Development of a High-Granularity Calorimeter

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IHEP, Beijing

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
PRISMA DETECTOR LAB
CALICE
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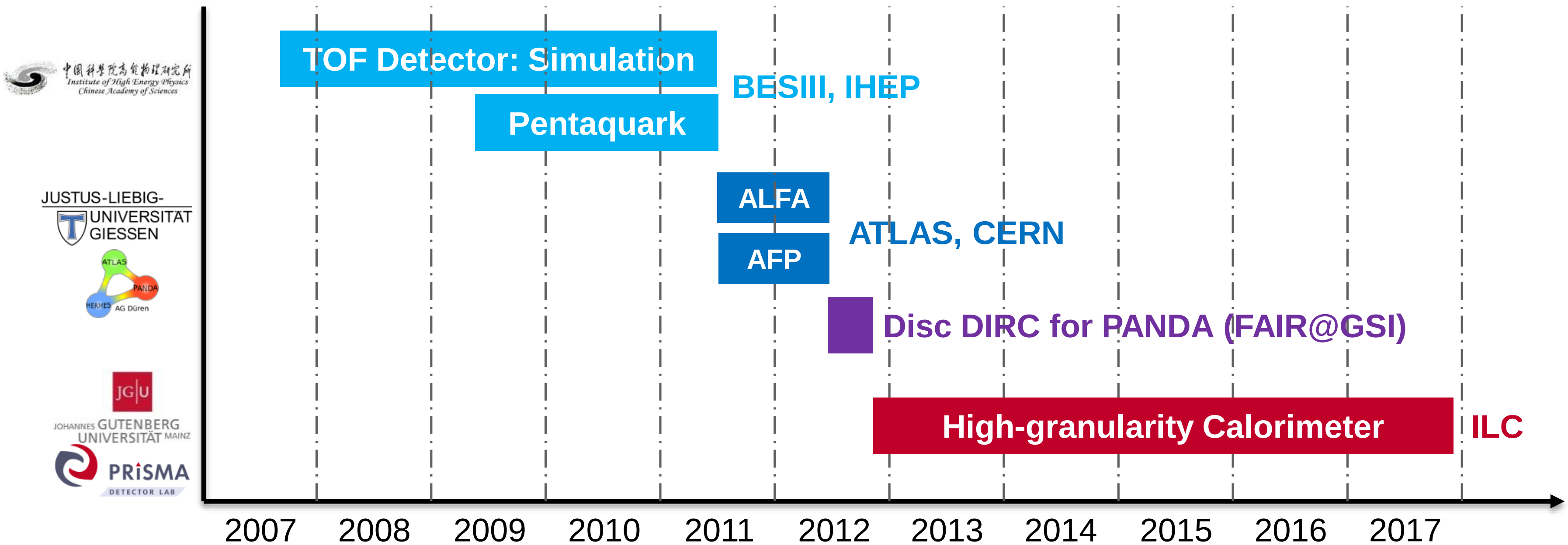
My world line

- Education and academic positions
  - 2002.9 - 2006.7: Wuhan University, Physics, Bachelor
  - 2006.9 - 2011.7: Institute of High-Energy Physics, CAS, Ph.D.
  - 2011.8 - 2012.11: University of Gießen, Germany, Postdoc
  - 2012.11 - now: University of Mainz, Germany, Postdoc
- Research experiences

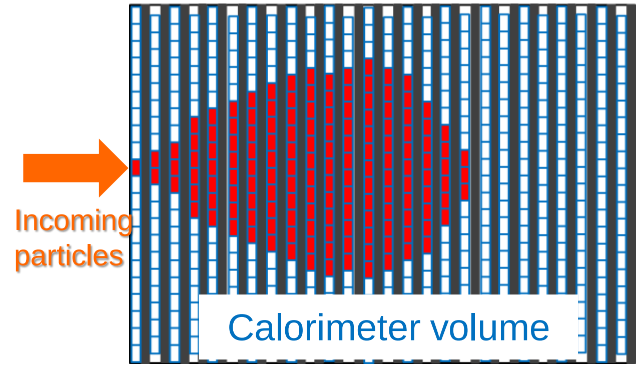


Outline

- Calorimeter in a nutshell
  - Why high granularity?
- Prototypes of a high-granularity hadronic calorimeter
  - Based on SiPM and scintillator tiles
  - Tile-on-SiPM design
  - Readout boards assembly, system integration
  - Beam test campaigns
- Ongoing and further R&D efforts
- Summary

Calorimeter: in a nutshell

- Calorimeter
  - For energy measurement of incident particles
    - Mostly also positions of energy depositions
  - Principles
    - Showers initiated by incident particle
    - Energy depositions in various forms
      - Ionization, atom excitation, Cherenkov light…
    - Signal ~ total deposited energy



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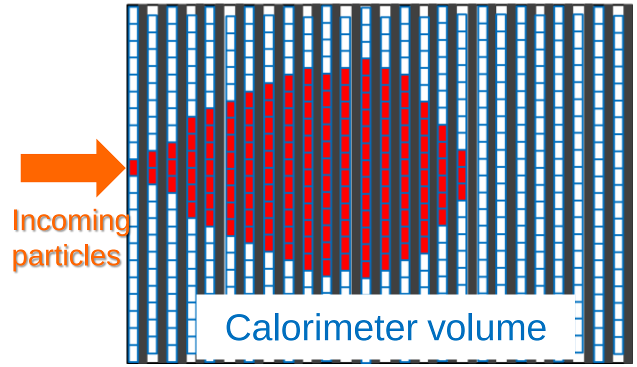

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- Categorized by structures
  - Homogeneous calorimeters
    - One material (high-density)
    - Same for both absorber and active medium
  - Sampling calorimeters
    - Absorber: only constrain shower (passive)
      - Typical material: Fe, Pb, U, …
    - Sensitive elements (that generate signals)
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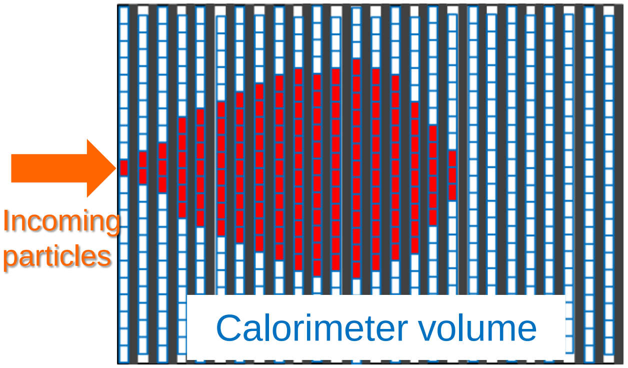

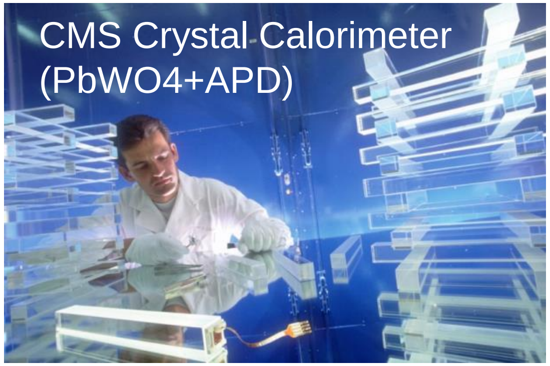

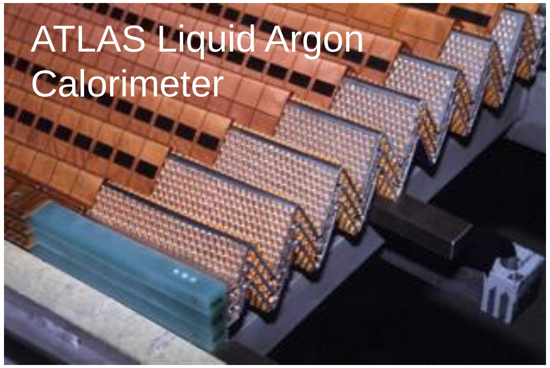

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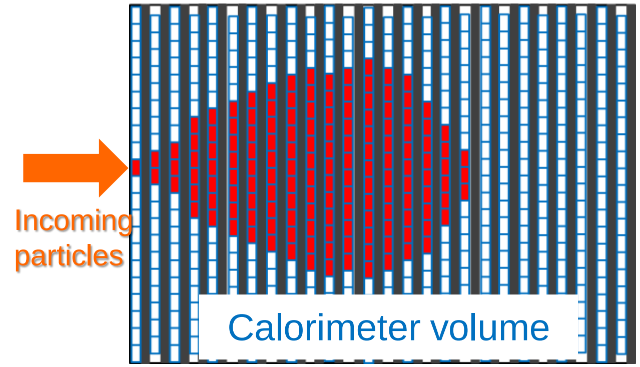

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  - For electromagnetic (EM) showers
    - Gammas, electrons, positrons
  - For hadronic showers
    - Protons, neutrons, pions, kaons
    - EM component: compact (e.g. $\pi^0 \rightarrow \gamma\gamma$)
    - Hadronic component: sparse (more depth)
      - undetectable energy: nuclear binding, ν's
      - $e/h > 1$ (compensation necessary)
      - f_{EM} fluctuations

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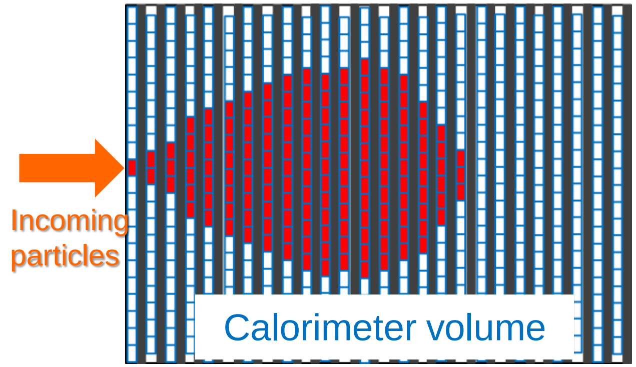
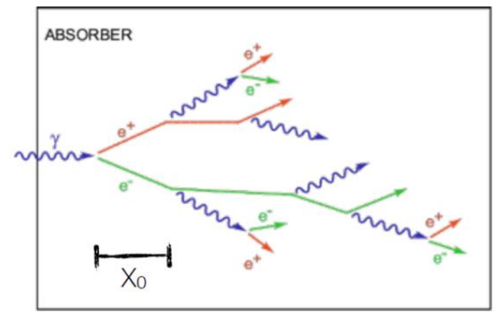
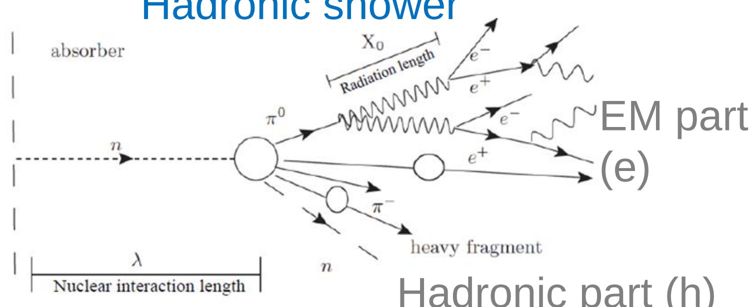


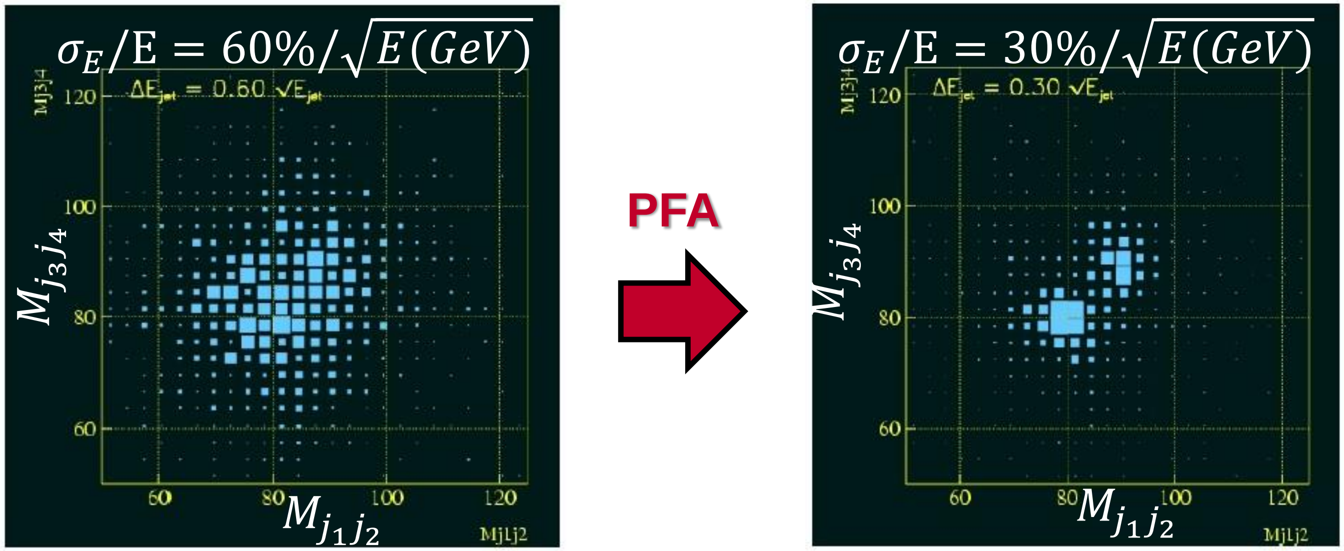
EM shower



Hadronic shower



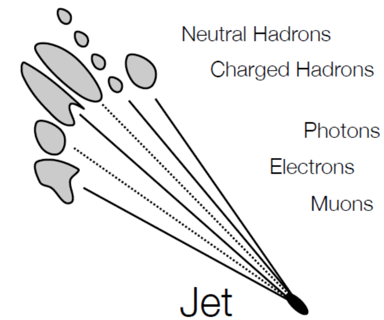
Precision physics and calorimetry



$ee \to ZHH$

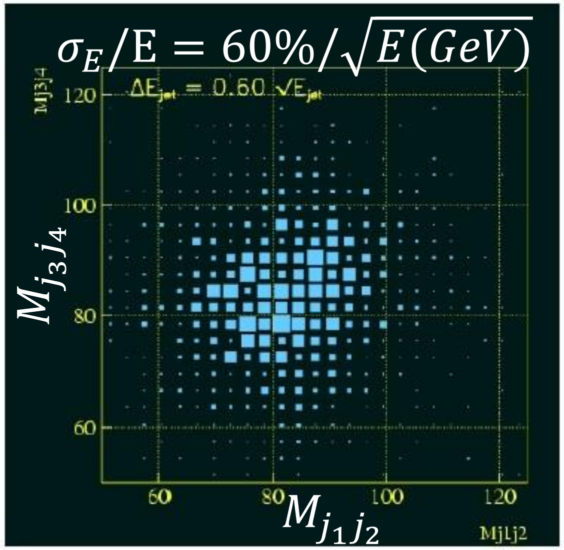
$ee \to \nu\nu WW \to \nu\nu qq$

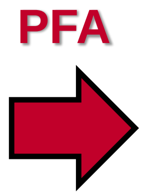
$ee \to \nu\nu ZZ \to \nu\nu qq$

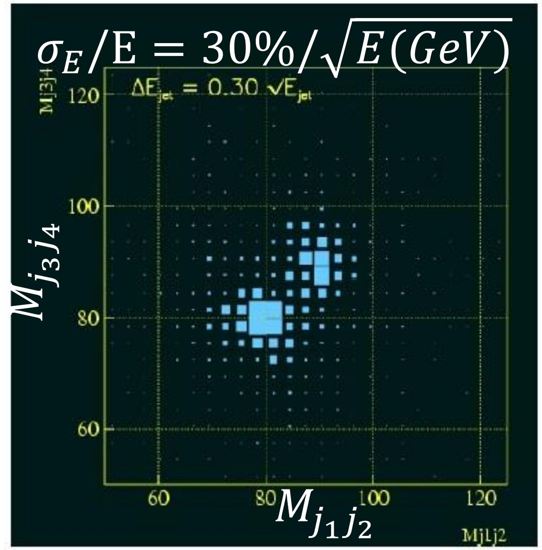


- Precision measurements at future collider experiments
  - CEPC, CLIC, FCC-ee, ILC, etc.
  - Higgs properties, rare decays in Standard Model, searches for new particles
  - Categorized by multi-jet states and small cross-sections
  - Jet energy resolution directly influences precision measurements

Precision physics and calorimetry







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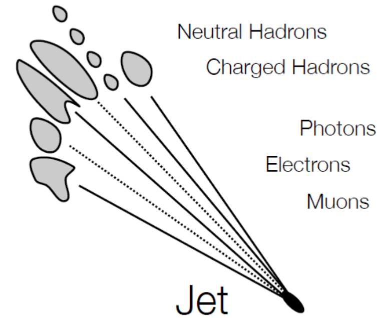

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  - Jet energy resolution directly influences precision measurements
- High-granularity (imaging) calorimeters based on particle-flow algorithm
  - Limited intrinsic energy resolution of hadronic calorimeter (HCAL)
  - Reduce the role of HCAL for hadrons

Particle-flow algorithm

Components in jets	**Detector**	**Energy Fraction**	**Energy Resolution**
charged particles ($X^{\pm}$)	Tracker	$60\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$30\%\ E_j$	$0.15\sqrt{E_\gamma}$
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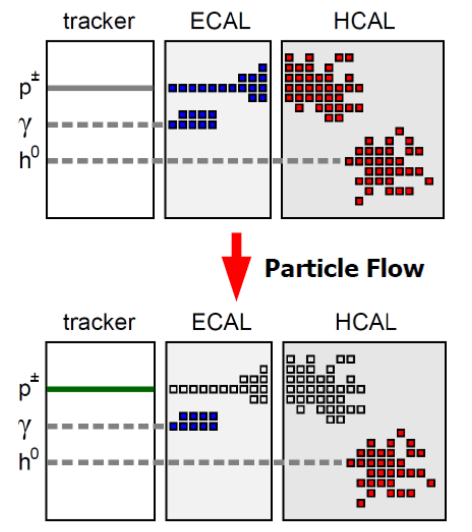

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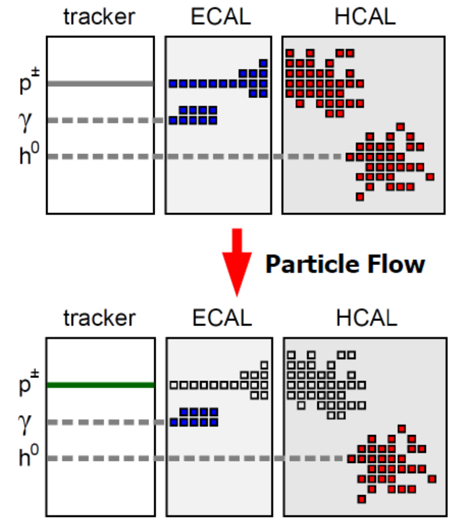

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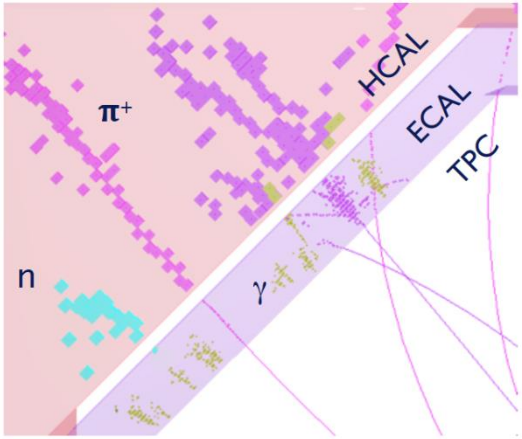
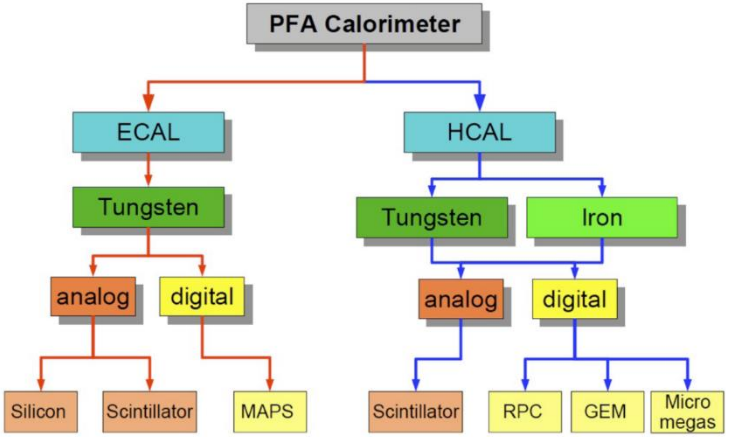
- Imaging calorimeter
  - Calorimeter hardware: highly granular (explosion of total channel number)

High-granularity calorimeters





- Crucial for particle-flow algorithm (PFA)
  - Typical jet energy: 50-250 GeV
- Technologies developed within CALICE
  - Sensitive: silicon, gas, scintillator
  - Absorber: stainless steel, tungsten

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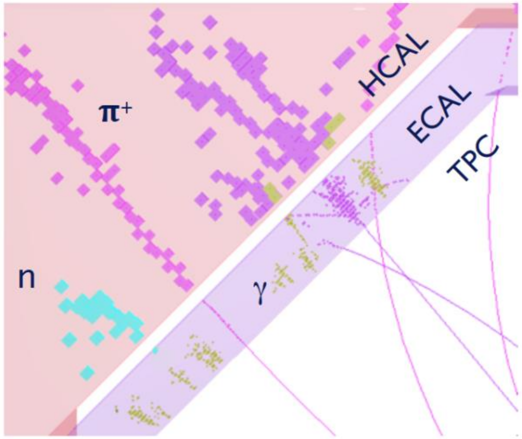

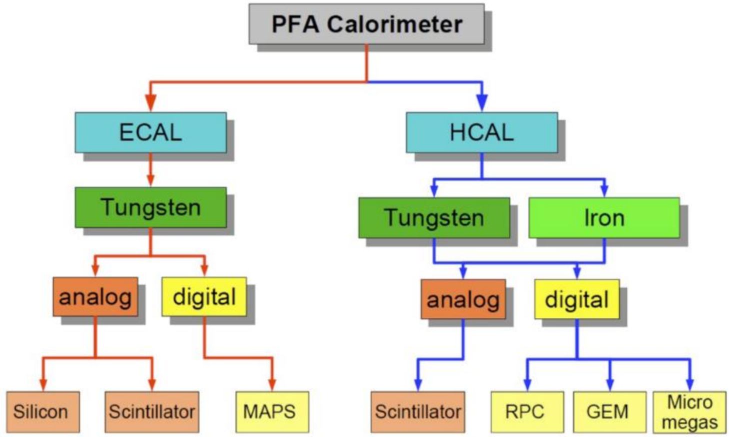

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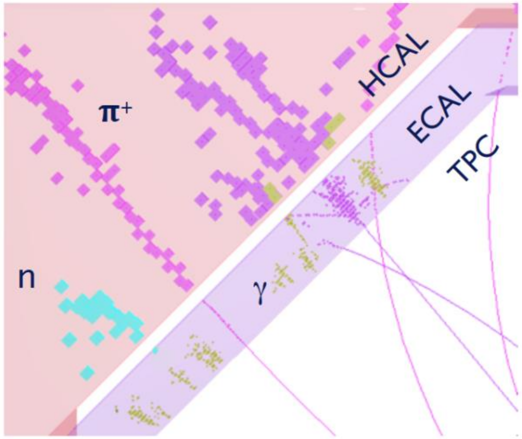

