38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
AUGUST 3 - 10, 2016
CHICAGO

Technologies for highly granular electromagnetic and hadronic calorimeters

Huong Lan Tran (DESY, Germany)
on behalf of the CALICE collaboration
August 4, 2016

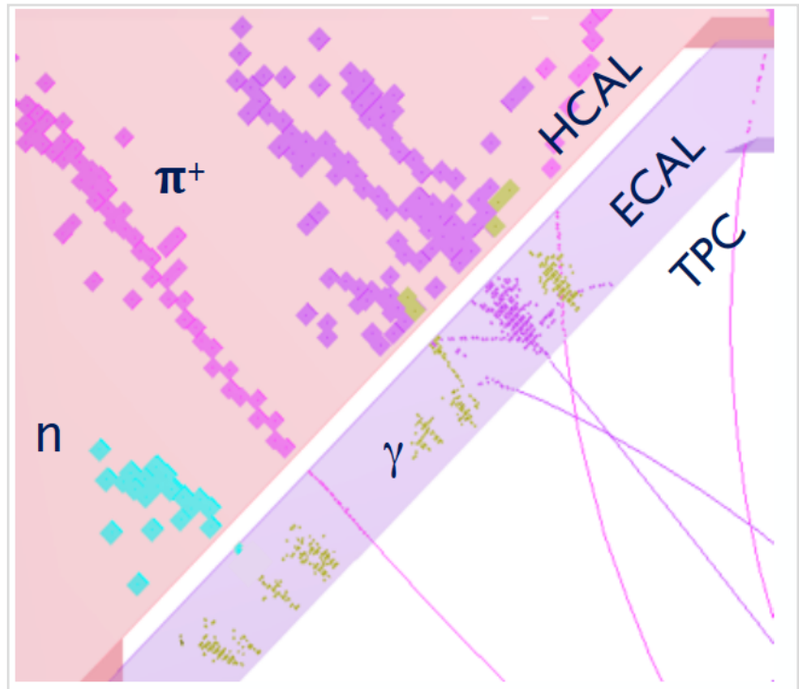
Motivation for highly granular calorimeters

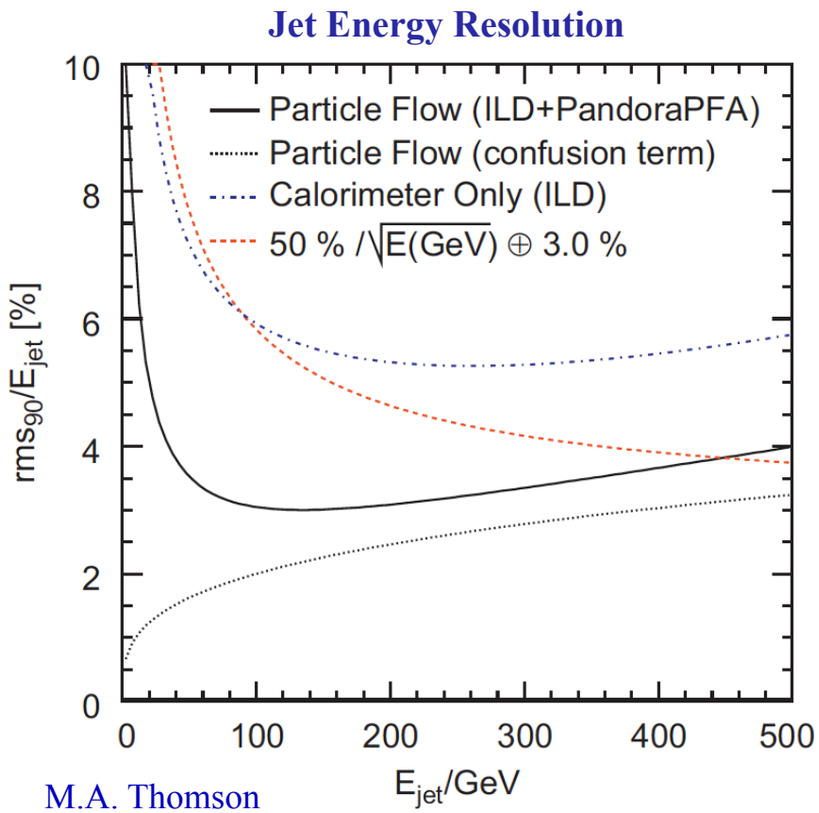
- Highly granular calorimeter: prerequisite requirement for particle separation in *Particle Flow reconstruction*
- In a typical jet:
  - 60% energy in charged particles
  - 30% in photons
  - 10% in neutral hadrons

- Traditionally jet energy measured using electromagnetic and hadronic calorimeters: $E_{JET} = E_{ECAL} + E_{HCAL}$

  ➢ rather limited resolution

- Particle Flow reconstruction: *trace individual particles* with high granularity calorimeters
  - Measure charged particle energy through track momentum
  - Photon energy measured in electromagnetic calorimeter (ECAL)
  - Neutral hadron energy measured in hadronic calorimeter (HCAL)
  - Jet energy is therefore: $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

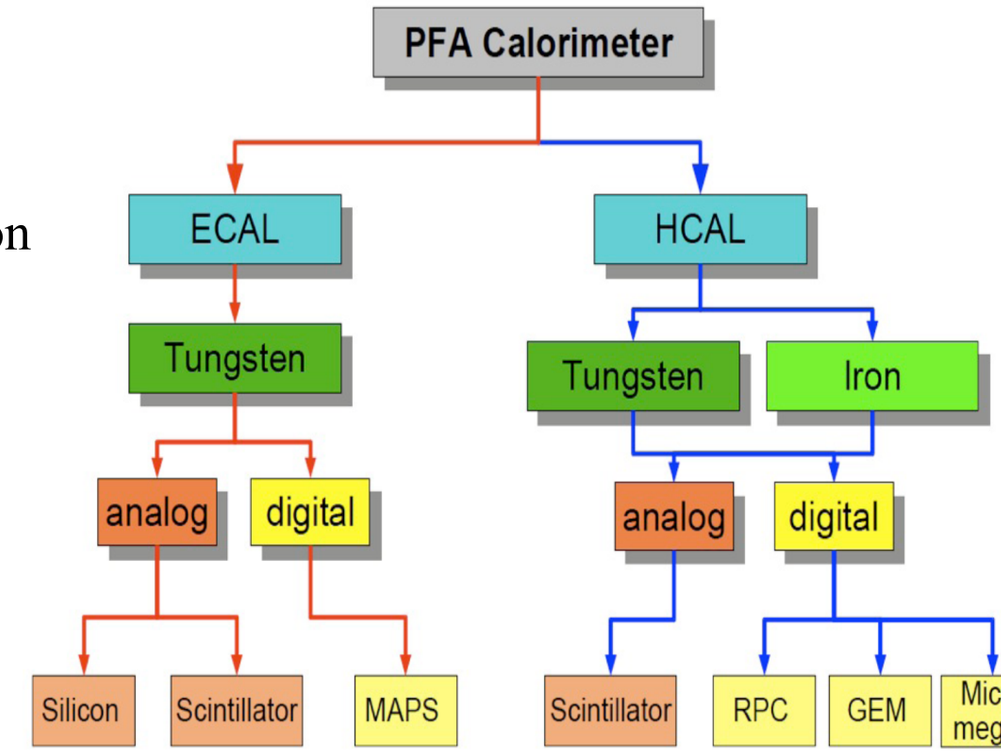




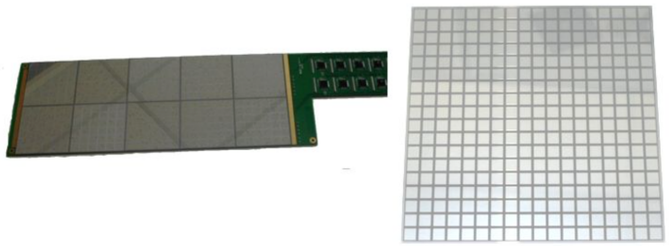
M.A. Thomson
Nuclear Instruments and Methods A 611 (2009) 25-40

The CALICE collaboration

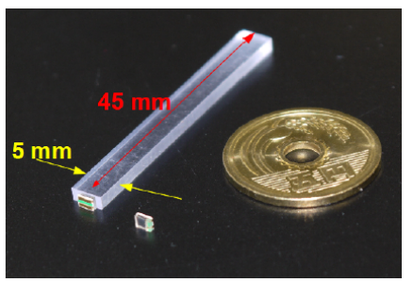
- **Goal**: Research and development of highly granular calorimeters for future lepton colliders
- **Technologies**:

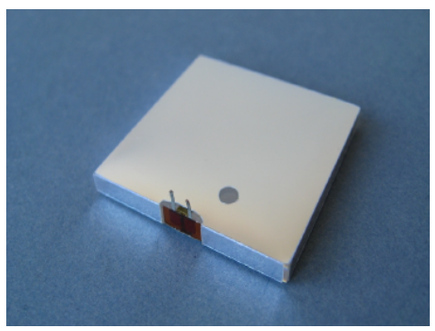


- ***Silicon***:
  - Compact, stable calibration
  - 0.5-1.0 cm^2 cells

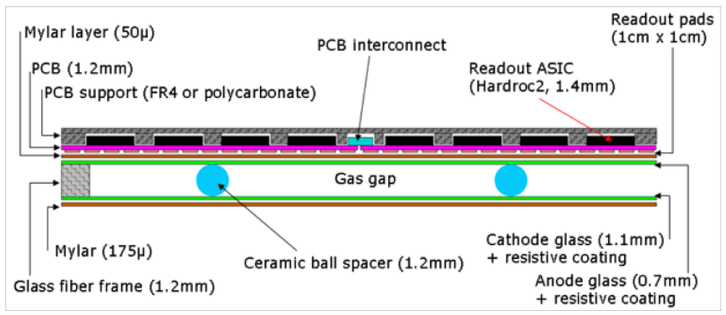


- ***Scintillator***:
  - Robust and reliable
  - Easy to machine, various cell sizes
  - Silicon Photomultiplier (SiPM) read-out





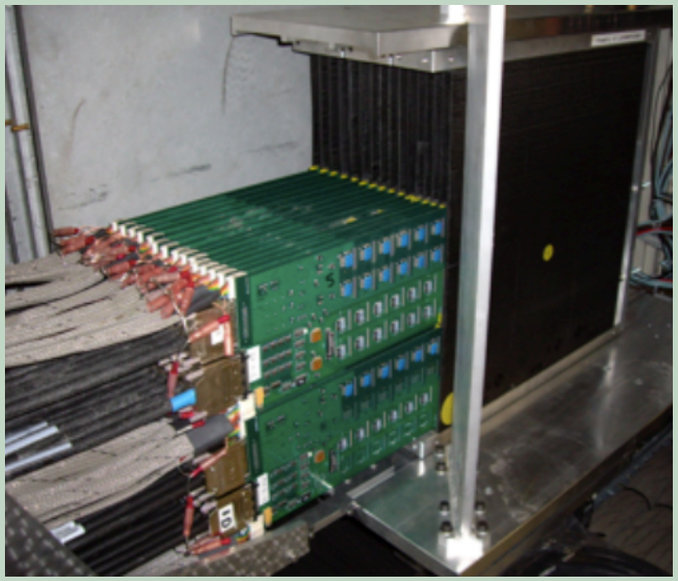
- ***Gaseous***:
  - Easily segmented 1x1 cm^2
  - Glass RPCs (GRPC): good and well-known technology



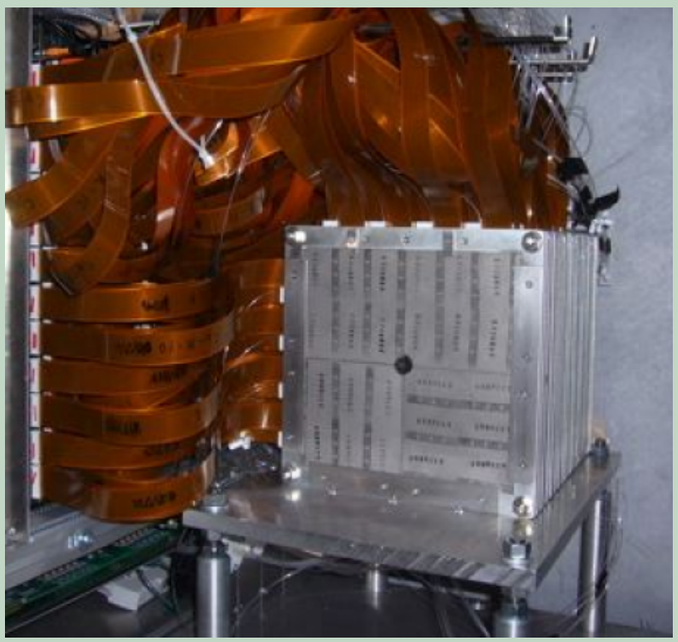
- ***Other technologies***:
  - Micro Pattern Gaseous Detectors (MPGD): GEMs, Micromegas

The CALICE physics prototypes

ECAL

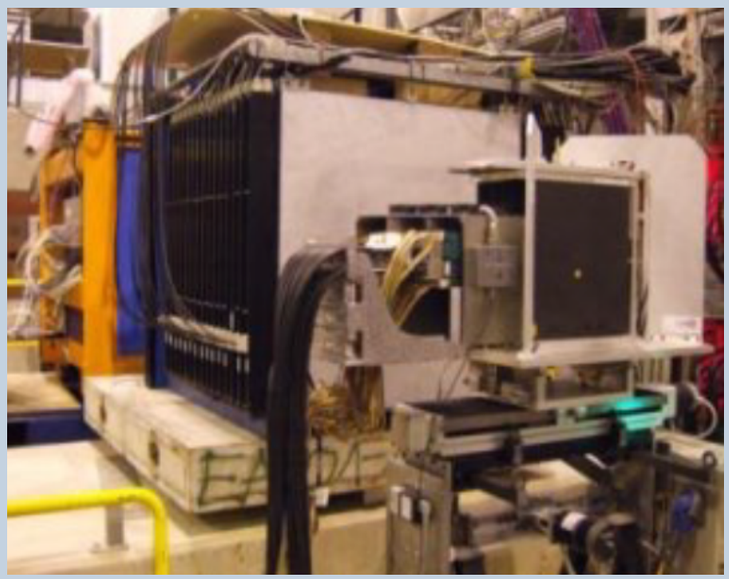


Si-W ECAL: 30 layers, 1x1 *cm² cells*

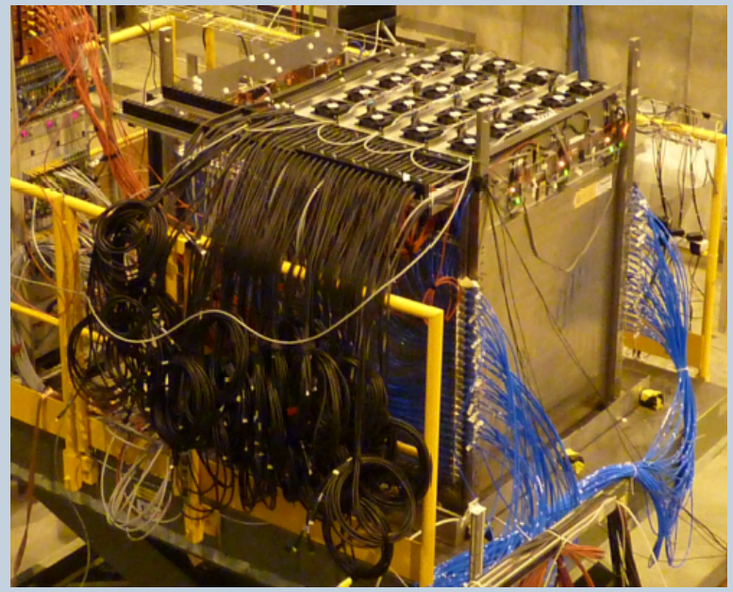


Sc-W ECAL: 30 layers, 1x4.5 *cm² cells*

HCAL



Sc-AHCAL, Fe&W: 38 layers, 3x3 *cm² cells*



GRPC-SDHCAL, Fe: 48 layers, 1x1 *cm² cells*

RPC-DHCAL, Fe&W: 54 layers, 1x1 *cm² cells*

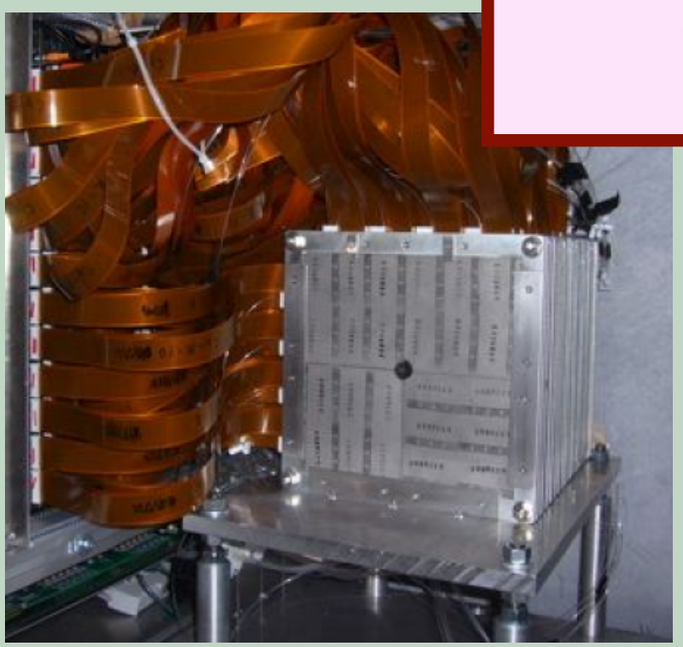
- Various beam tests
- Detector concepts validated with physics prototypes

