Performance of the CALICE calorimeters

36th International Conference on High Energy Physics
Melbourne Convention and Exhibition Centre
Jul. 4th – 11th, 2012

Tamaki Yoshioka
Kyushu University
On behalf of the CALICE collaboration

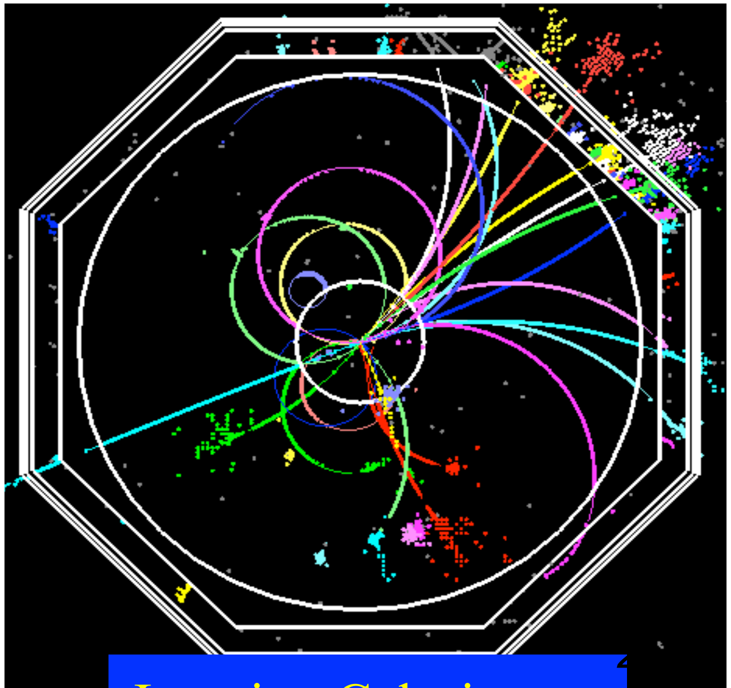
The CALICE Collaboration

- The **CALICE** is a collaboration of Calorimeter R&D for a future linear collider.

- ~330 physicists/engineers from 57 institutes and 17 countries.

Calorimeter for ILC

- **Final Goal :**
  Construct fine granular calorimeter optimized for the Particle Flow measurement of multi-jets final state at a future linear collider.
- **Intermediate task :**
  Build prototype calorimeters in order to
  - establish the technology
  - collect hadronic showers data to tune clustering algorithm and validate existing MC models



Imaging Calorimeter

Why fine granular? →Particle Flow Calorimetry

- Most of the important physics processes to be studied at a future linear collider have multi-jets in final state.

→ **Jet energy resolution plays an important role.**

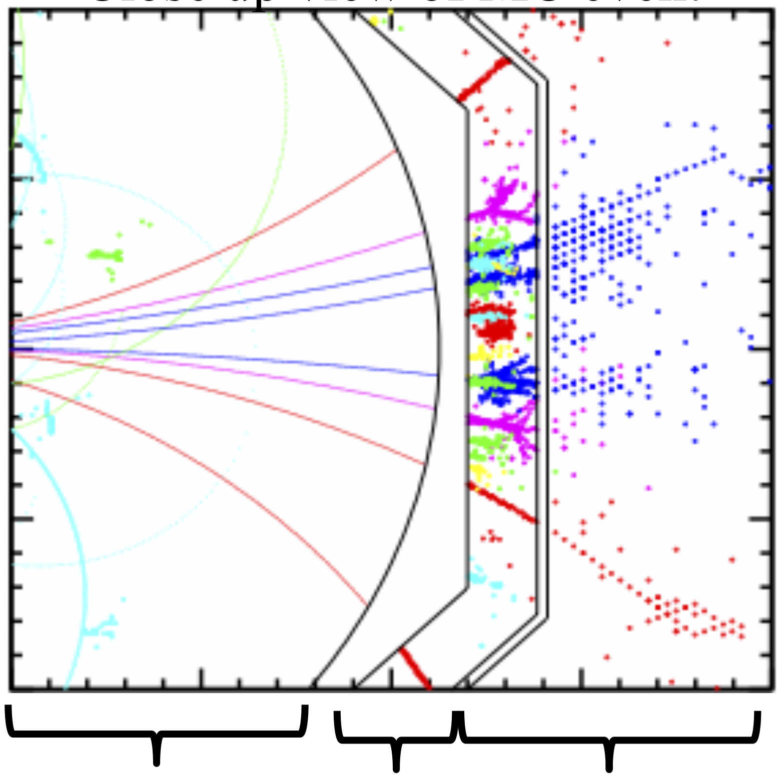
- The best energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among Trackers and Calorimeters.
  - Charged particles (~60%) measured by Trackers.
  - Photons (30%) by electromagnetic calorimeter (ECAL).
  - Neutral hadrons (10%) by ECAL + hadron CAL (HCAL)

$$E_{TOTAL} = p_{\text{Lepton}} + p_{\text{Charged Hadron}} + E_{\gamma} + E_{\text{Neutral Hadron}}$$

→Particle Flow Calorimetry

Separation of particles (showers) in the calorimeters is crucial for the particle flow, high granular calorimeters are therefore essential.

Close up view of MC event



Charged hadron : Red, Blue
Electron : Pink
Photon : Green

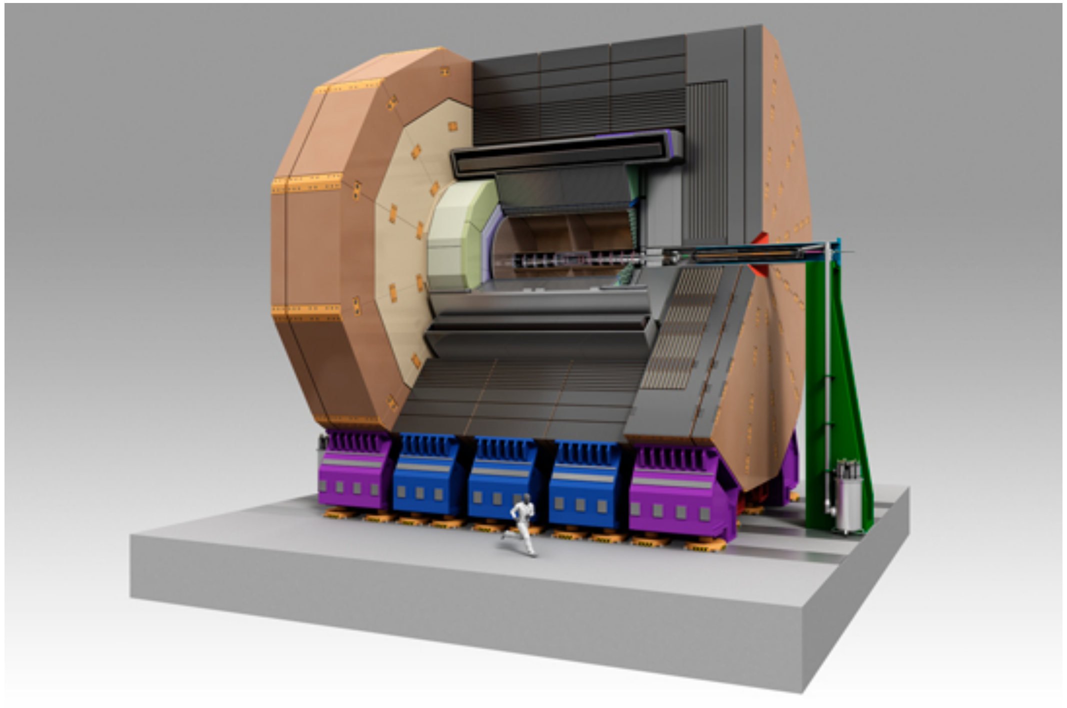
Detectors optimized for Particle Flow

- Figure of Merit for PFA: $$\frac{BR^2}{\sqrt{\sigma^2 + R_M{}^2}}$$

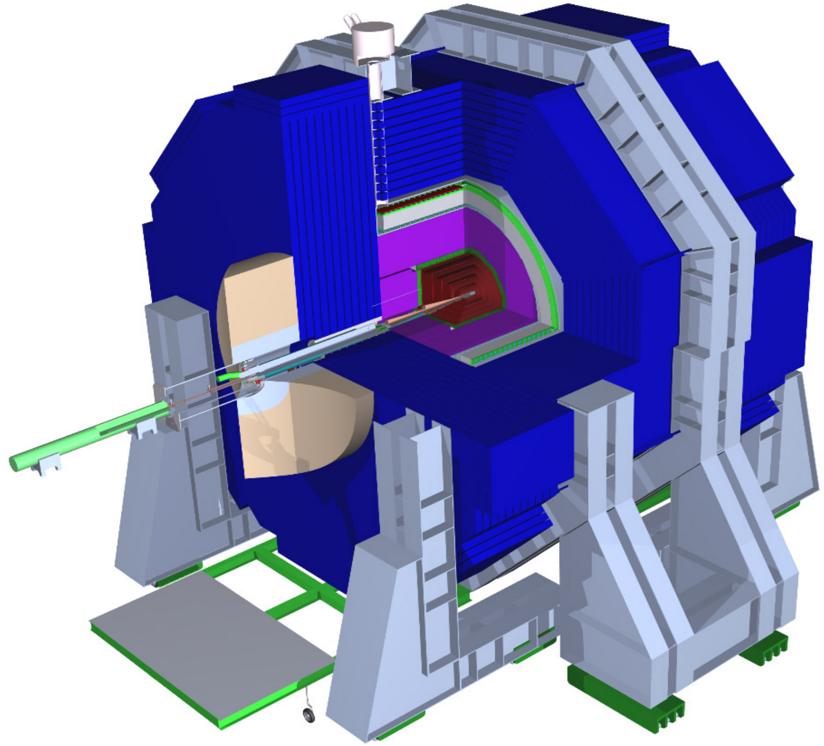
B : Magnetic field
R : calorimeter inner radius
σ : calorimeter granularity
R_M : Moliere radius

→ Large inner radius, large B field and fine granular calorimeter are favored.

