# SiW ECAL
# Test beam results

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## Disclaimer

This talk will report exclusively results obtained
For beam tests with Silicon as active material

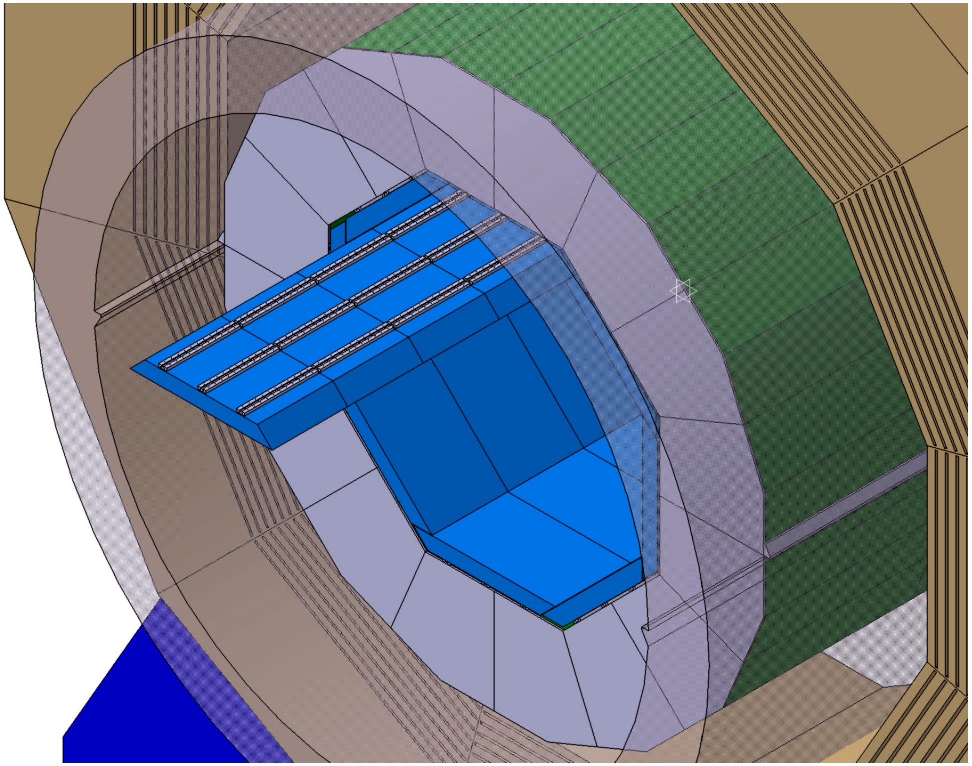
This is the technology fostered in France in the last ~10 years

The ILC detector concepts comprise also an option with scintillator as active material

Apologises for not mentioning this

# SiW Ecal - Basics

The SiW Ecal in the ILD Detector



## Basic Requirements

- Extreme high granularity
- Compact and hermetic

## Basic Choices

- Tungsten as absorber material
  - $X_0$=3.5mm, $R_M$=9mm, $\lambda_I$=96mm
  - Narrow showers
  - Assures compact design
- Silicon as active material
  - Support compact design
  - Allows for pixelisation
  - Large signal/noise ratio

SiW Ecal designed as Particle Flow Calorimeter

# The CALICE Collaboration

Calorimeter for ILC

## Calorimeter R&D for the ilc

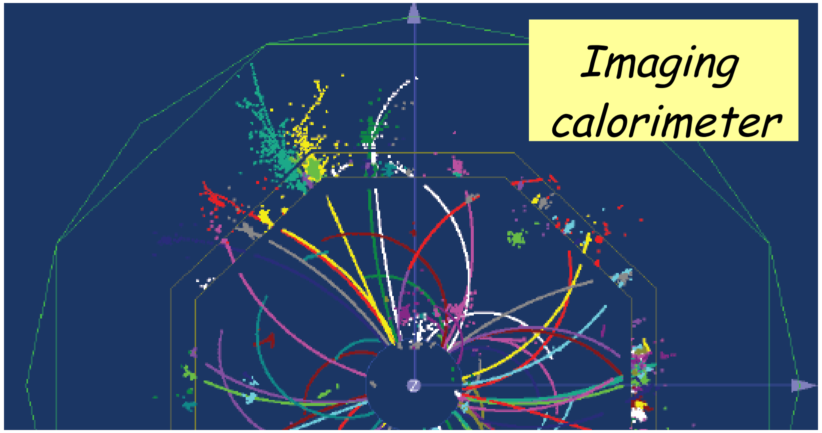
~330 physicists/engineers from 57 institutes
and 17 countries from 4 continents

- Integrated R&D effort

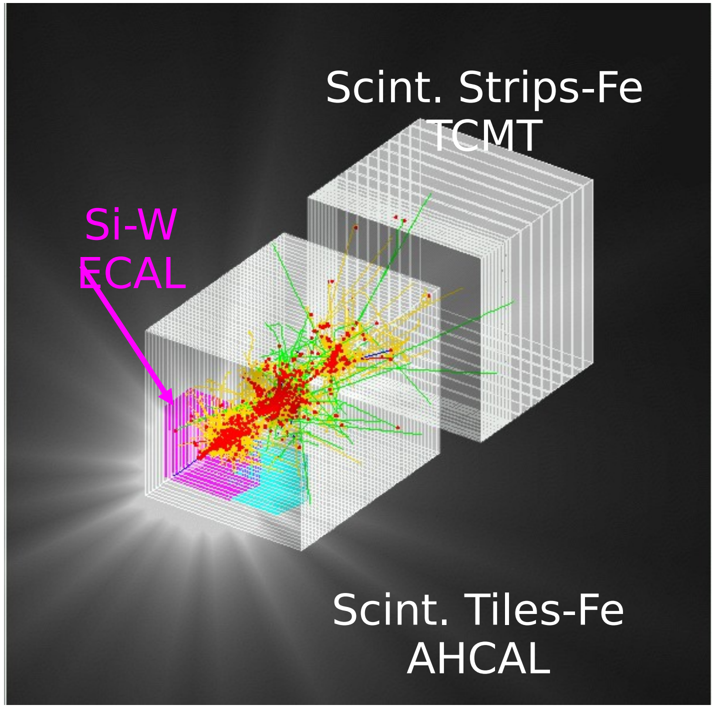
- Benefit/Accelerate detector development due to *common* approach

# The Calice Mission

## Final goal:



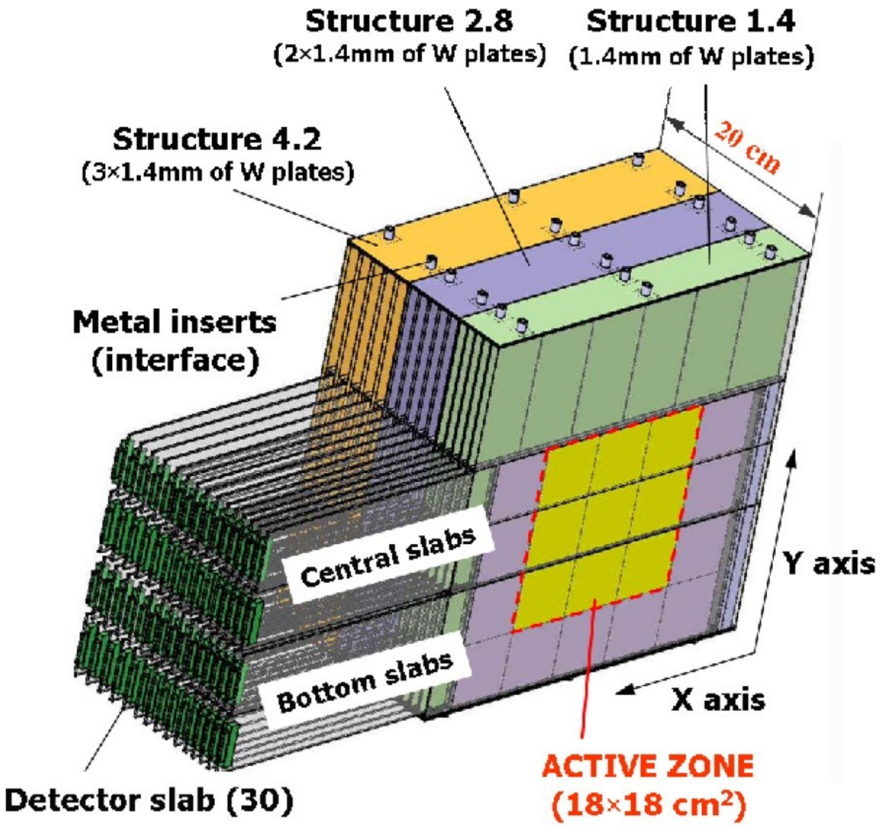

A highly granular calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider




## Intermediate task:

Build prototype calorimeters to
- Establish the technology
- Collect hadronic showers data with unprecedented granularity to
  - tune clustering algorithms
  - validate existing MC models

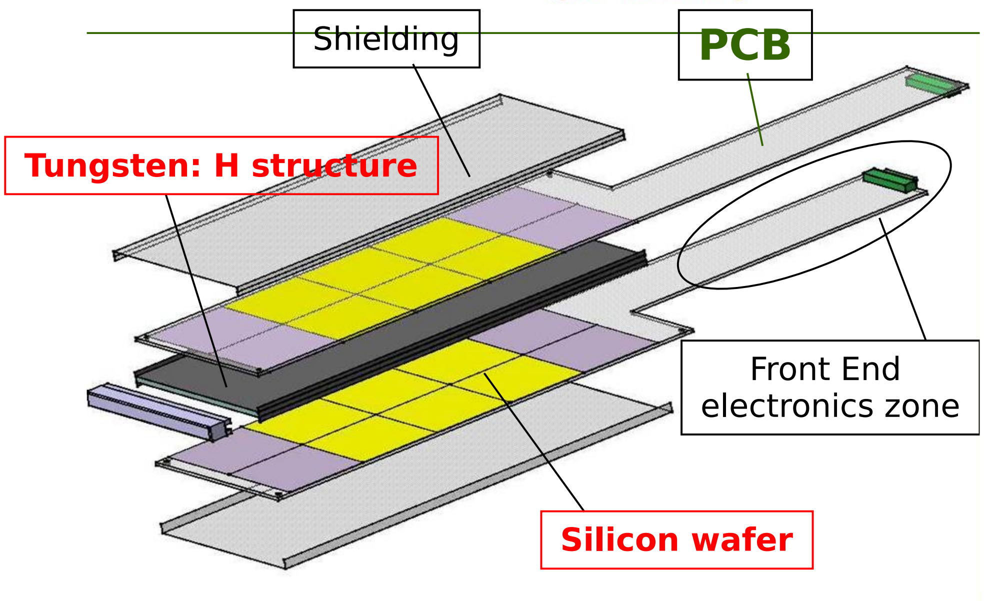
# SiW Ecal Physics Prototype




30 layers of Tungsten:

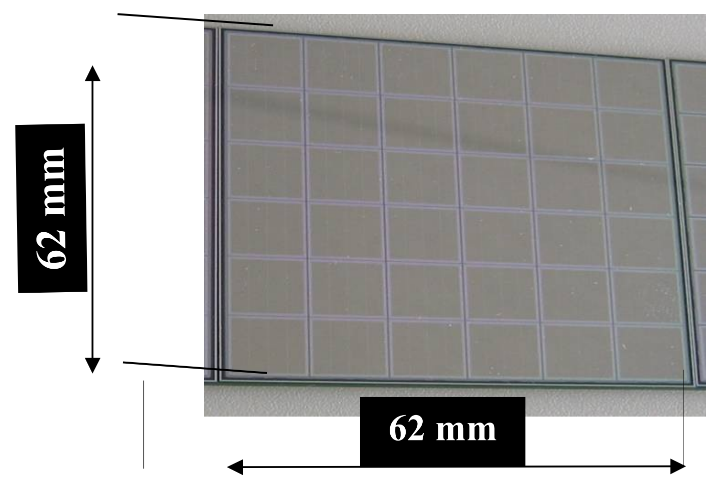
- 10 x 1.4 mm (0.4 $X_0$)
- 10 x 2.8 mm (0.8 $X_0$)
- 10 x 4.2 mm (1.2 $X_0$)
  - 24 $X_0$ total, 1 $\lambda_I$

½ integrated in detector housing
⇒ Compact and self-supporting detector design




## 6x6 PIN Diode Matrix

Resistivity: 5kΩcm - 80 (e/hole pairs)/µm




Thickness: 525µm

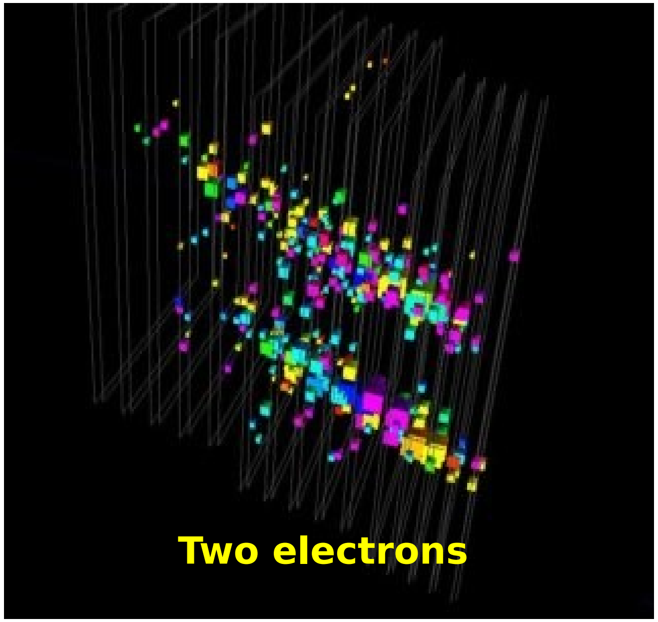
Total: 9720 Pixels/Channels

# Large Scale Beam Tests

## Experimental Setup

Zoom into Ecal

Particle Distance~ 5 cm
→ No Confusion !!!




- 2006, Ecal 2 / 3 equipped
  Low energy electrons (1-6 GeV at DESY), high energy electrons (6-50 GeV at CERN)

- 2007, Ecal nearly completely equipped
  High energy pions (6-120 GeV CERN), Tests of embedded electronics

- 2008 FNAL, Ecal completely equipped
  Pions at low energy,

- 2008 FNAL, Ecal completely equipped
  Pions at low energy,

# Summary of experience with physics prototype

- Successful running of SiW Ecal physics prototype between 2005 and 2011

- Quick installation and easy operation

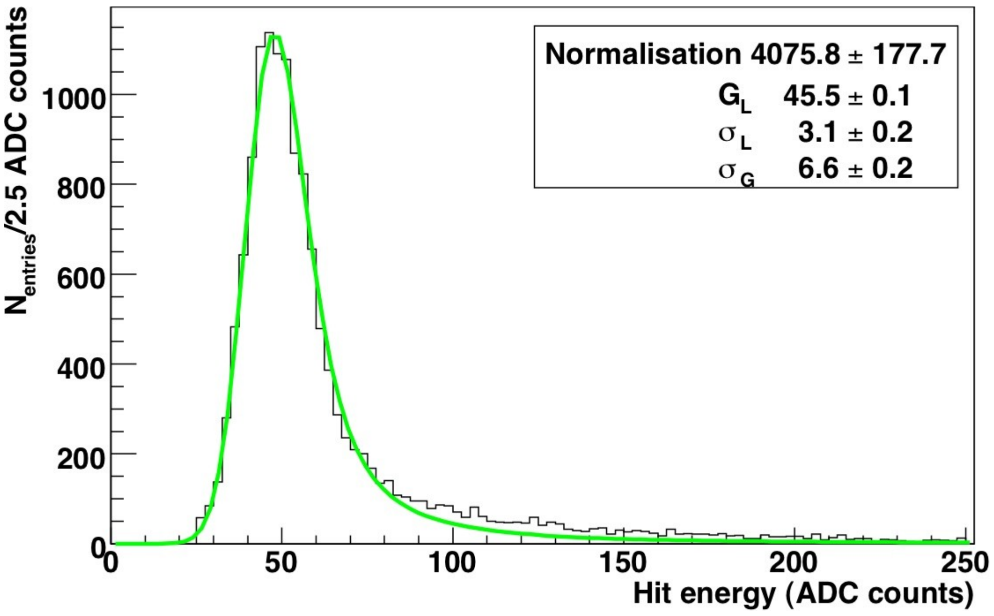
- Stable response over 6 years

- Occurring noise problems could be largely remedied by careful revision of detector grounding
  Offline corrections

- Calibration procedure fairly simple

- Slow control and diagnostics to be improved for next prototype
  e.g. was very tedious to spot a broken wafer in 2011

