Imaging Calorimeters

-- what have we learned so far

Lei Xia
Argonne National Laboratory

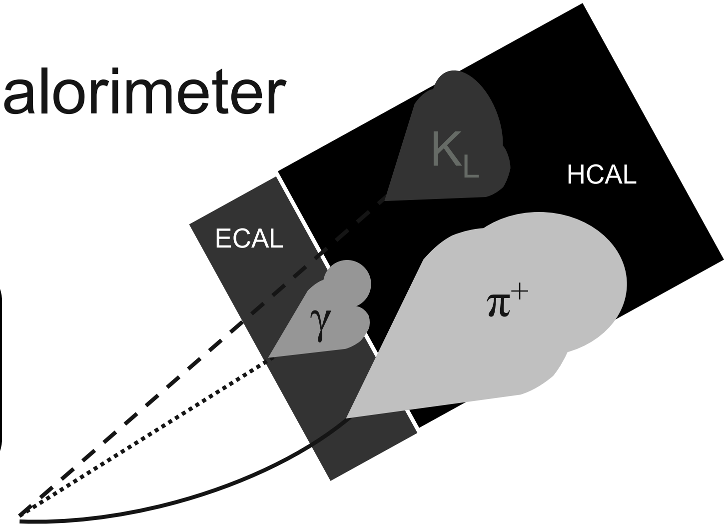
Motivation: physics at the next lepton collider

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	$Q_{jet/vtx}$	
$ee \to Zh \to \ell\ell X$		x									x			
$ee \to Zh \to jjbb$	x	x	x			x				x	x			
$ee \to Zh,h \to bb/cc/\tau\tau$	x		x							x	x			
$ee \to Zh,h \to WW$	x		x		x				x	x	x			
$ee \to Zh,\ h \to \mu\mu$	x	x									x			
$ee \to Zh,\ h \to \gamma\gamma$				x	x		x							
$ee \to Zh,h \to invisible$			x			x	x							
$ee \to \nu\nu h$	x	x	x	x			x			x	x			
$ee \to tth$	x	x	x	x	x		x	x	x		x			
$ee \to Zhh,\ \nu\nu hh$	x	x	x	x	x	x	x		x	x	x	x	x	x
$ee \to WW$										x			x	
$ee \to \nu\nu WW/ZZ$						x	x		x	x	x			
$ee \to \tilde{e}_R\tilde{e}_R$ (Point 1)		x						x			x			x
$ee \to \tilde{\tau}_1\tilde{\tau}_1$	x	x						x						
$ee \to \tilde{t}_1\tilde{t}_1$	x	x							x	x		x		
$ee \to \tilde{\tau}_1\tilde{\tau}_1$ (Point 3)	x	x			x	x	x	x	x					
$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$ (Point 5)									x	x				
$ee \to HA \to bbbb$	x	x								x	x			
$ee \to \tilde{\tau}_1\tilde{\tau}_1$			x											
$\chi^0_1 \to \gamma + \not{E}$					x									
$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$			x					x						
$ee \to tt \to 6\ jets$	x		x						x	x	x			
$ee \to ff\ [e,\mu,\tau;b,c]$	x		x				x		x		x		x	x
$ee \to \gamma G$ (ADD)				x	x			x						x
$ee \to KK \to f\bar{f}$		x									x			
$ee \to ee_{fwd}$						x	x	x						
$ee \to Z\gamma$		x		x	x	x	x							

– Physics Benchmarks for the ILC Detectors

Required: excellent Jet energy/mass resolution **Solution**: Particle Flow Algorithm (PFA)

Particle Flow Algorithms and Imaging Calorimeter



The idea…

Charged particles	measured with the	**Tracker**
Neutral particles		**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 combined: 18%/√E)

Requirements for detector system

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

↳ **Imaging Calorimeter**: see the detail of every particle shower

PFA: current status

- Relevant jet energy scale

√s	#fermions	Jet energy
250 GeV	4	~60 GeV
500 GeV	4 – 6	80 – 125 GeV
1 TeV	4 – 6	170 – 250 GeV
3 TeV	6 – 8	375 – 500 GeV

ILC - like

CLIC - like

- PFA performance: PandoraPFA + ILD + uds jets

rms$_{90}$

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %

★ Equivalent stochastic term shown for comparison, PFA resolution is not stochastic, CONFUSION

ILC Goals: ~3.5 % jet energy resolution for 50 – 250 GeV jets

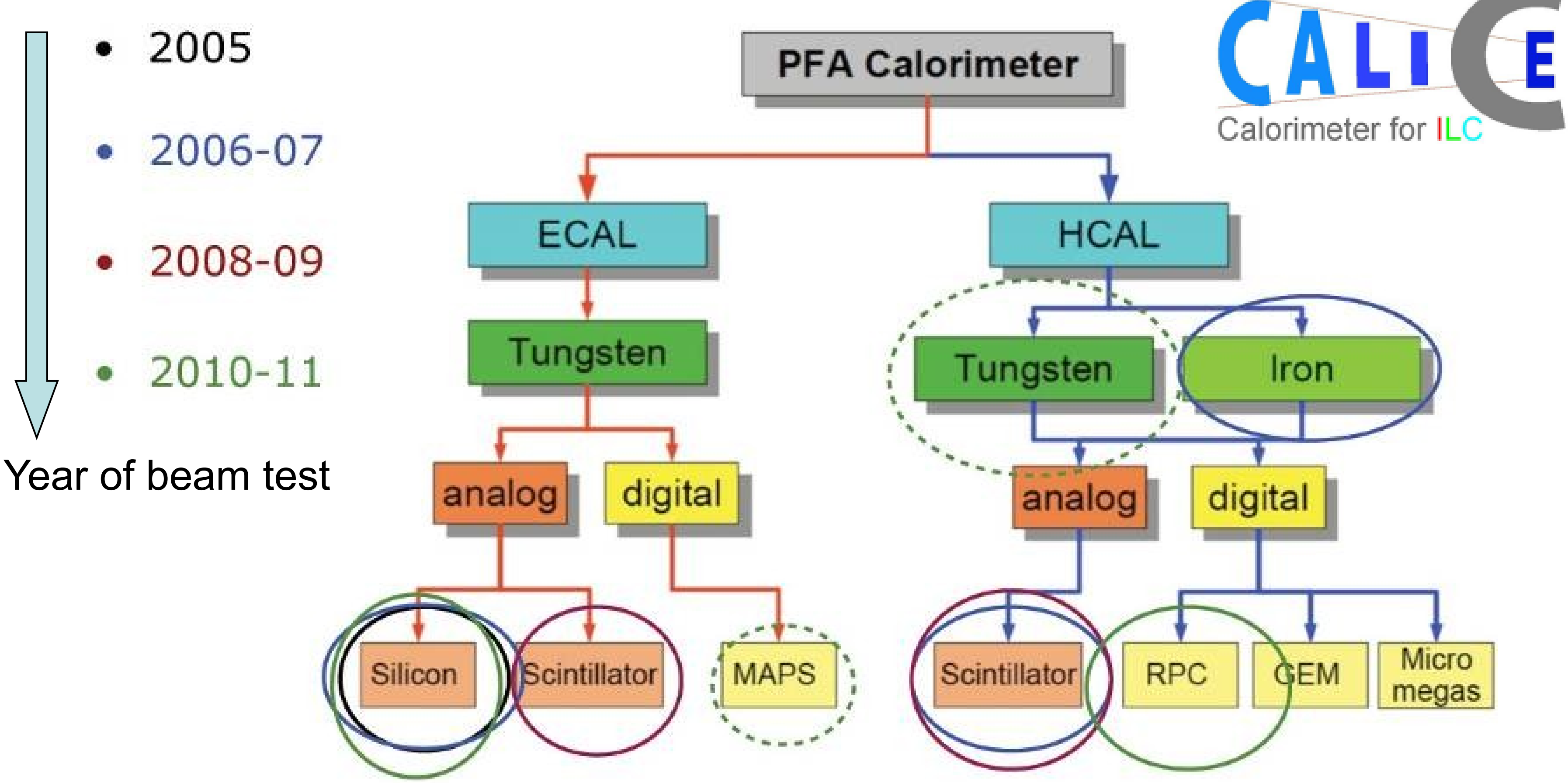
CLIC Goals: ~3.5 % jet energy resolution for 100 – 500 GeV jets

