeter has a very large integration time relative to bunch spacing:
  - **Out-of-time** pile-up contributions
  - bi-polar shape compensates, on average, for out-of-time, but out-of-time effects vary significantly within sub-detectors (eta-dependence)
  - **ATLAS needs both in-time and out-of-time pile-up corrections**
- CMS is mostly insensitive to out-of-time pile-up:
  - 2 time-slices (TS) for integration

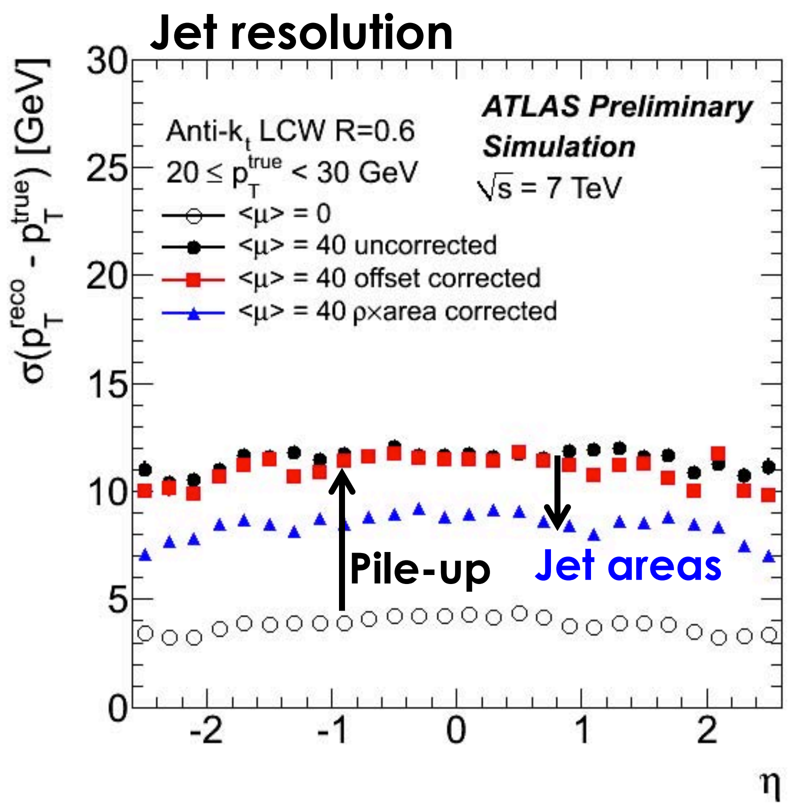




Average offset and jet-areas

- **Average offset:**
  - Determined from Monte Carlo and validated insitu (systematic uncertainties)
  - Accounts for in-time and out-of-time pile-up
  - No resolution improvement
- **Jet areas correction:**
  - Only accounts for in-time pile-up (needs additional out-of-time pile-up residual correction)
  - Reduces fluctuations by ~30%
  - Challenging in the forward region due to coarser granularity + noise suppression

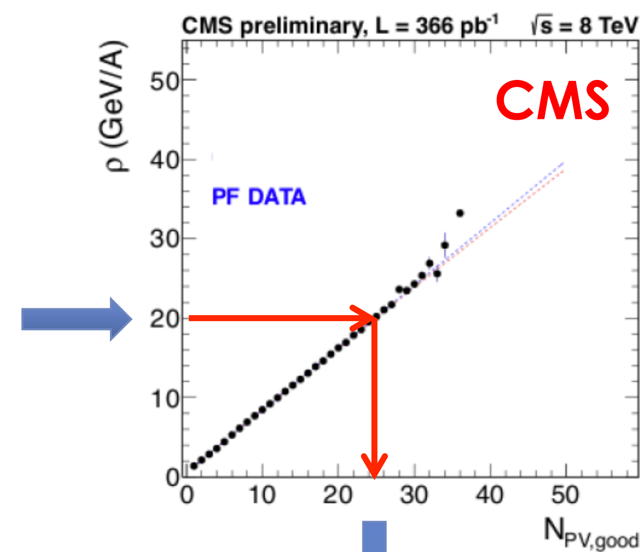


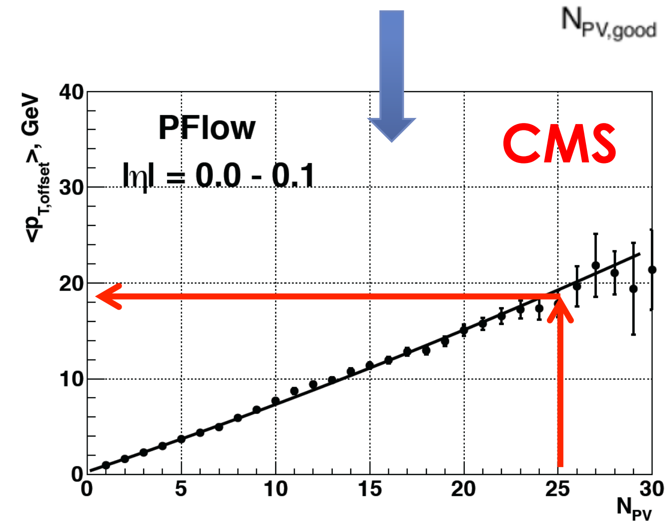


Experimental issues of jet areas pile-up subtraction

- out-of-time pile-up
- eta-dependence of the jet response
- Coarse calorimeter granularity in forward region and noise suppression:
  - Too low occupancy to compute ρ
  - Different occupancy inside/outside jets