- ILD/SiD for ILC/CLIC



large TPC, B = 3.5 T



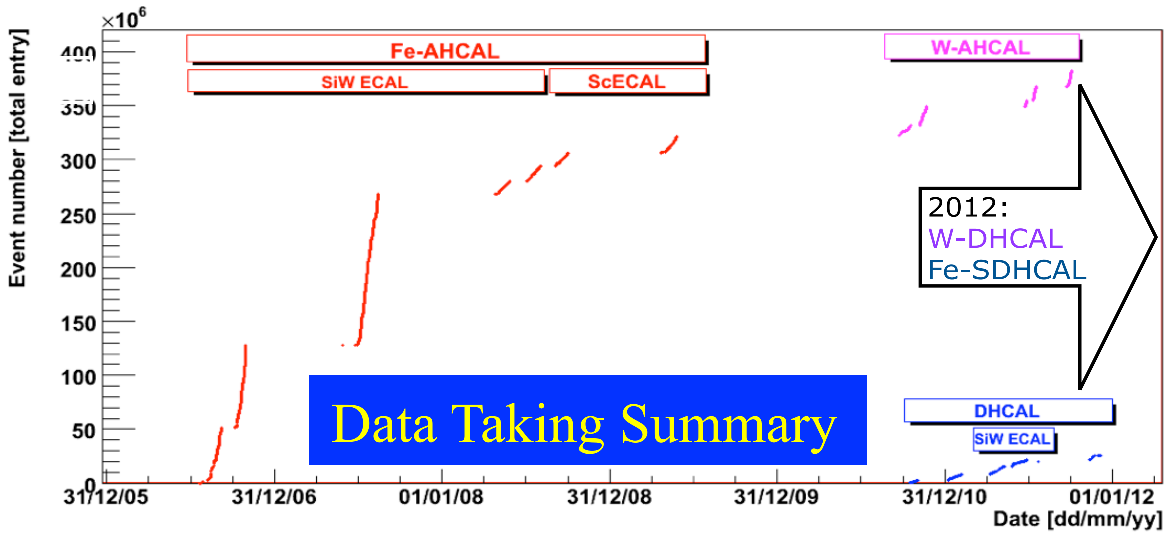
all Si tracker, B = 5T

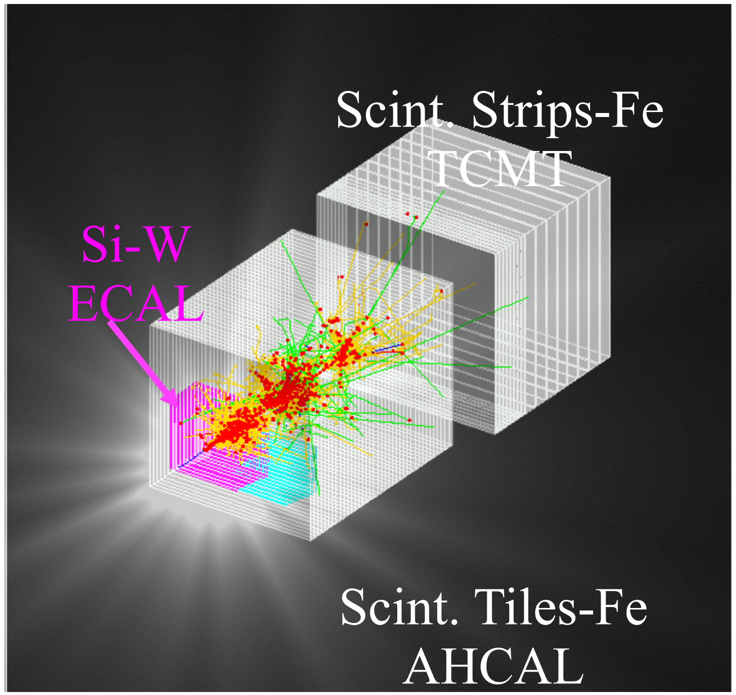
Calorimeter Technologies and Test Beam

- **All calorimeters are designed for the Particle Flow = Fine granular.**

Type	ECAL			HCAL			
Absorber Layer	Tungsten			Tungsten/Iron			
Readout	Analog		Digital	Analog	(Semi)Digital		
Sensitive Layer	Silicon	Scintillator Strip	MAPS	Scintillator Tile	RPC	GEM	Micro Megas

- **A number of test beam have been carried out since 2006 at CERN, DESY, and FNAL.**

