Calorimetry Test Beam Results

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"Physics at the Terascale"

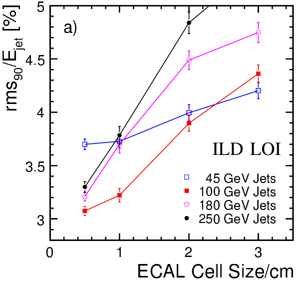
Content

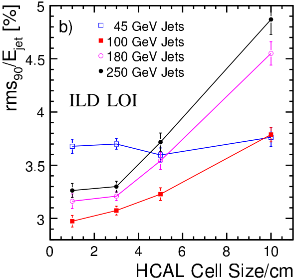
Calorimeters for future lepton colliders

- "Novel detector concepts for e^+e^- physics" by Philipp Roloff

- Jet energy resolution goal
  - 4-3 % at ILC
  - 5-3.5 % for 50 GeV-1 TeV jets at CLIC

- Possible solution
  - Particle Flow Analysis
    - Low mass tracker for charged particles
    - High granularity ECAL for photons, electrons
    - High granularity HCAL for neutral hadrons

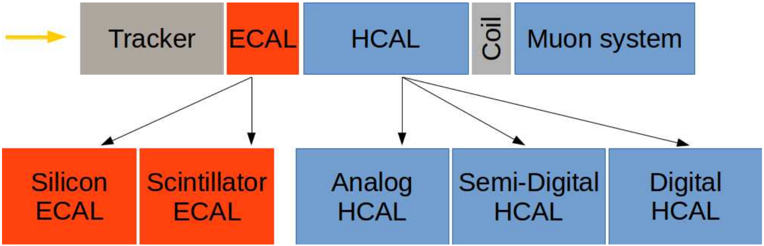




Aim of calorimeter test beam experiments

- Characterisation of calorimeter prototypes
  - Linearity: E_{rec} versus E_{beam}
  - Resolution: $\sigma_{E_{\mathrm{rec}}}/E_{\mathrm{rec}}$
- Characterisation of particle showers
  - Shower shapes
  - Substructure
  - Time structure
- Electro-magnetic processes
  - Well understood
  - Cross check detector calibration
  - Understand requirements for details needed in simulations
- Hadronic nuclear interactions
  - Not a priori understood
  - Test models of hadronic showers

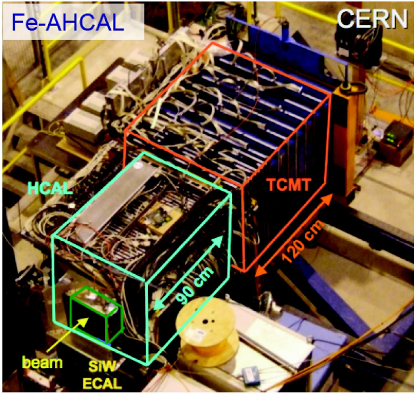
CALICE calorimeter prototypes

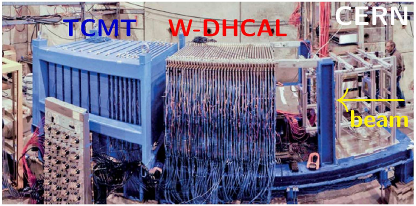


	Silicon ECAL	Scintillator ECAL	Analog HCAL	Semi-Digital HCAL	Digital HCAL
Granularity	$1 \times 1\,cm^2$	$4.5 \times 0.5\,cm^2$	$3 \times 3\,cm^2$	$1 \times 1\,cm^2$	$1 \times 1\,cm^2$
Readout	Silicon PIN diodes	Scint. strips+ Silicon Photo Multipliers	Scint. tiles+ Silicon Photo Multipliers	RPCs or MicroMegas	RPCs
Absorber	W	W	Fe or W	Fe	Fe or W