- Alternative: **use of event-by-event p_T density instead of N_{PV} to compute the jet offset**



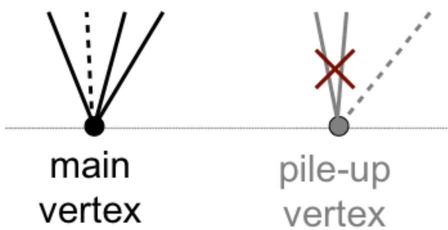


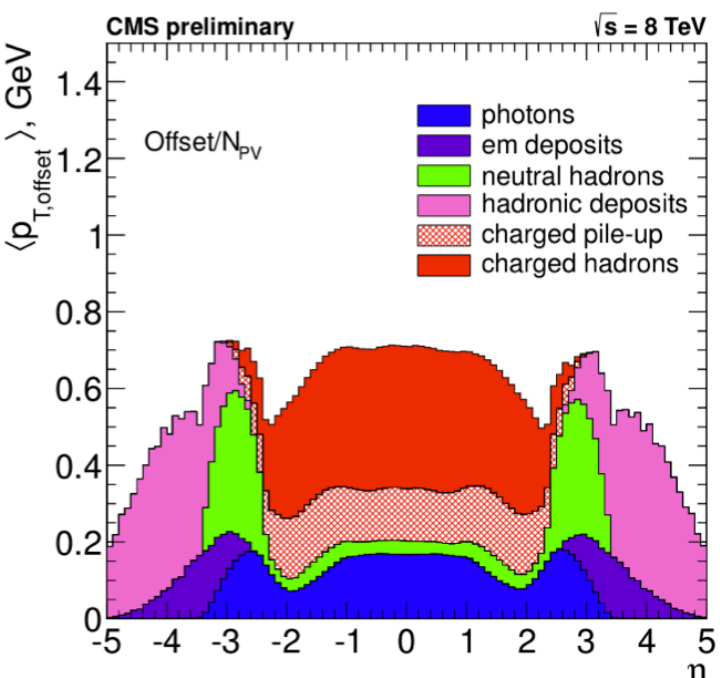
- Correction scale factor:
  - $C^{\eta}_{Fastjet-based}(\rho, A, p_T^{RAW}) = 1 - A\frac{<\frac{Offset(\rho)}{A}>}{p_T^{RAW}}$

Advanced pile-up corrections

Charged Hadron Subtraction (CMS)

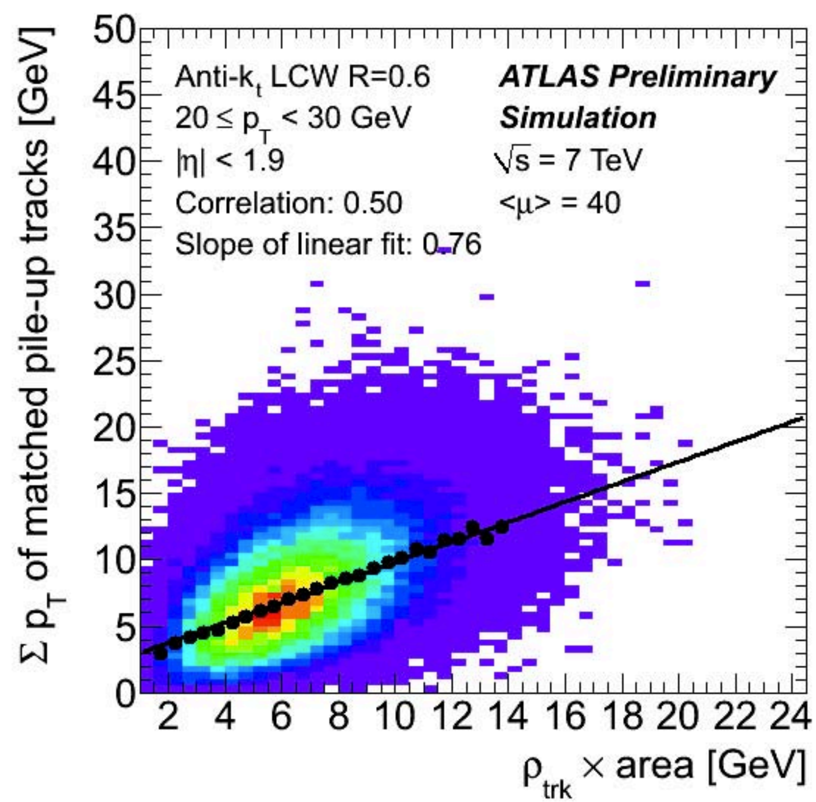
- Removes charged particles from pile-up vertices
- Used in combination with jet-areas



