Jet finding techniques at LHC

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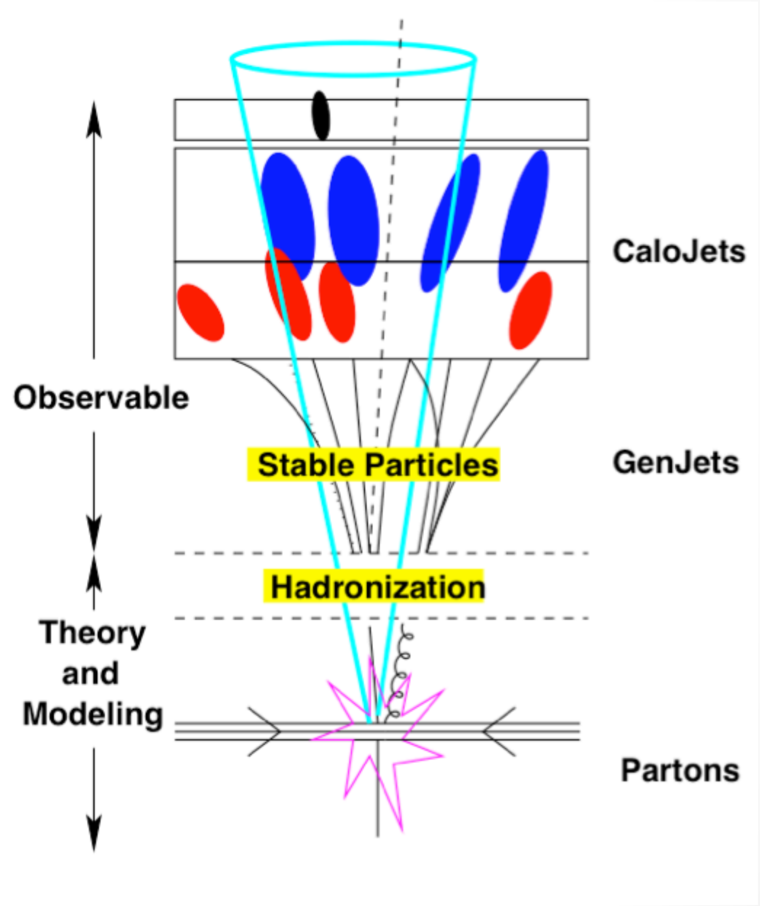
Outline

- Introduction
- ATLAS and CMS detectors
- Jet reconstruction and calibration
- Jet substructures
- Conclusion

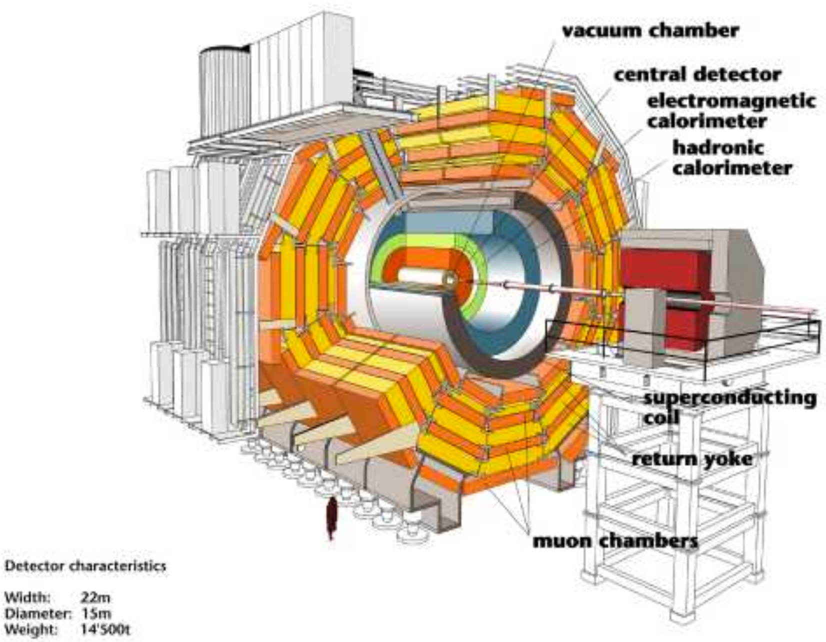
Introduction

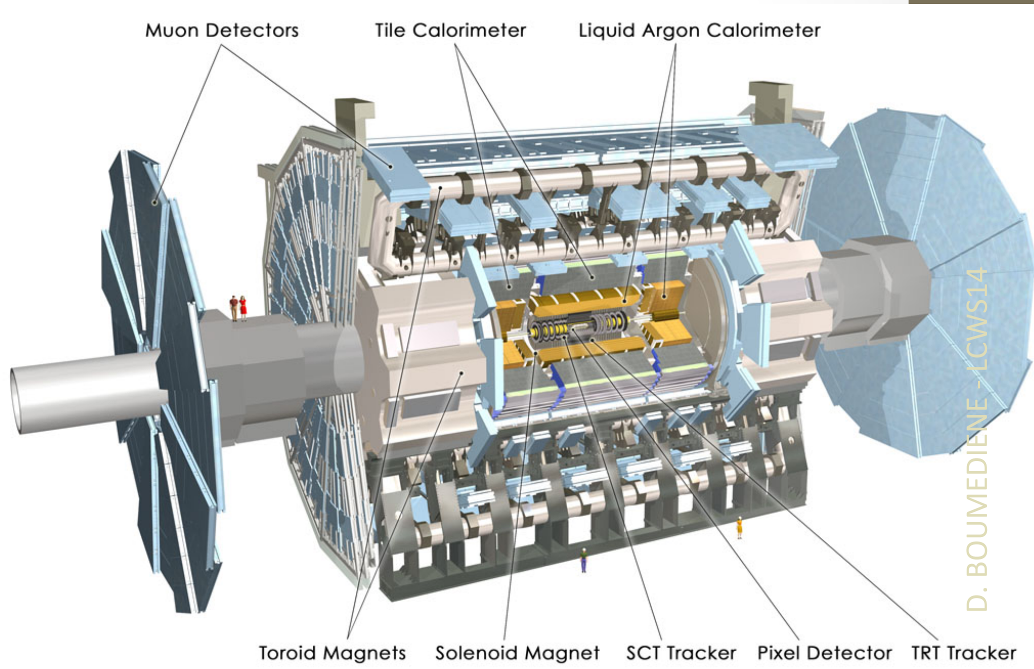
- Jets are collimated stable particles originating from partons (quarks & gluons)
- Reconstructed using algorithms
- Related measurements are corrected and calibrated



- LHC explores the TeV scale
- Many multi-jet final states
- Many models predict heavy particles which give a boost to their decay products leading to merged jets

