Development of a High-Granularity Calorimeter

Yong Liu
Johannes Gutenberg Universität Mainz

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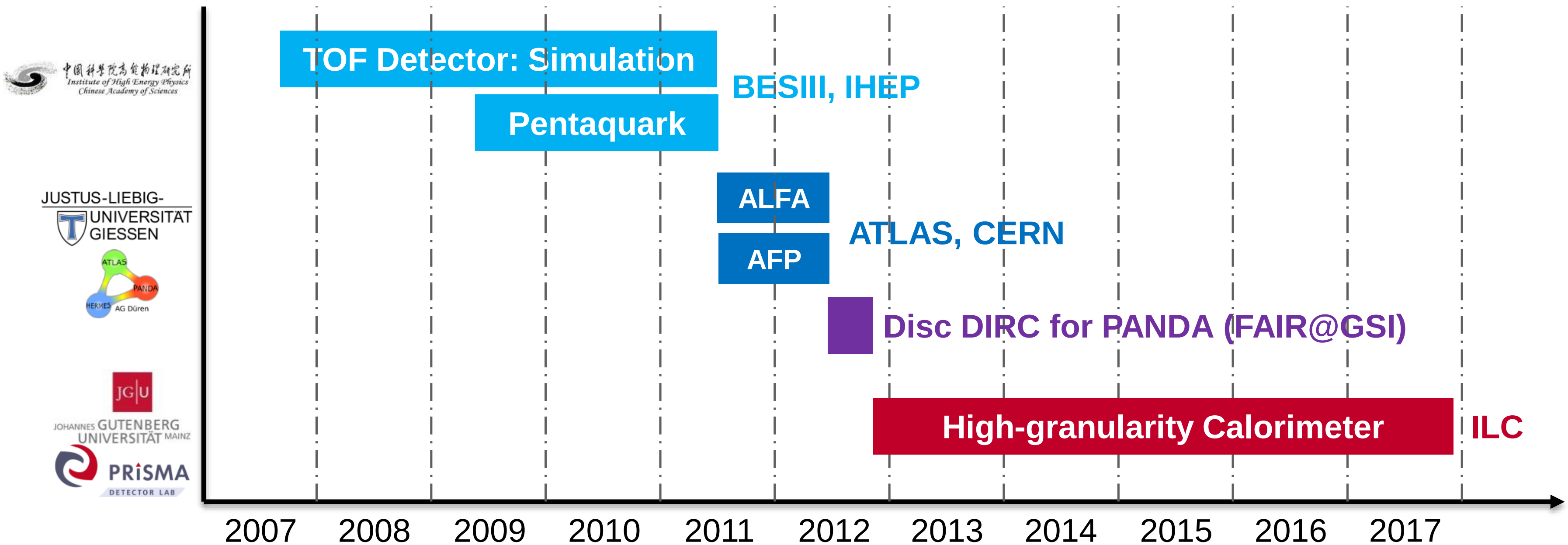
IHEP, Beijing

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

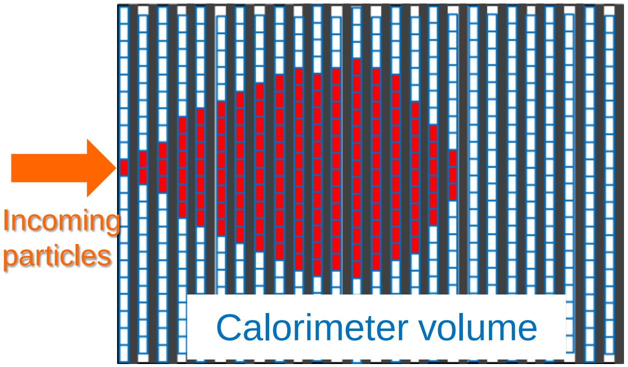


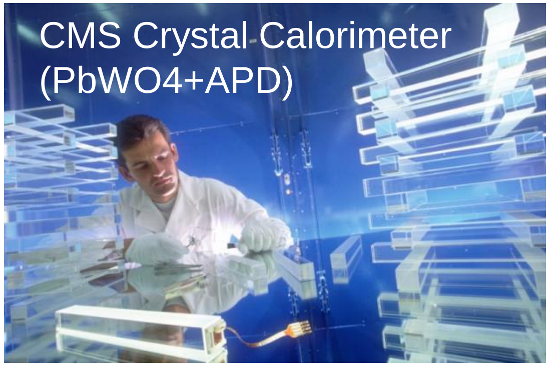
Outline

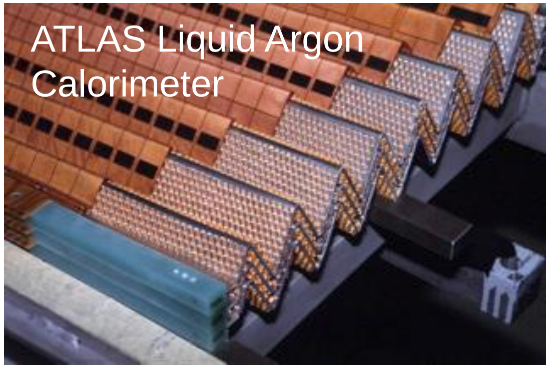
- Calorimeter in a nutshell
  - Why high granularity?
- Prototypes of a high-granularity hadronic calorimeter
  - Based on SiPM and scintillator tiles
  - Tile-on-SiPM design
  - Readout boards assembly, system integration
  - Beam test campaigns
- Ongoing and further R&D efforts
- Summary

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
- 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)
      - Typical: scintillator, noble liquid, semiconductor, gas chamber, …







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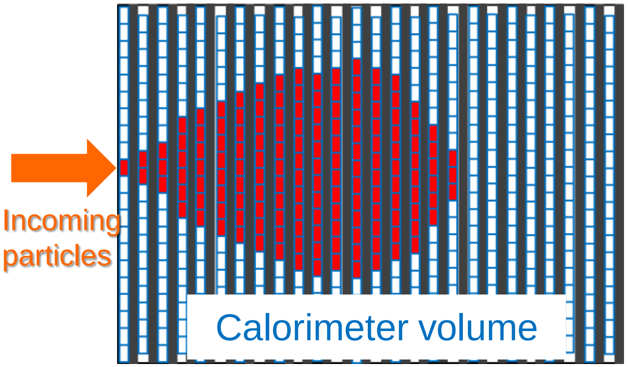
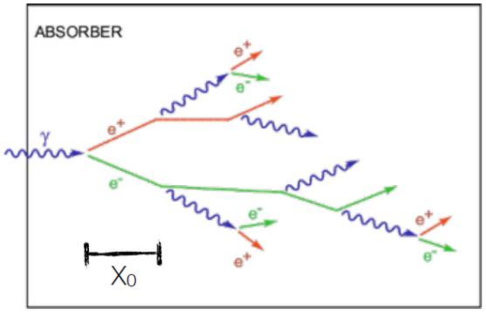
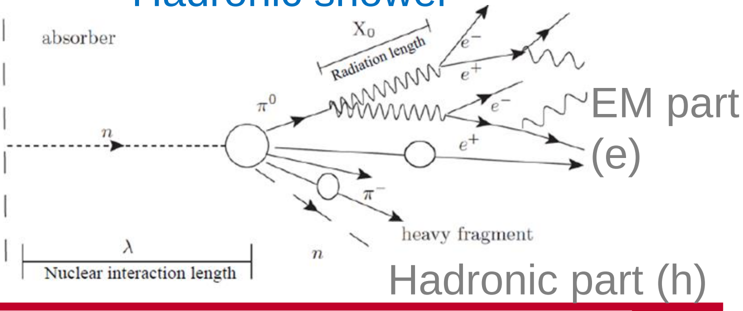
- Categorized by showers
  - For electromagnetic (EM) showers
    - Gammas, electrons, positrons
  - For hadronic showers
    - Protons, neutrons, pions, kaons
    - EM component: compact (e.g. $\pi^0 \rightarrow \gamma\gamma$)
    - Hadronic component: sparse (more depth)
      - undetectable energy: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



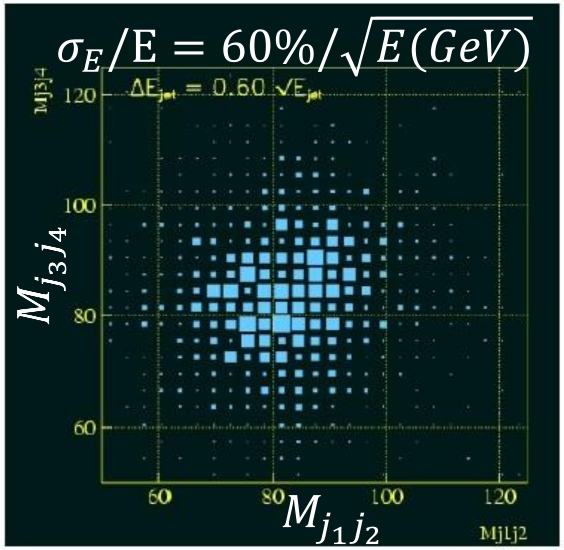
EM shower



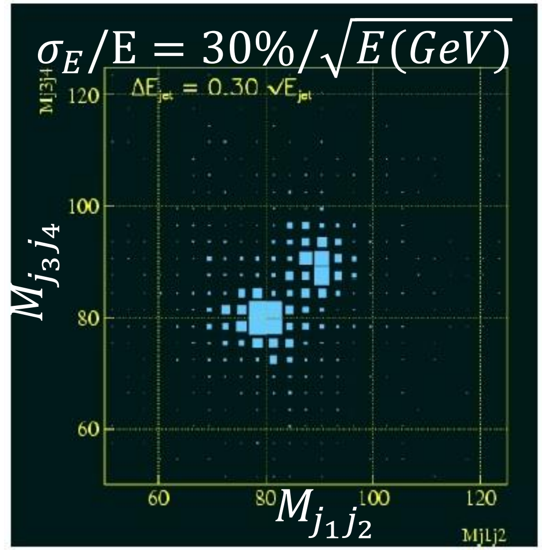
Hadronic shower



Precision physics and calorimetry



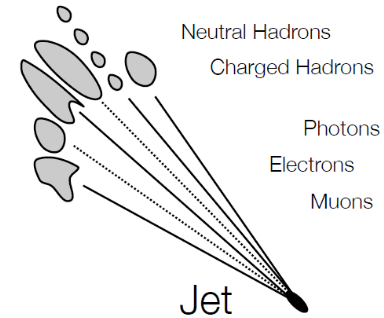
PFA



$ee \to ZHH$

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

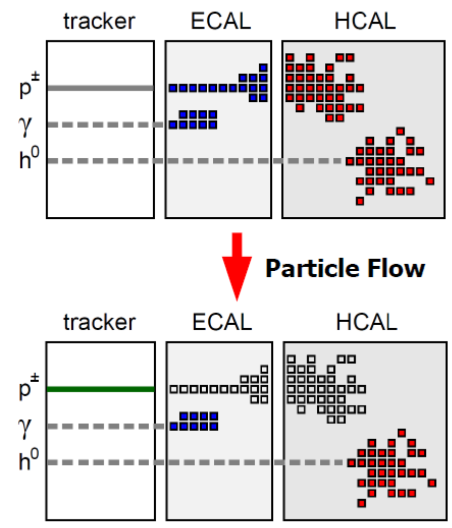
$ee \to \nu\nu ZZ \to \nu\nu qq$



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

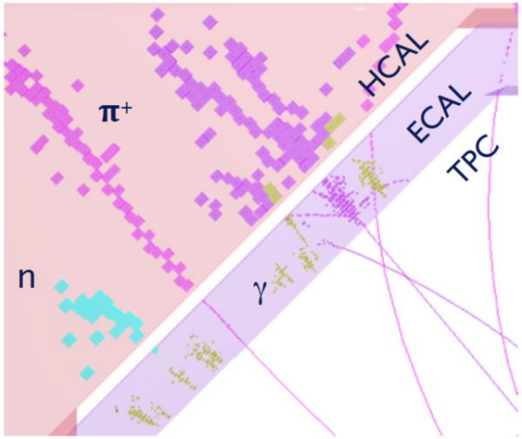
Particle-flow algorithm

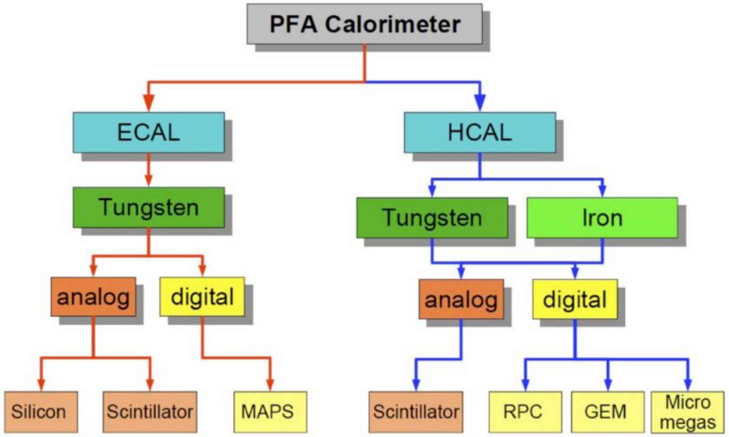
Components in jets	Detector	Energy Fraction	Energy Resolution
charged particles ($X^{\pm}$)	Tracker	$60\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$30\%\ E_j$	$0.15\sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$10\%\ E_j$	$0.55\sqrt{E_h}$



