Development of Particle Flow Calorimetry

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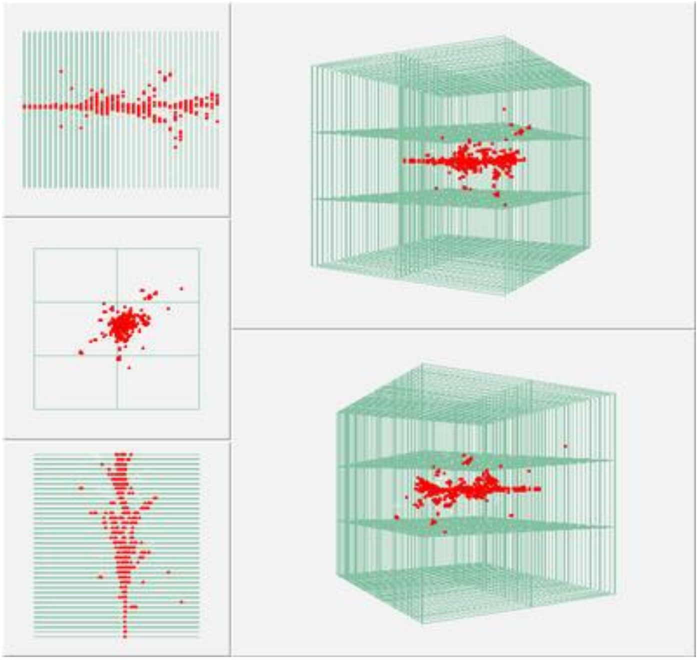


DPF meeting, Providence, RI
August 8 – 13, 2011

Jet Energy Resolution at a future Lepton Collider

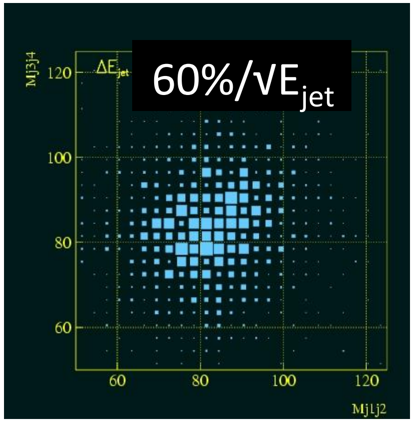
Benchmark Physics Reactions

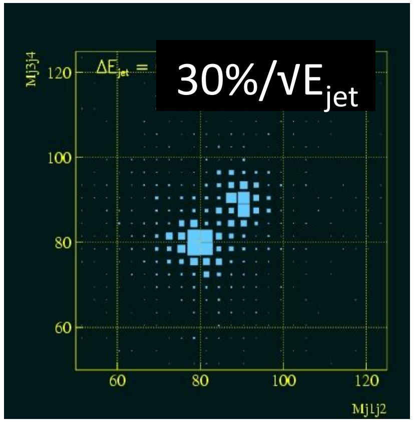
Process	Vertex	Tracking		Calorimetry		Fwd		Very Fwd	Integration					Pol.
	σ_{IP}	$\delta p/p^2$	ϵ	δE	$\delta\theta$, $\delta\phi$	Trk	Cal	θ^e_{min}	δE_{jet}	M_{jj}	ℓ-Id	V^0-Id	$Q_{jet/vtx}$	
$ee \to Zh \to \ell\ell X$		×									×			
$ee \to Zh \to jjbb$	×	×	×			×				×	×			
$ee \to Zh, h \to bb/cc/\tau\tau$	×		×							×	×			
$ee \to Zh, h \to WW$	×		×		×				×	×	×			
$ee \to Zh,\ h \to \mu\mu$	×	×									×			
$ee \to Zh,\ h \to \gamma\gamma$				×	×		×							
$ee \to Zh, h \to invisible$			×			×	×							
$ee \to \nu\nu h$	×	×	×	×			×			×	×			
$ee \to tth$	×	×	×	×	×		×	×	×		×			
$ee \to Zhh,\ \nu\nu hh$	×	×	×	×	×	×	×		×	×	×	×	×	×
$ee \to WW$										×			×	
$ee \to \nu\nu WW/ZZ$						×	×		×	×	×			
$ee \to \tilde{e}_R\tilde{e}_R$ (Point 1)		×						×			×			×
$ee \to \tilde{\tau}_1\tilde{\tau}_1$	×	×						×						
$ee \to \tilde{t}_1\tilde{t}_1$	×	×							×	×		×		
$ee \to \tilde{\tau}_1\tilde{\tau}_1$ (Point 3)	×	×			×	×	×	×	×					
$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$ (Point 5)									×	×				
$ee \to HA \to bbbb$	×	×								×	×			
$ee \to \tilde{\tau}_1\tilde{\tau}_1$			×											
$\chi^0_1 \to \gamma + \not{E}$					×									
$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$			×					×						
$ee \to tt \to 6\ jets$	×		×						×	×	×			
$ee \to ff\ [e, \mu, \tau; b, c]$	×		×				×		×		×		×	×
$ee \to \gamma G$ (ADD)				×	×			×						×
$ee \to KK \to f\bar{f}$		×									×			
$ee \to ee_{fwd}$						×	×	×						
$ee \to Z\gamma$		×		×	×	×	×							

Physics BSM

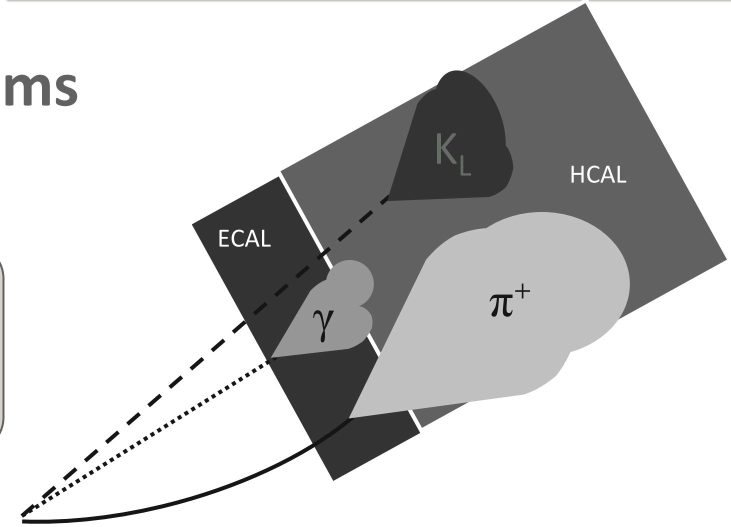
Many signatures involve Z's and W's

Separate $e^+e^- \to W^+W^-\upsilon\upsilon$ and $Z^0Z^0\upsilon\upsilon$ (in hadronic decay mode)





New approach: Particle Flow Algorithms



The idea...

Charged particles } measured with the { **Tracker**

Neutral particles } measured with the { **Calorimeter**

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

(Charged + Photons + Neutral Hadrons) } 18%/√E

Requirements for detector

→ Need excellent tracker and high B – field

→ Large R_l of calorimeter

→ Calorimeter inside coil

→ Calorimeter with **extremely fine segmentation**

→ Calorimeter as dense as possible (short X_0, λ_I)

Imaging Calorimeters I

Dense, compact calorimeters with extremely fine segmentation

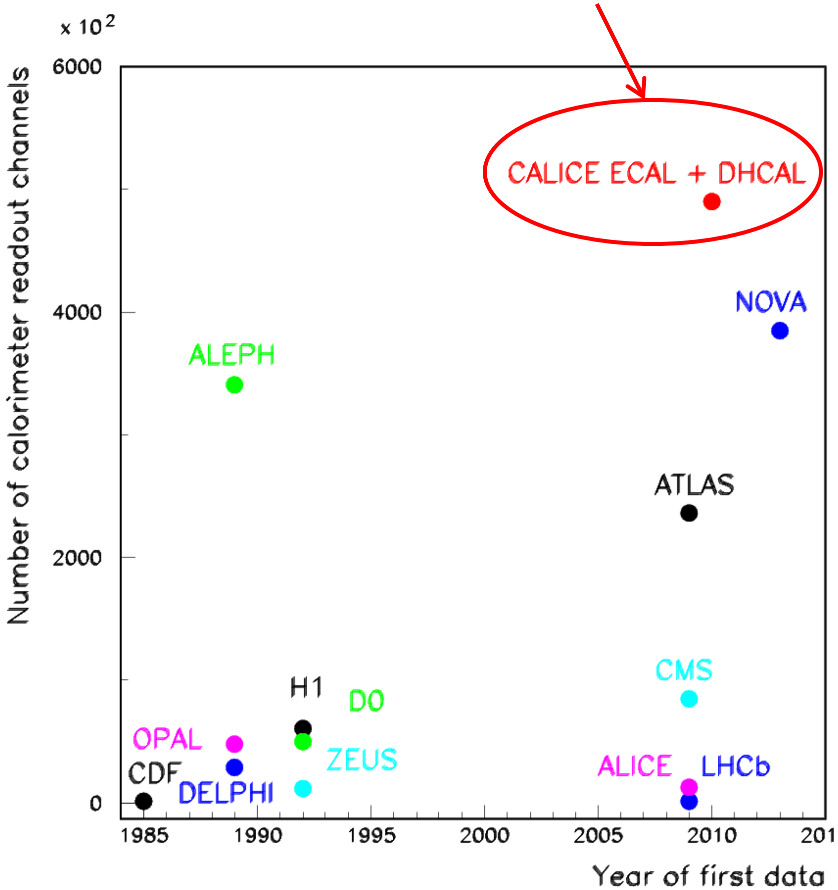
Cell readout size

Layer-by-layer

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 x100 more



Imaging Calorimeters II

Offer additional advantages

Reconstruct **every shower** in an event individually

Reconstruct **direction of showers**
→ important for some exotic physics signals

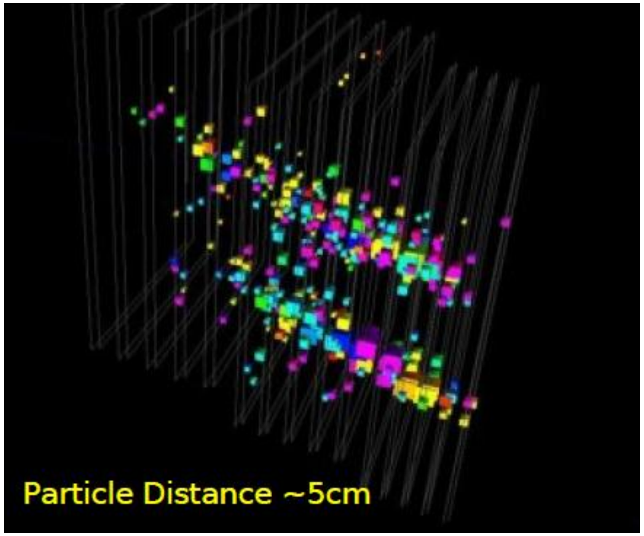
Apply separate calibration factors to the em and hadronic shower components
→ **Software compensation**

