Upgrade: Calorimetry
Towards High-Granularity

S. Paganis (NTU Taiwan) for ALICE, ATLAS, CMS and LHCb

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Introduction/Outline

At the high luminosity of phase-2, physics exploitation could be compromised due to the presence of high pileup and high radiation levels in particular in the forward regions. HG, both lateral and longitudinal, can allow experiments to:

- ID and reconstruct EM and jet objects with the required efficiency/resolution,
- remove PU effects by exploiting granularity and timing,
- resolve object constituents as in boosted EM and hadronic objects,
- offer significant improvements like tagging to VBF/VBS analyses.

- ALICE Forward Calorimeter: **FoCal**
- ATLAS High Granularity Timing Detector: **HGTD**
- CMS MIP Timing Detector: **MTD**

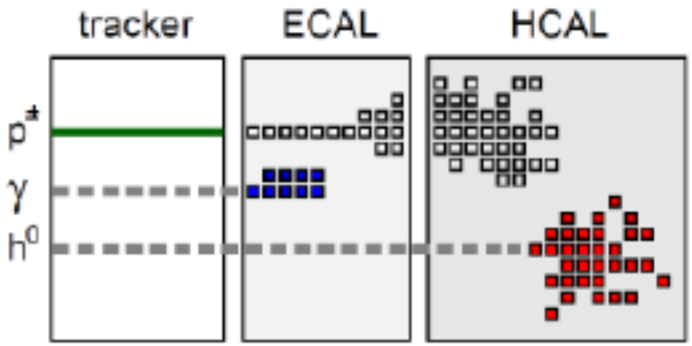
Timing Detectors
See R E Geertsema's talk

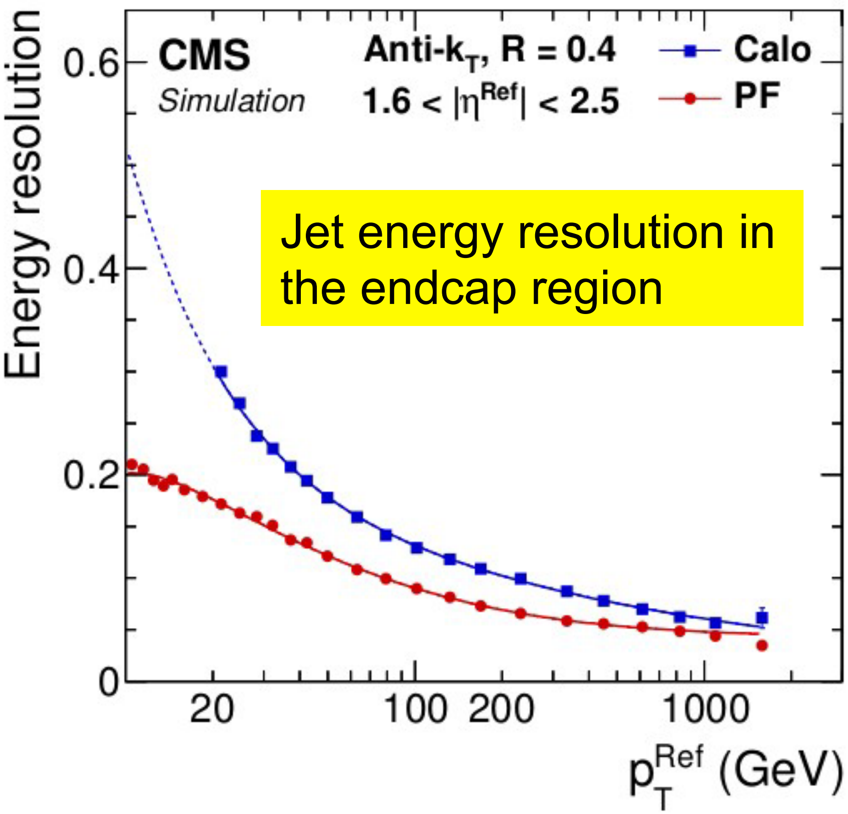
- LHCb Spaghetti Calorimeter: **SpaCal**, and **Shashlik** array
- CMS High Granularity Calorimeter: **HGCAL**

Motivation for HG Calorimetry

Case for HG Calorimeter in the forward region

- Allows PF measurements to extend from the tracker into the calorimeter
- Allows the subtraction of the energy from pileup events leading to a good energy resolution even in a high pileup environment.

