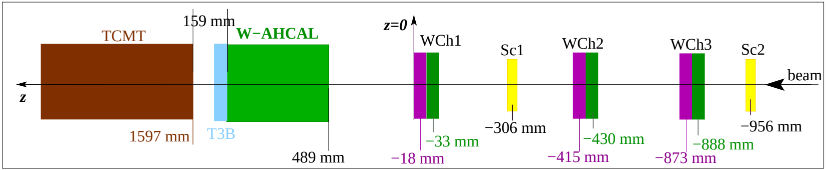
Analysis of CALICE W-AHCAL Data at 1 - 300 GeV

Eva Sicking (CERN)
on behalf of the CALICE W-AHCAL group

CLIC Detector and Physics Meeting,
October 1, 2013 – CERN

Test Beam Experiments in 2010/2011 at CERN PS/SPS



- 2010 at CERN PS
- $1 \leq p_{\text{beam}} \leq 10$ GeV
- Mixed beam of $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, p
- **W-AHCAL** (30 layers)

→ Note CAN-036

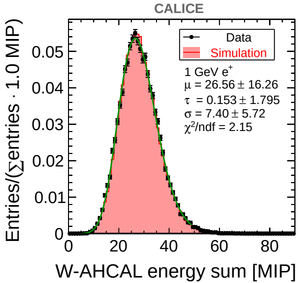
- 2011 at CERN SPS
- $10 \leq p_{\text{beam}} \leq 300$ GeV
- Mixed beam of $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, p, $K^{\pm}$
- **W-AHCAL** (38 layers) + **TCMT**

→ Note CAN-044 (≤ 100 GeV)

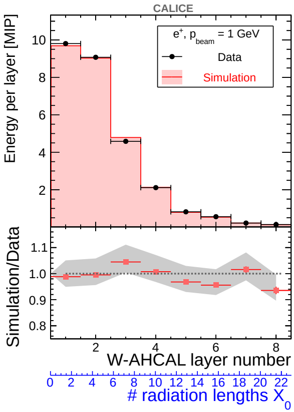
→ Ongoing analysis $p_{\text{beam}} \leq 300$ GeV

Electron Data in 2010 and 2011

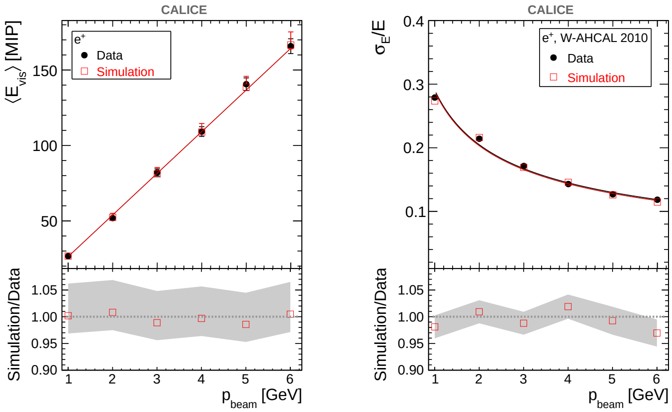
- $e^{\pm}$ event selection based on
  - Cherenkov threshold counter
    LCD-Note-2013-006
  - HCAL information: one calorimeter cluster, early shower, no tracks, low number of hits
- Describe energy sum using Novosibirsk fit (Gaussian with tail)



- $e^{\pm}$ data at 1-6 GeV in 2010, $e^{\pm}$ data at 15-40 GeV in 2011
- Good agreement between data and MC up to 20 X_0

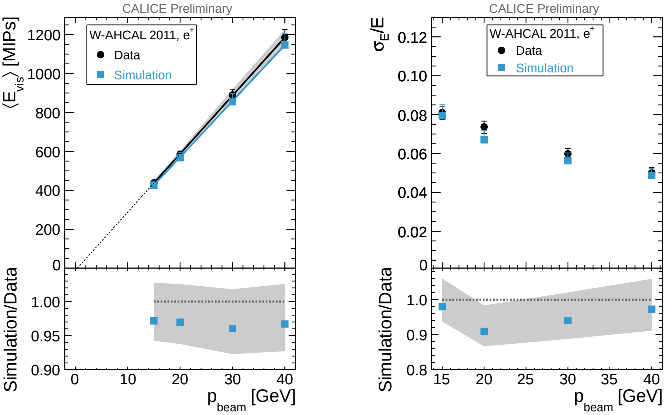


Electron Data 2010: Linearity and Resolution



- Visible energy increases with p_{beam} following linear fit
- Resolution descreases with p_{beam} following $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\text{GeV}]}} \oplus b \oplus \frac{c}{E[\text{GeV}]}$
- W-AHCAL: $a = (28.8 \pm 0.8)\,\%/\sqrt{E}$, ▸ Fe-AHCAL: $a = (21.9 \pm 0.4)\,\%/\sqrt{E}$