Correct for leakage using last layers/shower start

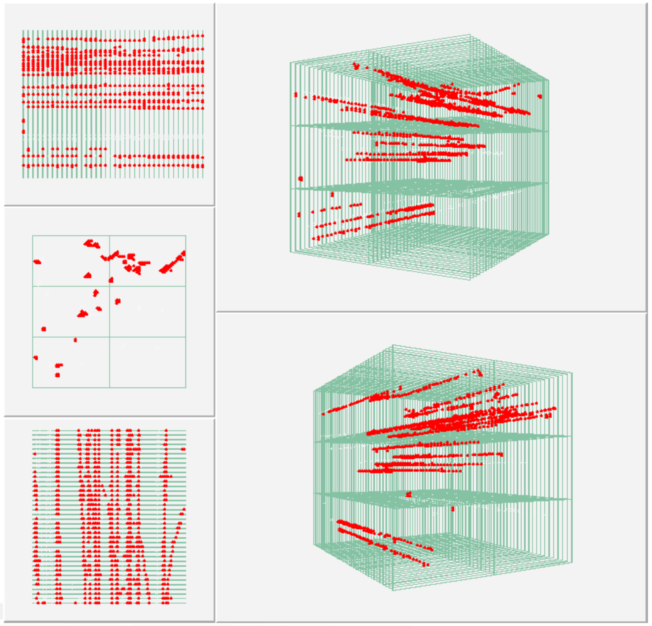
Reconstruct **momentum of charged particles** within showers (not exploited yet)

Identify **noise hits** (and eliminate)

2 electrons in the Silicon-W ECAL

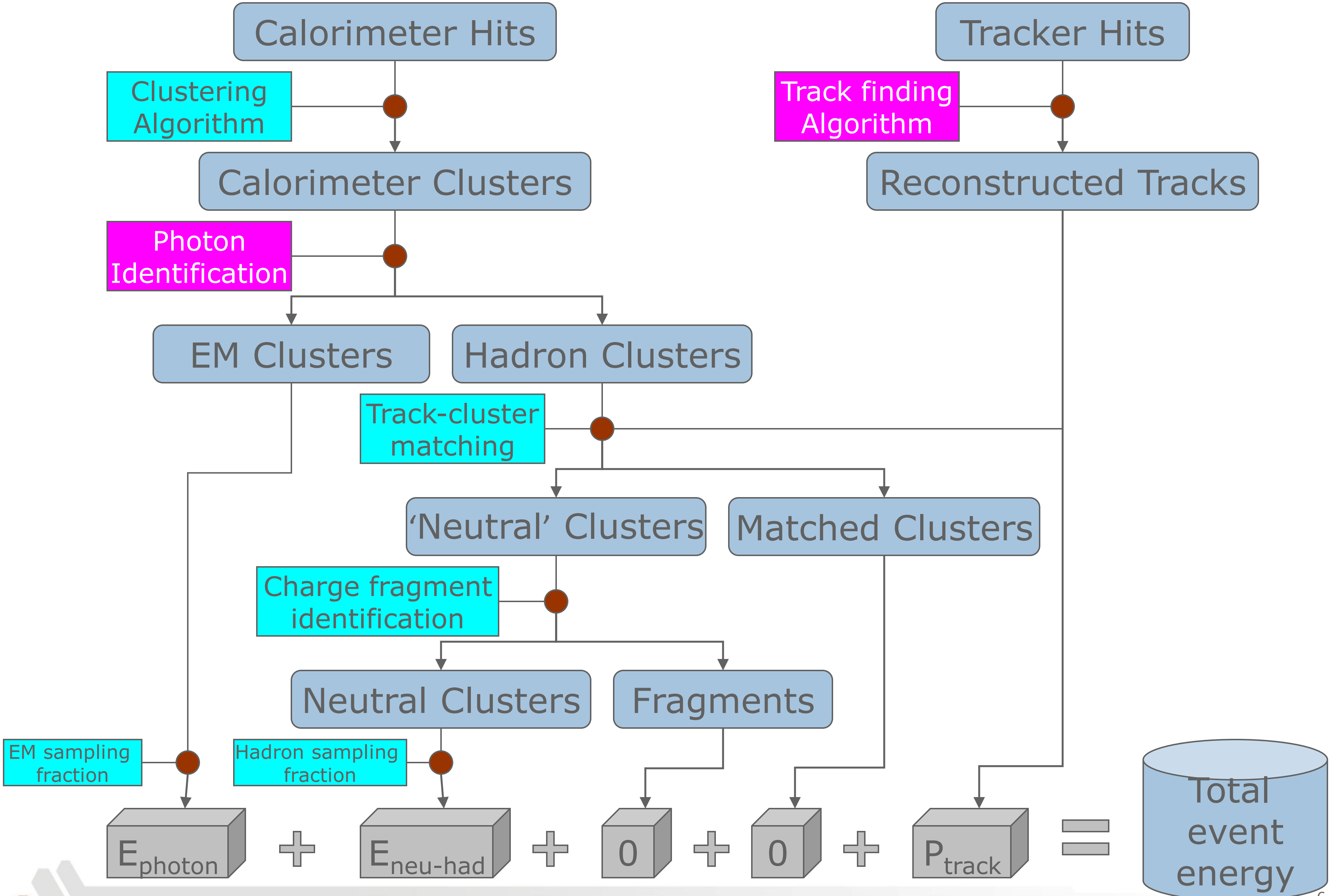


~ 15 muons in the RPC HCAL



How PFAs work

Example taken from L Xia



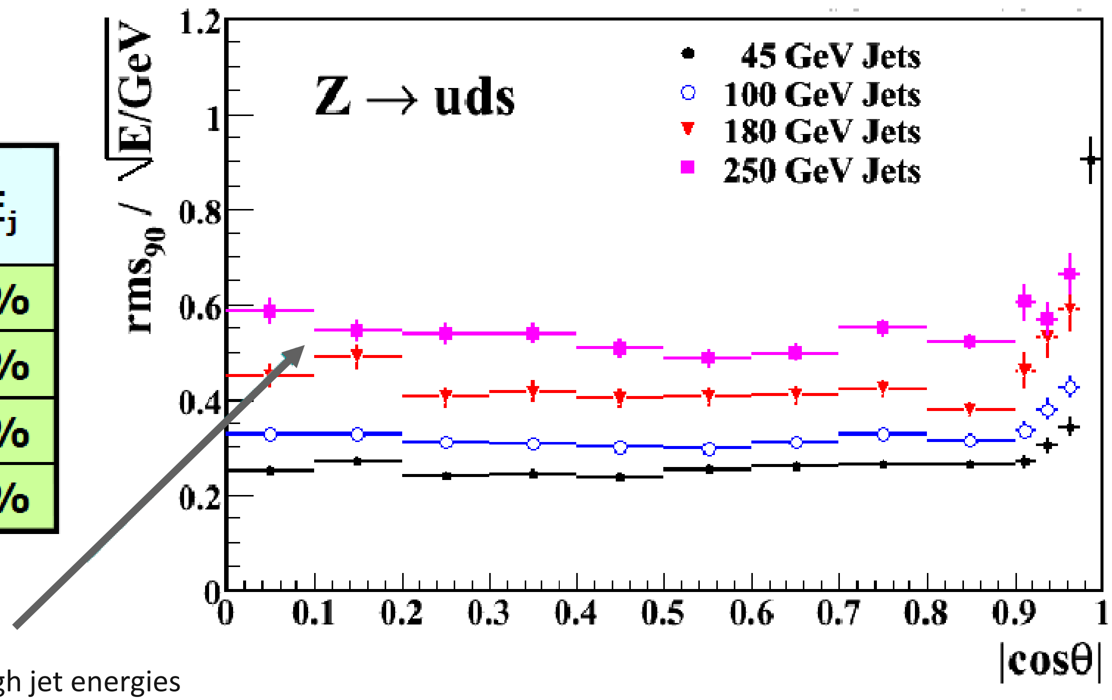
Example: Pandora PFA

Developed by

Mark Thomson (University of Cambridge)
Based on GEANT4

Current performance

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	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 %



Leakage at high jet energies

ILC/CLIC performance goals achieved

Open – ended development

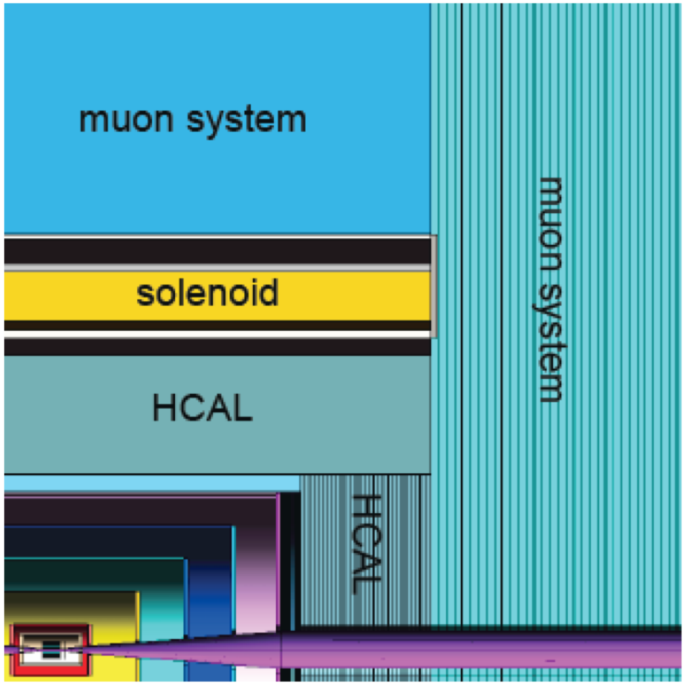
Resolution still mostly dominated by confusion
Second order corrections (e.g. leakage, SW compensation) not yet implemented