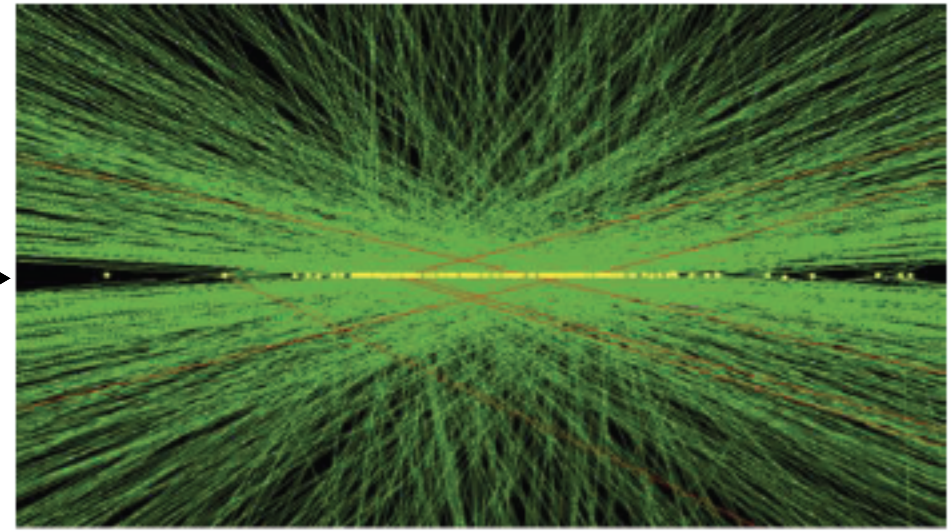


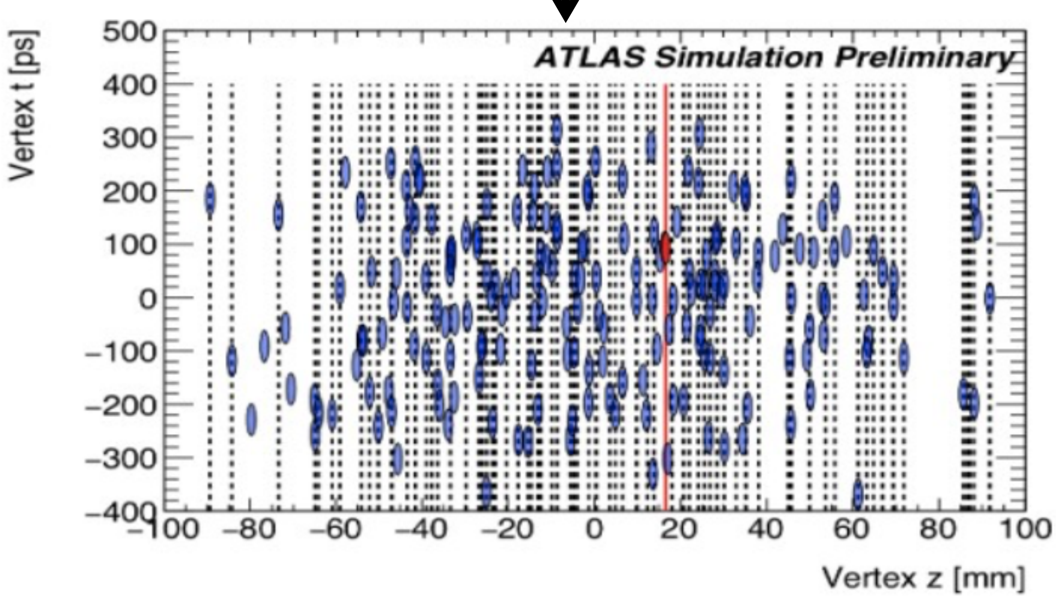


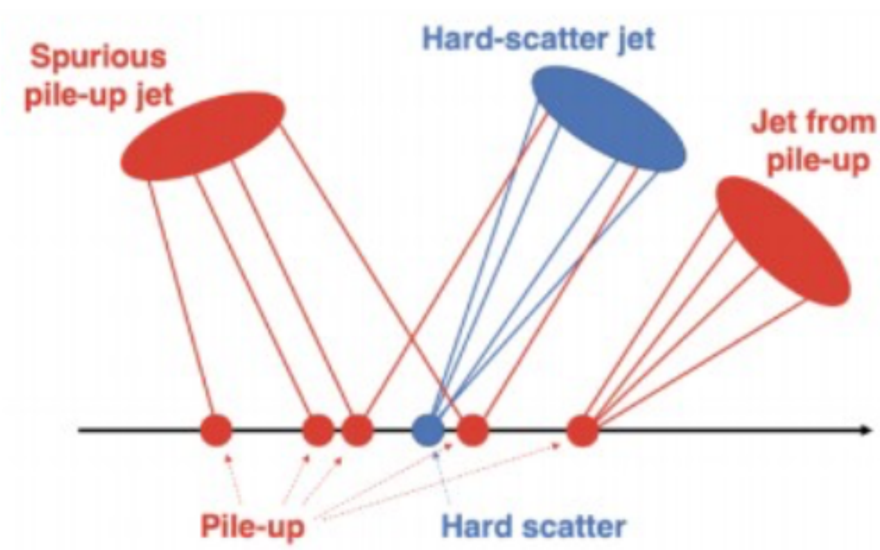
- Merged jets can be reconstructed with higher efficiency and better energy resolution improving the boosted object reconstruction performance
- The high lateral granularity allows the tagging of narrow jets originating from the production mode of the VBF Higgs boson as well as jets from the weak vector boson scattering.
- HG also allows efficient e/γ reconstruction/PID in the presence of PU in the forward region.
- Small expected constant term that typically dominates the energy resolution at high energies will lead to an EM resolution similar to the current detector.