Credit: Mark Thomson, CALOR'2010 talk

PFA is up to the task ← if we DO have an imaging calorimeter system

Imaging calorimeter R&D: current status

Most R&D efforts are within the CALICE collaboration*

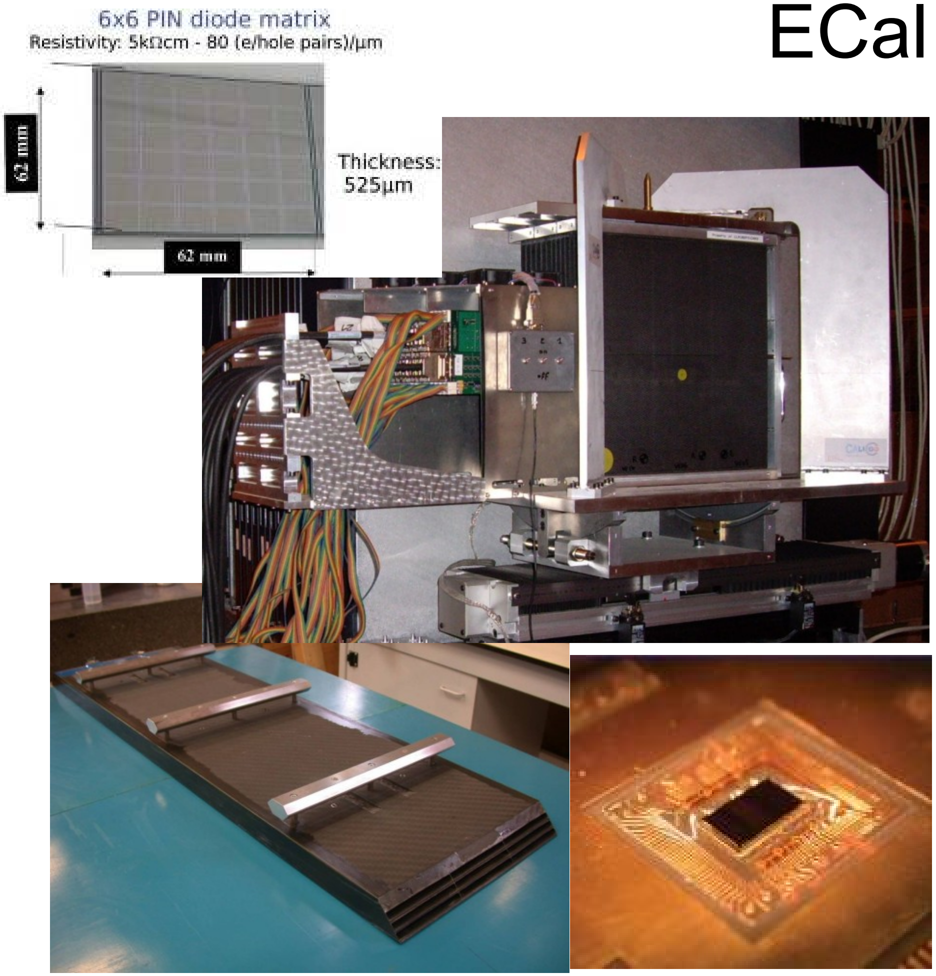


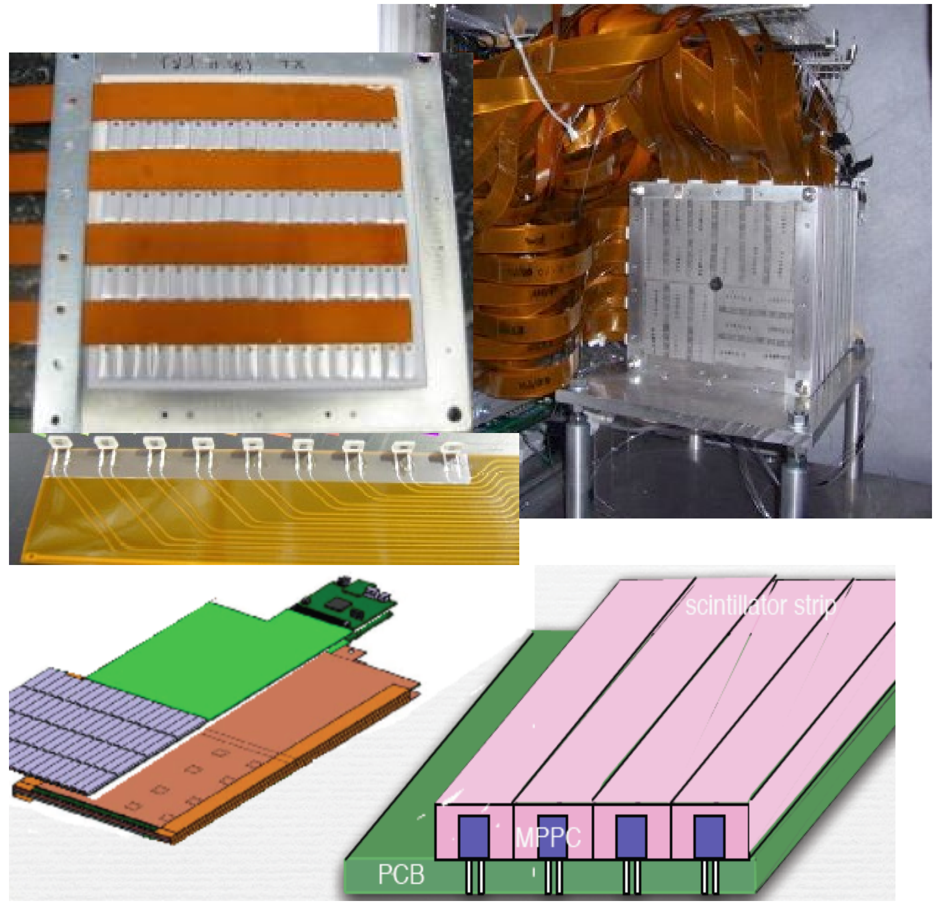
* Except SiD Si/W ECal effort

Readout cell size: 144 - 9 cm^2 → 4.5 cm^2 → 1 cm^2 → 0.25 cm^2 → 0.13 cm^2 → 2.5x10^{-5} cm^2

Technology: Scintillator + SiPM/MPPC | Scintillator + SiPM/MPPC | Gas detectors Silicon | Silicon | Silicon | Silicon (MAPS)

ECal efforts



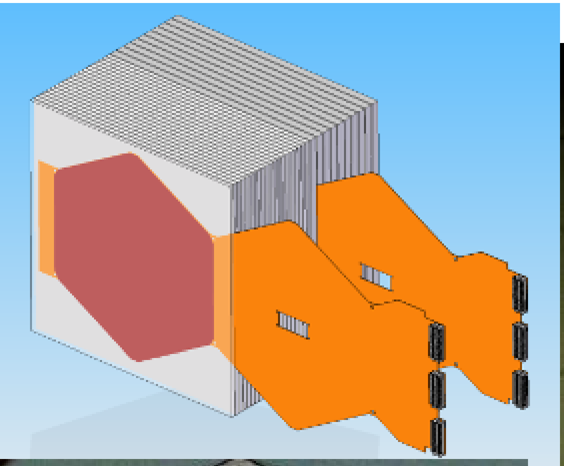


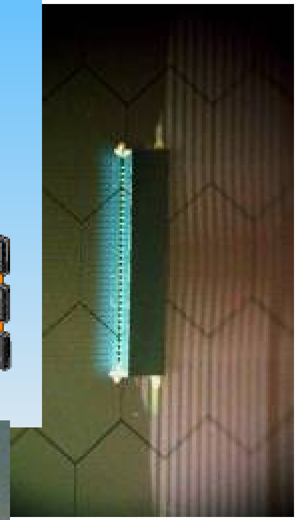
CALICE Si/W ECal:
- Physics prototype* tested in beam (1x1cm^2)
- Data analysis well advanced
- R&D/construction for Technical prototype**
- Readout cell reduced to 0.25cm^2 for 2nd prototype

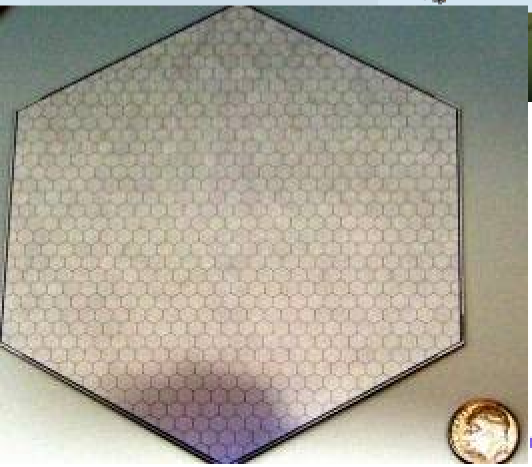
CALICE Sci/W ECal:
- Physics prototype tested in beam (1x4.5cm^2)
- Data analysis done
- R&D for technical prototype

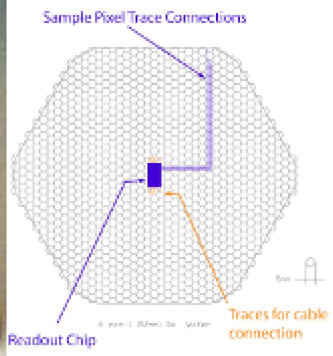
*** Physics prototype: proof of principle device***
***** Technical prototype: prototype close to a real detector***