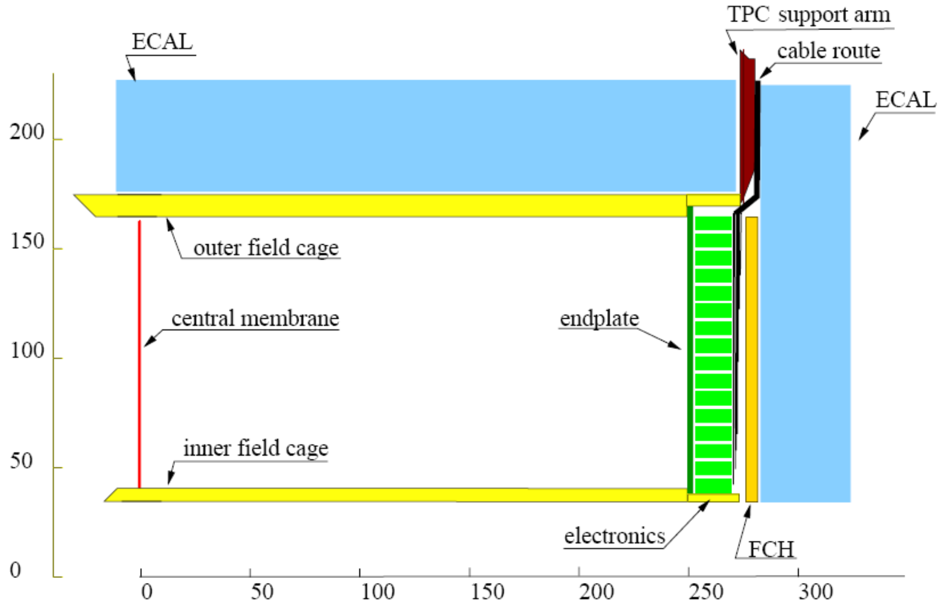
The PFA Detector Concepts: ILD and SiD

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

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





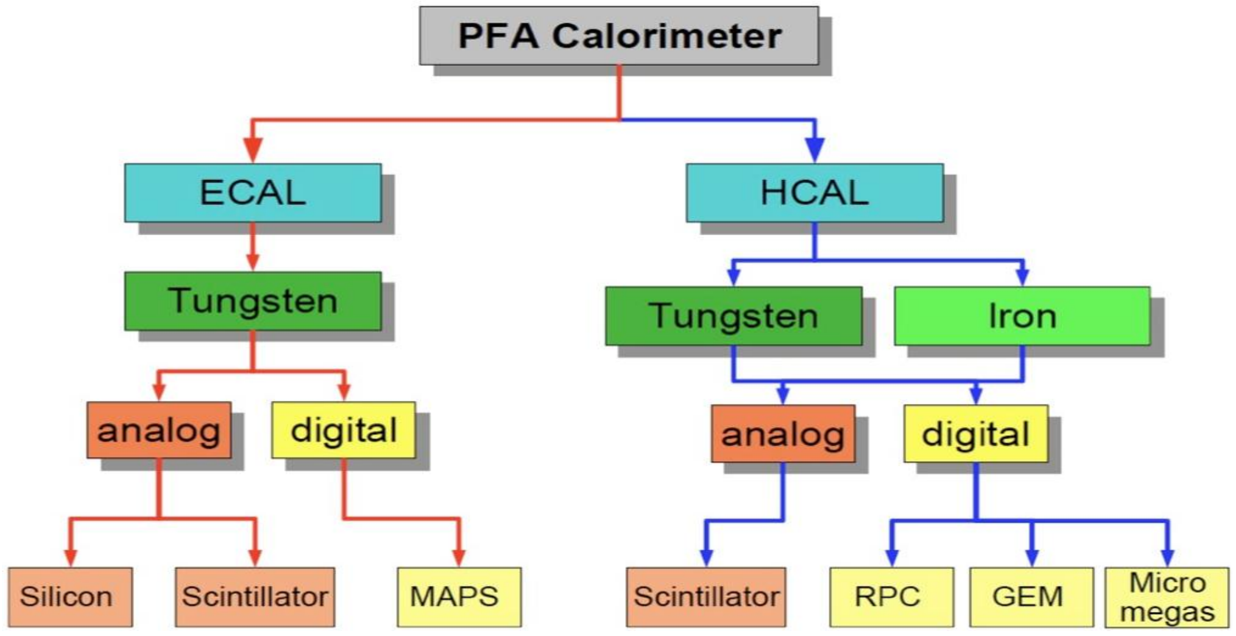
Major difference between SiD and ILD

- SiD – Pure Silicon tracker
- ILD – Time Projection Chamber + Silicon layers

Calorimeter Developments

Stages

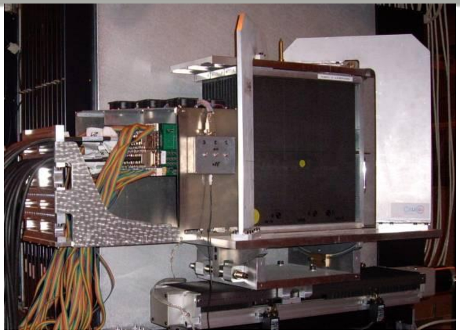
Physics prototype – Proof technological approach, measure hadronic showers
Technological prototype – Address all technical issues, not necessarily with a full module
Module 0 – Implements all aspects of a module for a colliding beam detector

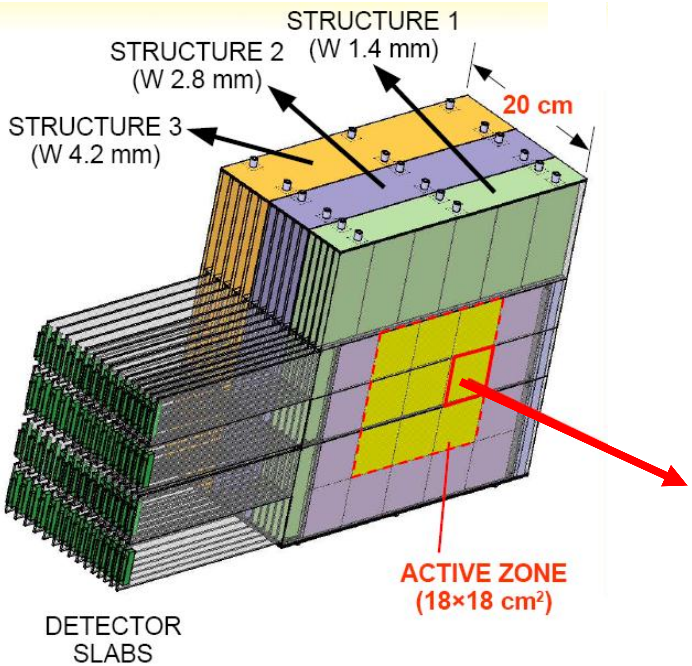


Analog = multi-bit
Digital = single-bit

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

Silicon – Tungsten ECAL





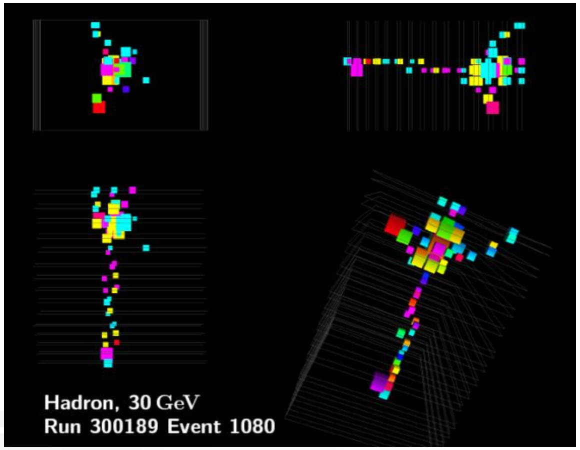
X_0^W = 3.5 mm

Physics prototype

3 structures with different W thicknesses
30 layers; 1 x 1 cm^2 pads
18 x 18 cm^2 instrumented
→ 9720 readout channels

