CALICE highly granular calorimeters with Si-Pad and SiPM readout

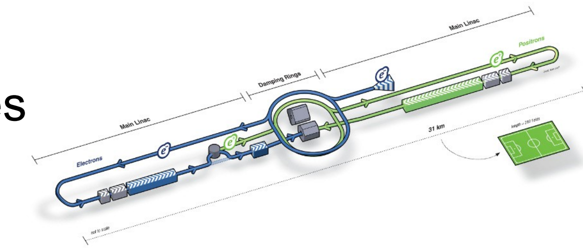
- CALICE: Calorimeters for Linear Collider Experiments
- Silicon ECAL
- Scintillator ECAL
- Scintillator HCAL
  - SiPMs and tiles
  - prototypes and testbeam plans

Katja Krüger (DESY)

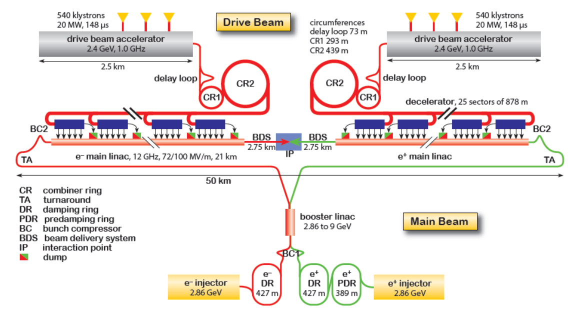
10th Terascale Detector Workshop
DESY, Hamburg
11 April 2017

Motivation: Future Linear Colliders

- future e+e- colliders offer unique physics possibilities
  - precise model-independent Higgs couplings
  - precision measurements of W, Z and top properties
  - indirect and direct searches for BSM physics



- ILC: proposed in Japan
  - $\sqrt{s}$ up to 500 GeV, upgradeable to 1 TeV
  - 31 km long, superconducting RF cavities
- CLIC: proposed at CERN
  - $\sqrt{s}$ up to 3 TeV
  - 50 km long, two-beam acceleration



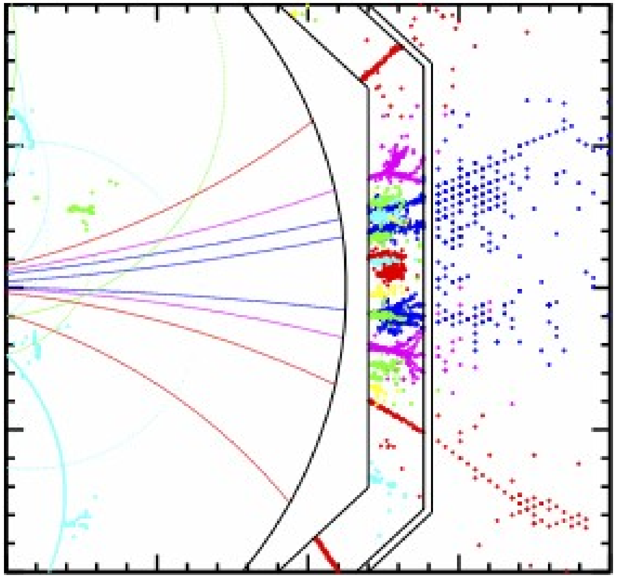
- main interest for calorimeters at linear colliders: jet energies

Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \rightarrow q\bar{q}b\bar{b}$ $Zh \rightarrow ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \rightarrow WW^*)$ $\sigma(e^+e^- \rightarrow \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%

from ILC TDR

Jet reconstruction at a Linear Collider

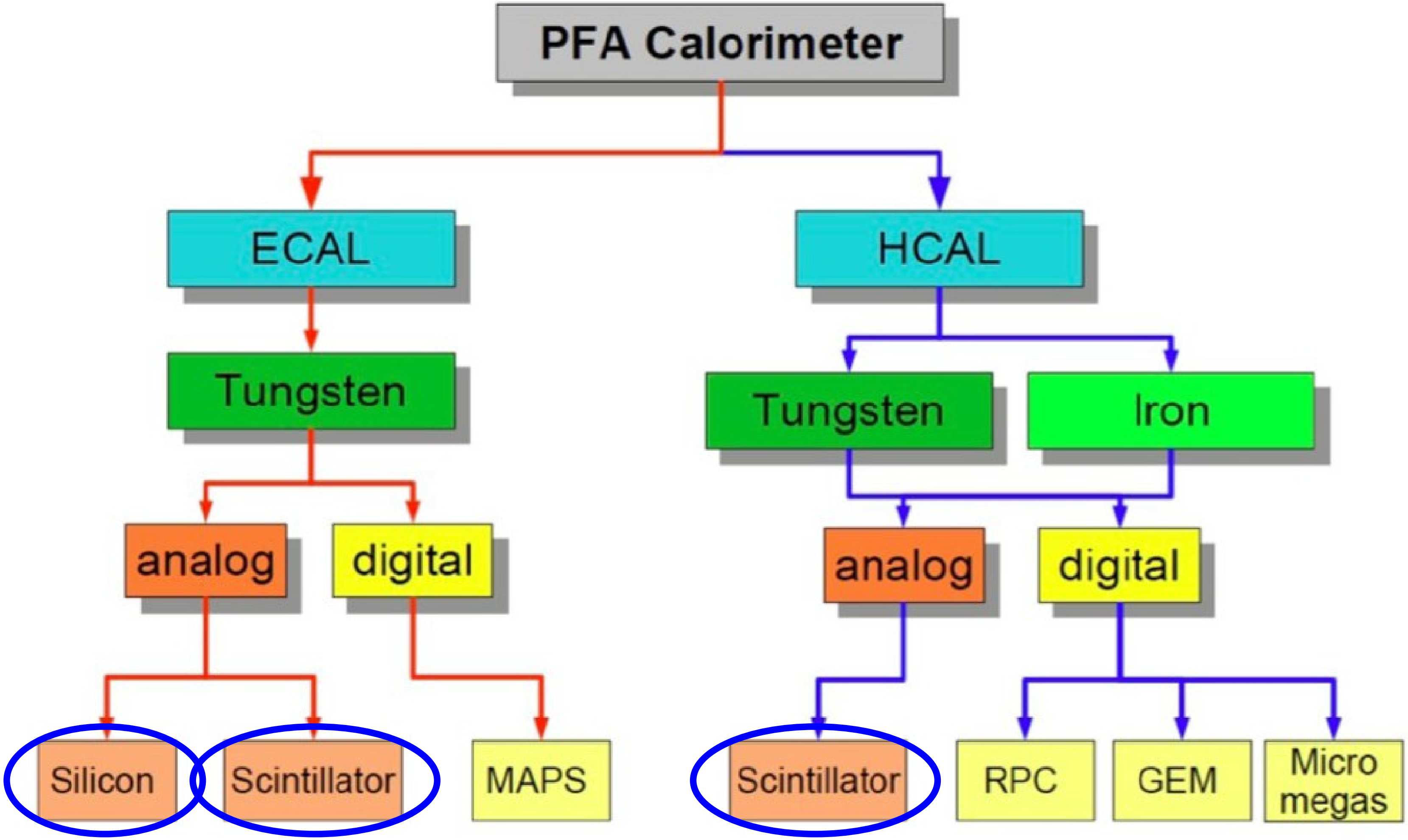
- goal: want to distinguish $Z \rightarrow$ jet jet from $W \rightarrow$ jet jet
- requires $\sigma(E)/E \approx$ 3-4%
- can be reached by particle flow algorithms (PFA)
  - for each particle within a jet: use the subdetector with optimal resolution
  - need to avoid double counting
- need an imaging calorimeter!



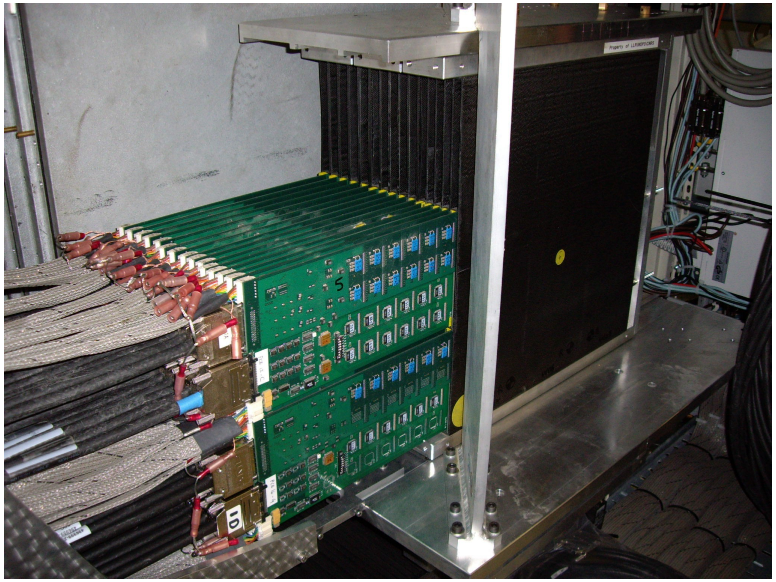
from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

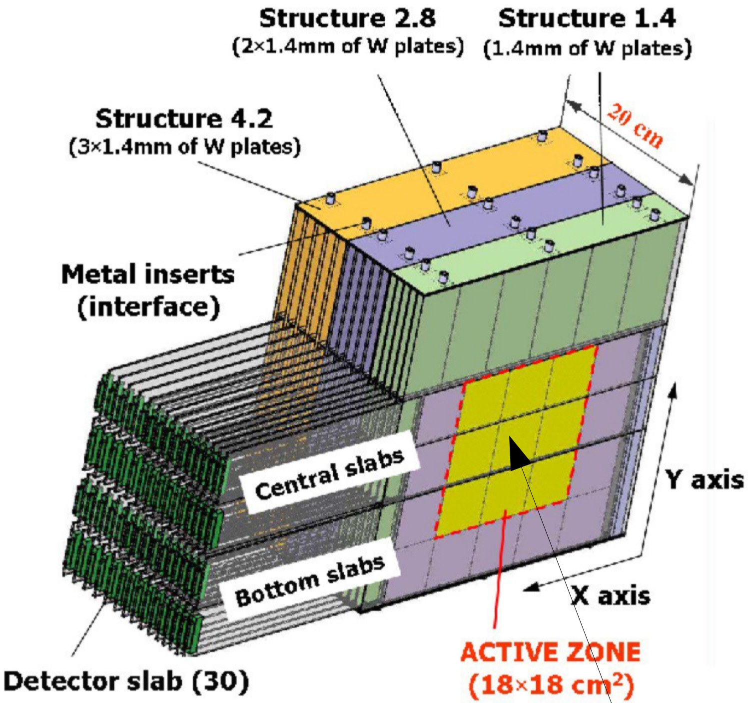
- requirements for the calorimeter:
  - highly granular
  - reconstruction of neutral particles: good energy resolution
  - calorimeter has to be within magnet coil: very compact

