EPS HEP Conference
Grenoble 22.07.2011

Tests of High Granularity Particle Flow Calorimetry for Linear Colliders

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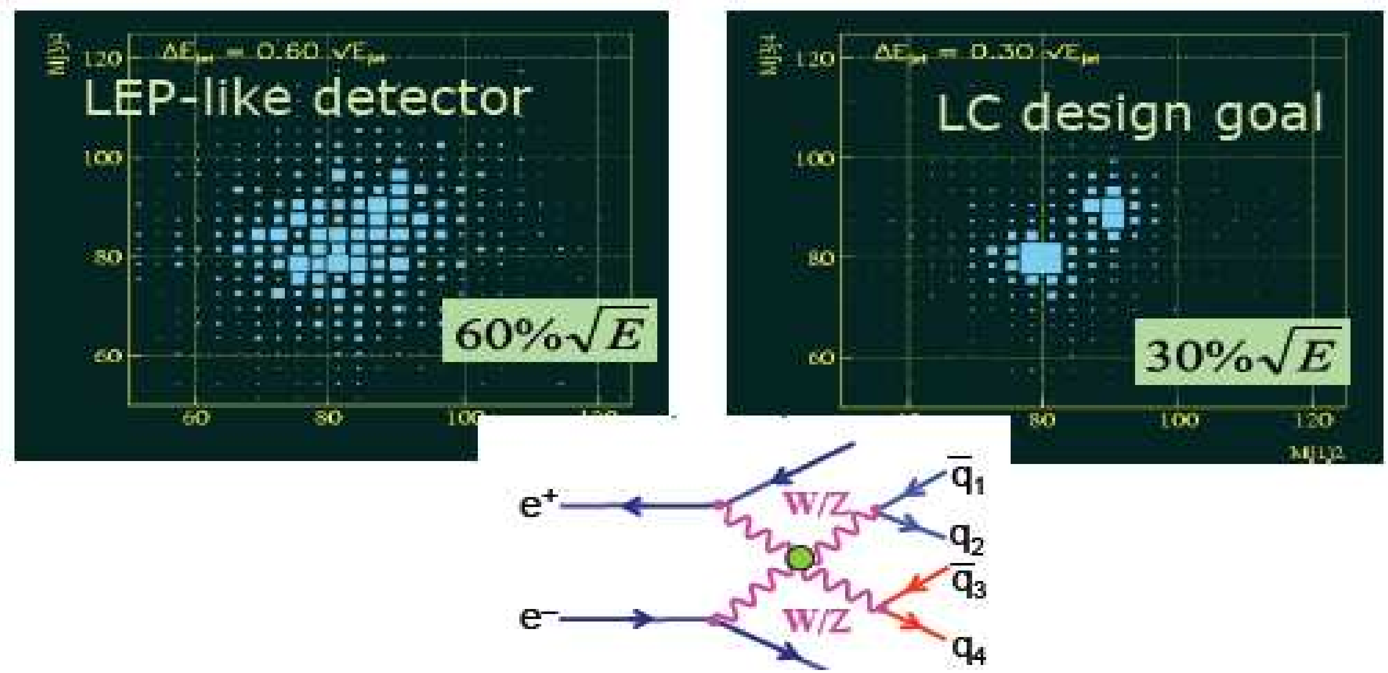
On behalf of the CALICE Collaboration

~350 people from 17 countries

Motivation for PF Calorimetry

Need twice better jet energy resolution in order to use hadronic boson decays

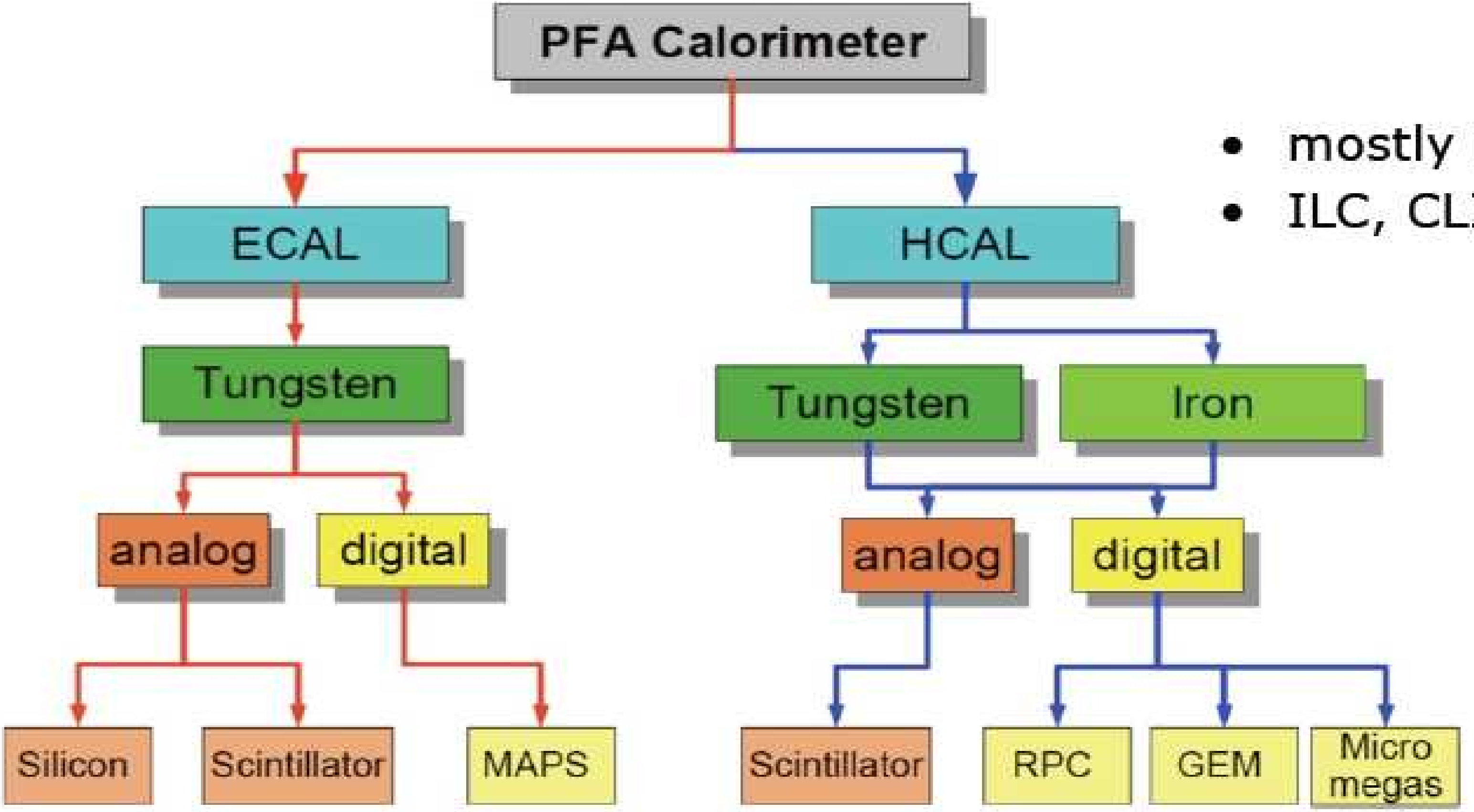


Proposed solution – Particle Flow Algorithm

- Charged energy (65% in jet) – perfectly measured in tracking
- Photons (25%) – precisely measured in ECal
- n/K_L (only 10%) – measured in HCal with modest resolution
- Confusion error in separation of showers is dominant

Separation of showers requires high segmentation

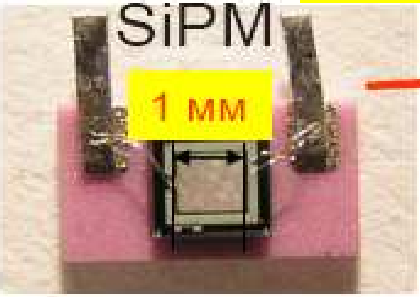
CALICE Collaboration develops different technologies for PFA