[Details in CALICE analysis poster - Monday 8th August]

The CALICE physics prototypes

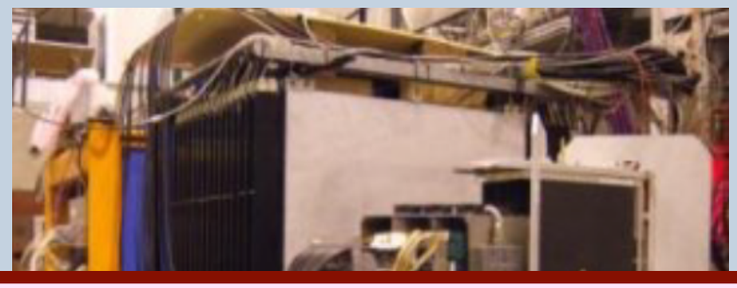
ECAL

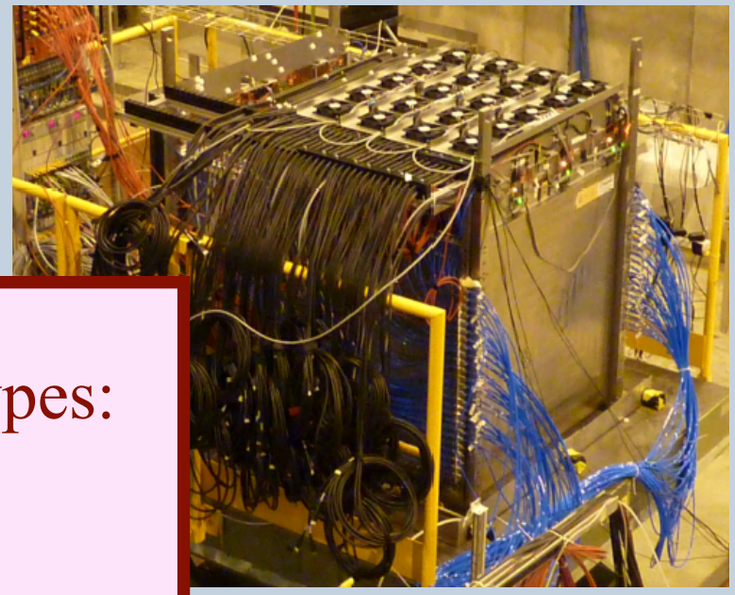
Si-W ECAL: 30 layers, 1x1



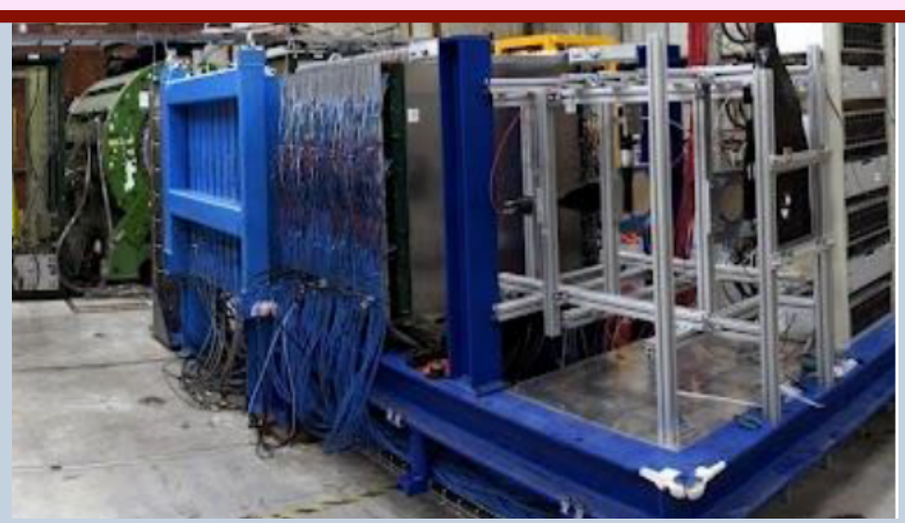
Sc-W ECAL: 30 layers, 1x4.5 *cm² cells*

HCAL





CAL, Fe: 48 layers, 1x1 *cm² cells*



RPC-DHCAL, Fe&W: 54 layers, 1x1 *cm² cells*

Moving towards technological prototypes:

- Fully integrated electronics
- Scalable to full detector
- Mass production

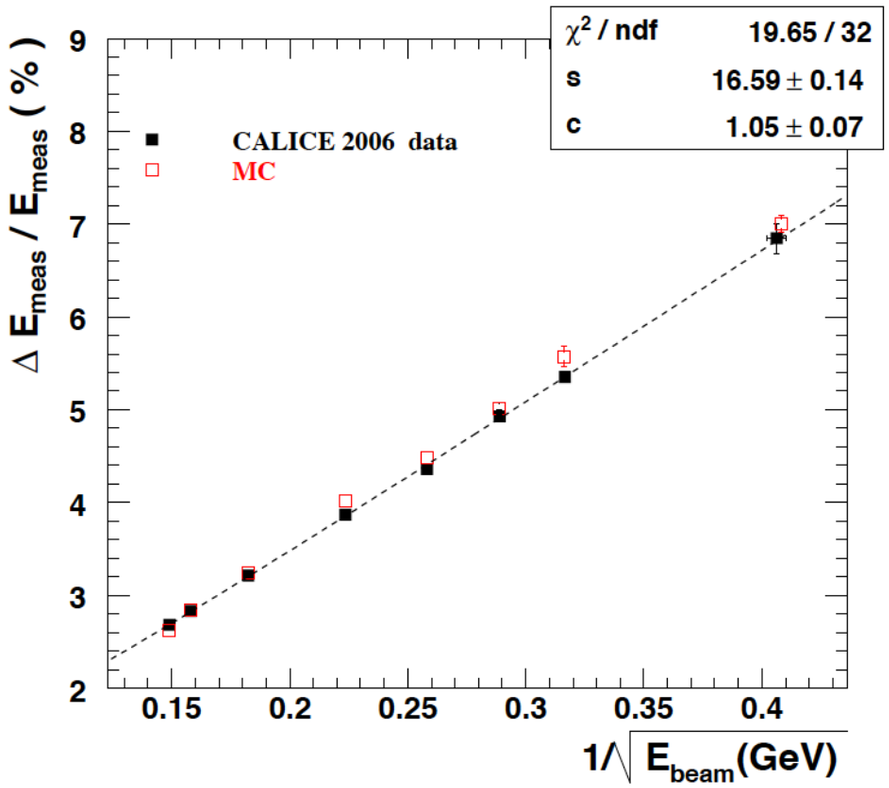
- Various beam tests
- Detector concepts validated with physics prototypes

[Details in CALICE analysis poster - Monday 8th August]

Silicon-Tungsten ECAL

- Si-W ECAL in various beam tests with nice results
  - Energy resolution measured on electron and positron beams
    - Stochastic term: $(16.6 \pm 0.1)\%/\sqrt{E(\mathrm{GeV})}$
    - Constant term: $(1.1 \pm 0.1)\%$

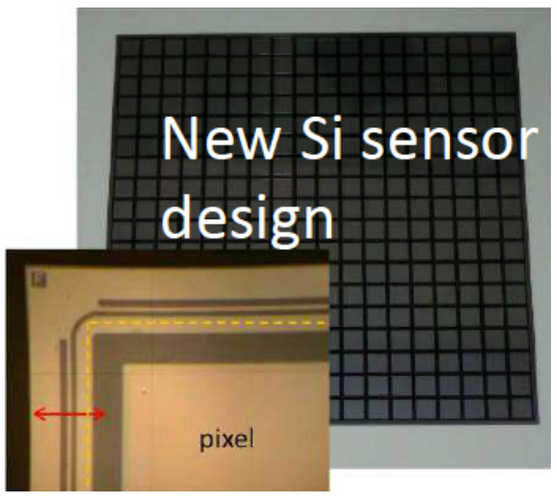
Si-W relative energy resolution as a function of beam energy (data collected at CERN 2006)

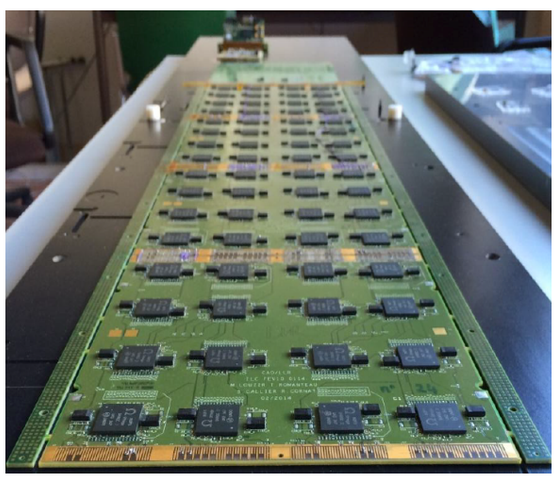


[NIM A608 (2009) 372]

Silicon-Tungsten ECAL

- Si-W ECAL in various beam tests with nice results
- **Road to full detector:** new hardware designs
  - Long slab:
    - 4 cards connected, 3 read-outs
    - Power distribution, clock distribution

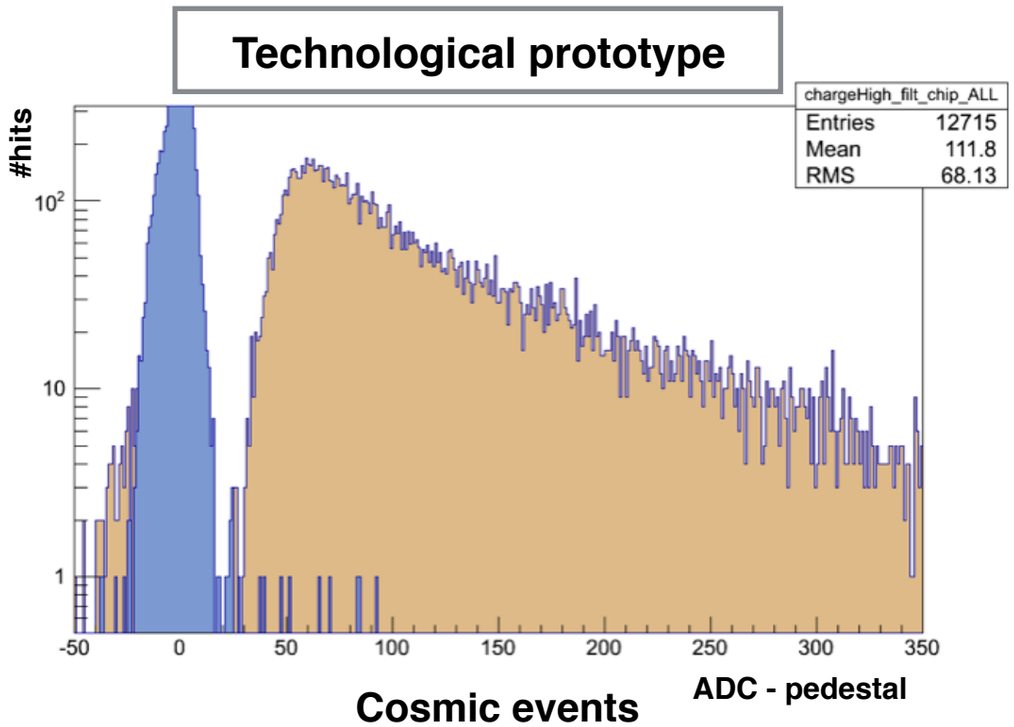




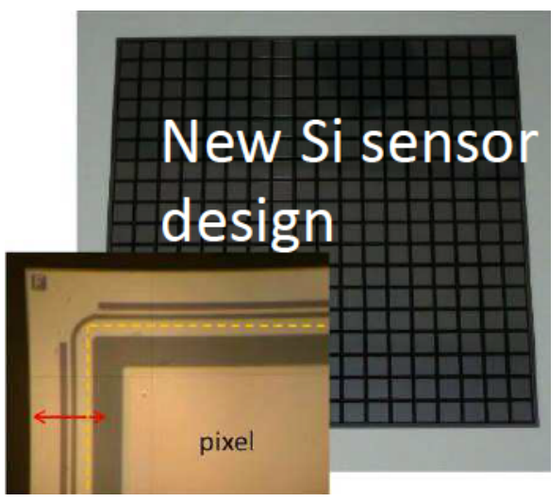
Si-W ECAL long slab

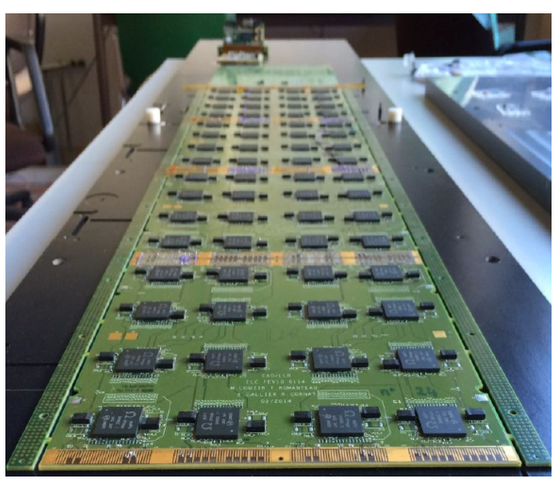
Silicon-Tungsten ECAL

- Si-W ECAL in various beam tests with nice results
- **Road to full detector:** new hardware designs
  - Long slab:
    - 4 cards connected, 3 read-outs
    - Power distribution, clock distribution
  - 4-layer beam test at CERN 2015
    - Very smooth running
    - Data with muons, electrons and pions collected
  - Common beam test with SDHCAL in June 2016 at CERN
    - 10 ECAL layers + full SDHCAL