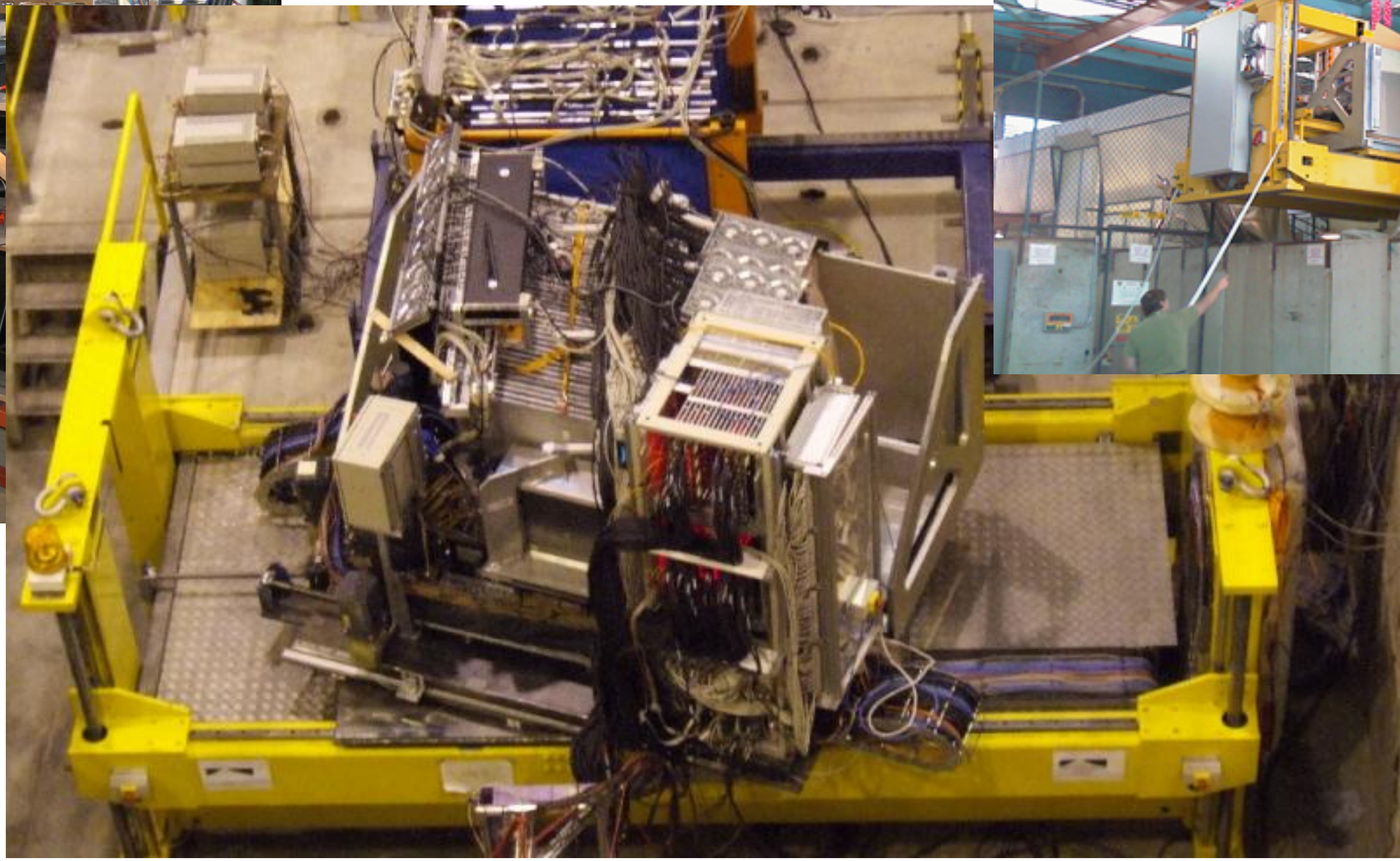




Test Beam 2006~2009

DESY 2005
SiECAL

CERN 2006-2007
add Scint HCAL



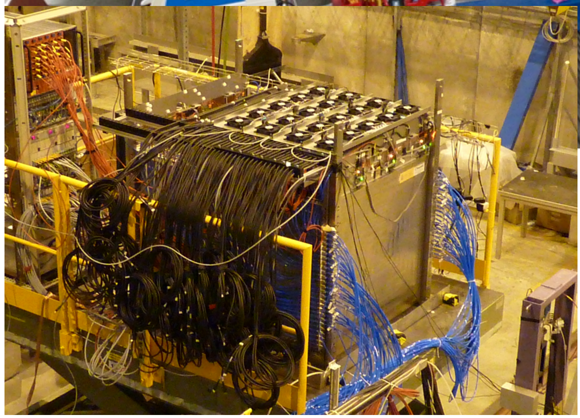
FNAL 2008-09
Si -> Sci ECAL

Test Beam 2010~

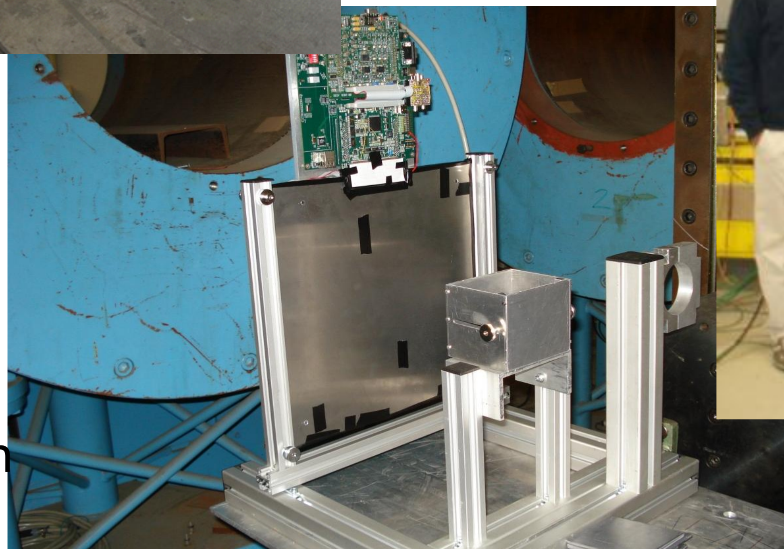
CERN
2010-11
W abs.
AHCAL

2012:
DHCAL

FNAL2010-11:
Scint AHCAL → RPC DHCAL



2012: m^3 SDHCAL



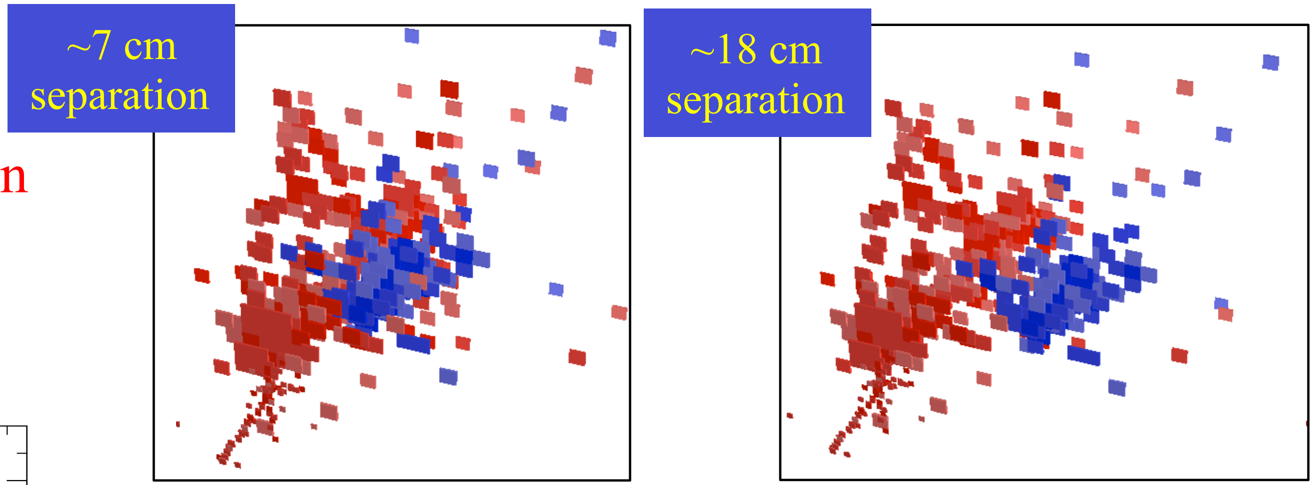
DESY
2nd generation
scint HCAL

Highlight from Test Beam Result

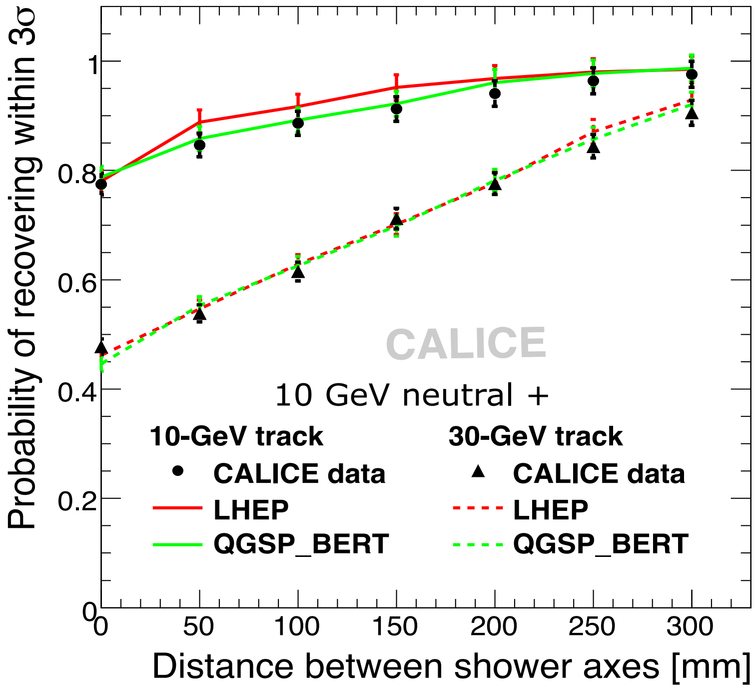
- Demonstration of Two particle separation

✓ Si/W ECAL & Scint. AHCAL

✓ Injected 30GeV Charged hadron and 10GeV Neutral Hadron



JINST 6 (2011) P07005



- Resolution degrades as second particle comes closer.
- MC well reproduces the data.

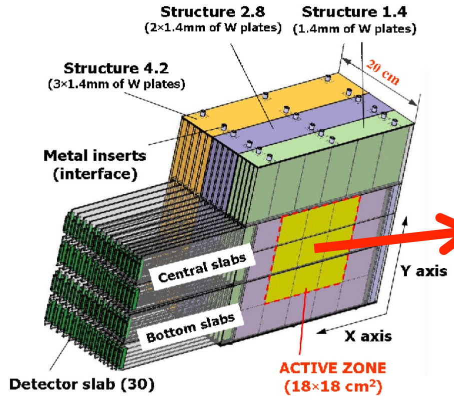
→ Particle Flow works well with fine granular calorimeters!

Si/W ECAL

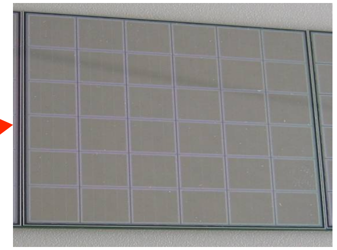
- **Physics Prototype**

✓ Silicon-pad as sensitive layer → $24X_0$, 1 λ_I (30 layers)
✓ Tungsten as absorber layer

- Test of new silicon sensors (5mm x 5mm cell size) are on going at Ecole Polytechnique/Kyushu Univ.

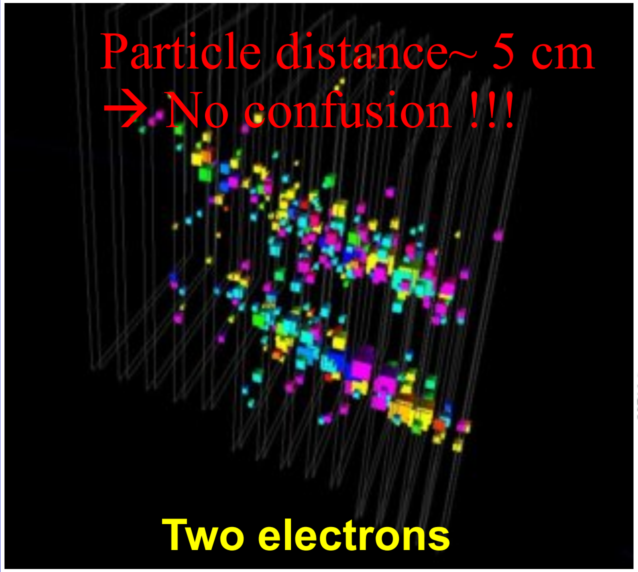


Prototype Si-pad
(1cm x 1cm cell size)

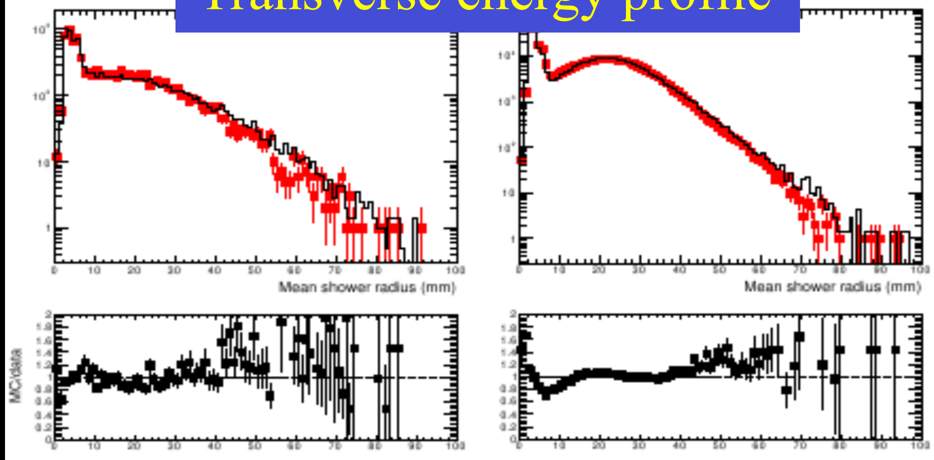


- **Test beams**

✓ 2006, ECAL 2/3 equipped, Low energy electrons (1-6 GeV at DESY), high energy elecrons (6-50 GeV at CERN)
✓ 2007, ECAL nearly completely equipped, High energy pions (6-120 GeV at CERN), Tests of embedded electronics
✓ 2008, FNAL, ECAL completely equipped, Pions at small energy



Transverse energy profile



(a) 2 GeV (e) 10 GeV

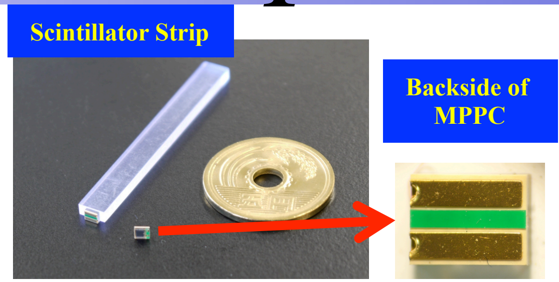
JINST 5 (2011) P05007

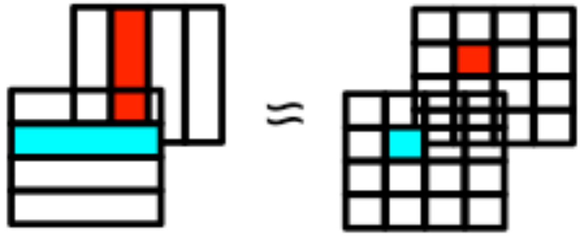
These data are very fruitful for validation of GEANT4 models.

e.g.) For transverse energy profile, QGSP_BERT reproduces the data well especially for higher energies.

Scintillator Strip ECAL

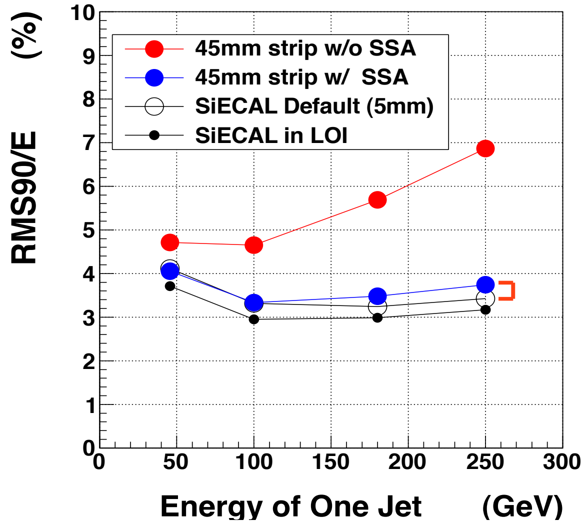
- Sensor : **Scintillator strip + MPPC**
  - ✓ Scintillator strip : 45 x 5 x 2 mm^3
  - ✓ MPPC : 1.4 x 1.4 x 0.6 mm^3





- Scintillator strip in odd layers are orthogonal with respect to those in even layers.

