Shower development of particles with momenta from 10 to 100 GeV in the CALICE scintillator-tungsten AHCAL

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on behalf of the CALICE W-AHCAL group

Introduction

- For experiments at CLIC: calorimeters with **tungsten** absorber
- Tungsten mostly used for electromagnetic calorimeters, seldom for hadron calorimeters (e.g. ATLAS FCAL tungsten/LAr)

Test beams with CALICE scintillator W-AHCAL

- 2010 CERN PS: 1 GeV$\leq p_{\text{beam}} \leq$ 10 GeV
- 2011 CERN SPS: 10 GeV$\leq p_{\text{beam}} \leq$ 300 GeV

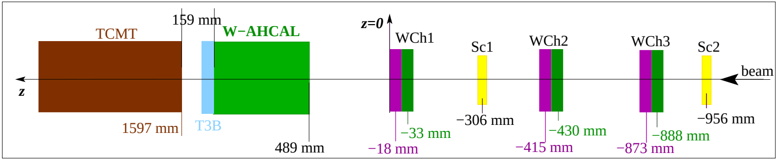
Publications based on CALICE W-AHCAL test beams

- CAN-036 (2010 analysis)
- Proceedings in NIM
- Paper 15 (under review)
- CAN-044/LCD-Note-2013-002 (2011 analysis)
- CIN-021 (additional information to 2011 analysis)
- LCD-Note-2012-002 (beam line instrumentation)
- LCD-Note-2011-001 (temperature studies)
- LCD-Note-2013-006 (particle identification)

2011 data taking

- CERN SPS: June, July and September 2011
- W-AHCAL (38 layers) + Tail Catcher and Muon Tracker, TCMT
- Energies: from 10 to 300 GeV

- Beam: mix of pions, protons, kaons, muons and electrons ⇒ particle identification with threshold Cherenkov counters, see **talk by Dominik Dannheim**



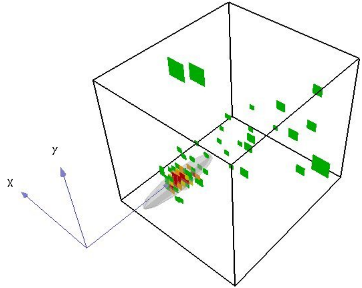
- This talk: analysis of data with $p_{\text{beam}} \leq 100$ GeV (CAN-044)
- For higher energies need to consider the TCMT, see **talk by Eva Sicking**

Analysis of $e^{\pm}$ data

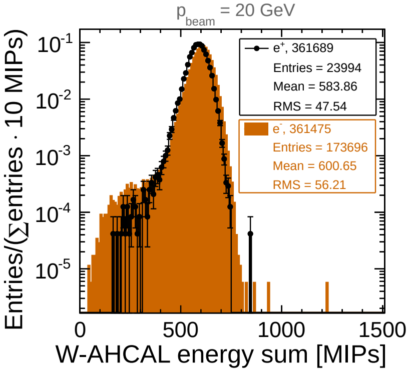
Selection of $e^{\pm}$ events

- Tungsten: dense material (about 3 X_0 per layer) $\rightarrow$ electromagnetic showers will form a cluster in the first calorimeter layers

- Selection:
  - one identified cluster
  - there should be no tracks



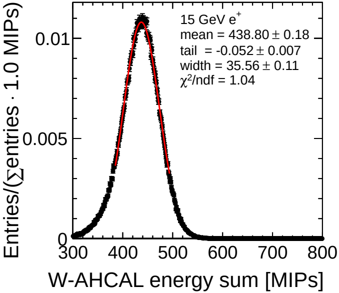
- e^- response about 3% higher than for e^+ (not understood, negative runs taken in July, positive ones in September 2011)

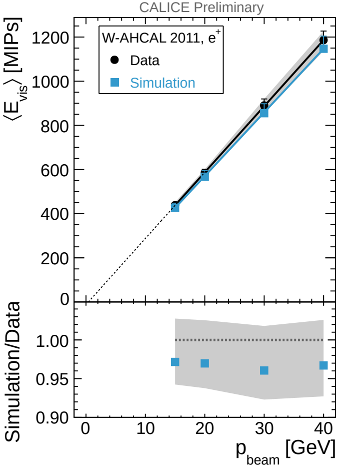


"Real knowledge is to know the extent of one's ignorance" (Confucius)