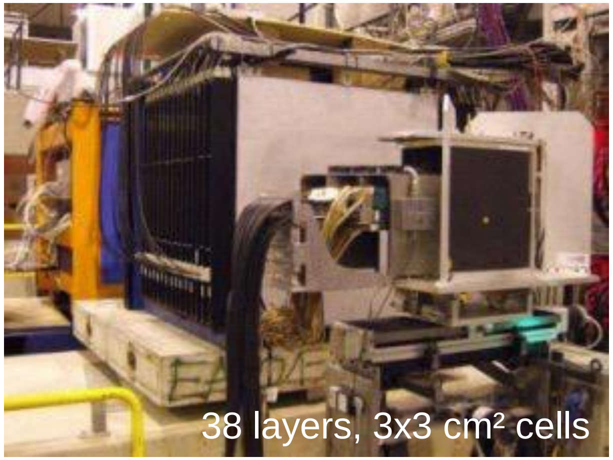
- Particle Flow
  - Choose sub-detector best suited for each particular particle type
    - Charged particles measured in tracker
    - Photons in ECAL
    - Neutral hadrons in HCAL
  - Separation of energy depositions of close-by particles in the calorimeters
- Imaging calorimeter
  - Jet energy resolution: $\sigma_E/\mathrm{E} = 30\%/\sqrt{E(GeV)}$
  - Calorimeter hardware: highly granular (explosion of total channel number)

High-granularity calorimeters





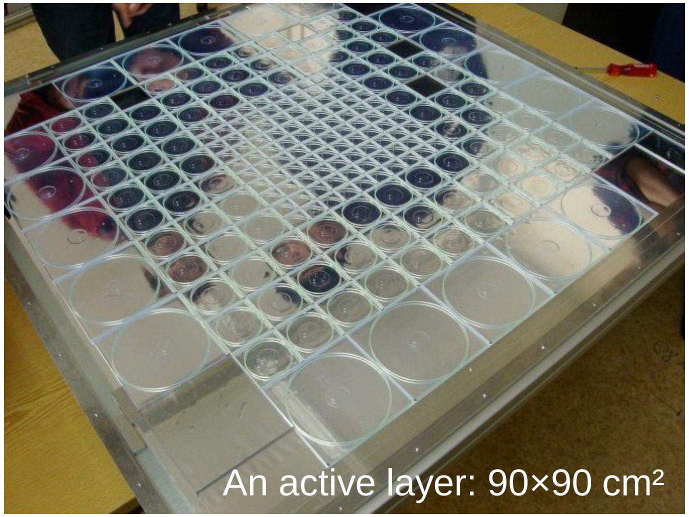
- Crucial for particle-flow algorithm (PFA)
  - Typical jet energy: 50-250 GeV
- Technologies developed within CALICE
  - Sensitive: silicon, gas, scintillator
  - Absorber: stainless steel, tungsten
- Physics prototypes
  - PFA: proof of principle
  - Validate simulation models
    - Test-beam data: various particles/energies
    - Detailed studies on showers in Fe and W



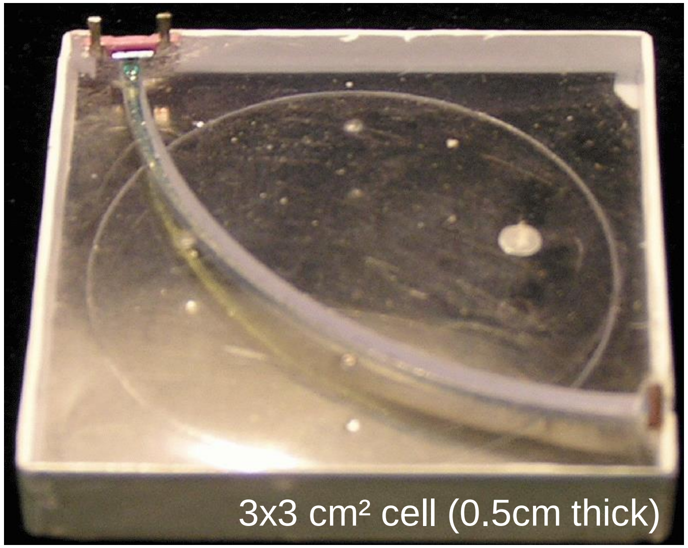
Physics prototype of Sc-HCAL with Fe/W

Analogue HCAL: physics prototype

- Sensitive layers
  - Scintillator tiles
  - Silicon Photomultipliers (SiPMs)
  - Light collection via WLS fiber
  - Higher granularity in the layer center
- Absorber structures
  - Steel: 38 layers ($4.5\lambda_I$)
  - Tungsten: 38 layers ($4.9\lambda_I$)
- In total ~ 8000 channels
  - Built in 2006
  - Taken data till 2011 (11 papers)
    - Beam tests at CERN and FNAL



An active layer: 90×90 cm²

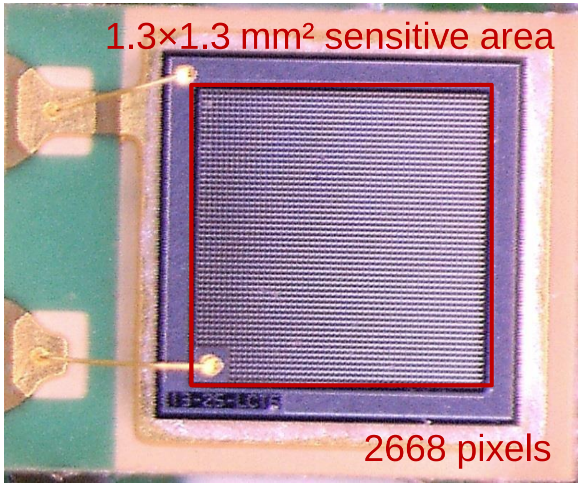


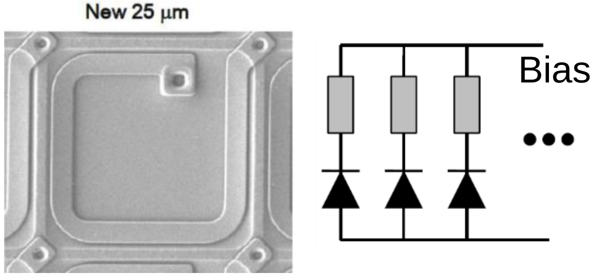
3x3 cm² cell (0.5cm thick)

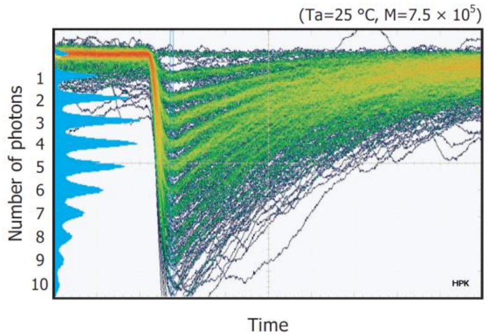
SiPM: in a nutshell

- 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

- GM-APD (aka cell, pixel, etc.)
  - Intrinsic binary counter
  - Usually analogue readout in electronics
    - Current, or voltage, or integrated charge

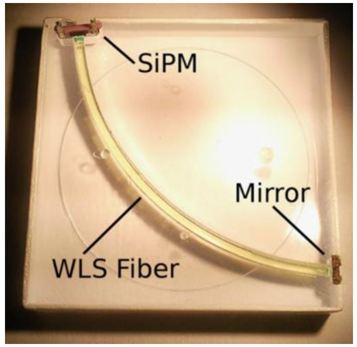


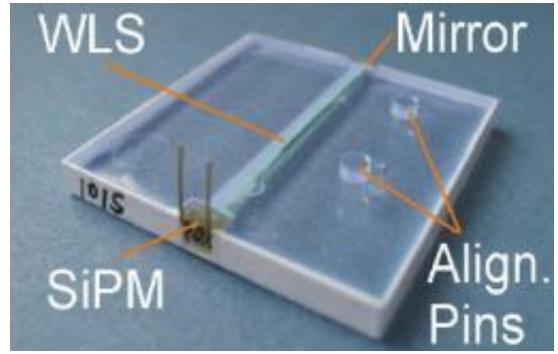




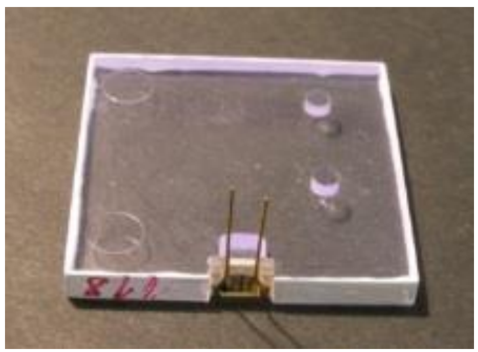
Tile-SiPM design

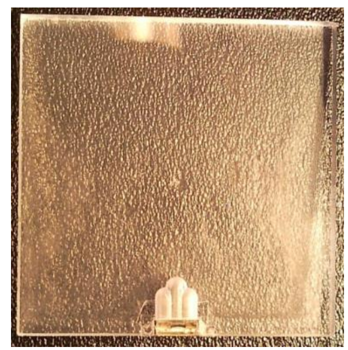
SiPM detects light via WLS fiber

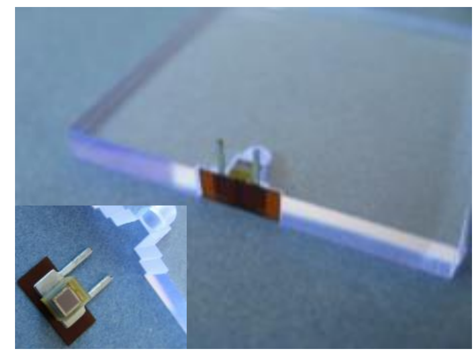




SiPM directly collects light from tile (wo fiber)

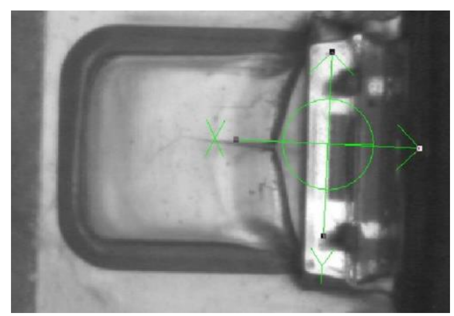






First glue SiPM to tile,
then solder SiPM onto PCB

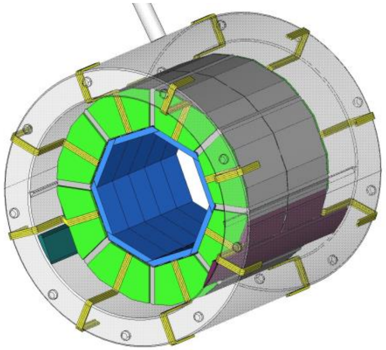
Feasible via manual handling, but not suitable for <u>mass assembly</u>

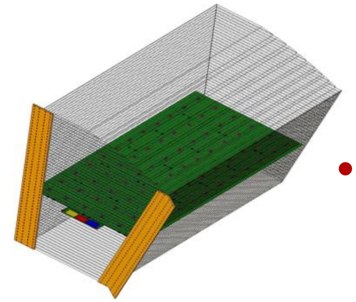


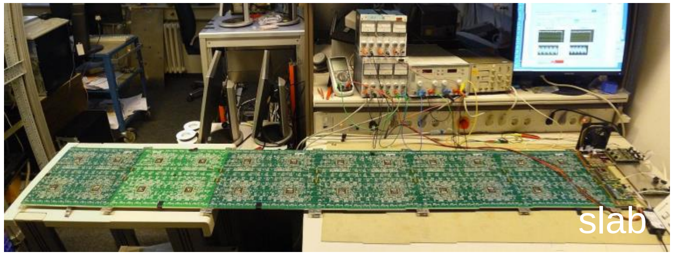
Scintillator partially (near SiPM) melted during soldering, due to heat transfer via soldering pads

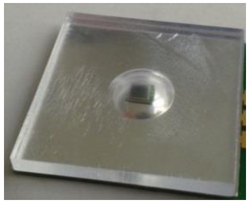
Why mass assembly?

