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**Validation of the Local Hadronic Calibration Scheme of ATLAS
with Combined Beam Test Data
in the End-Cap and Forward Regions of ATLAS**

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Outline

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- Conclusions

Introduction

Calorimeter system of the ATLAS detector

- Electromagnetic calorimeters: lead/liquid argon (LAr)
 - barrel: $|\eta| < 1.475$
 - end-cap: $1.375 < |\eta| < 3.2$
- Hadronic Tile calorimeter: iron/scintillator
 - barrel: $|\eta| < 1.0$
 - extended barrel: $0.8 < |\eta| < 1.7$
- Hadronic end-cap calorimeter: copper/LAr, $1.5 < |\eta| < 3.2$
- Forward calorimeter: $3.1 < |\eta| < 4.9$
 - electromagnetic module: copper/LAr
 - hadronic modules: tungsten/LAr

Coverage	Number of channels	Weight	Length	Diameter
$ \eta < 4.9$	~ 200000	4000 tons	~ 13 m	~ 8.5 m

Introduction

Energy reconstruction and calibration in ATLAS calorimeters

1. Measurement of energy at electromagnetic (EM) scale in all calorimeter cells
2. Reconstruction of clusters from calorimeter cells
3. Application of the hadronic calibration scheme to correct for:
 - invisible energy due to the non-compensating nature of ATLAS calorimeters
 - energy losses in regions not instrumented with read-out
 - energy losses due to unavoidable (at LHC conditions) threshold cuts in the signal reconstruction
4. Jet finding, missing transverse energy reconstruction with calibrated clusters as an input
5. Further energy corrections (to restore the true jet energy, for example)

Local hadronic calibration (LC)

- LC is one of the hadronic calibration schemes developed for the ATLAS calorimeter system
- Input for the local hadronic calibration is topological clusters reconstructed at EM-scale
- Validation of this calibration scheme is done with data obtained during combined beam tests of modules of ATLAS end-cap and forward calorimeters

3D Topological Clusters

Clustering algorithm

- Cells with absolute energy $|E| > 4\sigma_{\text{noise}}$ seed clusters
- All neighbouring cells (within the calorimeter layer and those overlapping in η and φ in adjacent layers and/or calorimeter systems) are added to the cluster
- Cells with $|E| > 2\sigma_{\text{noise}}$ also collect all their neighbours within the cluster
- Two clusters are merged if they share a cell with absolute energy above $2\sigma_{\text{noise}}$
- Clusters are split around local cell maxima with a fixed threshold of $E=500$ MeV
- Two clusters including the same cell share its energy

Cluster moments

- Cluster moments describe shapes and characteristics of reconstructed clusters

$$\langle x^n \rangle = \sum_i E_i x_i^n / \sum_i E_i$$

where i runs over all cluster cells with $E > 0$

- Moments used for the local hadronic calibration:
 - cell energy density ρ
 - shower depth λ_{center} — distance between a shower center and a calorimeter front face
 - isolation parameter — fraction of cells neighbouring the cluster not included in other clusters

Local hadronic calibration scheme

1. **Classification** of clusters as electromagnetic or hadronic
 2. **Weighting** of cluster energy according to the cluster origin
 3. **Out-of-cluster corrections**: to correct for energy deposits inside the calorimeter but outside calorimeter clusters due to the noise thresholds
 4. **Dead material corrections**: to compensate for energy deposits in materials outside of active calorimeter volumes
- Steps 2-4 may be applied in any order
 - Weights and corrections are determined from the detailed Monte Carlo (MC) simulations of single pions
 - LC is based fully and solely on calorimetric signal features
 - It does not depend on initial physics processes

Combined beam tests of ATLAS end-cap and forward calorimeters

- Beam tests in 2004 in the H6 beamline at the CERN SPS
- Modules of three ATLAS calorimeters:
 - electromagnetic end-cap EMEC
 - hadronic end-cap HEC
 - forward calorimeter FCal (FCal1 — electromagnetic module, FCal2 — hadronic module)

Schematic view of the calorimeter set-up in beam tests

Position of scanned points on the front face of the calorimeter

- Beams of charged pions, electrons and muons of the beam energy (E_{BEAM}) from 6 to 200 GeV
- Energy scans in 10 impact points
- Vertical and horizontal scans
- Exposed zone corresponds to the ATLAS pseudorapidity region of $2.5 < |\eta| < 4.0$