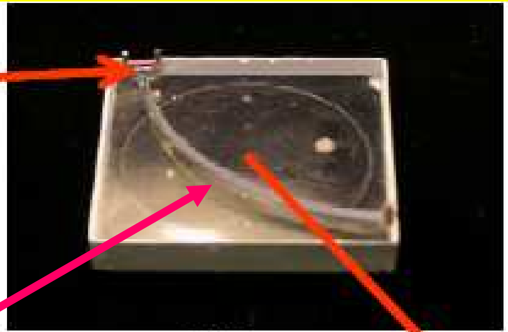


- mostly ILD, SiD
- ILC, CLIC

I'll concentrate on test beam results with analog approach
(Scintillator HCAL and Silicon ECAL)

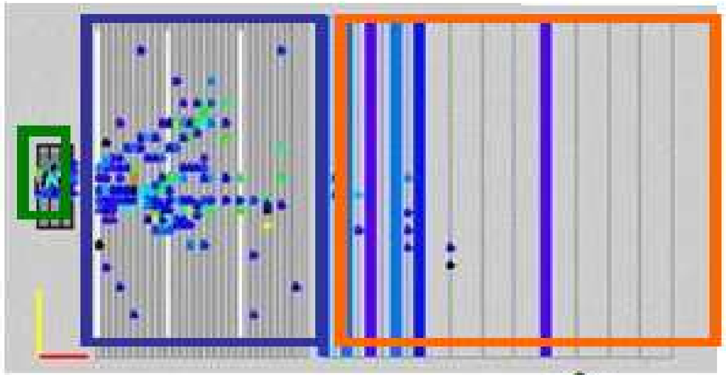
CALICE AHCAL prototype built in 2005-2007
(7608 channels)

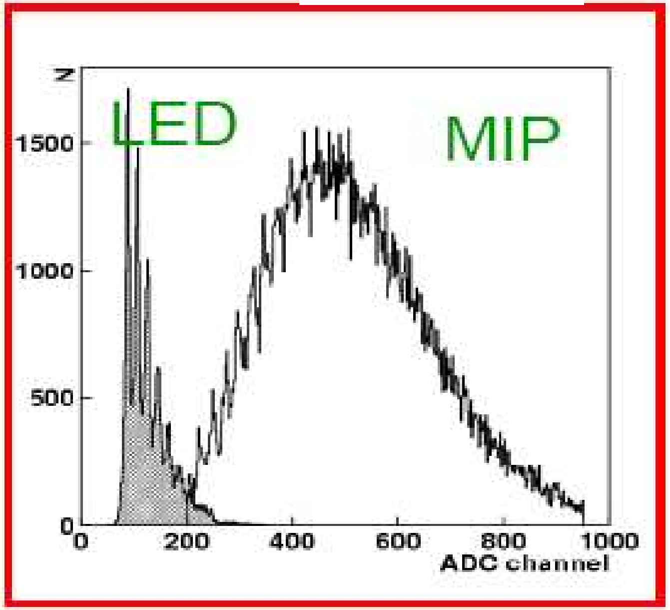




WLS fiber

Tile
3x3cm^2





38 layers
of 2cm Fe

5.3 λ

Calorimeter plane
90x90cm^2

AHCAL with novel SiPM readout demonstrated very reliable performance during beam tests at CERN and FNAL in 2006-09

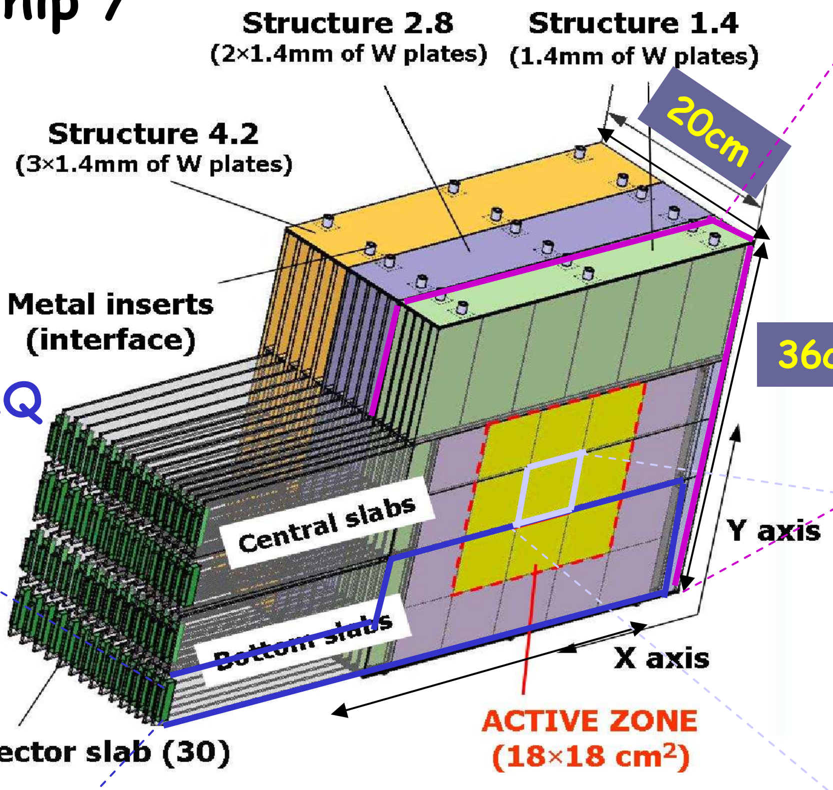
2010_JINST_5_P05004

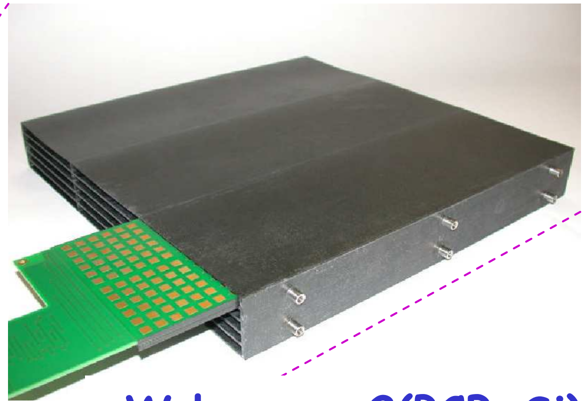
In 2010-11 Fe absorber was changed to 38 layers of 1cm W.
Now WHCAL is under tests at CERN for a CLIC detector development

Silicon/W ECAL Prototype

2008_JINST_3_P08001

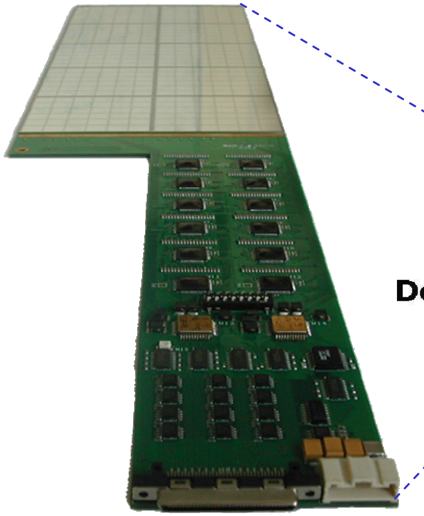
- 30 layers, 9720 channels, 3 W thicknesses, $24X_0$
- Active silicon layers interleaved
- Very Front End chip / readout on PCB