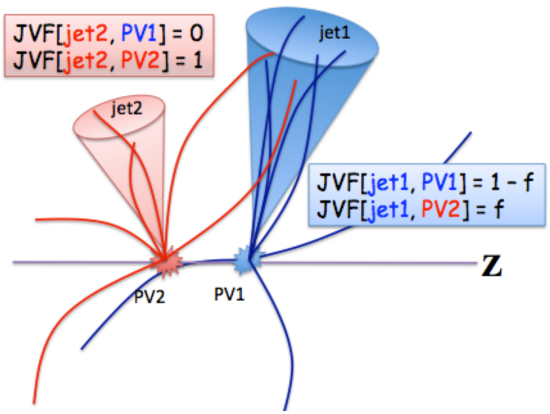


Track-based pile-up corrections (ATLAS)

- Use track-jet p_T from pile-up vertices in offset correction
- Exploit local fluctuations to improve resolution
- Not commissioned yet

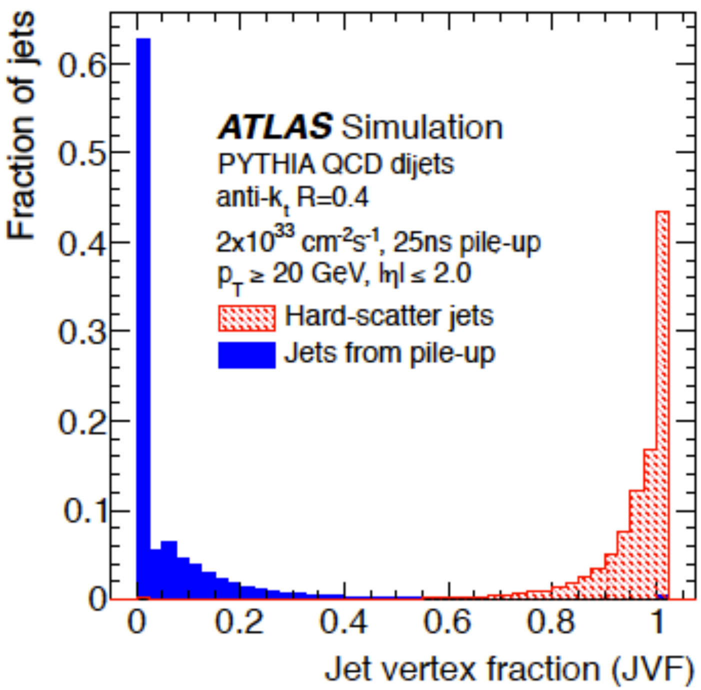


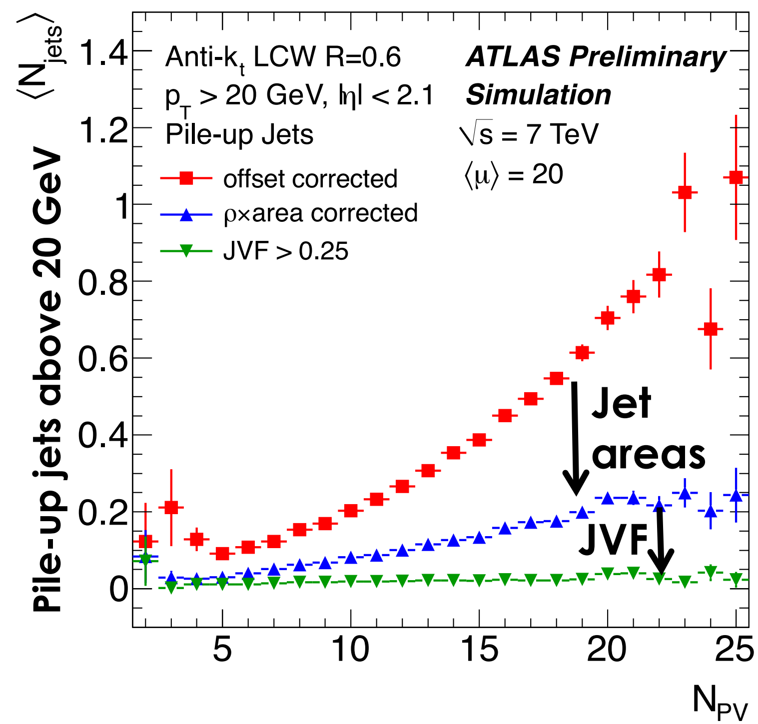
Pile-up suppression



- **Pile-up local fluctuations within a same event can lead to fake pile-up jets:**
  - Uniform distribution of particles from multiple interactions
  - Anomalous jet structure with no high p_T jet core
- **Reject fake jets from pile-up fluctuations:**
  - Jet vertex fraction algorithm
  - Investigating the use of **jet substructure** and jet shape information