ATLAS and CMS detectors

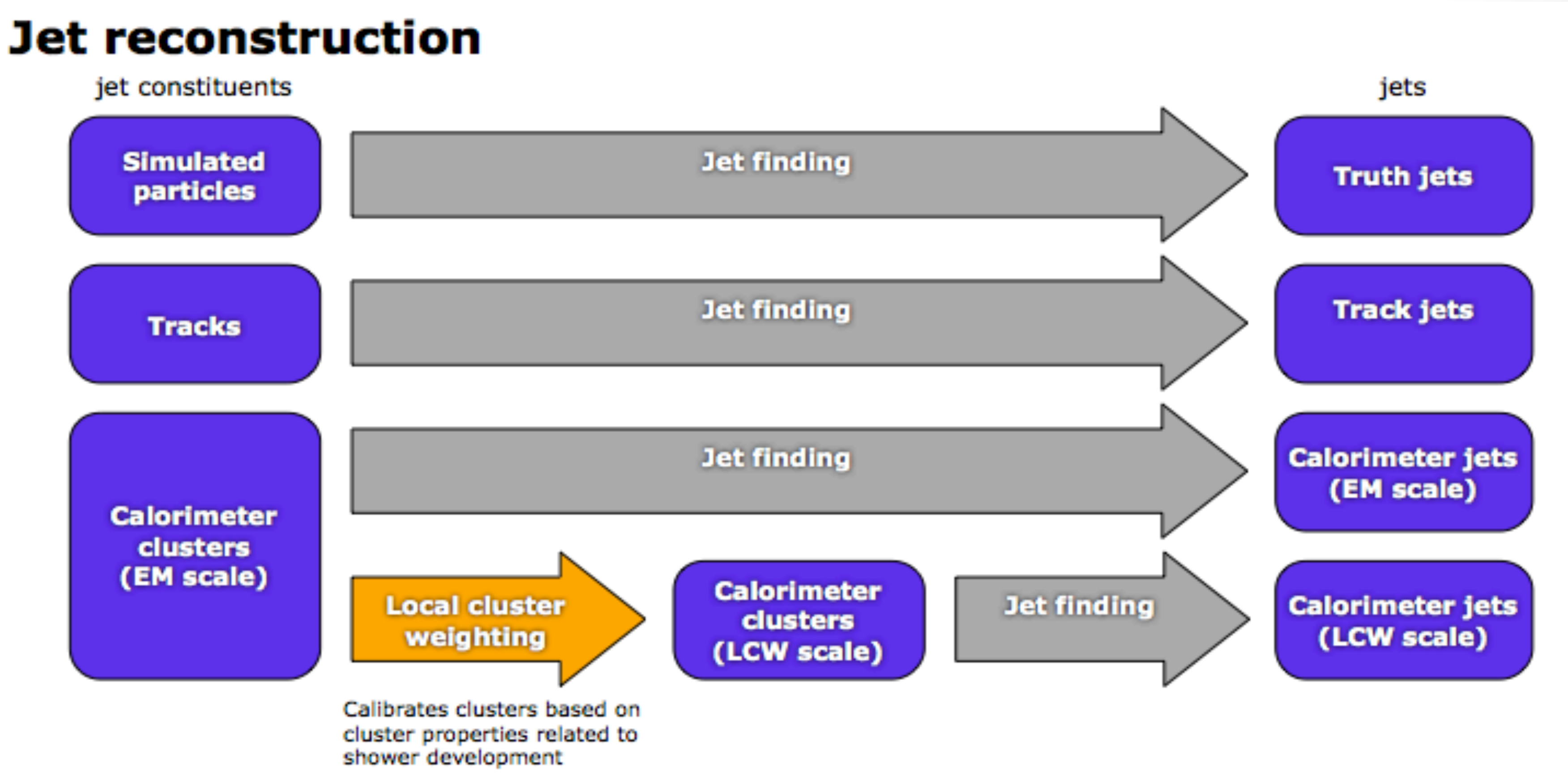




- 4T strong magnetic field
- Small Moliere radius in Ecal
- Precise tracking, calorimeters in Magnet

- Good intrinsic resolution on hadrons
- Hcal outside solenoid

Jets in ATLAS



ATLAS-CONF-2013-004

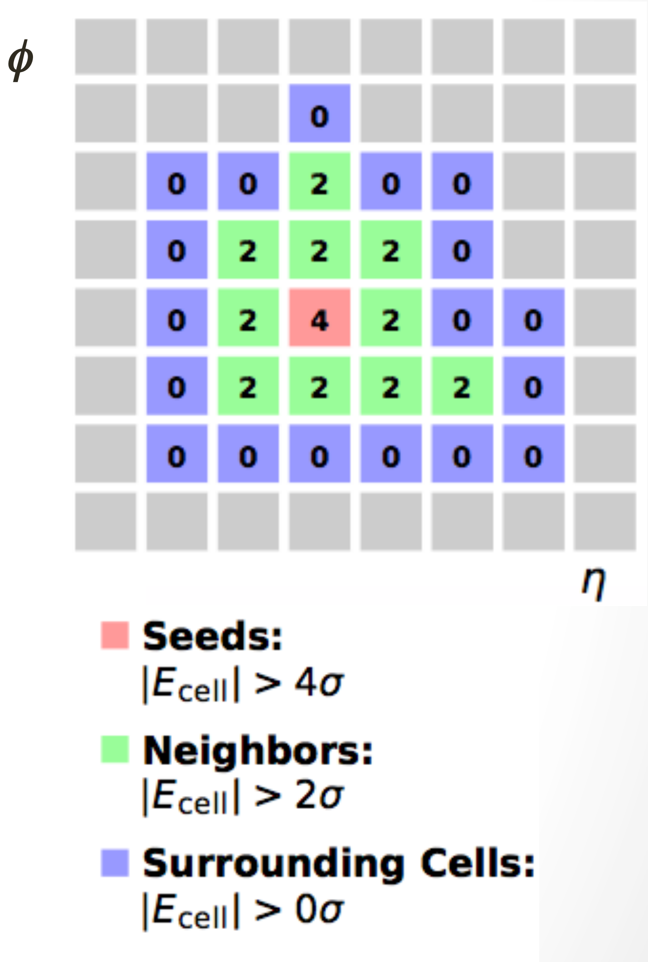
Calorimeter Jets in ATLAS

- 3D Topo-clusters:
  - Group of neighbouring calorimeter cells topologically connected.
  - Cells selected based on energy significance (|E|/σ) where σ is the cell noise

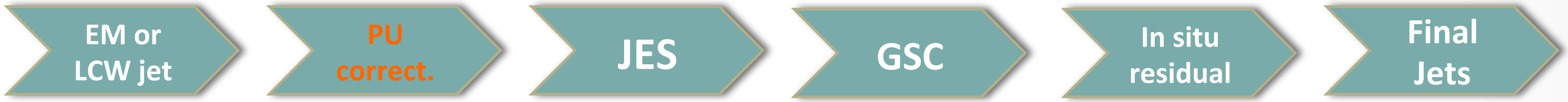
- Topo-cluster calibration:
  - EM scale
  - Identify hadronic clusters
  - Apply weights for hadronic response

  → defines Local hadronic Cluster Weighting scale (LCW scale)

- Calibrated Topo-clusters used as inputs for anti-kt R=0.4 or 0.6 jets



Jet calibration in ATLAS



- Starting from EM or LCW jets
- Jet area based **Pile-Up (PU) correction**

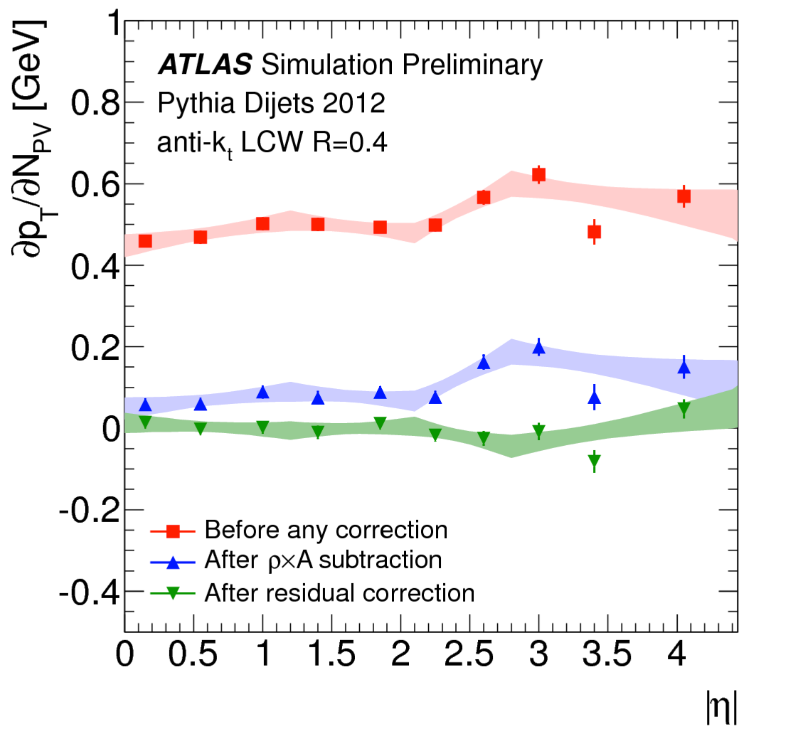
  - 2012: Jet-areas correction of event-by-event fluctuations, same for all jet definition (modulo residual correction)

    $p^{corr}_T = p_T - A.\rho$ where ρ=Median p_T density

    + residual offset correction.

