Analysis of CALICE W-AHCAL Data at 10 - 100 GeV

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on behalf of the CALICE W-AHCAL group and the CLIC detector and physics study

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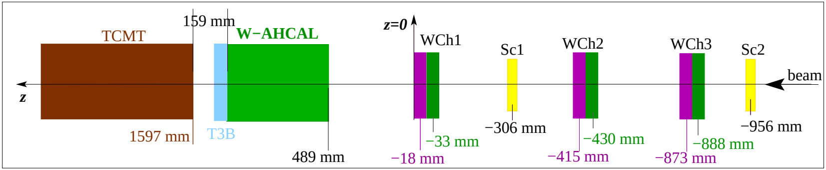
W-AHCAL Test Beam Experiments



- 2011 at CERN SPS
- $10 \leq p_{\text{beam}} \leq 300$ GeV
- Dedicated $e^{\pm}$ beam, mixed beam of $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
- **W-AHCAL** ($\sim 4\,\lambda_{\text{I}}$) + **TCMT** ($\sim 5.5\,\lambda_{\text{I}}$)

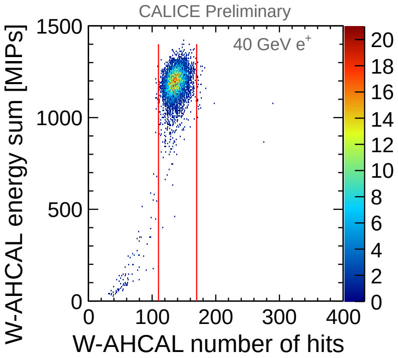
- Comparison to simulations: GEANT4 version 9.5.p01

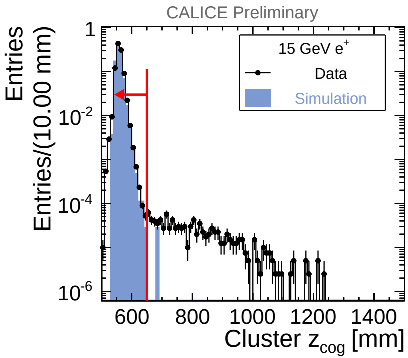
→ CALICE analysis note on data up to 100 GeV CAN-044

→ Ongoing analysis $p_{\text{beam}} \leq 300$ GeV

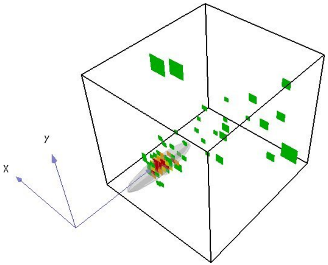
Electron Event Selection

- Use only dedicated $e^{\pm}$ runs of high purity
- Further selection based on W-AHCAL information
  - One calorimeter cluster
  - No tracks
  - Number of hits within range



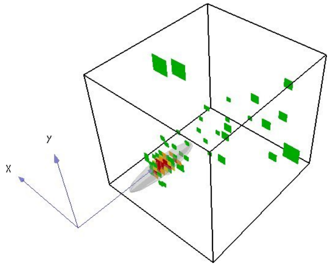


Electron Data



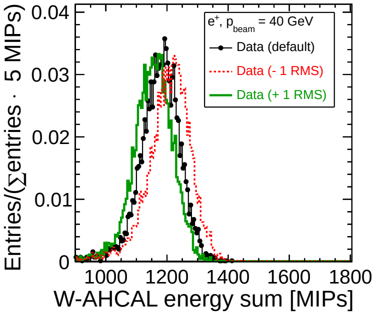
- Tungsten very dense absorber: $\sim 3\,X_0$ per W-AHCAL layer
- Compact $e^{\pm}$ showers
- Large impact of uncertainty of the SiPM saturation scaling factor ($\rightarrow$ backup)

Electron Data



- Tungsten very dense absorber: $\sim 3\,X_0$ per W-AHCAL layer
- Compact $e^{\pm}$ showers
- Large impact of uncertainty of the SiPM saturation scaling factor ($\rightarrow$ backup)

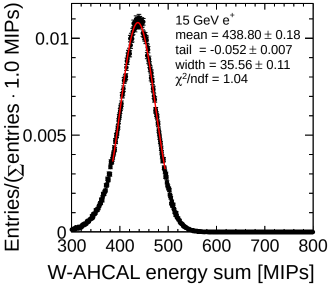
- Vary SiPM scaling factor for highest energy tile ($\pm$1 RMS)
- Saturaton scaling factor uncertainty significant at high energy densities in electromagnetic showers