# Calibration – Uniformity of Response



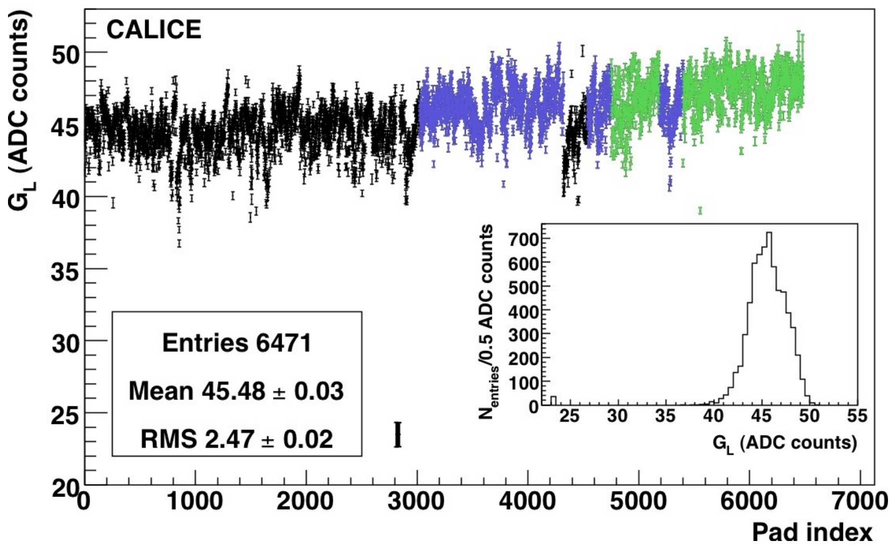

Calibration with with wide spread μ-beam

18 Mio. Events
Uniform response of all cells
only 1.4‰ DEAD CELLS

Differences in Response can attributed to different

- Manufacturers
- Production series

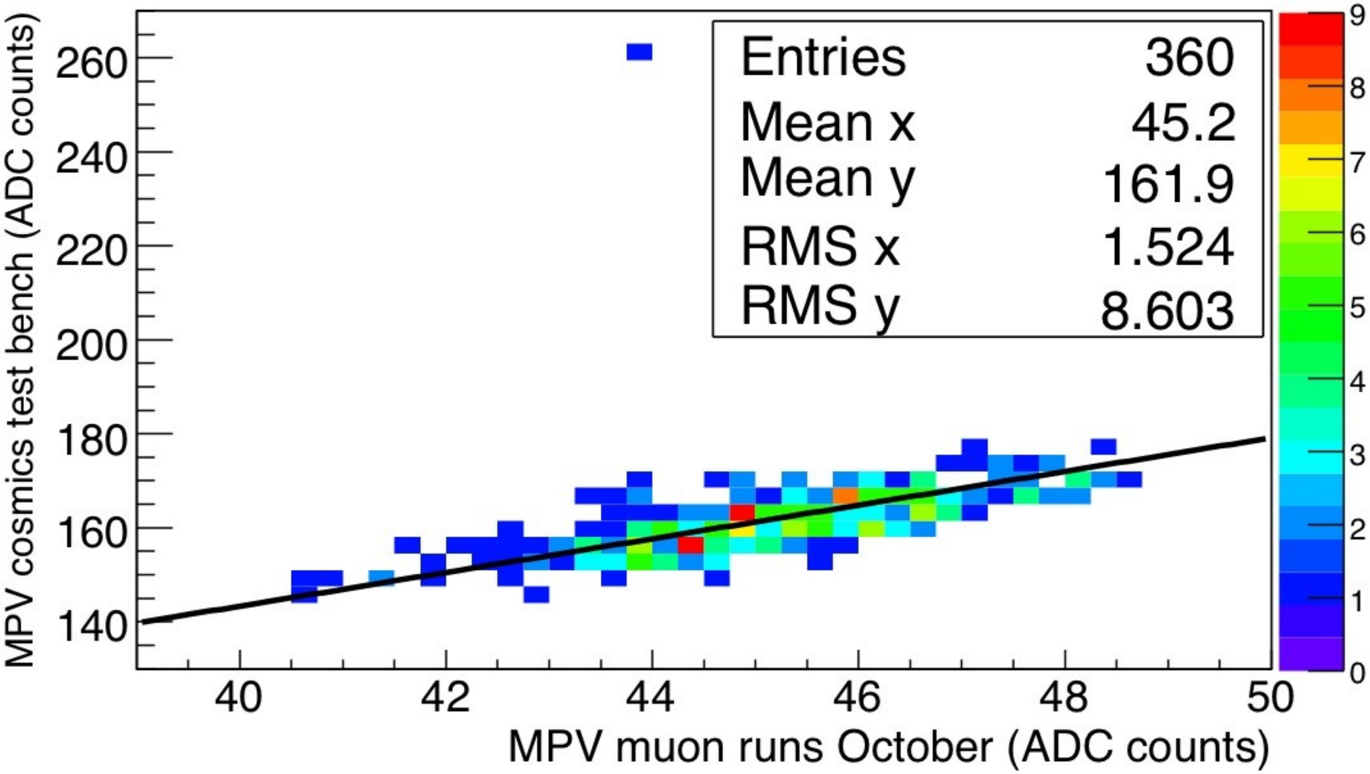
Experience to deal with different manufacturers and production series
Essential for final detector
~3000m$^2$ of Silicon needed



# Stability of Calibration?

Affects both: precision and operability of detector: ~$10^8$ calo cells in ILC Detector

Calibration Constants on testbench and in beam test campaign

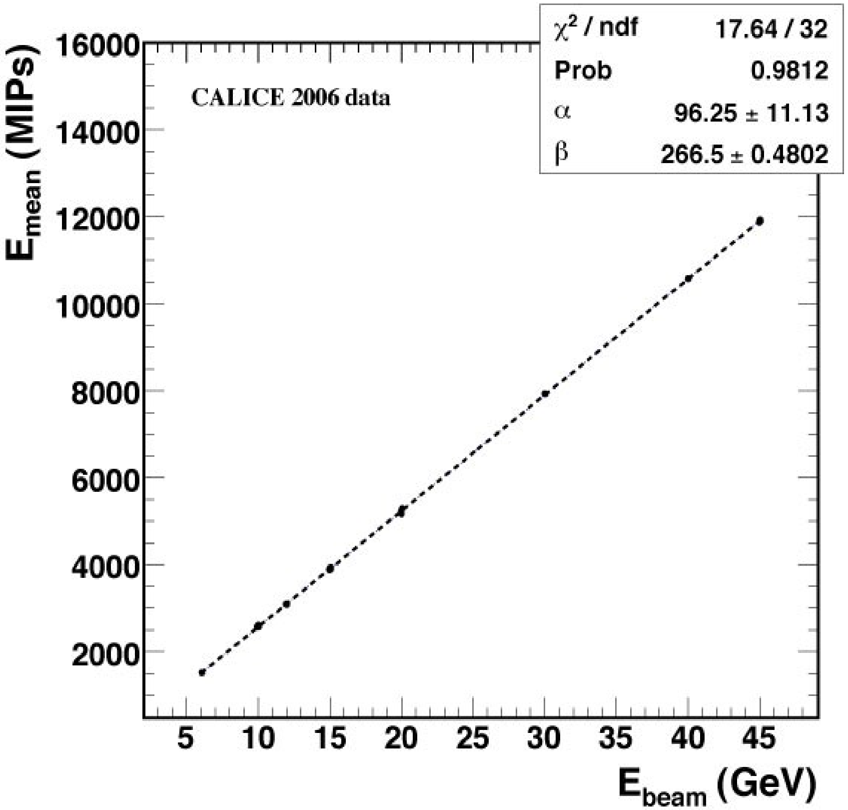



High Correlation between calibration constants
Result confrimed for 2008 and 2011 data

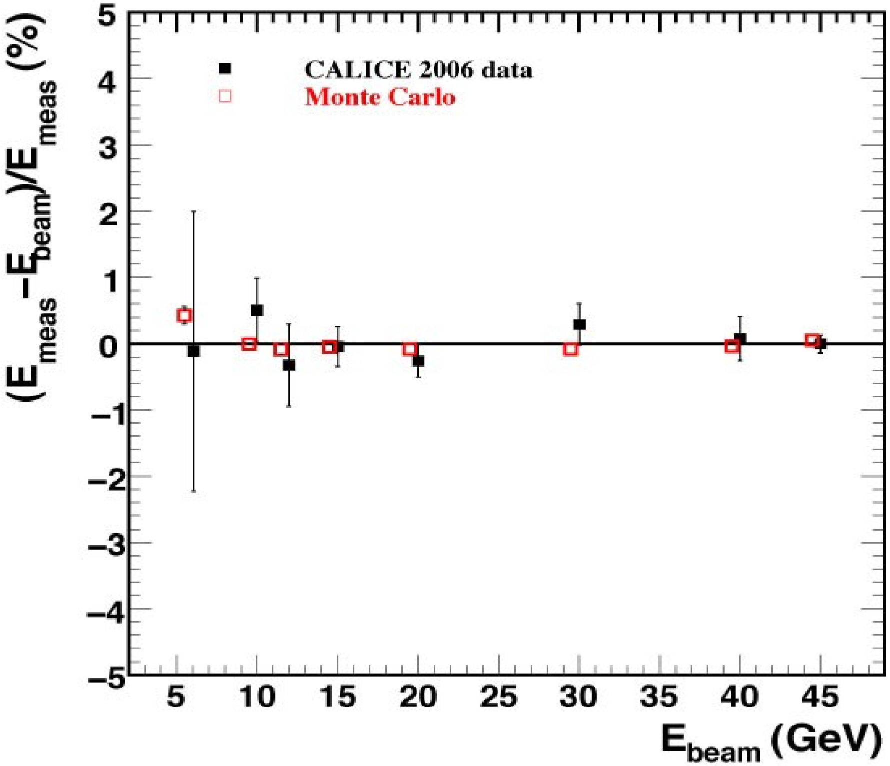
For “final” detector:
Detector modules can be calibrated in beam test prior to installation

# Linearity of Response

Overview




Residuals

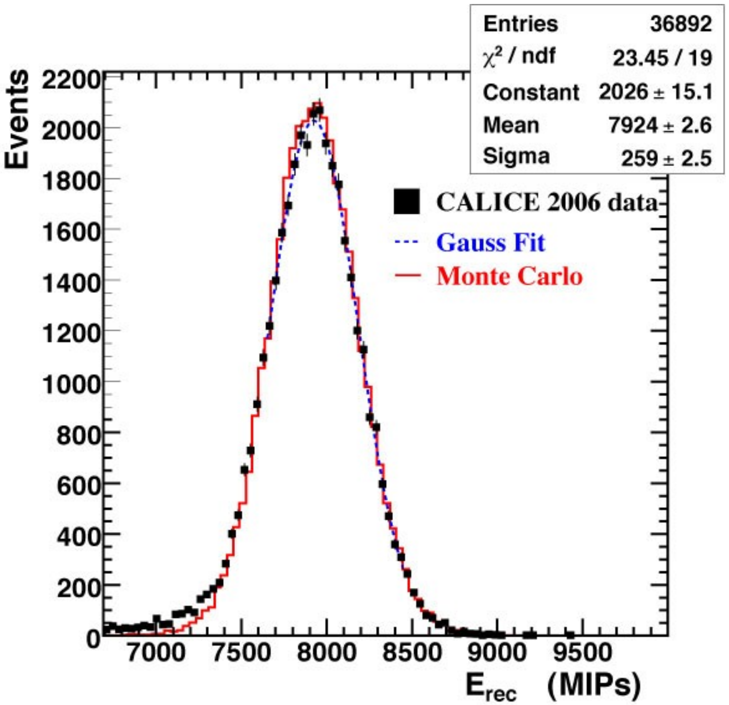


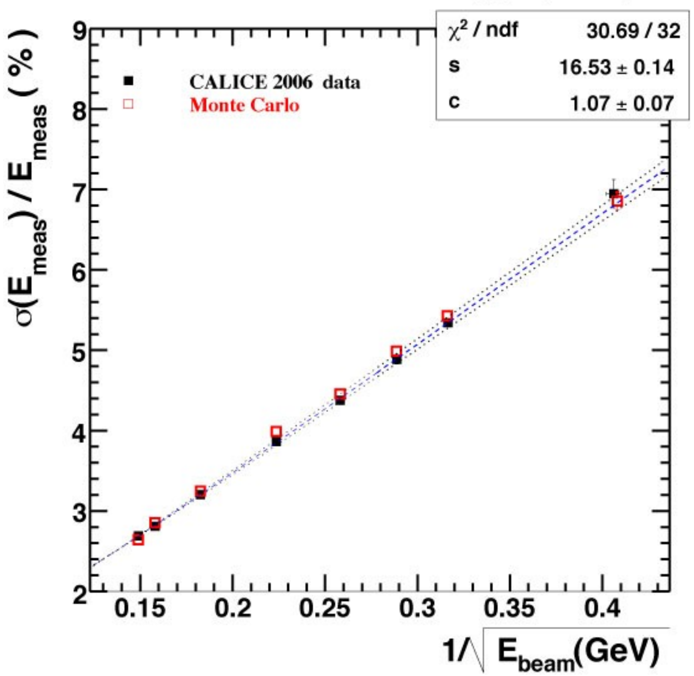

- Highly linear response over large energy range

- Linearity well reproduced by MC
  MIP/GeV ~ 266.5 [1/GeV]

- Non-Linearity O(1%)

# Energy Resolution




Example 30 GeV electron beam:

Gaussian like Calorimeter Response

Resolution curve shows typical √E dependency

$$\frac{\Delta E_{meas.}}{E_{meas.}} = \left[ \frac{16.6 \pm 0.1\,(stat.)}{\sqrt{E\,[\mathrm{GeV}]}} \oplus (1.1 \pm 0.1) \right] \%$$

- Resolution well described by MC
- Confirms value used in LOI

Design emphasises spatial granularity over energy resolution

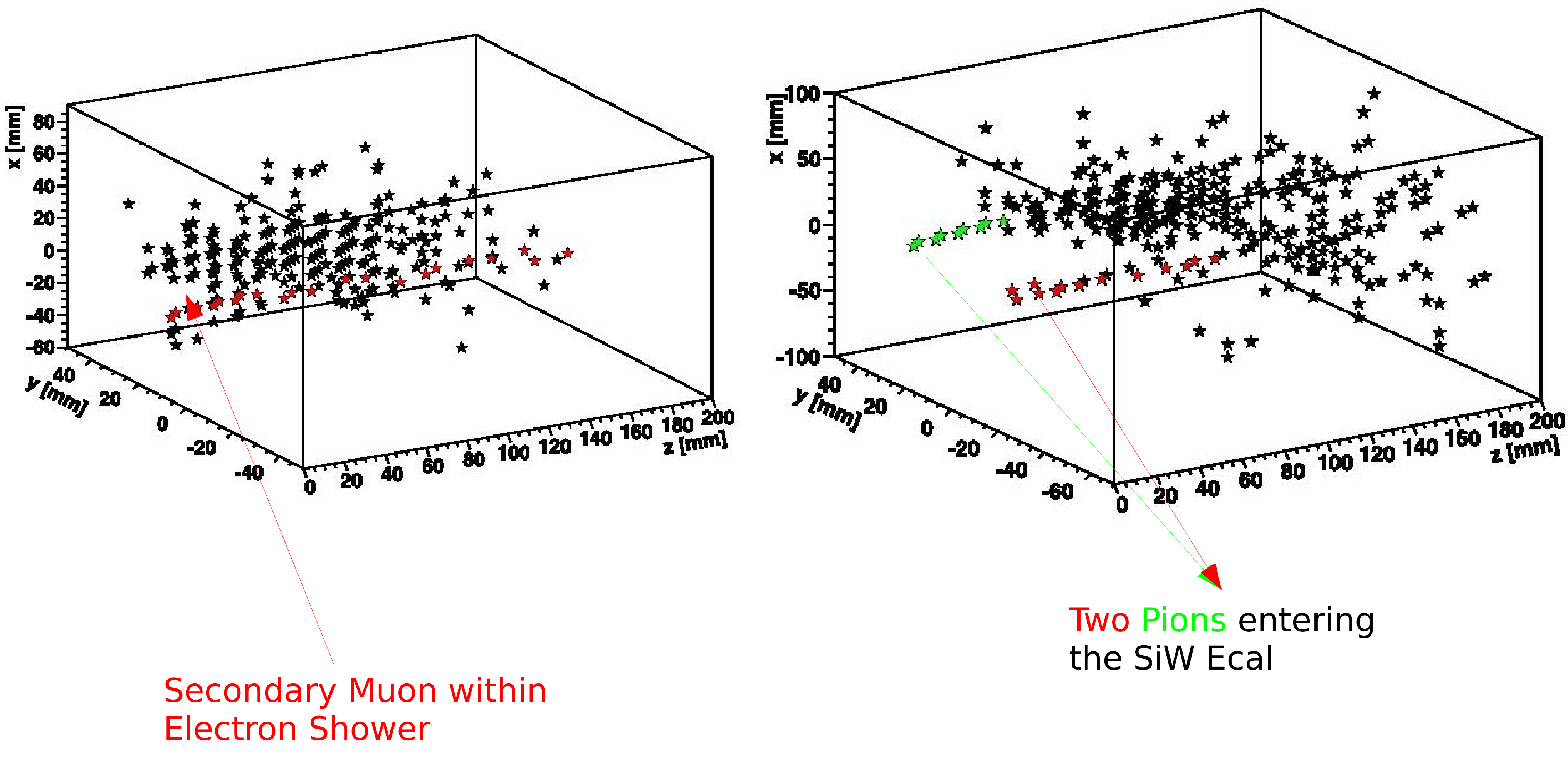
**Calorimeter for Particle Flow**

# Exploiting the High Granularity I – Particle Separation

High granularity allows for application of advanced imaging processing techniques