  - In 2011: Only average correction parametrised by Number of Primary Vertices (NPV) and <μ>

ATLAS-CONF-2013-083



Jet calibration in ATLAS

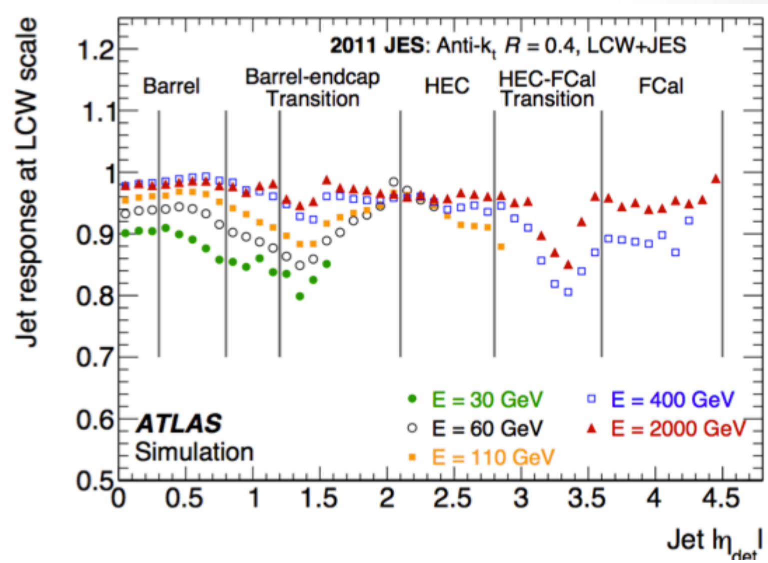
EM or LCW jet → PU correct. → **JES** → GSC → **In situ residual** → Final Jets

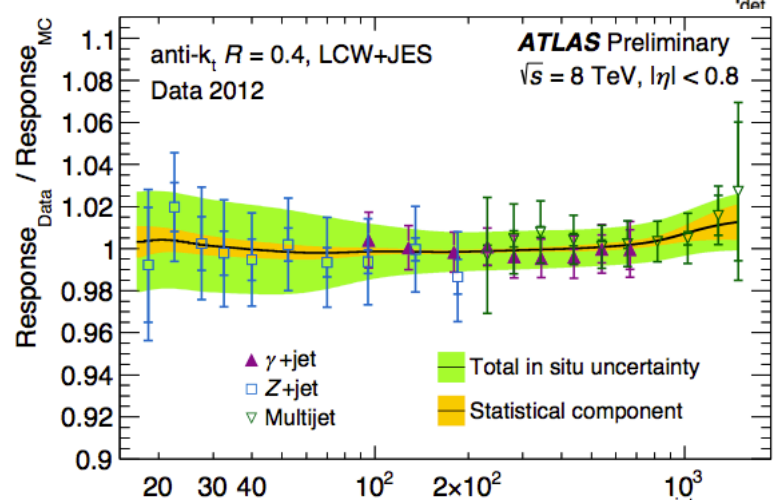
- **Jet Energy Scale (JES)**: calibration through multiplicative factor based on jet response.
  - E, *p*T dependent correction factors
  - Energy and η corrections

$$R^{\mathrm{EM(LCW)}} = \left\langle \frac{E_{\mathrm{jet}}^{\mathrm{EM(LCW)}}}{E_{\mathrm{jet}}^{\mathrm{truth}}} \right\rangle$$

- Residual **in-situ calibration** applied to data only.
  - Based on correction factor:
  - Exploit *p*T balance between jet and reference object.

$$\frac{\mathrm{Response}_{\mathrm{MC}}}{\mathrm{Response}_{\mathrm{Data}}} = \frac{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{MC}}}{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{Data}}}$$

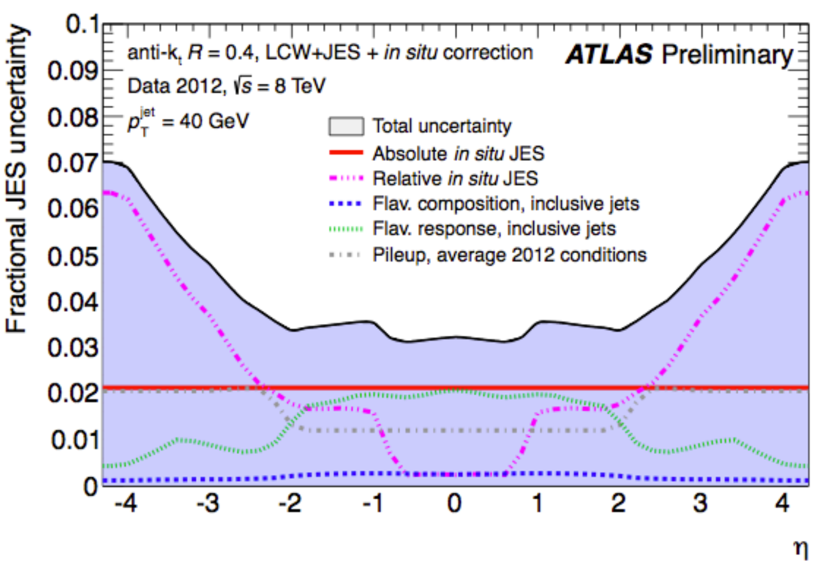


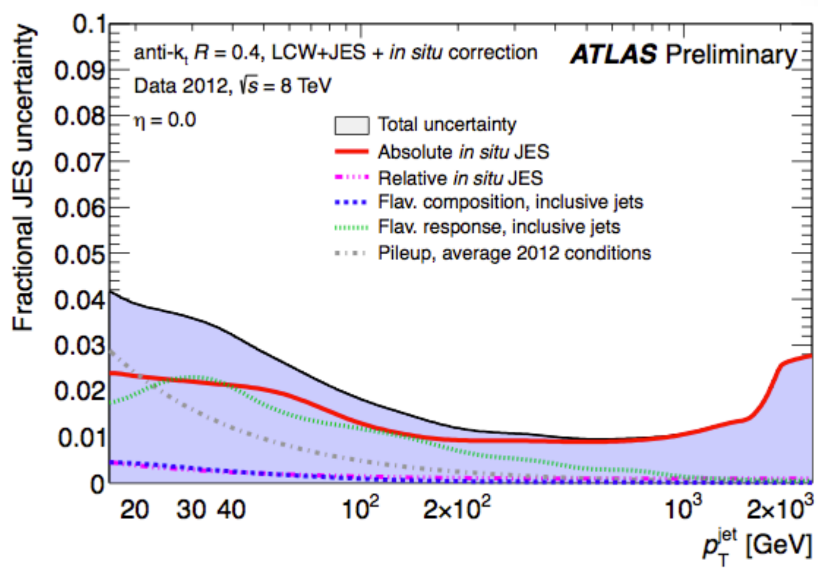


ATLAS-CONF-2013-004

JES performance

- Jet Energy Uncertainty components can be sorted in 3 main categories:
  - In situ JES
  - Flavour composition and response
  - Pileup uncertainty

