Highly Granular Calorimeters: Technologies and Results

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on behalf of the CALICE Collaboration

Instrumentation for Colliding Beam Physics (INSTR17)
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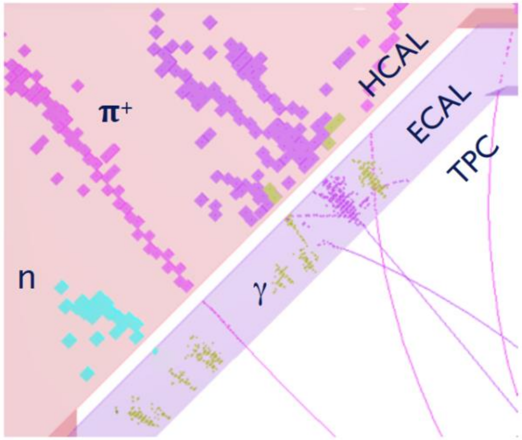
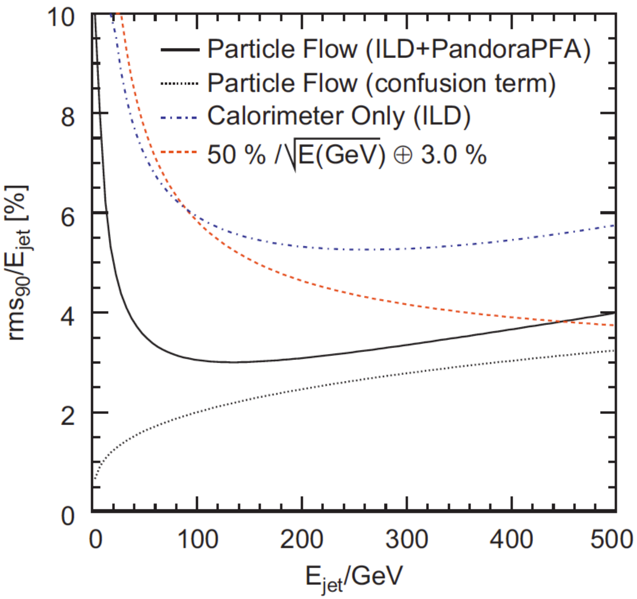
Highly granular calorimeters: motivations

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



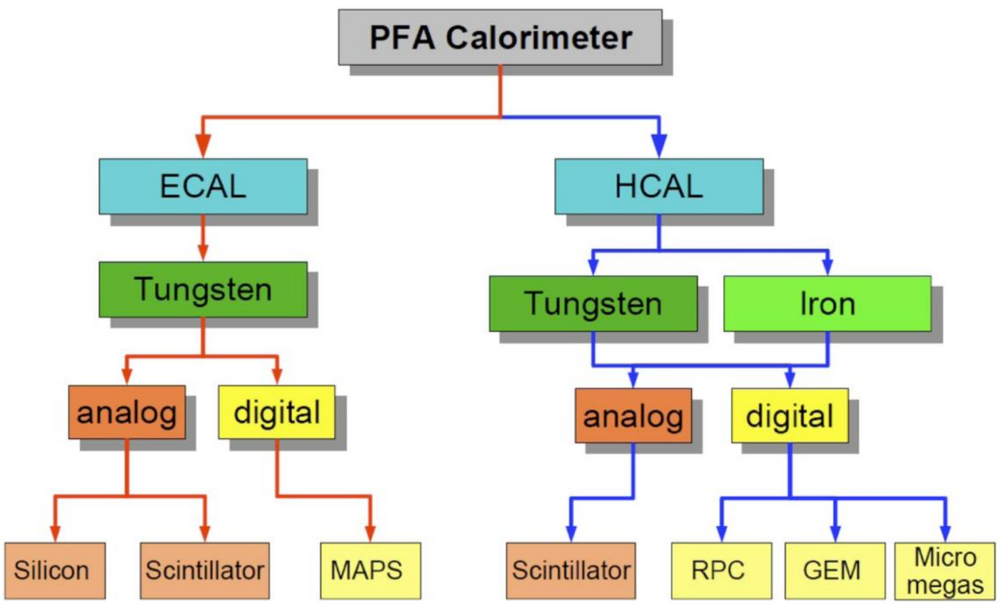


M.A. Thomson: Nuclear Instruments and Methods A 611 (2009) 25-40

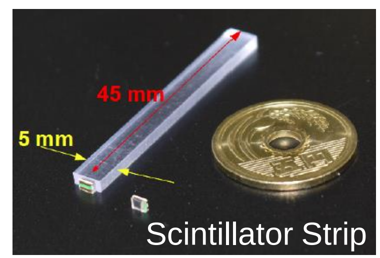
The CALICE collaboration

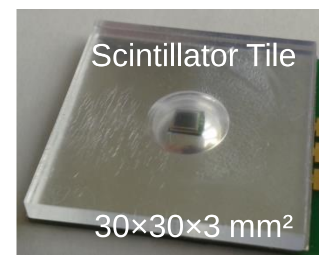
https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

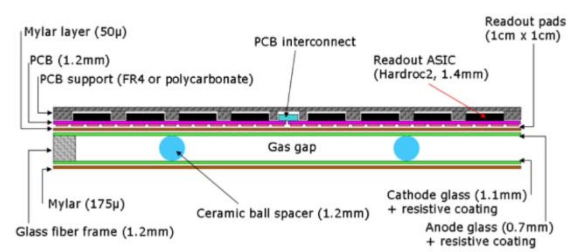
- CALICE collaboration today
  - 55 institutes in 19 countries (4 continents)
  - ~ 350 members
- Goal
  - Research and development of highly granular calorimeters for future lepton colliders
- Technologies
  - A rich program exploring full spectrum of imaging calorimeter technologies



Selected examples in the technology tree

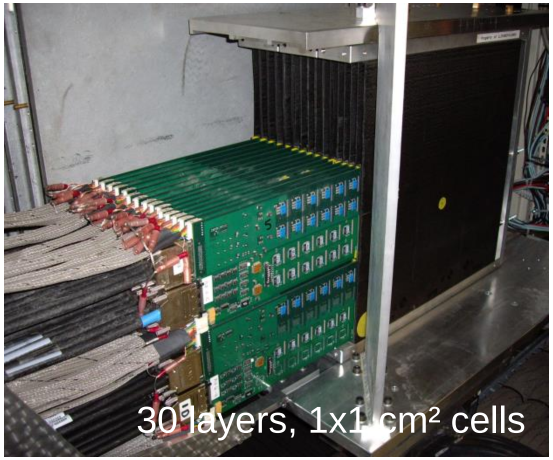






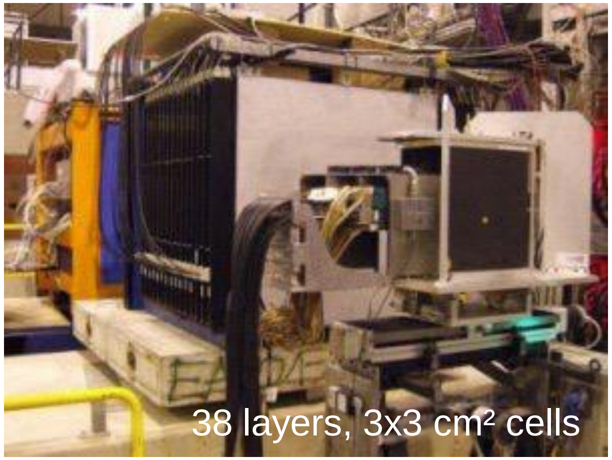
The CALICE physics prototypes

Si-W ECAL



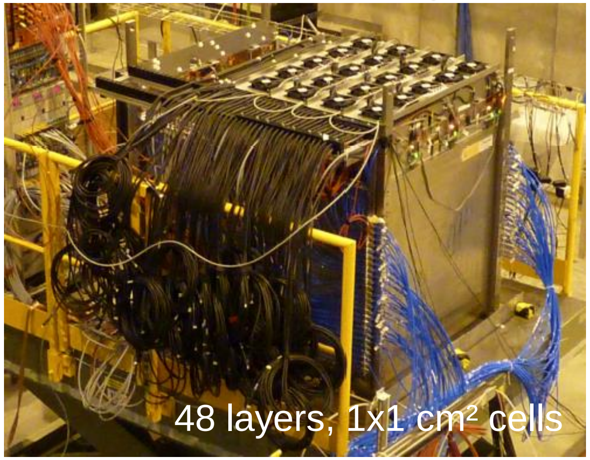
30 layers, 1x1 cm² cells

Sc-AHCAL, Fe&W



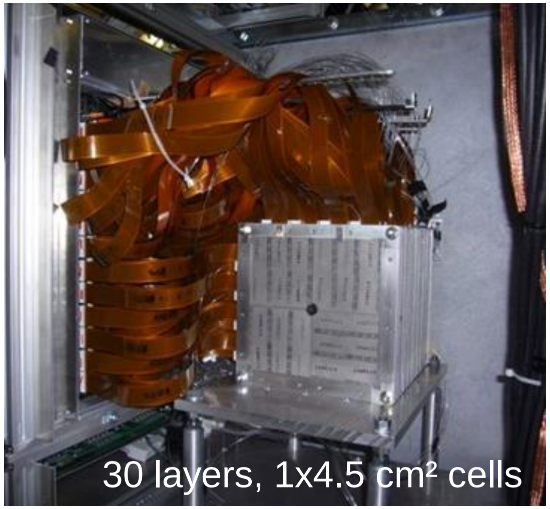
38 layers, 3x3 cm² cells

GRPC-SDHCAL, Fe



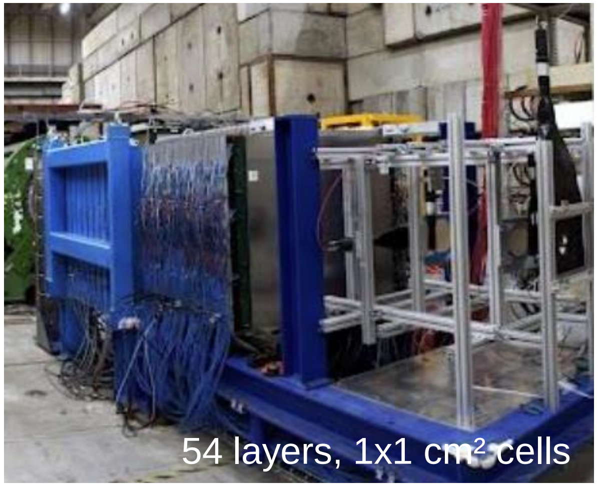
48 layers, 1x1 cm² cells

Sc-W ECAL



30 layers, 1x4.5 cm² cells

RPC-DHCAL, Fe&W



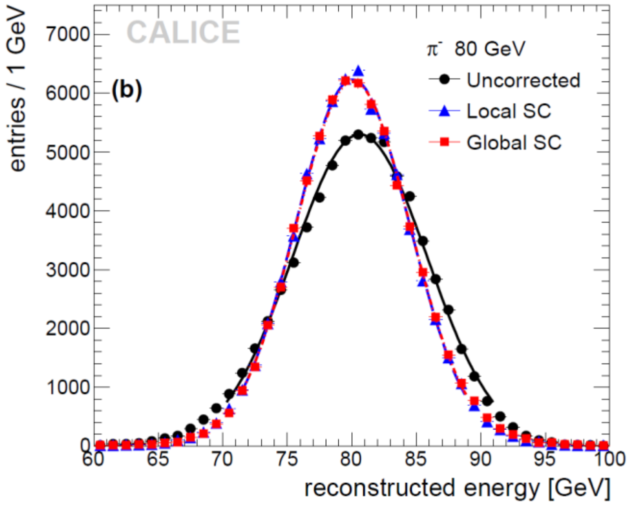
54 layers, 1x1 cm² cells

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

Performance of CALICE Physics Prototypes

- Sizeable experimental data for different calorimeter technologies
  - Performance info e.g. linearity, resolution, calibration, etc.
  - Only show a few selected examples

Fe-AHCAL: Energy Reconstruction



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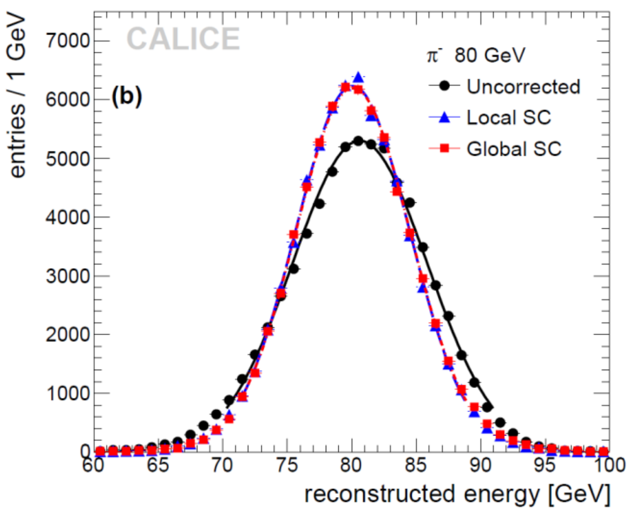

