Prototype Tests for a Highly Granular Scintillator-based Hadron Calorimeter

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on behalf of the CALICE Collaboration

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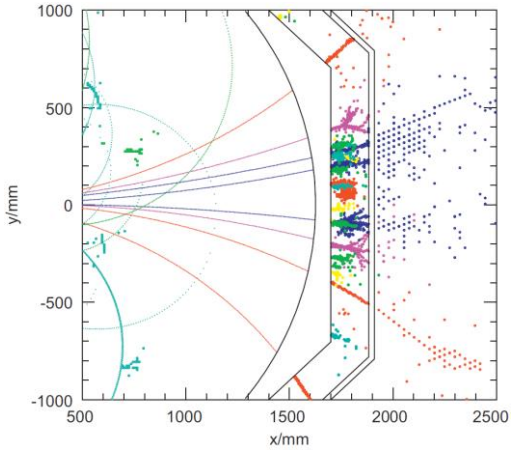
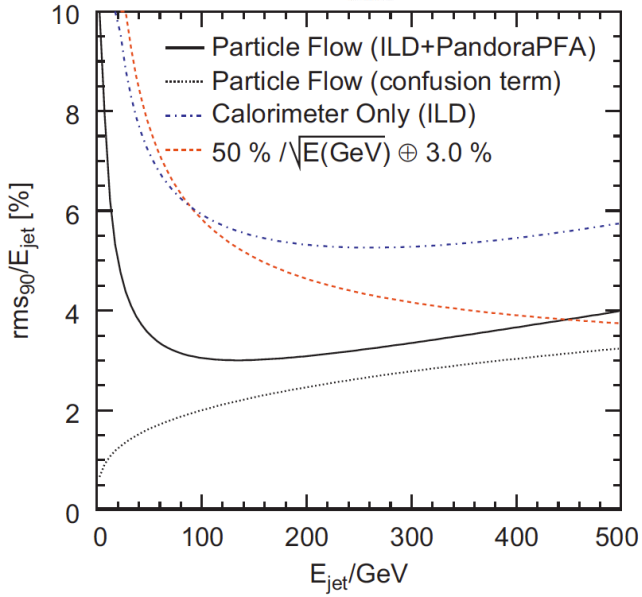
PRISMA DETECTOR LAB

CALICE

Highly granular calorimeters: motivations

- Highly granular calorimeters
  - Motivated by requirements from precision physics programs at future lepton colliders
  - Prerequisite for Particle Flow reconstruction
- Particle Flow
  - Separate energy depositions from close-by particles: high granularity is essential
  - Connecting information from all sub-detectors
    - Charged particles measured in Tracker
    - Photons measured in Electromagnetic Calorimeter (ECAL)
    - Neutral hadrons measured in Hadronic Calorimeter (HCAL)
- To achieve excellent jet energy resolution
  - Goal at ILC: $\lesssim 30\%/\sqrt{E(GeV)}$ for di-jet energies in the order of ~100 GeV



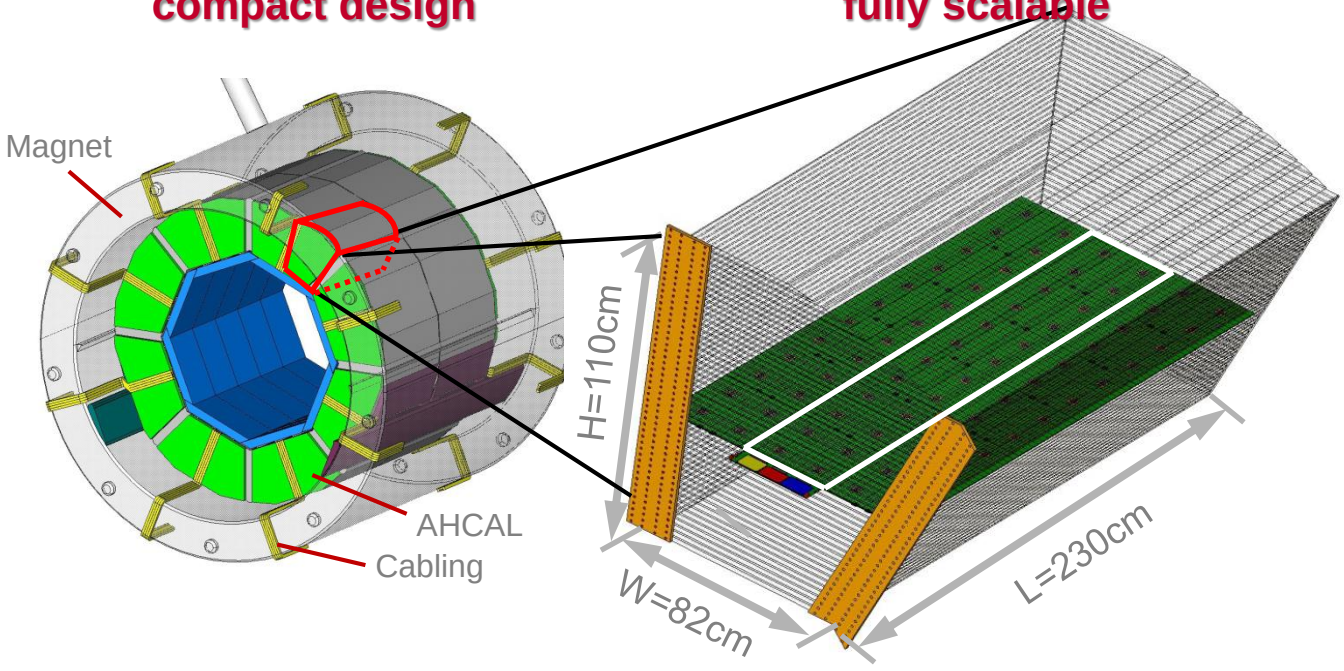


M.A. Thomson: Nuclear Instruments and Methods A 611 (2009) 25-40

Scintillator-based Hadronic Calorimeter

AHCAL inside magnet:
compact design

Technological Prototype:
fully scalable



- Sandwich calorimeter based on scintillator tiles (3×3cm²) read out by Silicon Photomultipliers (SiPMs)
- Electronics fully integrated into active layers
- HCAL Base Unit (HBU): 144 channels (4 ASICs)

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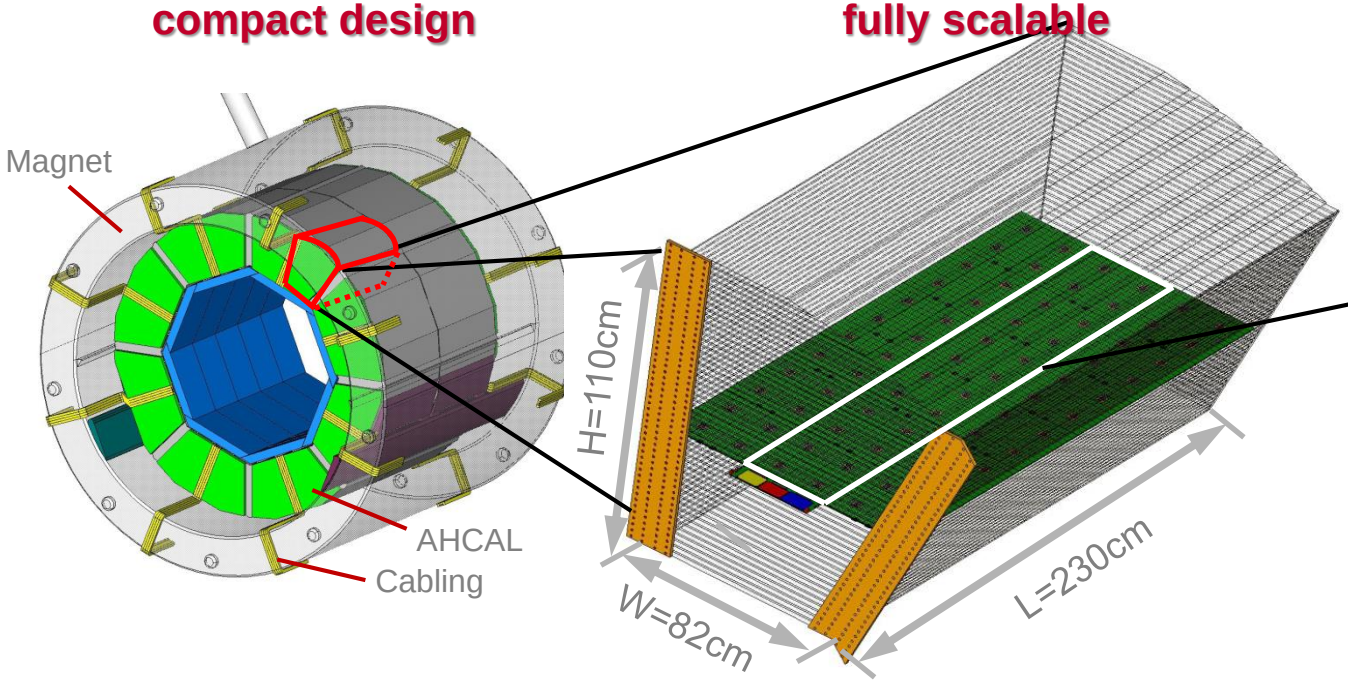

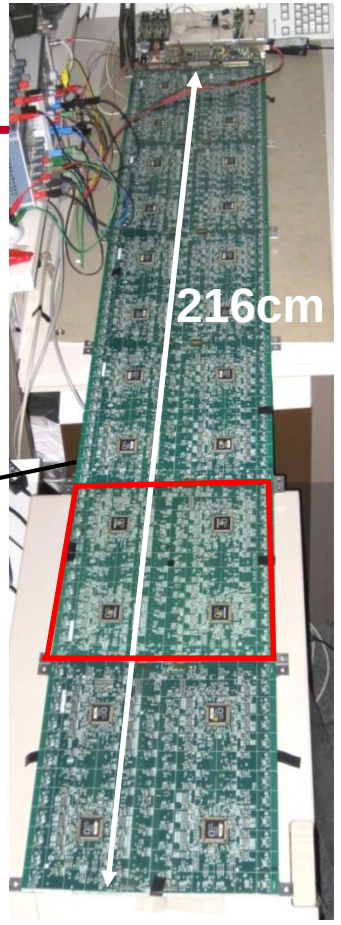

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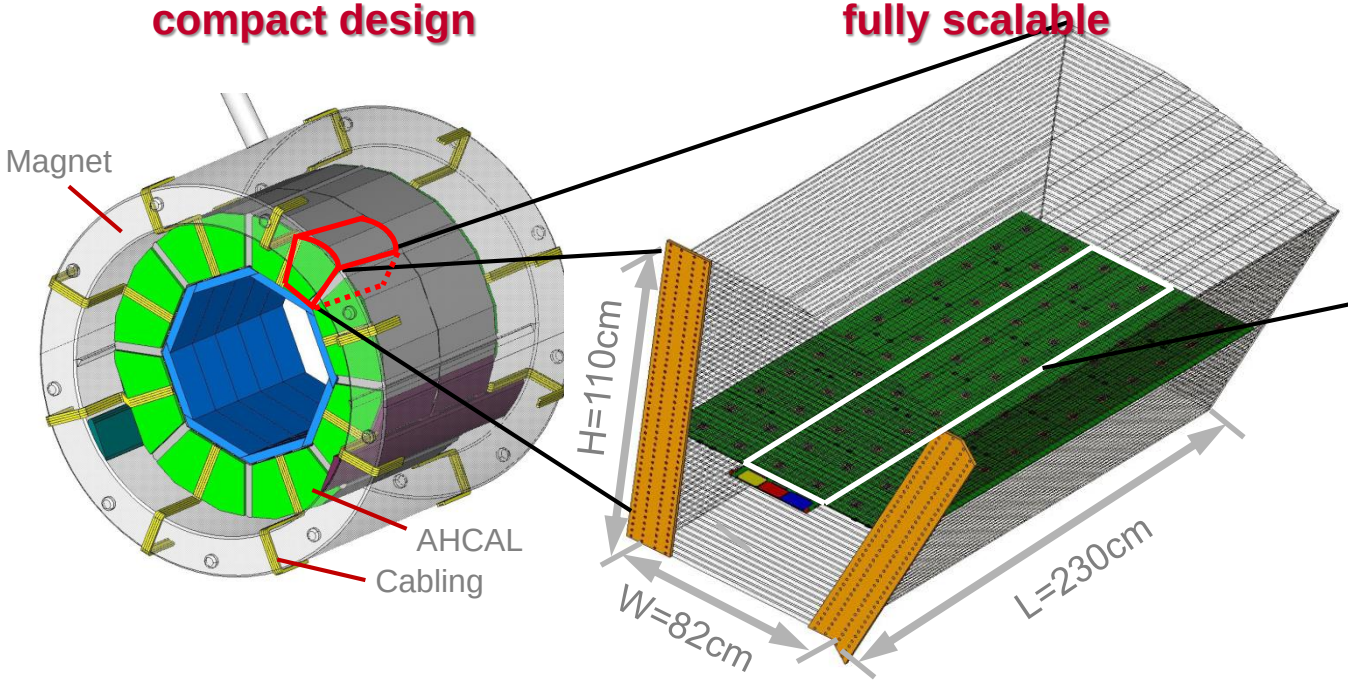

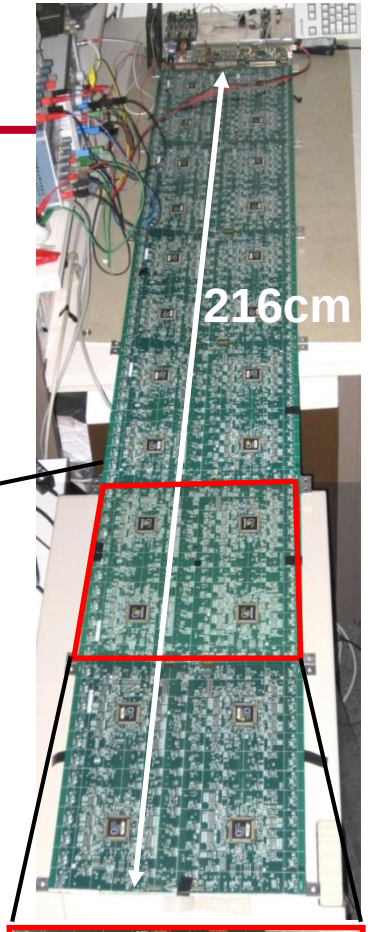

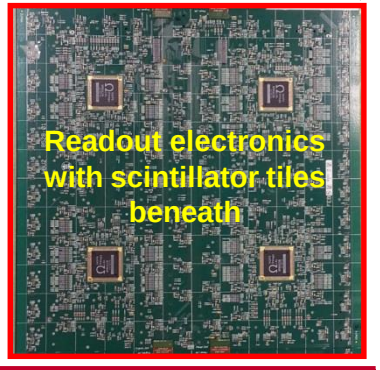

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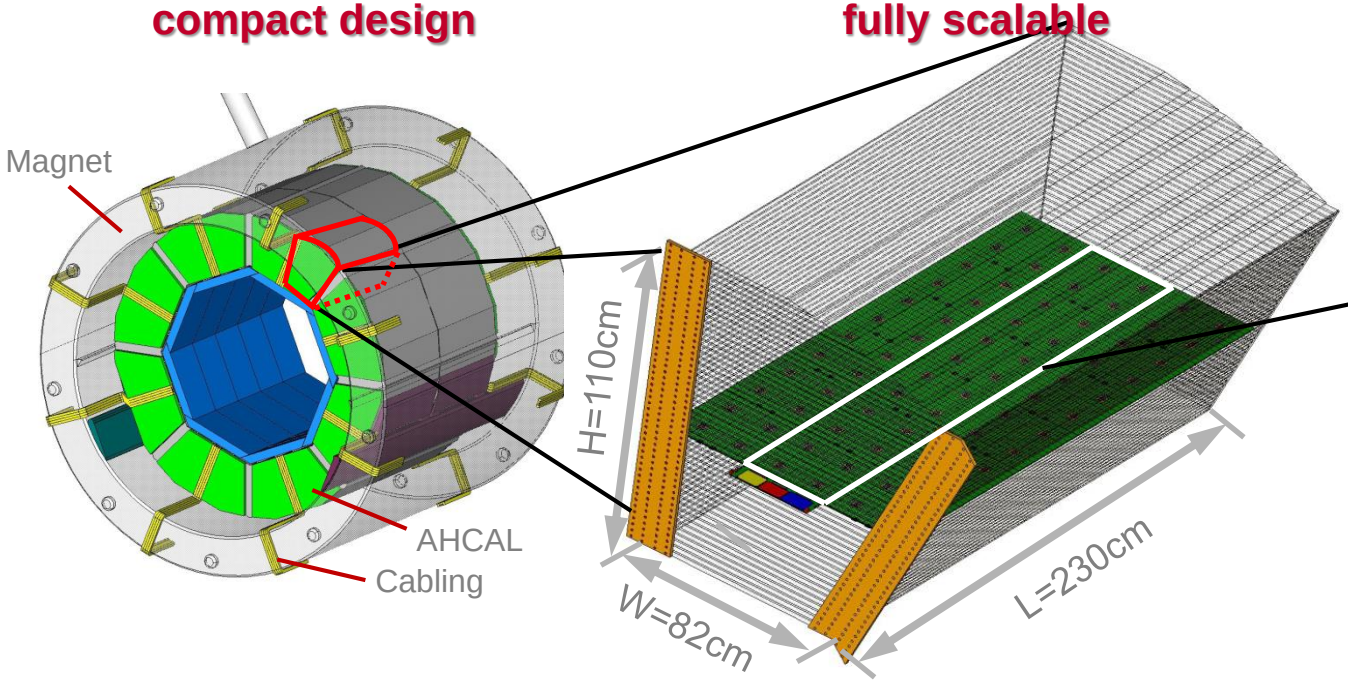

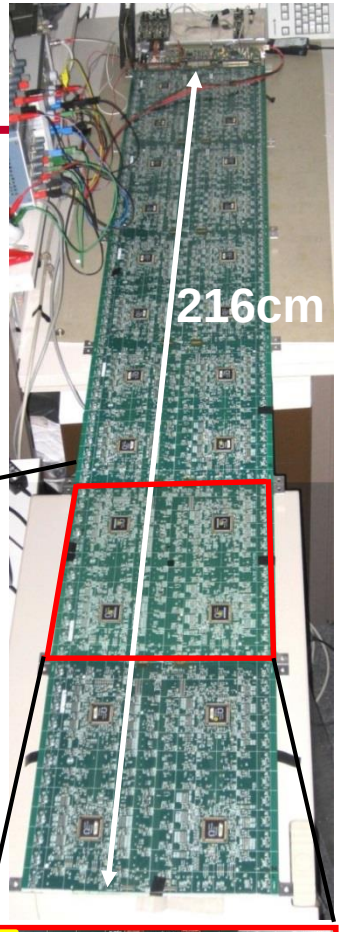

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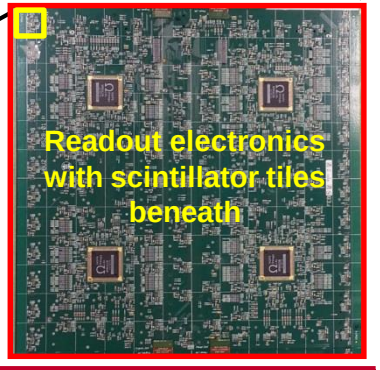