Calorimeter for ILC

Electron Data: Linearity

- $e^{\pm}$ data at 15-40 GeV
- Describe energy sum using Novosibirsk fit with $\pm 1.5\sigma$ (Gaussian with tail)



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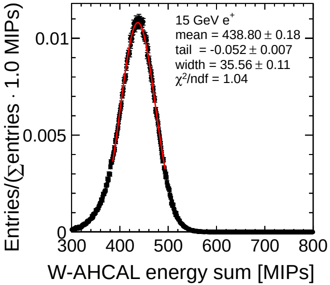
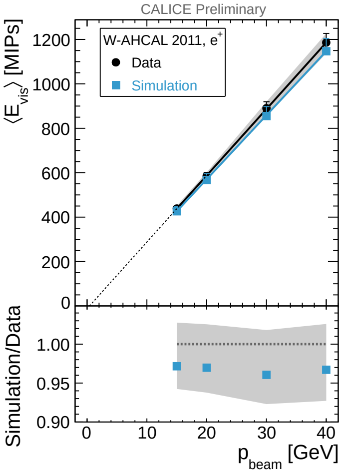
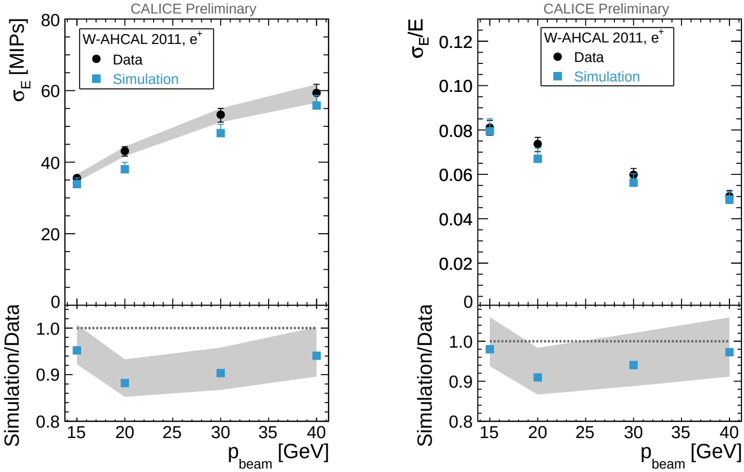




- Visible energy increases with p_{beam}
- Within uncertainties of $\sim 4\,\%$, data and MC agree
- MC tends to show lower response

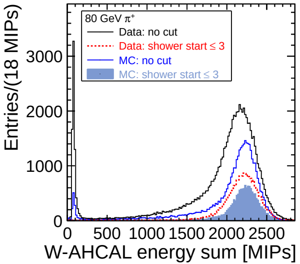
Electron Data: Energy Resolution

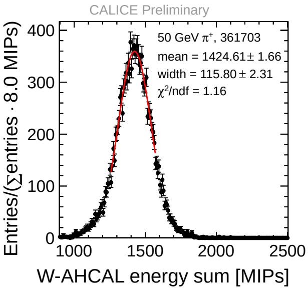


- Within systematic uncertainties, data and MC agree for energy resolution
- MC tends to show better energy resolution