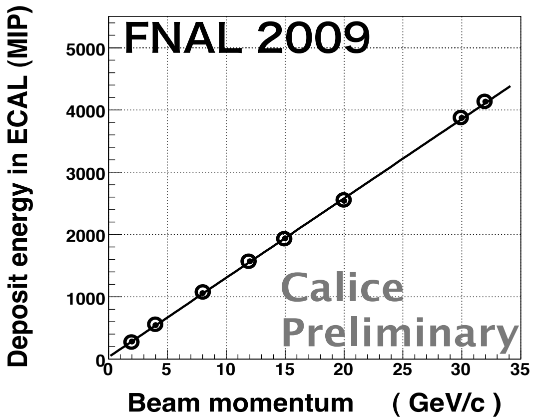
→Effectively 5 x 5 mm^2 lateral granularity (Same as the silicon pad). We can expect the cost reduction compared to the Si/W ECAL.

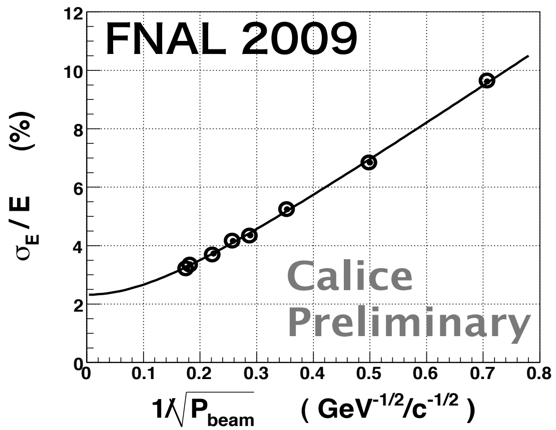


- Need to develop special software algorithm to extract the effective lateral granularity.

- Test Beams since 2007~
  - ✓ Linearity Deviation : <1.5%
  - ✓ Stochastic Term : 13.16+-0.05 %
  - ✓ Constant Term : 2.32+-0.02 %

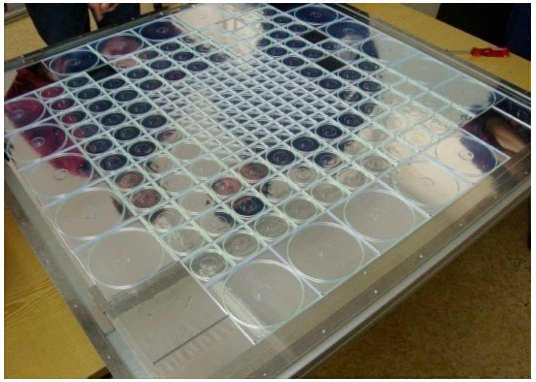
CALICE PRELIMINARY

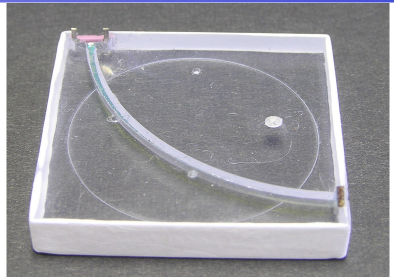


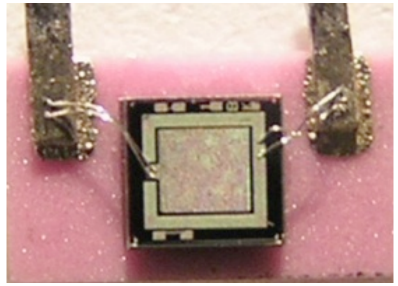


Analog HCAL

- **<u>Physics Prototype</u>**
  - ✓ Sensitive layers: 212 scintillator tiles.
  - ✓ Light collection via WLS fiber and SiPM readout.
  - ✓ **Iron** as absorber layer.

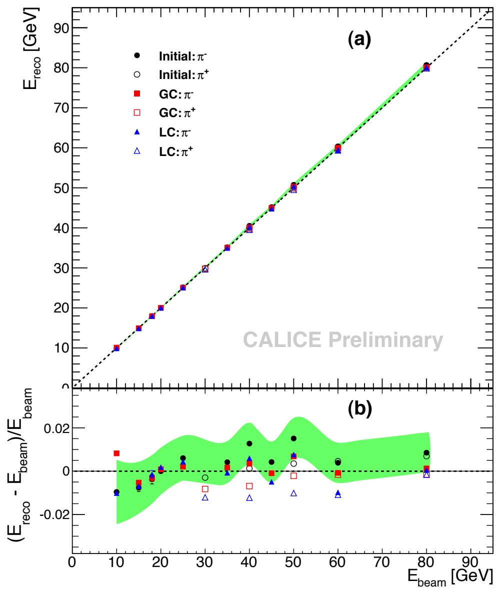


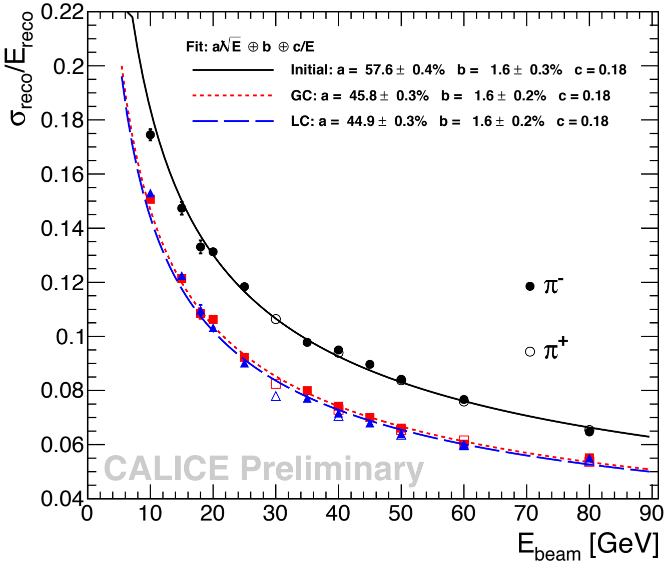




- Test beam was performed in 2006-2011
  - ✓ Excellent electromagnetic performance

- The calorimeter is non-compensating. High granularity can be used to distinguish electromagnetic and hadronic energy deposit.
  →Software compensation

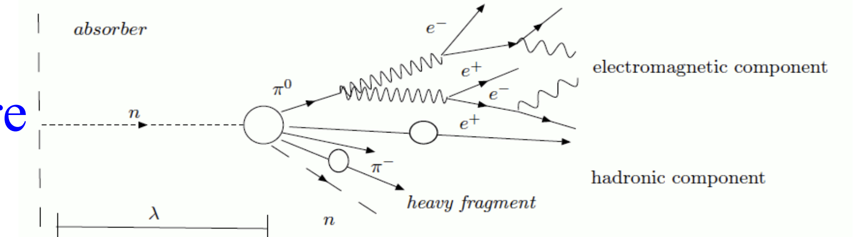




Resolution 57.6% → 45% Linearity : < 1.5 %

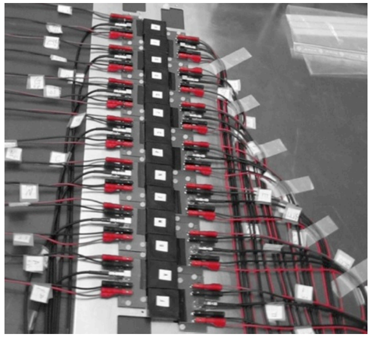
Study of Time Structure of Hadronic Shower

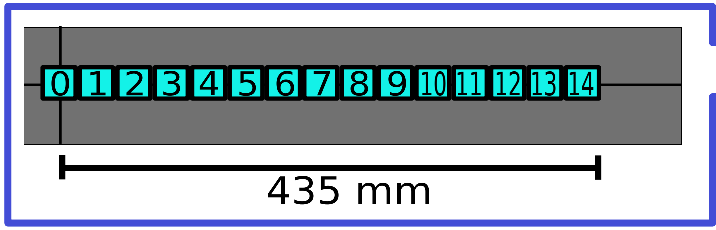
- T3B (Tungsten Timing Test Beam) is first dedicated experiment to study the time structure of hadronic shower for CLIC HCAL.



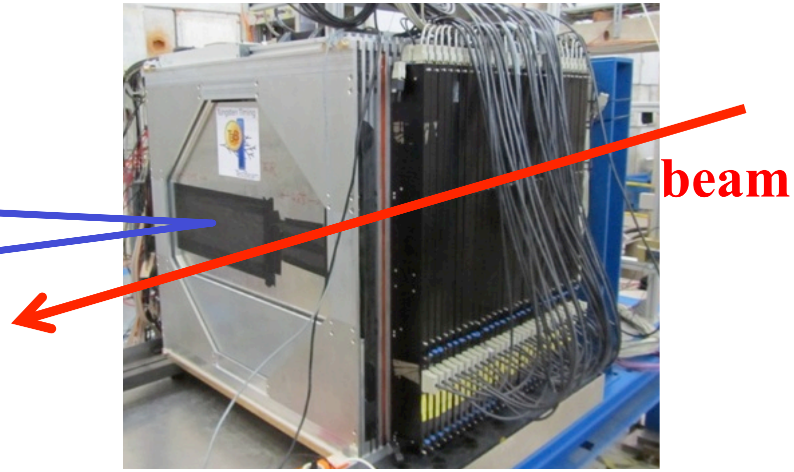
Hadronic Shower : Complicated (Time) Structure

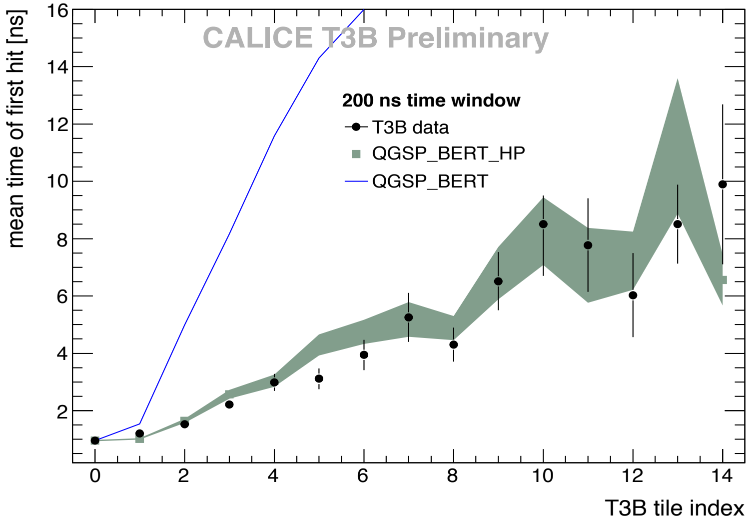
- 15 3 x 3 cm^2 scintillator cells were installed downstream of **CALICE Tungsten HCAL** to study the radial extent of the hadronic shower

