Measurement of Jet Energy Scale and Resolution at ATLAS and CMS at $\sqrt{s}$ = 8 TeV

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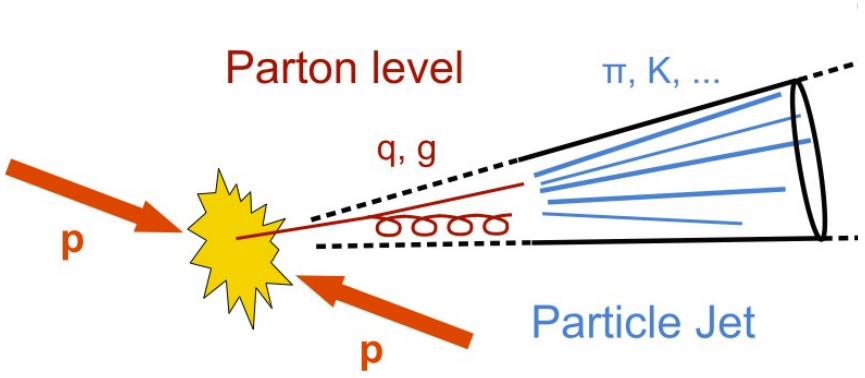
  - Flavour-dependent systematics and corrections
- Jet Energy Uncertainties
- Jet Resolution Measurements

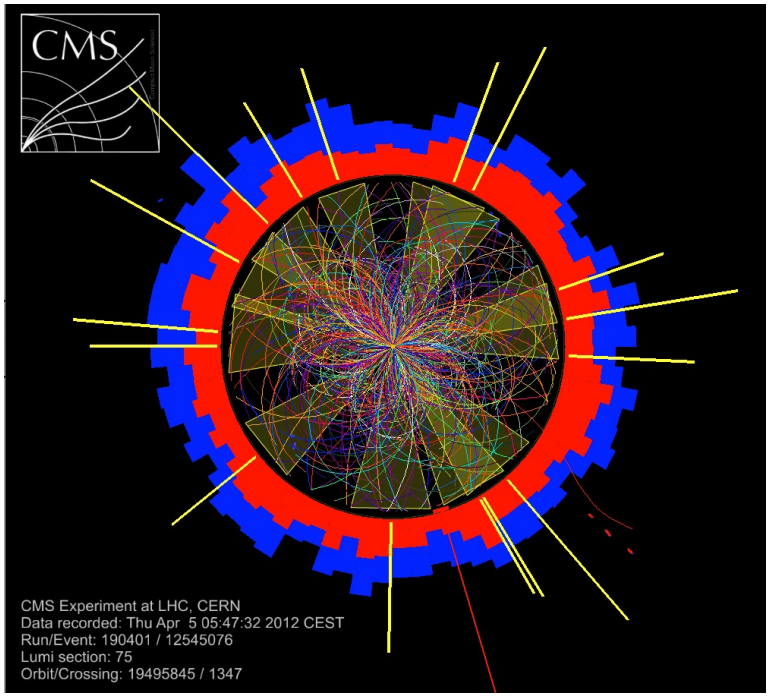
Introduction: What are Jets?

- A **(particle) jet is the experimental signature of a parton** (quark or gluon) after fragmentation and hadronisation



- Jets are **ubiquitous at hadron colliders** (many from pile-up interactions)

CMS Multijet-Event

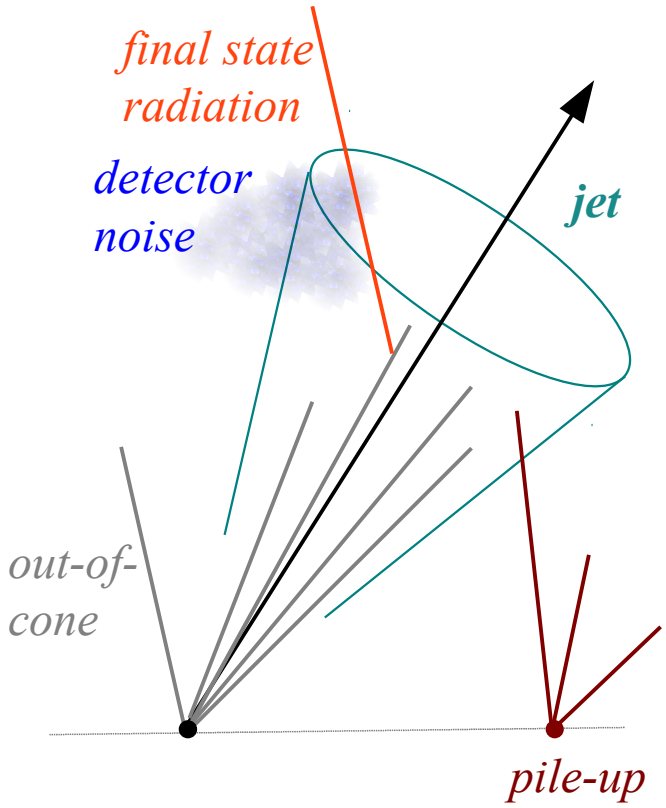


- Important signature for many physics processes (Higgs, top, SUSY, ...)

- **Important for almost all LHC physics analyses!**

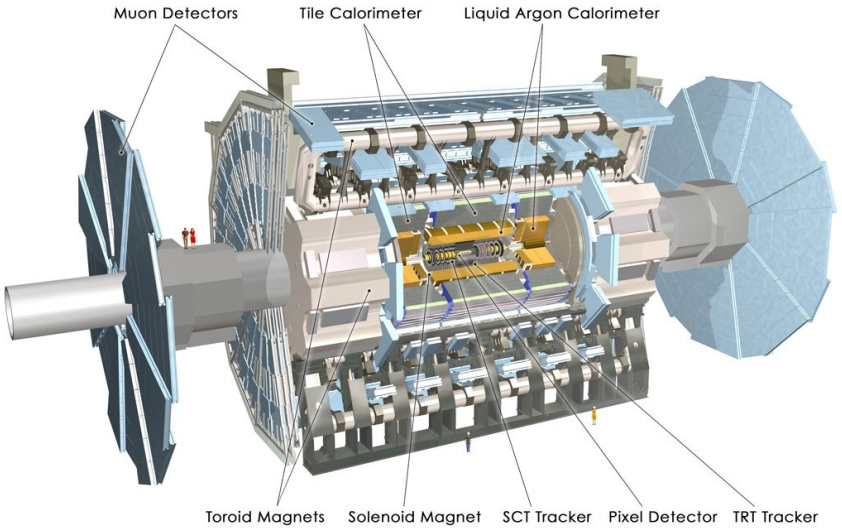
Introduction: Why Jet Energy Corrections?

- Many systematic effects that complicate jet (energy) measurements:
  - Pile-up, initial and final state radiation, out-of-cone effects, detector response, ...
- Jet energy uncertainties are often the **largest systematic uncertainties**
- Precise corrections of the jet energy and an understanding of the uncertainties and correlations are mandatory
- **The precision in jet calibration determines the uncertainty on many physics results!**

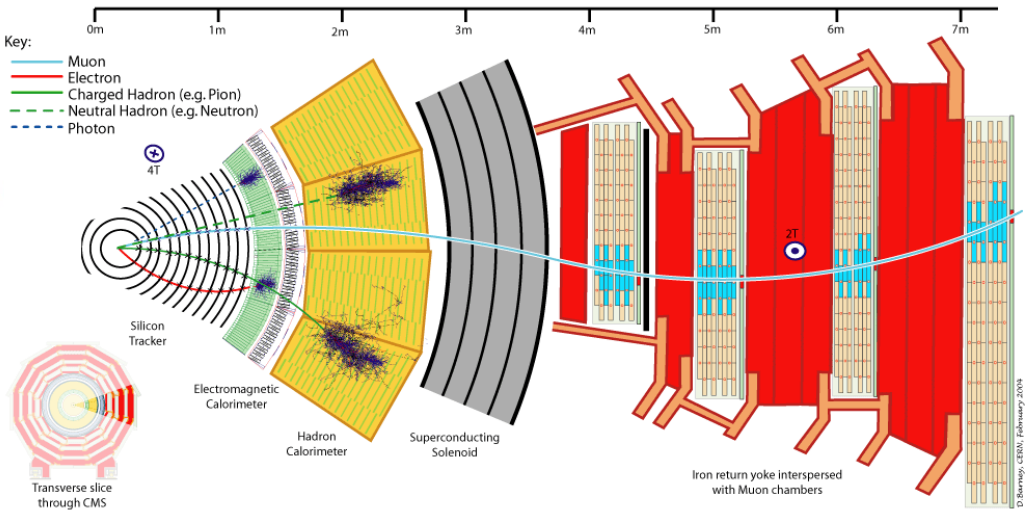


The ATLAS and CMS Detectors

ATLAS in 3D



Slice of CMS



- **Similarities:** composed of several subsystems:
  tracker, electromagnetic and hadronic calorimeters, magnet, muon chambers
- **Differences** in design (magnet) and material choice (calorimeter)
  → Different resolution and reconstruction performance
  → Different calibration and correction methods

