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West Coast ATLAS Forum – September 7, 2011

Jets in ATLAS: Reconstruction, Calibration and Characterization

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Roadmap to Jets in ATLAS

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Jet reconstruction

- Understanding input signals from calorimetry and tracking
- Calorimeter energy scales
- Jet definitions

Jet calibration

- Calibration approach
- Jet energy scale and its uncertainties
- Performance evaluation in collision environment

Characterization of jets

- Jet fragmentation
- Jet mass and shape
- Jet substructure

Conclusions & outlook

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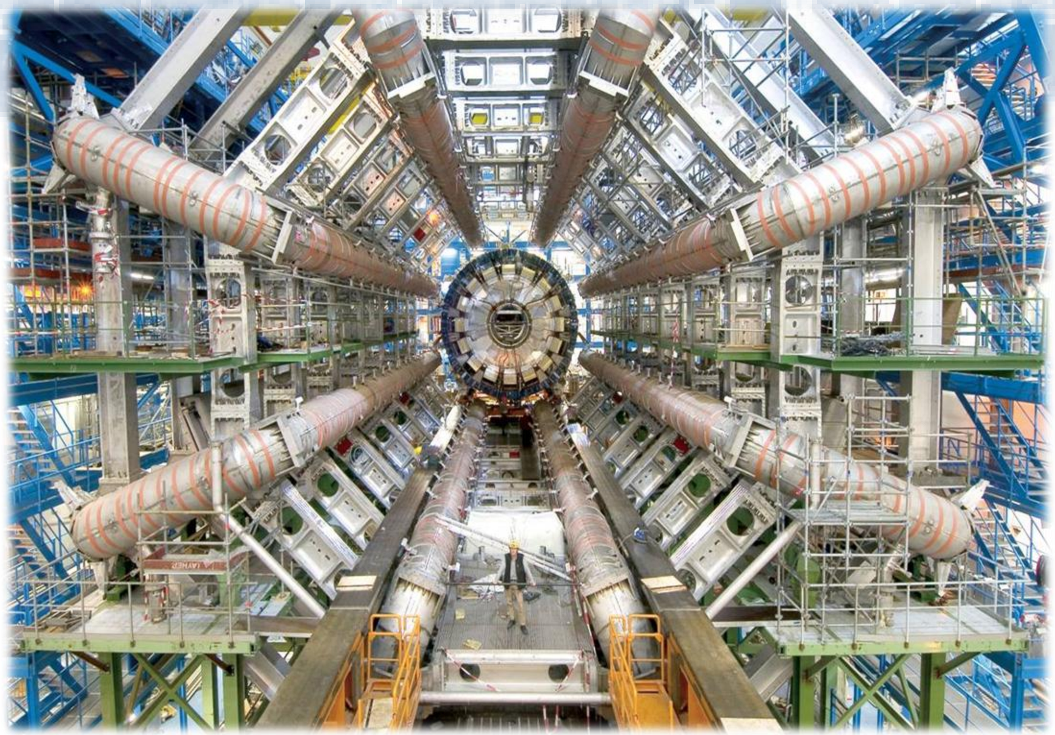
The ATLAS Detector



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ATLAS

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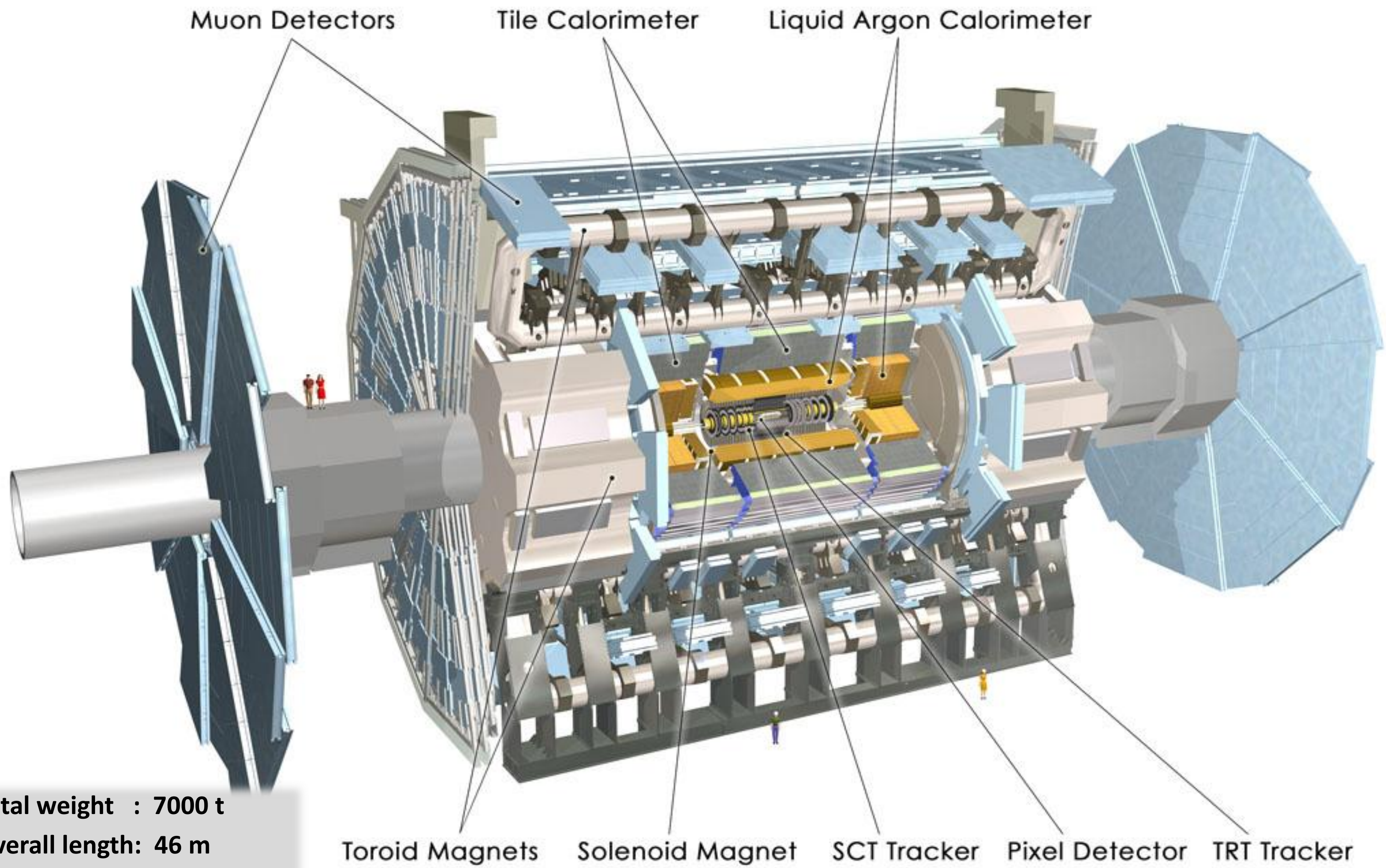

Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

The ATLAS Calorimeter

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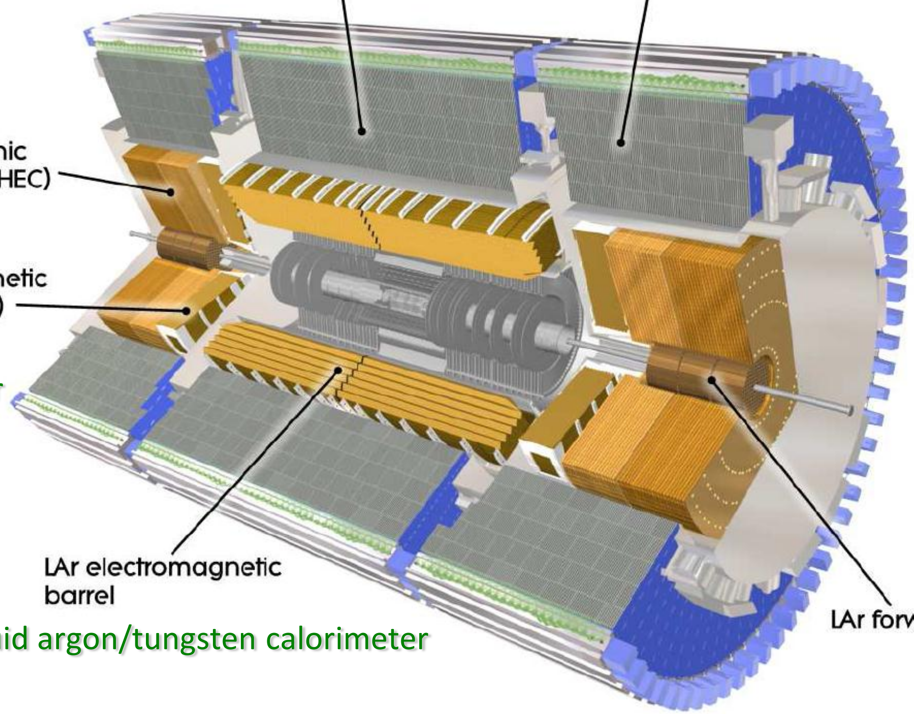
Basic calorimeter setup

- Large full coverage calorimeter system
  - |η|<4.9 pseudorapidity coverage
  - No azimuthal cracks & discontinuities
- Mixed technologies matching precision requirements
  - Electromagnetic liquid argon/lead calorimeters with accordion absorber
  - Central hadronic iron/scintillator calorimeter with tiled sampling structure
  - Hadronic liquid argon/copper with parallel plate absorbers
  - Forward liquid argon/copper and liquid argon/tungsten calorimeter with tubular electrodes



Basic calorimeter readout features

- Low noise readout with fast shaping time
  - High sensitivity to small energy deposits
  - Pile-up suppression by bi-polar signal shaping (LAr) or fast uni-polar shaping (tile)
- Non-compensating calorimeters
  - Typical e/π signal ratio is 1.3
- Highly granular detector with up to 7 longitudinal segments
  - Allows measuring electromagnetic and hadronic shower shapes
  - About 190,000 individual readout channels
  - Allows for dynamic calibration approach for hadrons and jets

ATLAS Calorimetry

Electromagnetic Calorimetry $|\eta| < 3.2$

- Pb/LAr calorimeters (accordion sampling)
- 22-26 X_0 , 1.2 λ
- 3 longitudinal sections
- $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025 \rightarrow 0.1 \times 0.1$
- $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Central Hadronic Calorimetry $|\eta| < 1.7$

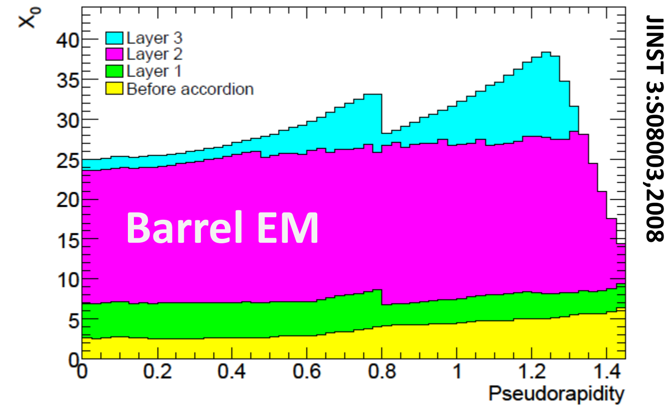
- Fe/scintillator calorimeter (tiled sampling)
- $\approx 7\lambda$
- 3 longitudinal sections
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1 \rightarrow 0.2 \times 0.1$
- $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

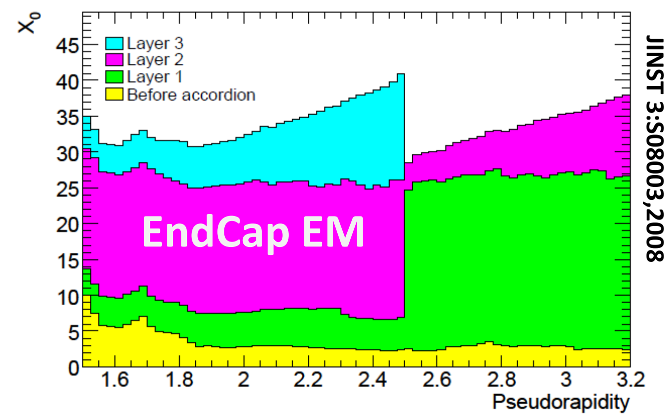
Endcap Hadronic Calorimetry $1.7 < |\eta| < 3.2$

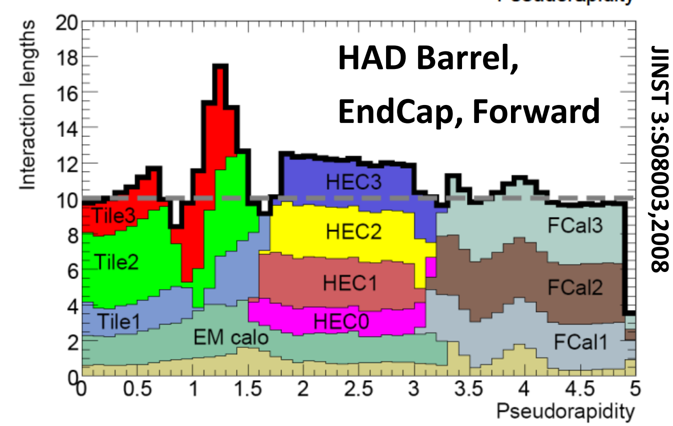
- Cu/LAr calorimeter (parallel plate sampling)
- $\approx 10\lambda$
- 4 longitudinal sections
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1 \rightarrow 0.2 \times 0.2$
- $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

Forward Calorimetry $3.2 < |\eta| < 4.9$

- Cu/LAr, W/LAr calorimeters (tube sampling)
- $\approx 10\lambda$
- 1 EM + 2 HAD longitudinal segments
- $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2 \rightarrow 0.4 \times 0.4$ (non-pointing)
- $\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$



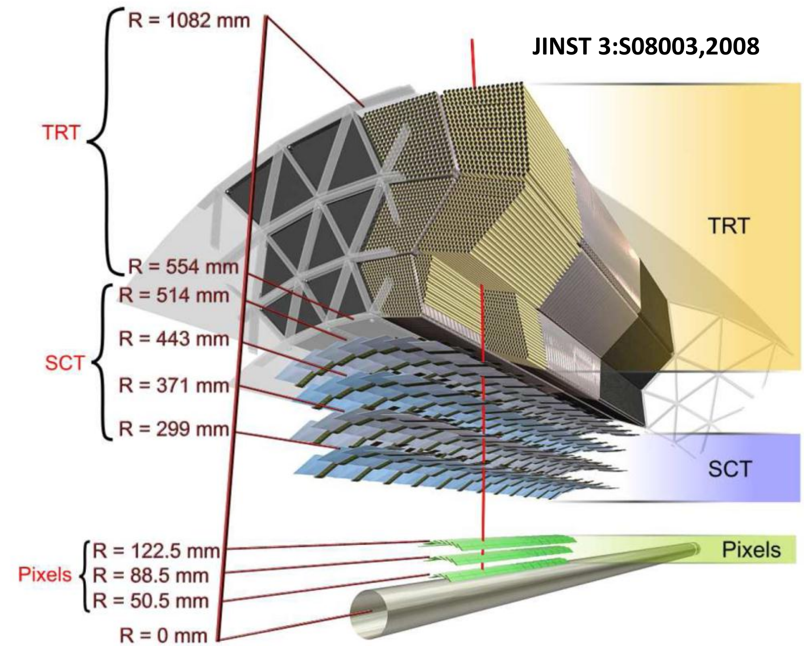




ATLAS Tracking

Inner detector |η|<2.5

- Silicon Pixels
  - High precision tracker
  - 3 cylindrical layers central
  - 2 x 3 disks end-cap
- Silicon Microstrip Tracker (SCT)
  - High precision tracker
  - 4 cylindrical layers central
  - 2 x 9 disks end-cap
- Transition Radiation Tracker (TRT)
  - Large radius tracking
  - 73 straw planes central
  - 160 straw planes end-cap



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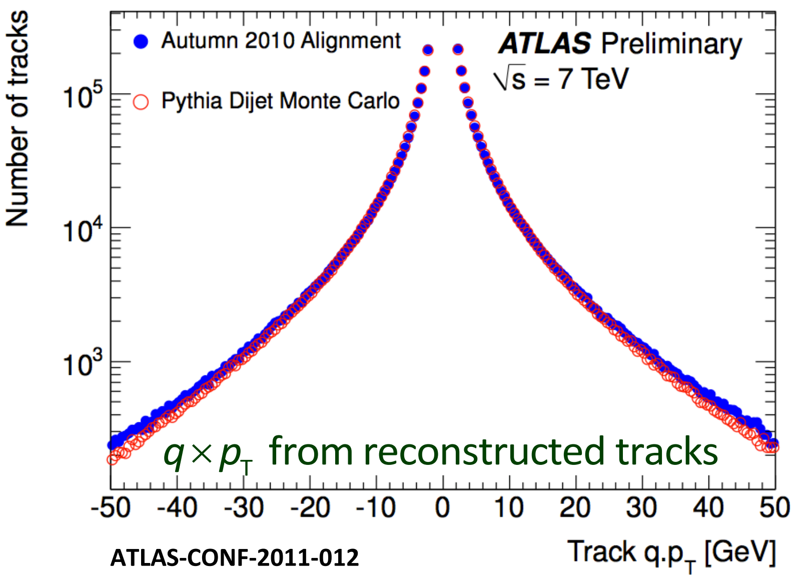

$q \times p_T$ from reconstructed tracks

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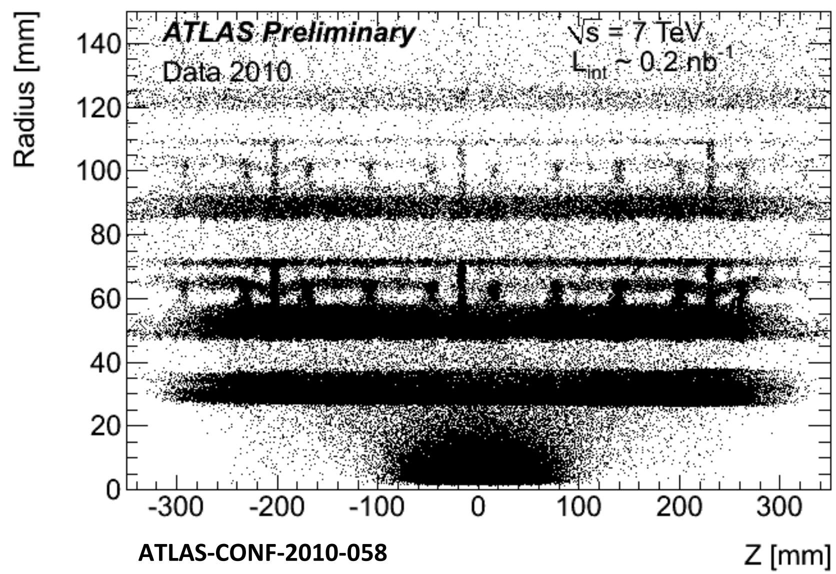

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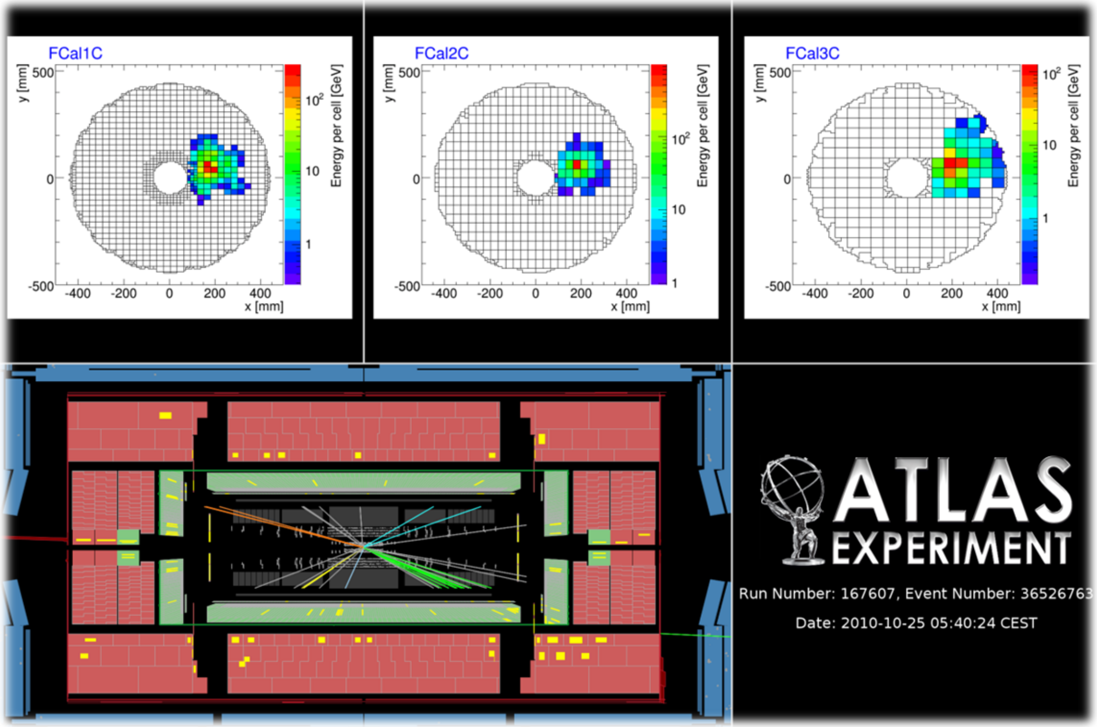
Jet Reconstruction in ATLAS



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Calorimeter Signals (1)

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Calorimeter cells

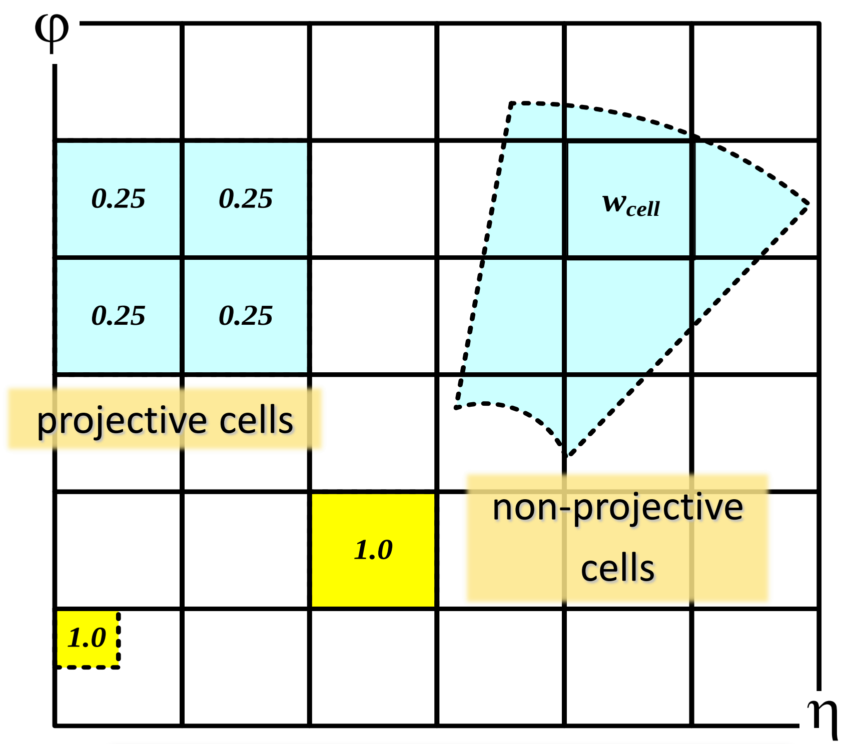
- Smallest reconstructed independent signal unit
  - Associated with 1 (LAr) or 2 (Tile) readout channels
  - Provides basic energy, timing and signal quality
- Representation in ATLAS
  - Associated with space point in detector – converted to directions with vertex assumption
  - Massless four-momentum (E = p)
- Limitations
  - Individual cell signals in non-compensating calorimeters hard to understand without context

Calorimeter towers

- Project cell directions onto regular grid
  - $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- Sum weighted cell energies in bin
  - All cells or only cells surviving noise suppression
  - Applies geometrical weight for overlapping areas
- Massless pseudo-particle representation

Tower grid can be filled with all or selected cells only!