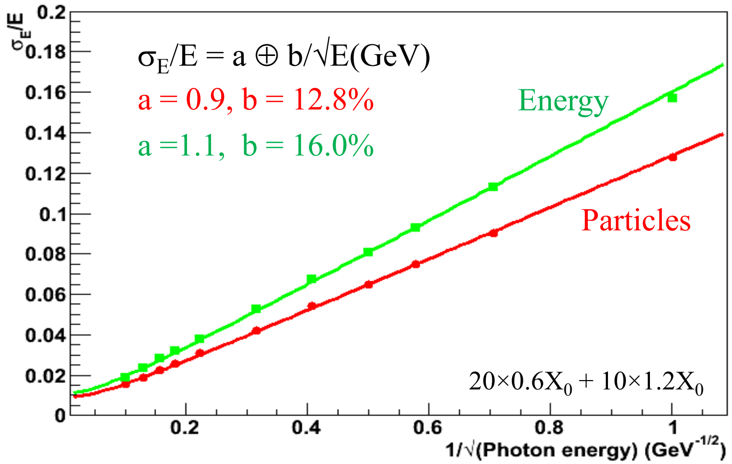
ECal efforts

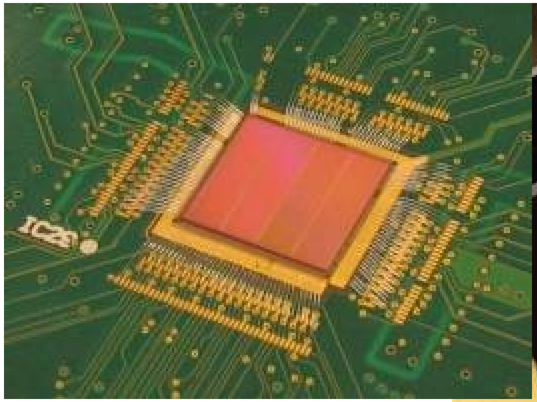


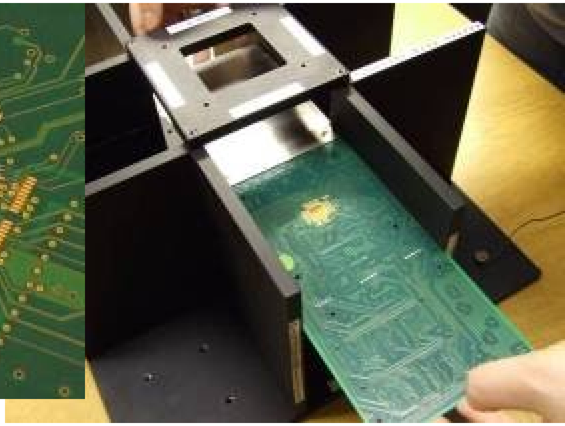








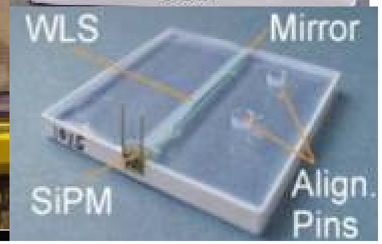


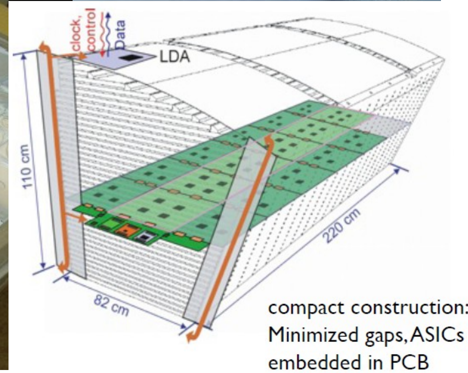


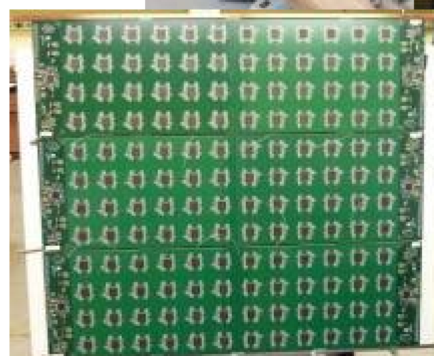
SiD Si/W ECal:
- Target at very compact readout and small cell (~0.13cm^2)
- Address all technical issues from the beginning
- Push technical limits in many aspects
- Total active medium thickness targets at ~1mm
- Test beam module expected soon

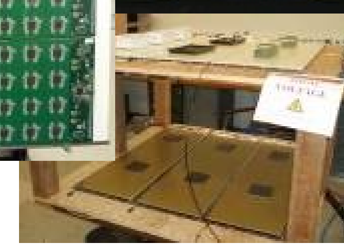
CALICE MEPS Digital ECal:
- Extremely small cell size (0.005x0.005cm^2)
- Working on sensor R&D
- Did sensor test beam

HCal Efforts









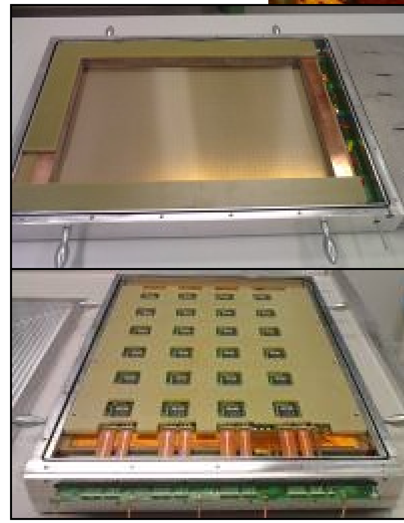
CALICE Sci/SiPM Analog HCal (AHCal):

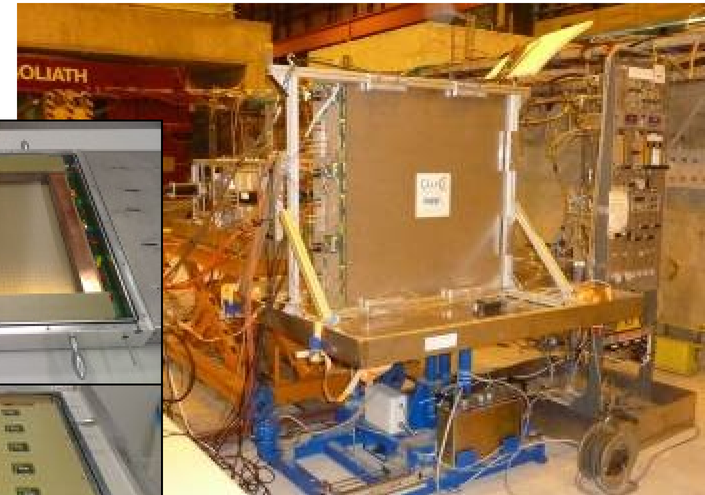
- Physics prototype (Fe) tested in beam (3x3cm^2)
- Data analysis well advanced
- Physics prototype (W) beam test this year
- R&D/construction for Technical prototype

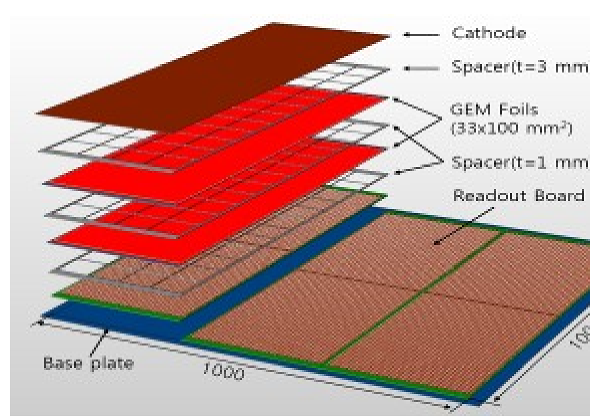
CALICE RPC Digital HCal (DHCal):

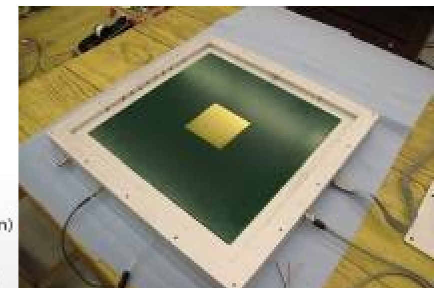
- Large (1m^3) prototype (Fe) is being tested in beam (1cm^2)
- Embedded Front End readout, 480K (!) readout channels
- Data analysis started
- Beam test with W absorber planned
- R&D for Technical prototype started

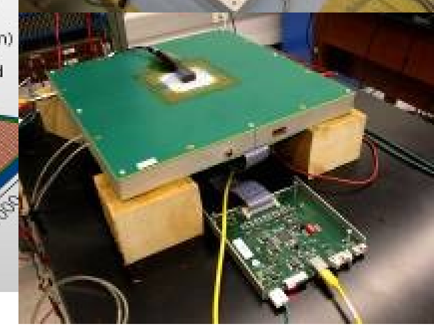
HCal Efforts











CALICE RPC semi-Digital HCal (sDHCal):

- Large prototype ($1m^3$) under construction ($1cm^2$)
- Beam test expected later this year
- Addressed some technical issues for real detector
- Explore 3-threshold readout