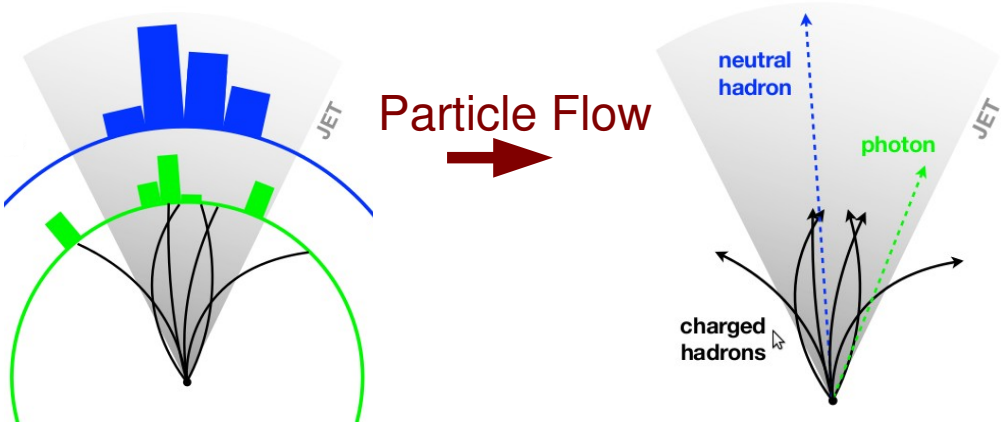
Jet Reconstruction in ATLAS and CMS

- Jet reconstruction procedure:

  input objects (e.g. particles) → apply *jet finding algorithm* → jet

  ATLAS and CMS: common algorithm, different cone sizes

- **Reconstructed jets**:
  - ATLAS: using calorimeter topo-clusters as input → **Calo-Jets**
    - Calibration was applied to calorimeter cells and topo-clusters
  - CMS: using Particle-Flow (PF) reconstructed particles as input → **PF-Jets**



Main Jet Energy Correction Steps

1. **Pile-up offset**: Remove additional energy from pile-up
   → *pile-up mitigation and correction methods*

2. **Simulation corrections:** Correct for differences between η / p_T regions
   → derived from simulation

3. **Data-driven corrections**: Correct for residual data/simulation differences
   → derived from *data-driven balancing methods*

4. **Flavour corrections**: Correct for jet flavour differences (quark/gluon, heavy flavours)
   → derived from *simulation and data-driven tagging methods*

   → **Addressing each problem with different methods!**

1. Pile-up Mitigation and Correction

- On average **20 pile-up collisions** per event!

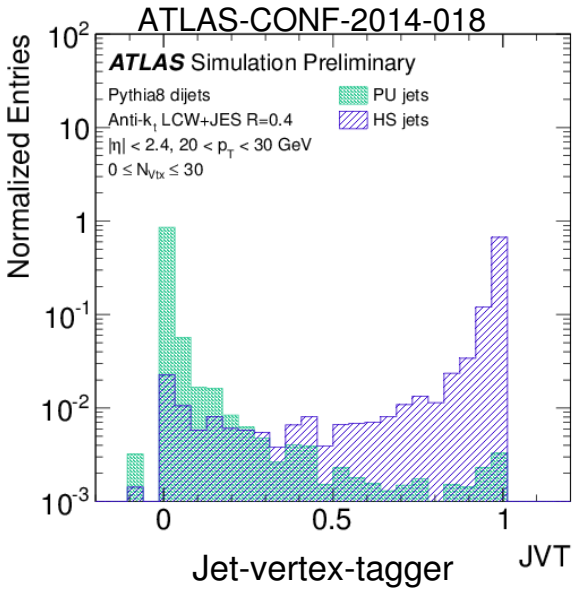
- **Mitigation:** remove pile-up particles and jets
  - *Remove pile-up particles* prior to jet clustering
  - Multivariate (track-vertex-based) methods to *distinguish pile-up jets from hard-scatter jets*

- **Correction:** remove pile-up energy from jet
  - Jet area method:

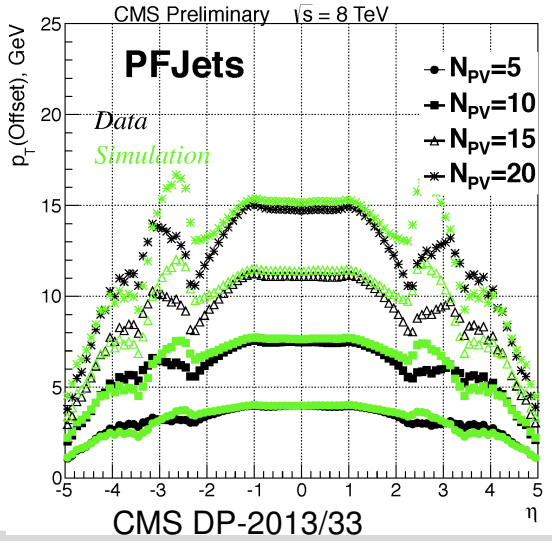
    Remove offset energy depending on *event pileup density* and *jet area*

    → *combining individual jet and event information* for estimation of pile-up contribution

ATLAS Pile-up Tag



CMS Pile-up Corrections



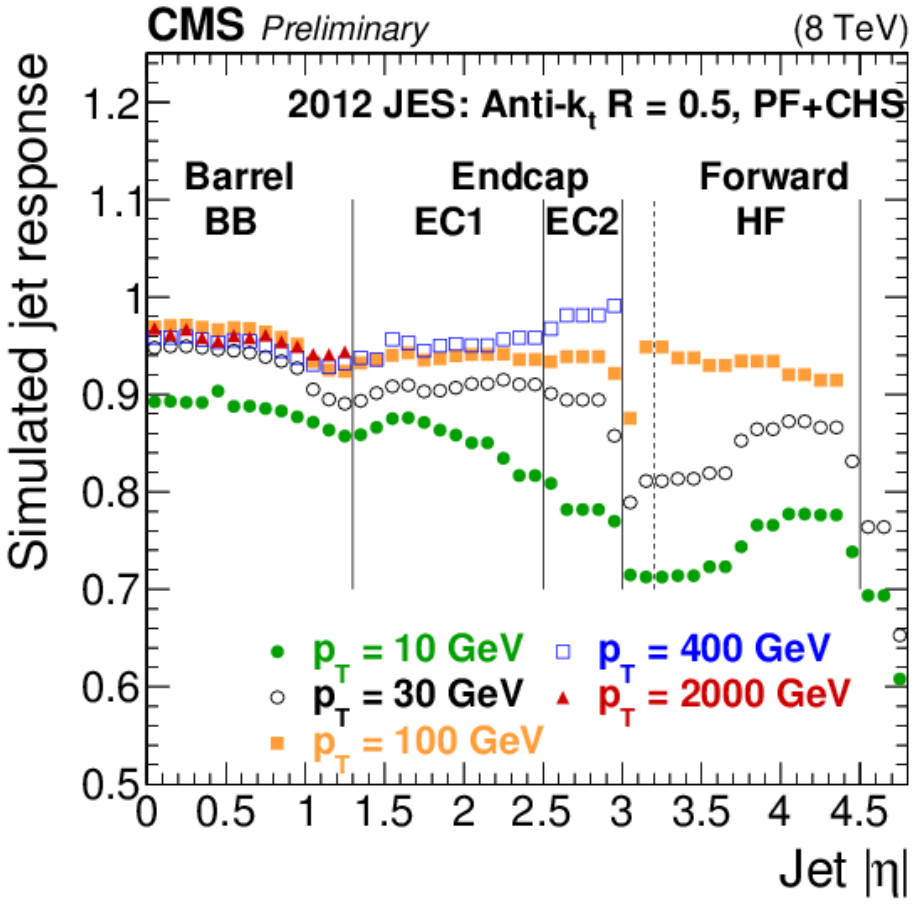
2. Simulation Corrections

1) **Match** reconstructed jet to simulated jet (in η-φ-space)
2) **Calculate p_T-ratio** of simulated and reconstructed jet
   → simulated response
3) **Corrections** as inverse of the simulated response

   → Correct for all known systematic effects

- However, **data-driven validation and correction mandatory** (due to possible simulation imperfections and unknown features)

CMS Simulated Response for Different |η| / p_T Values



3. Data-Driven Corrections: Balancing Techniques

- Idea: **Compare well-understood *tag* object with *probe* object (jet)**
  - On average: no transverse momentum in initial state

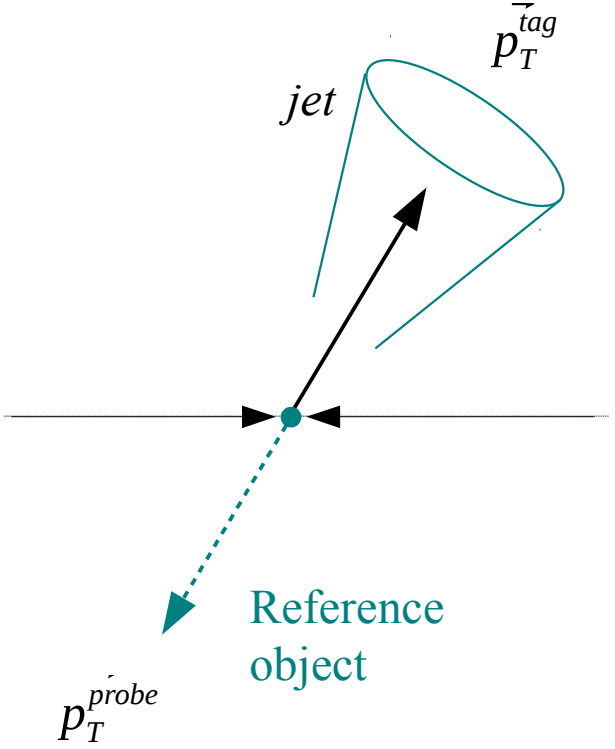
    $\rightarrow \quad \vec{p}_T^{\,tag} + \vec{p}_T^{\,probe} = 0$

