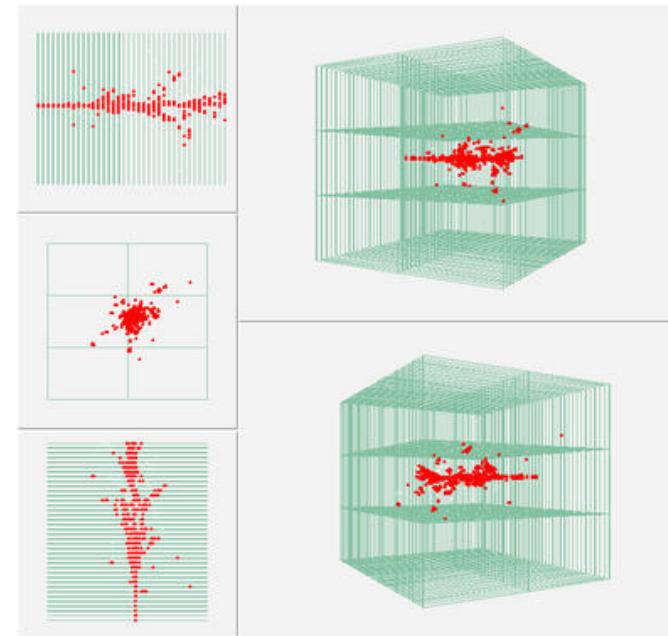


Development of Particle Flow Calorimetry

José Repond

Argonne National Laboratory



Workshop on the LHeC
Chavannes-de-Bogis, Switzerland
June 14-15, 2012

Introduction

At high collision energies

Need to measure hadronic jets as best as possible

- information about underlying hard collision process
- kinematical reconstruction
- reconstruct W's and Z's in their hadronic decay mode

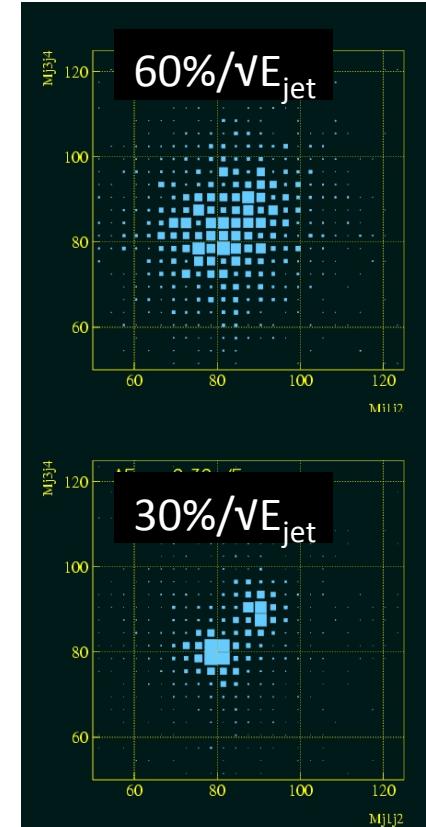
Traditionally

Jets measured with the calorimeter
(best so far the compensating ZEUS calorimeter)

New approaches

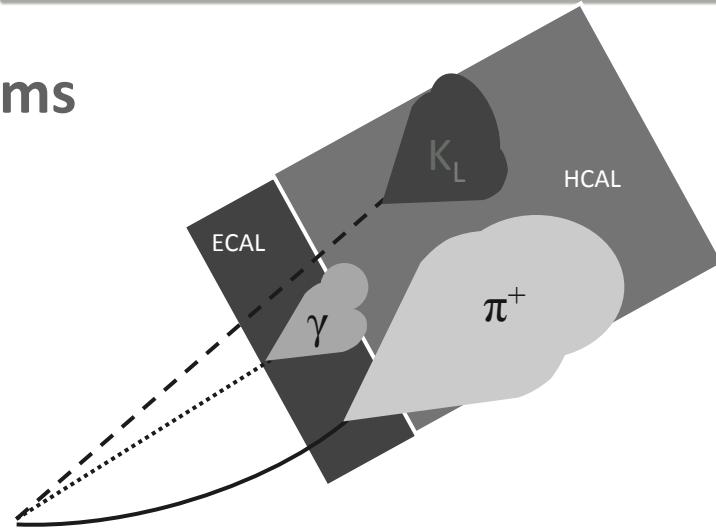
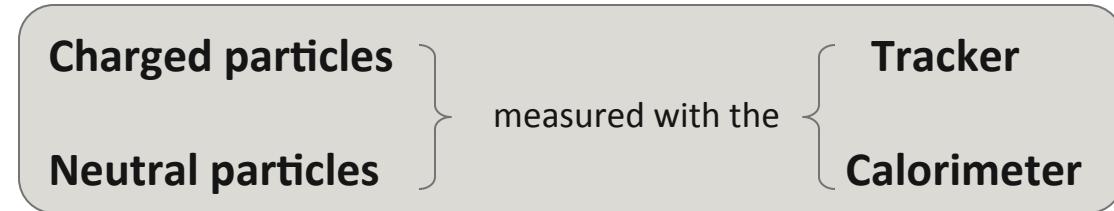
Dual readout (attempt to reconstruct em fraction in showers and correct for it)
Particle Flow Algorithms (attempt to utilize both tracker and calorimeters)

→ Goal = Factor x2 better than previously achieved



New approach: Particle Flow Algorithms

The idea...



Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]	
Charged	65 %	Tracker	Negligible	
Photons	25 %	ECAL with $15\%/\sqrt{E}$	$0.07^2 E_{jet}$	
Neutral Hadrons	10 %	ECAL + HCAL with $50\%/\sqrt{E}$	$0.16^2 E_{jet}$	
Confusion		Required for $30\%/\sqrt{E}$	$\leq 0.24^2 E_{jet}$	$18\%/\sqrt{E}$

Requirements for detector

- Need excellent tracker and high B – field
- Large R_I of calorimeter
- Calorimeter inside coil
- Calorimeter with **extremely fine segmentation**
- Calorimeter as dense as possible (short X_0, λ_I)

CALICE Collaboration



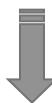
Goals

Development and study of finely segmented calorimeters for PFA applications

Strategy

Study of physics, proof of technological approach → **physics prototypes**
Development of scalable prototypes → **technical prototypes**

At a recent collaboration meeting in Casablanca



4 regions



17 countries



57 institutes



357 physicists

Imaging Calorimeters I

Dense, compact calorimeters with extremely fine segmentation

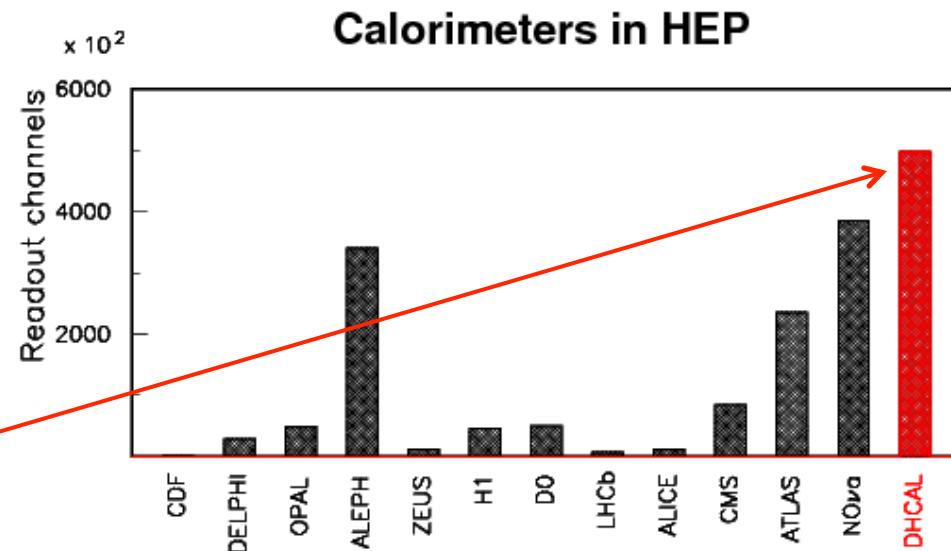
Cell readout

Layer-by-layer
and laterally...

Calorimeter Prototype	Cell size
Scintillator pad HCAL	144 – 9 cm ²
Scintillator pad ECAL	4.5 cm ²
RPC/GEM/Micromegas HCAL	1.0 cm ²
Silicon pad ECAL	1.0 → 0.25 , 0.13 cm ²
MAPS ECAL	0.000025 cm ²

Large number of channels

Only a prototype calorimeter
 4π calorimeter roughly $\times 100$ more



Imaging Calorimeters II

Offer additional advantages

Reconstruct **every shower** in an event individually

Reconstruct **direction of showers**

→ important for some exotic physics signals

Reconstruct **dijet masses**, even if jets close-by

Apply separate calibration factors to the
em and hadronic shower components

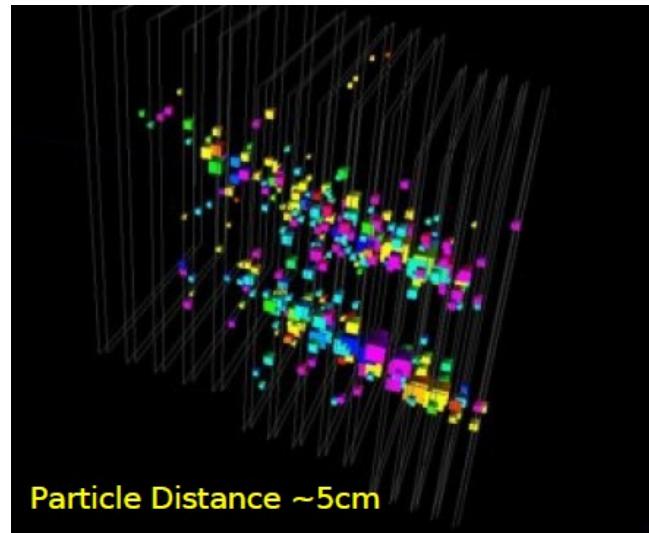
→ **Software compensation**

Correct for leakage using last layers/shower start

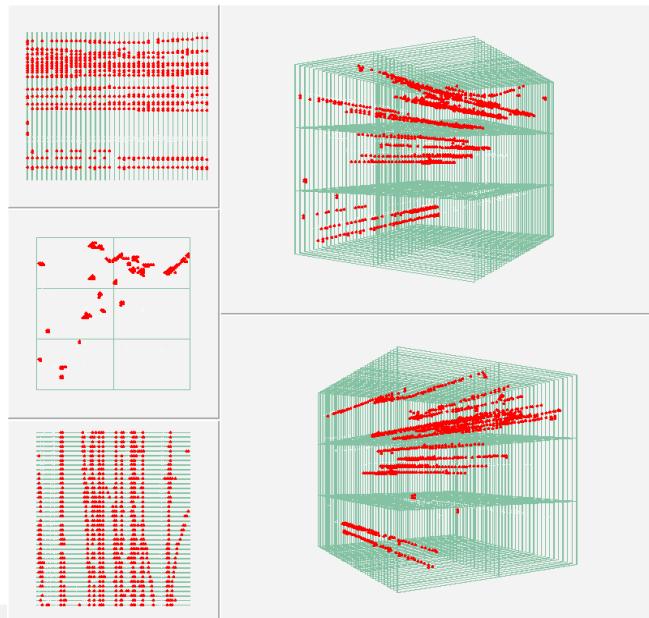
Reconstruct **momentum of charged particles**
within showers (not exploited yet)