Motivation for HG timing

- For $\langle N_{PU} \rangle$=200, on average 1.6 vertices/mm.
- Pile-up adds jets, creates spurious jets, alters the properties of hard scattered jets, degrading physics performance.
- Timing information σ_t~30-50ps can mitigate the effect of pile-up (x6 pileup rejection)







ALICE Forward Calorimeter

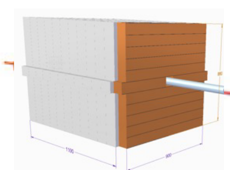
Observables:

- π^0 (and other neutral mesons)
- Isolated (direct) photons
- Jets (and di-jets)
- J/ψ (Y), W, Z
- Event plane and centrality

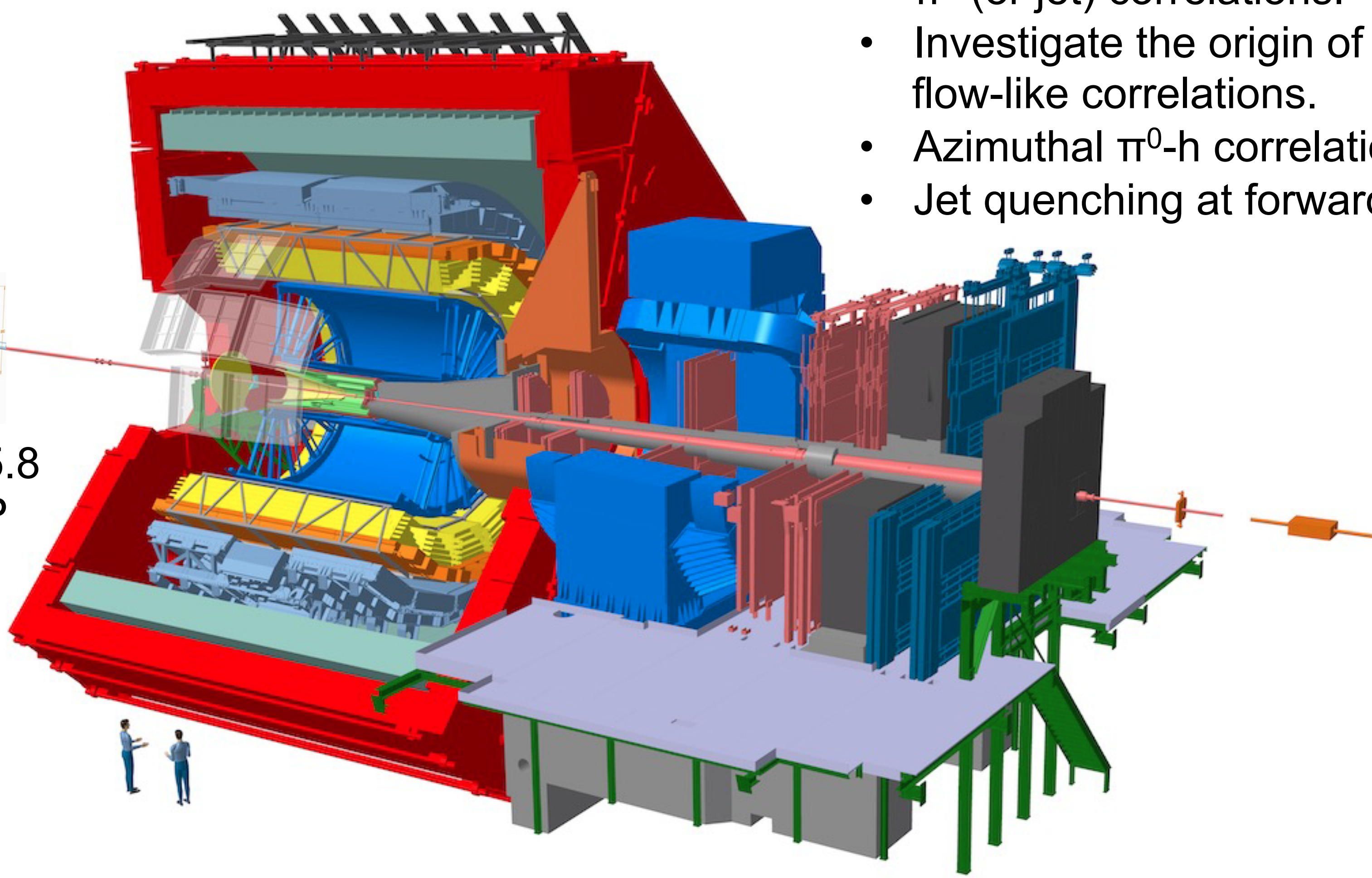
Physics measurements:

- Nuclear modification of gluon density at small-x.
- Isolated γ in pp and pPb collisions.
- Explore non-linear QCD evolution.
- Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations.
- Investigate the origin of long range flow-like correlations.
- Azimuthal π^0-h correlations.
- Jet quenching at forward rapidity.

FoCal
(A-side)