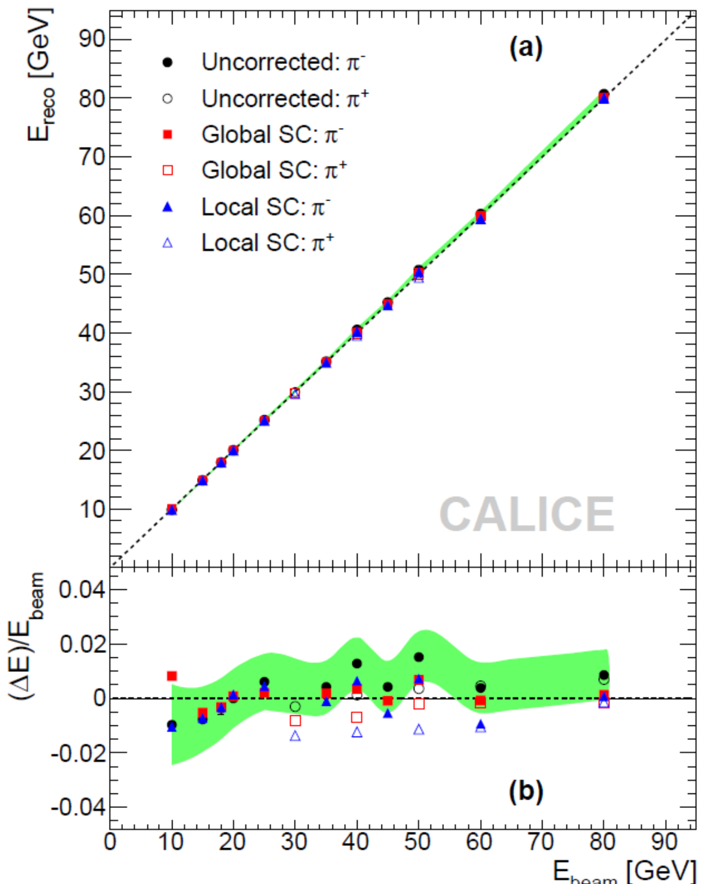

- Linearity of energy response within $\pm 1.5\%$ (AHCAL+TCMT)
- High granularity allows software compensation
  - Use shower density to correct for different responses to EM and purely hadronic showers

JINST 7, P09017 (2012)

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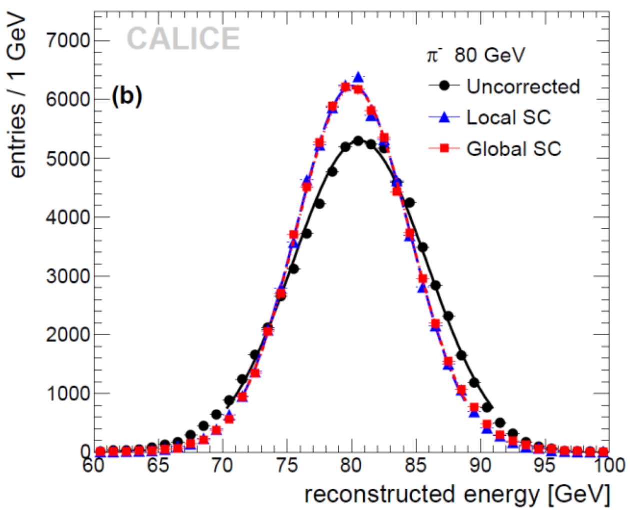

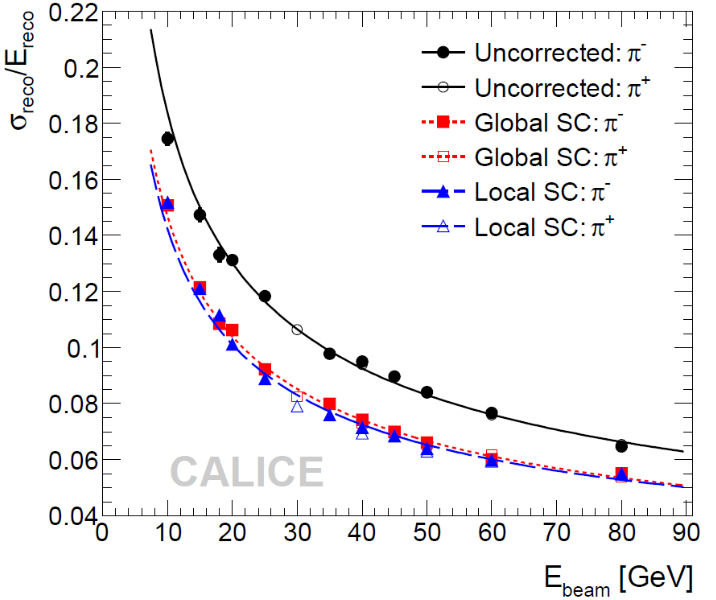

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Excellent energy resolution achieved:

$$45\%/\sqrt{E(GeV)} \oplus 1.8\%$$

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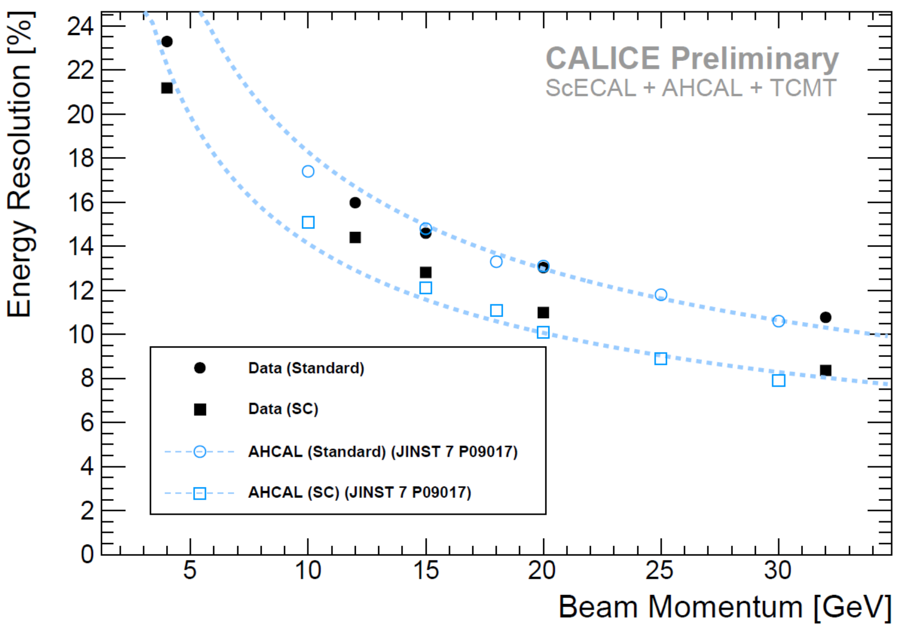
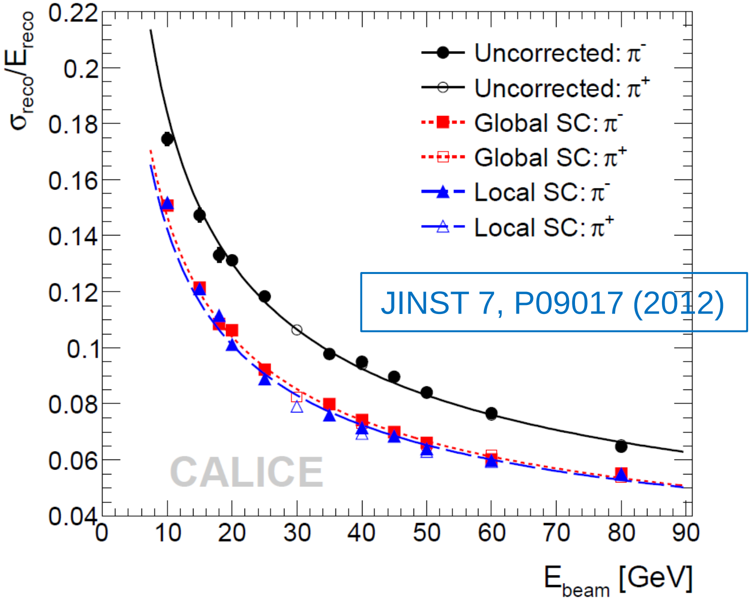


Similar energy resolution achieved in 2 combined calorimeter setups: only different with ECAL technologies (Silicon vs Scintillator)



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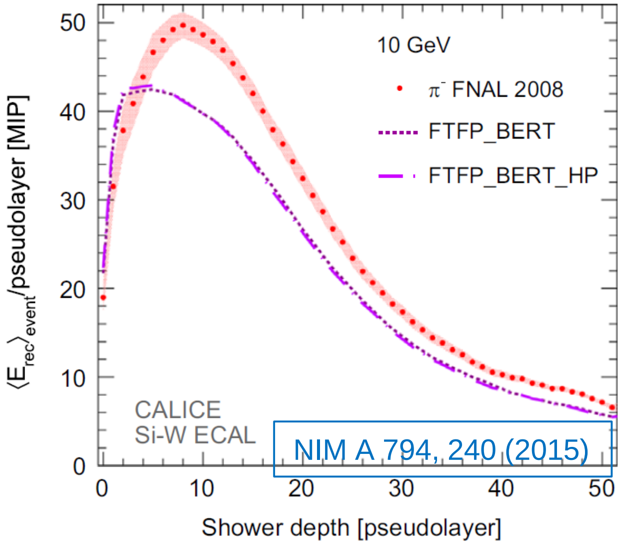
CALICE data: understanding better hadronic showers

First interactions



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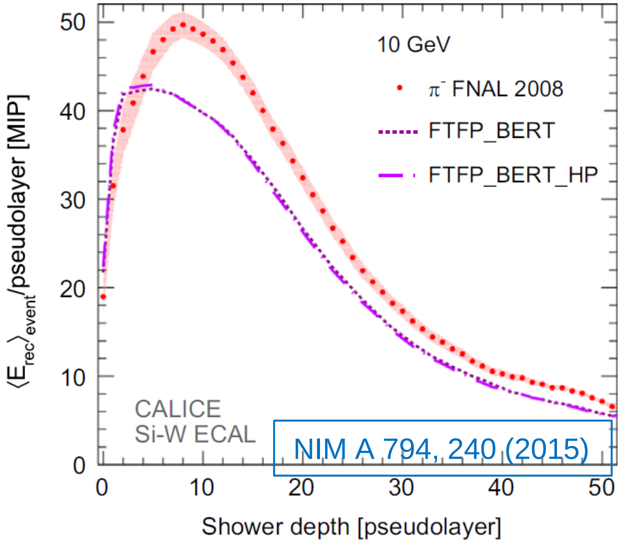
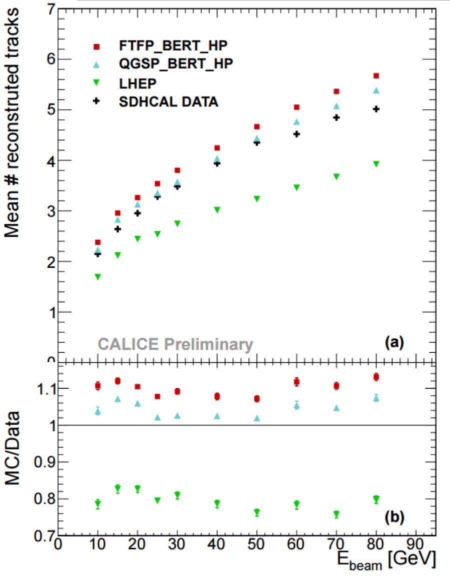
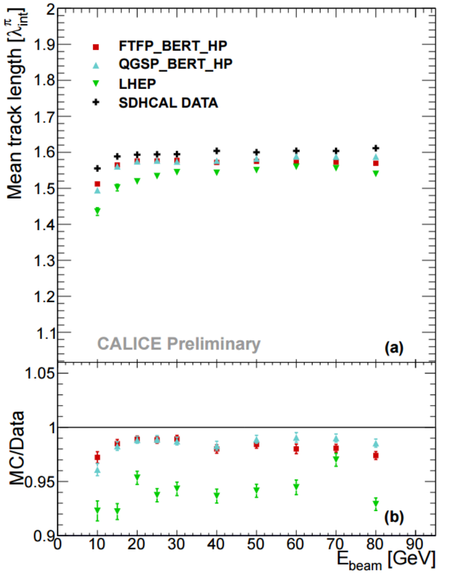