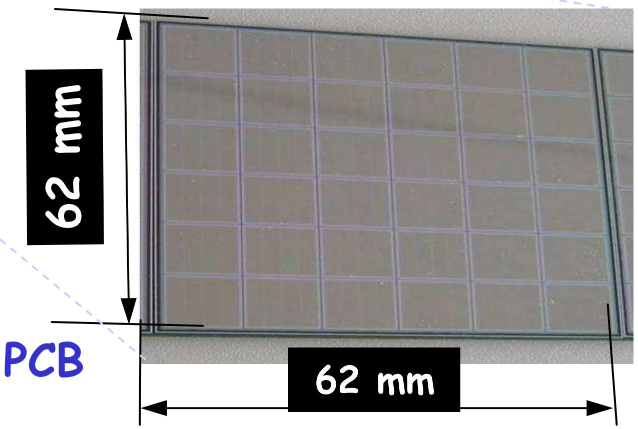




W layer + 2(PCB+Si) layers: 8.5 mm

14 layer PCB, VFE analogue signals → DAQ

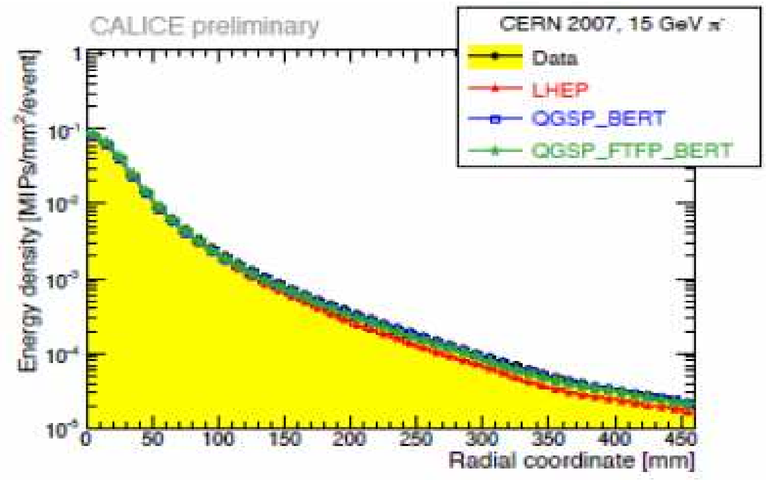


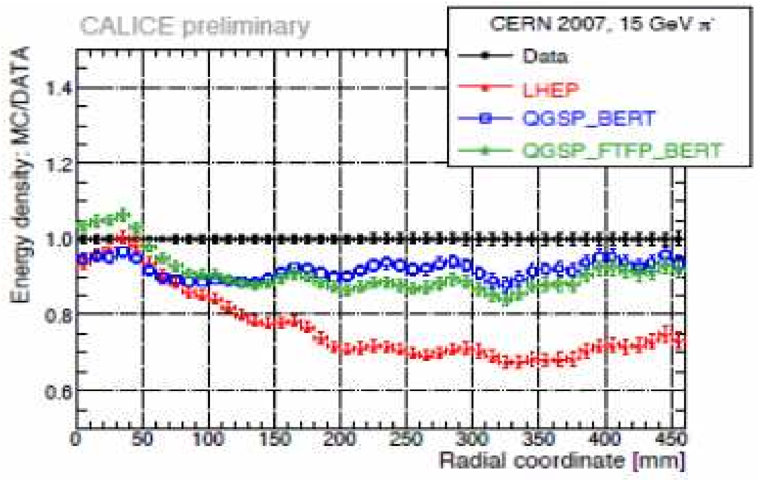


- 6x6 1x1cm^2 Si pads
- Conductively glued to PCB

Lateral shower profile

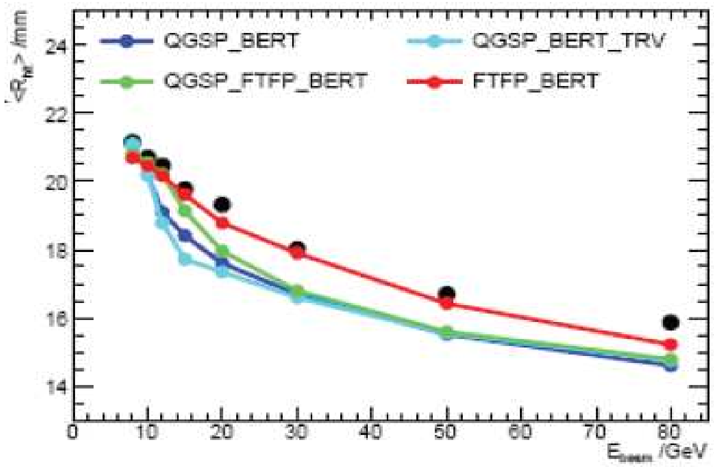
Lateral shower profile is critical for PFA performance

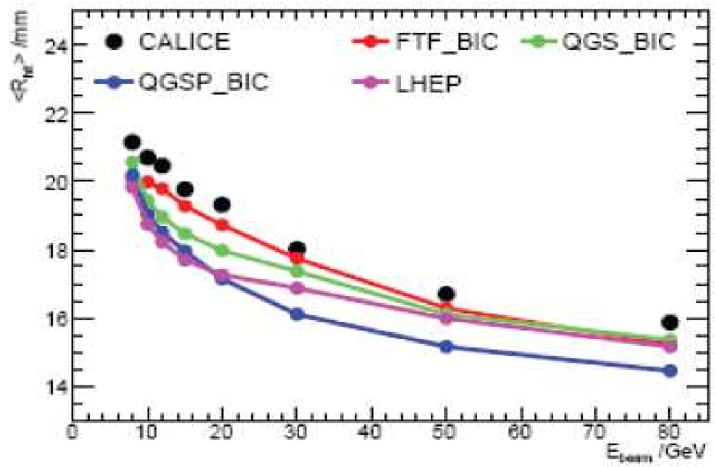




Lateral shower profile measurements in Fe/Scintillator AHCAL

Modern MC models agree with data within ~10%





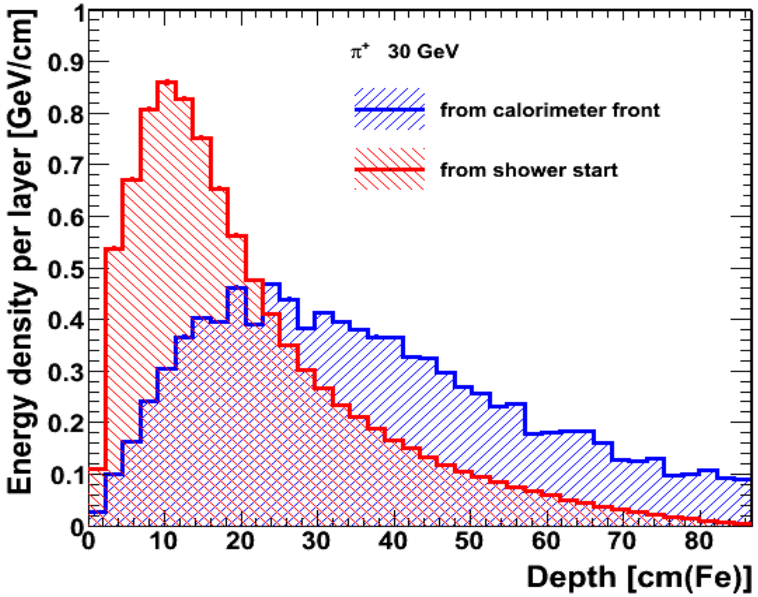
Mean pion shower radius measurements in Si/W ECAL

2010_JINST_5_P05007

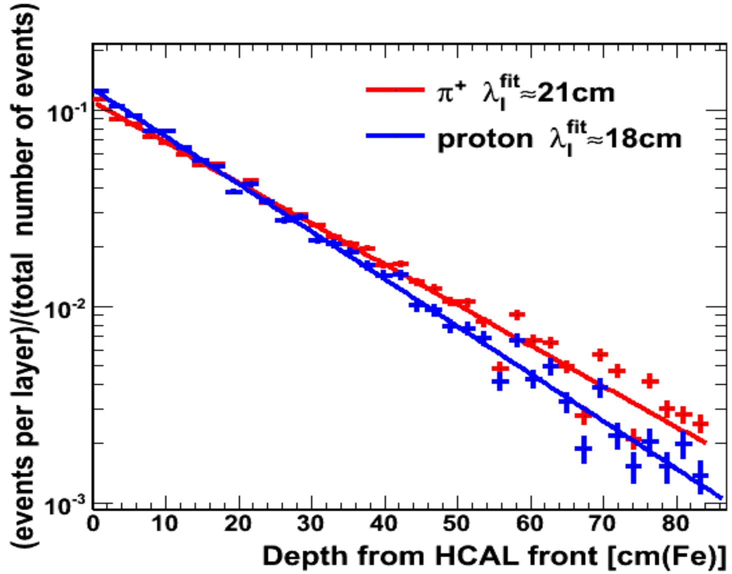
Most models underestimate mean radius. FTF (v4.9.3) fits data best