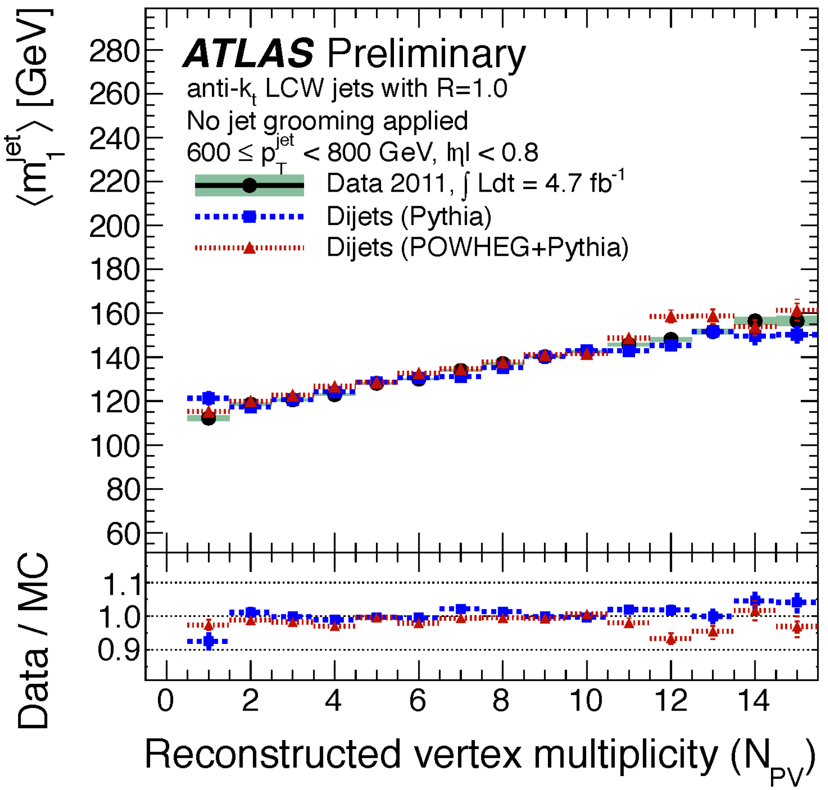
Jet Vertex Fraction (JVF)