Test beam setups

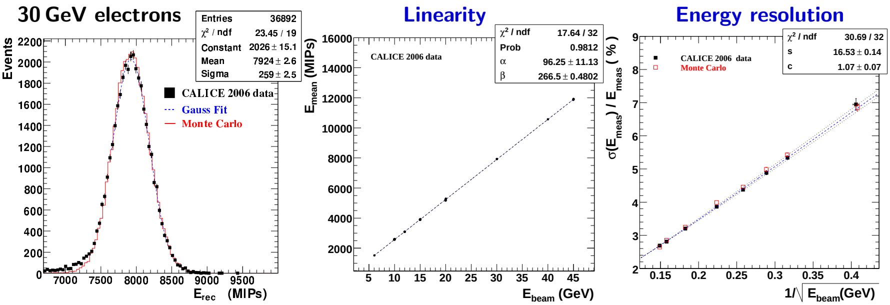
- Test beam experiments in 2006-2012 at DESY, CERN, FNAL
- Prototypes of up to $\sim 1\,\mathrm{m}^3 \rightarrow$ contain full shower at tested energies





Electromagnetic Calorimeters

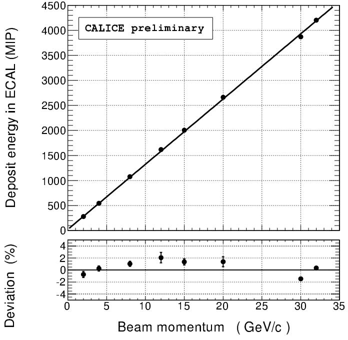
Si-W-ECAL: Electrons

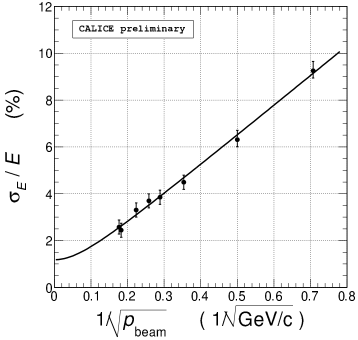


- Electrons at 6-45 GeV
- **Linearity**: E_{rec} versus E_{beam} better than 1 % (small offset)
- **Energy resolution**: $\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus b \rightarrow \frac{16.6\,\%}{\sqrt{E}} \oplus 1.1\,\%$
- Good agreement between data and simulation for full energy range

▸ NIM A608 2009 372 ▸ 2010 JINST 5 P05007

Sc-W-ECAL: Electrons

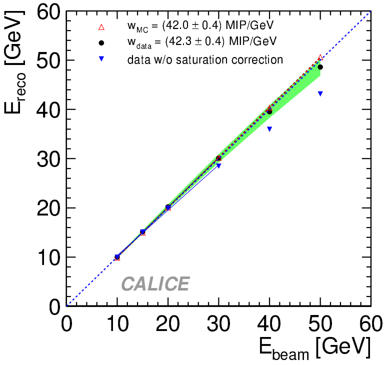


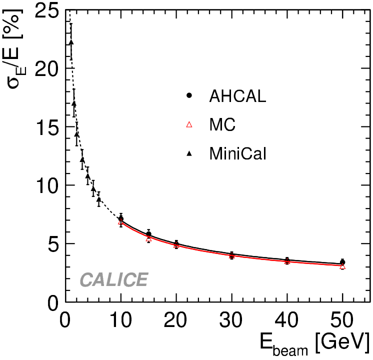


- Electrons at 2-32 GeV ▸ CAN-16b
- Careful treatment of temperature corrections, saturation effects, and beam momentum spread
- Linearity within 2 % , energy resolution $\approx \frac{12.9\,\%}{\sqrt{E}} \oplus 1.2\,\%$