Simulations

- GEANT4 simulation toolkit (version 9.2)
- Used physics lists (set of processes for the simulation of hadronic interactions):
 - QGSP-BERT (Quark-Gluon-String and Bertini cascade models)
 - FTFP-BERT (FRITIOF string model and Bertini cascade model)
- Two set of MC samples were produced:
 1. Simulation of charged and neutral pions — to derive weights and correction coefficients for the local hadronic calibration
 - flat coverage of the whole beam test space: $\pi/2 < \varphi < \pi$ and $2.0 < \eta < 4.0$
 - beam energies in the interval from 1 to 400 GeV logarithmically flat
 - storing “calibration hits” (energy depositions due to ionization, invisible and escaped energies in active and passive parts of the beam test setup)
 2. Simulations of energy and position scans with charged pions and electrons — to compare with available experimental data

Results of the LC validation with test beam data

- Energy scans in the end-cap region ($\eta \simeq 2.75$ in ATLAS)
 - electrons
 - charged pions
- Energy scans in the forward region ($\eta \simeq 3.6$ in ATLAS)
 - electrons
 - charged pions
- Vertical (i.e. pseudorapidity) scan with charged pions over the entire calorimeter system

Energy scans

- Energy reconstruction:
 - sum of energies of all clusters
 - Gaussian fit within $\pm 3\sigma$ around peak value E_0
- Analysed variables:
 - cluster moments: energy density and shower depth
 - pion energy response E_0/E_{BEAM}
 - pion energy resolution σ/E_0

Electrons in the end-cap region

- Six beam energies: from 6 to 193 GeV
- MC simulations with QGSP-BERT
- Average number of clusters per beam electron: 1.2 (for data and MC)

Average energies in the EMEC

- Good agreement between data and MC predictions (for $E_{\text{BEAM}} \geq 30$ GeV)
- Few percent difference between the measured energies and the corresponding beam energies:
 - energy losses in the material in front of the EMEC
 - longitudinal leakage to the HEC

Electrons in the end-cap region

Cluster moments

Reasonably good agreement between data and MC

Charged pions in the end-cap region

- Seven beam energies: from 10 to 200 GeV
- MC simulations with the two physics lists: QGSP-BERT and FTFP-BERT
- Average number of clusters per beam pion:

E_{BEAM}	10 GeV	200 GeV
Data	1.6	3.0
Both MC	1.6	2.6

Cluster moments

Charged pions in the end-cap region

Cluster moments (cont'd)

- Average energy density predicted by both simulations is 3-6 % larger than in the data (for $E_{\text{BEAM}} \geq 40$ GeV). Hadronic showers are hence more compact in simulations than in data.
- Difference between MC predictions and data for the mean values of shower depth stays below 3 % (for $E_{\text{BEAM}} \geq 60$ GeV).
- In general, there is agreement between the two simulations and the data in the end-cap region for all studied cluster moments except for those which are related to the transverse shape of hadronic showers. For them the MC predicts a smaller shower size.

Charged pions in the end-cap region

Energy response

- Ratio of the response (MC to Data): $R = \frac{(E_0/E_{\text{BEAM}})_{\text{MC}}}{(E_0/E_{\text{BEAM}})_{\text{Data}}} = \frac{E_0^{\text{MC}}}{E_0^{\text{Data}}}$

Response at EM-scale

- Non-linear response indicates the non-compensating nature of end-cap calorimeters
- QGSP-BERT overestimates the experimental response by 2 %, while FTFP-BERT overestimates the data by 4 %

Successive application of LC-steps

- +W cluster classification and weighting
- +OOC out-of-cluster corrections
- +DM dead material corrections

Charged pions in the end-cap region

Energy response at LC-scale

- The LC-scale experimental response is correctly reconstructed by the QGSP-BERT-based corrections
- The application of the native LC-weights and corrections to the corresponding simulations slightly overestimates the energy response
- Agreement between data and MC predictions is better at LC-scale than at EM-scale

Charged pions in the end-cap region

Energy response (cont'd)