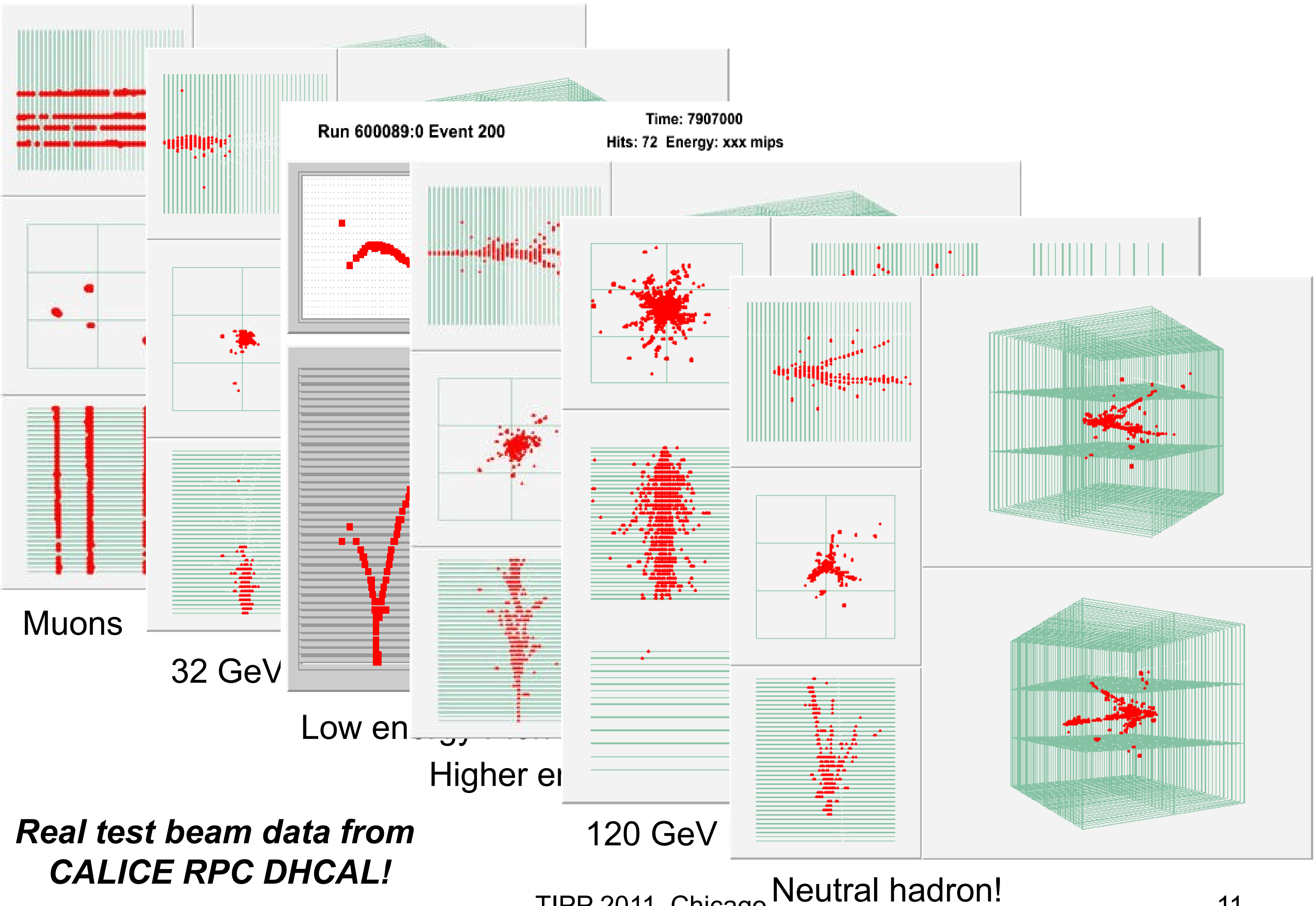
CALICE Micromegas/GEM Digital HCal:

- Prototype layer constructed/expected ($1x1cm^2$)
- Prototype layer beam test done/expected
- Both technologies can handle very high rates

What have we learned from these beautiful devices (so far)?

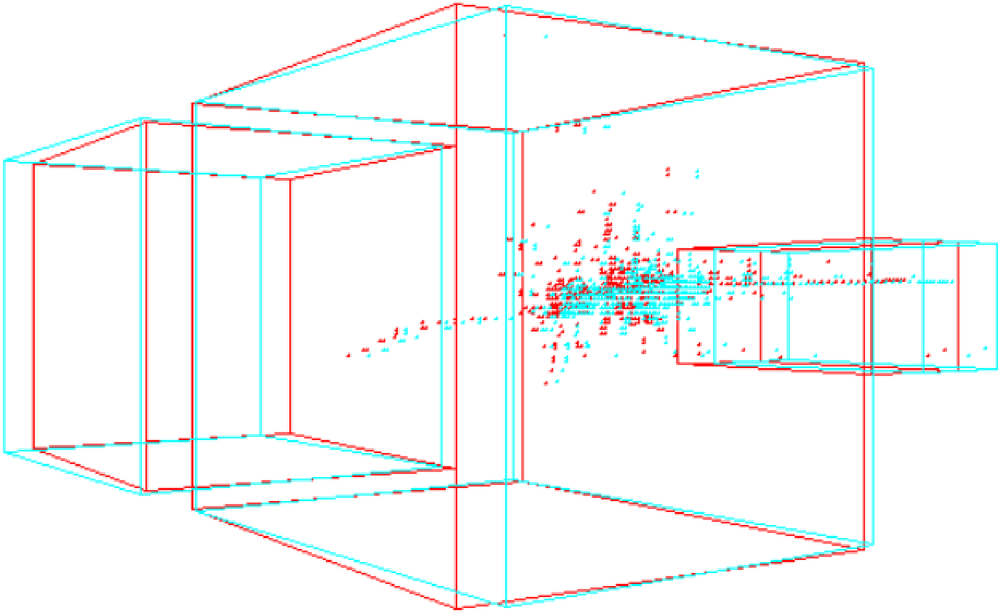
Will show some nice results, according to my personal taste…

First: let's see the particle showers!



Real test beam data from CALICE RPC DHCAL!

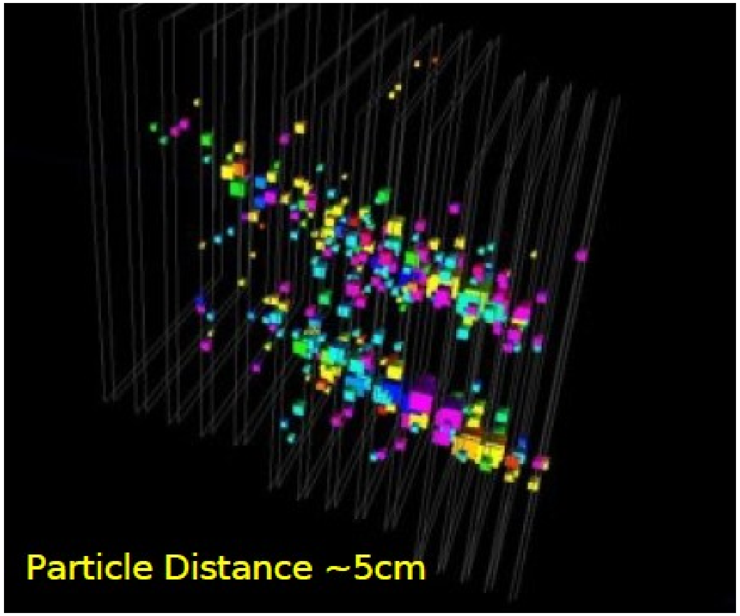
Just for fun: 3-D display is also available!