E.g. Hough Transformation

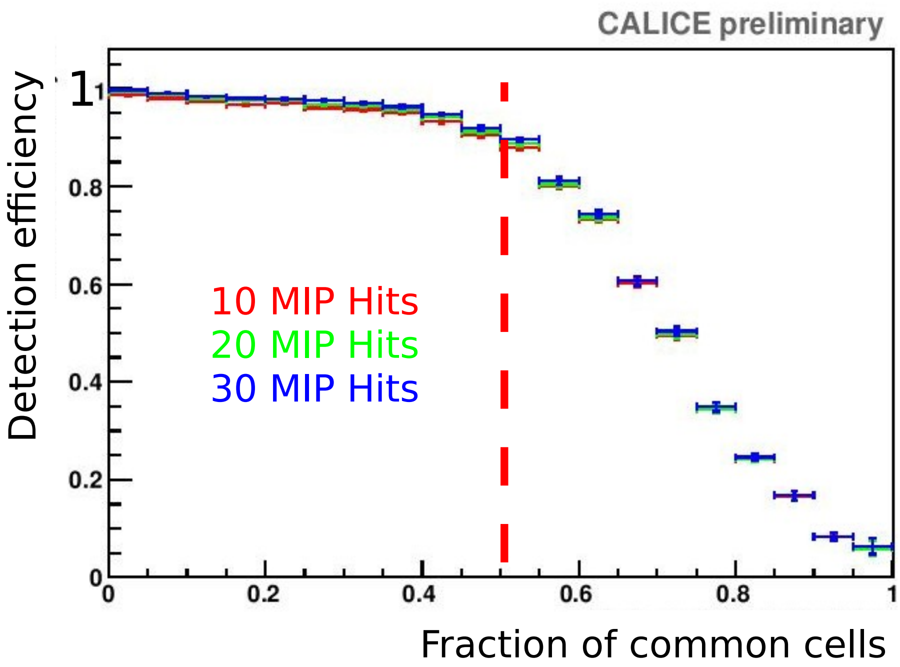
Events recorded in test beam

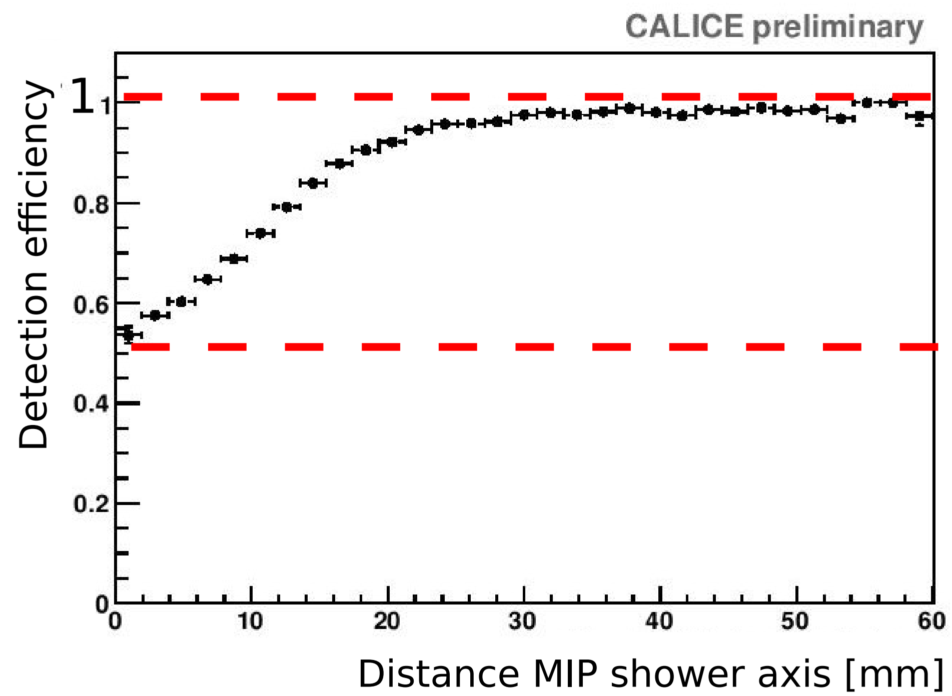


# Particle Separation – cont'd

## Efficiency of Particle Separation

### Separation MIP <-> Electron




ε -> 100% for up to 50% shared hits

Independent of hits generated by MIP

Full separation for distances > 2.5 cm

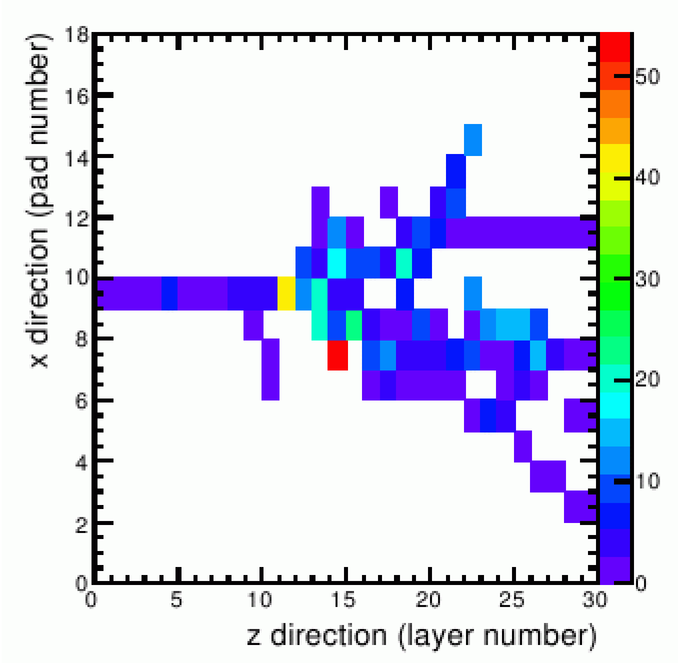
N.B.: Analysis still on CAN-Note level, pity that it has not been turned into a paper

# Granularity and Hadronic Cascades

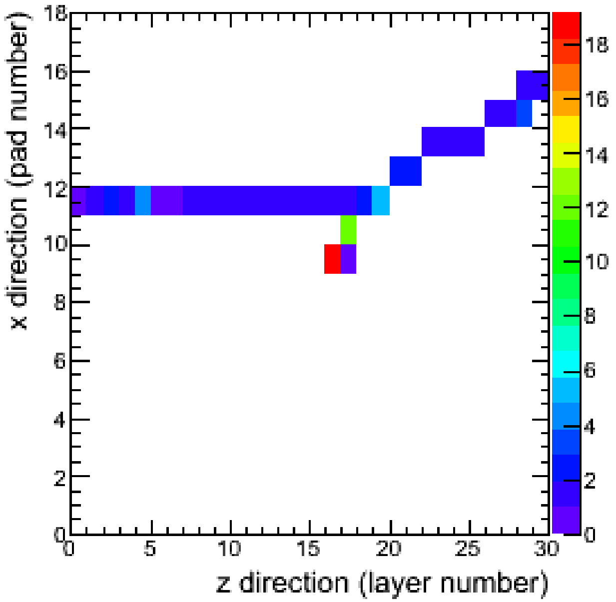
## (Start of) Hadronic Showers in the SiW Ecal

Finding the interaction is ...

... easy at high energies




..involved at small energies




Check for absolute increase
of energy in consecutive layers

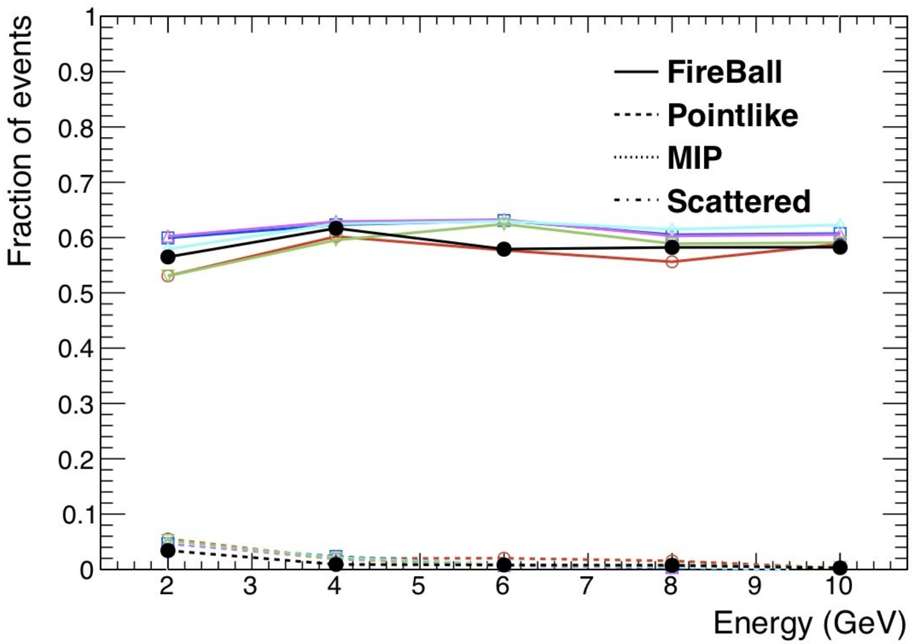
Check for relative increase
of energy in consecutive layers

Efficiency: 10 GeV 84%
Efficieny: 2 GeV 63% (compare with 25% with naive method!!!)

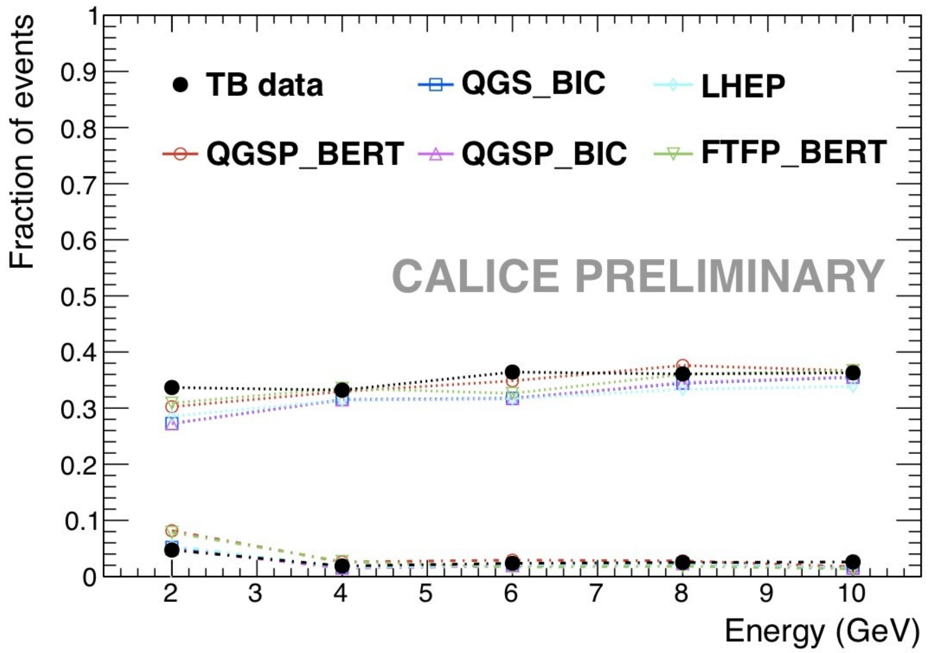
Event types and ratees

Aim: Explore and understand of what we can “see” with the SiW Ecal

Events with found hadronic interaction




Events w/o found hadronic interaction




Cross sections of underlying scattering processes well modelled by GEANT4

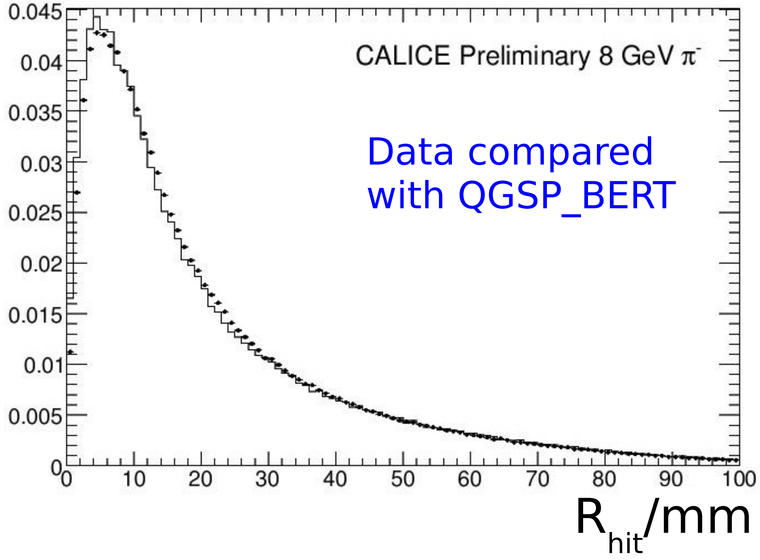
Decomposition of interactions demonstrate sensitivity to details of interactions

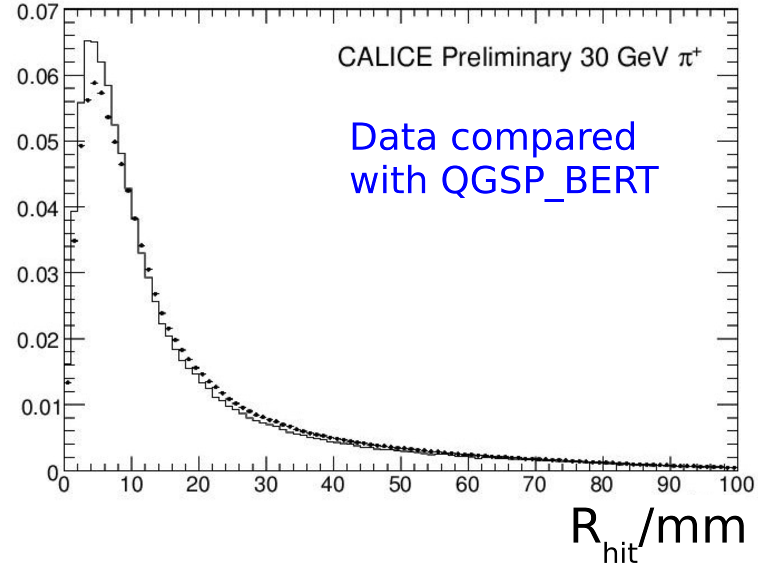
CAN-025 -> Publication in progress

# Transversal Shower Profiles and Shower Radius

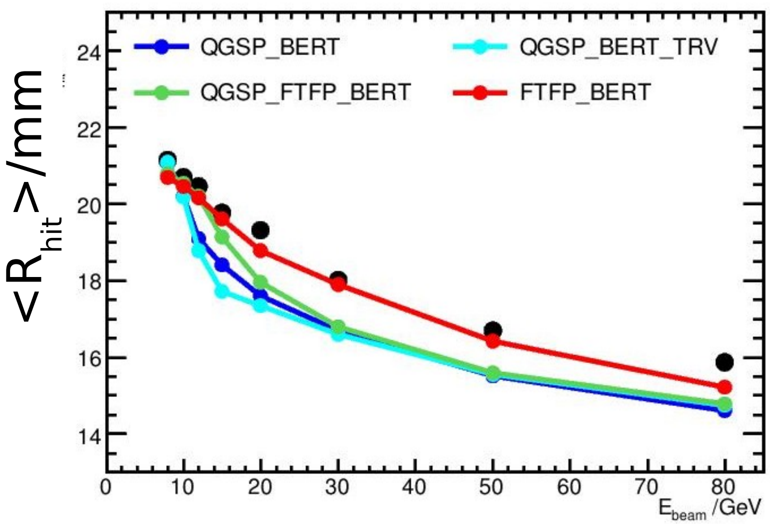
Affects overlap of showers <-> Importance for PFA

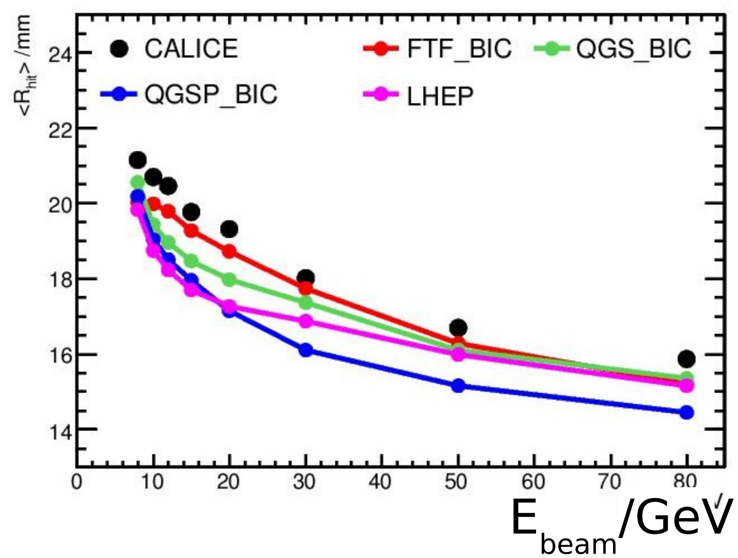
Transverse Profiles




Shower Radius

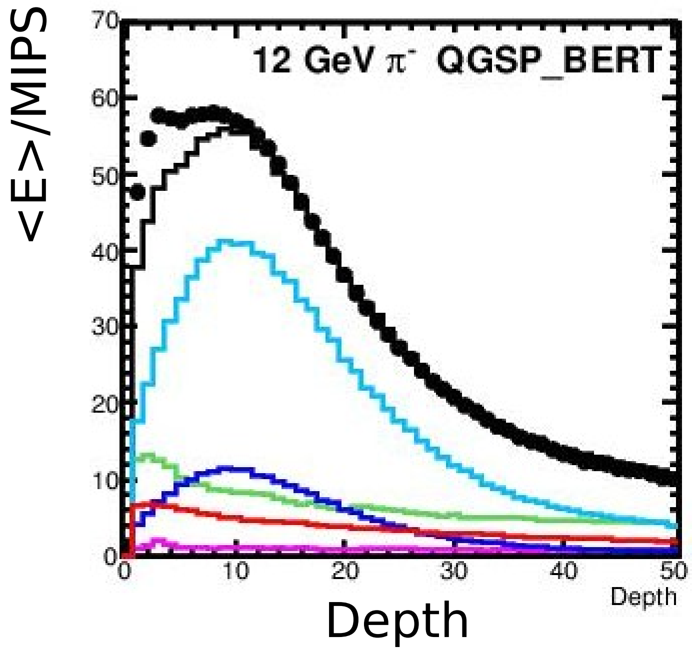


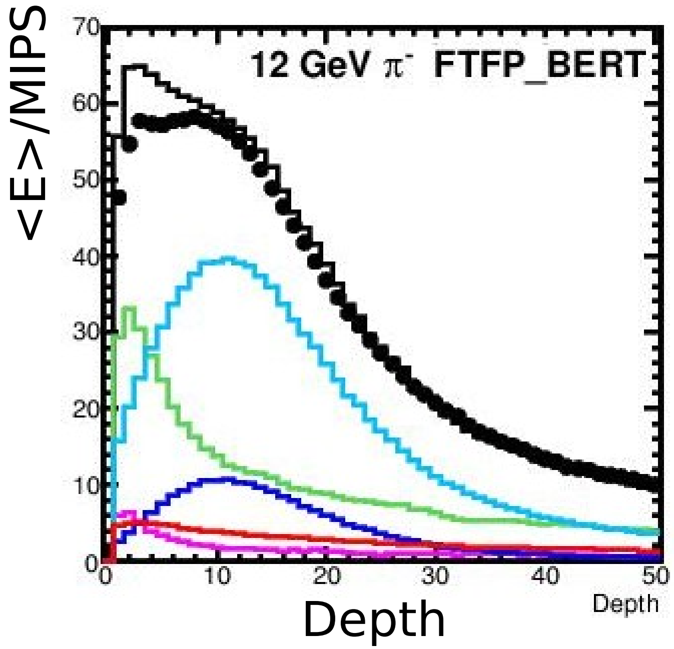




Small Energy ok for 'BERT' models
Towards high energy: Underestimation of Content in SiW Ecal
Relatively small difference between models (~15%)