Hadronic Calorimeters

Sc-Fe-AHCAL: Electrons

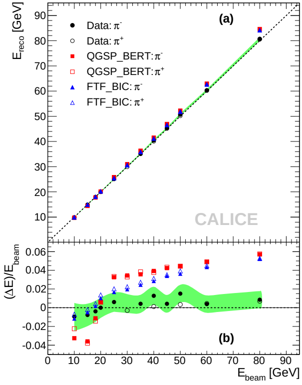




- Electrons at 10-50 GeV ▸ 2011 JINST 6 P04003
- Study electro-magnetic showers in HCAL
  - Demonstrate that all corrections are under control, e. g. saturation
  - Linearity within 2 %
  - Energy resolution $\frac{22\,\%}{\sqrt{E}} \oplus 1\,\%$

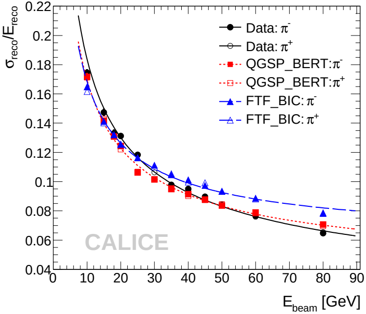
Sc-Fe-AHCAL: Pions

- Pions at 10-80 GeV [2012 JINST 7 P09017] [2013 JINST 8 P07005]
- Combined test beam with Si-W-ECAL + Sc-Fe-AHCAL + tail catcher
- Comparison of **data** and Geant4 models QGSP_BERT and FTF_BIC



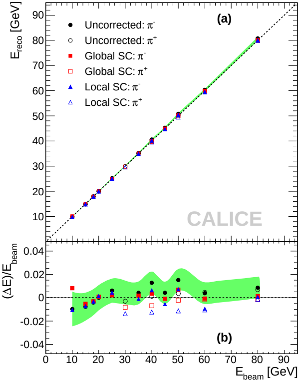
- Models differ up to 6 %

- Energy resolution
  - → Stochastic term **58 %**, 52 %, 49 %
  - → Constant term **1.6 %**, 4.0 %, 6.1 %



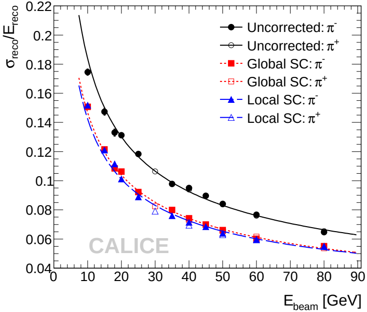
Sc-Fe-AHCAL: Re-weighting of energy deposit

- Re-weighting of energy deposits ("software compensation")
- Global: overall weighting factor for each shower derived from cell energy distribution
- Local: cell-by-cell re-weighting of energy deposits

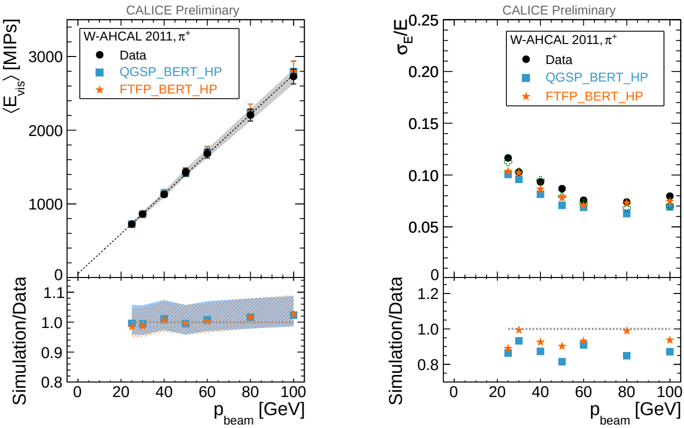


- Linearity within 2 %

- Software compensation improves resolution
  → Stochastic term: **58 %** → 46 %, 44 %
  → Constant term not affected