NIM A 794, 240 (2015)

MIP-like tracks (within hadronic showers)





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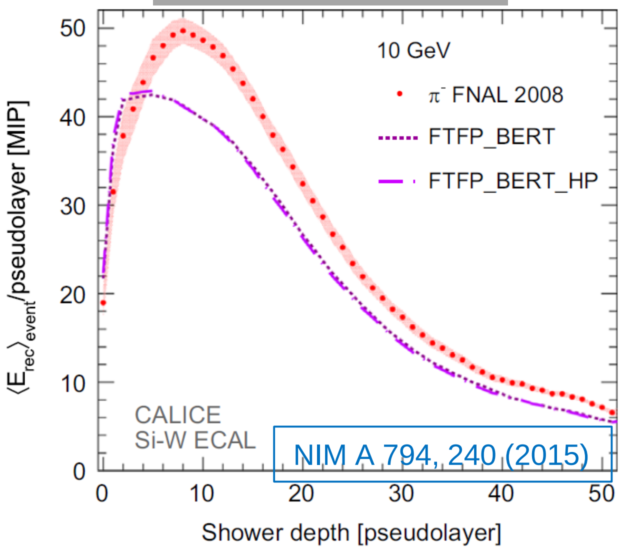

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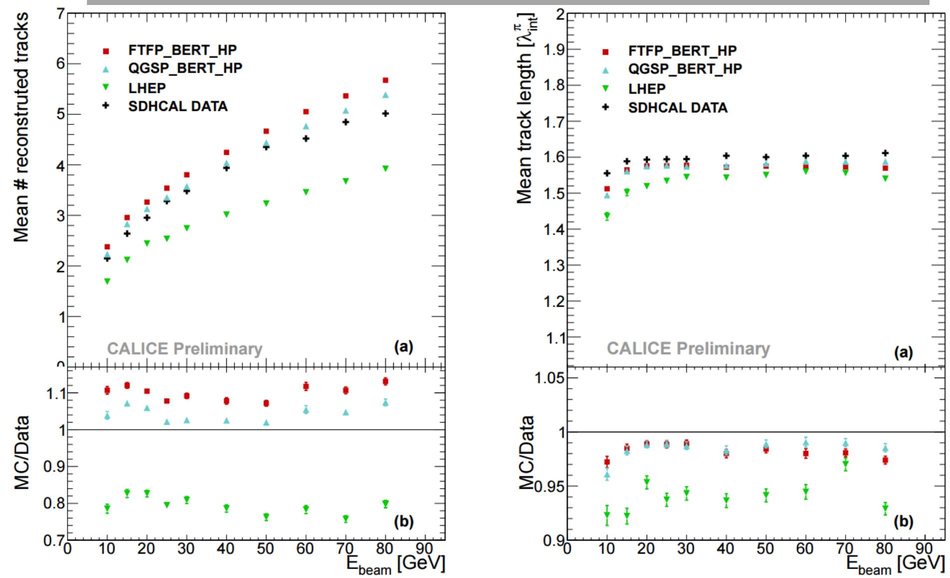
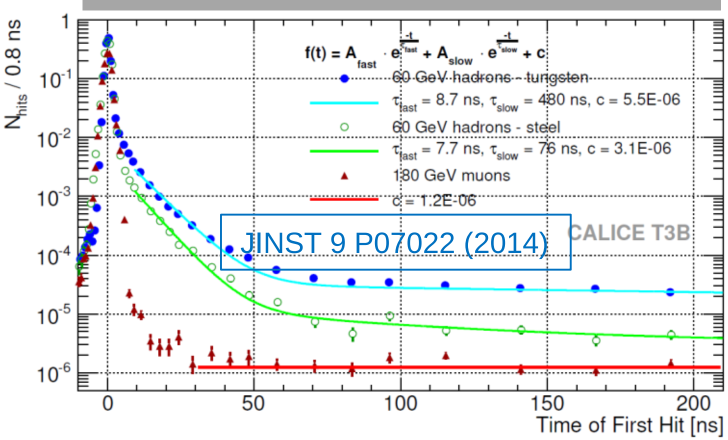


Timing behavior of components



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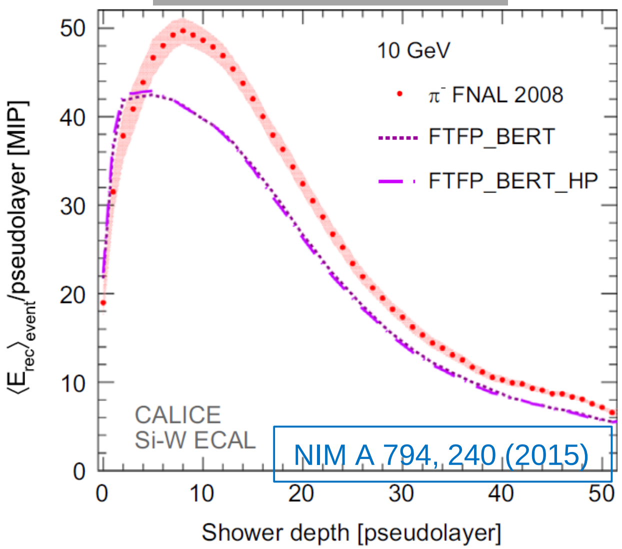

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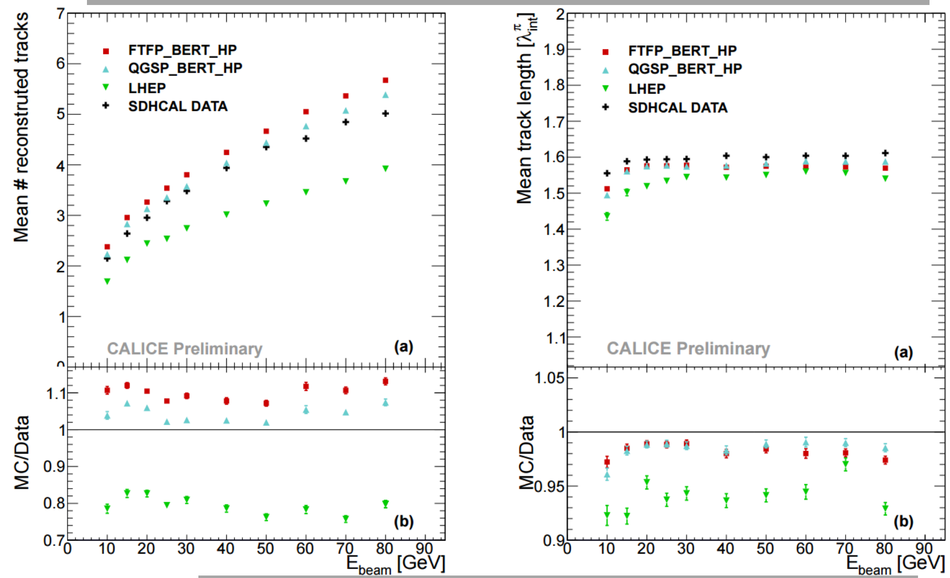

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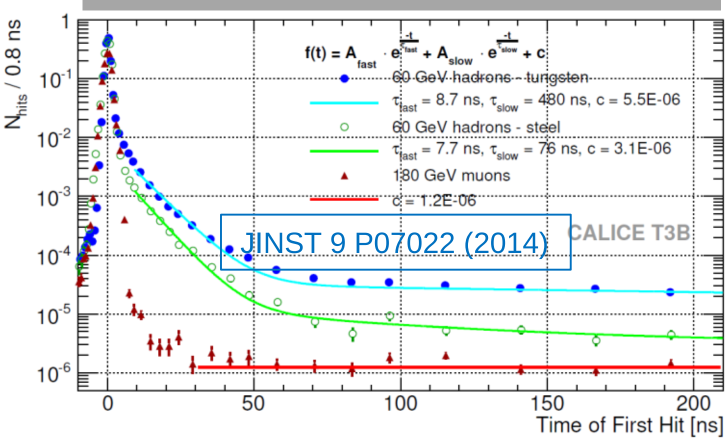
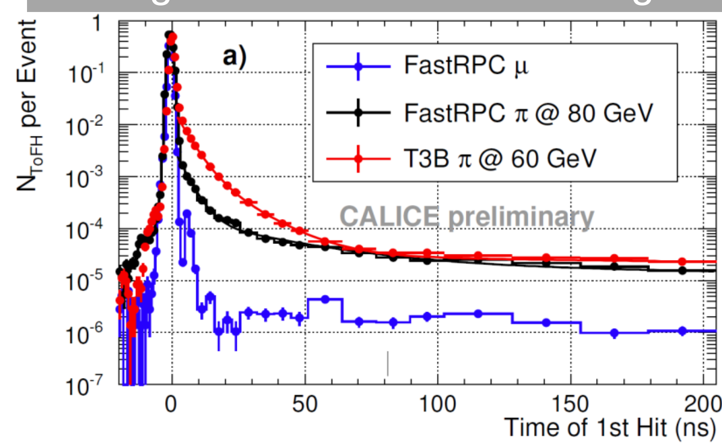
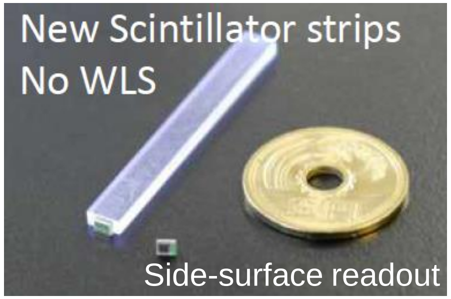


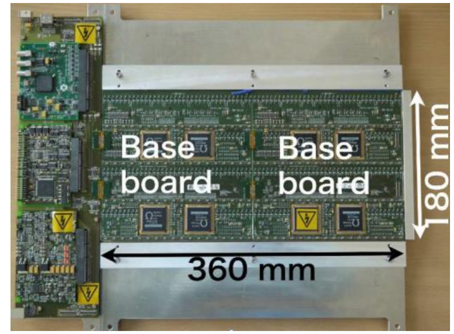
Timing structure: scintillator vs gas

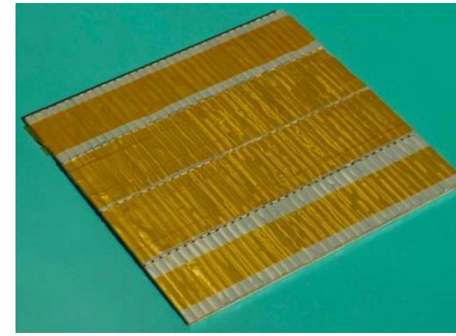


CALICE ECAL technological prototypes

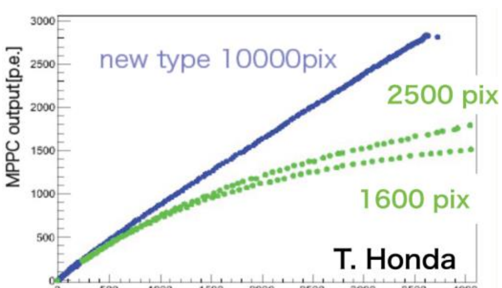
Scintillator-Tungsten ECAL







- Towards a full Sc-W ECAL detector
  - Scintillator strips 45×5×2 mm³ per layer, with direct SMD-SiPM readout
    - Crossed layers to achieve effective granularity 5×5 mm²
  - Front-end electronics fully integrated into each active layer
  - New bottom readout to reduce dead area; new SiPM with 10k pixels on 1x1 mm²
  - Combined beam tests with Sc-Fe AHCAL at CERN/DESY: working smoothly