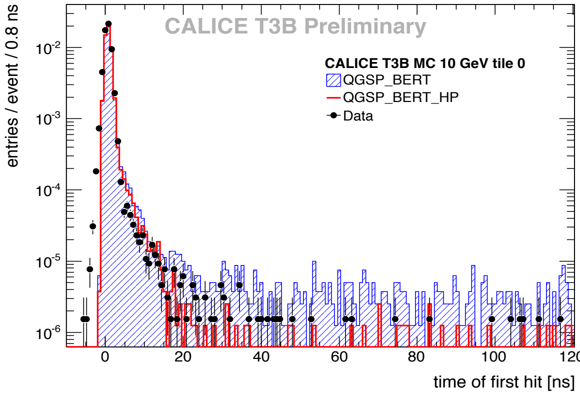




Beam axis through cell 0





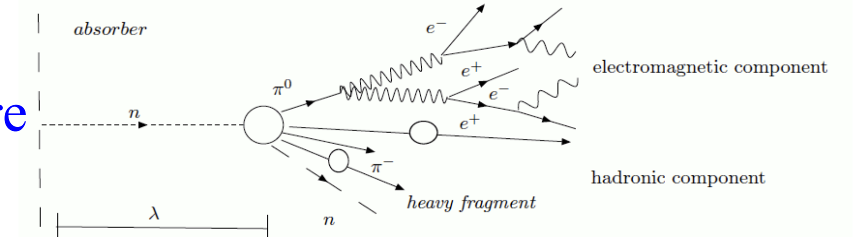


- Mean time of first hit is compared to Geant4.

→ **Data is consistent with the QGSP_BERT_HP.**

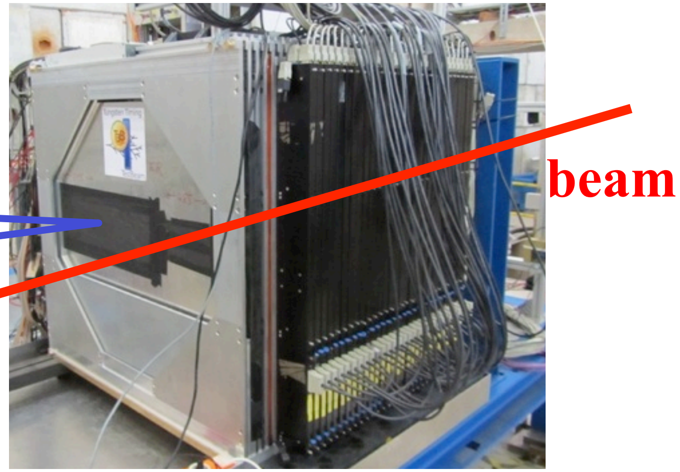
Study of Time Structure of Hadronic Shower

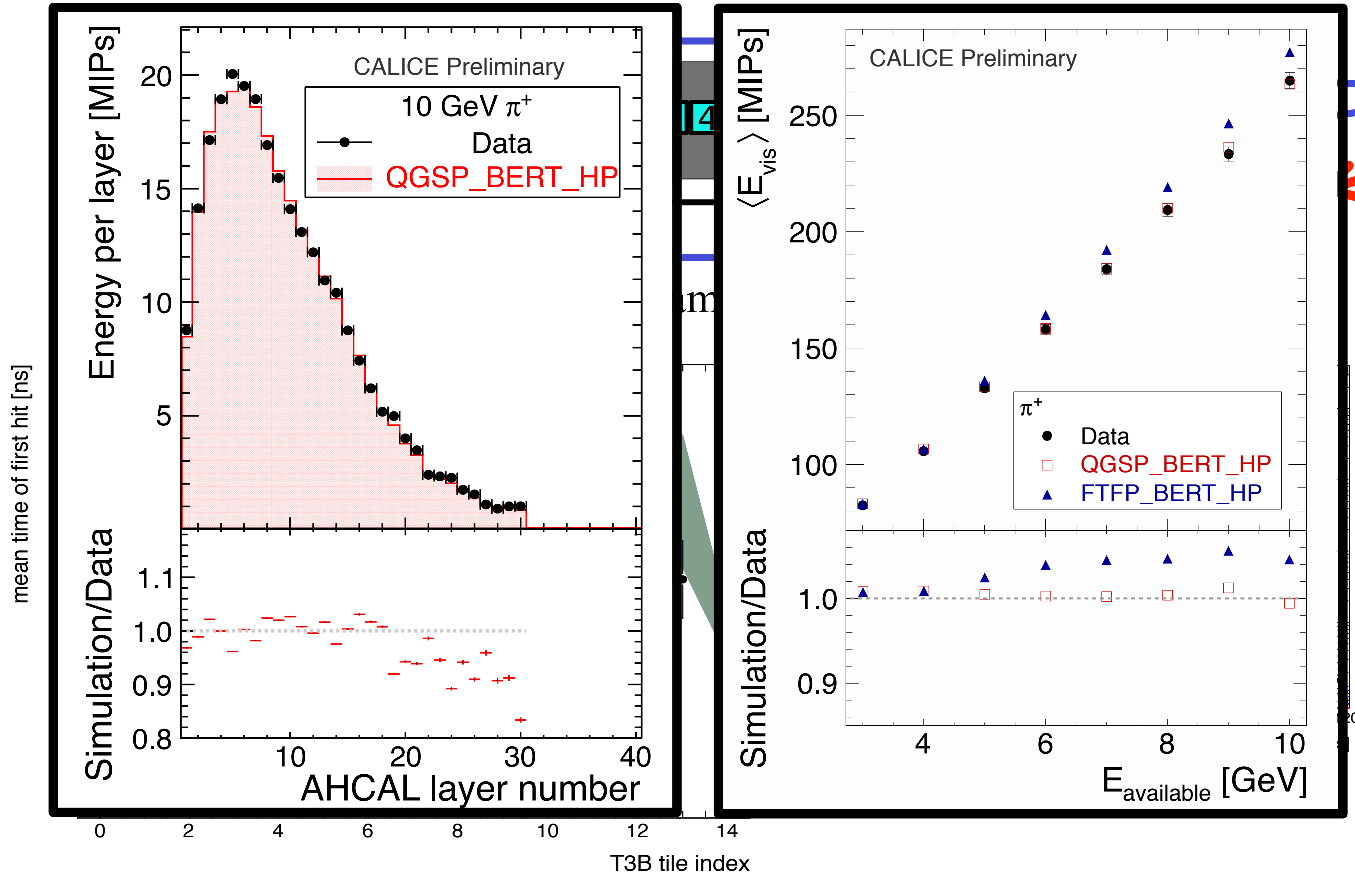
- T3B (Tungsten Timing Test Beam) is first dedicated experiment to study the time structure of hadronic shower for CLIC HCAL.



Hadronic Shower : Complicated (Time) Structure

- 15 3 x 3 cm^2 scintillator cells were installed downstream of **CALICE Tungsten HCAL** to study the radial extent of the hadronic shower



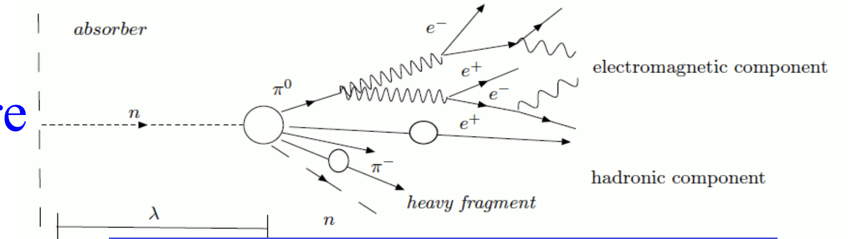


- Mean time of first hit is compared to Geant4.

→ **Data is consistent with the QGSP_BERT_HP.**

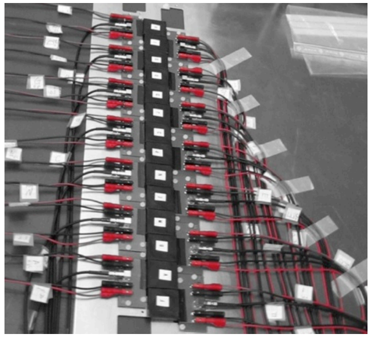
Study of Time Structure of Hadronic Shower

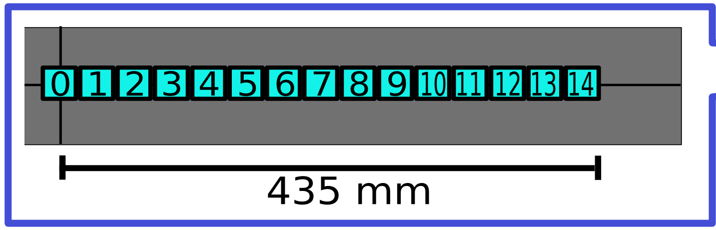
- T3B (Tungsten Timing Test Beam) is first dedicated experiment to study the time structure of hadronic shower for CLIC HCAL.