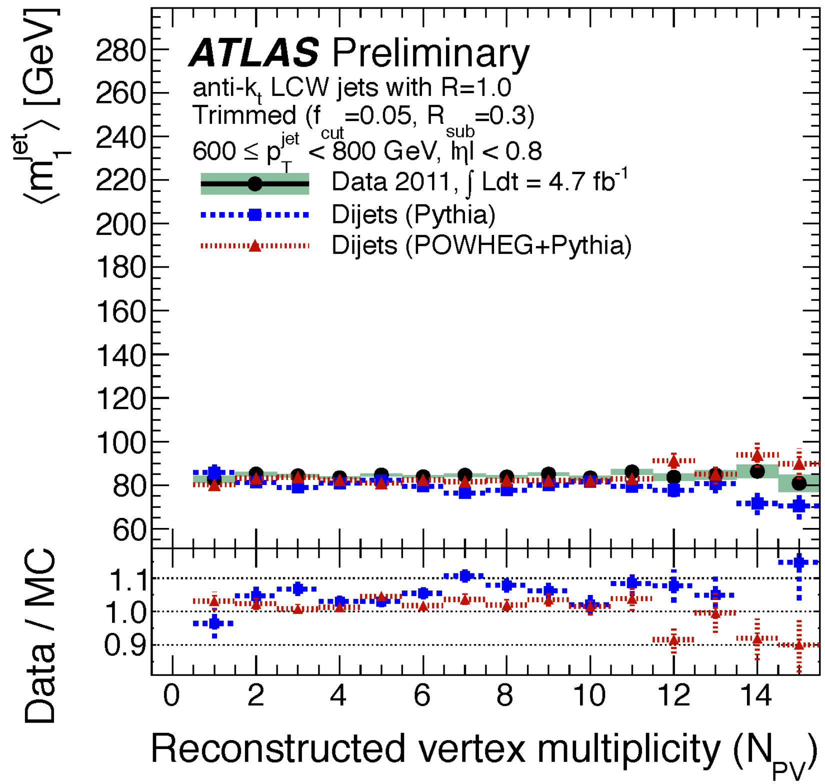




Grooming

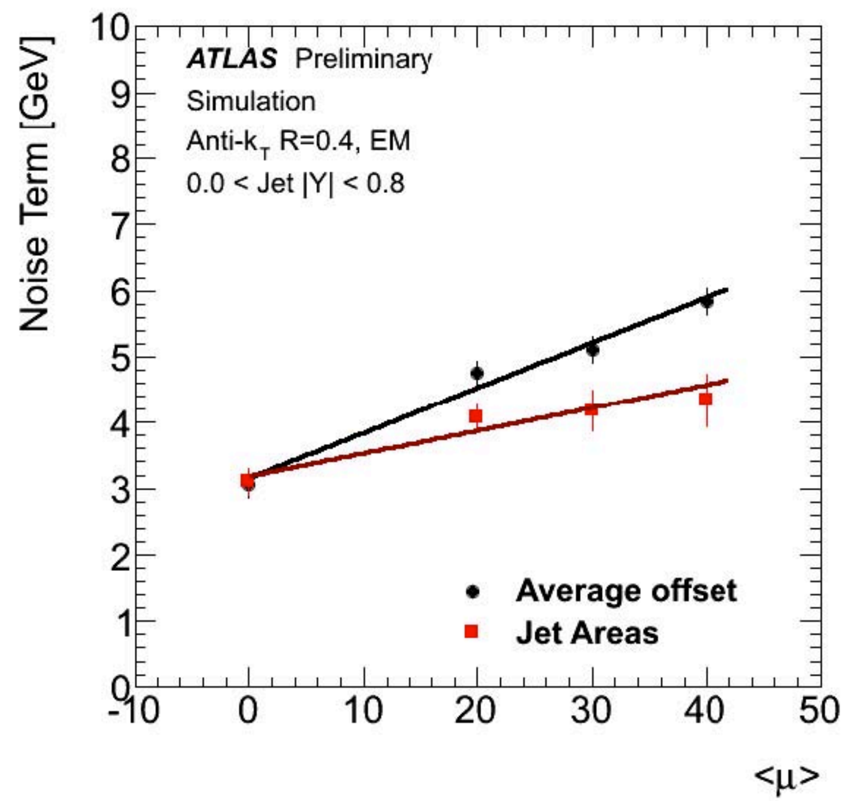
- Grooming algorithms significantly reduce sensitivity to pile-up (reduced jet area)





Towards very high luminosity

- Luminosity upgrades will require to understand and optimize jet reconstruction at very high luminosity (80-150 additional pile-up interactions)
  - Topoclustering and local hadron calibration
  - Particle flow (JetPlusTrack)
  - **Grooming algorithms**
    - Small-R jets
    - Sub-jet pile-up subtraction
  - Jet substructure for pile-up suppression
  - **Key to reduce pile-up fluctuations:**
    - Jet areas in combination with techniques to reduce local fluctuations



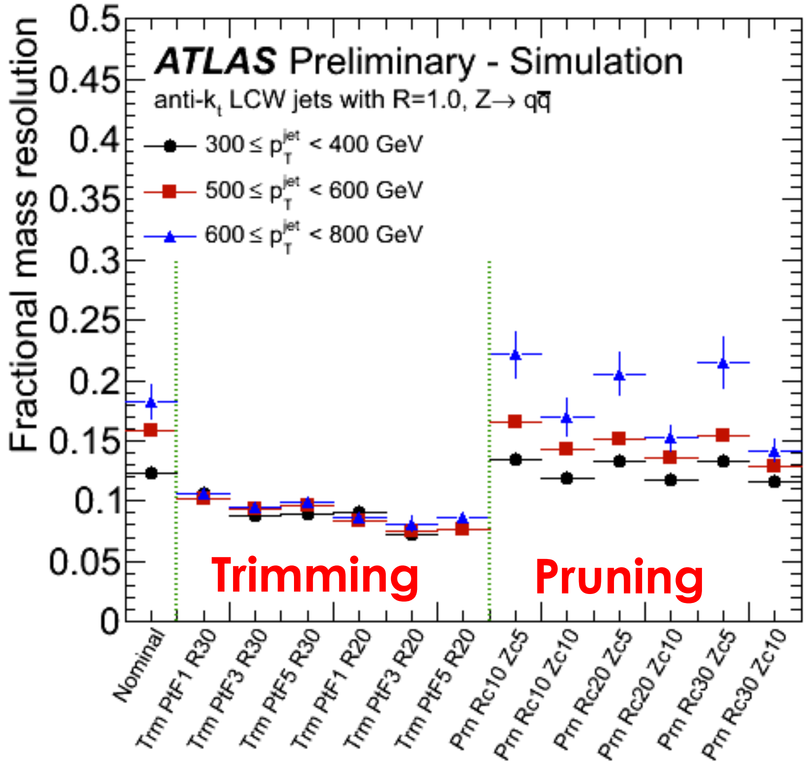
Extrapolated noise term at μ =150:
14 GeV (average offset)
8 GeV (jet-areas)

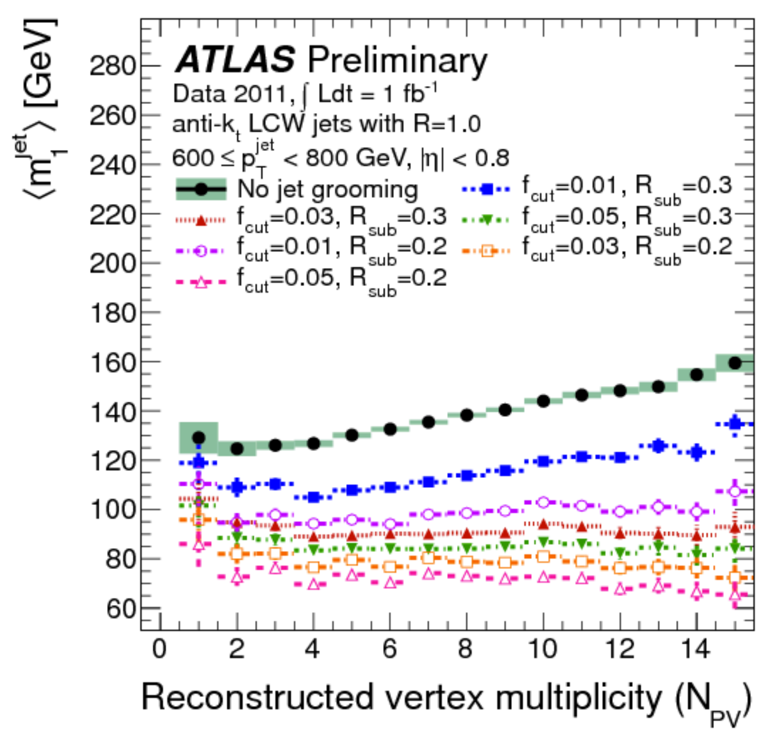
Jet algorithms, grooming, jet mass and substructure