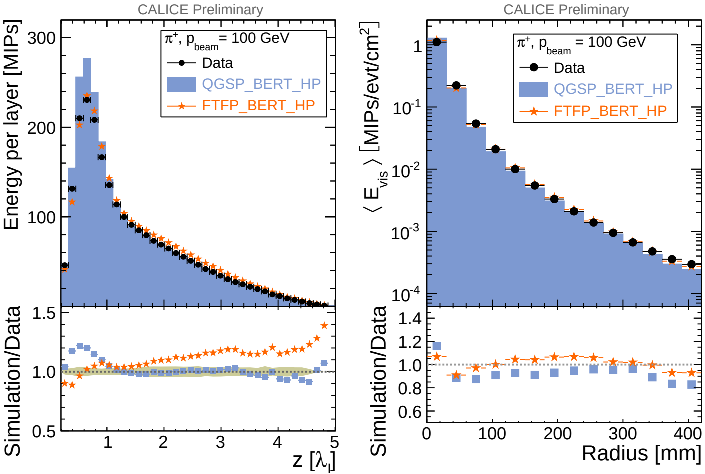


Sc-W-AHCAL: Pions



- Electrons and hadrons (1-100 GeV) ▸ JINST 9 2014 01004 and ▸ CAN-044
- Good agreement between data and QGSP_BERT_**HP** and FTFP_BERT_**HP**
- **H**igh **P**recision: Transports neutrons (≤ 20 MeV) down to thermal energies
- Models show better energy resolution than data

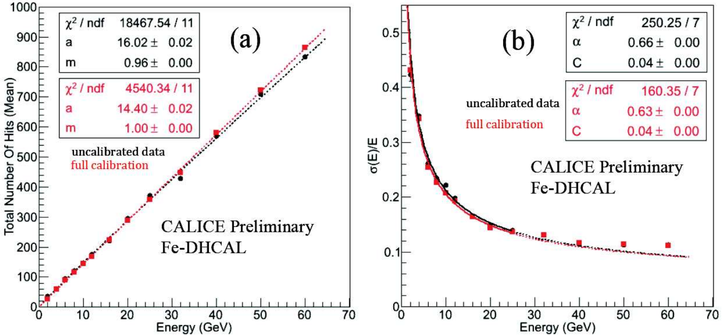
Sc-W-AHCAL: Pion shower shapes



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

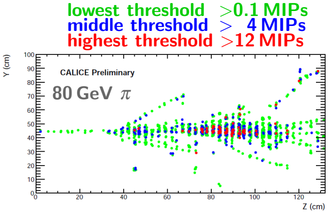
RPC-Fe-DHCAL: Pions

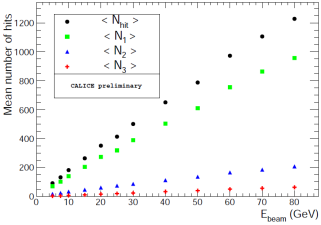
- Digital readout → single threshold
  - Measure number of hits
  - Need to control multiplicity and efficiency to calibrate data

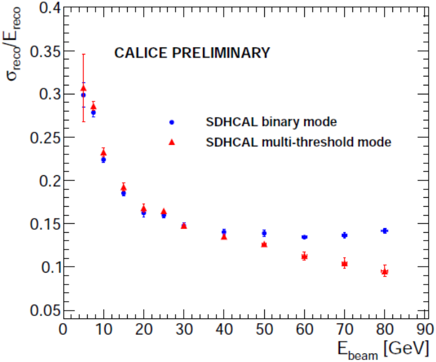


- Fe-DHCAL: pions at 2-60 GeV ▸ CAN-042, W-DHCAL ▸ CAN-039
- Detector calibration improves linearity and resolution
  → Stochastic term after detector calibration 63 % in Fe-DHCAL