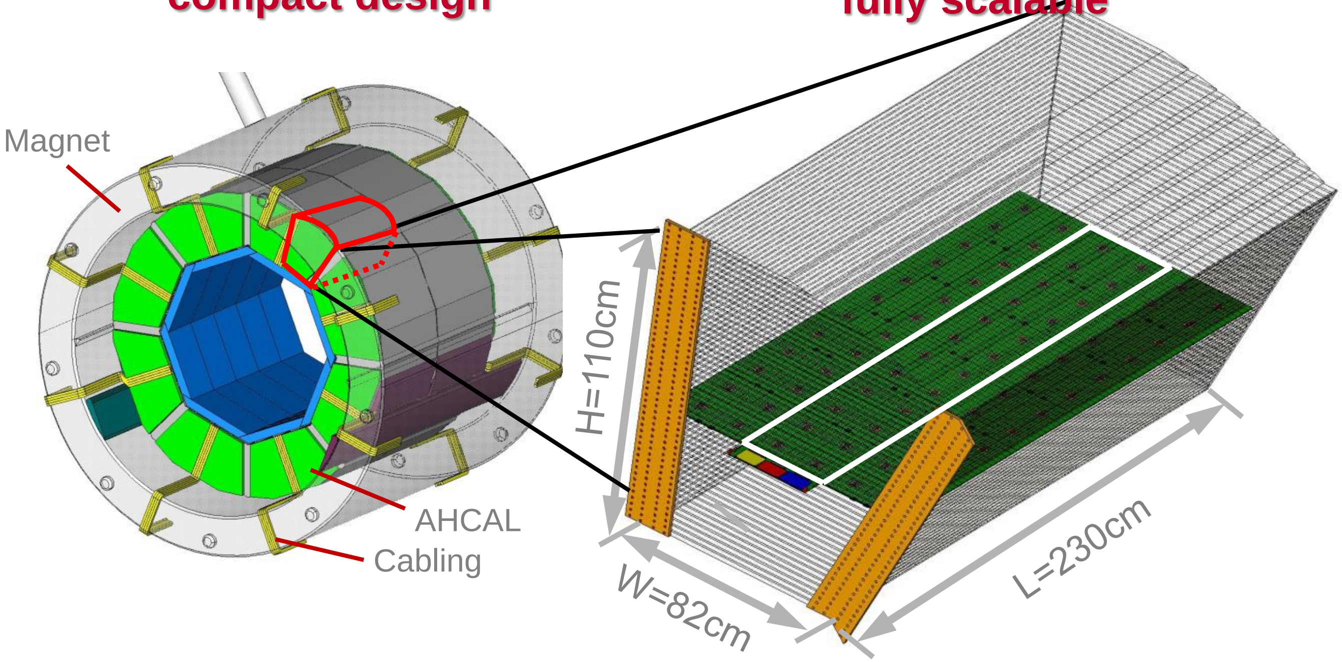
Silicon-Tungsten ECAL

Details in Vladislav Balagura's talk in the same session

AHCAL overview

HCAL inside magnet:
compact design

Technological Prototype:
fully scalable



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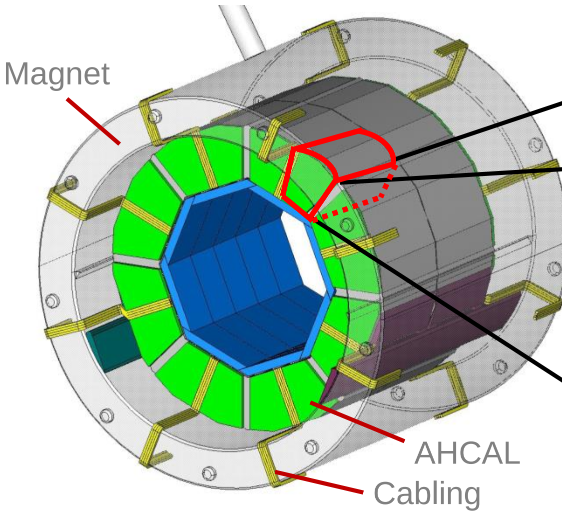

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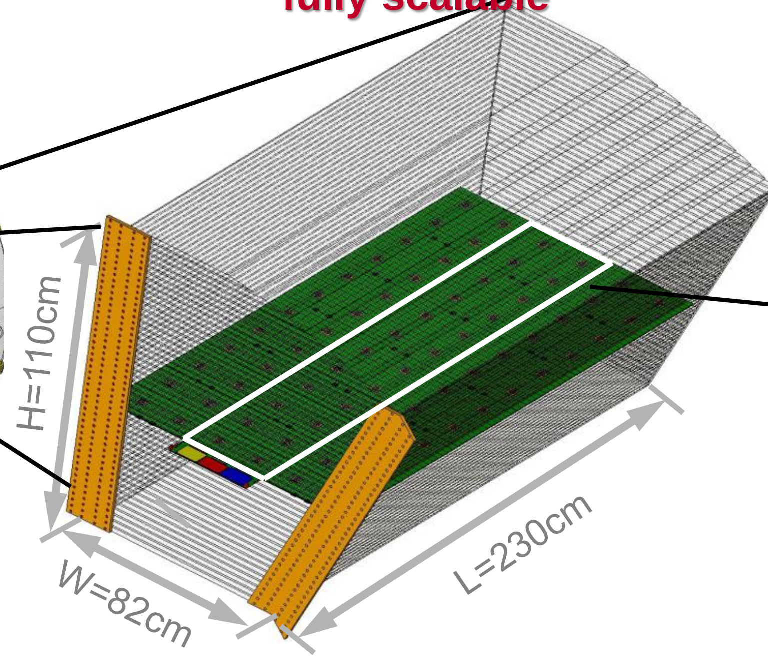

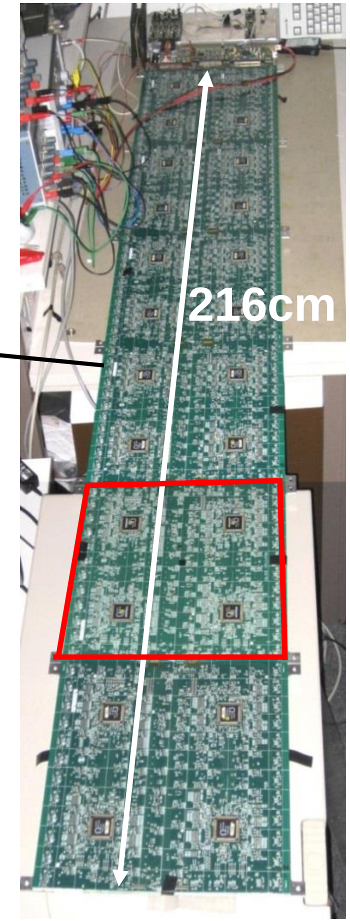

Electronics fully integrated into active layers
(6 readout boards in a slab)

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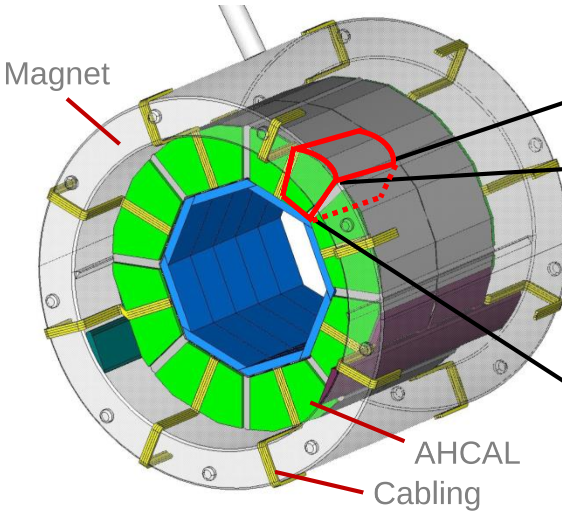

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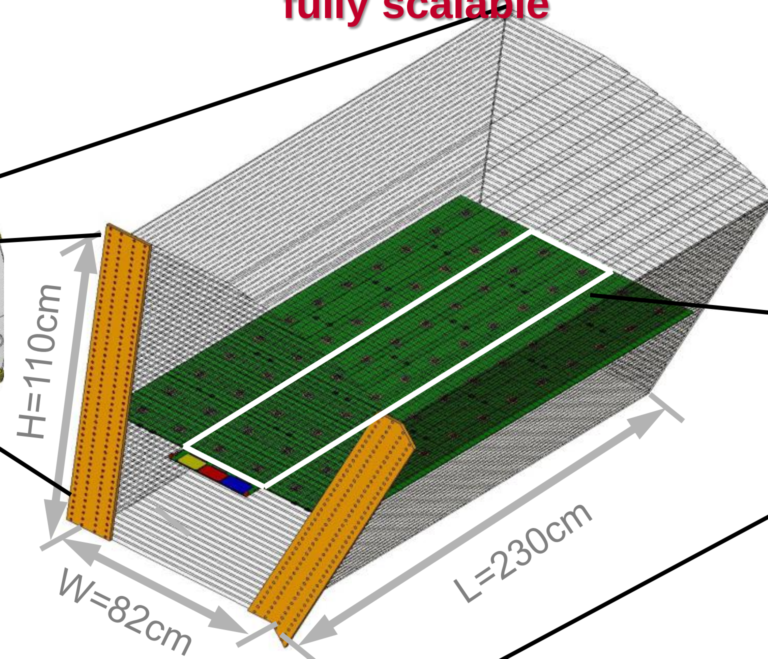

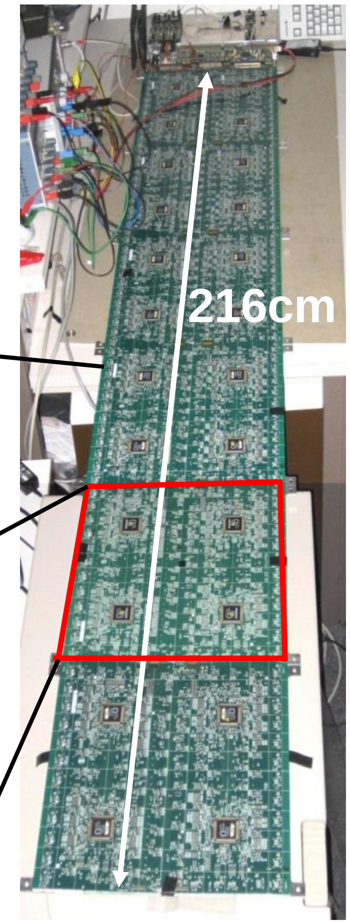

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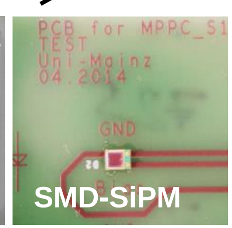
HCAL Base Unit (HBU)



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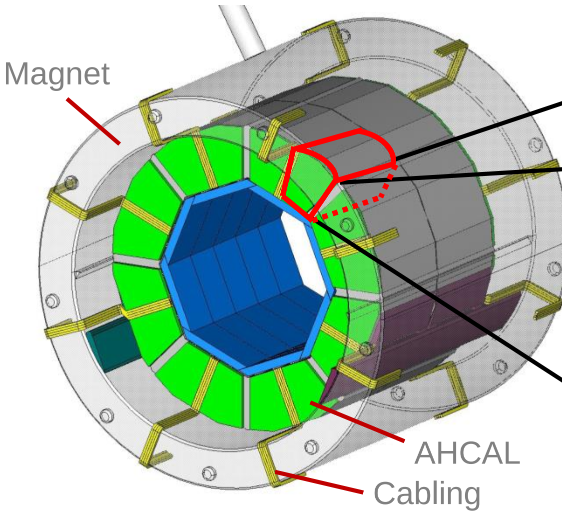

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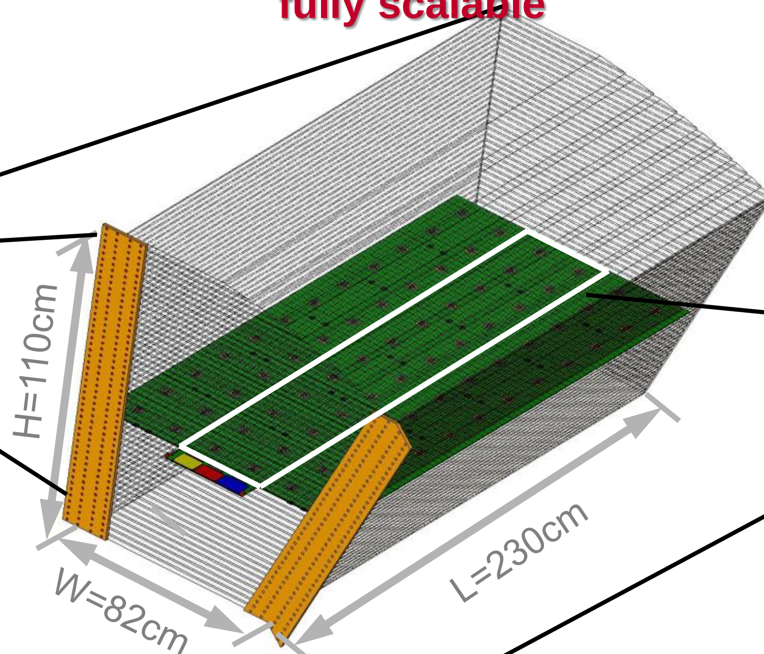
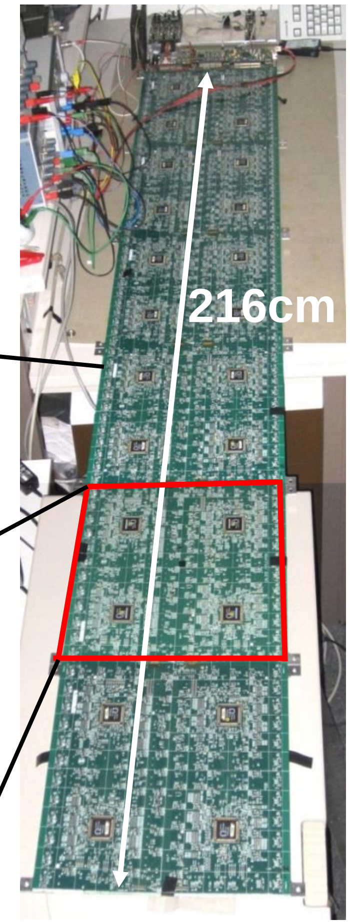