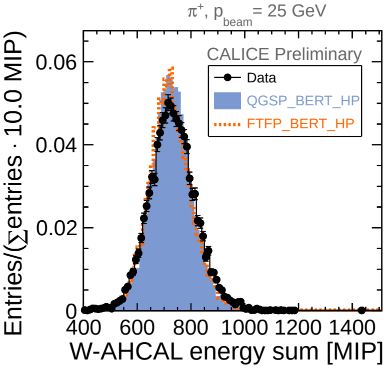
Hadron Event Selection

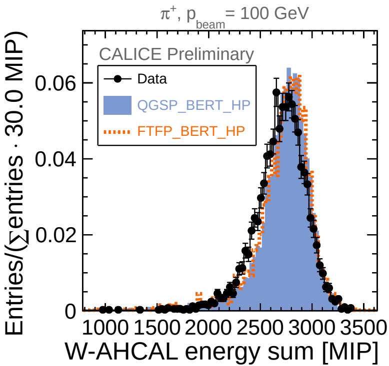
- Cherenkov threshold counter
  ▸ LCD-Note-2013-006
  - π: 15-100 GeV (purity $> 94\,\%$)
  - p: 15-100 GeV (purity $> 85\,\%$)
  - K: 50,60 GeV (purity $> 82\,\%$)
- Layer of the primary interaction in any of the first 3 calorimeter layers
  - Muon rejection
  - Aim to contain hadron showers in W-AHCAL ($\sim 4\lambda_{\mathrm{I}}$) up to 100 GeV
- E and σ_E from Gaussian fit in the central region containing 80 % of the statiscs





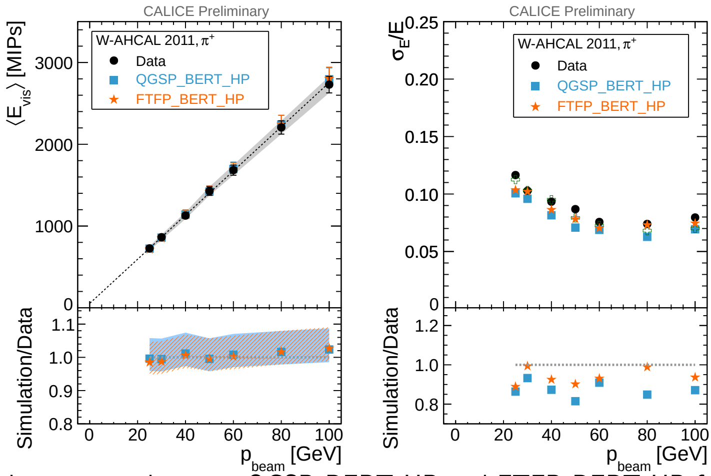
Pion Data: Energy Sum





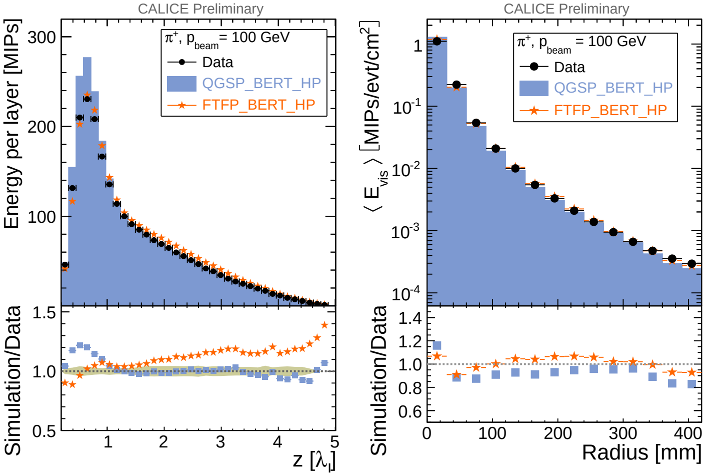
- Good agreement between data and QGSP_BERT_HP and FTFP_BERT_HP

Pion Data: Linearity and Resolution



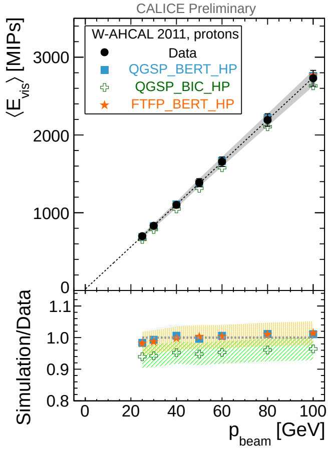
- Good agreement between QGSP_BERT_HP and FTFP_BERT_HP for π^+
- Leveling off of relative resolution at high p_{beam} indicates leakage effects
- MC tends to show better energy resolution

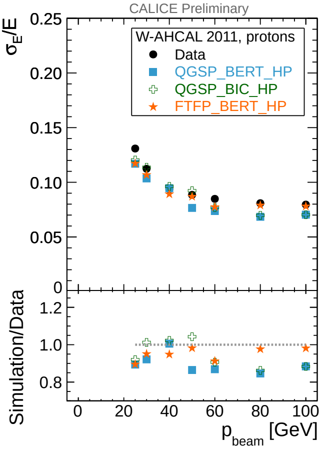
Pion Data: Shower Profiles



- Longitudinal profile (here, from shower start): QGSP_BERT_HP best, overestimates energy deposition in first part of shower
- Radial profile: MCs overestimate energy density in shower core