Difference in the response for QGSP-BERT and FTFP-BERT physics lists

- $\sim 2\%$ at EM-scale
- $\sim 0\%$ after application of the native LC-weights and corrections
- $\sim 5\%$ after application of the non-native LC-weights and corrections

Double ratio of the response

- To assess the systematic uncertainty of the local hadronic calibration, the EM-scale difference should be factored out
- Double ratio of the response = R_{LC}/R_{EM}

- Double ratio of the energy response differs from unity by 1.0-1.3 %
- Similar results are obtained for both physics lists

Charged pions in the end-cap region

Energy resolution

Successive application of LC-steps

- Weighting step improves the energy resolution at higher beam energies
- Out-of-cluster corrections improve the energy resolution at lower beam energies

Resolution at EM-scale

- Two physics lists give close results (for $E_{\text{BEAM}} \geq 40$ GeV)
- They predict better resolution than experimental values by 10-15 %

Charged pions in the end-cap region

Energy resolution at LC-scale

- Improvement of the energy resolution after application of the local hadronic calibration is about 5-15 % for data and simulations
- Resolution improvement at LC-scale with respect to EM-scale is slightly better for simulations than for experimental data

Electrons in the forward region

- Six beam energies: from 6 to 193 GeV
- MC simulations with QGSP-BERT
- Average number of clusters per beam electron:
varies from 1.3 at 6 GeV to 1.9 at 193 GeV (for data and MC)

Average energies in the FCal1 (electromagnetic module)

- Good agreement between data and MC predictions (for $E_{\text{BEAM}} \geq 30$ GeV)
- Difference between the measured energies and the corresponding beam energies is due to energy losses in the material in front of the FCal

Electrons in the forward region

Cluster moments

Good agreement (within 1 %) between data and MC

Charged pions in the forward region

- Seven beam energies: from 10 to 200 GeV
- MC simulations with the two physics lists: QGSP-BERT and FTFP-BERT
- Average number of clusters per beam pion:

E_{BEAM}	10 GeV	200 GeV
Data	1.6	3.4
QGSP-BERT	1.5	3.2
FTFP-BERT	1.6	3.1

Cluster moments

Charged pions in the forward region

Cluster moments (cont'd)

- Both physics lists predict similar shapes of hadronic showers
- Showers are more dense and have smaller depth in the simulations than in the data
- In general, MC predicts earlier start of hadronic showers and they are more compact than observed experimentally in the forward region

Charged pions in the forward region

Energy response at EM-scale

- Non-linear response reflects the non-compensating nature of the FCal
- FTFP-BERT describes the experimental response well
- QGSP-BERT underestimates the response by 3-8 %

Charged pions in the forward region

Energy response at LC-scale

- Experimental response is best reconstructed with FTFP-BERT-based LC-corrections
- Application of native LC-weights and corrections to the corresponding simulations yields an underestimate of the response by 2-4 %
- A good agreement between the experimental response and response predicted by FTFP-BERT existing at EM-scale becomes worse at LC-scale (up to 3 %)
- For QGSP-BERT a disagreement observed at EM-scale becomes larger at LC-scale

Charged pions in the forward region

Energy response (cont'd)

Difference in the response for QGSP-BERT and FTFP-BERT physics lists

- $\sim 3\%$ at EM-scale
- $\sim 0\%$ after application of the native LC-weights and corrections
- $\sim 5\text{--}7\%$ after application of the non-native LC-weights and corrections

Double ratio of the response

- Double ratio of the energy response differs from unity up to 3 %
- Results obtained for both physics lists are similar

Charged pions in the forward region

Energy resolution

Successive application of LC-steps

- Weighting step improves the energy resolution at higher beam energies
- Out-of-cluster corrections improve the energy resolution at lower beam energies

Resolution at EM-scale

- Two physics lists give similar results (for $E_{\text{BEAM}} \geq 40$ GeV)
- They predict worse energy resolution at EM-scale than experimental values by 5-15 % there

Charged pions in the forward region

Energy resolution at LC-scale

- After application of the local hadronic calibration the resolution in general improves by 10-25 % for both data and simulations
- The local hadronic calibration significantly improves the agreement between experimental and predicted values of the resolution, especially for the FTFP-BERT physics list