$3.4 < \eta < 5.8$
7m from IP



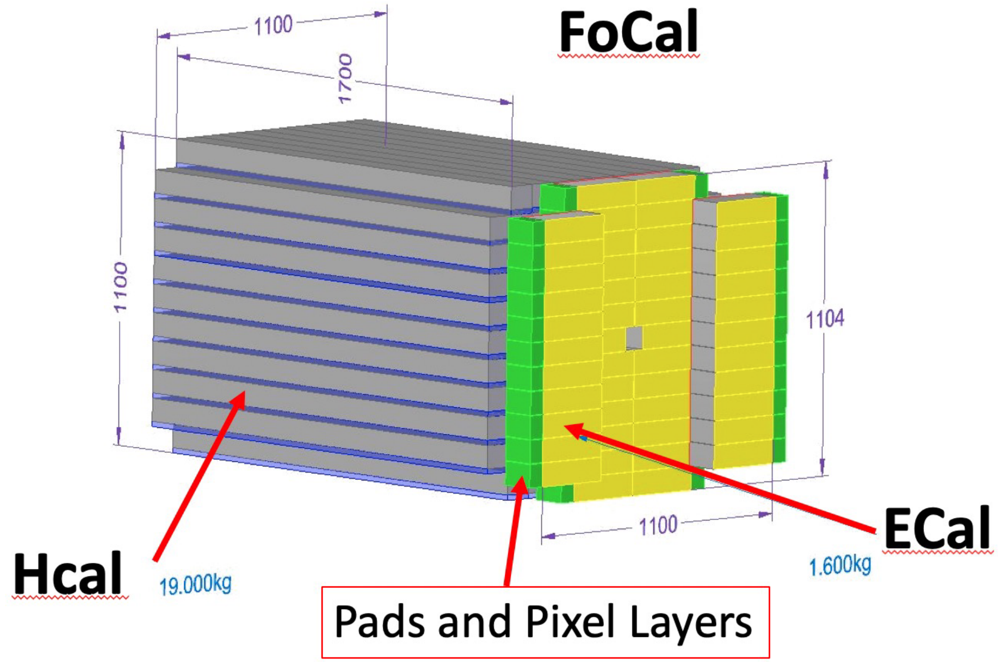
ALICE upgrade: FoCal

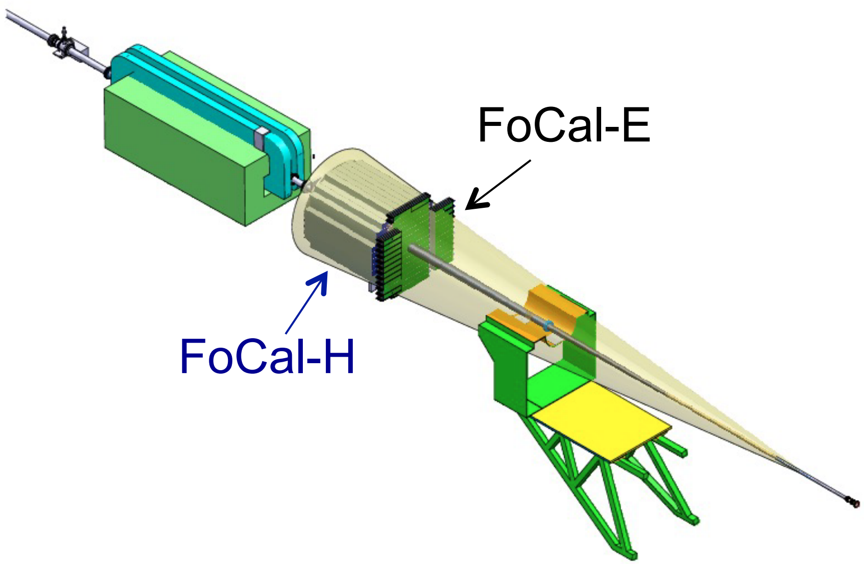
FoCal-E: a highly granular Si+W electromagnetic calorimeter (photons and $\boldsymbol{\pi}^0$)

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

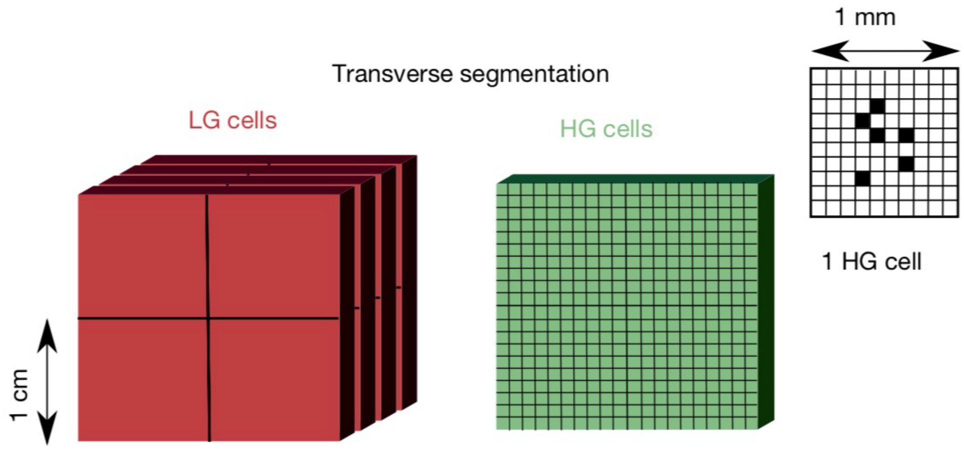
- Unique capability to measure small-x gluon distributions via prompt photon production
- Measurements with mesons, photons, and jets to explore the dynamics of hadronic matter at small x down to 10^{-6}