Analysis of e^+ data: Monte Carlo comparison

- Novosibirsk fit (Gaussian with tail) in a region defined by $mean \pm 1.5\ \sigma$





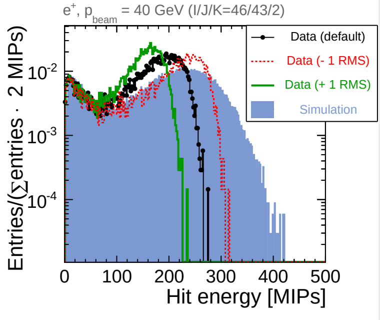
- Simulation predicts about 3% lower response than observed
- Implementation of detector material in Mokka was checked
- But: significant systematics from the scaling factor of the SiPM response curves

Scaling factor of the SiPM response curves

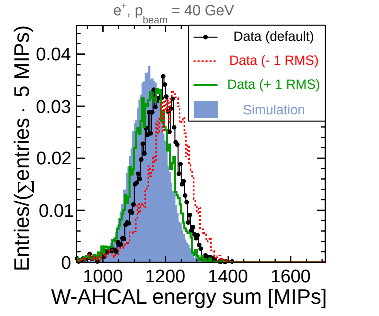
- To estimate systematics due to scaling factor s: find the highest energetic cell and re-run the reconstruction with modified scaling factor for that cell: $s \pm 1$ RMS

Example: 40 GeV e^+

- The highest energy cell contains more than 60% of the total energy in layer 2



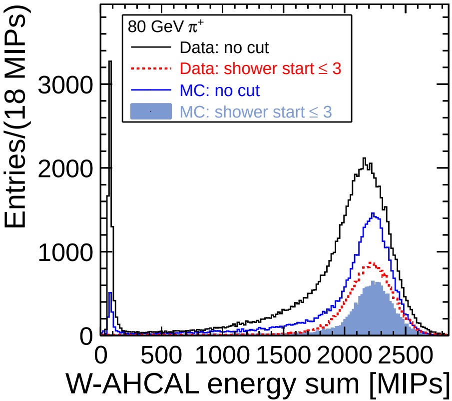
- Impact of scaling factor on the average energy at 40 GeV: $\langle E \rangle = 1186^{+3\%}_{-2\%}$ MIPs



Analysis of hadron data

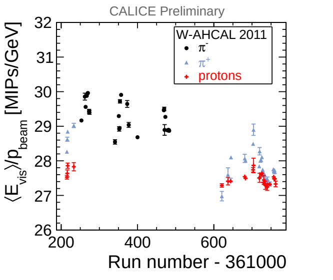
Hadron selection

- First level of particle identification based on Cherenkov threshold counters $\rightarrow$ purity of selected events better than 94% (85%) for $\pi^{\pm}$ (protons)
- Muons rejected by requesting that the layer of the primary interaction is in any of the first 3 calorimeter layers

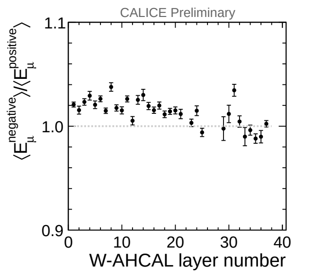


Hadron analysis: variation of detector response with time

- Calorimeter response to protons is stable with time, but variations observed for π^+ and π^-
- For the analysed energies: π^- higher response than π^+

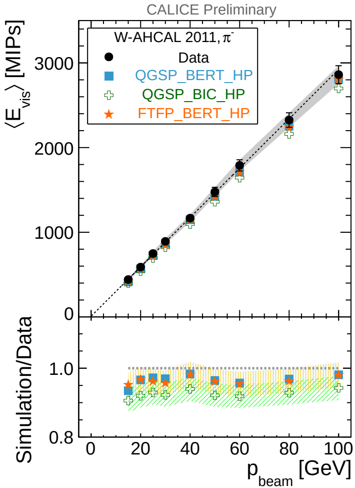


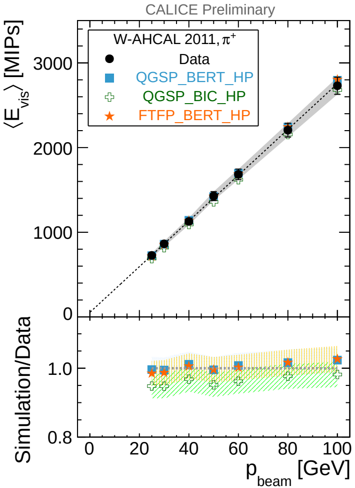
- Similar variations observed in the muon response:



$\Rightarrow$ Part of variations seem to be related to the calorimeter itself (not clear if due to charge, or just time dependence)

Analysis of $\pi^{\pm}$ data: $\langle E_{vis} \rangle$ vs p_{beam}

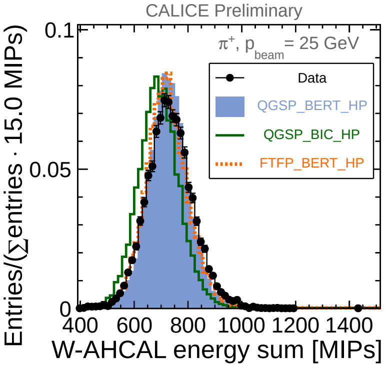


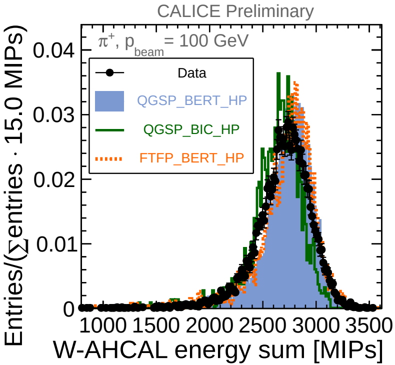


- Energy for π^- higher than for π^+
  (variations of detector response in time of about 3%)
- Agreement between data and QGSP_BERT_HP/FTFP_BERT_HP for π^+

Analysis of π^+ data: energy sum

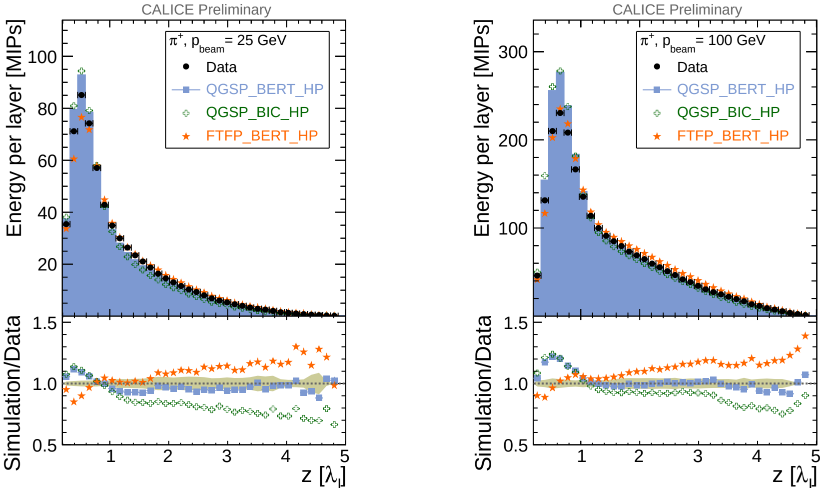
- π^+: good agreement between data and QGSP_BERT_HP/FTFP_BERT_HP for all analysed energies





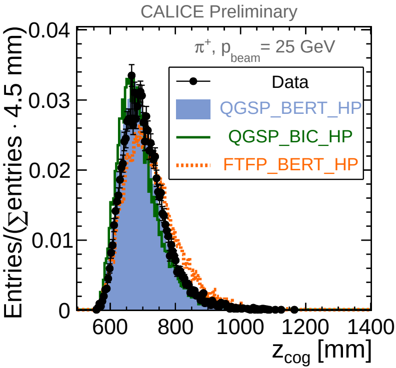
Analysis of π^+ data: longitudinal profile from shower start