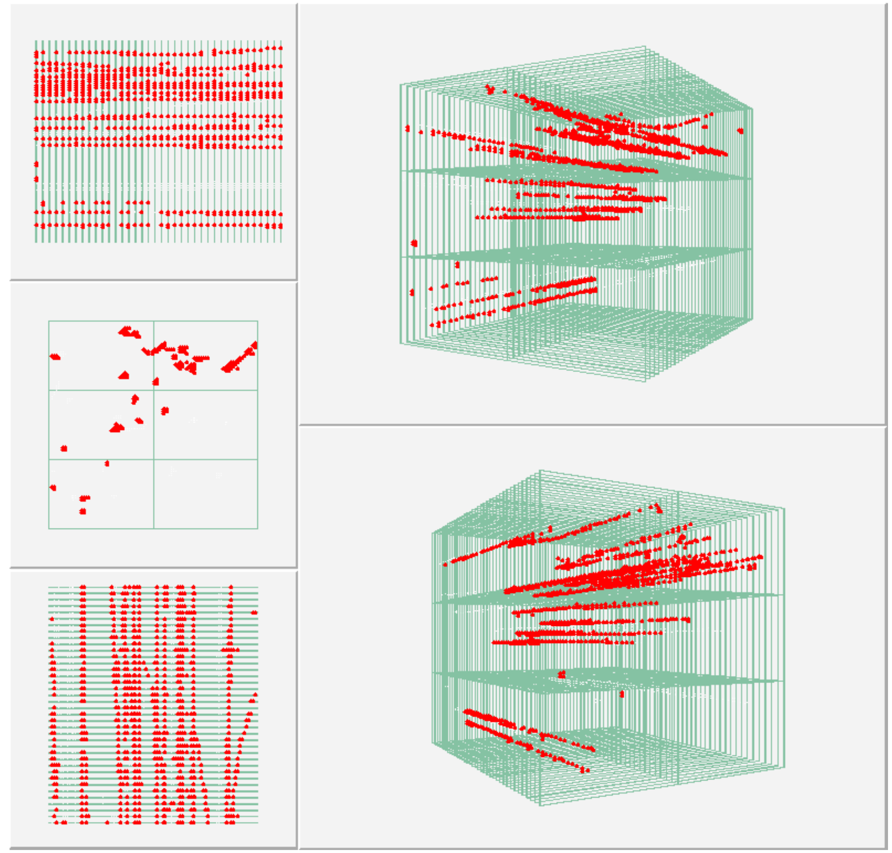
CALICE SiW ECAL + RPC DHCAL + RPC TCMT

Go to http://polywww.in2p3.fr/~jeans/threeD_DispWeb/welcome.html for more fun

Sometimes multiple particles come together…



Two electrons ~5cm apart
CALICE SiW ECAL



~20 muons in 1m^2 area
CALICE RPC DHCAL

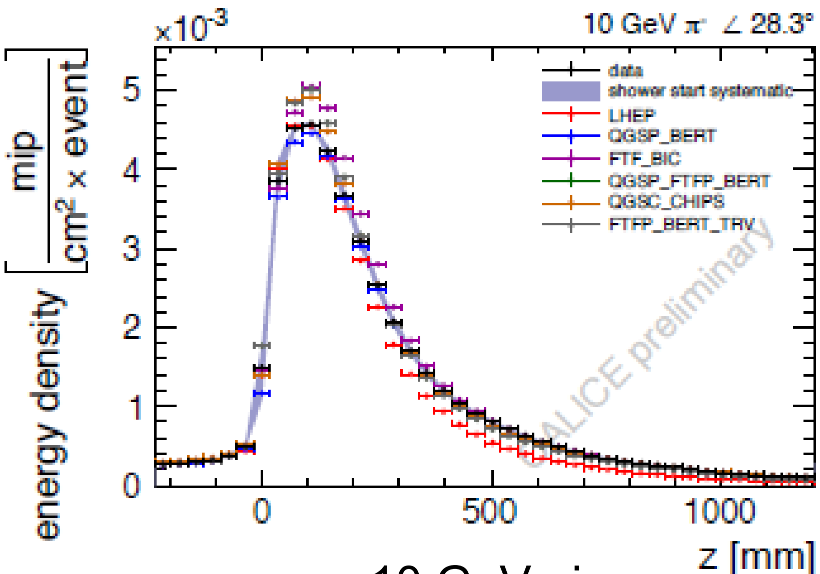
We have no problem distinguishing these particles
--- a good PFA should have no problem in a calorimeter like this neither!

Shower profile: data/MC comparison

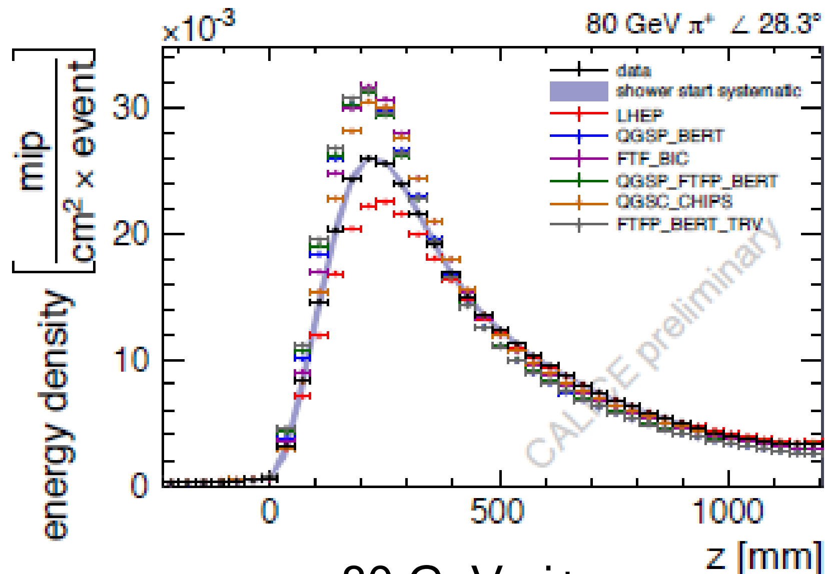
- One of the key roles of the test beam prototypes: provide data to validate hadronic shower simulation
- This is a critical step in PFA validation
- The imaging calorimeter prototypes provided unprecedented details in shower measurement

Longitudinal shower profile

CALICE AHCAL



10 GeV pi-



80 GeV pi+

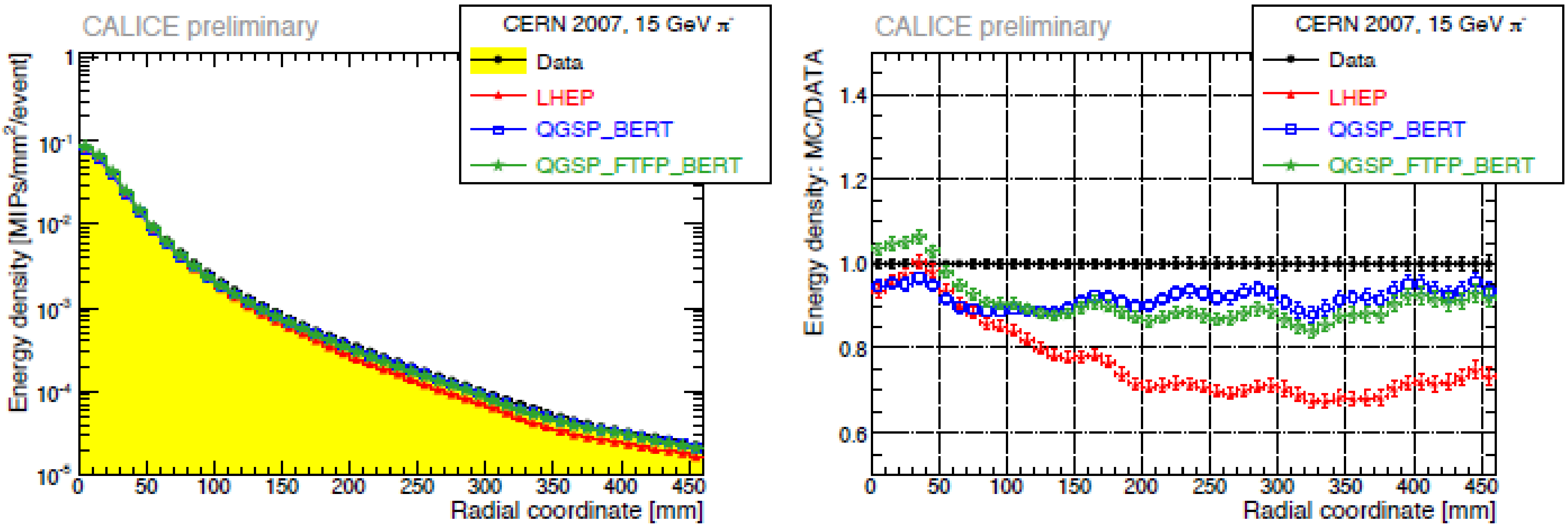
Longitudinal shower profile measured relative to **shower starting point** **(NOT** a convolution of showers starting at different depth**)**

- QGSP_BERT works best at low energy
- None of them work terribly well at high energy

Ref arXiv:1008.2318

Lateral shower profile

CALICE AHCAL



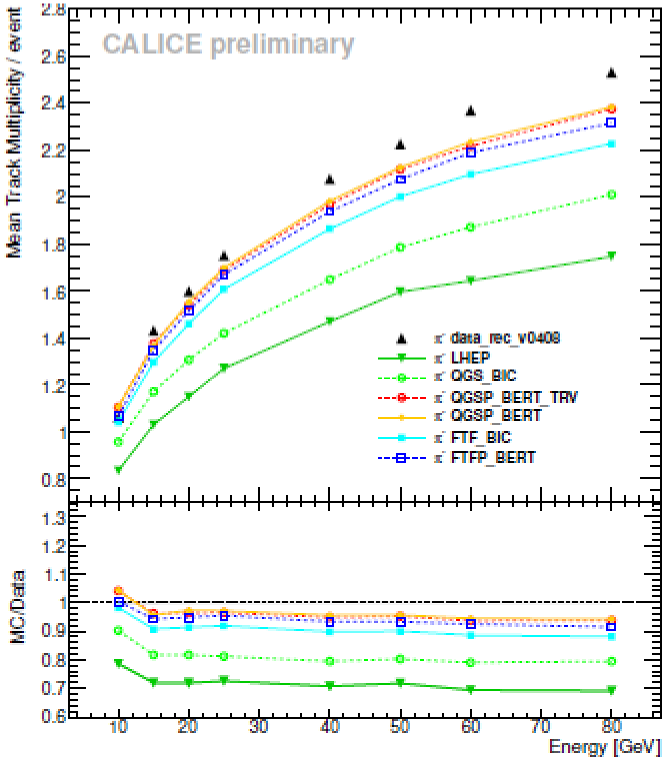
Lateral shower profile of 15 GeV pi-

Lateral shower profile is critical for PFA performance
The 'modern' hadronic models works reasonably well