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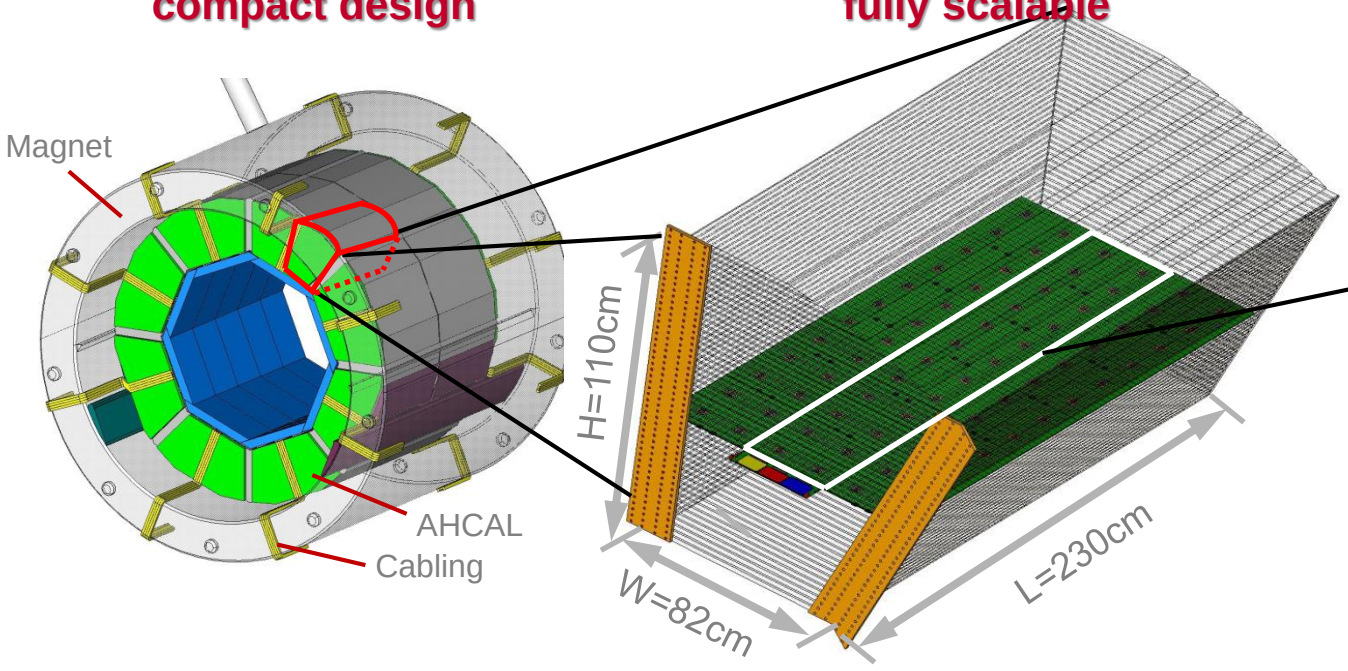
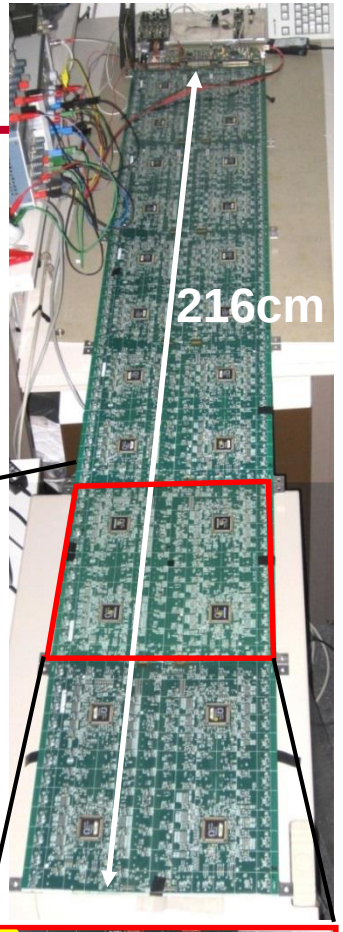
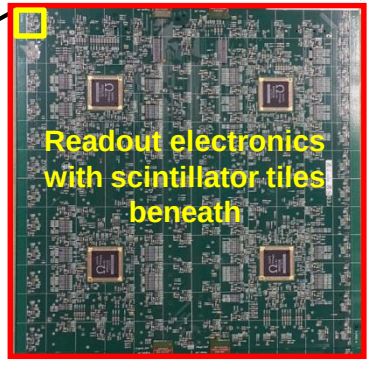


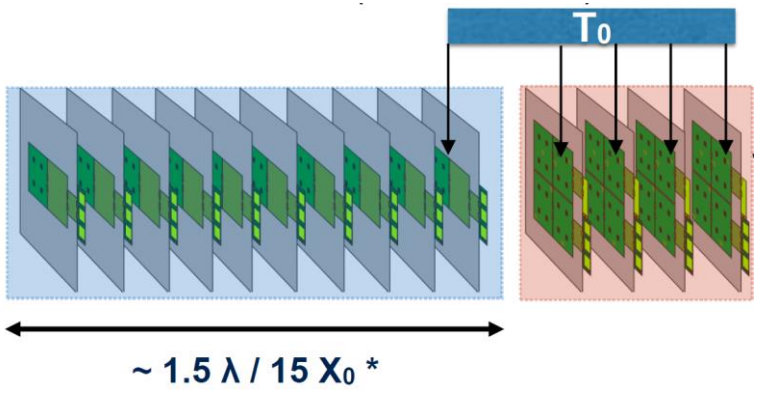


- Sandwich calorimeter based on scintillator tiles (3×3cm²) read out by Silicon Photomultipliers (SiPMs)
- Electronics fully integrated into active layers
- HCAL Base Unit (HBU): 144 channels (4 ASICs)
- High granularity: 8M channels in total
  - Challenges for mass assembly and data concentration



AHCAL: 2015 beam tests at CERN SPS

- AHCAL prototype (in Fe and W absorbers)
  - 14 layers (3744 channels) in total
  - 10 layers (shower start finder) + 4 large layers



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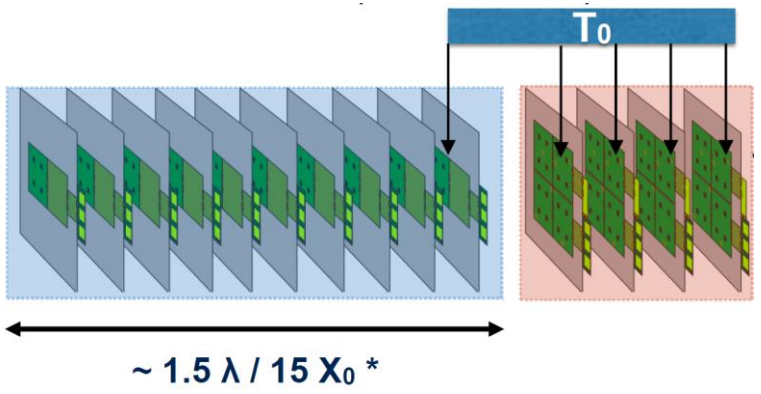

AHCAL prototype in steel stack

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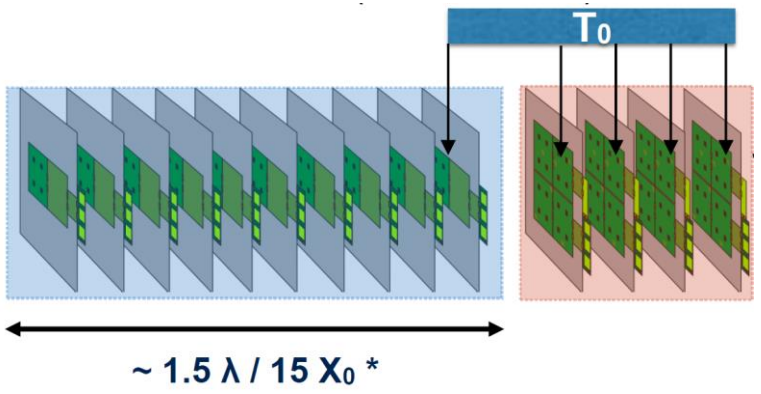

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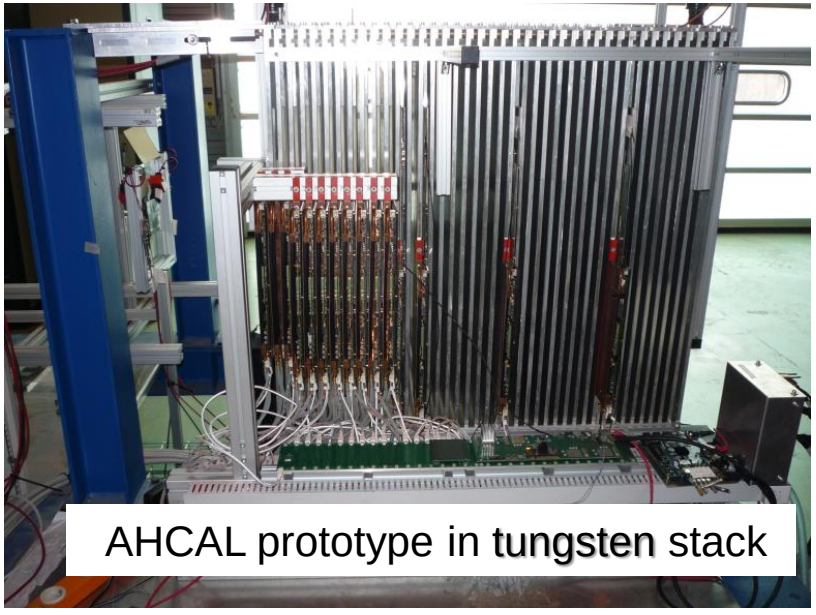
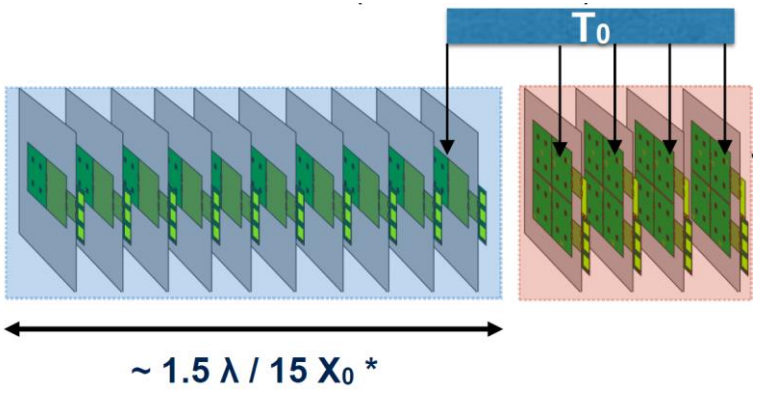


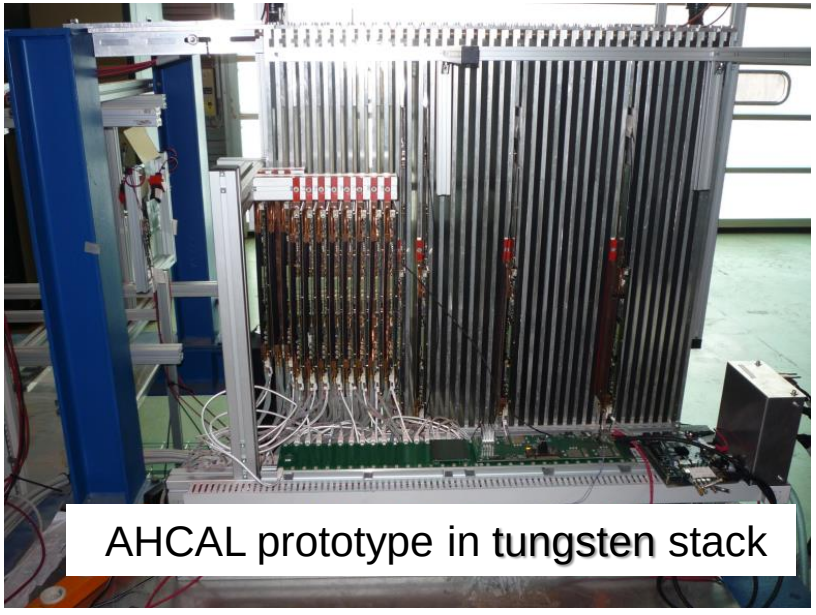
AHCAL prototype in tungsten stack

AHCAL: 2015 beam tests at CERN SPS

- AHCAL prototype (in Fe and W absorbers)
  - 14 layers (3744 channels) in total
  - 10 layers (shower start finder) + 4 large layers
- Data sets
  - Muons (180 GeV): calibration
  - Electrons (10-50 GeV): cross check
  - Pions (10-90 GeV): detailed shower studies

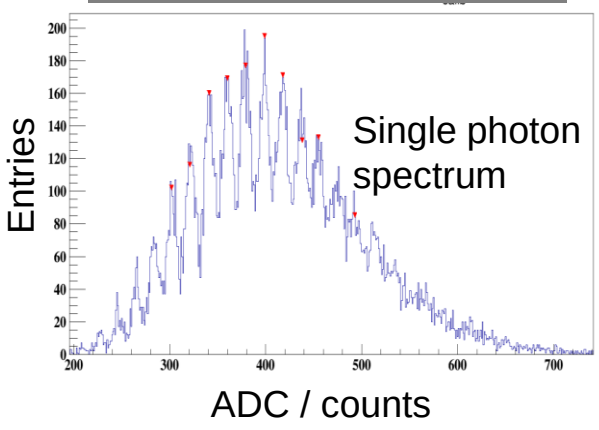



AHCAL prototype in steel stack

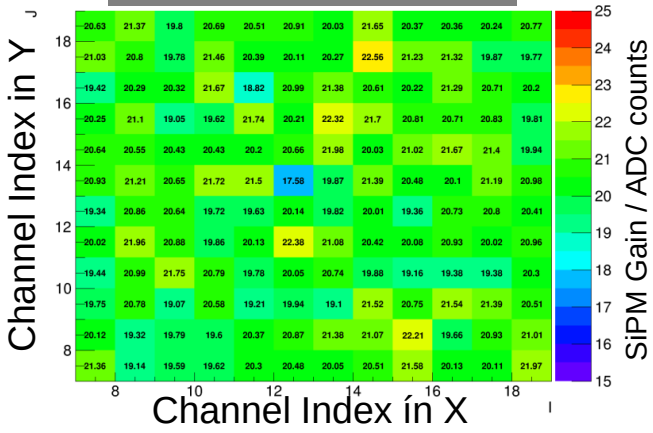

AHCAL prototype in tungsten stack

Commissioning: LED calibration and MIP response

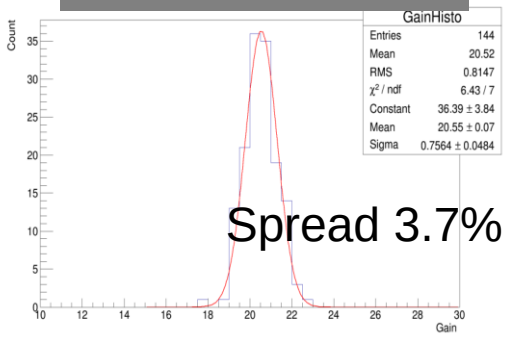
SiPM response to LED light



Gain Mapping of a HBU



SiPM Gain of a HBU (144 channels)



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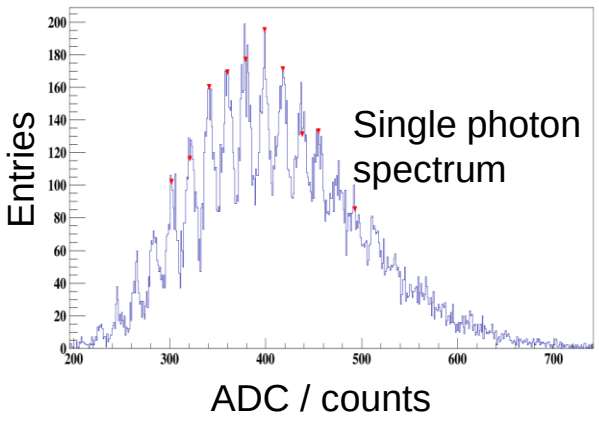

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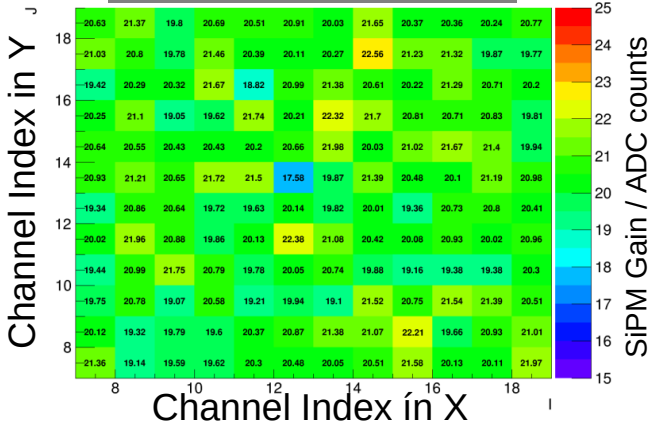
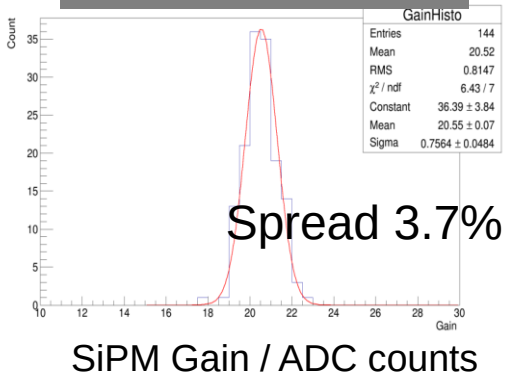
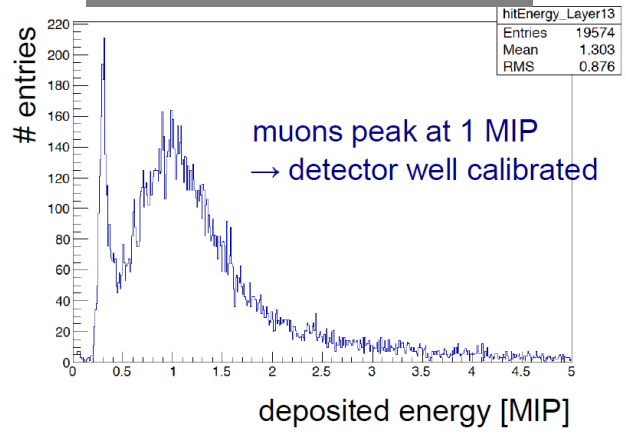


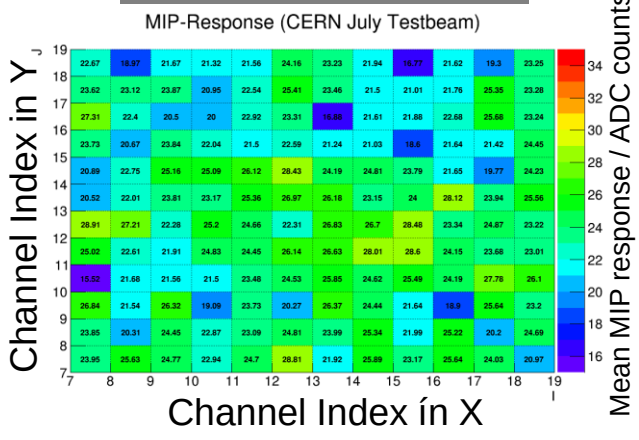
SiPM Gain of a HBU (144 channels)



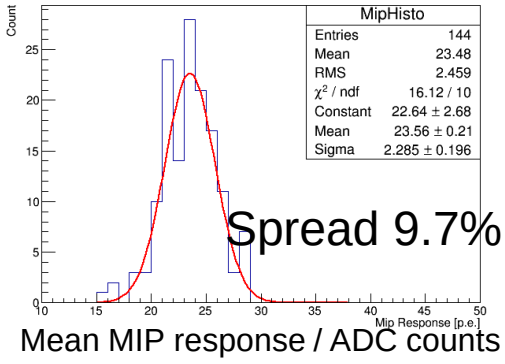
SiPM response to muons



MIP Mapping of a HBU



MIP Responses of a HBU (144 channels)