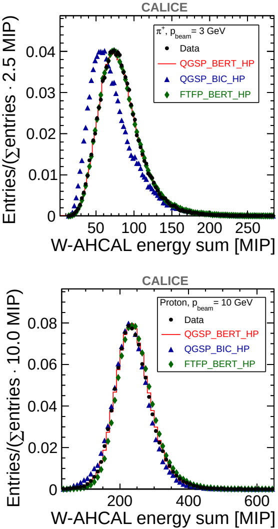
Electron Data 2011: Linearity and Resolution



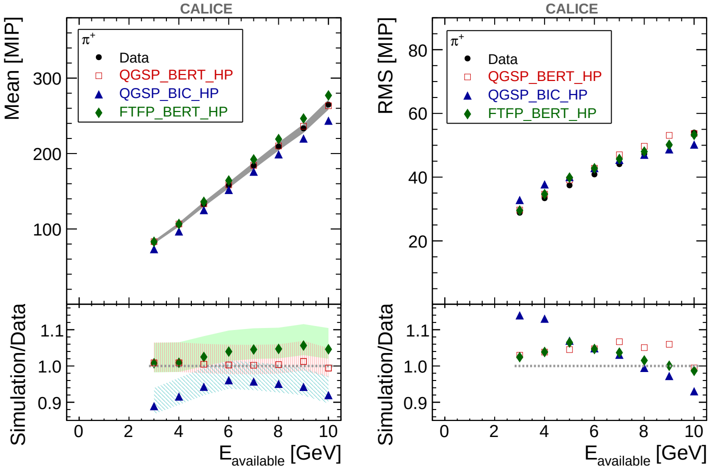
- Visible energy increases with p_{beam} following linear fit (deviation from linearity $< 1\,\%$)
- Large systematic from scaling factor of SiPM ($\rightarrow$ backup)
- Within uncertainties, data and MC agree, however, MC tends to show lower response and better energy resolution

Hadron Data in 2010 and 2011 ($p_{\text{beam}} \leq 100$ GeV)

- Hadron selection
  - Cherenkov threshold counter
    LCD-Note-2013-006
  - Muon rejection based on HCAL: cut on track number and length, cut on number and position of clusters
- Comparison of low-E hadron results
  - E_{sum} is non-Gaussian with high-E tails (present also in MC)
  - Use mean and RMS of distribution for energy resolution $\frac{\sigma_E}{E} = \frac{\text{RMS}}{\text{Mean}}$
- Pions: 3-10 GeV and 15-100 GeV (purity > 94 %)
- Protons: 4-10 GeV and 15-100 GeV (purity > 85 %)
- Kaons: 50 and 60 GeV (purity > 82 %)

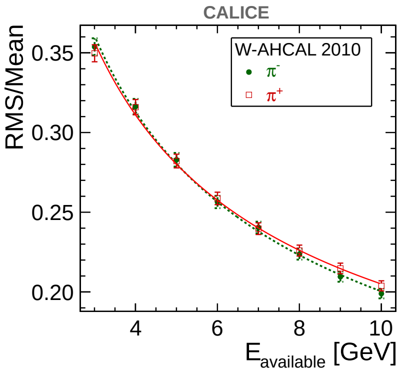


Pion Data in 2010: Linearity and Width



- Analysis as a function of $E_{\text{available}} = \sqrt{p_{\text{beam}}^2 + m_\pi^2}$
- QGSP_BERT_HP describes mean best, all MCs give slightly broader RMS

Pion Data in 2010: Resolution



- Energy resolution for $\pi^{\pm}$ follows $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus b \oplus \frac{c}{E[\mathrm{GeV}]}$
- Stochastic term:

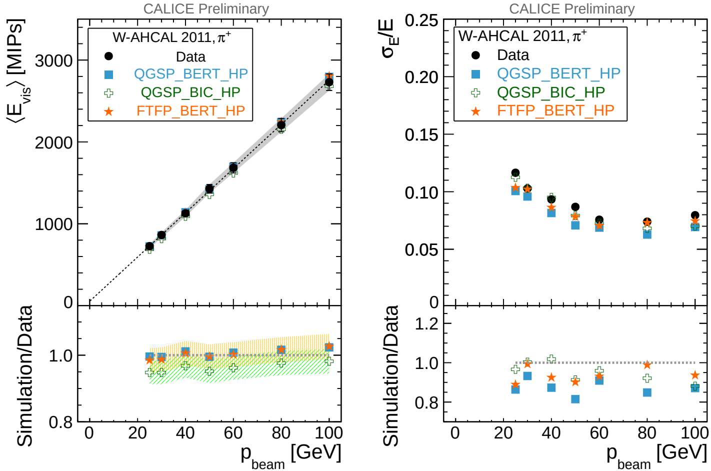
  W-AHCAL

  $a = (61.9 \pm 1.0)\,\%\sqrt{E[\mathrm{GeV}]}$

  Fe-AHCAL

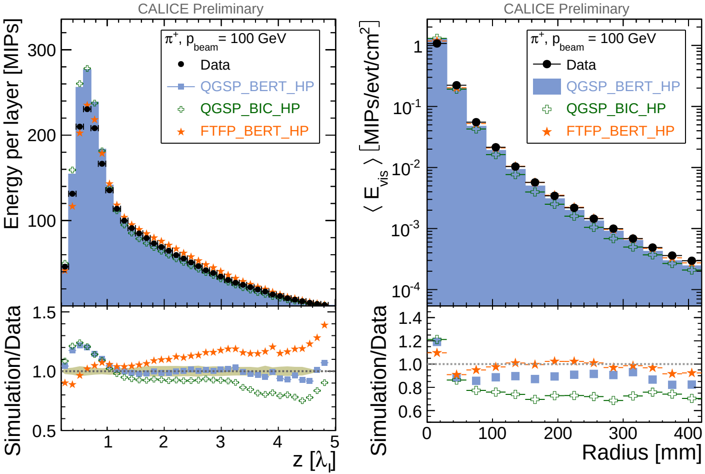
  $a = (57.6.9 \pm 0.4)\,\%\sqrt{E[\mathrm{GeV}]}$

Pion Data in 2011: Linearity and Resolution



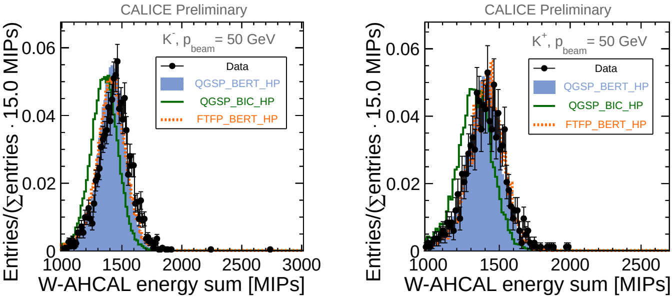
- Good agreement between QGSP_BERT_HP and FTFP_BERT_HP for π^+
- Leveling off of relative resolution at high p_{beam} indicates leakage effects
- Energy resolution is overestimated by MC

Pion Data in 2011: Shower Profiles



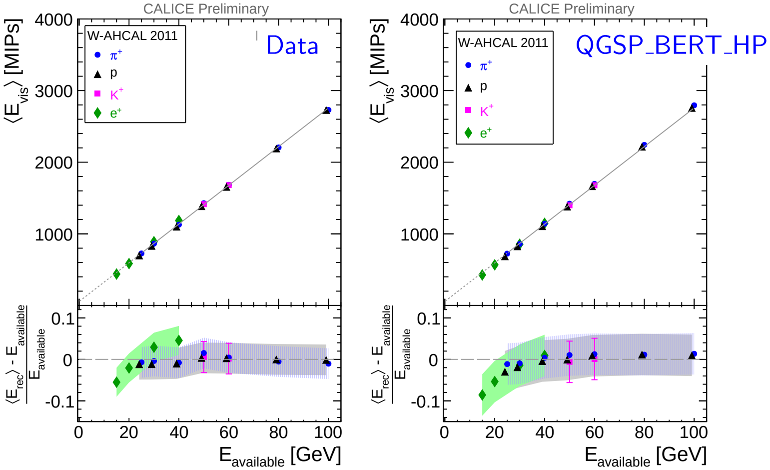
- Longitudinal profile (here, from shower start):
  QGSP_BERT_HP best, overestimates energy deposition in first part of shower
- Radial profile: MCs overestimate energy density in shower core

Kaon Data: Energy Sum



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

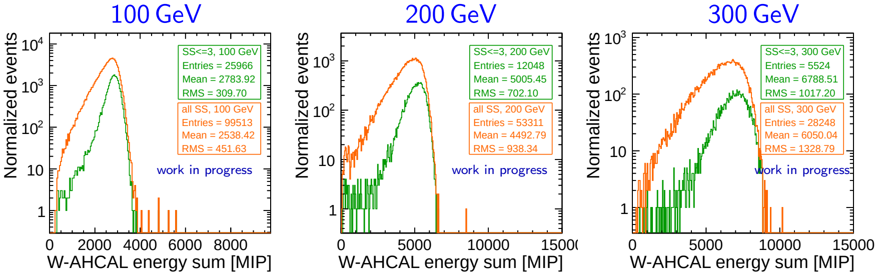
Summary of Results at $p_{\text{beam}} \leq 100\,\text{GeV}$



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

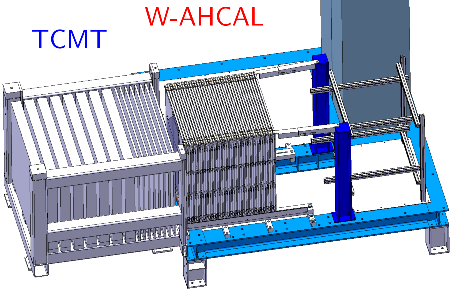
Hadron Data at $p_{\text{beam}} \geq 100$ GeV

- W-AHCAL shows leakage effects
  - at high beam energy: compare 100, 200, and 300 GeV
  - when accepting events with late shower starts:
    compare, "only early shower starts" and "all shower starts"



Tail Catcher (TCMT)