Identify **noise hits** (and eliminate)

2 electrons in the Silicon-W ECAL

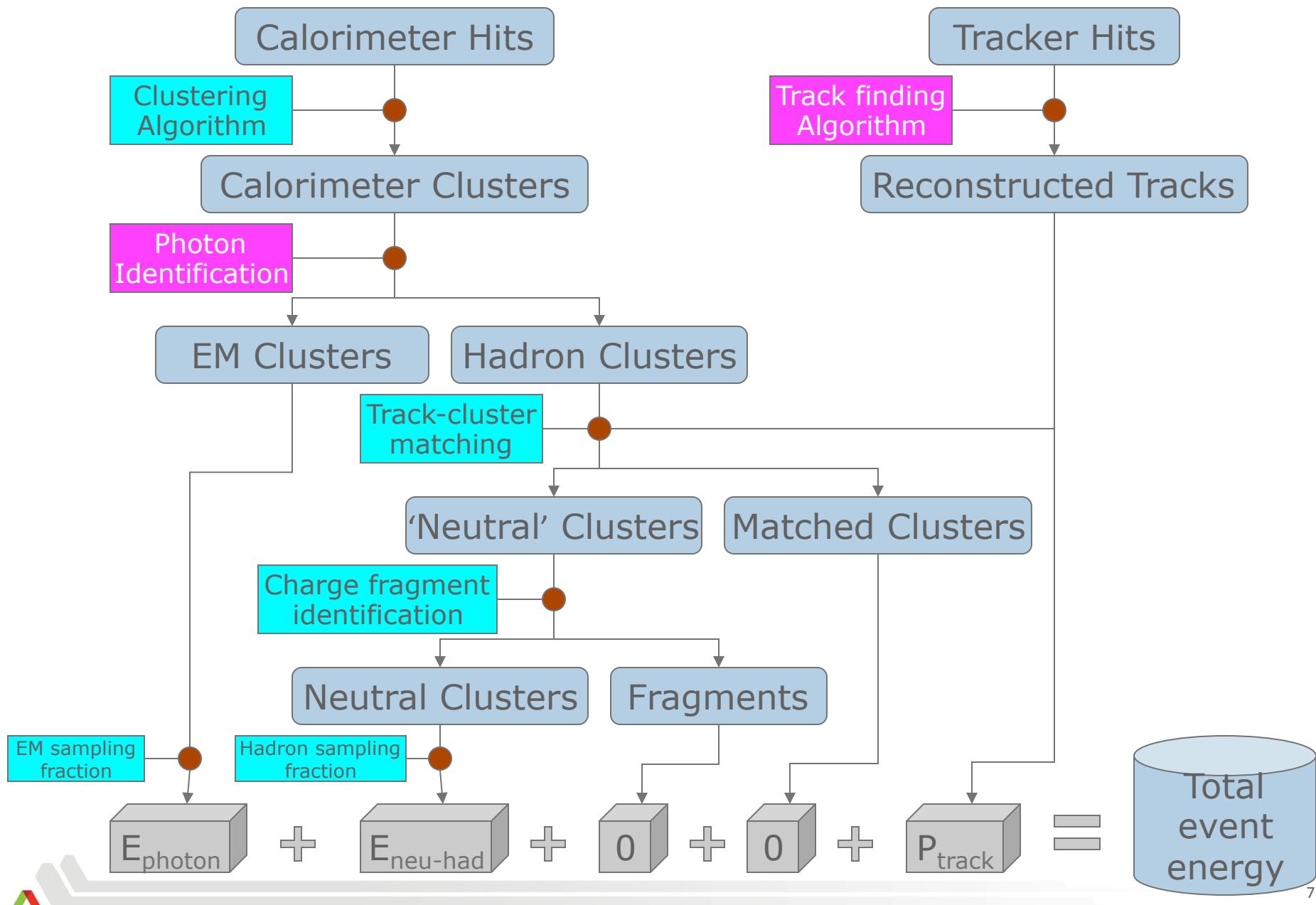


~ 15 muons in the RPC -DHCAL



How PFAs work

Example taken from L Xia



Example: Pandora PFA

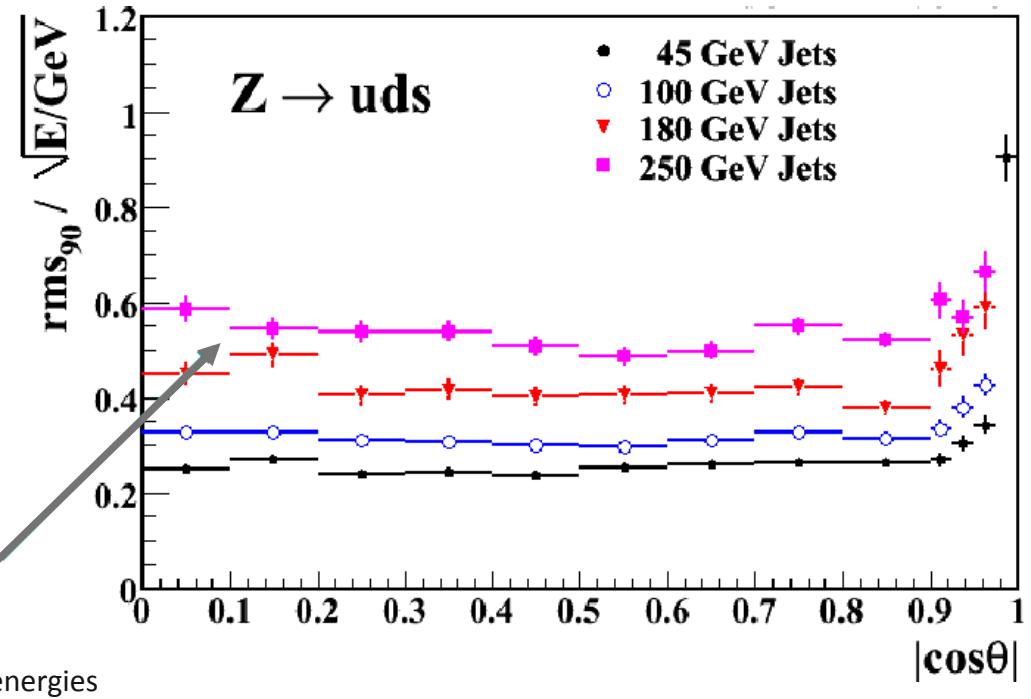
Developed by

Mark Thomson (University of Cambridge)

Based on GEANT4

Current performance

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $ \cos\theta < 0.7$	σ_E/E_j
45 GeV	24.9 %	3.7 %
100 GeV	30.7 %	3.1 %
180 GeV	43.0 %	3.2 %
250 GeV	52.2 %	3.3 %



ILC/CLIC performance goals achieved

Open – ended development

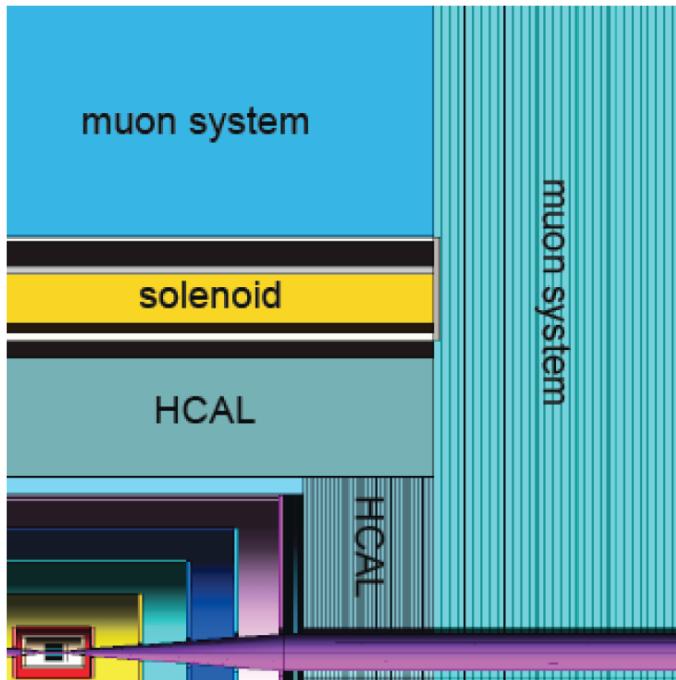
Resolution still mostly dominated by confusion