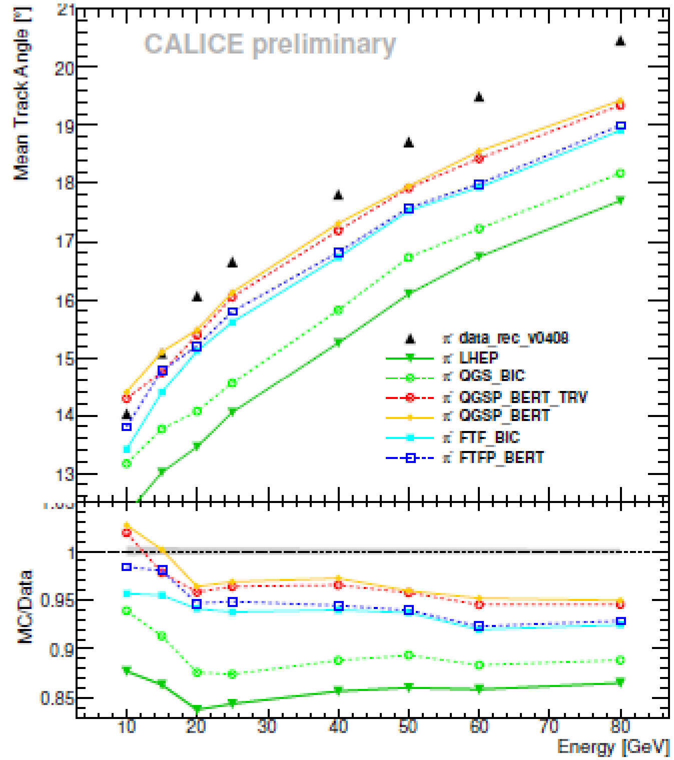
Ref arXiv:1008.2318

CALICE AHCAL

Shower substructure



Average track multiplicity



Average track angle

3D shower substructure: finding track segments (isolated track, at least 6 layers)

Again, some hadronic models are doing pretty well

These track segments point to an interesting possibility:

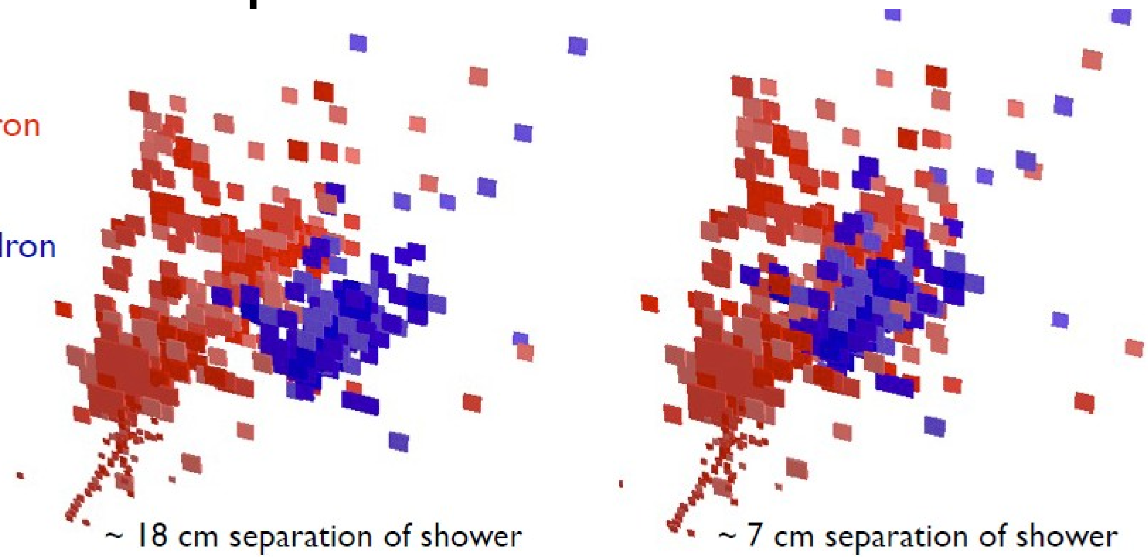
- Using physics data to self-calibrate the imaging calorimeter performance
- CALICE RPC DHCal is currently using similar technique to measure time dependent calibration constant with shower data at the test beam

Shower separation: test of PFA & MC

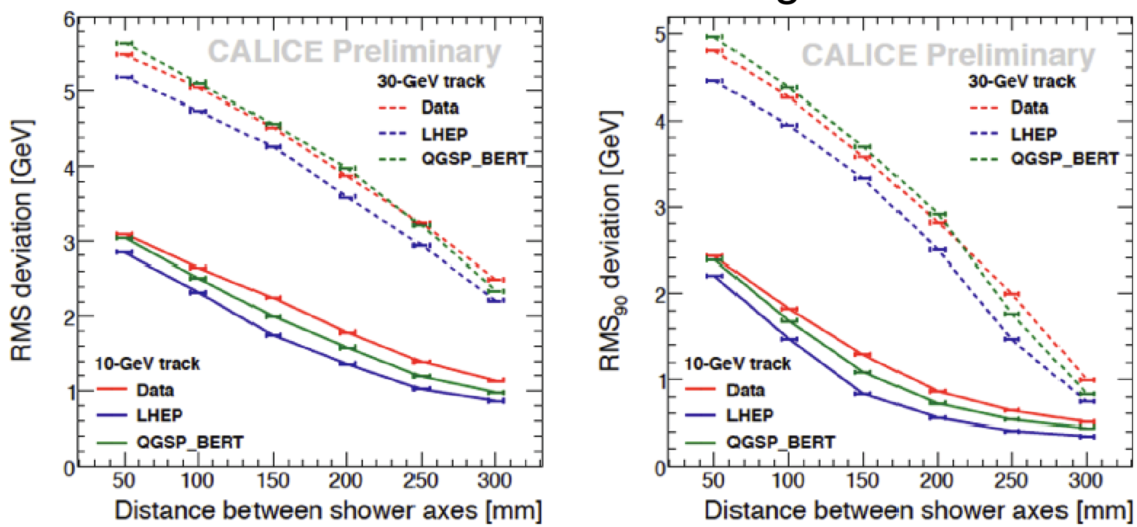
30 GeV
charged hadron

10 GeV
"neutral" hadron

CALICE
SiW ECAL + AHCAL



Using real particle showers to assemble interesting event to test PFA & MC



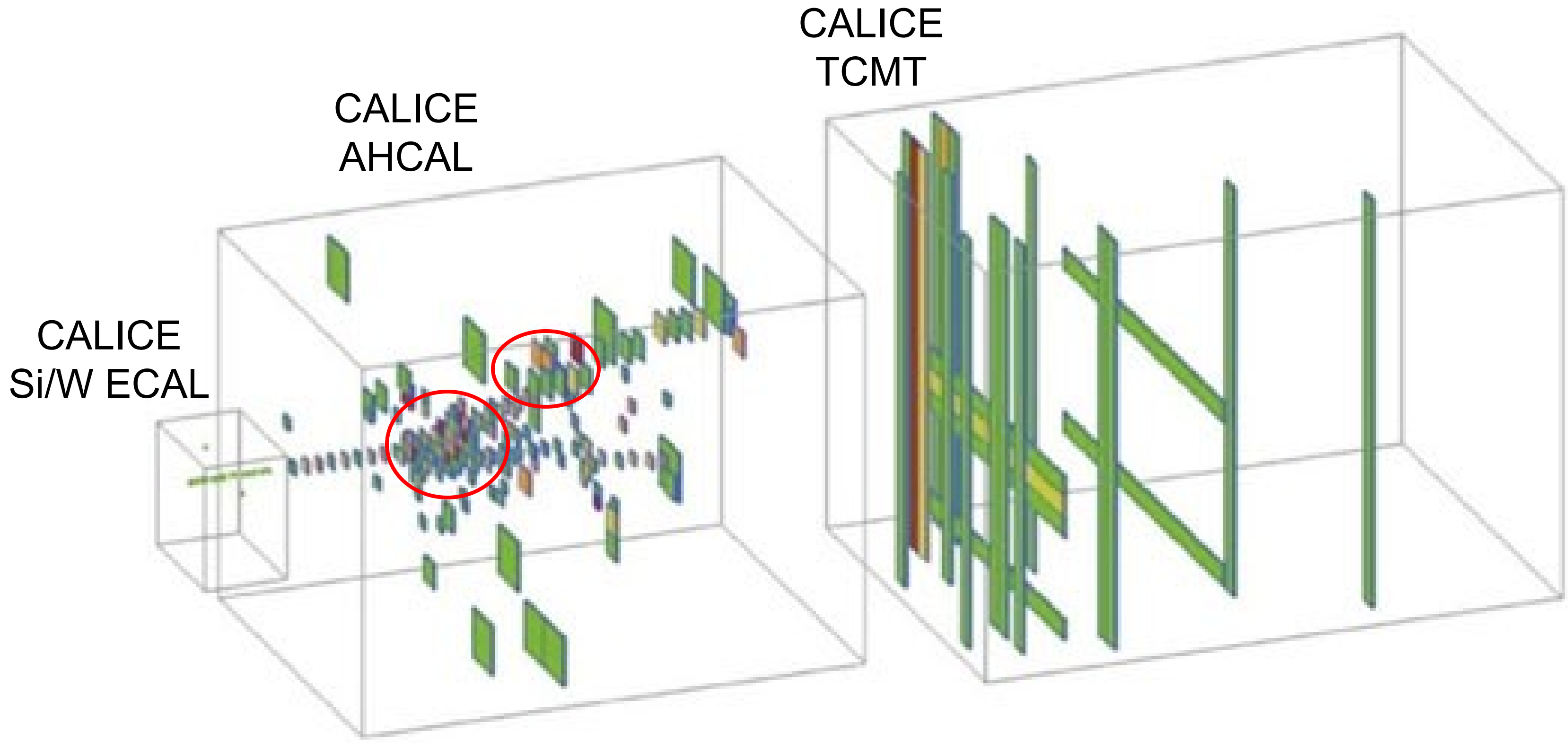
Energy recovery for neutral hadron close to a 10(30) GeV track

Bottom line: PFA + MC passed test, we can trust them!