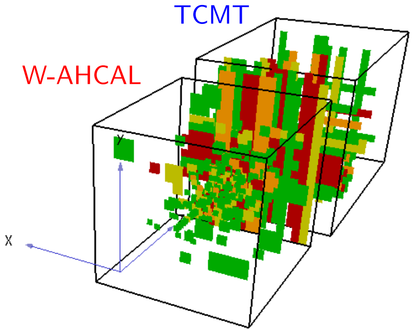
- Test beam experiments at CERN SPS using W-AHCAL+TCMT
- Purpose of TCMT
  - At SPS energies, hadronic shower can leak out of the W-AHCAL of $\sim 4\lambda_I$
  - Catch tail of shower using additional $\sim 5.5\lambda_I$ of tail catcher
  - Combination of W-AHCAL + TCMT $\rightarrow$ improve energy resolution

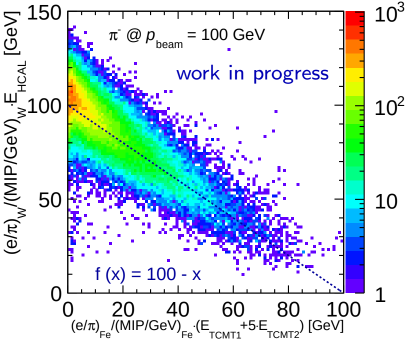


- W-AHCAL: 38 tungsten layers, each 10 mm thick
- $TCMT_1$: 8 steel layers, each 20 mm thick
- $TCMT_2$: 8 steel layers, each 100 mm thick
- TCMT readout: scintillator strips and SiPM

TCMT in High-Energy Hadron Showers

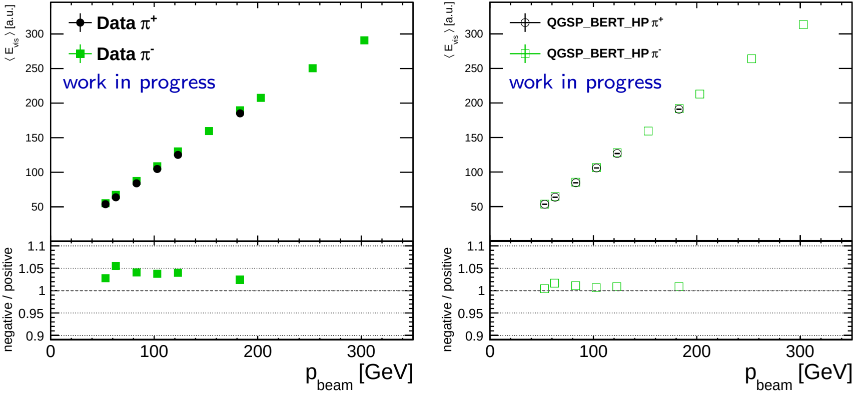
- Example pion shower at $p_{beam} = 100$ GeV
- TCMT recovers energy leaked out of W-AHCAL





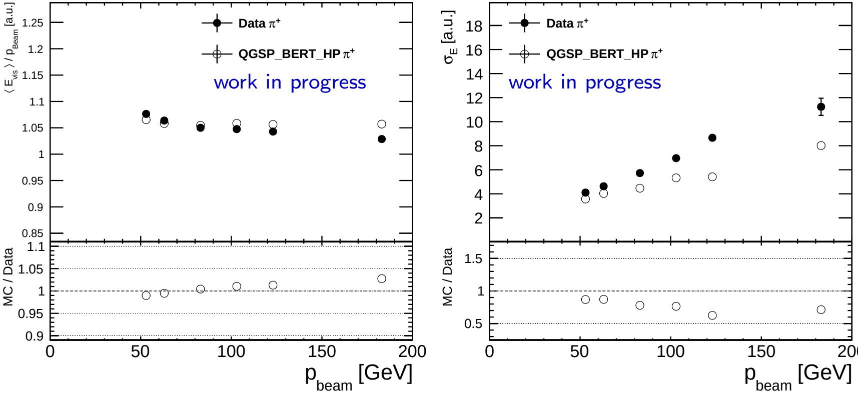
- W-AHCAL: scintillator tiles
- TCMT: scintillator strips

π^+ and π^-: Linearity in W-AHCAL+TCMT



- Data:
  - Response for π^- is up to 5 % higher than for π^+
  - Effect discussed already in CAN-044

π^+: Linearity and Width in W-AHCAL+TCMT

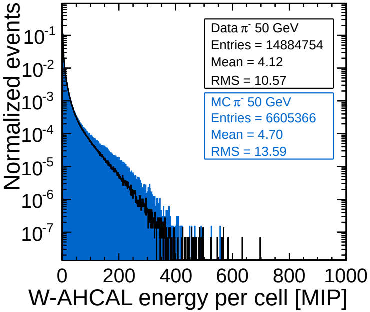


- E_{vis}/p_{beam} for MC is constant, data points falls as a function of p_{beam}
- Width is smaller in MC than in data

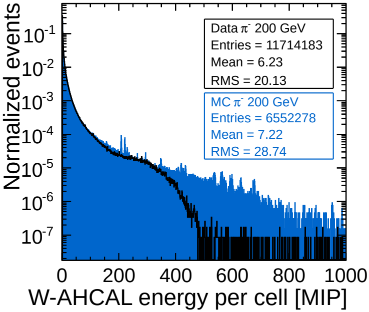
Saturation Effects in High-Energy W-AHCAL Data