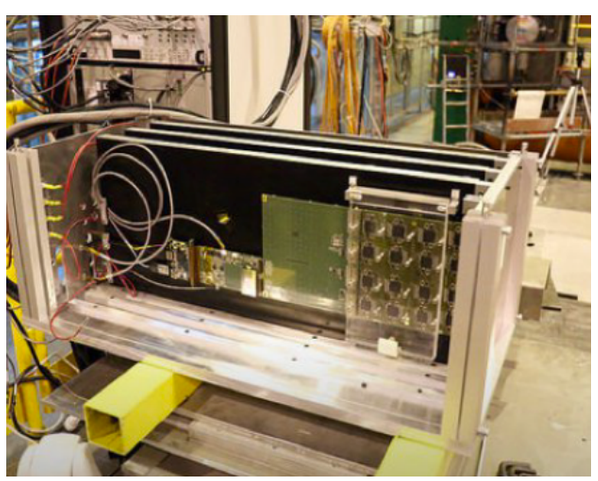


Ref: Kostiantyn Shpak's poster
Monday 8th August





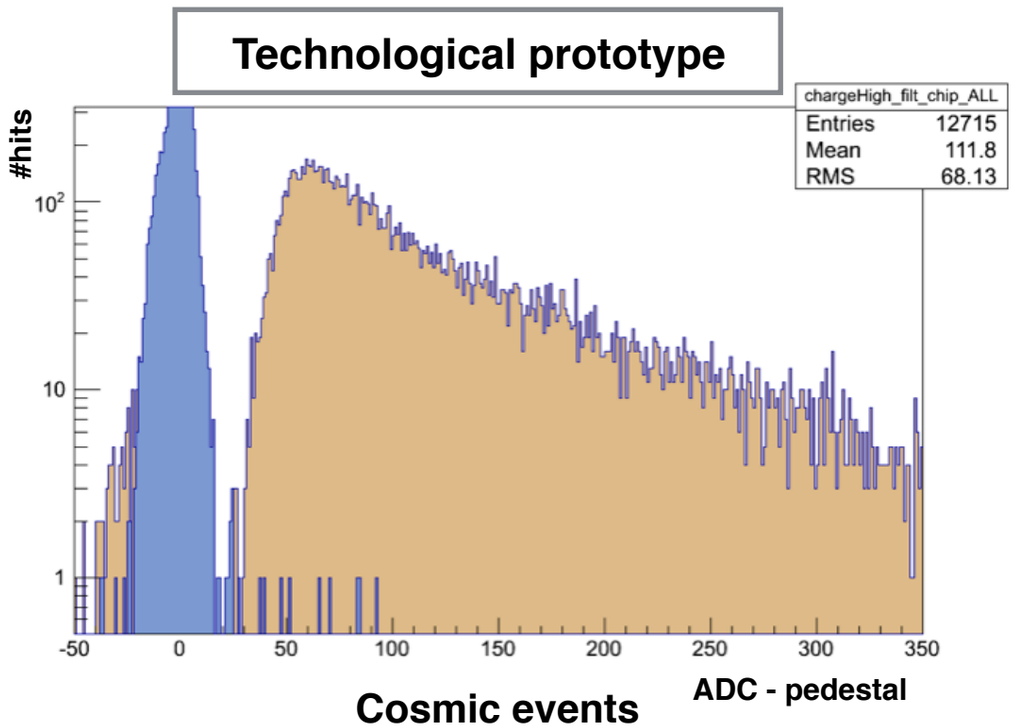
Si-W ECAL long slab



4 layers Si-W ECAL

Silicon-Tungsten ECAL

- Si-W ECAL in various beam tests with nice results
- **Road to full detector:** new hardware designs
  - Long slab:
    - 4 cards connected, 3 read-outs
    - Power distribution, clock distribution
  - 4-layer beam test at CERN 2015
    - Very smooth running
    - Data with muons, electrons and pions collected
  - Common beam test with SDHCAL in June 2016 at CERN
    - 10 ECAL layers + full SDHCAL
- Alveolar absorber structure for ILD-ECAL



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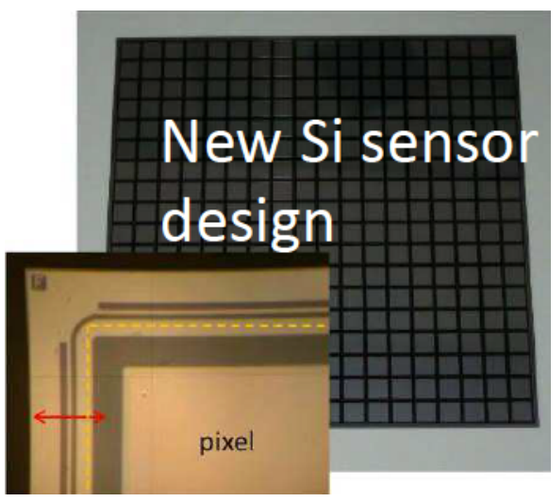
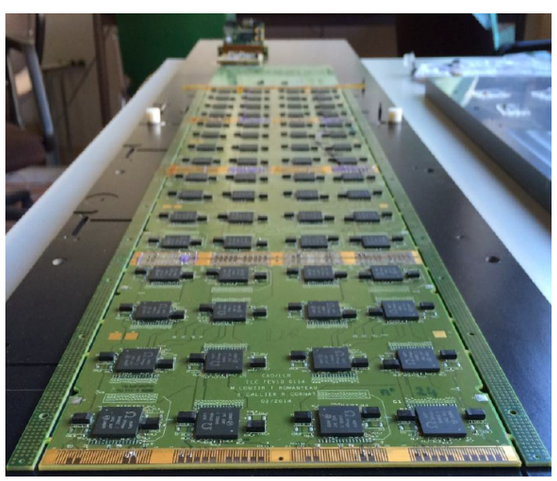
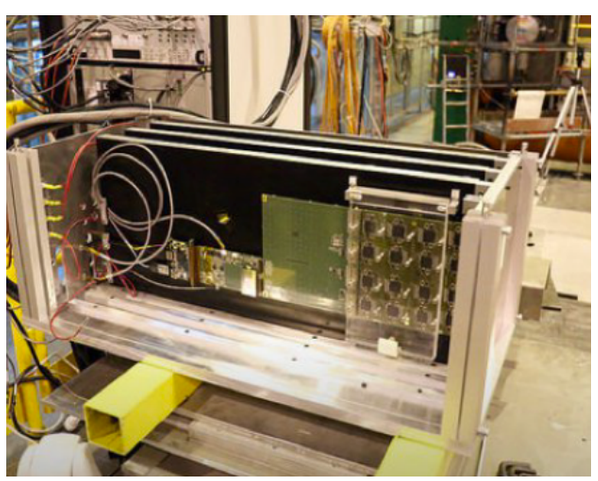




Si-W ECAL long slab



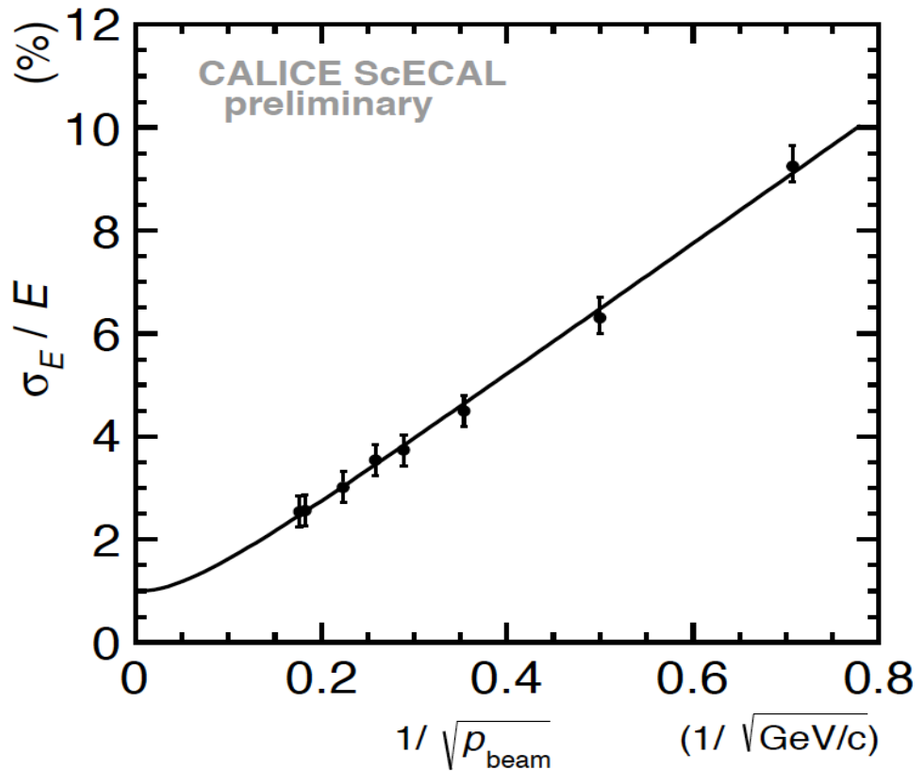
4 layers Si-W ECAL

Alveolar structure

Scintillator-Tungsten ECAL

- Sc-W ECAL achieve good resolution in Fermilab beam tests
  - Stochastic term: $(12.8 \pm 0.1(stat.) \pm 0.4(syst.))\%/\sqrt{E(GeV)}$
  - Constant term: $(1.0 \pm 0.1(stat.)^{+0.5}_{-1.0}(syst.))\%$

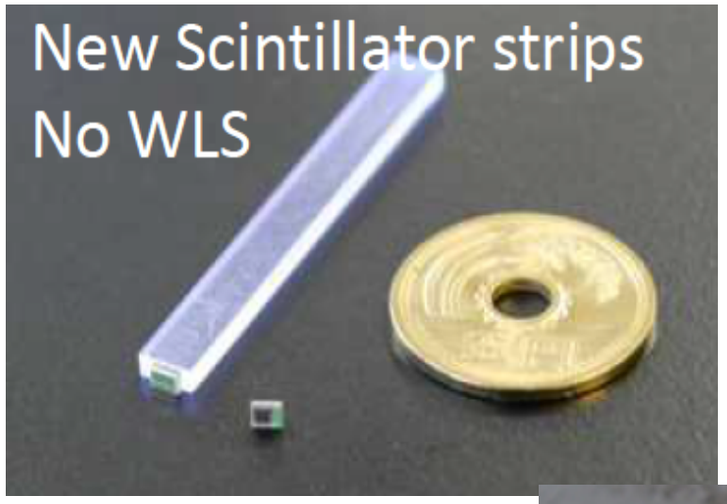
Sc-W energy resolution (Fermilab beam tests)

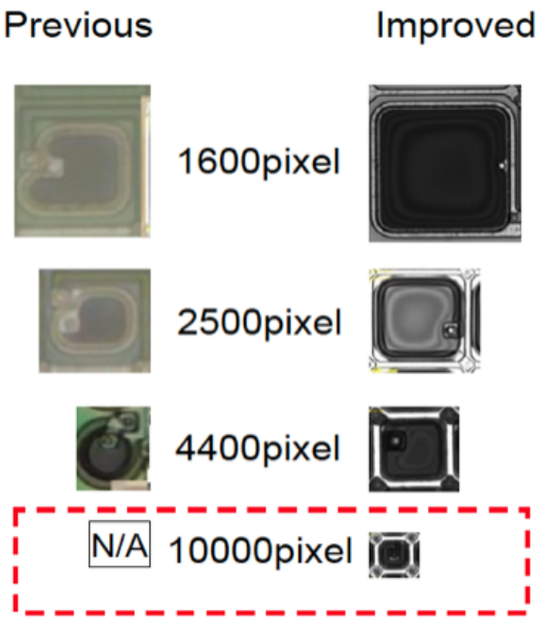


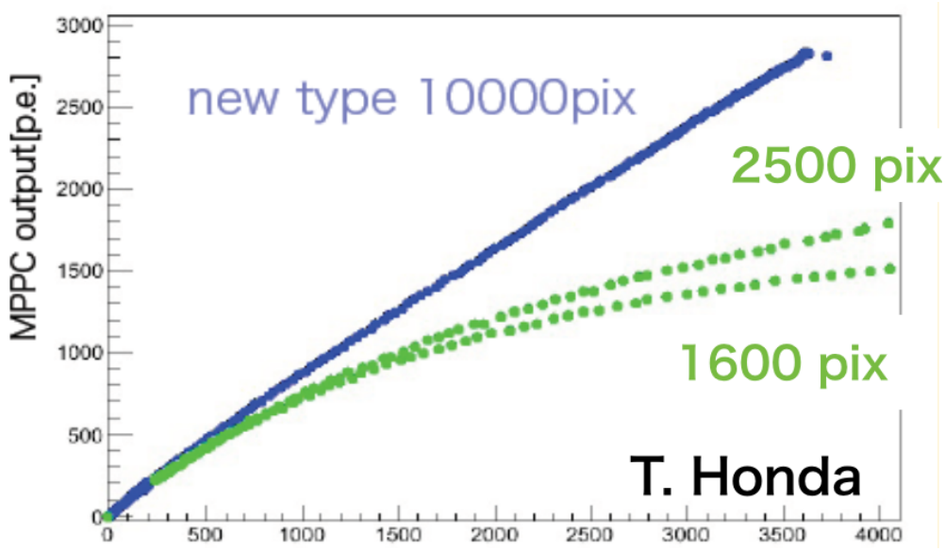
[Ref: CALICE Note CAN-016]

Scintillator-Tungsten ECAL

- Sc-W ECAL achieve good resolution in Fermilab beam tests
- **Road to full detector:**
  - New scintillator w/o Wave Length Shifting (WLS) fibers 45x5 mm^2
  - Bottom readout to reduce dead space
  - New MPPC 10k pixels for wide dynamic range







Scintillator-Tungsten ECAL

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- **Road to full detector:**
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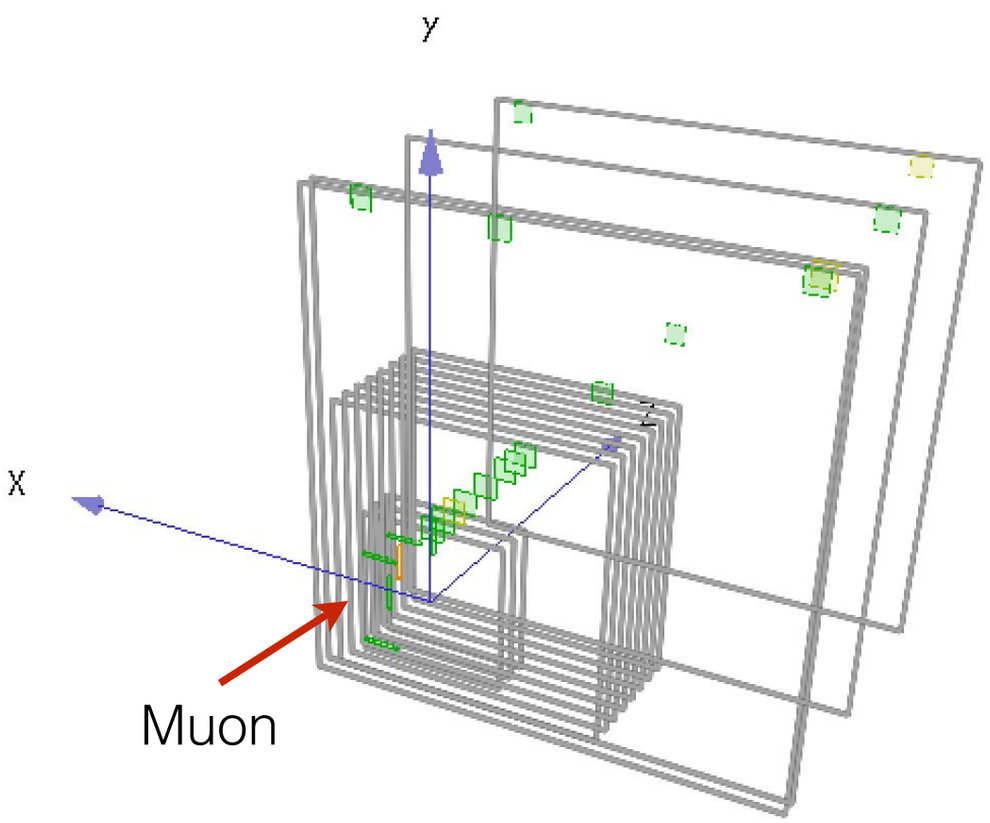
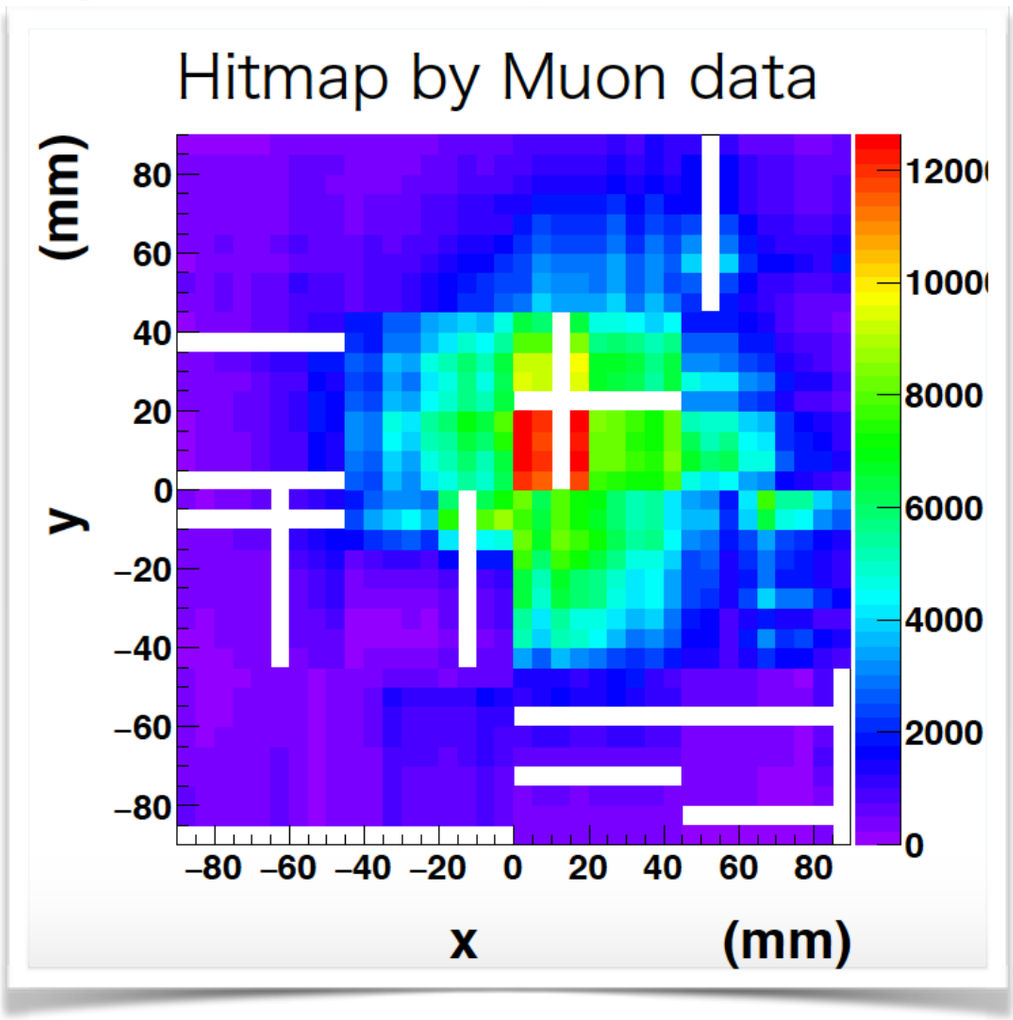
  - Bottom readout to reduce dead space
  - New MPPC 10k pixels for wide dynamic range
  - Combined beam tests with Sc-Fe AHCAL @CERN/DESY, common DAQ
    - 3 EBUs (2 transverse, 1 parallel) ➢ 5x5 mm^2 effective segmentation
    - Works smoothly, room for improvement