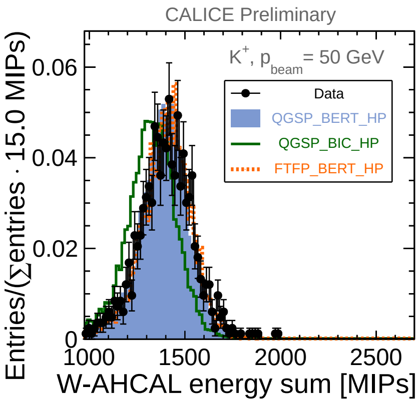
Proton Data: Linearity and Resolution





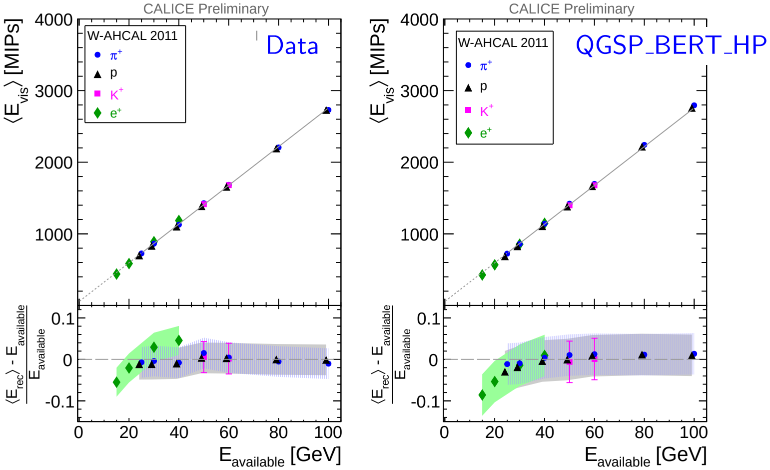
- Linear response and resolution as good as for $\pi^{\pm}$
- Data and BERT models agree well at all energies
- QGSP_BIC_HP underestimates data slightly (within uncertainties)
- MC tends to show better energy resolution

Kaon Data: Energy Sum



- Data and QGSP_BERT_HP and FTFP_BERT_HP agree well for K^+
- QGSP_BIC_HP predicts too low energy

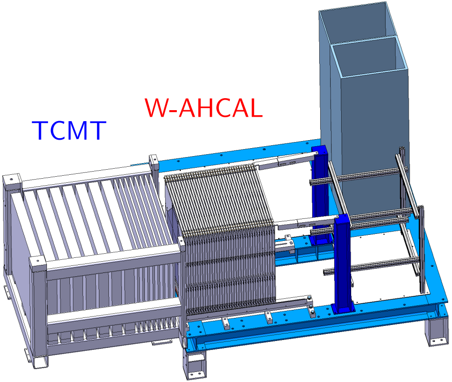
Summary of Results at $p_{beam} \leq 100$ GeV



- Quantify compensation level: Residuals to linear fit of π^+ data
- Deviation better than $\pm 2\%$ for π^+ and protons, worse for e^+

High Energy Hadron Showers: Tail Catcher (TCMT)

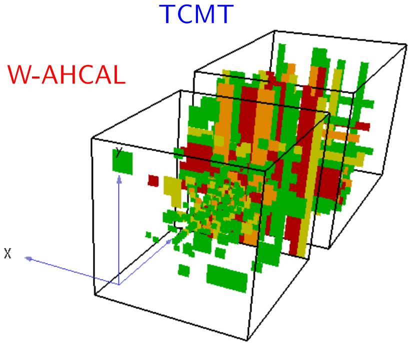
- Test beam experiments at CERN SPS using W-AHCAL+TCMT
- Purpose of TCMT
  - At SPS energies, hadronic shower can leak out of the W-AHCAL of $\sim 4\lambda_I$
  - Catch tail of shower using additional $\sim 5.5\lambda_I$ of tail catcher
  - Combination of W-AHCAL + TCMT $\rightarrow$ improve energy resolution