# Longitudinal Energy Profiles

Sensitivity to different shower components




Shower Components:

- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum

Significant Difference between Models

- Particularly for short range component (protons)

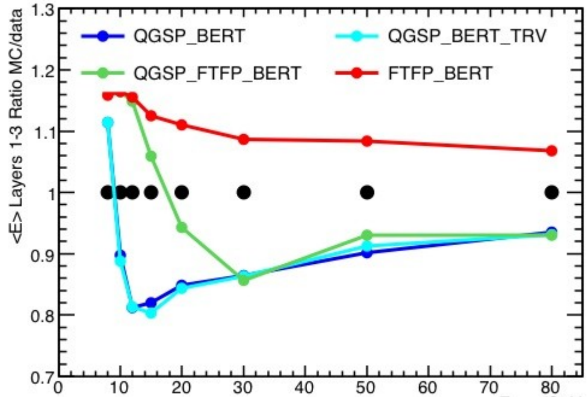
Granularity of SiW Ecal allows (some) disentangling of components

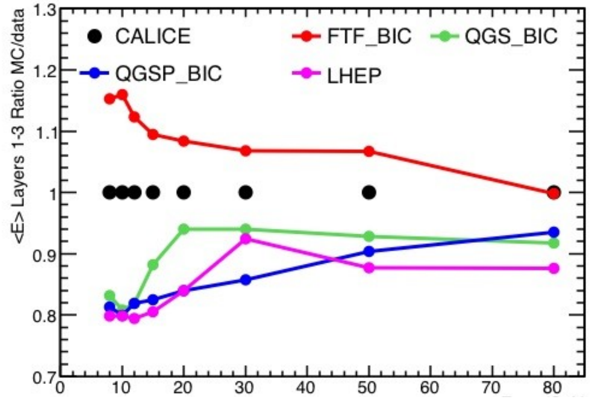
Further studies for shower decomposition are ongoing

# Energy depositions in different calorimeter depths

Layer 1-3:

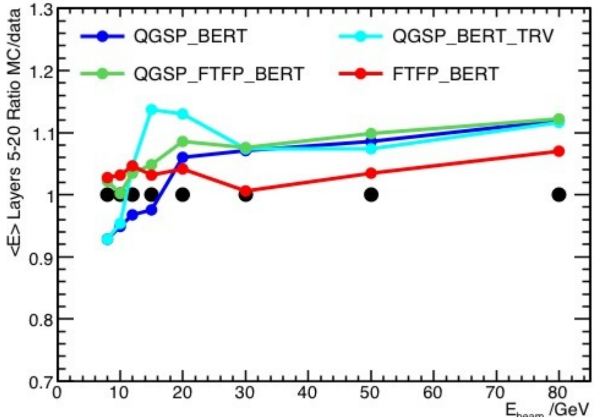
Nuclear breakup

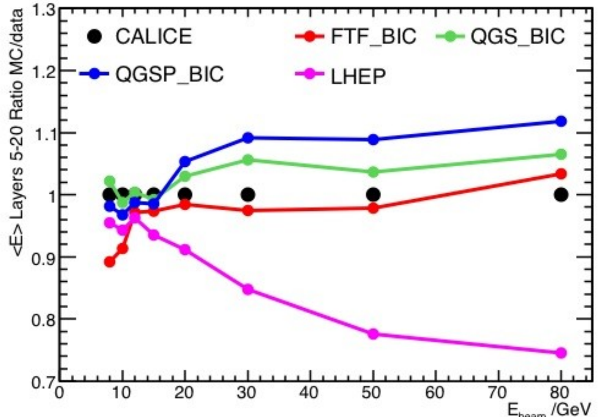



Layer 5-20:

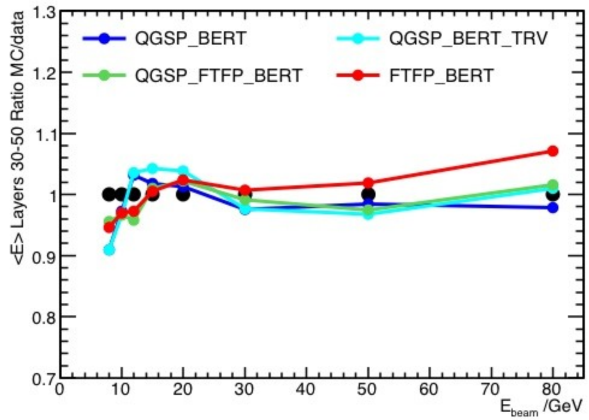
elm. component

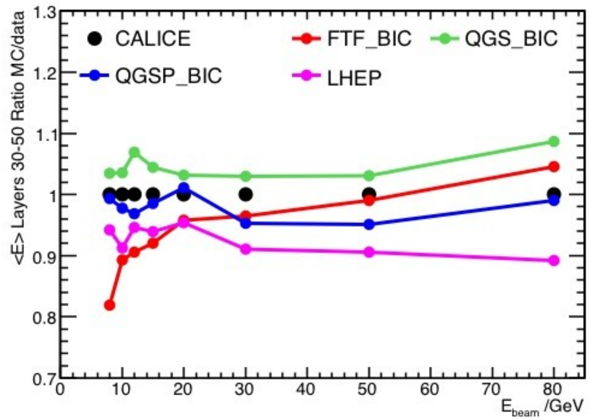


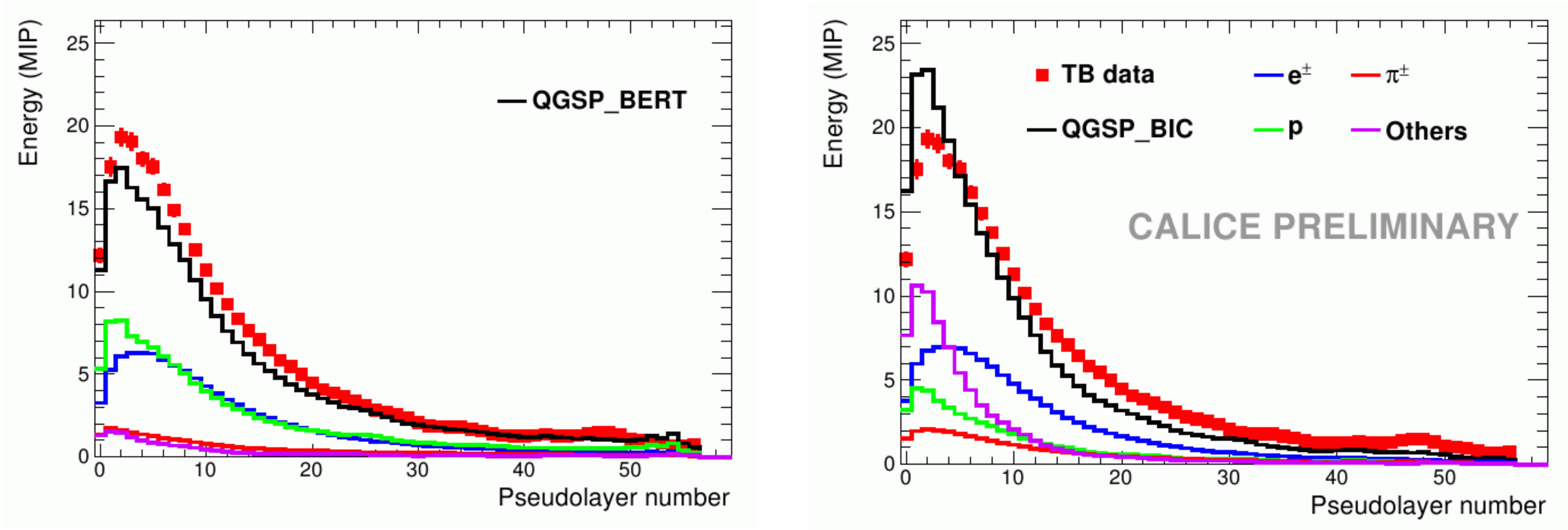

Layer 30-50:

Shower hadrons

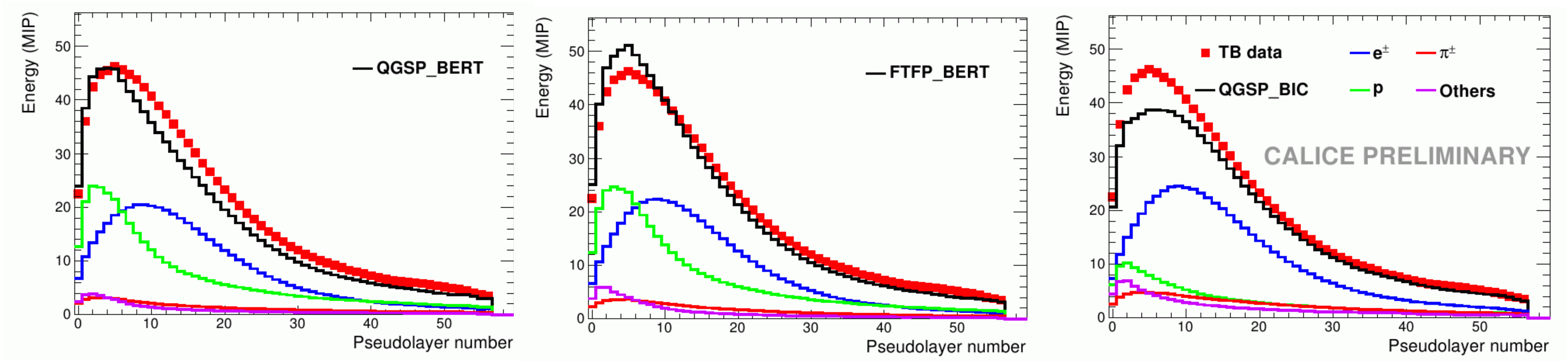


# Pi @ 2GeV Inelastic reactions




# Pi @ 8GeV Inelastic reactions



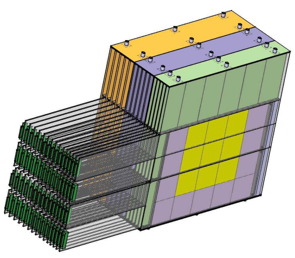

No satisfactory description of longitudinal shower profile - Tails about right

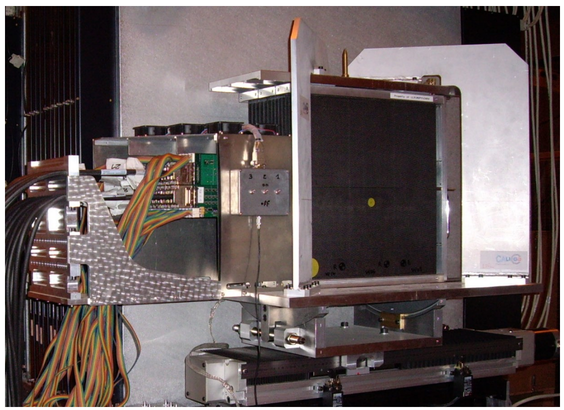
Large sensitivity to model differences close to interaction region

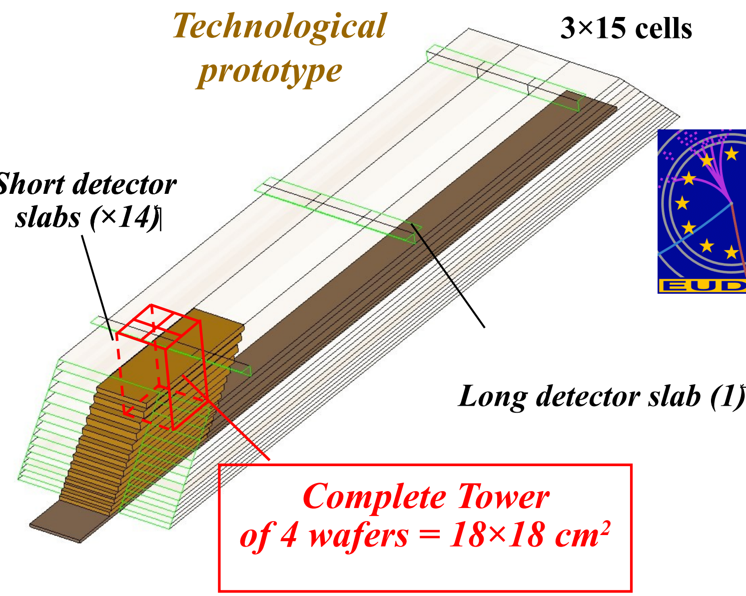
CAN-025 -> Publication on small energy hadrons in progress

# Technological Prototype

Technical solutions for the/a final detector








- Realistic dimensions

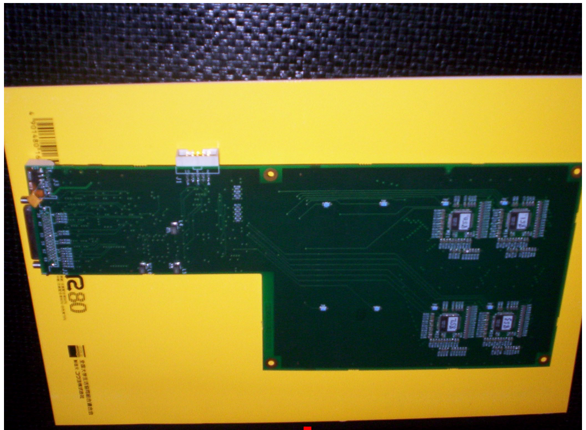
- Integrated Front End Electronics

- Small power consumption
  Power pulsed electronics

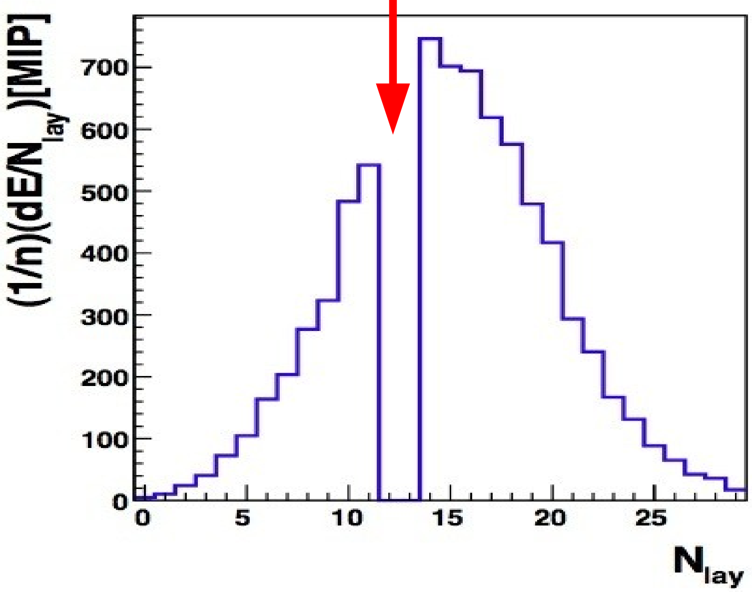
- Construction 2009 – ..., Testbeams > 2011