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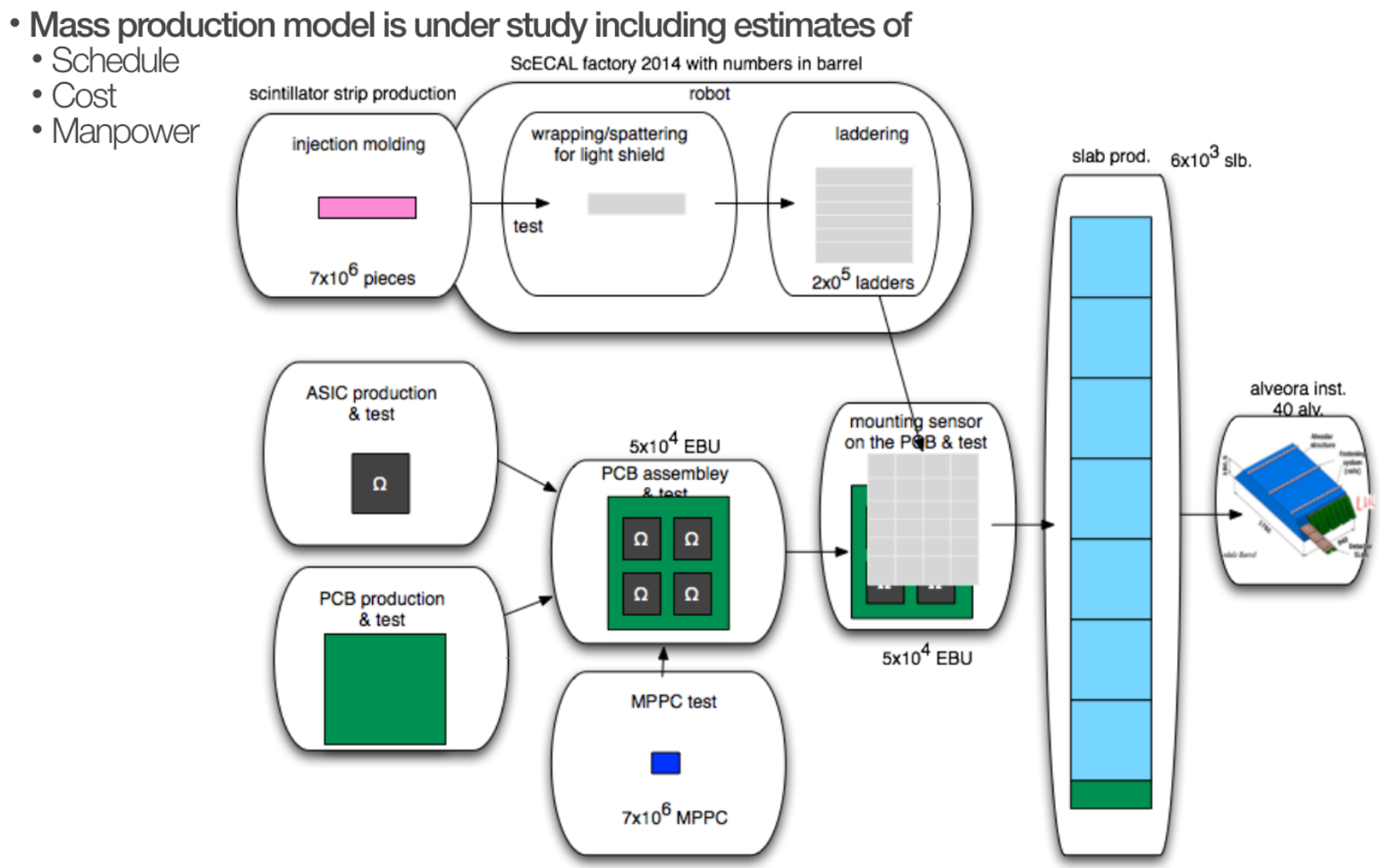
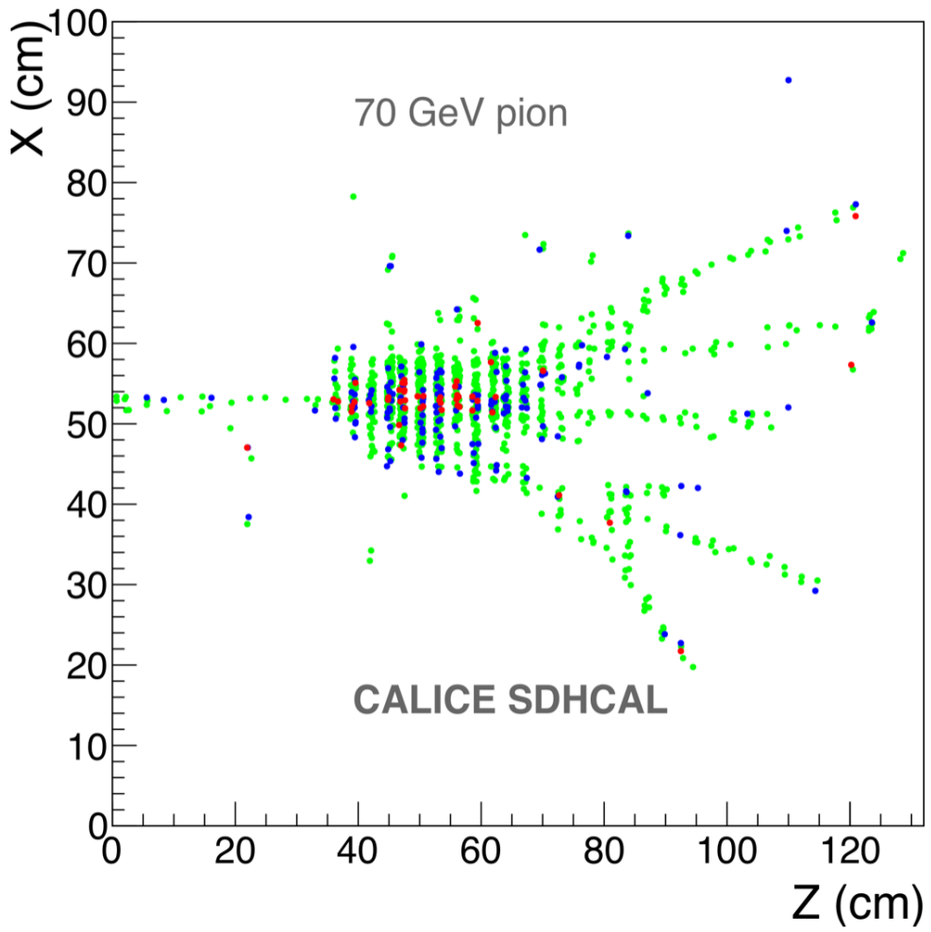
  - New MPPC 10k pixels for wide dynamic range
  - Combined beam tests with Sc-Fe AHCAL @CERN/DESY, common DAQ
  - ***Mass production scheme:***



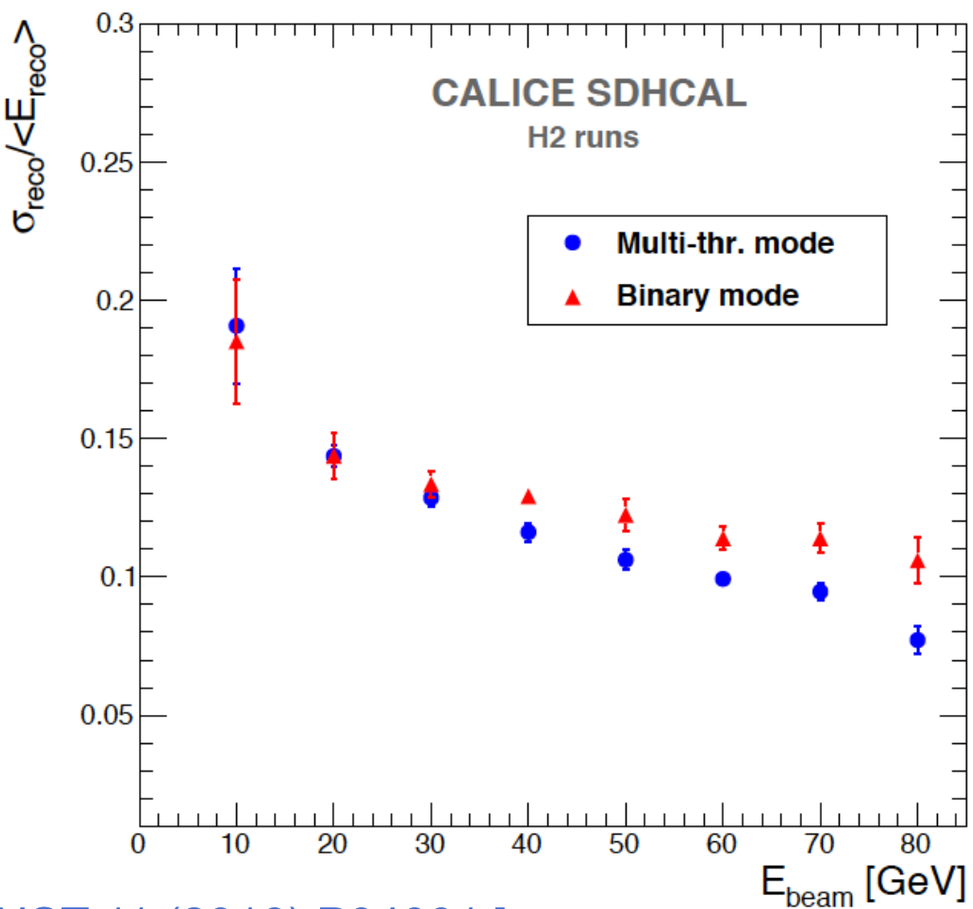
Semi-Digital HCAL

- 1 m^3 technological prototype GRPC-Fe with almost no dead zone operating in avalanche mode
  - 1x1 cm^2 pads, 2 bits readout - 3 thresholds
  - Auto-triggering, power pulsing using SPS spill structure used for power consumption reduction
- Very promising results achieved

CERN SPS beam tests



Single particle energy resolution



[Ref: JINST 11 (2016) P04001]

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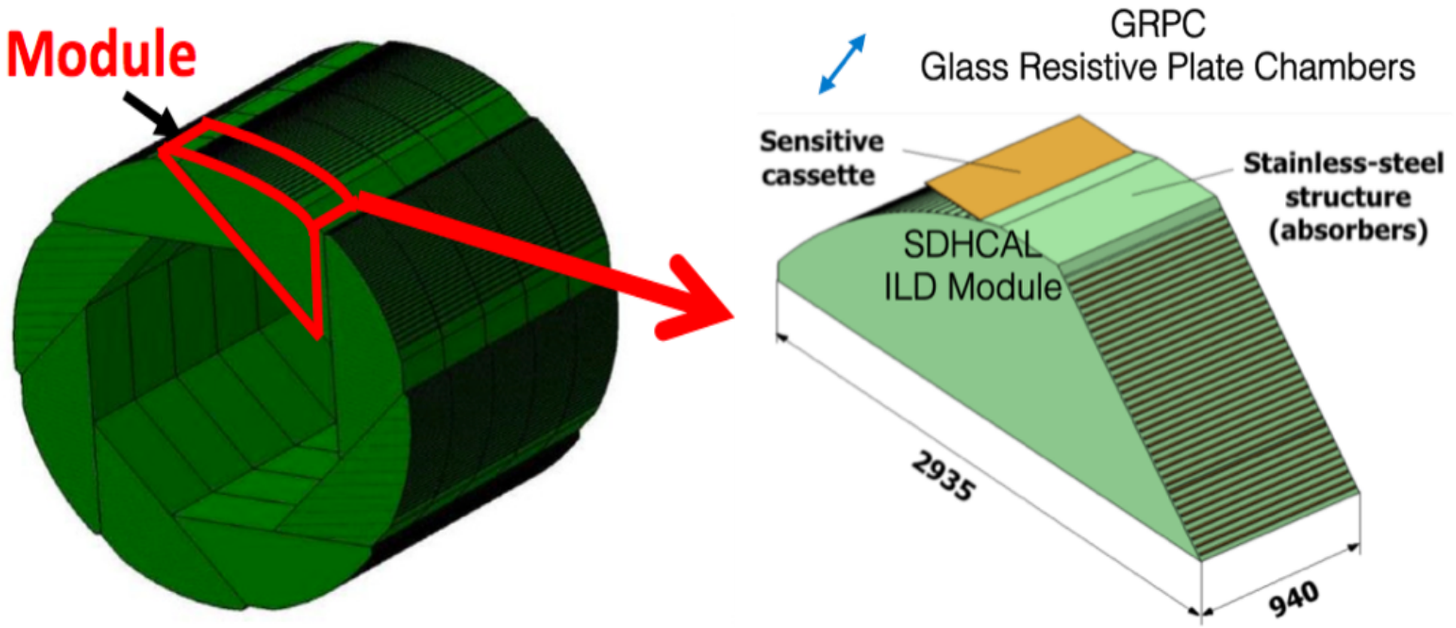
  - 1x1 cm^2 pads, 2 bits readout - 3 thresholds
  - Auto-triggering, power pulsing using SPS spill structure used for power consumption reduction
- Very promising results achieved
- **Road map to full detector**



- ***Construction of 1-layer prototype corresponding to biggest layer in ILD-module:***
  - GRPC-Fe
  - Newest generation electronics:
    - Independent channels
    - Zero suppress
    - Extended dynamic range
  - New Detector Interface (DIF):
    - Handle up to 432 readout chips (48 readout chips in previous version)
  - ILD-designed mechanical structure