Tests at DESY/CERN/FNAL

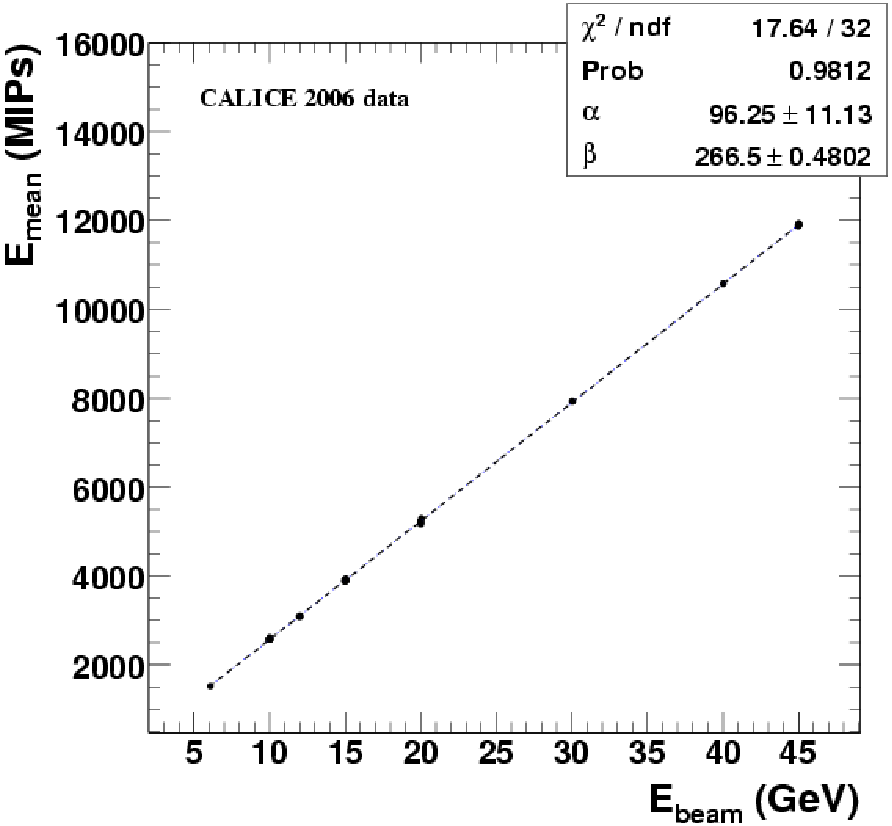
Electrons 1 – 45 GeV
Pions 1 – 180 GeV



Electronic Readout

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

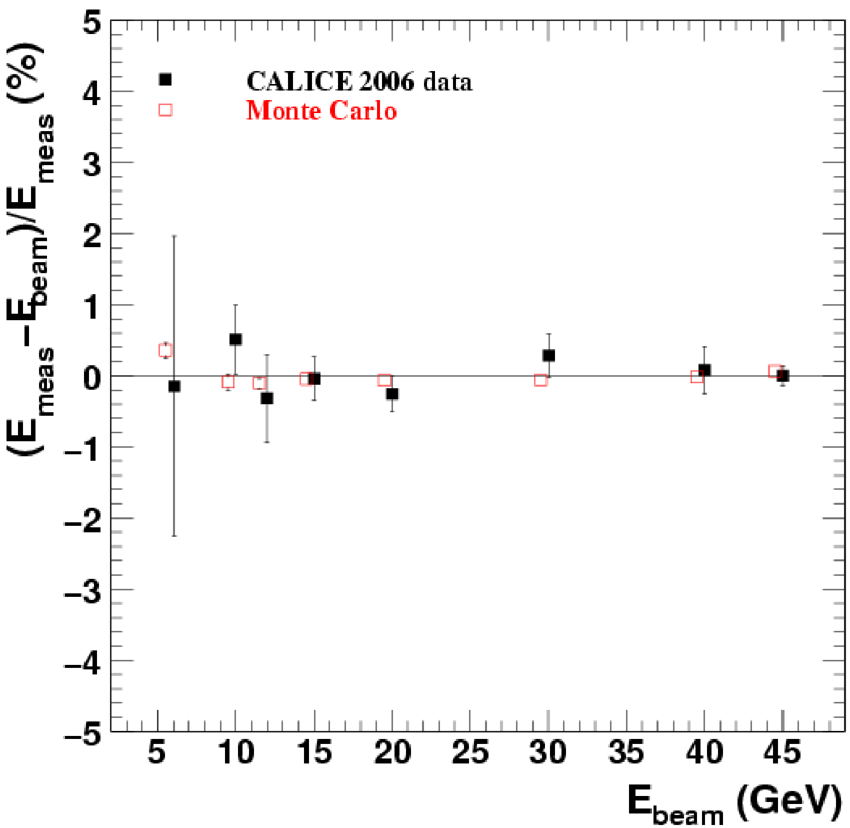
Linearity of the response to electrons



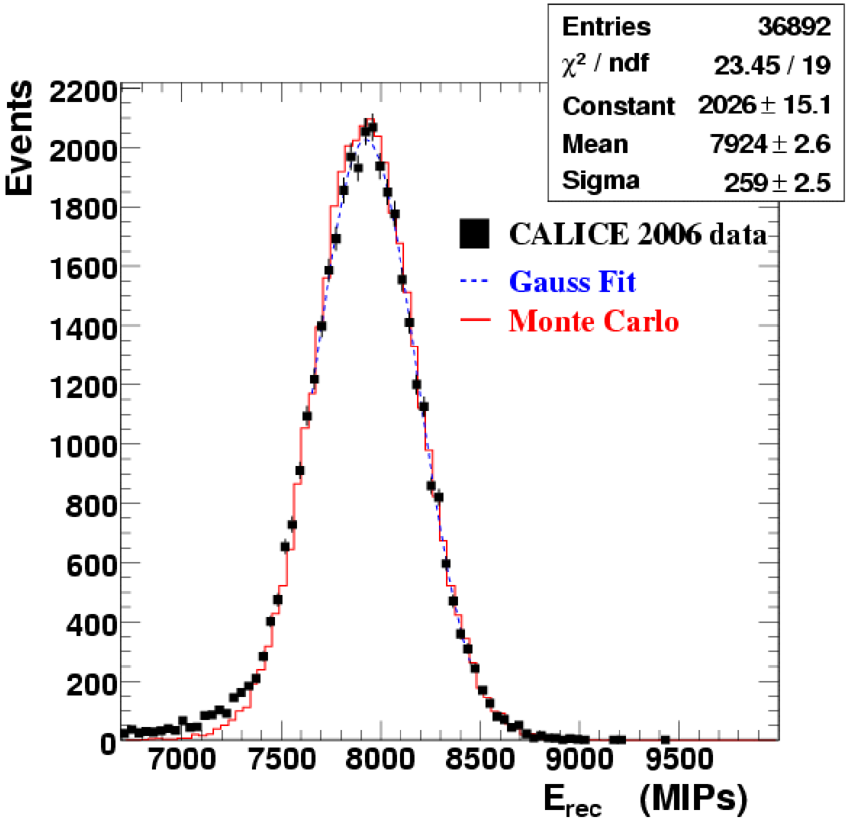
Linear response between 6 and 45 GeV

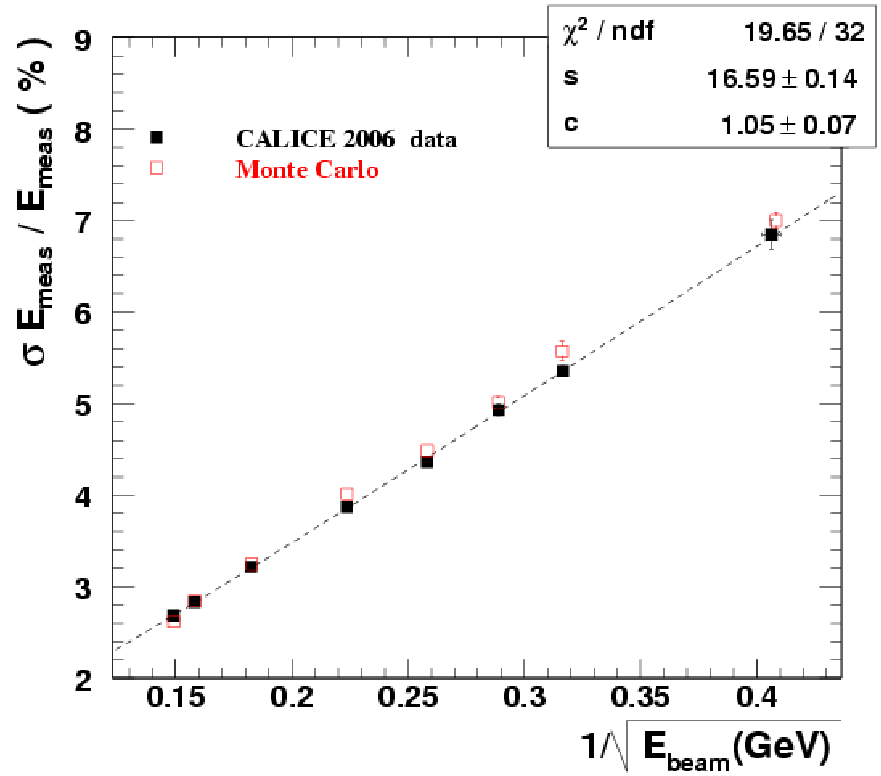
Residuals < ± 1%

Excellent agreement with simulation



Resolution for electrons





Good agreement with simulation

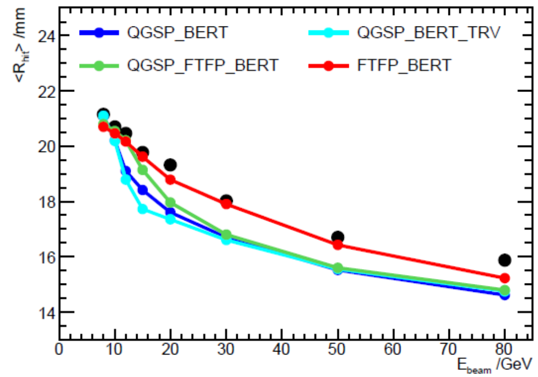
Energy resolution as expected
(and sufficient for PFA)

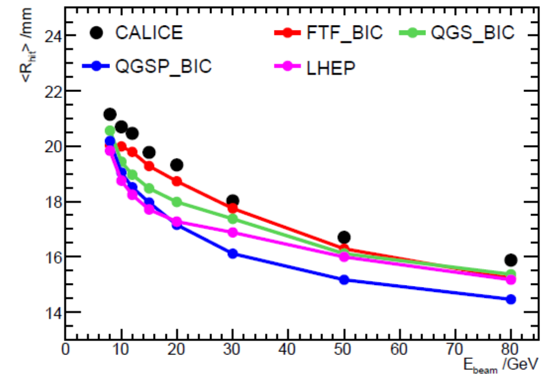
$$\frac{\sigma_E}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E(GeV)}} \oplus (1.1 \pm 0.1) \right) \%$$