ATLAS rules for geometry weighted cell signal contribution when projecting cells onto the tower grid



$$E_{\eta\varphi} = \sum_{\left(A_{\text{cell}}^{\eta\varphi} \cap A_{\eta\varphi}\right) \neq 0} w_{\text{cell}} E_{\text{cell}}$$

$$w_{\text{cell}} = \begin{cases} 1 & \text{if } A_{\text{cell}}^{\eta\varphi} \leq \Delta\eta \times \Delta\varphi \\ <1 & \text{if } A_{\text{cell}}^{\eta\varphi} > \Delta\eta \times \Delta\varphi \end{cases}$$

Calorimeter Signals (2)

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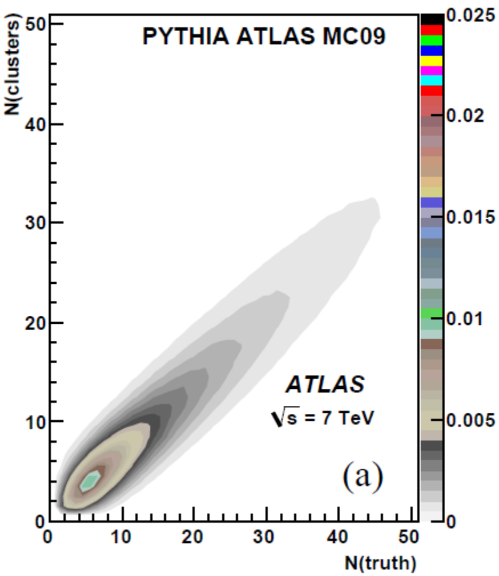
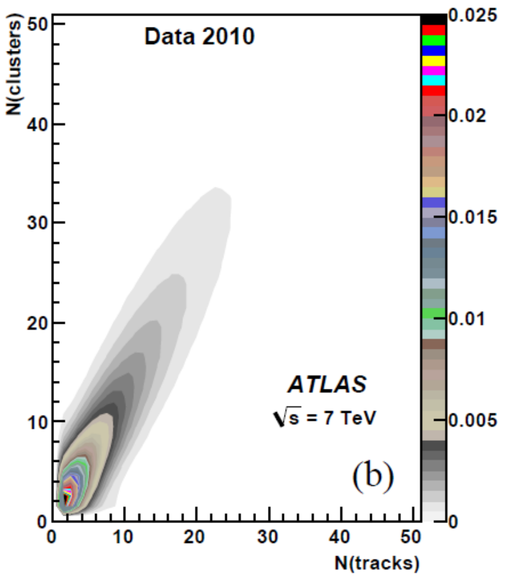
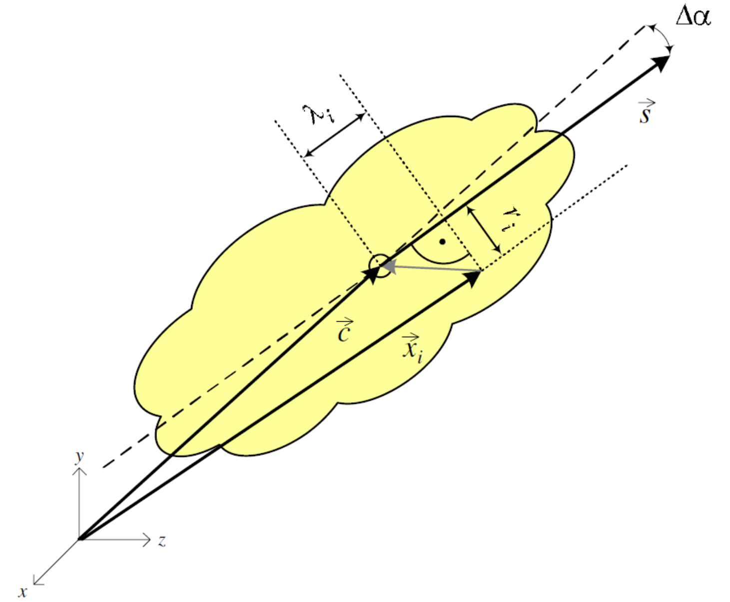
Topological cell clusters

- Attempt to reconstruct particle showers
  - Cluster grows around seeds following spatial signal patterns in 3 dimensions
    - Signal significance guides formation
  - Splitting algorithm applied to extract particle flow + shower structures
    - Split cluster between local maxima
  - Clustering algorithms derived from single particle signal distributions
    - Principal attempt to reconstruct particle showers
- Implement noise suppression
  - Significant signal or neighboring signal required for cell to be collected
    - Efficient extraction of low density (hadronic) signals
- Clusters have shapes
  - Sensitive to shower development
    - Basis for dynamic (hadronic) calibration – cluster by cluster
  - Resolution for shape variables depends on environment and event topology
    - Inside/outside jets, calorimeter readout granularity
- Complements charged particle flow from tracking with neutral particle flow
  - E.g., used in underlying event measurement in ATLAS
- Massless pseudo-particle representation

ATLAS Coll., arXiv:1103.1816, *to be published in* **Eur.Phys.J. C**







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Calorimeter Energy Scales (1)

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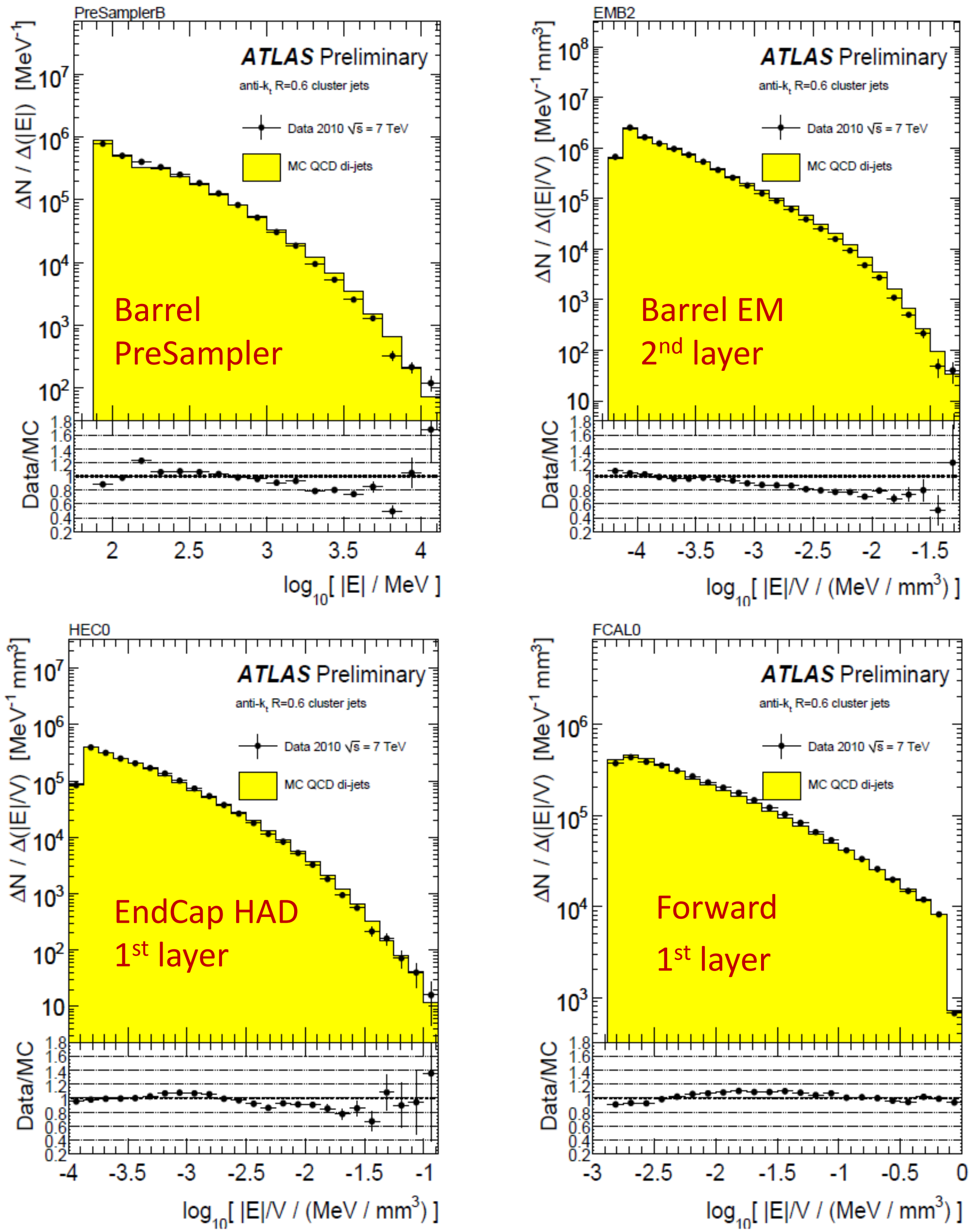
Basic electromagnetic (EM) scale

- Extracted for all ATLAS calorimeter regions from electron test beams and simulations
  - Energy independent calibration factors applied
- Suffers from large fluctuations due to calorimeter signal inefficiencies
  - Static calibration without jet-by-jet corrections for hadronic signal features

Global hadronic calibration (GCW) in jet context

- Attempt to reduce signal fluctuations dynamically
  - Implicit use of calorimeter signal feature like cell energy density and spatial cell signal distribution
- Global cell weighting
  - Apply cell signal weights derived in resolution minimization fits of matching particle level and calorimeter jets in MC
  - Correlates dead material and other jet particle energy losses (magnetic field) with weights from non-compensation
- Can be applied to cells in clusters or towers
  - Universal application independent of calorimeter jet input signal choice
- Validation
  - E.g., requires cell energy density distributions in jets modeled correctly



(*all plots from* **ATLAS-CONF-2010-053**)

Calorimeter Energy Scales (2)

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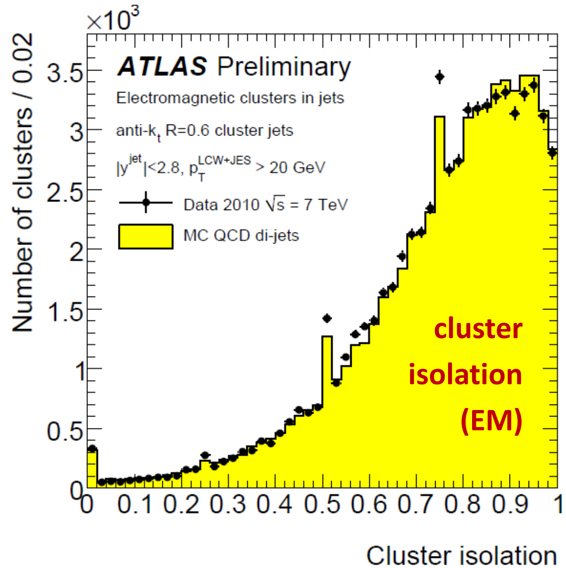
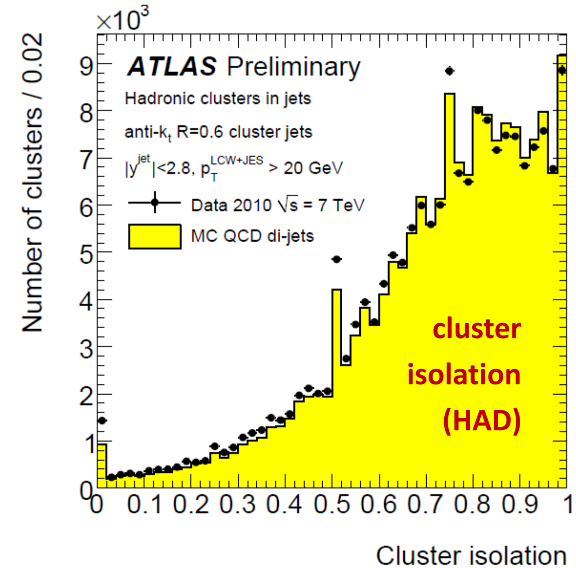
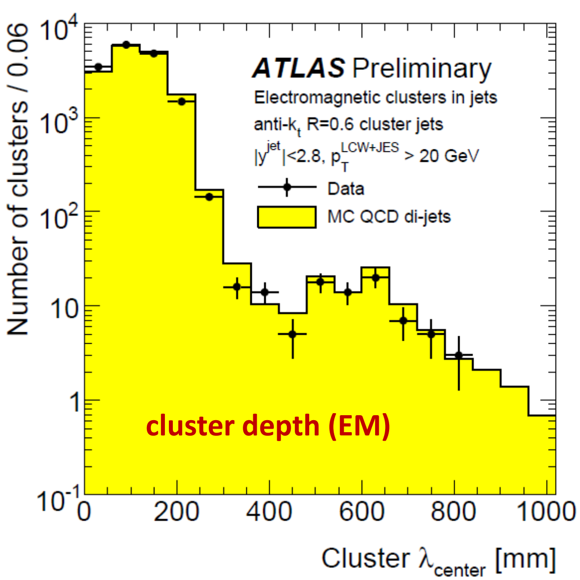
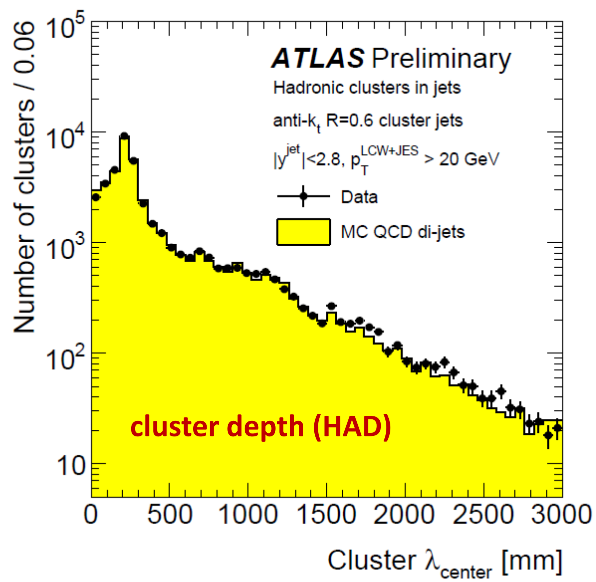
Local Hadronic Calibration (LCW) in cluster context

- Attempt to reduce signal fluctuations dynamically
  - Explicit use of calorimeter signal features, e.g. cell energy density, spatial cell signal distribution
- Applied at topological cell cluster level
  - Exploits cluster kinematics, shapes & location









- Complex cluster observables well described in MC
  - Distributions affected by shower structures, detector geometries, noise patterns, …
  - Simulation works well inside and outside of jets

(*all plots on this slide from* **ATLAS-CONF-2010-053**)

Calorimeter Energy Scales (3)

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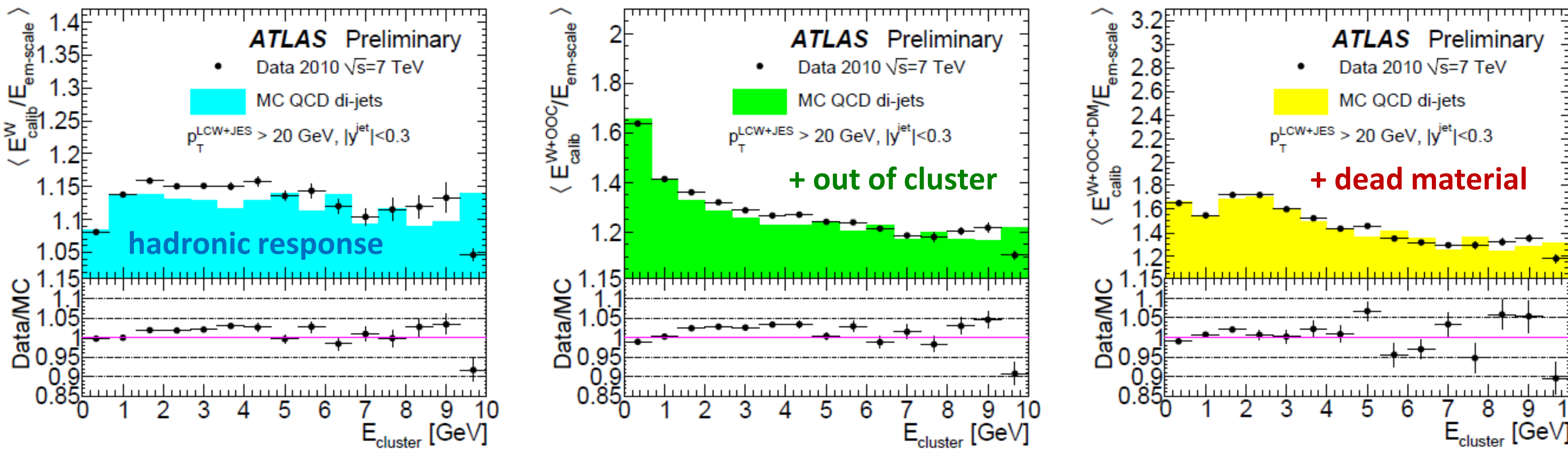
LCW – cluster context hadronic calibration

- Highly factorized scheme
  - Implements cluster classification specific calibration chains for electromagnetic and hadronic clusters
  - Corrections derived independently using detailed single particle simulations
  - All corrections derived from deposited energies at or around cluster location and their relation to the signal features
- High demand on (detector) simulation quality
  - Each step validated with collision data

(*all plots from* **ATLAS-CONF-2010-053**)



- Calibration signal calibrations & corrections well reproduced even for clusters inside jets
  - Non-trivial confirmation of approach due to complex variable space and single particle source for parameters and functions
  - No significant quality variations as function of cluster location or transverse momentum

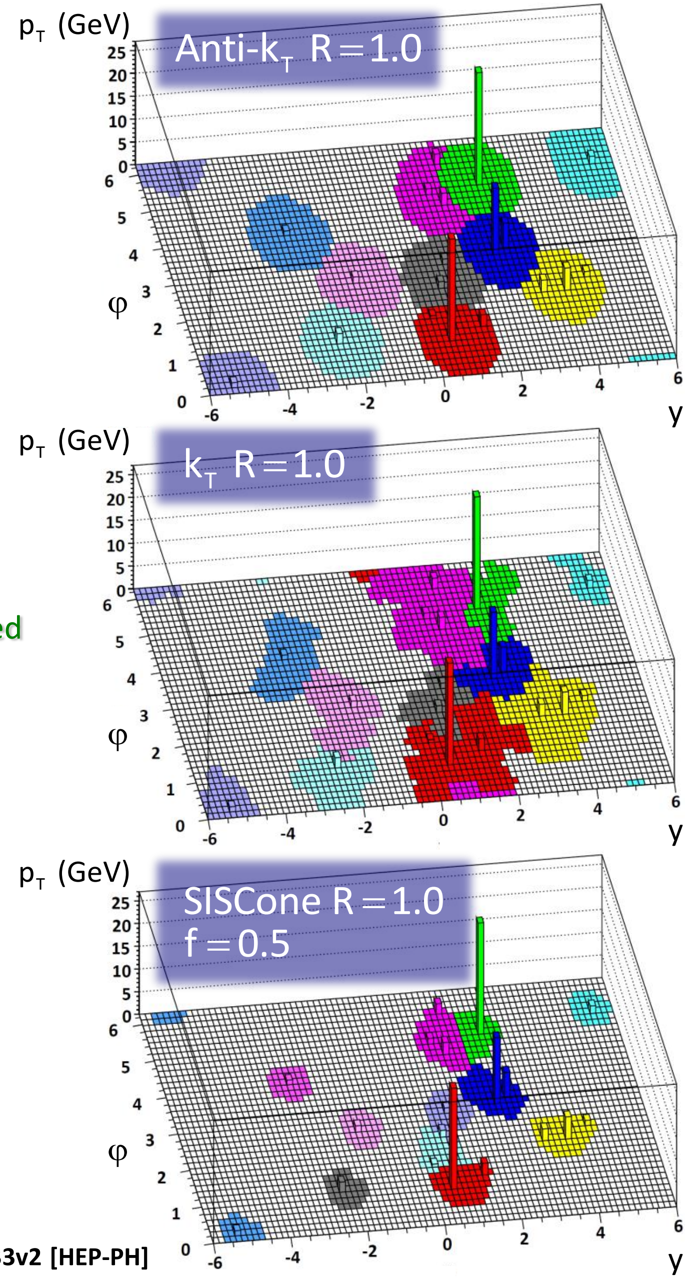
Jet Finding

Physics motivated jet finders

- Infrared safety & collinear stability
  - Recursive recombination algorithms preferred over seeded cones
- ATLAS default is Anti-k_T
  - Very predictable and regular shape
    - Area well determined for pile-up estimates
  - Employed with two different distance parameters
    - R = 0.4 (narrow), R = 0.6 (wide)
- Other jet finders available
  - **SISCone** – infrared safe cone algorithm
    - Cone size R, split/merge fraction f
  - **k_T** – classic recursive recombination with intrinsic pT motivated distance measure
    - Distance parameter R (inclusive)
  - **Cambridge/Aachen** – classic recursive recombination ordered by angular distance
    - Distance parameter R (inclusive)
- Default recombination scheme
  - Full four-momentum recombination at each iteration of the jet finder
    - Jets are reconstructed as massive objects

Common implementations

- No ATLAS specific jet finder implementations anymore
  - External FastJet library for kT-type algorithms
  - External SISCone library
- Identical code for all jets
  - Calorimeter, tracking, energy flow objects, generated particles in Monte Carlo…



Figures adapted from **G. Salam, *Towards Jetography*, arXiv:0906.1833v2 [HEP-PH]**

Experimental Jet Finder Input In ATLAS

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Calorimeter towers

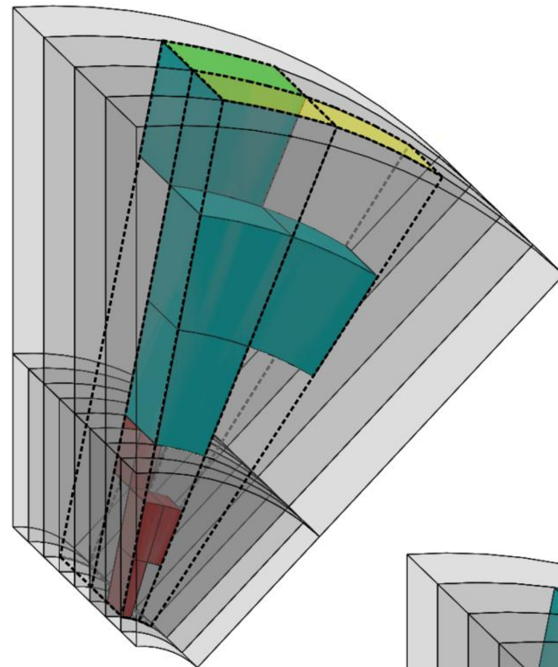
- Noise-suppressed towers
  - Cells in towers from topological clusters
- EM scale only
  - Photon/hadron response imbalanced during jet formation
  - Least algorithm bias

Calorimeter cell clusters

- EM scale option
  - Same as for tower input
- Provide calibrated jet finder input
  - Local hadronic scale balances responses better during jet formation in recursive recombination algorithms like Anti-k_T and k_T

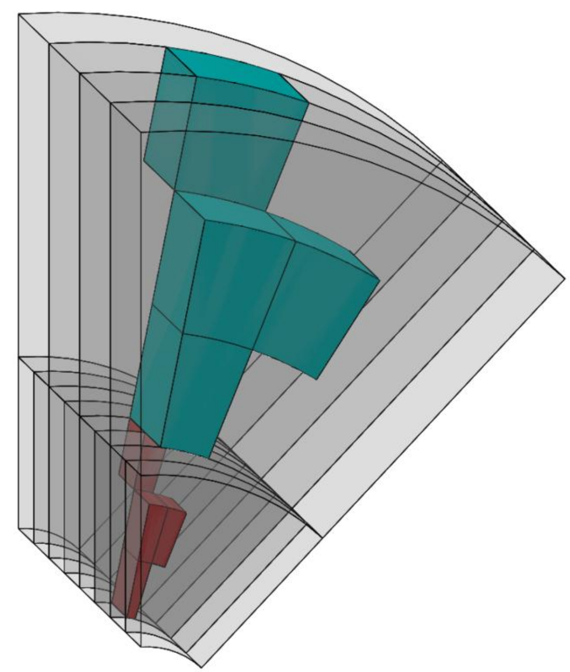
Reconstructed tracks

- Charged stable particles only
  - Resulting jets are incomplete
- Very useful for characterization of calorimeter jet
  - Large charged p_T fraction indicates hadron-rich jet



Calorimeter towers filled with cells from topological clusters applies noise suppression to tower signal

Topological calorimeter cell clusters locate "blobs of energy" inside the detector following shower and particle flow induced signal structures



Drawings by R. Walker (Arizona), inspired by K. Perez (Columbia)

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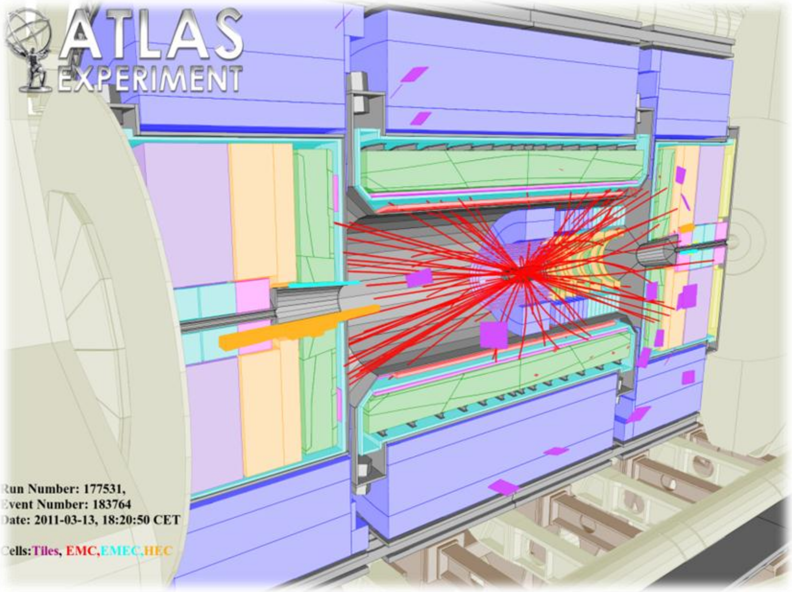
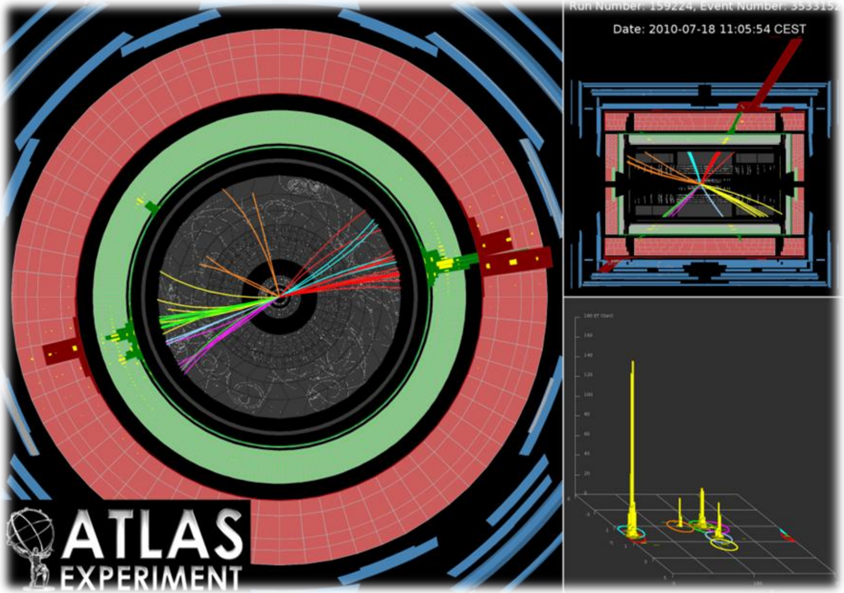
Jet Calibration in ATLAS





Default ATLAS Jet Calibration 2010 (1)

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Default for first data focuses on "simplicity"

- EM scale + additional corrections
  - Least algorithmic impact & sensitivity to modeling details
    - Very few correction levels
  - Basic EM scale independently validated with data from $Z \to ee$
    - Basic systematic uncertainty in most calorimeter regions derived independently from jet response
- No significant improvements in resolution expected
  - Calibration uses only average event environment and jet reponse features

More dynamic calibrations under commissioning for 2011+ data

- Use hadronic calorimeter scales and jet features
  - GCW, LCW, GS
- Expect jet energy resolution improvements
  - Corrections are applied jet by jet

EM Scale Jet

$$\begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}} = \sum_{E_{\mathrm{EM,cluster}}>0}^{\mathrm{clusters}} \begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{cluster}}$$

See also D. Schouten's talk!