Semi-Digital HCAL

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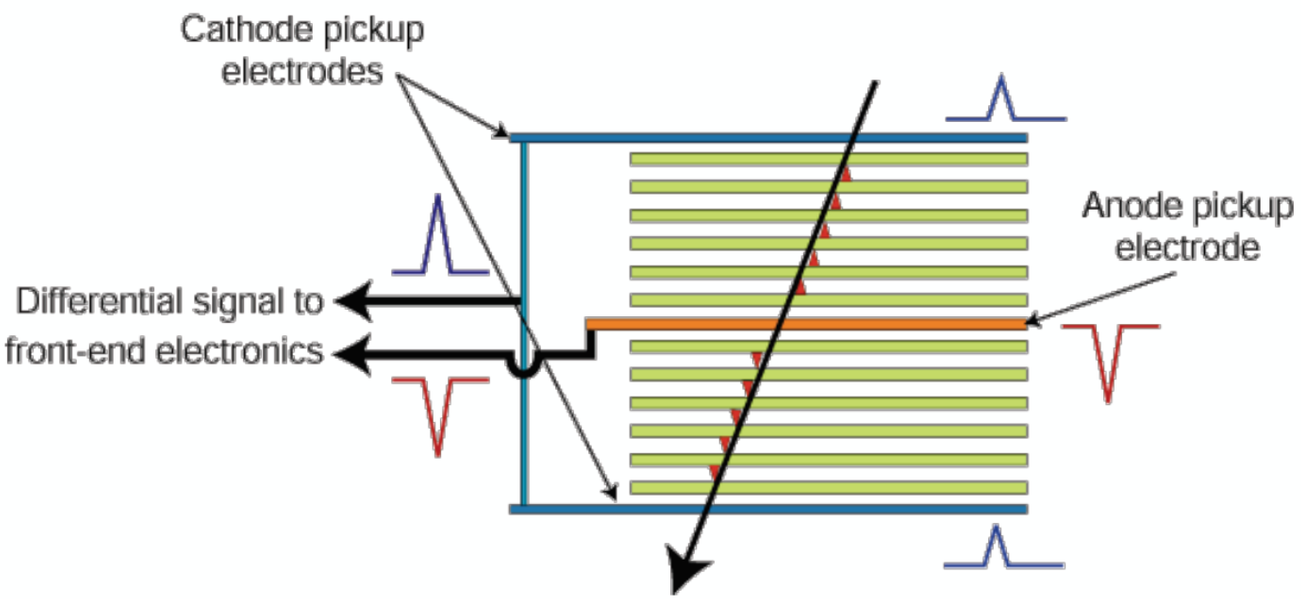
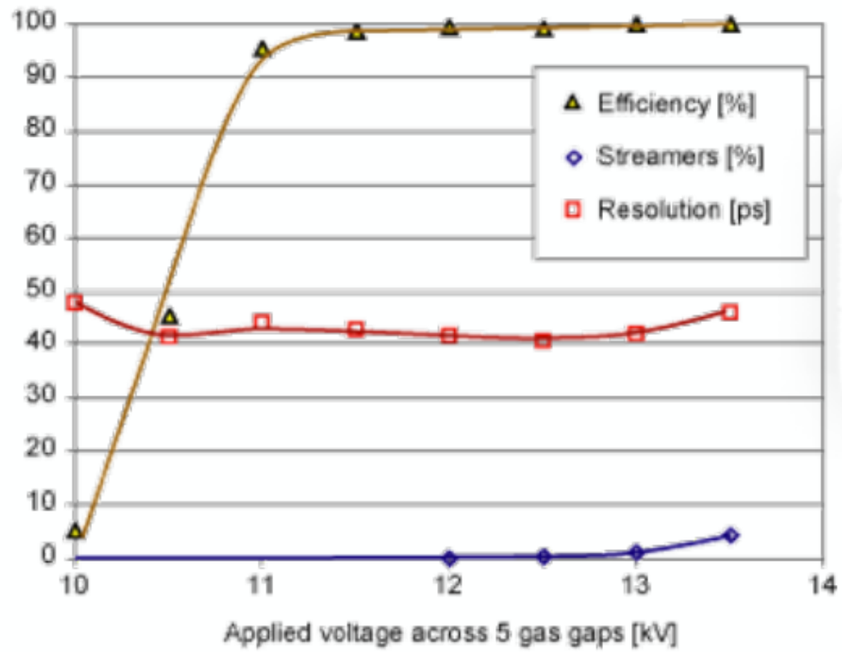
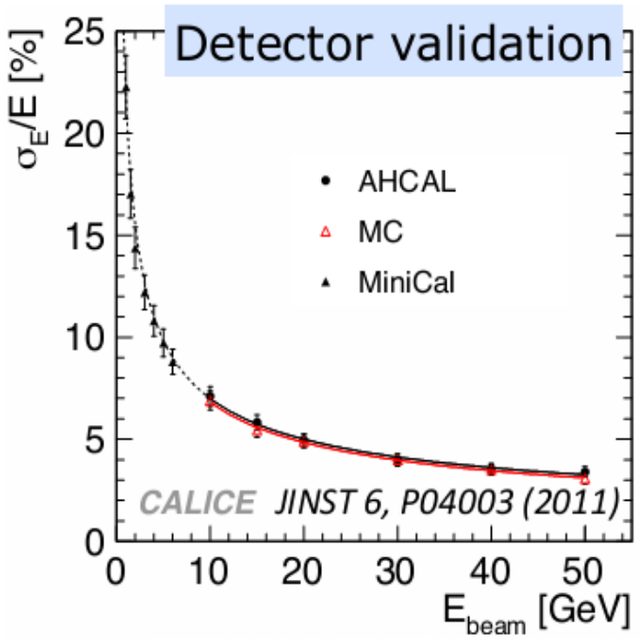
  - 1x1 cm^2 pads, 2 bits readout - 3 thresholds
  - Auto-triggering, power pulsing using SPS spill structure used for power consumption reduction
- Very promising results achieved
- Road map to full detector
- Alternative active layers with Multi-gaps RPCs
    - Better time resolution
    - Large efficiency plateau with no streamers
    - Can be produced for large areas with reasonable cost

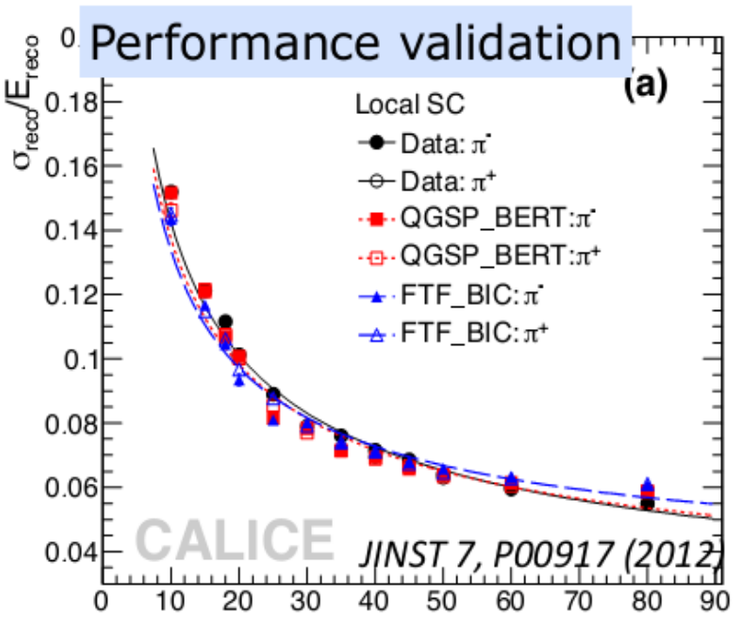


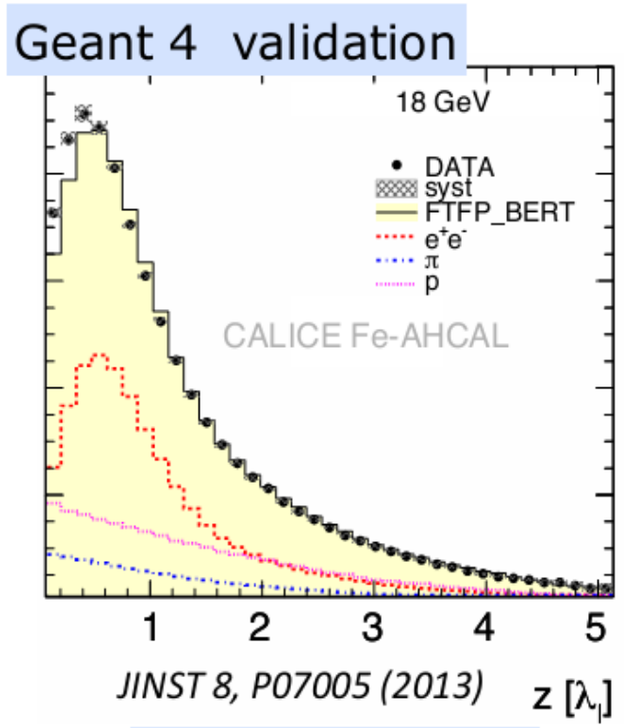


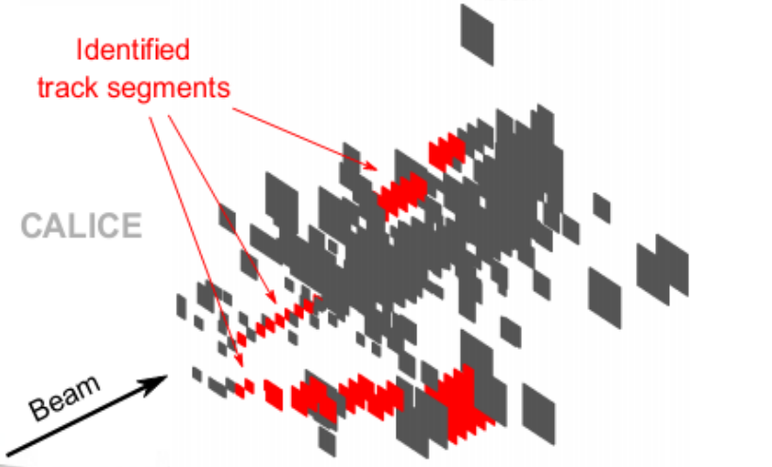
Analog HCAL

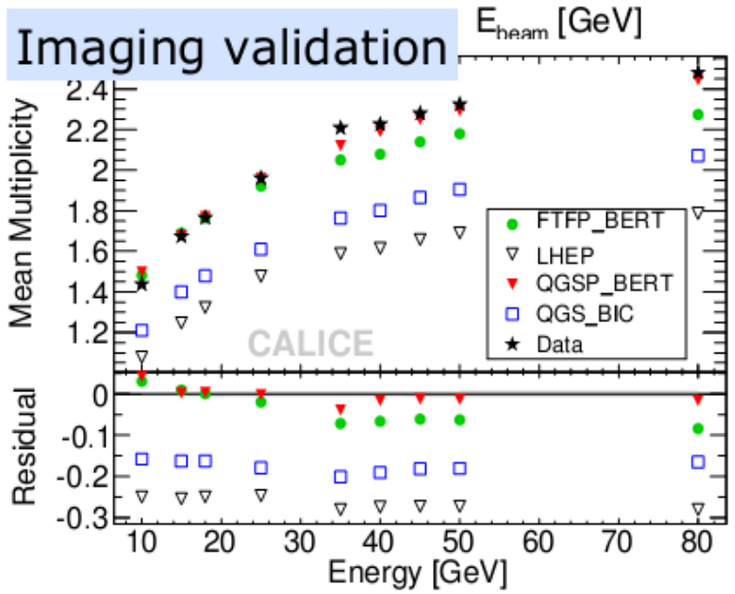
- 1 m^3 physics prototype Scintillator-Fe in various beam tests
  - 3x3 cm^2 cell sizes in central part
  - Results demonstrated the capability to deliver the desired physics

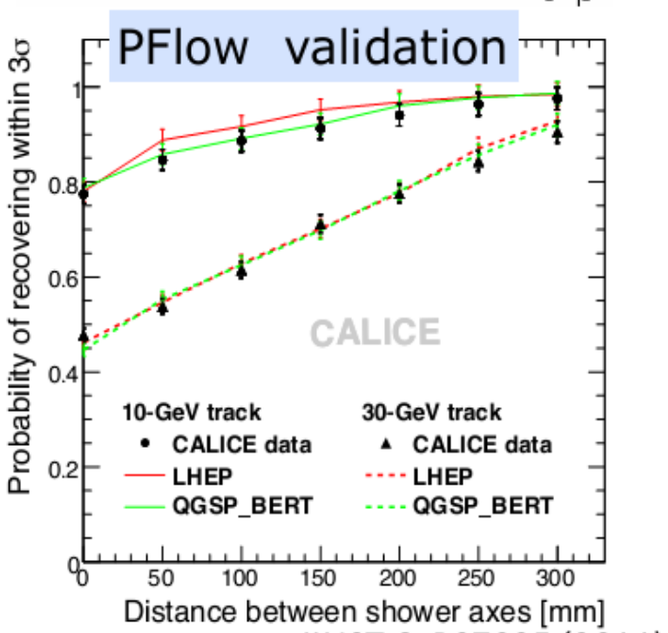










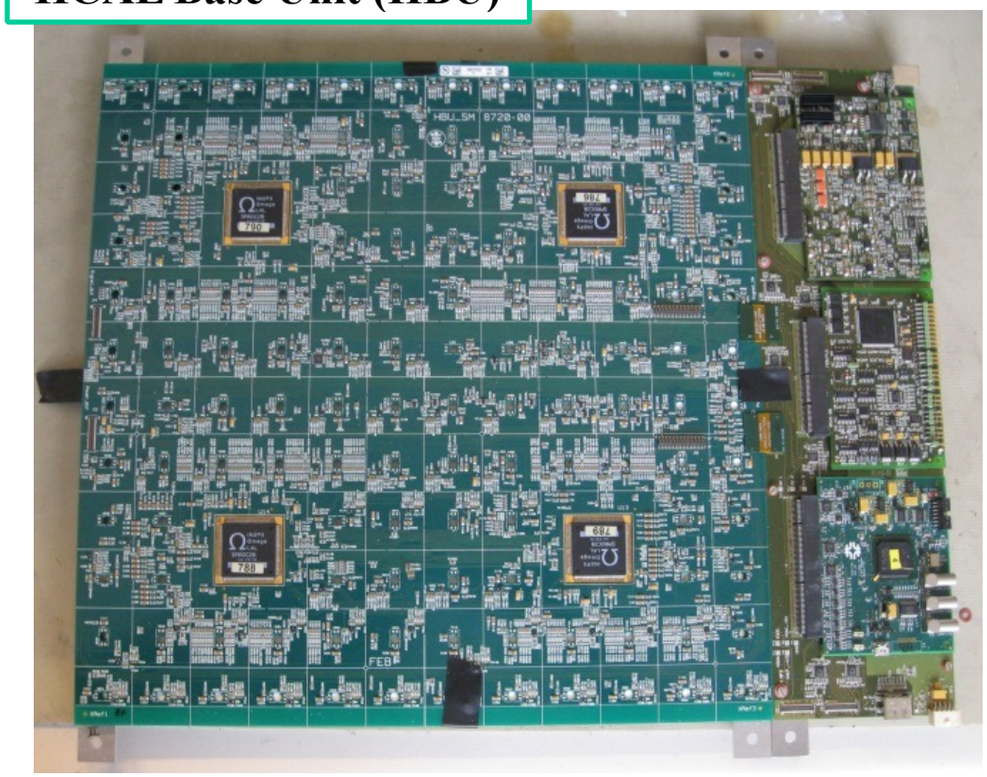


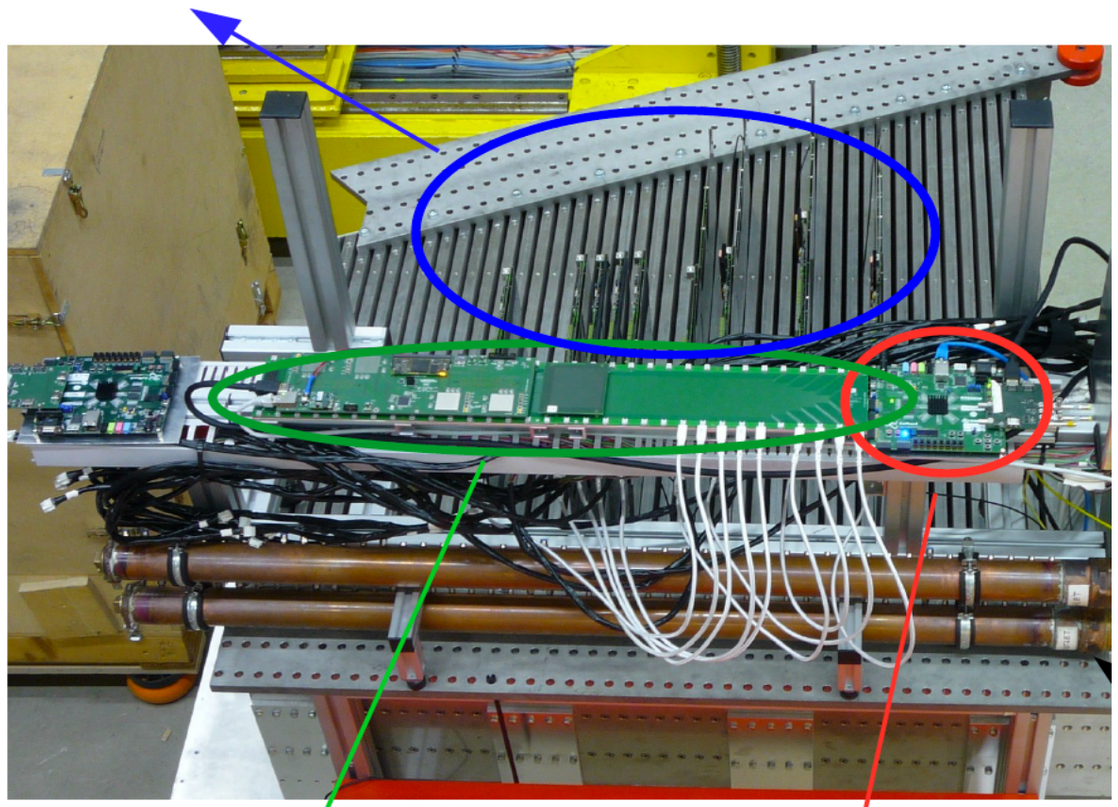
Calorimeter for ILC

Analog HCAL

- 1 m^3 physics prototype Scintillator-Fe in various beam tests
  - 3x3 cm^2 cell sizes in central part
  - Results demonstrated the capability to deliver the desired physics
- **Road map to full detector:** technological prototype in ILD-designed absorber structure
  - Fully integrated electronics
    - Auto-trigger & external trigger mode
    - Water cooling only for power boards