- Different tag/probe objects:
  - **Central jet vs forward jet**

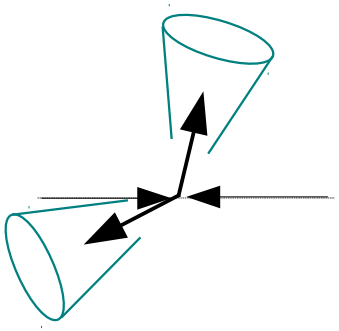
    Calibrate forward jets
  - **High-p_T jet vs recoil jets**

    Calibrate high-p_T jets
  - **Z/γ vs jet**

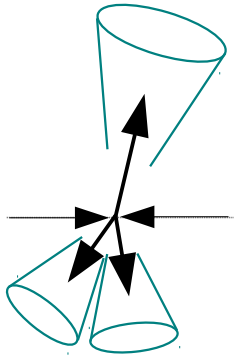
    Calibrate absolute jet energy scale



3. Data-Driven Corrections: Dijet and Multijet Balancing

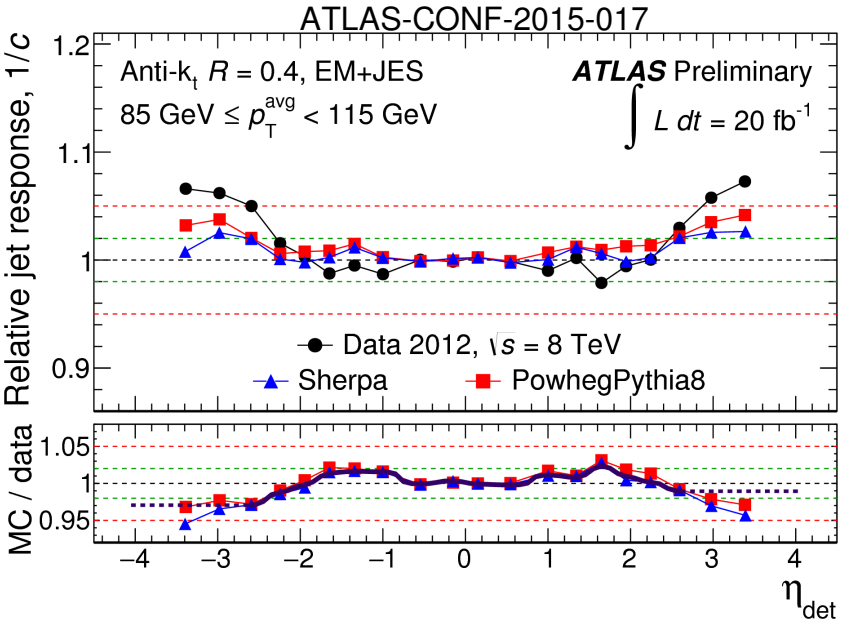


central jet vs.
forward jet



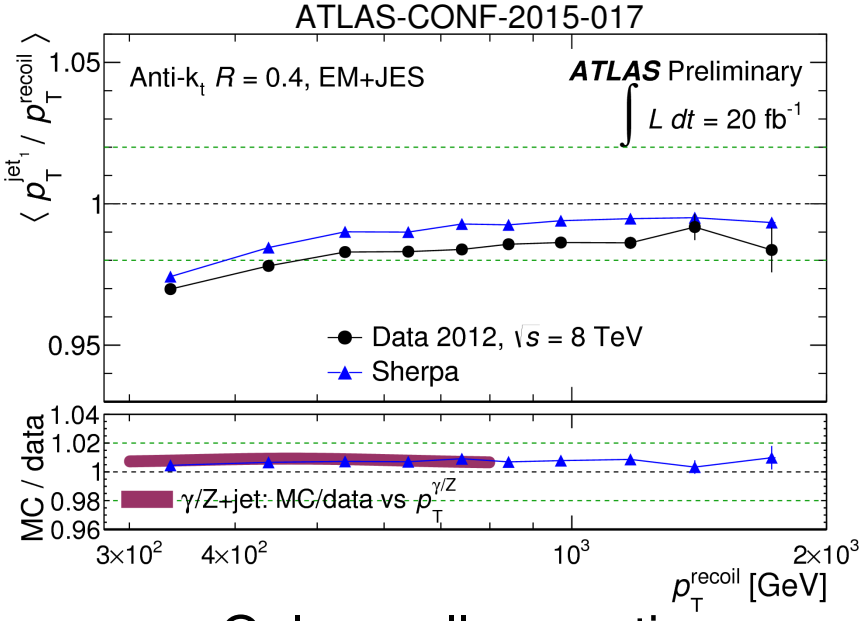
high-p_T jet vs.
multijet-recoil-system

ATLAS Dijet Balance



< 3% correction in endcap and forward regions

ATLAS Multijet Balance



Only small corrections (~1%) for TeV-jets

3. Data-Driven Corrections: Z/γ+Jet and MPF Method

- Absolute scale: Z/γ+jet balancing
  - Z→μμ: independent of calorimeter scale

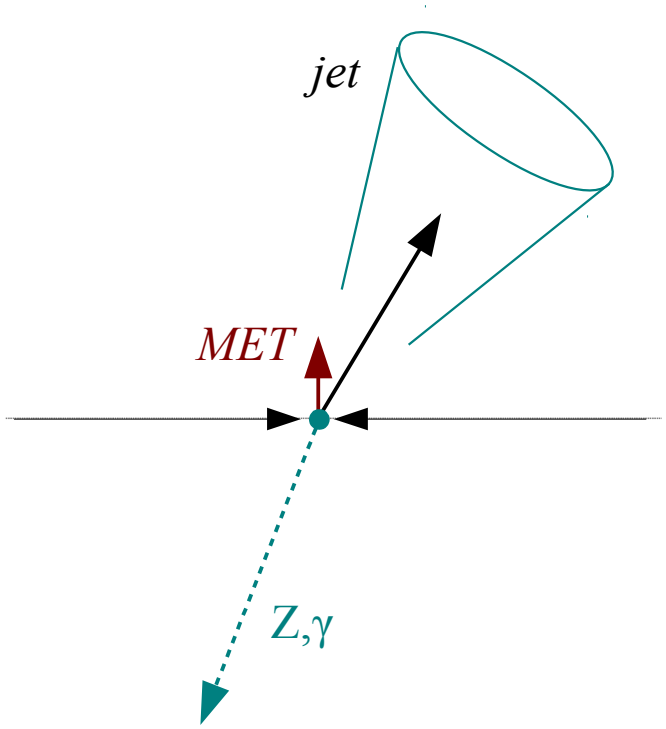
- Additional to p_T balancing:

  MPF method
  - Use Missing Transverse Energy (MET) to estimate jet response

$$R_{MPF} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_T^{Z}}{\left(p_T^Z\right)^2}$$

  → Takes entire event and detector into account

  → Less dependent on initial and final state radiation (ISR/FSR)

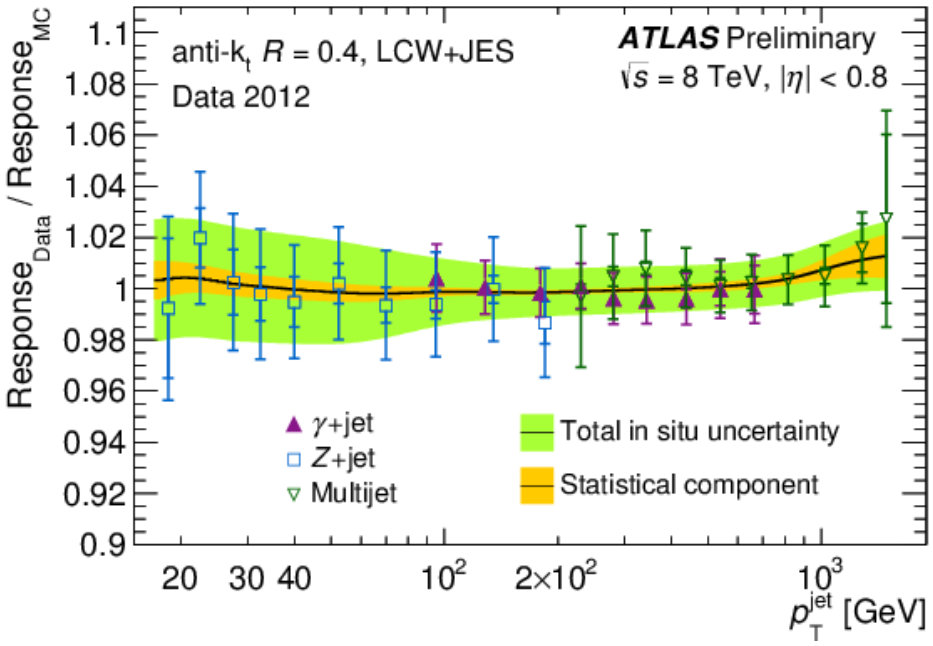


3. Data-Driven Corrections: Combination of Channels

- Combine data/MC ratios from different channels: Z+jet, γ+jet, Mulijet

ATLAS

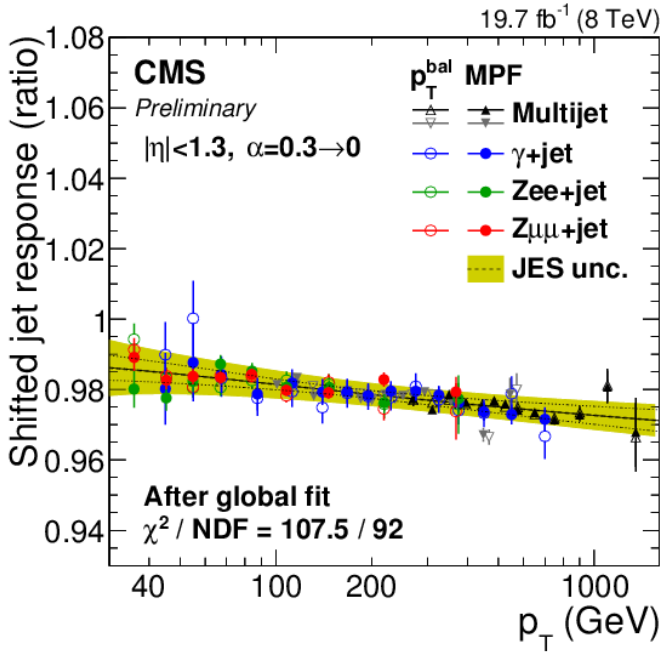
Weighted average in p_T bins and smoothing procedure