Default ATLAS Jet Calibration 2010 (2)

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Calibration sequence for EM scale jets

(1) Pile-up correction from data

Average additional energy from pile-up is subtracted

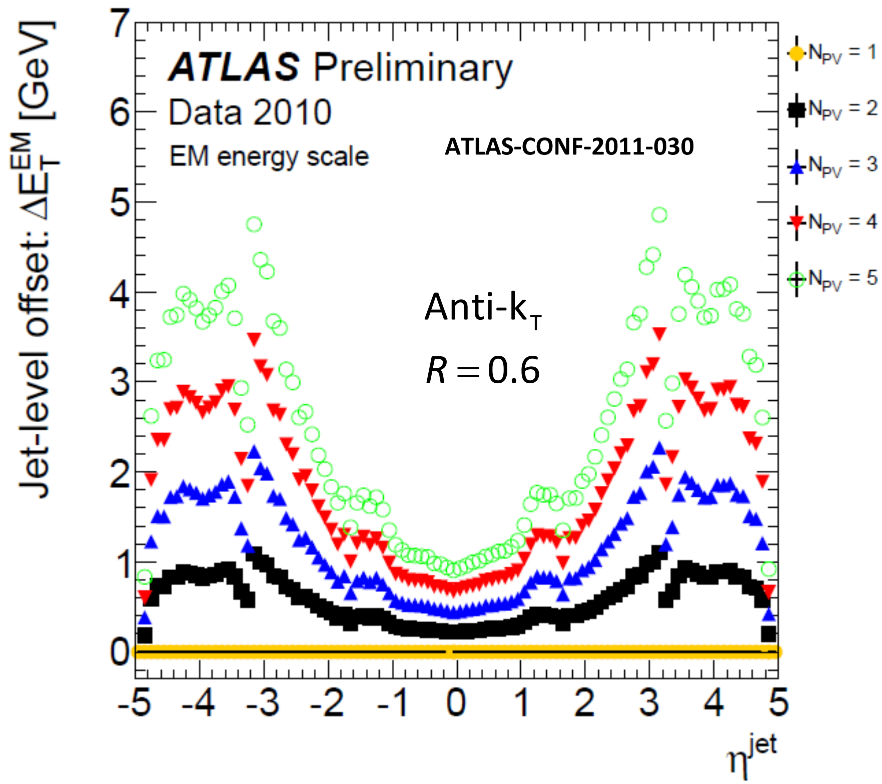
EM Scale Jet

$$\begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}} = \sum_{E_{\mathrm{EM,cluster}}>0}^{\mathrm{clusters}} \begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{cluster}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}}) \cdot \cosh\eta \\ \left(E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}}) \cdot \cosh\eta\right) / E_{\mathrm{EM}} \cdot \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}}$$

Derived from minimum bias data by measuring: $\dfrac{\langle E_{\mathrm{T}} \rangle}{\Delta\eta \times \Delta\varphi}(N_{\mathrm{PV}}, \eta)$



Default ATLAS Jet Calibration 2010 (3)

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Calibration sequence for EM scale jets

(1) Pile-up correction from data

(2) Vertex correction from data to improve angular resolution and p_T response

Jet and constituent directions recalculated from reconstructed primary event vertex

Only jet constituents and jet direction re-calculated after vertex shift – jet energy unchanged!

EM Scale Jet

$$\begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}} = \sum_{E_{\mathrm{EM,cluster}}>0}^{\mathrm{clusters}} \begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{cluster}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}})\cdot\cosh\eta \\ \left(E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}})\cdot\cosh\eta\right)/E_{\mathrm{EM}}\cdot\vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU+Vtx}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \otimes \vec{X}_{\mathrm{vertex}} \end{pmatrix}_{\mathrm{jet}}$$

Calibration sequence for EM scale jets

(1) Pile-up correction from data

(2) Vertex correction from data to improve angular resolution and p_T response

(3) Response calibration with MC truth jet

Match MC particle jet with simulated calorimeter jet

Restores calorimeter jet energy to particle jet reference for given jet finder configuration, physics and detector response modeling

EM Scale Jet

$$\begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}} = \sum_{E_{\mathrm{EM,cluster}}>0}^{\mathrm{clusters}} \begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{cluster}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}})\cdot\cosh\eta \\ \left(E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}})\cdot\cosh\eta\right)/E_{\mathrm{EM}}\cdot\vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU+Vtx}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \otimes \vec{X}_{\mathrm{vertex}} \end{pmatrix}_{\mathrm{jet}}$$

MC

$$\begin{pmatrix} E_{\mathrm{EM+PU+Resp}} \\ \vec{p}_{\mathrm{EM+PU+Vtx+Resp}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU+Vtx}} \end{pmatrix}_{\mathrm{jet}} \times \Re_{\mathrm{jet}}^{-1}(E_{\mathrm{EM+PU}}, \eta_{\mathrm{det}})$$

Corrects for detector effects & acceptance – parameterized as function of the original calorimeter jet direction η_{det} and EM scale energy after pile-up correction

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Default ATLAS Jet Calibration 2010 (4)

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Calibration sequence for EM scale jets

(1) Pile-up correction from data

(2) Vertex correction from data to improve angular resolution and p_T response

(3) Response calibration with MC truth jet

EM Scale Jet

$$\begin{pmatrix} E_{EM} \\ \vec{p}_{EM} \end{pmatrix}_{jet} = \sum_{E_{EM,cluster}>0}^{clusters} \begin{pmatrix} E_{EM} \\ \vec{p}_{EM} \end{pmatrix}_{cluster}$$

DATA

$$\begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM} - \Delta E_T(A_{jet}) \cdot \cosh\eta \\ \left(E_{EM} - \Delta E_T(A_{jet}) \cdot \cosh\eta\right) / E_{EM} \cdot \vec{p}_{EM} \end{pmatrix}_{jet}$$

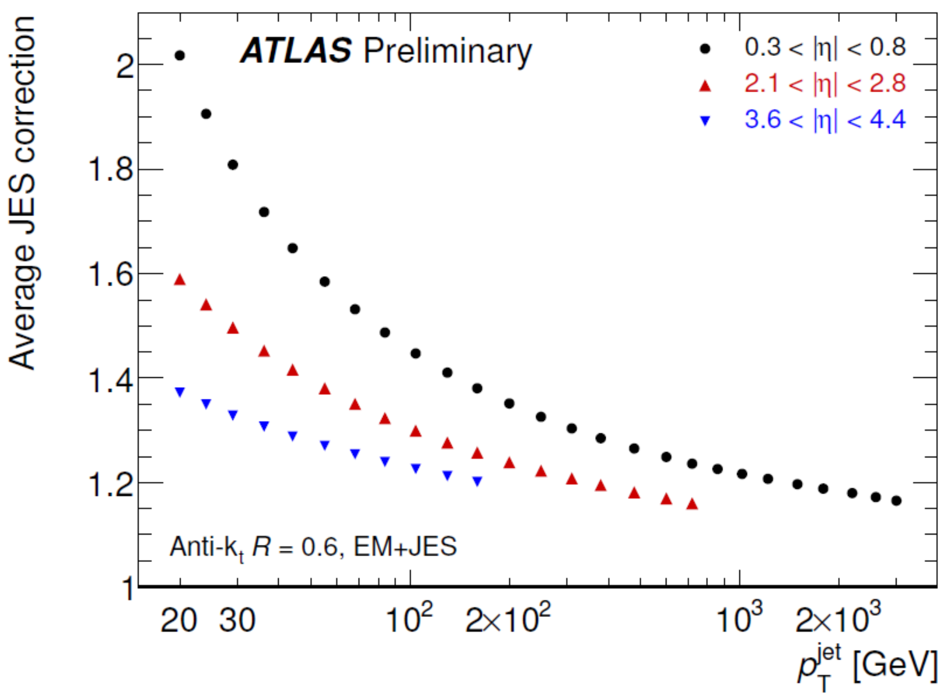
DATA

$$\begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU+Vtx} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU} \otimes \vec{X}_{vertex} \end{pmatrix}_{jet}$$

MC

$$\left(\ldots sp \right)_{jet} = \begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU+Vtx} \end{pmatrix}_{jet} \times \Re^{-1}_{jet}(E_{EM+PU}, \eta_{det})$$

ATLAS-CONF-2011-032



Calibration sequence for EM scale jets

(1) Pile-up correction from data

(2) Vertex correction from data to improve angular resolution and p_T response

(3) Response calibration with MC truth jet

(4) Final direction correction from MC

- Small correction to reduce bias in direction measurement
  - Introduced by poorly instrumented transition regions in calorimeter

EM Scale Jet

$$\begin{pmatrix} E_{EM} \\ \vec{p}_{EM} \end{pmatrix}_{jet} = \sum_{E_{EM,cluster}>0}^{clusters} \begin{pmatrix} E_{EM} \\ \vec{p}_{EM} \end{pmatrix}_{cluster}$$

DATA

$$\begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM} - \Delta E_T(A_{jet}) \cdot \cosh\eta \\ \left(E_{EM} - \Delta E_T(A_{jet}) \cdot \cosh\eta\right) / E_{EM} \cdot \vec{p}_{EM} \end{pmatrix}_{jet}$$

DATA

$$\begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU+Vtx} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU} \otimes \vec{X}_{vertex} \end{pmatrix}_{jet}$$

MC

$$\begin{pmatrix} E_{EM+PU+Resp} \\ \vec{p}_{EM+PU+Vtx+Resp} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM+PU} \\ \vec{p}_{EM+PU+Vtx} \end{pmatrix}_{jet} \times \Re_{jet}^{-1}(E_{EM+PU}, \eta_{det})$$

MC

EM+JES Jet

$$\begin{pmatrix} E_{EM+JES} \\ \vec{p}_{EM+JES} \end{pmatrix}_{jet} = \begin{pmatrix} E_{EM+PU+Resp} \\ \vec{p}_{EM+PU+Vtx+Resp} \otimes \Delta\eta \end{pmatrix}_{jet}$$

Correction parameterized as function of detector jet direction and energy

Default ATLAS Jet Calibration 2010 (5)

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Calibration sequence for EM scale jets

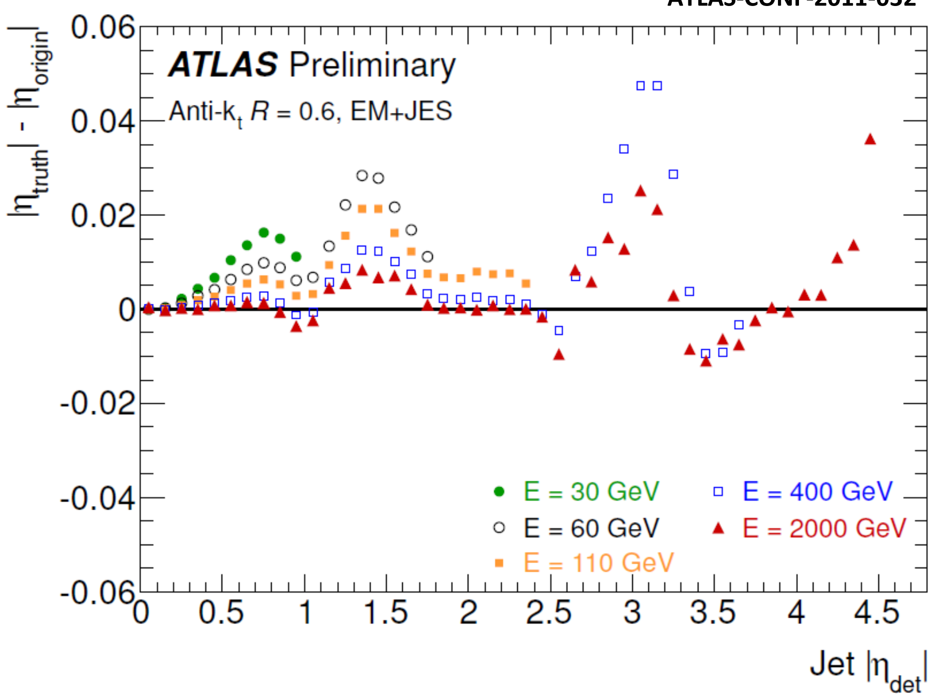
(1) Pile-up correction from data

(2) Vertex correction from data to improve angular resolution and p_T response

(3) Response calibration with MC truth jet

(4) Final direction correction from MC

ATLAS-CONF-2011-032



EM Scale Jet

$$\begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}} = \sum_{E_{\mathrm{EM,cluster}}>0}^{\mathrm{clusters}} \begin{pmatrix} E_{\mathrm{EM}} \\ \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{cluster}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}}) \cdot \cosh\eta \\ \left(E_{\mathrm{EM}} - \Delta E_{\mathrm{T}}(A_{\mathrm{jet}}) \cdot \cosh\eta\right) / E_{\mathrm{EM}} \cdot \vec{p}_{\mathrm{EM}} \end{pmatrix}_{\mathrm{jet}}$$

DATA

$$\begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU+Vtx}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU}} \otimes \vec{X}_{\mathrm{vertex}} \end{pmatrix}_{\mathrm{jet}}$$

MC

$$\begin{pmatrix} \\ \ldots p \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU}} \\ \vec{p}_{\mathrm{EM+PU+Vtx}} \end{pmatrix}_{\mathrm{jet}} \times \Re_{\mathrm{jet}}^{-1}(E_{\mathrm{EM+PU}}, \eta_{\mathrm{det}})$$

MC

EM+JES Jet

$$\begin{pmatrix} E_{\mathrm{EM+JES}} \\ \vec{p}_{\mathrm{EM+JES}} \end{pmatrix}_{\mathrm{jet}} = \begin{pmatrix} E_{\mathrm{EM+PU+Resp}} \\ \vec{p}_{\mathrm{EM+PU+Vtx+Resp}} \otimes \Delta\eta \end{pmatrix}_{\mathrm{jet}}$$

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Jet Calibration Under Commissioning

LCW calibrated jets

- Jet four-momentum from LCW clusters
  - No correction for inefficiencies not correlated with the cluster signals
    - Charged particles in magnetic field
    - Particle losses in dead material with only trace signals
  - Can be addressed with jet energy scale correction methods similar to EM+JES

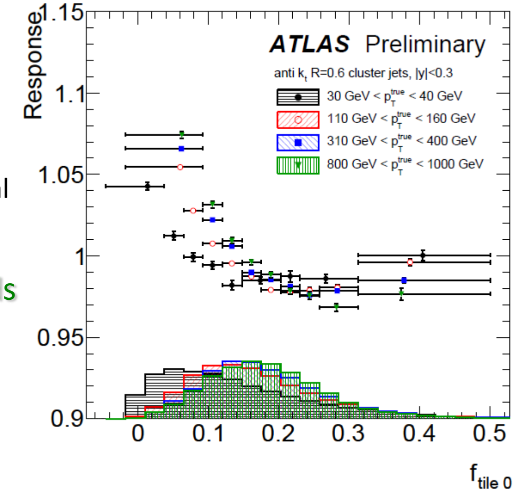
GCW calibrated jets

- Jet four-momentum from weighted cell signals
  - Partly corrects for all jet level inefficiencies
  - Residual (small) corrections to be addressed similar to EM+JES

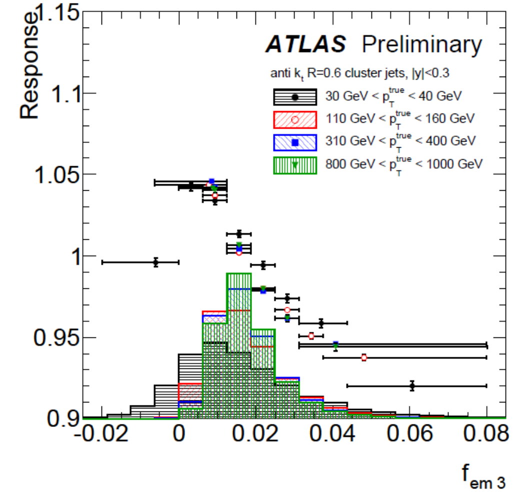
Global sequential (GS) calibration

- Uses jet shapes as input to calibration
  - Can be derived for EM, LCW, GCW jets
  - Jet width and longitudinal energy sharing in calorimeter main input variables

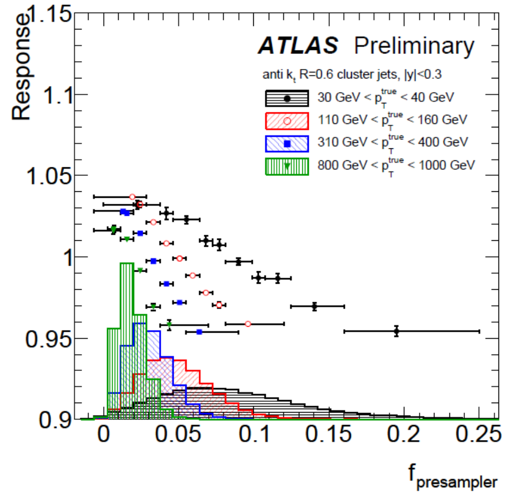
Basics for GS calibration: jet response variations as function of several sensitive variables



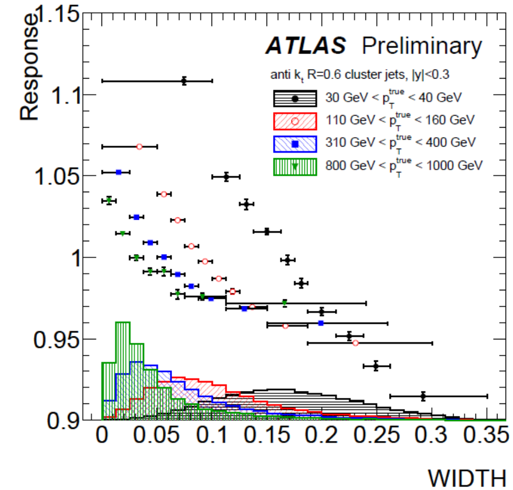
Energy fraction 1st layer Tile



Energy fraction 3rd layer EM



Energy fraction PreSampler



Calorimeter jet width

(*all plots from* **ATLAS-CONF-2010-053**)

Quality Of MC Based Jet Calibration

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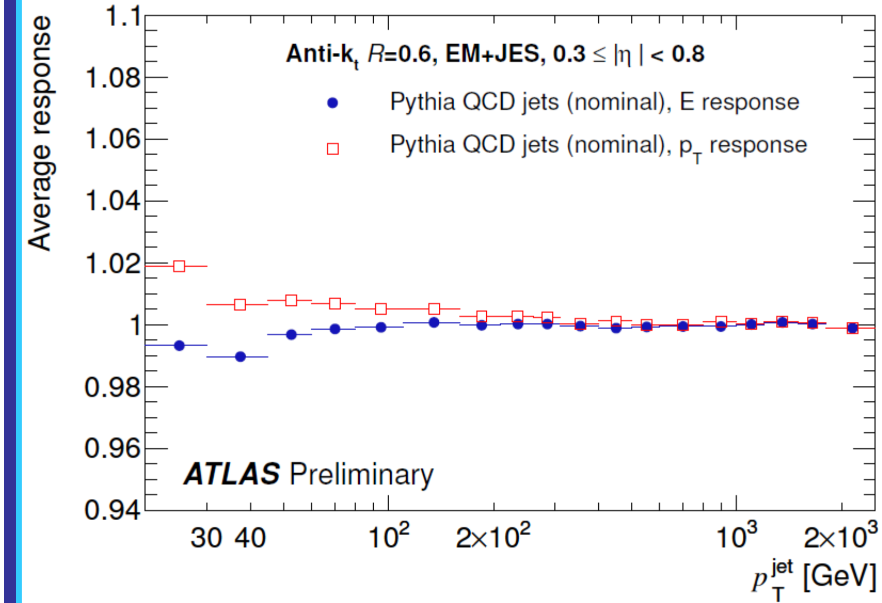
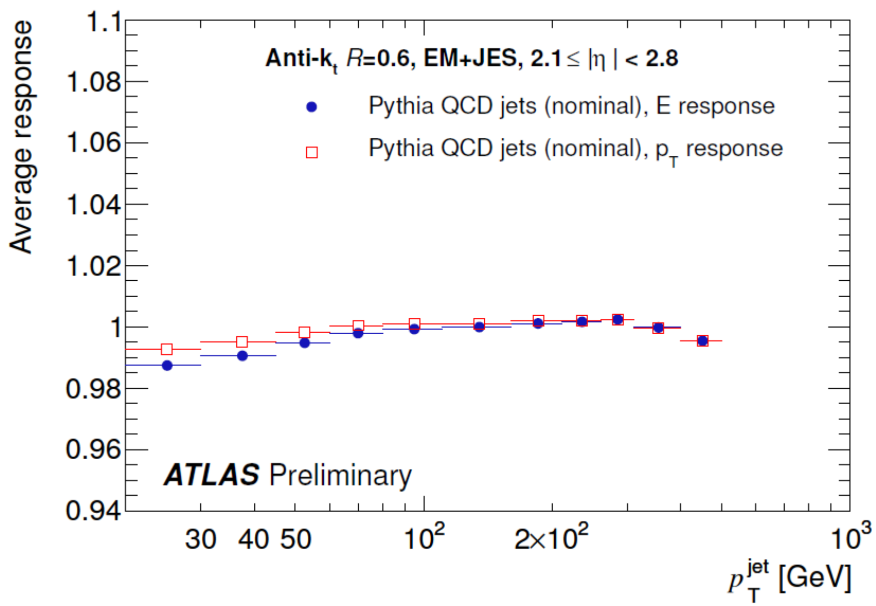
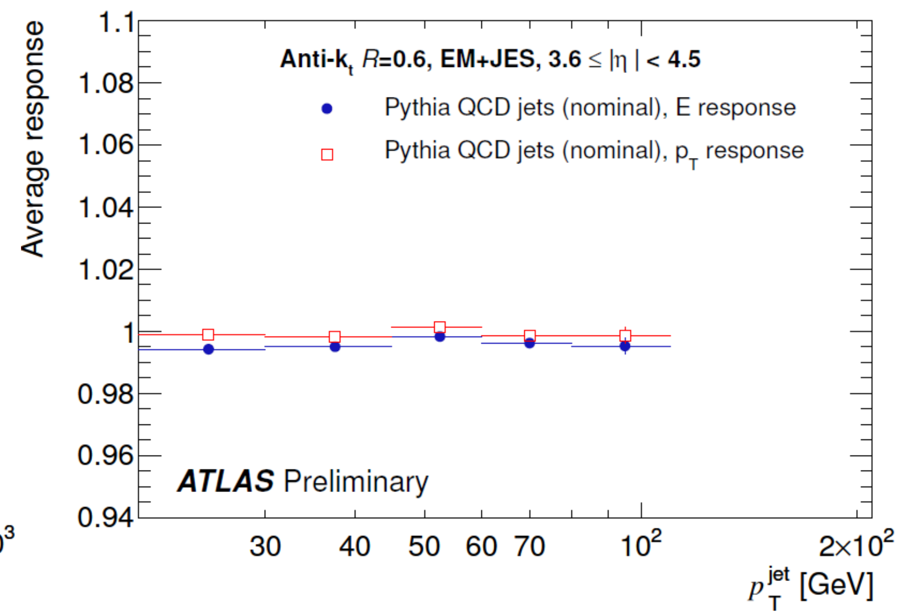