HCAL Base Unit (HBU)

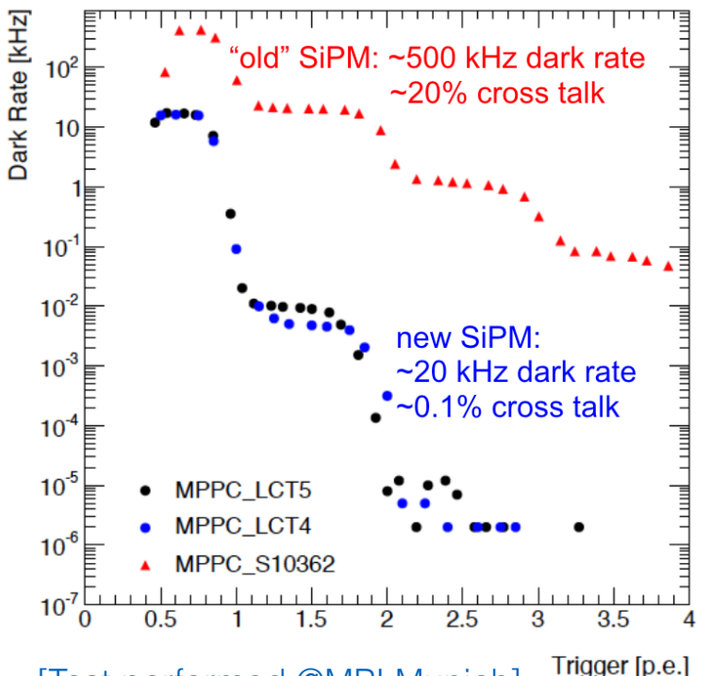




Analog HCAL

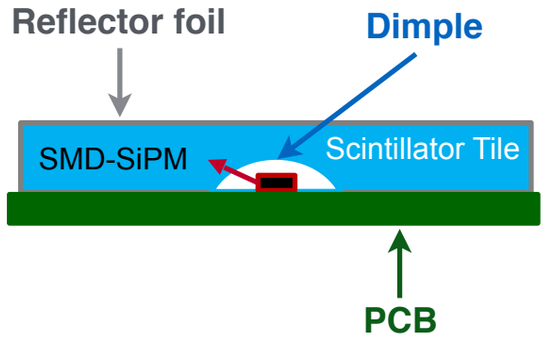
- 1 m^3 physics prototype Scintillator-Fe in various beam tests
  - 3x3 cm^2 cell sizes in central part
  - Results demonstrated the capability to deliver the desired physics
- **Road map to full detector:** technological prototype in ILD-designed absorber structure
  - Fully integrated electronics
  - New detector components

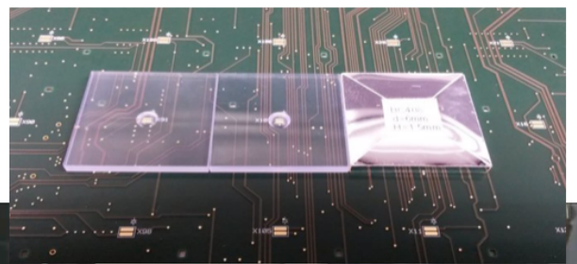
New generation SiPM:
- Excellent uniformity (operating voltage, gain)
- Dramatically reduced dark rate and cross talk
- Noise free allows auto-trigger operation



[Test performed @MPI Munich]

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

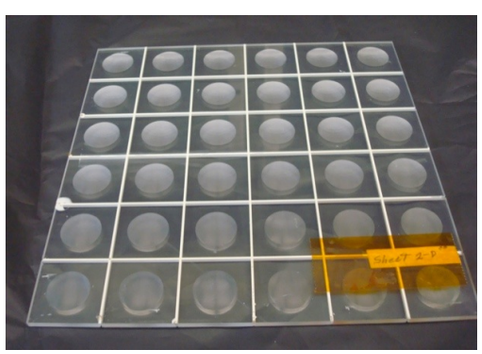




Simplified tile & HBU design:
- Surface-mount SiPMs ➢ improved tile uniformity
- Individually wrapped tiles
- Pick-and-place machine

➢ Suitable for mass assembly

Alternative design: Megatiles with surface mount SiPMs



Analog HCAL

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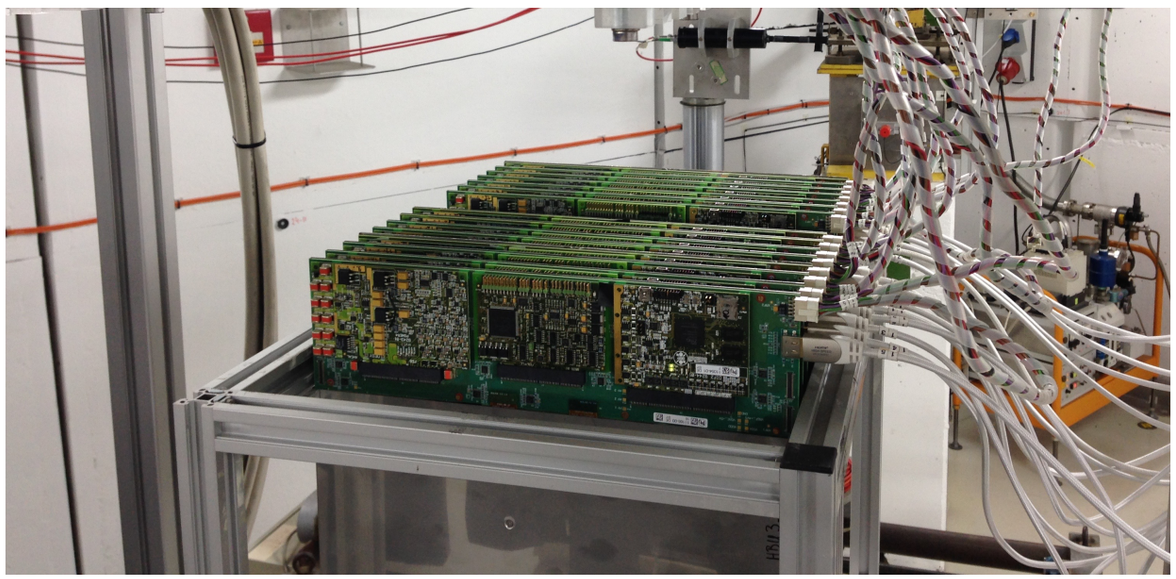
  - 3x3 cm^2 cell sizes in central part
  - Results demonstrated the capability to deliver the desired physics
- **Road map to full detector:** technological prototype in ILD-designed absorber structure
  - Fully integrated electronics
  - New detector components
  - Technological prototype in various beam tests w/ or w/o Sc-ECAL
    - Important system tests on scalable DAQ and monitoring
    - Integrate common DAQ framework (EUDAQ2)
    - **On-going two weeks of testbeam (25/7-7/8) @ DESY:** 15 layers of single HBU, all with new SiPMs and 6 with new design tiles ➢ demonstrate EM performance & system test



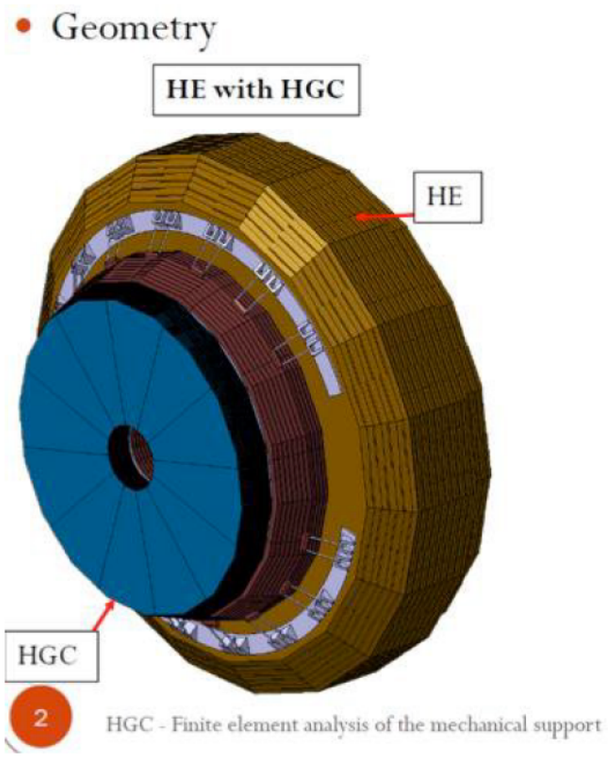
Applications to LHC experiments

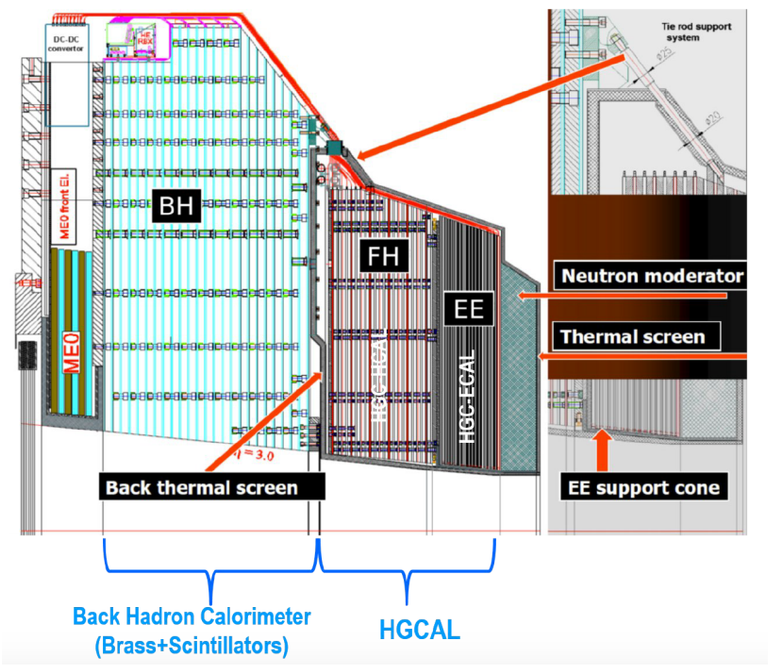
- Phase II upgrades of LHC experiments face many challenges (high pile-up, irradiation,…)
- High Luminosity LHC: expect up to 200 interactions per crossing
  - ➢ Need good spatial resolution ➢ highly granular detectors
  - ➢ Timing separation between vertices can improve detector performance ➢ detectors with good timing resolution
- Phase II upgrades of both ATLAS and CMS detectors involve technologies developed by CALICE

CMS: High Granular Calorimeter (CMS-HGCAL)

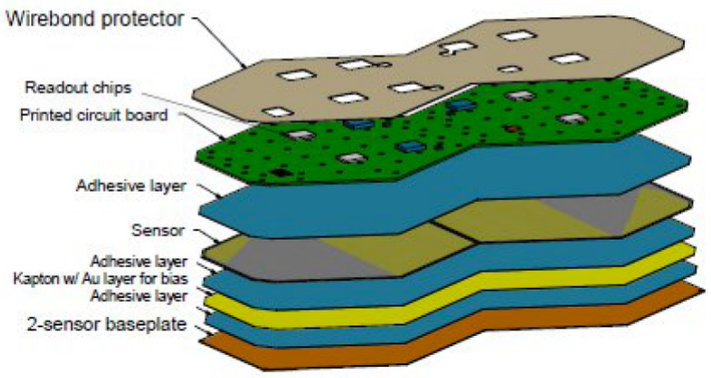
Using technologies developed for Si-W ECAL

- 28 layers ECAL + 12 layers HCAL, both using hexagonal Silicon wafers
- Absorber materials: Brass for HCAL, W/Cu for ECAL
- 30 ps timing ID with ToT
- New readout chip (SKIROC2-CMS) being prepared by Omega+LLR





Modules with two 6” sensors



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- High Luminosity LHC: expect up to 200 interactions per crossing