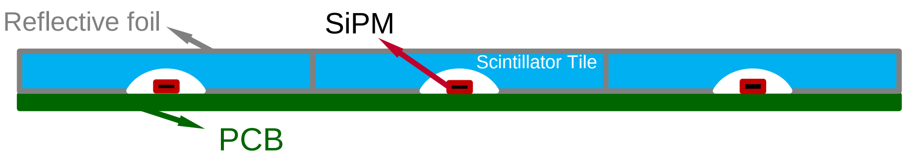


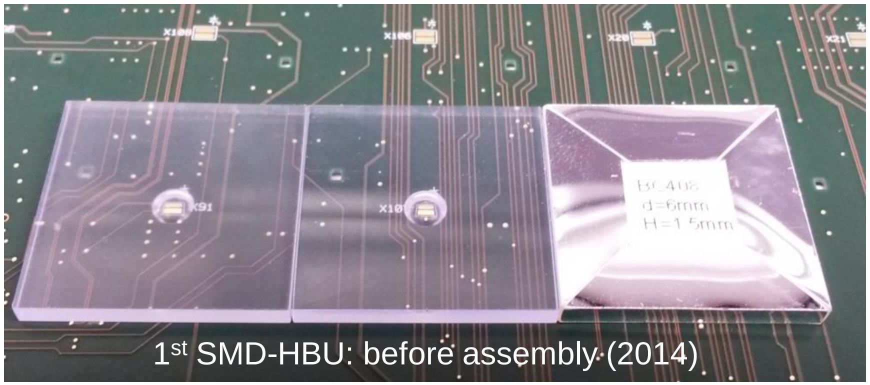
HCAL Base Unit (HBU)

High-granularity Calorimeter optimized by PFA:
challenge of ~ 8 million channels in final design

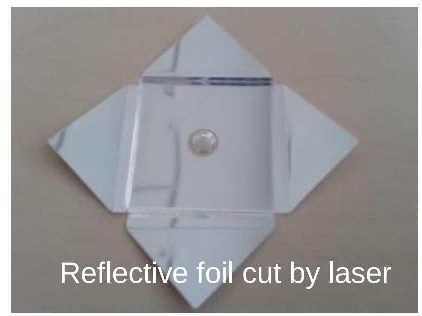
Electronics fully integrated into active layers
(6 readout boards in a slab)

AHCAL mass assembly: from design to reality

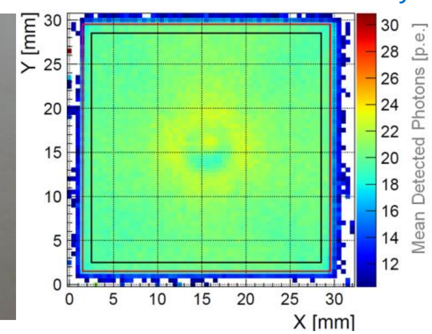



1st SMD-HBU: before assembly (2014)

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


Reflective foil cut by laser

Achieved excellent uniformity



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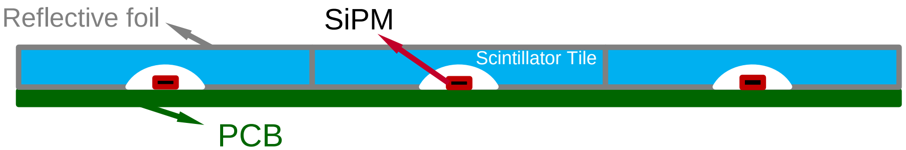

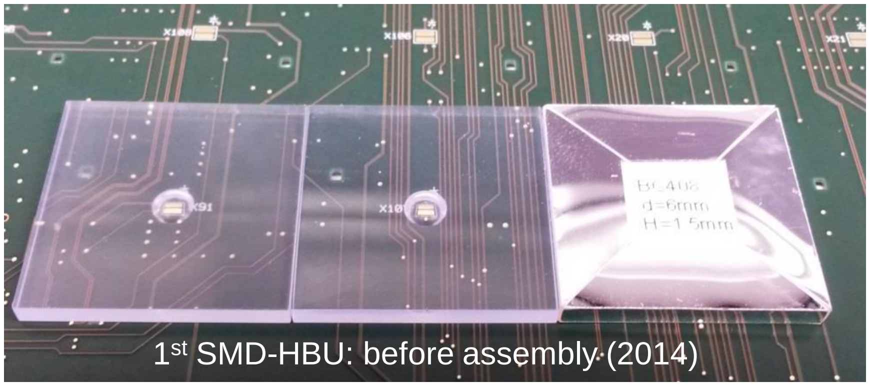
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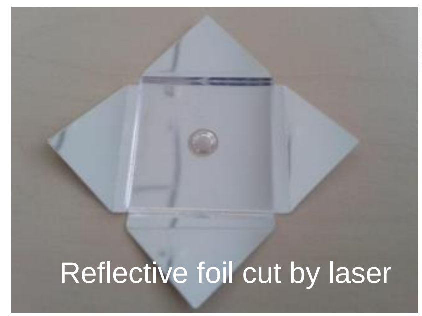
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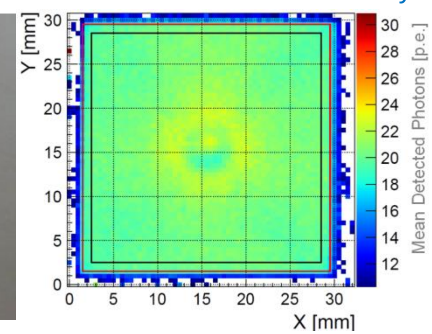
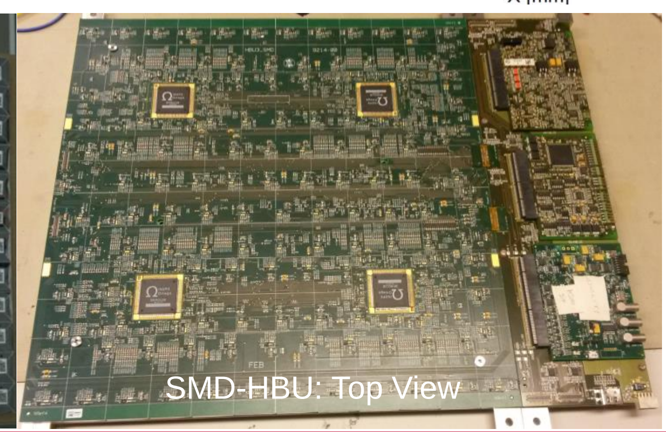
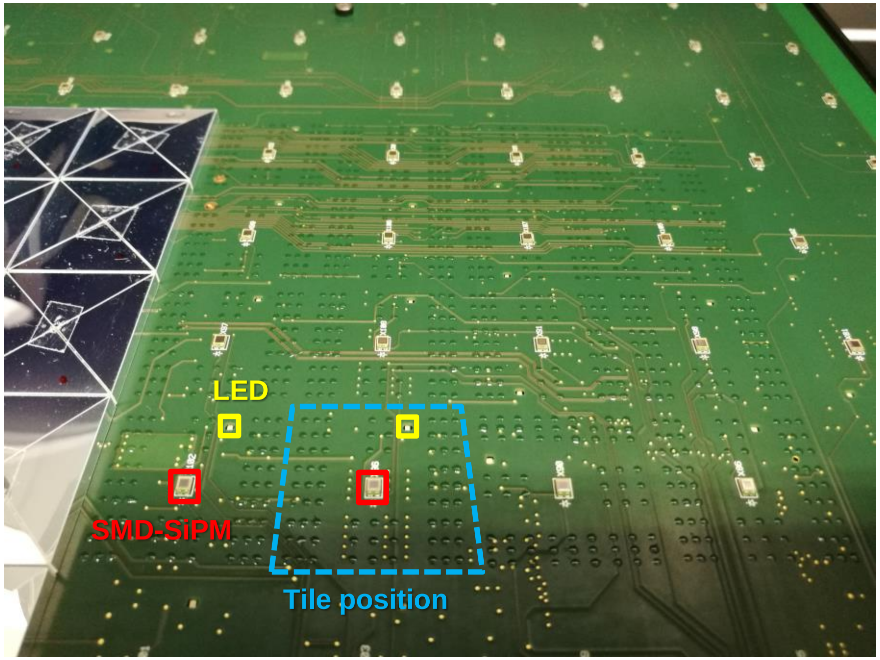



mass assembly with a pick-and-place machine

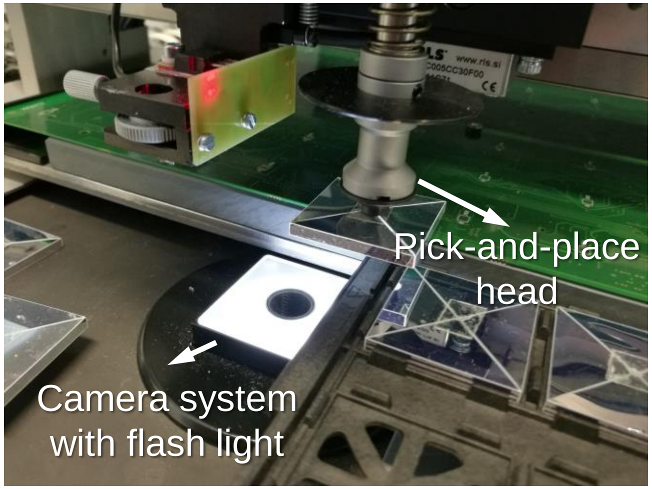

SMD-HBU: Bottom View

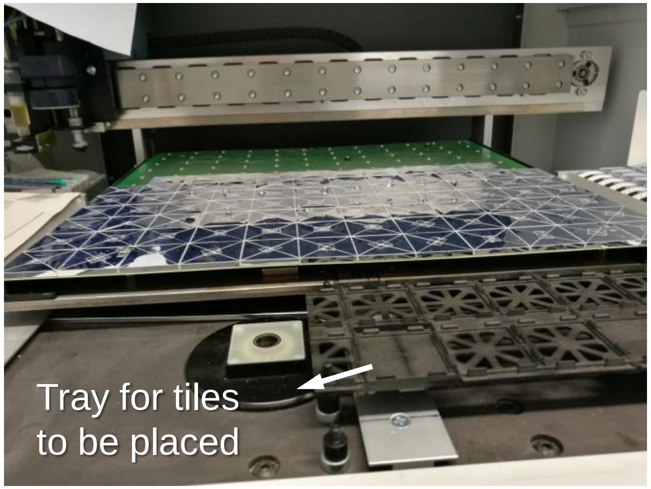

SMD-HBU: Top View

AHCAL: latest mass assembly activities



- Surface-mount tile design
  - Adopted as a baseline design for the tech. prototype
  - 6 new SMD-HBUs assembled in 2016
    - New SiPMs with updated tile design
  - 2017: ~170 new boards will be fully assembled and tested
    - Collaboration-wide efforts ongoing





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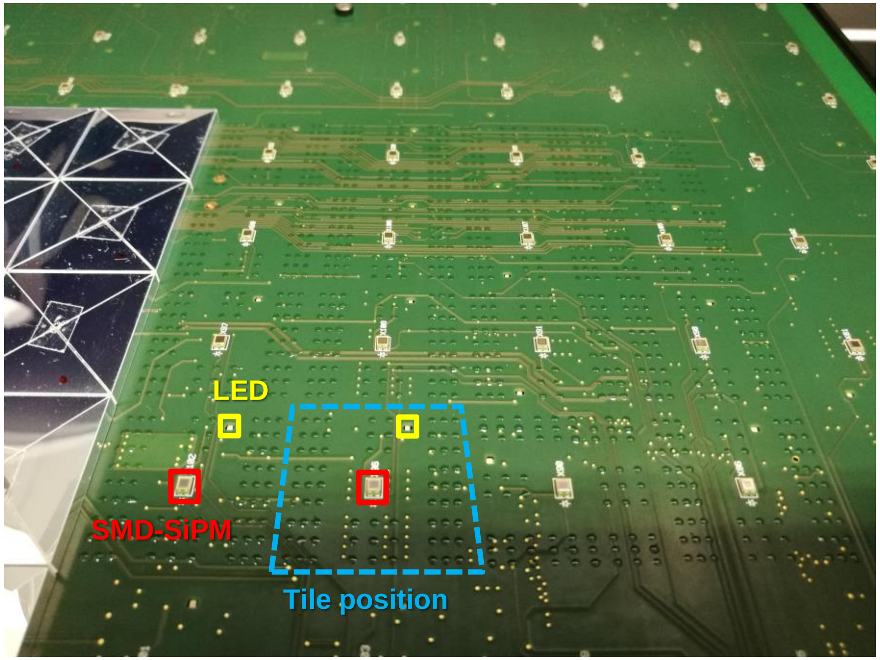