Longitudinal shower profiles

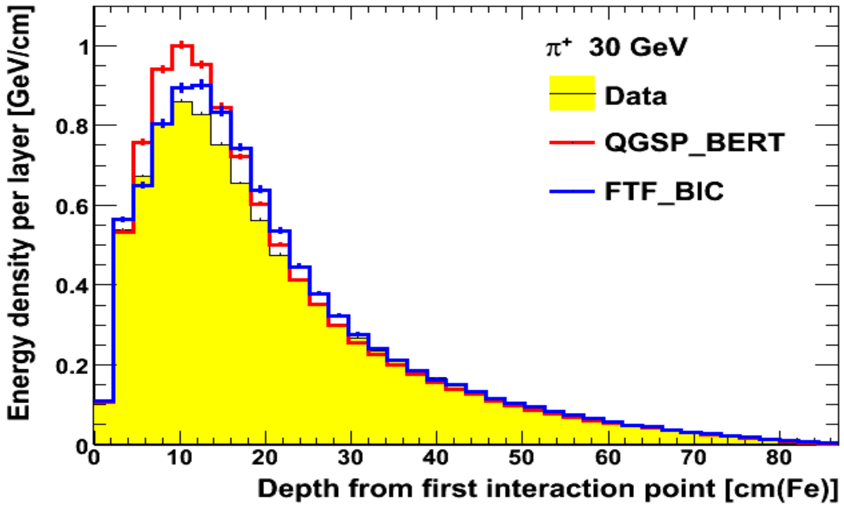
Logitudinal shower profile from HCAL front and from found first interaction point for 30-GeV π^+ in high-granular hadronic calorimeter



Distributions of found first interaction point for 30-GeV pions and protons



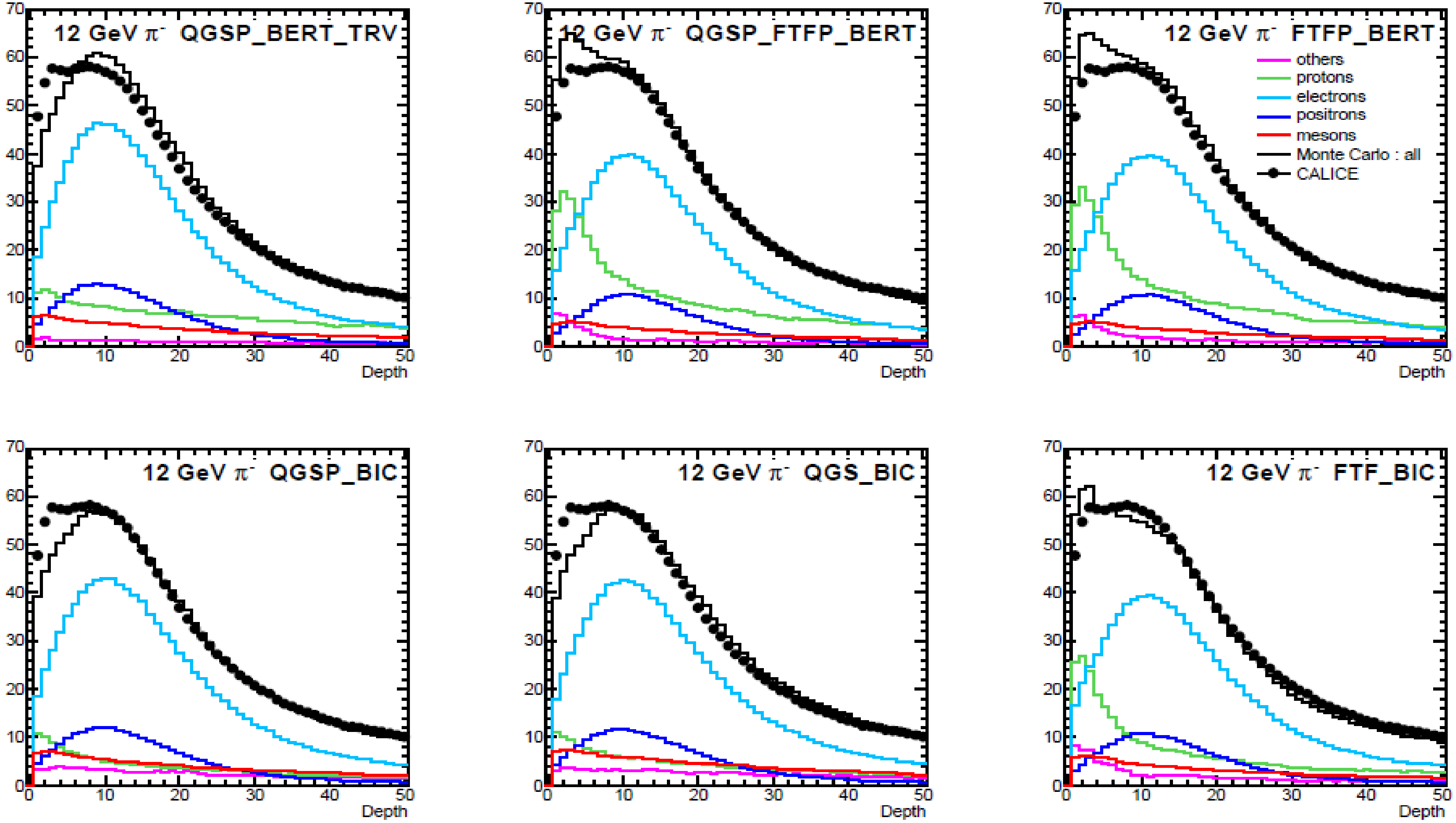
Data-MC comparison of pion shower longitudinal profiles



Longitudinal shower profiles in Si/W ECAL

2010_JINST_5_P05007

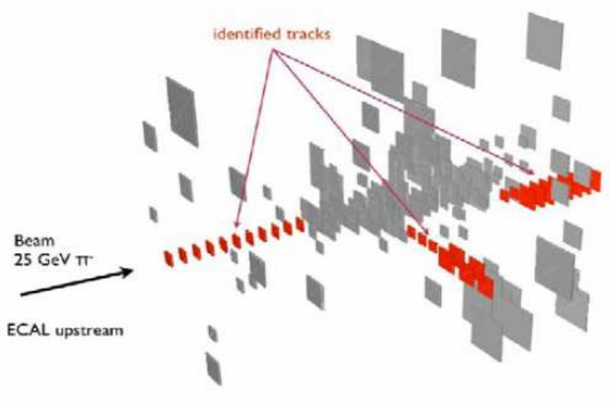
Sensitive to particle composition of showers



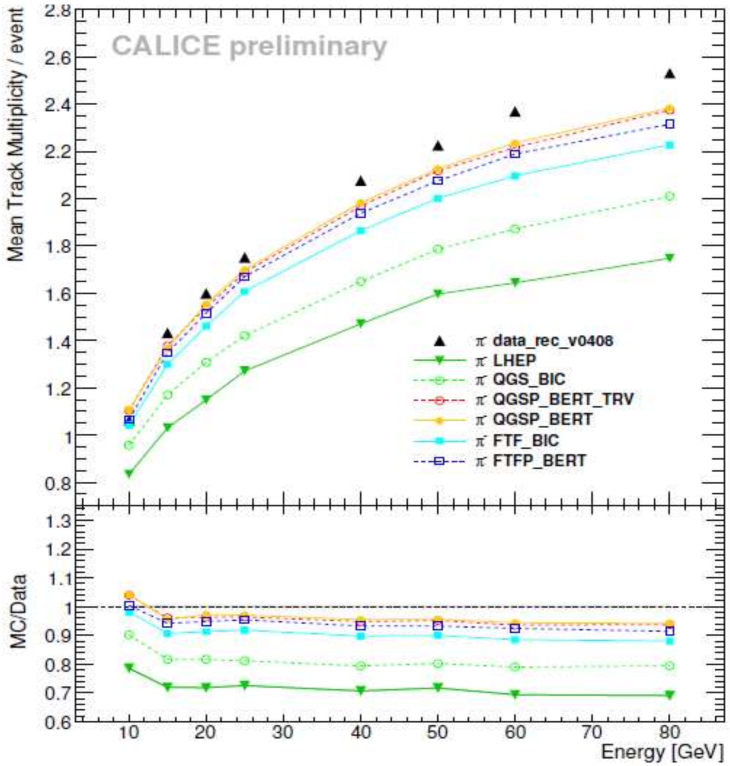
All models have problems in reproducing longitudinal profile