RPC-Fe-SDHCAL: Pions

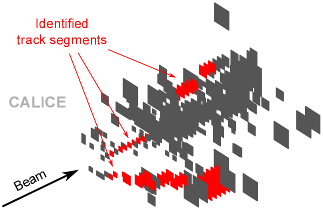


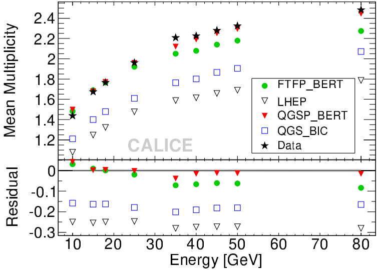


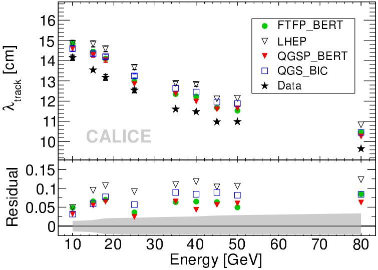


- Pions at 5-80 GeV ▸ CAN-037 ▸ CAN-047
- Record number of hits with threshold information
- $E_{\mathrm{rec}} = \alpha N_1 + \beta N_2 + \gamma N_3$, best parametrization via χ^2 minimization
- Multi-threshold capabilities improve resolution above 30 GeV

Substructure of hadronic shower



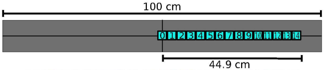




- Pions at 10-80 GeV in Fe-HCAL
- Identify track segments of minimum-ionising particles within hadron showers
- Best agreement between data and QGSP_BERT and FTFP_BERT
- Agreement crucial for simulation studies of Particle Flow Analysis

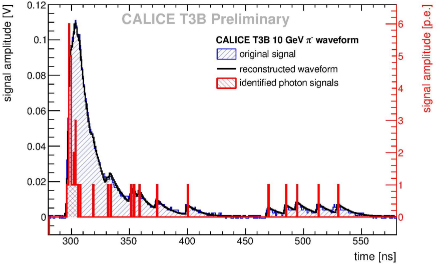
2013 JINST 8 P09001 and CAN-047

Time structure of hadronic shower - T3B

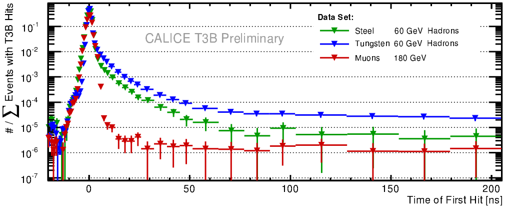


- HCAL read-out without timing information
- T3B: Tungsten Timing Test Beam
- Scintillator cells placed behind HCAL
- Read out $3000 \times 800\,\mathrm{ps} \approx 2\,\mu\mathrm{s}$ to sample the full shower development

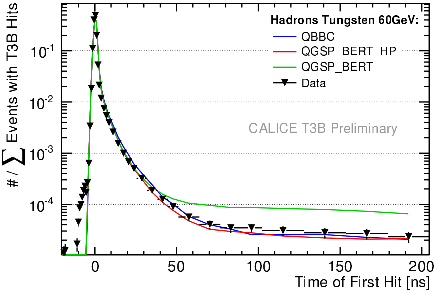
- Time structure of hadronic showers
  - Delayed component due to nuclear deexcitation, neutron propagation etc.
- Identify time of first hit through analysis of time dependence of waveform

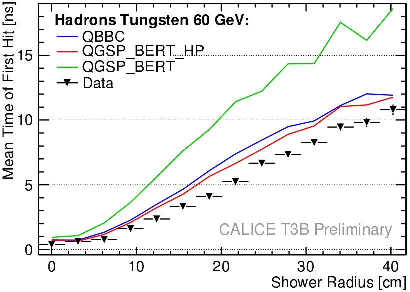


Time structure of hadronic shower - T3B



- Tungsten has more late hit time entries than steel
- High precision (HP) neutron tracking improves agreement for tungsten
- Late energy deposits are more important in outer region of shower