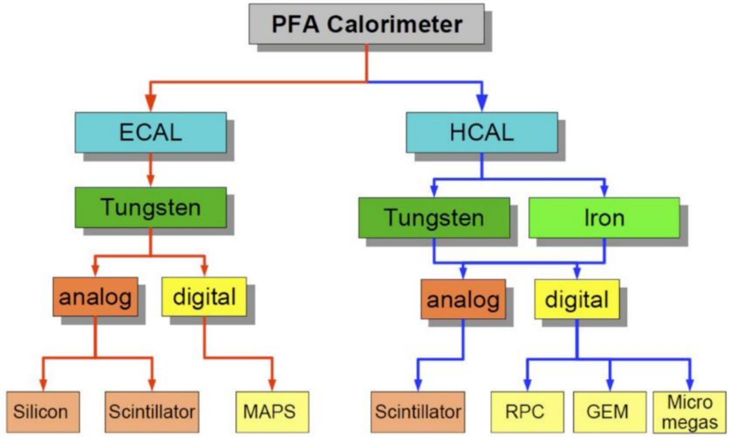

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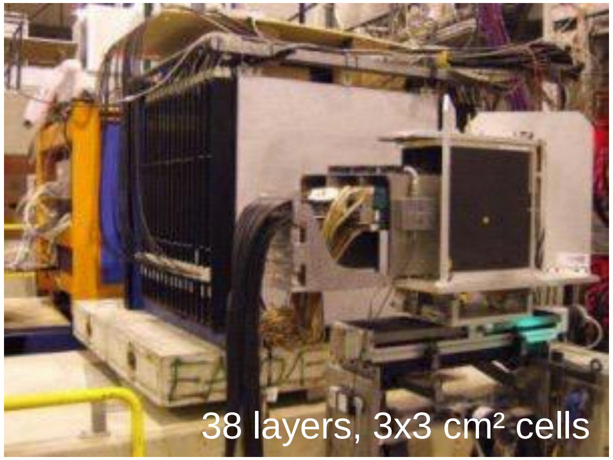
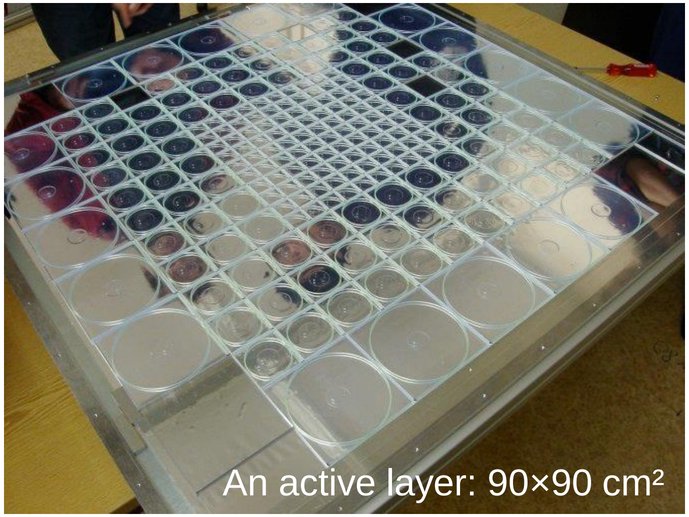


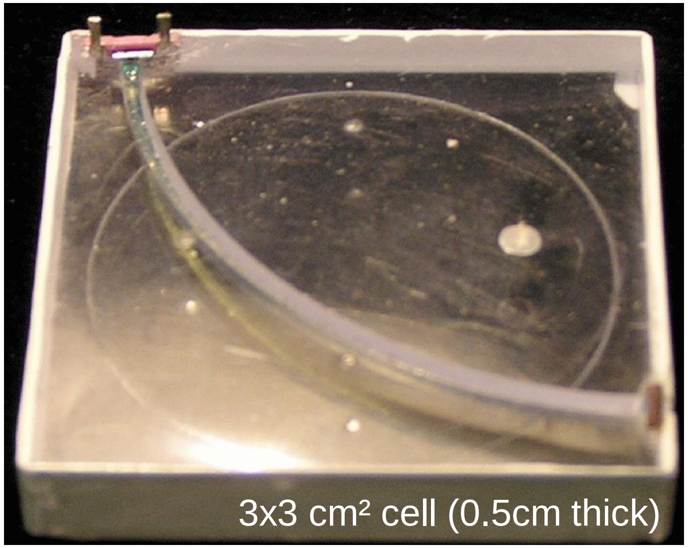
Physics prototype of Sc-HCAL with Fe/W

Analogue HCAL: physics prototype

- Sensitive layers
  - Scintillator tiles
  - Silicon Photomultipliers (SiPMs)
  - Light collection via WLS fiber
  - Higher granularity in the layer center



An active layer: 90×90 cm²



3x3 cm² cell (0.5cm thick)

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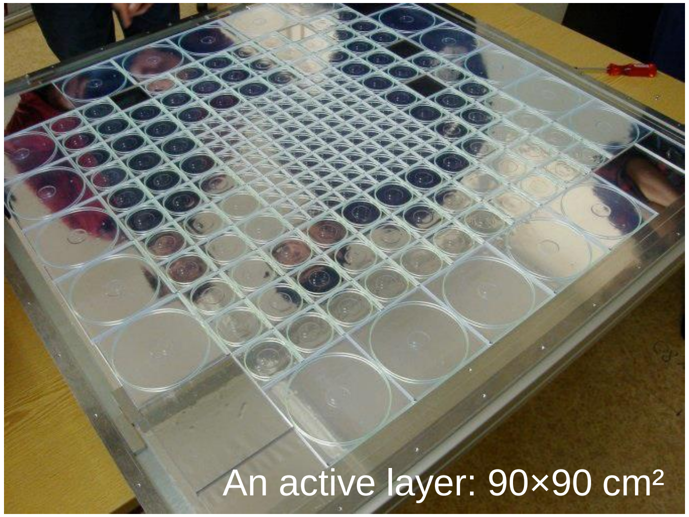
- Absorber structures
  - Steel: 38 layers (4.5λ)
  - Tungsten: 38 layers (4.9λ)

- In total ~ 8000 channels
  - Built in 2006
  - Taken data till 2011 (11 papers)
    - Beam tests at CERN and FNAL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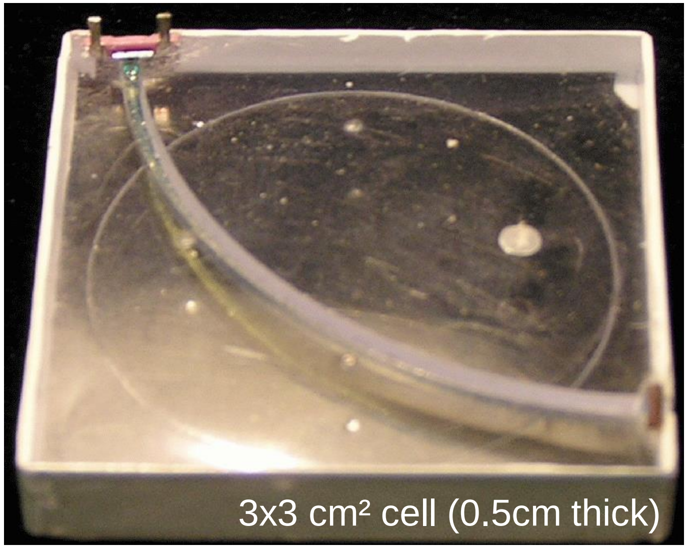
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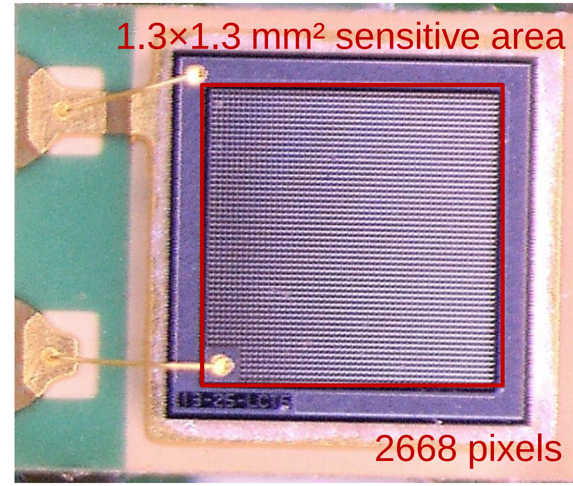
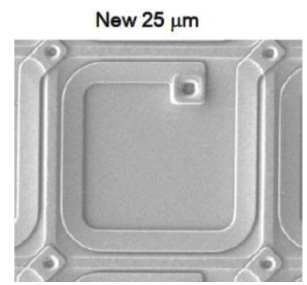
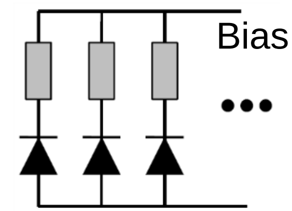
SiPM: in a nutshell

- Photon detector
  - Matrix of avalanche photo-diodes (APDs)
  - Operated in Geiger Mode
    - Reversely biased voltage (<100 V)
      - Above breakdown voltage
    - Large avalanche current
    - High gain: typically $o(10^6)$
    - Able to detect single photons
  - Sensitive to $o(100)$-nm photons
    - Plastic scintillator: typically 350-520 nm







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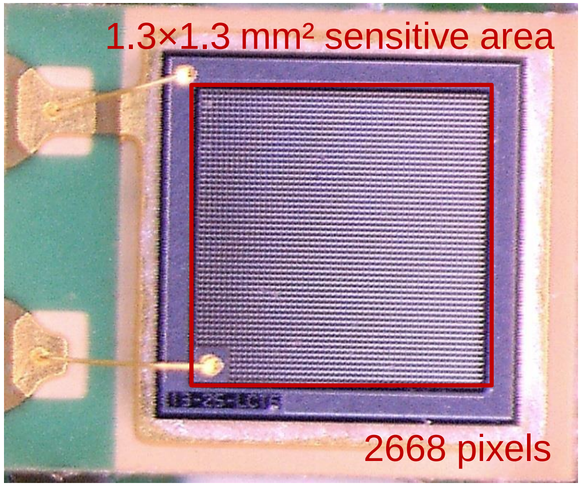

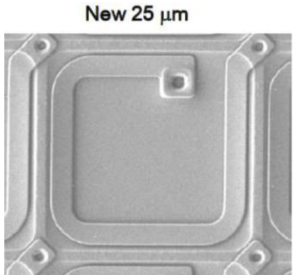

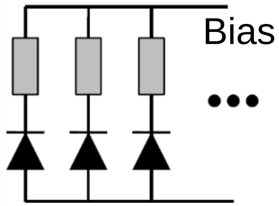

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  - Intrinsic binary counter
  - Usually analogue readout in electronics
    - Current, or voltage, or integrated charge

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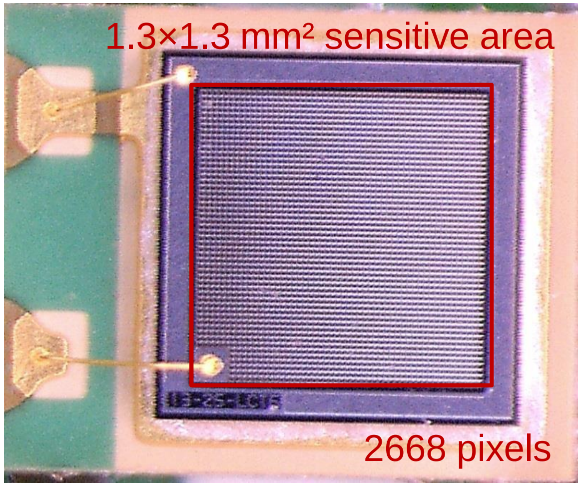
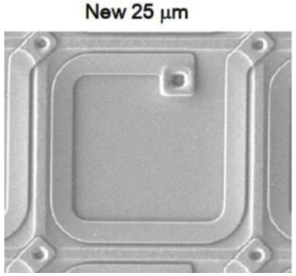
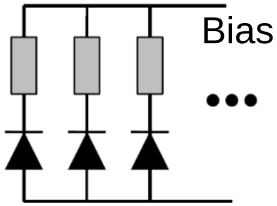
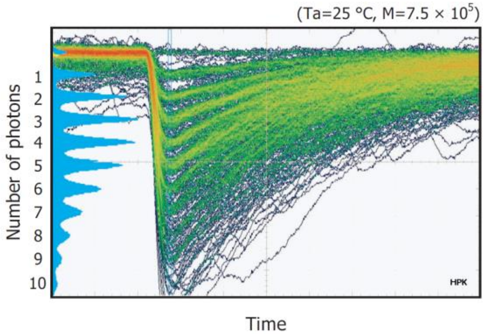


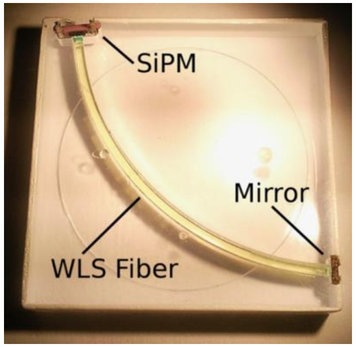


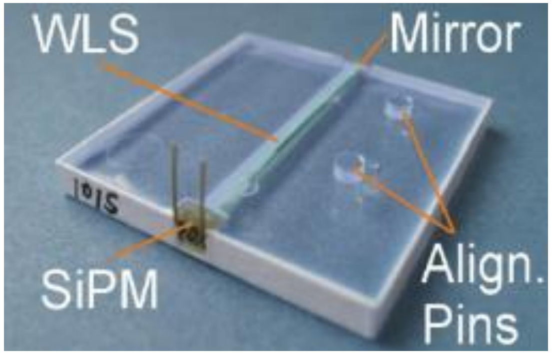




Tile-SiPM design

SiPM detects light
via WLS fiber





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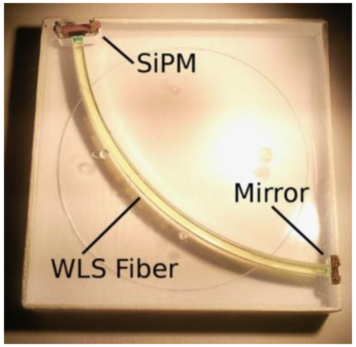
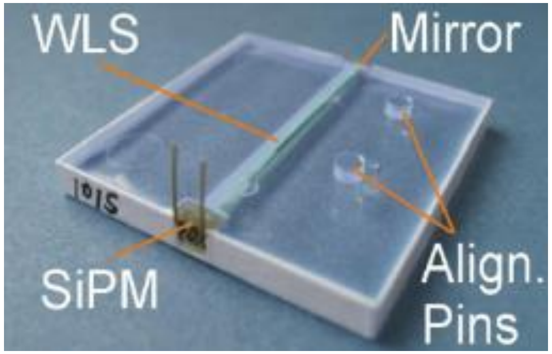
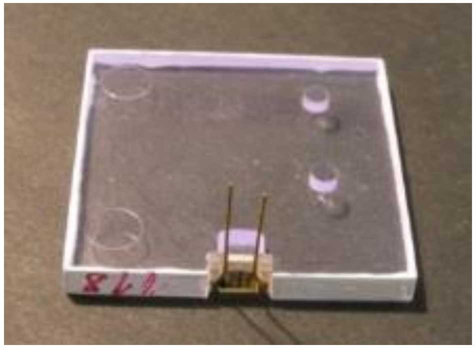
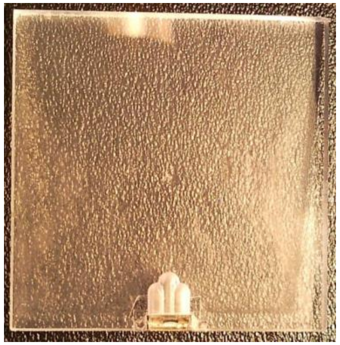
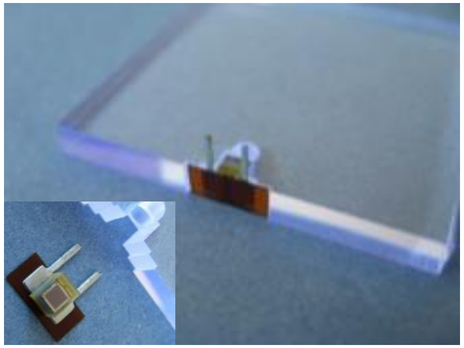




SiPM directly collects
light from tile (wo fiber)

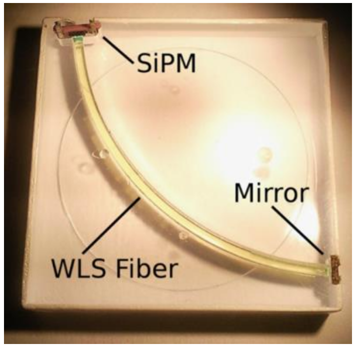


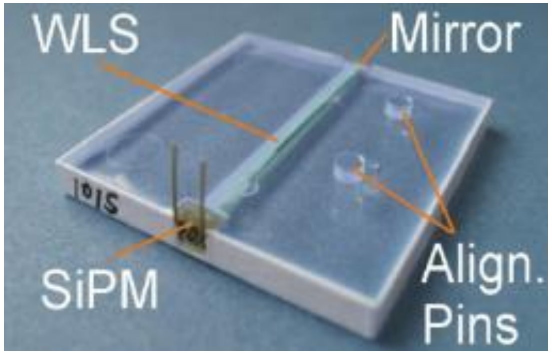




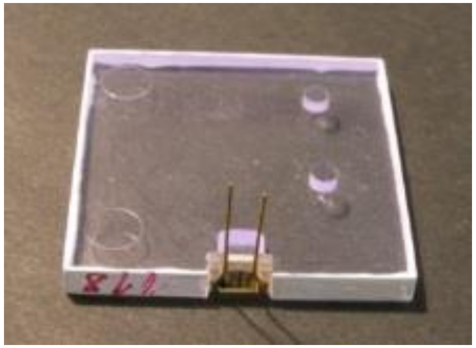
Tile-SiPM design

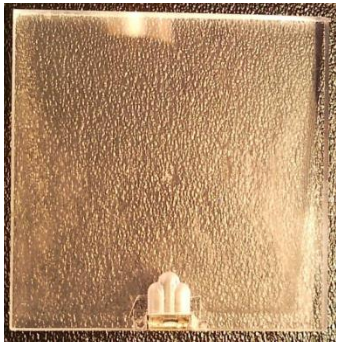
SiPM detects light via WLS fiber

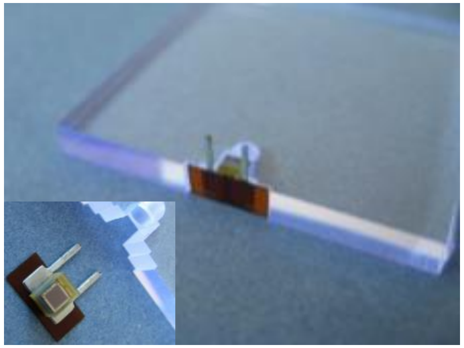




SiPM directly collects light from tile (wo fiber)

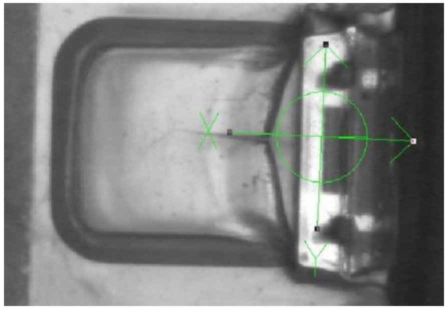






First glue SiPM to tile,
then solder SiPM onto PCB

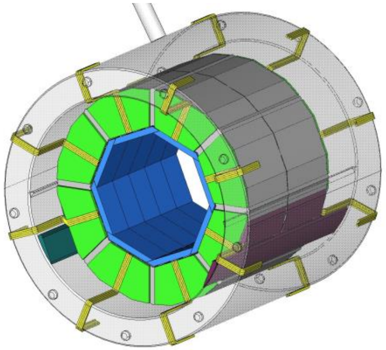
Feasible via manual handling, but not suitable for <u>mass assembly</u>

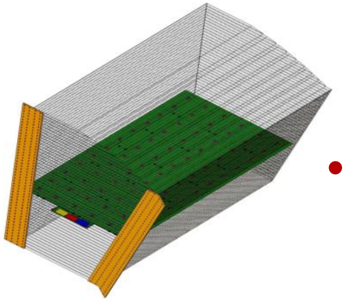


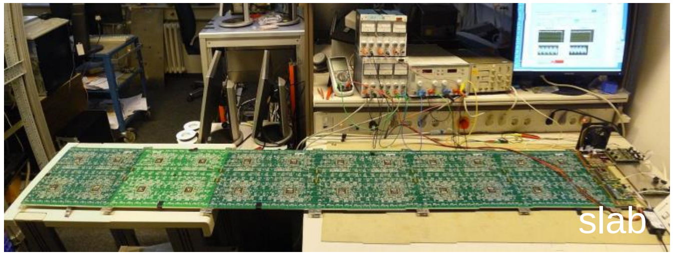
Scintillator partially (near SiPM) melted during soldering, due to heat transfer via soldering pads

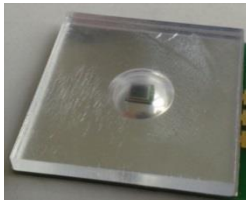
Why mass assembly?

- AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200,000 ASICs
- 8,000,000 SiPMs + tiles





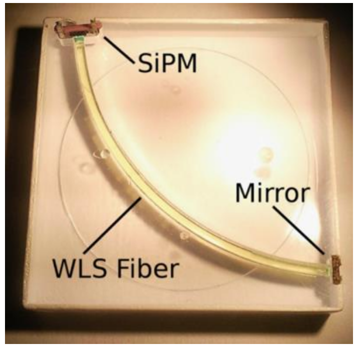


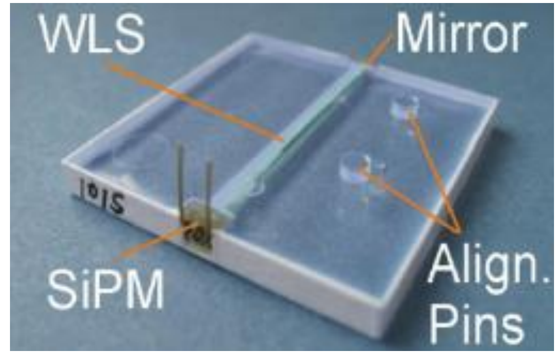


- 1 year
- 46 weeks
- 230 days
- 2,000 hours
- 120,000 minutes
- 7,200,000 seconds

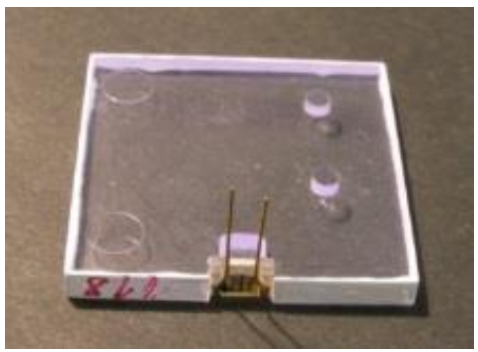
Tile-SiPM design: evolution

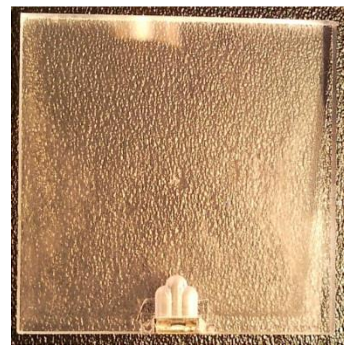
SiPM detects light via WLS fiber

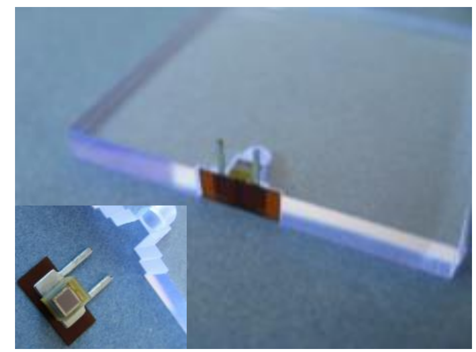




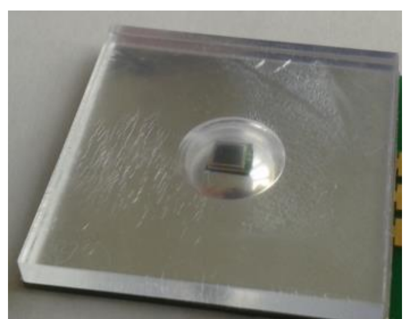
SiPM directly collects light from tile (wo fiber)





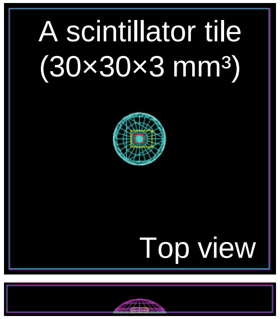


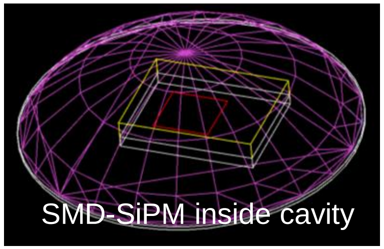
New tile-on-SiPM design suitable for mass assembly

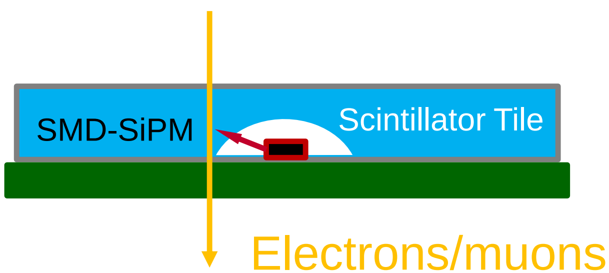


SMD-SiPMs first soldered as the other SMD components, then tiles placed on top of SiPMs

Tile-SiPM design: evolution

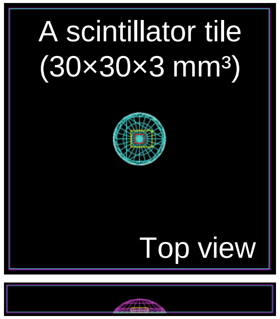


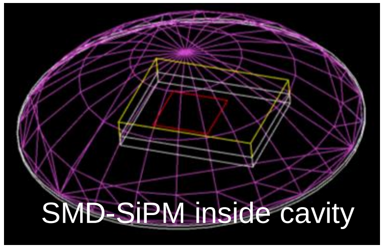


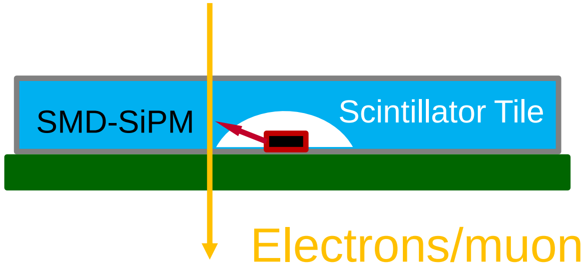


- Prototyping guided by simulation
  - How to couple SiPM to scintillator tile?
  - Vary cavity shapes, sizes, surface properties…
- Simulation based on Geant4
  - All (related) physics processes
  - Detailed geometry descriptions
  - Wavelength-dependent parameters

Tile-SiPM design: evolution







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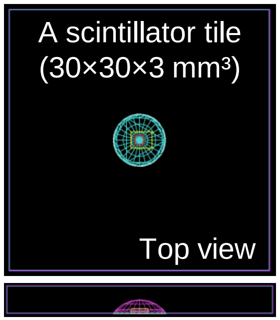
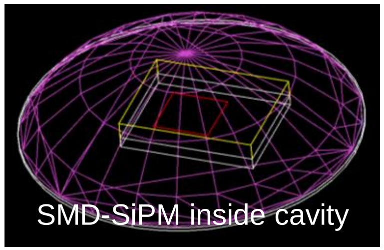
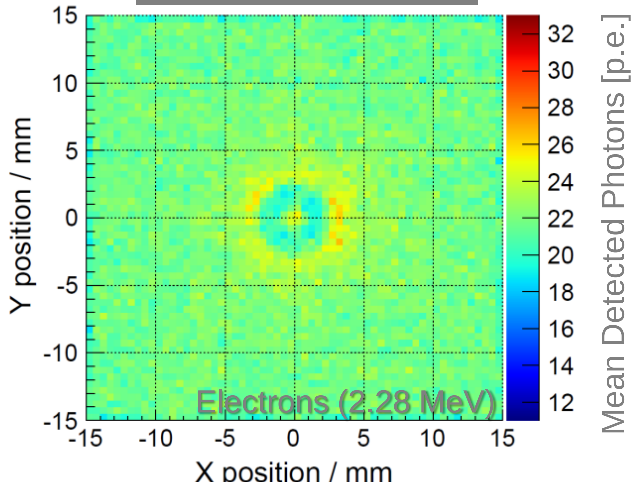
  - How to couple SiPM to scintillator tile?
  - Vary cavity shapes, sizes, surface properties…
- Simulation based on Geant4
  - All (related) physics processes
  - Detailed geometry descriptions
  - Wavelength-dependent parameters
- Aims
  - High efficiency for light collection
  - Good response uniformity across tile area
- Final tile design
  - A cavity to contain the whole SiPM package
  - Simple geometry: easy to produce and polish

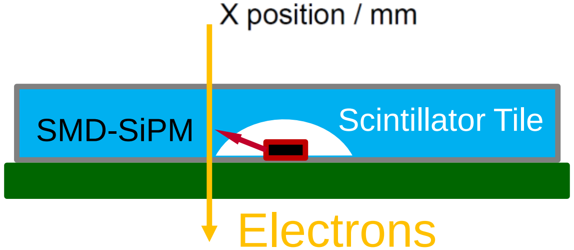
Tile-SiPM design: evolution



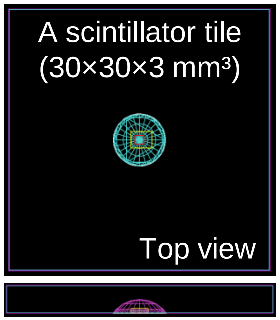


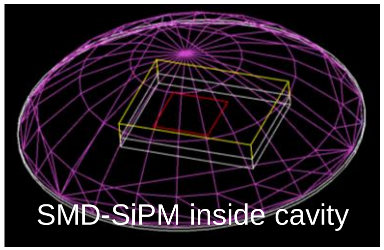
Geant4 simulation

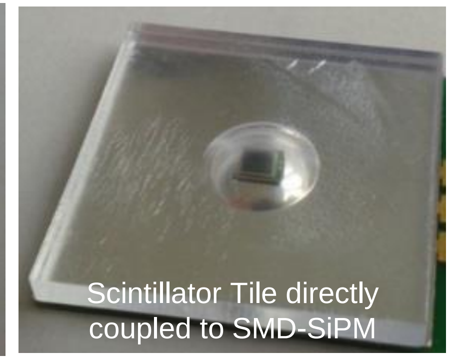




Tile-SiPM design: evolution







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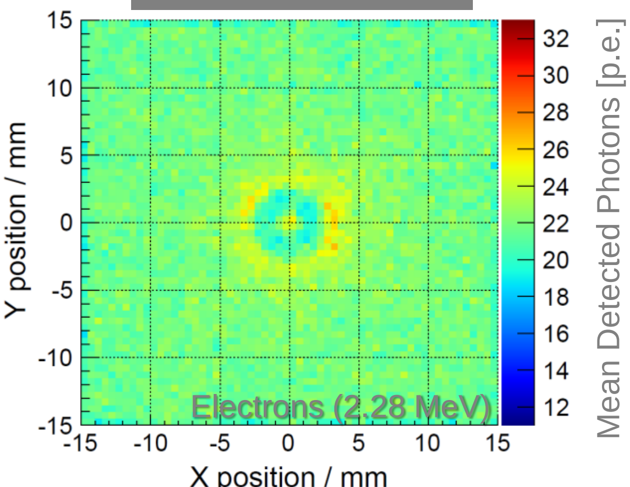
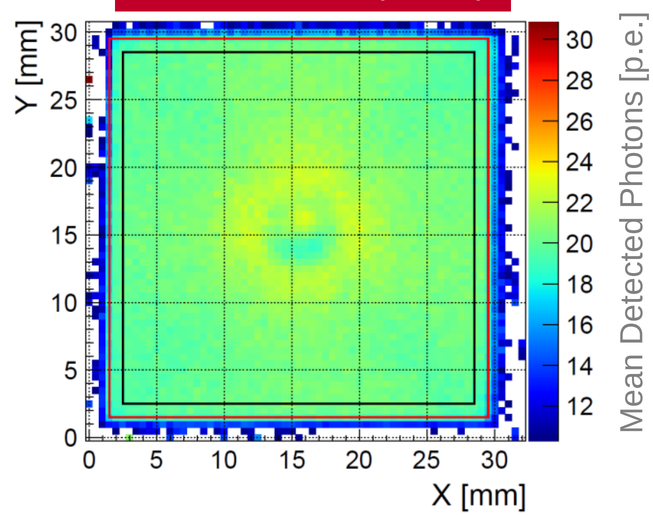
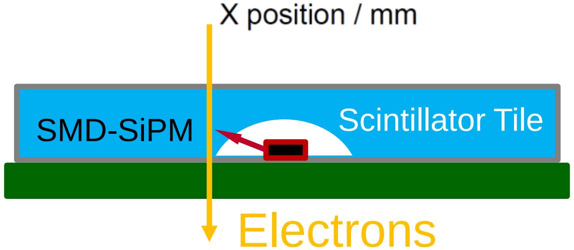
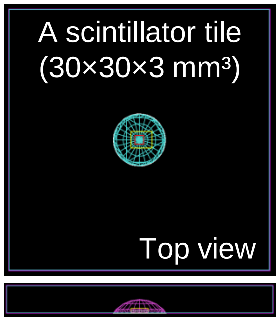


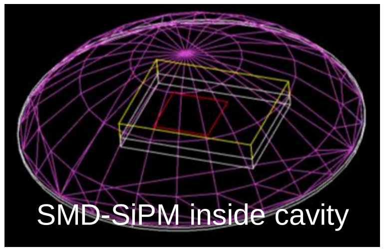
Measurement (Sr-90)

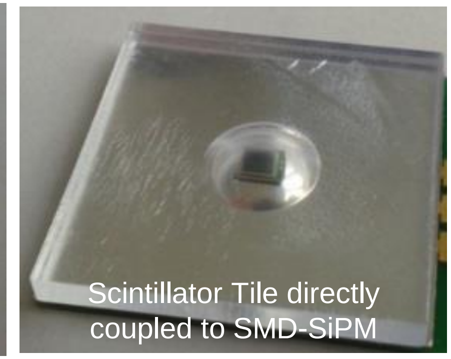




Tile-SiPM design: evolution







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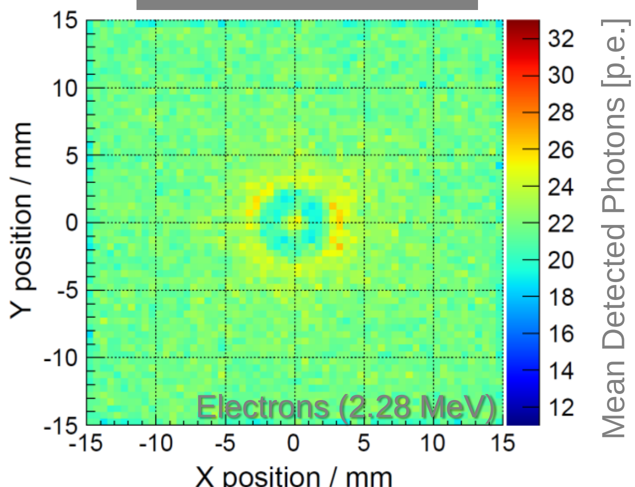

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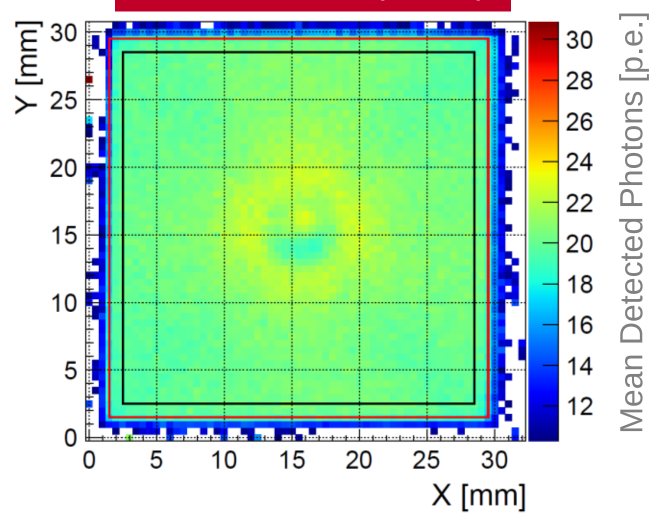
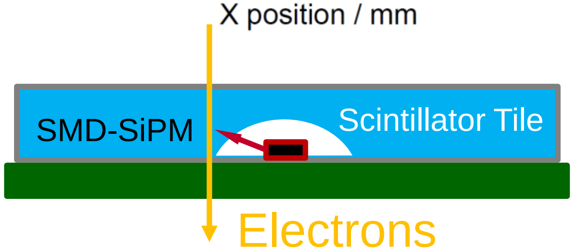
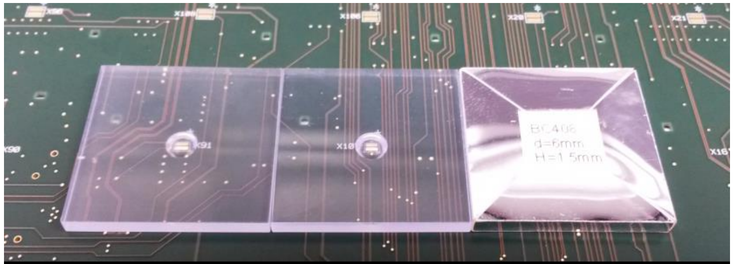




Optimal design achieved: suitable for mass assembly; good S/N; excellent response uniformity

Pioneering activities: mass assembly

- 1st AHCAL readout board with surface-mounted SiPMs
  - Implemented the optimal tile design: SMD-SiPMs directly soldered on PCB
  - Successfully built in 2014: 144 channels
    - Electronics established with DESY (SMD-HBU)
  - Proof-of-principle: the first to demonstrate mass assembly capability



1st generation of Mainz SMD-HBU: before assembly

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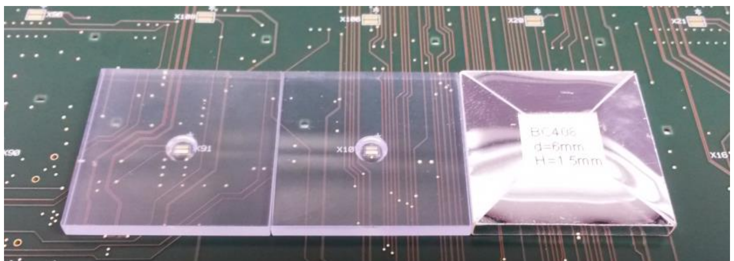

1^{st} generation of Mainz SMD-HBU:
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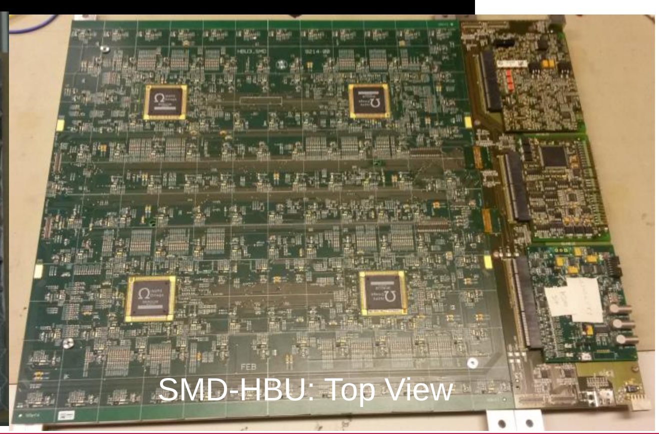
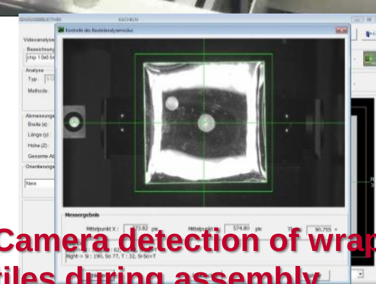
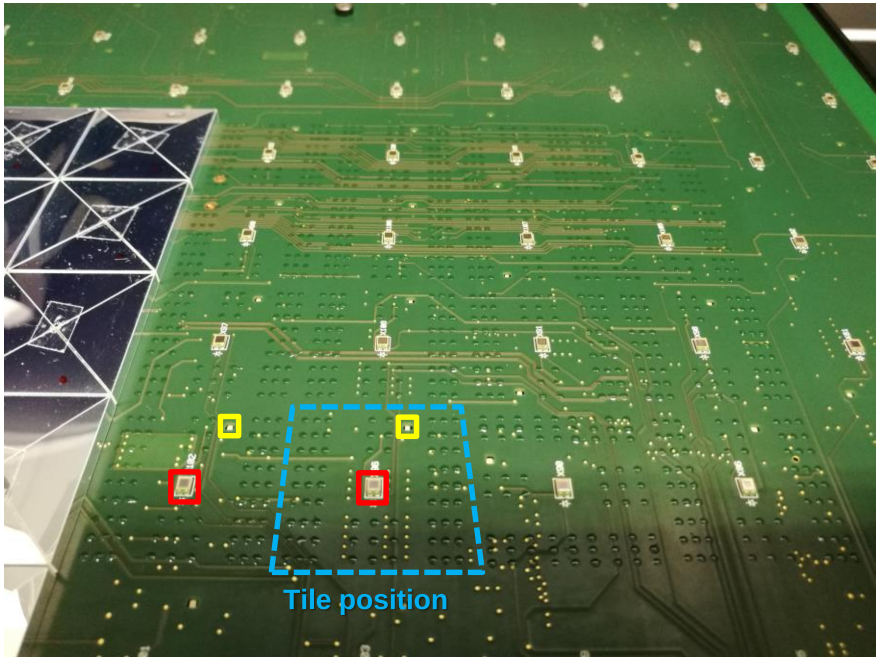


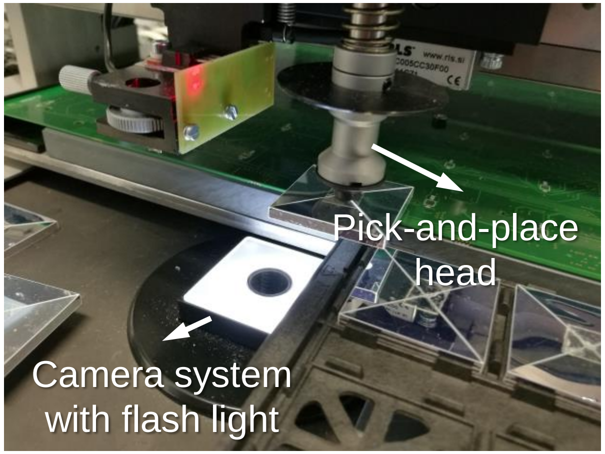


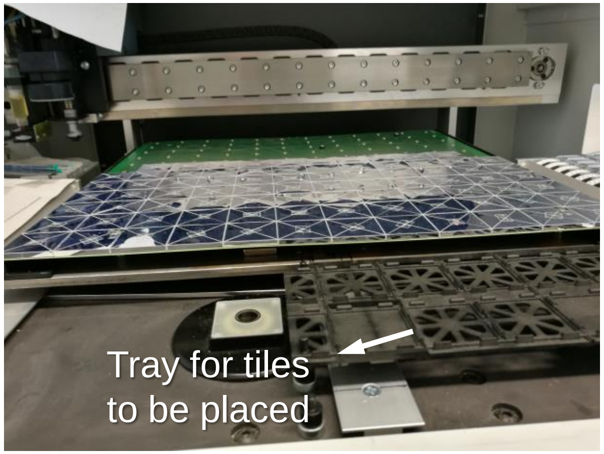
Camera detection of wrapped tiles during assembly

Mass assembly: routine procedure



- 6 SMD-HBUs assembled in 2016
  - Updated tile design
  - 1000 new low-noise SiPMs
- Proof of routine procedure
- Adopted as the baseline for the large tech. prototype

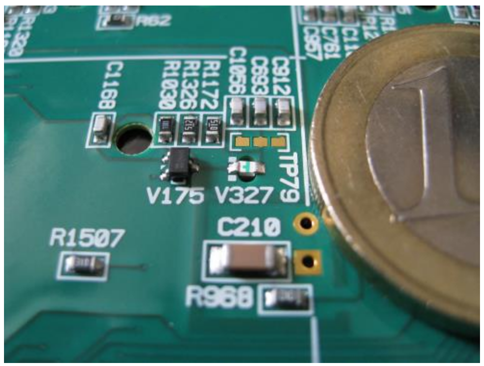




- 2017: ~170 new boards will be fully assembled and tested

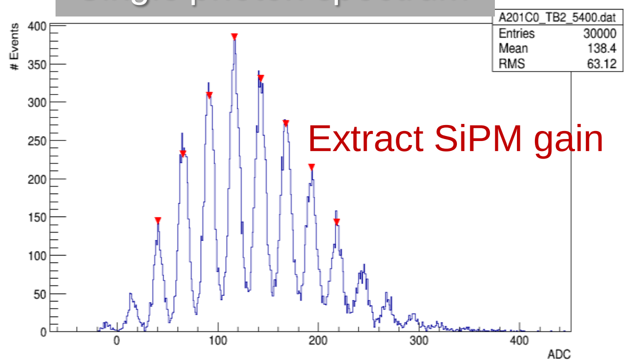
SMD-HBUs commissioning

- Test readout boards after mass assembly
  - LED: extraction of SiPM gain; temperature monitoring
  - Muons: measurements of MIP response in a dedicated cosmic-ray setup



LED (in a hole) emits light to a tile (equipped on the other PCB side)

Single photon spectrum



Gain mapping of one HBU

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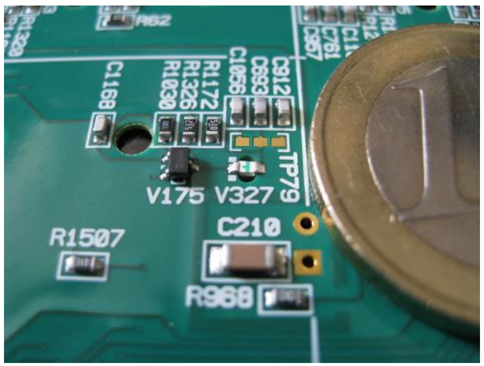