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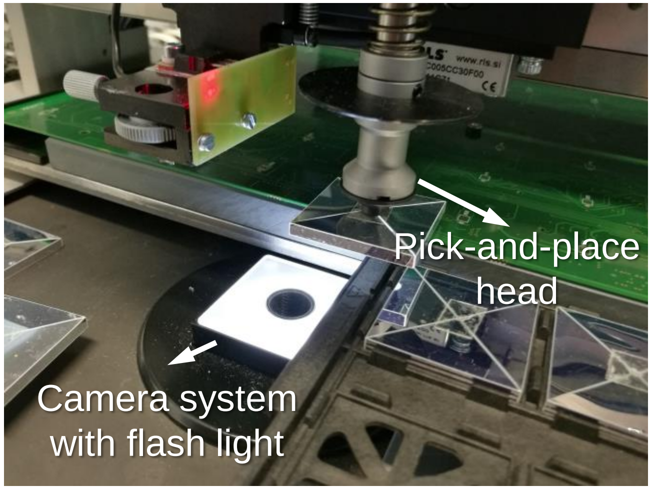
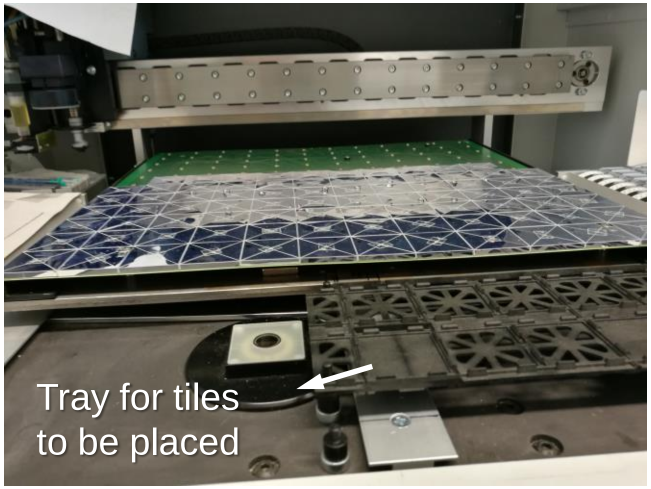
- New generation of SiPMs
  - Reduced DCR and low inter-pixel crosstalk
  - Noise free in AHCAL
  - Improved uniformity (SiPMs, also pixels)





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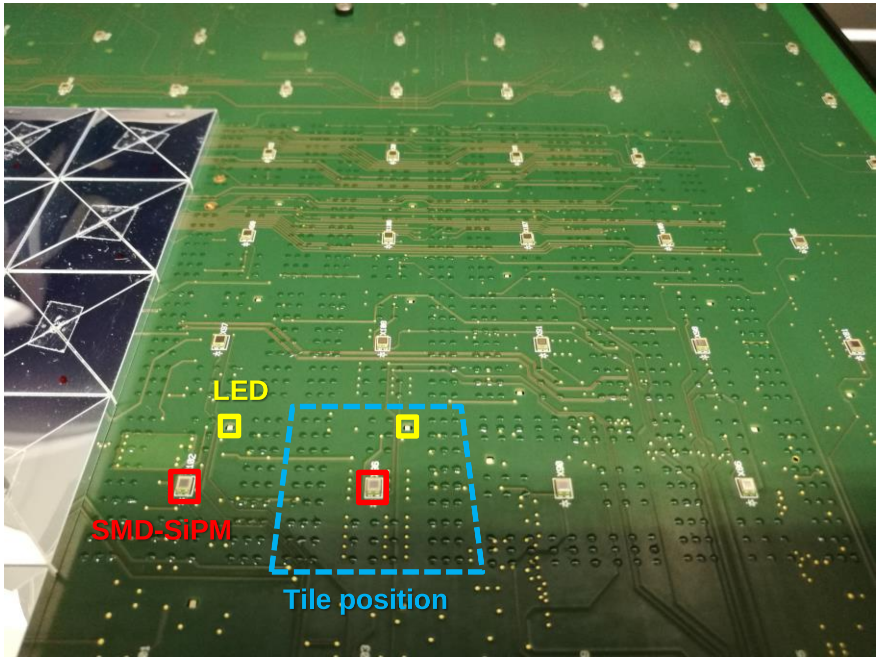
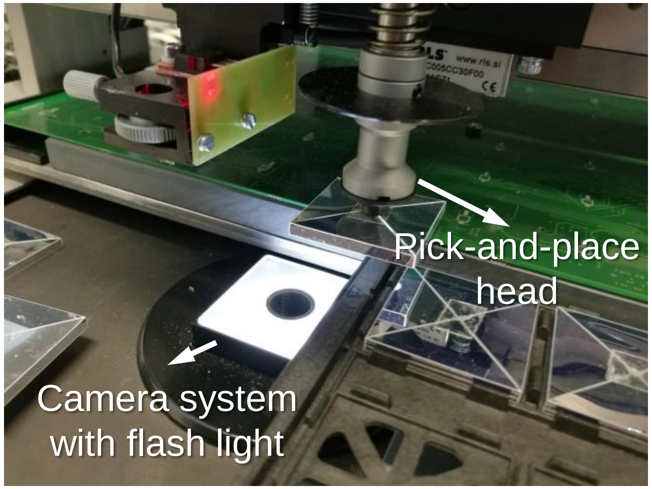
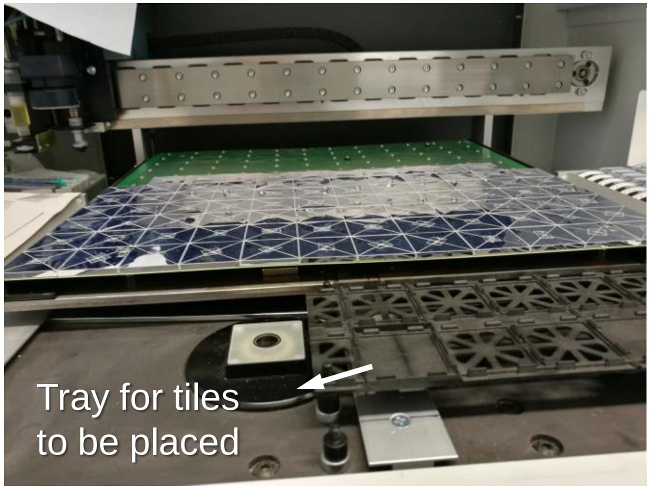
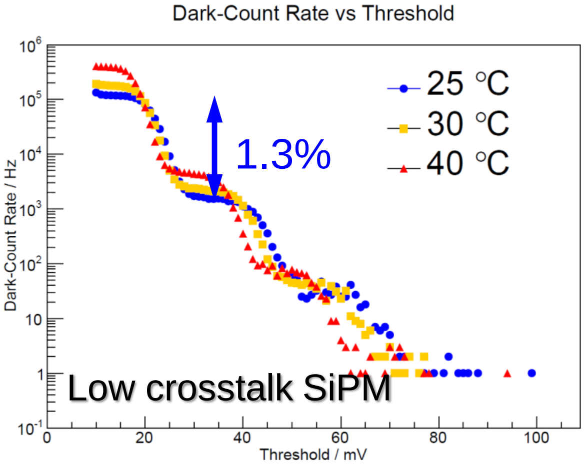


- Surface-mount tile design
  - Adopted as a baseline design for the tech. prototype
  - 6 new SMD-HBUs assembled in 2016
    - New SiPMs with updated tile design
  - 2017: ~170 new boards will be fully assembled and tested
    - Collaboration-wide efforts ongoing
- New generation of SiPMs
  - Reduced DCR and low inter-pixel crosstalk
  - Noise free in AHCAL
  - Improved uniformity (SiPMs, also pixels)

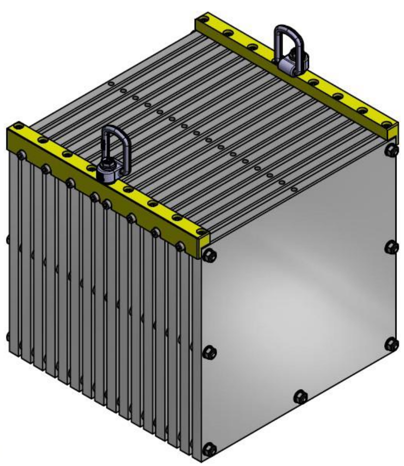






AHCAL: a new small prototype

- 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 (Hamamatsu MPPCs, 2 generations)
    - 8 HBUs with high-quality SiPMs, each coupled to a tile´s side-surface (SensL)
  - New interface boards for all layers
  - To demonstrate: achievable precision of EM showers, power-pulsing mode and temperature compensation for SiPM
- Tested in DESY testbeam in 2016
  - MIP calibration for all layers
  - EM shower data taken with and without power pulsing



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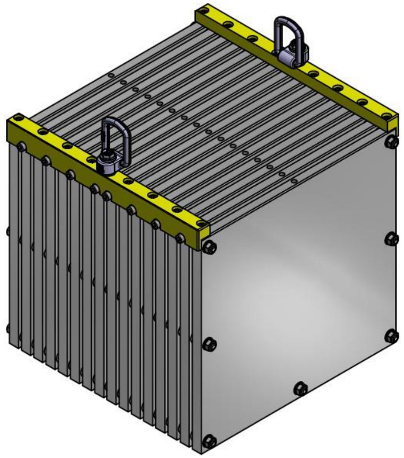
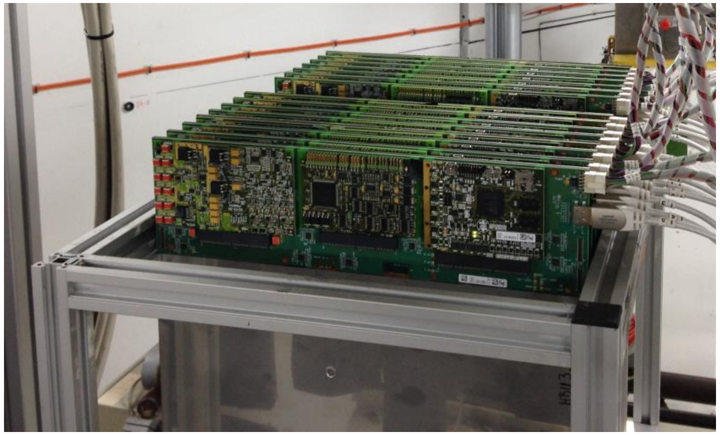
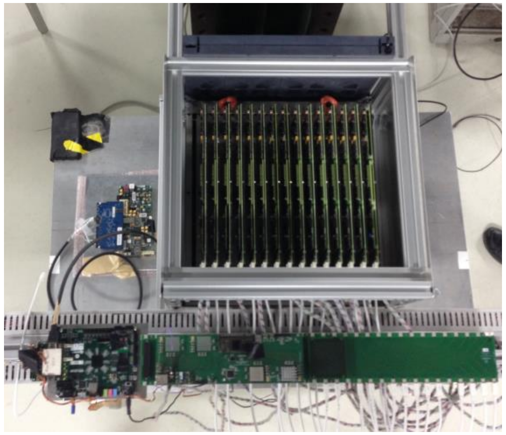
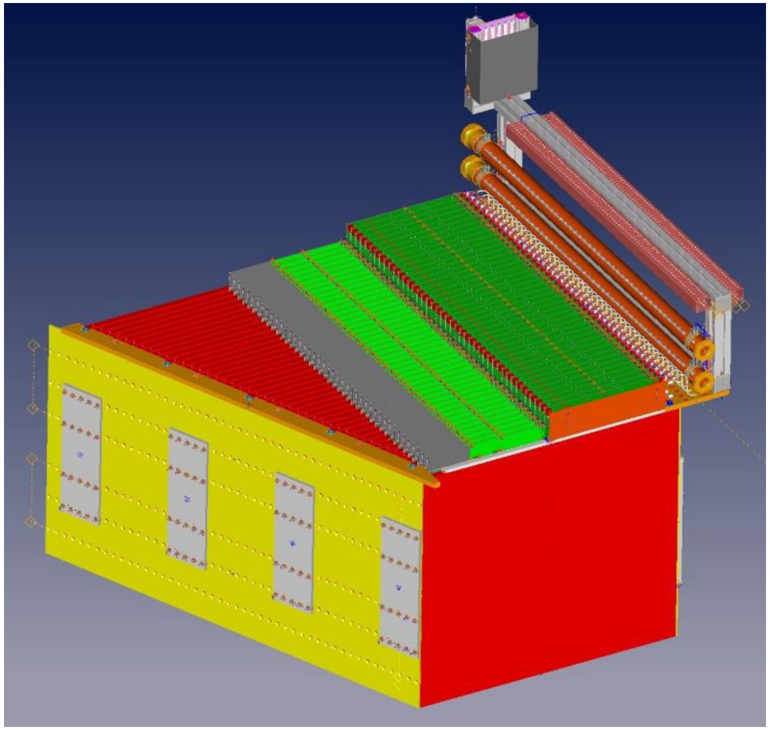