New jet algorithms

- LHC Experiments have commissioned and are using many jet algorithms, grooming, and jet substructure techniques
  - Large-R jets, anti-k_t, C/A, trimming, pruning, filtering, top-taggers, …
  - Calibration, performance under pile-up, energy and mass scale and uncertainties

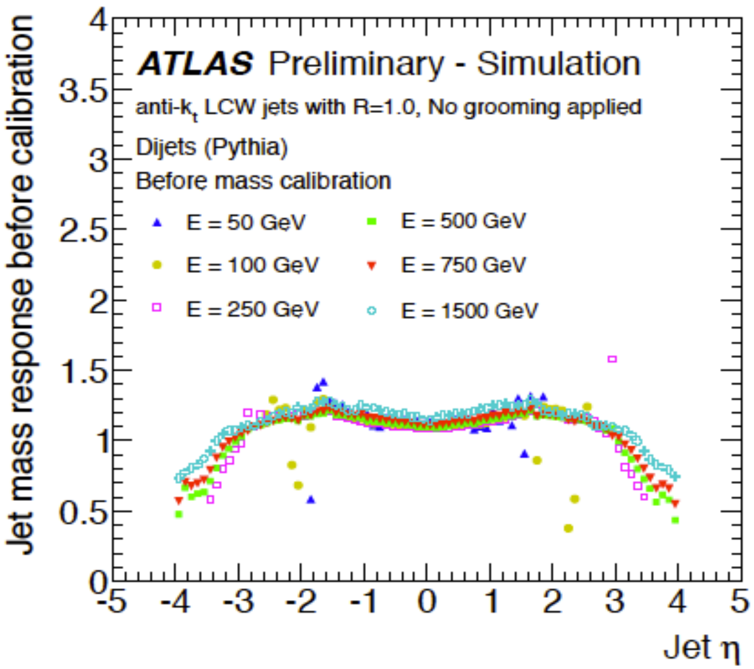
See Emily Thompson's talk

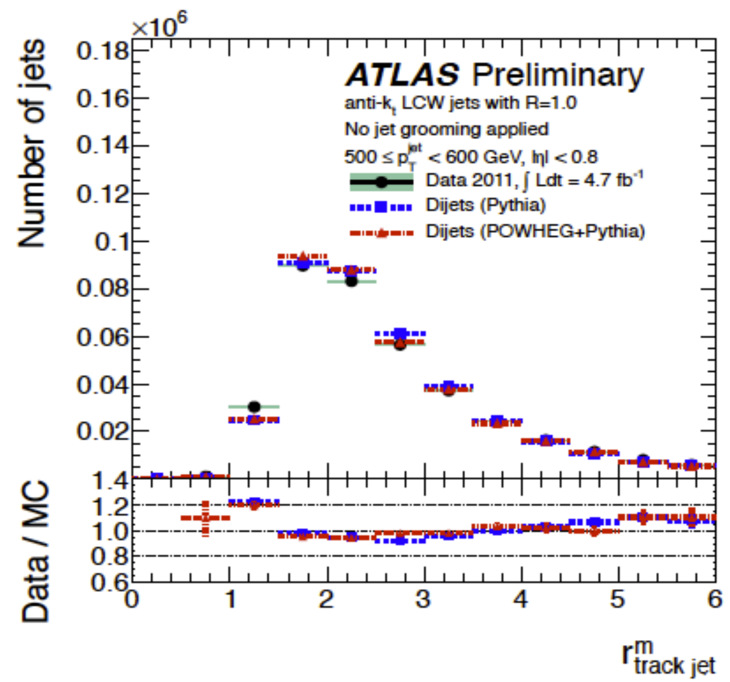




Jet mass calibration and uncertainty

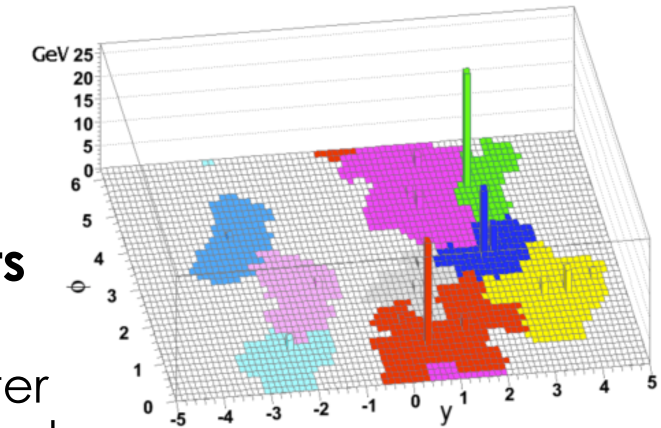
- Jet mass and energy calibration from QCD **Monte Carlo**
- Jet mass and energy scale uncertainty from **track-jet insitu** measurements
- Strong effect of pile-up on jet mass
  - **Use of grooming**
  - Starting to explore the use of jet-areas in conjunction with grooming