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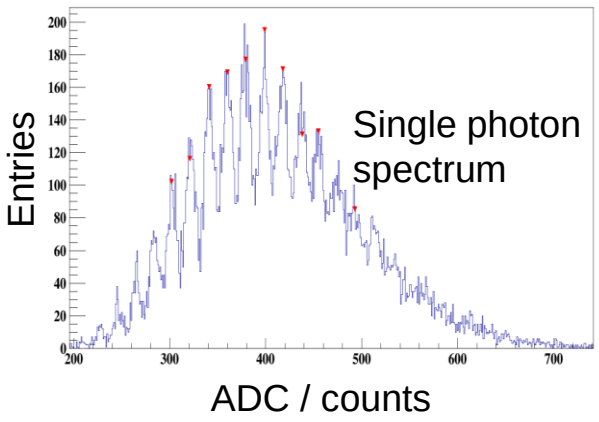

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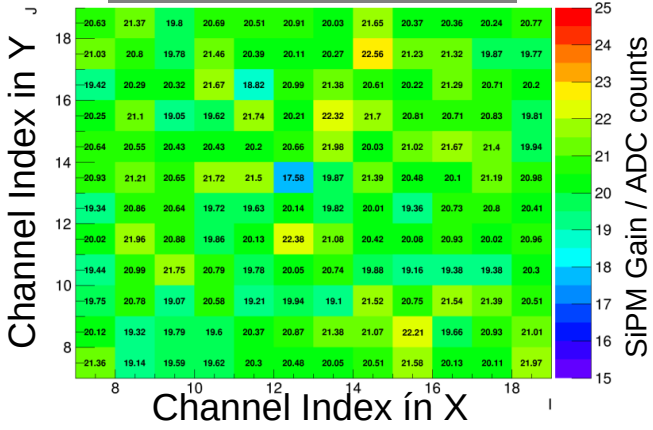

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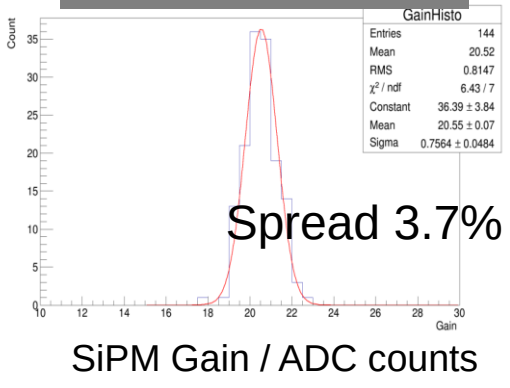

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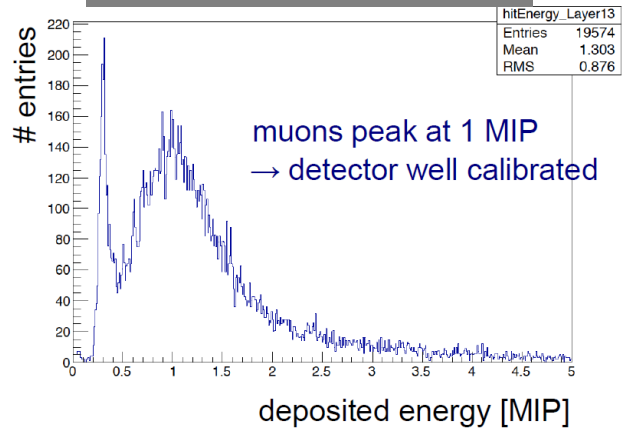

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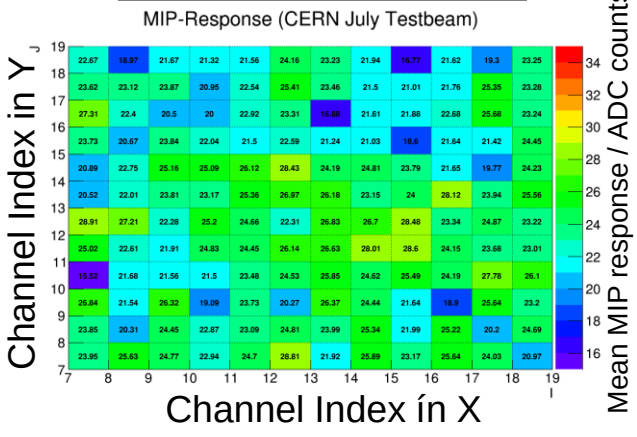

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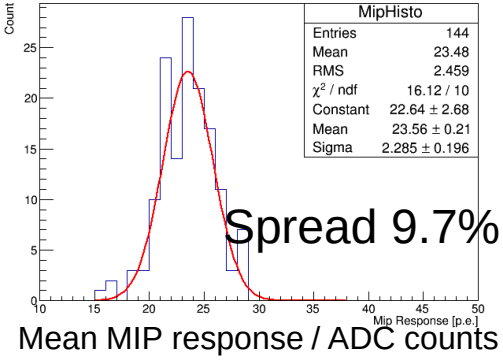
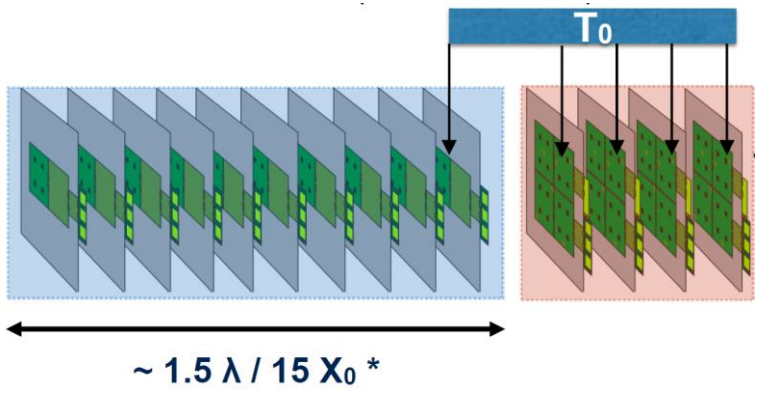


Promising performance achieved: uniform gain and MIP response

Timing analysis

Geant4 v10.01, Mokka v08-05-01

- Time reference: T0
  - Signal from trigger scintillator
  - Obtained from muon data
- Muon: time resolution
  - Time of hits relative to T0



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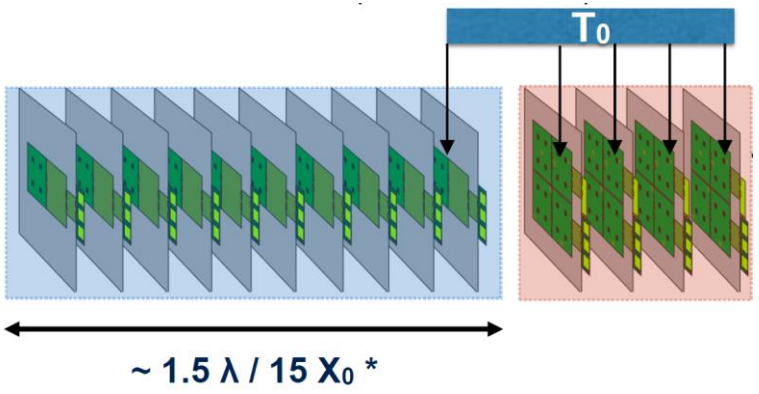

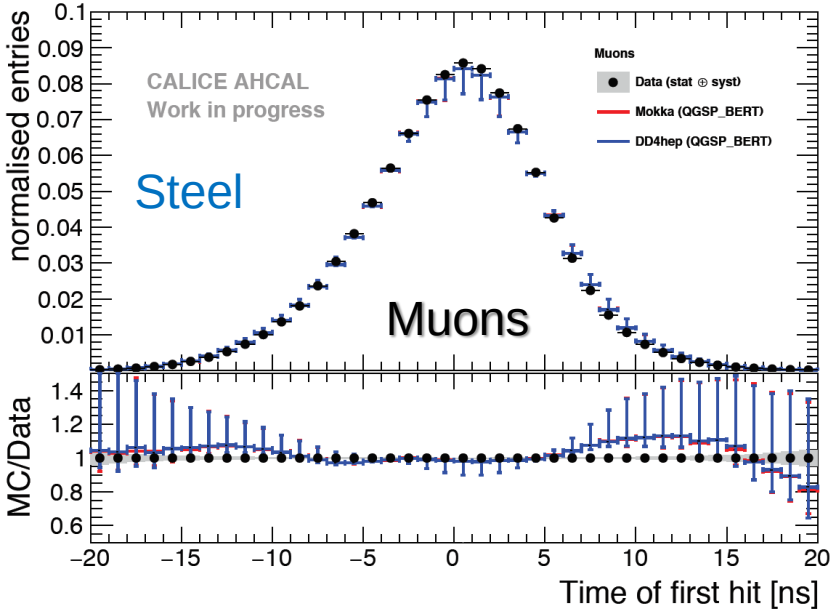

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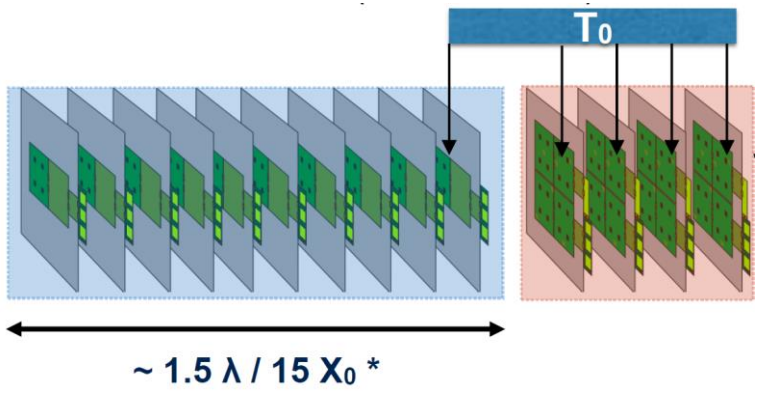
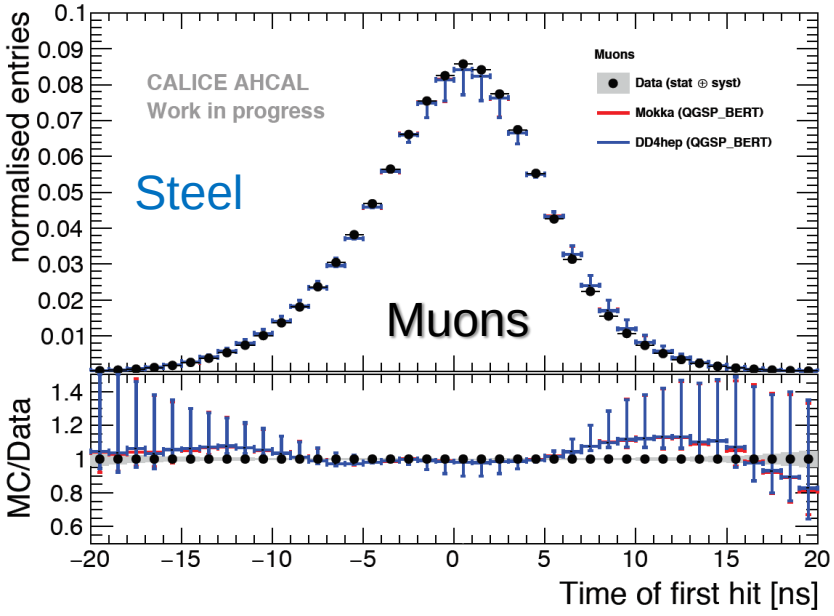
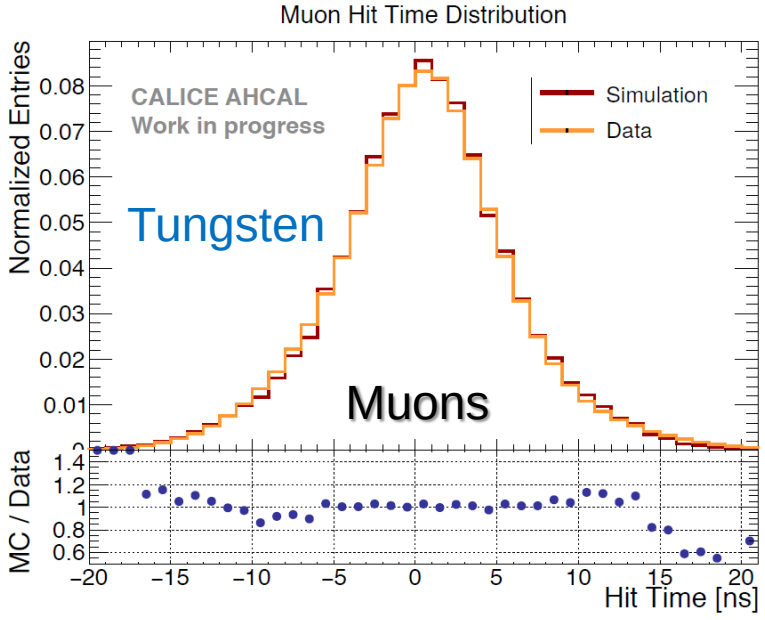


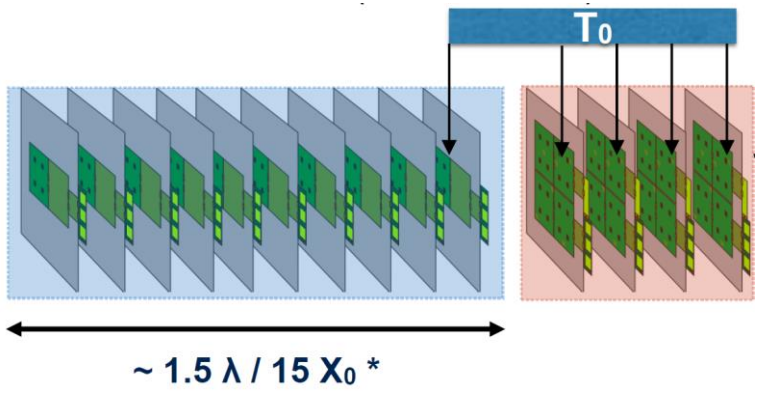


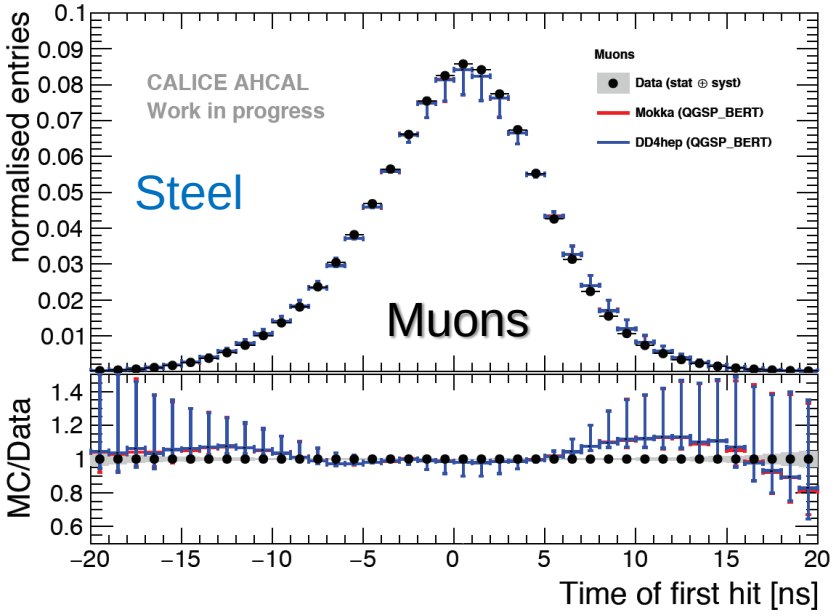


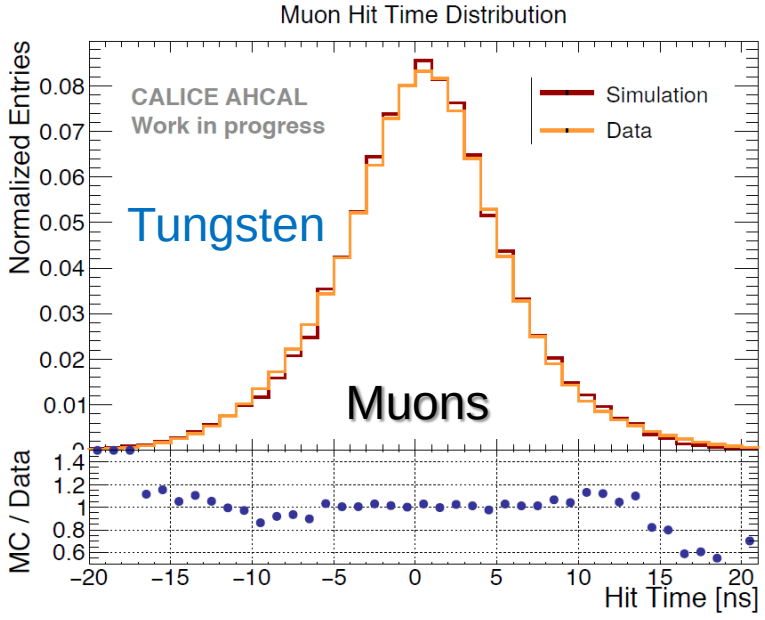
Timing analysis

Geant4 v10.01, Mokka v08-05-01

- Time reference: T0
  - Signal from trigger scintillator
  - Obtained from muon data
- Muon: time resolution
  - Time of hits relative to T0
  - MC tuned to describe the data
  - Similar results in steel and tungsten

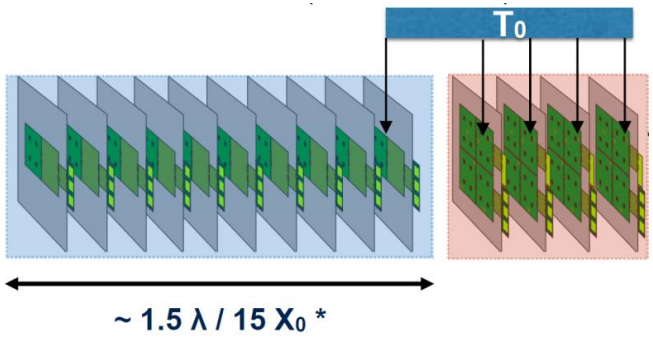




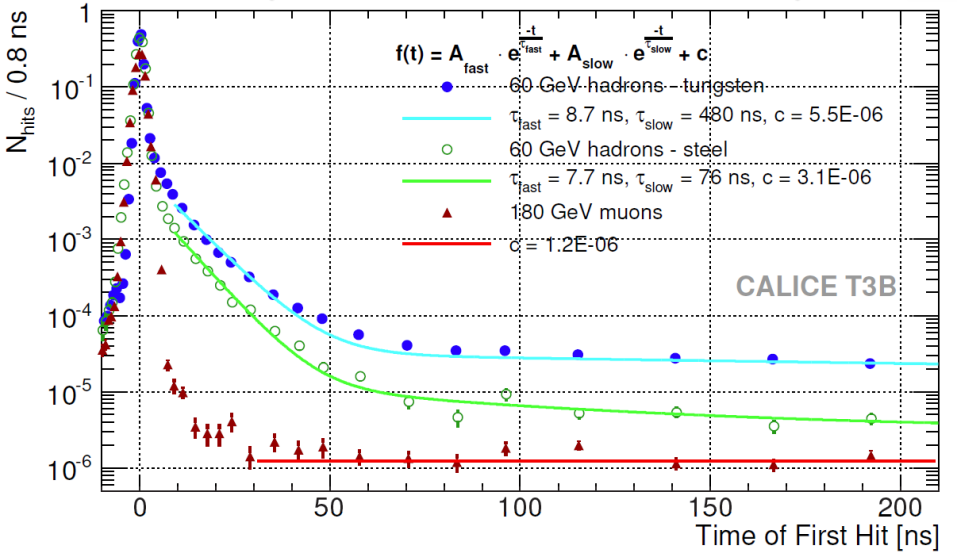


Timing analysis

- Time calibration procedure established
  - Based on muon data/MC
- Ongoing analysis of electrons and pions