# Embedded electronics - Parasitic effects?

Exposure of front end electronics to electromagnetic showers

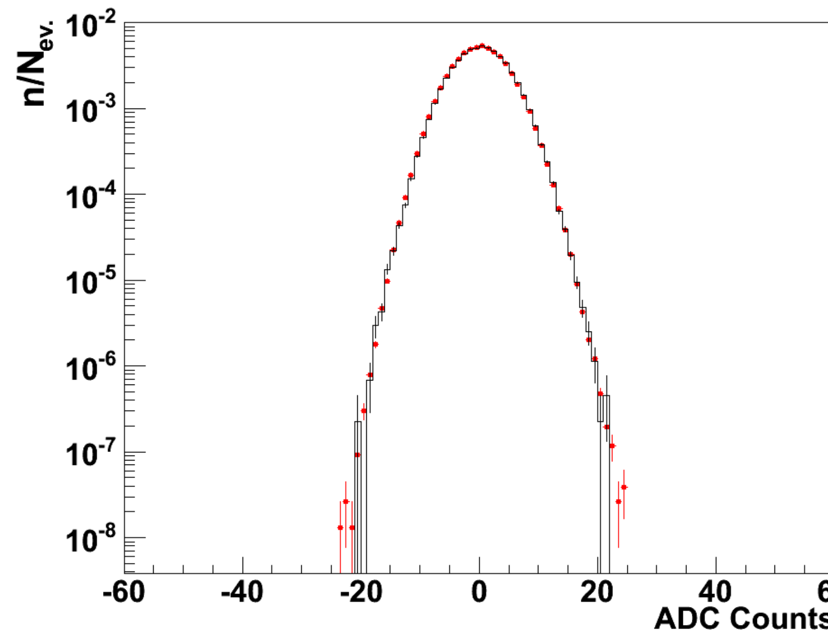


Chips placed in shower maximum
of 70-90 GeV elm. showers




Possible Effects: Transient effects
Single event upsets

Comparison: Beam events
(Interleaved) Pedestal events




- No sizable influence on noise spectra by beam exposure

  $\Delta$Mean < 0.01% of MIP $\Delta$RMS < 0.01% of MIP
- No hit above 1 MIP observed

  => Upper Limit on rate of faked MIPs: $\sim 7\times10^{-7}$

NIM A 654 (2011) 97

# Test beams with technological prototype

## DESY – April, July 2012 and February 2013

TA: AIDA-DESY-2012-003, AIDA-DESY-2012-007, AIDA-DESY-2013-001

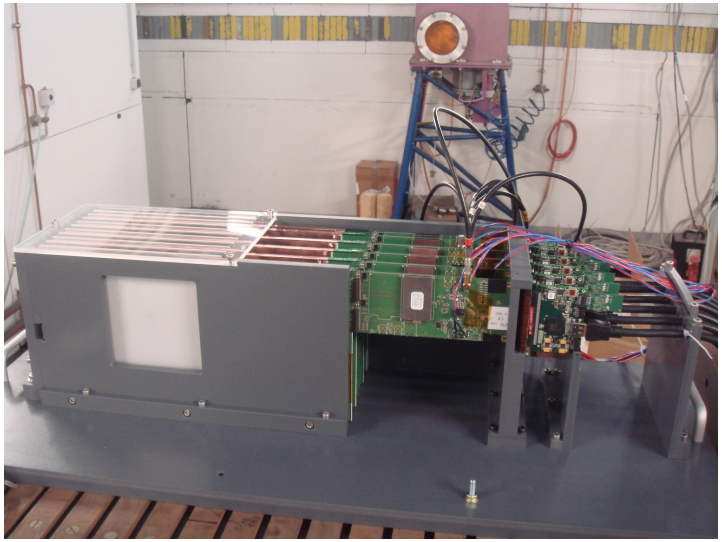
- Up to 10 layers (FEV8)
  - Internal trigger

**Total = 1536 channels**

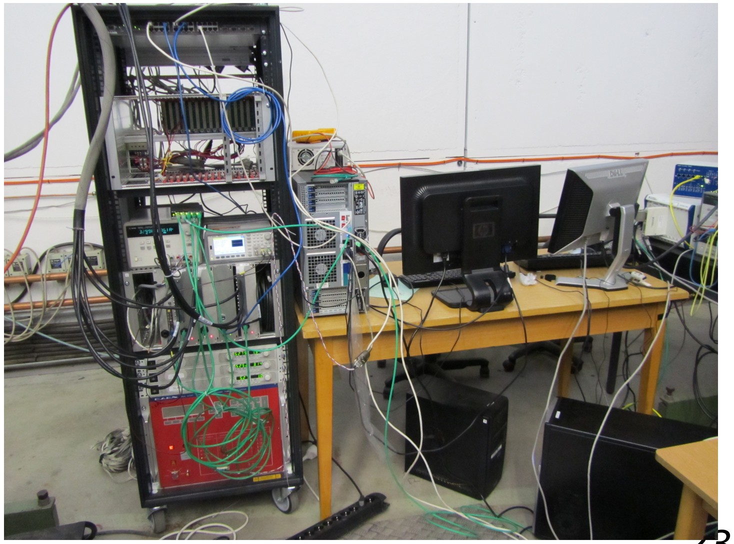
PreAmplifiers of noisy channels are switched off

**total active channels = 1278**

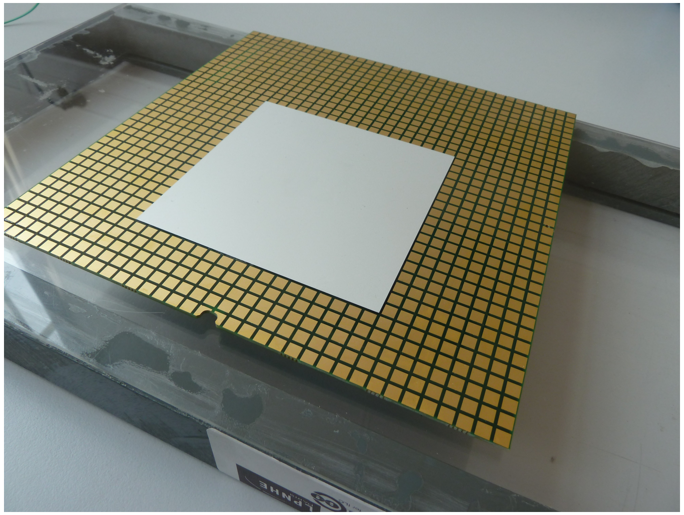
Detector read out by CALICE DAQ2
(continuation of EUDET DAQ)
+ Software (CALICOES) to operate detector
→ Details on DAQ tomorrow

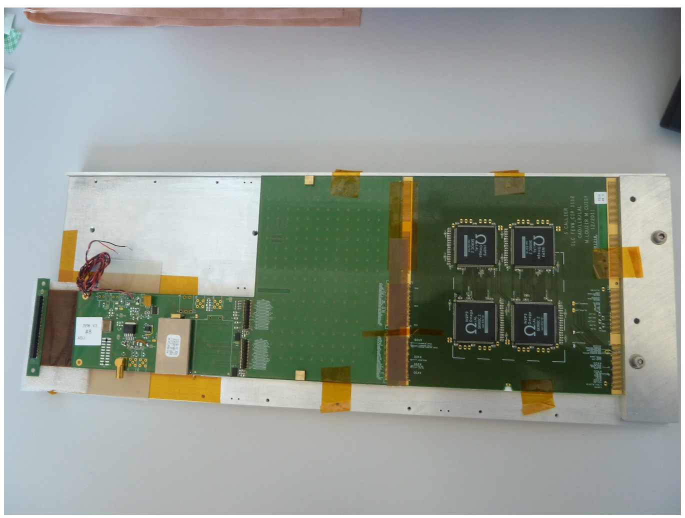


- Test program
  - 2012: Commissioning
    Test of highly integrated electronics
    in conservative mode
  - 2013 Test of power pulsing
    Tests in magnetic field
-



# Layer design for beam tests





ASU is the entity of
Si Wafer, ASICs and PCB

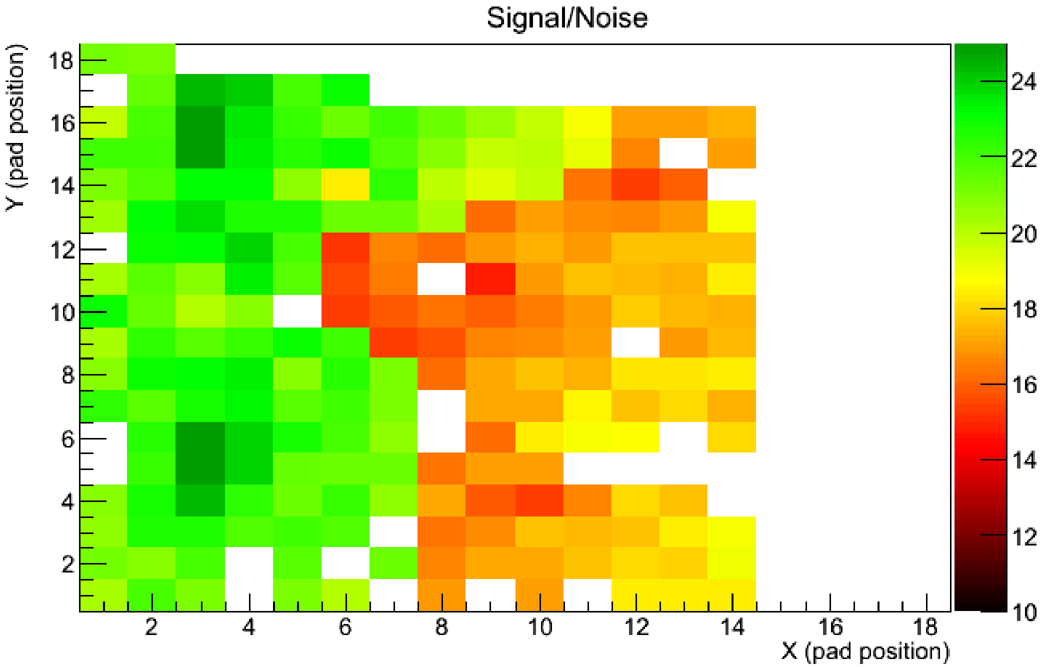
Conservative ASU design for beam tests

- 1 Si Wafer with 256 pixels of 5X5 mm2 and thickness of 325 mum
  compare with 4 wafers for final design

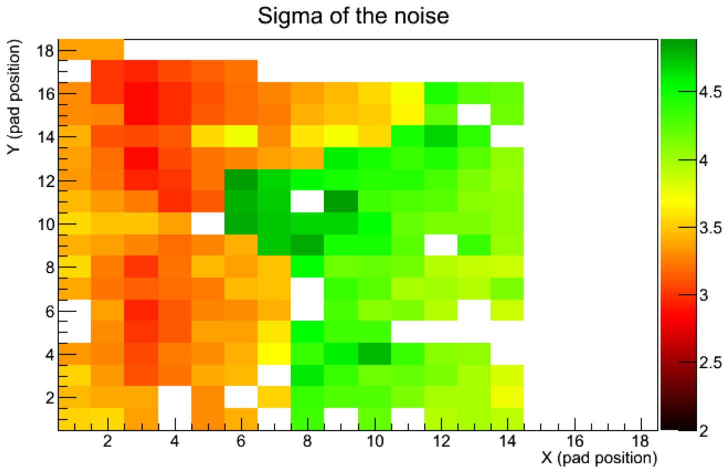
- Wafer glued onto PCB
  EPOTEK-4110, development of automatised procedure

- 4 ASICs in PQFP package
  Compare with 16 ASICs wire bonded (→ later) or in very thin BGA package

# Data Analysis 2012 – Signal over noise ratio



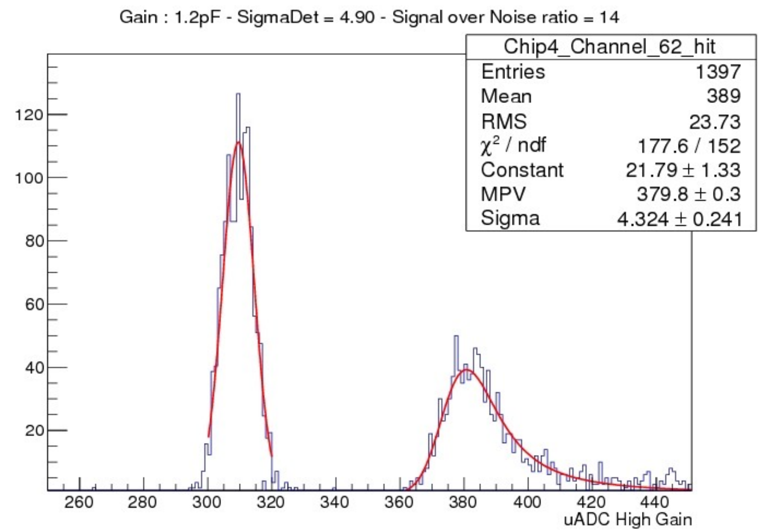

Results after setting of trigger thresholds and event filtering
(see backup slides)
White spots = Noisy cells
noice induced by PCB routing

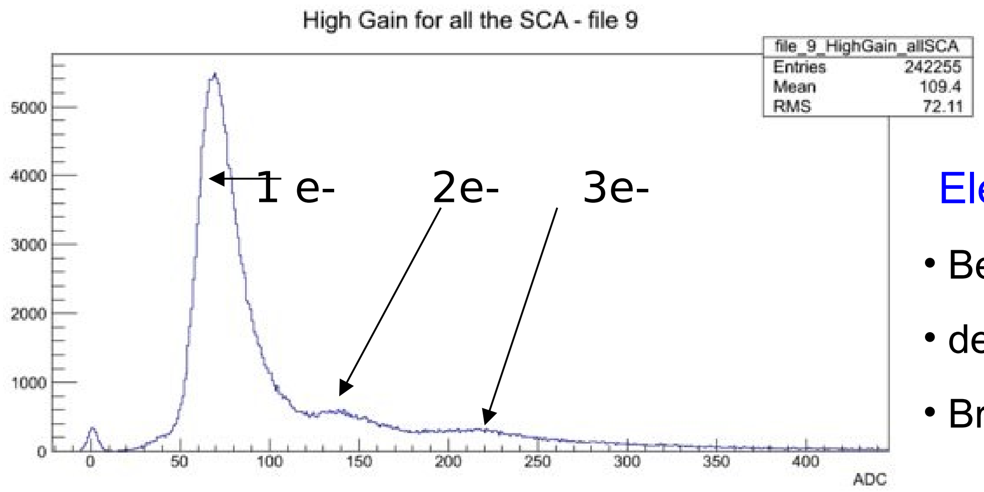



- S/N > 10
- (for all gains available with SKIROC2)
- R&D target is 10:1

*Publication in progress*
*Results published as proceedings of VCI conference*

# 2012 Data - Energy measurement



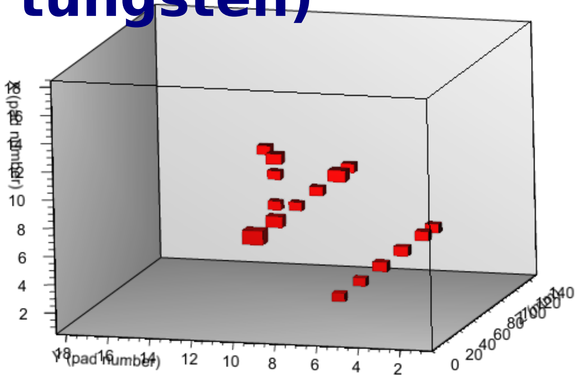




**Electron sources:**

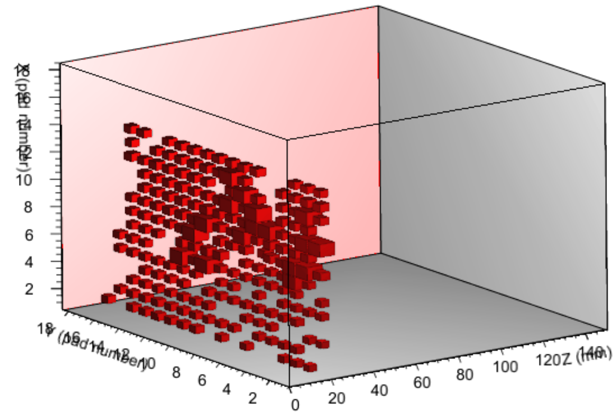
- Beam
- delta rays
- Bremsstrahlung + gamma conversion (2e-) + Compton

# Event displays (Search the error ;-) )

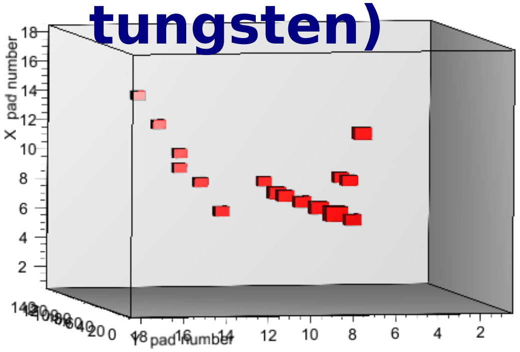
**2 e- (3 GeV, no tungsten)**



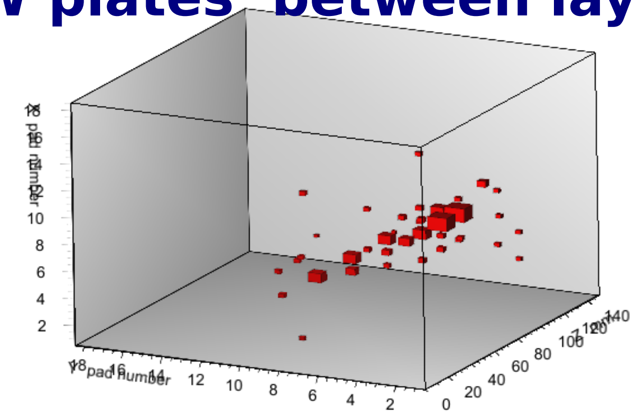

'Plane events???'