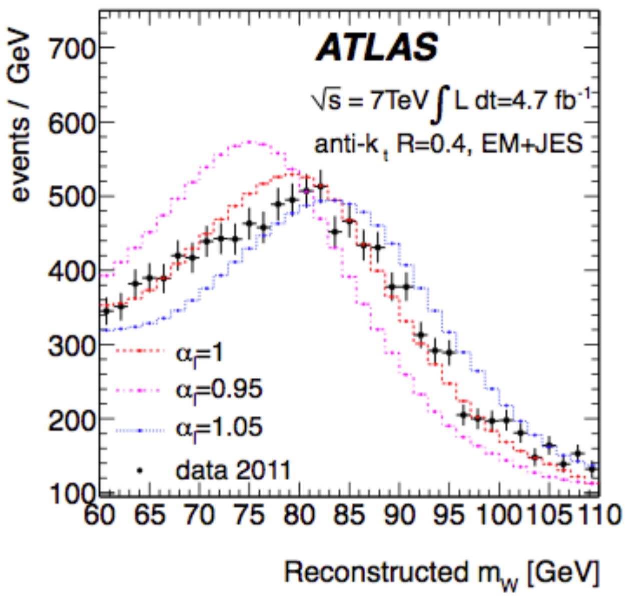


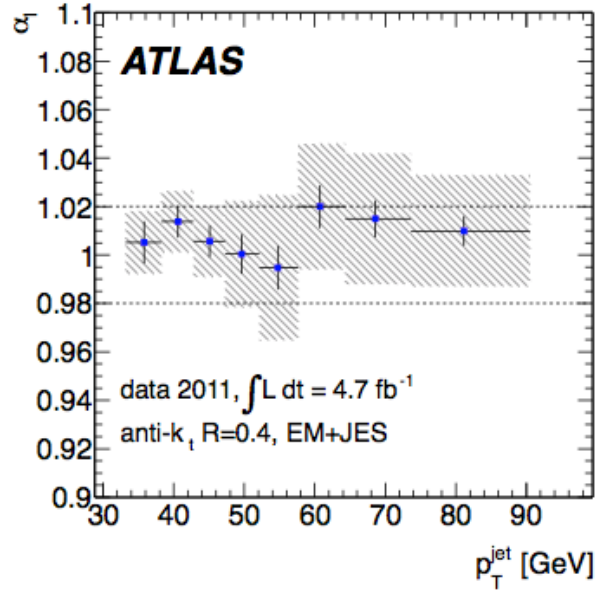


ATLAS-CONF-2013-004

Performance with top events

- Cross-check using W decaying into jet pairs in top events
- W mass peak is sensitive to the JES



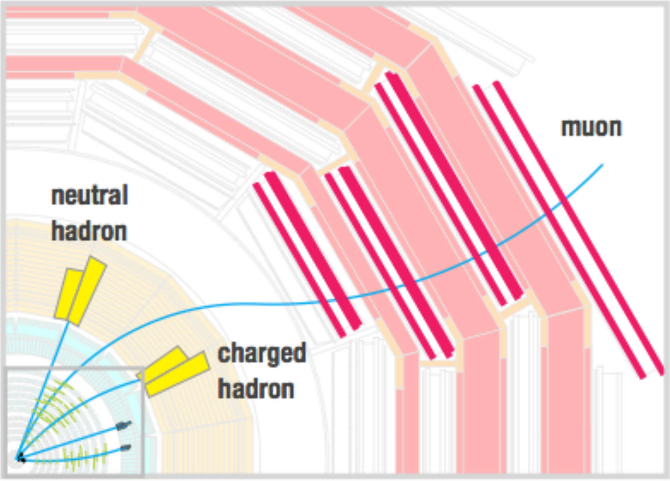


- Relative light JES is extracted, binned in pT, η
- Mean $\alpha_l = 1.0130 \pm 0.0028 \pm 0.027$

arXiv:1406.0076v2, Submitted to European Physics Journal C

Jet reconstruction in CMS

- Particle Flow (PF) algorithm:
  - Primary reconstruction algorithm in CMS
  - Uses all CMS detector subsystems
  - Reconstructs four momenta of all visible stable particles → PF candidates
  - Identifies each candidate as muon, electron, charged hadron, photon, or neutral hadron

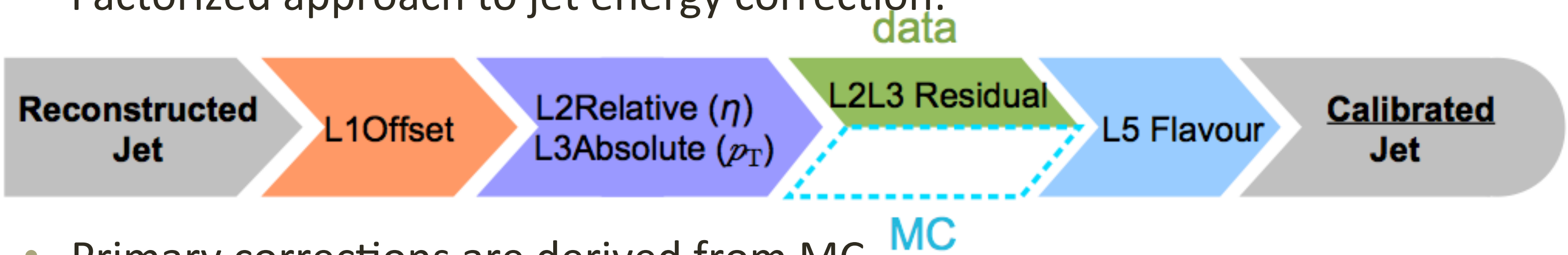


- PF particles are clustered with jet algorithms (anti-kT)
- PF jet 4 momentum is the sum of PF particles momenta

$$p_\mu^{\mathrm{raw}} = \left(\sum_{i \in \mathrm{jet}} E^{\mathrm{i}}, \sum_{i \in \mathrm{jet}} p_x^{\mathrm{i}}, \sum_{i \in \mathrm{jet}} p_y^{\mathrm{i}}, \sum_{i \in \mathrm{jet}} p_z^{\mathrm{i}} \right)$$

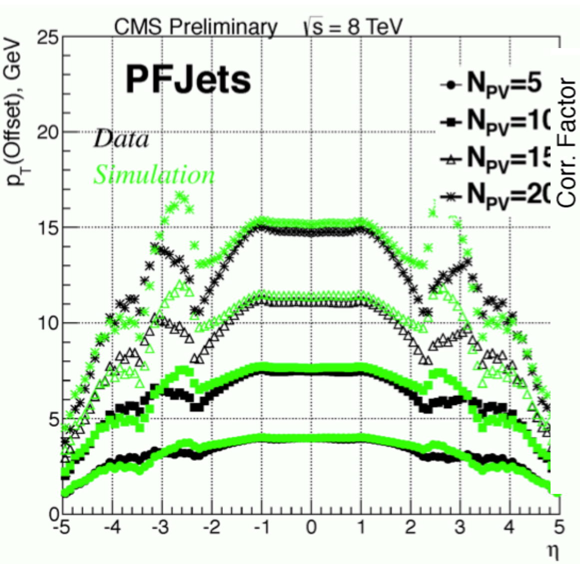
Jet energy corrections in CMS

- Factorized approach to jet energy correction:

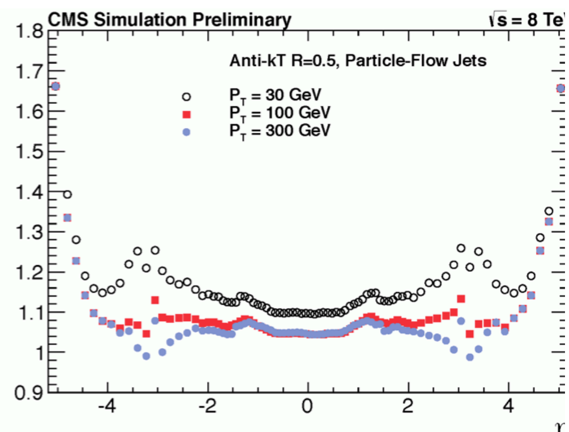


- Primary corrections are derived from MC
- Residual corrections describe Data MC differences

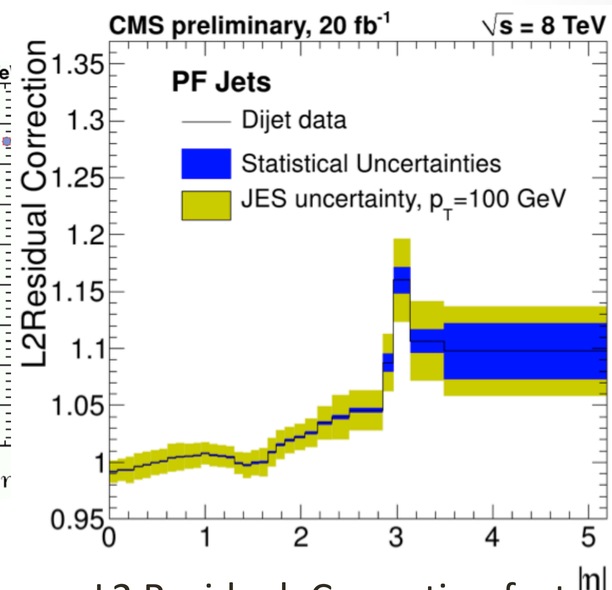
CMS-DP-2013-33



L1Offset: Estimate pT offset in bins of η and NPV



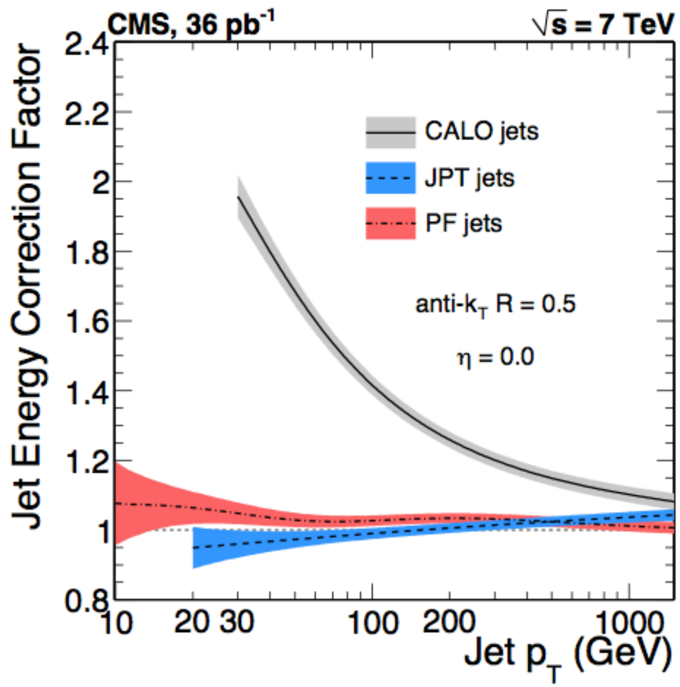
L2L3 MC corrections: η, pT dependent scaling factor fully derived from MC

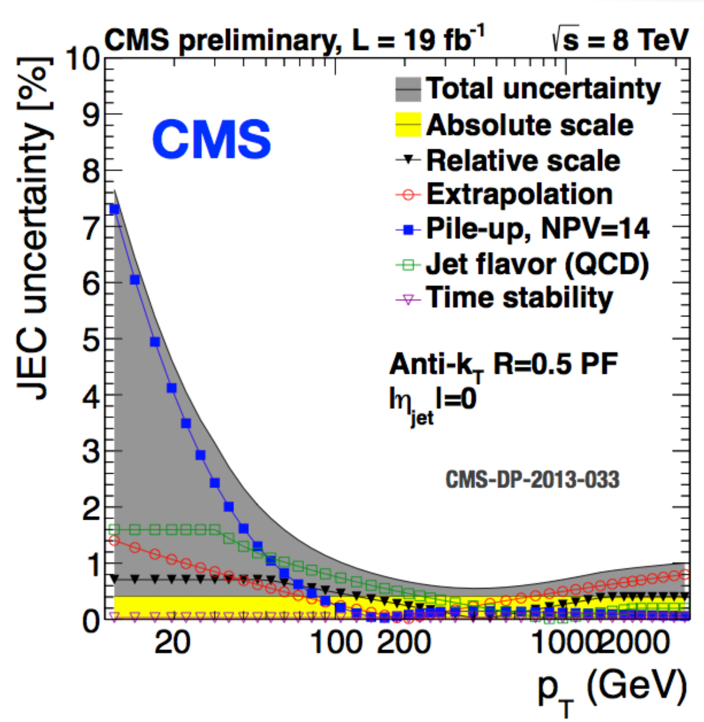


L2 Residual: Correction factor derived from dijet-balancing

Performance

CMS-DP-2013-033





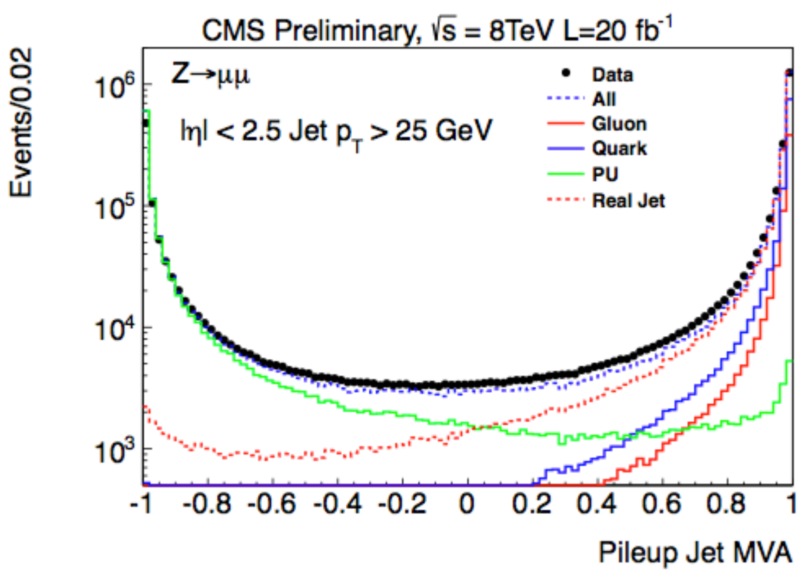
- PF jets have small correction factors (compared to CMS calo jets)
- Larger pileup uncertainty in low pT region
- MC JES uncertainty @ 100 GeV extrapolated to high pT region