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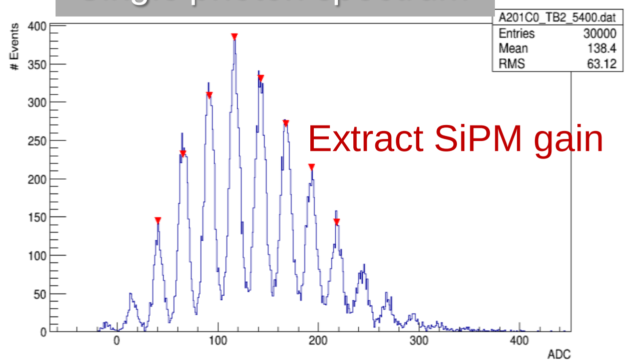
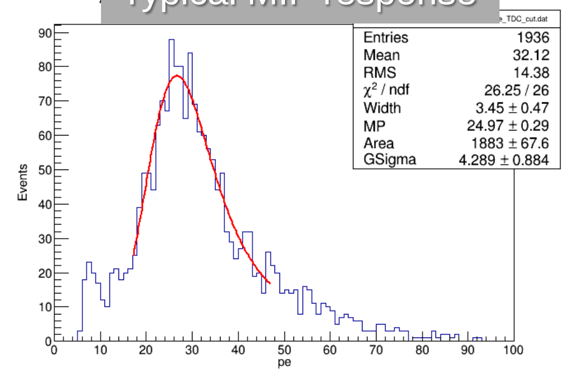
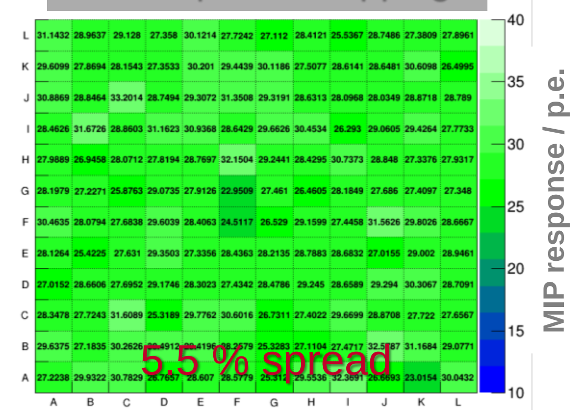


Typical MIP response



Gain mapping of one HBU

MIP response mapping



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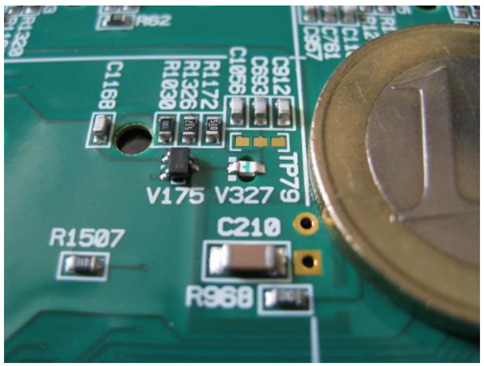

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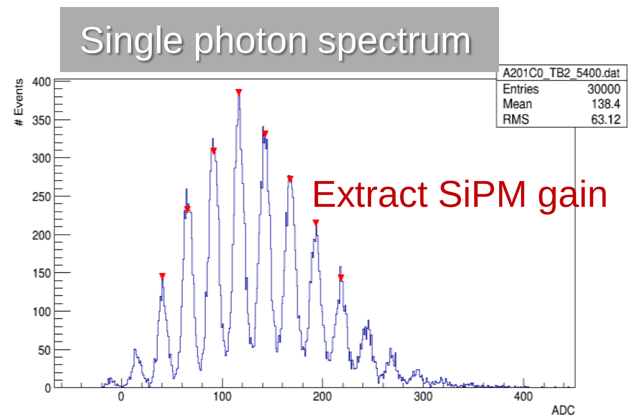
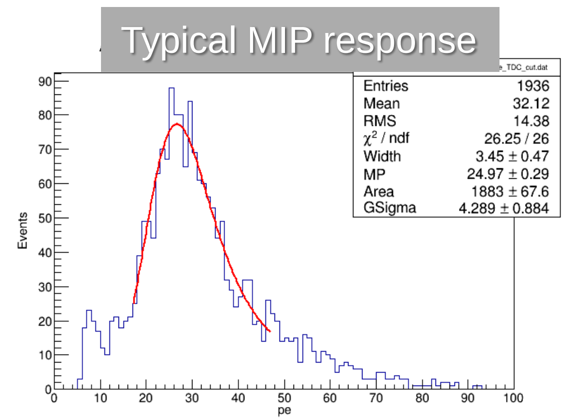
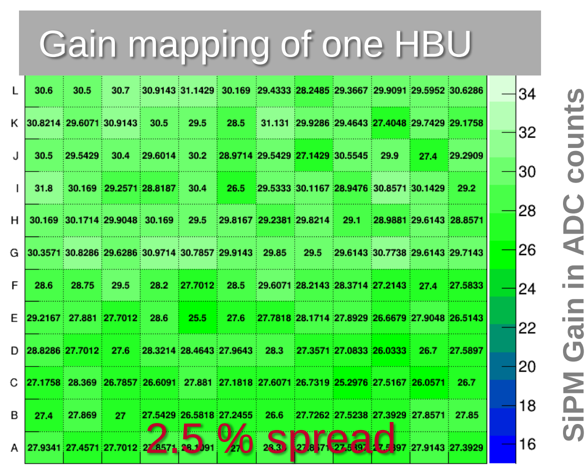
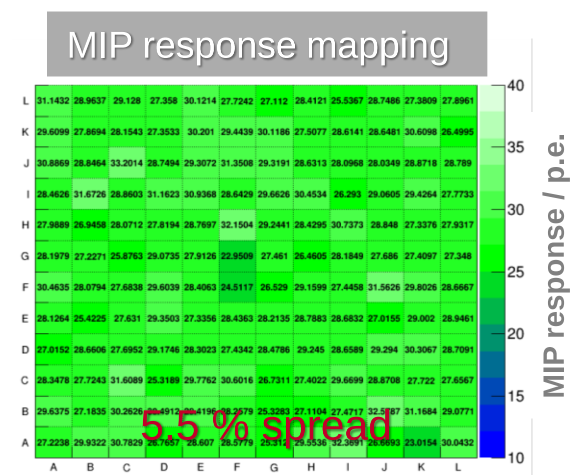


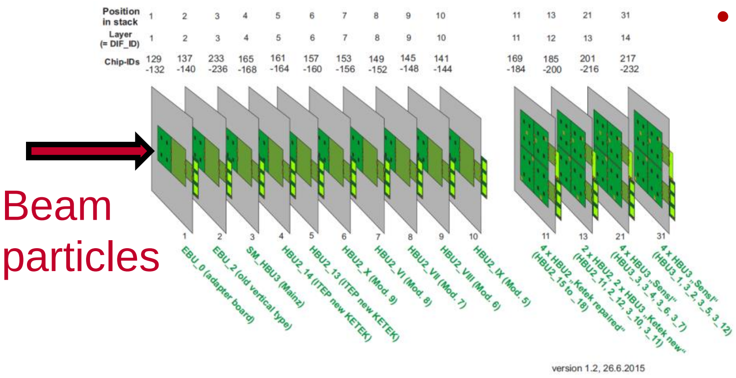






Excellent performance:
all channels (1k) working;
low spread (gain, MIP)

Test beam campaigns: CERN-SPS in 2015

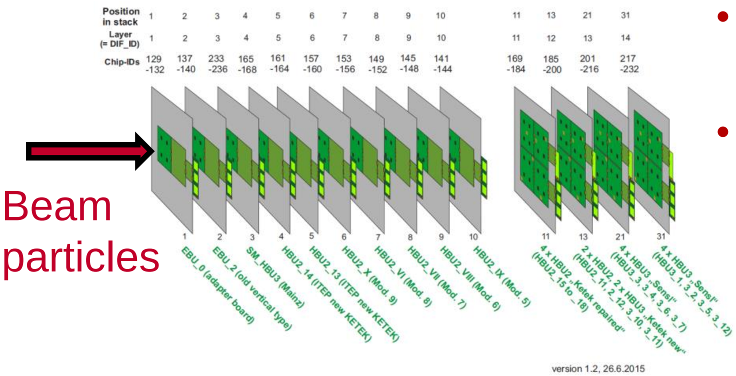


- Tested both steel and tungsten stacks
  - Infrastructure for 48 layers; partially instrumented

AHCAL prototype in steel stack

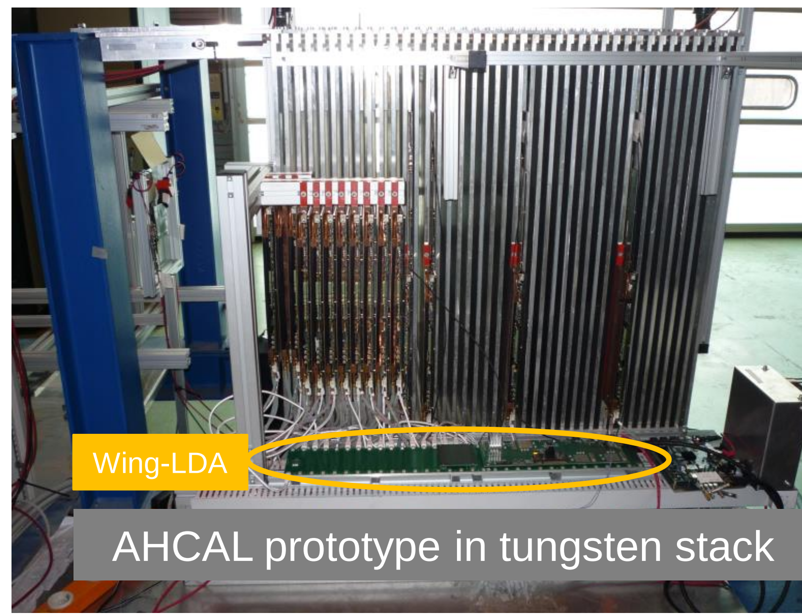
AHCAL prototype in tungsten stack

Test beam campaigns: CERN-SPS in 2015



- Tested both steel and tungsten stacks
  - Infrastructure for 48 layers; partially instrumented
- System integration: scalable setup
  - Interface boards (Power, DIF, Calib): can handle a full layer
    - Power board: optimized for power pulsing
    - DIF board: equipped new FPGA to communicate with ASICs
    - Wing-LDA: data aggregator designed for ILD-AHCAL
  - Water cooling: only for interface boards (thanks to the power-pulsing mode)

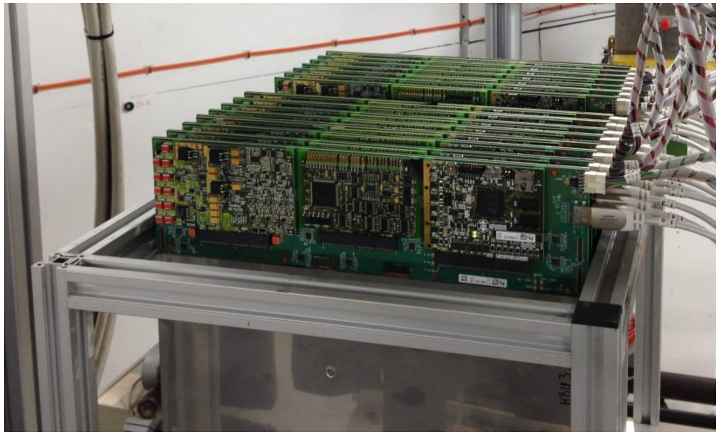
AHCAL prototype in steel stack

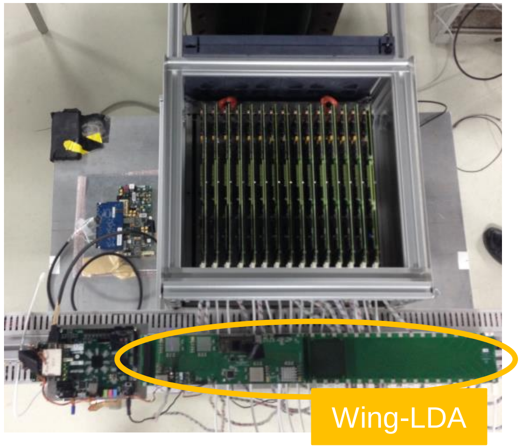


AHCAL prototype in tungsten stack

Test beam campaigns: DESY in 2016

- A small prototype for electromagnetic showers with high-quality SiPMs
  - 15 layers, single HBU per layer
    - 7 HBUs with SMD-SiPMs built via mass assembly, Tile-on-SiPM
    - 8 HBUs with high-quality SiPMs, side-surface coupling
  - New interface boards for all layers
  - To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM





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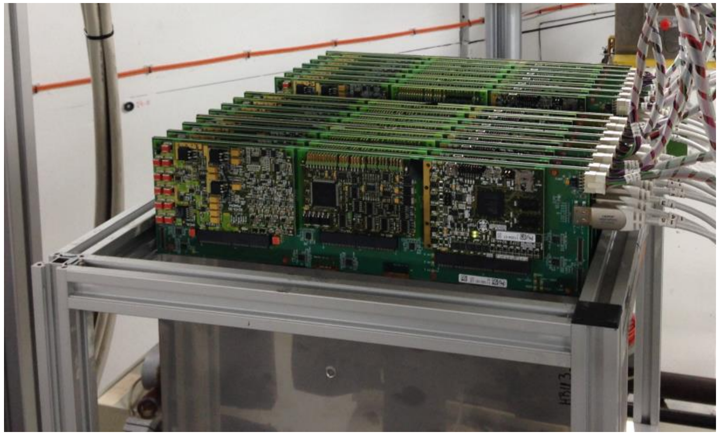
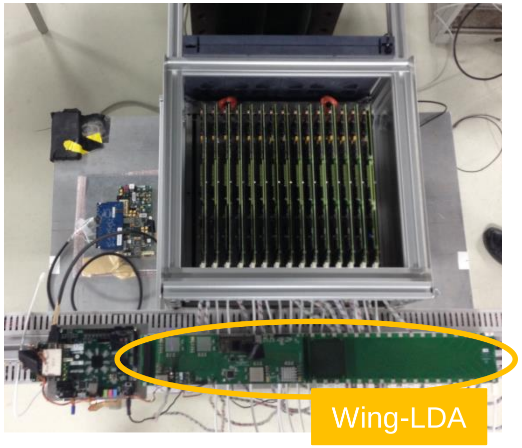
  - New interface boards for all layers
  - To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM
- Tested in DESY test beam facility in 2016
  - MIP calibration for all layers
  - EM shower data taken with and without power pulsing

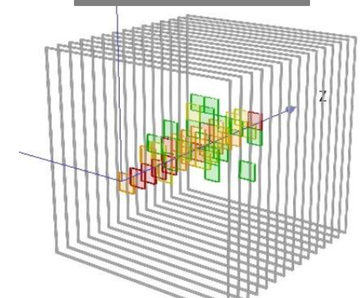


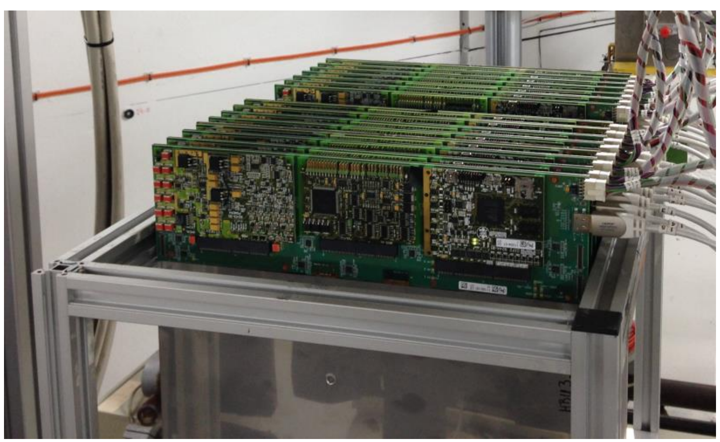


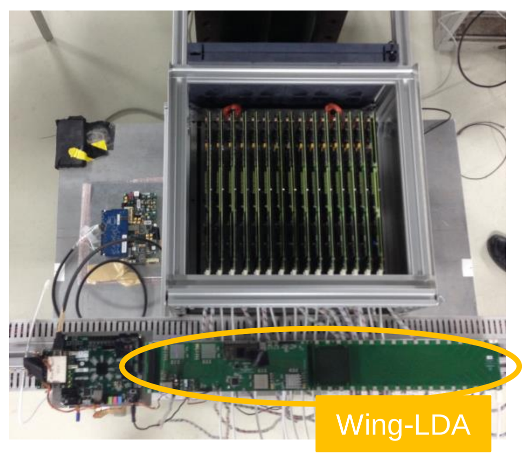
Test beam campaigns: DESY in 2016

- A small prototype for electromagnetic showers with high-quality SiPMs
  - 15 layers, single HBU per layer
    - 7 HBUs with SMD-SiPMs built via mass assembly, Tile-on-SiPM
    - 8 HBUs with high-quality SiPMs, side-surface coupling
  - New interface boards for all layers
  - To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM
- Tested in DESY test beam facility in 2016
  - MIP calibration for all layers
  - EM shower data taken with and without power pulsing

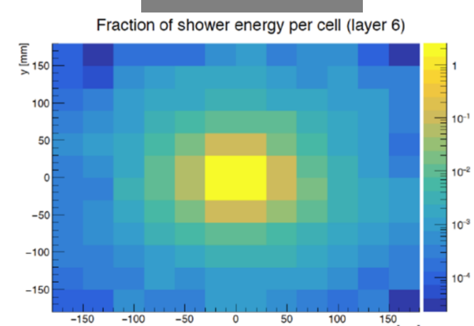
Event Display







EM Showers



Test beam campaigns: CERN-SPS in 2017

- CALICE beam test with magnetic field
  - Only 1.5 T possible (aimed 3T)
- Technical aim
  - Power pulsing in magnetic field
- Physics aim
  - Performance with electrons

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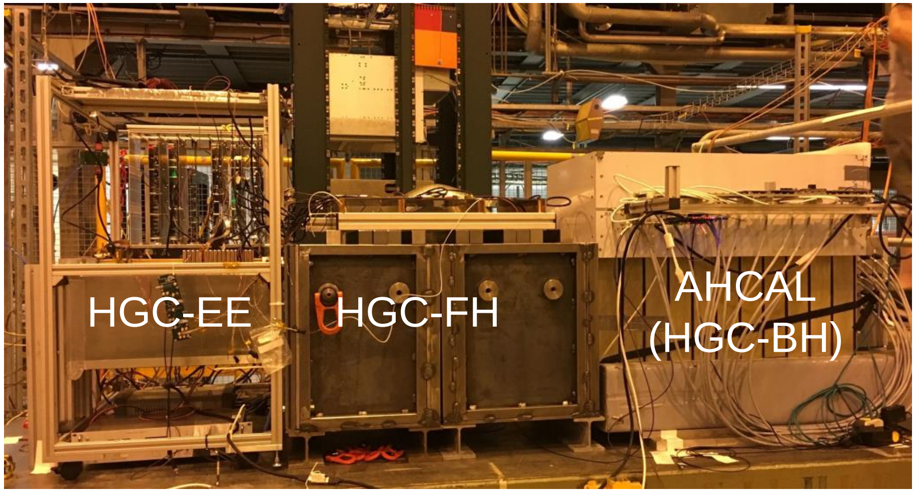

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- CALICE beam test with magnetic field
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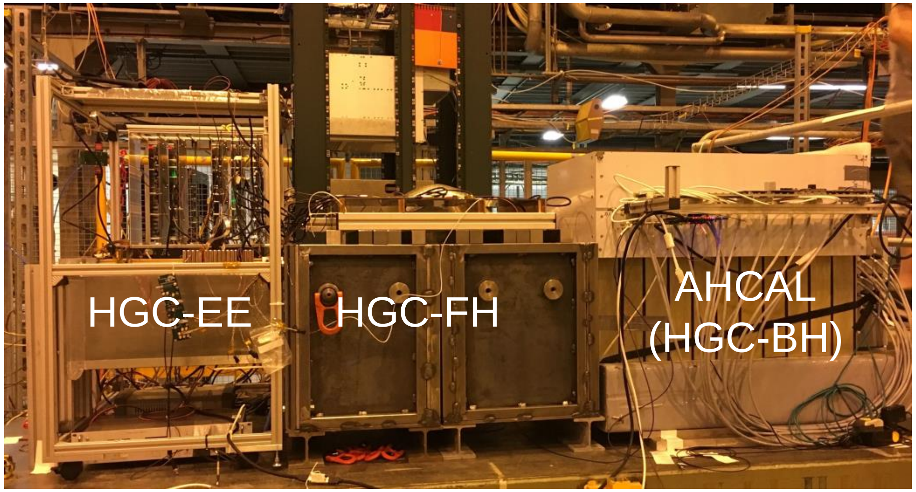
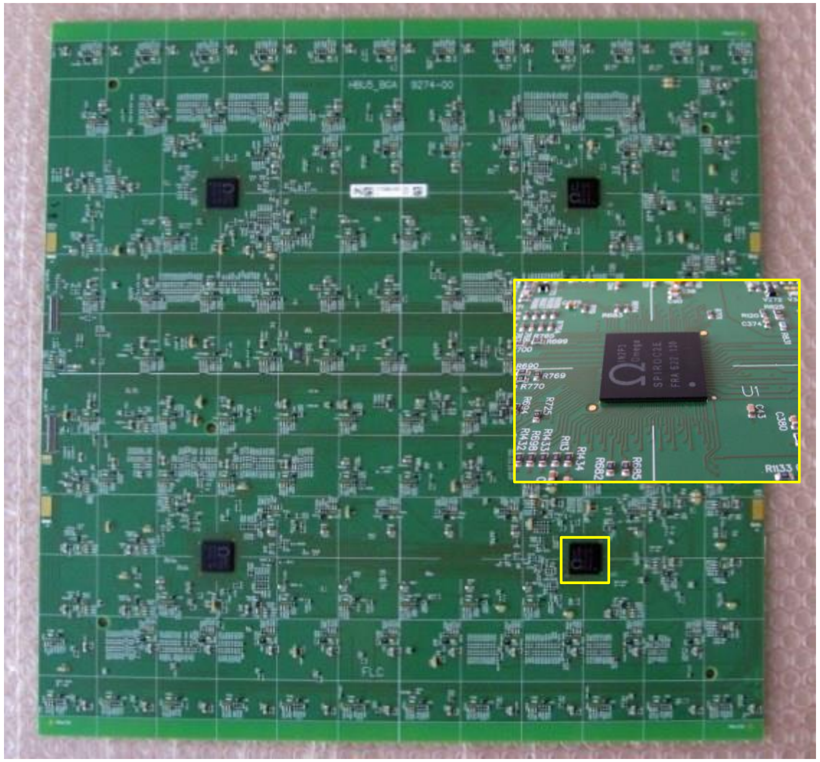
- CALICE-CMS common beam test
  - DAQ integration: EUDAQ
  - Active temperature compensation for SiPMs



New electronics

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



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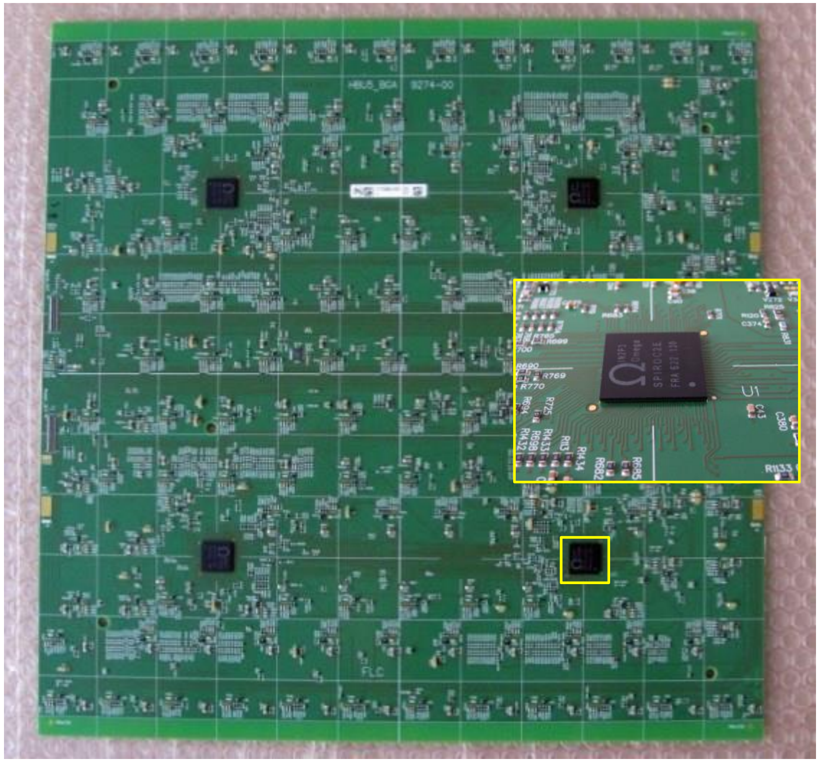
  - Power board: reduced heat dissipation, optimized for power-pulsing, etc.