All channels in agreement

CMS

Combined fit for all channels after ISR/FSR-corrections

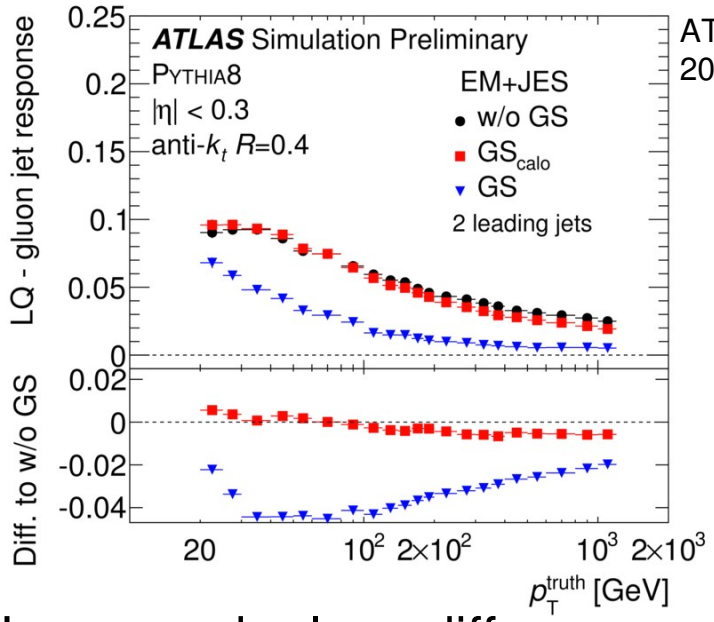


MPF and p_T balance agree for all channels

4. Flavour Corrections

- Detailed studies on **response differences between jet flavours**
  - E.g. wider fragmentation for gluons, neutrinos from b-jets
- **Multivariate flavour-tagging techniques** for data-driven studies
  - Quark-gluon-tag and b-tag

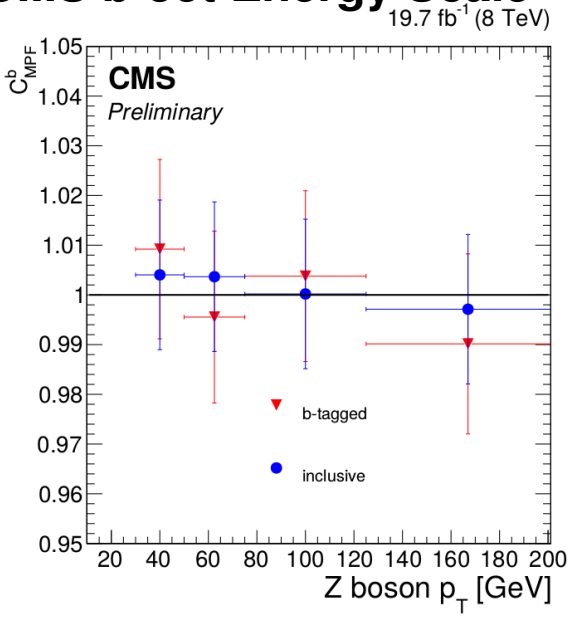
ATLAS Light-Quark/Gluon Differences



ATLAS-CONF-2015-002

- Less quark-gluon differences after full (*Global Sequence*) corrections

CMS b-Jet Energy Scale



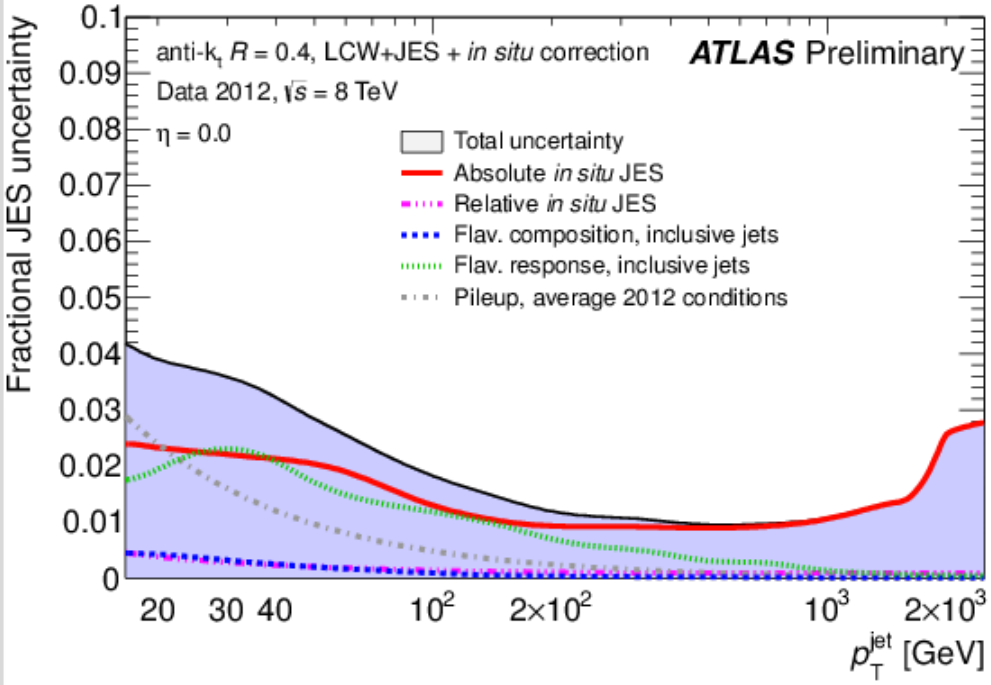
CMS JME-13-001

- Data-driven Z+b-jet study:
  No additional corrections needed

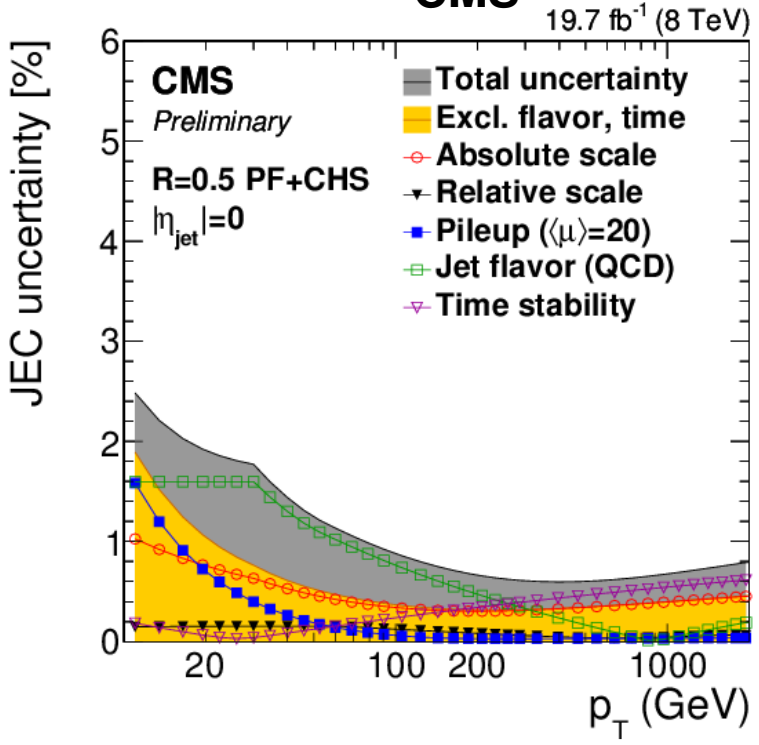
Jet Energy Uncertainties

- Relative uncertainty as a function of jet p_T:

ATLAS



CMS

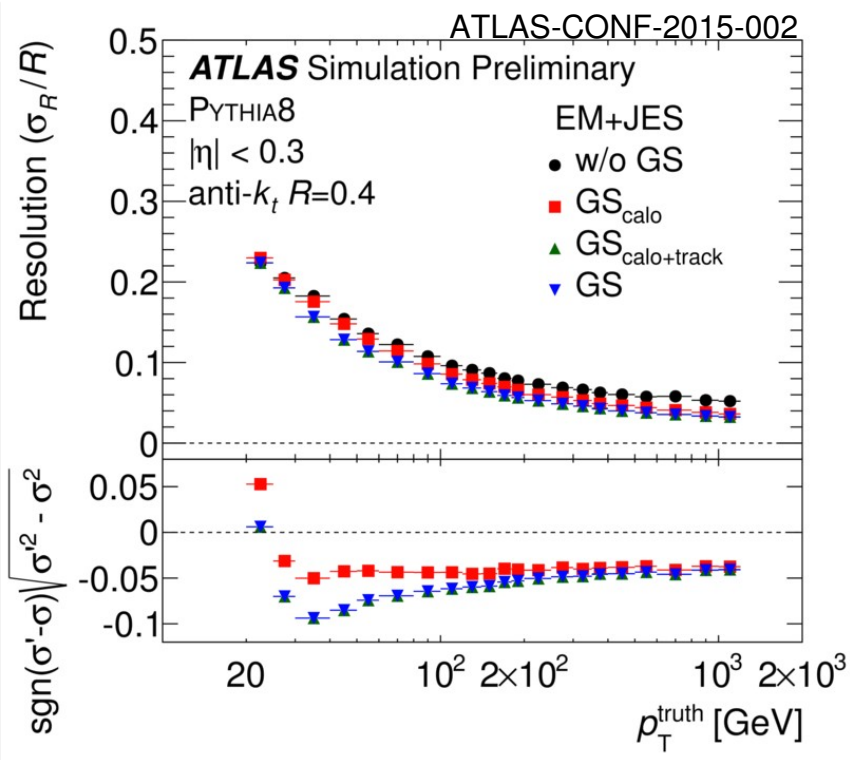


- At low p_T: pile-up and flavour uncertainty dominating
- **Both ATLAS and CMS: total uncertainty at percent level**

Jet Resolution Measurements

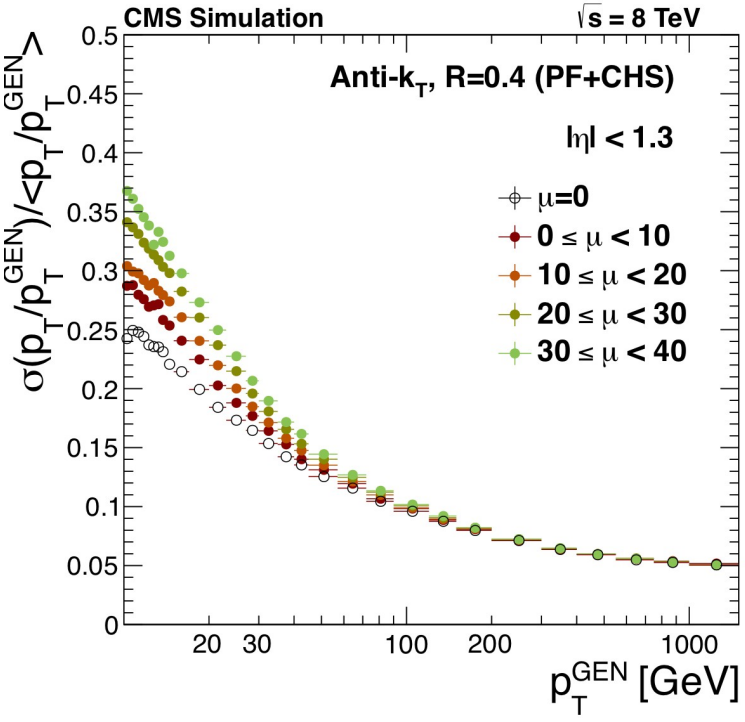
- Instead of the **mean** of the jet response distribution, look at its **width:**

ATLAS: Different Correction Methods



- Improved resolution after full (*Global Sequence*) corrections

CMS: Different Pile-up Scenarios

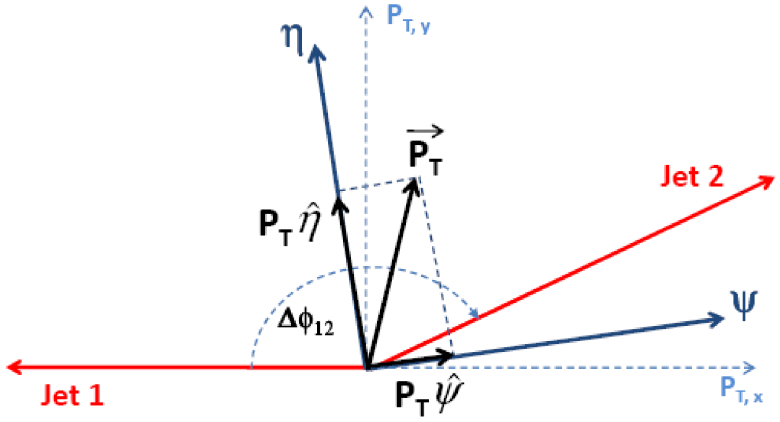


- Pile-up affects jet resolution especially at lower p_T

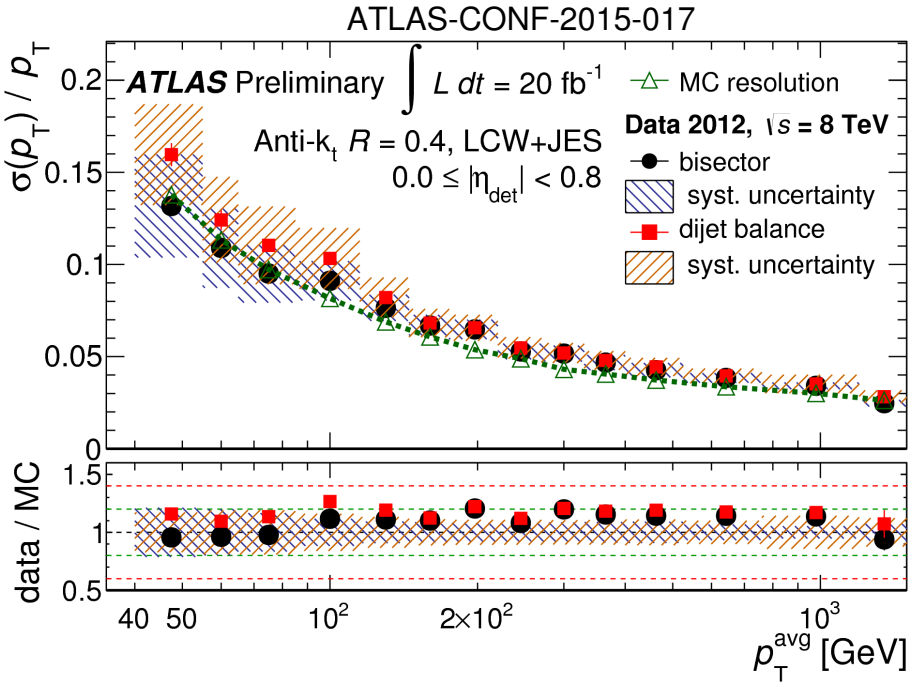
Jet Resolution: Data-Driven Measurements

- Data-driven jet resolution study to validate results from simulation
  - Comparing resolution from *dijet balance* and *bisector method*

Bisector method:



Detector effects only in Ψ-component,
physics and detector effects in η-component



- Dijet balance and bisector method agree
- **Resolution in data: only minor differences compared to MC**

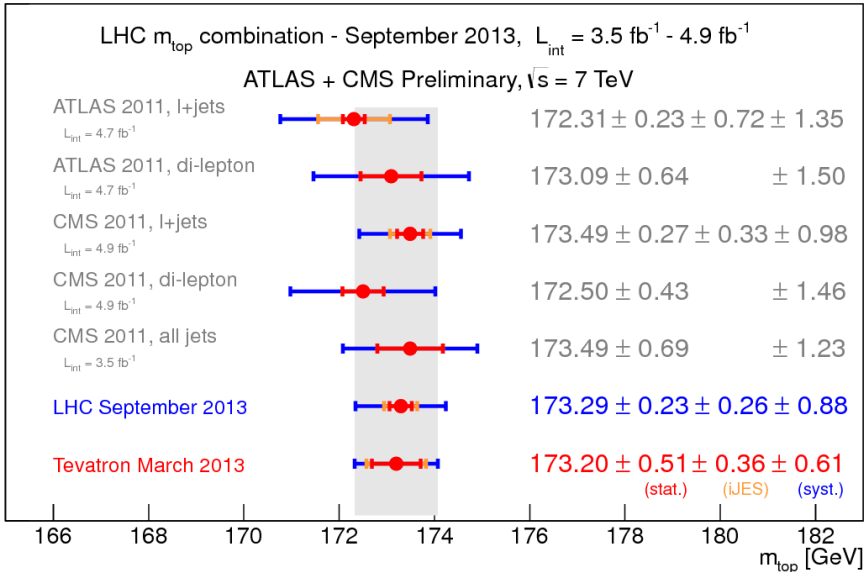
ATLAS and CMS Joint Efforts

- Combine measurements to reduce total experimental uncertainty
  → study **jet energy uncertainty correlations** between ATLAS and CMS

- Joint ATLAS and CMS working group
- Jet energy uncertainties found to be *mostly uncorrelated*, except e.g. jet flavour or MC modelling uncertainty

→ Combination of precision measurements (e.g. top mass)

- These efforts have **improved the understanding of the uncertainties** and **facilitated the cooperation between the experiments**



CMS PAS JME-14-003 ATL-PHYS-PUB-2014-020

Conclusion

- **ATLAS and CMS have achieved excellent performance in Run 1**
  - Jet energy uncertainty at percent level
- Robust data-driven methods and advantages of simulation studies are combined for calibration
- Many novel techniques to tackle the challenges at the high-energy, high-luminosity frontier
- Successful cooperation between the experiments
- **Well prepared for LHC Run 2!**