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





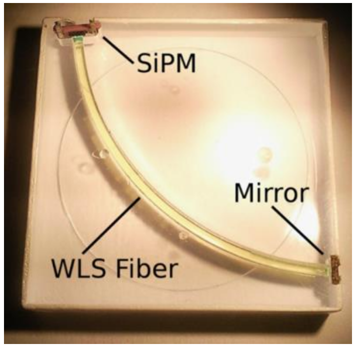


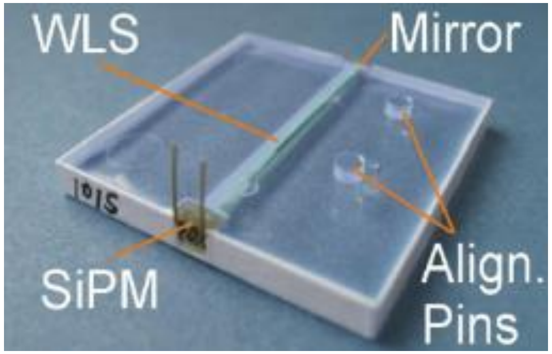


- 1 year
- 46 weeks
- 230 days
- 2,000 hours
- 120,000 minutes
- 7,200,000 seconds

Tile-SiPM design: evolution

SiPM detects light via WLS fiber





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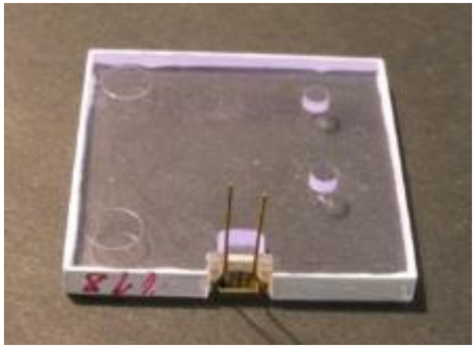
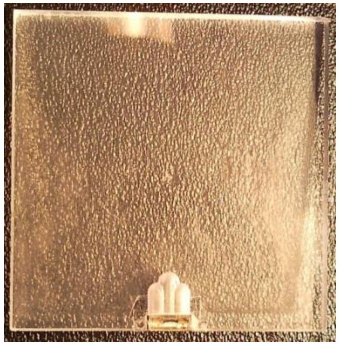
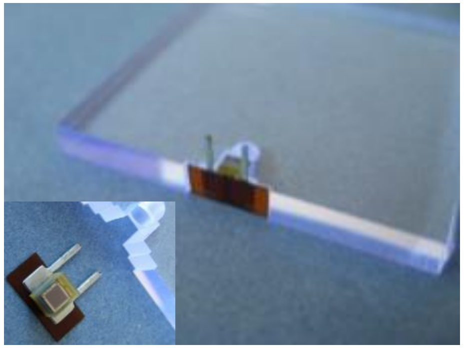
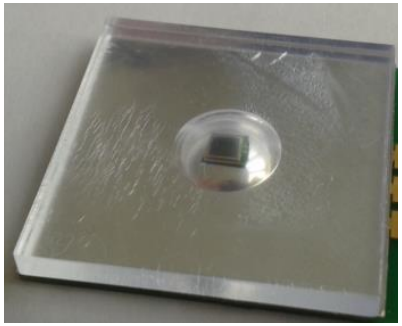




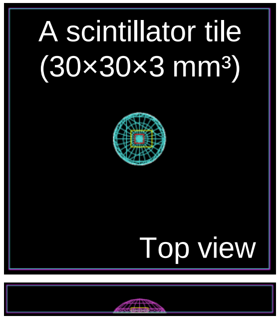


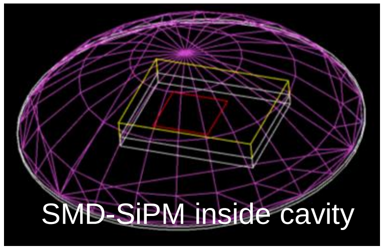
New tile-on-SiPM design suitable for mass assembly

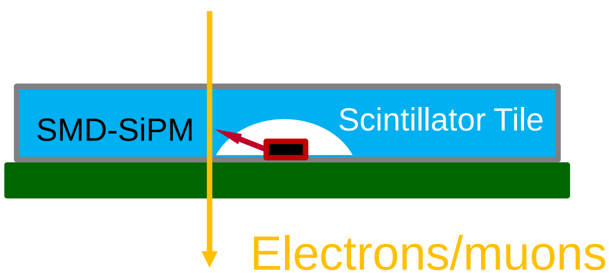


SMD-SiPMs first soldered as the other SMD components, then tiles placed on top of SiPMs

Tile-SiPM design: evolution

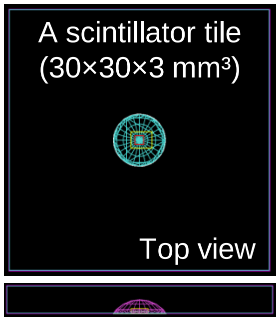


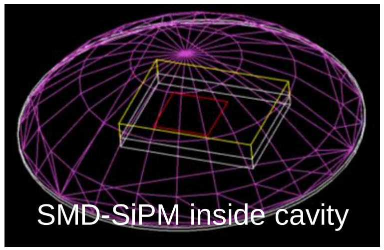


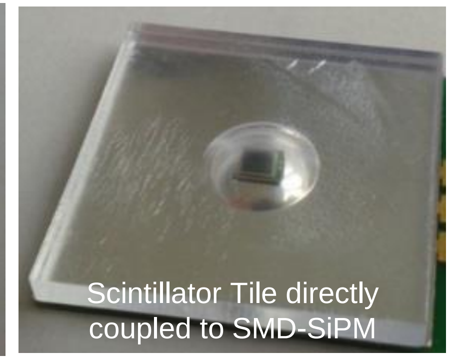


- Prototyping guided by simulation
  - How to couple SiPM to scintillator tile?
  - Vary cavity shapes, sizes, surface properties…
- Simulation based on Geant4
  - All (related) physics processes
  - Detailed geometry descriptions
  - Wavelength-dependent parameters
- Aims
  - High efficiency for light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

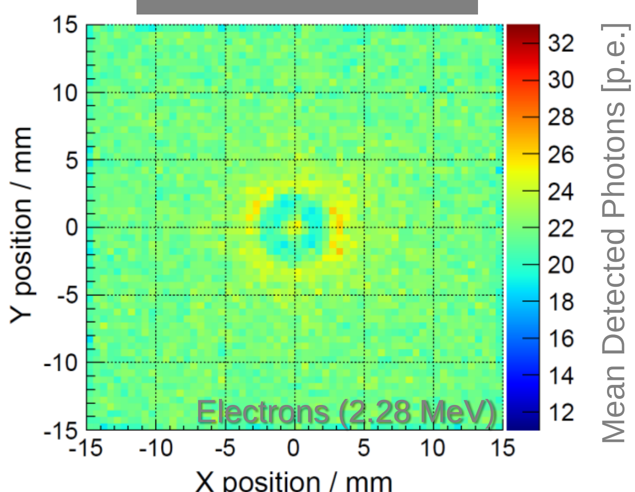
Tile-SiPM design: evolution



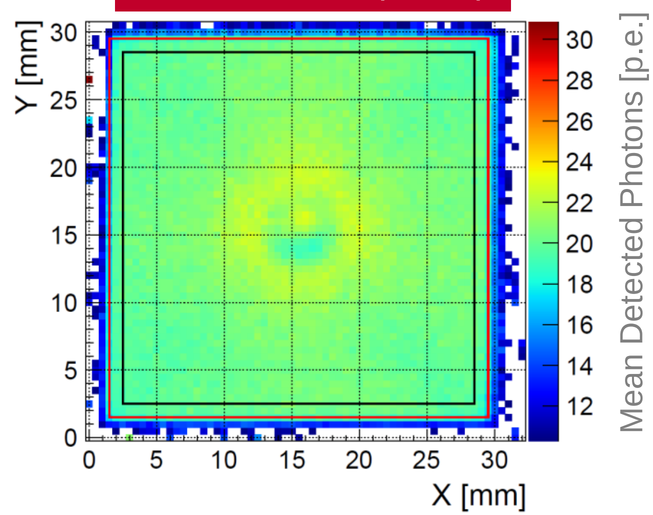


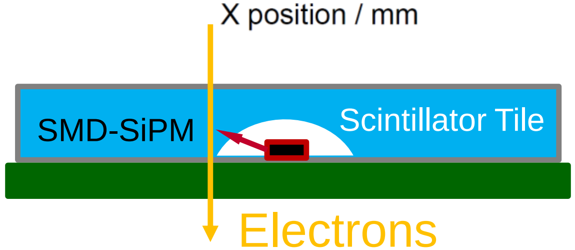


Geant4 simulation



Measurement (Sr-90)

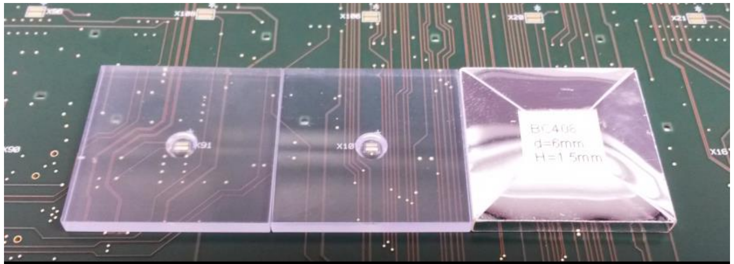




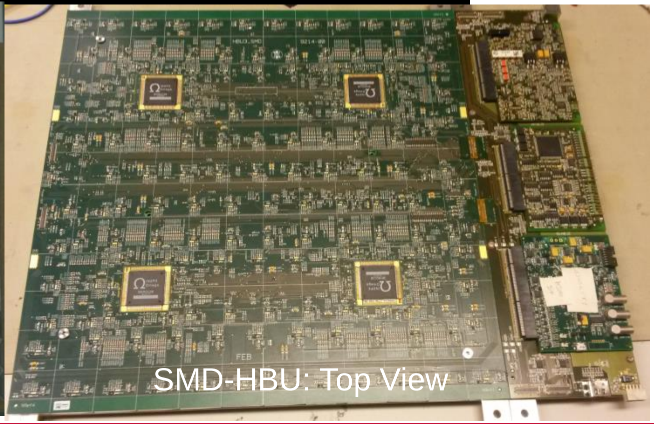
Optimal design achieved: suitable for mass assembly; good S/N; excellent response uniformity