The power of imaging calorimeters I: Pions in the ECAL

Radial shower shape

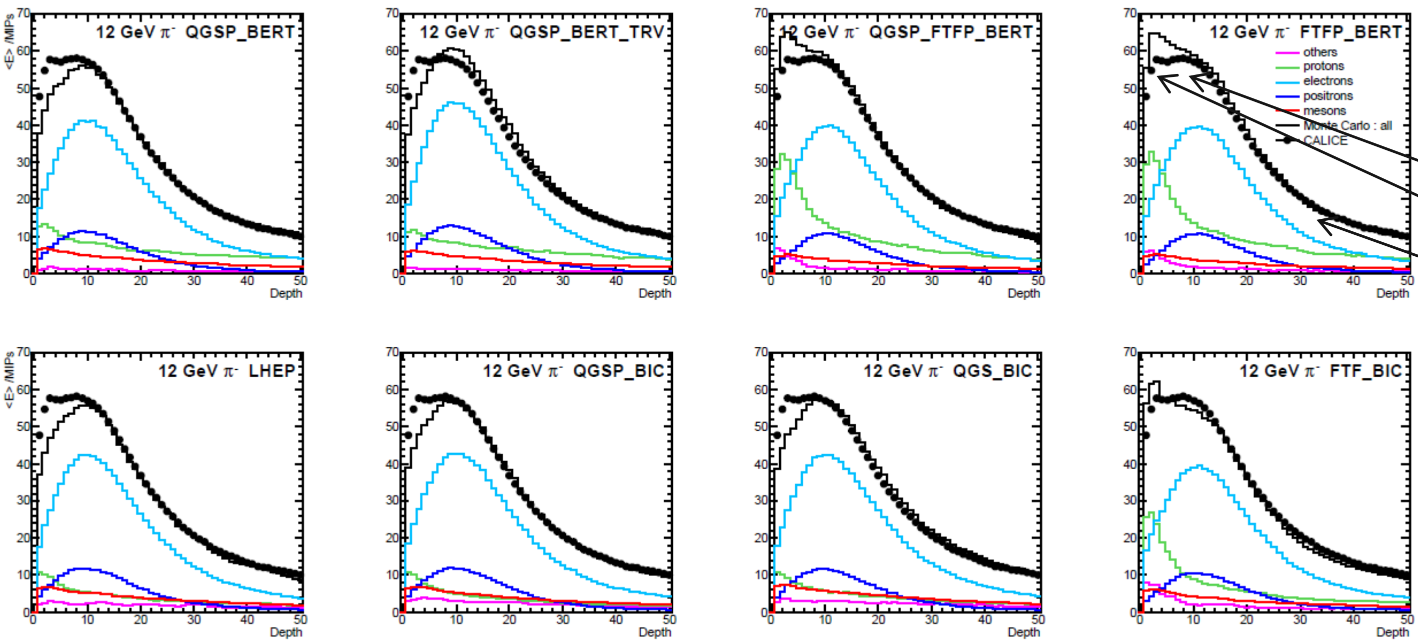
Weighted shower radii versus E_π
Comparison with various GEANT4 models





Longitudinal shower shape

For E_π= 12 GeV (taken from first hadronic interaction)
Comparison with various GEANT4 models
Decomposition into contributions from different particle species



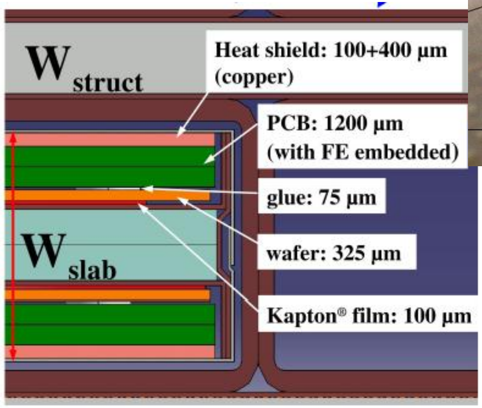
Separate contributions from

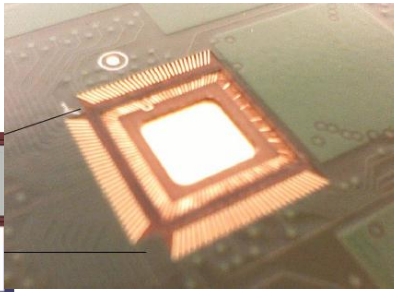
- photons
- nuclear fragments
- energetic hadrons

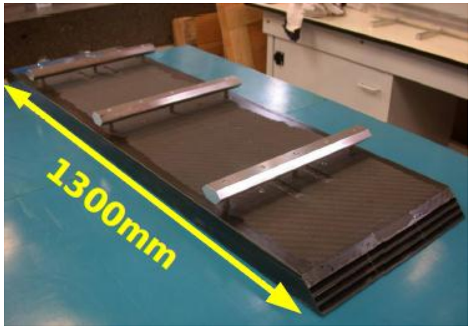
CALICE Calorimeter for ILC

2010 JINST 5 P05007

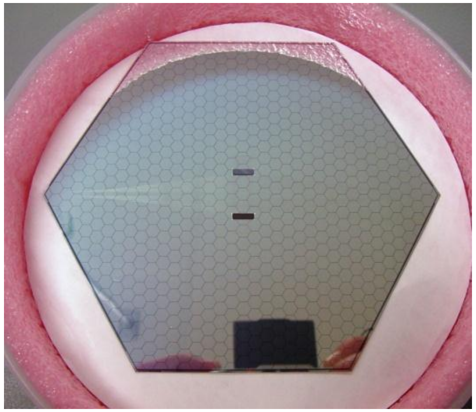
Silicon – Tungsten ECAL: Technical Prototypes

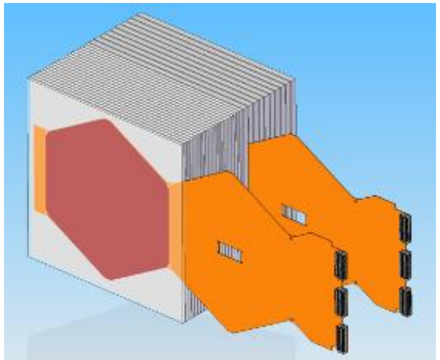


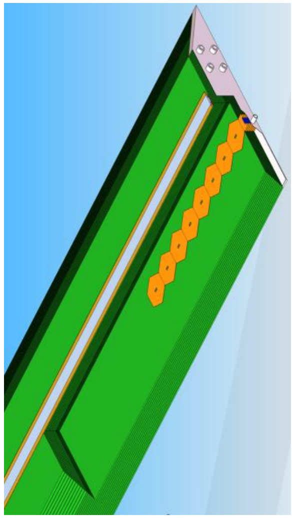




- Based on experience with physics prototype
- Reduced cell size (~0.25cm^2)
- Embedded front-end electronics
- Address 'all' technical issues
- Total active medium thickness 3 – 4 mm
- Test beam module being assembled



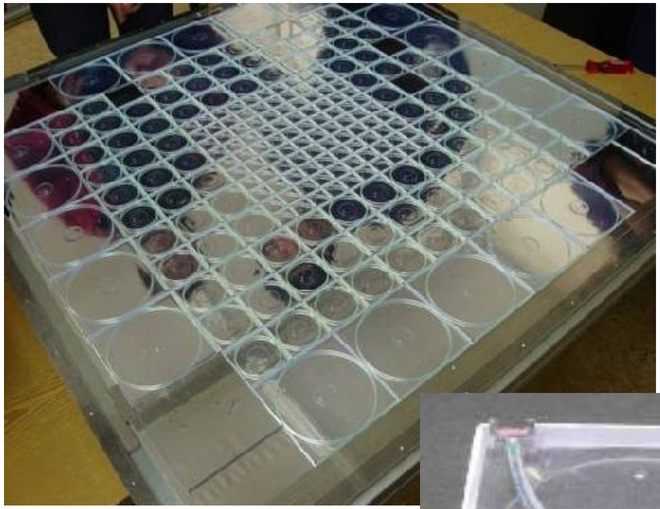




- Target at very compact readout and small cell (~0.13cm^2)
- Address many technical issues from the beginning
- Push technical limits in many aspects
- Uses KPiX chip with 1024 channels for front-end readout
- Total active medium thickness targets at ~1mm
- Test beam module expected soon

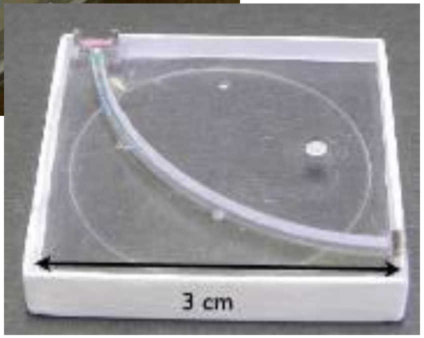
Scintillator – Steel HCAL (analog)

First calorimeter to use SiPMs



Physics prototype

38 steel plates with a thickness of 1.1 X_0 each
Scintillator pads of 3 x 3 → 12 x 12 cm^2
→ ~8,000 readout channels