Ref arXiv:1105.3417

Software compensation

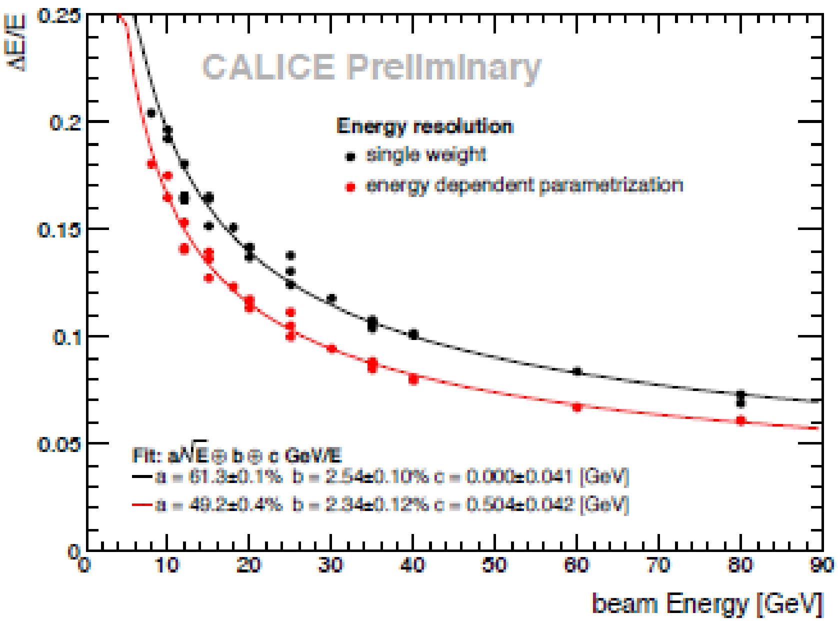
With fine segmentation, software compensation becomes ‘easy’

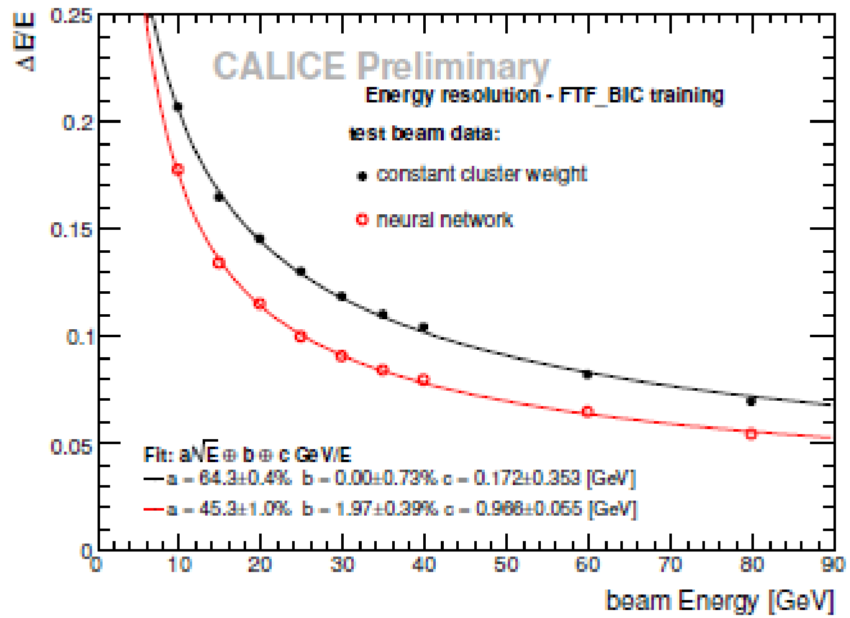


π^0’s can be easily identified within hadronic showers (at least by eye)

Software compensation in CALICE AHCal

CALICE AHCAL





Local software compensation

- Single cell energy density based weights
- Apply to ECal + AHCal + TCMT
- ~20% improvement

Global software compensation

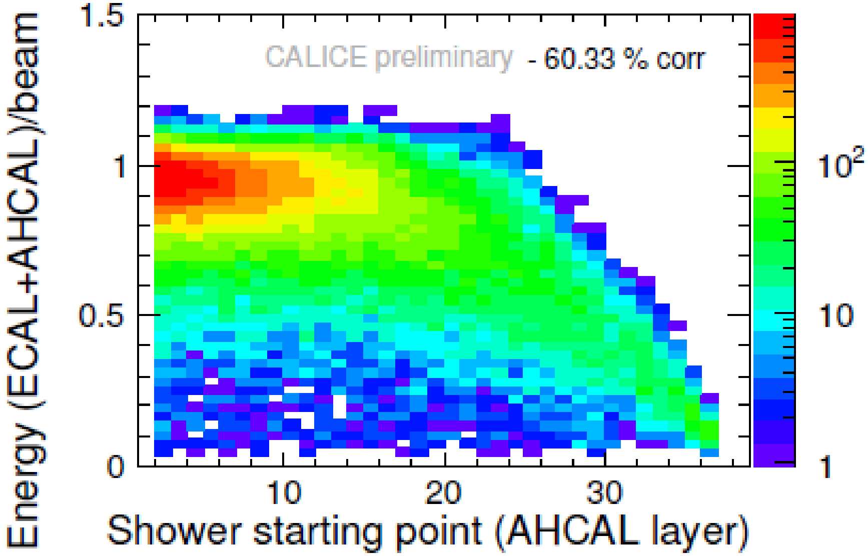
- Use events that didn't shower in ECal
- Define shower with clustering algorithm
- Calculate shower parameters from cluster
- Feed into Neural Net → energy estimate
- ~25% improvement

Better single particle energy resolution can further improve PFA performance

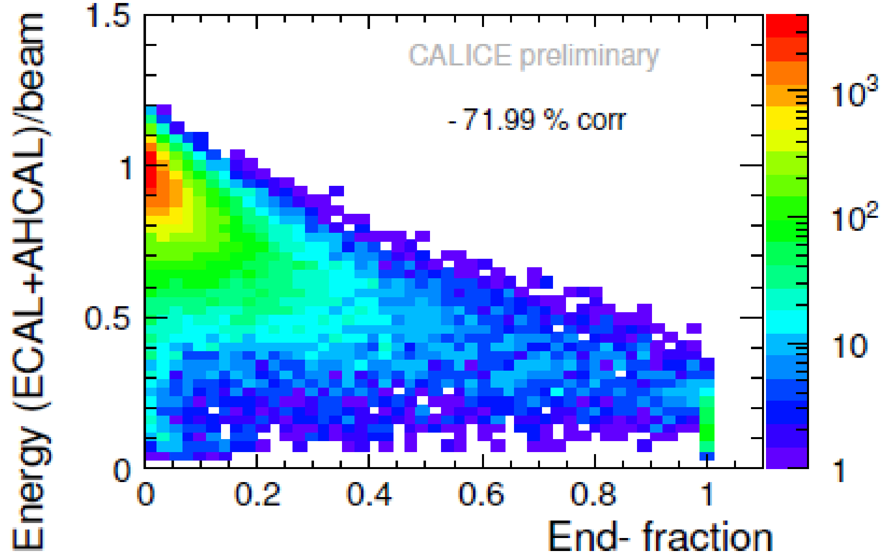
Leakage correction

- Ideally, one should build very deep calorimeter
- But this is not always affordable
- Imaging calorimeter enables meaningful leakage correction

Useful variables:

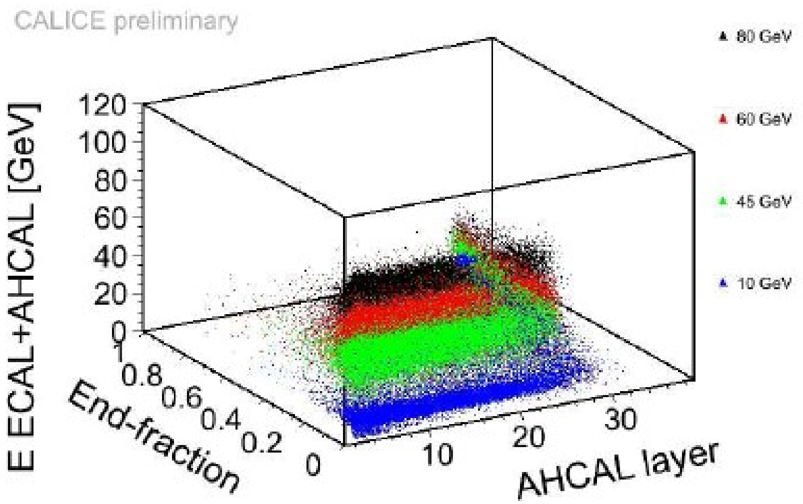


CALICE SiW ECAL + AHCAL + TCMT

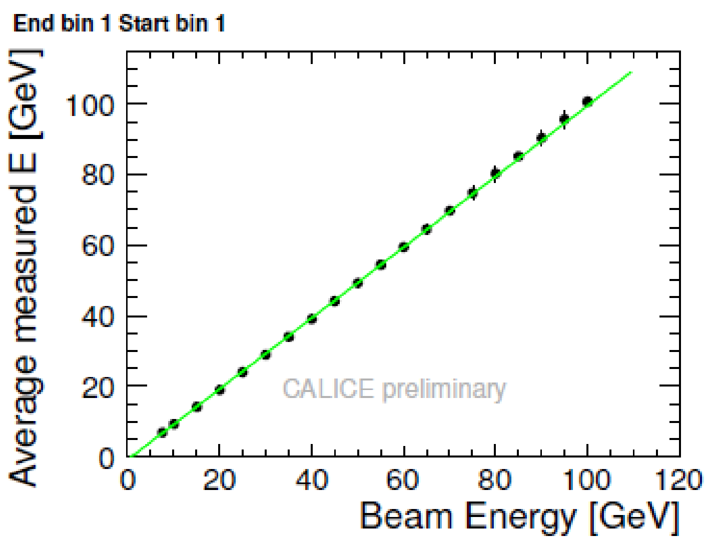


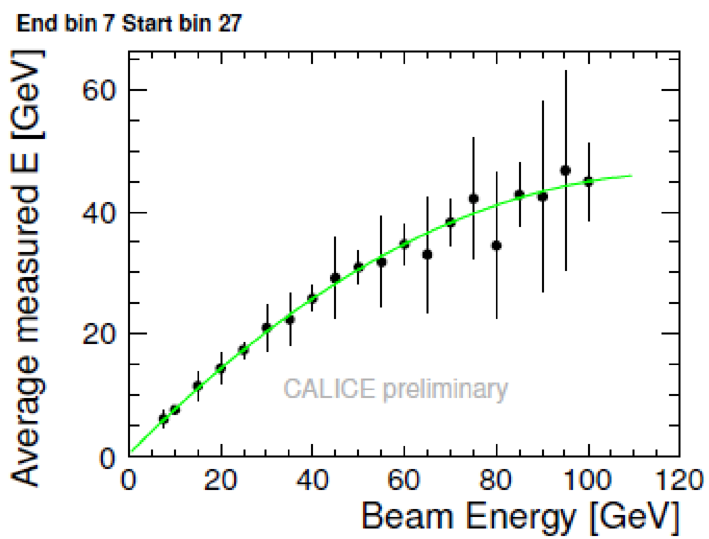
(energy fraction in the last 5 AHCal layers)

Leakage correction



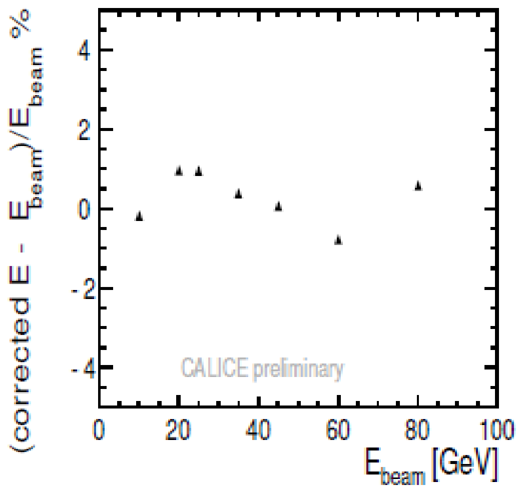
- A large set of templates is generated according to the correlation among start-layer, end-fraction and observed E
- One template for each (start-layer, end-fraction) bin
- Each template provide a relationship between observed E and beam E
- template generated by MC simulation or independent data set

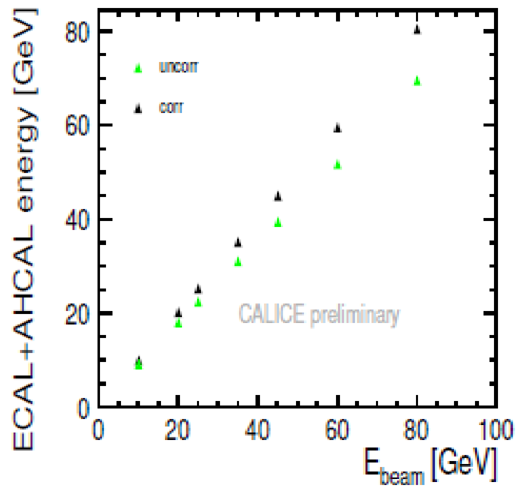


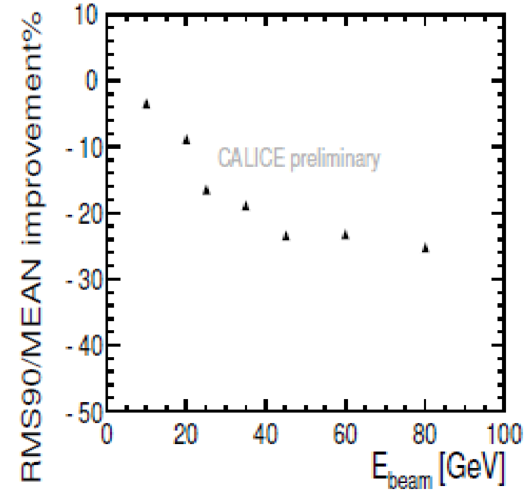


Example templates for two bins

Leakage correction

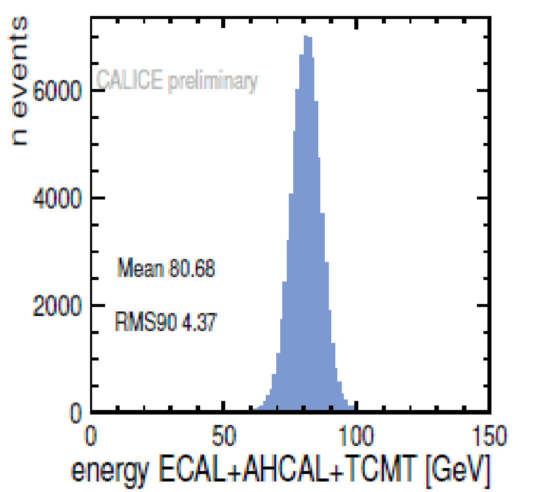




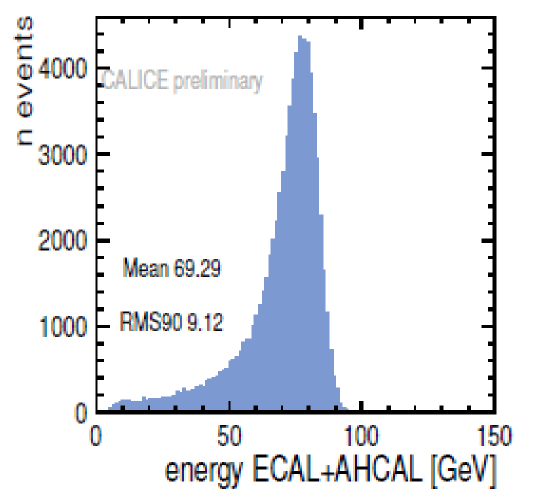


Leakage correction using templates generated from independent data

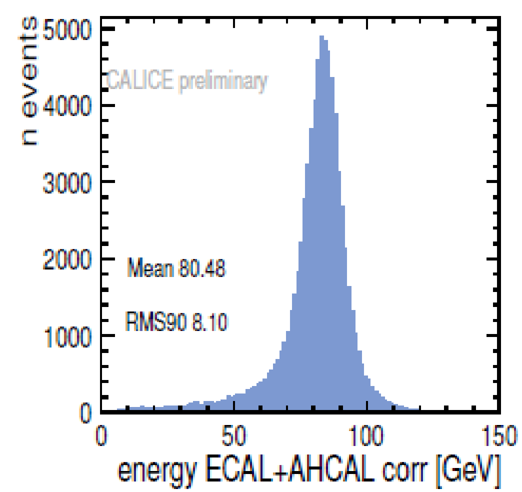
Example: 80 GeV Pion



Measure leakage in TCMT



Do nothing about leakage



Correct for leakage

Having measurement > leakage correction > no leakage correction

Not possible to show you all the nice and unique things of an imaging calorimeter

Didn't even mention the technological advances brought by the R&D efforts

Embedded readout
Compact sensitive layer
ASIC's
Data multiplexing
Cooling
Sensor technology
…

Summary

- Imaging calorimeter is a key ingredient of a detector system optimized for PFA
- A lot of R&D efforts world wide, a lot of progress made
  - Proof of principle is done for imaging calorimeter
  - Close to be able to build a real detector
- A lot of unique things about imaging calorimeter
  - Unprecedented detailed measurement of particle showers
  - Valuable data for MC simulation models
  - Validation for PFA
  - Self-calibration
  - Software compensation
  - Leakage correction
  - (and many more)
- A real breakthrough in calorimeter technology