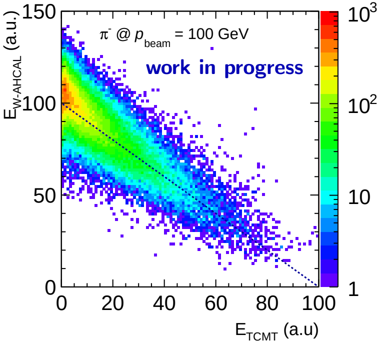


- W-AHCAL: 38 tungsten layers, each 10 mm thick
- $TCMT_1$: 8 steel layers, each 20 mm thick
- $TCMT_2$: 8 steel layers, each 100 mm thick
- TCMT readout: scintillator strips and SiPM

High Energy Hadron Showers: Tail Catcher (TCMT)

- Example pion shower at $p_{beam} = 100$ GeV
- TCMT recovers energy leaked out of W-AHCAL



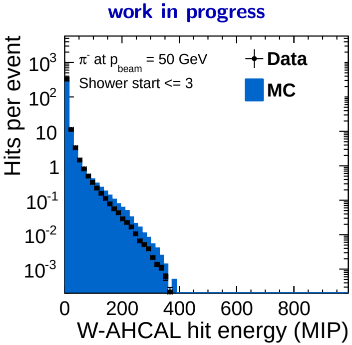


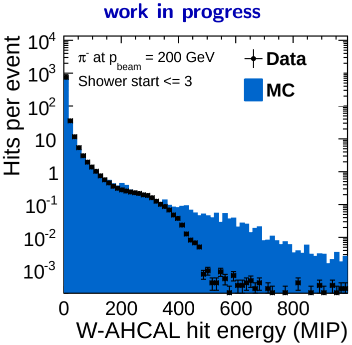
- W-AHCAL: scintillator tiles
- TCMT: scintillator strips

- Ongoing study on how to combine W-AHCAL and TCMT energies

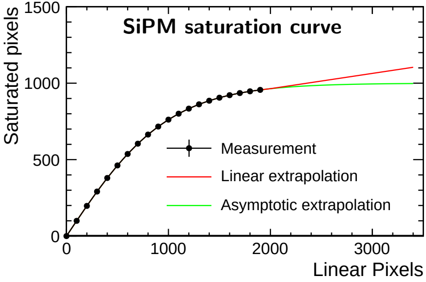
High Energy Data: Saturation Effects in W-AHCAL

- At low p_{beam}, hit energy reach in MC and data agree well
- At high p_{beam}, MC and data start to differ
  $\rightarrow$ MC reaches much higher energy depositions per cell
- Sign of saturation effect in data which is not accounted for in MC



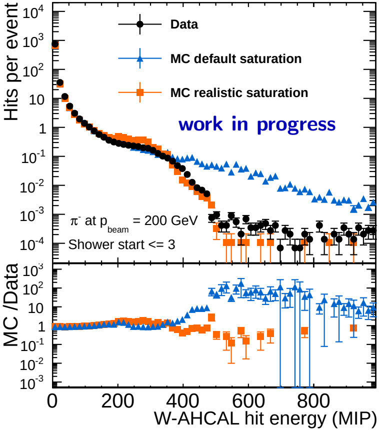


High Energy Data: Saturation Effects in W-AHCAL



- **Data**
  - Linear extrapolation in reconstruction
- **MC with default saturation**
  - Linear extrapolation in digitization and reconstruction
- **MC with more realistic saturation**
  - Asymptotic extrapolation in digitization, linear extrapolation in reconstruction

- W-AHCAL hit energy distribution seen in data can be described well by MC when using more realistic saturation