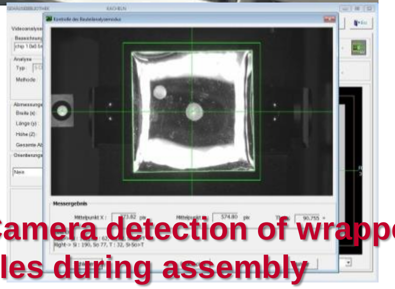
Pioneering activities: mass assembly

- 1^{st} 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

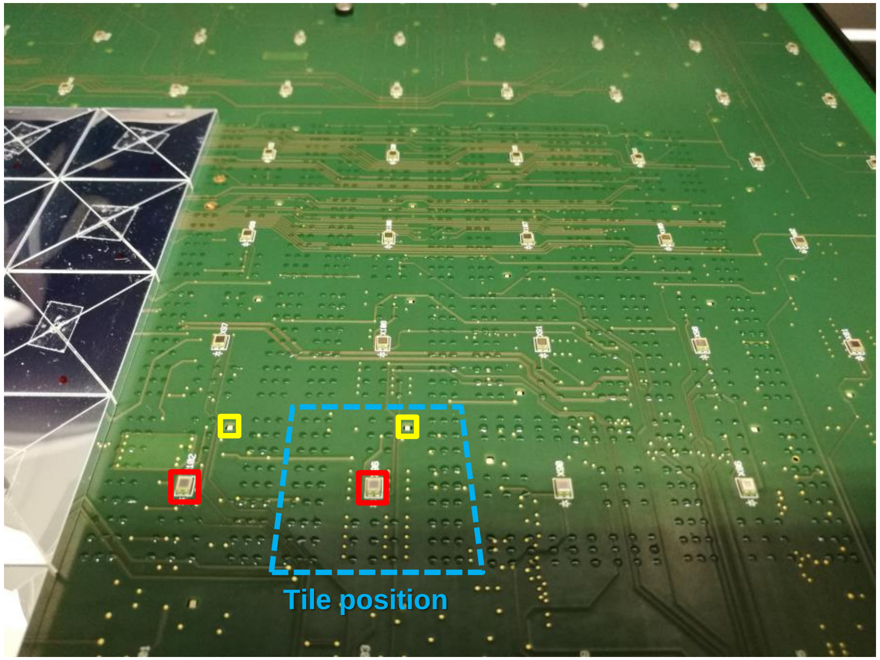


1^{st} generation of Mainz SMD-HBU: before assembly

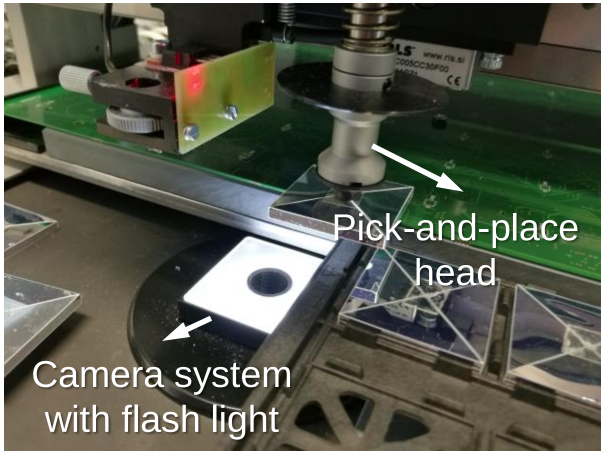


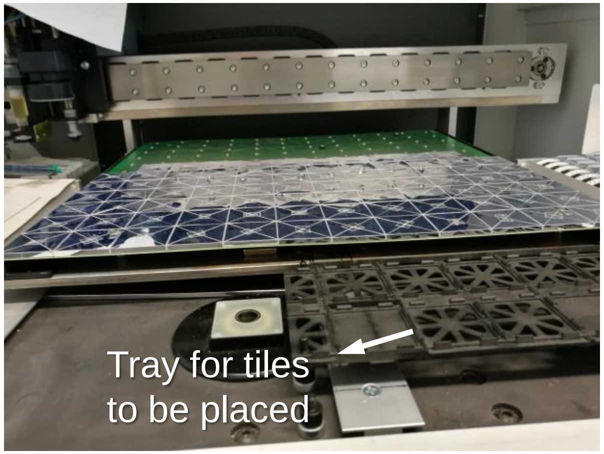


Mass assembly: routine procedure



- 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

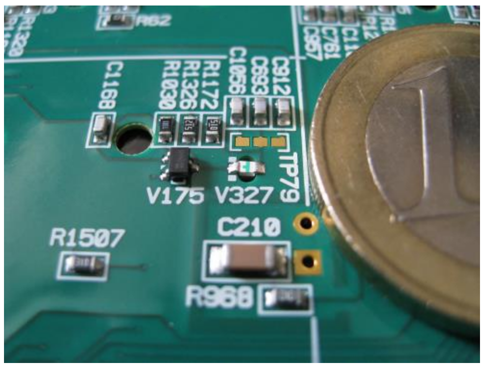




- 2017: ~170 new boards will be fully assembled and tested

SMD-HBUs commissioning

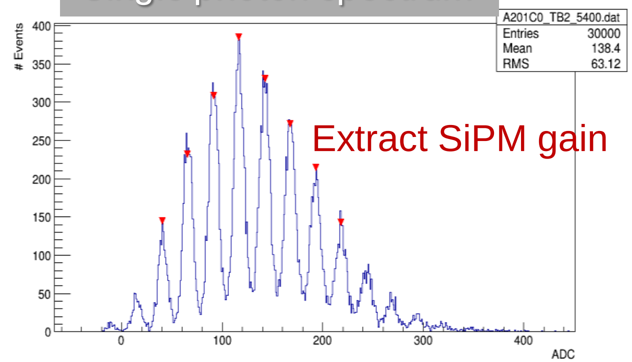
- Test readout boards after mass assembly
  - LED: extraction of SiPM gain; temperature monitoring
  - Muons: measurements of MIP response in a dedicated cosmic-ray setup



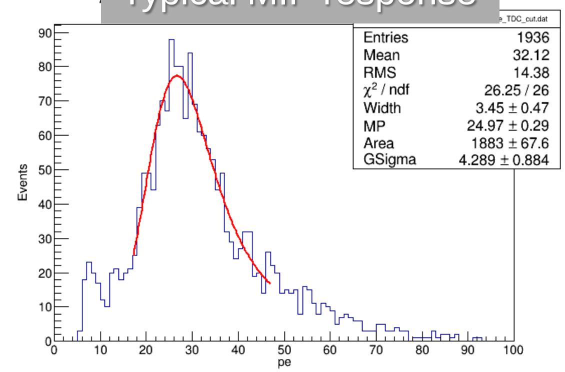
LED (in a hole) emits light to a tile (equipped on the other PCB side)

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

Single photon spectrum



Typical MIP response

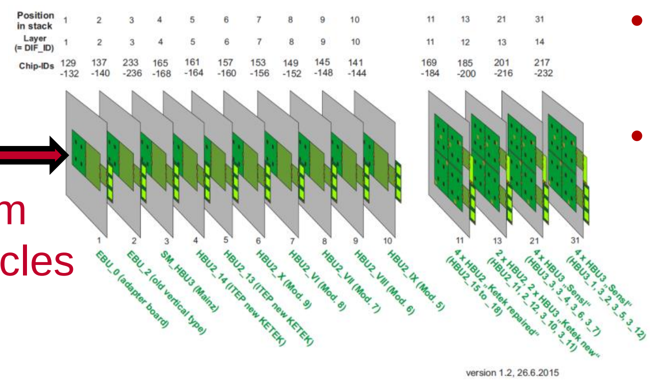


Gain mapping of one HBU

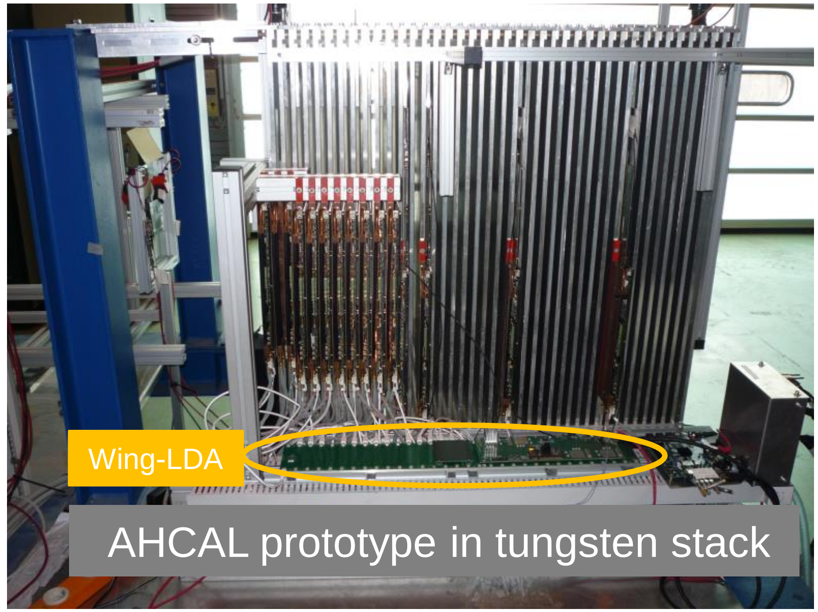
MIP response mapping

Test beam campaigns: CERN-SPS in 2015

Beam particles

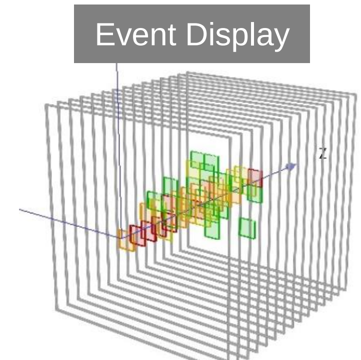


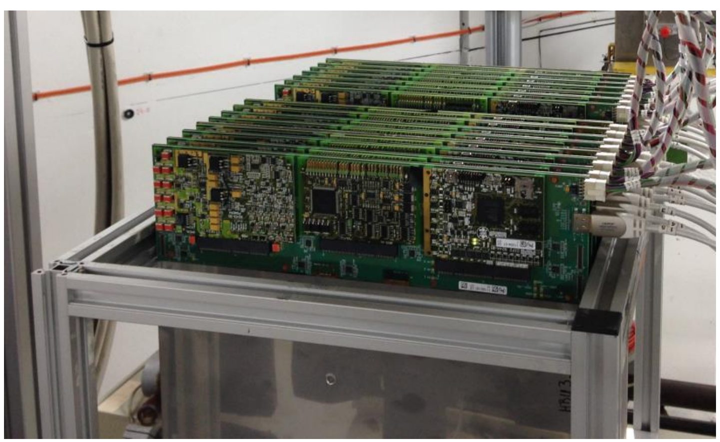
- Tested both steel and tungsten stacks
  - Infrastructure for 48 layers; partially instrumented
- System integration: scalable setup
  - Interface boards (Power, DIF, Calib): can handle a full layer
    - Power board: optimized for power pulsing
    - DIF board: equipped new FPGA to communicate with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

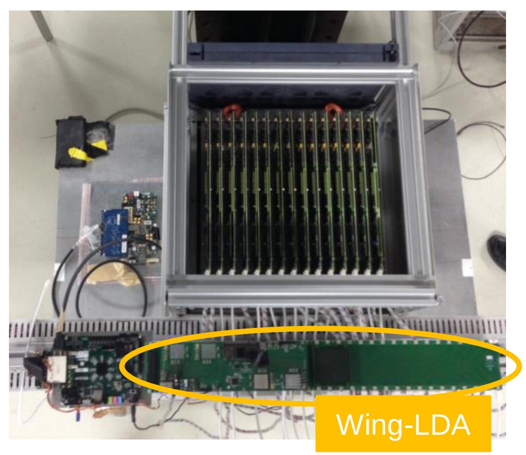


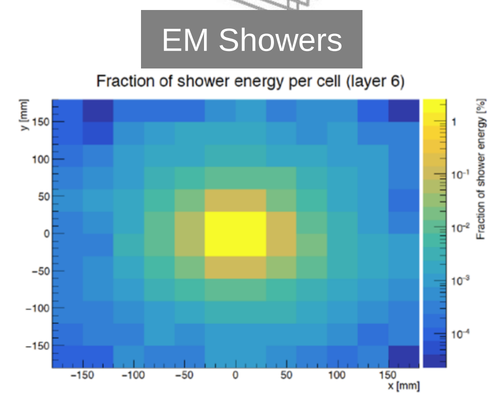
Test beam campaigns: DESY in 2016

- 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





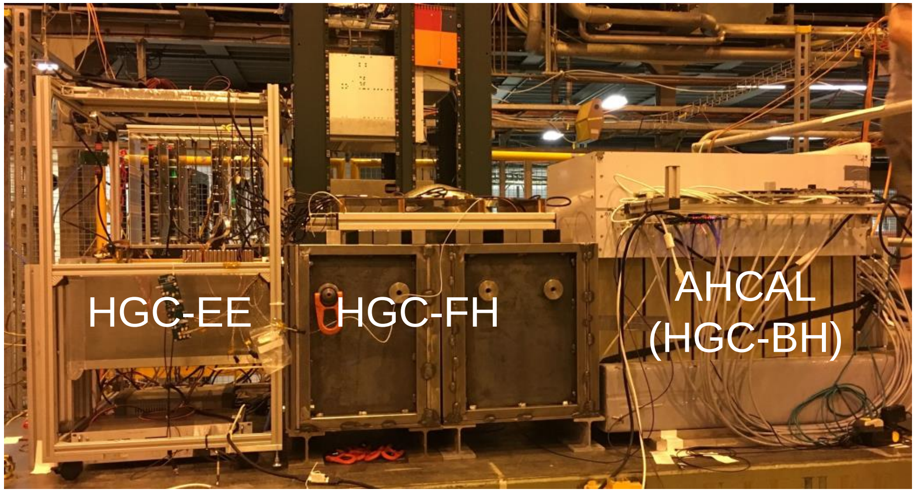




Test beam campaigns: CERN-SPS in 2017

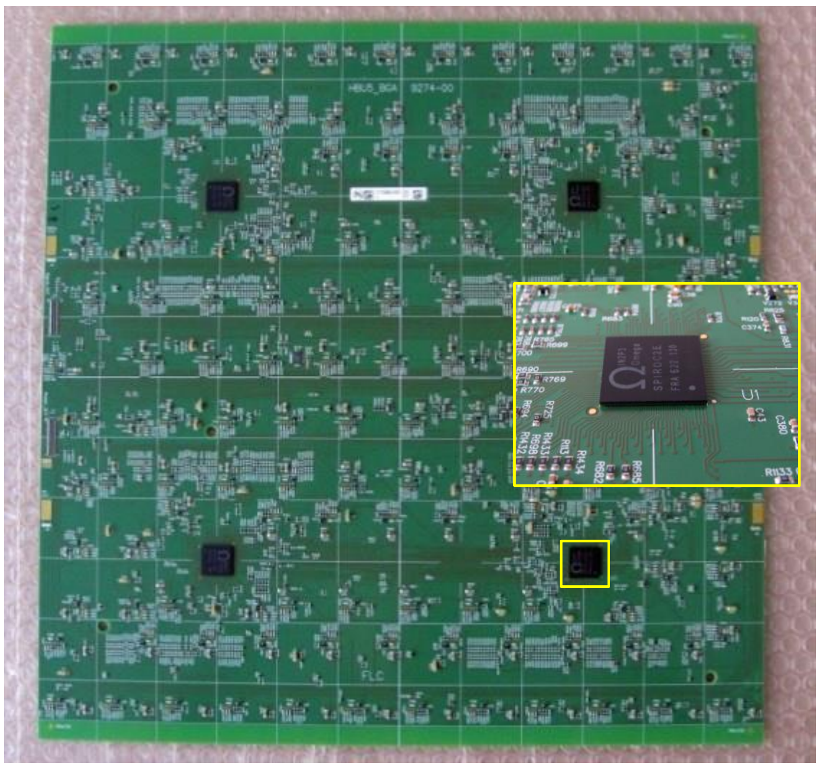
- CALICE beam test with magnetic field
  - Only 1.5 T possible (aimed 3T)
- Technical aim
  - Power pulsing in magnetic field
- Physics aim
  - Performance with electrons