- 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

work in progress

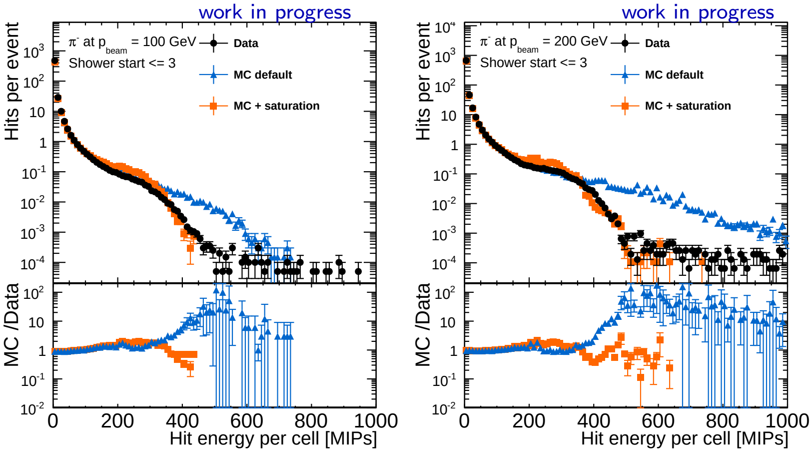


work in progress

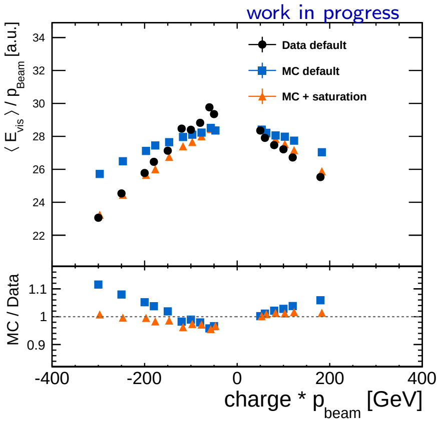


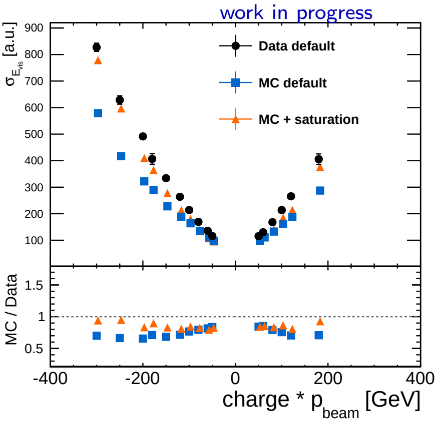
Hit Energy Per Cell in W-AHCAL-only

- More realistic saturation in MC
  $\rightarrow$ Hit energy distribution seen in data can be described well by MC



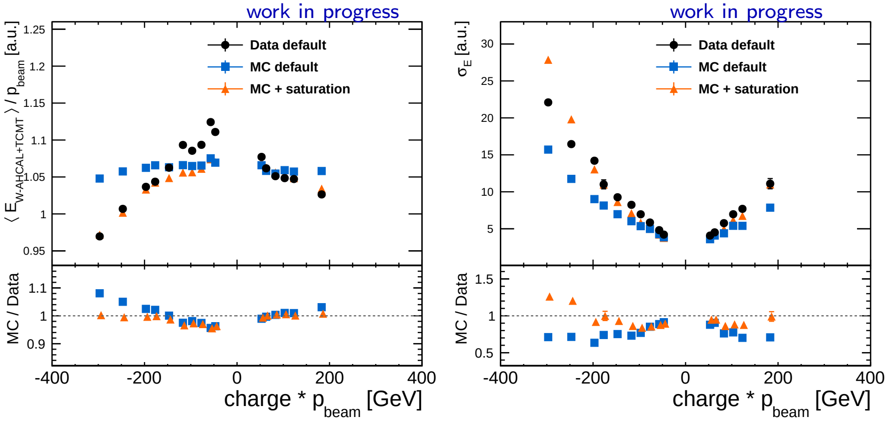
Linearity and Width for W-AHCAL





- More realistic saturation in MC gives better agreement with data for W-AHCAL

Linearity and Width for W-AHCAL+TCMT



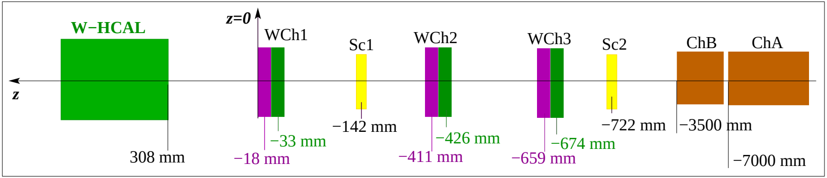
- More realistic saturation in MC gives better agreement with data for W-AHCAL+TCMT