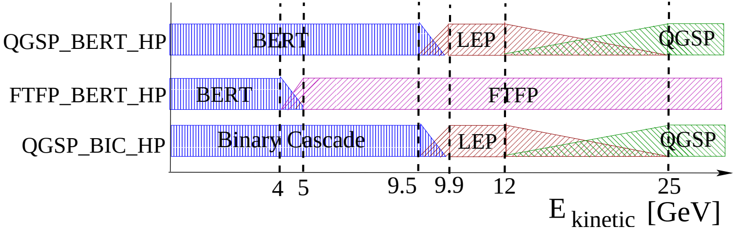
Summary & Outlook

- Analysis of W-AHCAL test beam data at $10 \leq p_{\text{beam}} \leq 100\,\text{GeV}$
  - W-AHCAL gives similar response for e^+, π^+, K^+ and p
  - Overall good agreement (percent level) between GEANT4 and data
  - Confident in accuracy of simulations used for the CLIC CDR
- Analysis of W-AHCAL+TCMT test beam data up to $p_{\text{beam}} \leq 300\,\text{GeV}$
  - Ongoing analysis
  - W-AHCAL leakage effects at high energy can be resolved using TCMT
  - Observation of saturation effects in W-AHCAL at high energies
    - Uncertainties in the high energy behaviour of the SiPM saturation curve become important

Backup

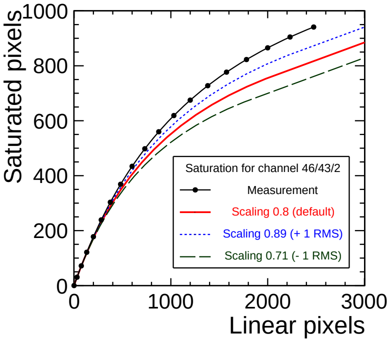
Comparison with GEANT4 Simulations

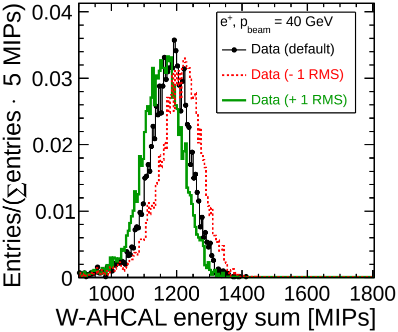
- Comparison of test beam data with GEANT4 simulations (version 9.5.p01)
  - So far, version 9.5.p01 is used
  - Compatible results are obtained also with 9.6.2
  - Update of MC analysis results under way
- Test various physics models combined to so-called physics lists
- Three example physics lists



Scaling factor of the SiPM response curves

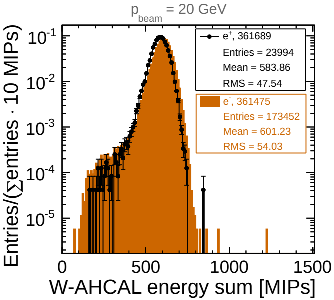
- Very dense showers in electro-magnetic data
- Uncertainties in scaling factor s have large impact on results
- Estimate systematic uncertainties: Find most energetic cell and re-run the reconstruction using $s' = s \pm 1$ RMS





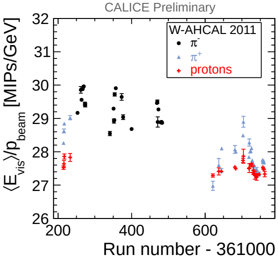
Electron Data

- e^- has systematically higher response than e^+
- Origin not yet understood
- Data taking at different times during 2011
- Detector was reinstalled between data taking periods of e^- and e^+



Pion Data

- Variation of HCAL response in time
  - Calorimeter response of protons stable in whole data taking period
  - Response of π^- and π^+ varies with time
  - Overall higher calorimeter response for π^- than for π^+
  - Origin not yet understood
  - Used full range of positive and negative data to estimate the systematic error due to detector stability



Systematic uncertainties

Particles	Measurement	Uncertainty	Total systematic uncertainty
40 GeV e^+	Total energy sum	$\pm 2.0\%$ (MIP scaling factor) $\pm 2.0\%$ (stability of detector response) $+3\%$, -2.0% (saturation scaling)	$+4.1\%$, -3.5%
	Energy sum per layer	$\pm 2.0\%$ (MIP scaling factor) $\pm 2.0\%$ (stability of detector response) $+9\%$, -10% (saturation scaling)	$+9.4\%$, -10.4%
Hadrons	Total energy sum	$\pm 2.0\%$ (MIP scaling factor) $\pm 3.1\%$ (stability of detector response) -0.5% (saturation scaling)	$\pm 3.7\%$

Table: Systematic uncertainties of the energy sum per calorimeter and per layer, which are considered in the analysis of the experimental data. For the e^+ data, only the 40 GeV case is indicated, as for this energy the systematic uncertainties are the highest. For the hadron data, the indicated uncertainties are valid for all analysed energies.