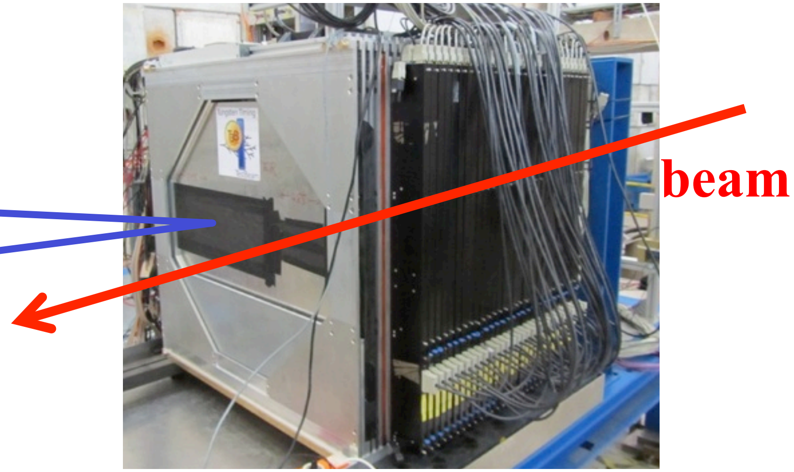
Hadronic Shower : Complicated (Time) Structure

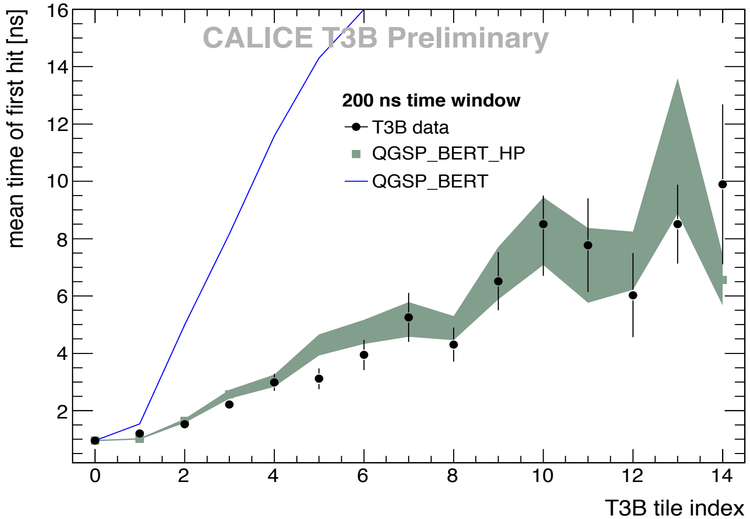
- 15 3 x 3 cm^2 scintillator cells were installed downstream of **CALICE Tungsten HCAL** to study the radial extent of the hadronic shower

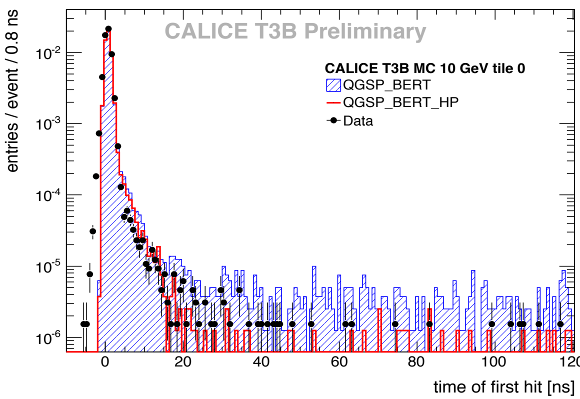




Beam axis through cell 0







- Mean time of first hit is compared to Geant4.

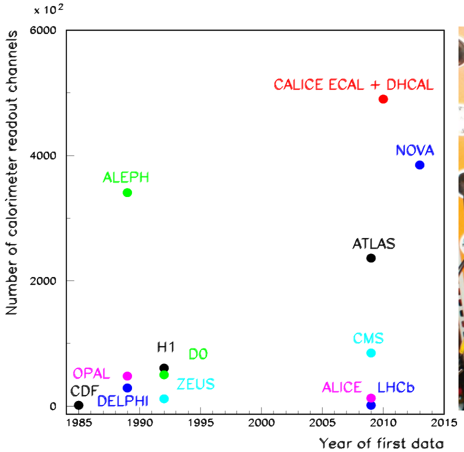
→ **Data is consistent with the QGSP_BERT_HP.**

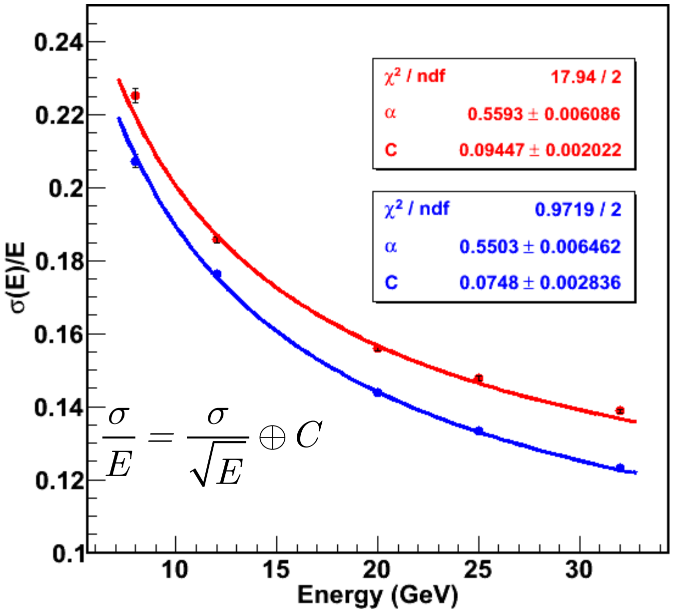
Digital HCAL

- Even finer granularity than analogue calorimeter. Binary (one-bit) readout is enough due to the large number of cells. **→Digital Calorimeter**

- **RPC/DHCAL**
  - ✓ RPC layers are inserted in the the existing CALICE AHCAL.

  →480k channels (World record!)

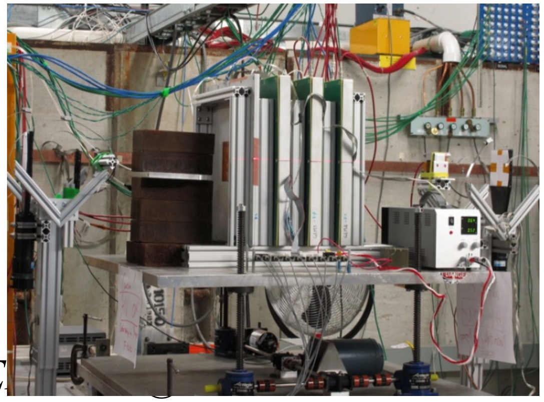


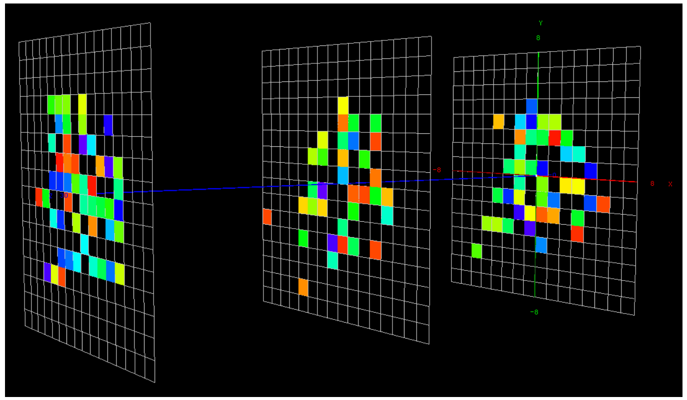


Standard pion selection

+ No hits in last two layers (No leakage)

- **GEM/DHCAL**
  - ✓ Test beam was carried out with the 30 x 30 cm^2 GEM chambers in Aug. 2011. Analysis is ongoing.