Multiplicity of tracks in hadronic showers

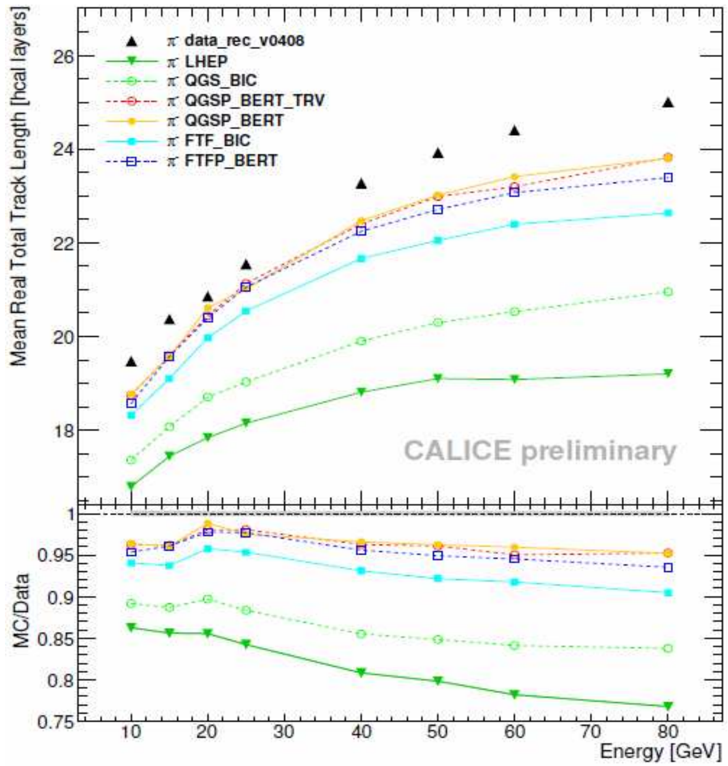
Identify MIP-like track segments in event



Such delicate variables are not well described by MC



Track multiplicity



Mean track length

MIP-like tracks Identified in shower can be used for calibration

Time structure of hadronic showers in W-Scintillator HCAL

CLIC detector needs thicker HCAL: Fe → W

Limited knowledge of hadronic showers in W → Test W/Sc calorimeter at CERN

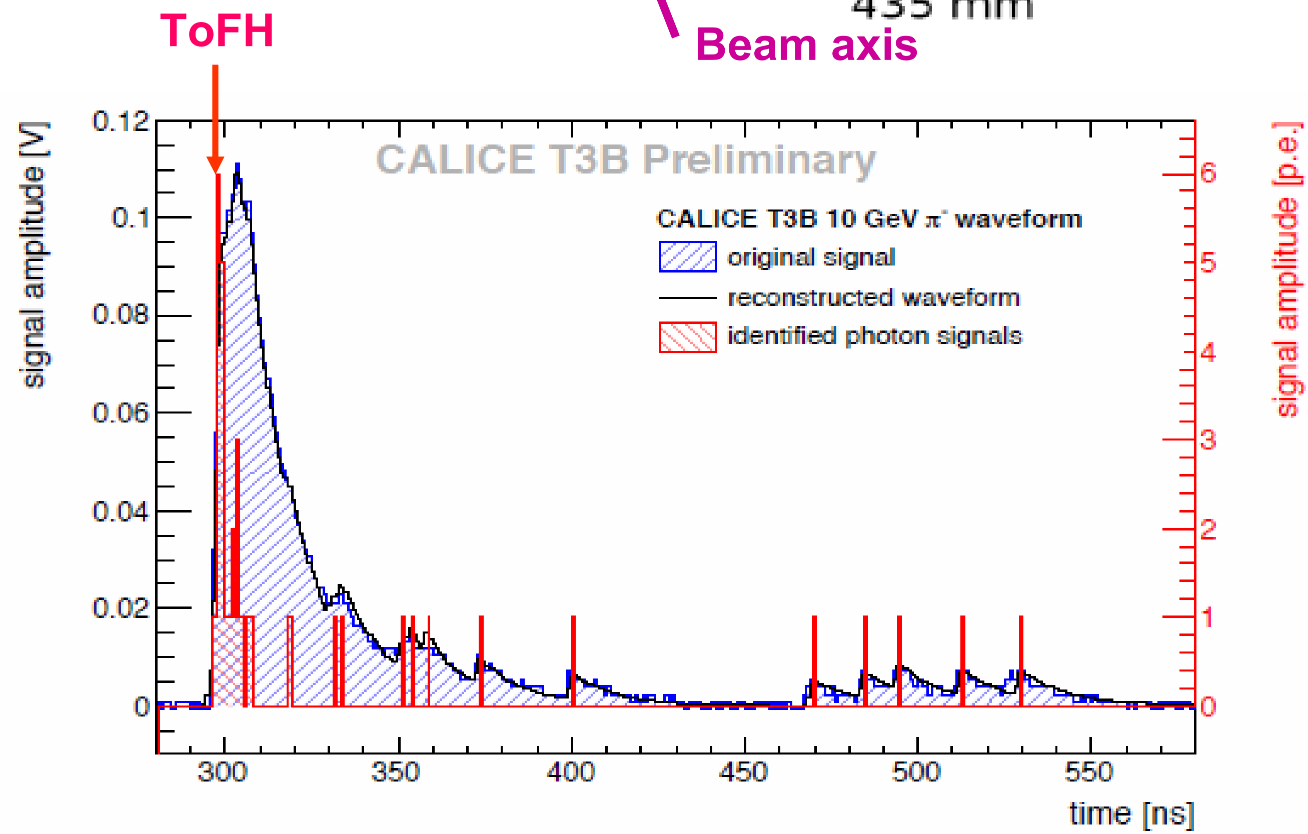
Time stamping important for CLIC in order to reduce background
Need to know the time structure of hadronic showers

Special timing layer of 3x3 cm^2 scintillator tiles (T3B) placed after WHCAL at CERN tests

Fit response to a sum of single photon signals

Determine Time of First Hit - min 8 p.e. (~0.4 MIP) within 9.6 ns

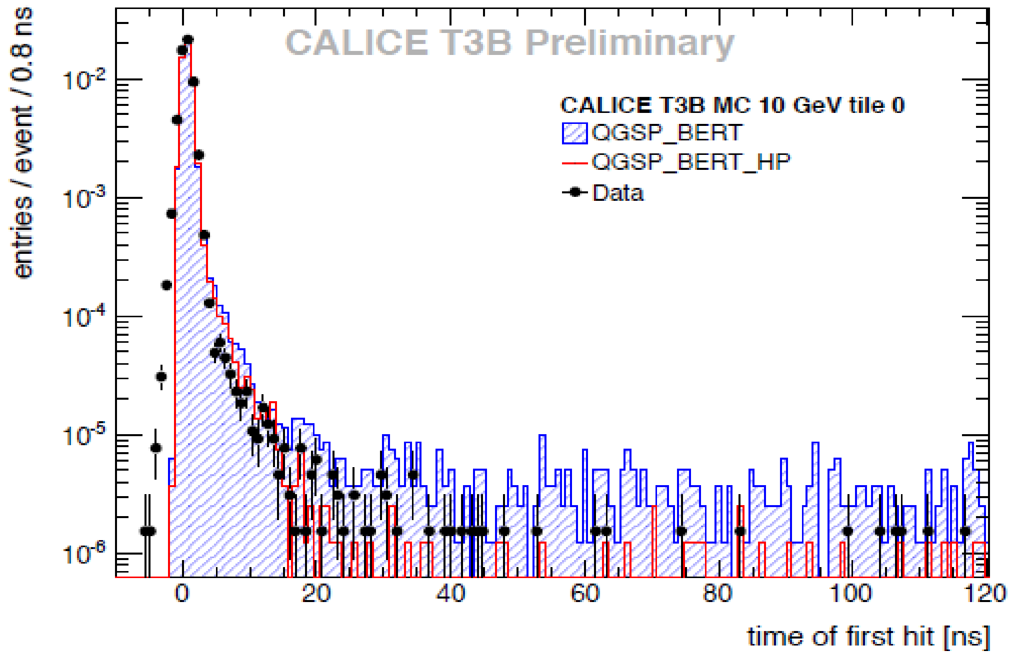
Time resolution for muons ~ 800 ps including trigger