Calorimeter Technologies for Linear Collider detectors

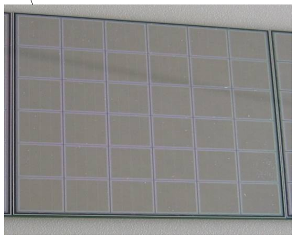


Silicon ECAL: Physics Prototype



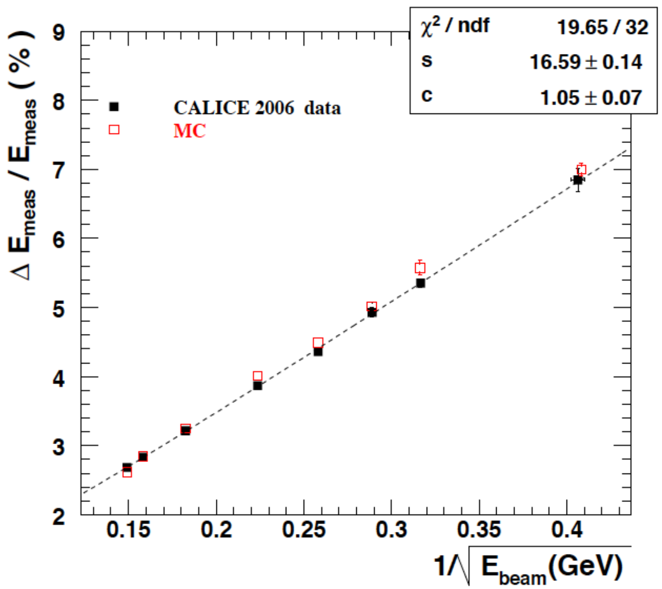


- absorber: tungsten plates 1.4 – 4.2 mm
- active material: silicon P-I-N diodes
  - thickness 525µm
  - granularity: 10x10 mm²



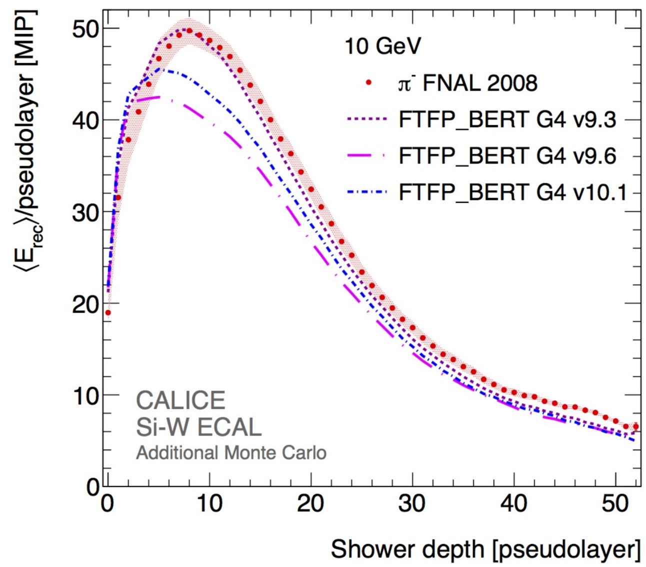
SiECAL: Physics Prototype Results

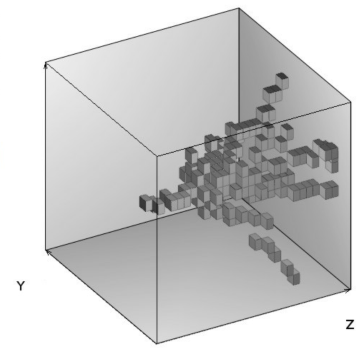
NIM A608 (2009) 372



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

NIM A794 (2015) 240

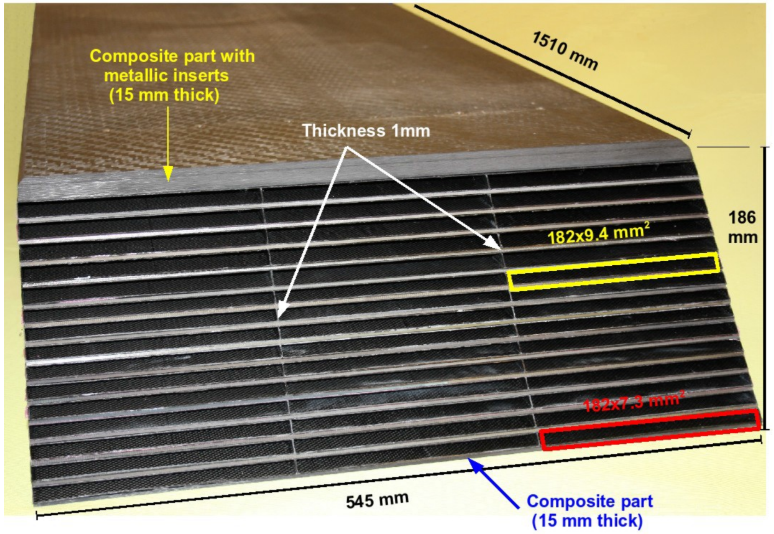


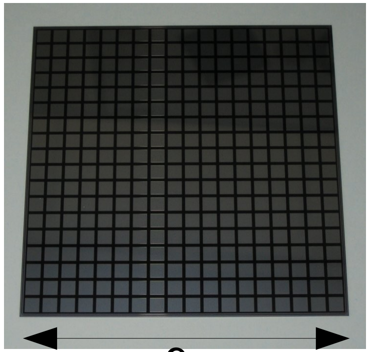


- reasonable energy resolution for electromagnetic showers
- can study hadron shower shapes with unprecedented granularity

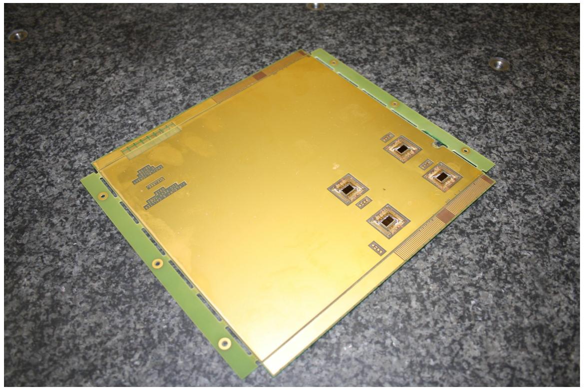
SiECAL: Technological Prototype

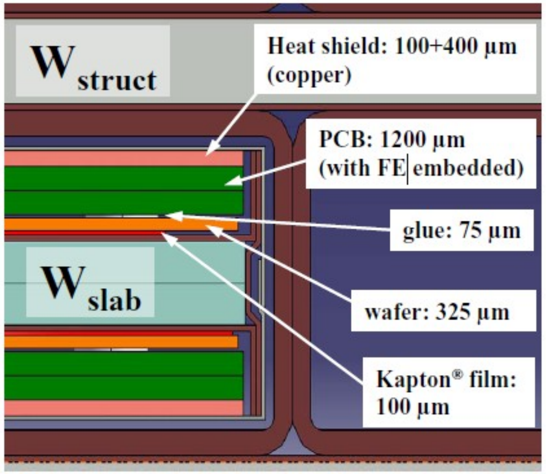
- 5x5 mm² pixels
- challenge: very compact structure with tungsten absorber
- alveolar structure: carbon fibre structure to hold the tungsten plates
- very thin gaps in absorber: PCB with embedded FE ASICs, conventional PCB with BGA also under discussion
- working on mass production scheme