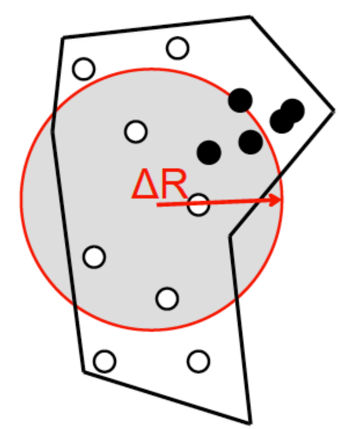


Tracking and b-tagging for jet substructure

- **Jet substructure relies on non-regular jet shapes and jet algorithms:**
  - o Requires better track-jet association schemes

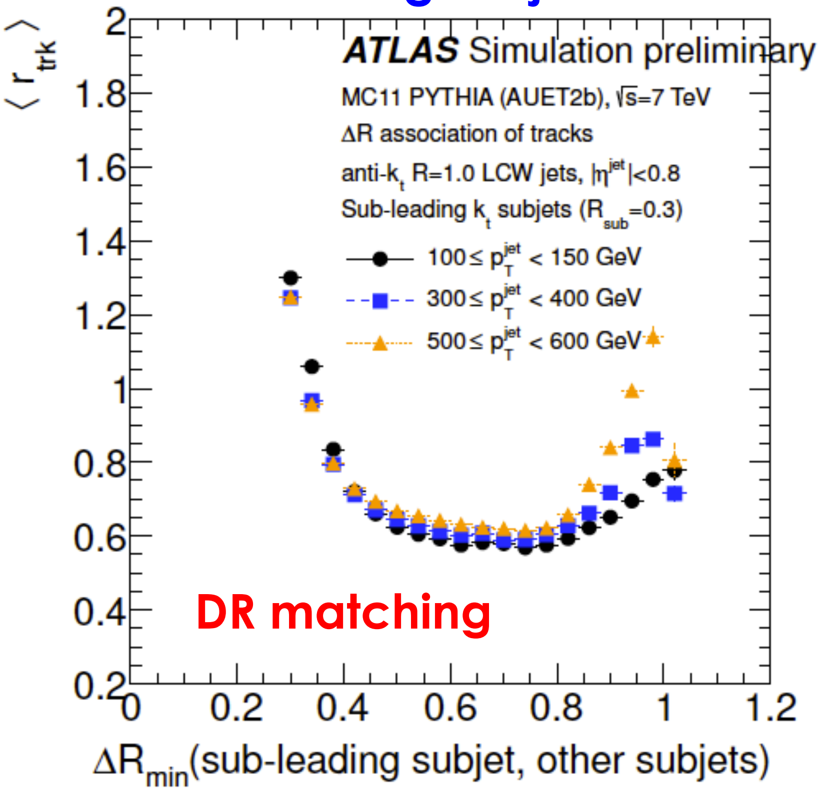


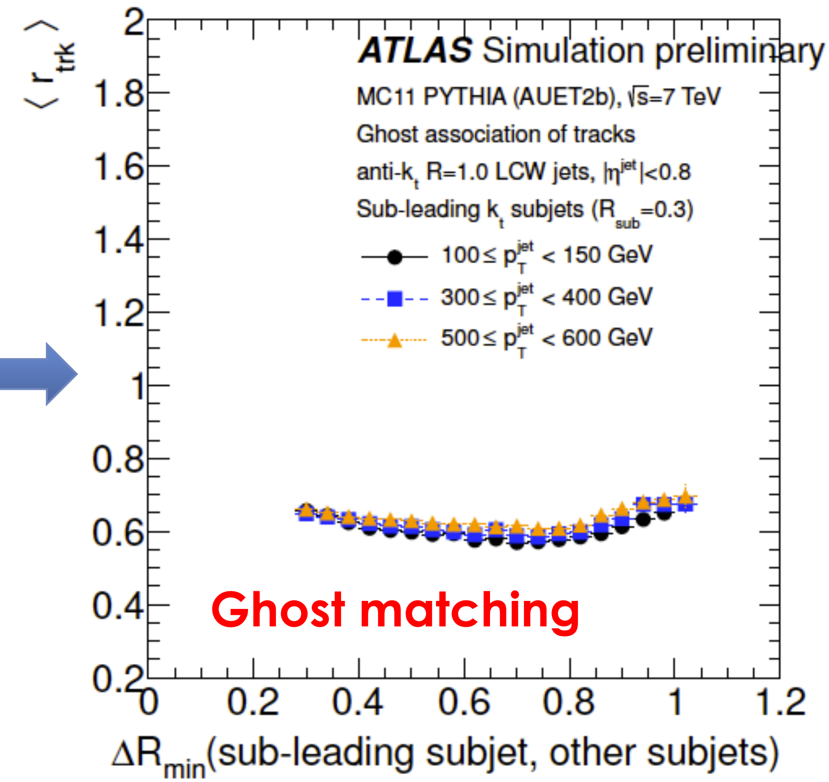
- **Use the active jet area to match tracks to jets (*ghost-association*) in ATLAS**
  - o Allow tracks (with epsilon momentum) to cluster with topological clusters during jet finding (ghost tracks)
    - Capture full jet shape
  - o Ghost-track-association has enabled the measurement of the energy scale of sub-leading subjets
    - use of tracks as a validation tool
  - o Fully characterize the pile-up structure of jets
  - o New possibility: identify b-tag objects independently of jets algorithms and *ghost-associate* b-tags to sub-jets