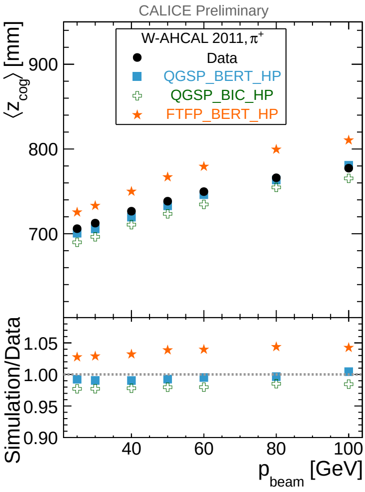
- QGSP_BERT_HP: tendency to overestimate the energy deposition in the first part of the shower



Analysis of π^+ data: z_{cog}

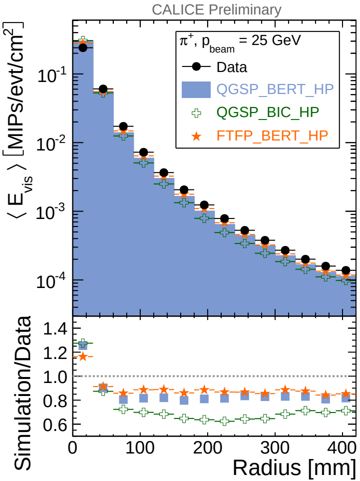
- z_{cog}: energy weighted centre-of-gravity
- Good agreement between data and QGSP_BERT_HP

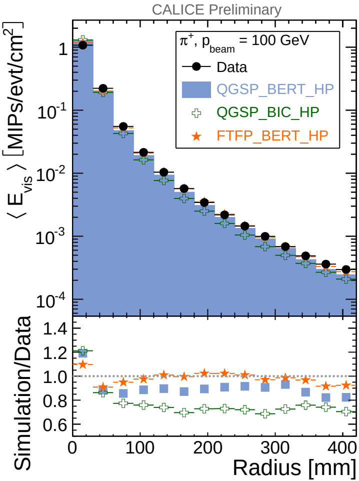




Analysis of π^+ data: radial profiles

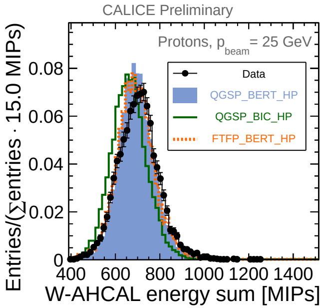
- Monte Carlo predicts a higher energy density in the core of the shower than observed

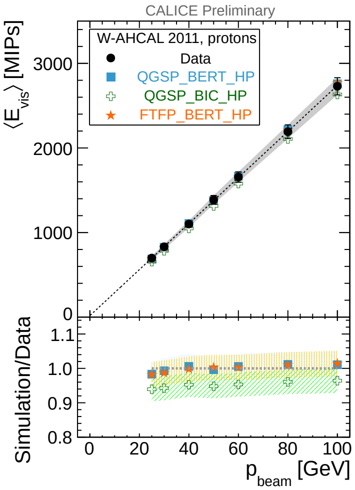




Analysis of proton data

- Good agreement between data and QGSP_BERT_HP/FTFP_BERT_HP



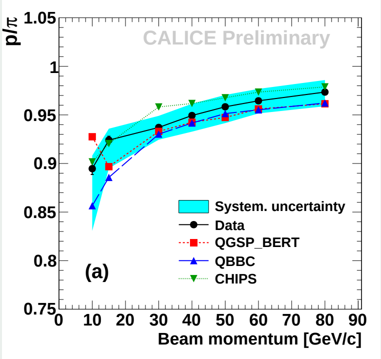


proton/π^+ ratio

- For a non-compensating calorimeter ($e/h > 1$), expect $E_{protons} < E_{\pi^+}$ (because $\pi^0 \rightarrow \gamma$ production is, on average, smaller in proton-induced showers)