Second order corrections (e.g. leakage, SW compensation) not yet implemented

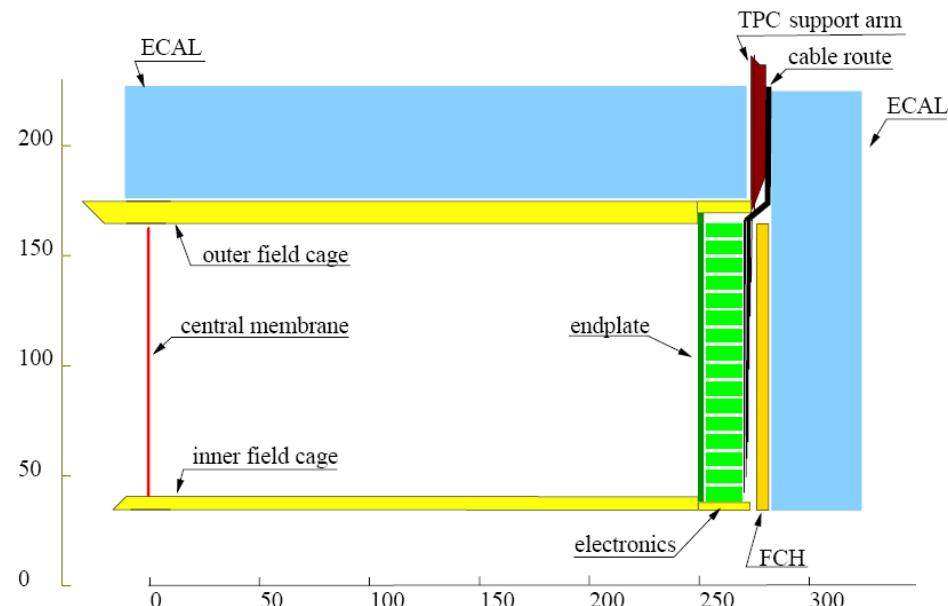
The PFA Detector Concepts: ILD and SiD

Similarities between SiD and ILD

- Pixel vertex detector
- Highly granular electromagnetic calorimeter
- Highly granular hadron calorimeter
- Calorimeters located inside the coil
- High magnetic field between 3 – 5 Tesla
- Instrumented return yoke for muon identification
- (Joint effort on) forward calorimetry



Being developed for both the ILC and CLIC
First detectors to be optimized for PFA applications



Major difference between SiD and ILD

SiD – Pure Silicon tracker

ILD – Time Projection Chamber + Silicon layers

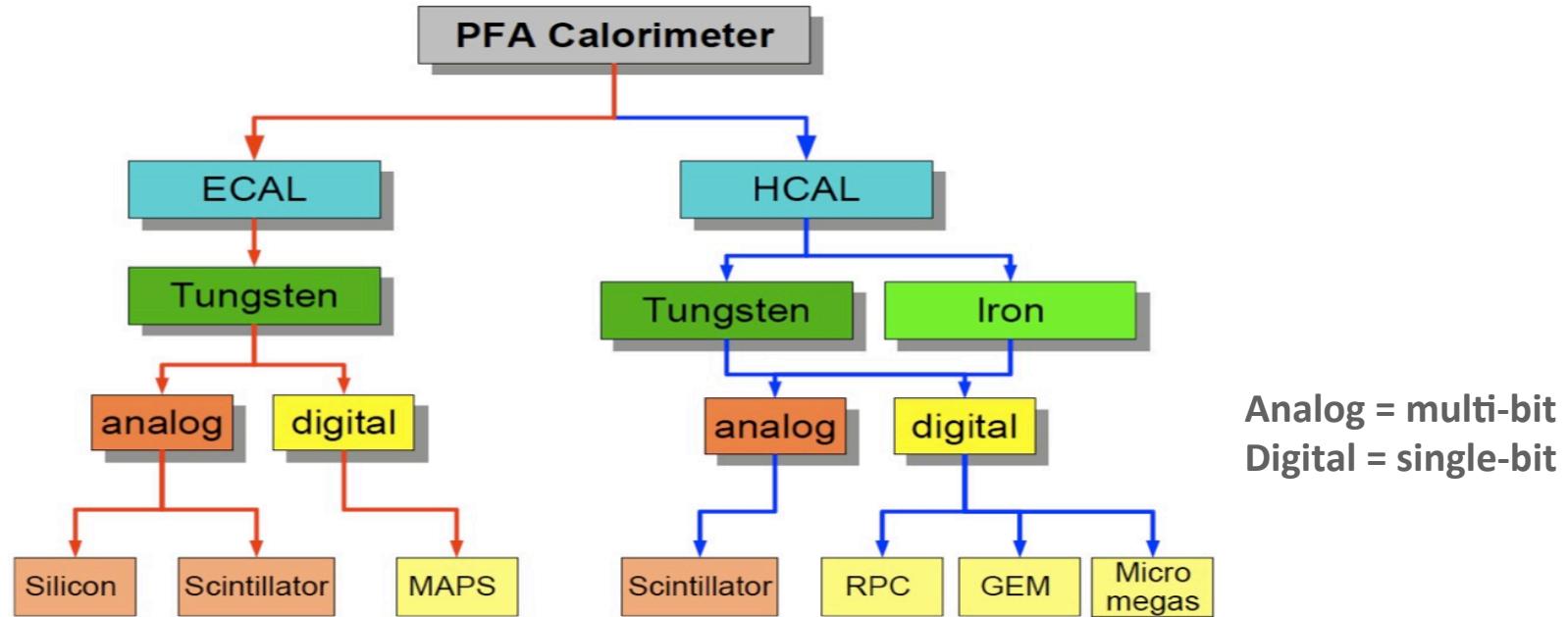
Calorimeter Developments

Stages

Physics prototype – Proof technological approach, measure hadronic showers

Technological prototype – Address all technical issues, not necessarily with a full module

Module 0 – Implements all aspects of a module for a colliding beam detector



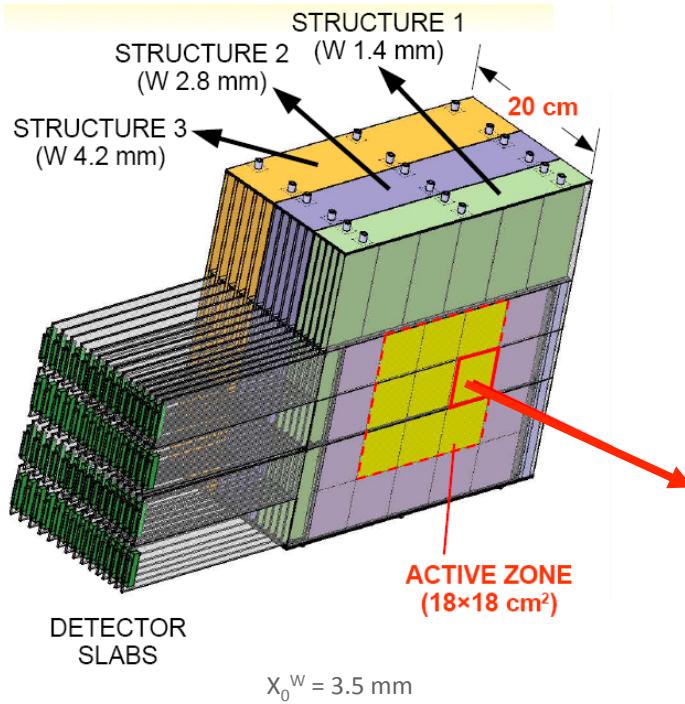
All work (apart from the SiD – Si-W ECAL) coordinated within the



collaboration

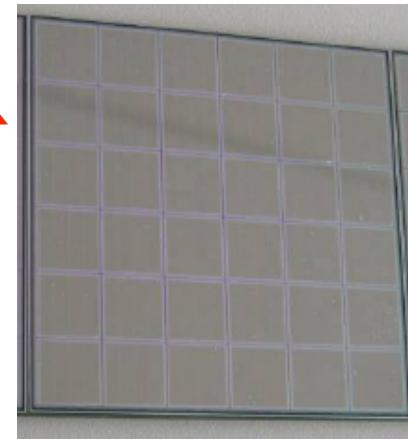
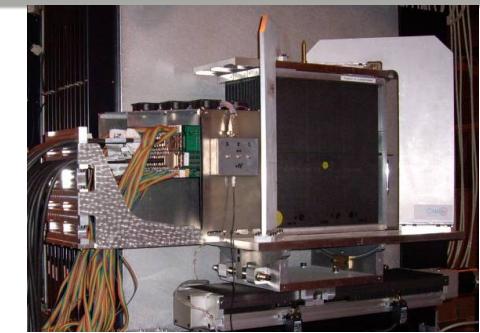


Silicon – Tungsten ECAL



Physics prototype

3 structures with different W thicknesses
 30 layers; 1 x 1 cm² pads
 18 x 18 cm² instrumented
 → 9720 readout channels

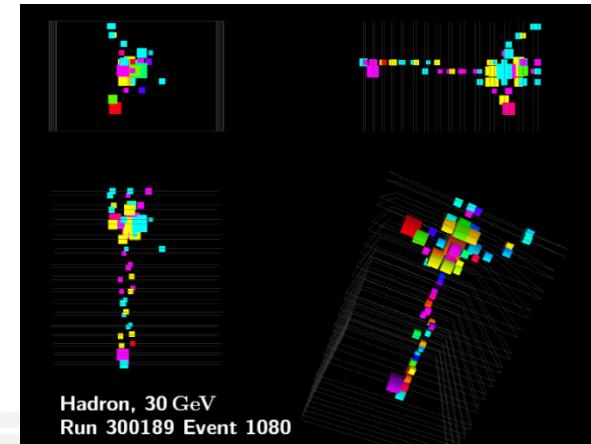


Electronic Readout

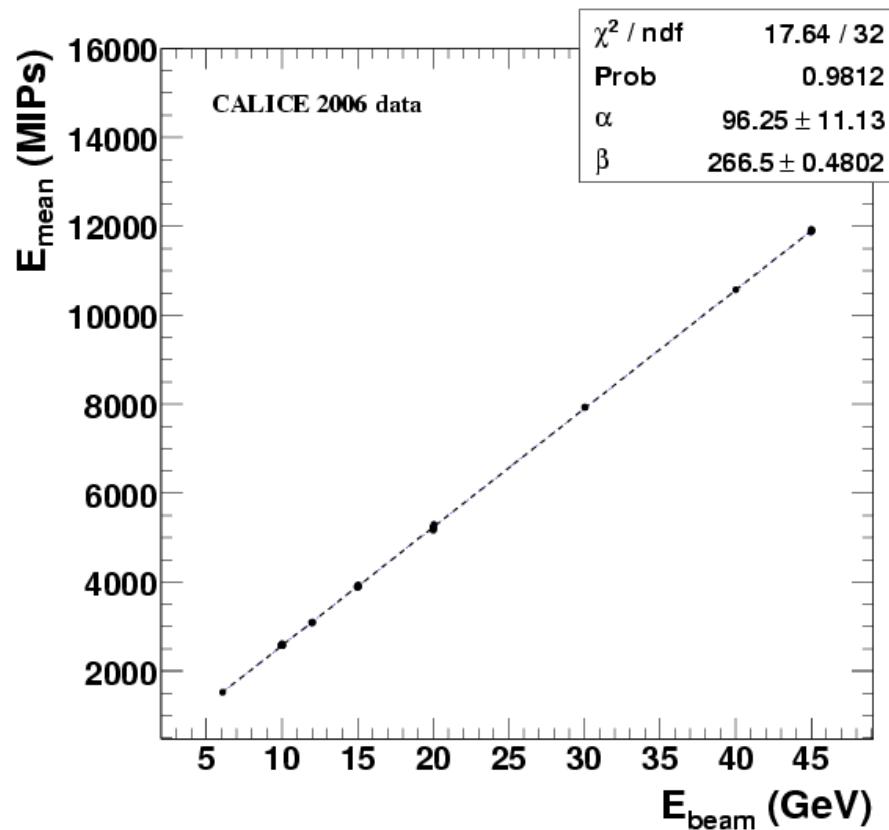
Front-end boards located outside of module
 Digitization with VME – based system (off detector)