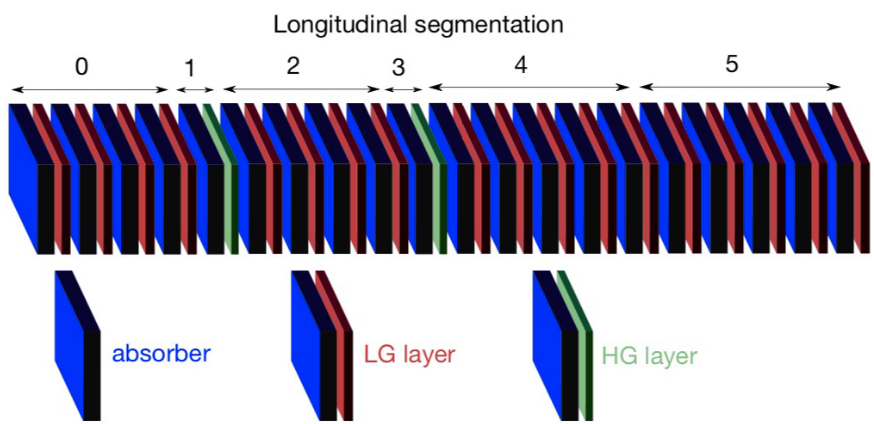
Focus in FoCal-E





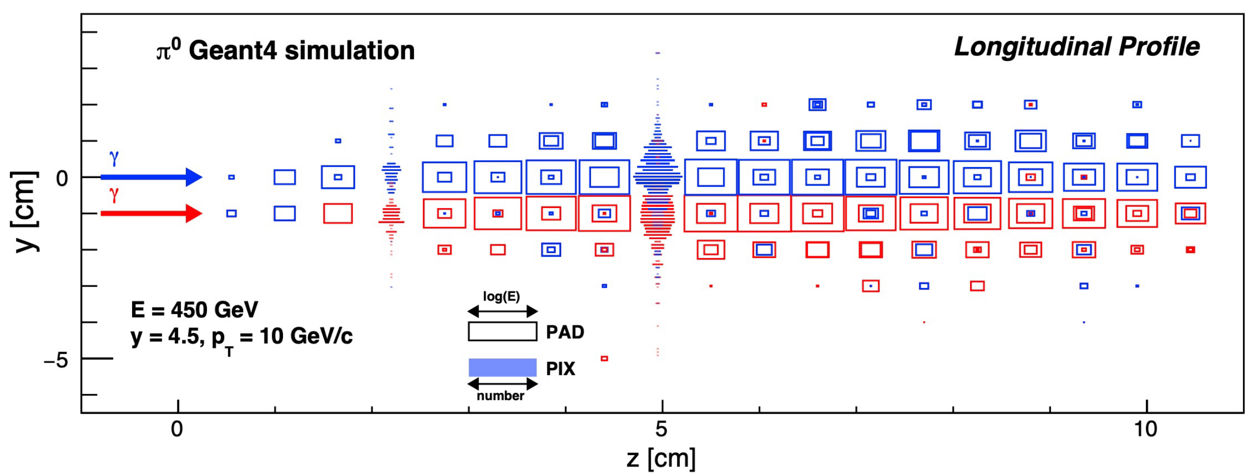
FoCal-E conceptual design

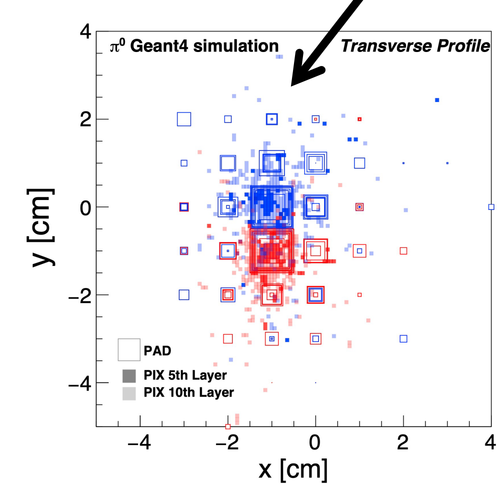




- **Goal: to separate γ/π^0 at high energies.**
  - **Two photon separation from π^0 decay (p_T=10 GeV, η=4.5) ~5mm**
  - **Requires small Molière radius and high granularity readout**
  - **Si-W calorimeter with effective granularity ≈ 1mm²**

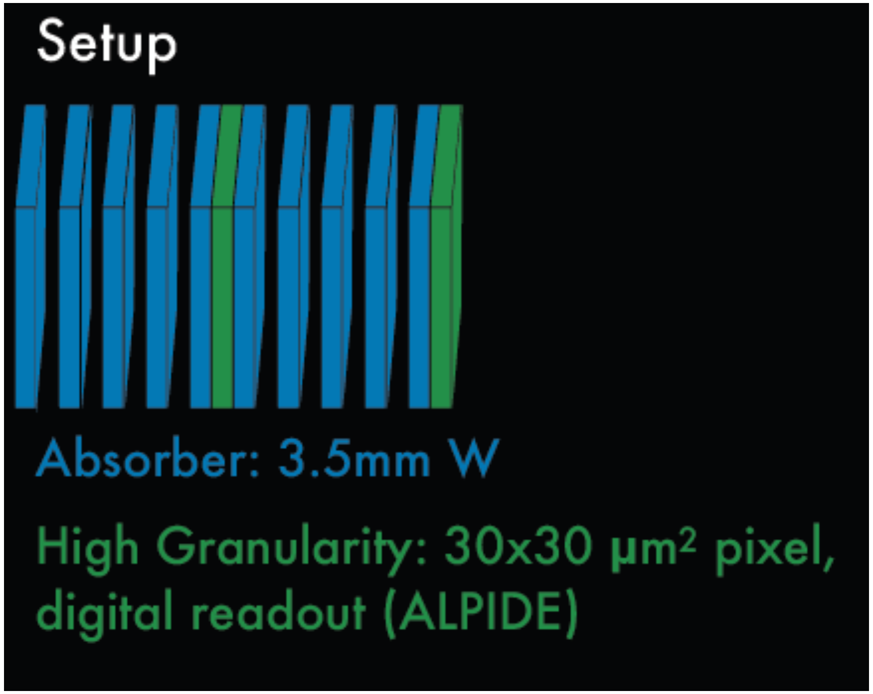
- W(3.5 mm ≈ $1X_0$) + silicon sensors
- Two types: **Pads (LG)** and **Pixels (HG)**
  - LG 1x1 cm², HG 1x1 mm²
- Pad layers provide shower profile and total energy
- Pixel layers (ALPIDE) provide position resolution to resolve overlapping showers