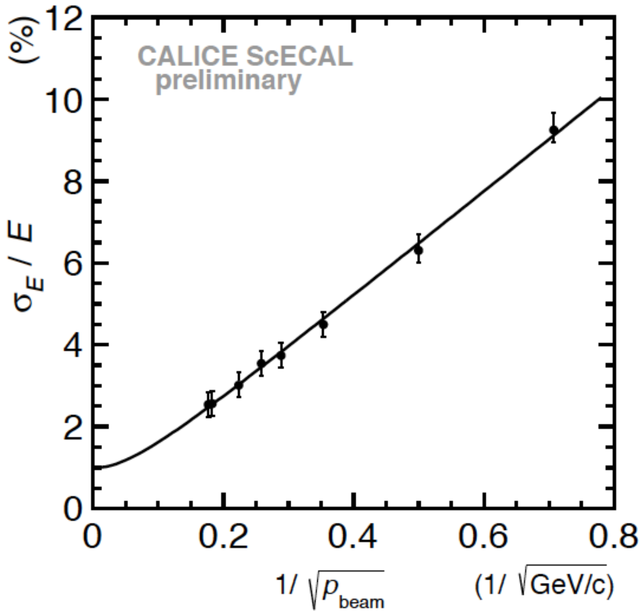
9cm
256 pixel

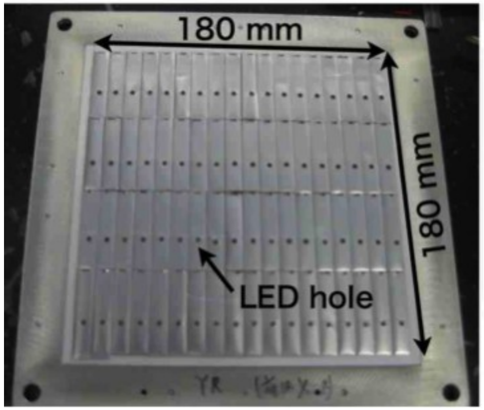


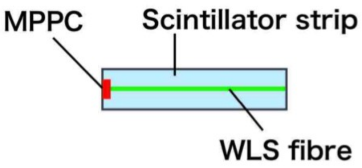


Scintillator ECAL: Physics Prototype

CAN-016c



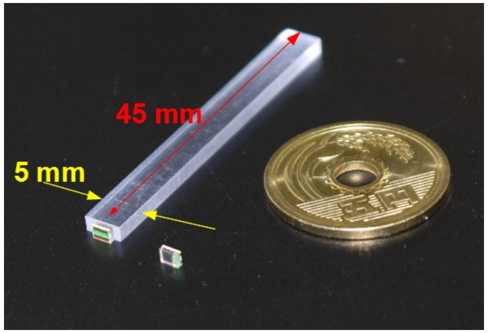




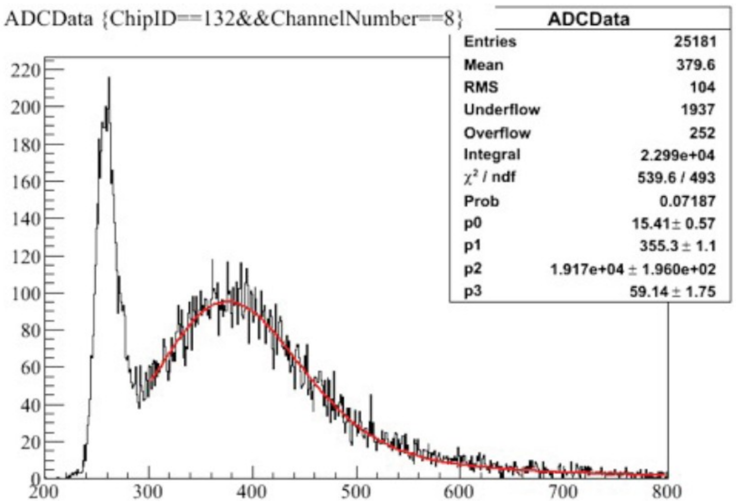
$$\frac{\sigma(E)}{E} = \left(\frac{12.8 \pm 0.4}{\sqrt{E}} \oplus (1.0\,^{+0.5}_{-1.0})\right)\%$$

- scintillator strips read out via WLS fibre by SiPMs
- reasonable energy resolution for electromagnetic showers

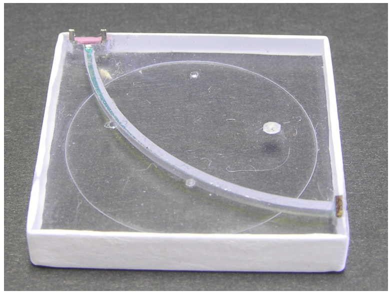
Scintillator ECAL: Technological Prototype

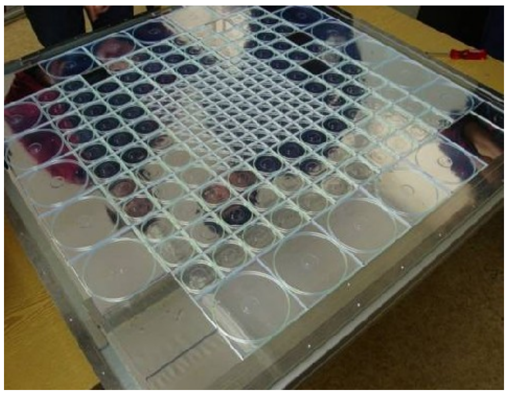


- 45x5 mm² strips for effective 5x5 mm² geometry
- many synergies with developments for scintillator HCAL
- stringent requirements for SiPMs: larger dynamic range than for HCAL, consequently
  - small pixel/MIP → low noise
  - large number of pixels

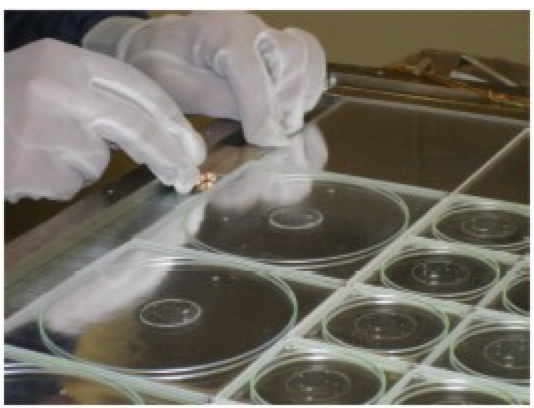


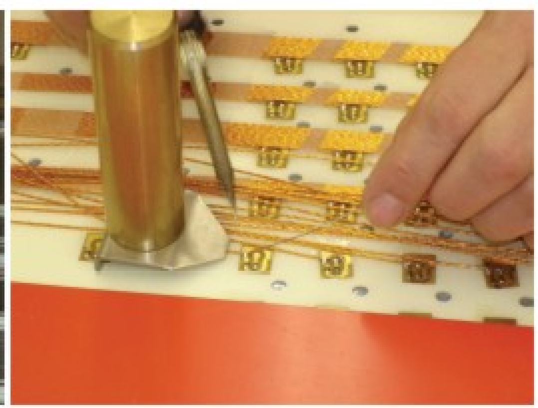
Scintillator HCAL: Physics Prototype

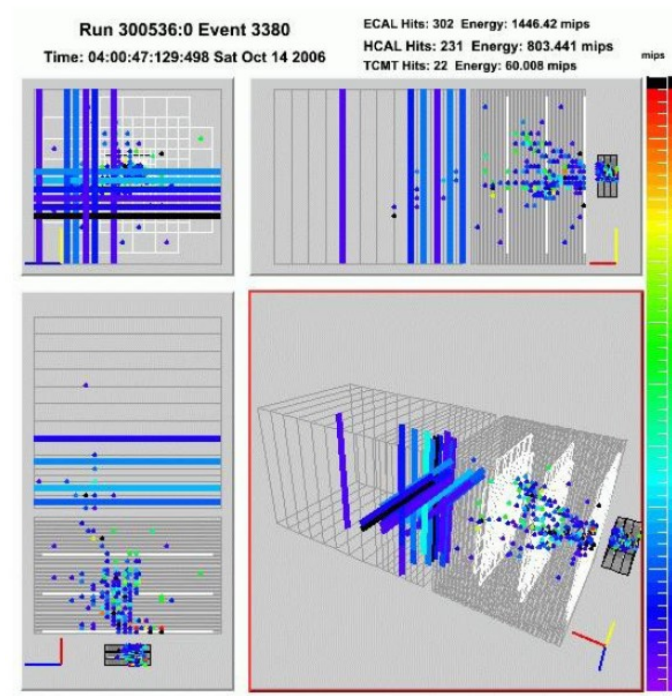




- based on scintillator tiles with WLS fibers, read out by SiPMs
  - $3*3$ cm^2 - $12*12$ cm^2 tiles, 7608 channels
  - analogue readout: 12 bit
- 1m^3 prototype in beam tests 2006-2012
  - first device using SiPMs at large scale

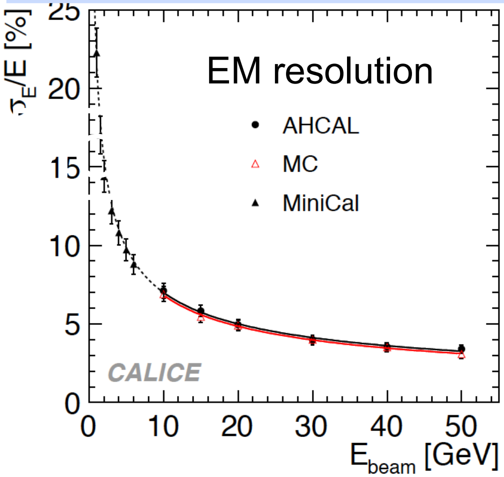






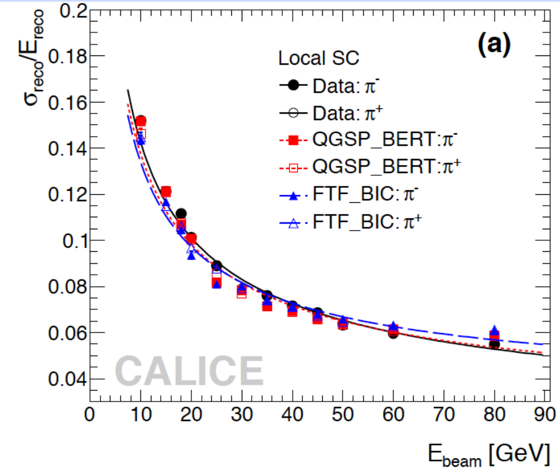
AHCAL physics prototype: results

Detector validation



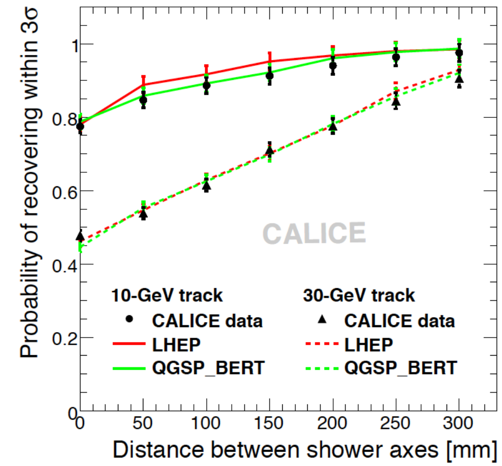
JINST 6, P04003 (2011)