Tests at DESY/CERN/FNAL

Electrons 1 – 45 GeV
 Pions 1 – 180 GeV



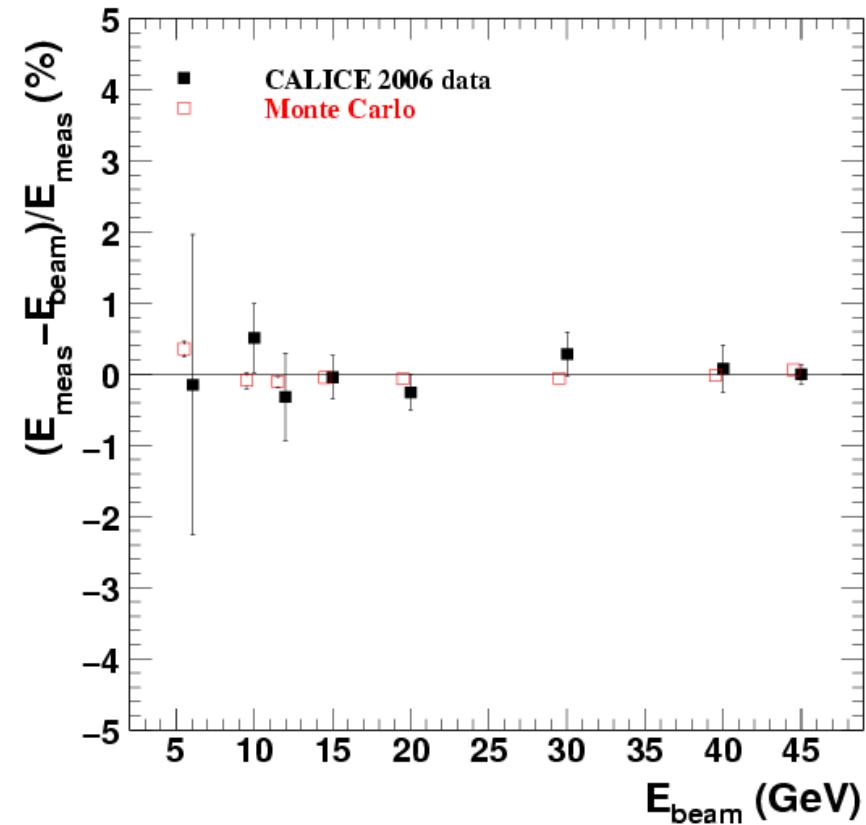
Linearity of the response to electrons



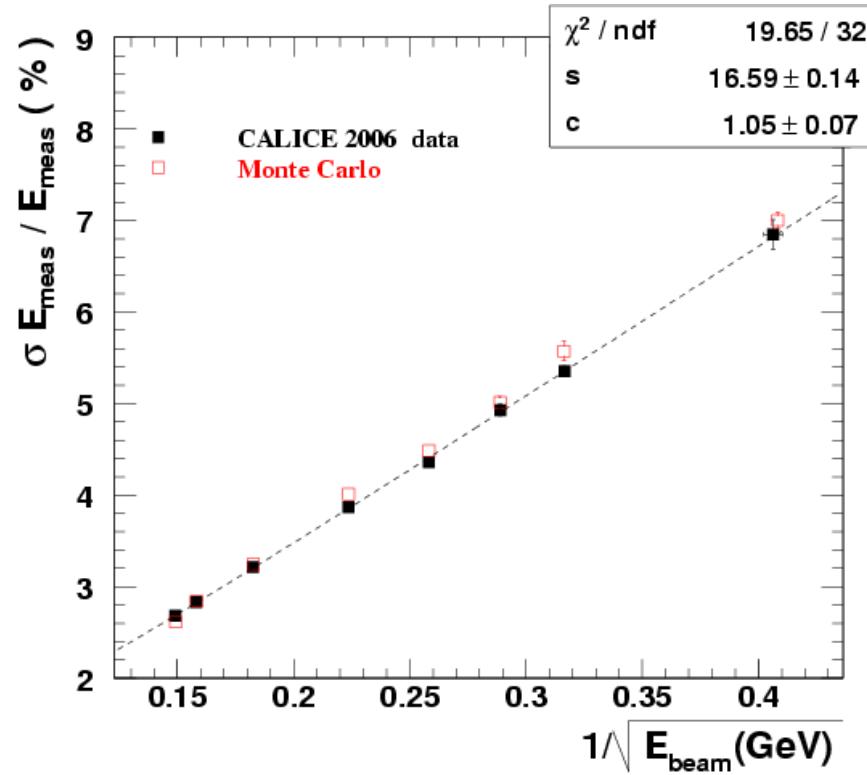
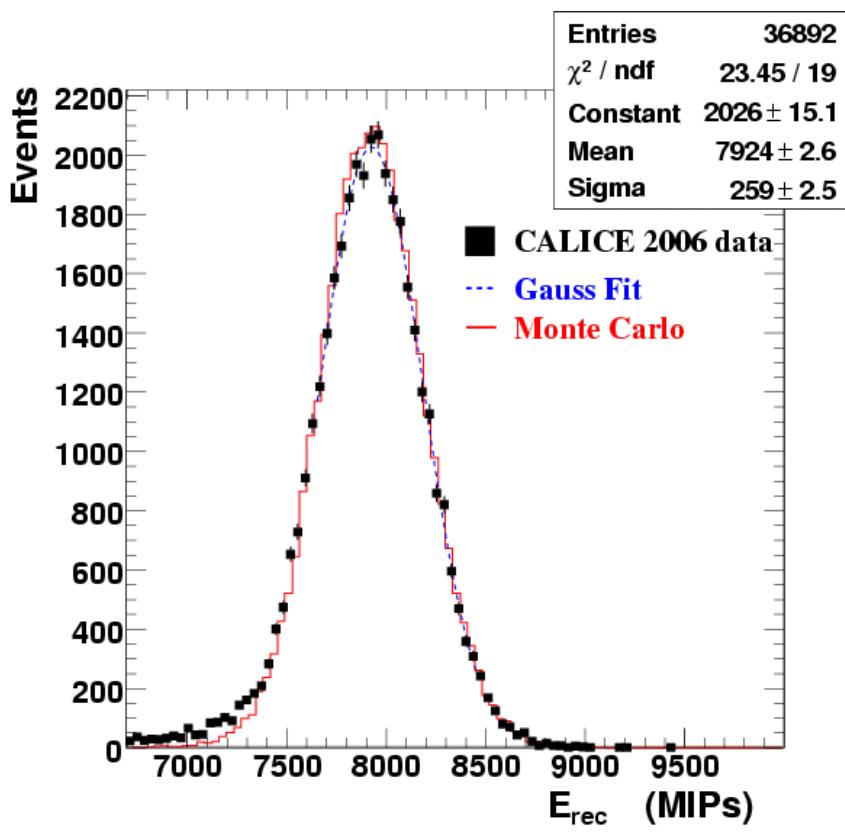
Excellent agreement with simulation

Linear response between 6 and 45 GeV

Residuals $< \pm 1\%$



Resolution for electrons



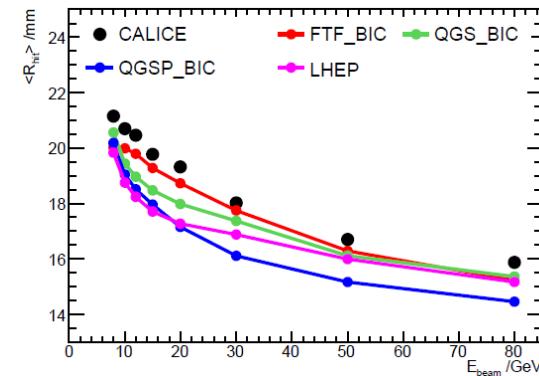
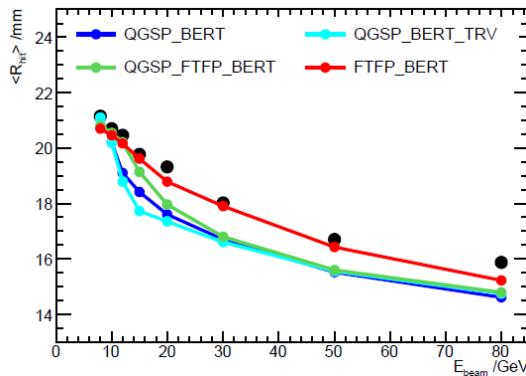
Good agreement with simulation
Energy resolution as expected
(and sufficient for PFA)

$$\frac{\sigma_E}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E(\text{GeV})}} \oplus (1.1 \pm 0.1) \right) \%$$