Closure test for MC calibration

- Apply calibrations and corrections to MC calibration sample
  - Expected true energy or p_T not perfectly restored after all calibrations and corrections
  - Residual non-closure is part of systematic uncertainty of jet energy scale
- Differences in energy and p_T linearity
  - Same correction factor applied
  - Reconstructed (non-zero) jet masses do not represent expected jet mass well – restoring only energy and direction leads to bias





(*all plots from* **ATLAS-CONF-2011-032**)

Jet Energy Scale Uncertainties

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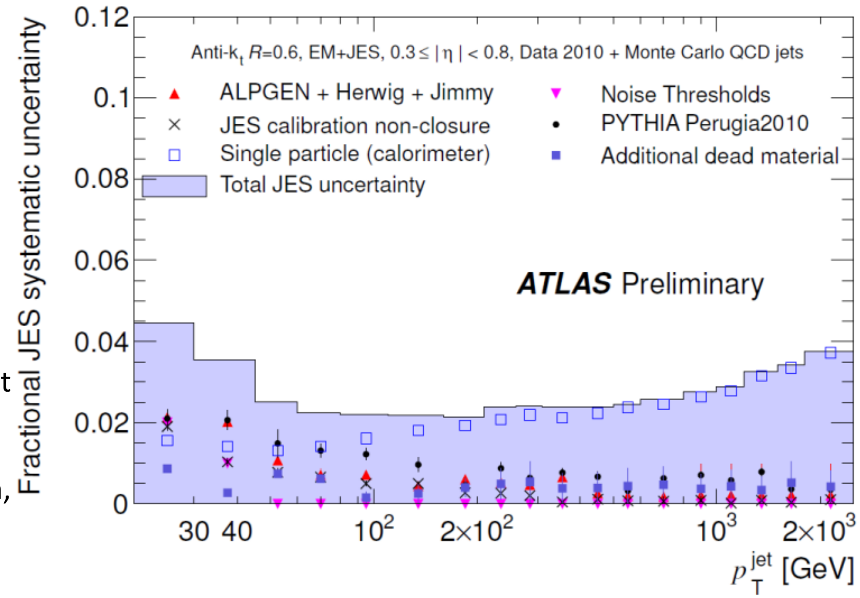
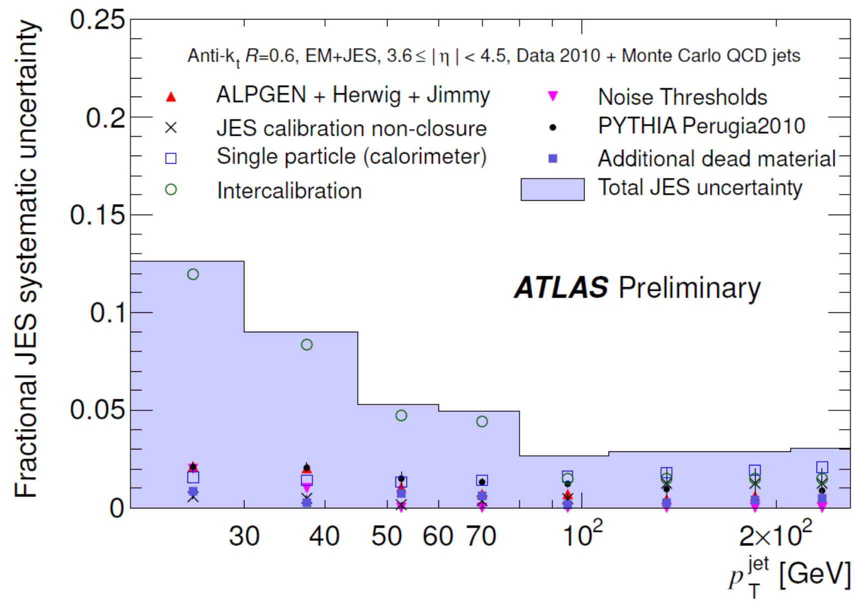
Contributions to systematic JES uncertainties in central region of ATLAS

- [MC] Non-closure of calibration
  - See previous slide
- [MC] model dependencies
  - Apply calibrations from reference sample to…
    - Different response simulation/Geant4 shower model
    - Detector description variations/material budget & alignment
    - Alternative physics simulation with different underlying event, fragmentation/hadronization, parton shower model…
- [MC,data] calorimeter response
  - Charged hadrons 0.5 < p < 20 GeV (see next slide)
    - E/p from isolated tracks in collisions
  - Charged hadrons 20 < p < 350 GeV
    - Test beam experiments
  - Basic energy scale and EM response
    - $Z \rightarrow ee$ in collisions
  - Neutral hadrons
    - Estimates from MC (conservative)
  - High energy particles in jet (p > 400 GeV)
    - Estimates from MC (conservative)

Extrapolation to end-cap and forward regions

- [data] p_T balance in QCD di-jet events
  - Constraints the forward energy scale





(*all plots from* **ATLAS-CONF-2011-032**)

Single Hadron Response

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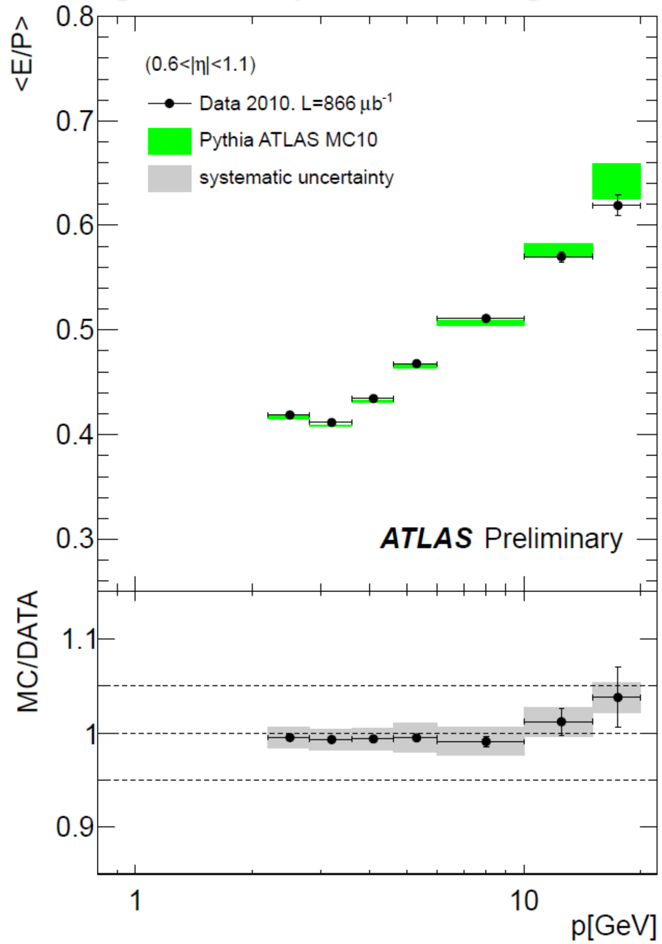
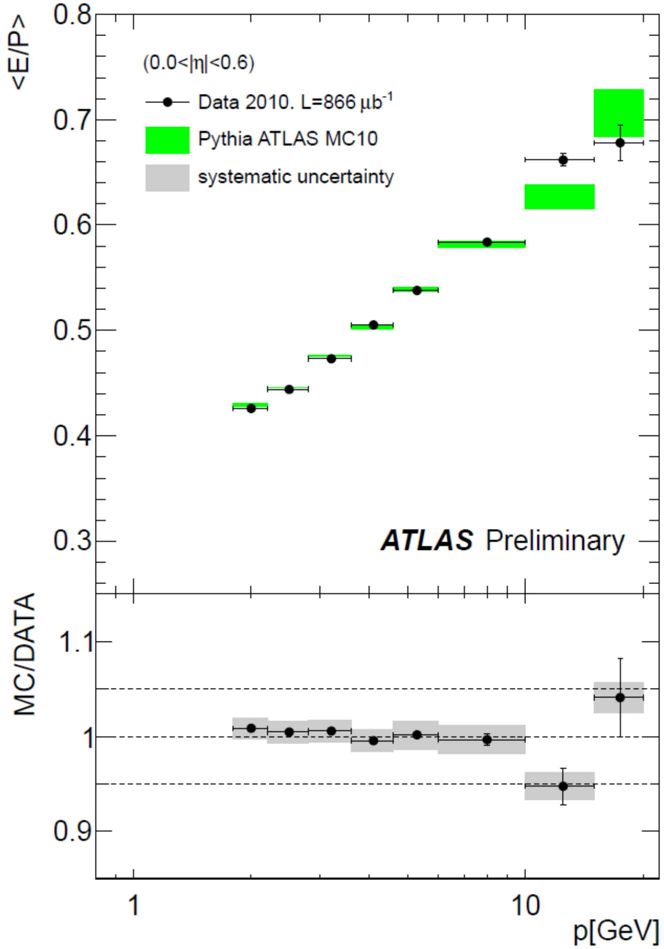
Determines basic response uncertainties at low energy

- Measure E/p for isolated tracks in collision events
  - 500 MeV < p < 20 GeV
- Data/MC response agree very well
  - Larger discrepancies at higher momentum





γ + Jet

(*from* **D. Schouten, In-situ measurements of Jet Energy Scale in ATLAS**, *talk given at "Workshop on Jet Measurements and Spectroscopy", Pisa, Italy, April 18-19, 2011*)

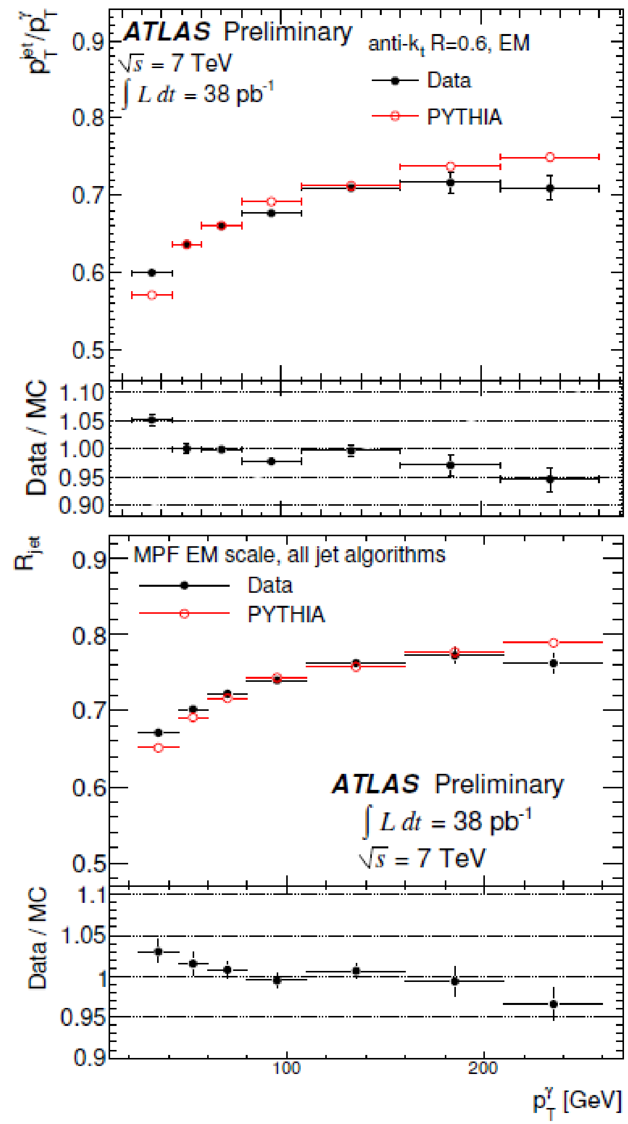
- jet response probed with two complementary methods[1]:
  1. direct p_T balance: p_T^{jet}/p_T^{γ}
  2. $\not{E}_T$ projection fraction (MPF): $1+\not{E}_T \cdot \hat{n}_{\gamma}/p_T^{\gamma}$

γ + jet analysis

- using $\int \mathcal{L} = 38\text{pb}^{-1}$
- γ selected based on shower shape, isolation[2]
- back-to-back topology ($\Delta\phi > \pi - 0.2$, $p_T^{j2}/p_T^{\gamma} < 0.1$)
- considered systematics from: QCD jet background, ISR/FSR mismodelling, γ energy scale, pileup

[1] both depend on p_T conservation but are differently sensitive to systematics

[2] corrected for UE and γ cluster leakage



JES In Situ Validations

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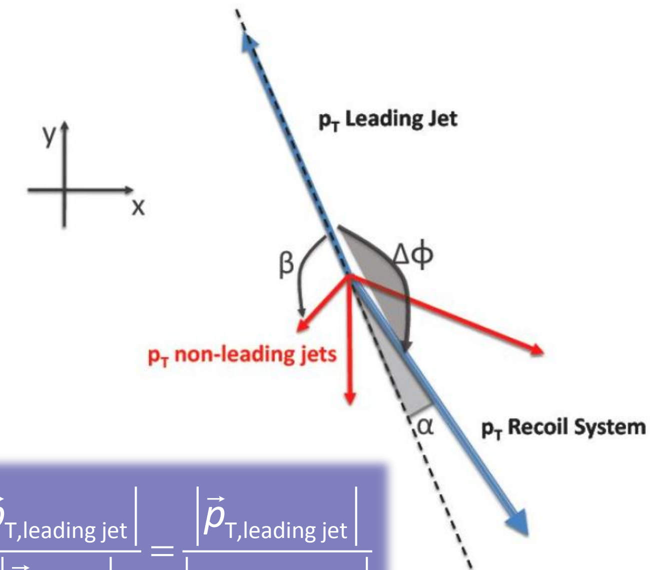
Photon-jet p_T balance

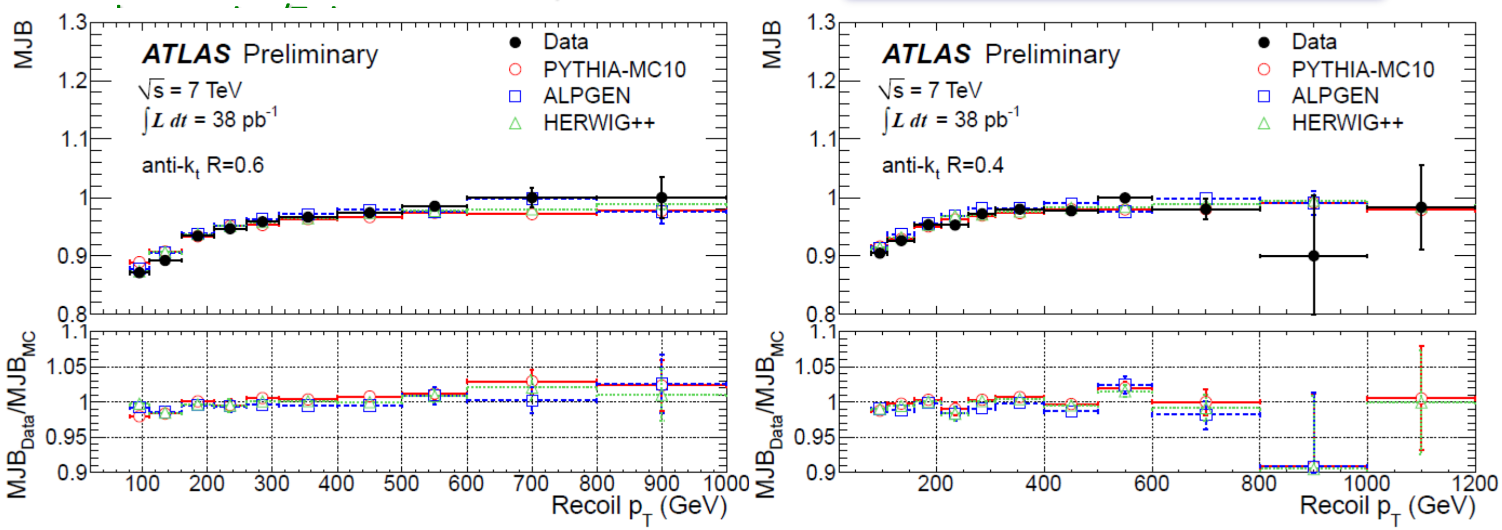
- Validate JES from MC
  - Balance jet p_T with well measured photon p_T
  - Compare data and MC predictions for central balance
- Kinematical limitations
  - $20 < p_T(\text{Jet}) < 300$ GeV at 2010 statistics

Multi-jet balance

- Validate leading jet p_T in multi-jet final states
  - Balance leading jet p_T (> 300 GeV) with several lower p_T jets (recoil, individual jet p_T < 300 GeV)
  - Assume that recoil system p_T is validated by



$$MJB = \frac{\left|\vec{p}_{T,\text{leading jet}}\right|}{\left|\vec{p}_{T,\text{recoil}}\right|} = \frac{\left|\vec{p}_{T,\text{leading jet}}\right|}{\left|\sum_{\text{other jets}} \vec{p}_{T,\text{jet}}\right|}$$



ATLAS-CONF-2011-029

JES In Situ Validations

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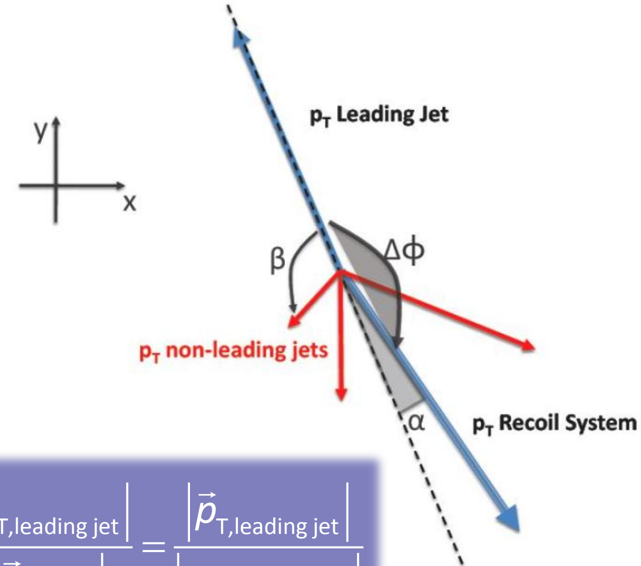
Photon-jet p_T balance

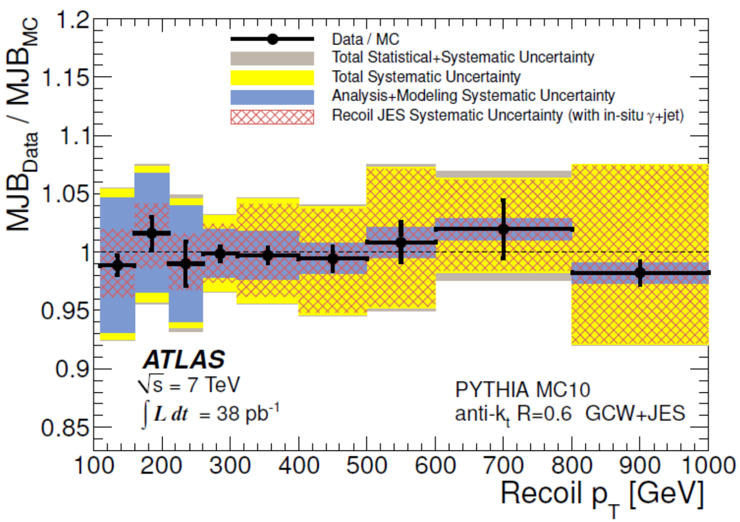
- Validate JES from MC
  - Balance jet p_T with well measured photon p_T
  - Compare data and MC predictions for central balance
- Kinematical limitations
  - 20 < p_T(Jet) < 300 GeV at 2010 statistics

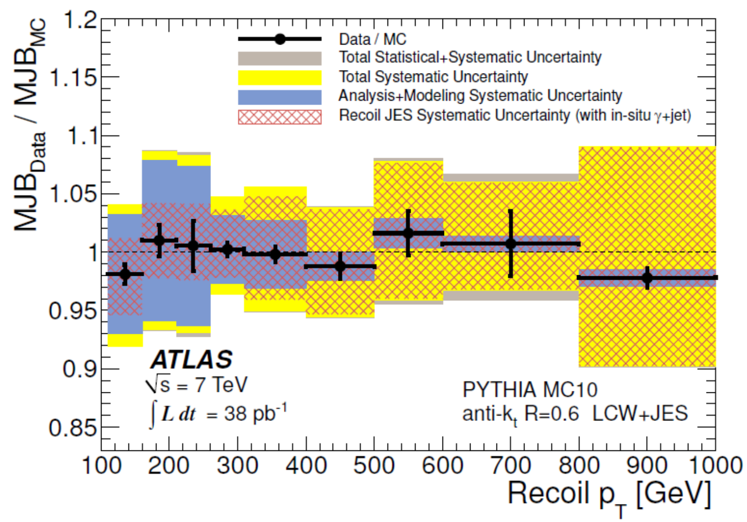
Multi-jet balance

- Validate leading jet p_T in multi-jet final states
  - Balance leading jet p_T (> 300 GeV) with several lower p_T jets (recoil, individual jet p_T < 300 GeV)
  - Assume that recoil system p_T is validated by photon+jet/Z+jet



$$MJB = \frac{\left|\vec{p}_{\mathrm{T,leading\ jet}}\right|}{\left|\vec{p}_{\mathrm{T,recoil}}\right|} = \frac{\left|\vec{p}_{\mathrm{T,leading\ jet}}\right|}{\left|\sum_{\mathrm{other\ jets}} \vec{p}_{\mathrm{T,jet}}\right|}$$





Di-jet Balancing

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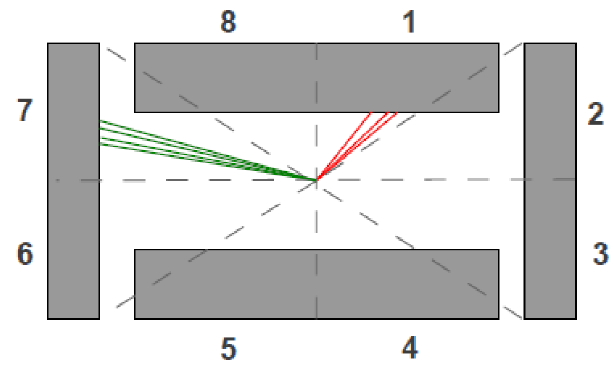
η Intercalibration (validate $C(E,\eta)$ in endcap)

- for jets in $|\eta| > 0.8$, the central results are extrapolated using dijet balance
  - CTB included only barrel Tile calorimeter
  - better knowledge of central geometry
- use matrix method to couple all regions
  - improves statistics since σ falls steeply with $\Delta\eta$

$$S = \sum_{i<j} \left(\frac{1}{\Delta R_{ij}} (\alpha_j \langle R_{ij} \rangle - \alpha_i) \right)^2 + \chi(\alpha)$$

- minimze S subject to constraint that $\langle \alpha \rangle_{\eta<0.8} = 1$
- yields coefficients $\alpha(p_T)|_\eta \pm \Delta$



$$A = \frac{p_T^i - p_T^j}{\frac{1}{2}\left(p_T^i + p_T^j\right)}$$

$$R_{ij} = \frac{2 - \langle A_{ij} \rangle}{2 + \langle A_{ij} \rangle} = \frac{\alpha_i}{\alpha_j}$$