Performance validation



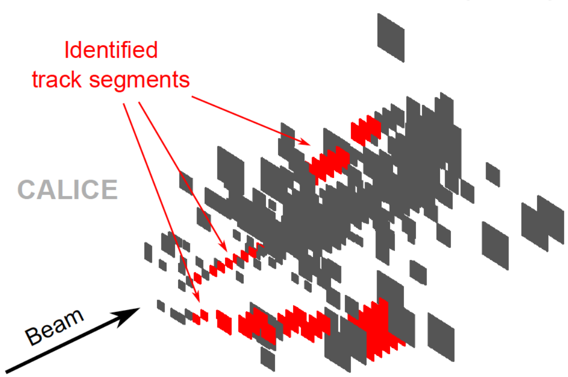
JINST 7, P00917 (2012)

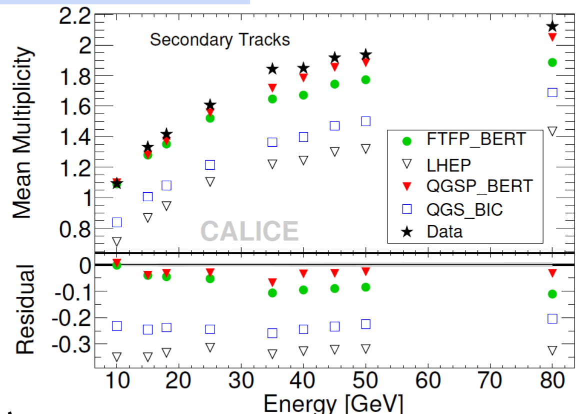
Particle Flow validation



JINST 6, P07005 (2011)

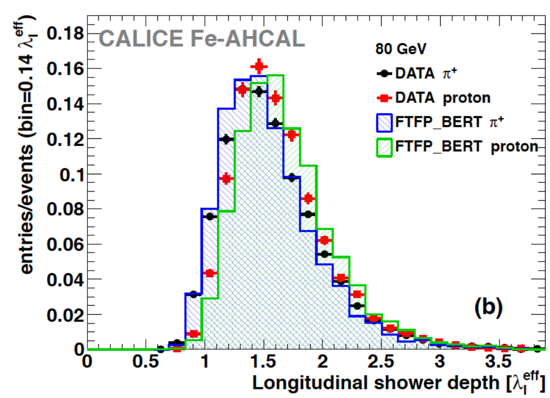
Imaging validation





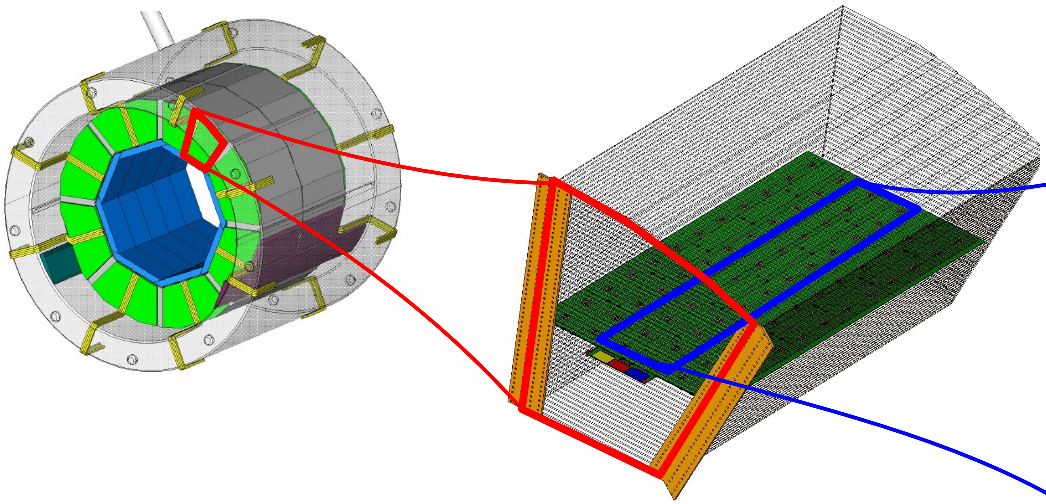
JINST 8, P09001 (2013)

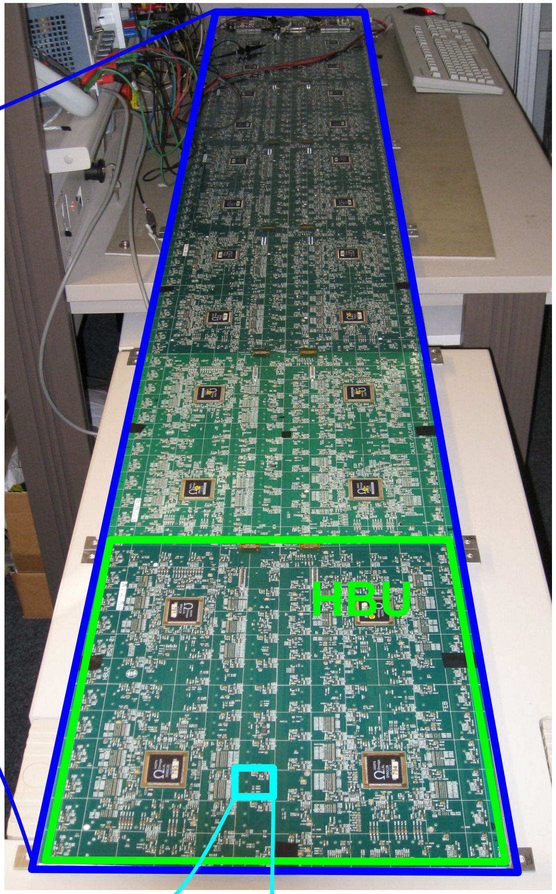
π/p comparison

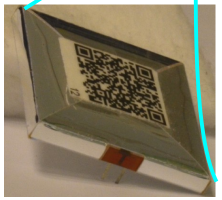


JINST 10, P04014 (2015)

Scintillator HCAL: Technological Prototype



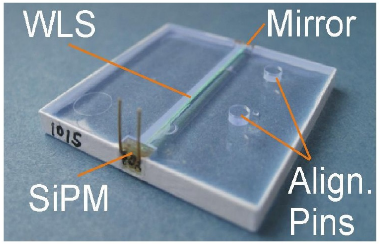


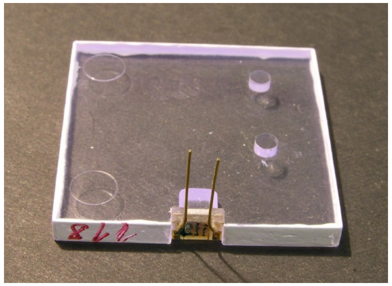


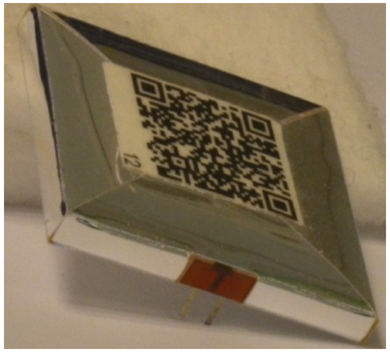
- fully integrated design
  - front-end electronics, readout
  - voltage supply, LED system for calibration
  - no cooling within active layers
- scalable to full detector (~8 million channels)
  - mechanics, electronics, sensors
  - production, commissioning

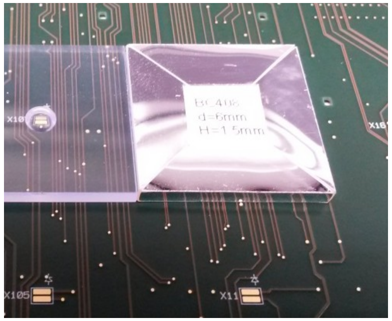
Evolution of Tiles and SiPMs

variety of scintillator tile designs and SiPM types tested









> tiles with straight WLS fibre
- CPTA SiPMs with 800 pixels

> tiles without WLS
- Ketek SiPMs with 12000 pixels

> individually wrapped tiles
- Ketek SiPMs with 2300 pixels
- sensl SiPMs with 1300 pixels

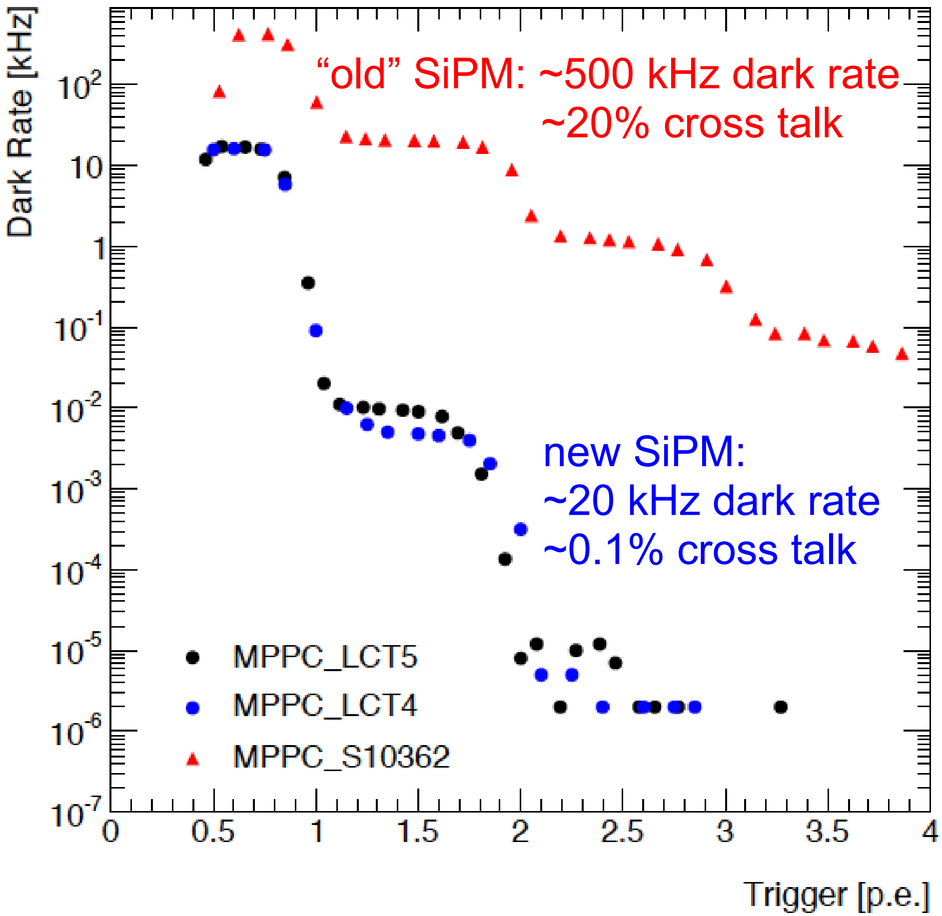
> surface mount SiPMs with individually wrapped tiles
- Hamamatsu MPPCs with 1600 pixels (no trenches)