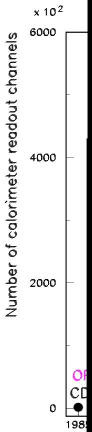


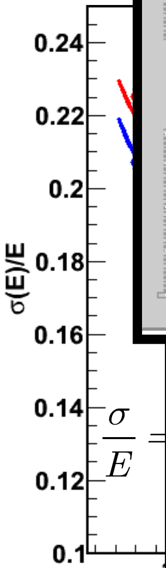
tal F

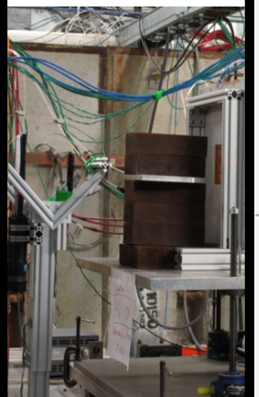
calorime

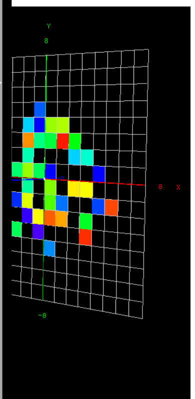
igital Ca

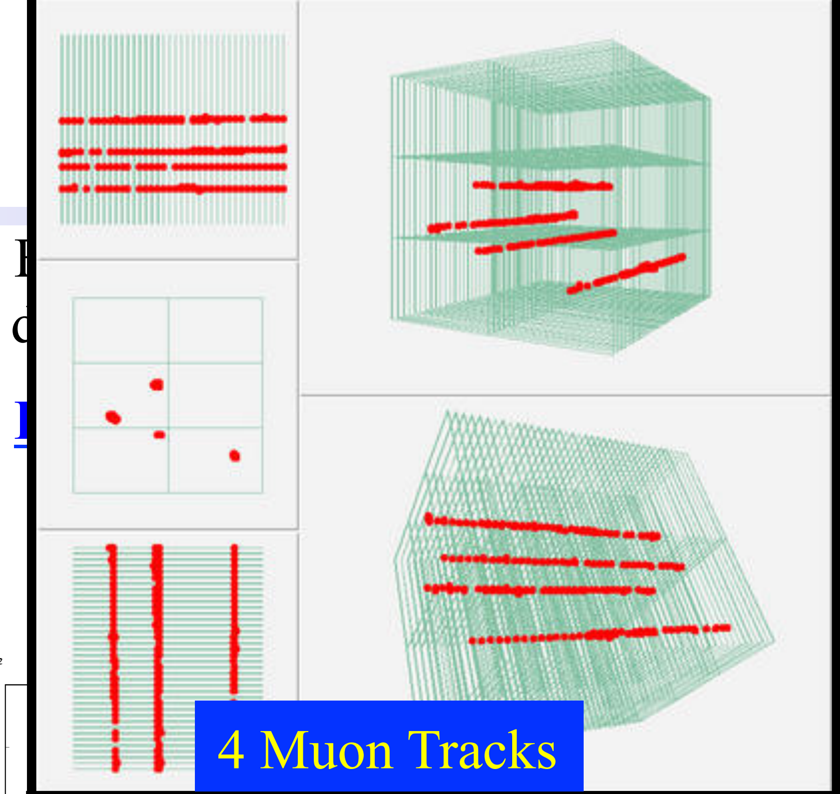
e

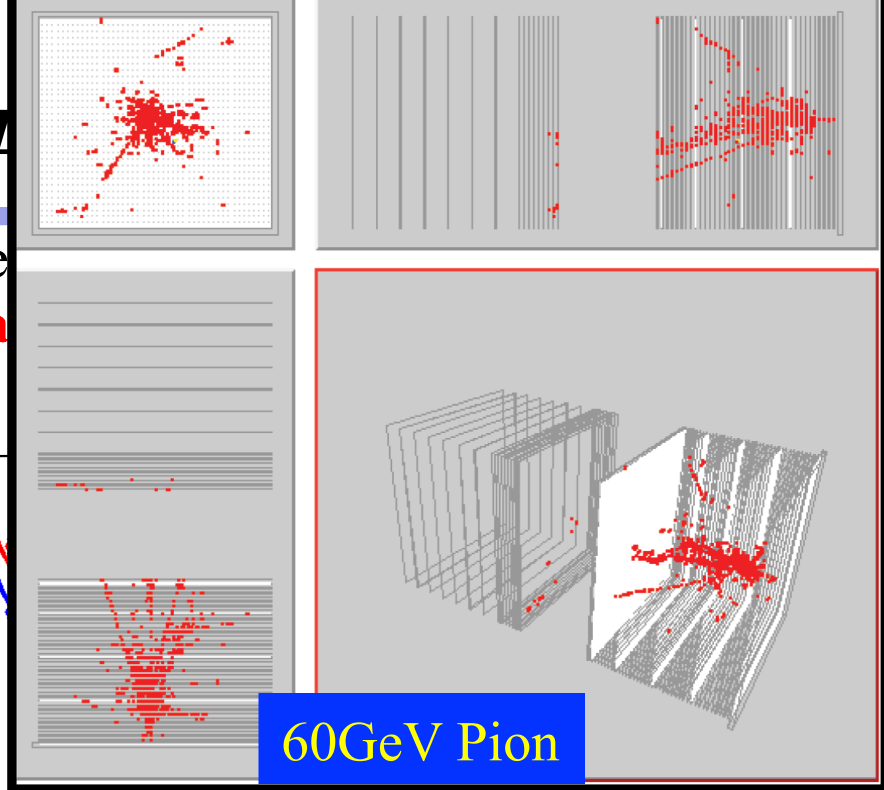






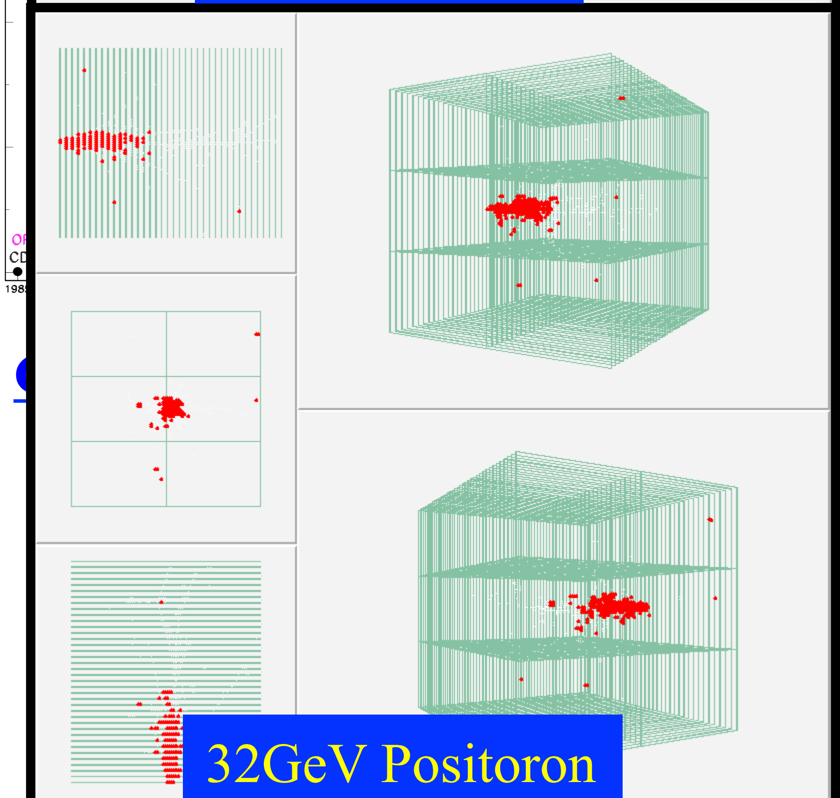


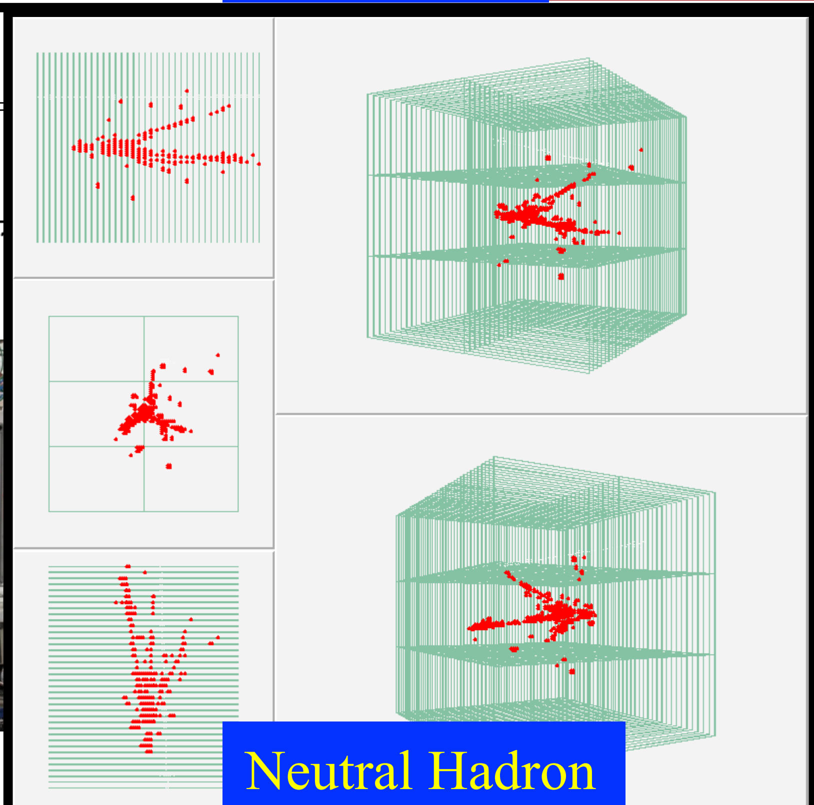

4 Muon Tracks


60GeV Pion

st two

akage)


32GeV Positoron

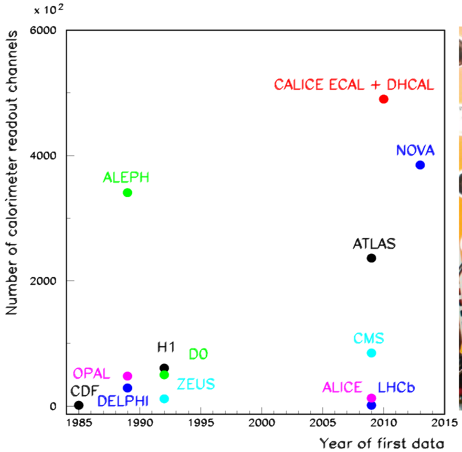

Neutral Hadron

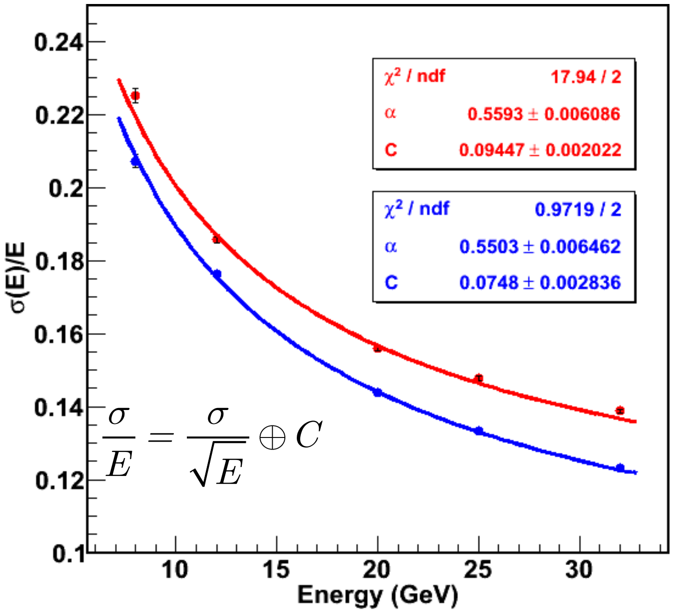
Digital HCAL

- Even finer granularity than analogue calorimeter. Binary (one-bit) readout is enough due to the large number of cells. →**Digital Calorimeter**

- **RPC/DHCAL**
  - ✓ RPC layers are inserted in the the existing CALICE AHCAL.

  →**480k channels (World record!)**

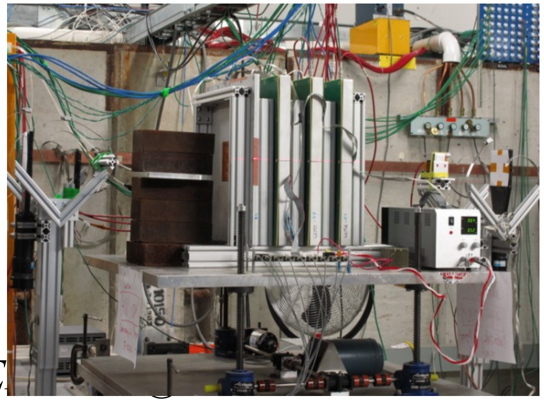


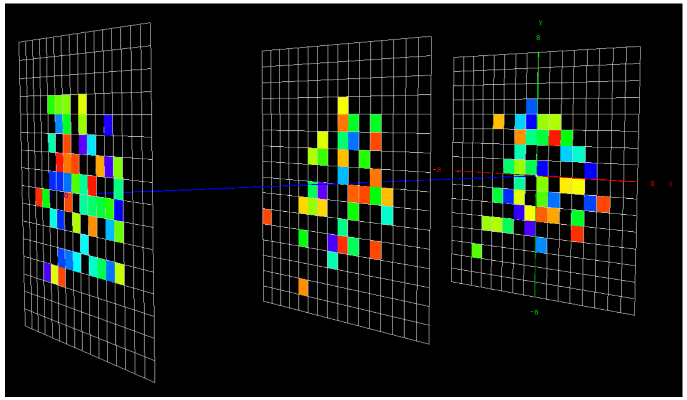


Standard pion selection

+ No hits in last two layers (No leakage)

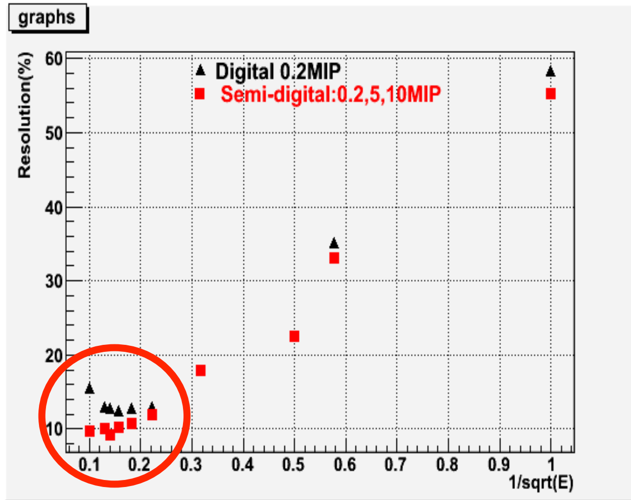
- **GEM/DHCAL**
  - ✓ Test beam was carried out with the 30 x 30 cm^2 GEM chambers in Aug. 2011. Analysis is ongoing.