Electronic readout

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

Tests at DESY/CERN/FNAL in 2006 - 2009

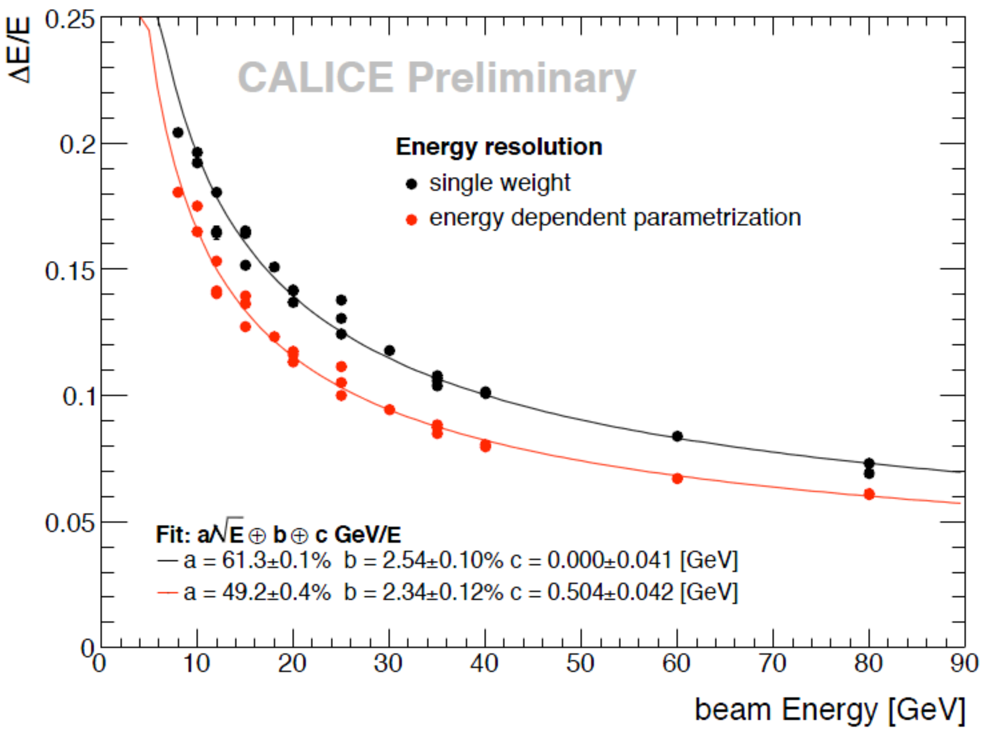
Electrons 1 – 45 GeV
Pions 6 – 50 GeV

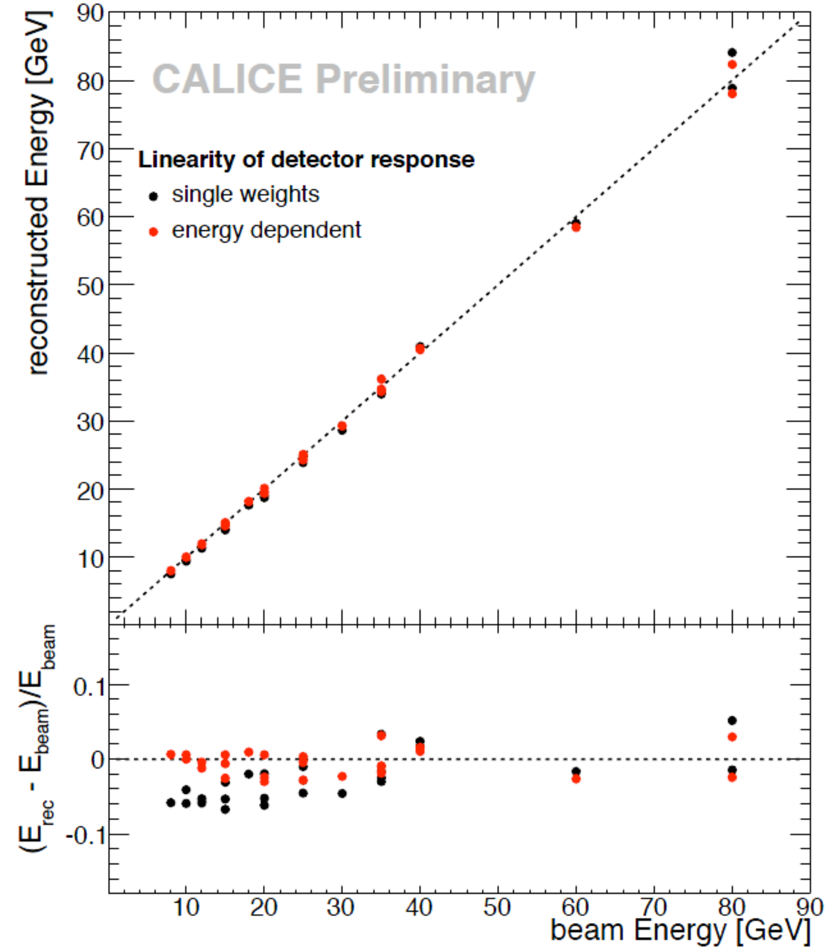
The power of imaging calorimeters II: Linearity and resolution

Pions between 8 and 80 GeV/c

Software compensation

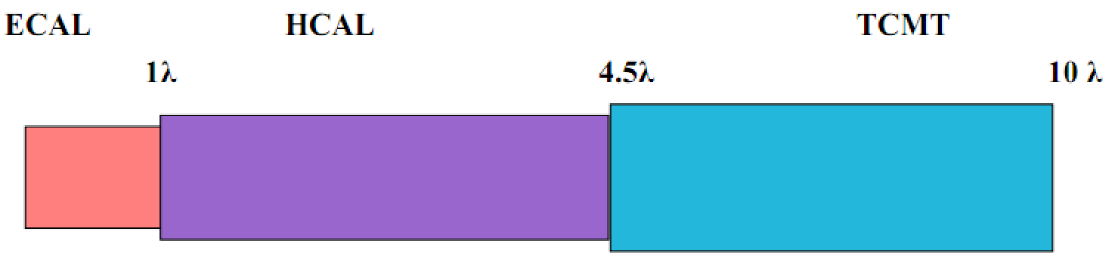
- Based on energy density weights
- Improves both linearity and resolution





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)

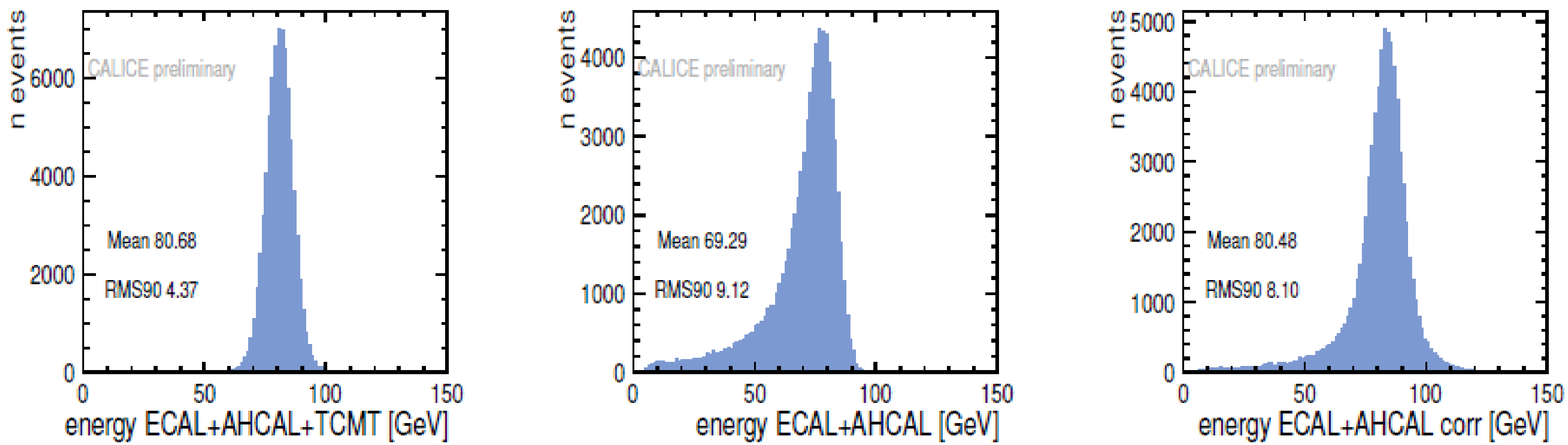
Fraction of energy in last 4 layers

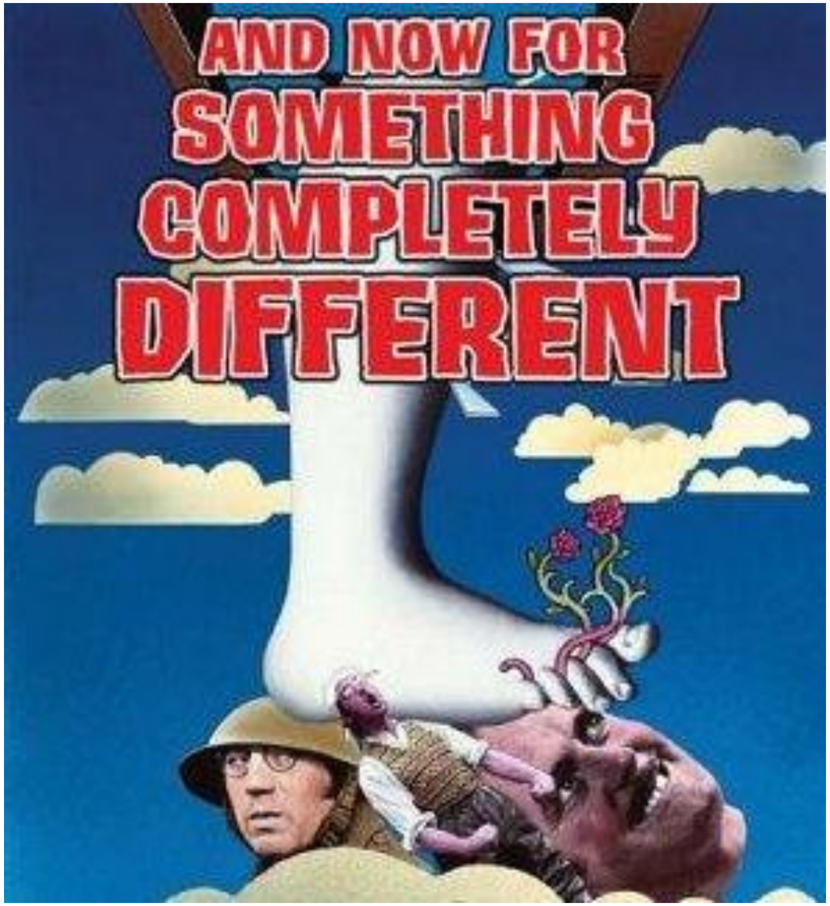
Correction

Restores mean value

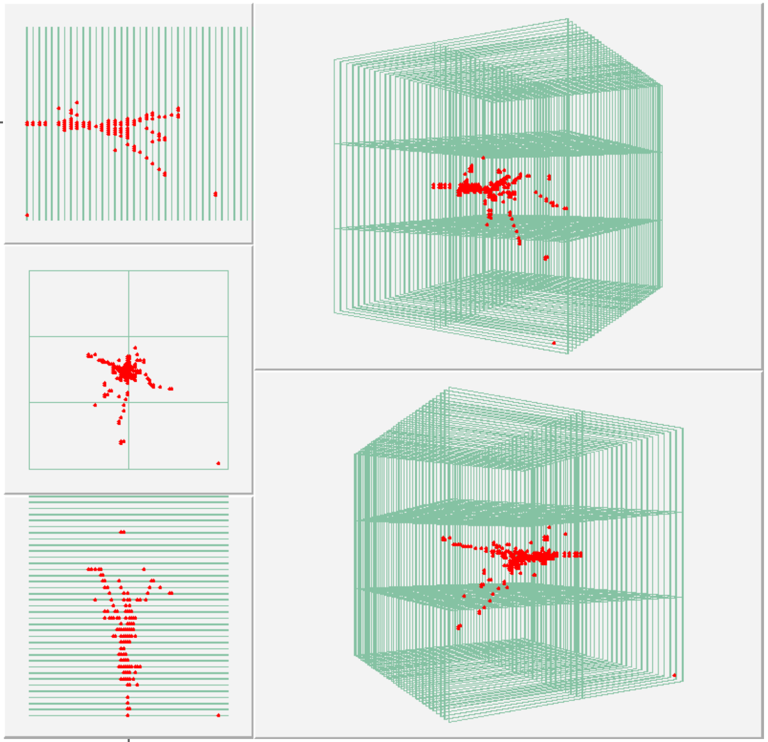
Reduces RMS by ~ 24%

(by still worse than direct measurement)




AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

Digital Hadron Calorimeter



High density of cells

- Layer – by – layer
- 1 x 1 cm^2 laterally

Single bit readout/cells → digital readout

Reconstruct energy as

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

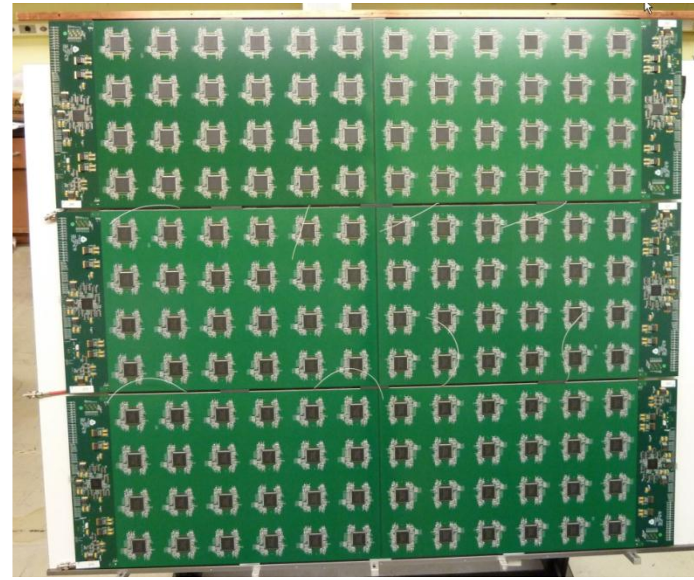
Active media

- Resistive Plate Chambers (RPCs)
- Gas Electron Multipliers
- Micromegas

➡ **DHCAL prototype**

CALICE Calorimeter for ILC

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 x 1 m^2
RPCs (32 x 96 cm^2) as active medium

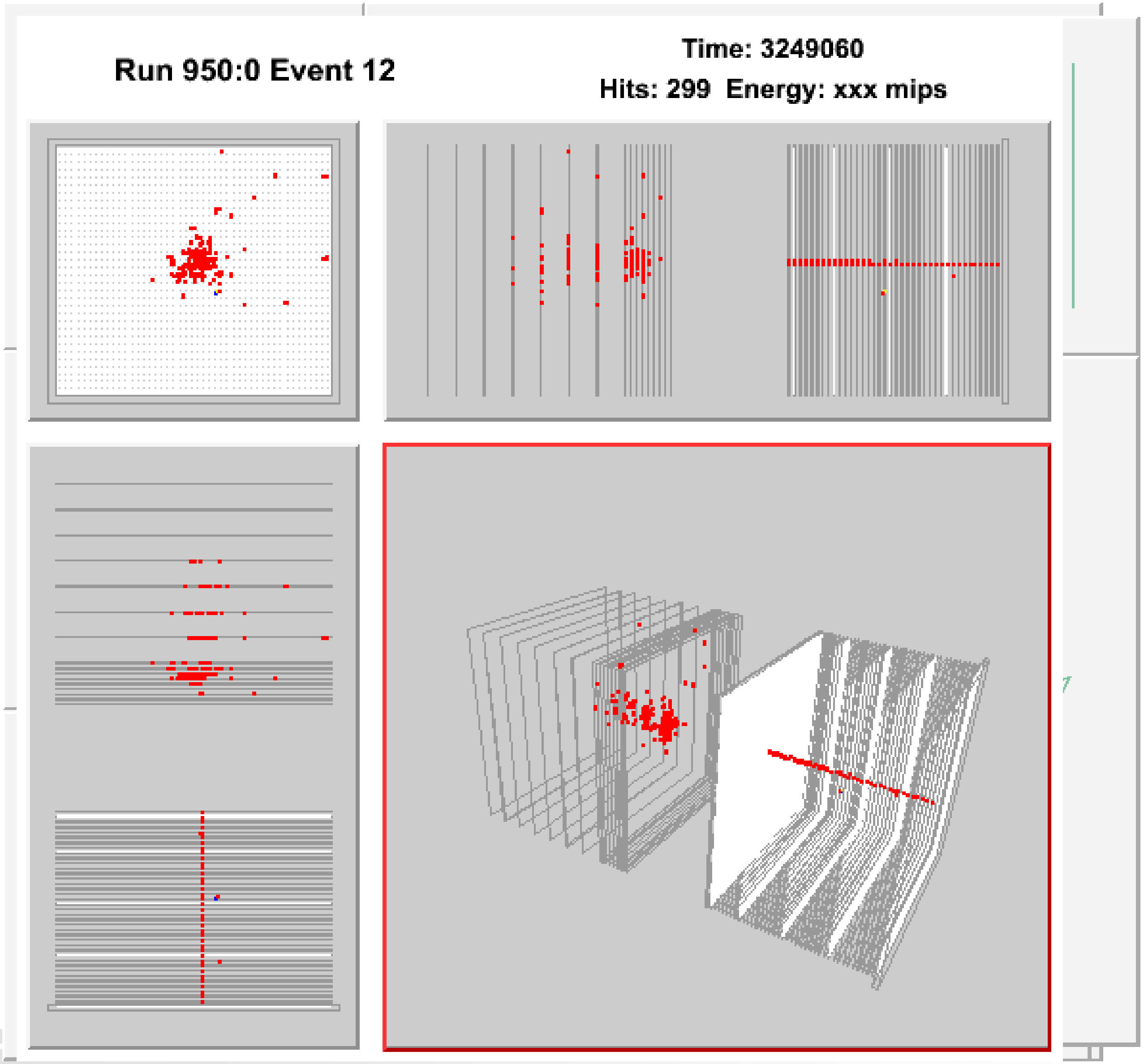
Electronic readout

Embedded on the detector plane
Based on the DCAL III chip (64-channels)
Common threshold to all channels on a chip
480,000 readout channels

Tests at FNAL in 2010 - 2011

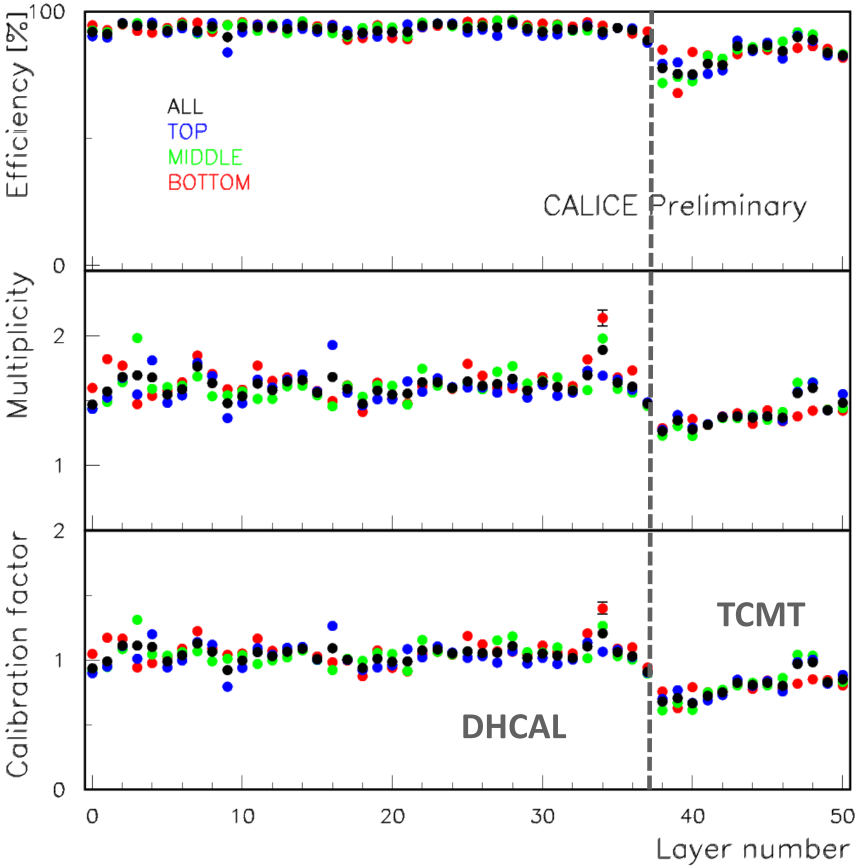
Broadband muons
2 – 60 GeV/c secondary beam
120 primary beam