> all types tested in beam tests in 2014 and 2015

> chose surface mount design, formulated requirements for SiPMs

New generation of SiPMs

- recent SiPMs show very much improved sample uniformity
  - operating voltage
  - gain
  - ➔ no need for equalisation
- very recently, **SiPMs with trenches** between pixels became available
  - dramatically reduced dark rate and pixel-to-pixel cross talk
  - for typical trigger threshold of HCAL (~7 p.e) **noise-free**
  - ➔ allows auto-trigger operation
- SiPMs are a rapidly evolving field
  - new generation fulfils HCAL requirements, ECAL requirements in reach

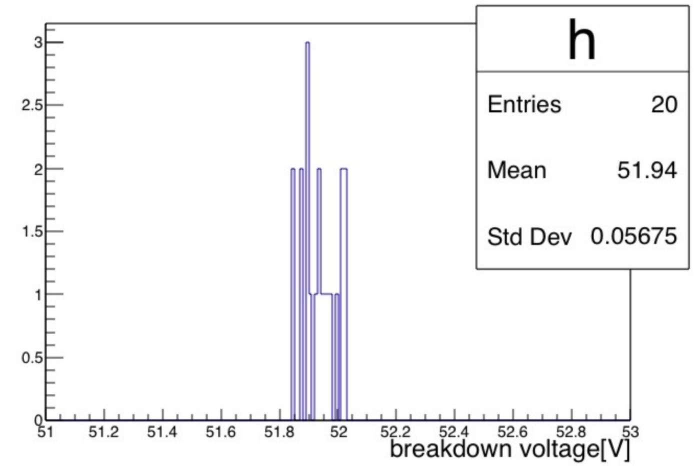


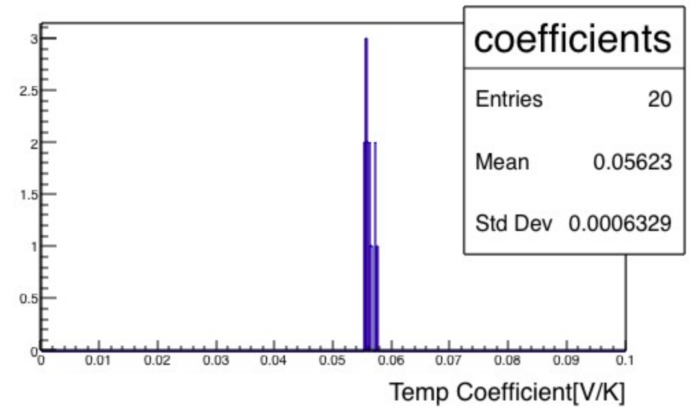
for comparison: SiPMs in physics prototype 2 MHz dark rate, 30% cross talk

HCAL Requirements for SiPMs

- plan to build a new large HCAL prototype with 40 layers with 576 SiPMs each
- SiPM requirements for tendering:
  - N(pixels) > 1500
  - dark count rate < 500kHz
  - cross-talk < 3%
  - photon detection efficiency (@420nm) >20%
  - gain $>3\times10^5$
  - dV/dT < 1% of excess bias voltage (~50mV/K)
  - breakdown voltage spread min-max: 200 mV (within a batch of 600 SiPMs)
- will test sample of 24 SiPMs per batch
- test of first batch:
  - still working on absolute PDE measurement
  - **all other requirements fulfilled**
  - **excellent uniformity**

Uni Heidelberg



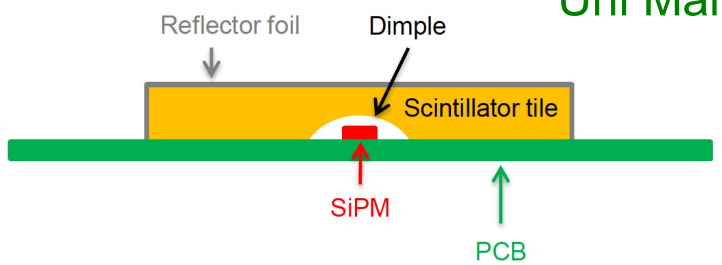


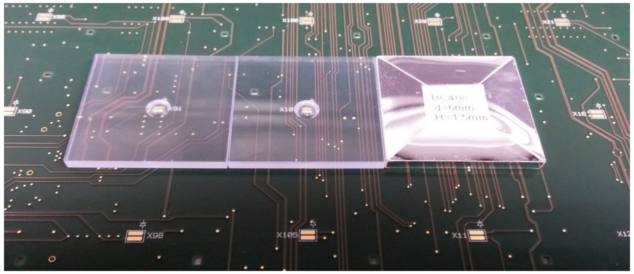
Towards mass production: simplified tile & HBU design

Uni Mainz

- tile design with SiPMs mounted on the side of the tile not suitable for mass assembly
- tiles with surface-mount SiPMs fulfill HCAL requirements
  - signal size
  - signal uniformity across tile
- new HBU design for surface-mount SiPMs:
  - SiPMs mounted directly on PCB
  - individually wrapped tiles

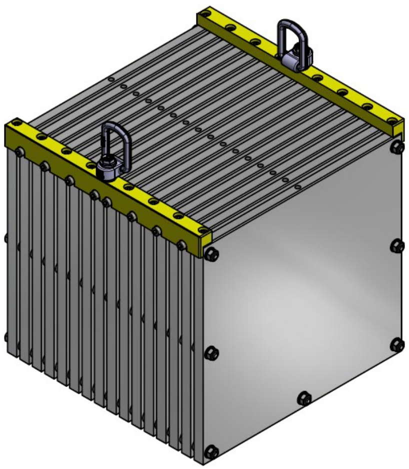
  ➔mass assembly with pick-and-place machine possible
- very positive experience in testbeam





New small HCAL prototype

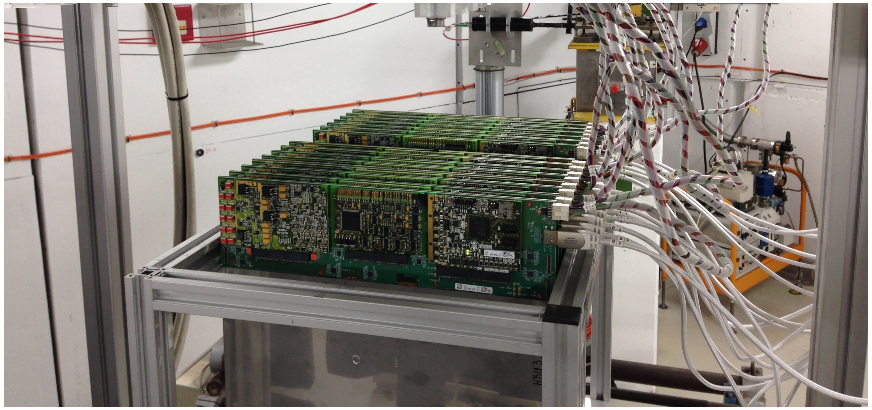
MPP München

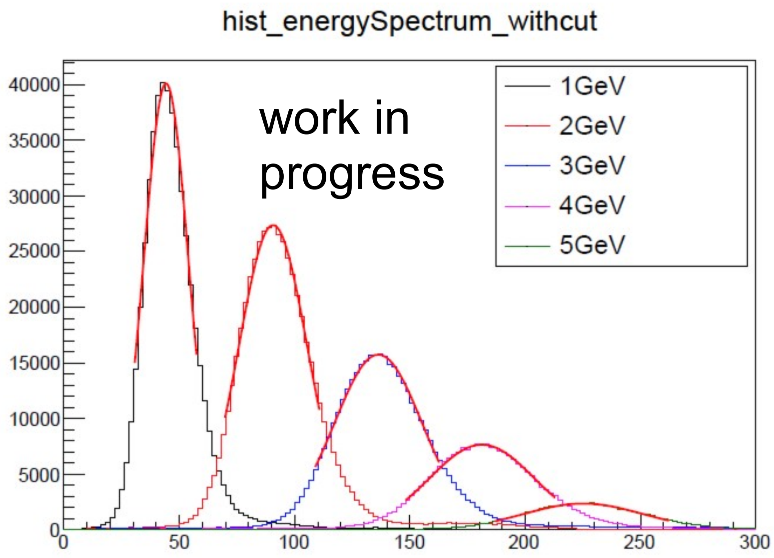


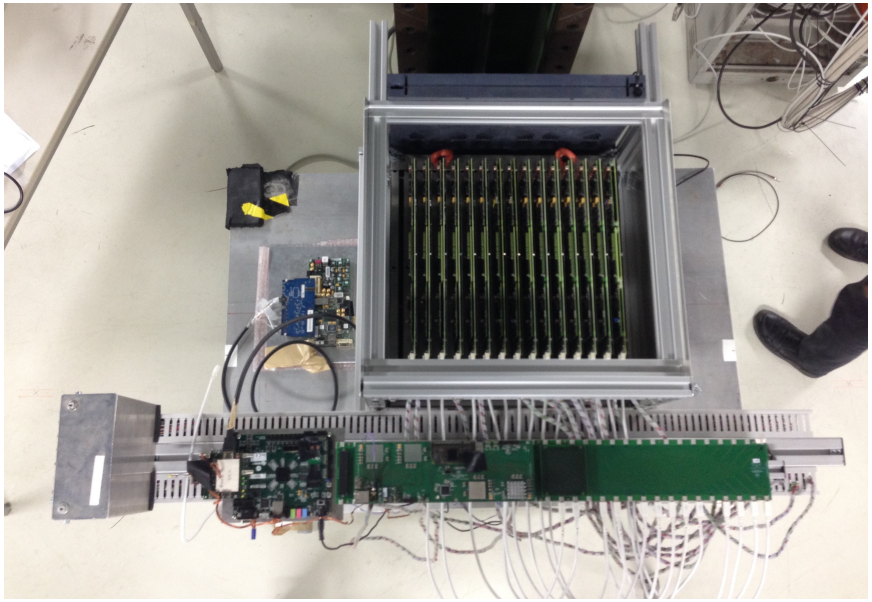
- small prototype for electromagnetic showers with high-quality photo-sensors in all channels
- 15 layers of 1 HBU
  - 6 new HBUs with new generation surface-mount MPPCs (Hamamatsu, trenches)
  - 1 HBU with previous generation surface-mount MPPCs (Hamamatsu, no trenches)
  - 8 HBUs with good quality previous generation SiPM on tile (sensl)
- demonstrate the precision we can reach for e.m. shower response and resolution
- demonstrate power pulsing behaviour for a (small) calorimeter system
- demonstrate temperature compensation