The power of imaging calorimeters I: Pions in the ECAL

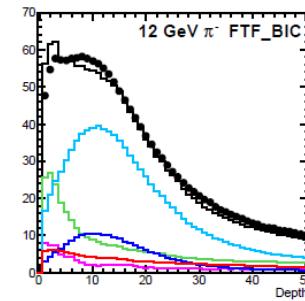
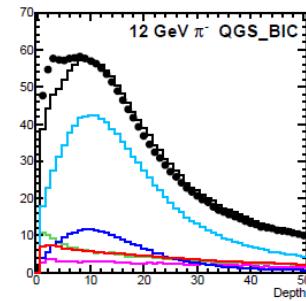
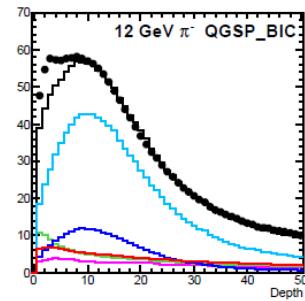
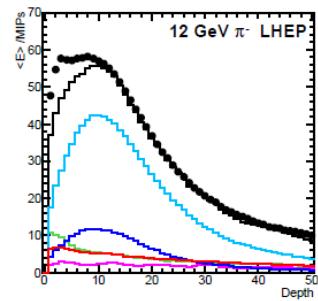
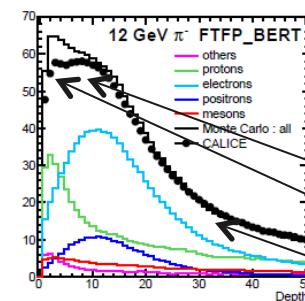
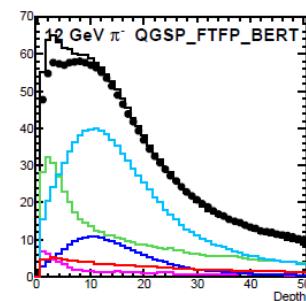
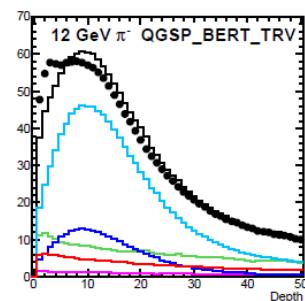
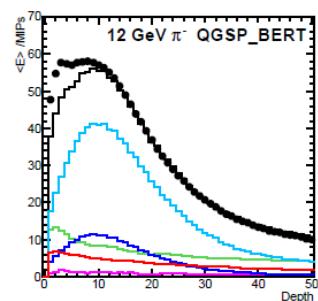
Radial shower shape

Weighted shower radii versus E_π
Comparison with various GEANT4 models



Longitudinal shower shape

For $E_\pi = 12 \text{ GeV}$ (taken from first hadronic interaction)
Comparison with various GEANT4 models
Decomposition into contributions from different particle species



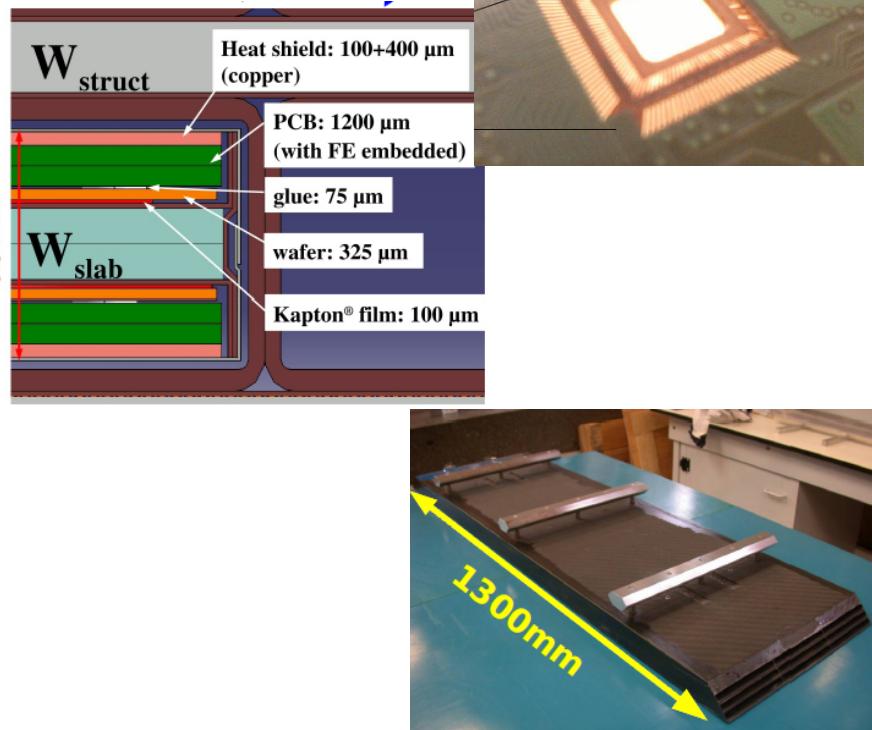
Separate contributions from

- photons
- nuclear fragments
- energetic hadrons

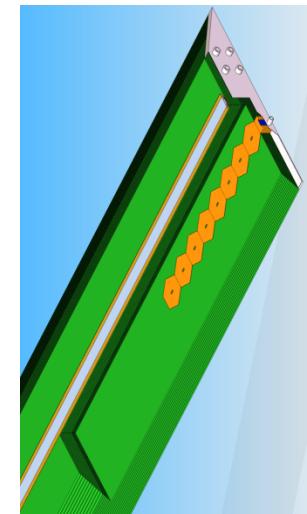
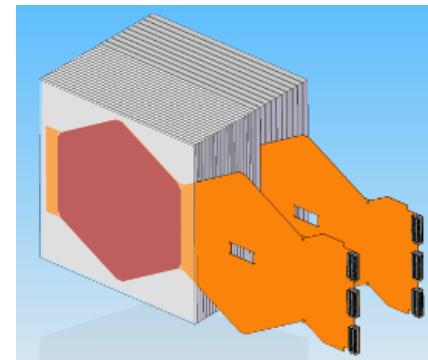
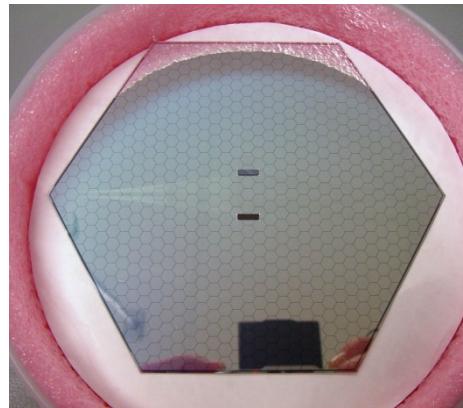


2010 JINST 5 P05007

Silicon – Tungsten ECAL: Technical Prototypes



- Based on experience with physics prototype
- Reduced cell size ($\sim 0.25\text{cm}^2$)
- Embedded front-end electronics
- Address ‘all’ technical issues
- Total active medium thickness 3 – 4 mm
- Test beam module being assembled



- Target at very compact readout and small cell ($\sim 0.13\text{cm}^2$)
- Address many technical issues from the beginning
- Push technical limits in many aspects
- Uses KPiX chip with 1024 channels for front-end readout
- Total active medium thickness targets at $\sim 1\text{mm}$
- Test beam module expected soon

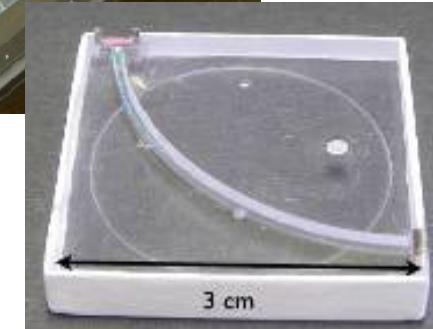
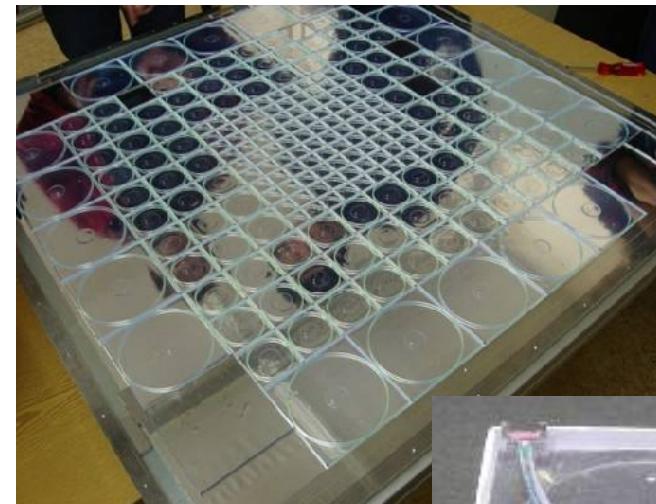
Scintillator – Steel HCAL (analog)



First calorimeter to use SiPMs

Physics prototype

38 steel plates with a thickness of $1.1 X_0$ each
Scintillator pads of $3 \times 3 \rightarrow 12 \times 12 \text{ cm}^2$
 $\rightarrow \sim 8,000$ readout channels



Electronic readout

Silicon Photomultipliers (SiPMs)
Digitization with VME-based system (off detector)