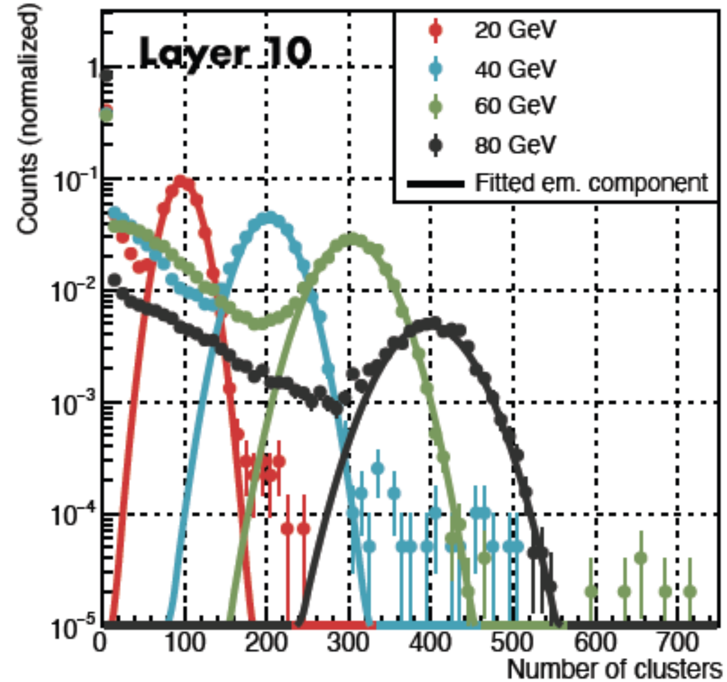


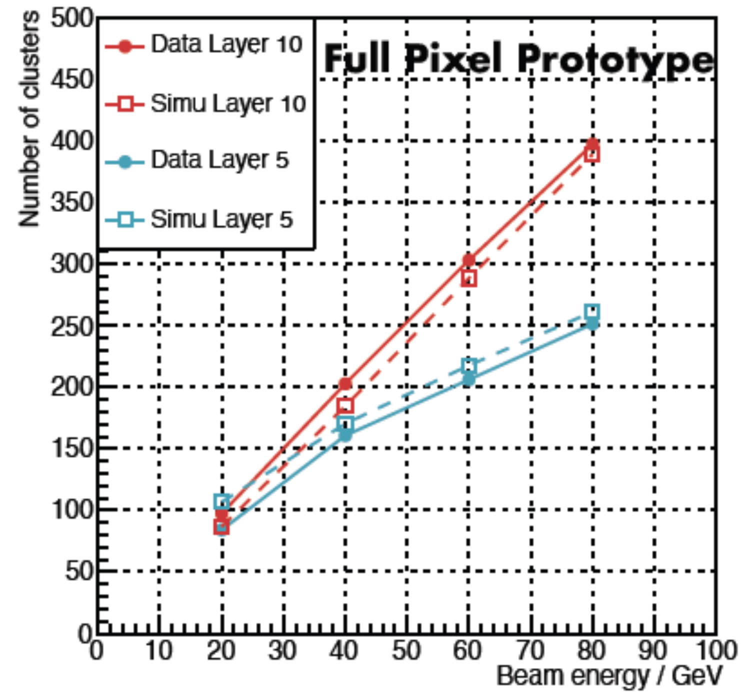


FoCal-E test beam

- Test beam at SPS in summer 2021 with four different energies: 20, 40, 60, 80 GeV
- Electron peaks visible in all energies, described well in MC simulations







Demonstration of FoCal concept in test beams, complete prototype under construction