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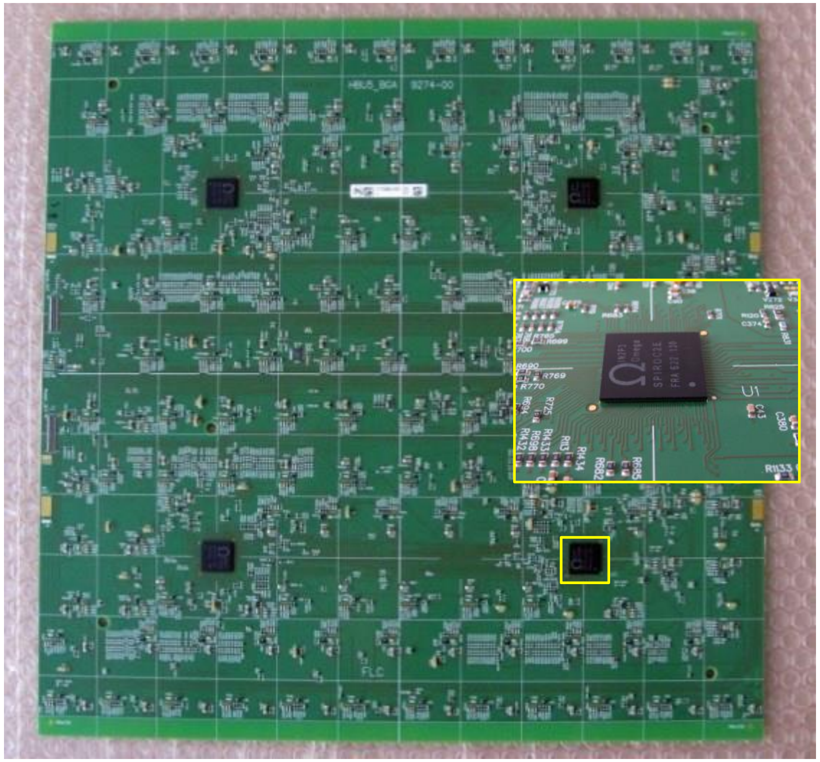

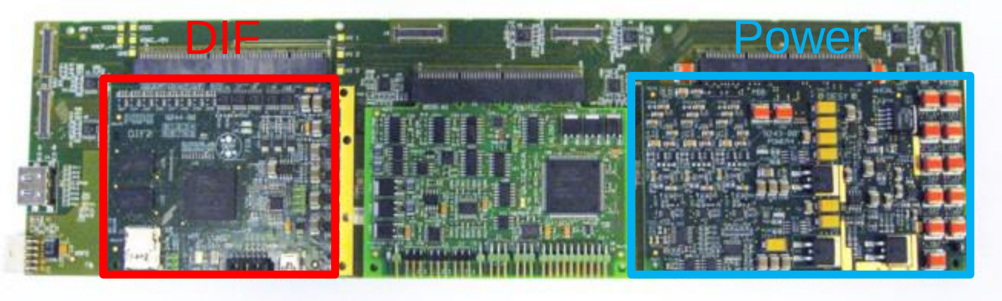

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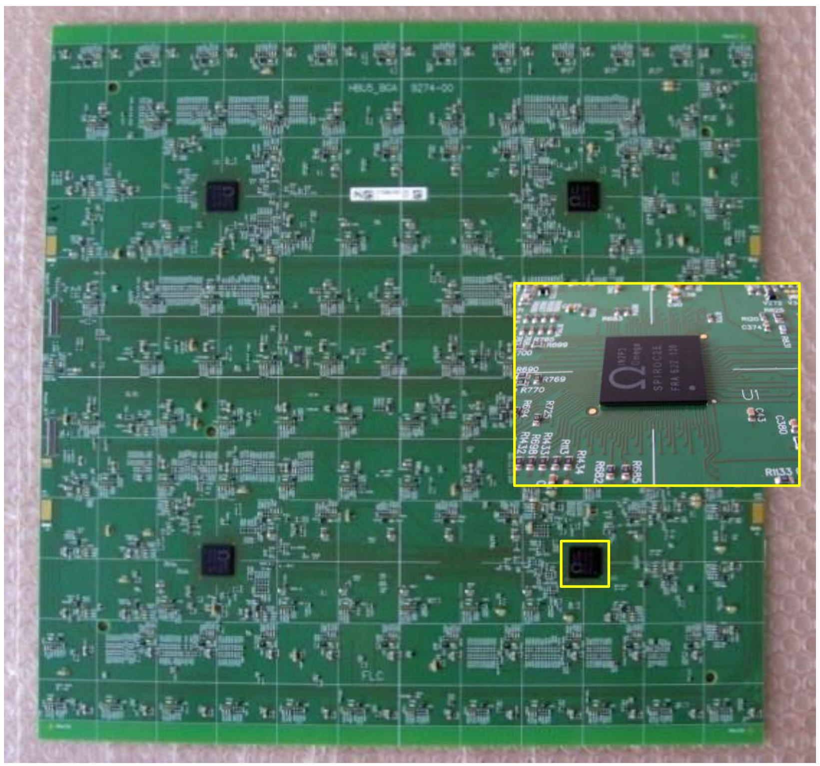
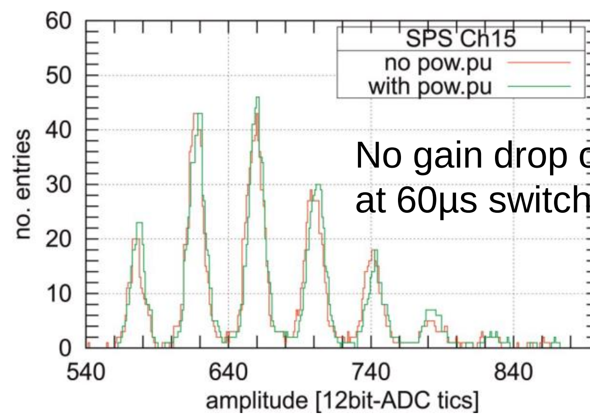


LED data w/wo power pulsing

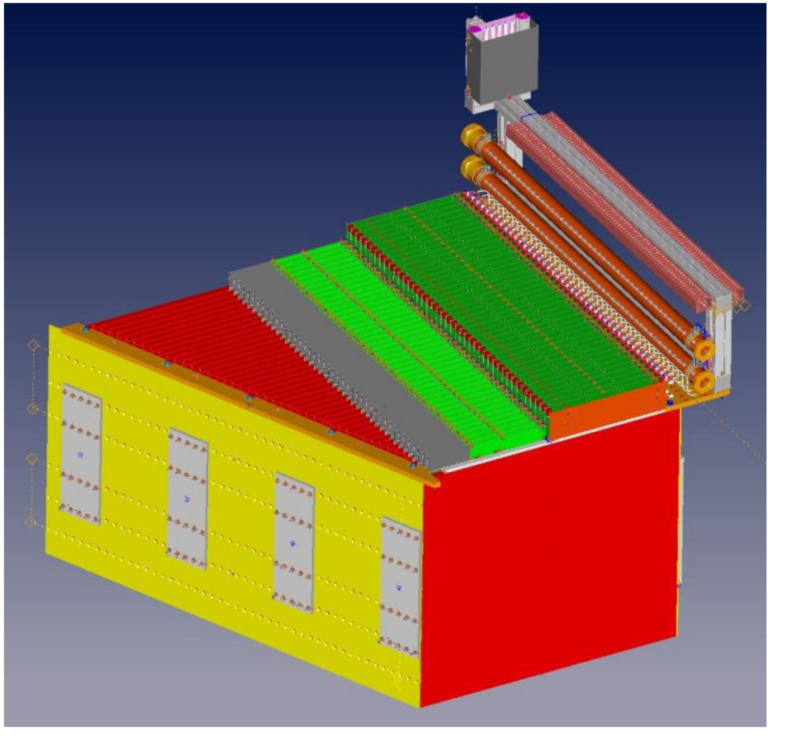


No gain drop observed at 60µs switch-on time

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

Towards 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



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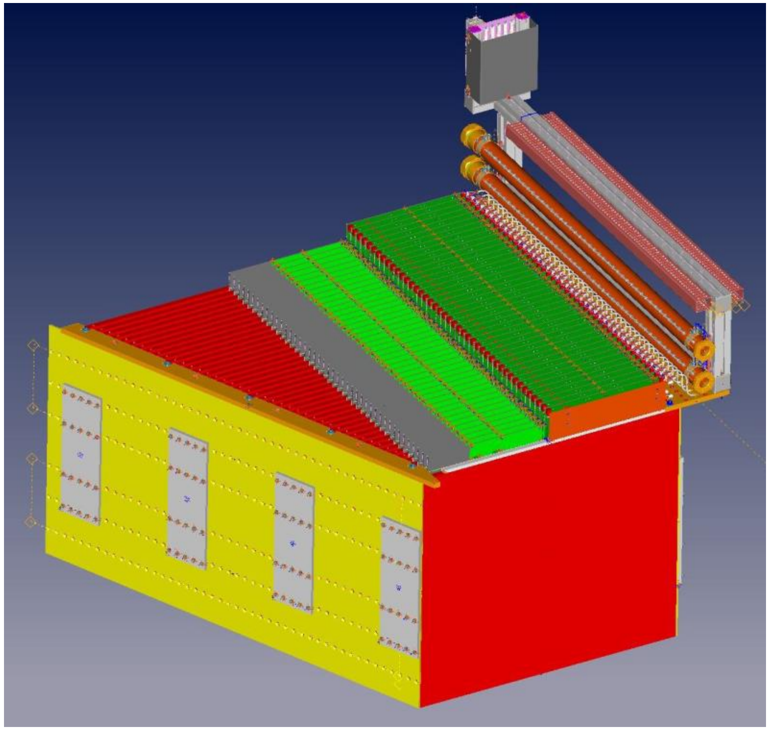
  - 40 layers in total; 4 HBUs in each layer
  - Big step towards mass production & QA
    - Tile mass production via injection molding



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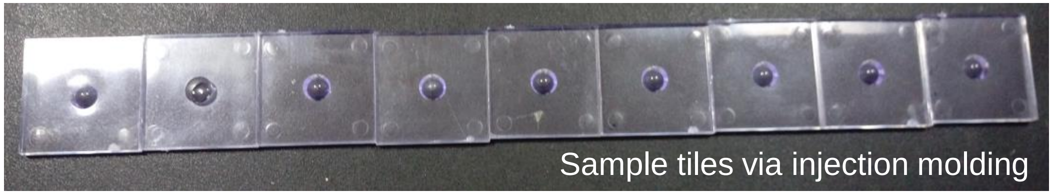
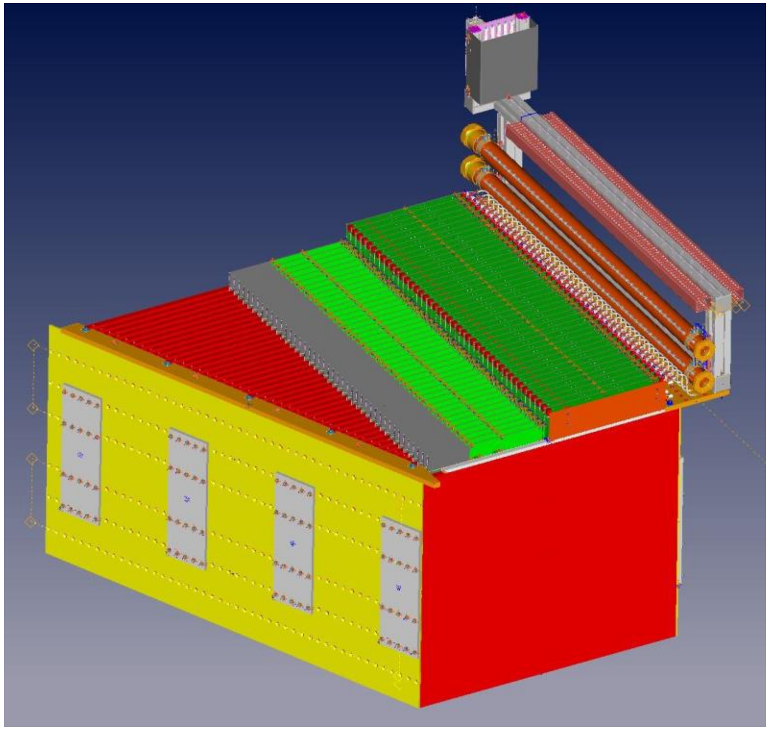

Sample tiles via injection molding



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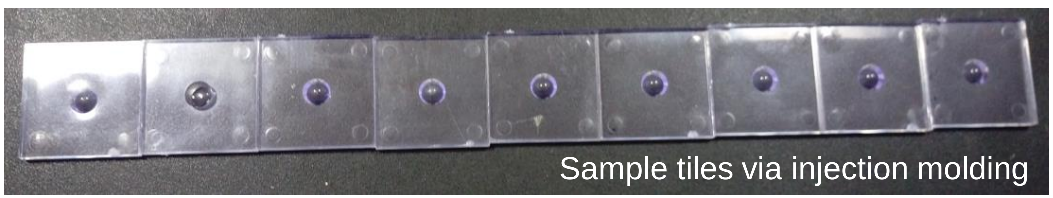
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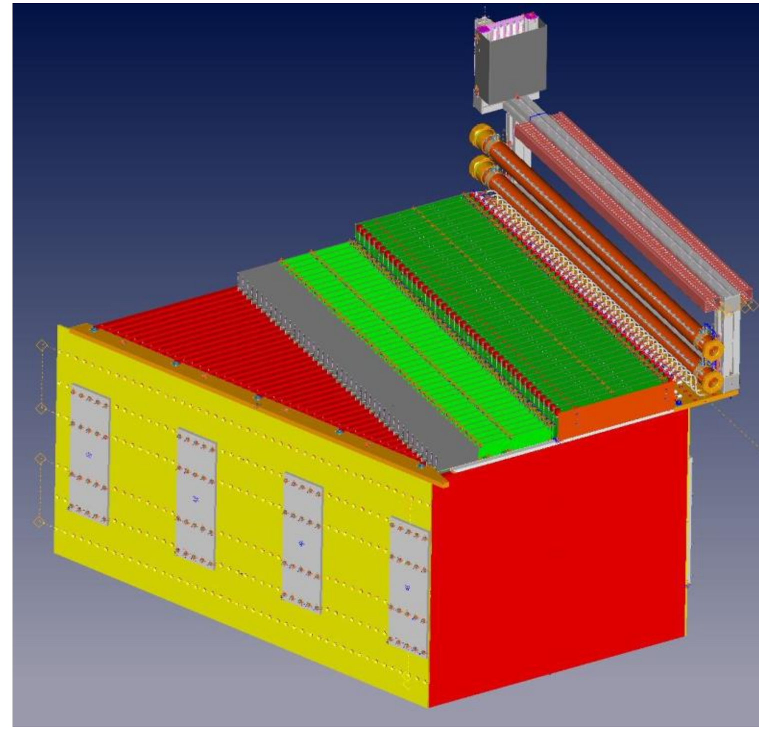

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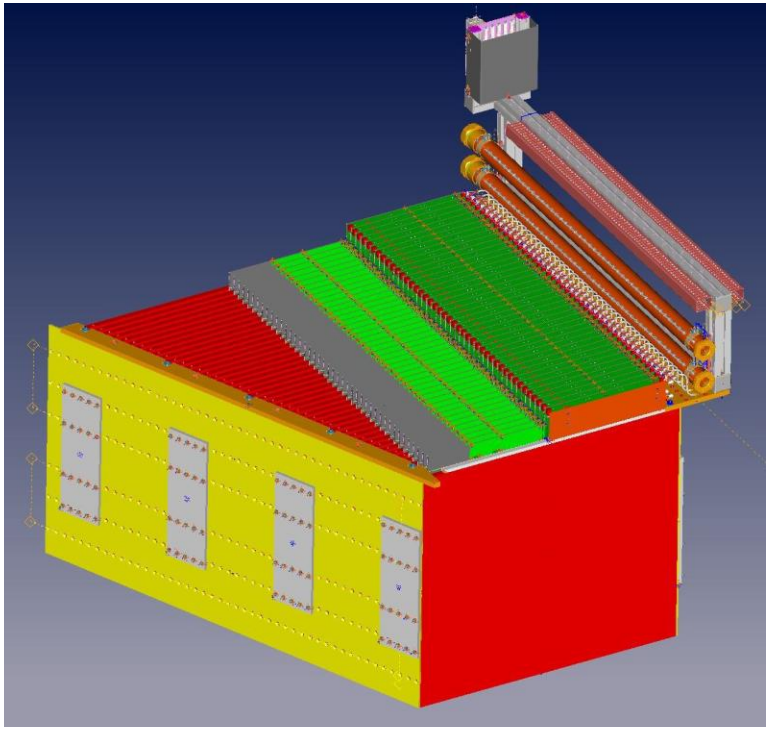

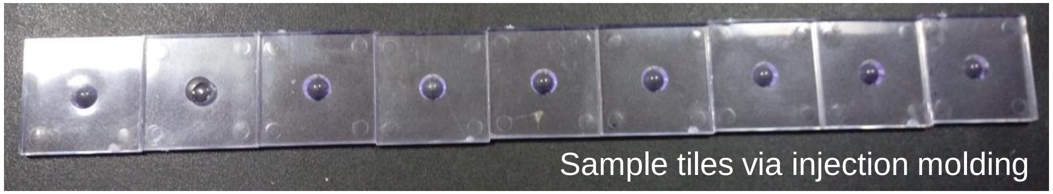
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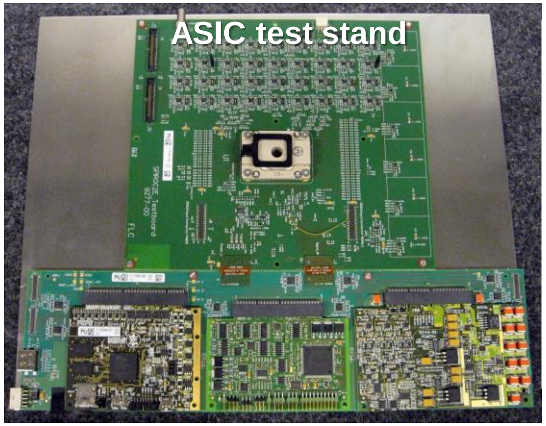
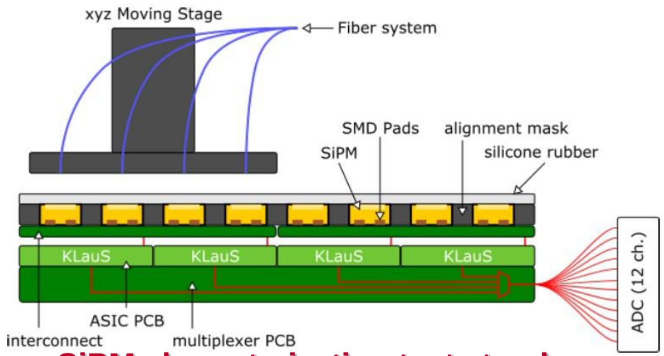
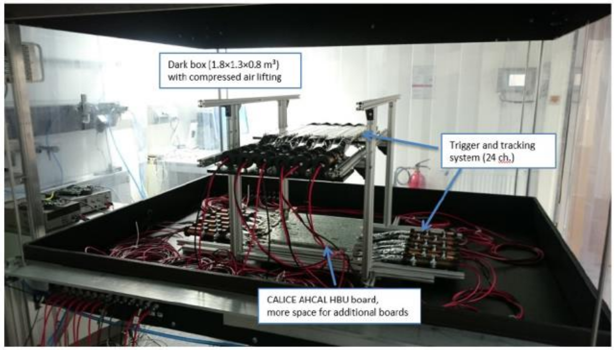

ASIC test stand



SiPM characterization test stand



Cosmic-ray test stand for HBUs

Development of key setups at Mainz

- Photosensor test stand
  - Selection of SiPMs for AHCAL, and full SiPM characterizations
  - Development (in parallel) of custom-designed fast preamps for SiPMs

Development of key setups at Mainz

PRISMA Detector Lab

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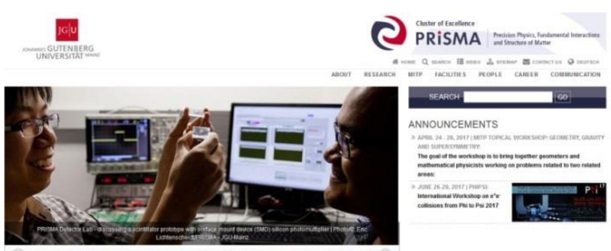
Photosensor test stand

Xenon lamp, monochromator, laser diode, lens system, XYZ stage, etc.