Tests at DESY/CERN/FNAL in 2006 - 2009

Electrons 1 – 45 GeV
Pions 6 – 50 GeV

The power of imaging calorimeters II: Linearity and resolution

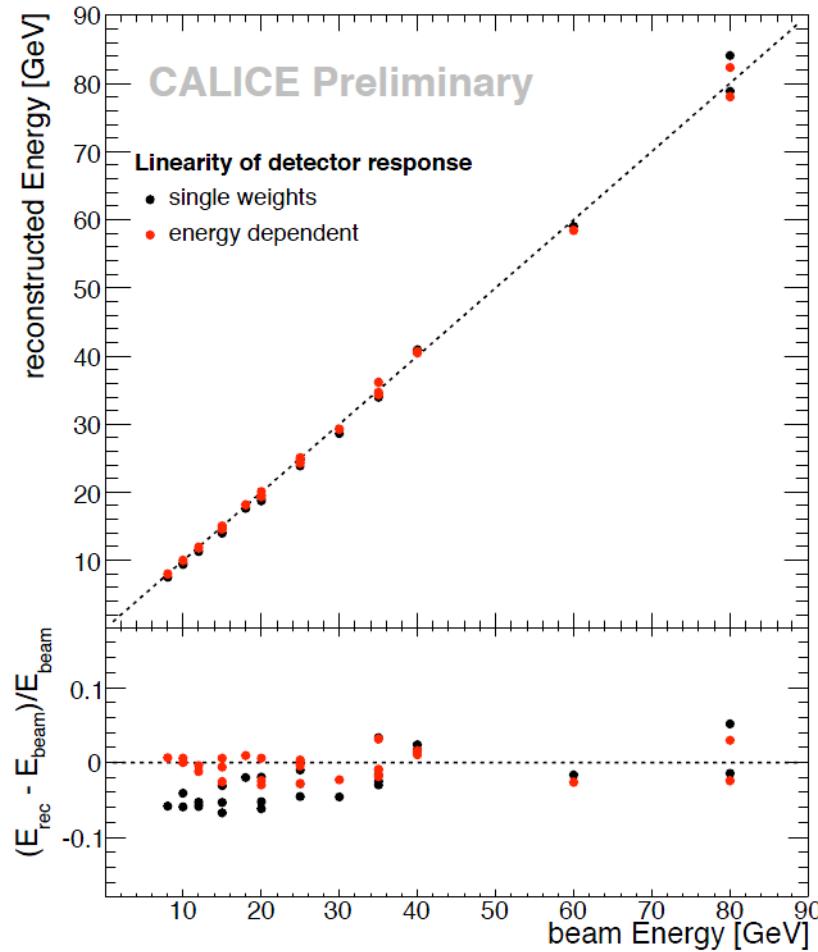
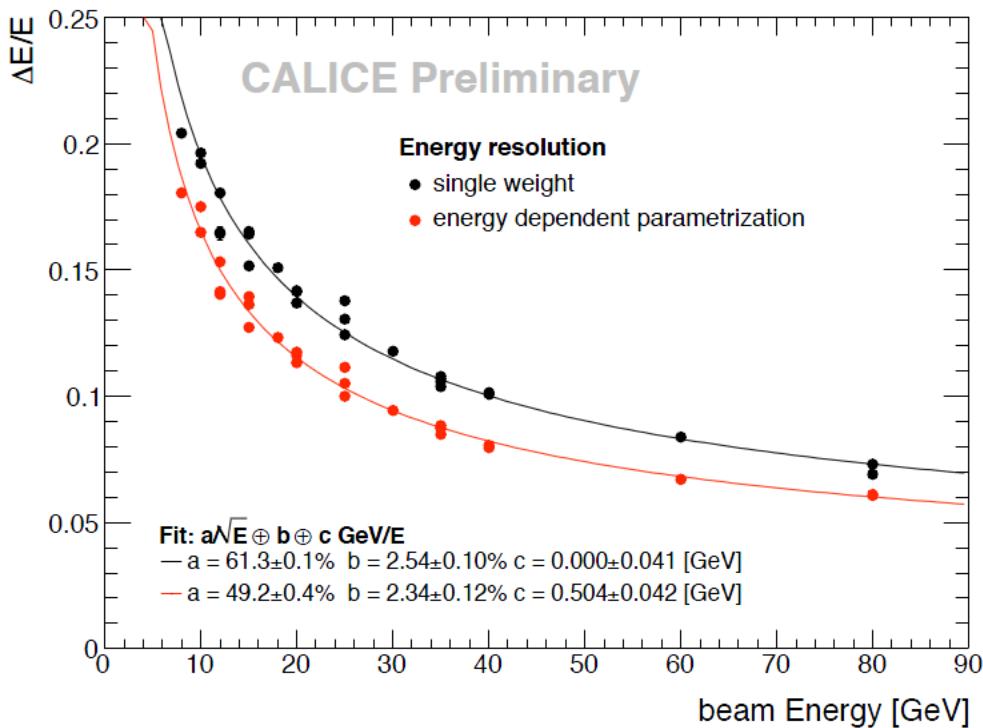
Pions between 8 and 80 GeV/c



Software compensation

Based on energy density weights

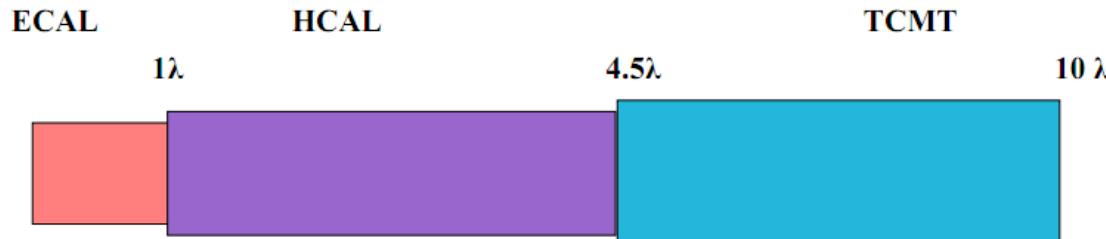
Improves both linearity and resolution



Software compensation works

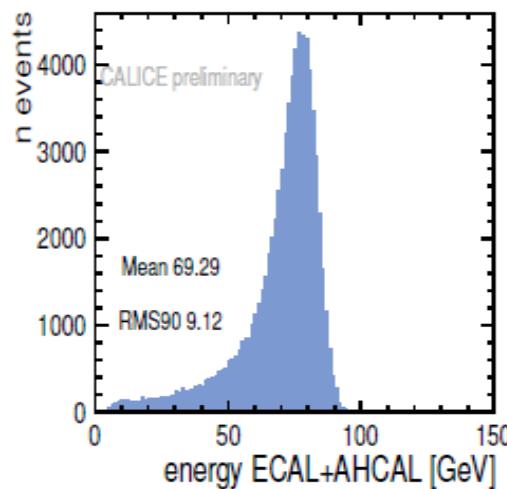
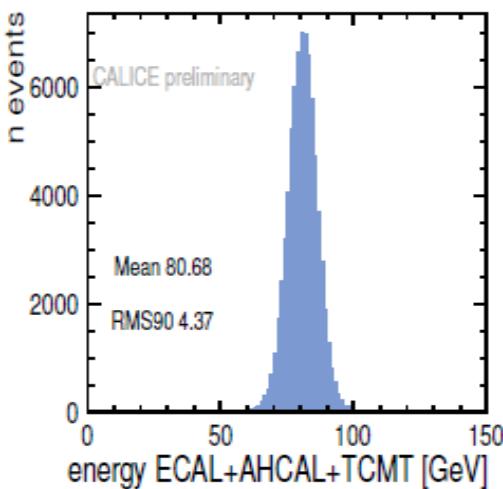


The power of imaging calorimeters III: Leakage correction

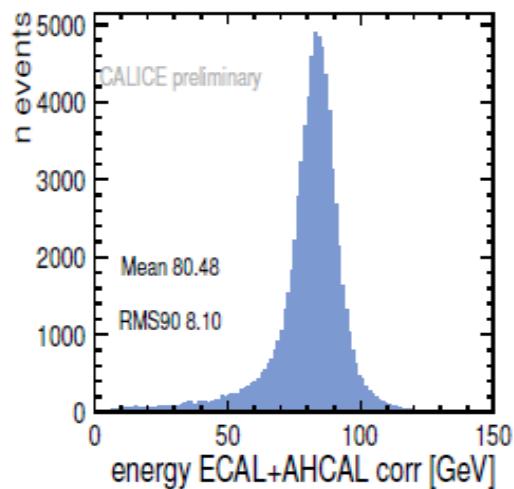


Select showers (80 GeV π) starting in first part of AHCAL
Apply corrections depending on

Interaction layer (shower start)
Fraction of energy in last 4 layers



Correction
Restores mean value
Reduces RMS by $\sim 24\%$
(but still worse than direct measurement)



**AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT**



Digital Hadron Calorimeter

High density of cells

Layer – by – layer
 $1 \times 1 \text{ cm}^2$ laterally

Single bit readout/cell → digital readout

Reconstruct energy as

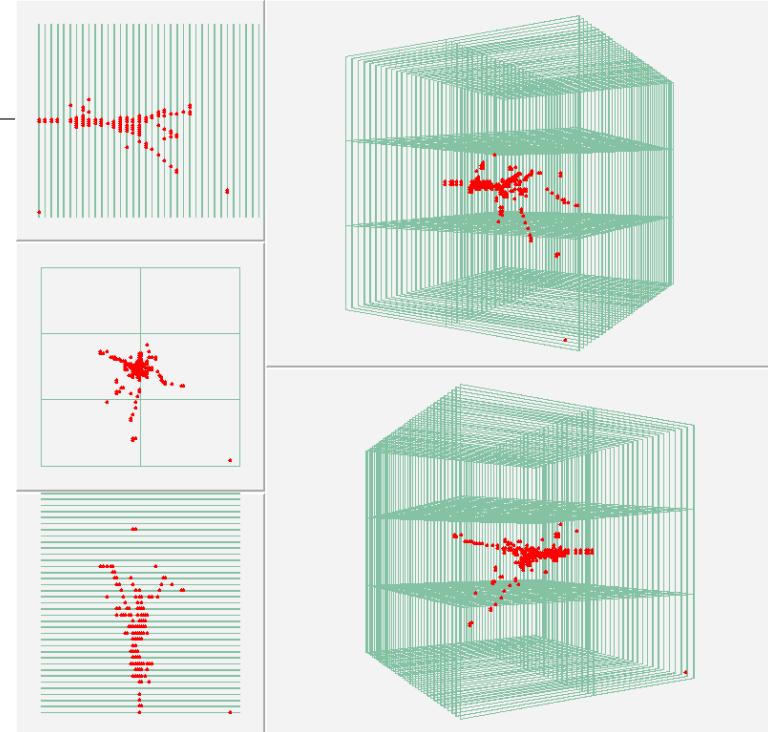
$$E_{rec} = \alpha_1 N_{hit} + (\alpha_2 N_{hit}^2 + \dots)$$

Active media

Resistive Plate Chambers (RPCs)
Gas Electron Multipliers
Micromegas



DHCAL prototype

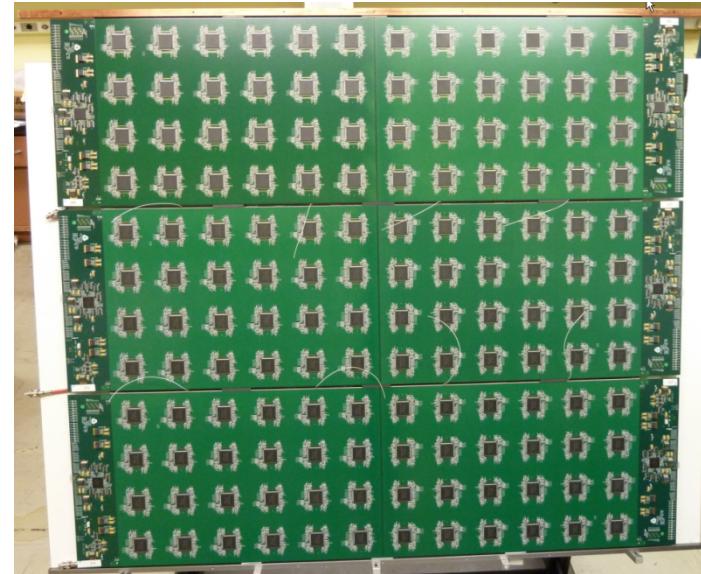


The DHCAL + TCMT

Calorimeter



38 steel plates with a thickness of $1.1 X_0$ each
8 steel plates with $1.2 X_0$ + 6 steel plates with $5.0 X_0$
Each plate $1 \times 1 \text{ m}^2$
RPCs ($32 \times 96 \text{ cm}^2$) as active medium