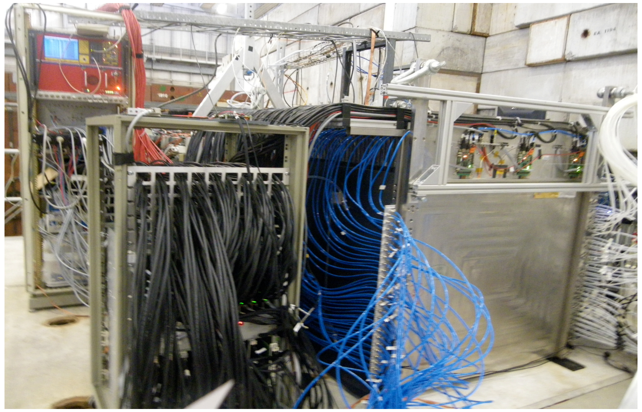


Semi-digital HCAL

- Good energy resolution can be achieved by the digital calorimeter.
- However, the shower core is very dense at high energy and saturation will occur. Two-bits readout improves the resolution.

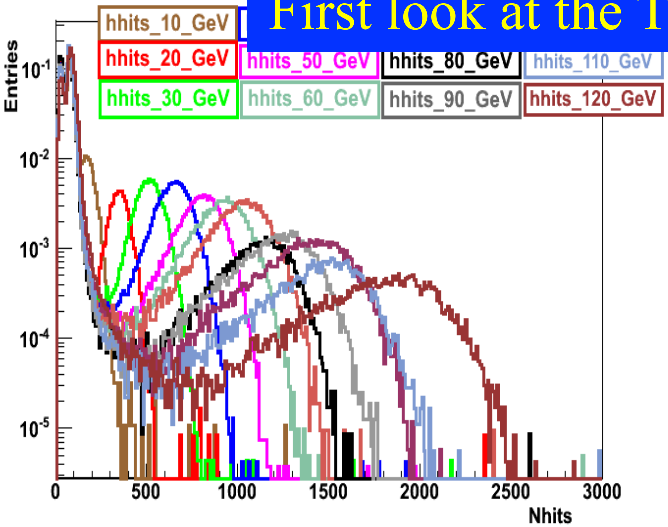


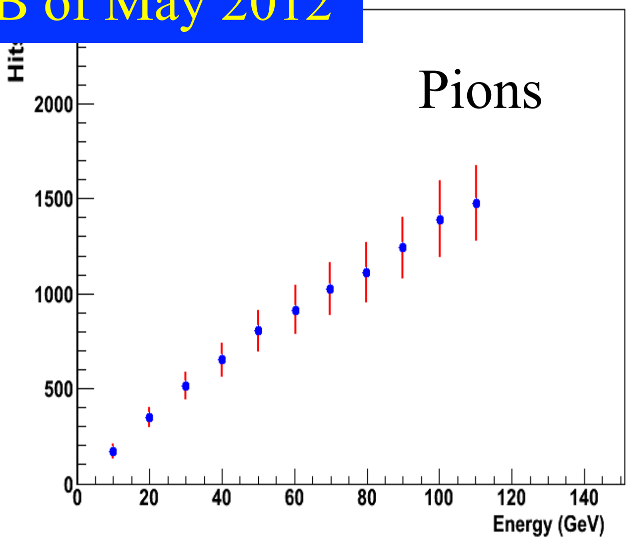
→Semi-digital calorimeter



- **GRPC/SDHCAL**
  - ✓ 48 GRPC as active layers
  - ✓ Iron as absorber layers
  - ✓ 1 x 1 m^2, $6\lambda_I$

First look at the TB of May 2012

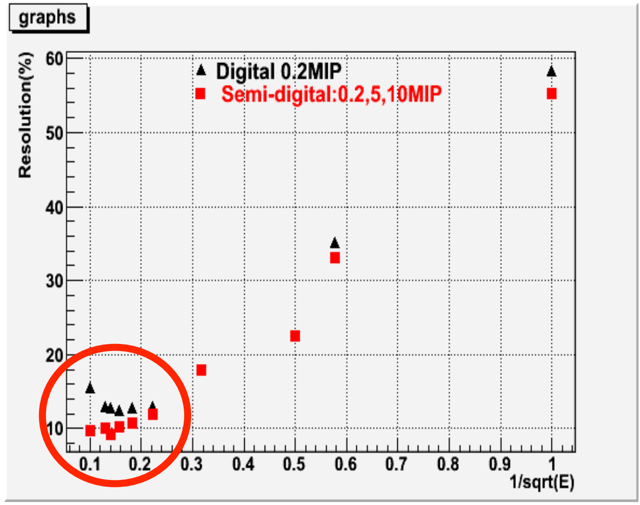




- Raw data
- No gain correction
- Only first threshold
- No selection except time hit clustering

Semi-digital HCAL

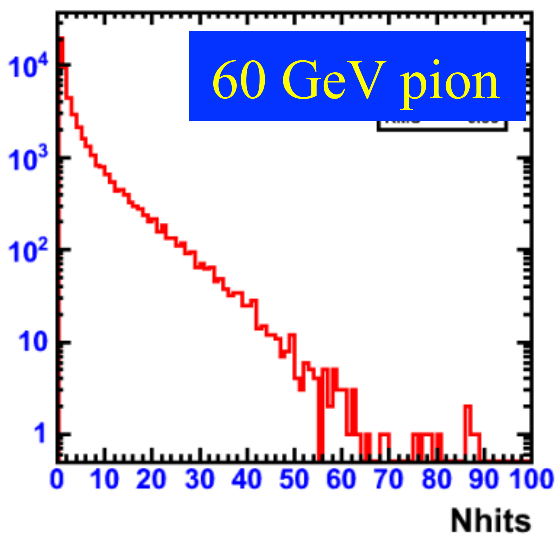
- Good energy resolution can be achieved by the digital calorimeter.
- However, the shower core is very dense at high energy and saturation will occur. Two-bits readout improves the resolution.

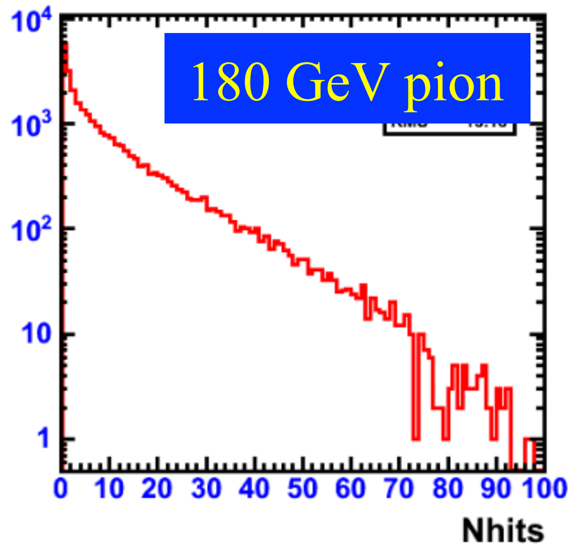


→**Semi-digital calorimeter**

- **Micromegas/SDHCAL**
  - ✓ 1 m^2 micromegas layer
  - ✓ 9216 pads of 1 cm^2
  - ✓ 7mm thickness

- 2 weeks operation in August 2011
  - ✓ Efficiency = 98%
  - ✓ Hit multiplicity = 1.15
  - ✓ Noise = 0.1Hz





- Test beam of 4 micromegas layers is expected in this year.

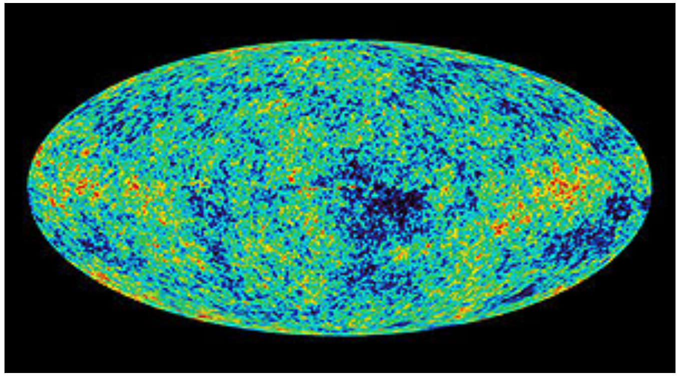
Summary

- The CALICE collaboration is aiming to establish high granular calorimeter system optimized for the particle flow measurement of multi-jets final state at a future linear collider.

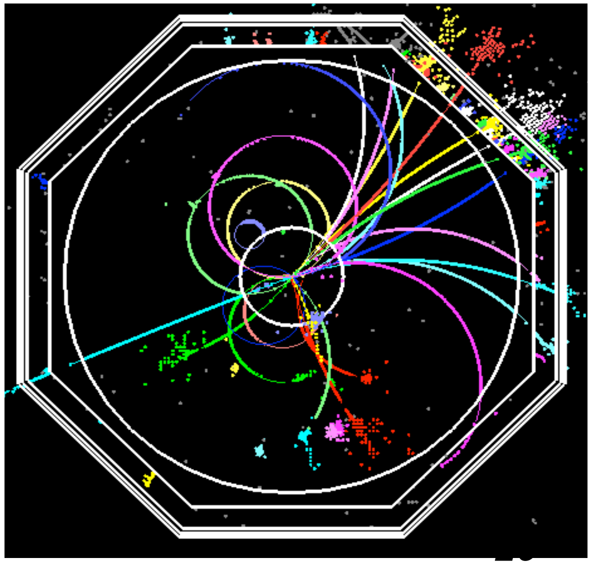
- A number of test beam have been intensively carried out since 2006 in order to prove the principle of each technologies.

  → Excellent performance has been shown, although some analyses are still ongoing or just started.

- We are now moving to next stage: **Physics Prototype** → **Technological Prototype**



Precise measurement tells us a lot!



Backup