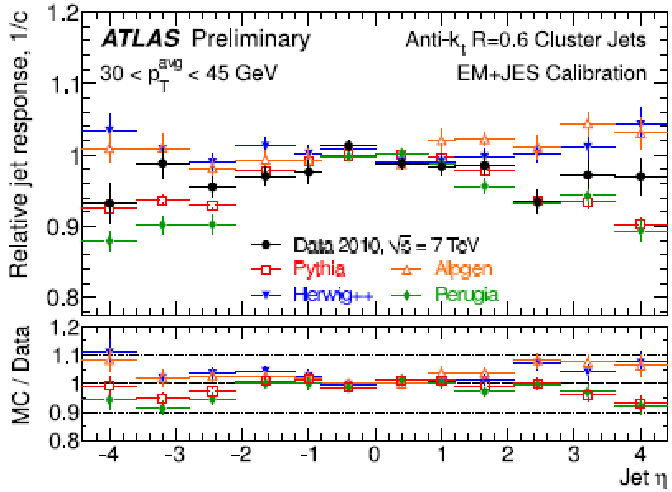
Intercalibration analysis

- use combination of minimum bias and jet triggers for different p_T regions
- require $\Delta\phi(j_1, j_2) > 2.6$, $p_T^{j3} < \max(0.15\, p_T, 7\ \mathrm{GeV})$

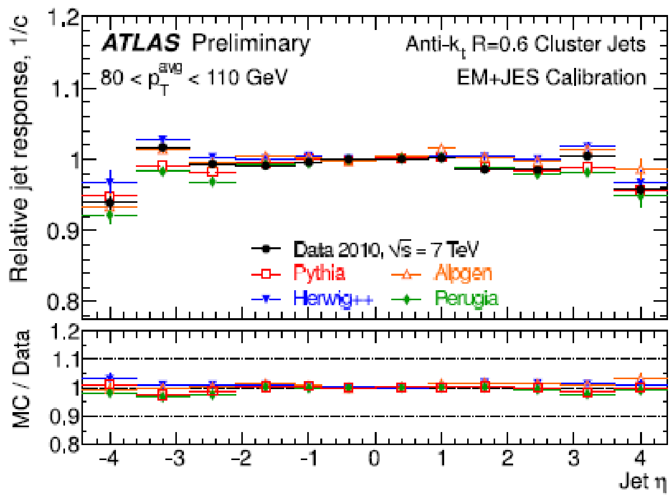
(*from* **D. Schouten, In-situ measurements of Jet Energy Scale in ATLAS**, *talk given at "Workshop on Jet Measurements and Spectroscopy", Pisa, Italy, April 18-19, 2011*)

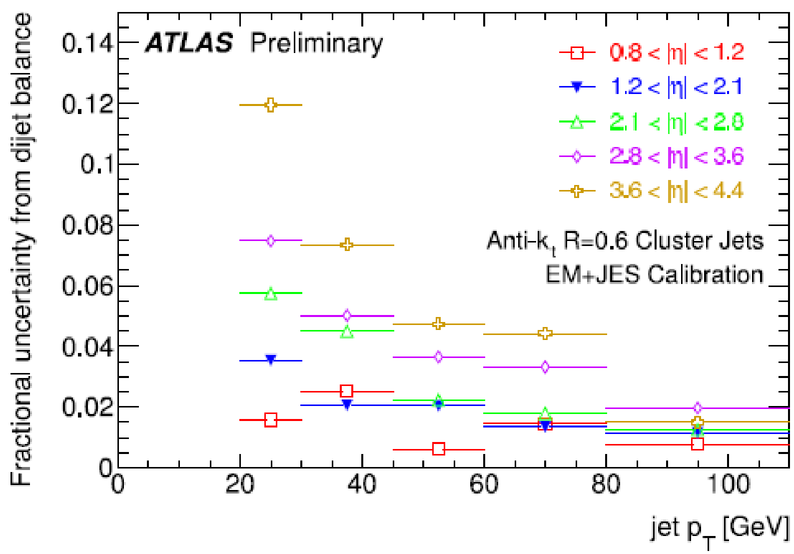
η Intercalibration (validate $C(E,\eta)$ in endcap)

(*from* **D. Schouten, In-situ measurements of Jet Energy Scale in ATLAS**, *talk given at "Workshop on Jet Measurements and Spectroscopy", Pisa, Italy, April 18-19, 2011*)



- puzzling inconsistency between Monte Carlo generators
  - compare Herwig++, Alpgen (cluster model, $2 \rightarrow N$) to Pythia and Perugia tune ($2 \rightarrow 2$, Lund string model)
  - effect is strongest in forward region, at low p_T
- use RMS deviation between MC and data as systematic uncertainty $\oplus$ uncertainty in central region

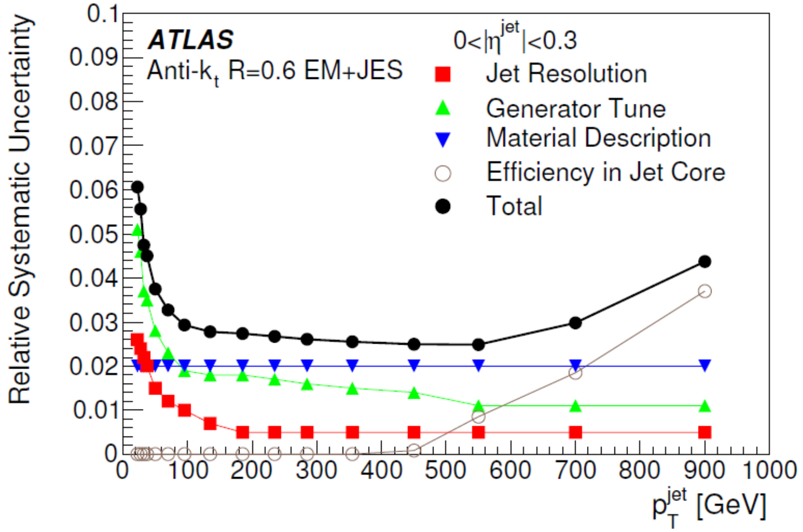


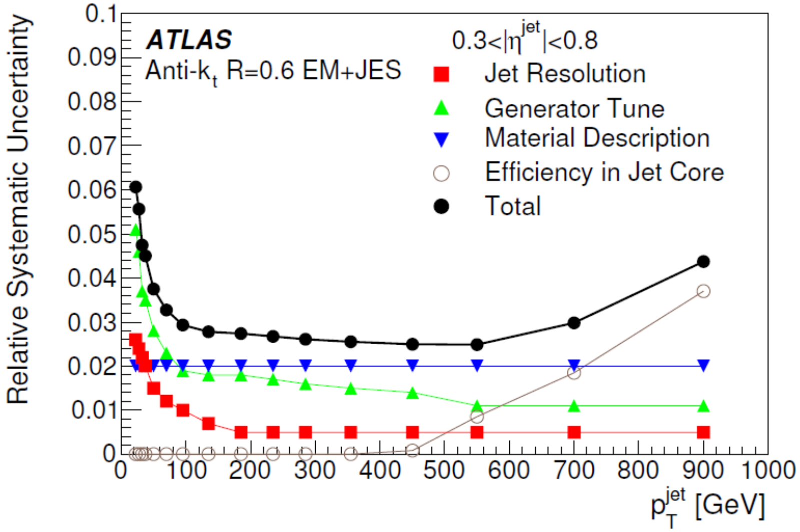


Track Jet Reference

Ratio of calorimeter jet/matching track jet pT

- Surprisingly well understandable from simulations
  - Average behaviour well constrained in the presence of relative large fluctuations
    - Not applicable jet-by-jet, requires significant statistics in each phase space bin considered
- Covers pT transition between photon-jet and multi-jet pT balance within tracking acceptance
  - ~200-~600 GeV jet pT
    - Sufficient overlap to avoid gaps in systematic error estimation
  - Track jets also good reference to understand calorimeter response in presence of pile-up
    - Track vertex assignment allows id of tracks from primary collision
  - Needs eta inter-calibration to extend to forward region
    - Larger errors expected – see before!





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Use of Track Jets

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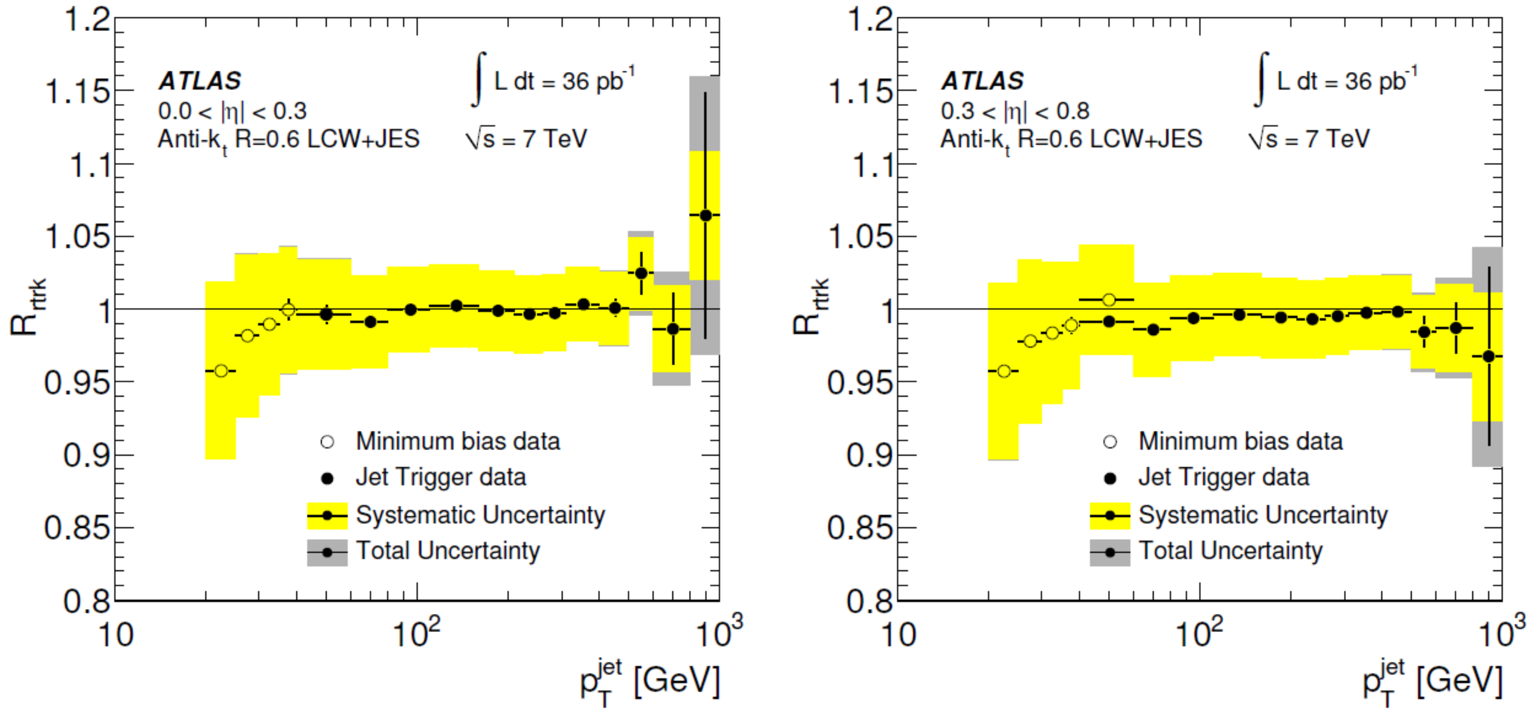
September 7, 2011

$$r_{\text{trk}} = \frac{p_{\text{T,calo}}}{p_{\text{T,tracking}}}$$ for matching jets

$$R_{\text{trk}} = \frac{r_{\text{trk}}^{\text{Data}}}{r_{\text{trk}}^{\text{MC}}}$$ test double-ratio



(a) $0 \leq |\eta| < 0.3$ (b) $0.3 \leq |\eta| < 0.8$

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Use of Track Jets

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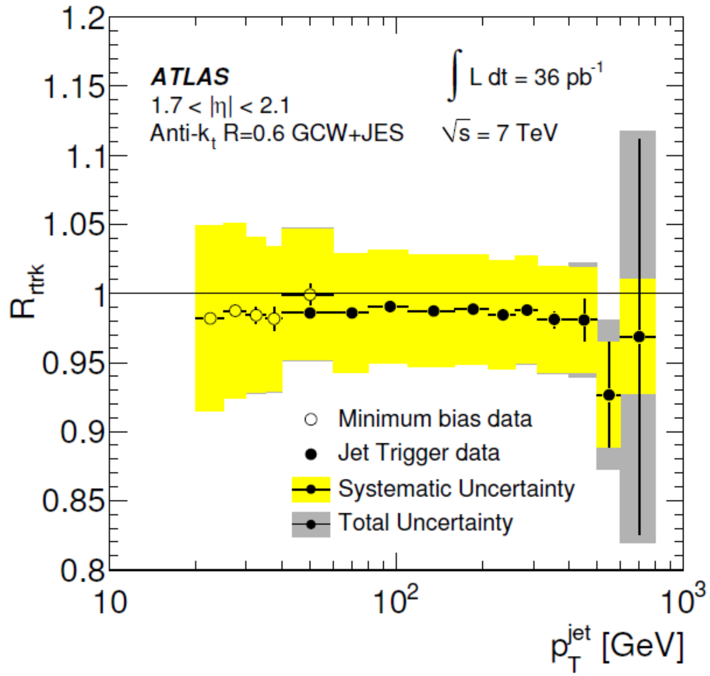
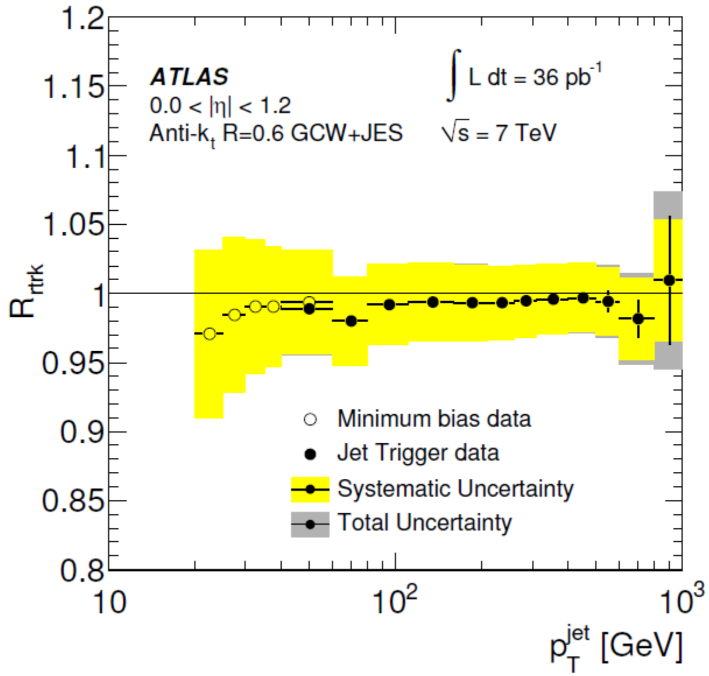
$$r_{\mathrm{trk}} = \frac{p_{\mathrm{T,calo}}}{p_{\mathrm{T,tracking}}}$$ for matching jets

$$R_{\mathrm{trk}} = \frac{r_{\mathrm{trk}}^{\mathrm{Data}}}{r_{\mathrm{trk}}^{\mathrm{MC}}}$$ test double-ratio



(e) $1.7 \leq |\eta| < 2.1$



(f) $0 \leq |\eta| < 1.2$

Combining In-situ Validations

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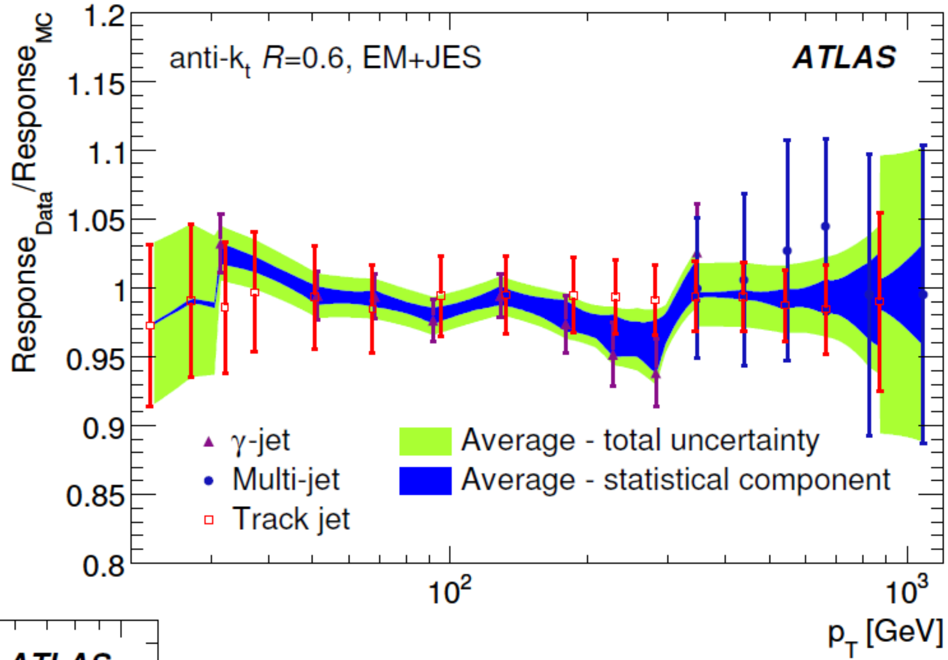
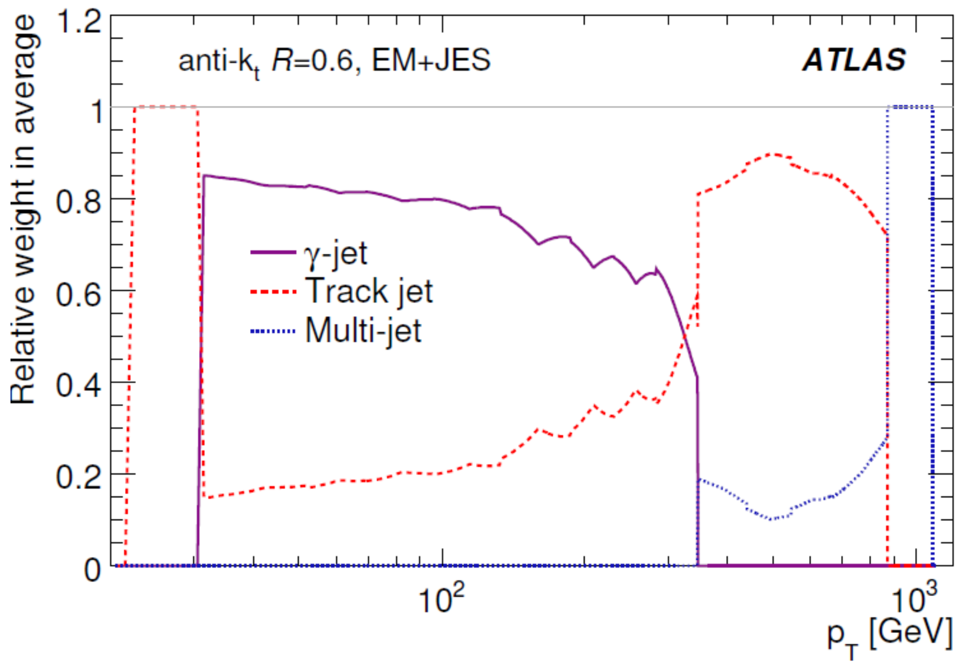
Combined systematic uncertainty from several in-situ techniques in ATLAS





Relative contribution from any given in-situ technique to the total systematic jet energy scale uncertainty in ATLAS

Jet Energy Resolution: Di-jet Balance

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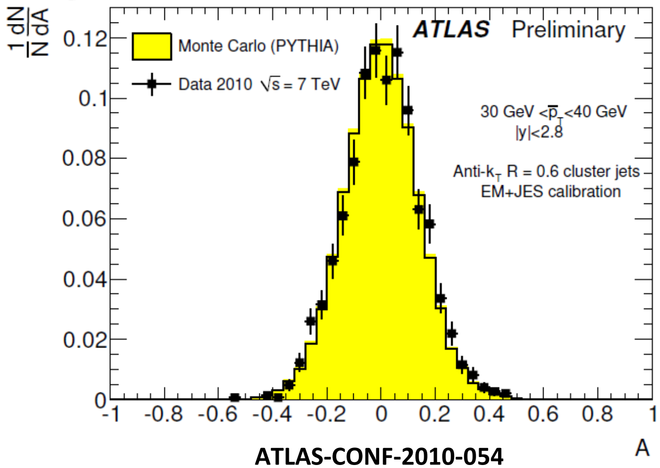
September 7, 2011

In-situ determination

Di-jet balance

$$A(p_{T,1},p_{T,2}) = \frac{p_{T,1}-p_{T,2}}{p_{T,1}+p_{T,2}}$$

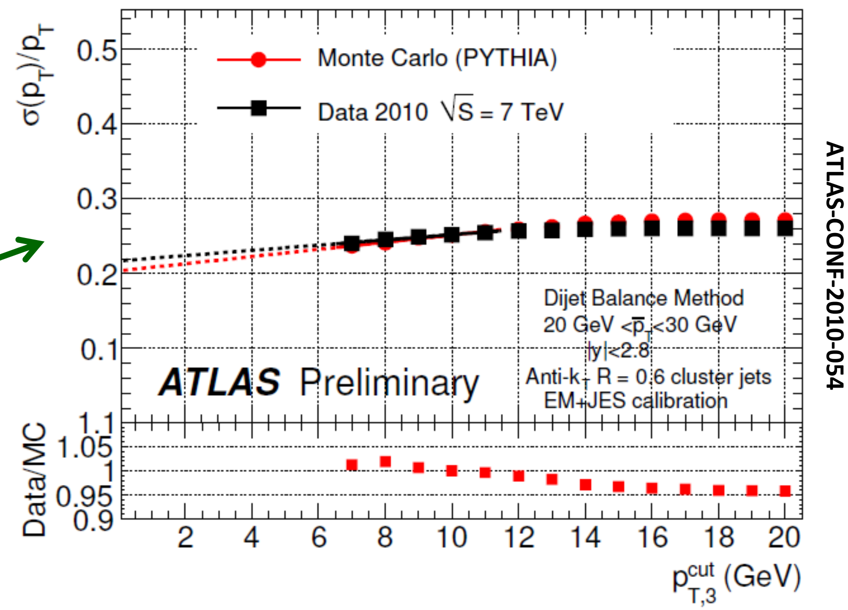
$$\sigma_A = \frac{\sqrt{\left(\sigma(p_{T,1})\right)^2+\left(\sigma(p_{T,2})\right)^2}}{p_{T,1}+p_{T,2}} \approx \frac{\sigma_{p_T}}{\sqrt{2}p_T} \Rightarrow \sqrt{2}\sigma_A = \frac{\sigma_{p_T}}{\sqrt{2}p_T}$$



ATLAS-CONF-2010-054

Soft radiation correction

Extrapolate 3rd jet pT → 0



Bi-sector method

Analyze fluctuations along bi-sectors in transverse pane

Suppress radiation contribution

Jet Energy Resolution: Bi-sector

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In-situ determination

Di-jet balance

ATLAS-CONF-2010-054

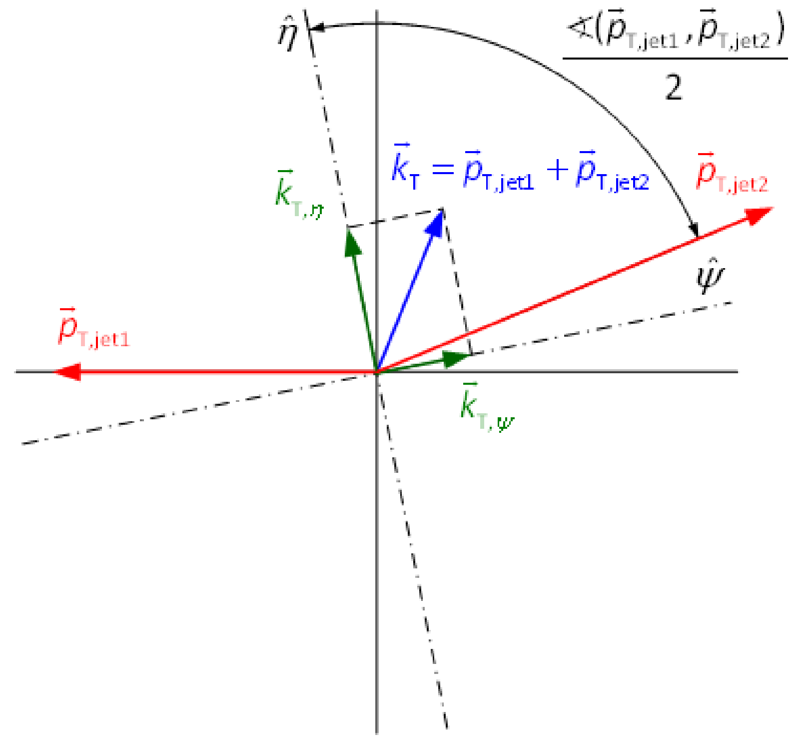
Soft radiation correction

Extrapolate 3rd jet pT ⟶ 0

Bi-sector method

Analyze fluctuations along bi-sectors in transverse pane

Suppress radiation contribution



$\vec{k}_{T,\psi}$ most sensitive to calorimeter resolution effects:

$\sigma_\psi^2 = \sigma_{E,calo}^2 + \sigma_{radiation,□}^2$, with $\sigma_{E,calo}$ □ $\sigma_{radiation,□}$

$\vec{k}_{T,\eta}$ most sensitive to (gluon) radiation effects:

$\sigma_\eta^2 = \sigma_{radiation,\perp}^2$

assume radiation is random wrt jet directions:

$\sigma_{radiation,\perp}^2 = \sigma_{radiation,□} \Rightarrow \sigma_{E,calo}^2 = \sqrt{\sigma_\psi^2 - \sigma_\eta^2}$

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Jet Energy Resolution 2010

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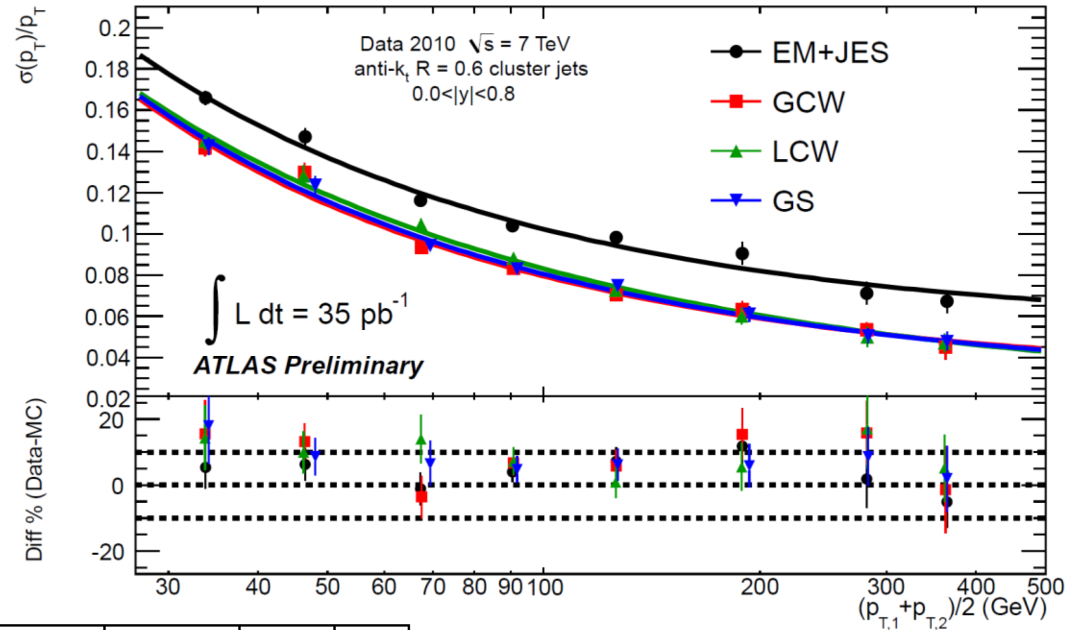
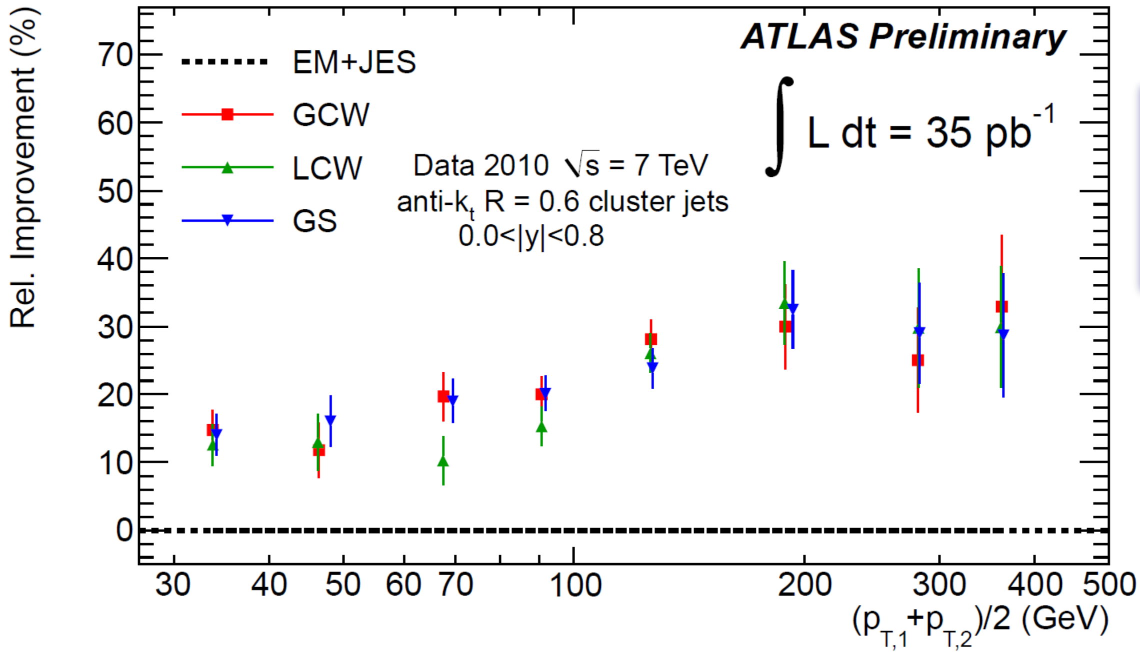
September 7, 2011

Preliminary results

- Clear resolution improvement for LCW, GCW, GS
  - No conclusive performance advantage for any of those
  - Data compares to MC at ~10% level
- Detailed look at performance gain
  - Present baseline calibration EM+JES not ideal –as expected
  - Commissioning of LCW/GCW/GS under way





Bi-sector method shown here – results from di-jet balance agree with present errors of the methods

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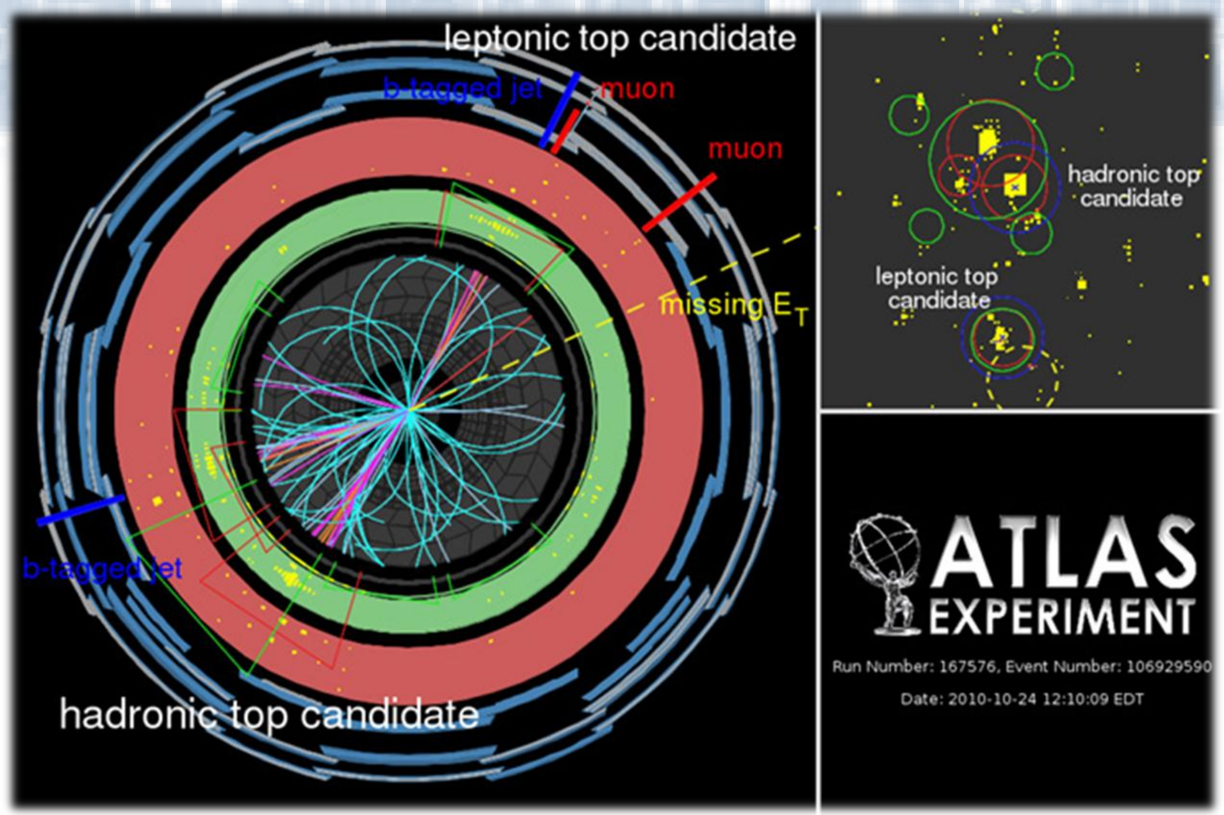
Jet Characteristics



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Internal Structure Of Jets

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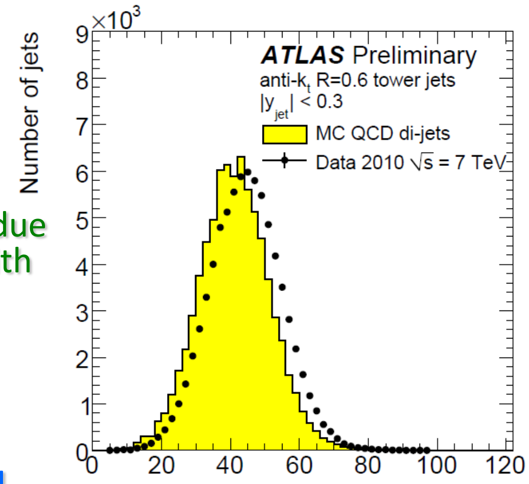
Expect some sensitivity to calorimeter signal definition

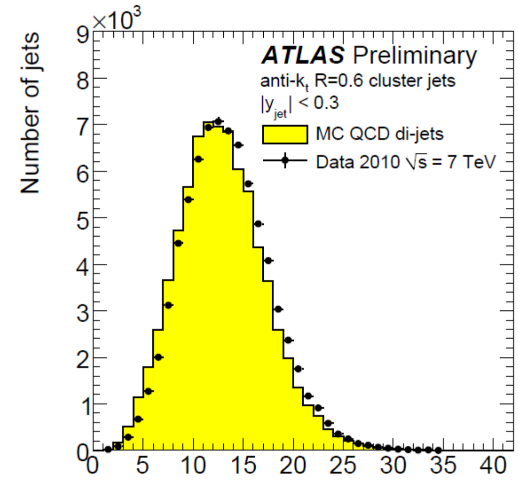
- Most obvious in number of constituents
  - Less clusters in jets expected due to “energy blob” formation with dynamic size
  - Slightly better modeled for cluster jets

Tracks in jets

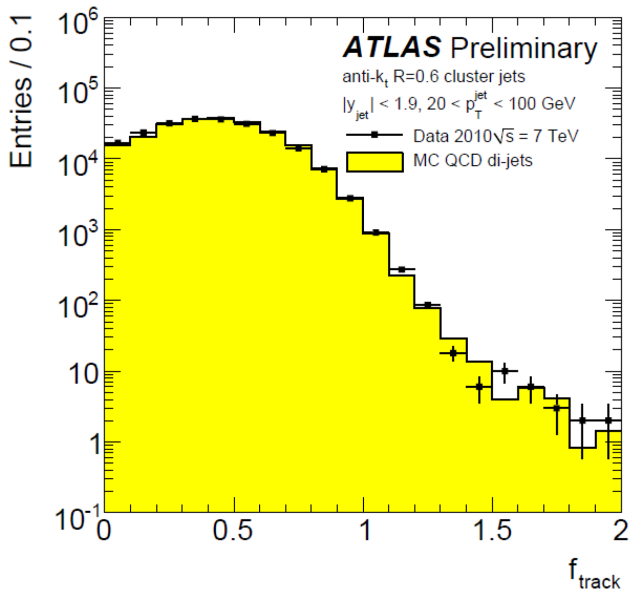
- Average number well correlated with jet p_T
- Charged particle p_T fraction well modeled

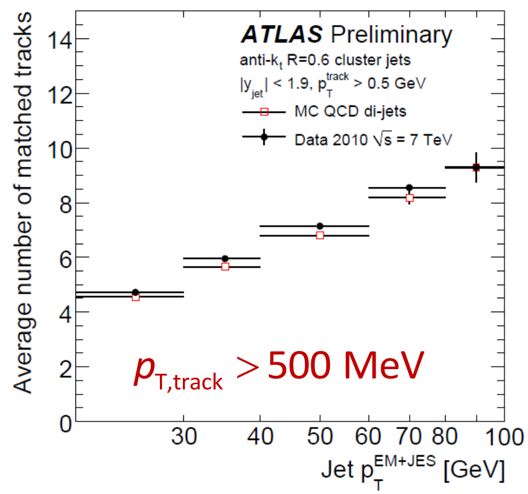


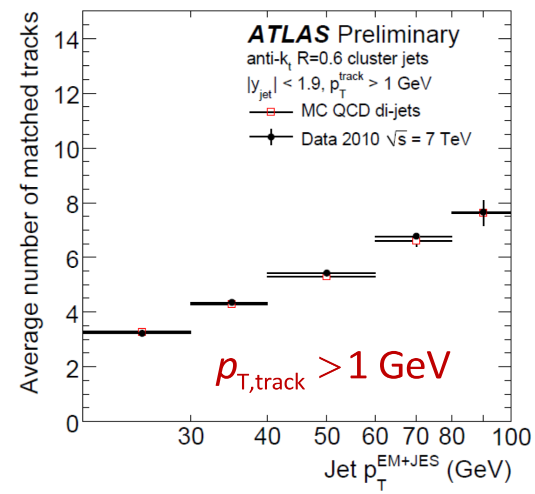
Number towers/jet



Number clusters/jet







$$f_{track} = \frac{\sum p_{T,tracks}}{p_{T,jet}}$$

All MC results from Pythia6 with pre-LHC data tuning!

(*all plots from* **ATLAS-CONF-2010-053**)

Jet Width Measurement

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U of Arizona
September 7, 2011

Calorimeter jet width

$$w_{\text{jet}} = \sum_{\text{constituents } i} r_i \times E_{T,i} \Big/ \sum_{\text{constituents } i} E_{T,i}$$

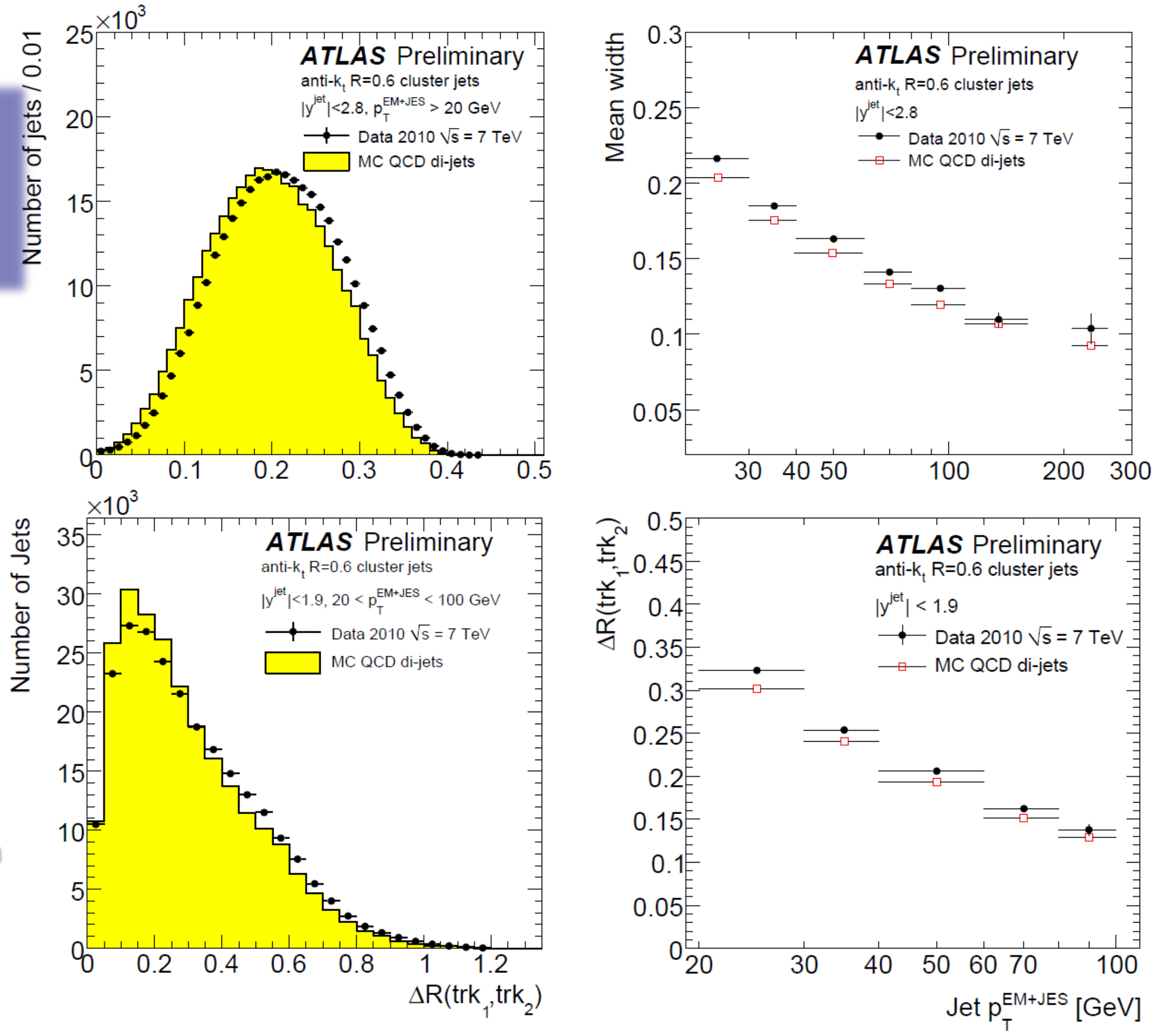
$$r_i = \sqrt{(\varphi_i - \varphi_{\text{jet}})^2 + (\eta_i - \eta_{\text{jet}})^2}$$

Jet core width from tracks

- Distance between two hardest tracks pointing to jet

MC jets too narrow

- Also confirmed in radial jet shape comparisons
  - Consistently observed both in calorimeter and track based shapes
- Very likely modeling problem in Pythia
  - About same level of disagreement also with other generators



All MC results from Pythia6 with pre-LHC data tuning!

(*all plots from* **ATLAS-CONF-2010-053**)

Jet Shapes Analysis

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September 7, 2011

Motivation

- Jet shapes at LHC can constrain phenomenological models
  - Soft gluon radiation
  - Underlying event activity
  - Non-perturbative fragmentation processes in final state

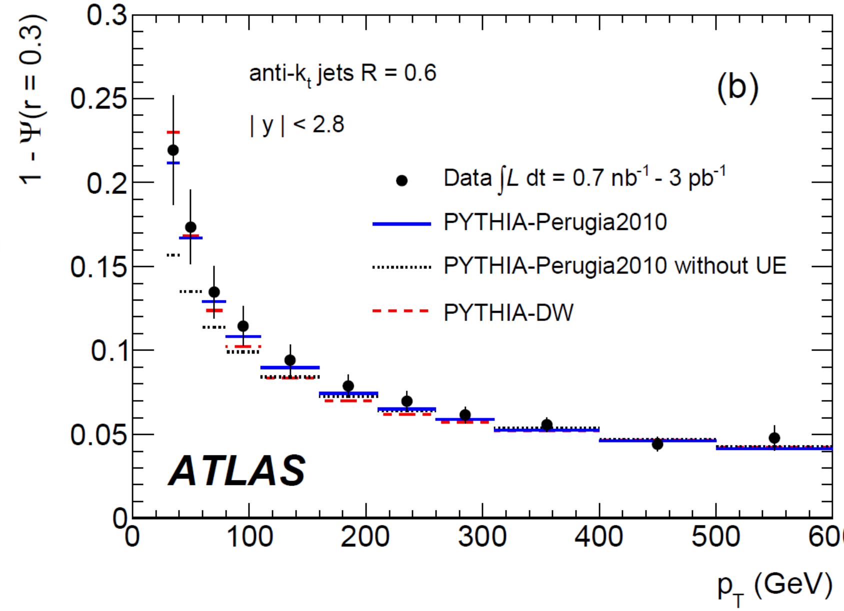
Experimental considerations

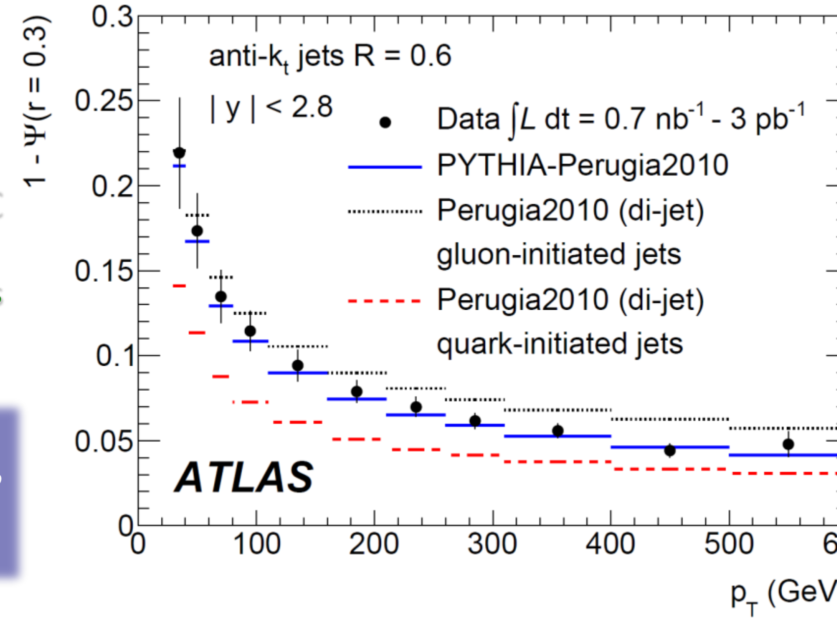
- Calorimeter jet shapes well understood
  - Comparisons to track based measures confirm significant sensitivity to physics
  - Well controllable detector effects allow for small unfolding corrections and associated errors
    - 0.95-1.1 for differential jet shapes
    - <5% for integrated jet shapes
- Clear deficiencies in some models

Applications

- ATLAS now uses differential jet shapes in MC tuning
  - E.g., for parton shower modeling parameters in Pythia

$$\Psi(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jets}} \left[\int_0^r p_T(r')\,dr' \Big/ \int_0^R p_T(r')\,dr' \right]_{\mathrm{jet}} ,\ 0 \le r \le R$$

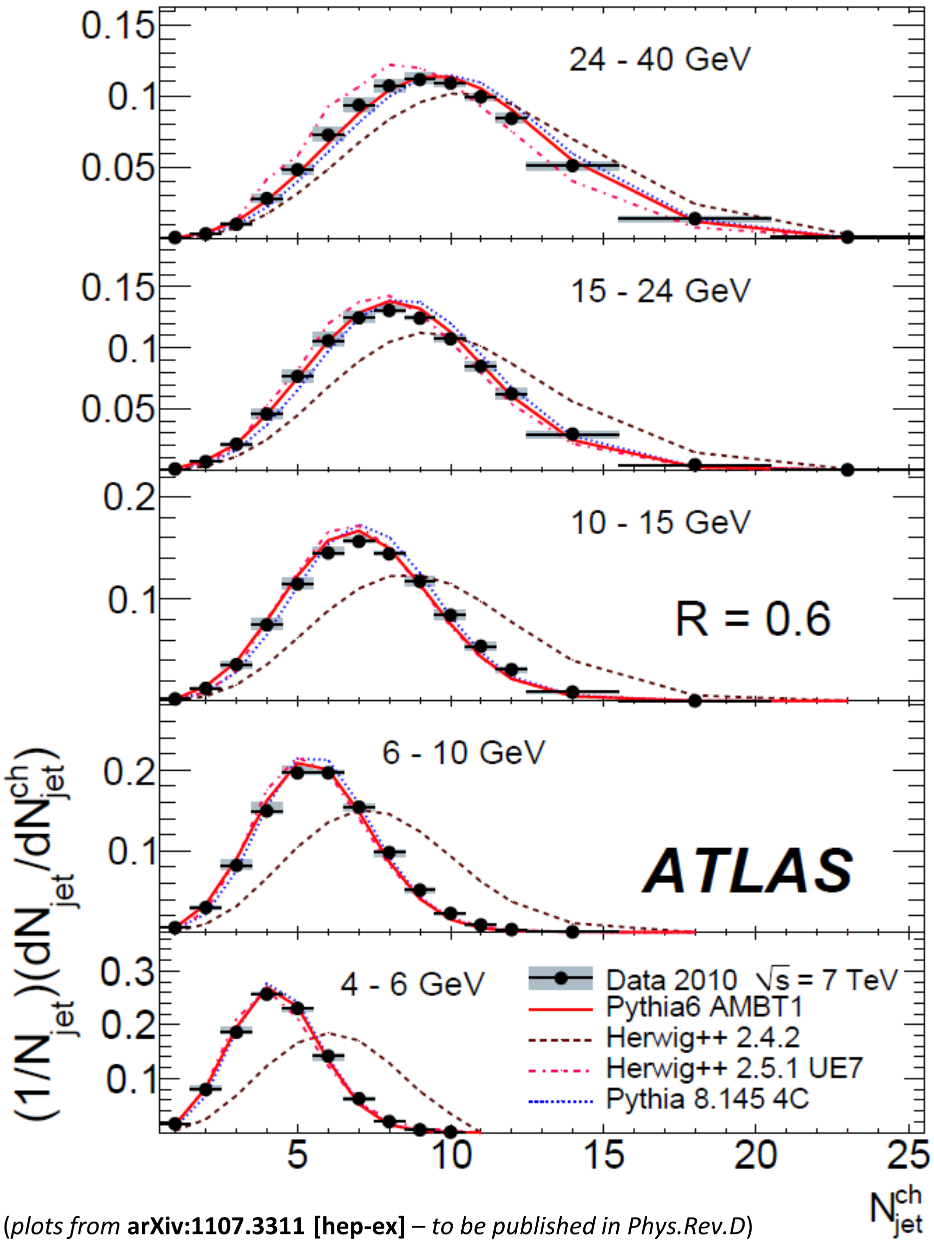




(*all plots from* **arXiv:1101.0070 [hep-ex]** – *to be published in Phys.Rev.D*)