Time of First Hit in central T3B cell

QGSP_BERT
(LHC standard used for CLIC detector studies)
shows a pronounced tail of late energy deposits

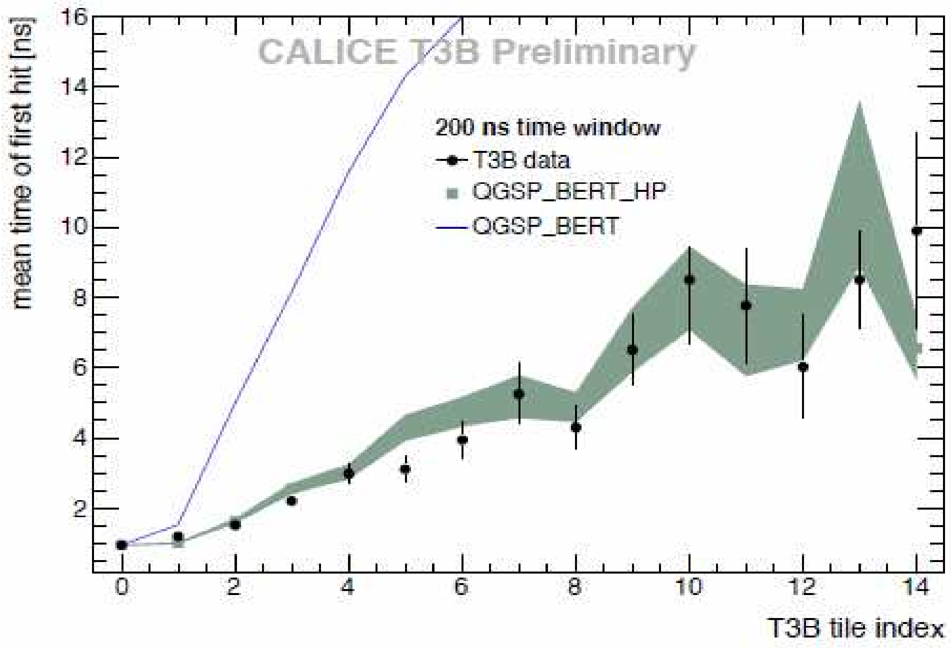
Data agrees better with QGSP_BERT_HP
(variant with high precision neutron tracking)



Mean Time of First Hit
calculated in 200 ns window
(-10ns to 190ns from maximum in tile 0)

Data described consistently by QGSP_BERT_HP

QGSP_BERT overshoots strongly

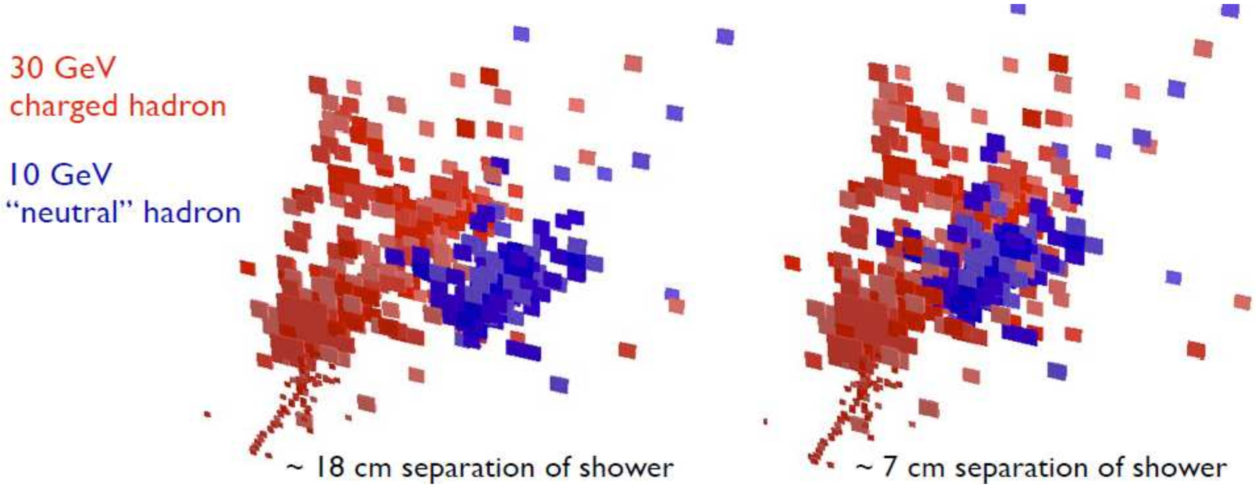


The separation of charged and neutral clusters, crucial for PFA performance, was studied with test beam data

2011_JINST_6_P07005

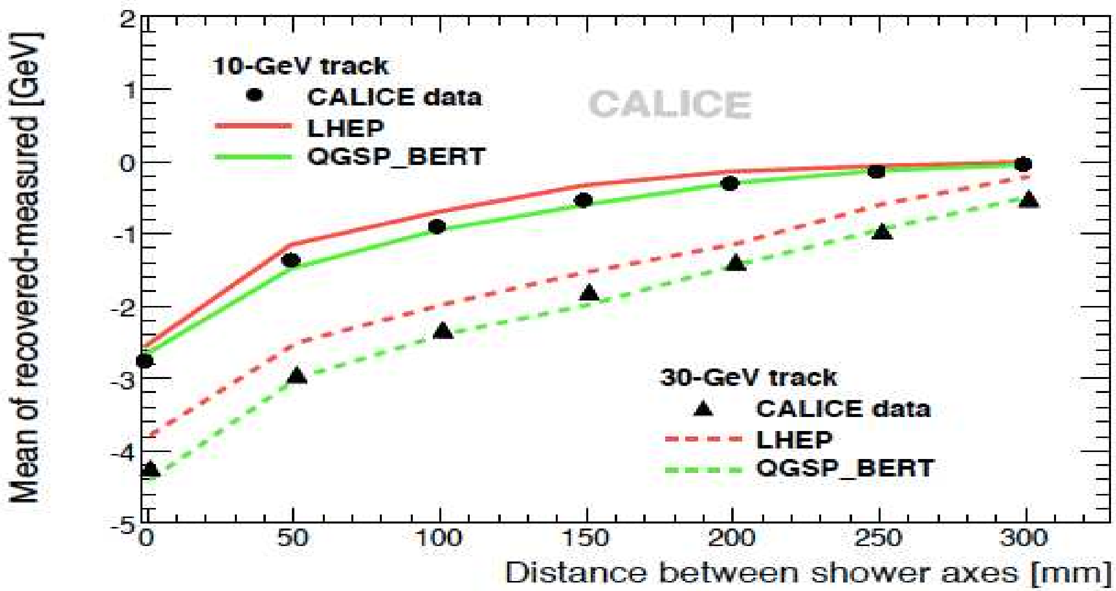
Two test beam showers were superimposed.