**1 cosmic + 1 e- (3 GeV, no tungsten)**




**1 e- (5 GeV)**
**5 W plates between layers**



# 2013 beam tests

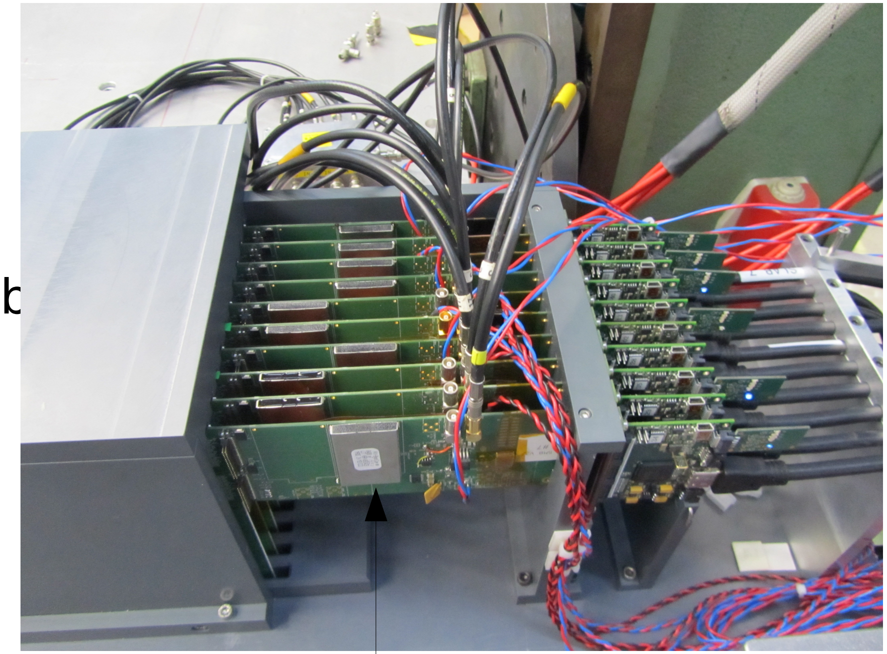
Alltogether 10 layers

- 4 continous operation
- 4 power pulsed
  Including h/w modifications see ab
- 2 could not be reliably operated

DAQ: Readout by 2 LDAs

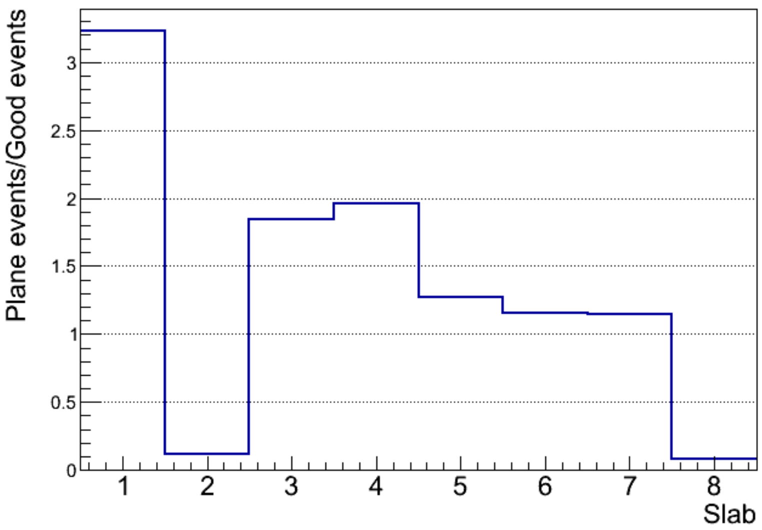
Power pulsing
Duty cycle 99%, 10Hz

Operation in power pulsing
Mode requires removal of
Decoupling capacitances
=> Do not expect as stable
performance as in continuous mode



Battery charger application
AVX BestCap BZ01
After regulator

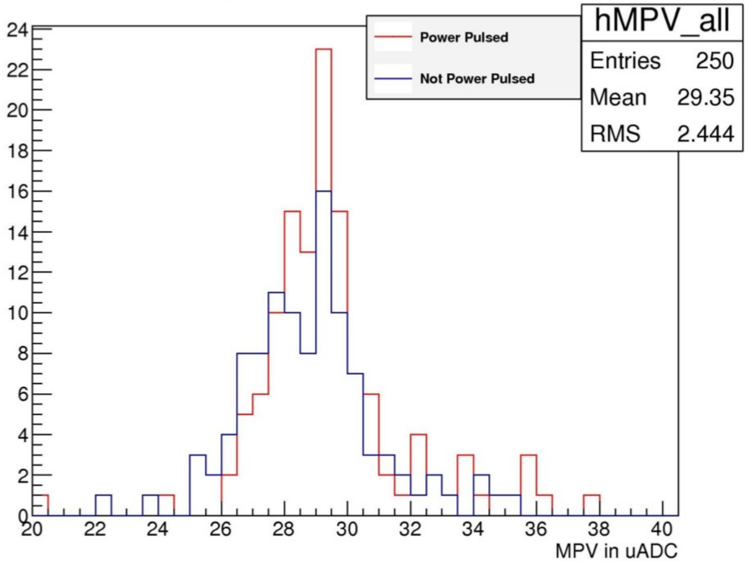
# 2013 beam tests first results




Frequency of plane events

- Slab 2 and 8 were subject to patches
- Smaller frequency of plane events observed
- However effects of retriggering are still under investigation

→ Stay tuned

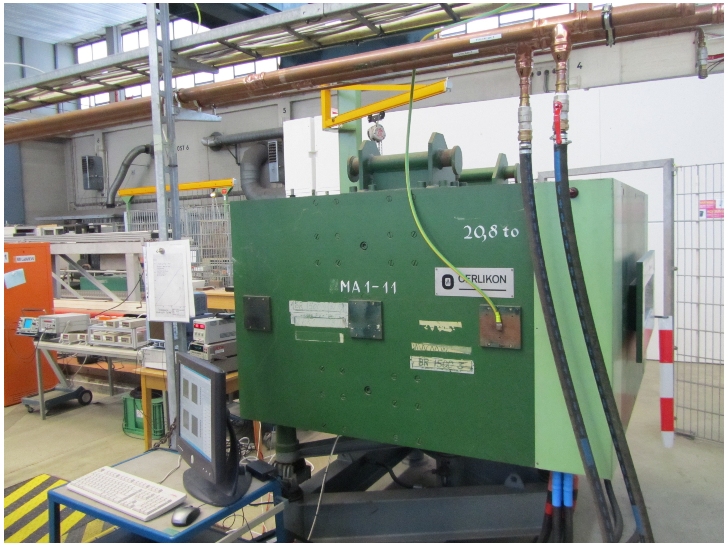


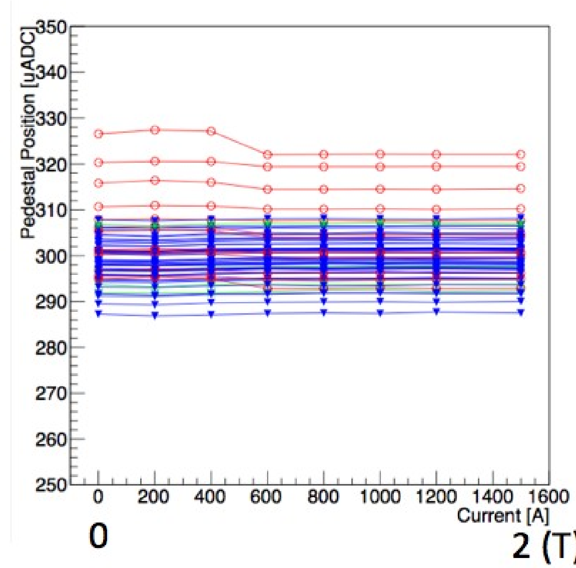

Comparison Power pulsing No power pulsing

- For good layer 2 same quality of MIP spectra

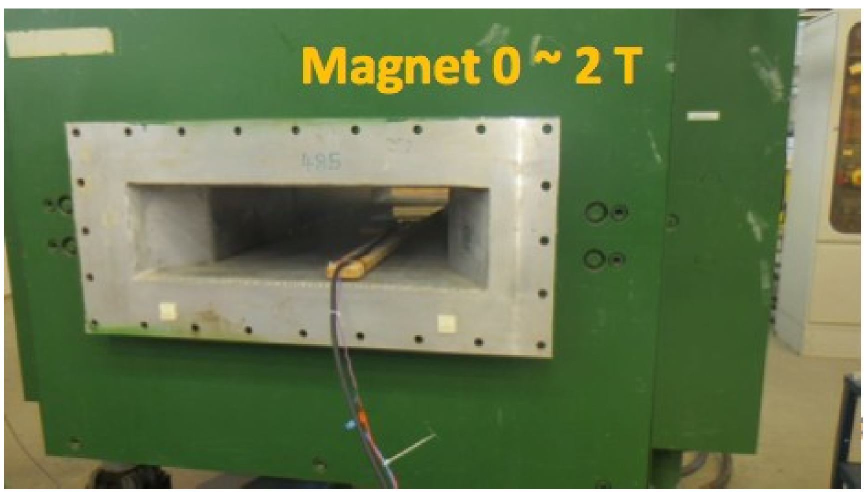
Ongoing analysis but result is encouraging

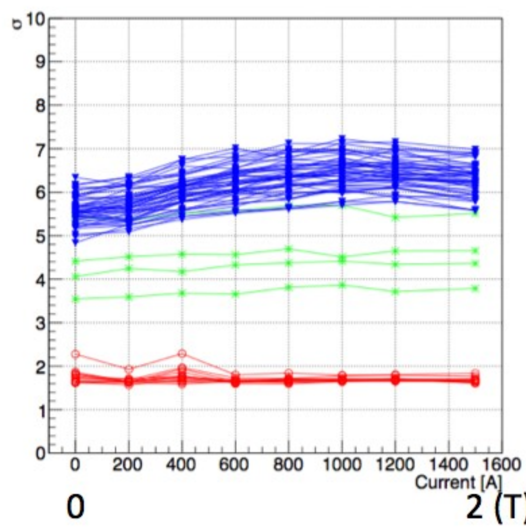
# Power pulsing tests in magnetic field I



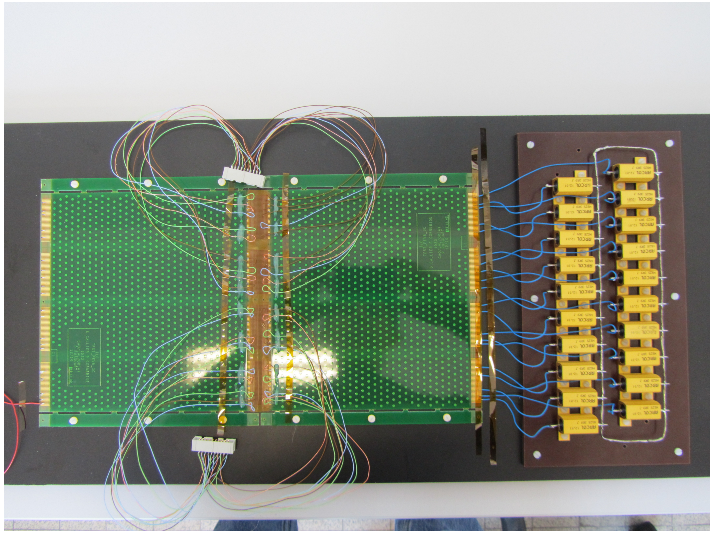

Pedestal position



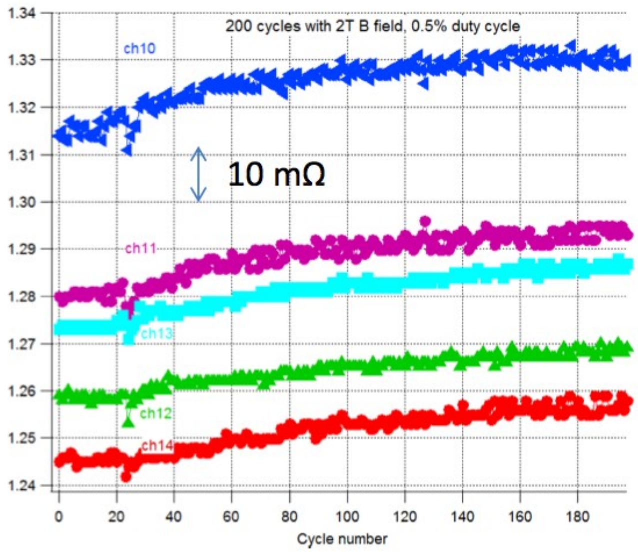




Pedestal width

# Tests in magnetic field II




Measurement of the ohmic resistance across the interconnection between two ASUs
With and w/o B-Field, various duty cycles and frequencies




Conclusion: The ohmic resistance
Varies by about 20 mOhm (thermal effect)

# Summary and Outlook

- Successful R&D for a highly granular electromagnetic calorimeter

Physics Prototype (2005-2011):

- Energy resolution ~17%/√E
- Signal to Noise Ratio ~8/1
- Stable calibration
- Capacity of separating particles impressively demonstrated by test beam analysis
- Unprecedented views into hadronic showers thanks to high granularity 'Modern bubble chamber'

Due to harsh cut in manpower around 2009/10 a lot of data still not analysed

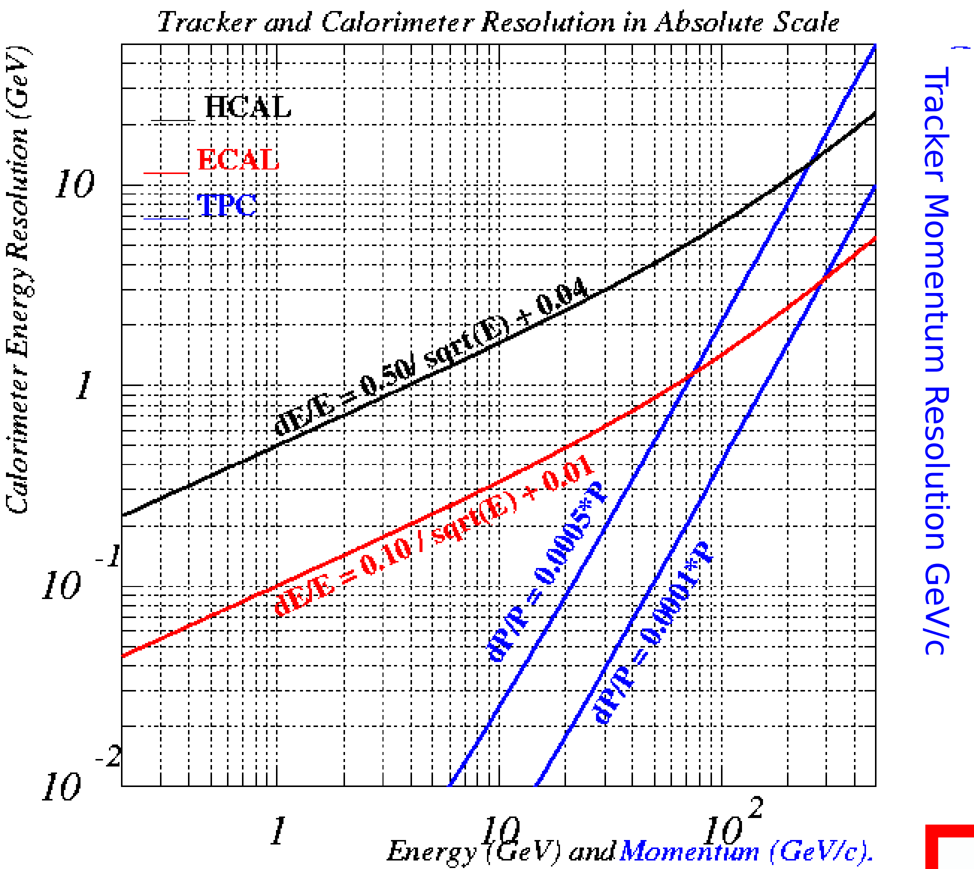
Technological Prototype (2009-...):

- Valuable experience with new r/o concept Globally, excellent S/N ratio (however needed to cope with some short comings of ASICs and PCBs)
- First experience with power pulsed electronics
- Mastering of new technology will grow as prototype and number of groups and people analysing the data grow

# Backup Slides

# Jet Energy Resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the <u>utmost</u> precision !




Jet energy carried by …

- Charged particles ($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$)): 65%
  Most precise measurement by Tracker
  Up to 100 GeV

- Photons: 25%
  Measurement by Electromagnetic
  Calorimeter (ECAL)