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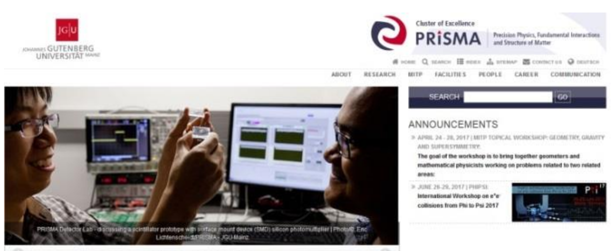

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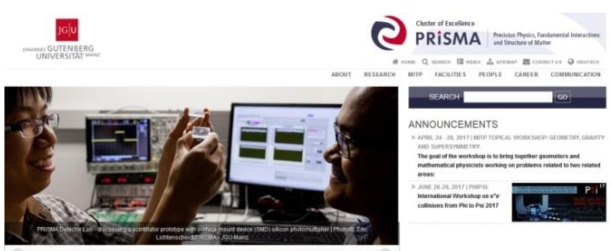

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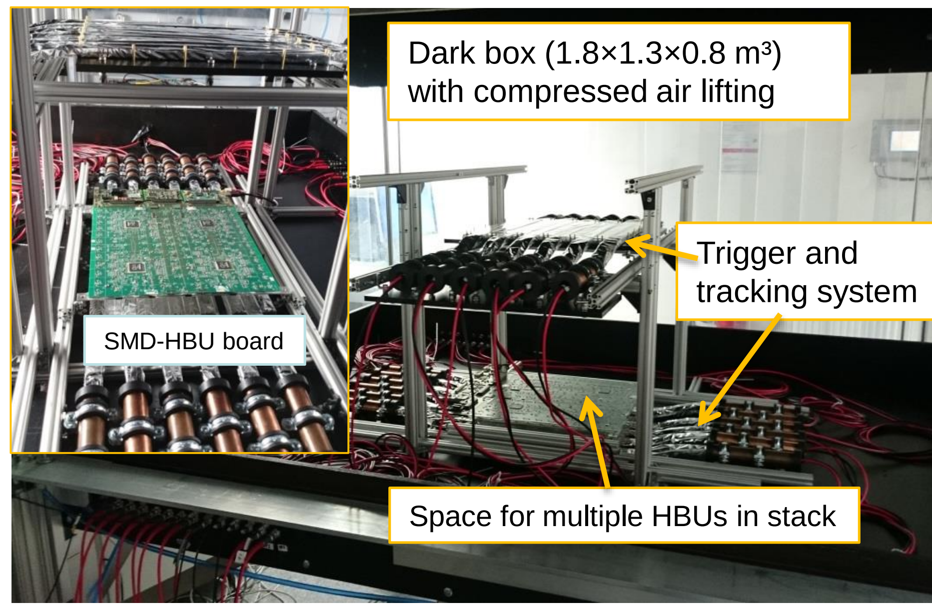
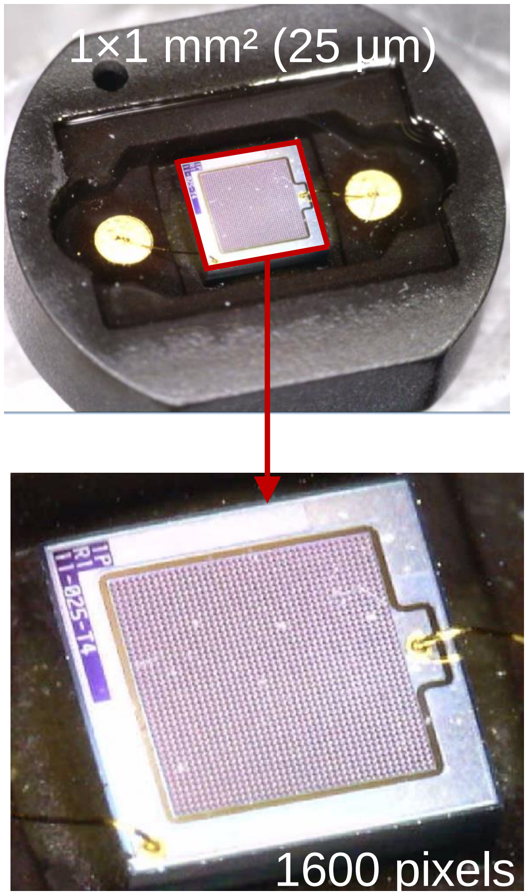
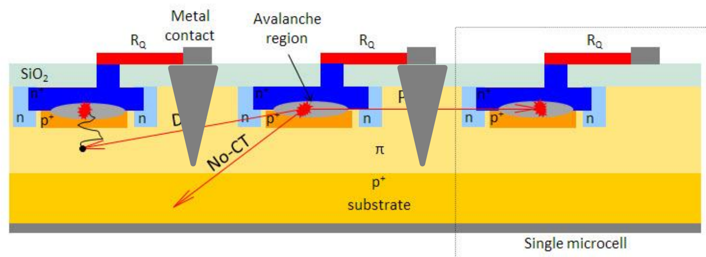


Test fully assembled boards using cosmic muons: measure MIP response in a relatively short time range

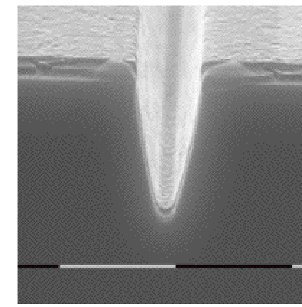
Photosensor test stand: low-noise SiPM

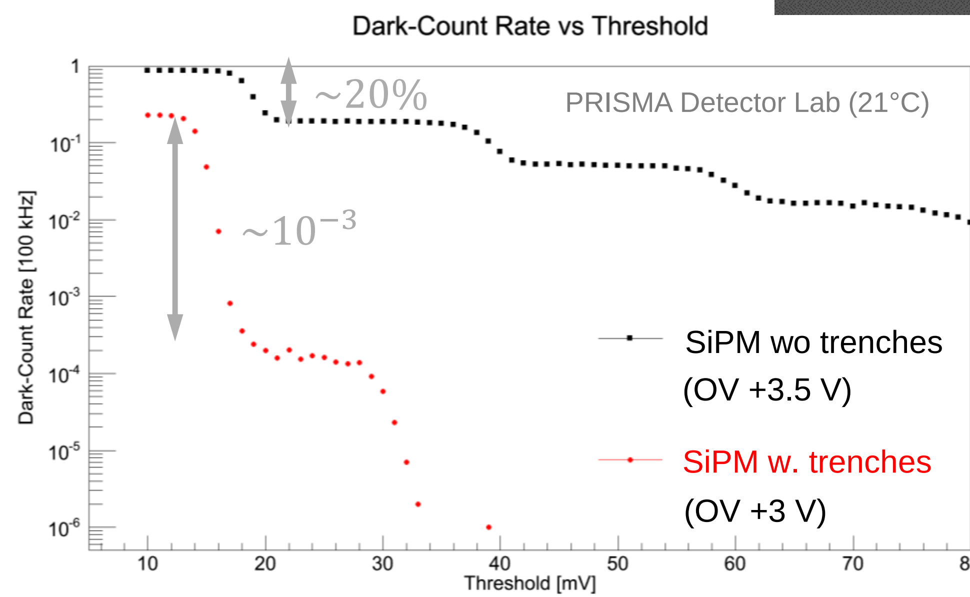
- Exploit the test stand for characterizations of various SiPMs





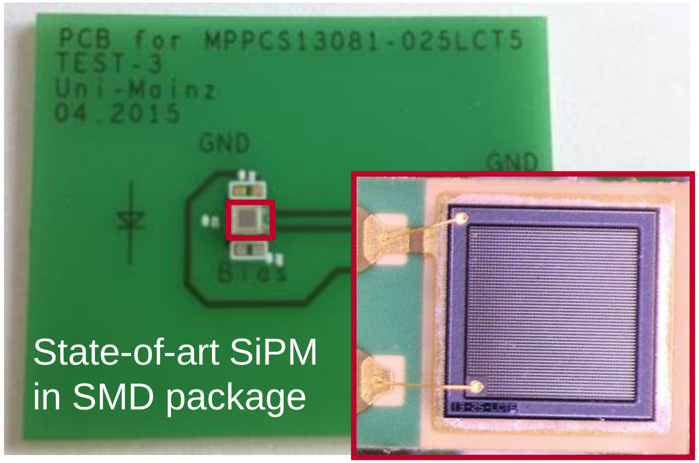
SiPM Resent Development and Applications, V. Saveliev, 2005





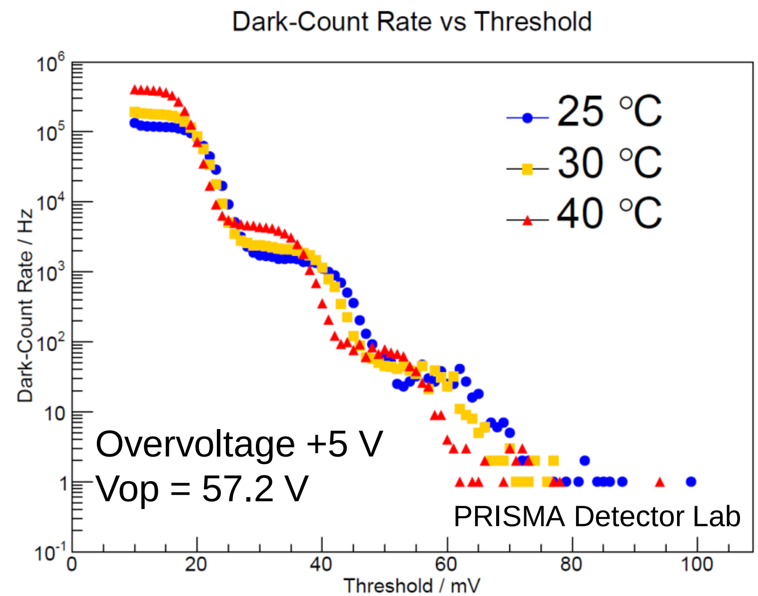
Dark-count noises drop fast with threshold

Photosensor test stand: SiPMs for tech. prototype



Fully characterize SiPM: DCR, gain, PDE, temperature behavior, pixel uniformity, etc.

- Exploit the test stand for characterizations of various SiPMs



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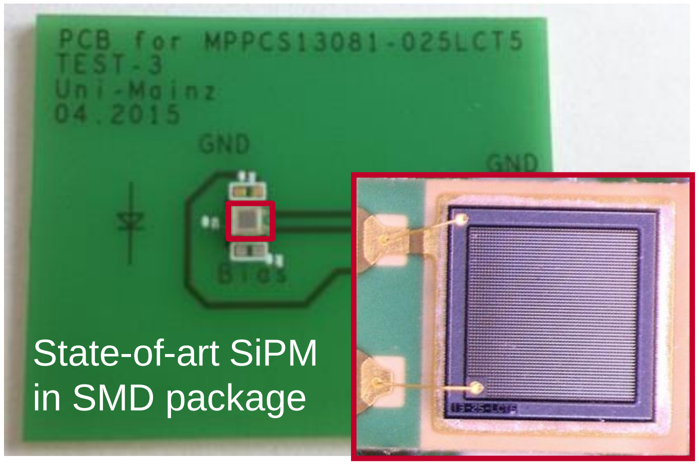

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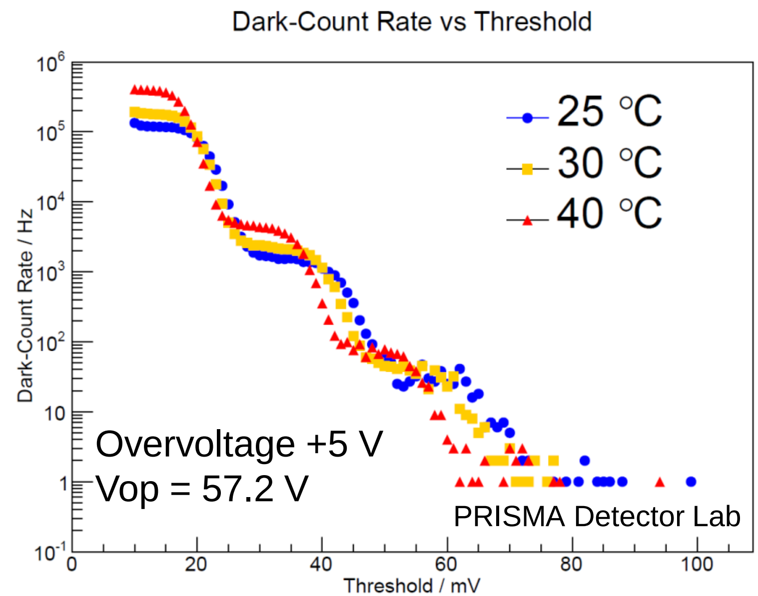

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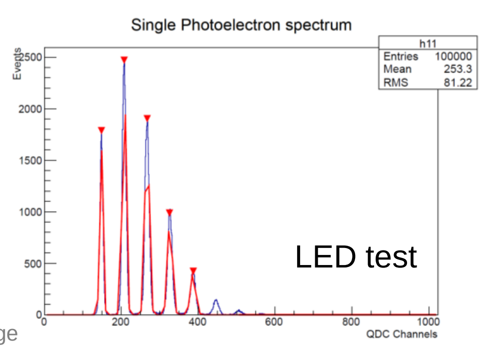

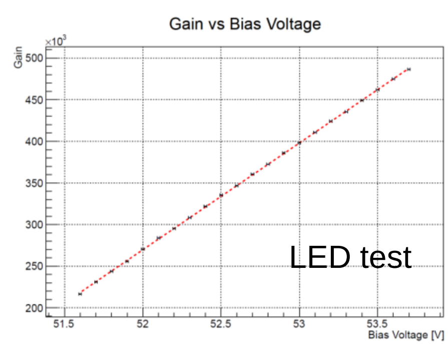

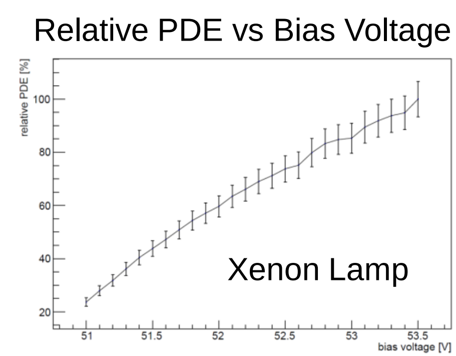

The 3 plots correspond to the SiPM prototype shown in the previous page

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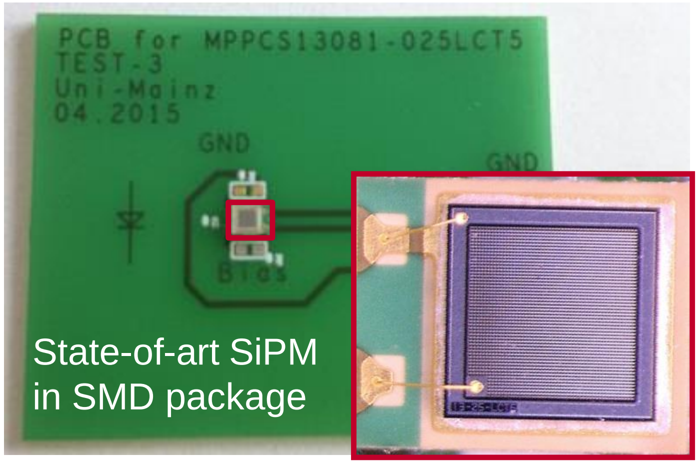
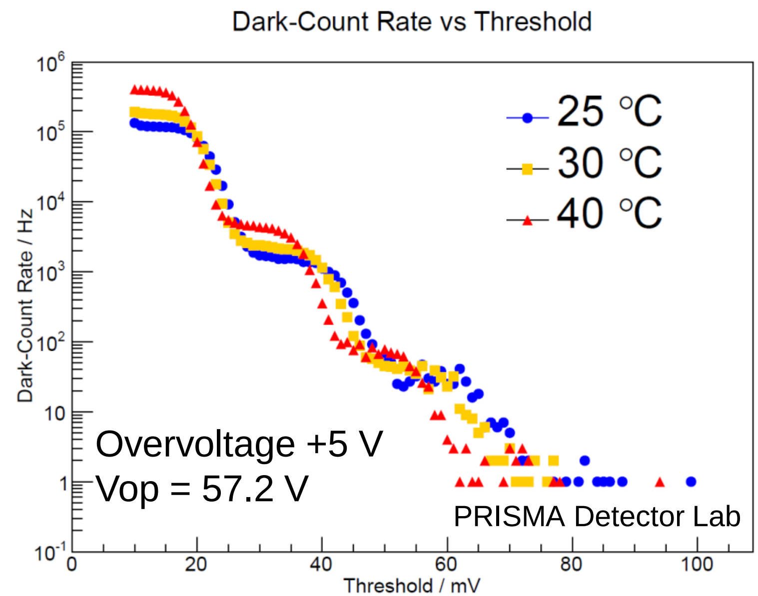
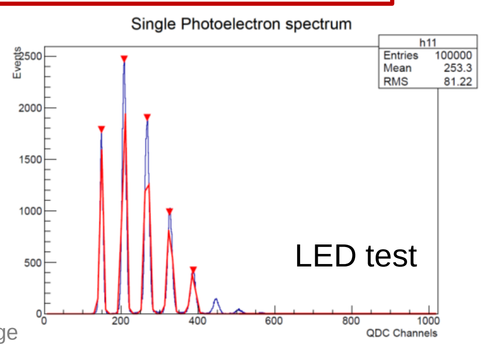


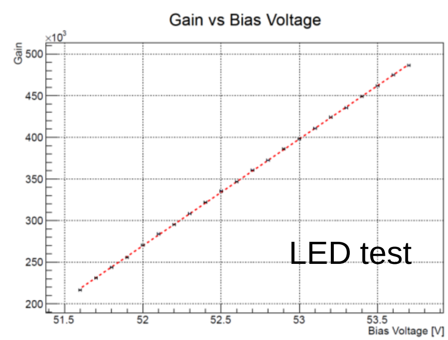
Fully characterize SiPM: DCR, gain, PDE, temperature behavior, pixel uniformity, etc.

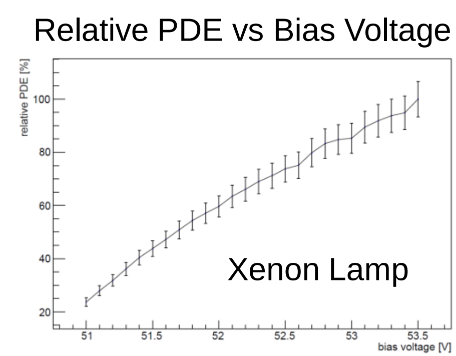
Chosen for the large tech. AHCAL demonstrator (23k pieces in total)

- Exploit the test stand for characterizations of various SiPMs









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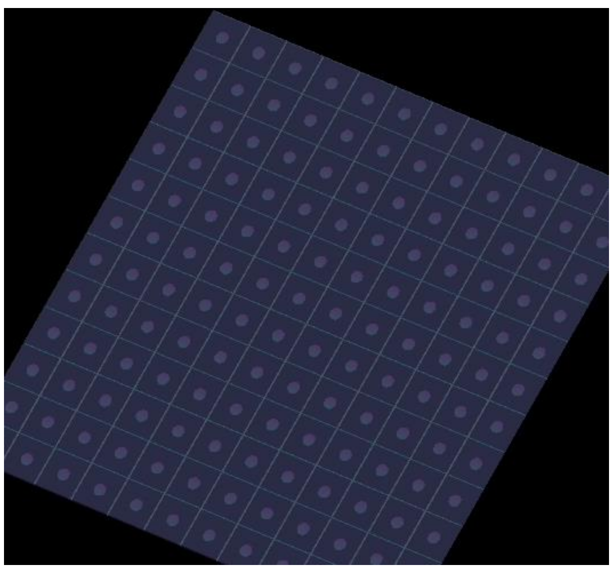
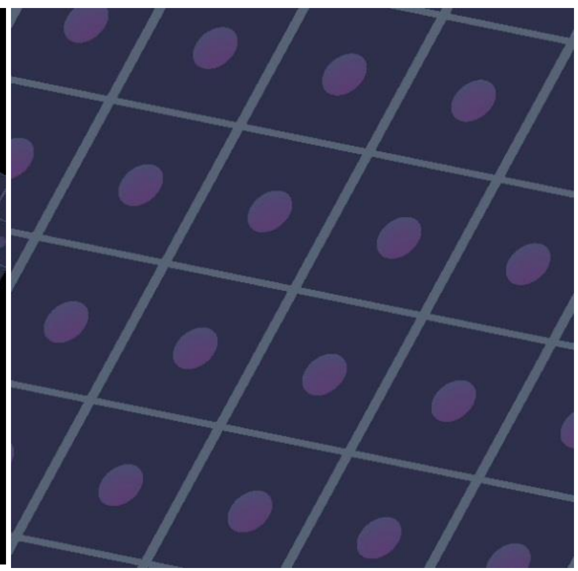
Ongoing development: mega-tile

- Motivations: further simplify mass assembly
  - Scintillator plates with embedded structures
  - Optically isolated for individual readout





Ongoing development: mega-tile

- Motivations: further simplify mass assembly
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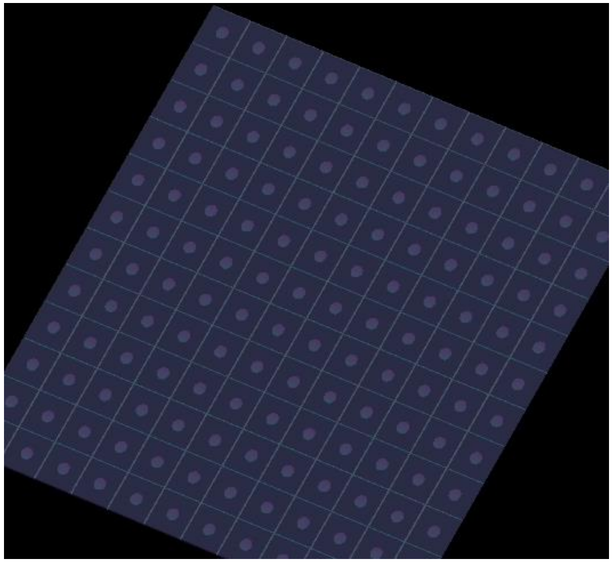
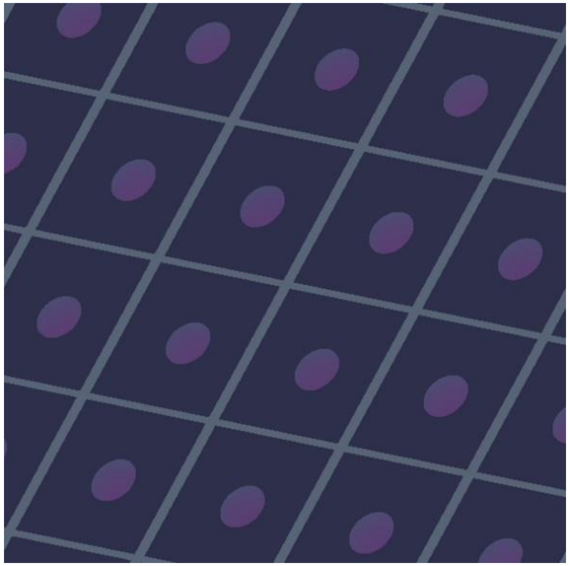
- Design: extensively optimized by Geant4 simulation
  - MIP response (moderate), cell-to-cell crosstalk (minimum)
- Several prototypes developed and fully tested





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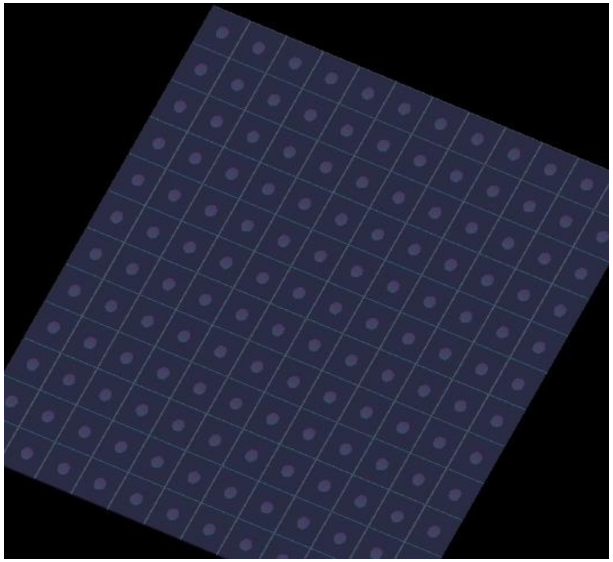
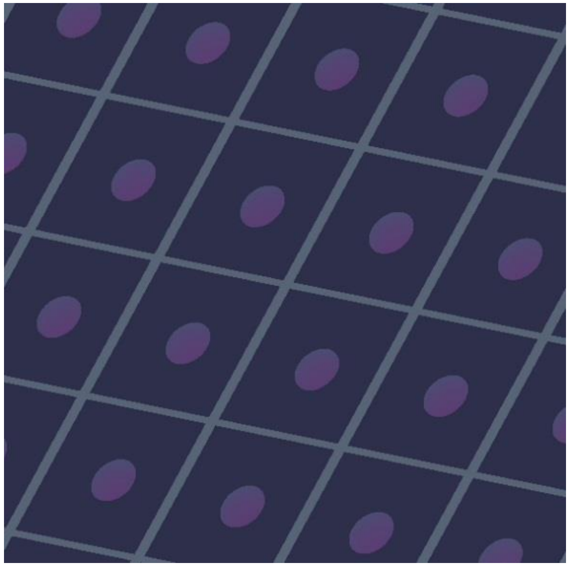
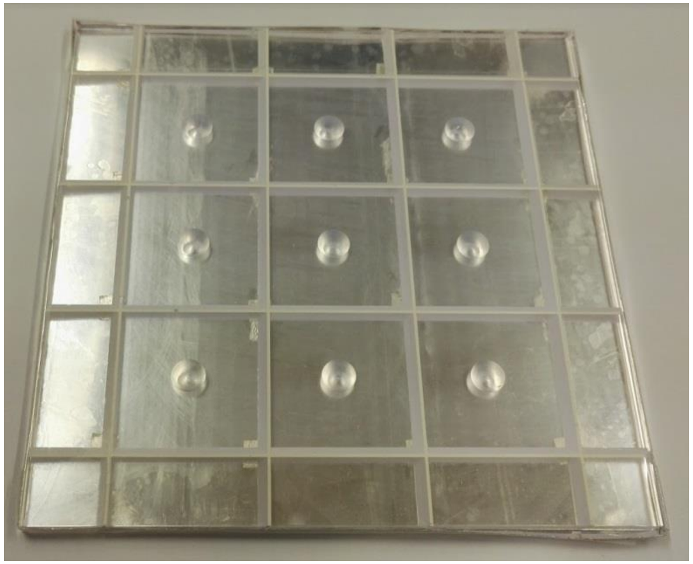
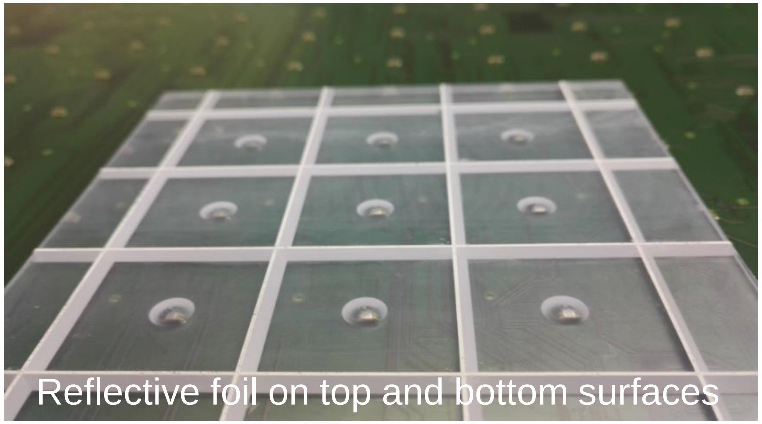