Timing behavior of shower components
(Reminder of T3B results)



JINST 9 P07022 (2014)

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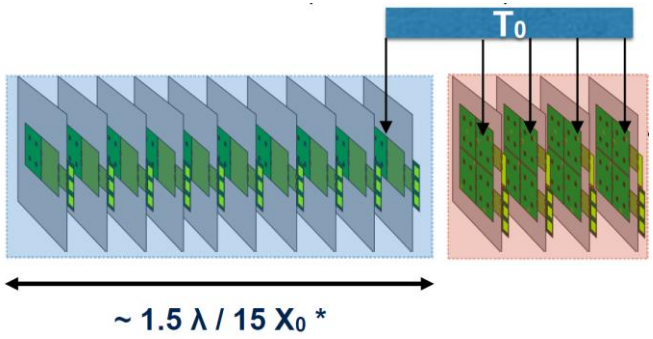
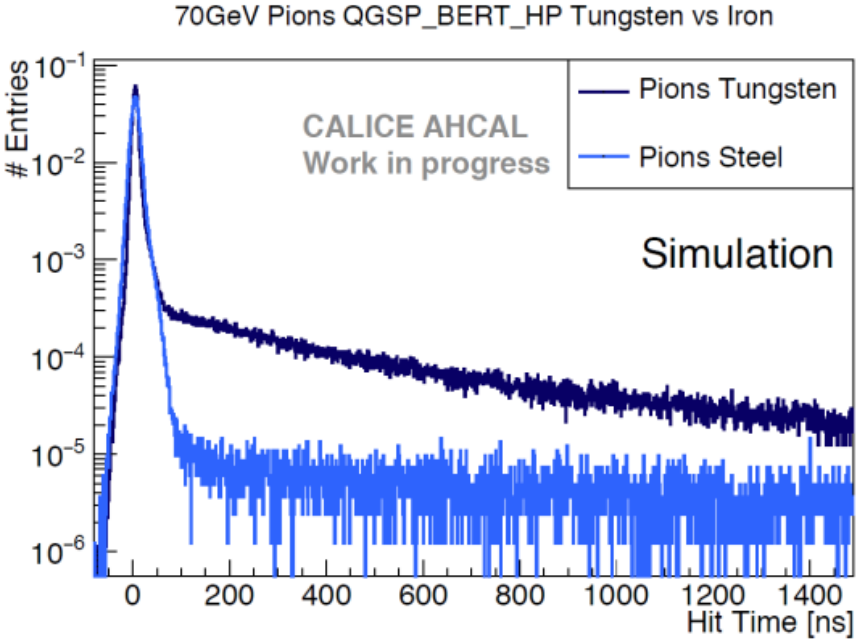


Teaser: comparison of absorbers in MC



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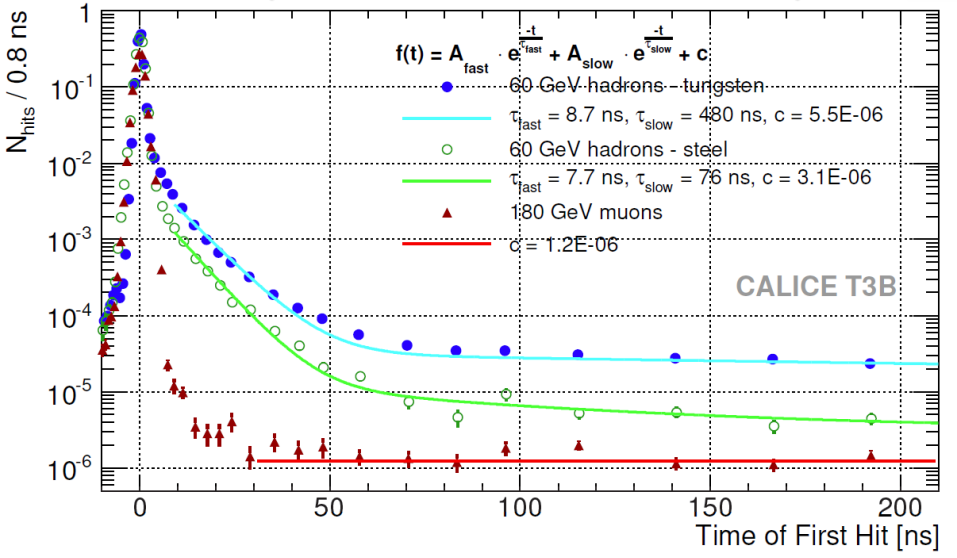
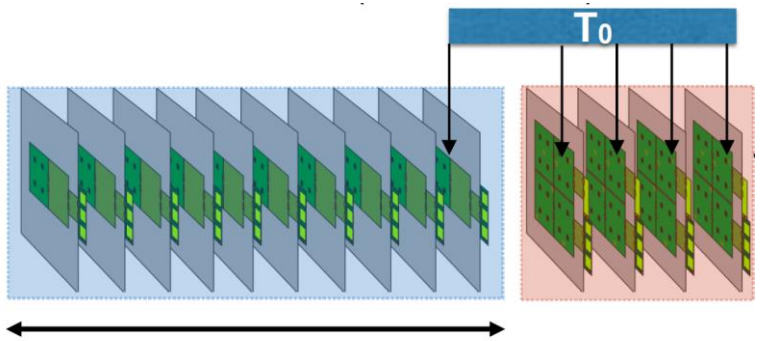


Ongoing efforts: same can be done for data

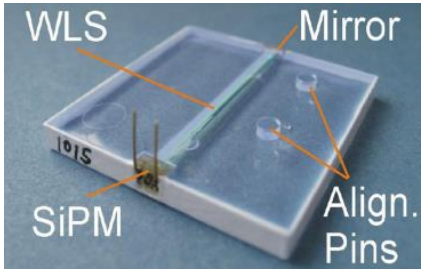
JINST 9 P07022 (2014)

Detector layers: tiles and SiPMs

- Experience from beam tests is essential
  - To choose an option for construction of a fully equipped prototype (40 layers)
- Active layers with different designs
  - Tiles with wavelength shifting fiber (WLS):
    - 5 layers, CPTA SiPMs (800 pixels)



~ 1.5 λ / 15 X_0 *



Detector layers: tiles and SiPMs

- Experience from beam tests is essential
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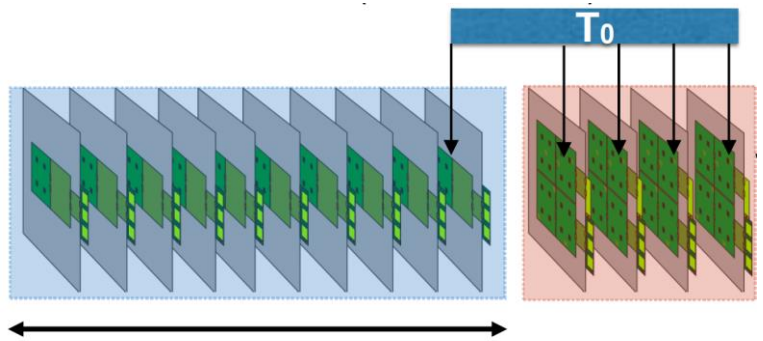

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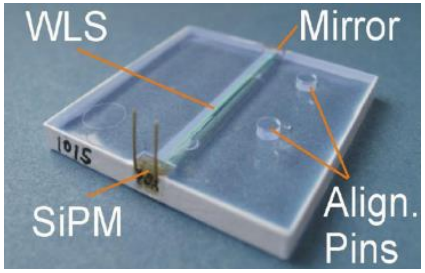

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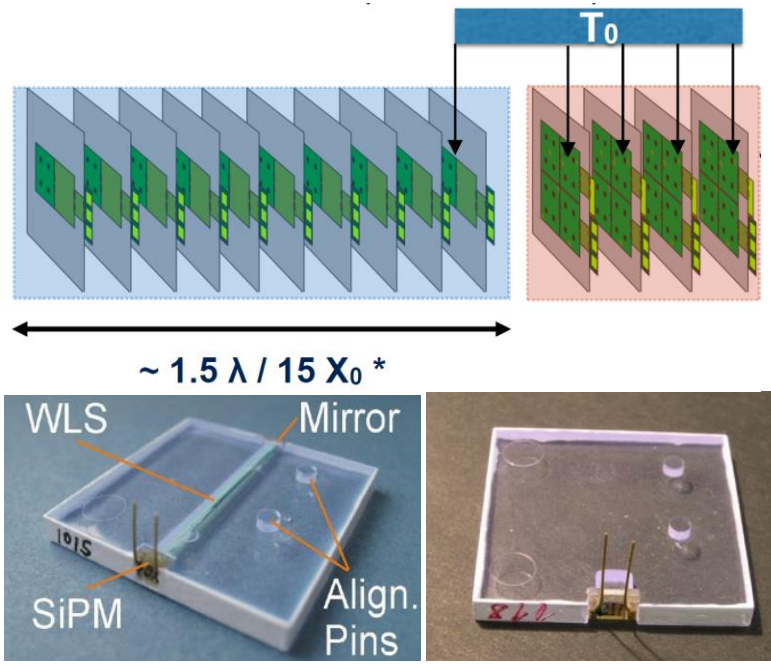

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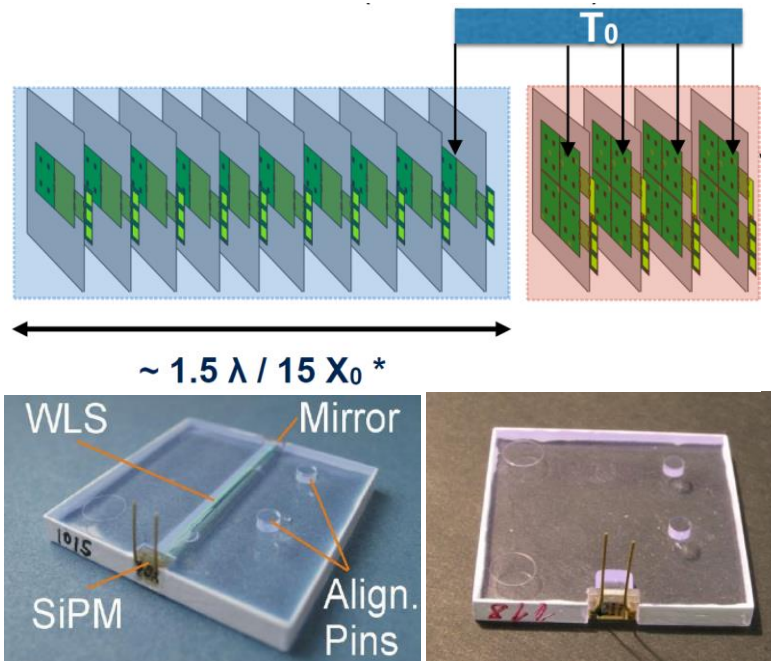

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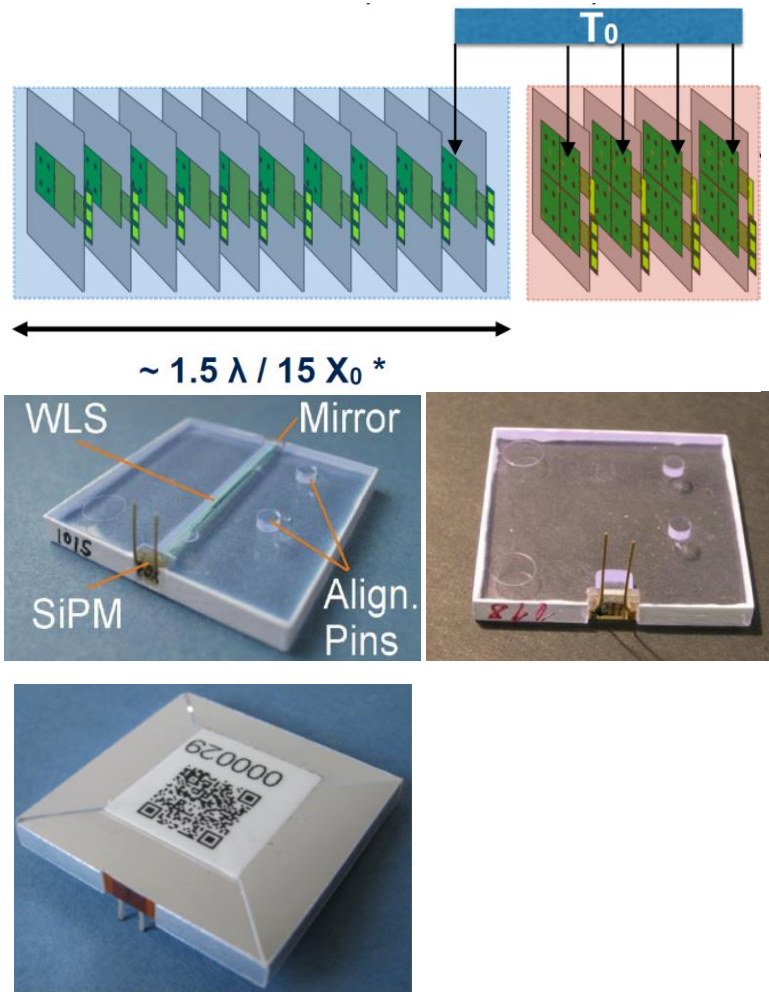

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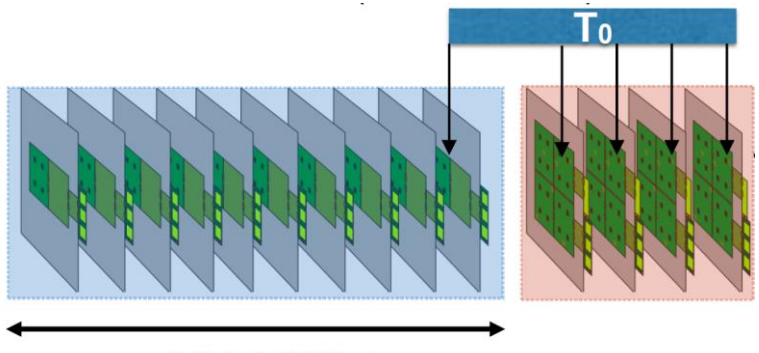

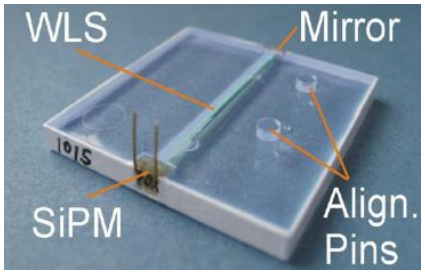

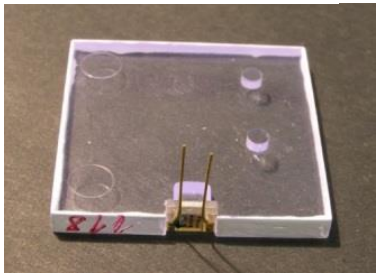

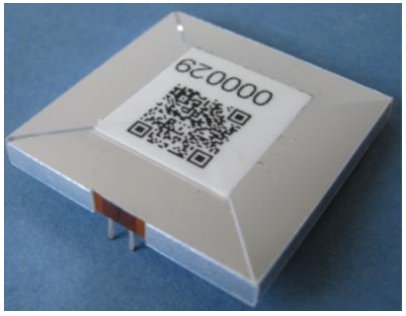

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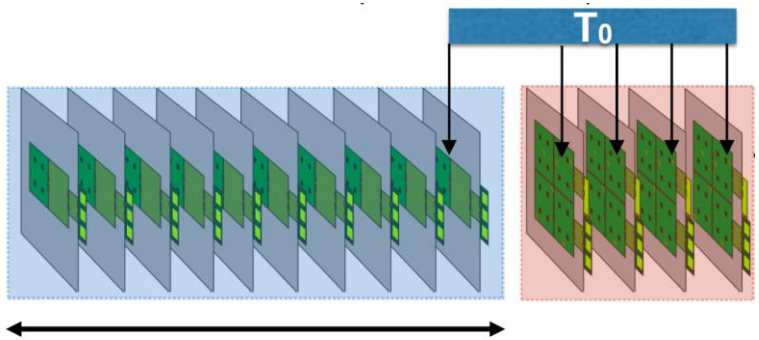

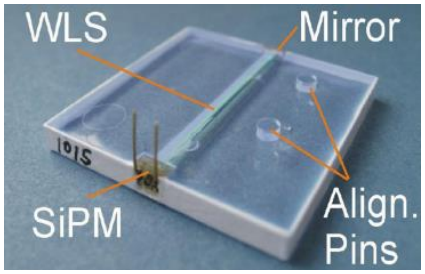

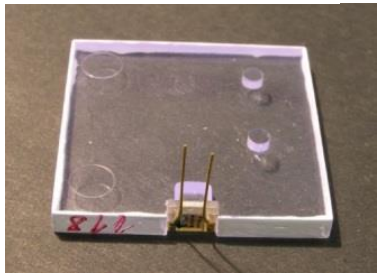

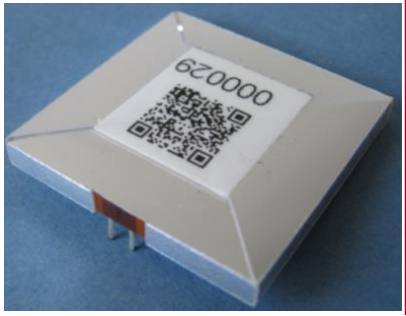

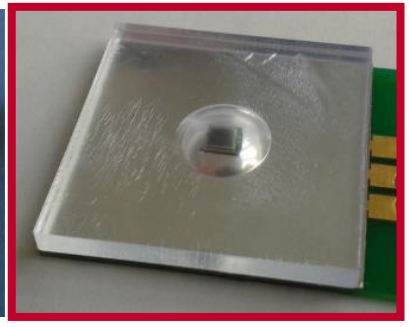

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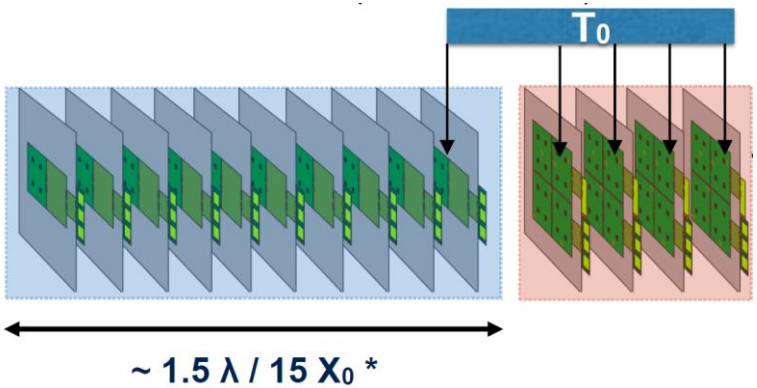
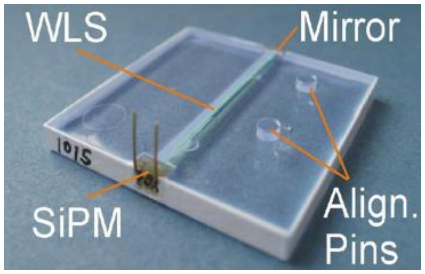
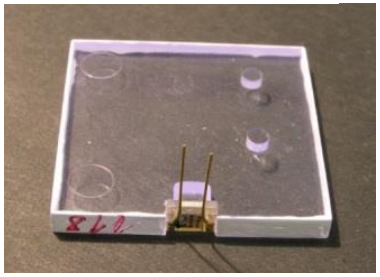
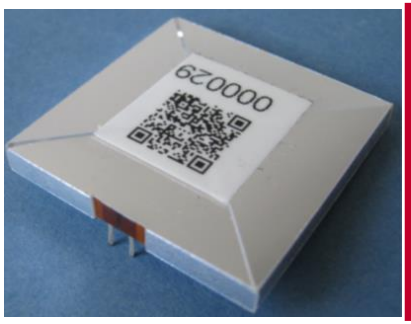
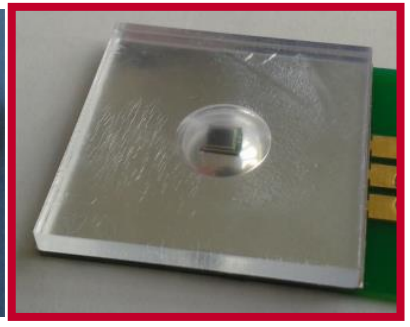