Backup

References ATLAS

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtMissCONFnotes

- Data-driven determination of the energy scale and resolution of jets reconstructed in the ATLAS calorimeters using dijet and multijet events at $\sqrt{s}$=8 TeV
  - ATLAS-CONF-2015-017
- Jet global sequential corrections with the ATLAS detector in proton-proton collisions at $\sqrt{s}$ = 8 TeV
  - ATLAS-CONF-2015-002
- Tagging and suppression of pileup jets with the ATLAS detector
  - ATLAS-CONF-2014-018
- Performance of pile-up subtraction for jet shapes in pp collisions at $\sqrt{s}$=8 TeV
  - ATLAS-CONF-2013-085
- Jet energy scale uncertainty correlations between ATLAS and CMS
  - ATL-PHYS-PUB-2014-020

References CMS

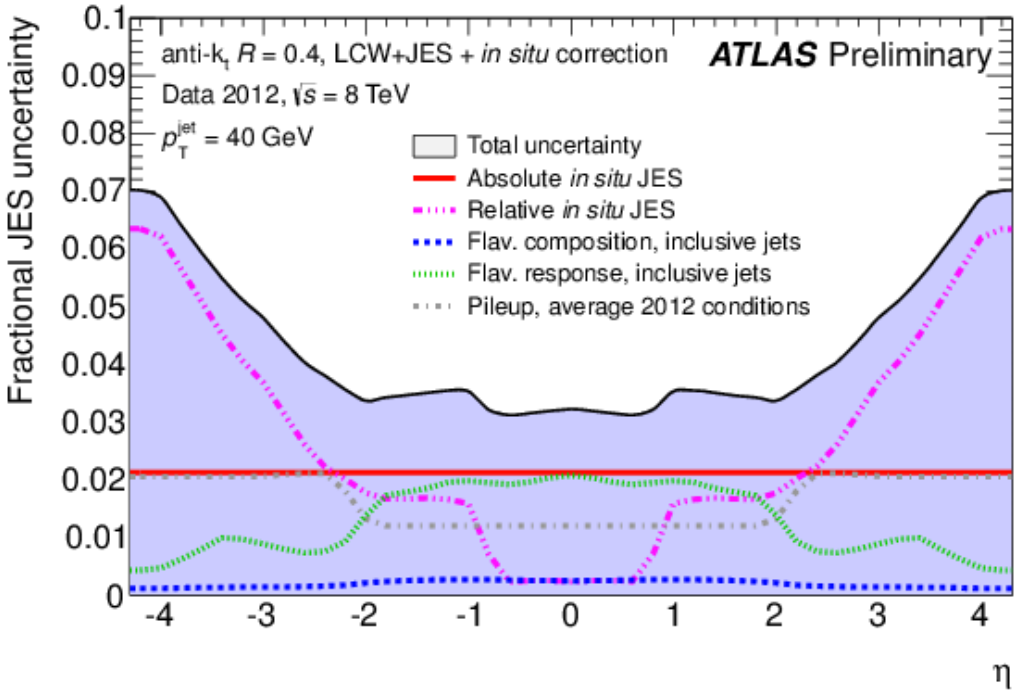
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME

- Jet energy scale uncertainty correlations between ATLAS and CMS
  - CMS-PAS-JME-14-003
- Calculation of Residual Energy Correction for b Jets Using Z+b Events in 8 TeV pp Collisions
  - JME-13-001
- Jet Energy Corrections for Multiple Cone Sizes
- Pileup Removal Algorithms
  - CMS-PAS-JME-14-001
- Performance of quark/gluon discrimination in 8 TeV pp data
  - CMS-PAS-JME-13-002
- Pileup Jet Identification
  - CMS-PAS-JME-13-005
- Jet energy scale uncertainty correlations between ATLAS and CMS
  - CMS PAS JME-14-003

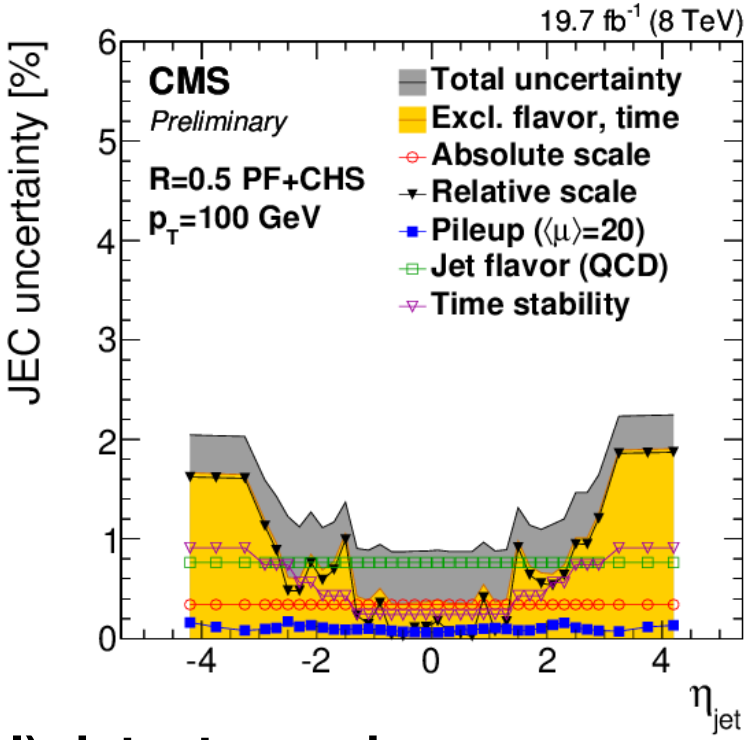
Jet Energy Uncertainties

- Relative uncertainty as a function of jet |η|:

ATLAS (Jet p_T = 40 GeV)

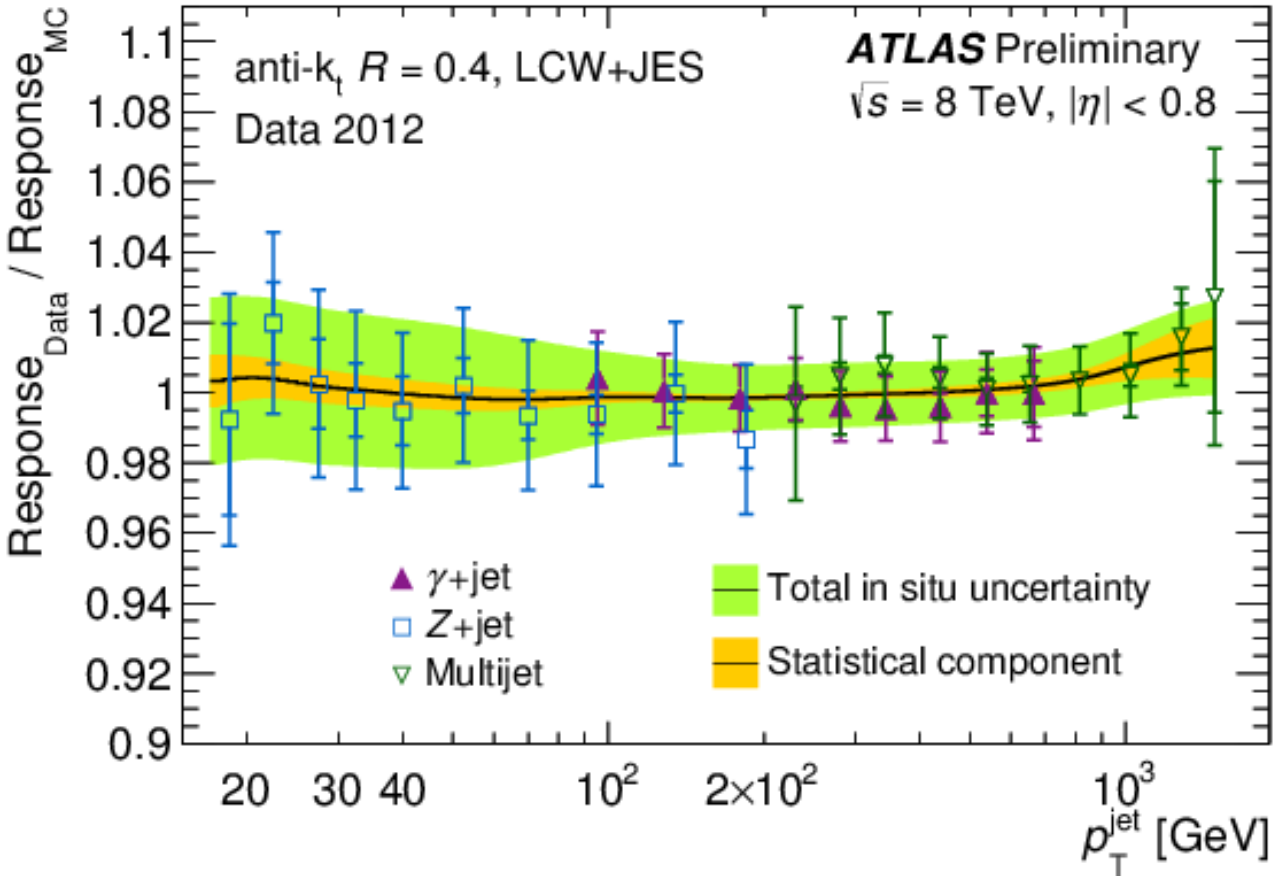


CMS (Jet p_T = 100 GeV)