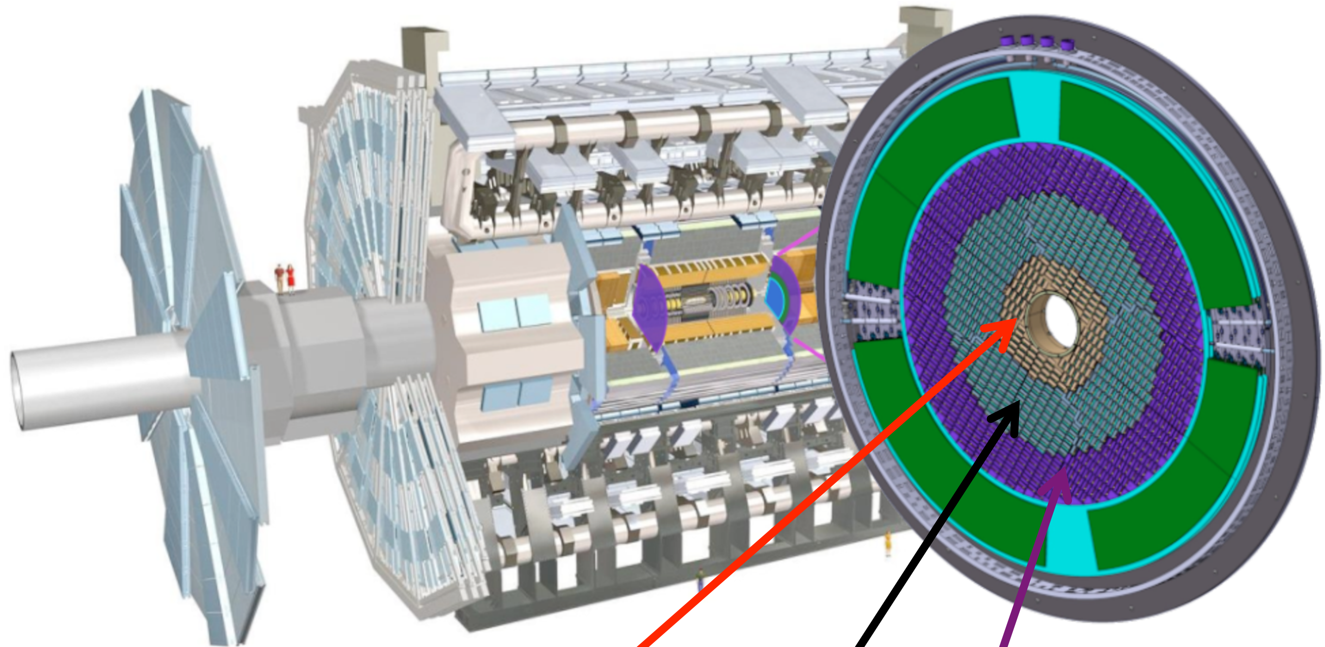
ATLAS HG Timing Detector

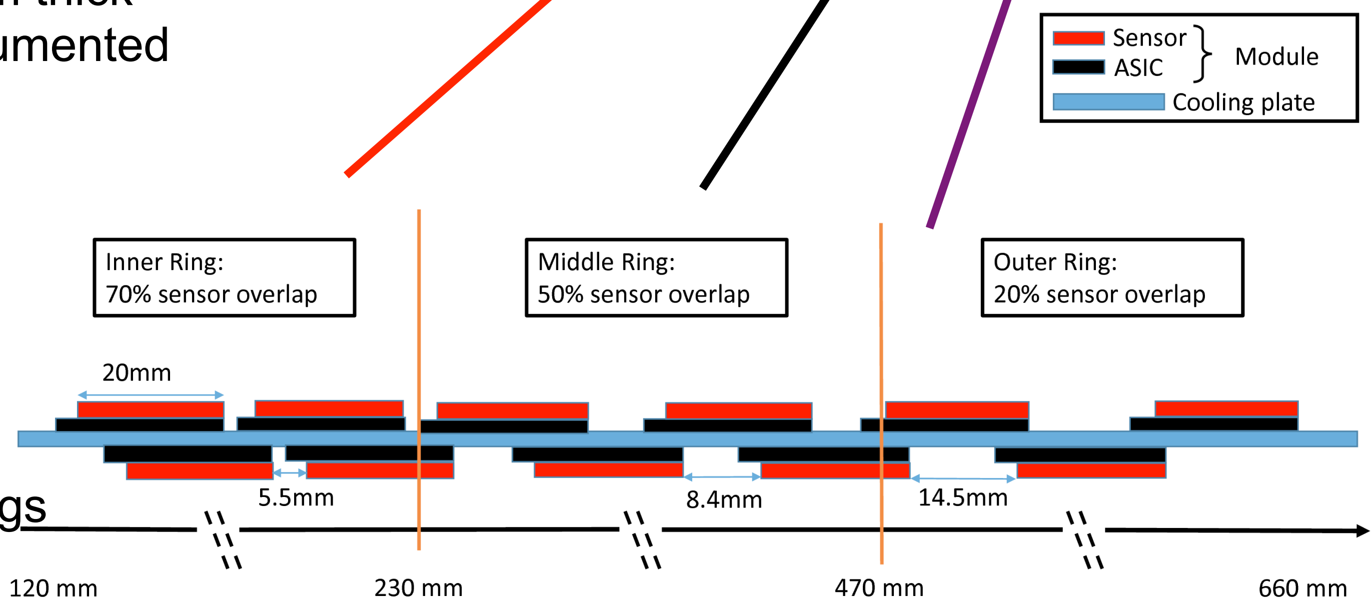
Timing:
- Aiming at 35-70ps per track
- Achieve σ_t<<170ps with up to 4 independent measurements