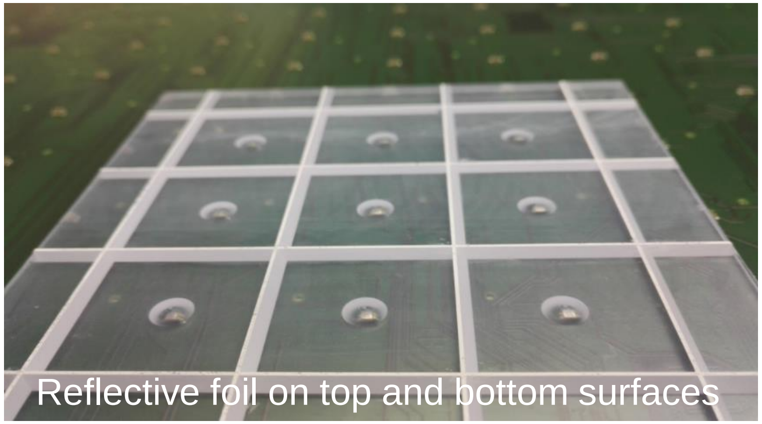
Mega-tile prototypes: highlights

Mega-tile prototype on SMD-HBU5


Reflective foil on top and bottom surfaces

Mega-tile prototypes: highlights

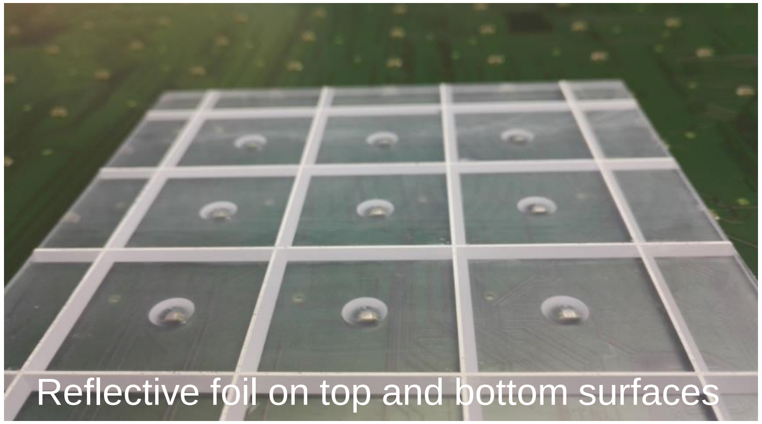
Mega-tile prototype on SMD-HBU5



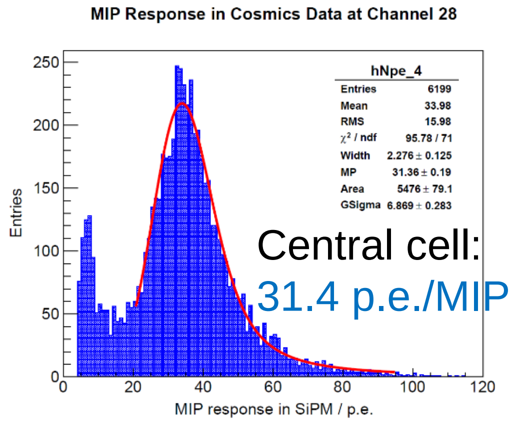
- Protoypes fully tested with
  - Cosmic muons
  - On-board LED

Mega-tile prototypes: highlights

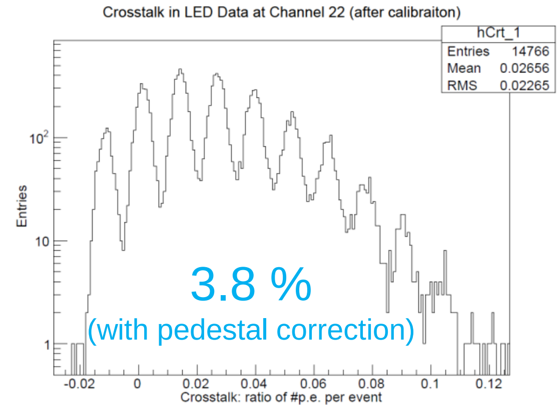
Mega-tile prototype on SMD-HBU5



MIP: cosmic muons



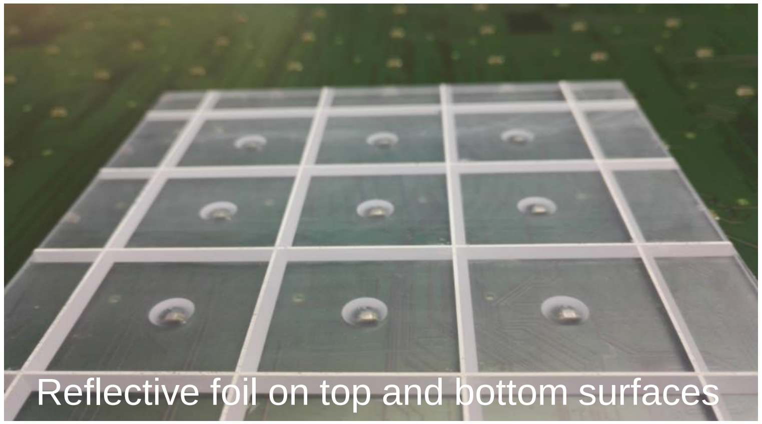
Optical crosstalk: UV light



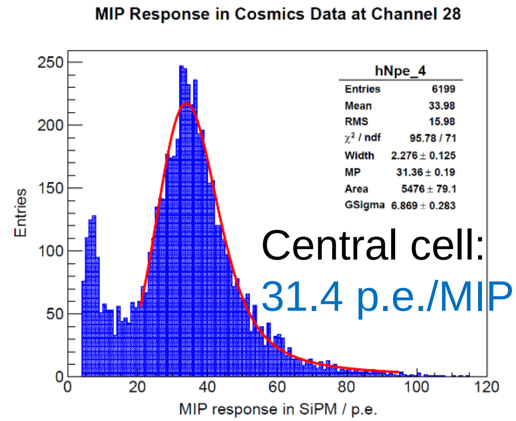
- Protoypes fully tested with
  - Cosmic muons
  - On-board LED

Mega-tile prototypes: highlights

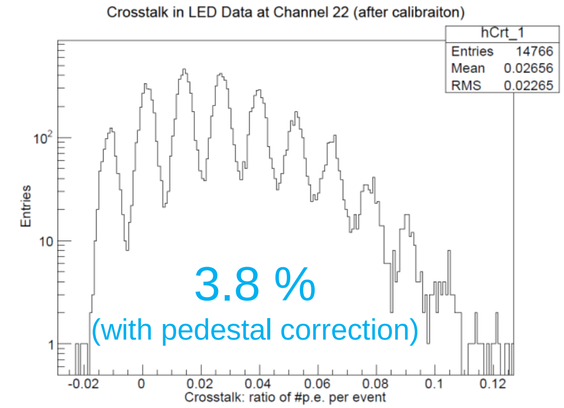
Mega-tile prototype on SMD-HBU5



MIP: cosmic muons



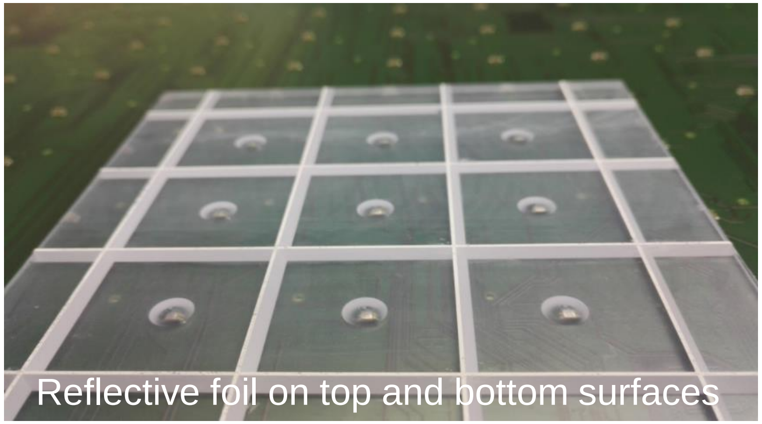
Optical crosstalk: UV light



- Protoypes fully tested with
  - Cosmic muons
  - On-board LED
- Excellent performance
  - Moderate MIP response
  - Low optical crosstalk

Mega-tile prototypes: highlights

Mega-tile prototype on SMD-HBU5



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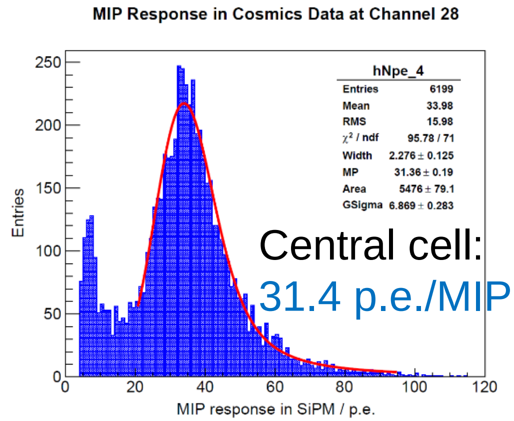
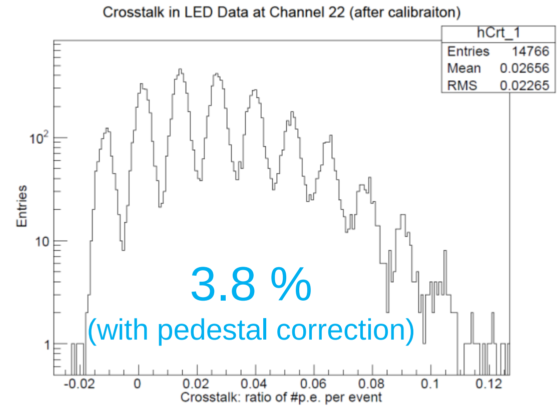


Optical crosstalk: UV light

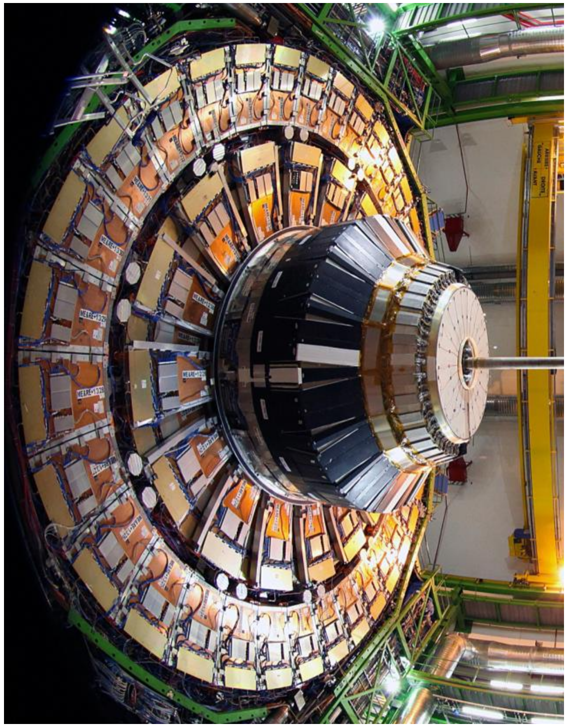


Full size mega-tile prototype

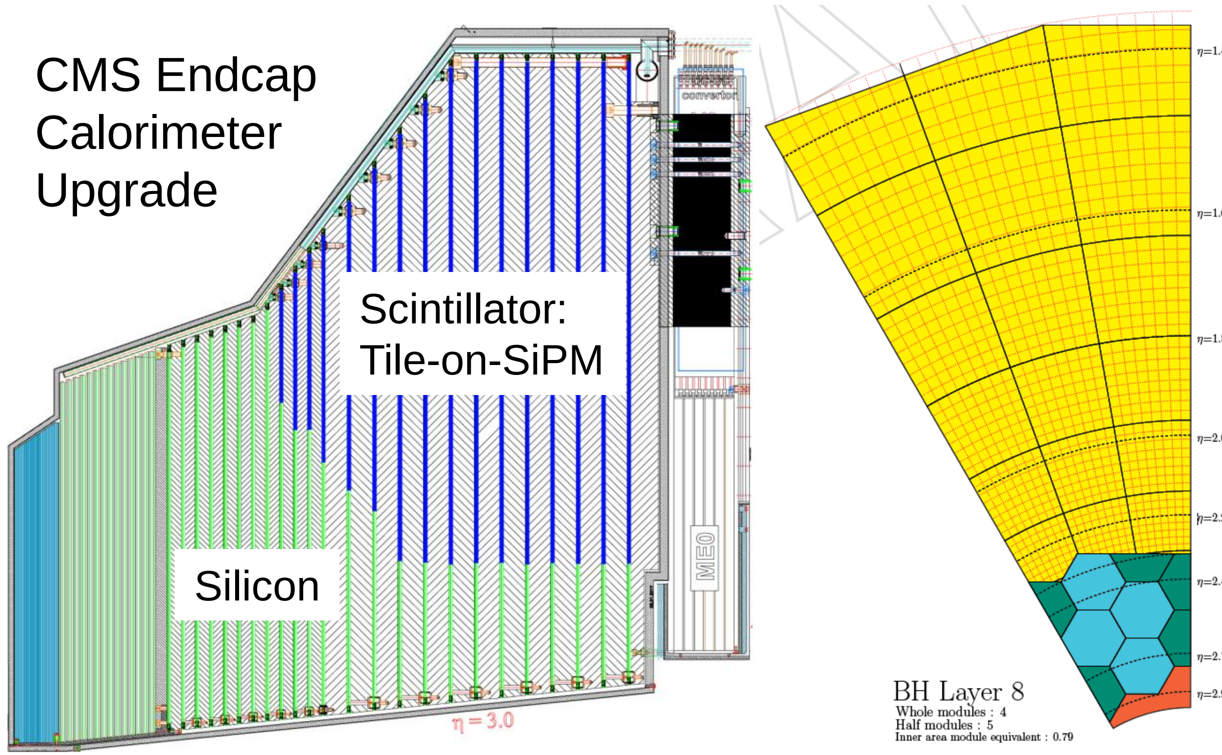
- Protoypes fully tested with
  - Cosmic muons
  - On-board LED
- Excellent performance
  - Moderate MIP response
  - Low optical crosstalk

- Mega-tile is proved to be a promising design for AHCAL

Other applications: CMS-HGC for HL-LHC

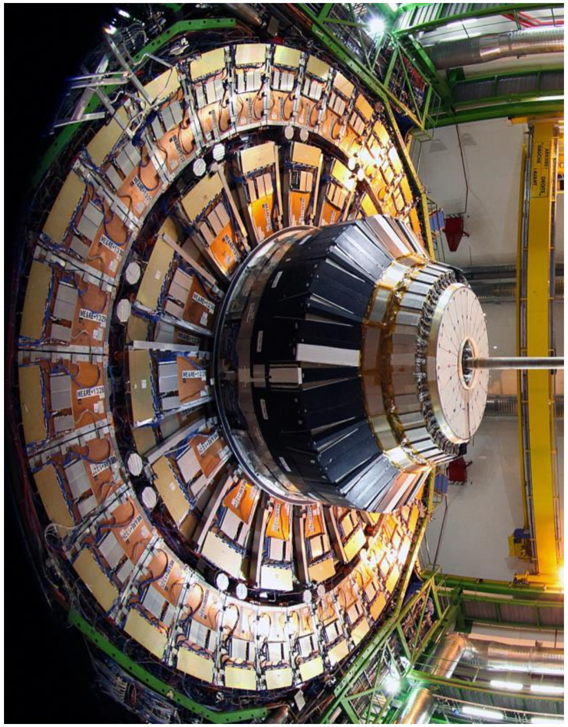


CMS Endcap Calorimeter Upgrade



- To cope with hash radiation environment at High-Luminosity LHC

Other applications: CMS-HGC for HL-LHC



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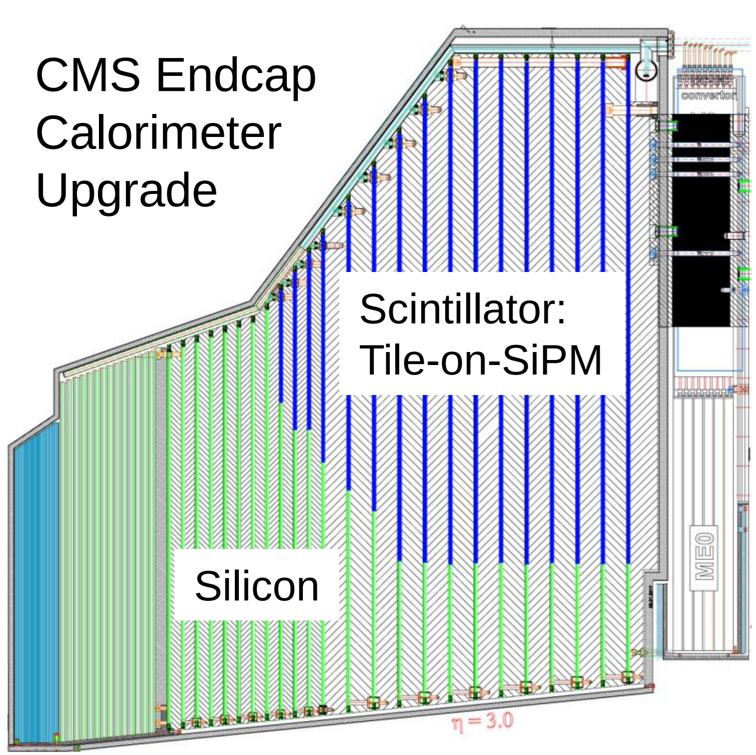
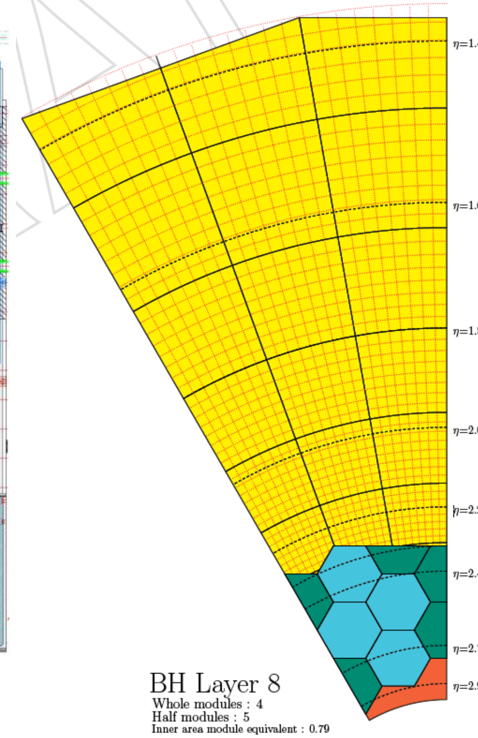
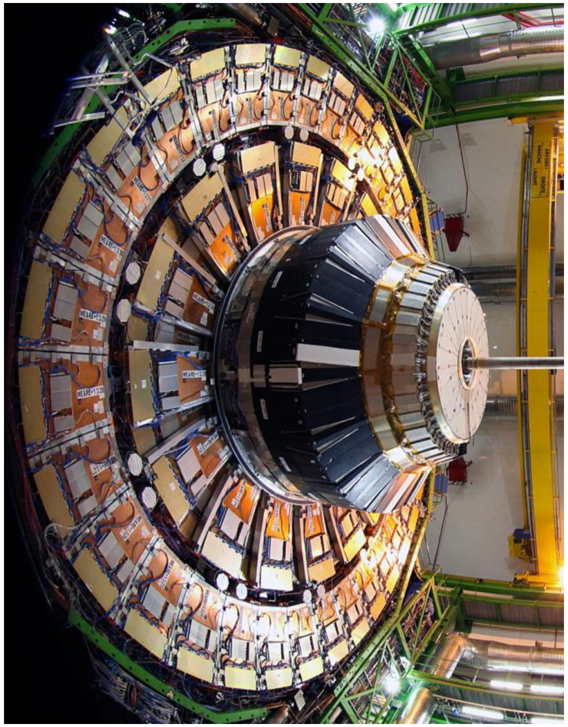


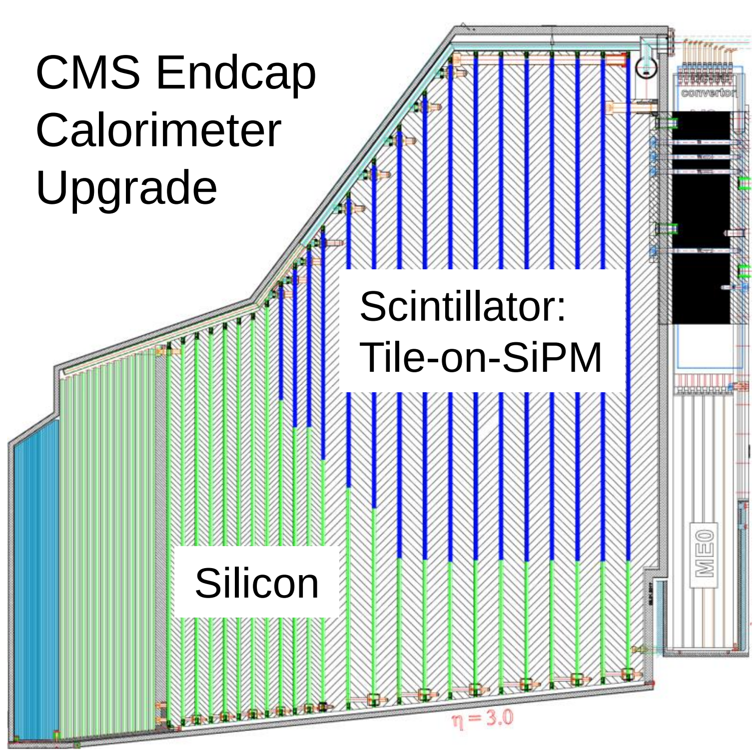


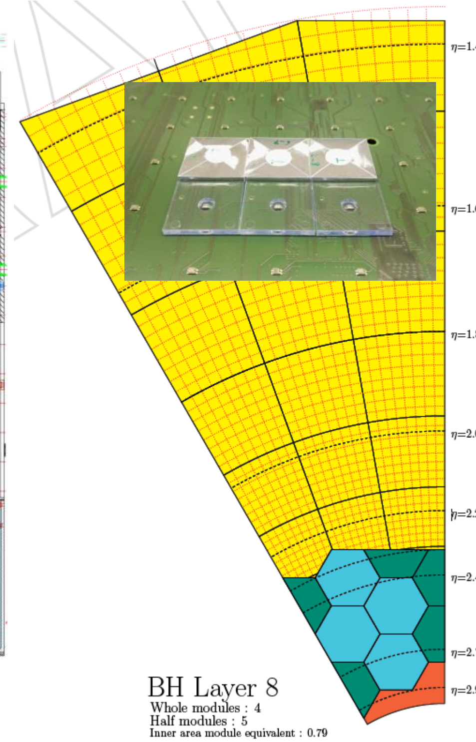
- To cope with hash radiation environment at High-Luminosity LHC
- Scintillator-SiPM technology in Back-HCAL (BH) part
  - Tile-on-SiPM design from CALICE
  - Operated at -30°C to migigate noises