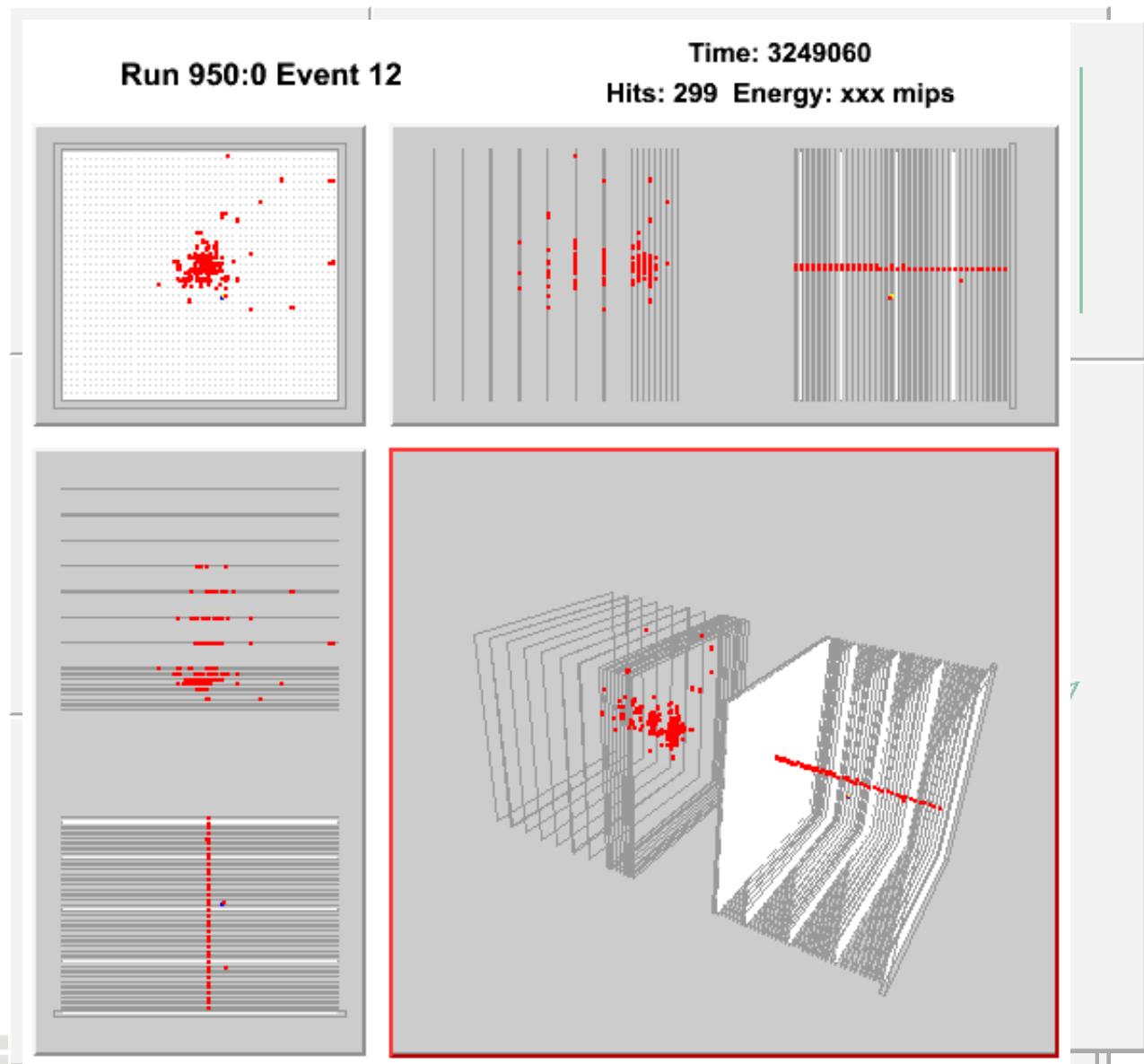
Electronic readout

Embedded on the detector plane
Based on the DCAL III chip (64-channels)
Common threshold to all channels on a chip
497,000 readout channels

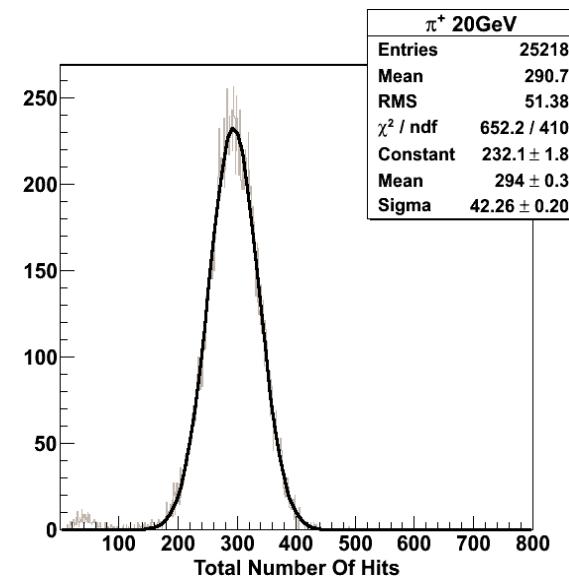
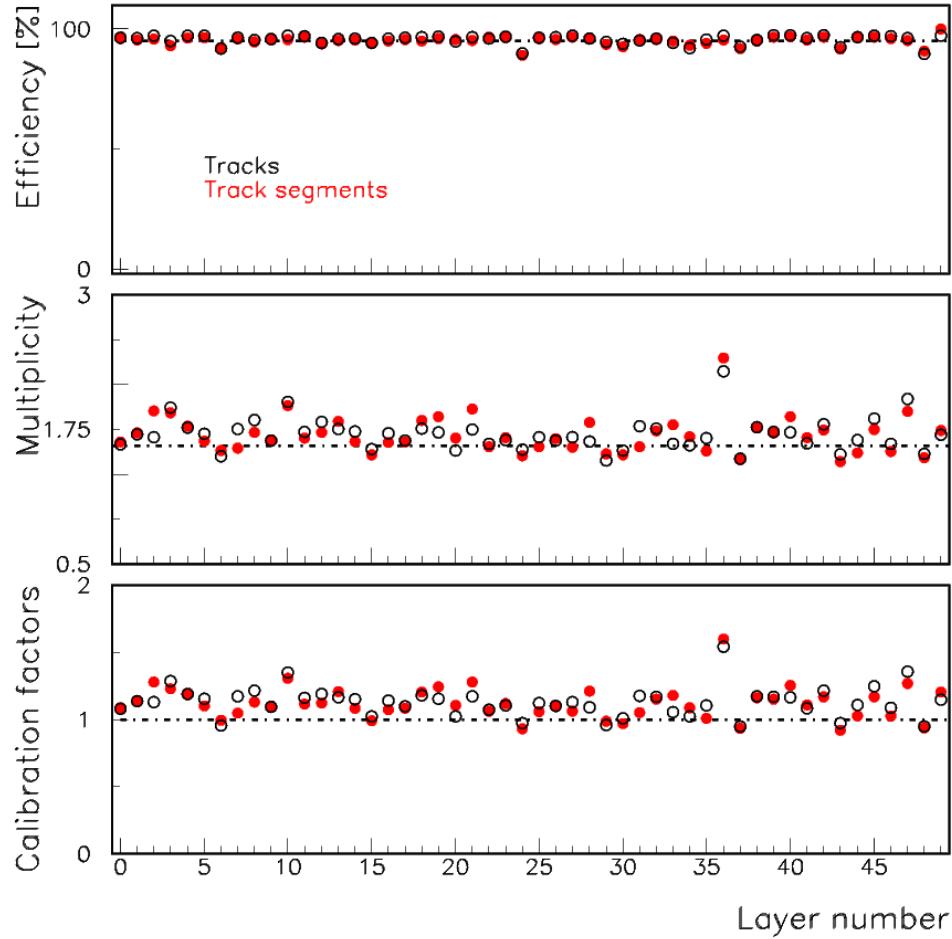
Tests at FNAL in 2010 – 2011 (Fe absorber)

Tests at CERN now (W absorber)

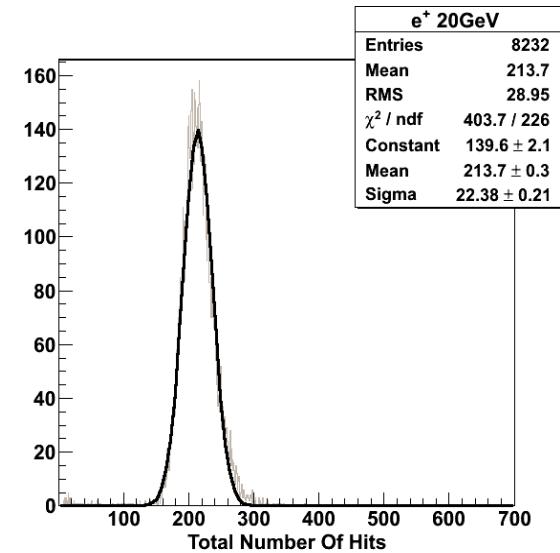
A few events...