AHCAL technological prototype

- Goal: to instrument AHCAL technological prototype in a steel stack
  - Correspond to ~ 1% of barrel HCAL at ILC
  - Scalable to a full HCAL at ILC
  - 40 layers totally; 4 HBUs in each layer
  - Big step towards mass production & QA
    - Tile mass production via injection molding
    - Quality assurance: ASICs, SiPMs, HBUs



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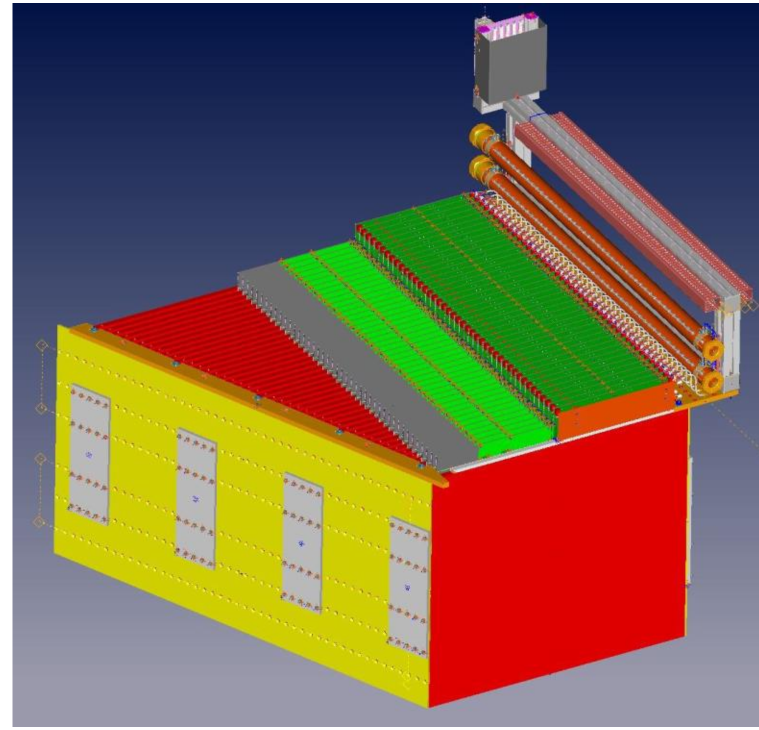
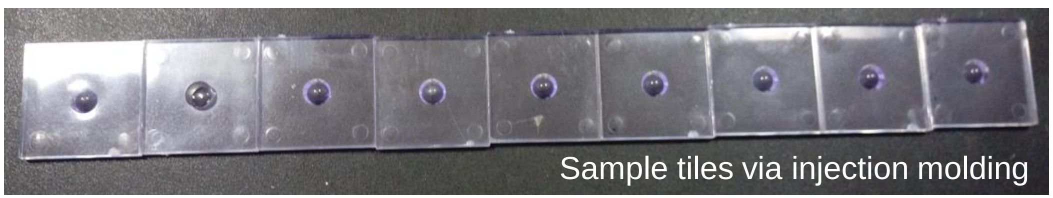
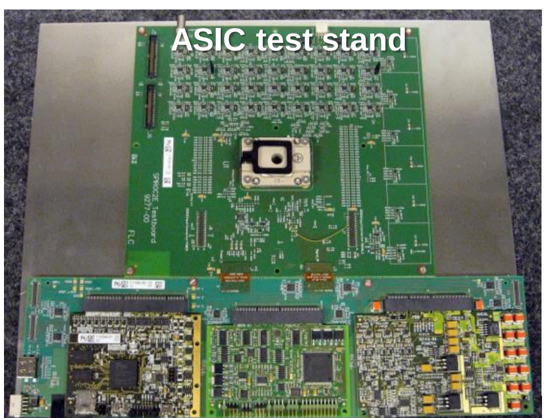
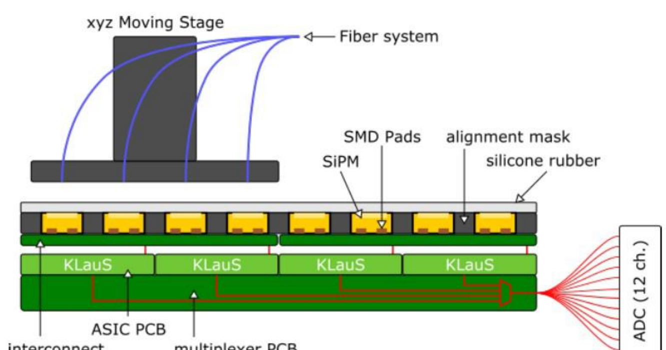




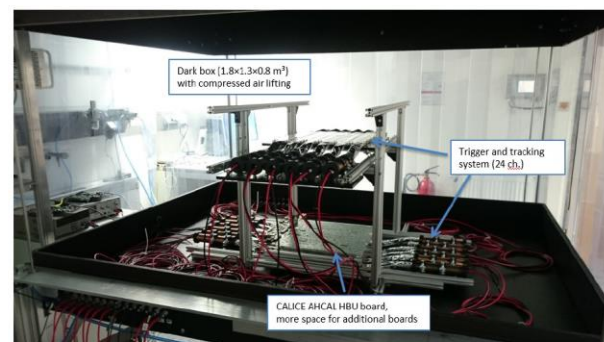
Sample tiles via injection molding



ASIC test stand



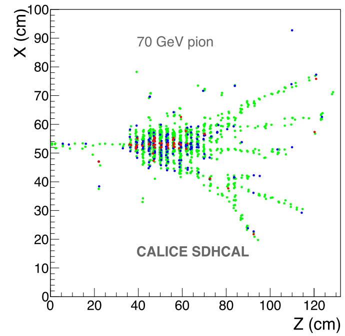
SiPM characterization test stand

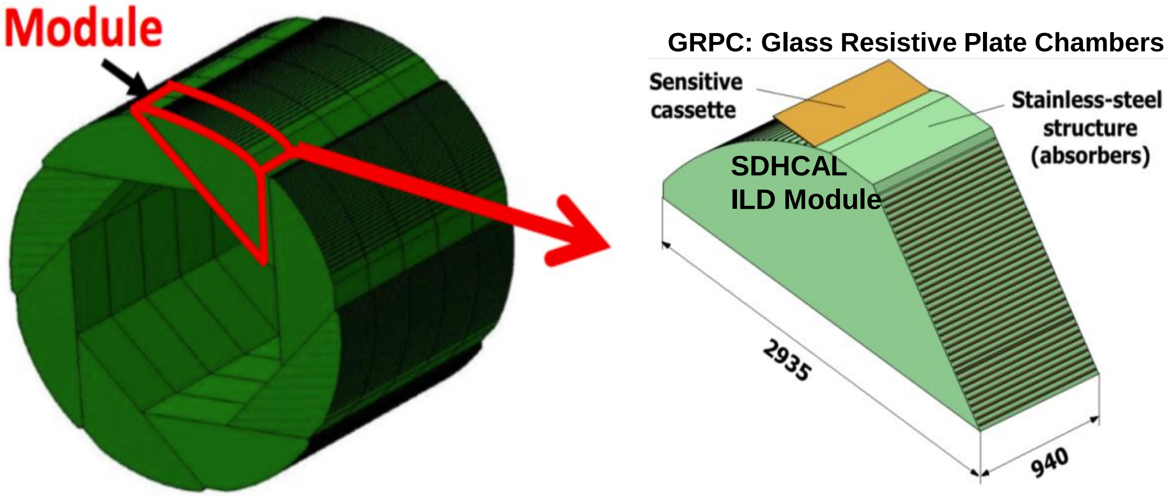


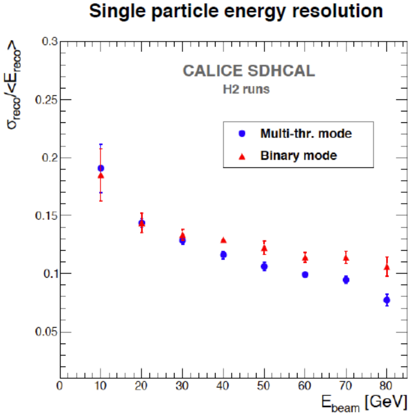
Cosmic-ray test stand for HBUs

Semi-Digital HCAL

- SDHCAL technological prototype: GRPC-Fe
  - 1×1 cm² pads, 48 layers (6λ), 3 thresholds
    - Operated in avalanche mode
  - Compact self-supporting structure design
    - Negligible dead zones; eliminates projective cracks
- Promising results achieved in beam tests
  - Auto-triggering mode tested, with external trigger kept
  - Power pulsing tested for reducing power consumption
  - Threshold information improves the energy reconstruction

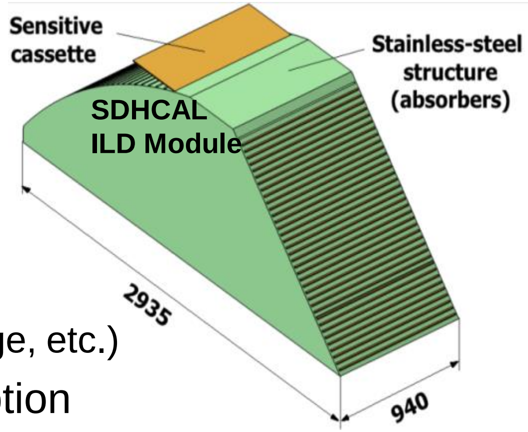




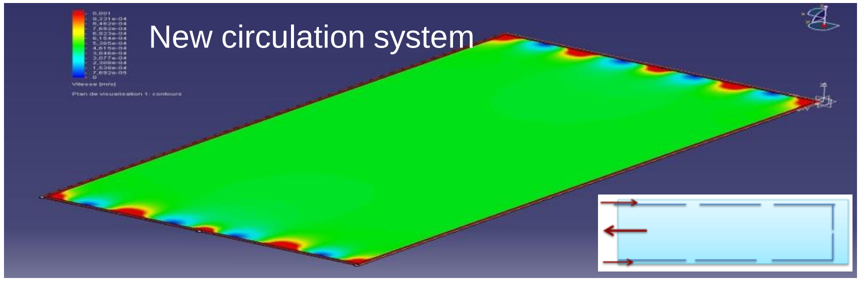


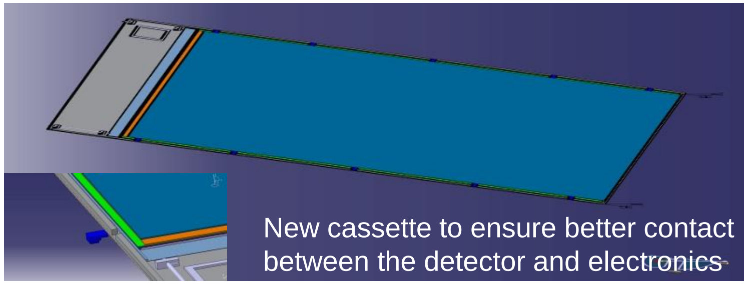
SDHCAL: road map to a full detector

- SDHCAL 1m³ prototype
  - Larger RPC (3×1 m²) under development
  - New electronics: for the final detector
    - DIF board: small dimensions to fit ILD small space
    - 1 DIF for 2 ASUs (Active Sensor Units) + PCB+ ASICs
    - 3 DIFs for a large GRPC layer (1m²)
    - ASIC: HARDROC3 (zero suppression, extended dynamic range, etc.)
  - New detector conception: gas distribution, cassette conception
  - Improved mechanical structure: excellent flatness (<1mm) for 3×1 m² plates