New small HCAL prototype in DESY testbeam

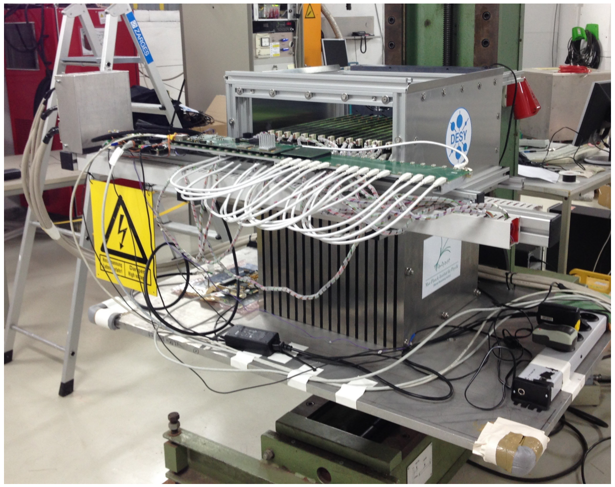
- July/August 2016
- MIP calibration for all layers
- e.m. shower data without and with power pulsing
- analysis started, first look into data very encouraging

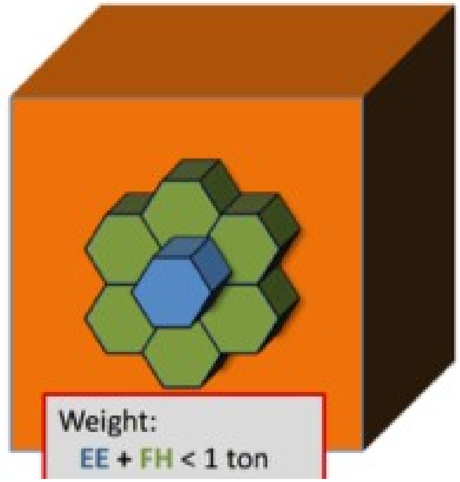






New small HCAL prototype: next steps





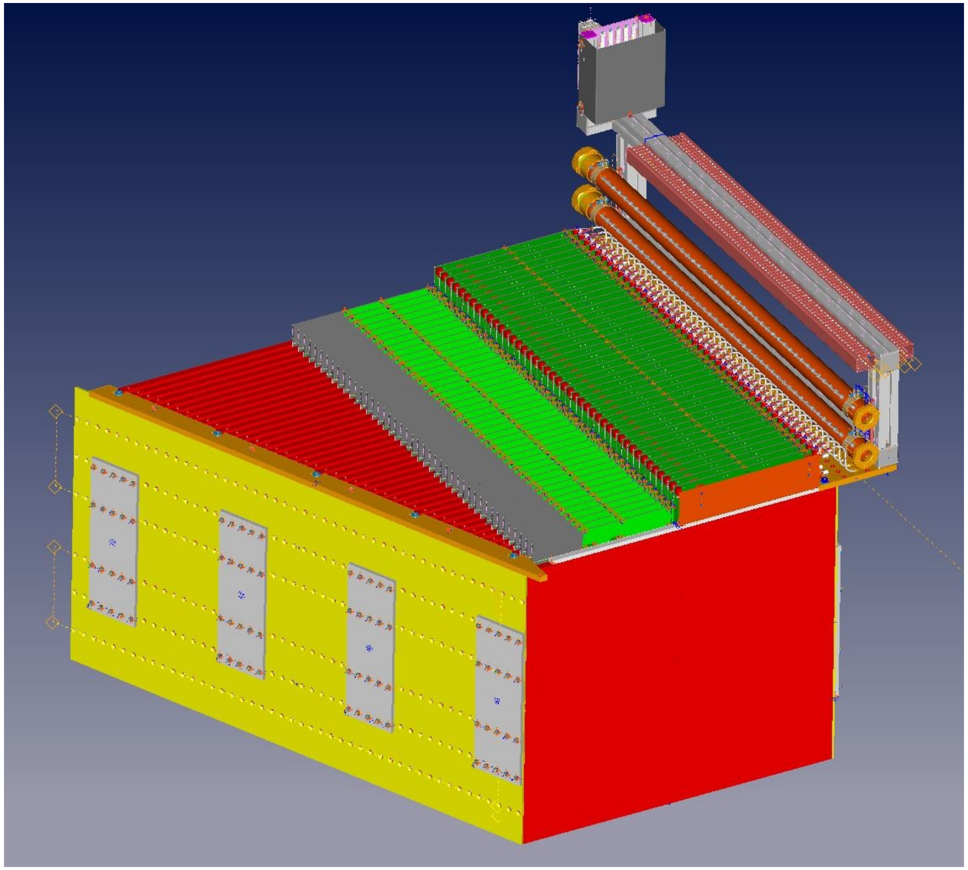
goal for 2017: fully exploit potential of small prototype

- power pulsing in magnetic field: 1 week of beam in ~3T at SPS
- as backing calorimeter of CMS HGCAL prototype at SPS
- plan to test compensation of response change due to temperature variations

Towards a large HCAL Technological Prototype

- goal: instrument EUDET steel stack as large prototype
  - corresponds to ~1% of barrel
  - 40 layers of 4 HBUs each
  - scalable to full linear collider detector
  - infrastructure as for linear collider detector
  - big step towards mass production
- procurement in progress
  - SiPMs ordered
- plan: assembly in 2017, hadron beam in 2018

Towards a large HCAL Technological Prototype



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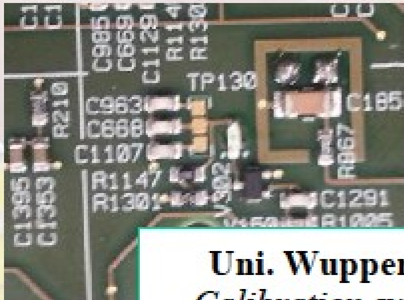
Conclusions and Outlook

- CALICE: development of highly granular calorimeters optimised for particle flow reconstruction algorithms
  - silicon or scintillator+SiPM for ECAL
  - scintillator+SiPM for HCAL (+ alternatives)
- physics prototypes: demonstrated detector performance and particle flow capabilities
- technological prototypes: demonstrate scalability to linear collider detector
  - new generation of SiPMs: low noise and much improved sample uniformity, fulfil HCAL requirements
  - simplified design, construction, commissioning and operation
- stay tuned for more testbeam results!

AHCAL Technological Prototype: International Cooperation



Strong contribution from different international & German institutes

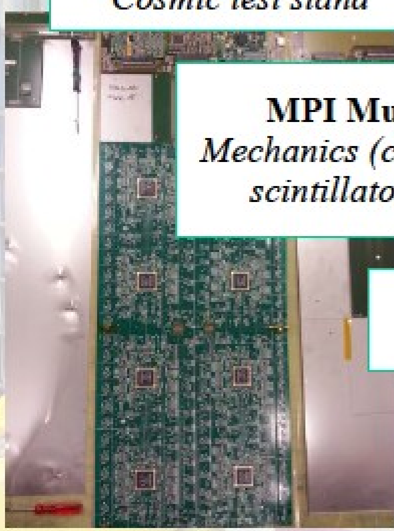
Uni. Hamburg
Tile & SiPM tests

Uni. Wuppertal
Calibration system
ASIC tests

DESY in leading role
Electronics & mechanics design
Commissioning
Testbeam software
Testbeam coordination

Uni. Heidelberg
Tile & SiPM tests
ASICs

Uni. Mainz
DAQ, assembly
Cosmic test stand



Uni. Sussex
Monitoring

MPI Munich
Mechanics (cassettes), scintillator tests

All institutes
Analysis of data

Lebedev I
Tile production

Omega (IN2P3)
ASICs

Prague
DAQ

CERN
Tungsten structure, test beam, logistics

R&D contribution from additional partners

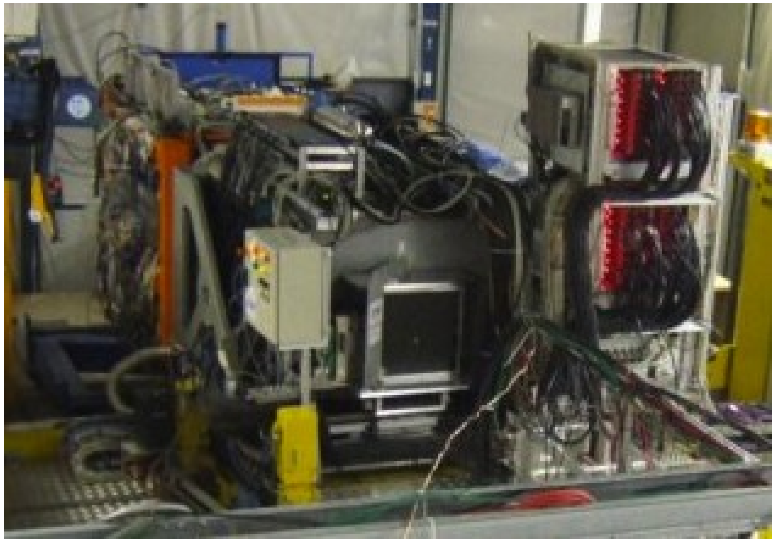
Shinshu Uni, Tokyo Uni (**Japan**)
JINR, Dubna, MEPHI, Moscow (**Russia**)
UT Arlington, Northern Illinois Uni (**USA**)