Jets from charged particles

- Reconstructed from track jets
  - Input are tracks with pT > 300 MeV, |η|<2.8
  - Charged particle jet properties unfolded from corrected track jets
  - Use Anti-kT with R = 0.4 and R = 0.6
- Fragmentation measures
  - Number of charged particles in jet
  - Longitudinal charged particle momentum projection onto jet momentum
  - Relative transverse momentum of charged particles wrt jet momentum
  - Charged particle number densities



(*plots from* **arXiv:1107.3311 [hep-ex]** – *to be published in Phys.Rev.D*)

Jets from charged particles

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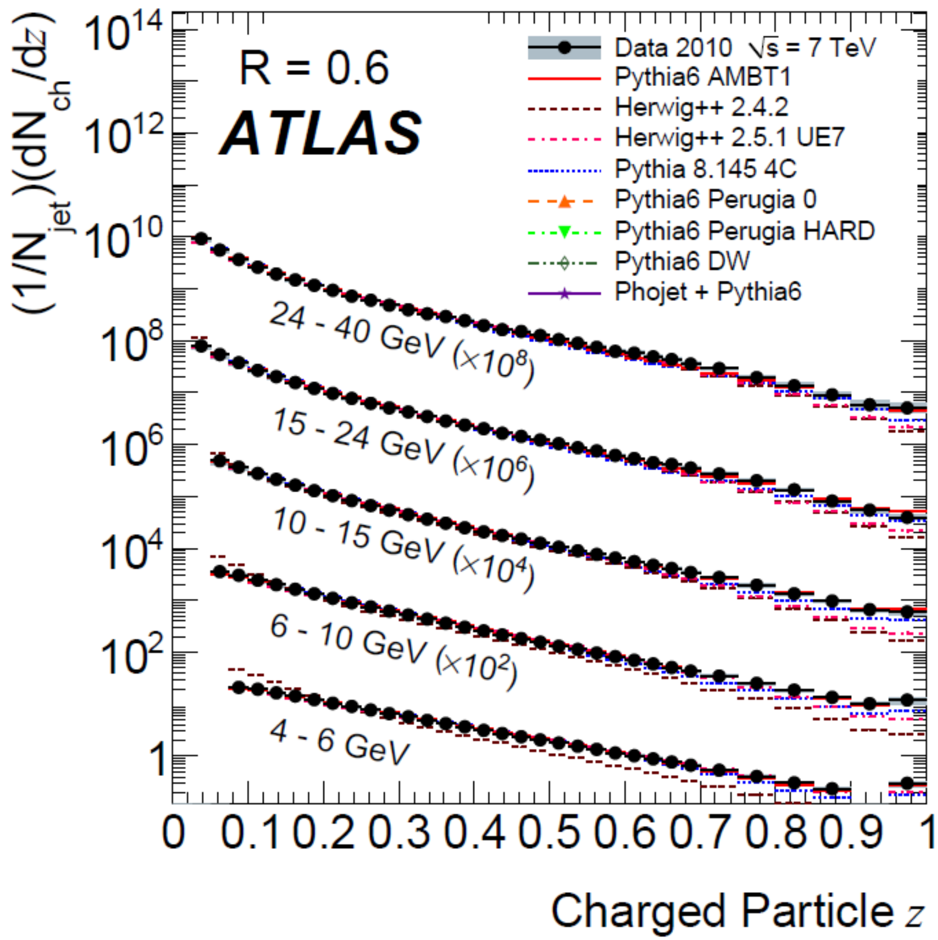

$$z = \frac{\vec{p}_{\text{charged}} \cdot \vec{p}_{\text{jet}}}{\left|\vec{p}_{\text{jet}}\right|^2}$$

(*plots from* **arXiv:1107.3311 [hep-ex]** – *to be published in Phys.Rev.D*)

Jet Fragmentation

Jets from charged particles

- Reconstructed from track jets
  - Input are tracks with pT > 300 MeV, |η|<2.8
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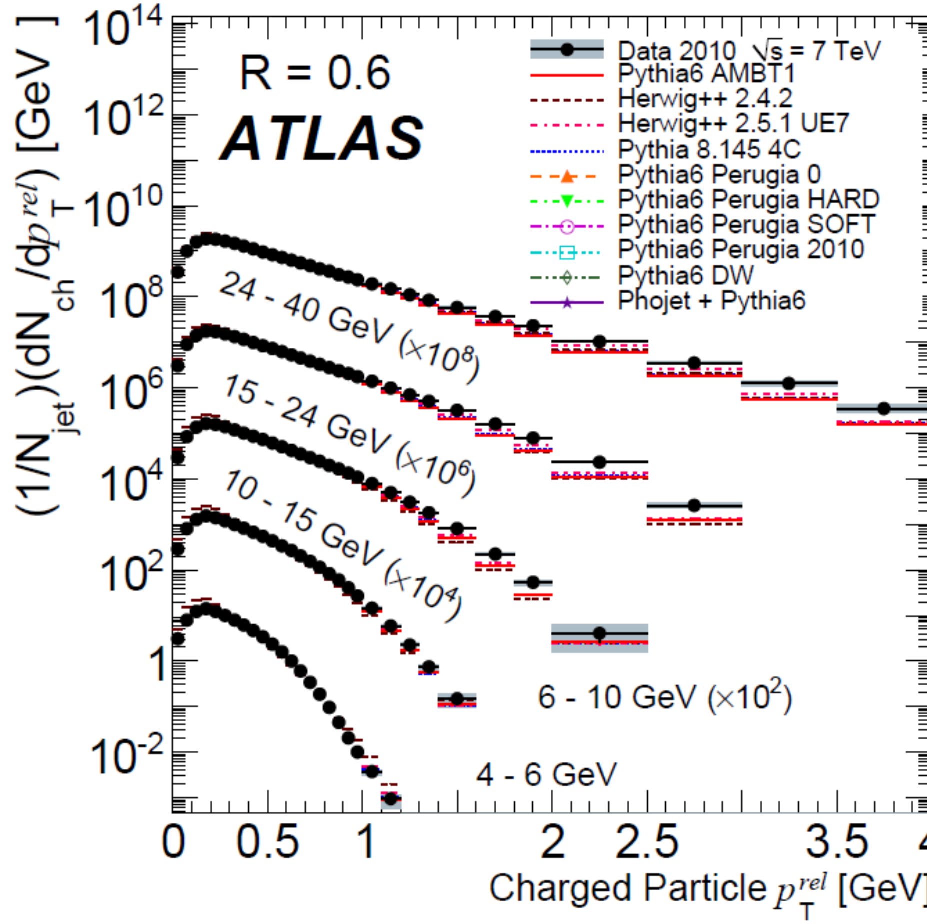

$$p_T^{rel} = \frac{\left|\vec{p}_{charged} \times \vec{p}_{jet}\right|}{\left|\vec{p}_{jet}\right|^2}$$

(*plots from* **arXiv:1107.3311 [hep-ex]** – *to be published in Phys.Rev.D*)

Jet Fragmentation

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September 7, 2011

Jets from charged particles

- Reconstructed from track jets
  - Input are tracks with pT > 300 MeV, |η|<2.8
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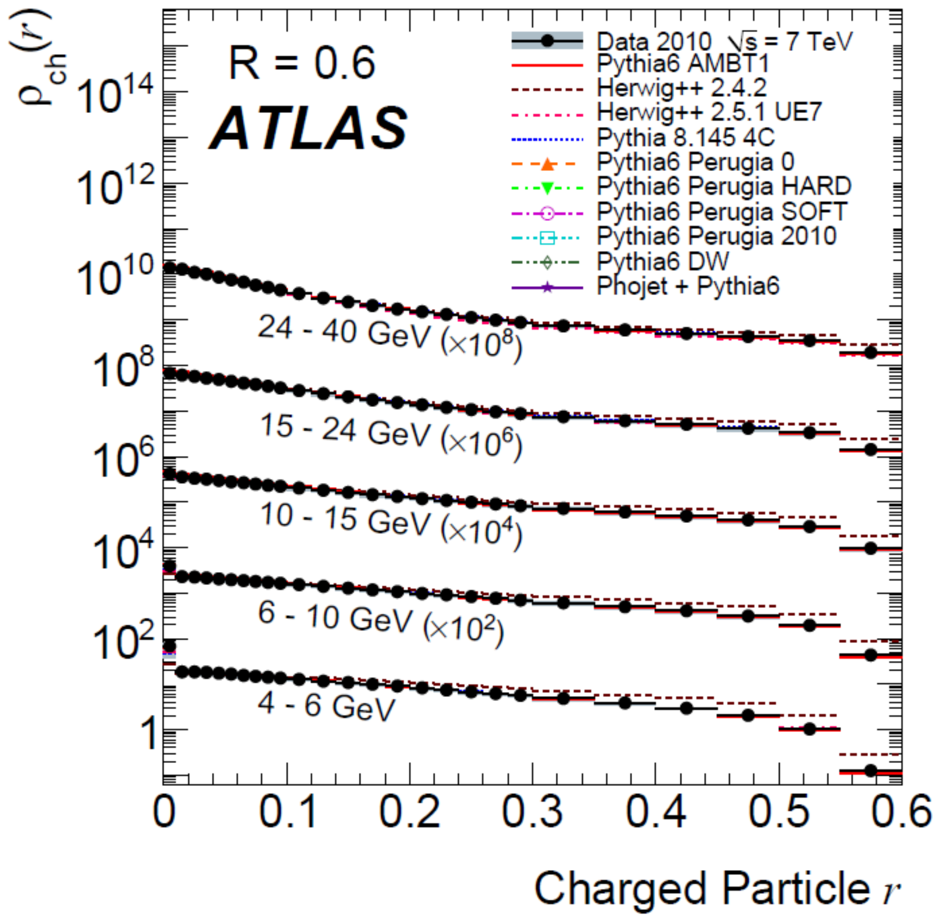
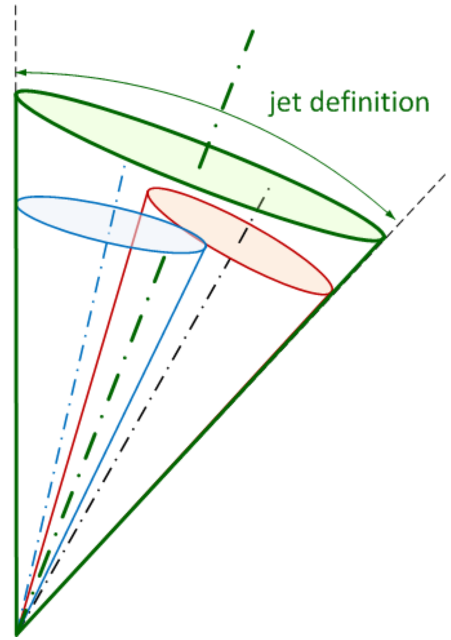


$$\rho_{\text{charged}} = \frac{1}{N_{\text{charged}}} \frac{dN_{\text{charged}}}{2\pi r dr}$$

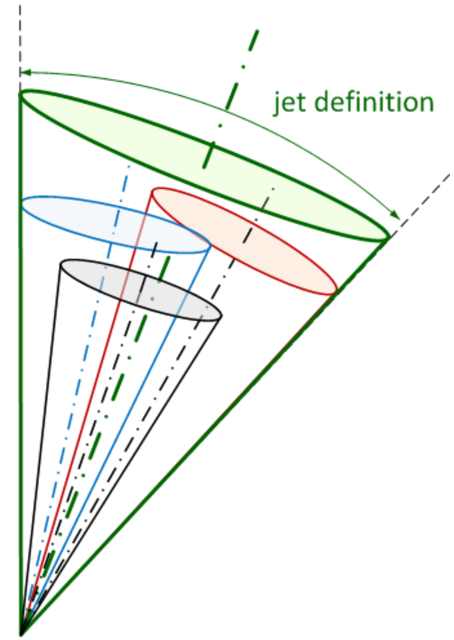
(*plots from* **arXiv:1107.3311 [hep-ex]** – *to be published in Phys.Rev.D*)

Particle flow inside a jet hints to source

- Jet can be a discovery tool by itself
  - In particular most interesting for boosted (new) heavy particle like Kaluza-Klein excitations
  - But also interesting for Standard Model particles like boosted top quarks
- Usefulness depends on the ability to resolve decay structure
  - E.g., 2-prong (like W) or 3-prong (top) decays
  - Resolution scale given by mass of particle (or by particle hypothesis) – to be reflected with detector capabilities



2 – prong decay inside reconstructed jet, e.g. from $W \rightarrow q\bar{q}$ (SM) or heavy new object like $\phi \rightarrow gg$ or $Z' \rightarrow q\bar{q}$ (BSM)



3 – prong decay inside reconstructed jet, e.g. from $t \rightarrow q\bar{q}b$ (SM) or heavy new object like $\phi_{KK} \rightarrow Q\bar{Q}b + X$ or $t' \rightarrow q\bar{q}b$ (BSM)

First Look At Jet Substructure (2010)

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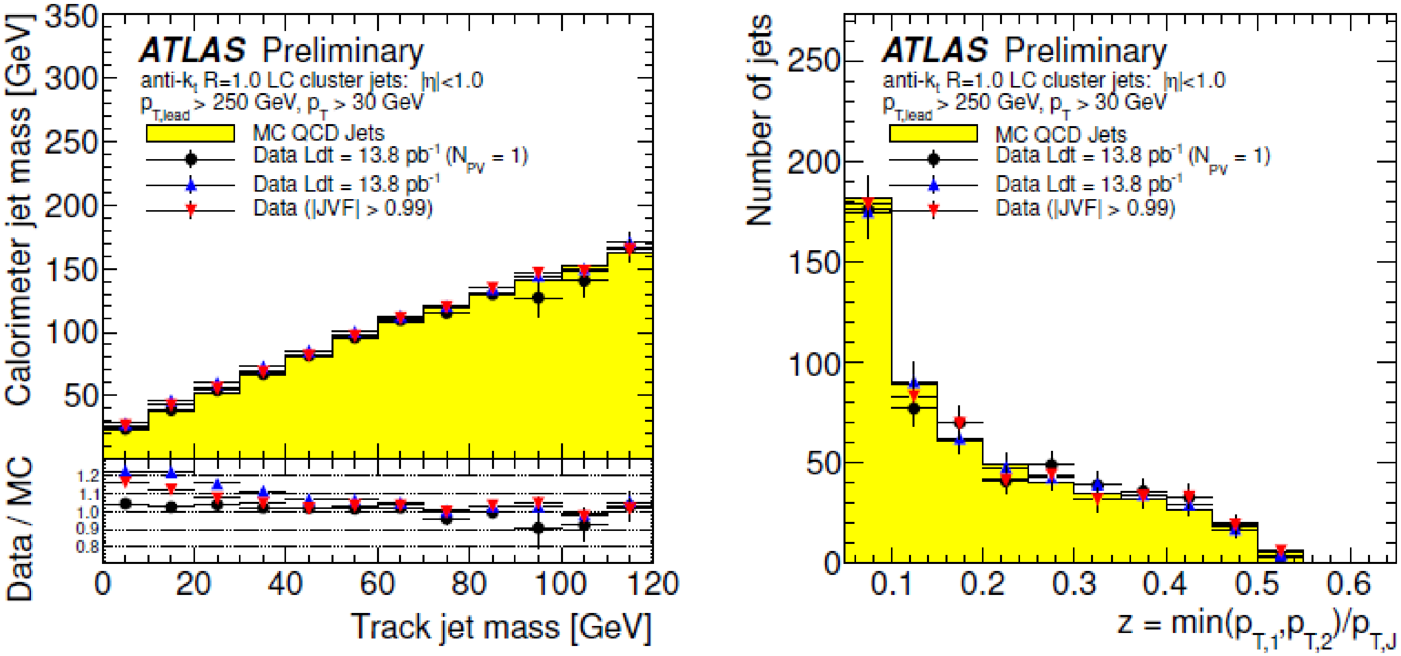
Motivation

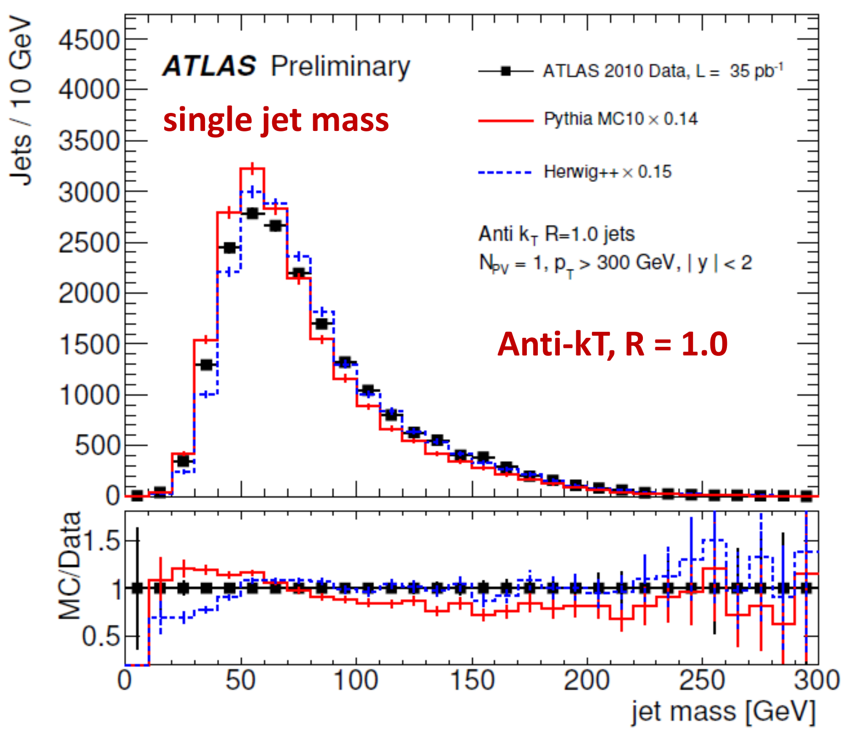
- Looking for boosted heavy particles
  - All decay products are reconstructed in one jet
  - Two-prong (like W→qq or new heavy particle Q* →qq/gg) and three prong (e.g., t →qqb) decay structure can be reconstructed using jet substructure tools at particle level
  - Need to understand experimental limitations introduced by detectors
- First look at calorimeter cluster jets
  - Jet mass reconstruction becomes especially meaningful if jet source is heavy particle
  - Pile-up may generate additional mass and worsen single jet mass resolution
    - Use vertex constraint track jet mass as unbiased reference scale for mass reconstruction
  - Sub-jet kinematics well modeled
    - Little effect from pile-up so far

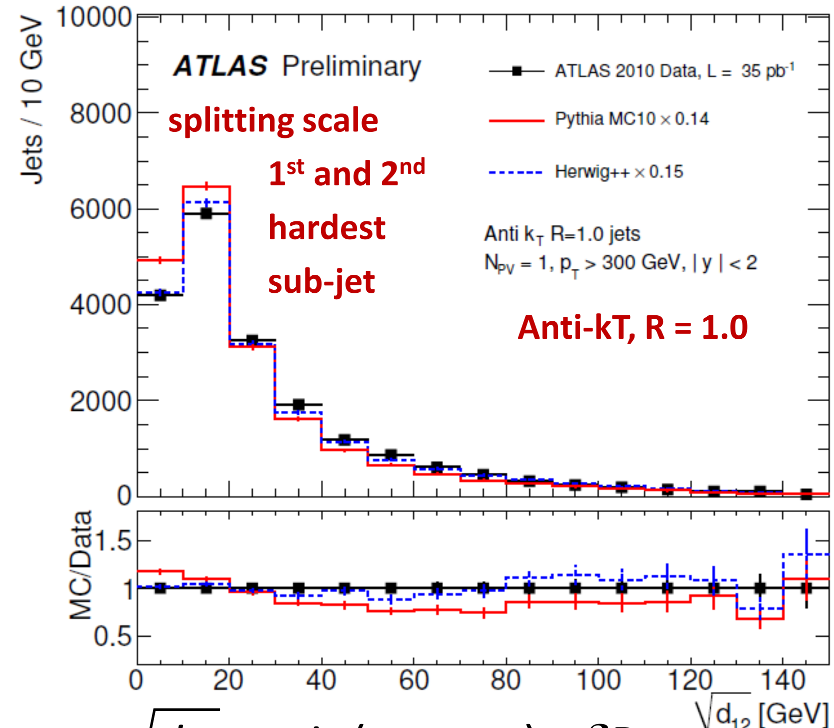


Mass and internal resolution scales for Anti-kT

- High pT jets reconstructed w/o meaningful clustering sequence
  - C/A, kT – meaningful cluster sequences based on distance scales
  - Anti-kT – regularly shaped jets with no specific meaning for the clustering sequence
- Internal distance scale experimentally challenging
  - Requires sufficient spatial resolution in clustering

(all plots from **ATLAS CONF-2011-073***)*





$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \times \delta R_{12}$$

First Look at Jet Substructure Systematics

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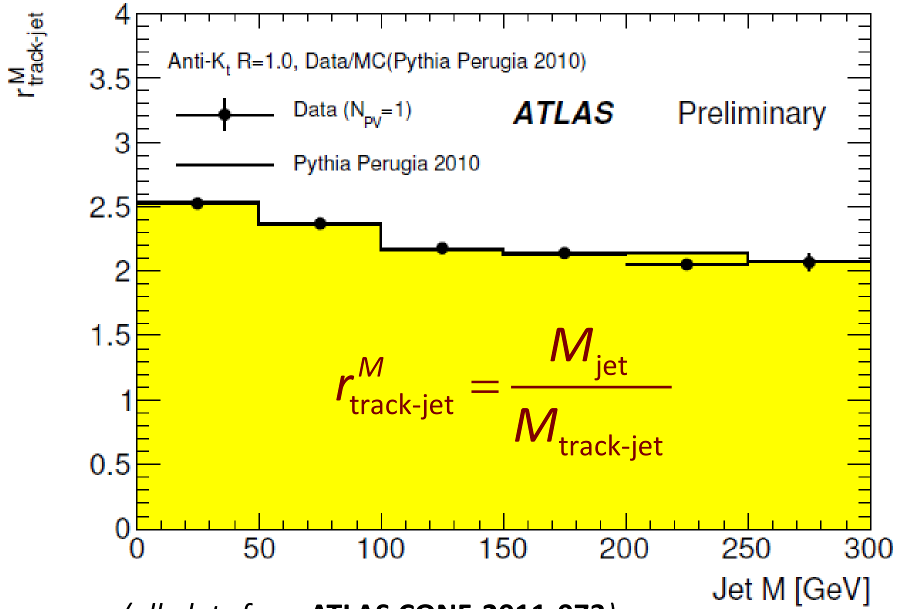
September 7, 2011