  ➢ Need good spatial resolution ➢ highly granular detectors

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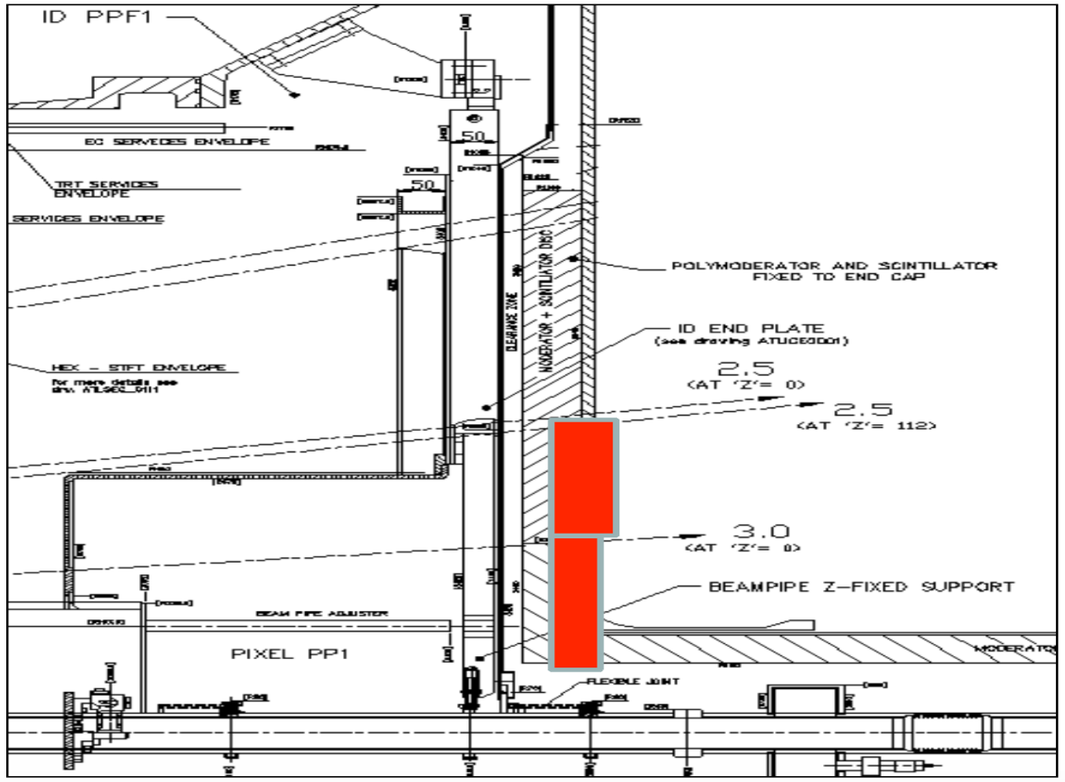
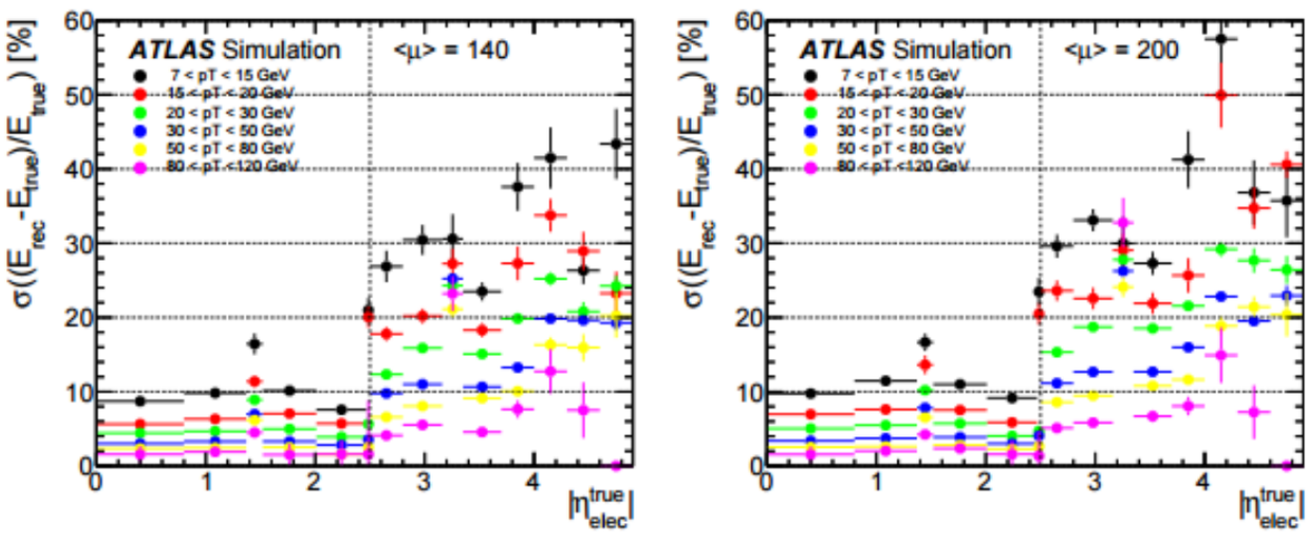
ATLAS: High Granularity Timing Detector (ATLAS-HGTD)



Using technologies developed for Si-W ECAL

- Position at z=3500mm & 2.5< η <5
- 2 parts, both with Si-sensors
  - Pre-shower: W absorber
  - Timing: no absorber
- Timing resolution: order of 50ps
- Capability to identify vertex origin of forward jets



ATLAS Simulation results: energy resolution of electrons

Summary & Outlook

- CALICE collaboration is developing **highly granular calorimeters** for Particle Flow reconstruction

- **Different technologies** have been tested in different particle beams
  - Detector concepts validated with physics prototypes
    - Beam test results from all prototypes show **expected energy resolution**
      - ➢ demonstrate feasibility of highly granular calorimeters
  - Technological prototypes: to prove that **design is scalable to full detector**
    - Fully integrated electronics
    - Mechanics, mass production

- **Technologies are validated**, remaining technological issues are being addressed

- **HL-LHC upgrades inspired** by CALICE-developed technologies: big award to many years of hard work

- Fruitful collaboration

Back-up slides

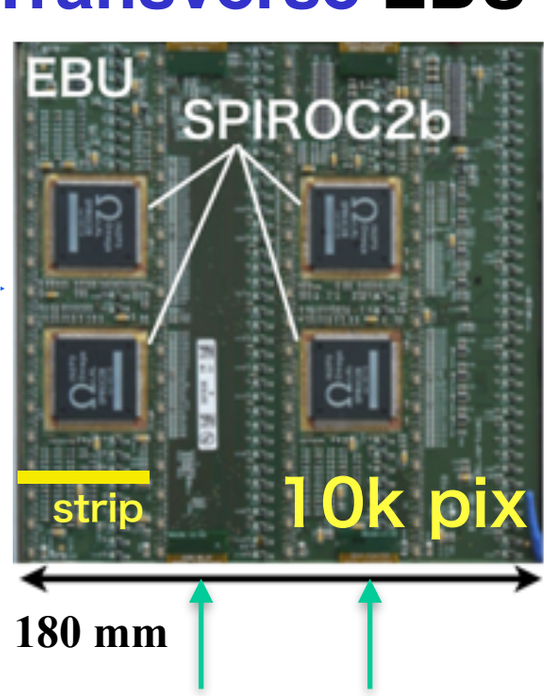
EBUs

- Two readout geometries:

New design

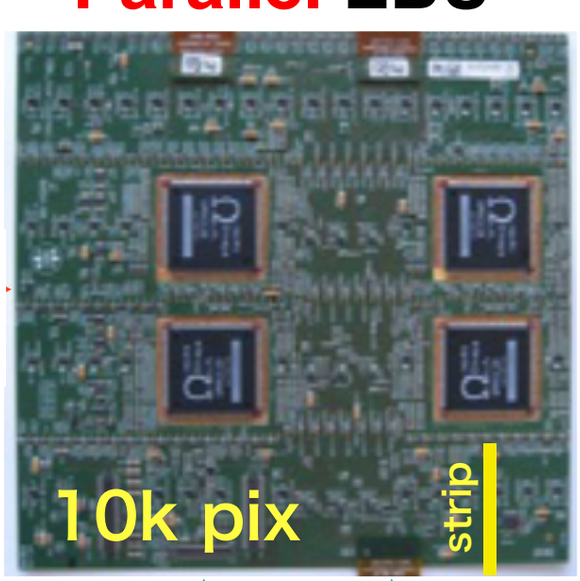
Baseline design

Bottom readout
Transverse EBU



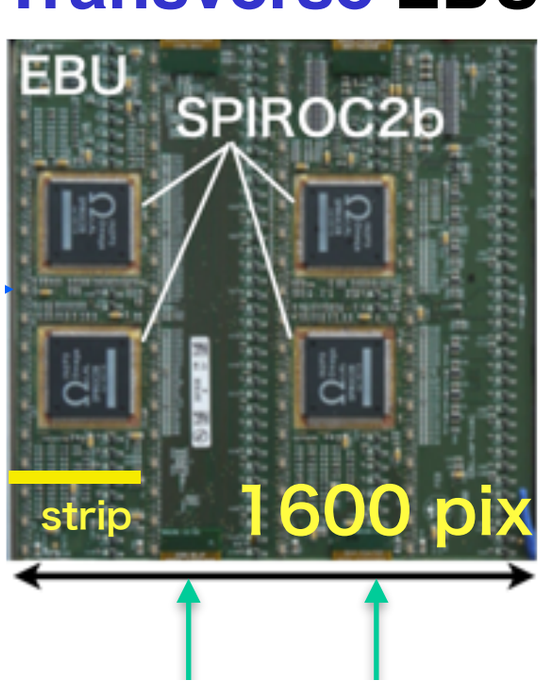
Flex-leads

Baseline readout
Parallel EBU



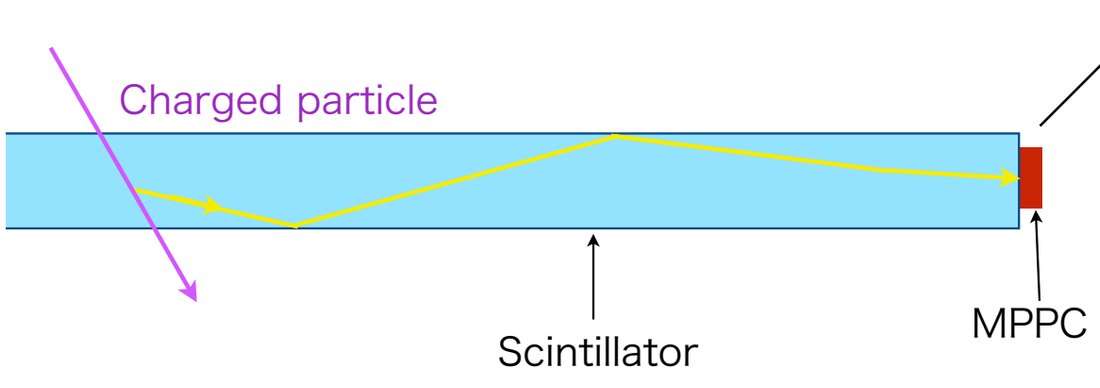
Flex-leads

Baseline readout
Transverse EBU



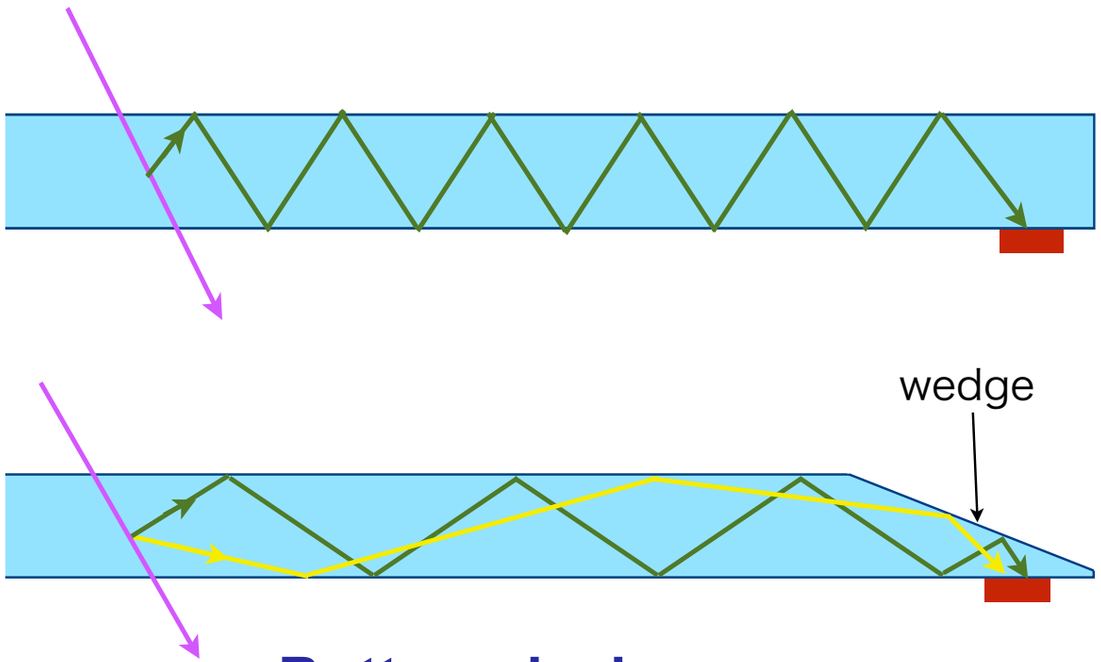
Flex-leads

EBUs



Baseline design

- High light yield (less number of reflections)
- Good uniformity
- Issues due to MPPC installation



Bottom design

- Gapless layout possible
- Wedge shape: prism to guide light to SiPM helps recover light yield
- Shorter path length for particle going through part near MPPC ➢ recover uniformity

Comparison of RPC operation modes

As an example for 1.2 mm gas gap…

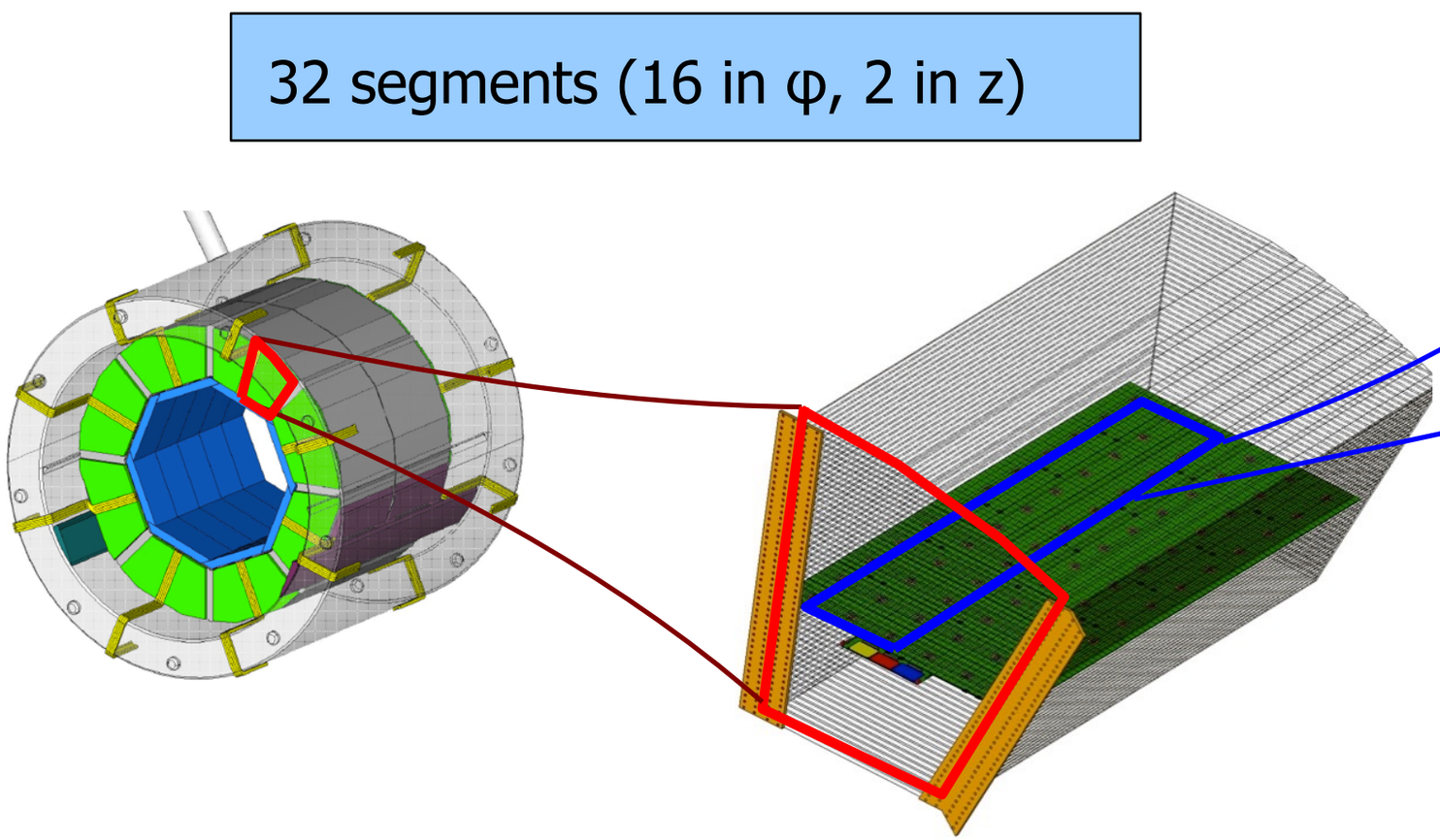
	Avalanche	**Streamer**
Gas mixture	TFE:IB:SF_6 = 93:5:2	TFE:IB:Ar = 85:10:5
HV working point	8.4 kV	7.0 kV
Induced charge	3.4 pC	**300 pC**
Threshold on 50 Ω	**1 – 2 mV**	50 – 200 mV
Efficiency	> 99 %	**~ 95 %**
σ_q/Q	~ 1	~ 0.6
Pad multiplicity	1.5	1.4 – 1.5
Noise	~0.5 Hz/cm^2	~0.1 Hz/cm^2
Rate capability	300 Hz/cm^2	**4 – 5 Hz/cm^2**
Ageing effects	None	**Observed**