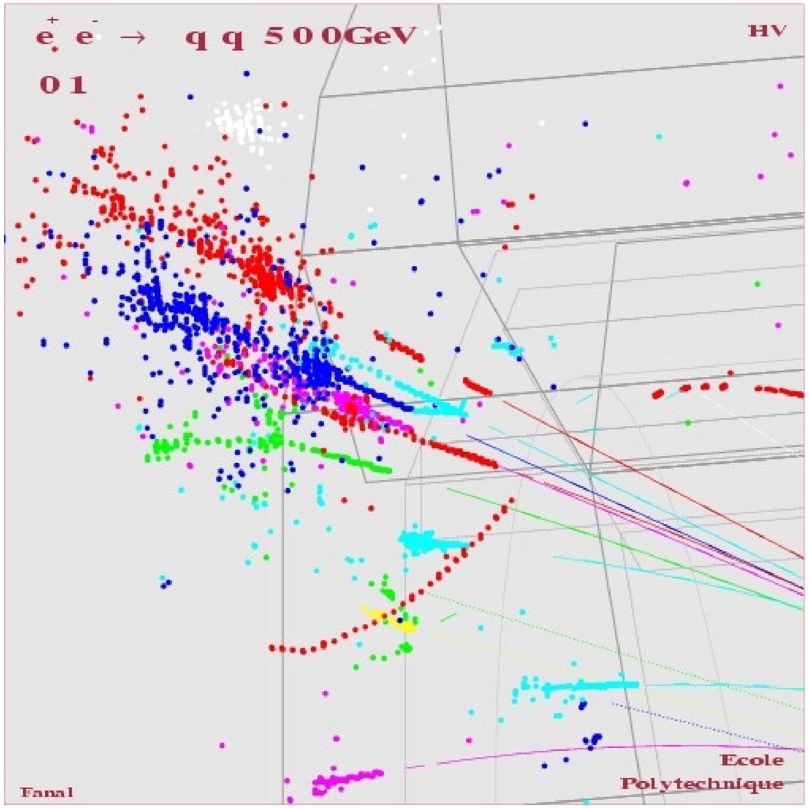
- Neutral Hadrons: 10%
  Measurement by Hadronic
  Calorimeter (HCAL) and ECAL

$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

# Confusion Term

- Base measurement as much as possible on measurement of charged particles in tracking devices

- Separate of signals by charged and neutral particles in calorimeter




- Complicated topology by (hadronic) showers

- Correct assignment of energy nearly impossible

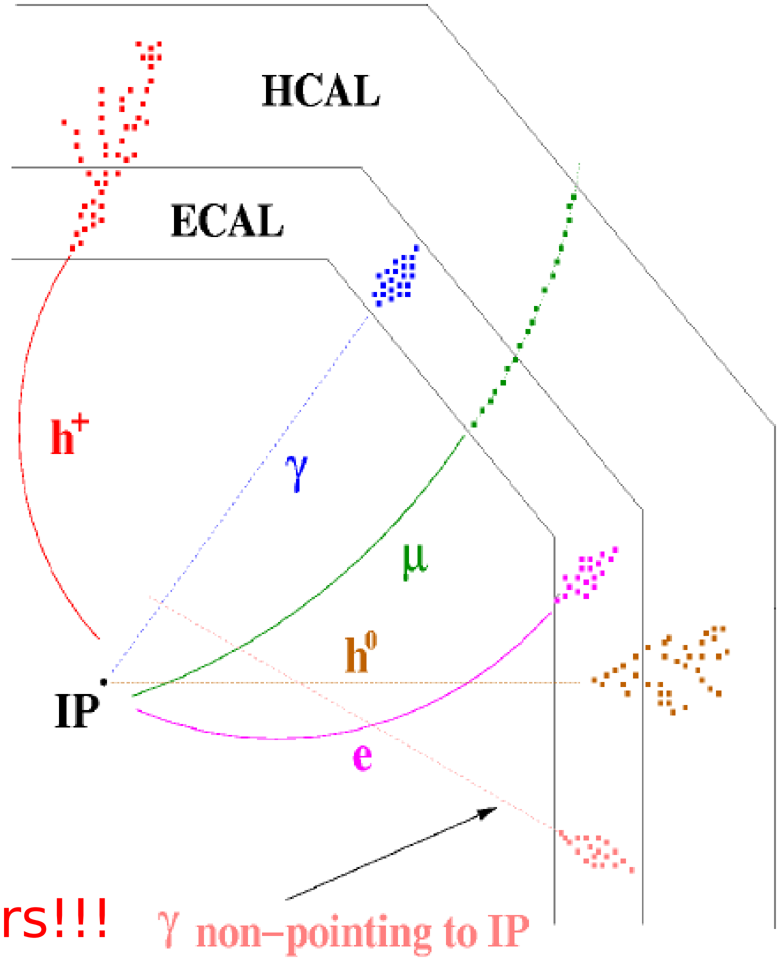
⇒ Confusion Term

Need to minimize the confusion term as much as possible !!!

# Detector and Calorimeter Concept – Particle Flow

Jet energy measurement by measurement of **individual particles**
Maximal exploitation of precise tracking measurement

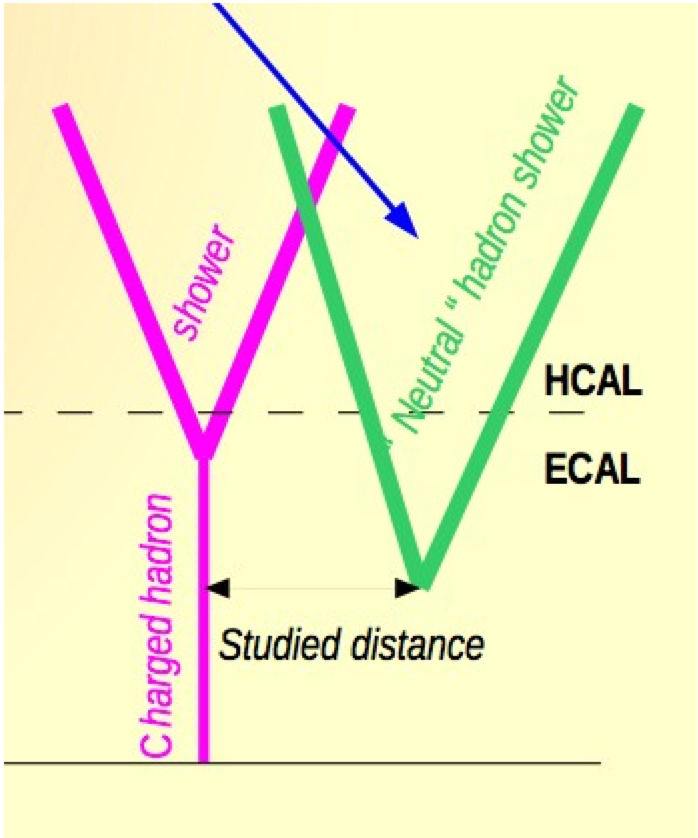
- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- "no" material in front of calorimeters
  - stay inside coil
- small Molière radius of calorimeters
  - to minimize shower overlap
- **high granularity of calorimeters**
  - to separate overlapping showers

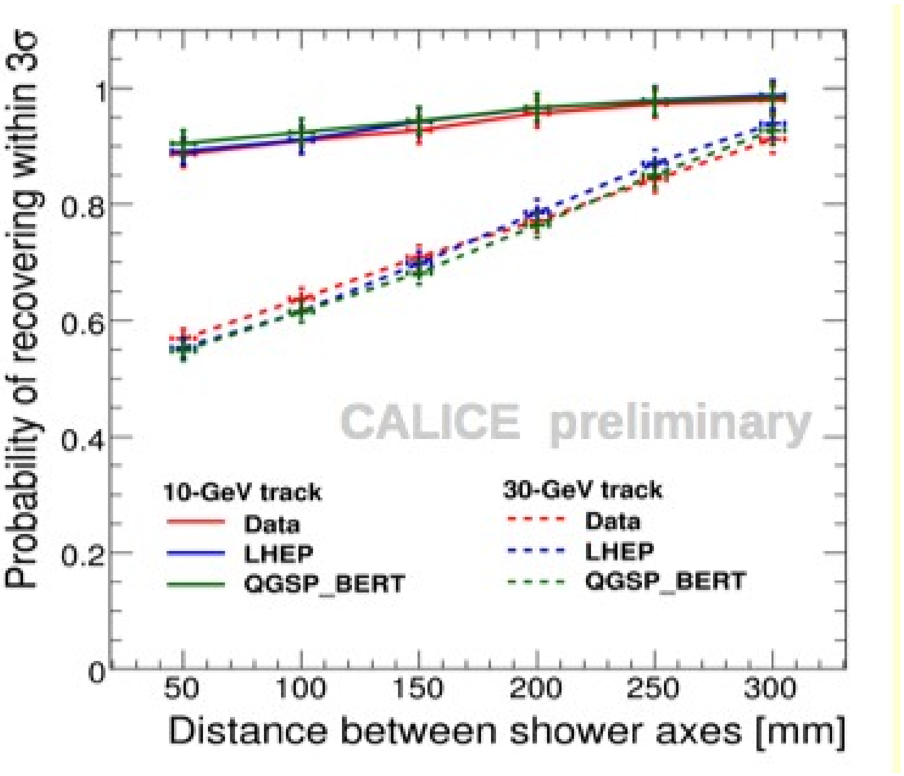



Physics Goals at the ILC demand the
Construction of Highly Granular Calorimeters!!!
Emphasis on tracking capabilities of calorimeters

# Results from earlier large scale testbeams

CALICE **Data** mapped onto ILD detector to test PFA

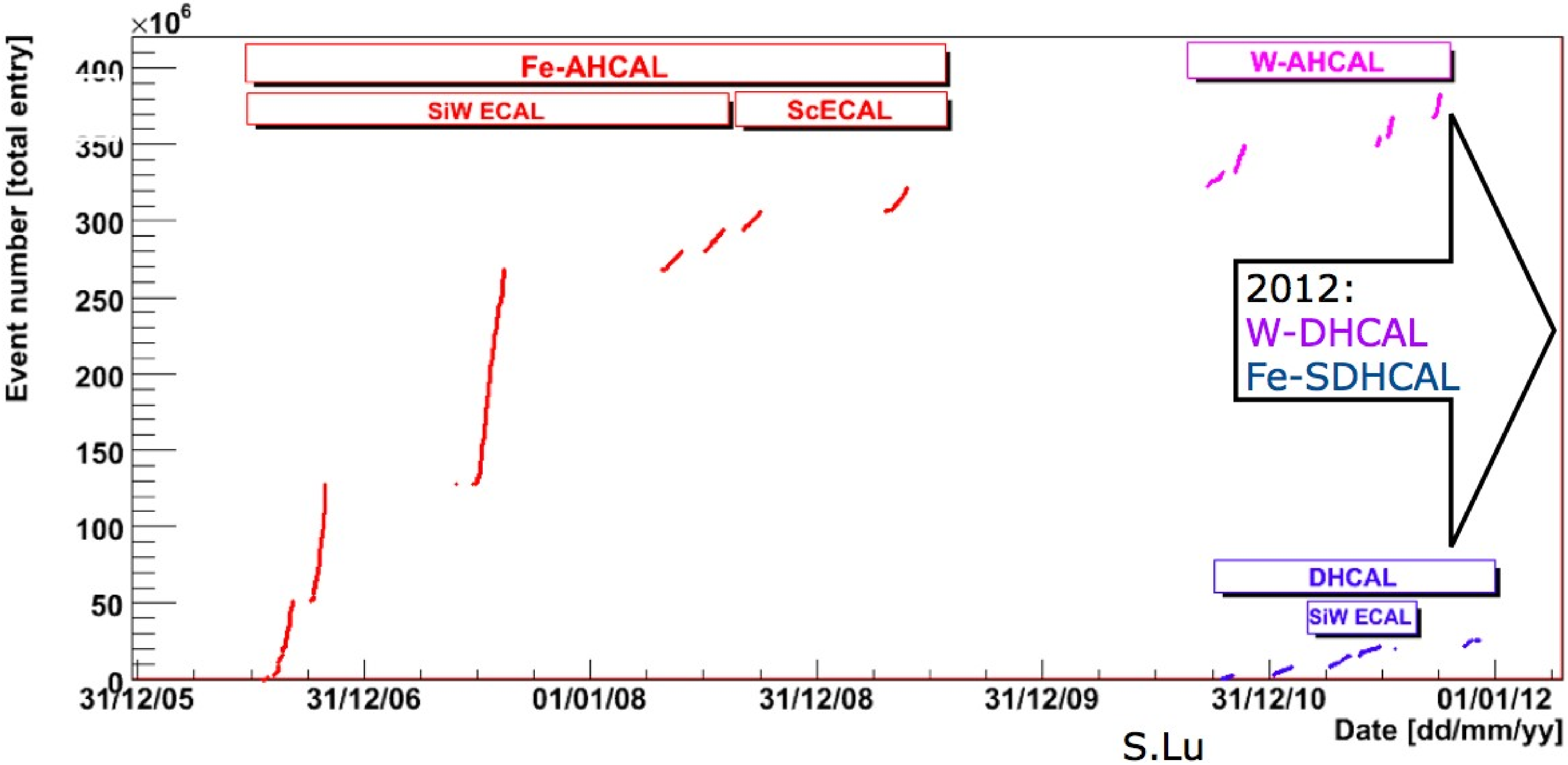



Transport of beam test data into physics studies

Successful Application of PFA to real data with highly granular calorimeters

Summary of recorded data



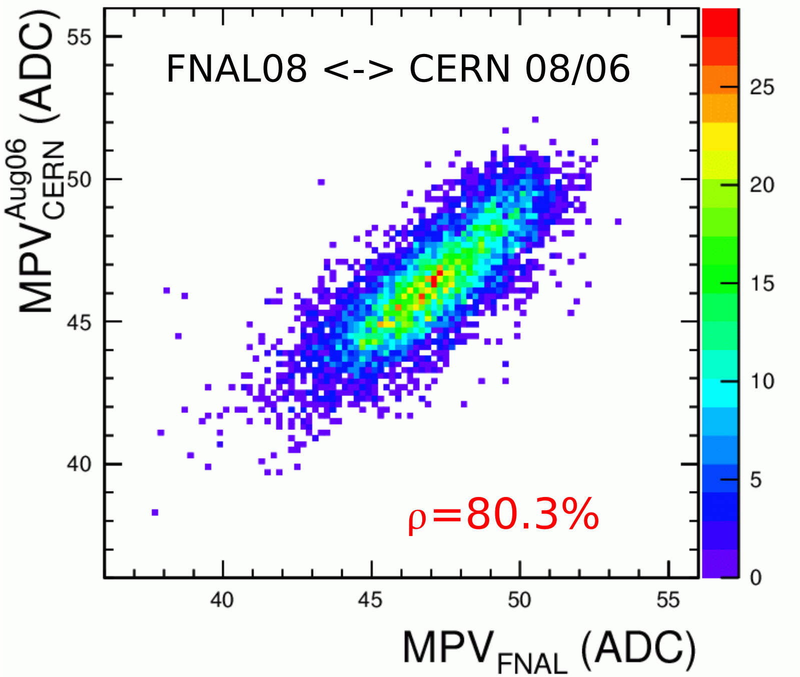

- Muon, LED calibration runs not included
- About 25 Tbyte of data stored on the grid

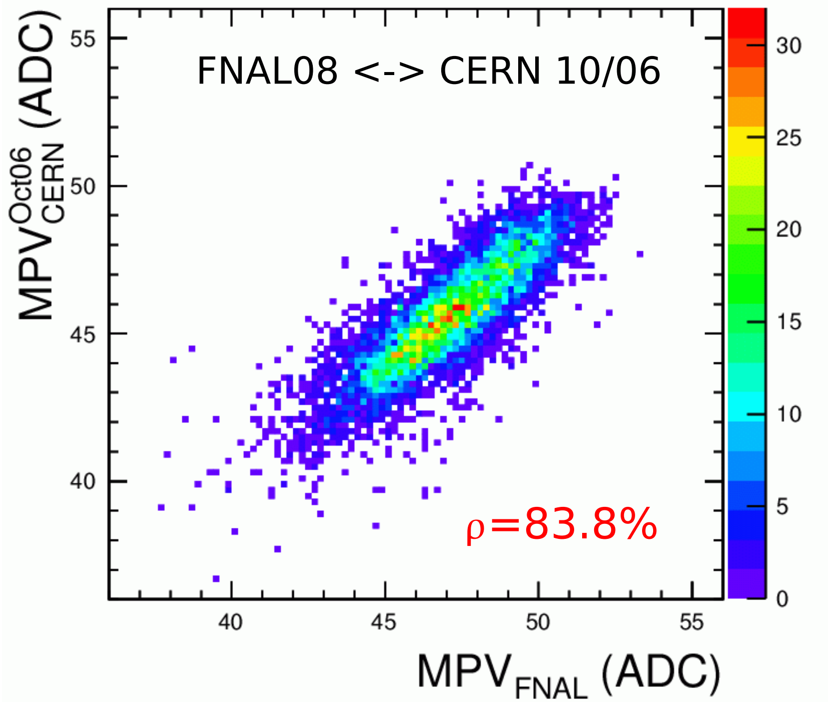
Since 2005 virtual organisation *calice* allows for world wide and transparent access to the data
Support at all major computer centres in the world

# Stability of detector – Example calibration

Calibration constants in different beam test campaigns

*PhD Thesis H. Li, LAL*



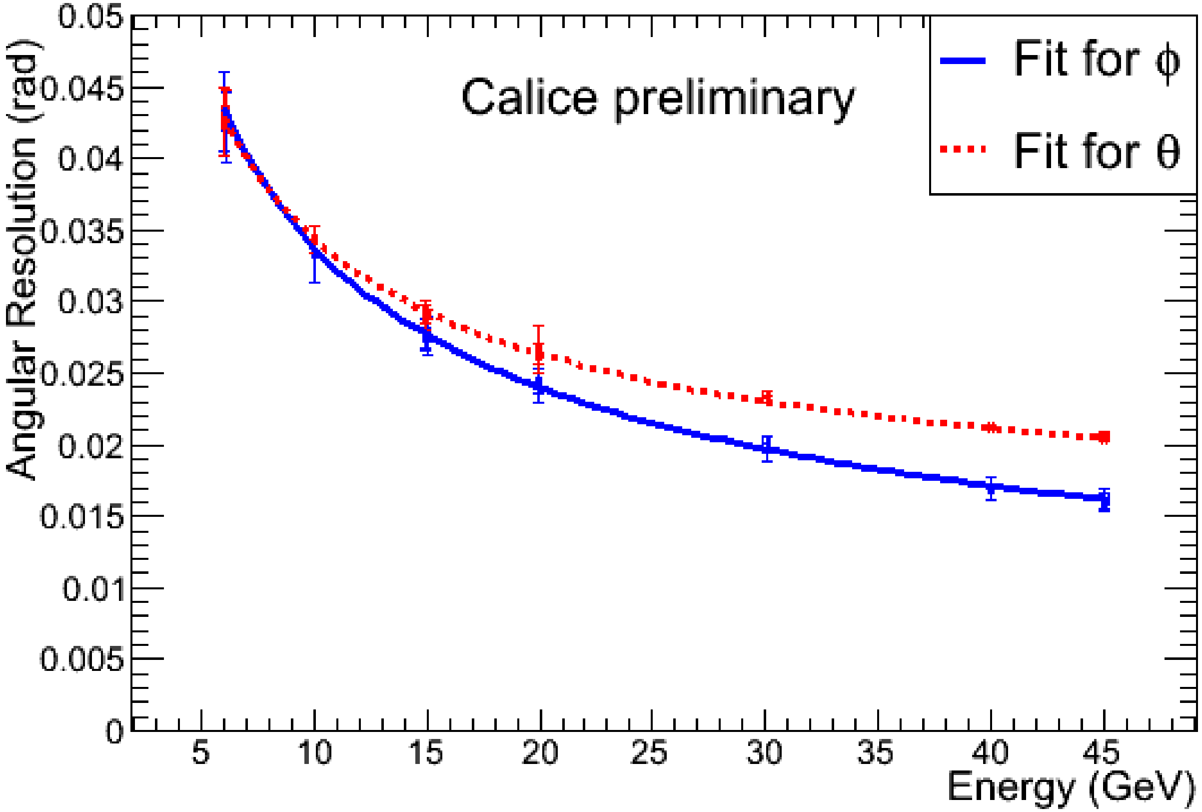

High correlation between calibration constants

Constants obtained in 2007 were still applied for 2011 online monitor

No sign of aging

Wafer Breakthrough in 2011?