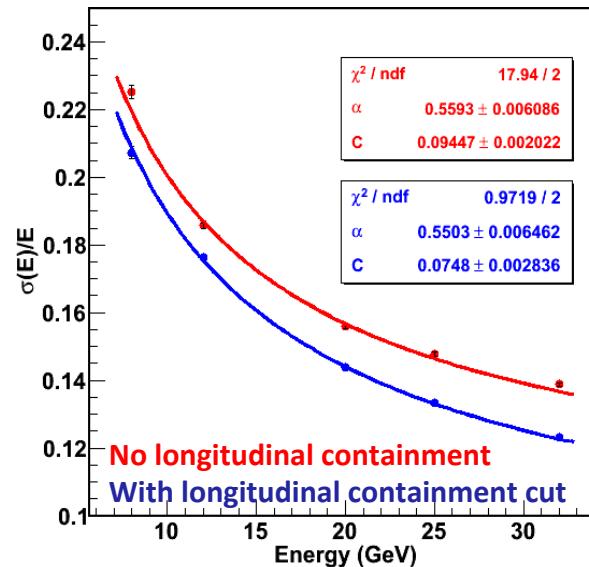
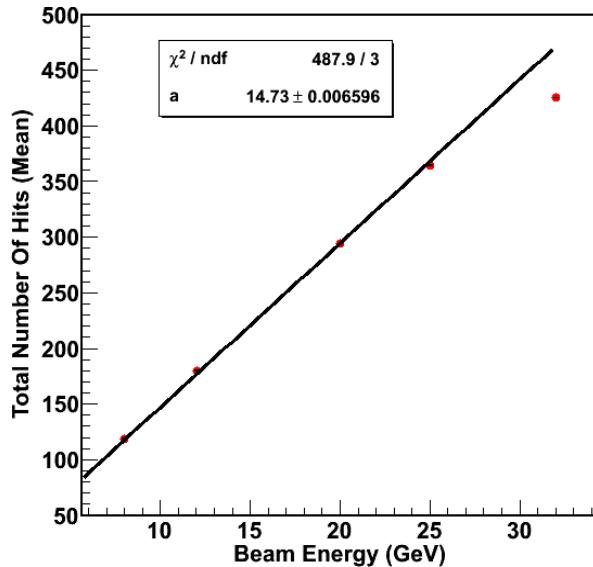
Some very first results



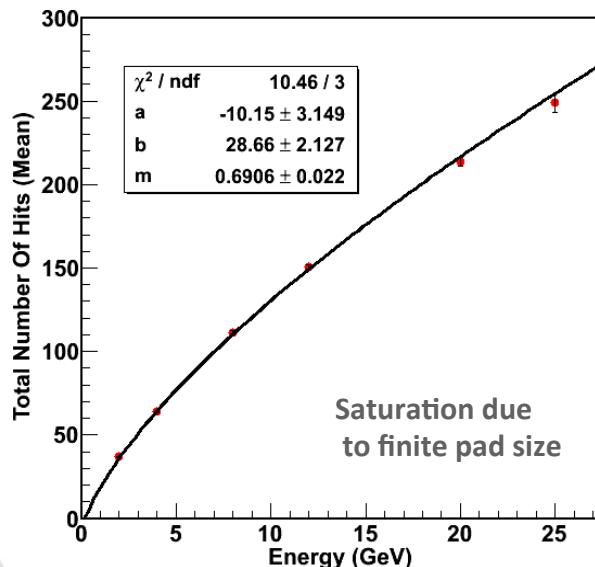
Single
particle
response



Pion response (not calibrated)



Positron response (not calibrated)

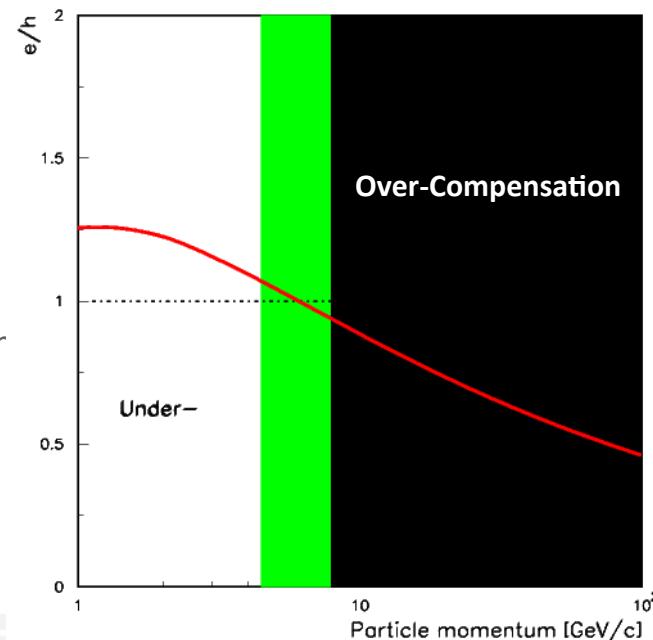


Software compensation
is expected to extend
the region of compensation



GEANT4 + RPC simulation
predicted $\sim 58\%/\sqrt{E}$

DHCAL Response with Fe Absorber



Semi-Digital Hadron Calorimeter

European based effort

Similar to the DHCAL

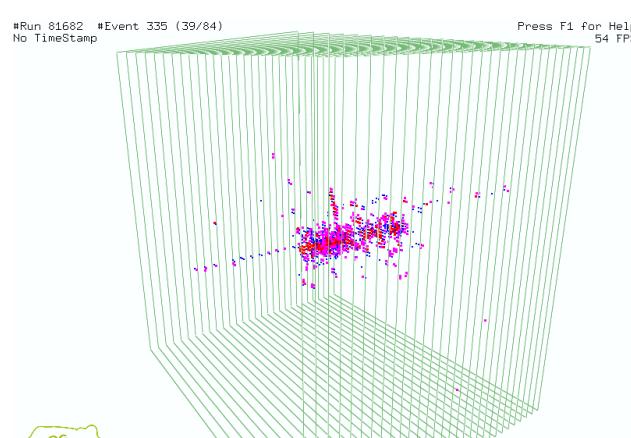
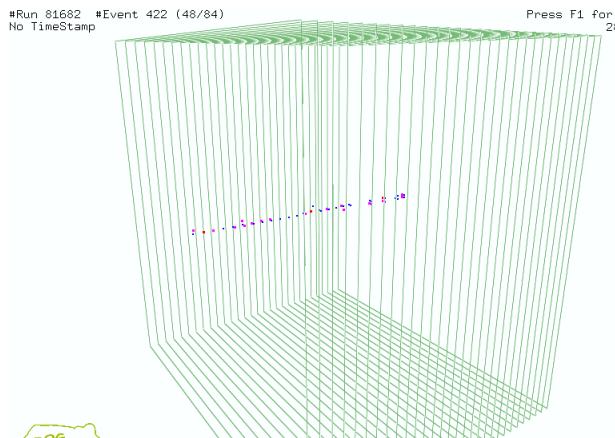
RPCs as active medium
Embedded front-end electronics
Based on HARDROC chip (64 channels)



Extra features

3 thresholds per channel (2-bits)
Power pulsing possible

Prototype assembled in 2011 and saw 1st beam



DHCAL with Minimal Absorber

Stack

50 layers

Cassette contain 2 mm Cu and 2 mm Fe

$0.27 X_0/\text{layer} \rightarrow 13.4 X_0 \text{ total}$

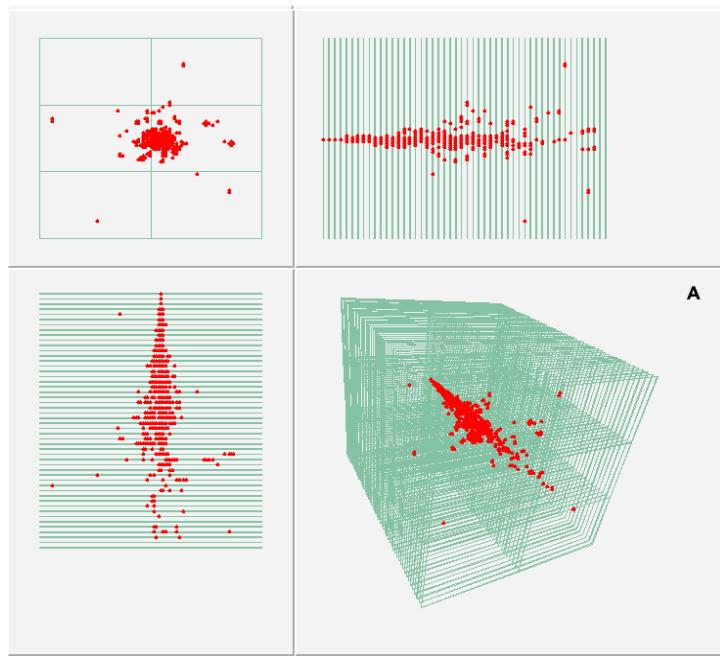
$0.038 \lambda_l/\text{layer} \rightarrow 1.9 \lambda_l \text{ total}$

Beam

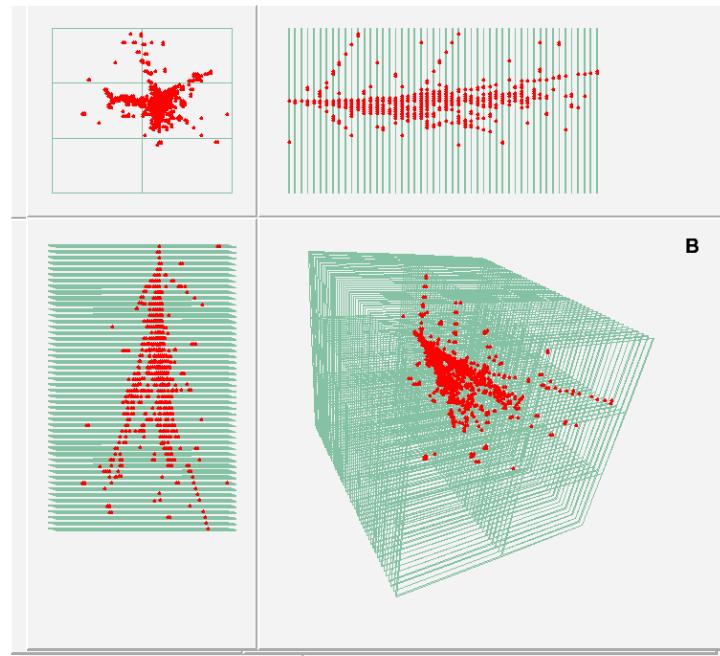
1,2,3,4,6,8,10 GeV/c secondaries



8 GeV e⁺



16 GeV/c π⁺



Summary

Particle Flow Algorithms

Powerful tool to improve the measurements of jets

→ Being implemented in LHC jet measurements

Shown to meet physics requirements at a future Lepton Collider

Development of detector concepts optimized for the application of PFAs

← never done before

Imaging calorimeters

Needed for PFAs

Offer many additional advantages (software compensation, leakage correction, angles...)

Strong R&D program mostly driven by the CALICE collaboration

Prototypes

Results from Si-W ECAL, Scintillator HCAL, DHCAL

→ Constraints on GEANT4 hadronic shower models