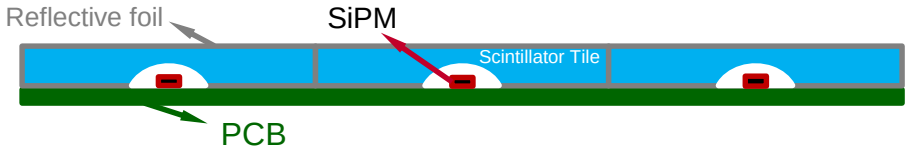


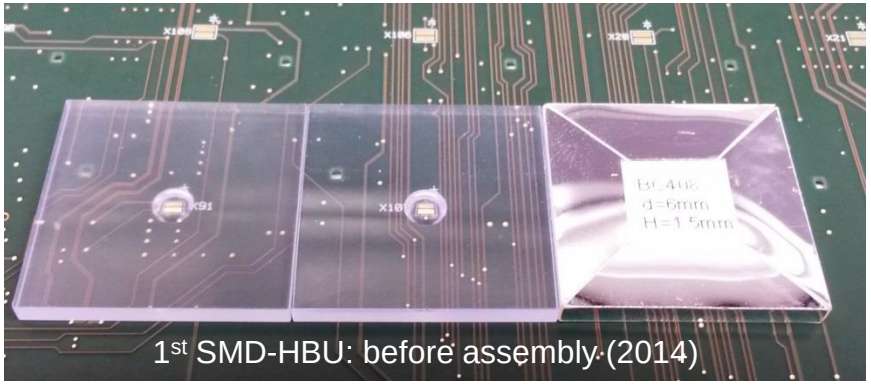


Only the surface-mounted design is suitable for mass assembly, which is crucial to demonstrate the scalability to build the final HCAL detector (~8M channels)

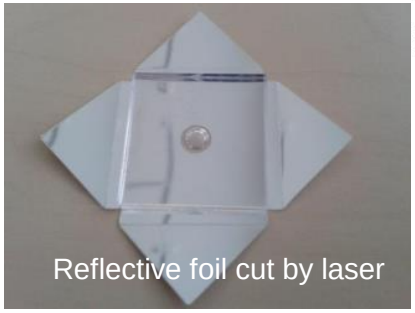
The surface-mounted design has been adopted as a baseline design for the large AHCAL demonstrator

AHCAL mass assembly: from design to reality

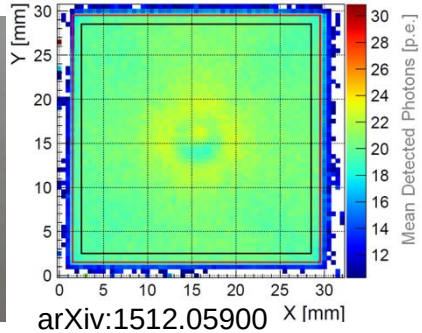




- Surface-mount tile design
  - Electronics for surface-mounted SiPMs established (SMD-HBU)
  - 1st prototype board (144 channels) successfully built in 2014
  - Scintillator tiles individually wrapped



Achieved excellent uniformity



arXiv:1512.05900

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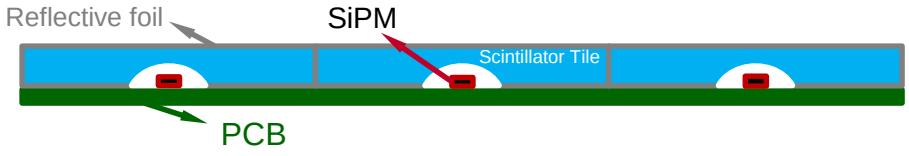

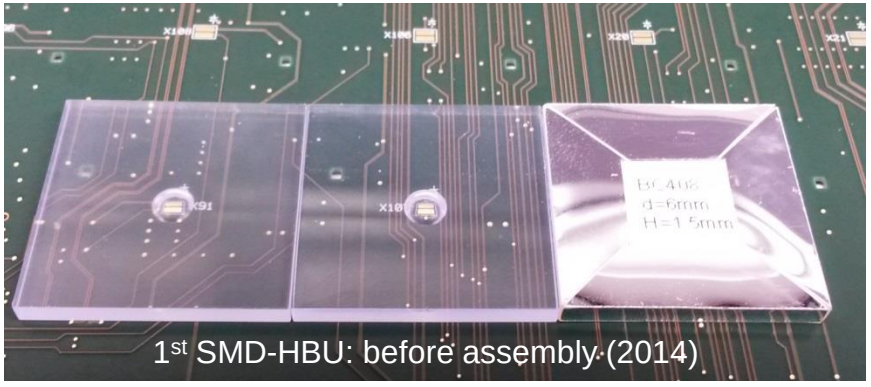

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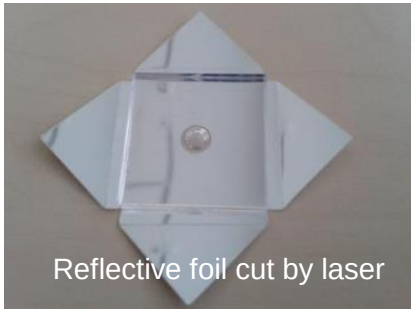

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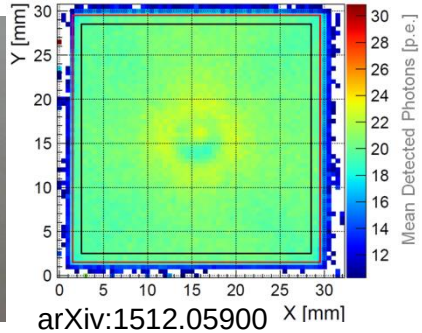

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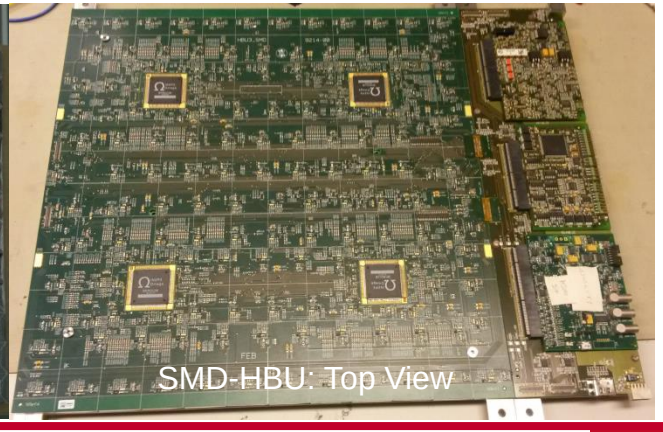
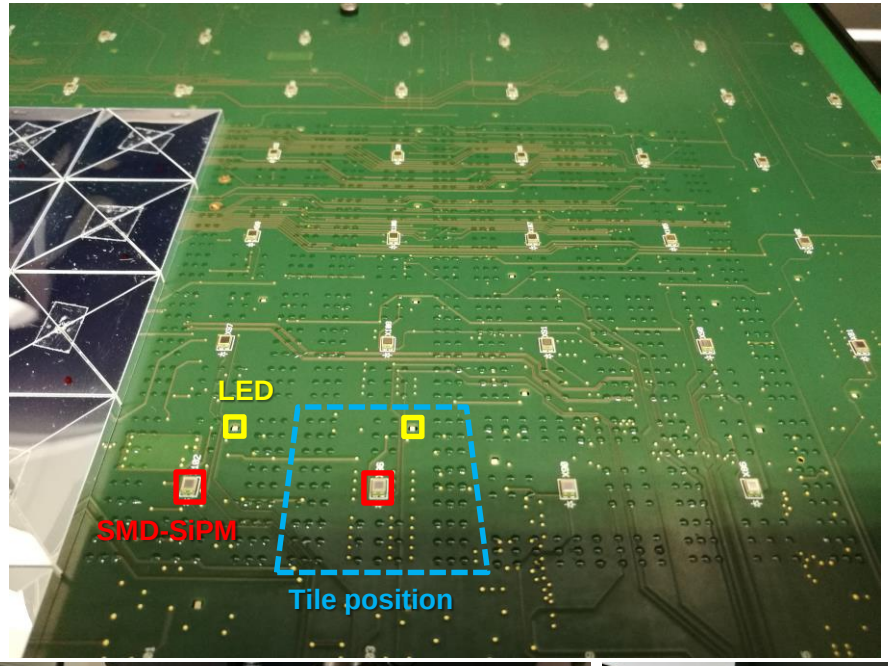


AHCAL: latest mass assembly activities



- Surface-mount tile design
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  - 6 new SMD-HBUs assembled in 2016
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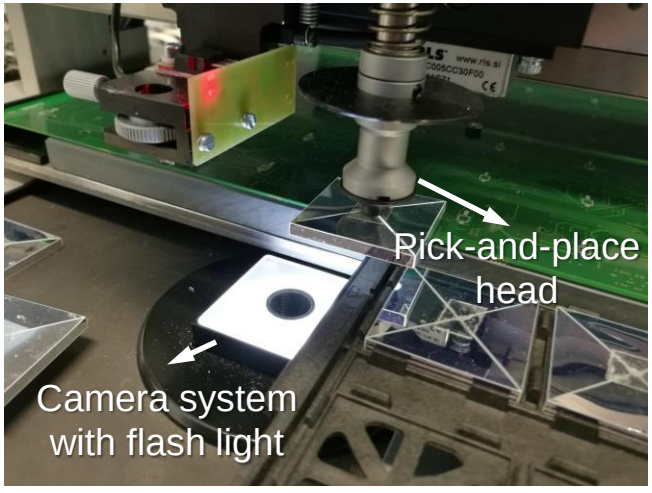

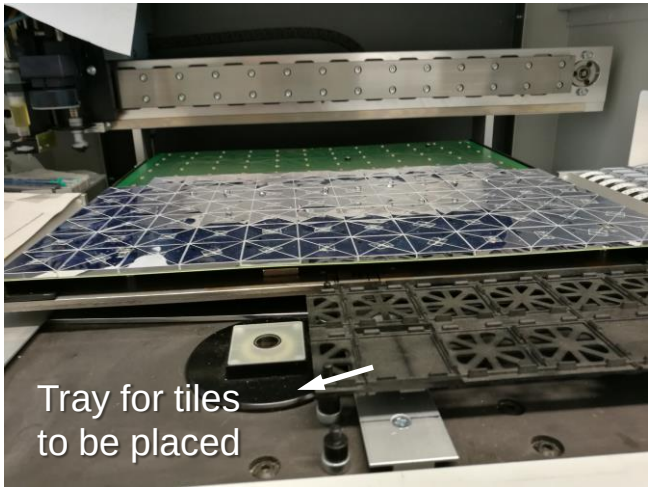

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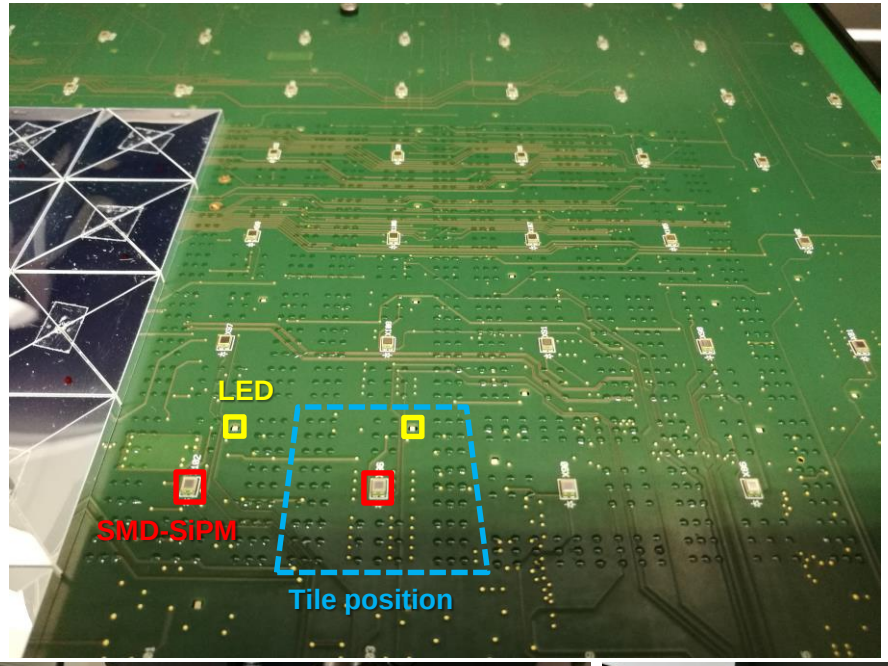

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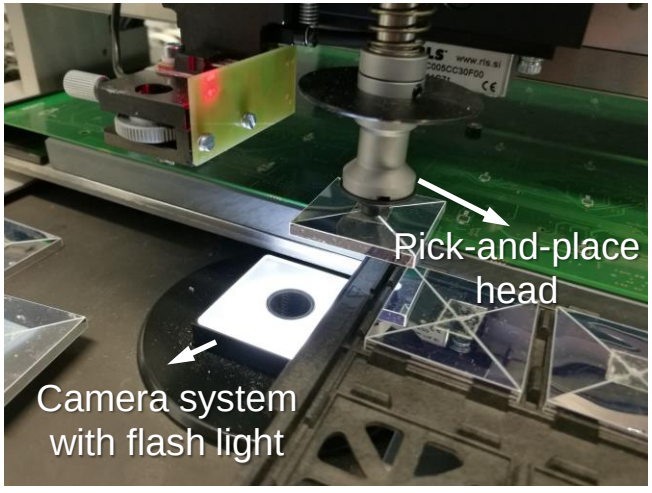

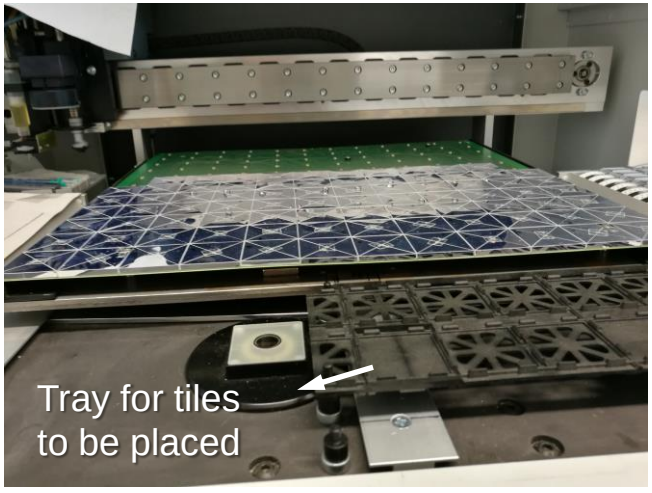

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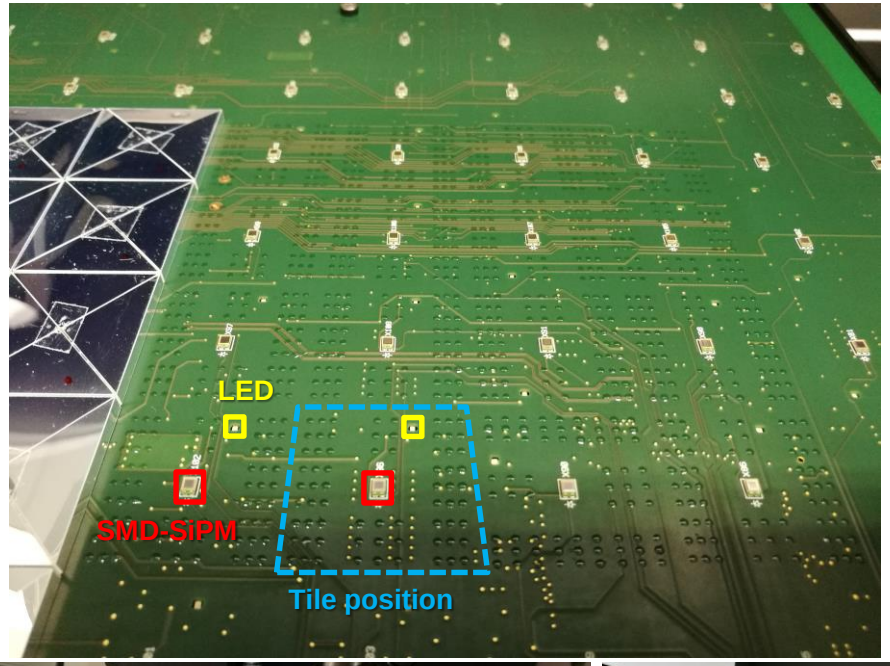

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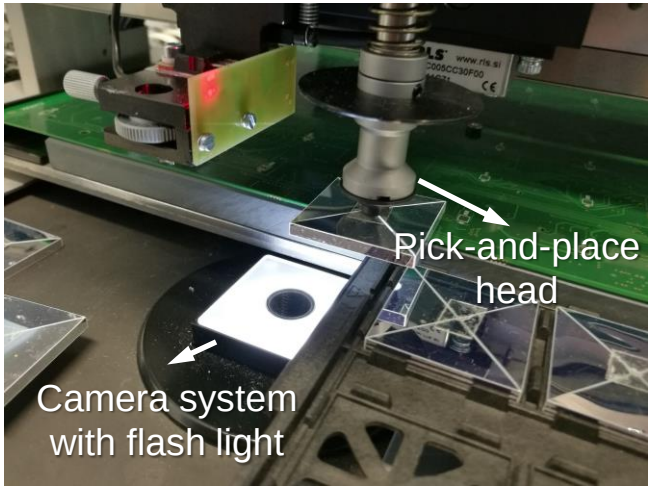
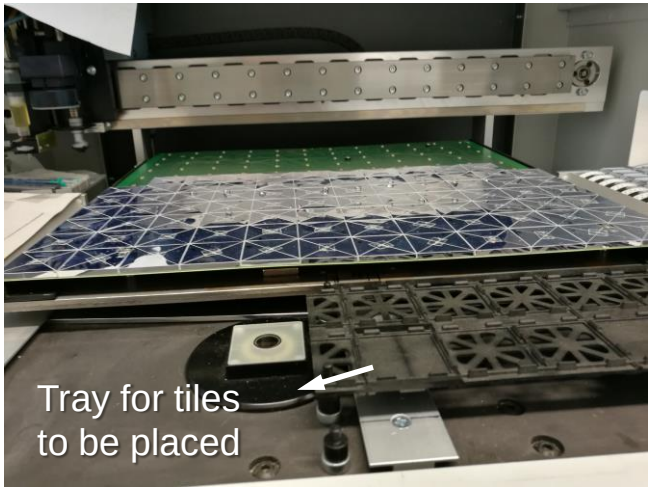
  - Noise free in AHCAL
  - Improved uniformity (SiPM- and pixel-wise)