Summary

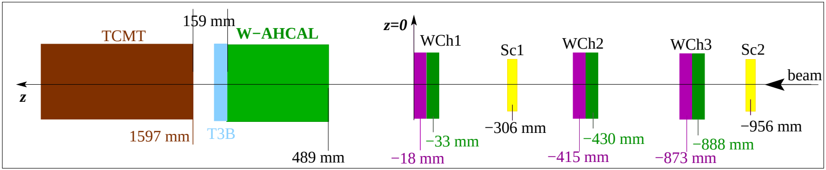
- Analysis of W-AHCAL test beam data at $1 \leq p_{\text{beam}} \leq 100\,\text{GeV}$
  - W-AHCAL gives similar response for e^+, π^+, K^+ and p
  - Overall good agreement between GEANT4 simulations and data
  - $\rightarrow$ Confident in accurateness of simulations used for the CLIC CDR
- Analysis of W-AHCAL+TCMT test beam data up to $p_{\text{beam}} \leq 300\,\text{GeV}$
  - Leakage effects at high energy can be resolved using TCMT
  - Observation of saturation effects at high energy
    - Uncertainties in the high energy behaviour of the SiPM saturation curve become important
    - For studied single particle energy range in tungsten HCAL, a larger dynamic range is required

Backup

Test Beam in 2010 at CERN PS

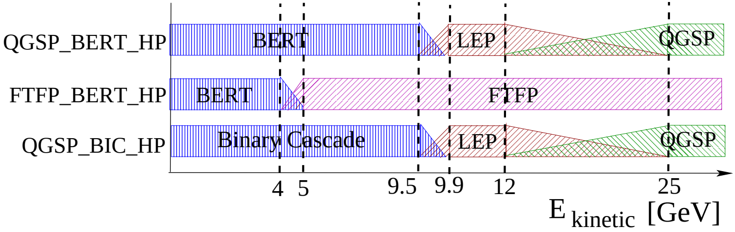


Test Beam in 2011 at CERN SPS



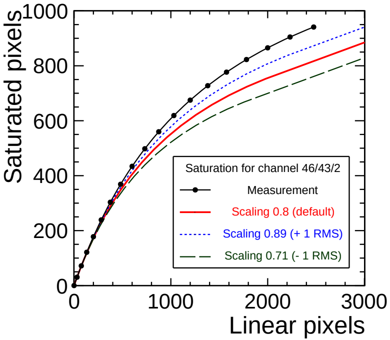
Comparison with GEANT4 Simulations

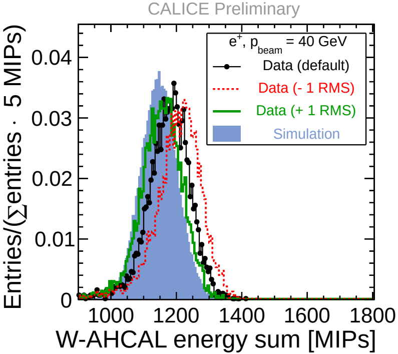
- Comparison of test beam data with GEANT4 simulations (version 9.3.4)
- Test various physics models combined to so-called physics lists
- Three example physics lists



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





W-AHCAL and Fe-AHCAL in Electron Analysis

- CAN-036
- Energy range: 1-6 GeV
- 3 X_0 per HCAL layer:
  4 mm Fe + 10 mm W
- Estimated visible energy using Novosibirsk fit (Gaussian with tail)

- Fe-AHCAL (1012.4343)
- Energy range 10-50 GeV
- 1.3 X_0 per HCAL layer:
  16 mm Fe
- Estimated visible energy using Gaussian fit ($\pm 2\sigma$)

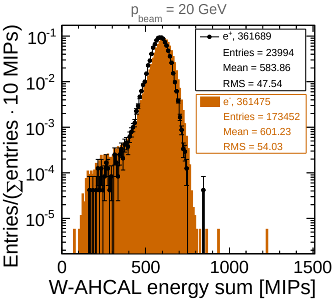
W-AHCAL and Fe-AHCAL Hadron Analyses

- CAN-036
- Energy range: 1-10 GeV
- Estimated visible energy using RMS

- Fe-AHCAL (1207.4210)
- Energy range 10-100 GeV
- Estimated visible energy using Gaussian fit ($\pm 2\sigma$)