Pileup jet suppression

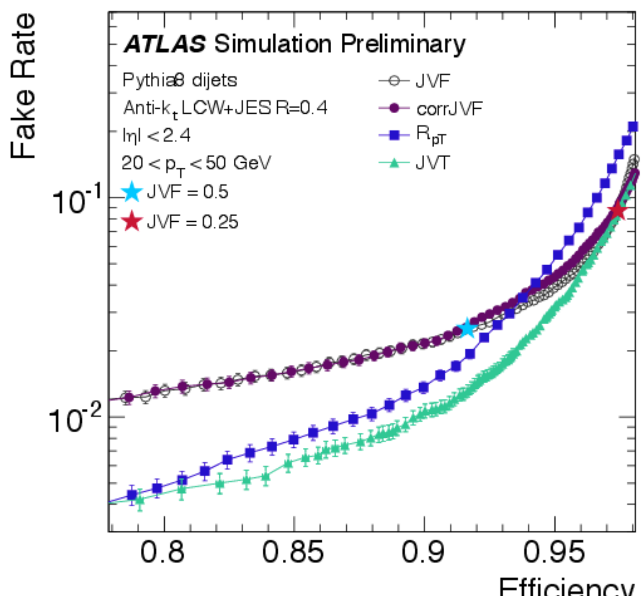
- ATLAS during run 1: Use of track based variable: Jet Vertex Fraction (JVF)
  - Fraction *p*T from tracks associated with the hard-scatter vertex
  - Sensitive to <μ>
  - JVF was used to reject Pileup jets

- ATLAS for run 2: Use of a new estimator, the Jet Vertex Tagger (JVT)
  - 2D Likelihood defined in space using track based information (including the JVF)
  - Using a set of hard-scatter and PU jets as training sample

- CMS: Pile-Up rejection with MVA discriminator combining jet kinematical and shape variables



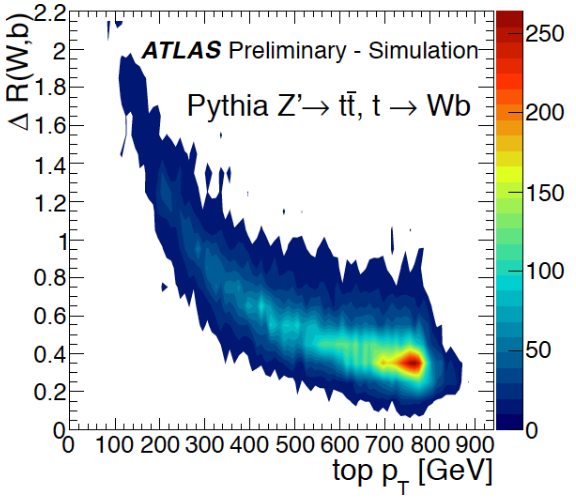
CMS PAS JME-13-005

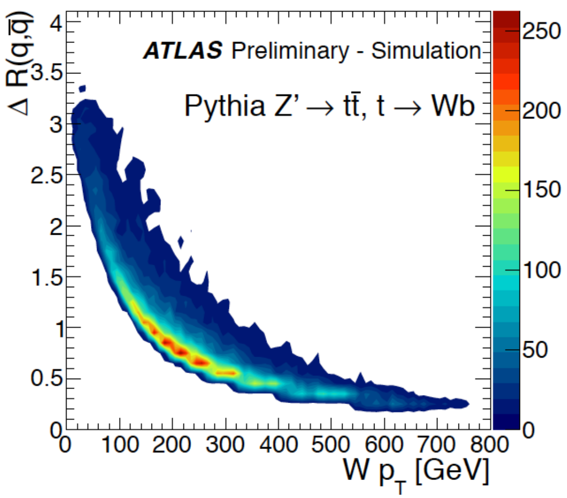


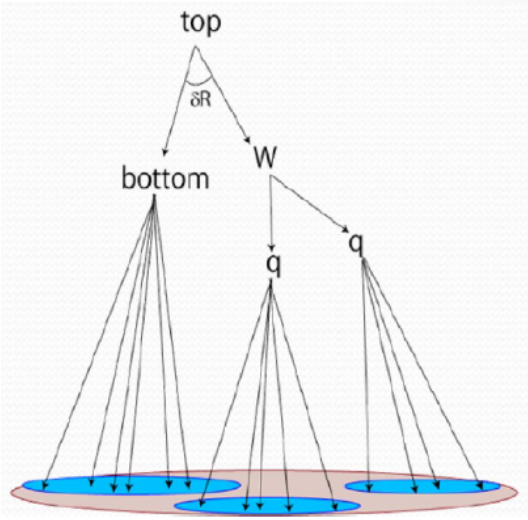
ATLAS-CONF-2014-018

Jet substructure in ATLAS and CMS

- At LHC, a heavy particle will give a boost to its decay products:
  - Boosted top, Higgs or W lead to overlapping jets → merged in one “fat” jet