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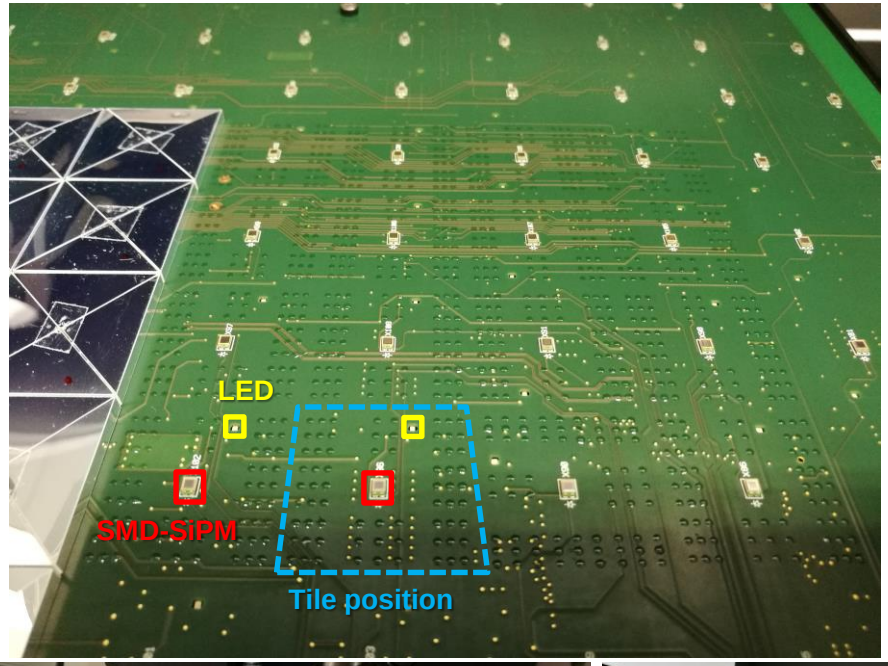

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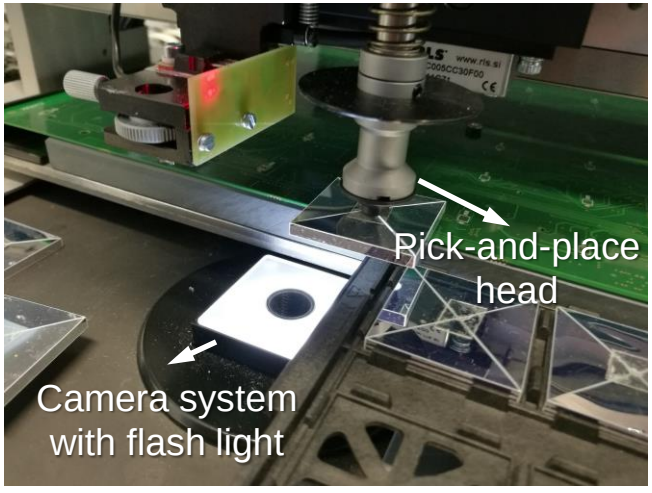
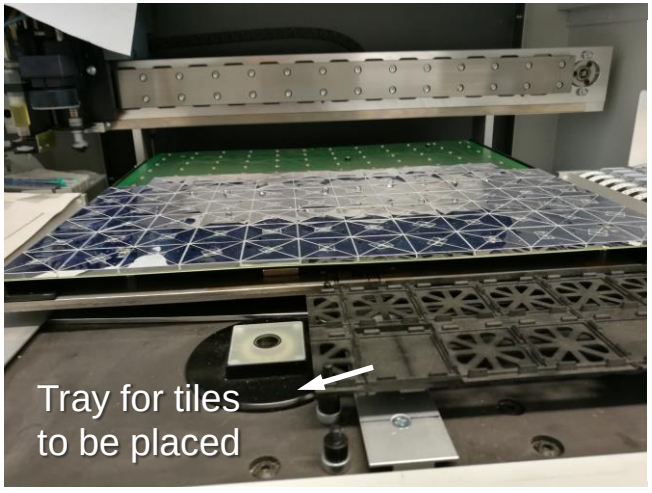
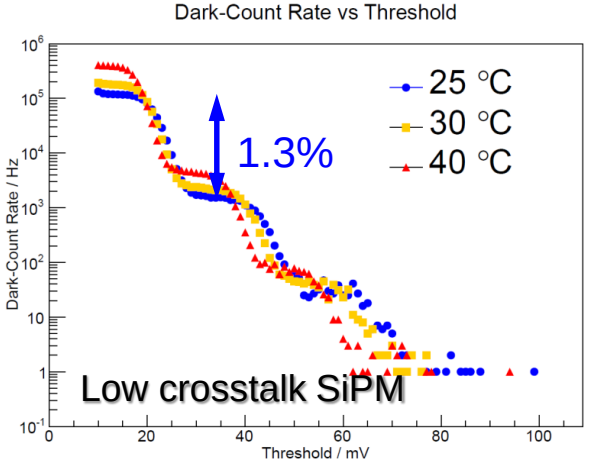
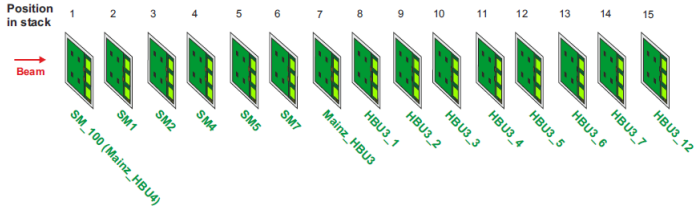






AHCAL: a new small prototype

- Setup
  - A small prototype with all high-quality SiPMs
  - 15 layers, single HBU per layer;
    - 7 HBUs with SMD-SiPMs built via mass assembly: bottom coupling (baseline design)
    - 8 HBUs with high-quality SiPMs, side-surface coupling
  - New interface boards for all layers



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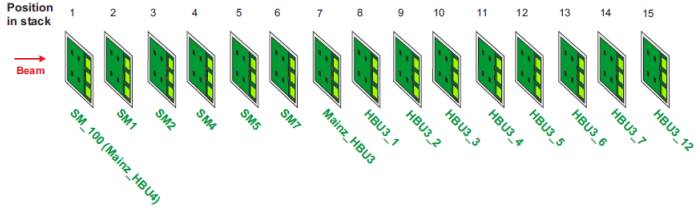

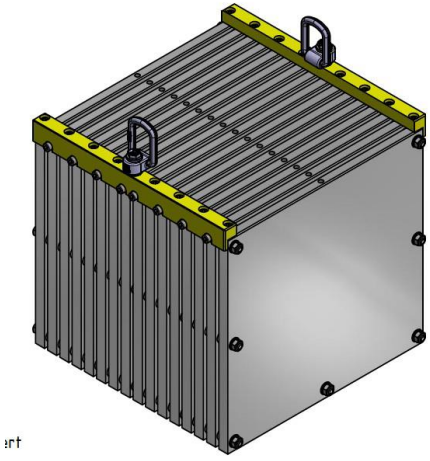

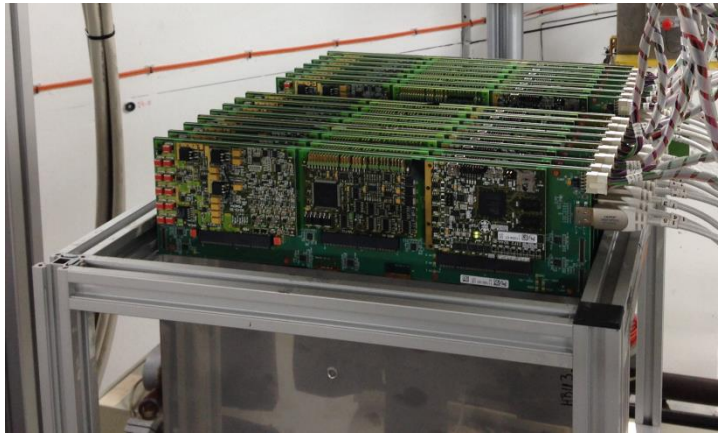

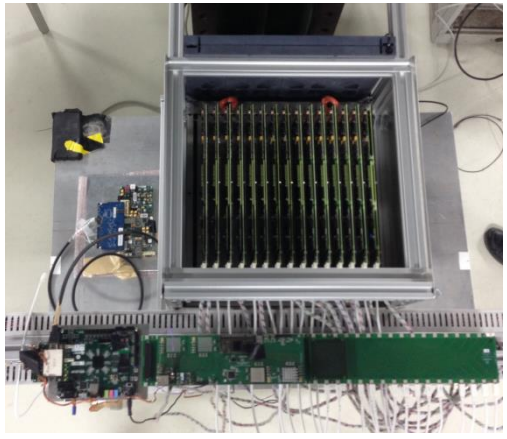

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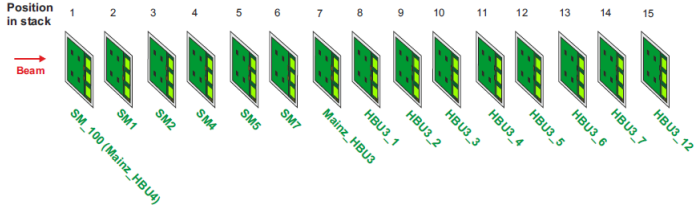
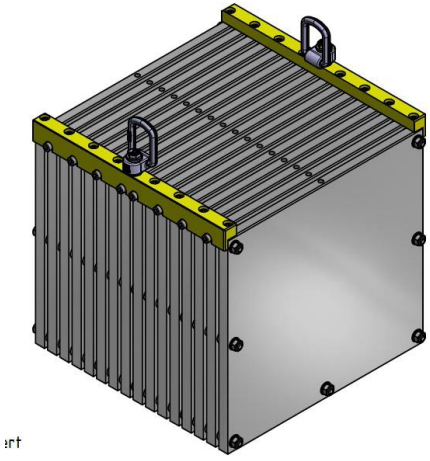
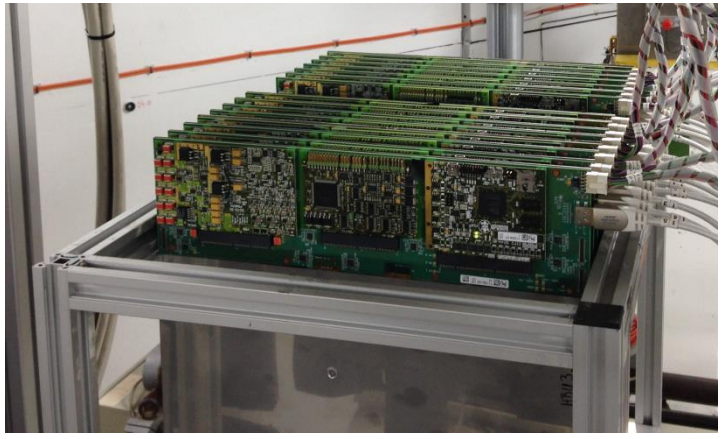
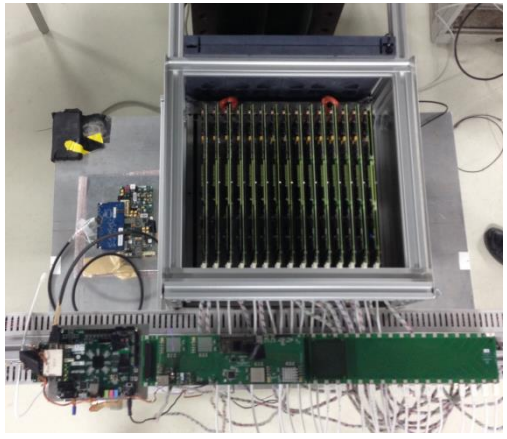
- Setup
  - A small prototype with all high-quality SiPMs
  - 15 layers, single HBU per layer;
    - 7 HBUs with SMD-SiPMs built via mass assembly: bottom coupling (baseline design)
    - 8 HBUs with high-quality SiPMs, side-surface coupling
  - New interface boards for all layers
- Aims
  - Precision measurements of EM showers
  - Power-pulsing mode: crucial for linear colliders
  - Temperature compensation for SiPMs



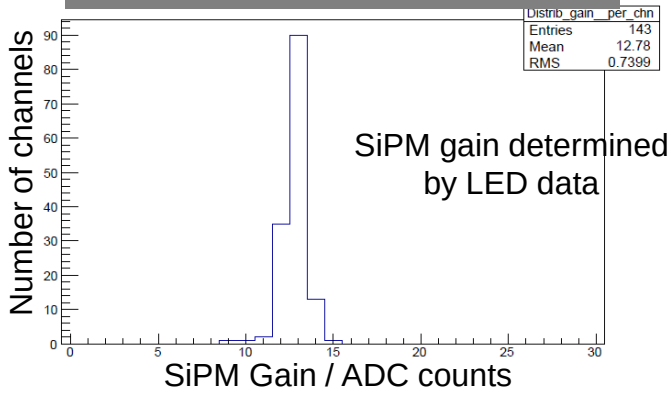




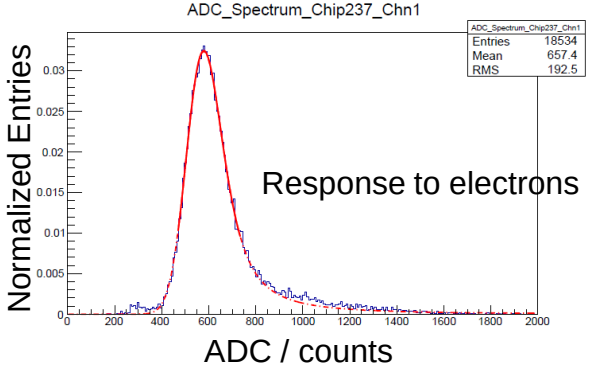


Commissioning and response to electrons

Distribution of SiPM Gains of 1 HBU



Typical MIP Spectrum (1 channel)

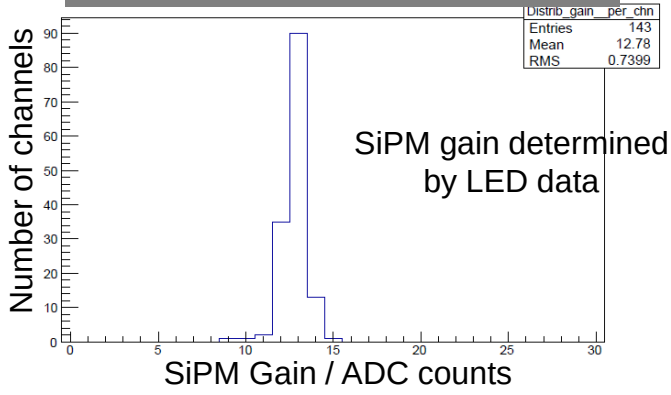


- Tested in DESY testbeam in 2016
  - 1~5 GeV electron beams
  - MIP calibration for all layers
  - EM shower data taken with/without power pulsing
- Promising performance
  - All channels working: very uniform SiPM gain

Air stack for MIP calibration

Commissioning and response to electrons

Distribution of SiPM Gains of 1 HBU



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- Ongoing efforts
  - Performance w/wo power pulsing
  - SiPM: saturation correction, temperature compensation

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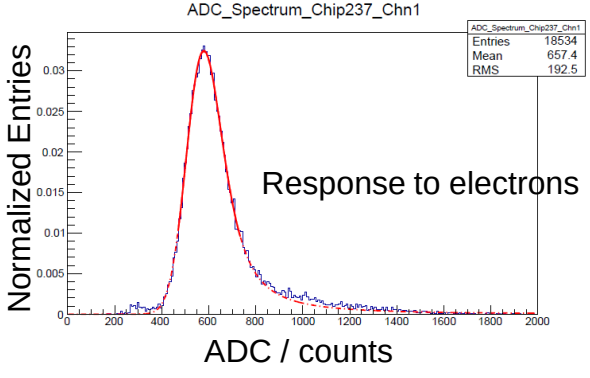

Air stack for MIP calibration

Commissioning and response to electrons

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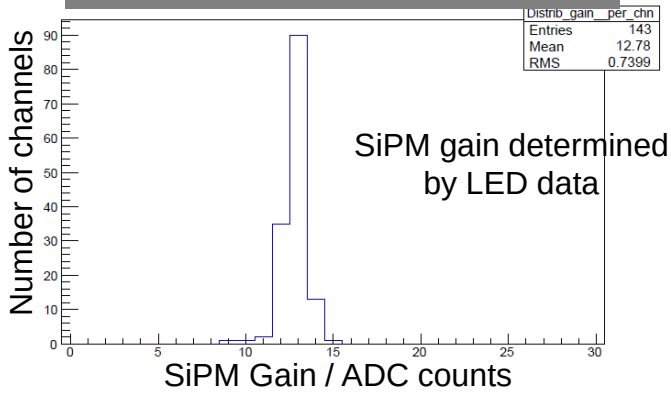

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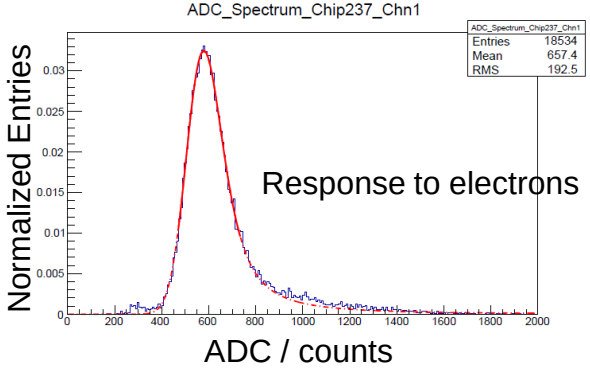
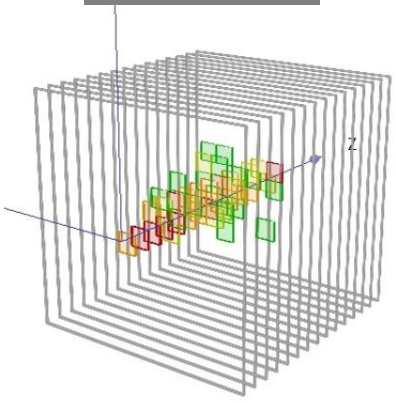
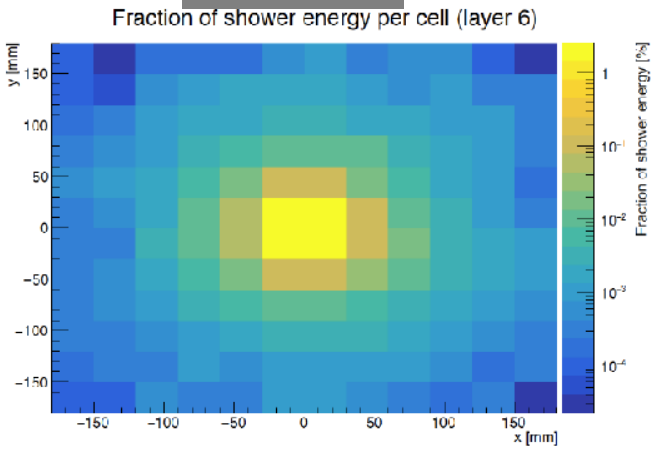


Air stack for MIP calibration

Event Display



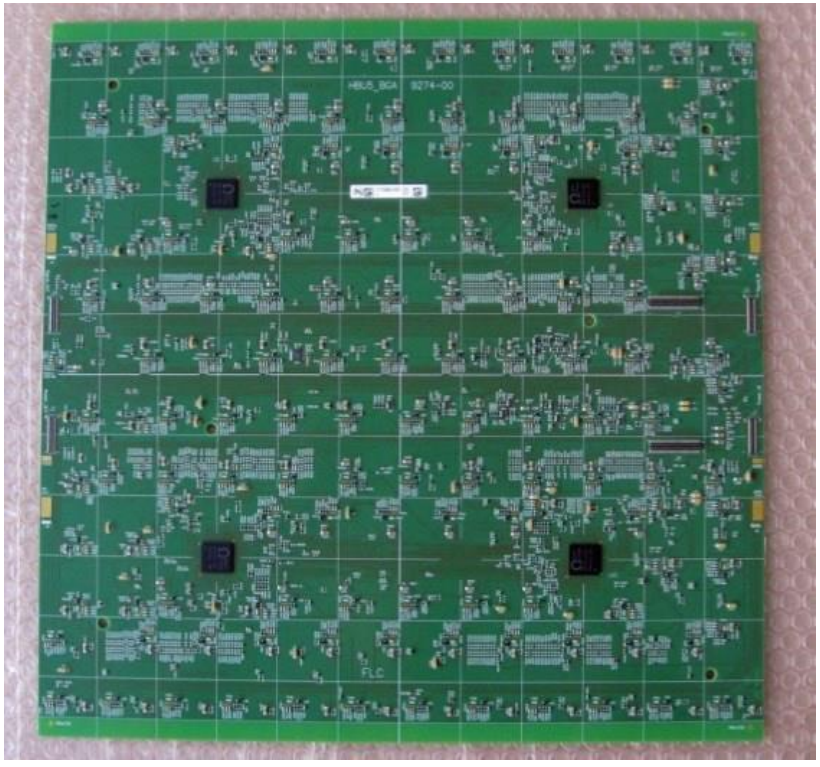
EM Showers



Steel stack for EM shower studies

New electronics

- New AHCAL readout boards (HBUs)
  - With updated ASIC chips (SPIROC2E) in new packages (BGA)