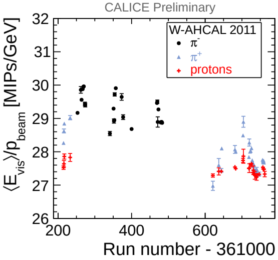
Electron Data in 2011

- 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^+

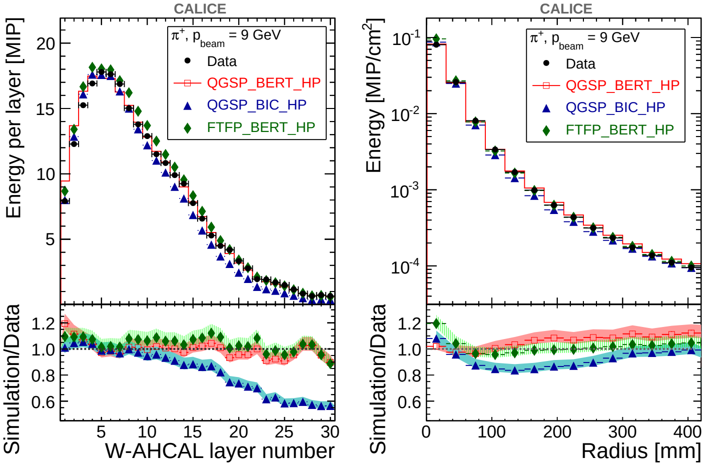


Pion Data in 2011

- 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

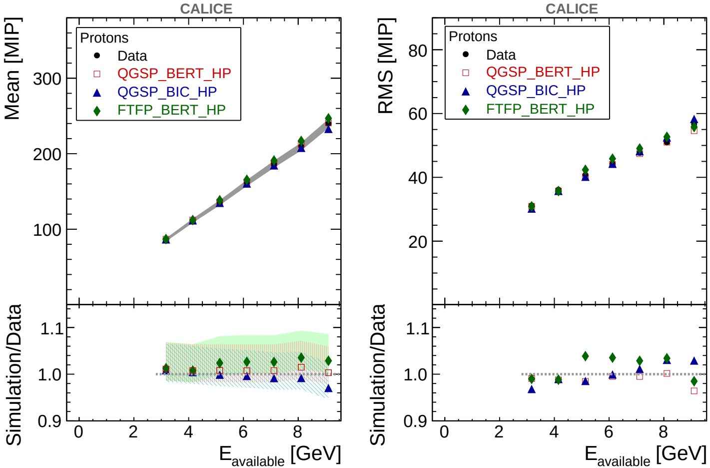


Pion Data in 2010: Shower Profiles



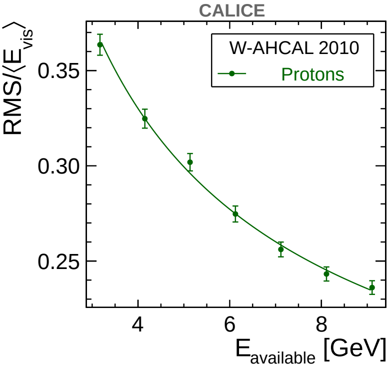
- Longitudinal and radial profile well described by BERT models
- QGSP_BERT_HP overestimates energy deposition in first part of calorimeter
- FTFP_BERT_HP overestimates energy density in shower core

Proton Data in 2010



- Proton data available at 4-10 GeV, analysis versus $E_{\text{available}} = \sqrt{p_{\text{beam}}^2 + m_{\text{p}}^2} - m_{\text{p}}$
- Best description by QGSP_BERT_HP; QGSP_BIC_HP good for protons, too

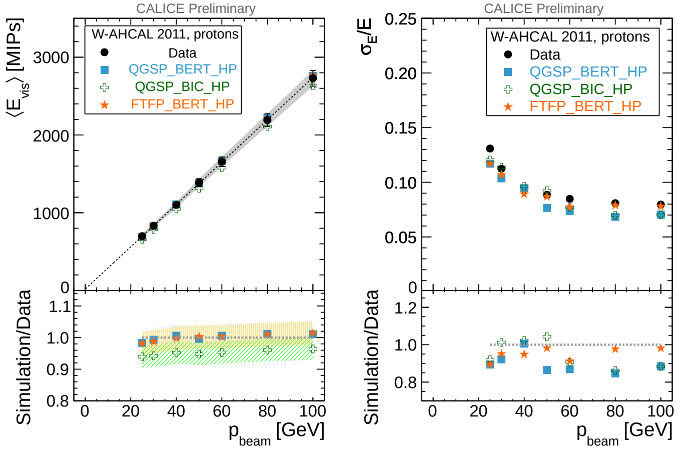
Proton Data in 2010: Resolution



- Linearity and Resolution as good as in $\pi^{\pm}$
- Results are compatible with expectations from simulations

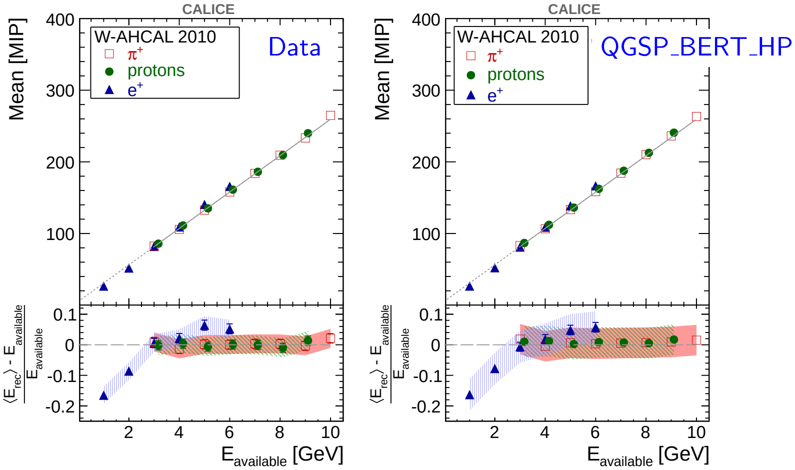
	π^{+}	p
a $[\%/\sqrt{E[\mathrm{GeV}]}]$	60.3 ± 1.0	61.9 ± 2.2
b [%]	7.5 ± 1.3	11.3 ± 1.9