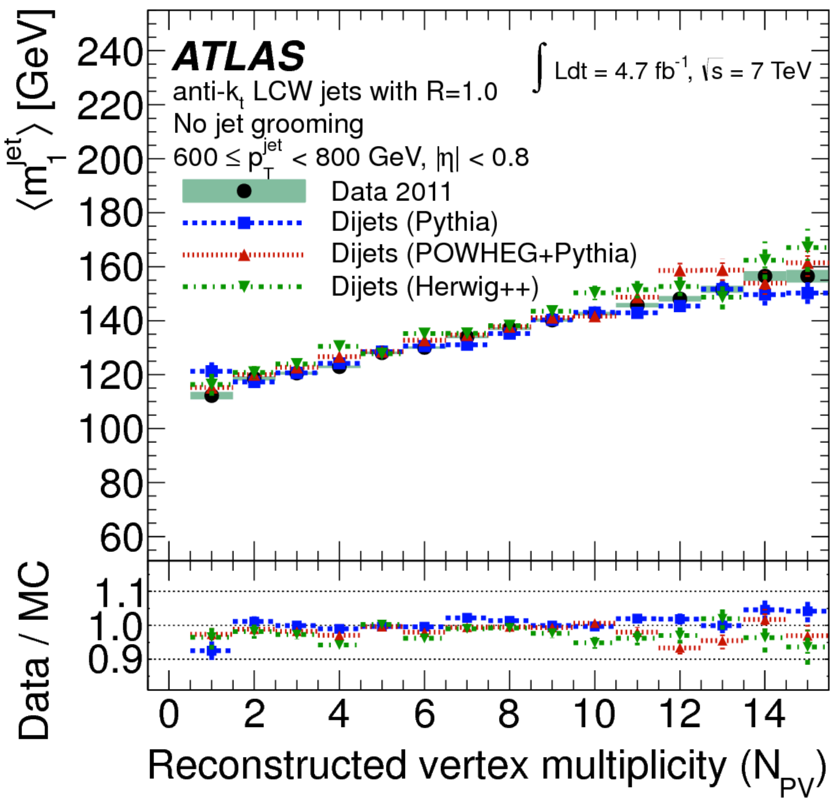


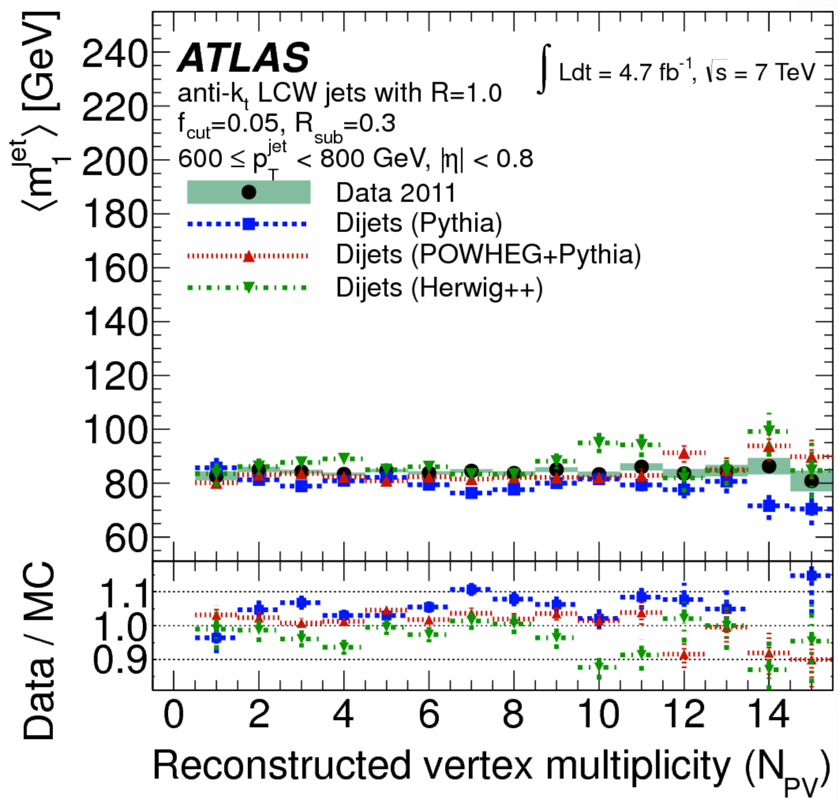


- Because of small distance between overlapping objects : dedicated tools and reconstruction are required
- Large radius jets + substructure studies:
  - Grooming → remove soft components in the jet and improve reconstruction.
  - Tagging → test if structure properties likely to come from a heavy particle of interest.

Grooming techniques against Pile-Up

- *Grooming* reduces the effective jet area, rejecting soft energy deposits
- This helps to uncover any hard substructure in the jet
- Jet *grooming* techniques provide better energy and mass resolution.
- Dependence to the number of primary vertices reduced





arXiv:1306.4945

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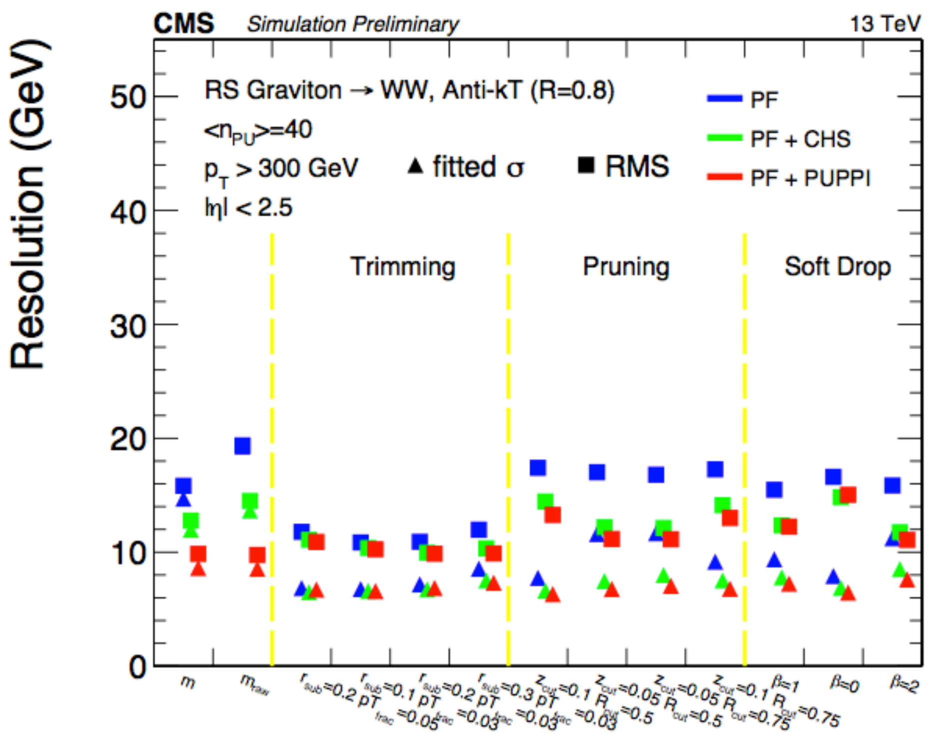
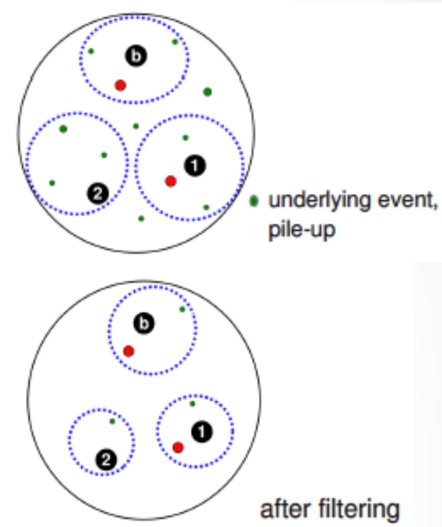
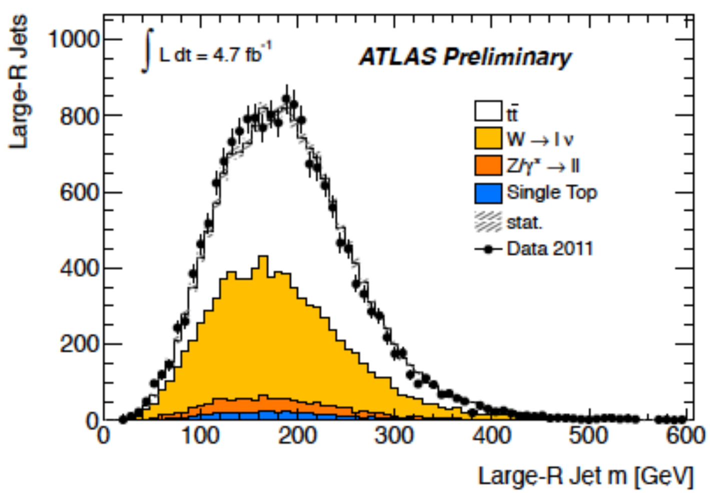


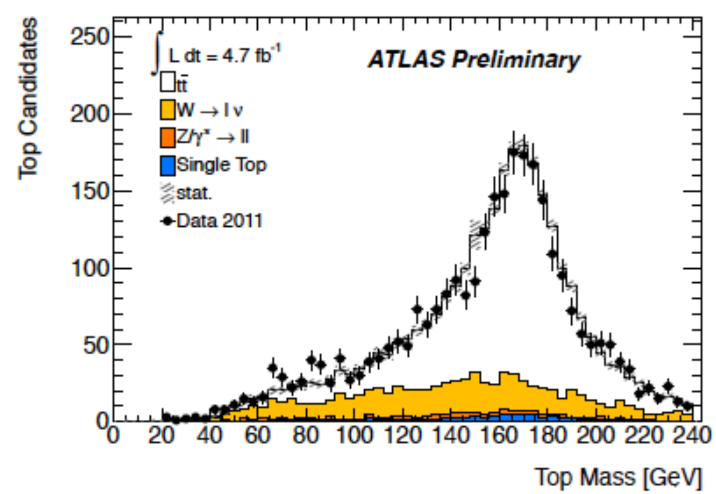
CMS PAS JME-14-001

Fat jets from Top in ATLAS

- Jet filtering and splitting (HEPTopTagger or HTT):
  - Starting from fat jets with Cambridge/Aachen (CA)
  - Iterative clustering with minimal mass cut at 50 GeV
  - Rejection of underlying event/pileup deposits
  - Sub-jets reconstruction
  - Recluster to 3 sub-jets with mass constraints