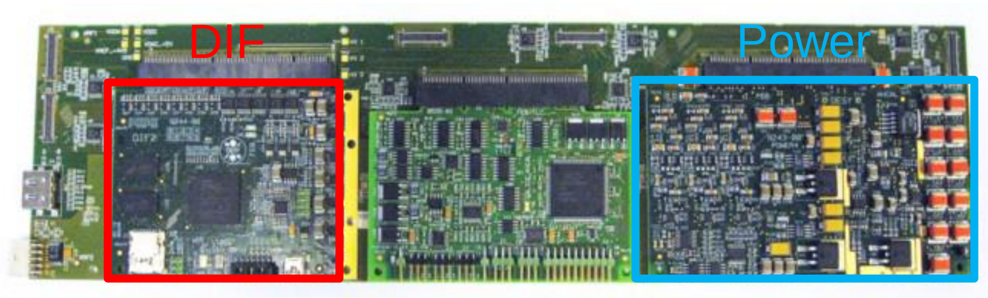
- CALICE-CMS common beam test
  - DAQ integration: EUDAQ
  - Active temperature compensation for SiPMs



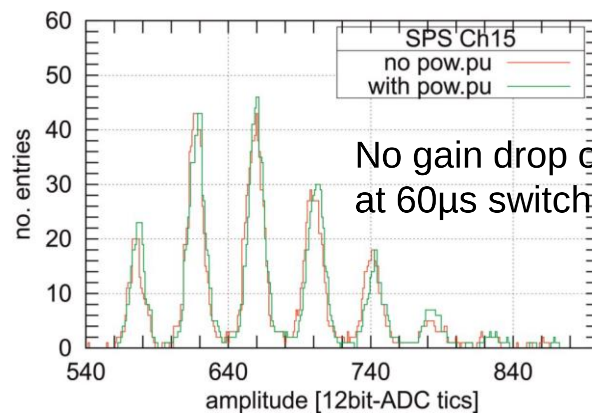
New electronics

- New AHCAL readout boards (HBUs)
  - With updated ASIC chips (SPIROC2E) in new packages (BGA)
- New interface boards
  - Detector Interface (DIF) board: equipped with modern FPGA
  - Power board: reduced heat dissipation, optimized for power-pulsing, etc.





LED data w/wo power pulsing

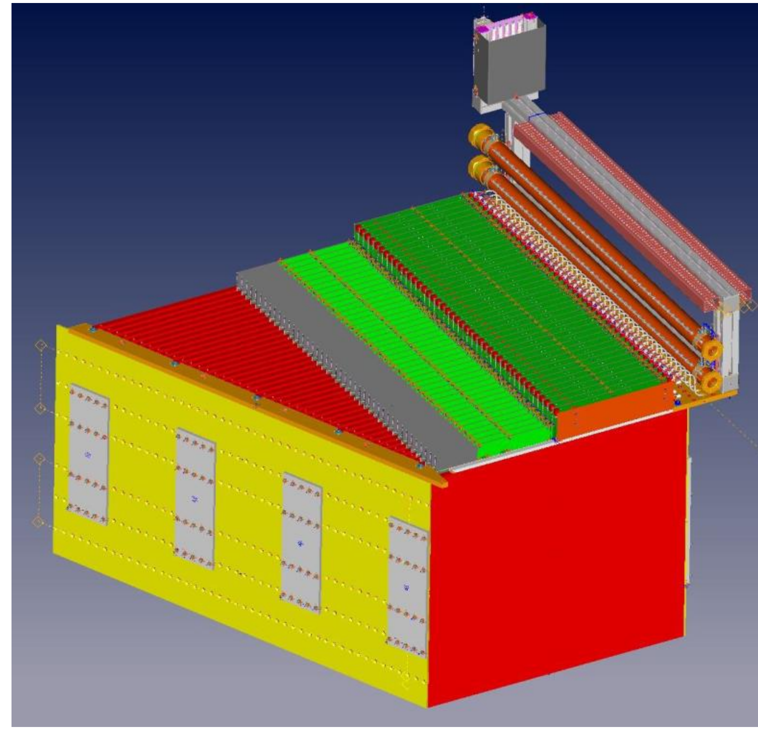


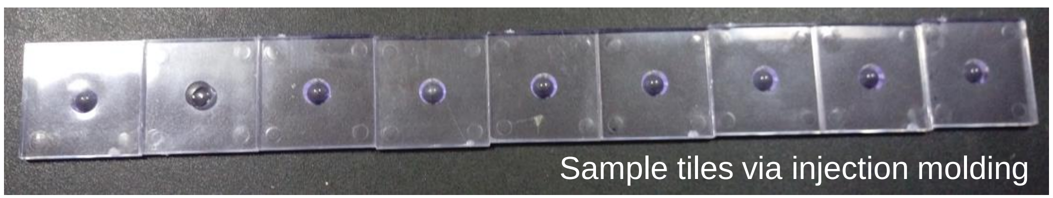
No gain drop observed at 60µs switch-on time

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

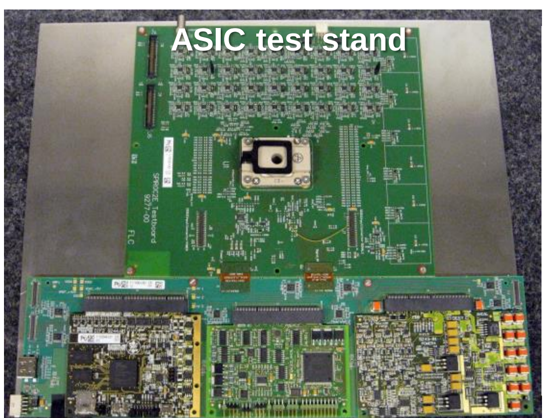
Towards AHCAL technological prototype

- 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
  - 40 layers in total; 4 HBUs in each layer
  - Big step towards mass production & QA
    - Tile mass production via injection molding
    - Quality assurance: ASICs, SiPMs, HBUs

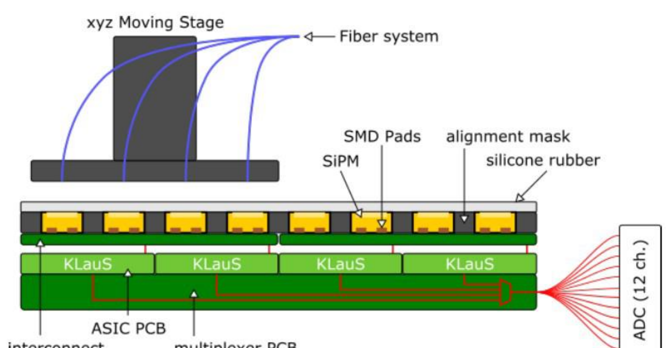




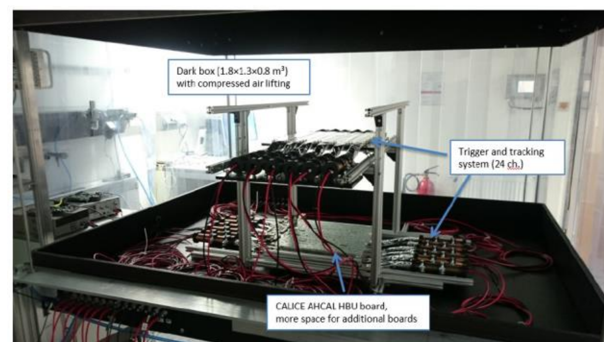
Sample tiles via injection molding



ASIC test stand



SiPM characterization test stand



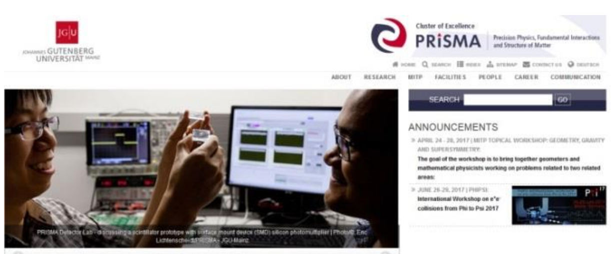
Cosmic-ray test stand for HBUs

Development of key setups at Mainz

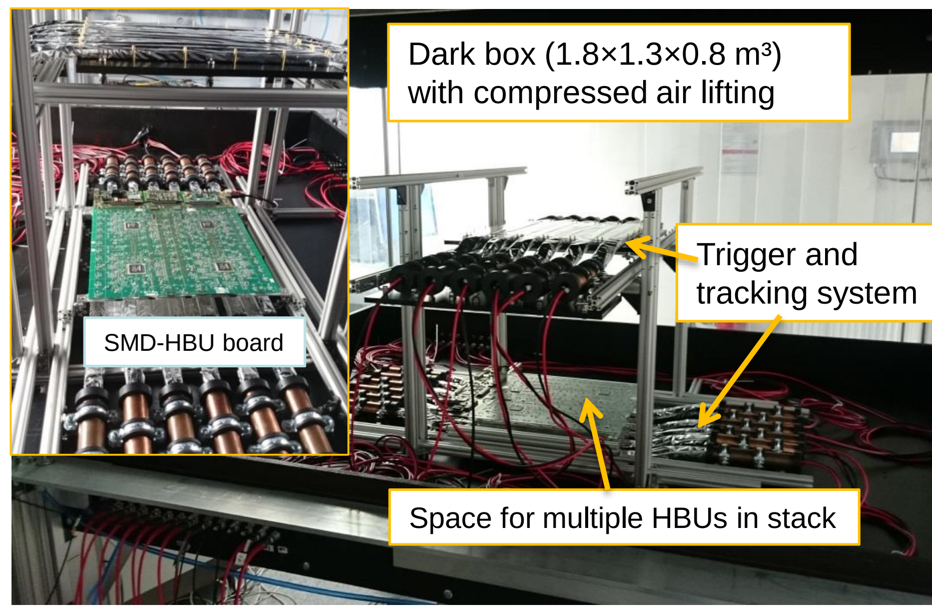
PRISMA Detector Lab

- Photosensor test stand
  - Selection of SiPMs for AHCAL, and full SiPM characterizations
  - Development (in parallel) of custom-designed fast preamps for SiPMs
- Cosmic-ray test stand
  - Commissioning all AHCAL HBUs after mass assembly (all at Mainz)

Photosensor test stand



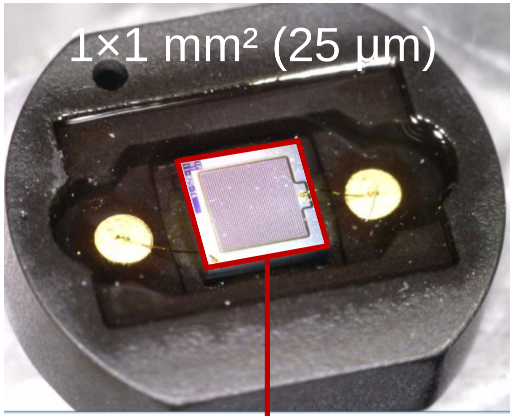
Cosmic-ray test stand

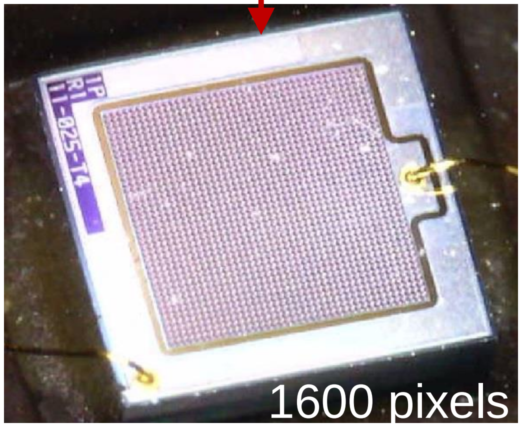


Test fully assembled boards using cosmic muons: measure MIP response in a relatively short time range

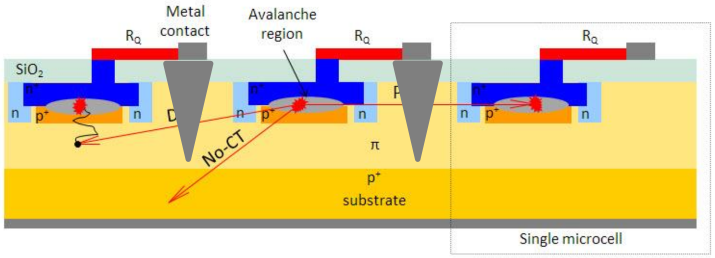
Photosensor test stand: low-noise SiPM

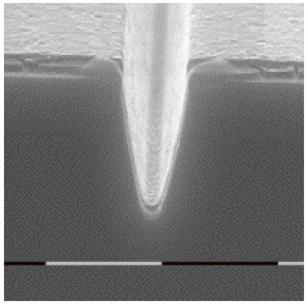
- Exploit the test stand for characterizations of various SiPMs