Results of disentangling by PandoraPFA was confronted with MC

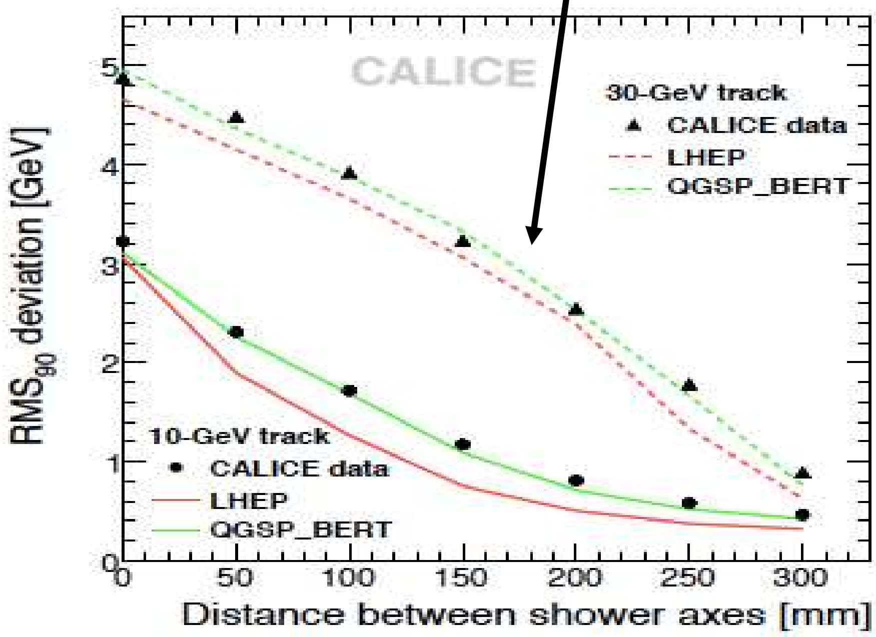


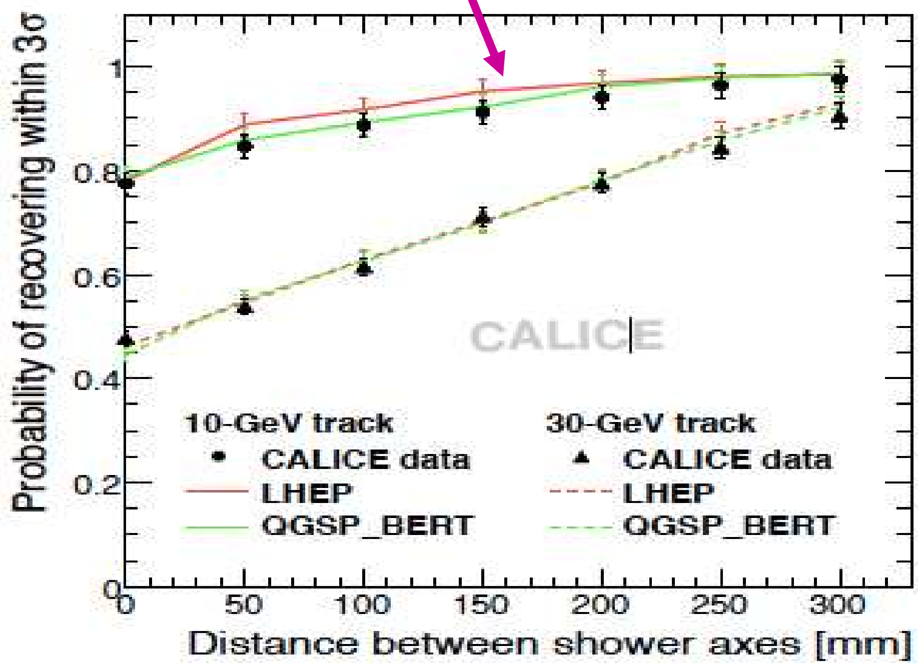
For comparison, the most sensitive characteristic was chosen - difference between the recovered and measured energy of the "neutral" shower

Two different MC physics models were studied for comparison



The results of shower disentangling for data and MC are in a good agreement for both the probability of correct reconstruction and for the confusion error





→ No hidden imperfections in the real data (wrong calibration, saturation correction, response non uniformity, dead or noisy channels, etc.) which could deteriorate the PFA performance were found

→ The agreement between data and MC makes reliable the detector optimization based on simulation.

Pandora PFA passed the exam with REAL DATA from REAL CALORIMETERS

Software Compensation

- π/e response ~ 0.8
  → increased fluctuations
- e/m parts of shower usually denser
- use software weighting to decrease fluctuations

Several methods
(global, local, neural networks)
tuned with data have been used

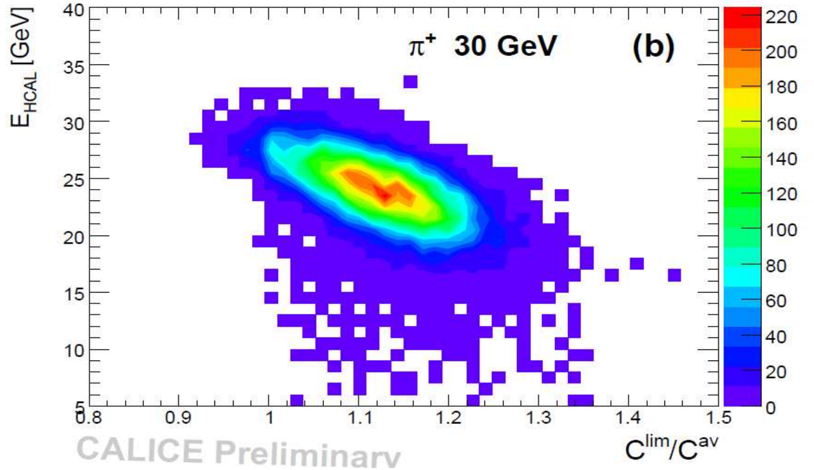
All give similar improvement
~15-20% in energy resolution
for 10-80 GeV energy range