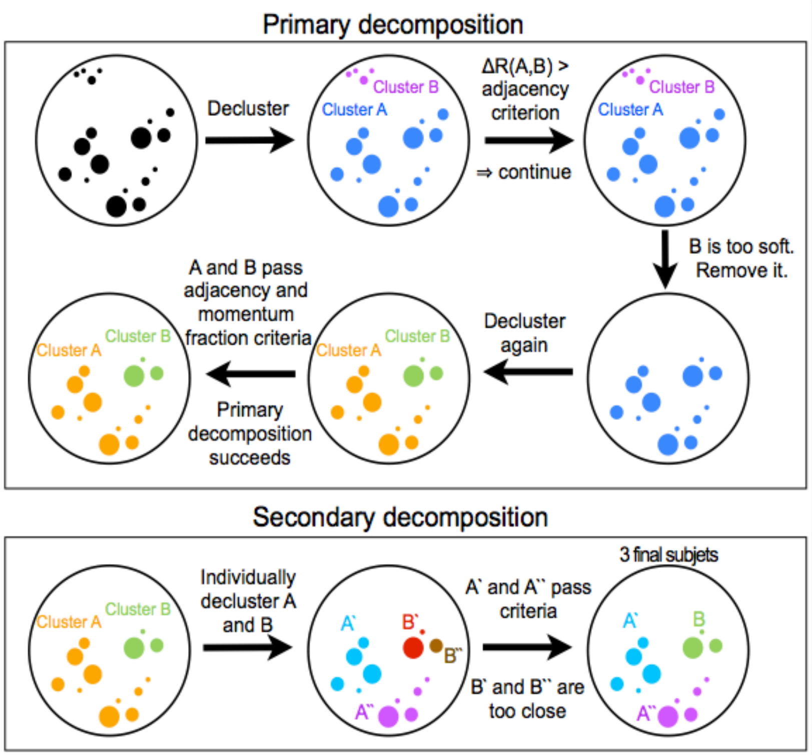
- HTT is also used in CMS

Using HEPTopTagger

ATLAS-CONF-2012-065

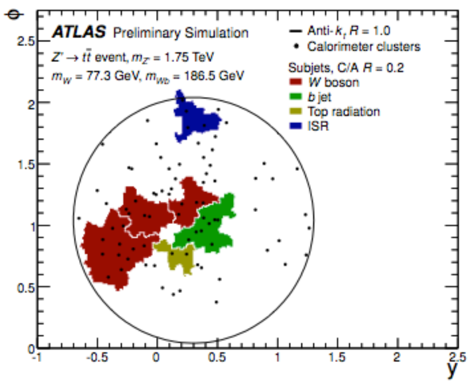
Fat jets from Top in CMS

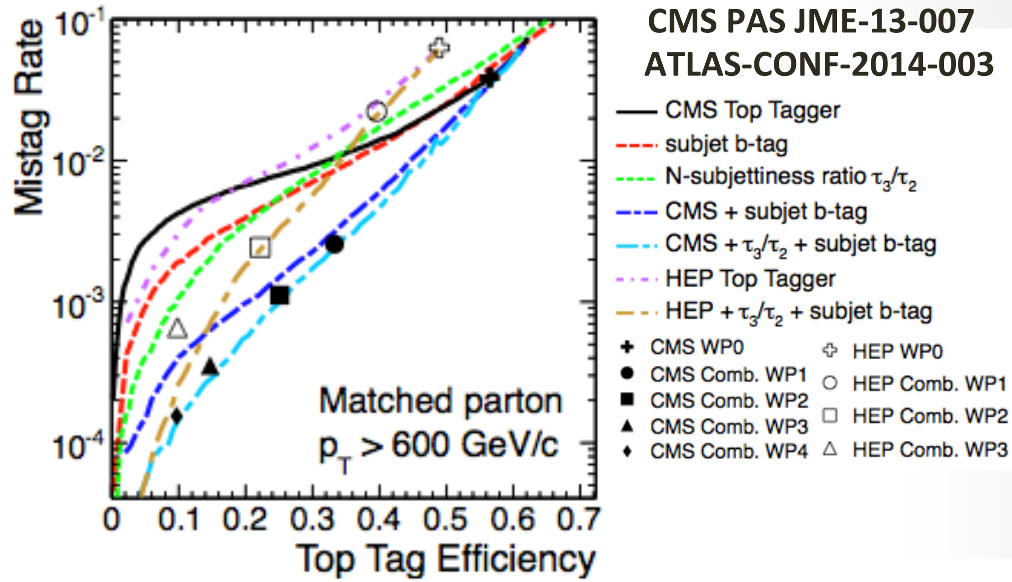
- CMS Top tagger
- Input CA R=0.8 jets
- Primary decomposition: find 2 well separated sub-clusters with significant p_T fraction
- If succeeds then do secondary decomposition
- Top tagged if jet mass close to top mass, at least two subjects and with a masse close to the W mass

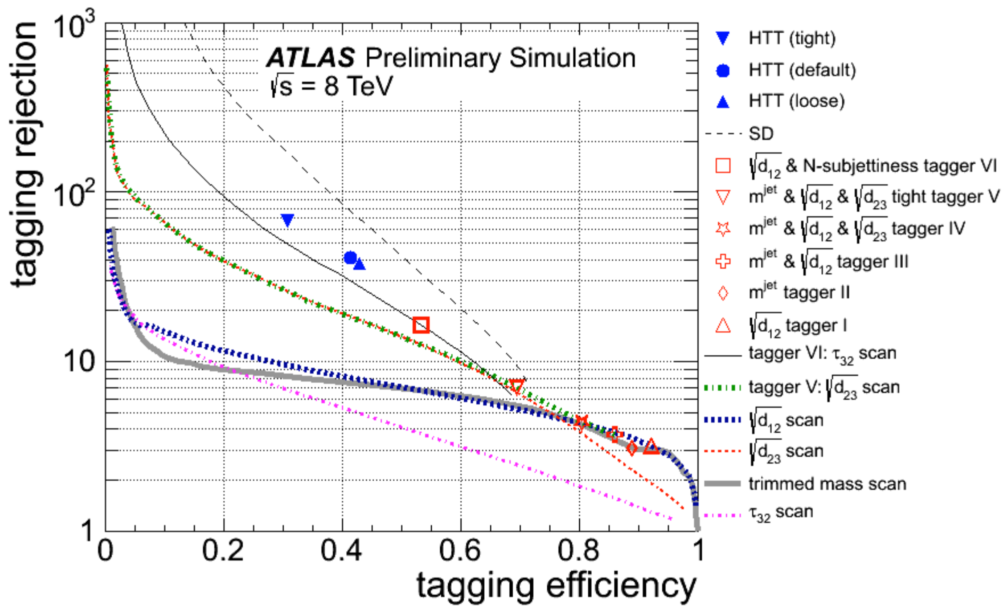


Fat jets in ATLAS and CMS

- Shower deconstruction (SD): Calculate the probability for the association between a subjet and a particle







- Performance comparisons of many algorithms:
  - ATLAS: HTT, SD, …
  - CMS: HTT, SD, CMS Top Tagger, ...
- Possible to use W taggers, Higgs taggers

Conclusion

- LHC physics requires efficient and precise jet measurements
- Jet finding techniques are adapted to the detectors:
  - Calorimeter jets with topo clusters which use the good calorimeter resolution to hadrons in ATLAS
  - Particle flow jets which use the precise tracker and the precise calorimeter track matching in CMS
- Jet calibration and correction take into account high pileup environment
- Energy scales explored at LHC can lead to fat jets: dedicated algorithms were developed and will become more and more important as LHC will restart at 13 TeV