Ghost track association

Sub-leading subjet





- Subjet energy scale using tracks
- DR matching leads to large energy scale dependence from incorrect geometrical matching

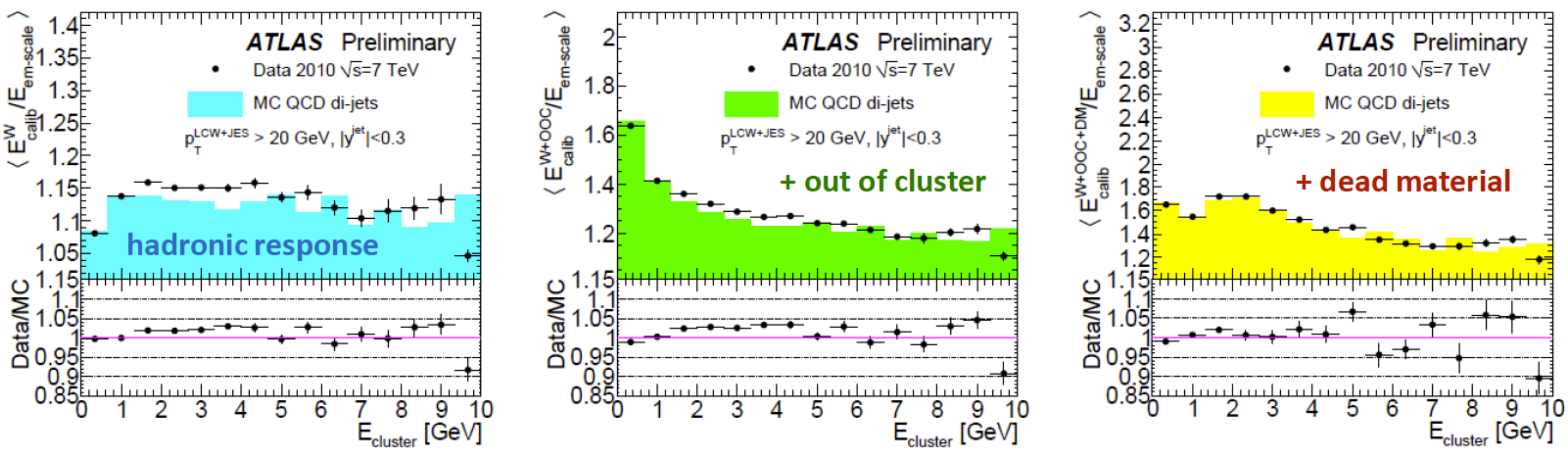
Summary

- **LHC Experiments have commissioned an impressive set of jet and jet substructure algorithms:**
  - anti-k_t, C/A, pruning, trimming, filtering, large-R jets, …
  - Achieved a very high precision and developed many novel techniques to address the main experimental challenges of the difficult LHC environment
    - 1% absolute response precision from insitu measurements
    - Sophisticated pile-up corrections
  - Innovative and ambitious program, with strong influence and interaction from the theory community
- **ATLAS and CMS use different approaches to jet reconstruction:**
  - CMS: integrated calorimeter+track reconstruction (PFlow)
  - ATLAS: topological cluster and local calibration plus track-based post-calibration corrections
  - <u>Choices motivated by different detectors</u>
- **Importance of reducing pile-up fluctuations:**
  - One of the main challenges for jet performance.
  - Grooming and jet-areas are emerging as key tools to maintain excellent jet performance at high luminosity
  - Jet substructure ideas are being applied to to reject of fake pile-up jets
- **The excellent jet reconstruction capability of the LHC Experiments and their simulation will continue to enable the development of new ideas to enhance the LHC discovery potential and precision**

Backup slides

Local cluster weighting

- Cell/cluster weights:
  - Hadronic response (cell E-density and cluster energy)
  - Out-of-cluster (cluster depth and energy around the cluster)
  - Dead material (fractional energy deposited in each calorimeter layer and cluster energy)
- 2% agreement between data and Monte Carlo simulation for the ratio of calibrated cluster energy over the un-calibrated cluster energy after each calibration step. Very good agreement between data and simulation for all inputs to LCW



Ghost track association

Leading subjet