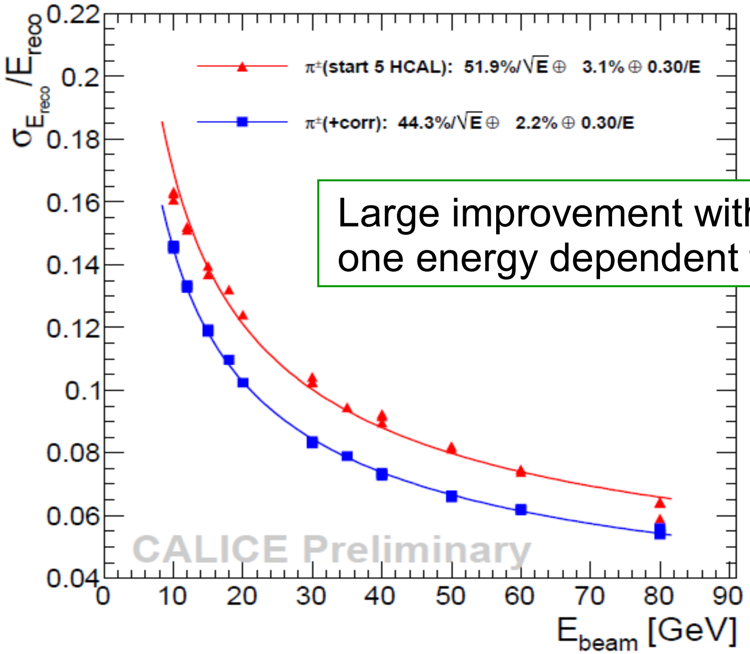
Linearity is within ±1.5%

GEANT4 reproduces results well
but not perfect

Global Method as example

Energy correlated with fraction of hits with high E

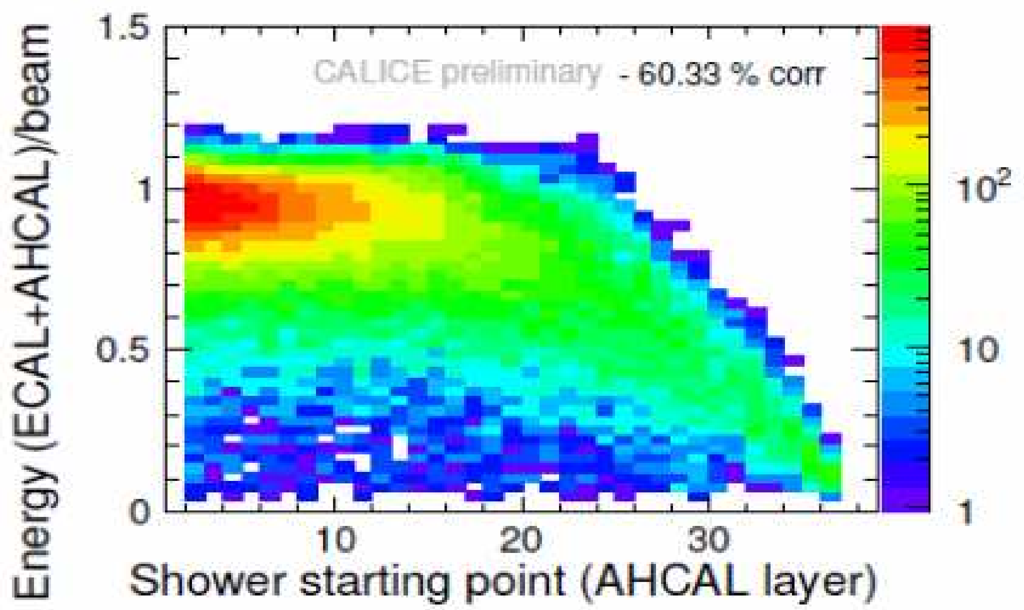


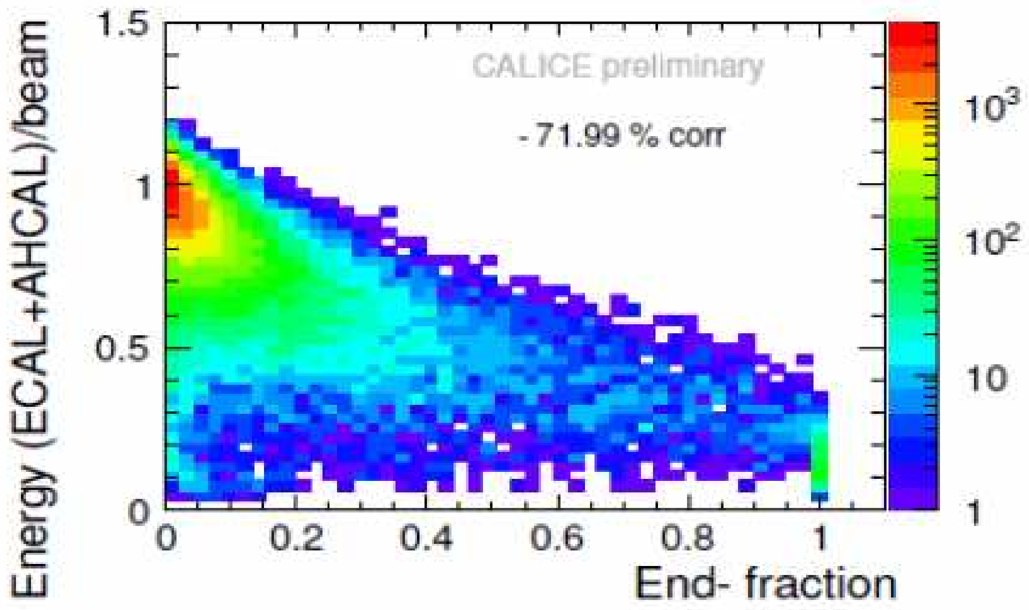


Large improvement with only one energy dependent factor

Leakage correction

Leakage strongly correlated with shower starting layer and energy in last 5 layers





AHCAL high granularity allows corrections for leakage →

Considerable improvement in linearity and resolution is expected

CONCLUSIONS

First generation of prototypes demonstrated a feasibility of highly granular calorimeters for PFA at LC

High granularity data allow very detailed studies of hadronic showers and tuning of MC models

MC models describe lateral and longitudinal shower profiles with 10-20% accuracy
Deviations are larger for more delicate variables like number of track segments

Shower time development critical for background reduction at CLIC was measured in W/Scintillator calorimeter and will be used for detector optimization

The most critical part of PFA –
neutral particle reconstruction in vicinity of another hadronic shower
was successfully tested using real data
(noisy and dead channels, nonuniformity, calibration errors and nonlinearity, etc. –
all taken into account)

High granularity allows to correct for e/π ratio with ~ 15-20% improvement in resolution

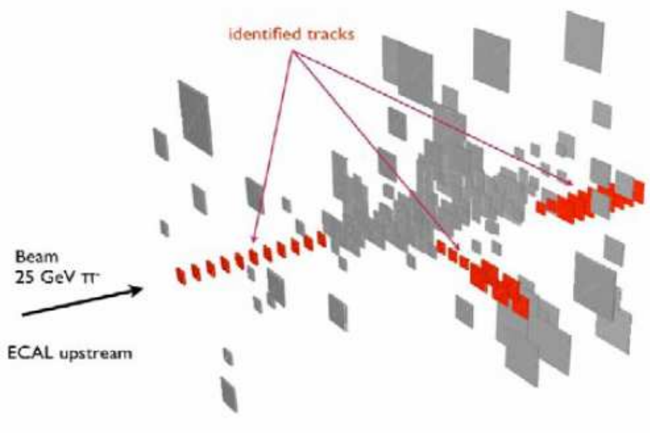
High granularity allows to correct for leakage.
Considerable improvement is expected in linearity and resolution

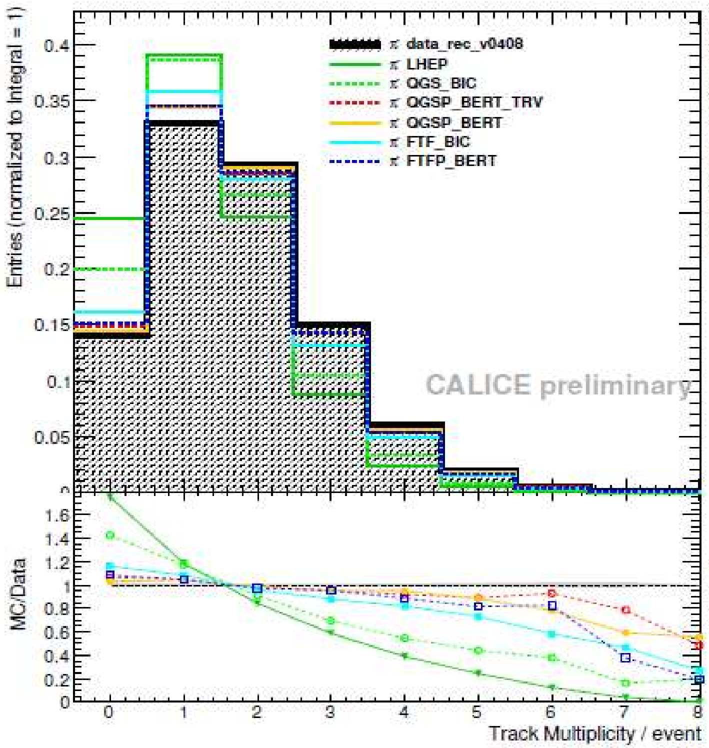
Back up slides

Multiplicity of tracks in hadronic showers

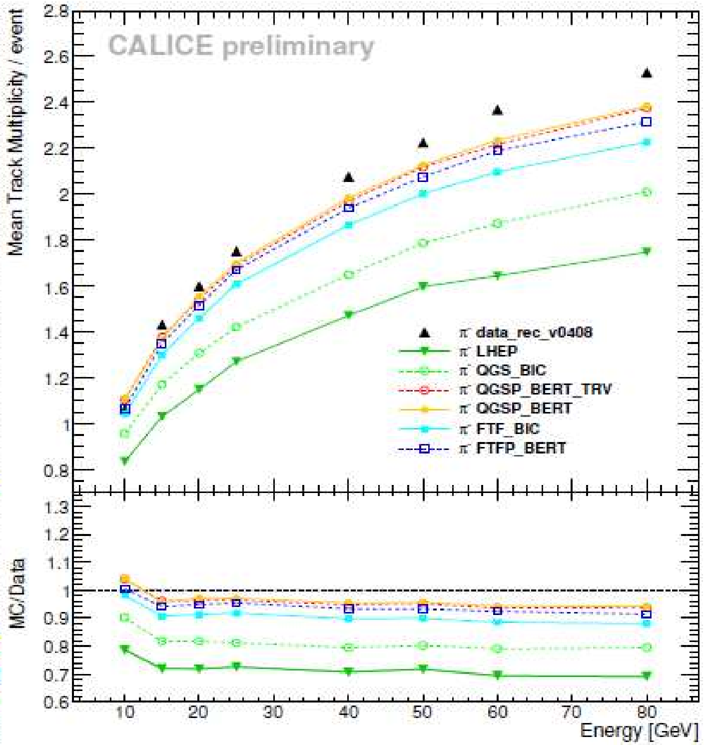
Identify MIP-like track segments in event

Such delicate variables are not well described by MC





Track multiplicity



Mean track multiplicity

MIP-like tracks Identified in shower can be used for calibration