Vertical scan with charged pions

- Vertical scan over the entire calorimeter system, corresponding to the pseudorapidity scan in the ATLAS coordinate system: $2.5 < \eta < 3.8$
- Covers:
 - EMEC and HEC: $\eta < 3.2$
 - FCal: $\eta > 3.1$
 - crack between the end-cap calorimeters and the FCal around $\eta \sim 3.2$ (non-projective)
 - support structure positioned in front of the FCal at $\eta \simeq 3.3$ (projective in ATLAS)
- Beam of 200 GeV charged pions
- MC simulations of the vertical with the two physics lists: QGSP-BERT and FTFP-BERT
- Position reconstruction:

beam Y -coordinate in the beam test system is converted to the pseudorapidity η_{BEAM} in the ATLAS coordinate system by using the correlations between (X, Y) - and (η, φ) -coordinates of reconstructed clusters
- Energy reconstruction:
 - sum of energies of all clusters
 - parameter E_0 as the mean of energy distributions
 - parameter σ as the RMS of energy distributions
- Analysed variables (as functions of η_{BEAM}):
 - cluster moments: energy density and shower depth
 - pion energy response E_0/E_{BEAM}
 - pion energy resolution σ/E_0
- LC-scale: QGSP-BERT-based corrections

Vertical scan with pions

Cluster moments

Energy density

Shower depth

- Pseudorapidity dependence of the energy density predicted by both simulations follows the experimental behaviour over the studied η -range
- But the values from simulations are shifted to higher densities relative to the data, as both physics lists predict more compact hadronic showers than observed experimentally
- Pseudorapidity dependence of the shower depth is rather constant across the end-cap and forward regions but varies significantly in the crack region
- Agreement between simulations and experimental data is rather good over the studied η -range

Agreement between the two simulations is very good

Vertical scan with pions

Energy response at EM-scale

- Agreement between data and simulations is reasonably good outside the crack region and becomes worse in the crack region
- Smooth drop of the response with the beam pseudorapidity in the end-cap region is due to the decrease of energy of clusters reconstructed closer to the crack between calorimeters

Vertical scan with pions

Energy response at LC-scale

- The energy response becomes at LC-scale close to one, as expected.
- The agreement between experimental data and simulations outside the crack region is moderate. In the crack region simulations follow the data.
- FTFP-BERT describes the experimental response at LC-scale for the full vertical scan better than QGSP-BERT.
- With respect to EM-scale the response dip in the crack region becomes smaller.
- Nevertheless the average energy response here is lower than E_{BEAM} by 10-15 % for the data:
 - low reconstruction inefficiency
 - cluster misclassification

Vertical scan with pions

Energy resolution

- Significant degradation of the resolution at **EM-scale** is observed in the crack region ($\eta \sim 3.2$) and in the region around $\eta \sim 3.0$
- In the latter case this is related to the changes of the cluster size near the boundary of the end-cap calorimeters, where the drop in response is observed as well
- There are also differences between data and MC predictions in this pseudorapidity region, which can be explained by more compact hadronic showers in simulations
- At other values of the pseudorapidity the agreement between data and simulations is rather good
- At **LC-scale** the resolution is improved for the full scan range, especially in the regions around $\eta \sim 3.0$ and $\eta \sim 3.2$
- Agreement between data and MC simulations also becomes better at LC-scale

Conclusions

The local hadronic calibration is an advanced method for reconstruction of energy deposited in the ATLAS calorimeter system. It uses modular corrections applied to cluster energies reconstructed at EM-scale.

This method is validated with data obtained during beam tests of modules of ATLAS end-cap and forward calorimeters, corresponding to the pseudorapidity range $2.5 < |\eta| < 4.0$. Validation is performed using detailed GEANT4 based simulations of combined beam tests.

The local hadronic calibration allows to reconstruct the initial energy of charged pions in the end-cap region with uncertainty below 1.5 %. In the forward region the uncertainty of the response is about 3 %. In the complicated transition zone between the calorimeters (including a crack at $\eta \sim 3.2$) the response is underestimated by 10-15 %.

One of the important features of the local hadronic calibration is a significant improvement of the energy resolution in all studied calorimeter regions.