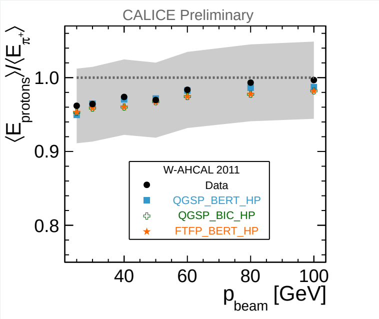
Fe-AHCAL

- Figure from CAN-040



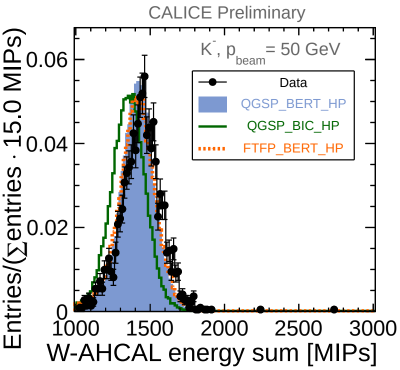
W-AHCAL

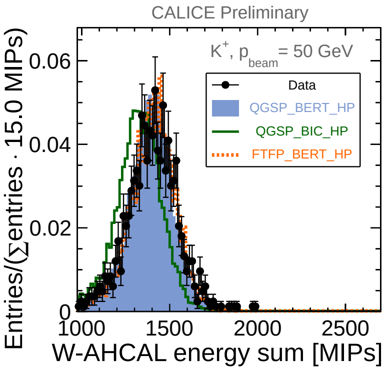
- W-AHCAL is closer to 'compensation'



Analysis of K^+ data

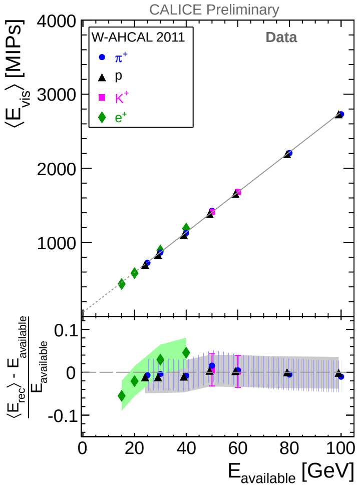
- K^+: good agreement between data and QGSP_BERT_HP/FTFP_BERT_HP
- QGSP_BIC_HP predicts too low energy

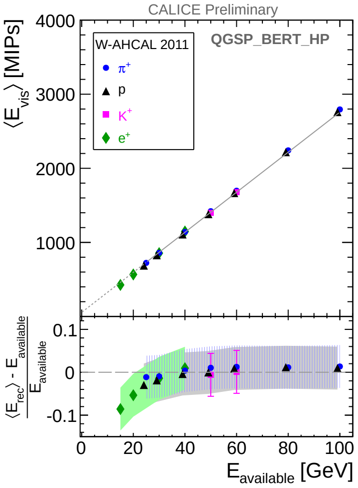




Comparison of the response for different particle types

- Residuals from the linear fit of π^+ experimental data
- Deviations better than $\pm 2\%$ for π^+ and protons, and worse for e^+





Summary and conclusions

- Negative polarity runs have higher response than positive polarity runs (variations of detectore response with time of about 3%)
- e^+: disagreement between data and simulation (partially explained by imperfect scaling factors of the SiPM response curves)
- π^+, protons and K^+: good agreement between data and QGSP_BERT_HP

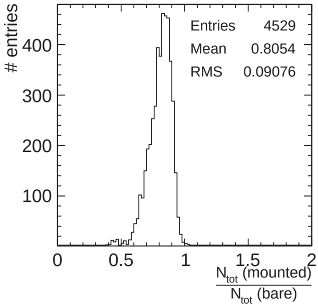
With the future behind me, and the past in front link

Thank you

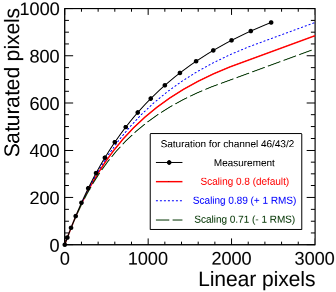
BACKUP

Scaling factor of the SiPM response curves

- SiPM response curves measured before mounting on the tiles
- Due to geometrical effects, maximum number of fired pixels in case of mounted SiPMs is about 80% of that for bare SiPM, with a large spread (from Fe-AHCAL em paper, arXiv:1012.4343)



- Example of saturation curves with different scaling factors, for a given cell



Systematic uncertainties

- **Data**:

Particles	Measurement	Uncertainty	Total sys. uncert.
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)	$\pm 3.7\%$

- **Simulation**: $+5\%$ in the energy scale due to imprecise knowledge of the cross-talk factor