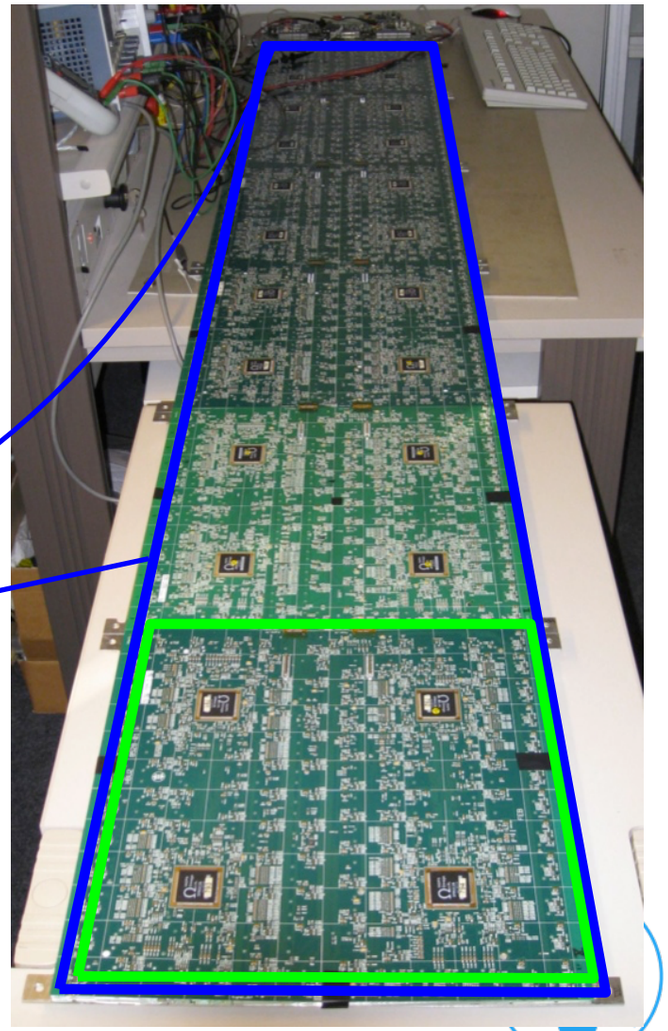
Favored

AHCAL overview

- **A**nalog **H**adronic **CAL**orimeter for ILD
- Sandwich calorimeter based on scintillator tiles (3x3cm^2)
- Read out using **Si**licon **P**hoto**M**ultipliers (SiPM)
- **H**CAL **B**ase **U**nit (HBU) : 36*cm* x 36*cm*
- 8 millions channels in total
- Principle demonstrated with physics prototype

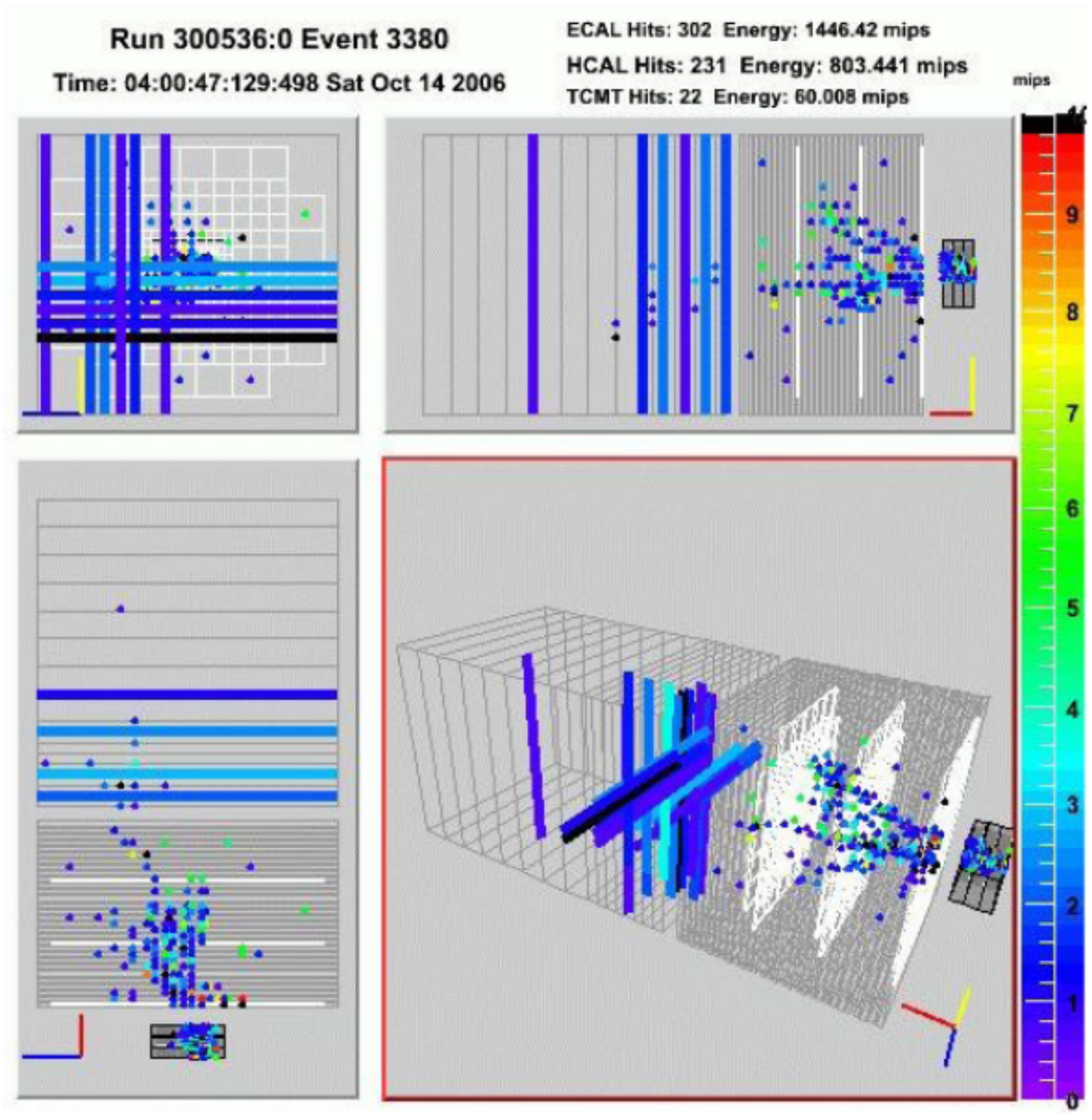
32 segments (16 in φ, 2 in z)

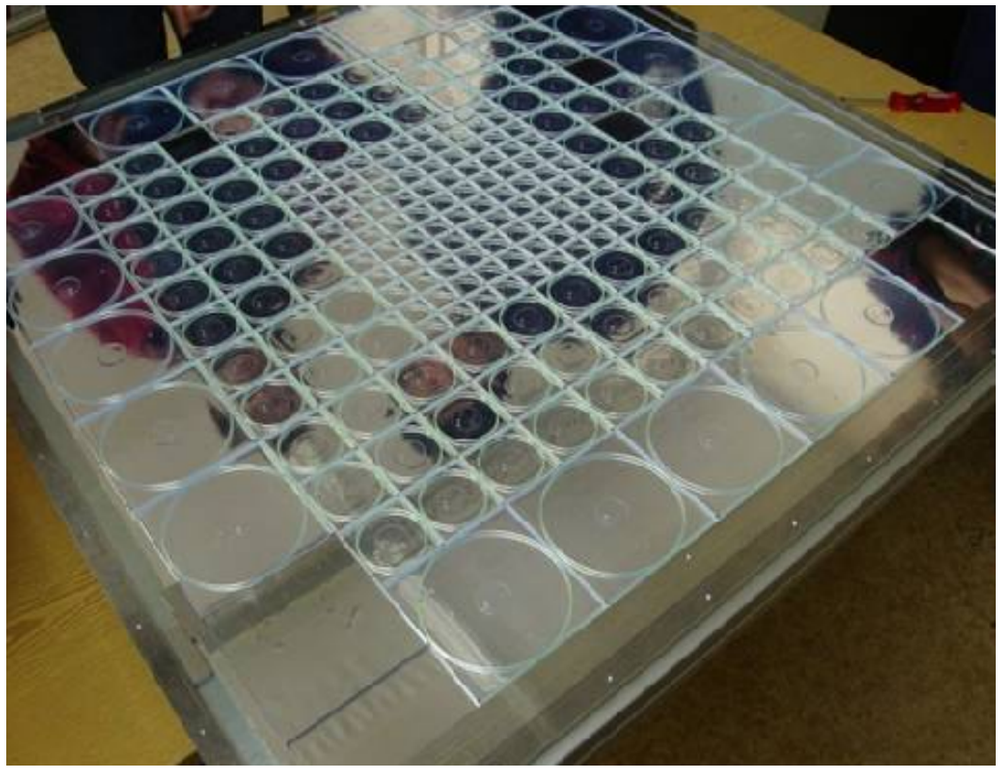




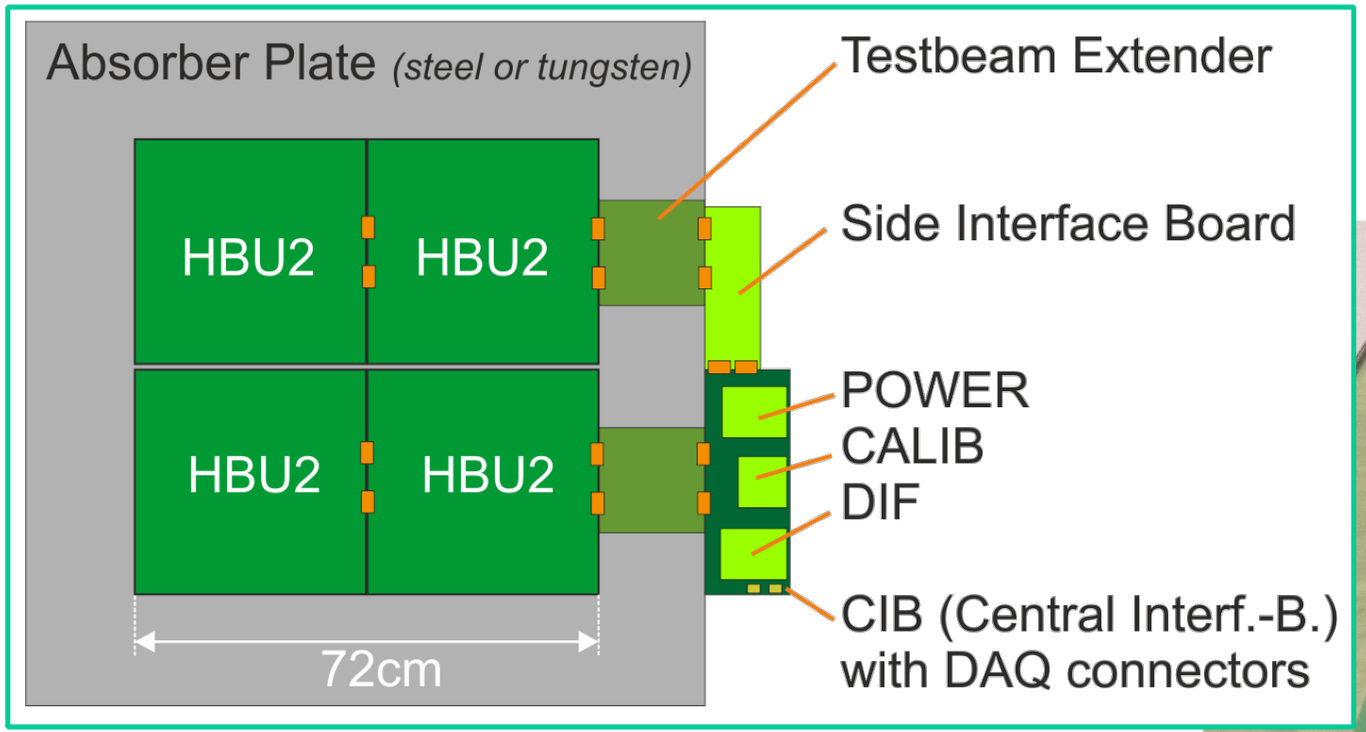
AHCAL physics prototype

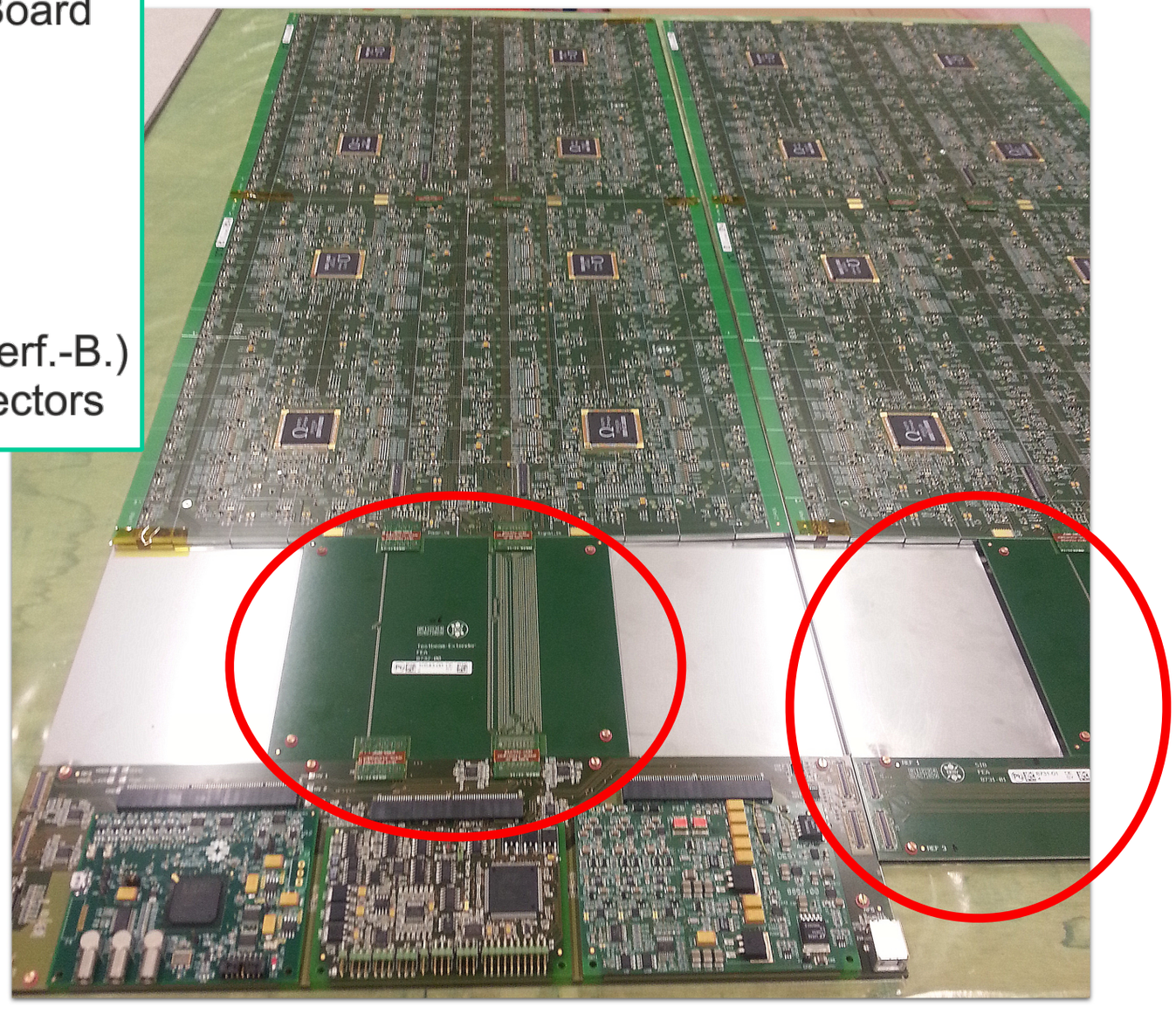
- ✓ $1m^3$ physics prototype used in different testbeams 2006-2012





AHCAL technological prototype - Extender boards





- Specifically for next testbeam
  - Extender boards for EBUs
  - Extender boards for HBUs
- Side Interface Board (SIB)
  (for ILD as well)