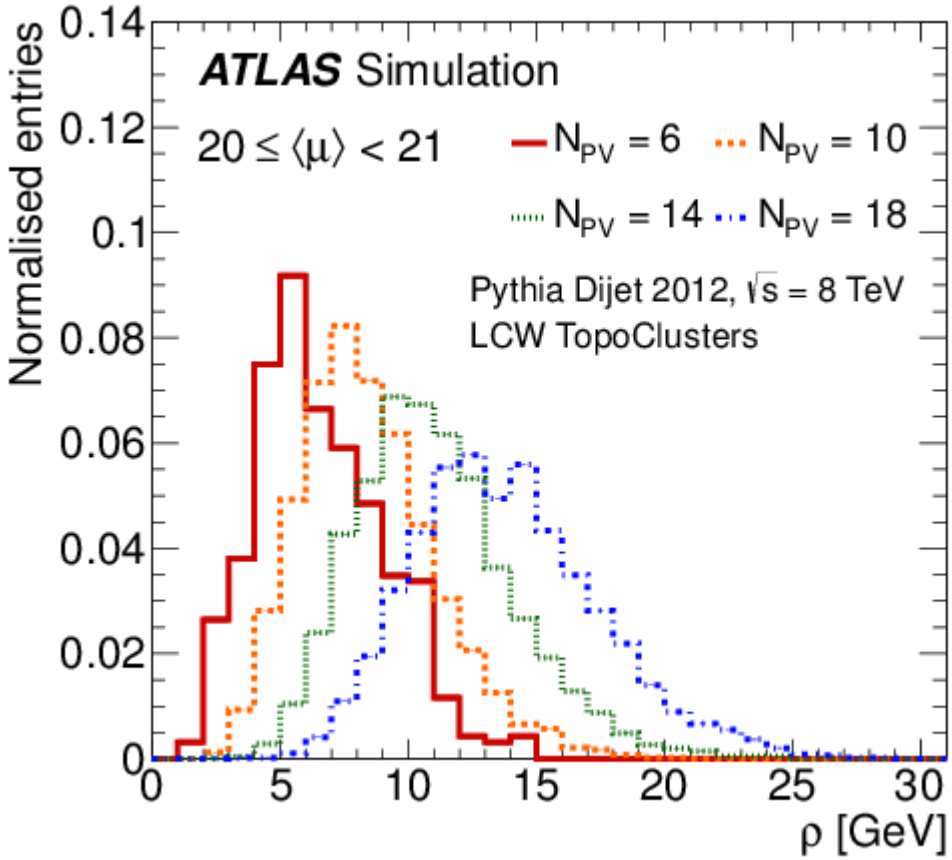


- **Lowest uncertainties in central (barrel) detector region**

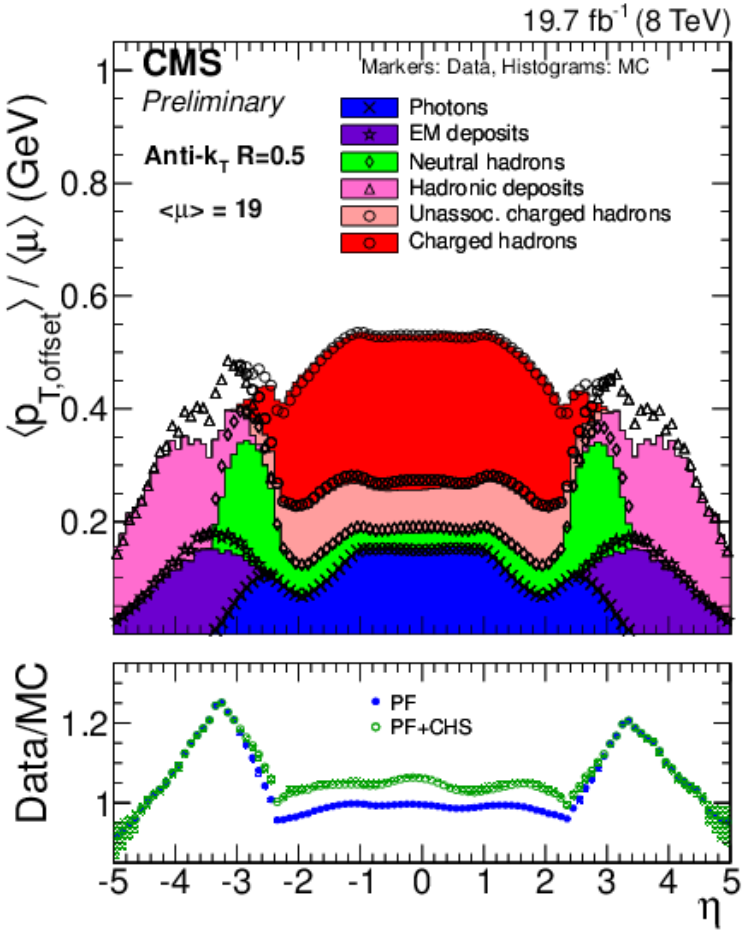
ATLAS: Response Fit



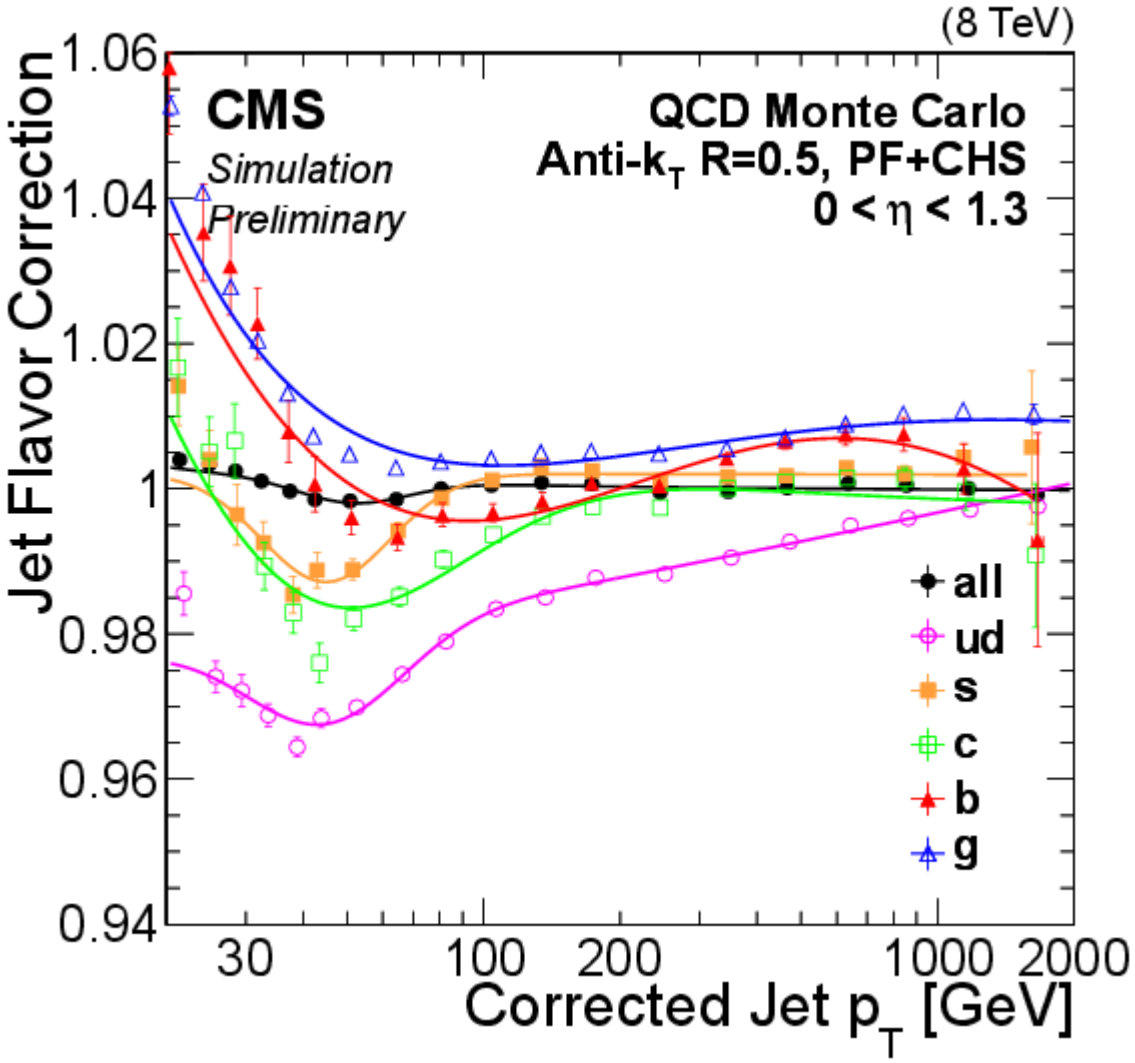
ATLAS: Rho distributions



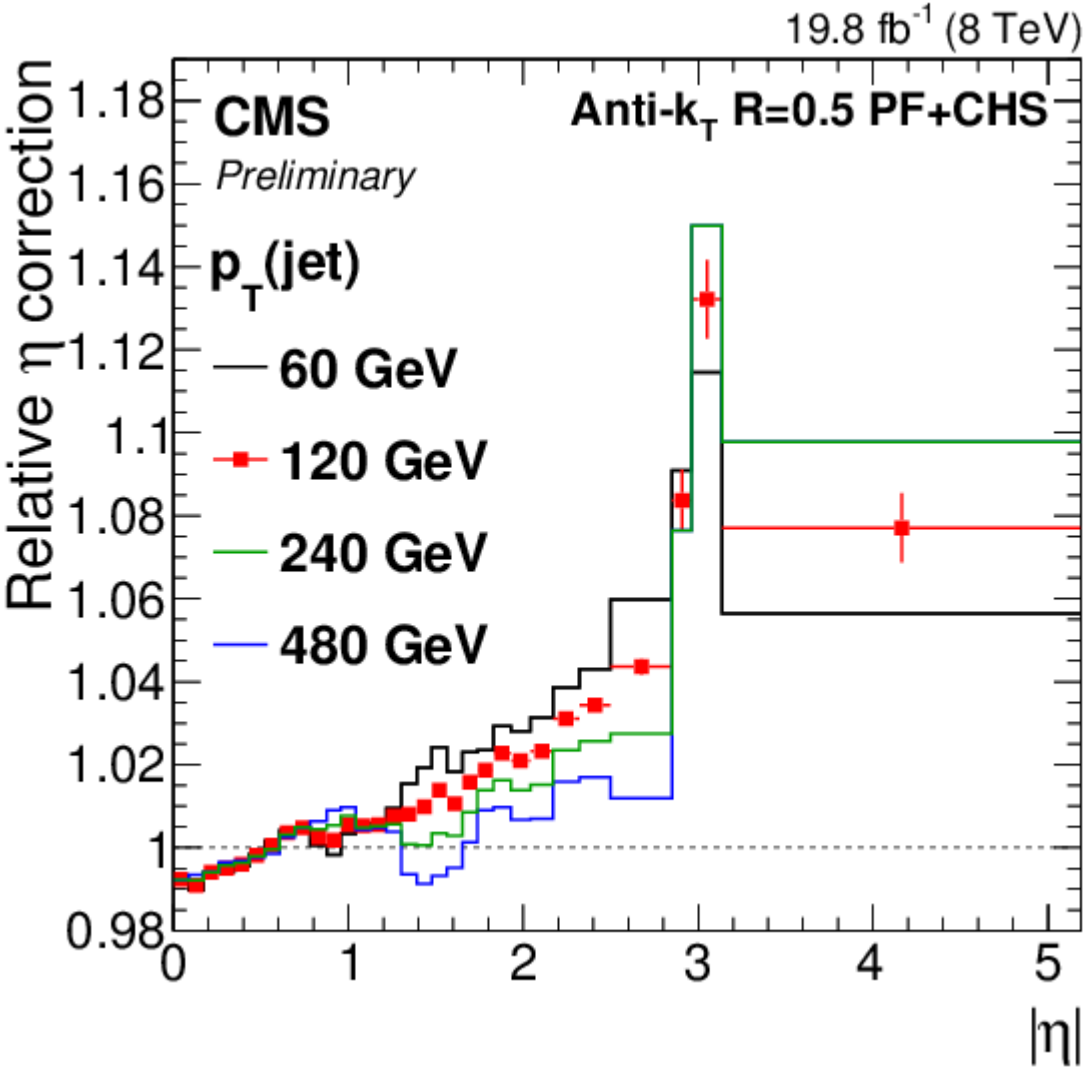
CMS: PU Offset



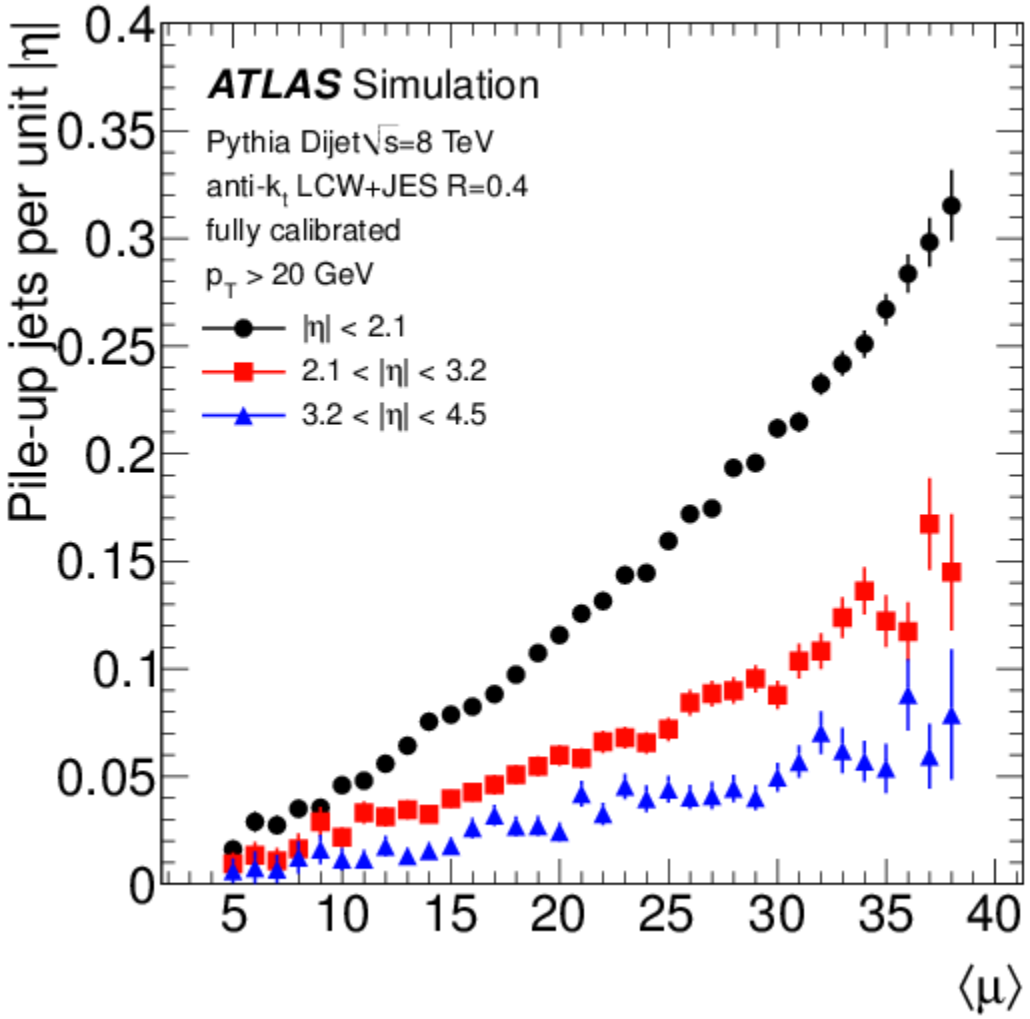
CMS: Flavour Response



CMS: Relative Corrections