Proton Data in 2011: 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)
- MCs overestimate proton energy resolution

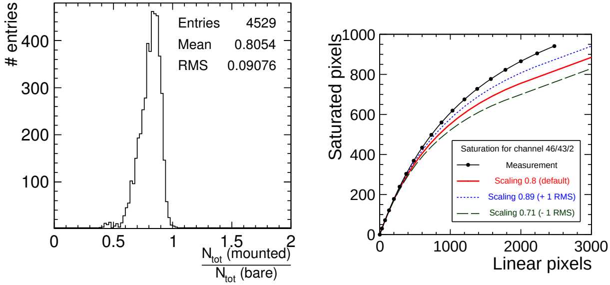
Summary of 2010 Results



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

Systematic Study of Saturation Effects

- Scaling and saturation curve used in data reconstruction



Figures from paper on el.-m. response of Fe-AHCAL and talk by Angela Lucaci-Timoce

- MC: sim+reco use linear extrapolation of saturation curve
  $\rightarrow$ saturation and de-saturation cancel out each other perfectly
- Use more realistic saturation correction in MC for study of systematics of saturation correction (Sergey Morozov)
  - Simulation using asymptotic saturation curve, reconstruction using linear extrapolation

How to combine W-AHCAL and TCMT

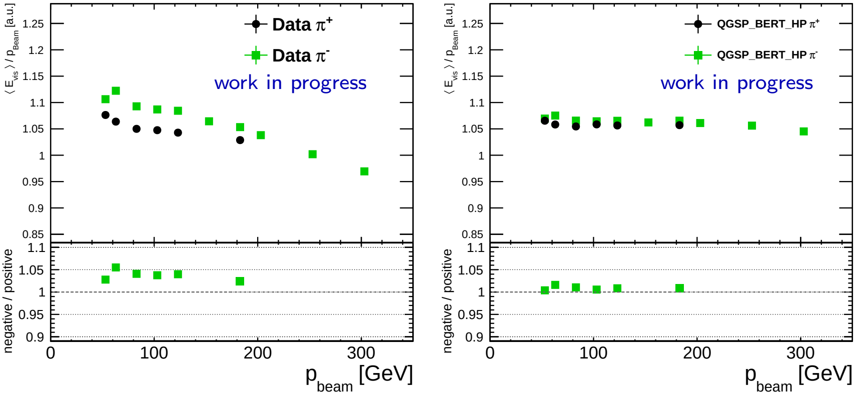
- Known detector response of W and Fe calorimeters
  - e/π-ratios
    - $(e/\pi)_{\mathrm{W}} = 1.0$
      $(e/\pi)_{\mathrm{Fe}} = 1.2$[1]
  - MIP/GeV factors
    - $(\mathrm{MIP/GeV})_{\mathrm{W}} = 27\,\mathrm{MIP/GeV}$
      $(\mathrm{MIP/GeV})_{\mathrm{Fe}} = 42\,\mathrm{MIP/GeV}$
  - Ratio of TCMT layer thicknesses: 5
    - TMCT_1: 20 mm
    - TMCT_2: 100 mm

First approximation: Weighted energies in GeV

- $E_{\text{W-AHCAL, weighted}} = (e/\pi)_{\mathrm{W}}/(\mathrm{MIP/GeV})_{\mathrm{W}} \cdot \quad E_{\text{W-AHCAL}}$
- $E_{\text{Fe-TMCT}_1\text{, weighted}} = (e/\pi)_{\mathrm{Fe}}/(\mathrm{MIP/GeV})_{\mathrm{Fe}} \cdot \quad E_{\text{Fe-TCMT}_1}$
- $E_{\text{Fe-TMCT}_2\text{, weighted}} = (e/\pi)_{\mathrm{Fe}}/(\mathrm{MIP/GeV})_{\mathrm{Fe}} \cdot 5 \cdot E_{\text{Fe-TCMT}_2}$

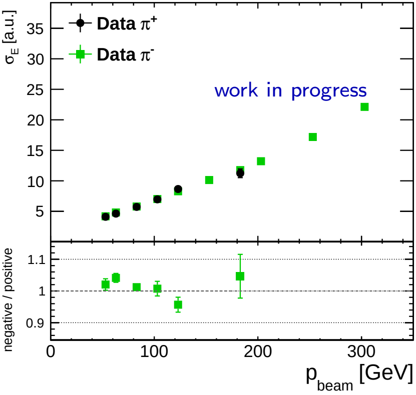
[1] Attention: (e/π) needs to be adjusted to TMCT layer thicknesses.

Pion: Linearity in W-AHCAL+TCMT



- Data:
  - Response for π^- is up to 5 % higher than for π^+
  - Effect discussed already in CAN-044
- MC results are constant, data falls as a function of p_{beam}

Pion: $\sigma_{E_{\text{vis}}}$ in W-AHCAL+TCMT



- Width grows as a function of p_{beam}
- Width is smaller in MC than in data