Other applications: CMS-HGC for HL-LHC



CMS Endcap
Calorimeter
Upgrade





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Summary

- Development of a high-granularity calorimeter (AHCAL)
  - Based on scintillator tiles, read out by SiPMs

- Tile design, system integration and testing
  - The first to demonstrate mass assembly (now routine)
  - Excellent performance achieved
  - Tile design adopted as the <u>baseline</u> for AHCAL technological prototype

- Key setups
  - Integrated test stands for SiPMs and AHCAL readout boards

- Further development of calorimeter active layers
  - Mega-tile: proved to be a promising alternative

- Synergy with CMS: endcap calorimeter upgrade (HGC)

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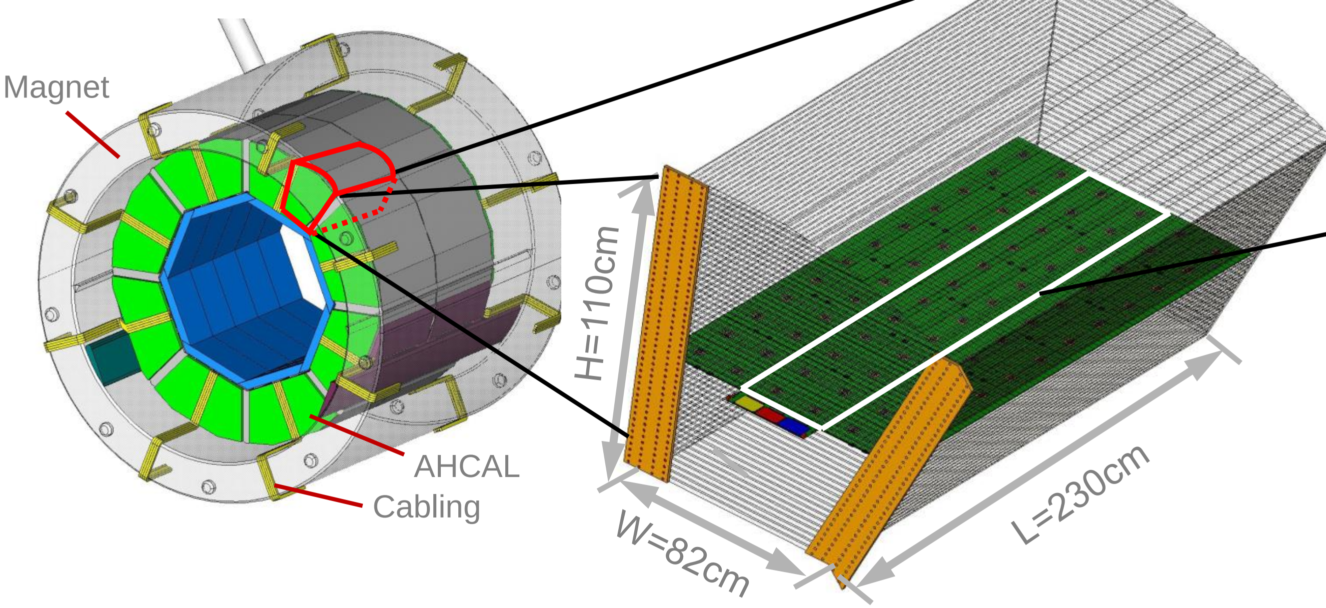
Thank you!

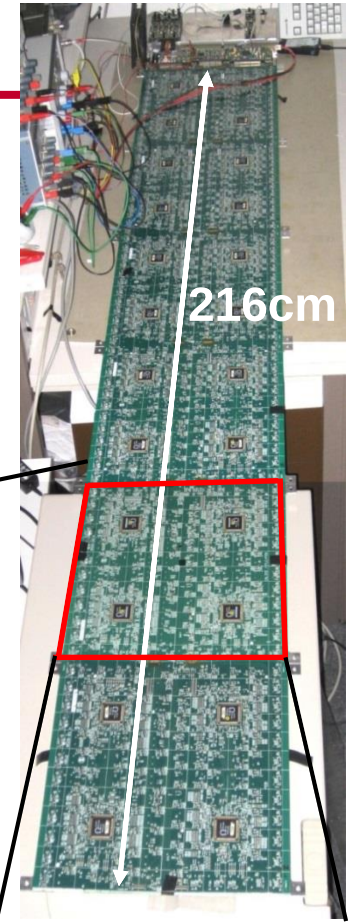
Backup

AHCAL overview

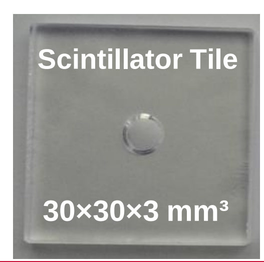
AHCAL inside magnet:
compact design

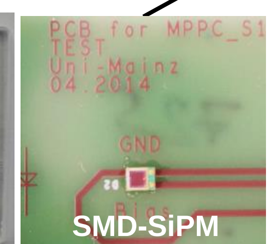
Technological Prototype:
fully scalable

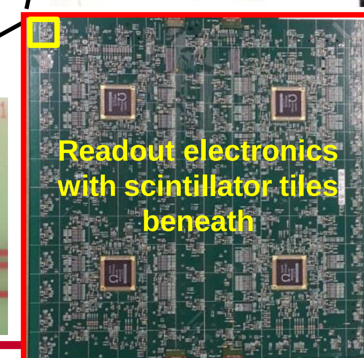




- Sandwich calorimeter based on scintillator tiles (3×3cm²) read out by Silicon Photomultipliers (SiPMs)
- Electronics fully integrated into active layers
- HCAL Base Unit (HBU): 144 channels (4 ASICs)
- High granularity: 8M channels in total
  - Challenges for mass assembly and data concentration

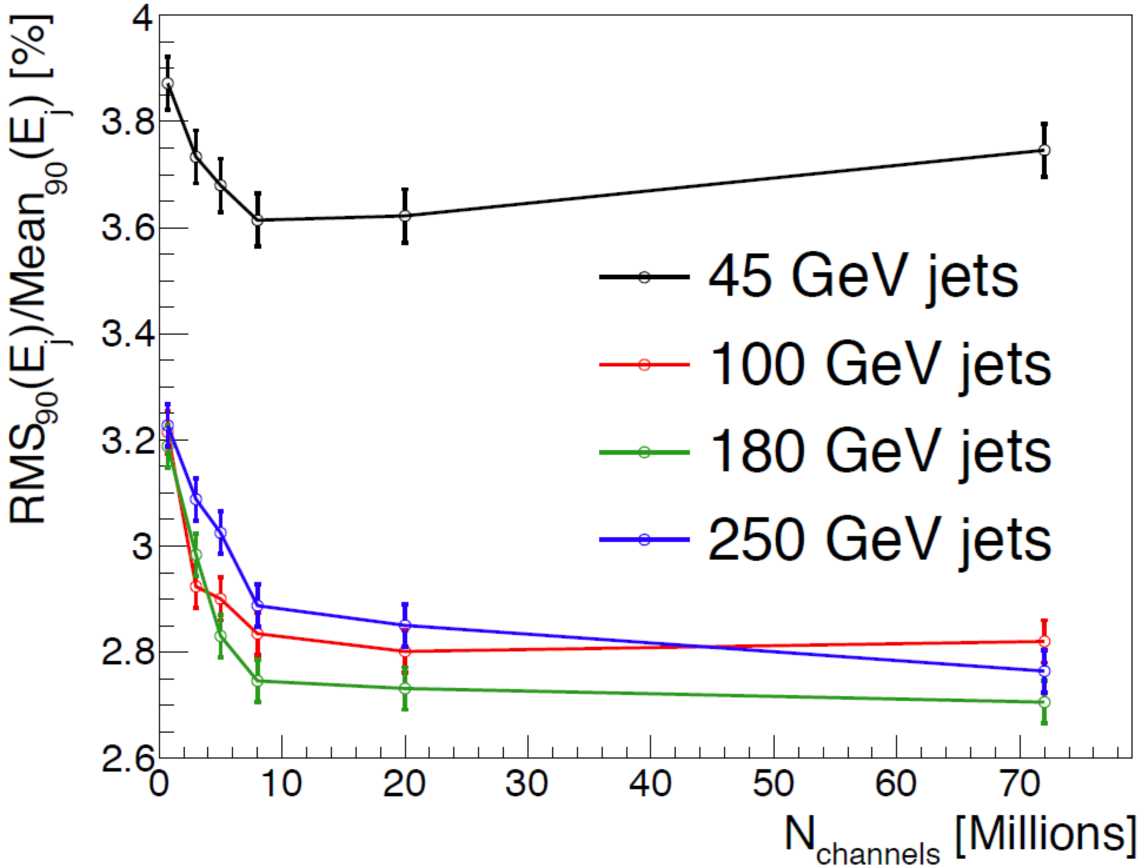






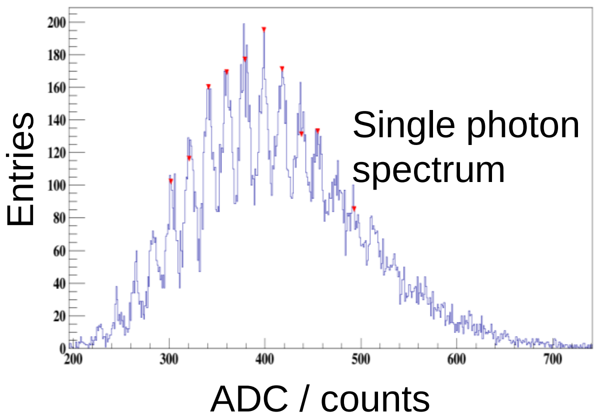
Calorimeter granularity optimization

- 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

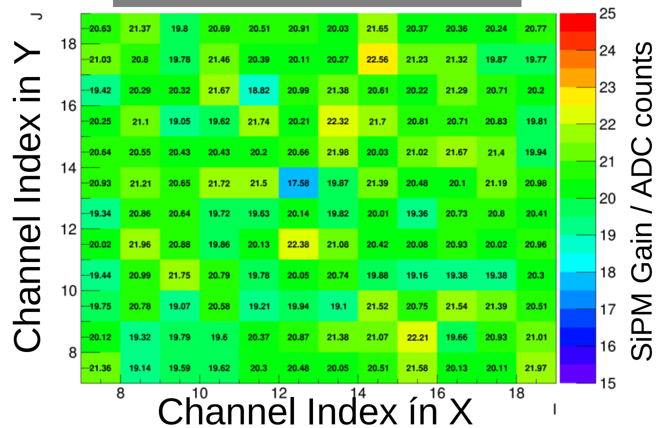


Commissioning: LED calibration and MIP response

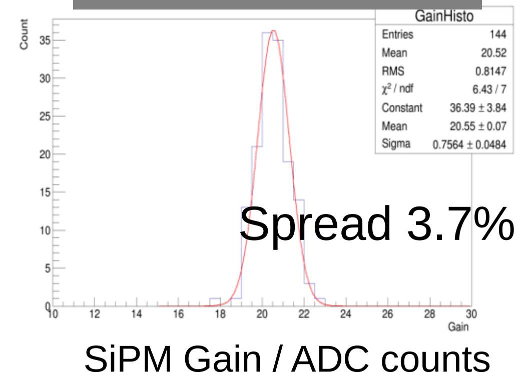
SiPM response to LED light



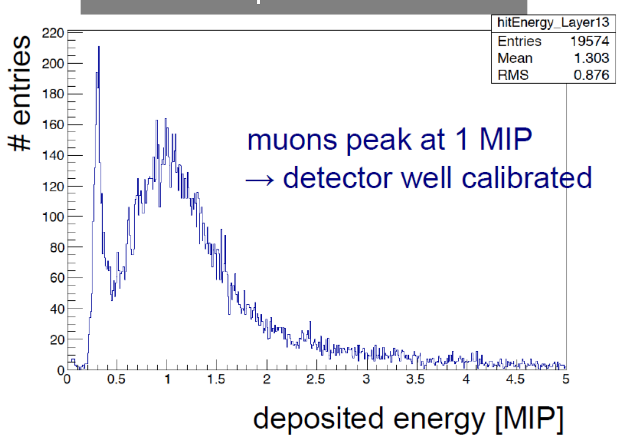
Gain Mapping of a HBU



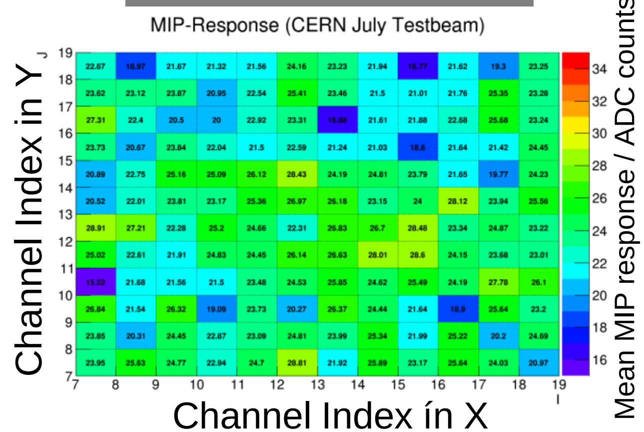
SiPM Gain of a HBU
(144 channels)



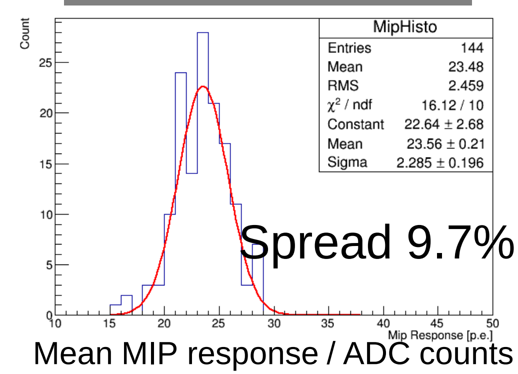
SiPM response to muons



MIP Mapping of a HBU



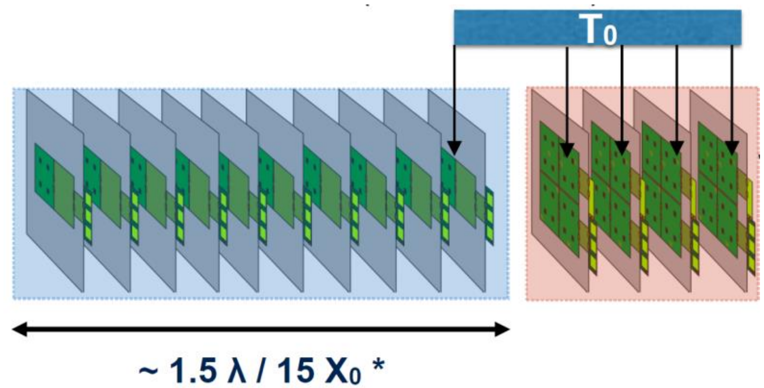
MIP Responses of a HBU
(144 channels)

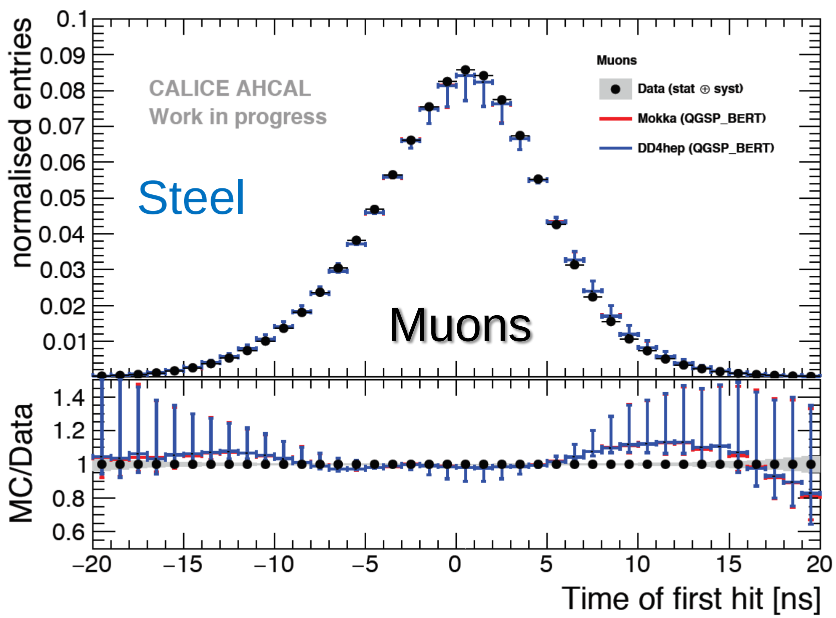


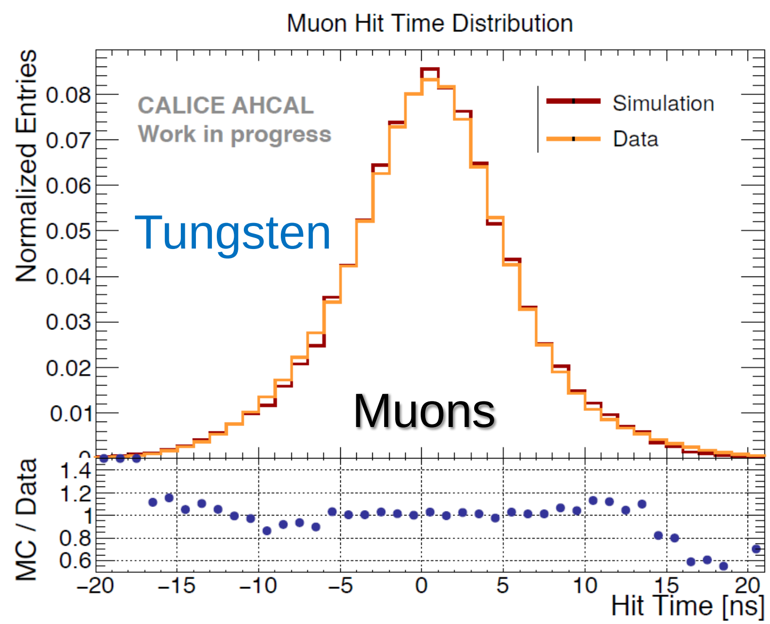
Promising performance achieved: uniform gain and MIP response

Timing analysis: muons

- 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



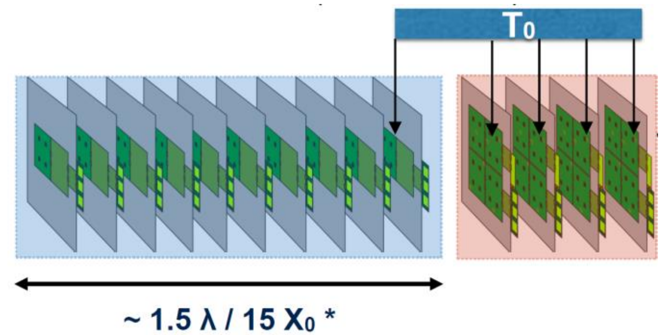




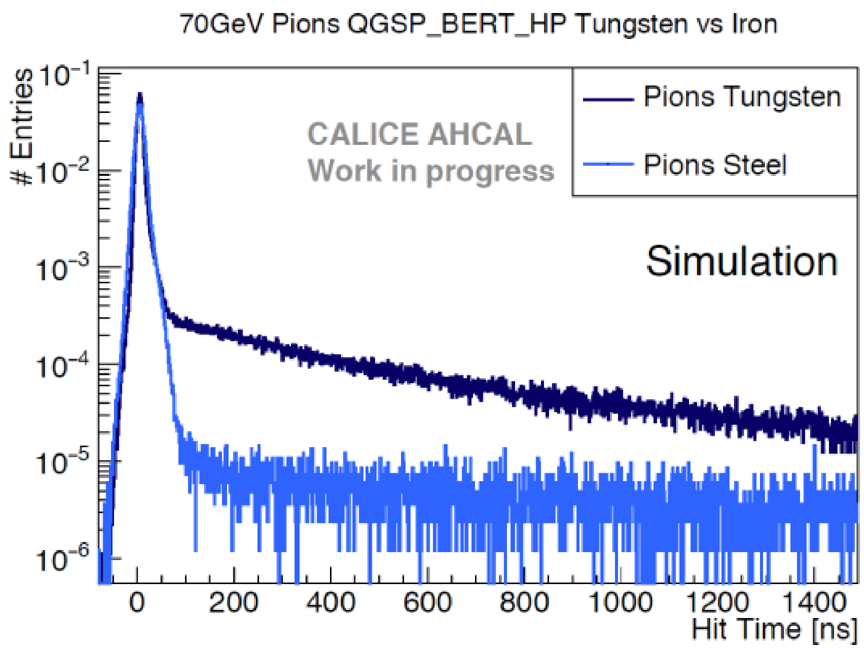
Timing analysis: pions

Geant4 v10.01, Mokka v08-05-01

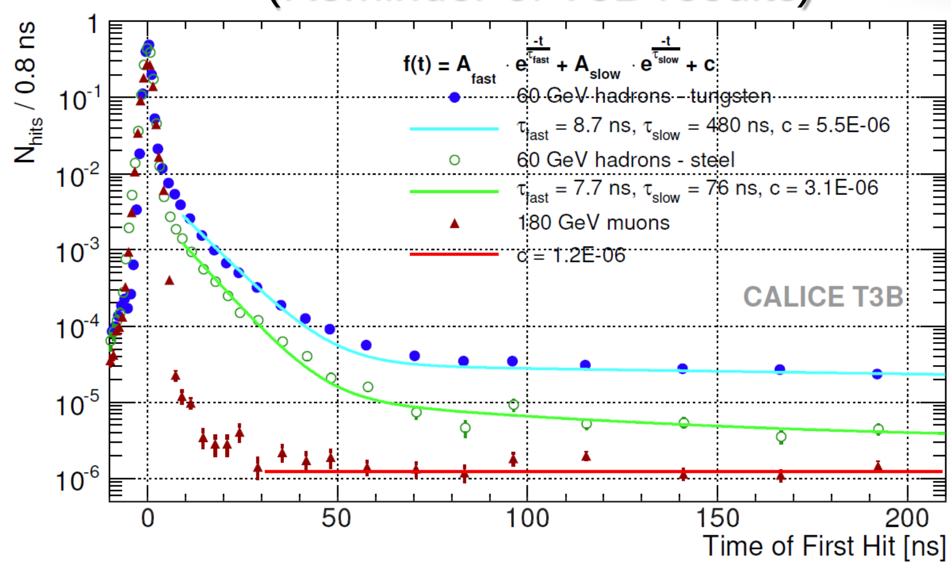
- Time calibration procedure established
  - Based on muon data/MC
- Ongoing analysis of electrons and pions



Teaser: comparison of absorbers in MC



Timing behavior of shower components (Reminder of T3B results)



Ongoing efforts: same to be done for data

JINST 9 P07022 (2014)