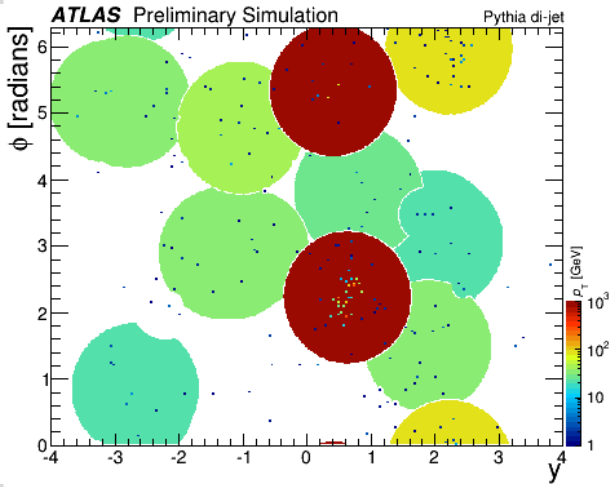


ATLAS: Pile-up Jets per η and μ

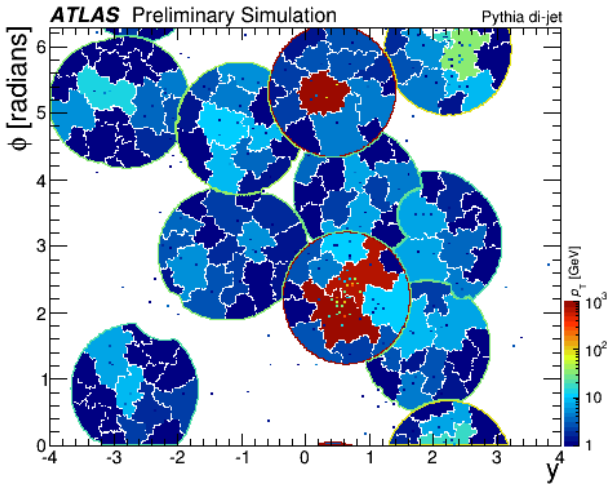


Jet Substructure

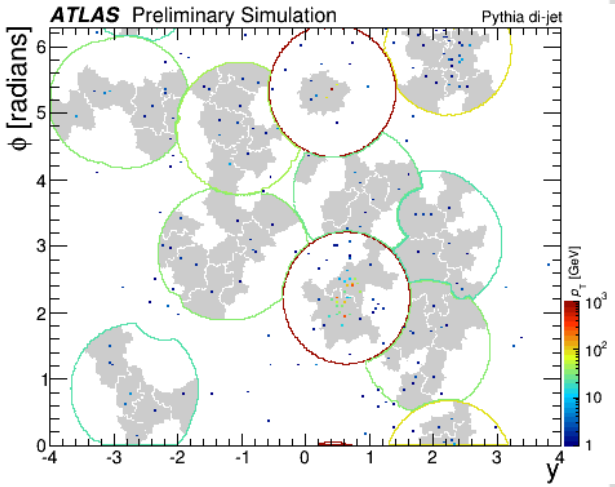
- Several techniques have been developed
- Grooming, Pruning, trimming (see below), ...



1. Large jets



2. identify subjets



3. remove low-pT subjets

- Explore substructure to increase understanding!

Plots