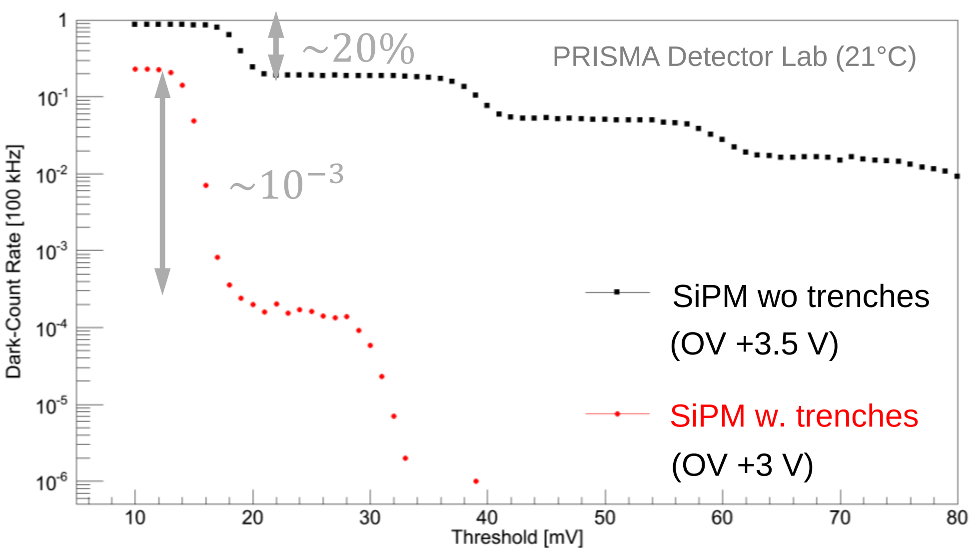




SiPM Resent Development and Applications, V. Saveliev, 2005

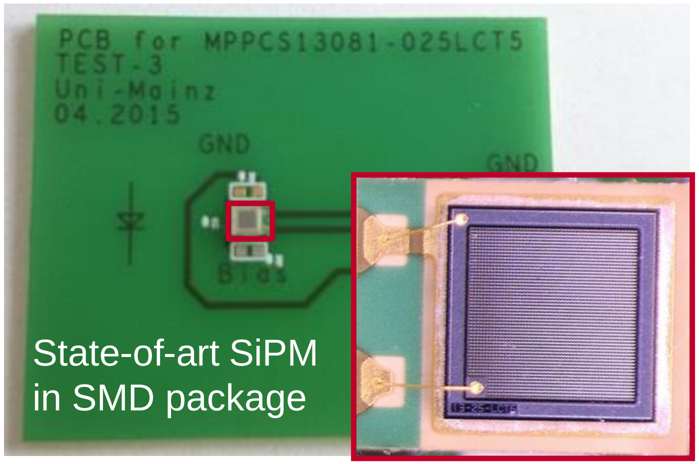




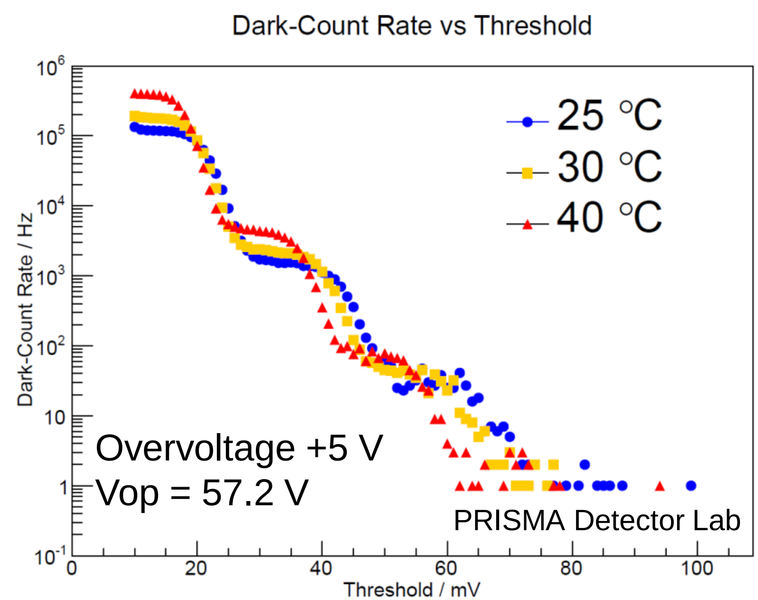


Dark-count noises drop fast with threshold

Photosensor test stand: SiPMs for tech. prototype

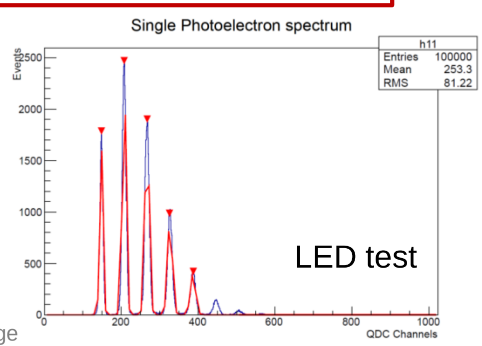


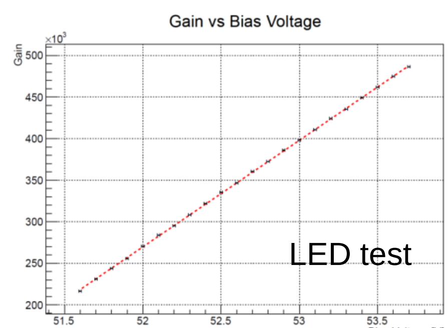
- Exploit the test stand for characterizations of various SiPMs

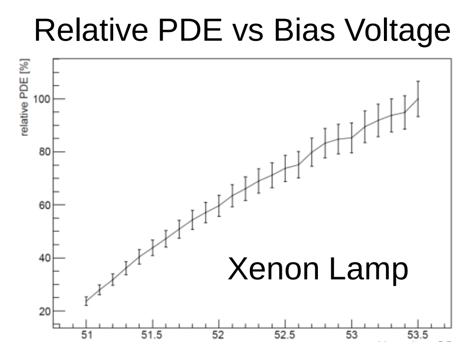


Fully characterize SiPM: DCR, gain, PDE, temperature behavior, pixel uniformity, etc.

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



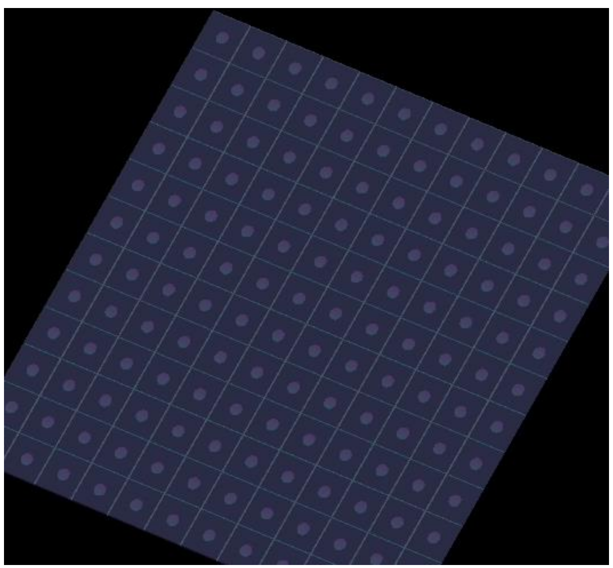
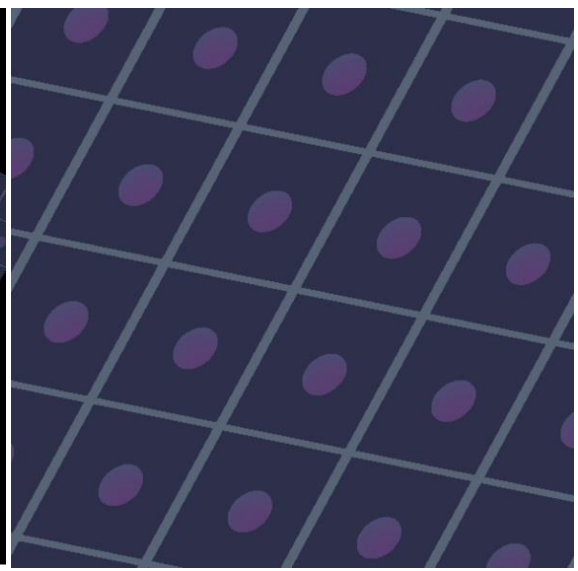
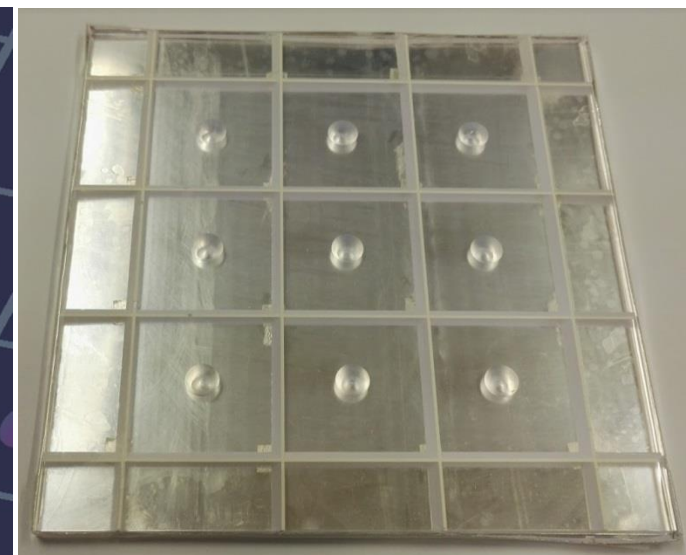




The 3 plots correspond to the SiPM prototype shown in the previous page

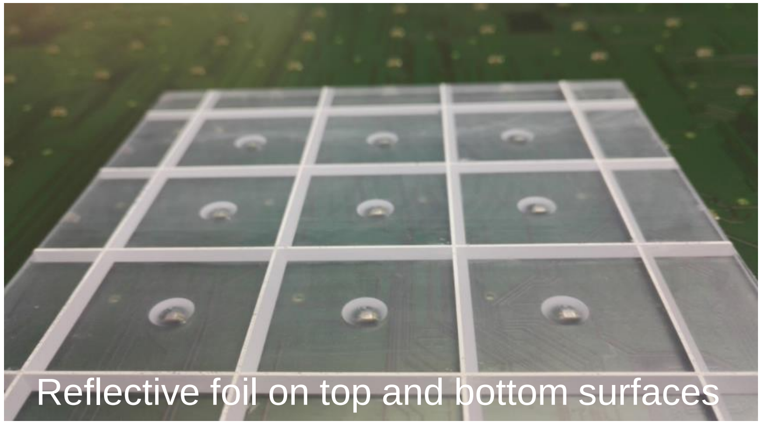
Ongoing development: mega-tile

- Motivations: further simplify mass assembly
  - Scintillator plates with embedded structures
  - Optically isolated for individual readout
- Design: extensively optimized by Geant4 simulation
  - MIP response (moderate), cell-to-cell crosstalk (minimum)
- Several prototypes developed and fully tested