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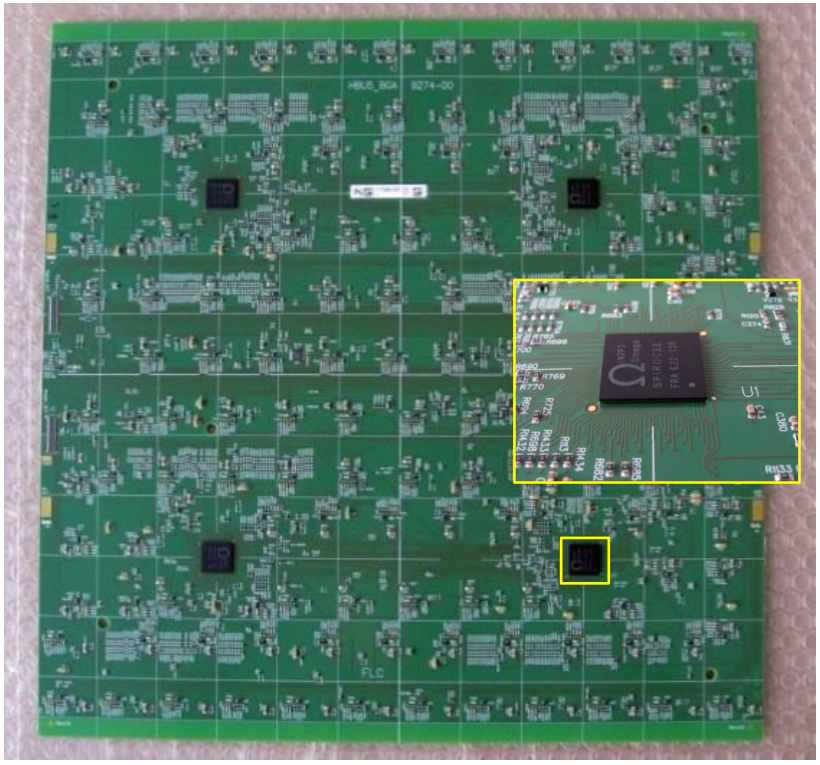

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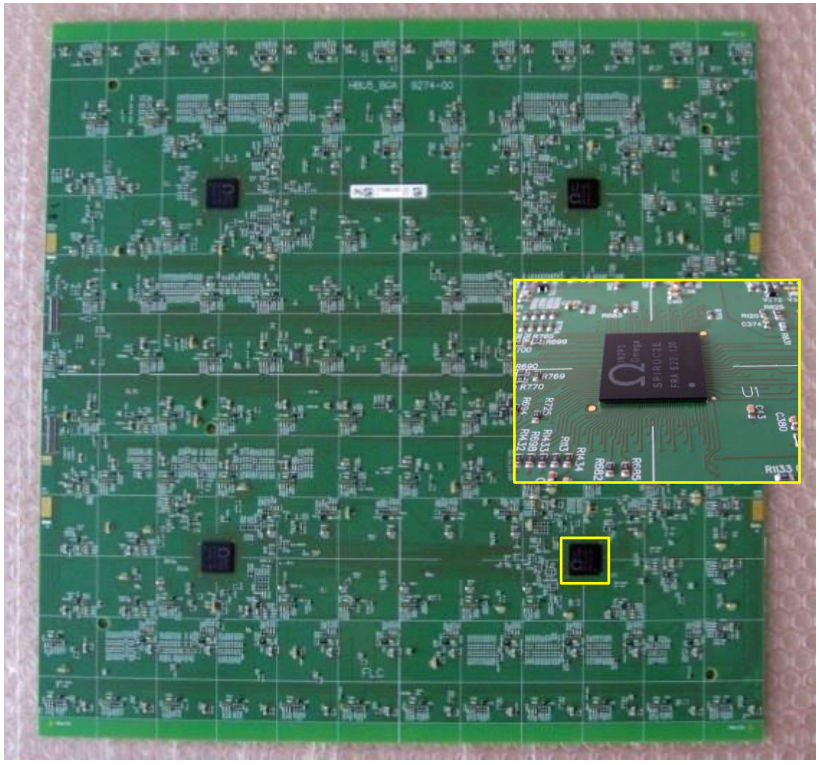
- New interface boards
  - Detector Interface (DIF) board: equipped with modern FPGA
  - Power board: reduced heat dissipation, optimized for power-pulsing, etc.



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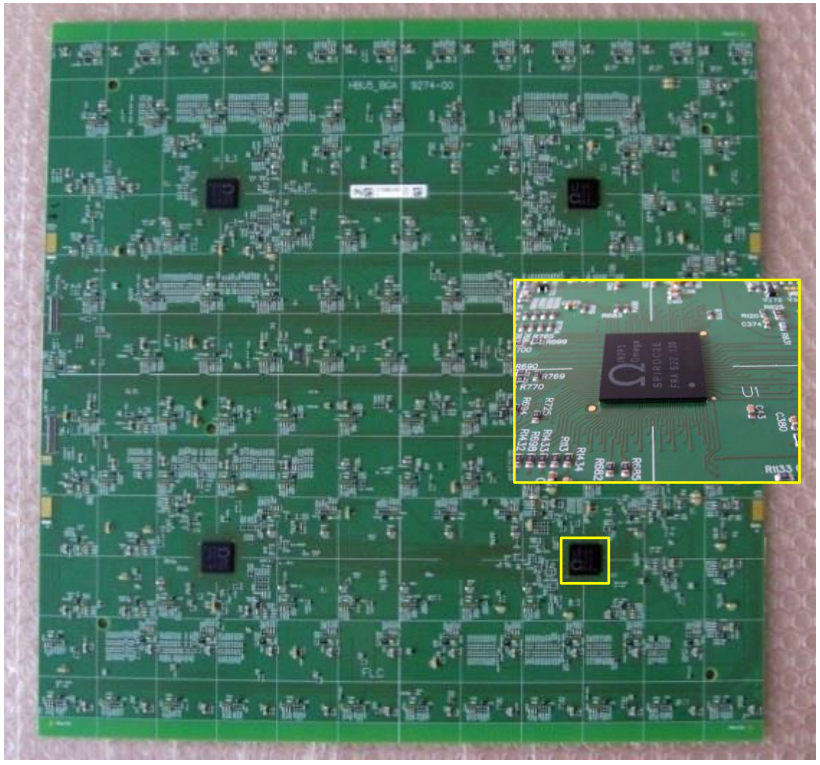

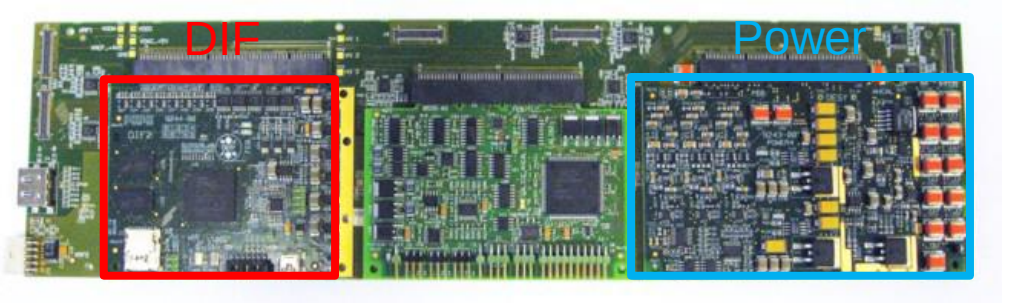

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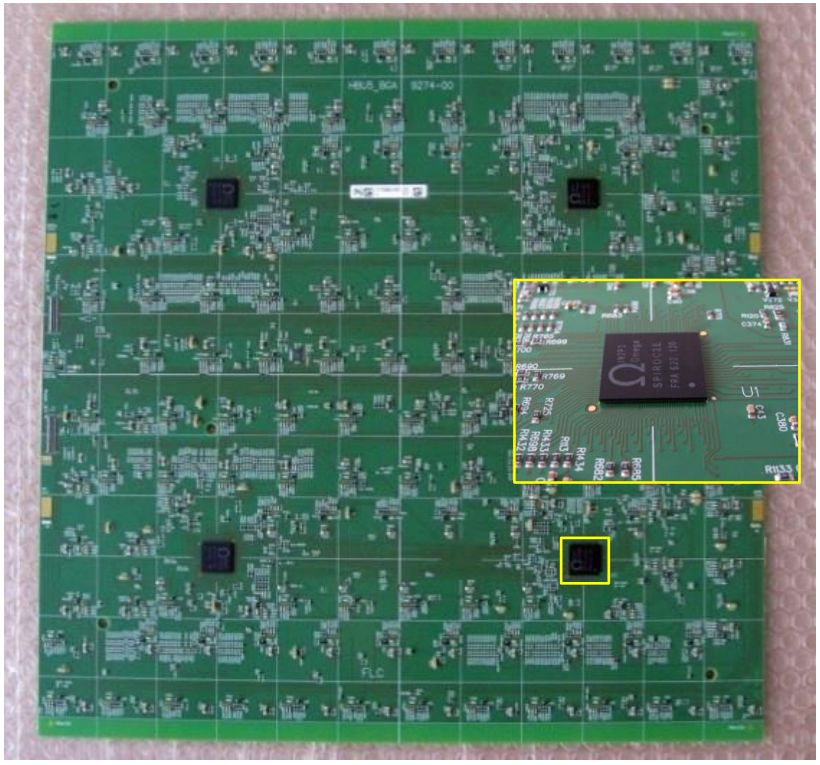
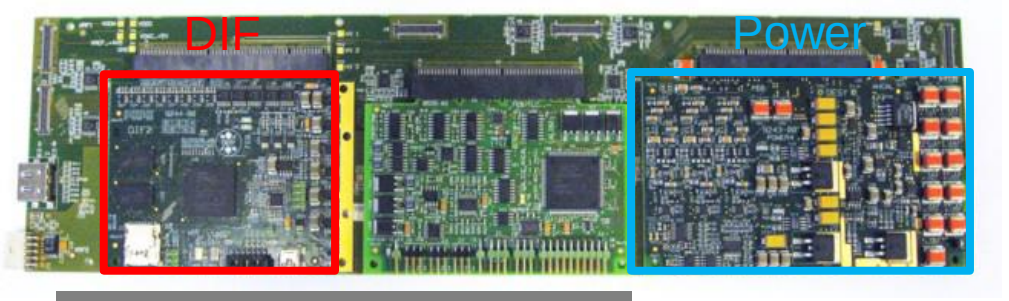
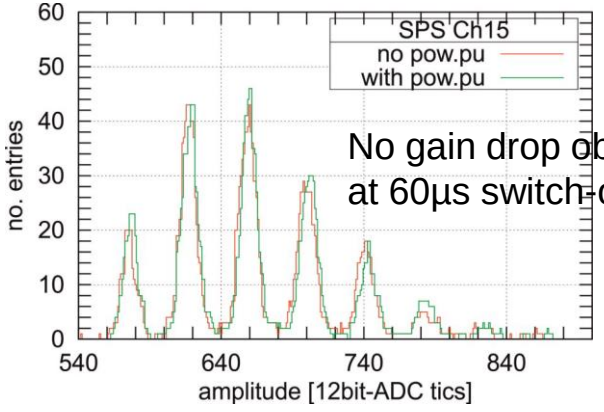




LED data w/wo power pulsing

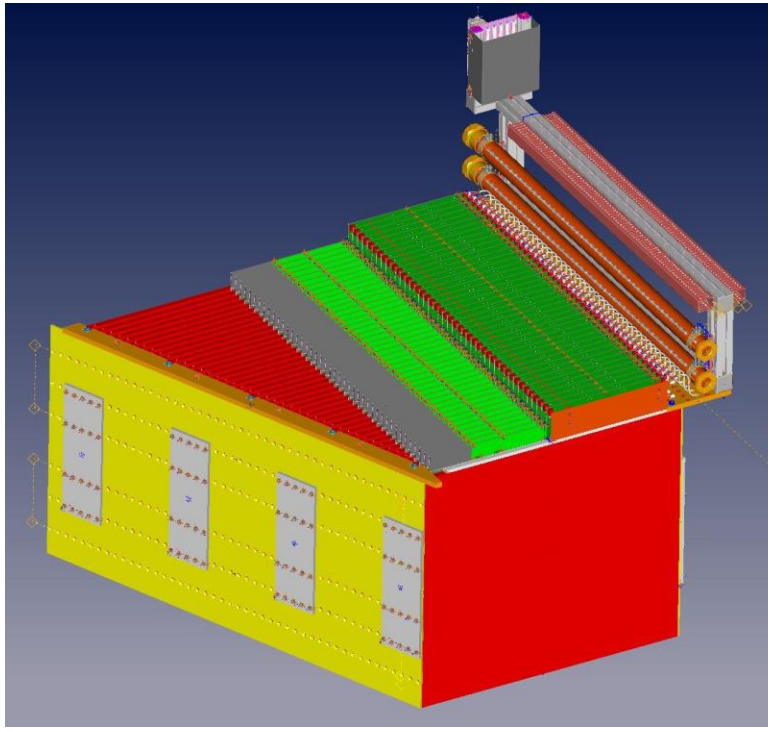


No gain drop observed at 60µs switch-on time

More tests ongoing for several HBUs connected (in a slab)

AHCAL technological prototype

- Goal: to instrument AHCAL technological prototype in a steel stack
  - Correspond to ~ 1% of barrel HCAL at ILC
  - Scalable to a full HCAL at ILC
  - 40 layers totally; 4 HBUs in each layer



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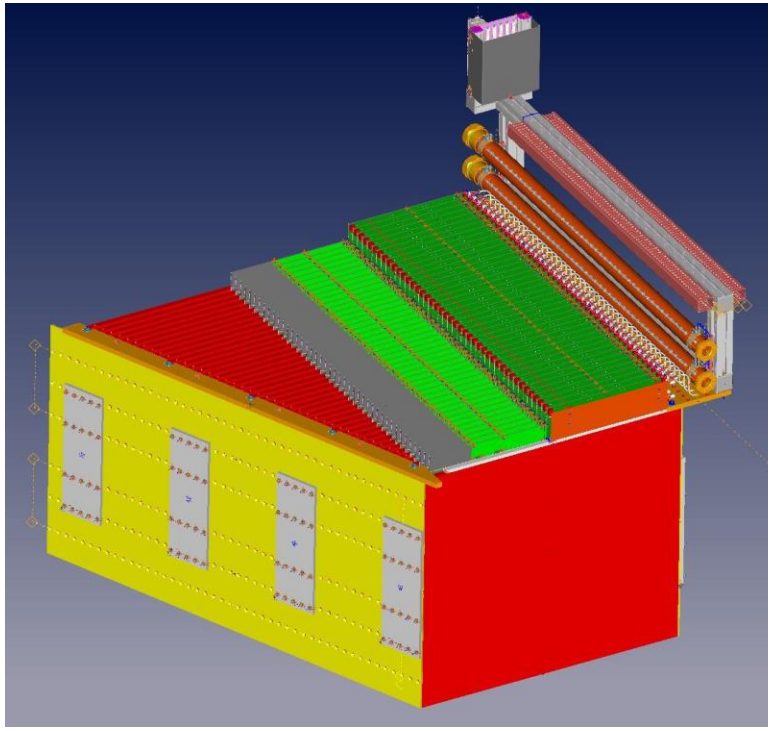

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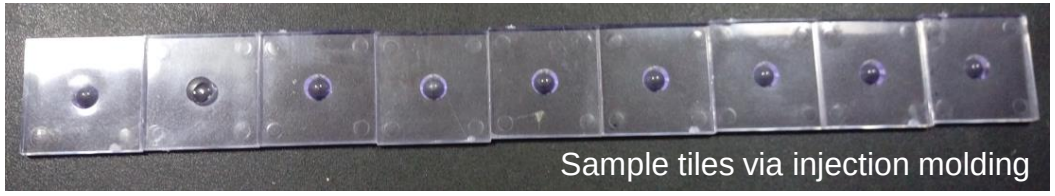
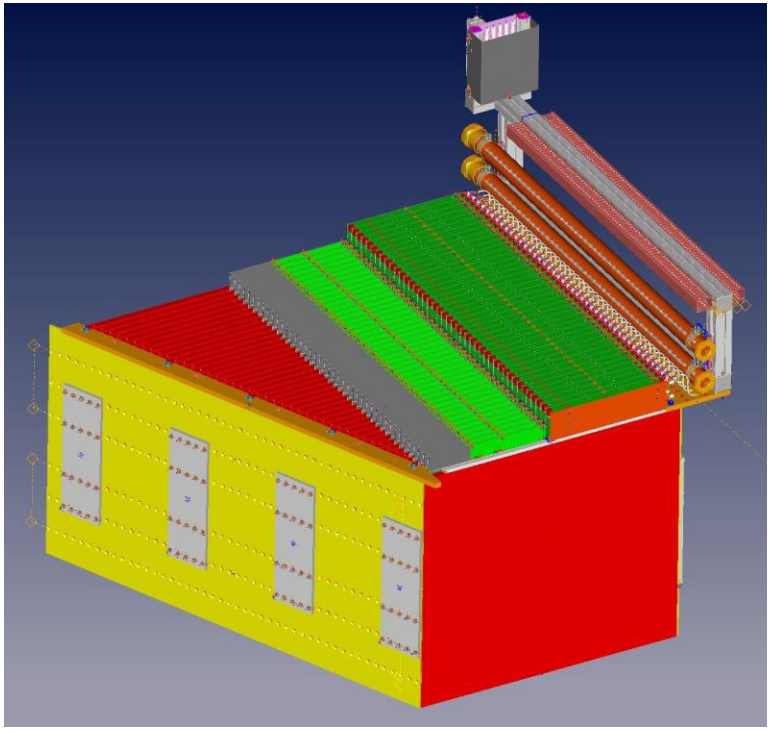

Sample tiles via injection molding



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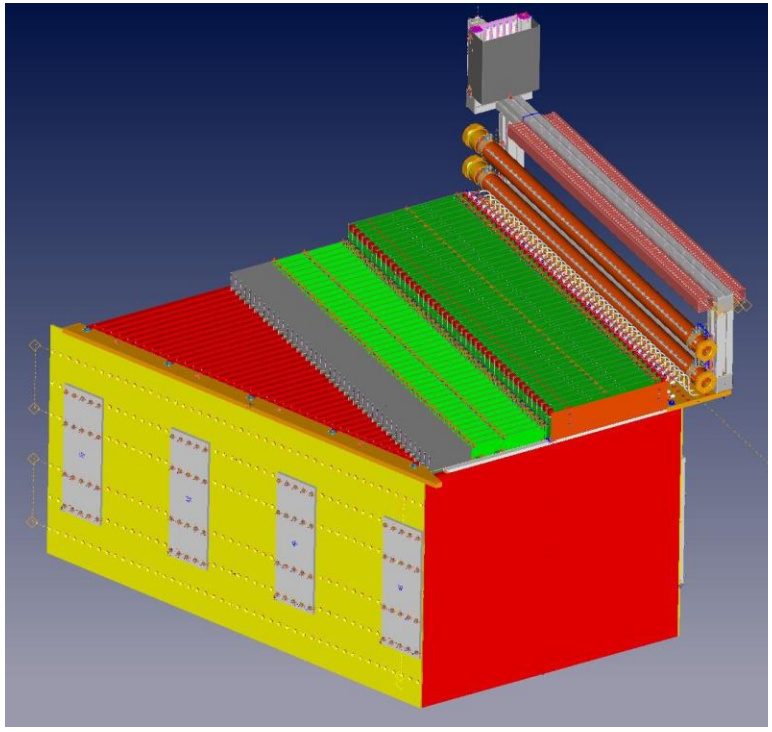