# Angular resolution




Fitted with:

$$\frac{p1}{\sqrt{E(GeV)}} \oplus p0$$

Φ, angle respect to X:

$$\left(\frac{106 \pm 2}{\sqrt{E(GeV)}} \oplus (4 \pm 1)\right) mrad$$

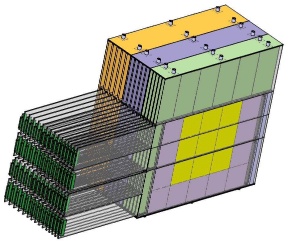
θ, angle respect to Y:

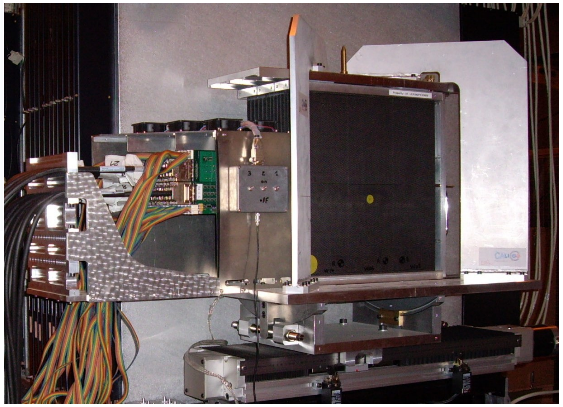
$$\left(\frac{100 \pm 2}{\sqrt{E(GeV)}} \oplus (14 \pm 1)\right) mrad$$

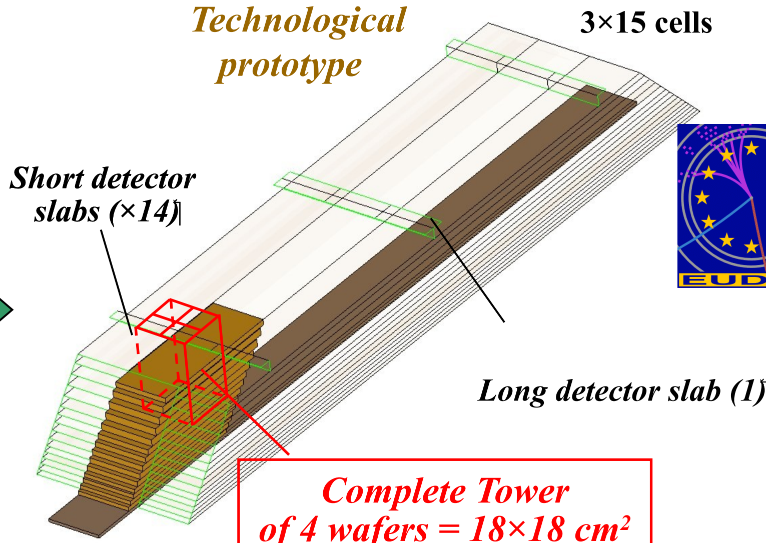
Differences due X and Y due to geometrical properties of Prototype (Staggering)

# Technological Prototype

- Physics prototype: Validation of main concept
- Techno. Proto : Study and validation of technological solutions for final detector
- Taking into account industrialisation aspect of process
- First cost estimation of one module







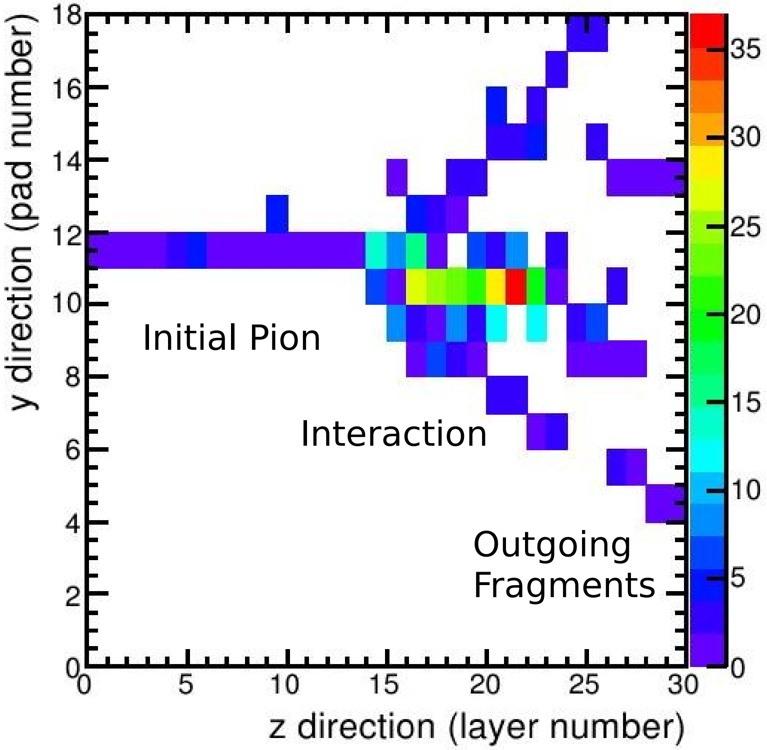

- **3 structures : 24 $X_0$ (10×1,4mm + 10×2,8mm + 10×4,2mm)**
- **sizes : 380×380×200 mm3**
- **Thickness of slabs : 8.3 mm (W=1,4mm)**
- **VFE outside detector**
- **Number of channels : 9720 (10×10 mm²)**
- **Weight : ~ 200 Kg**

- **1 structure : ~ 23 $X_0$ (20×2,1mm + 9×4,2mm)**
- **sizes : 1560×545×186 mm3**
- **Thickness of slabs : 6.8 mm (W=2,1mm)**
- **VFE inside detector**
- **Number of channels : 45360 (5×5 mm²)**
- **Weight : ~ 700 Kg**

# Granularity and Hadronic Cascades

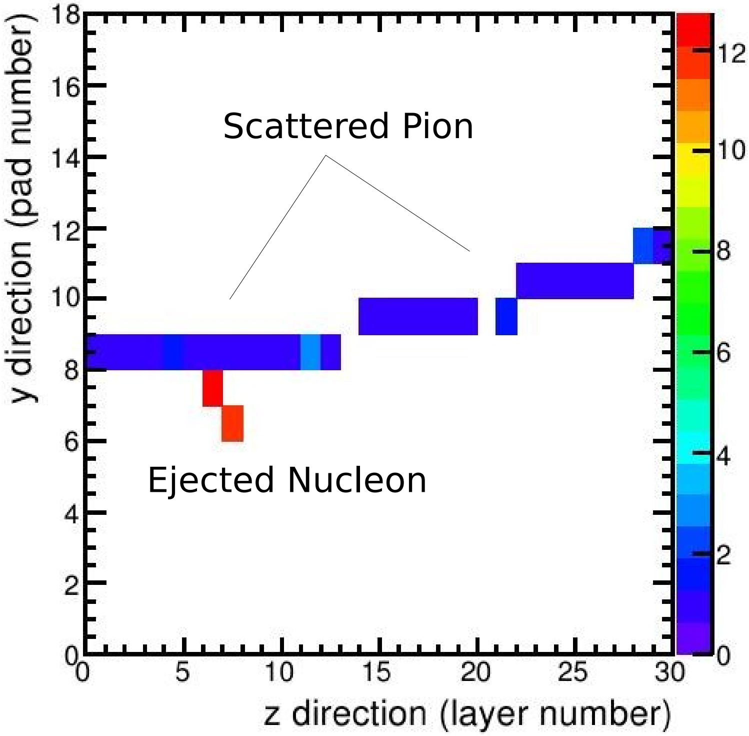
## (Start of) Hadronic Showers in the SiW Ecal

Complex and Impressive




Inelastic Reaction in SiW Ecal

Simple but Nice

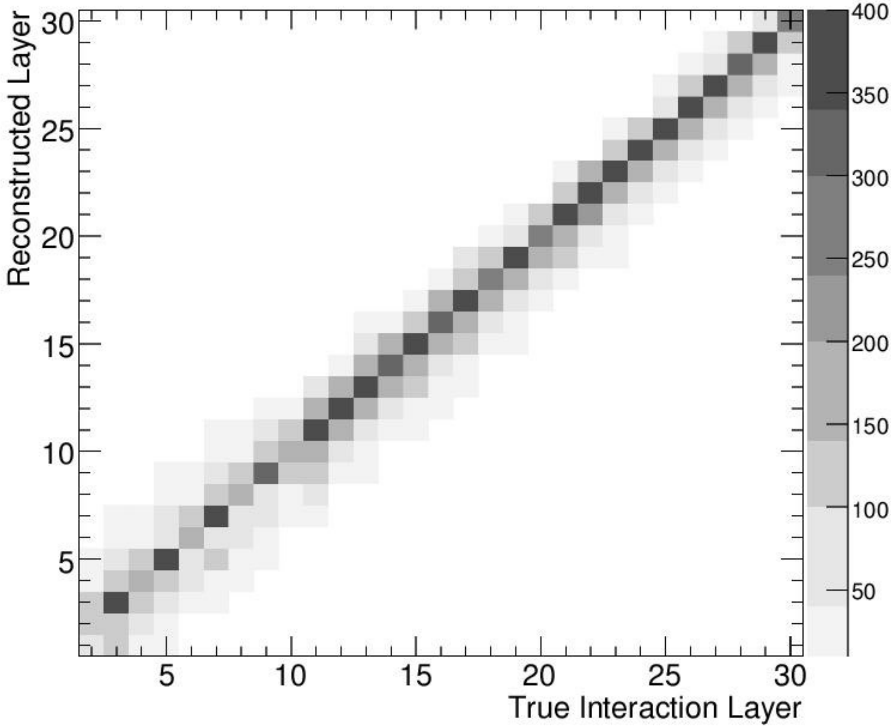



Nucleon Ejection in SiW Ecal

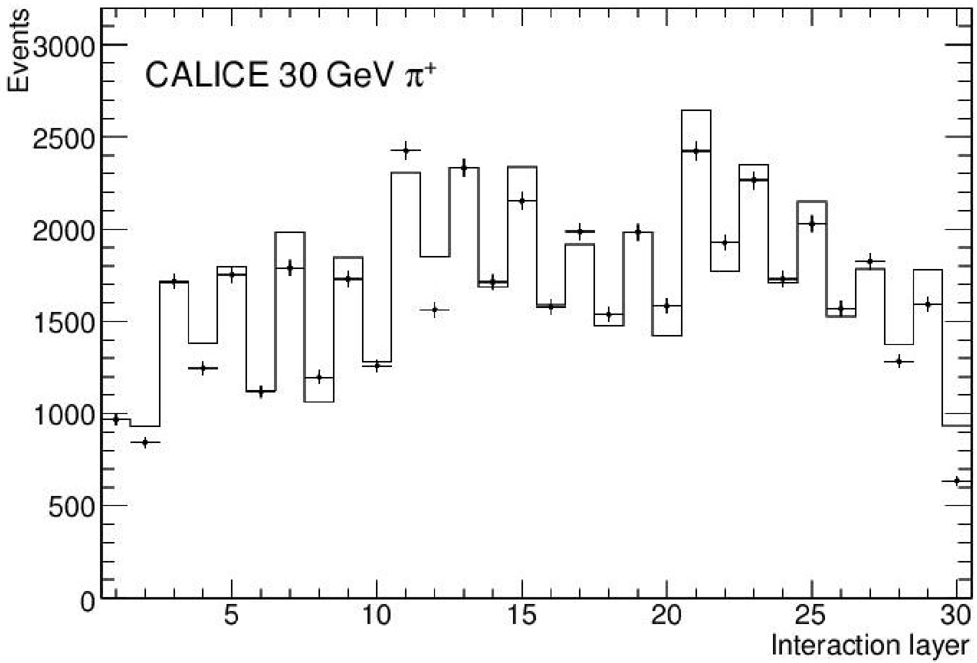
High granularity permits detailed view into hadronic shower

# Finding the Interaction in the SiW Ecal

Correlation:
True Interaction <-> Found Interaction




Distribution of found interaction layers



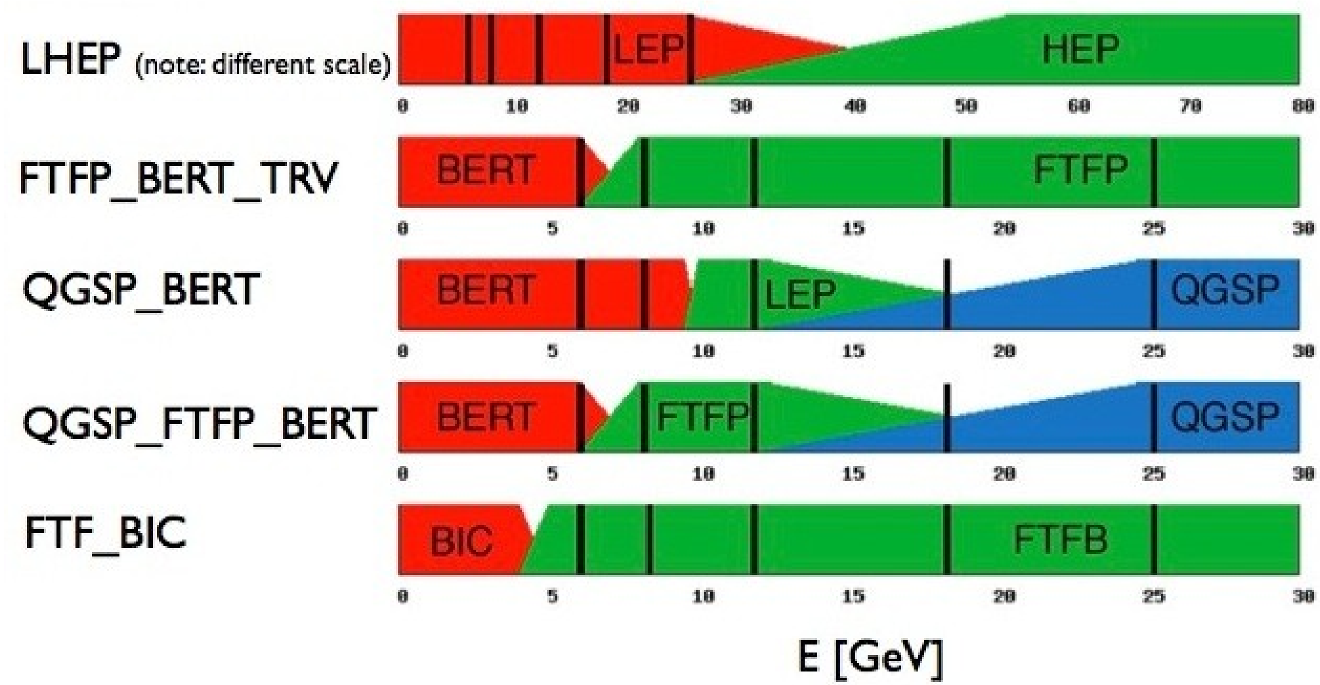

Determination precise to two layers
(Overall Layer thickness ~7mm max.)

Good agreement between Data and Simulation (G4, here QGSP_BERT)

Granularity allow for resolving interaction layer with high resolution
High energy cross sections well implemented in G4 simulation

# Hadronic models in GEANT4

Variety of models available to describe hadronic showers




**Discriminative power by high granularity !?**
**“Series of thin targets” (See A. Dotti's talk on G4)**