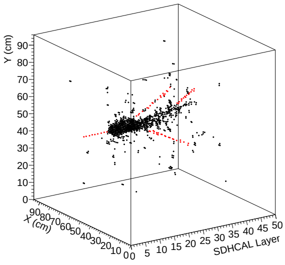


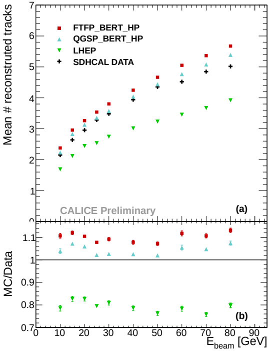
Summary

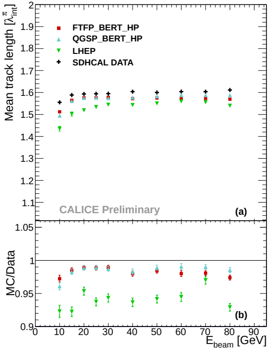
- Test beam experiments with ECAL and HCAL prototypes
  - Test of novel technologies in large-scale calorimeters
  - Demonstration of detector calibration capabilities
  - Characterisation of prototypes: linearity, resolution
  - Re-weighting of energy deposites ("software compensation")
  - Measurement of particle shower evolution
- Validate detector simulations using electromagnetic processes
  - Overall good agreement between data and detector simulation
- Validate models of hadronic nuclear interactions
  - Geant4 models reproduce hadronic data within few percent
  - High precision (HP) neutron tracking needed for tungsten simulation
  - Shower substructure reproduced
  - Shower time structure reproduced

Backup

Fe-SDHCAL: Track segments



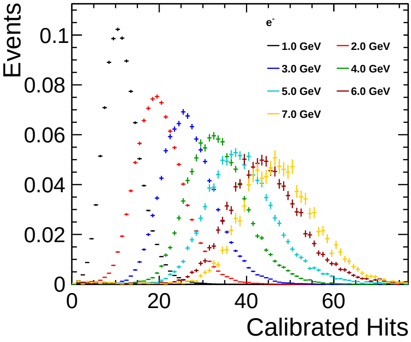


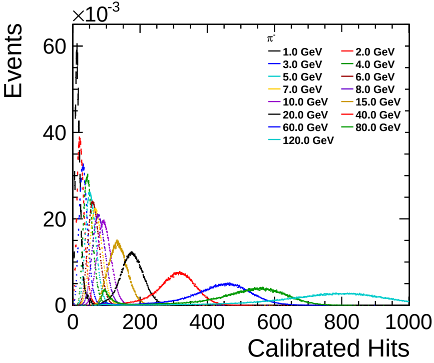


- Identify track segments of minimum-ionising particles within showers
- 10 GeV to 80 GeV pions
- Best agreement between data and QGSP_BERT and FTFP_BERT
- Agreement crucial for simulation studies of Particle Flow Analysis
- CAN-047

RPC-W-DHCAL response

- Electrons and hadrons at 1-300 GeV ▸ CAN-039
- Ongoing study of
  - Data quality
  - Full detector calibration
  - Realistic detector simulation

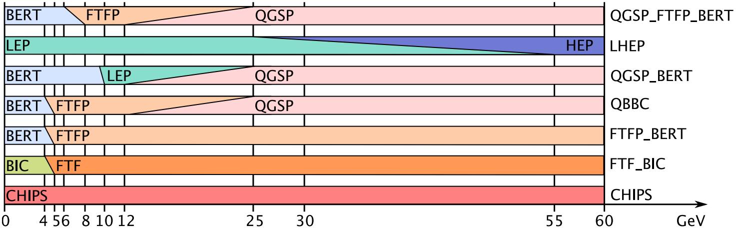




- Hit multiplicity distribution for e and π after detector calibration

Geant4 Physics Lists

- Hadronic intereactions in Geant4 based on phenomenological models
  - String parton models: QGS(P), FTF(P)
  - Parametrised models: LEP, HEP
  - Cascade models: BERT, BIC
  - Precompound model
- Models are combined in "physics lists"



- Model extensions
  - HP: High-precision neutron tracking
  - EMV: Reduced precision for improved timing performance