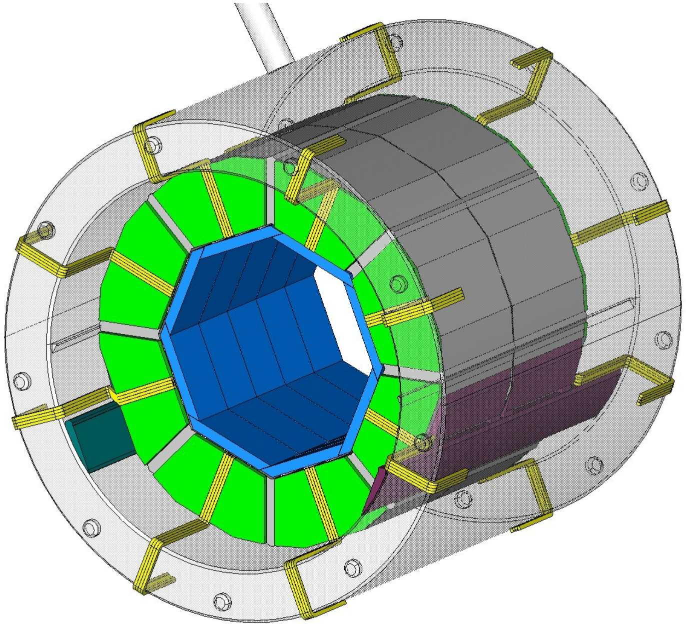
Backup

From physics prototype to technological prototype

- capabilities of a highly granular scintillator-steel (or tungsten) calorimeter successfully demonstrated with the “physics prototype”
- not scalable to a collider detector:
  - external electronics
  - external LED calibration system
  - labour intensive assembly

- goal for the “technological prototype”: develop, build and test a prototype scalable to the full ILC detector layout
  - integration of electronics into layers
  - realistic infrastructure
  - easy mass assembly

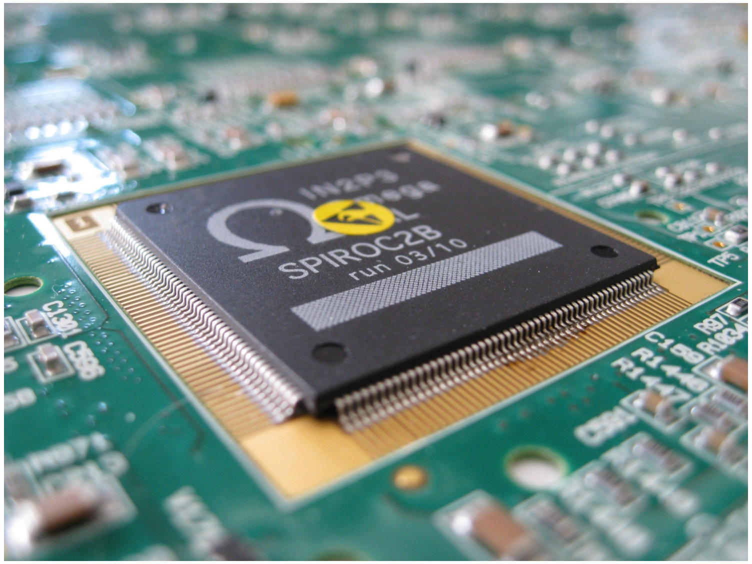


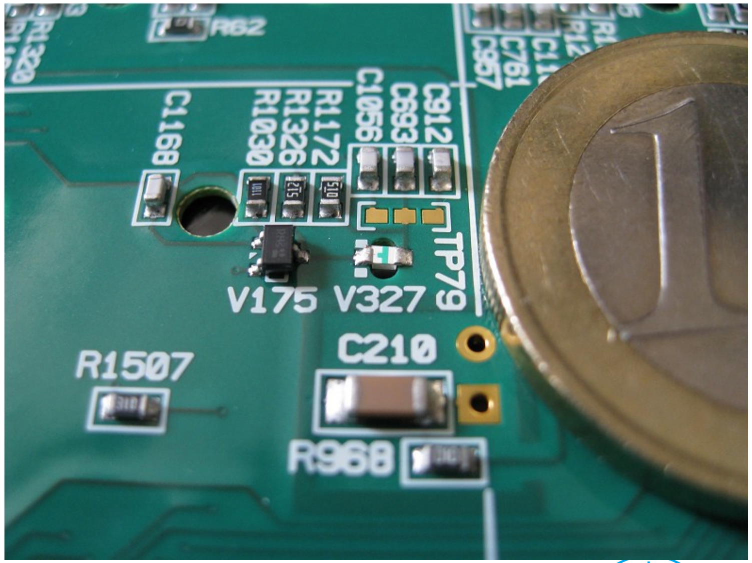


DESY

Electronics: HBU

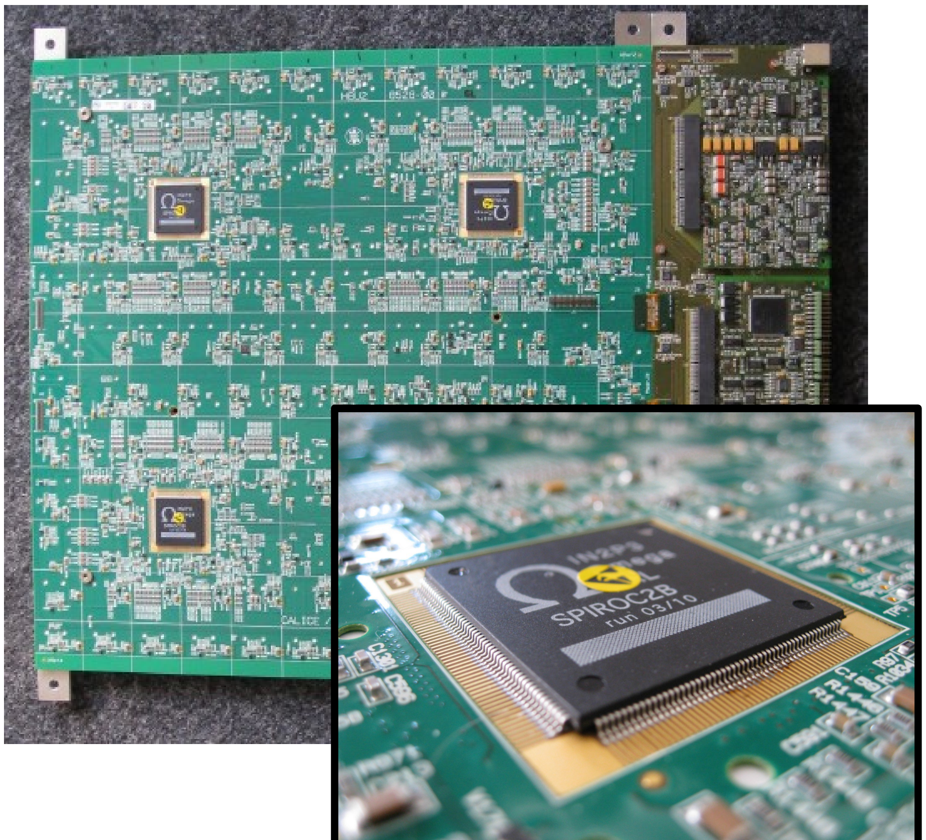
- HCAL Base Unit (HBU)
  - extra-thin PCB, cutout for ASICs
  - $36*36cm^2$, 144 channels
- readout ASIC: SPIROC2b
  - designed by OMEGA, France
  - alternative development: KlauS2
- integration
  - readout (DAQ), voltage supply
  - LED system for SiPM calibration
- flexible technology
  - can be used for different SiPMs
  - adapted versions for several scintillator geometries
  - plan to go to BGA-mounted ASICs for easier assembly