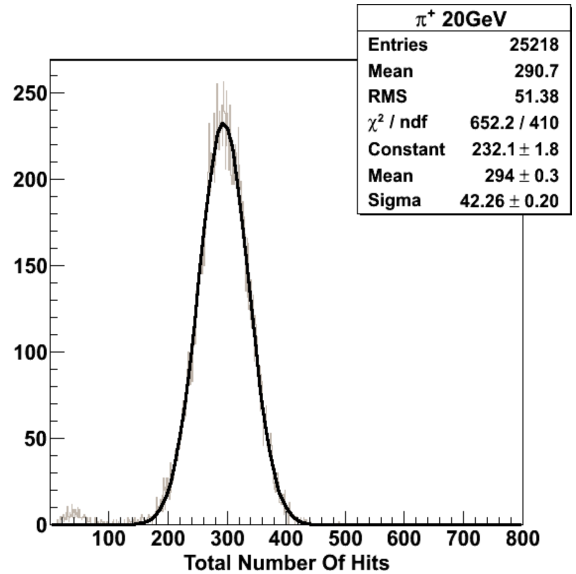
A few events…



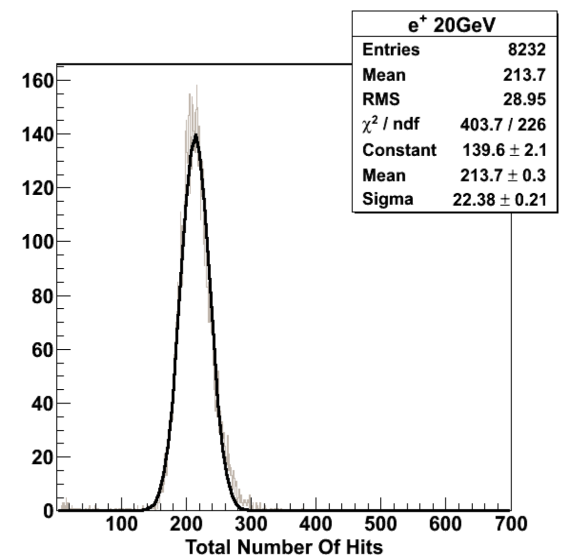
Some very first results

Calibration with muons

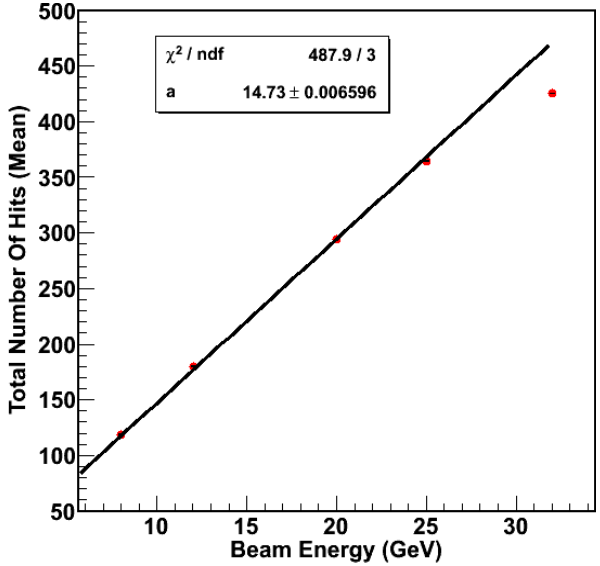


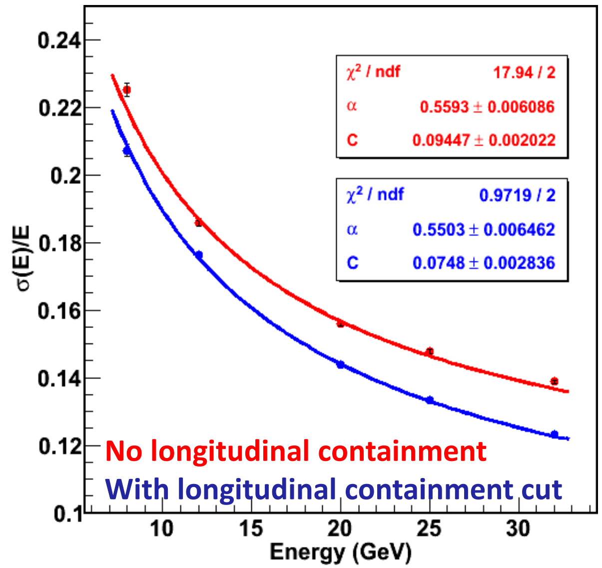


Single particle response



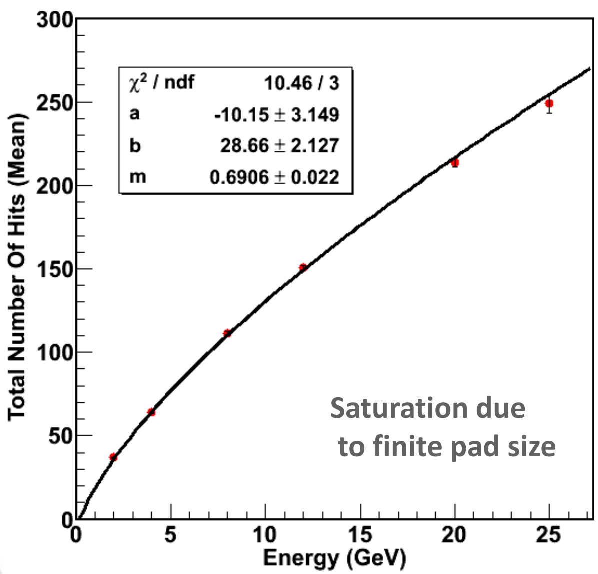
Pion response (not calibrated)



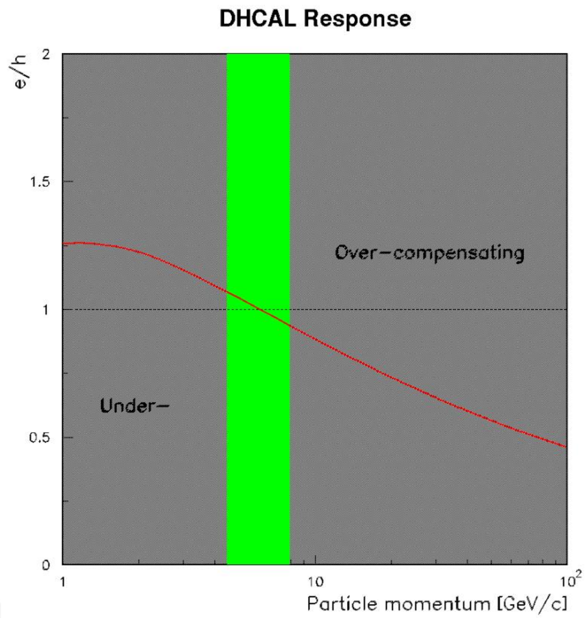


GEANT4 + RPC simulation
predicted ~ 58%/√E

Positron response (not calibrated)



Software compensation
is expected to extend
the region of compensation



Semi-Digital Hadron Calorimeter

European based effort

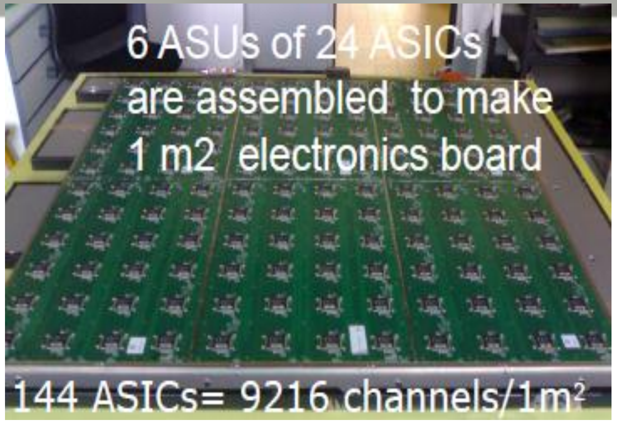
Similar to the DHCAL

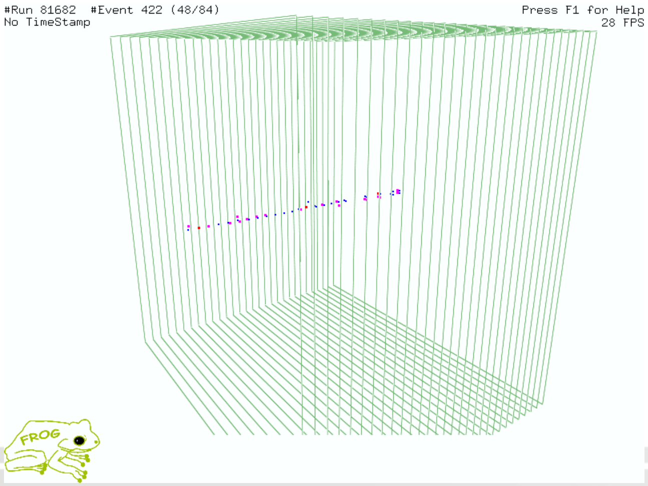
- RPCs as active medium
- Embedded front-end electronics
- Based on HARDROC chip (64 channels)

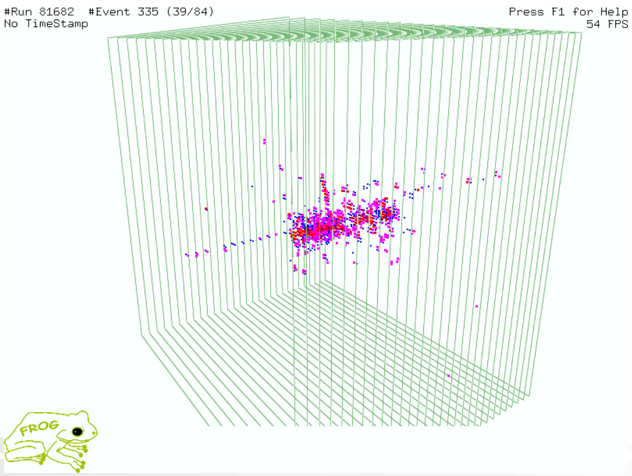
Extra features

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

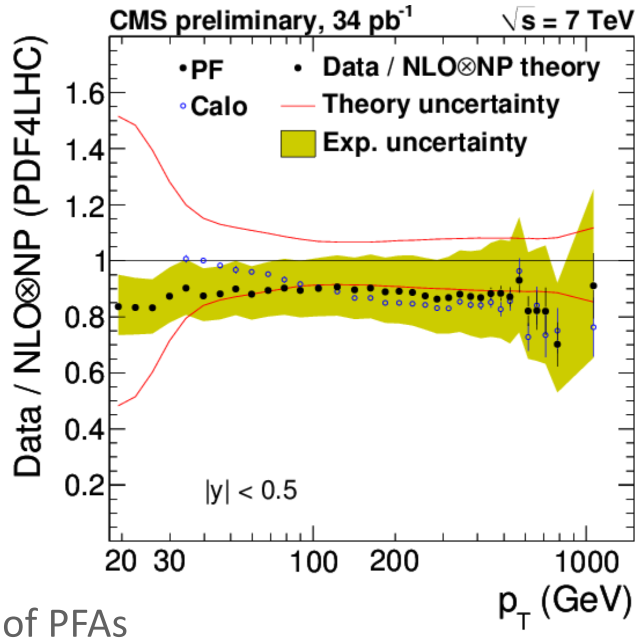
Prototype **assembled** in 2011 and saw 1st beam







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 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