Not easy to determine

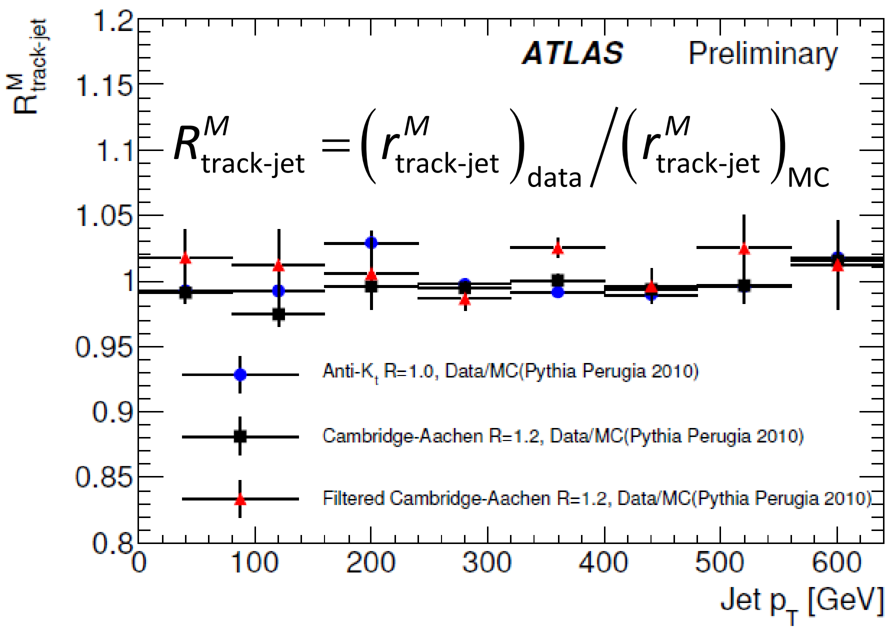
- Only full jet systematic uncertainties available
  - Local energy scales inside jet not well known
- Use track jet mass as unbiased reference for calorimeter mass measurement

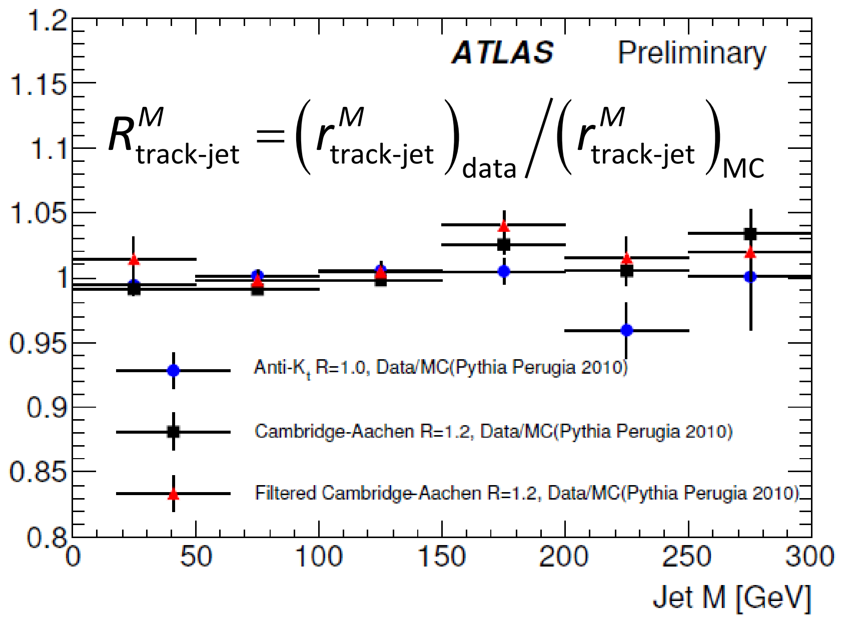
$$r^{M}_{\text{track-jet}} = \frac{M_{\text{jet}}}{M_{\text{track-jet}}}$$

- Double-ratio MC/data establishes systematics



(all plots from **ATLAS CONF-2011-073***)*





Fully Unfolded Jet Mass & Substructure

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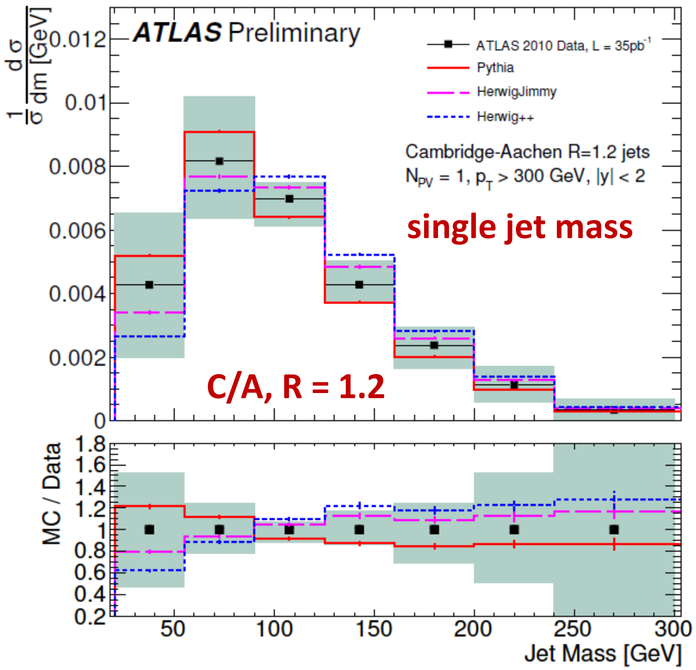

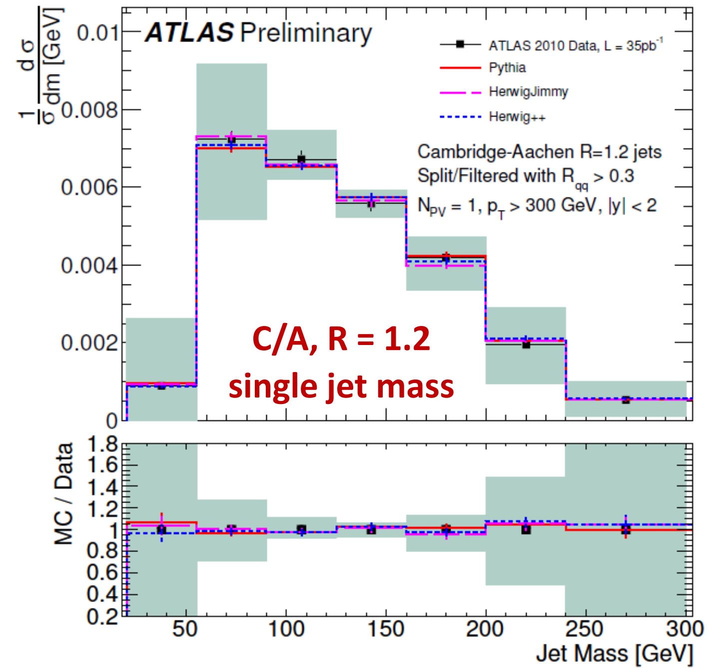

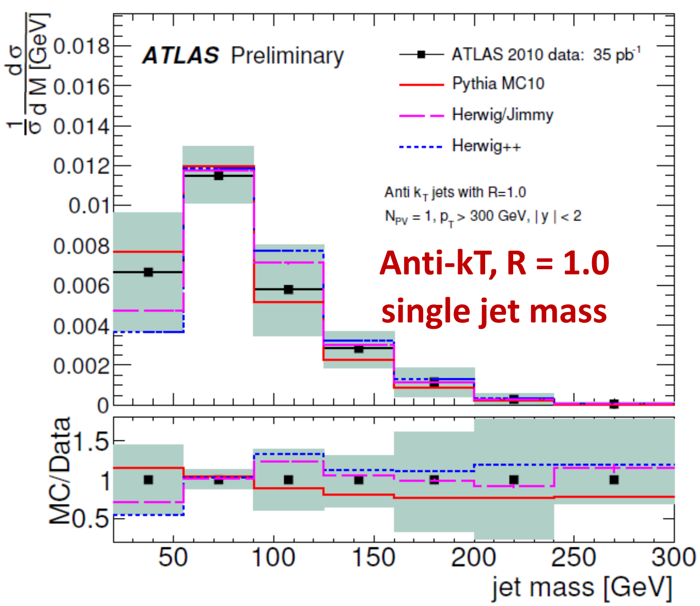

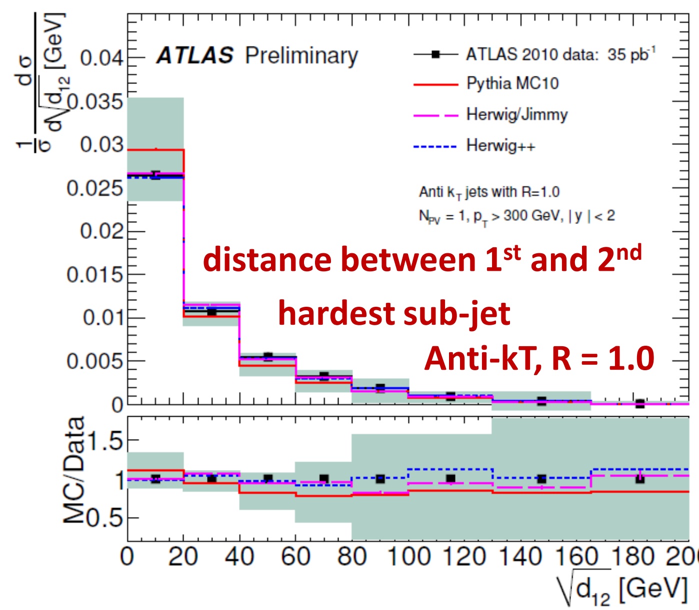

(all plots from **ATLAS CONF-2011-073***)*

Jet Mass Reconstruction in Pile-up

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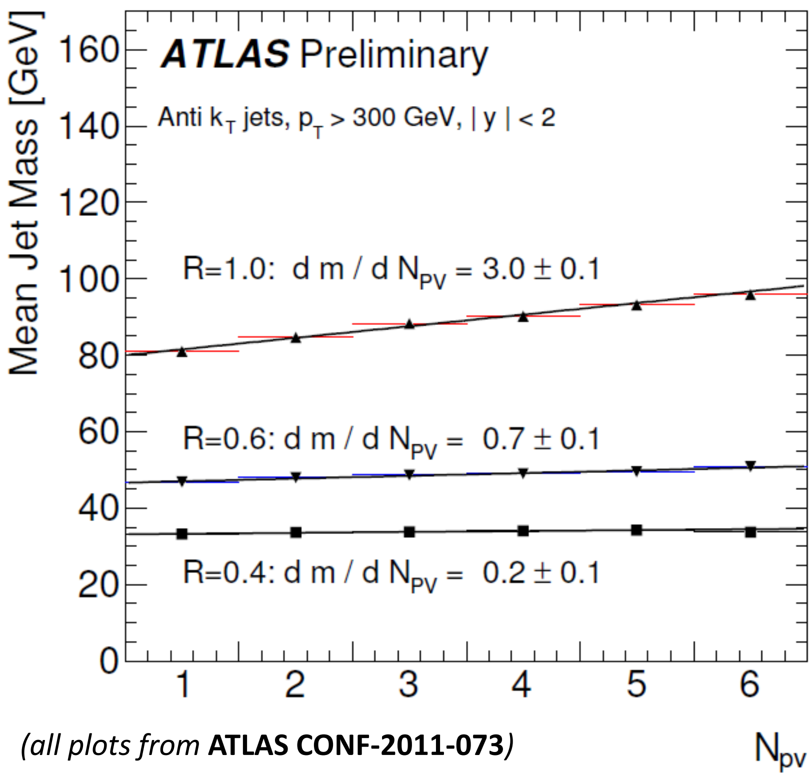
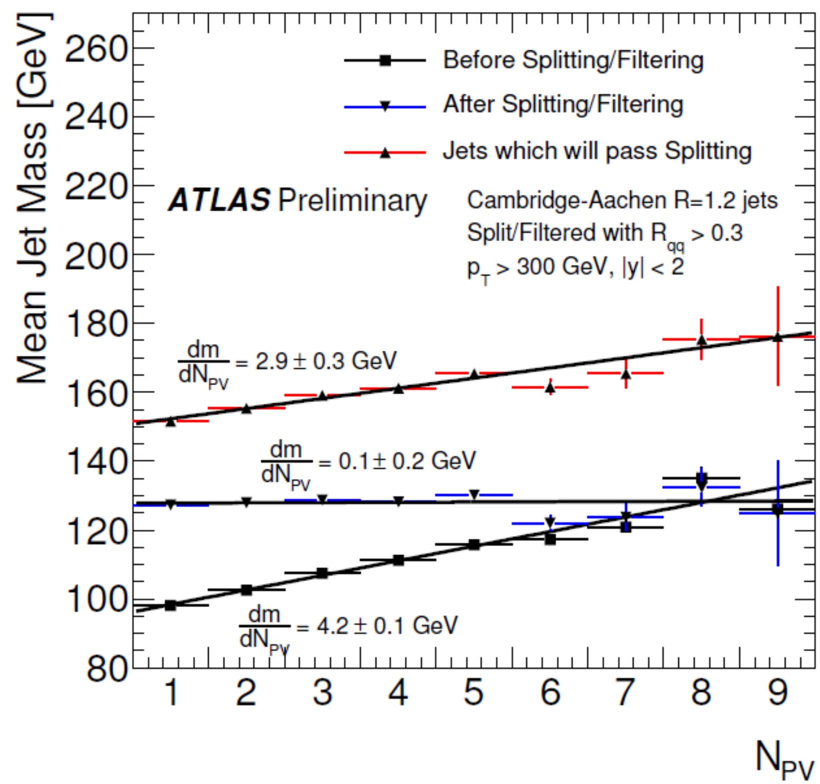
Pile-up "disturbs" particle flow inside jet

- Gain of mass with increasing pile-up expected
  - More energy added at larger distance from jet axis
- Pure in-time pile-up considered here
  - ATLAS 2010 data, no pile-up history
- Effect strongly reduced for narrow jets
  - That's why like Anti-kT with small distance parameter!

Boosted object search

- Prefers substructure in "fat jets"
  - Better extraction of decay structure
- Jet grooming suppresses pile-up
  - Focuses on hard sub-jet structure
  - Suppresses soft (pile-up and UE) contributions in jet
- First hints that cluster jets are useful for sub-structure analysis in more hostile environment





(all plots from **ATLAS CONF-2011-073***)*

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Hints of Boosted Objects in ATLAS

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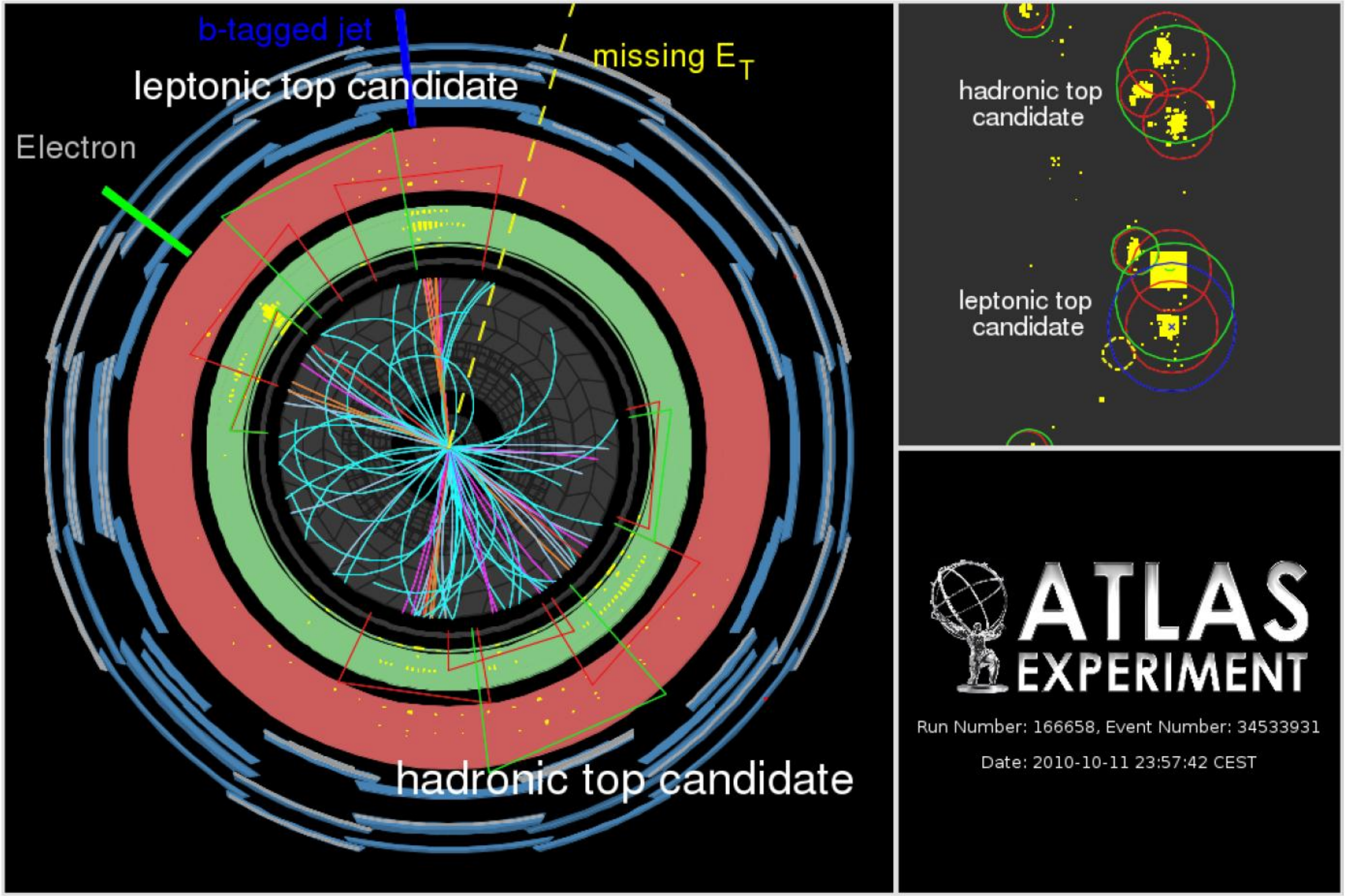
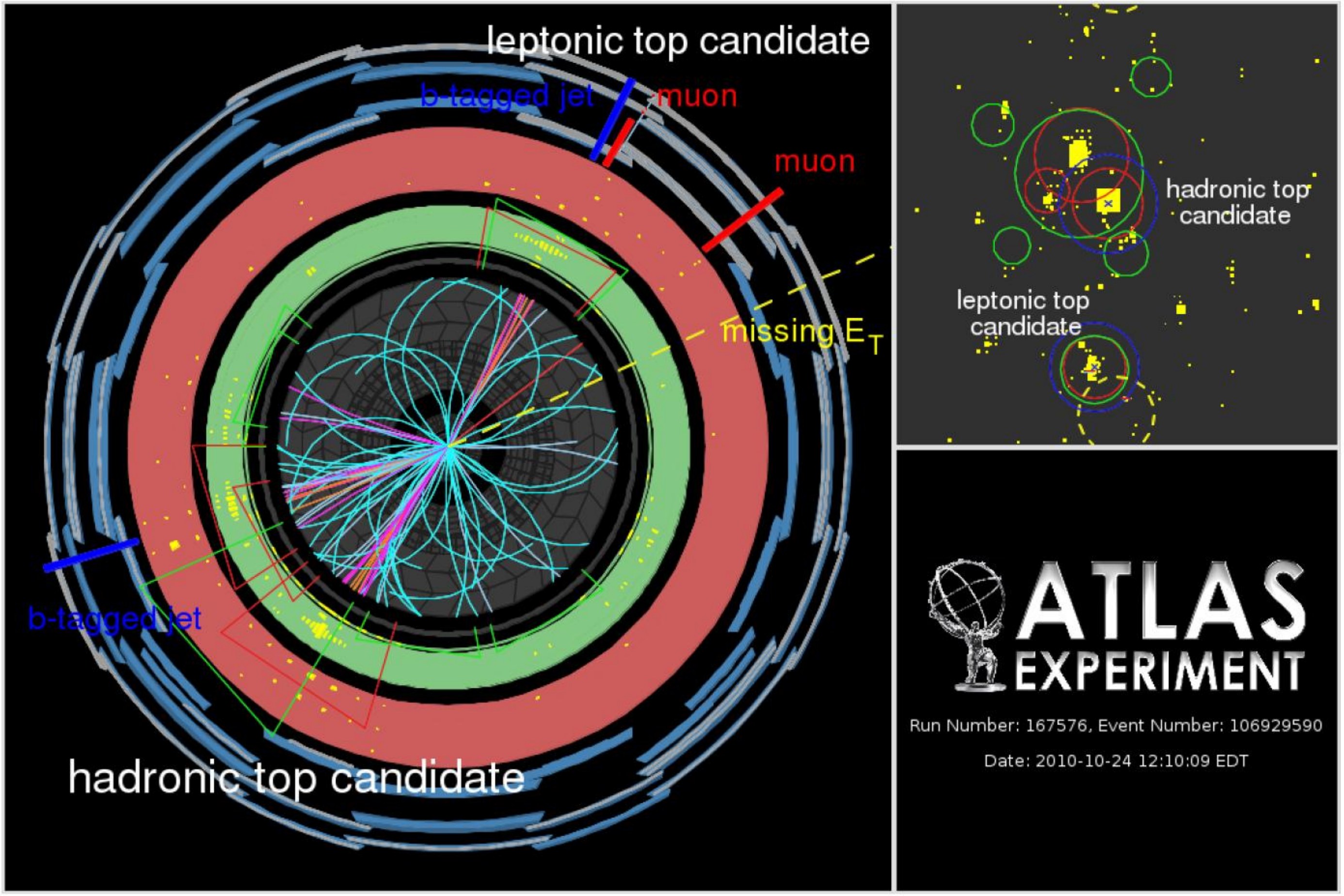


Leptonic top	E_T^{miss}: E_T = 36 GeV, ϕ = -1.5 electron: p_T = 145 GeV, η = 1.1, ϕ = 2.5 jet: index = 1, E_T = 194 GeV, η = 1.2, ϕ = 1.7, m_j = 17 GeV
Hadronic top (R =0.4 clustering)	jet 2, E_T = 155 GeV, η = 1.1, ϕ = -0.7 rad, m_j = 22.7 GeV + jet 3, E_T = 113 GeV, η = 1.3, ϕ = -1.7 rad, m_j = 14 GeV + jet 4, E_T = 54 GeV, η = 0.6, ϕ = -1.7 rad, m_j = 8 GeV
Hadronic top (R =1.0 clustering)	jet 1, E_T = 356 GeV, η = 1.3, ϕ = -1.1 rad, m_j = 197 GeV $\sqrt{d_{12}}$ = 110, $\sqrt{d_{23}}$ = 40

Hints of Boosted Objects in ATLAS



Leptonic top	E_T^{miss}: E_T = 159 GeV, ϕ = 0.4 muon: p_T = 114 GeV, η = 0.21, ϕ = 0.66 jet: index = 3, E_T = 90 GeV, η = -0.5, ϕ = 1.1, m_j = 11 GeV
Hadronic top (R =0.4 clustering)	jet 1, E_T = 205 GeV, η = -0.8, ϕ = -2.2 rad, m_j = 18.3 GeV + jet 2, E_T = 115 GeV, η = -0.2, ϕ = -2.8 rad, m_j = 10 GeV + jet 4, E_T = 49 GeV, η = -1.3, ϕ = -2.7 rad, m_j = 11 GeV
Hadronic top (R =1.0 clustering)	jet 1, E_T = 418 GeV, η = -0.8, ϕ = -2.4 rad, m_j = 225 GeV $\sqrt{d_{12}}$ = 105, $\sqrt{d_{23}}$ = 44

Conclusions & Outlook

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Conclusions

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September 7, 2011

Detector jet features and calibration well understood

- First extensive use of topological 3-dimensional calorimeter cell cluster reconstruction in a hadron-hadron collider experiment
  - Relevant signal shapes well described
  - Very good jet reconstruction performance from clusters
- Tracks in jets and track jets provide additional refinement for jet reconstruction
  - Allow in-situ reconstruction efficiency measurement for calorimeter jets
  - Provide additional observables to improve jet calibration
  - Allow jet vertex association and suppression of jets from pile-up in final state

ATLAS provides high precision jet measurements for physics

- Control of systematic uncertainties with present default jet energy calibration better than 3% in central region
  - After only one year of ~37/pb of data!
  - Basic signal reconstruction clearly not at peak of ATLAS jet reconstruction performance – but stable and controllable
- All relevant features of events with jet final states well reconstructed
  - Inclusive jet and di-jet cross section measurements clearly indicate need for NLO QCD models
  - Significant input for (published) Standard Model jet and event shapes and searches for new physics

Near future improvements and challenges in ATLAS jet measurements

- Commissioning of more complex and dynamic hadronic calibration approaches started
  - Cell signal weighting schemes in calorimeter – local at cluster level and global in jet context
  - Use of jet shapes for jet-by-jet energy measurement refinements
- Towards jet classification, mass and sub-structure reconstruction
  - Lack of boosted hadronic decays of heavy particles in 2010 data set for more performance evaluations
  - First look at substructure indicators and single jet mass reconstruction for available jet samples very promising
- Increased pile-up in 2011
  - 50 ns bunch spacing with up to ~1300 bunches
  - First tools for corrections under full development, including new approaches as well!