Detector Interface Board

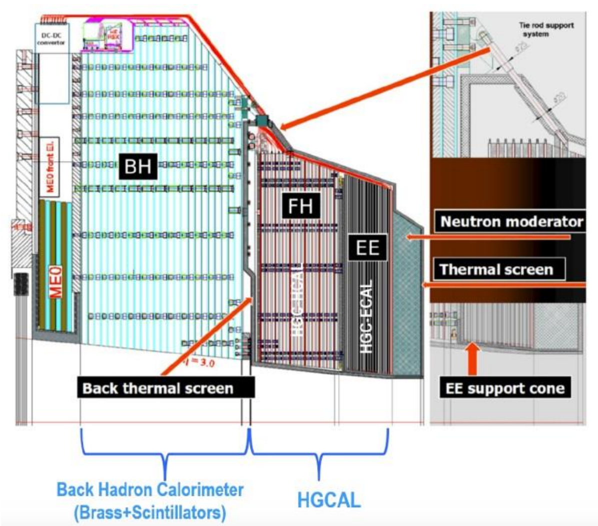


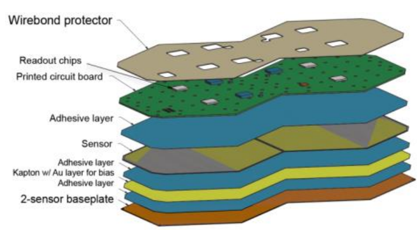


Applications to LHC experiments

- LHC experiments: Phase II upgrades to cope with high luminosity
  - Many challenges: high pile-up, high-level radiation, etc.
  - Good spatial resolution → high granularity
  - Timing separation between vertices → good timing resolution
- Phase II upgrades of both ATLAS and CMS detectors involve technologies developed by CALICE

CMS: High Granular Calorimeter (CMS-HGCAL)

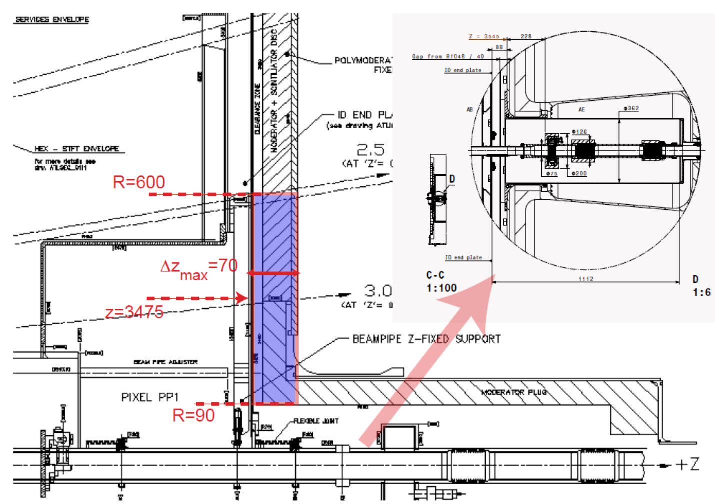




Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

ATLAS: High Granularity Timing Detector (ATLAS-HGTD)



Summary and outlook

- CALICE collaboration is developing high-granularity calorimeters based on Particle-Flow paradigm
- Detector concepts have been validated with physics prototypes
- CALICE data with different active and passive media
  - Possibilities to study hadronic showers in unprecedented granularity
  - Contributing substantially to further development of hadronic models in Geant4
- Technological prototypes with various technologies
  - To prove design can be scalable to a full detector
    - Fully integrated electronics, scalable DAQ, mechanics, mass production, etc.
  - Ongoing developments to address remaining technological challenges
- CALICE technologies find applications in future HL-LHC experiments
  - Fruits of creative ideas, hard work and close collaboration

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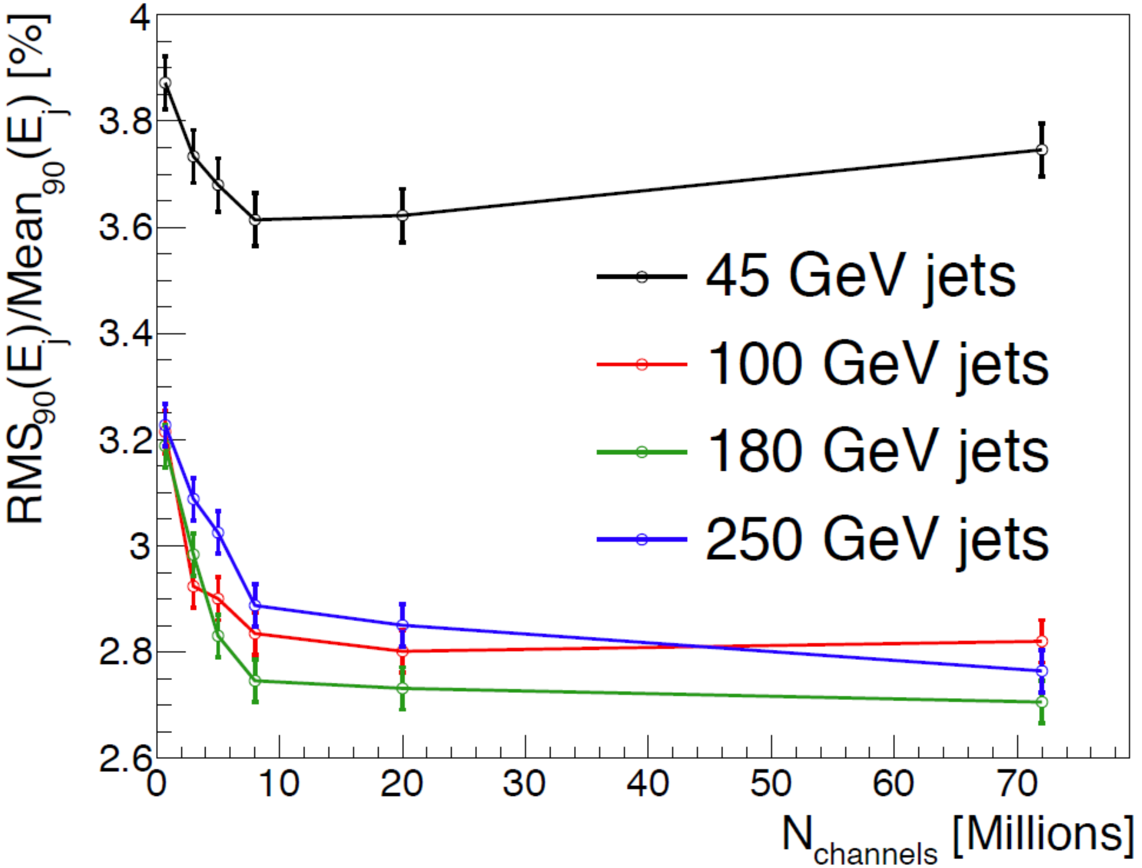
Thank you!

Backup

Calorimeter granularity optimization

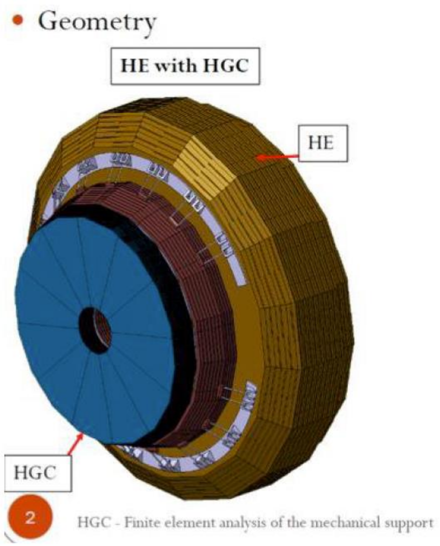
- Jet energy resolution versus the number of HCAL cells
  - Towards cost optimization
  - 3×3 cm² cell size is still a very reasonable choice: 8M cells

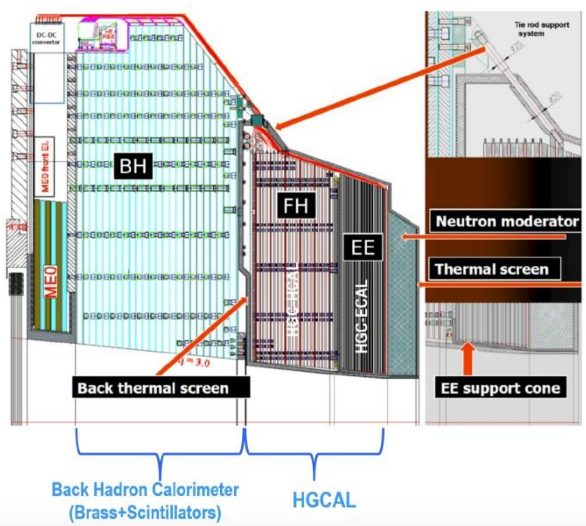


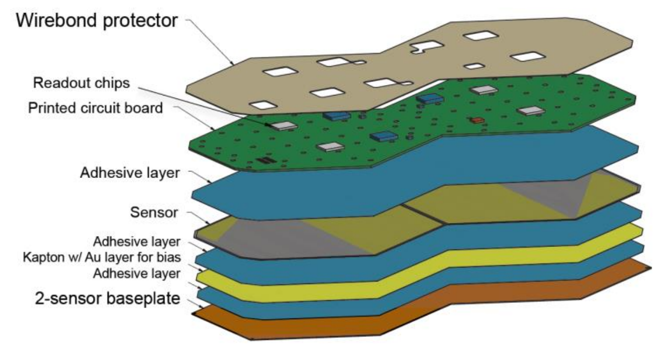
CALICE technology in CMS Phase-II upgrade

- CMS-HGCAL EE+FH: using technologies developed for Si-W ECAL
  - EE: 28 layers, Si+Brass, $\sim 26X_0$ (1.5λ)
  - FH: 12 layers, Si+Brass, 3.5λ
  - New readout chip (SKIROC2-CMS), 30 ps timing resolution
- CMS-HGCAL BH
  - Scintillator (with SiPM) + Steel: 12 layers (5λ), 450m² scintillator

CMS: High Granular Calorimeter (CMS-HGCAL)







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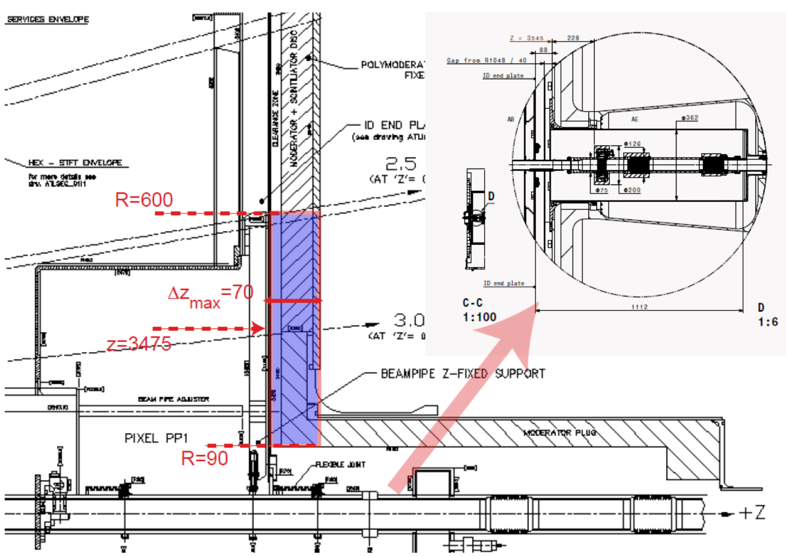
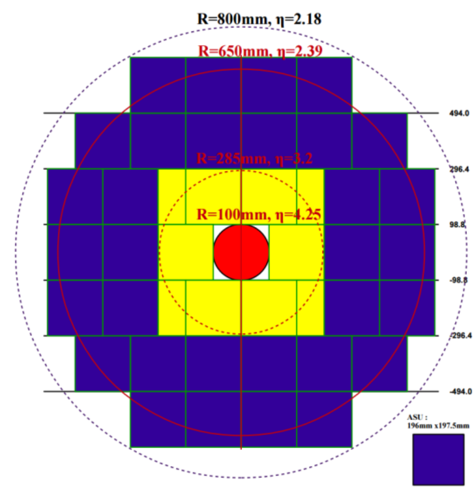
CALICE technology in ATLAS Phase-II upgrade

- ATLAS-HGTD: using technologies developed for CALICE Si-W ECAL
  - Location: z around 3500mm, Δz=60~70mm, R=90~600mm, $2.5 < \eta < 5$
  - Silicon detectors: 4~5 layers
  - Optionally Si-W pre-shower ($3\sim 4X_0$)
  - Intrinsic timing resolution: o(10) ps
  - Precision position and time info, for pile-up subtraction

ATLAS: High Granularity Timing Detector (ATLAS-HGTD)





Transverse plane of a HGTD layer