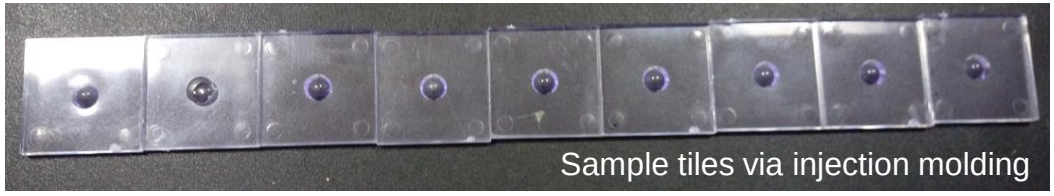

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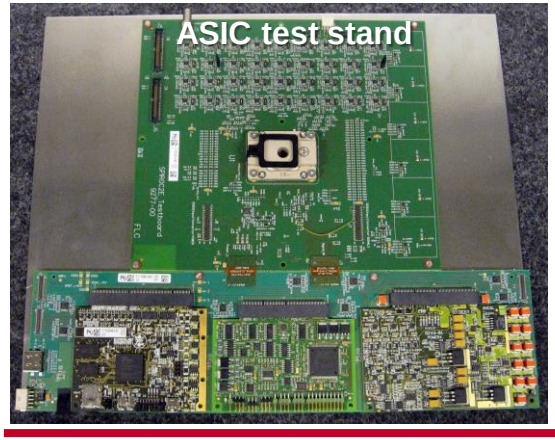

ASIC test stand

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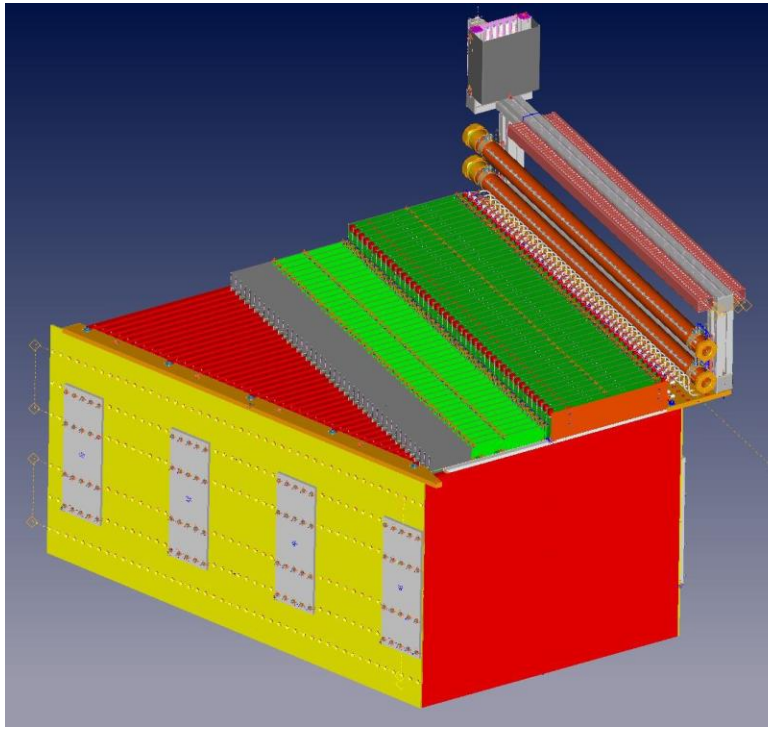
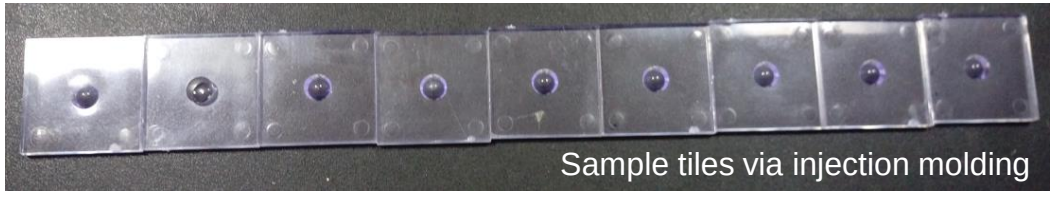
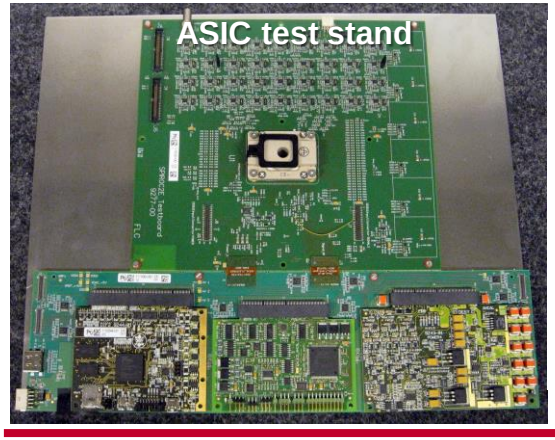
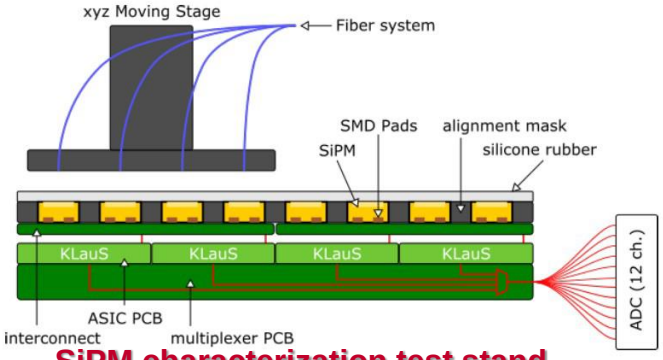



Sample tiles via injection molding





SiPM characterization test stand

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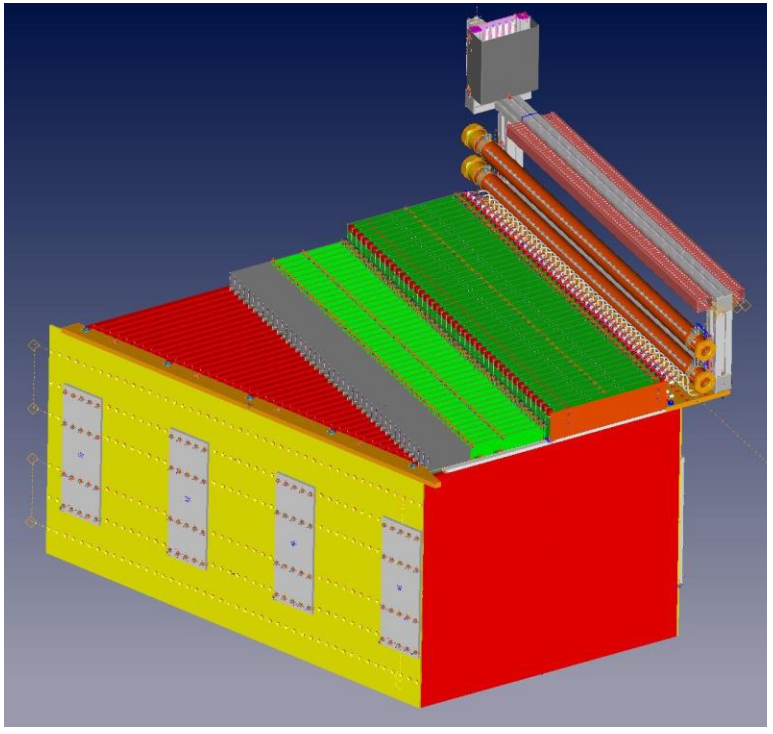

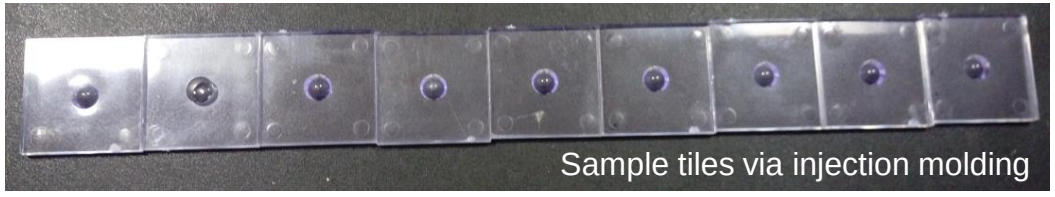

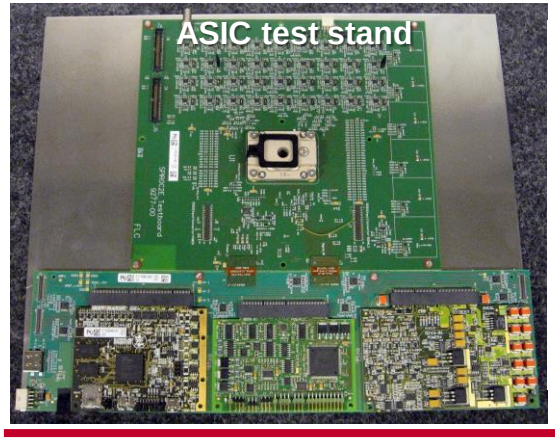

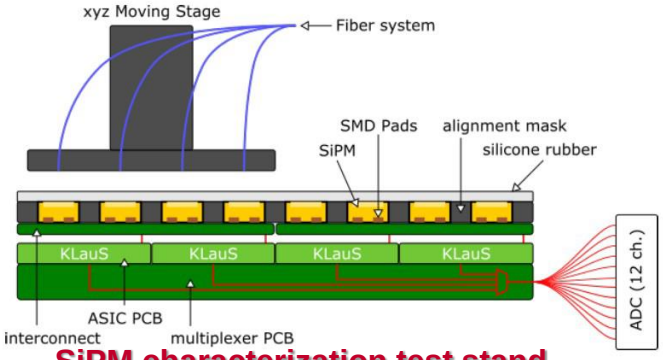

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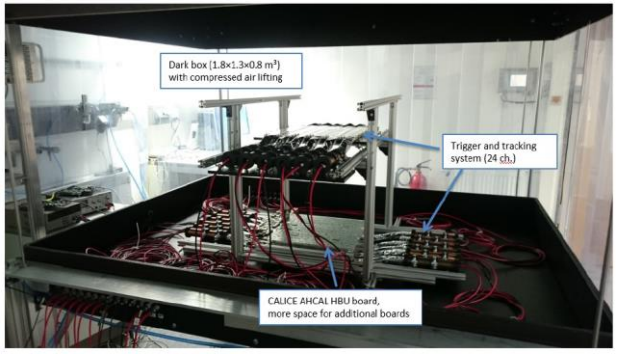

Cosmic-ray test stand for HBUs

Summary and outlook

- CALICE collaboration is developing high-granularity calorimeters based on Particle-Flow paradigm

- Scintillator-based hadron calorimeter (AHCAL)
  - AHCAL technological prototype is being built
  - Baseline design chosen, suitable for mass assembly
  - Promising performance in beam tests
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- 2017 and beyond
  - 160 boards (~23k SiPMs): scheduled to be built within 2017
  - Steady progress: mass assembly, electronics, DAQ, system integration, etc.
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  - Beam tests with hadrons in 2018

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Thank you!

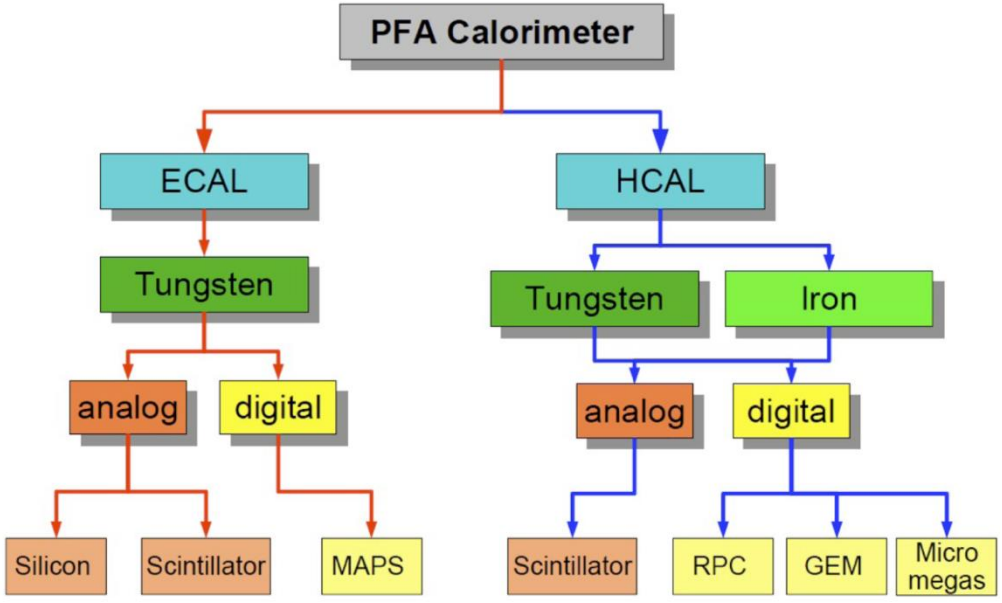
Backup

The CALICE collaboration

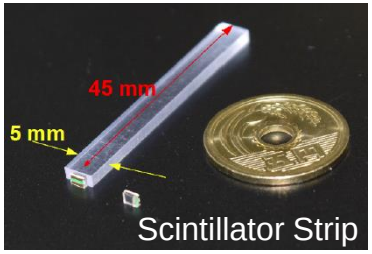
- CALICE collaboration today
  - 55 institutes in 19 countries (4 continents)
  - ~ 350 members

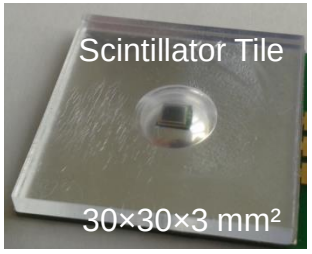
https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

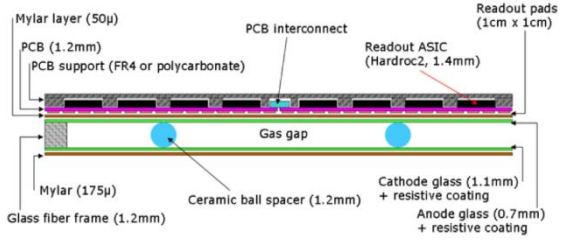
- Goal
  - Research and development of highly granular calorimeters for future lepton colliders
- Technologies
  - A rich program exploring full spectrum of imaging calorimeter technologies



A few examples in the technology tree

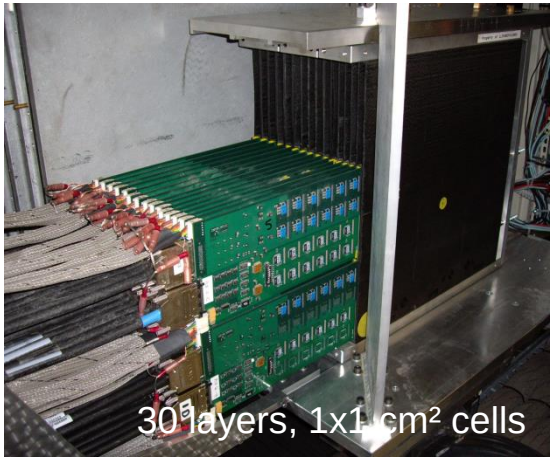




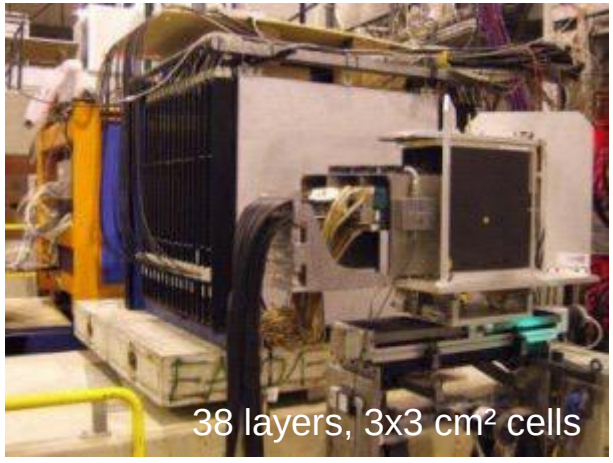


The CALICE physics prototypes

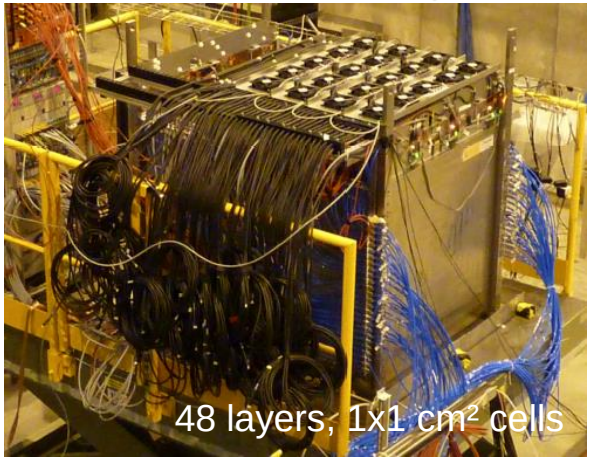
Si-W ECAL



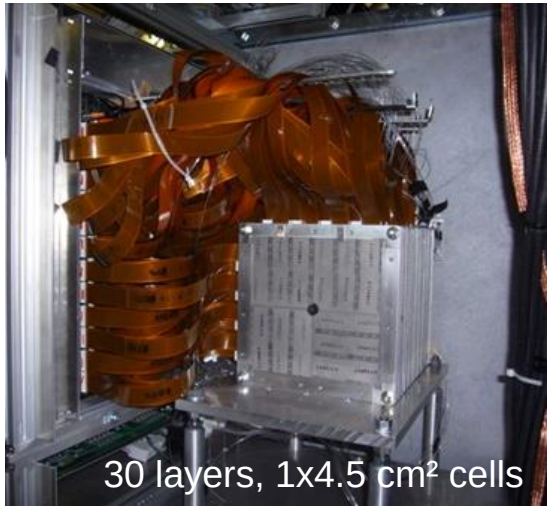
Sc-AHCAL, Fe&W



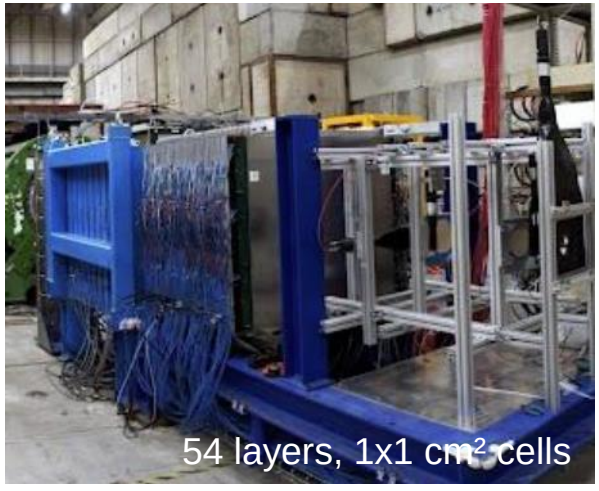
GRPC-SDHCAL, Fe



Sc-W ECAL



RPC-DHCAL, Fe&W



- Various beam tests
- Detector concepts validated with physics prototypes
- Large data sets for precision shower studies

Calorimeter granularity optimization

- Jet energy resolution versus the number of HCAL cells
  - Towards cost optimization
  - 3×3 cm² cell size is still a very reasonable choice: 8M cells