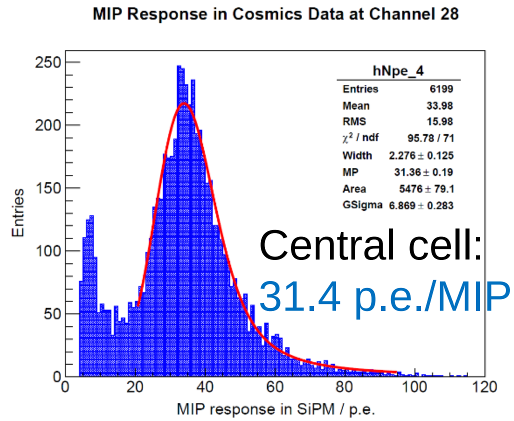




Mega-tile prototypes: highlights

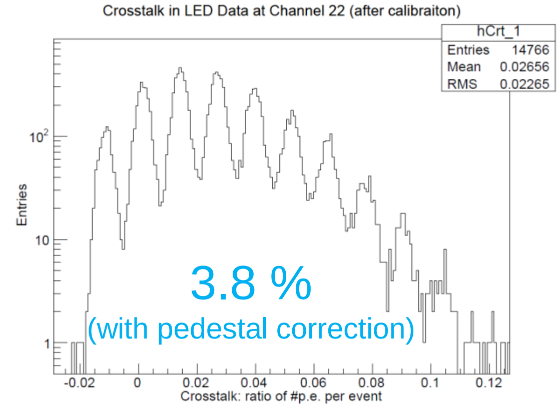
Mega-tile prototype on SMD-HBU5



MIP: cosmic muons



Optical crosstalk: UV light

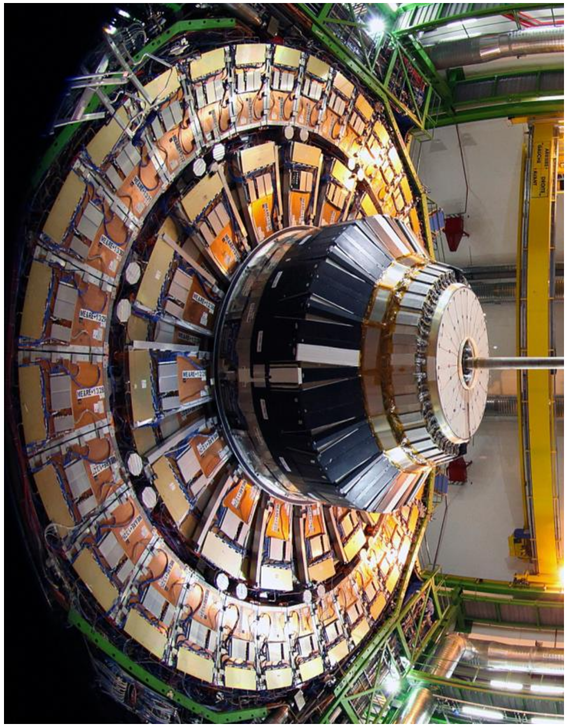


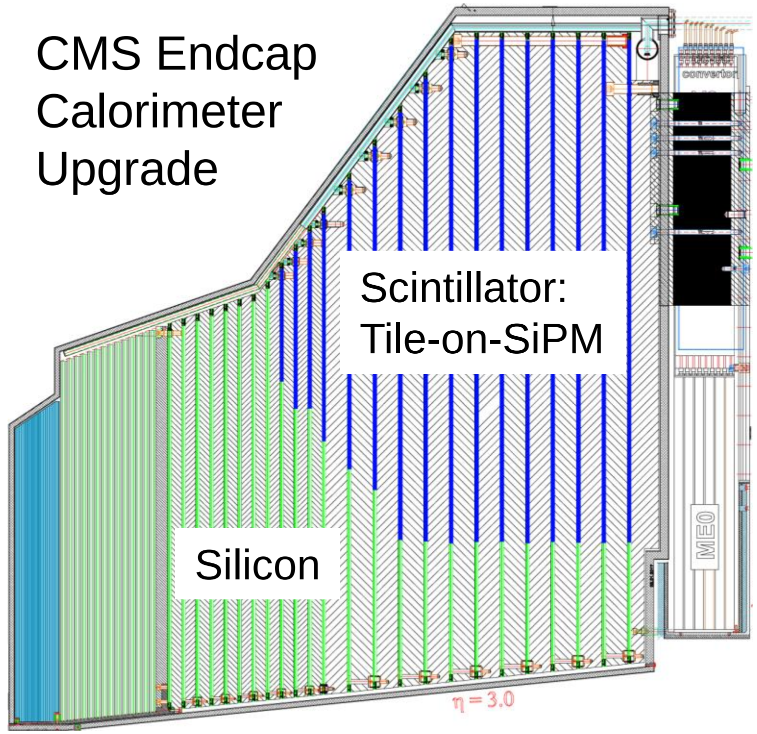
Full size mega-tile prototype

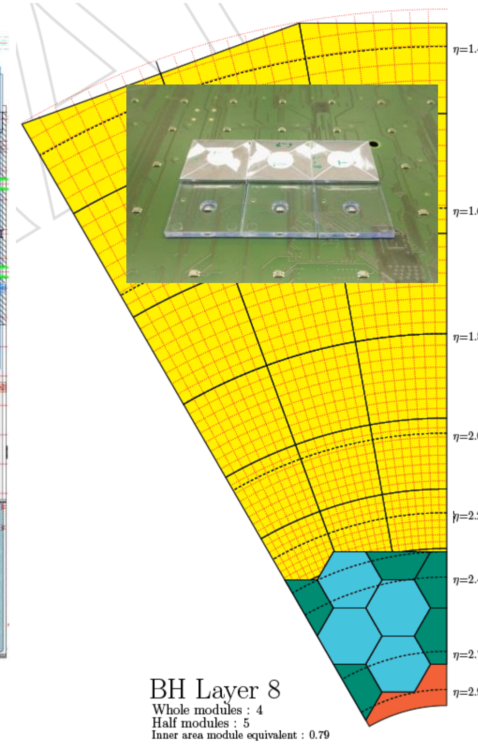
- Protoypes fully tested with
  - Cosmic muons
  - On-board LED
- Excellent performance
  - Moderate MIP response
  - Low optical crosstalk

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

Other applications: CMS-HGC for HL-LHC







- 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

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 baseline 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)

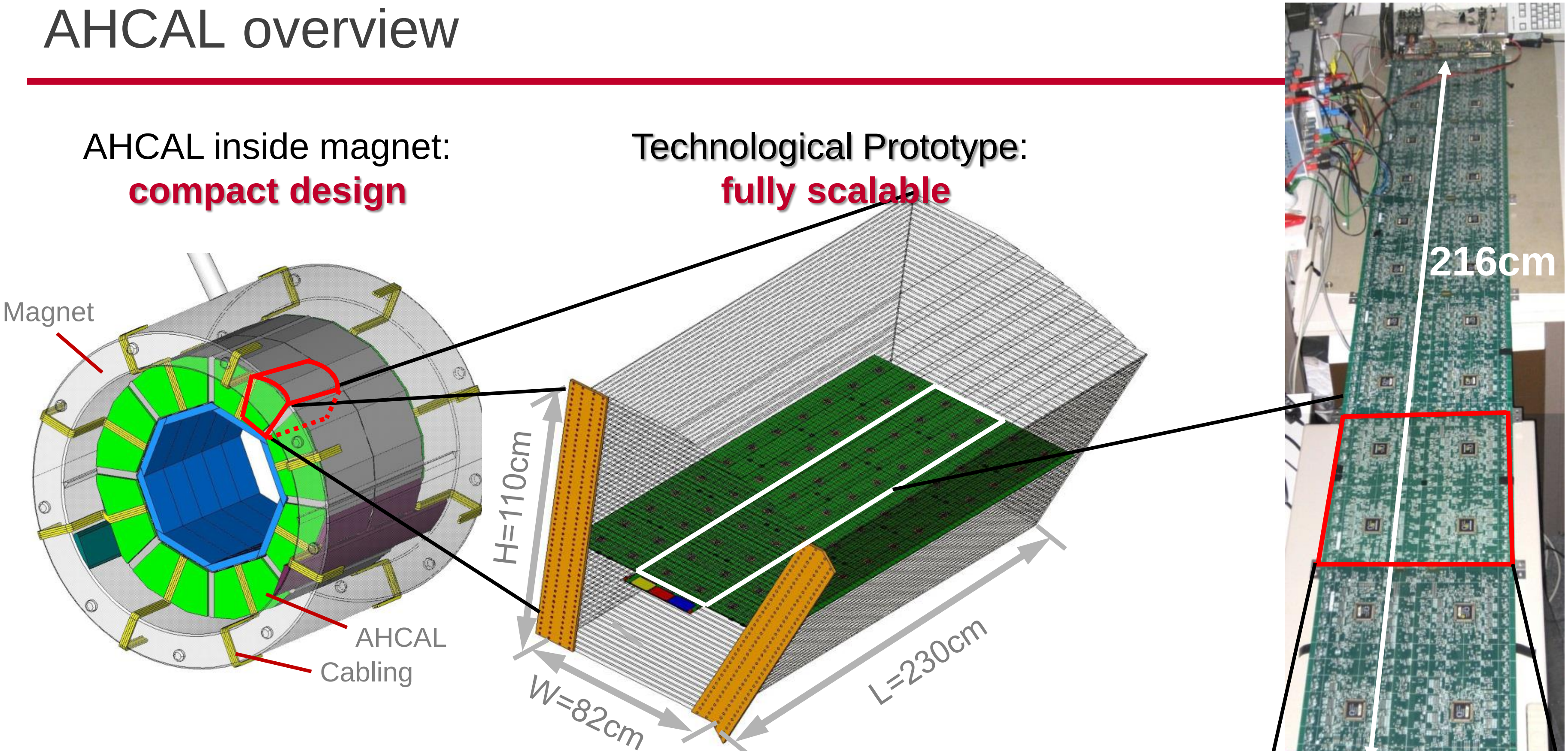
Thank you!