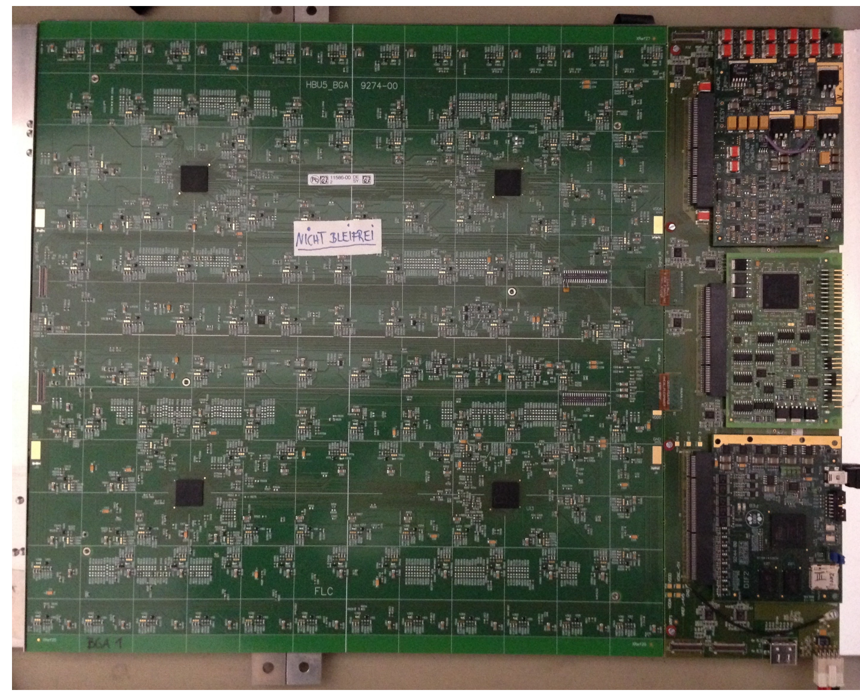




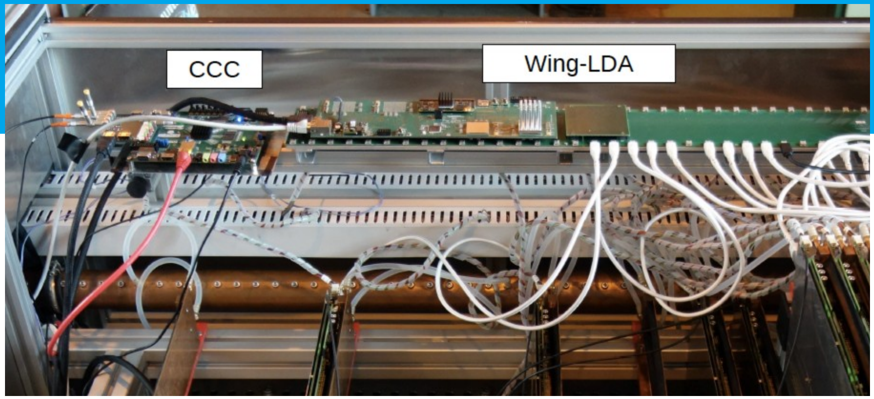
HBUs

- several revisions, following developments of components
- most recent:
  - adaptation from side-mount to surface mount SiPM
  - new ASIC in BGA package: simpler PCB production (no cutout), cheeper



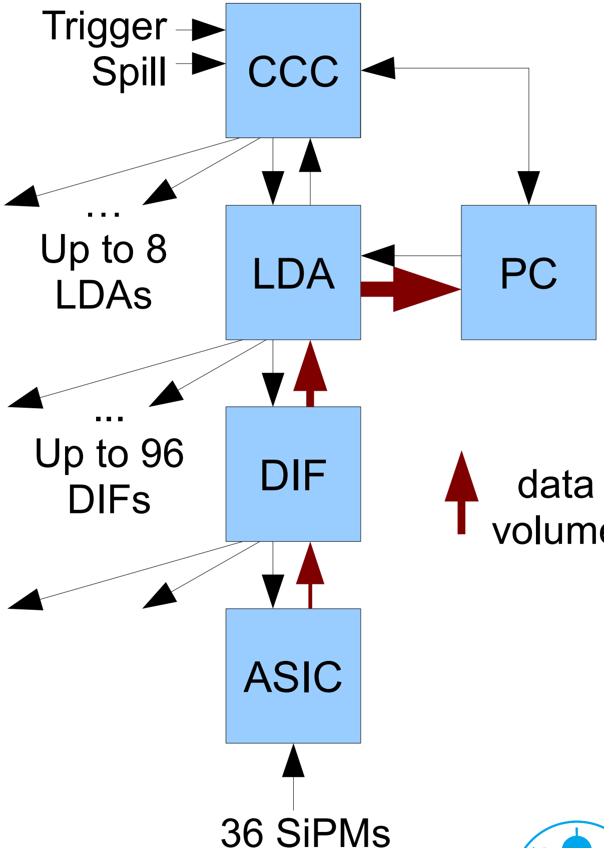


System integration: DAQ



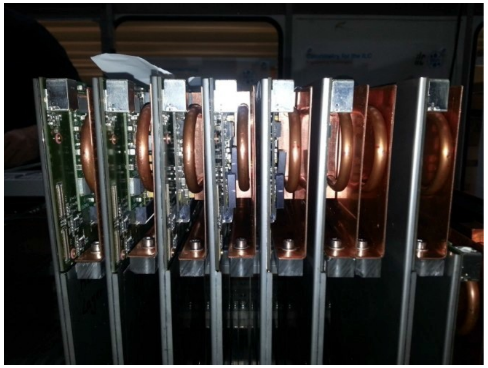
- modular hierarchical DAQ system
- HDMI based
- versatile for use in testbeam and in ILC-like conditions
- scalable to full collider detector
  - setup used in testbeam adapted to LC detector geometry, can read out 2*48 layers
- successfully operated in beam tests
  - stable running
  - power pulsing
  - reached ~30 readout cycles / s (requirement for ILC: 5)

    → >450 Hz sustained event rate
- tested also common running with other calorimeter prototypes



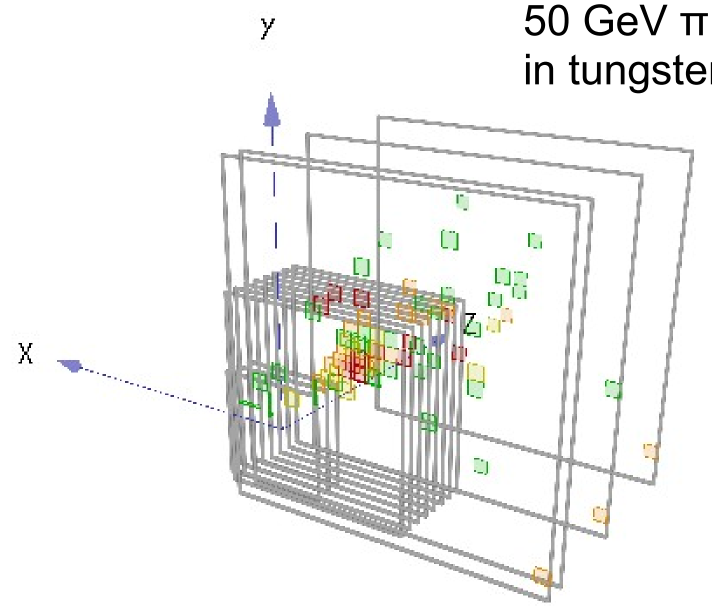
System integration: mechanics, power, cooling

- steel absorber structure for beam tests
  - realistic sizes and tolerances
  - corresponds to ~1% of ILC detector barrel
- horizontal steel structure for thermal tests
  - size of a full layer
- cooling for interface electronics
- power supply and distribution for full barrel sector

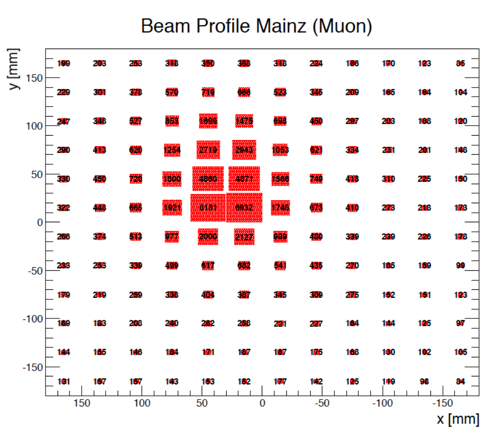


AHCAL Testbeams

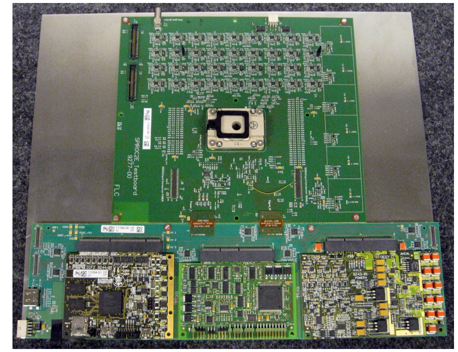
- 2 times 2 weeks of testbeam at SPS in 2015
  - steel and tungsten absorber
  - partly equipped active layers
  - muons and electrons for calibration
  - energy scans 10 – 90 GeV for pions to study shower shapes and hit timing
- one small layer with recent SiPMs and new tile design
  - very positive experience
- successful test of system aspects
  - DAQ, mechanics, power, cooling
  - online monitoring
  - distributed data analysis
  - simulation



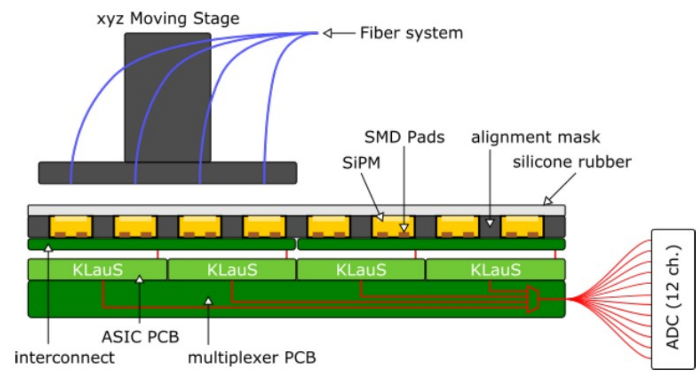
50 GeV π in tungsten



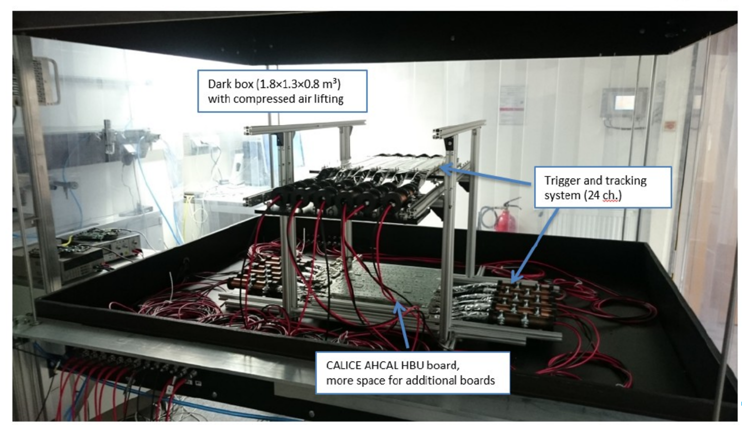
Towards the large prototype: Quality Assurance



- **ASIC test board**
  - goal: test all ASICs before assembly



- **SiPM characterisation**
  - goal: test small samples for each batch of SiPMs



- **Cosmic Ray test stand**
  - goal: test all assembled HBUs