Backup

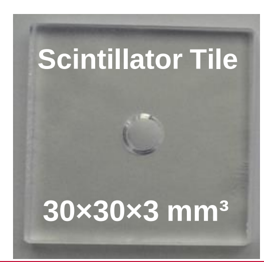
AHCAL overview

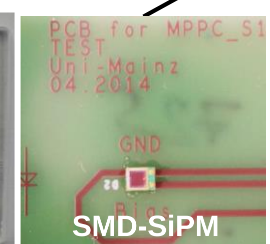
AHCAL inside magnet:
compact design

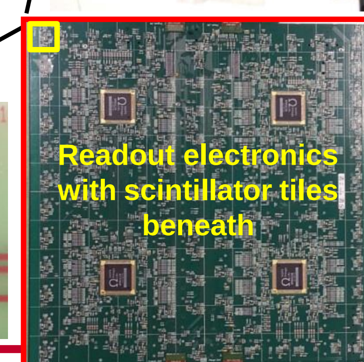
Technological Prototype:
fully scalable



- 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

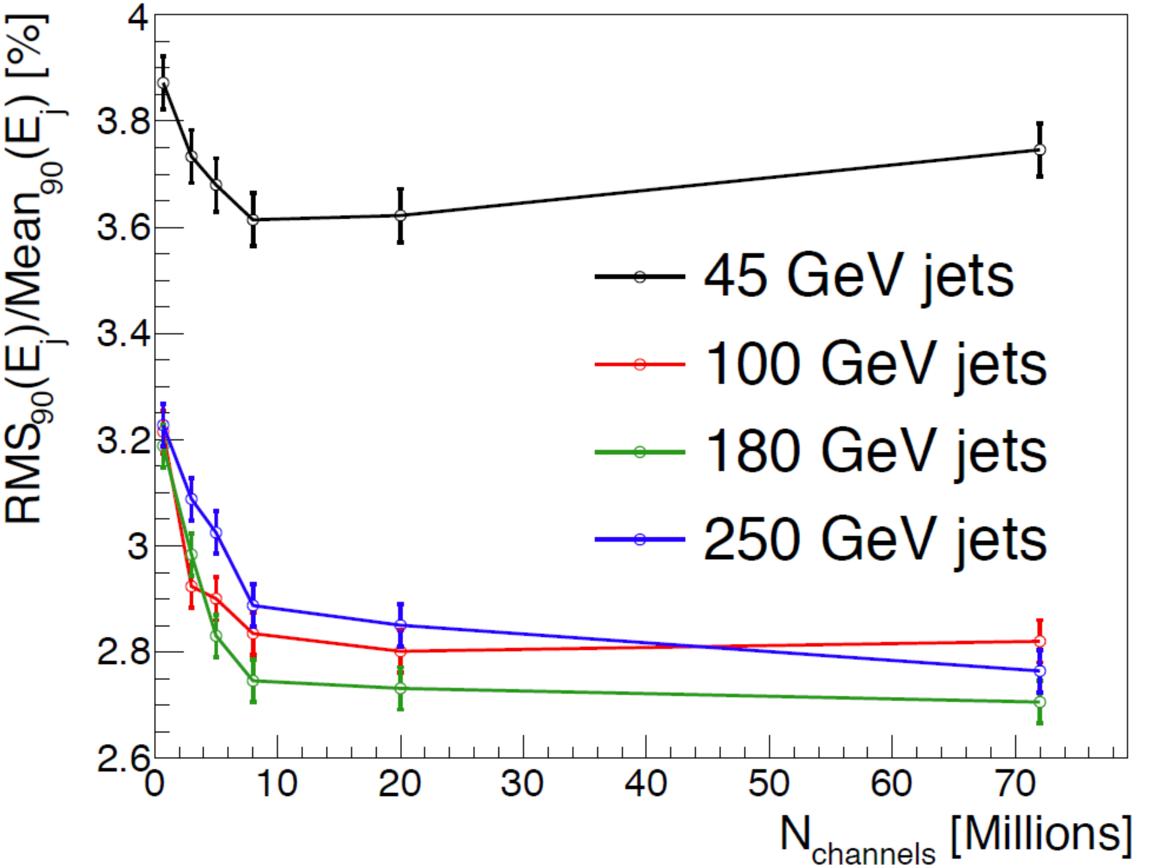






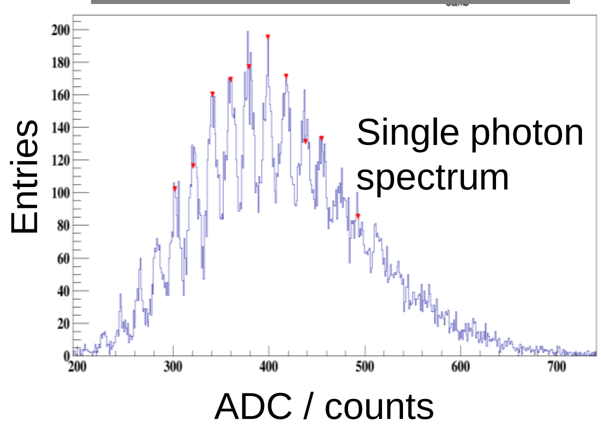
Calorimeter granularity optimization

- 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

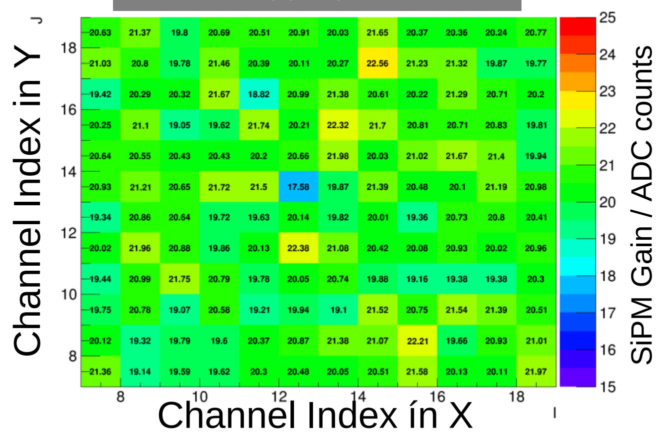


Commissioning: LED calibration and MIP response

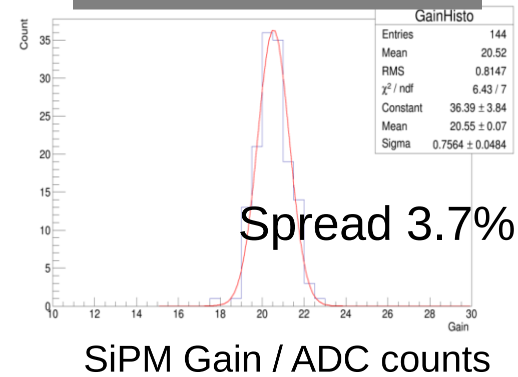
SiPM response to LED light



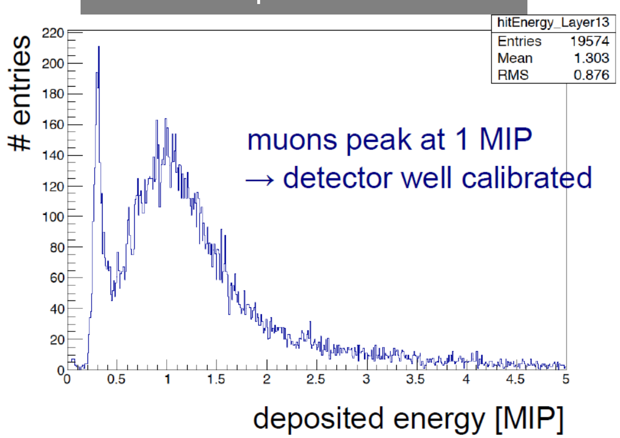
Gain Mapping of a HBU



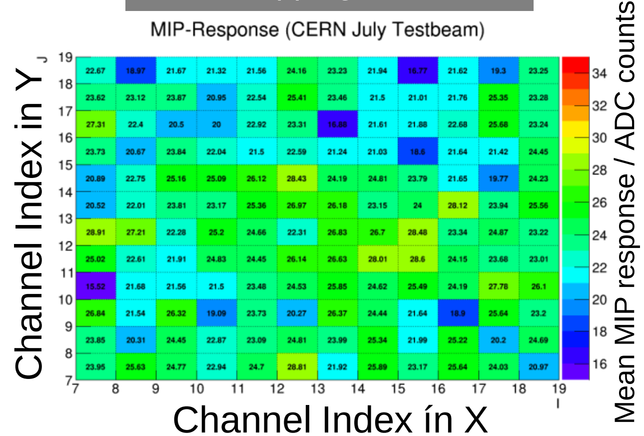
SiPM Gain of a HBU (144 channels)



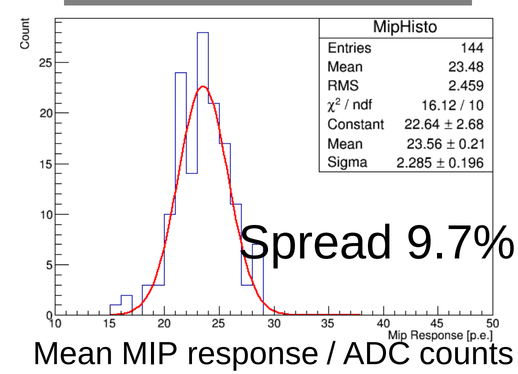
SiPM response to muons



MIP Mapping of a HBU



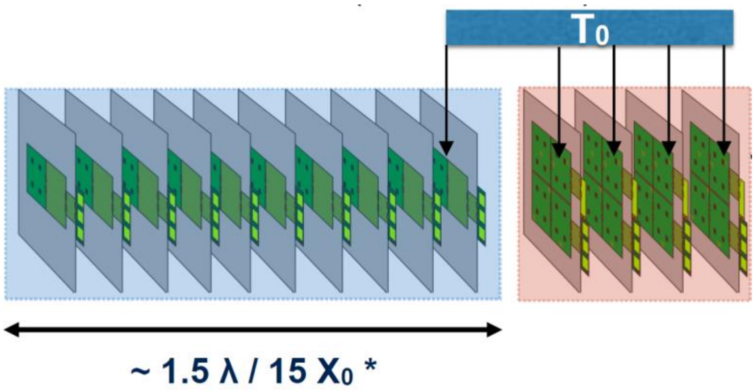
MIP Responses of a HBU (144 channels)

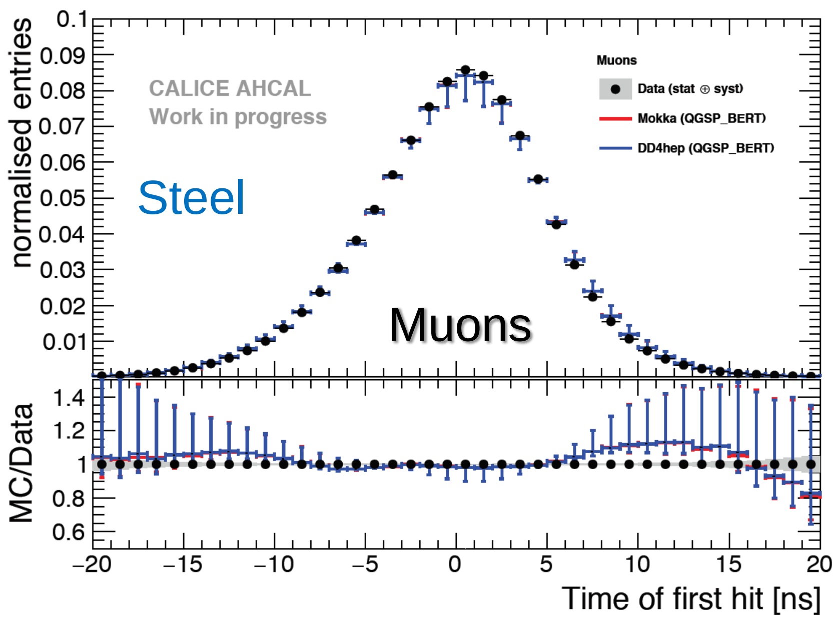


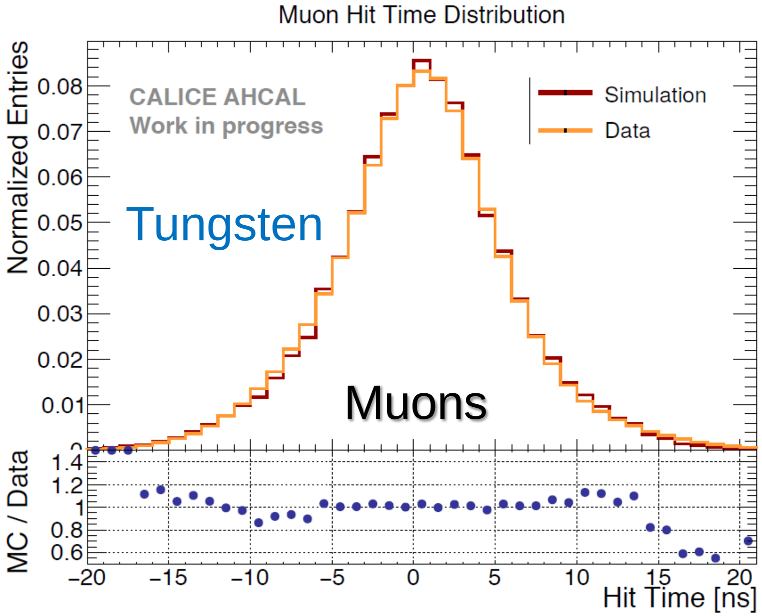
Promising performance achieved: uniform gain and MIP response

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



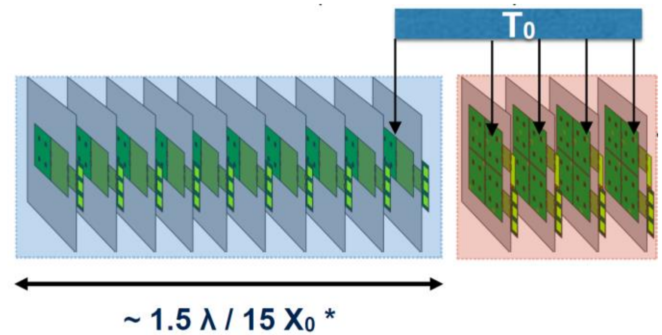




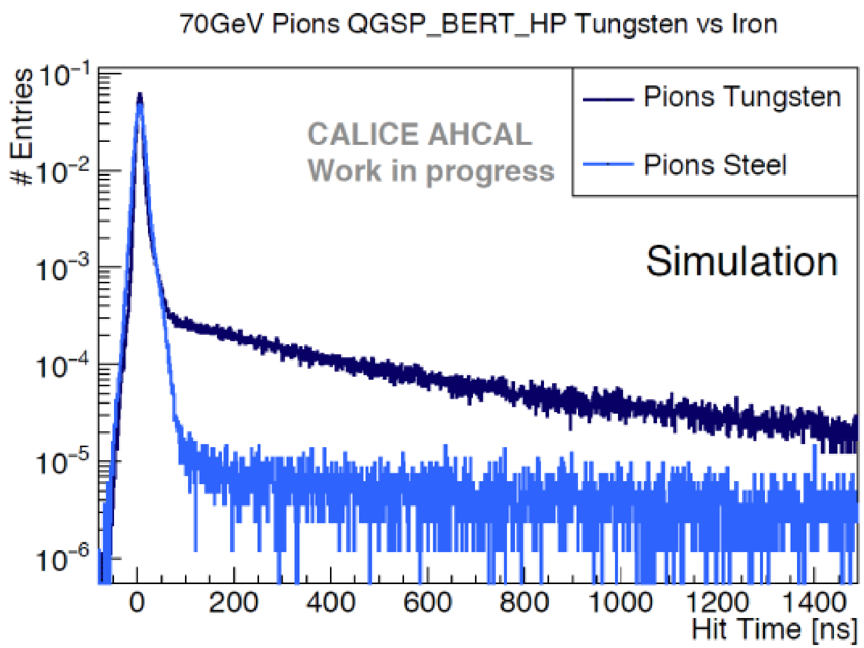
Timing analysis: pions

Geant4 v10.01, Mokka v08-05-01

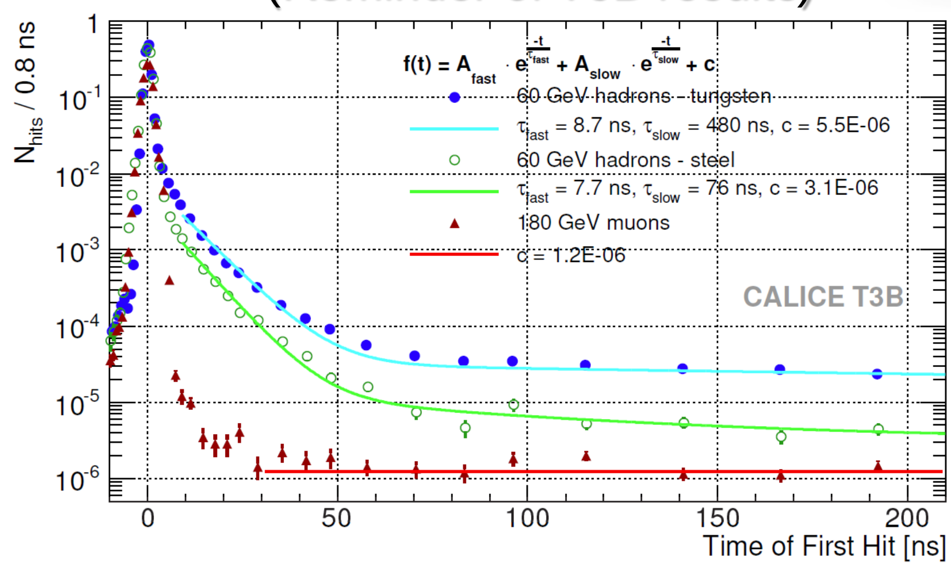
- Time calibration procedure established
  - Based on muon data/MC
- Ongoing analysis of electrons and pions



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)