Acceptance: 2.4 < |η|< 4
- 120 mm < r < 640 mm
- 3.6 M readout channels: 6.4 m^2

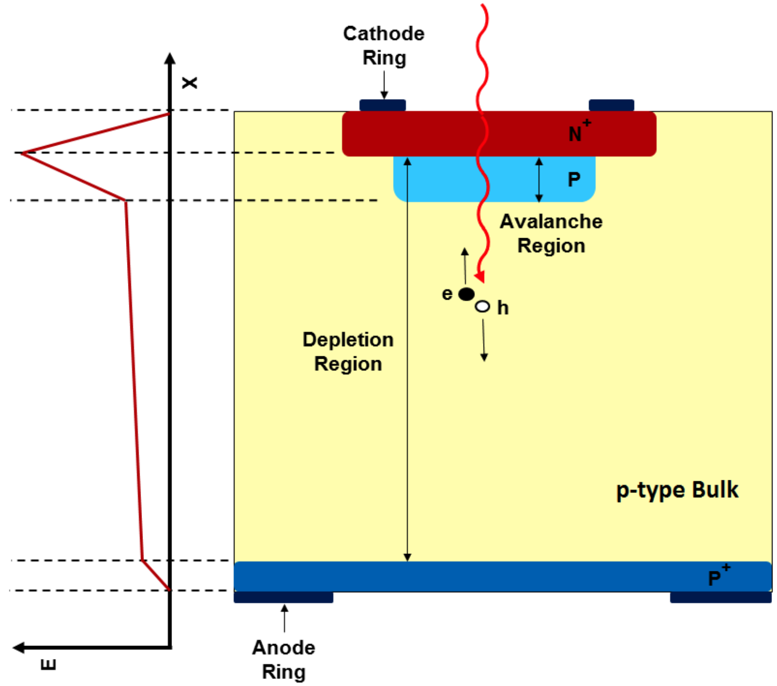
Technology: LGADs
- 15×15 pads, 1.3×1.3mm^2, 50μm thick
- Arranged on 2 disks each instrumented on both sides

Radiation tolerance:
- 2.5×10^{15} n_{eq} cm^{-2}, 2MGy
- Operation at -30 °C
- Arrangement in 3 rings
- Expect to replace innermost rings



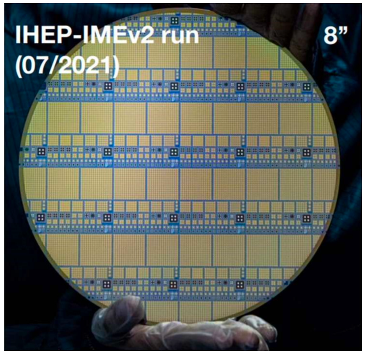


HGTD Sensors and Modules



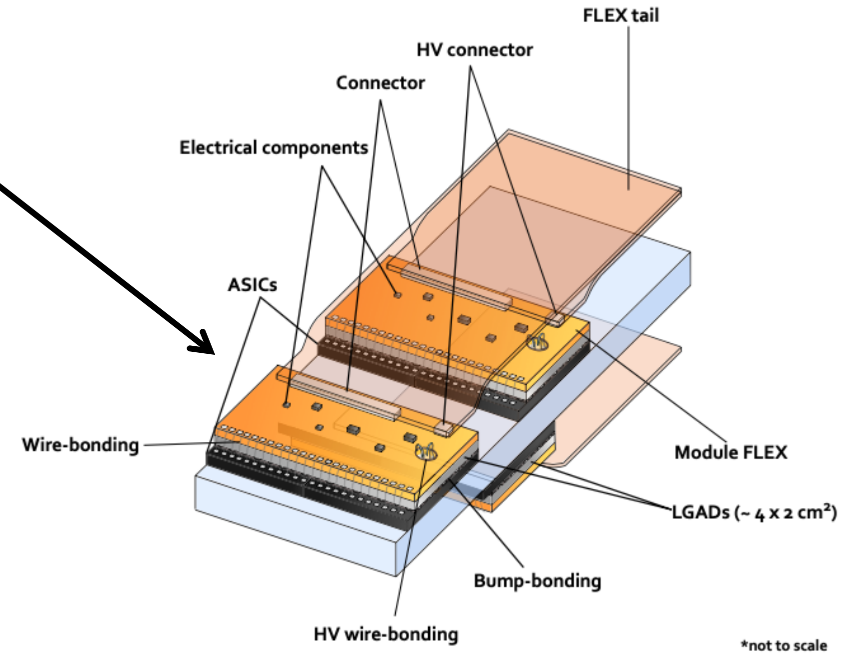
Low-gain avalanche detectors (LGADs)

- pad size: 1.3×1.3 mm^2 and thickness: 50μm
- 15×15 sensors now available from HPK (Japan), IME (China), FBK (Italy), NDL (China); CNM (Spain) expected.



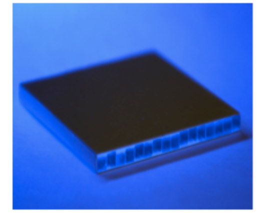
Sensors bump-bonded to ALTIROC ASICs

- 8032 modules: 2 sensors + 2 asics + flex flex tails carrying HV, LV and signals to/from peripheral electronics boards (PEB)
- HV set individually for each module
- Sensor temperature (-30 C) to be maintained by evaporative CO_2 cooling manifold in disks

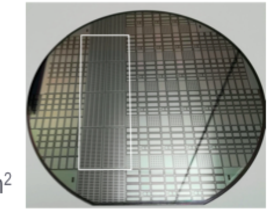


CMS MIP Timing Detector

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2

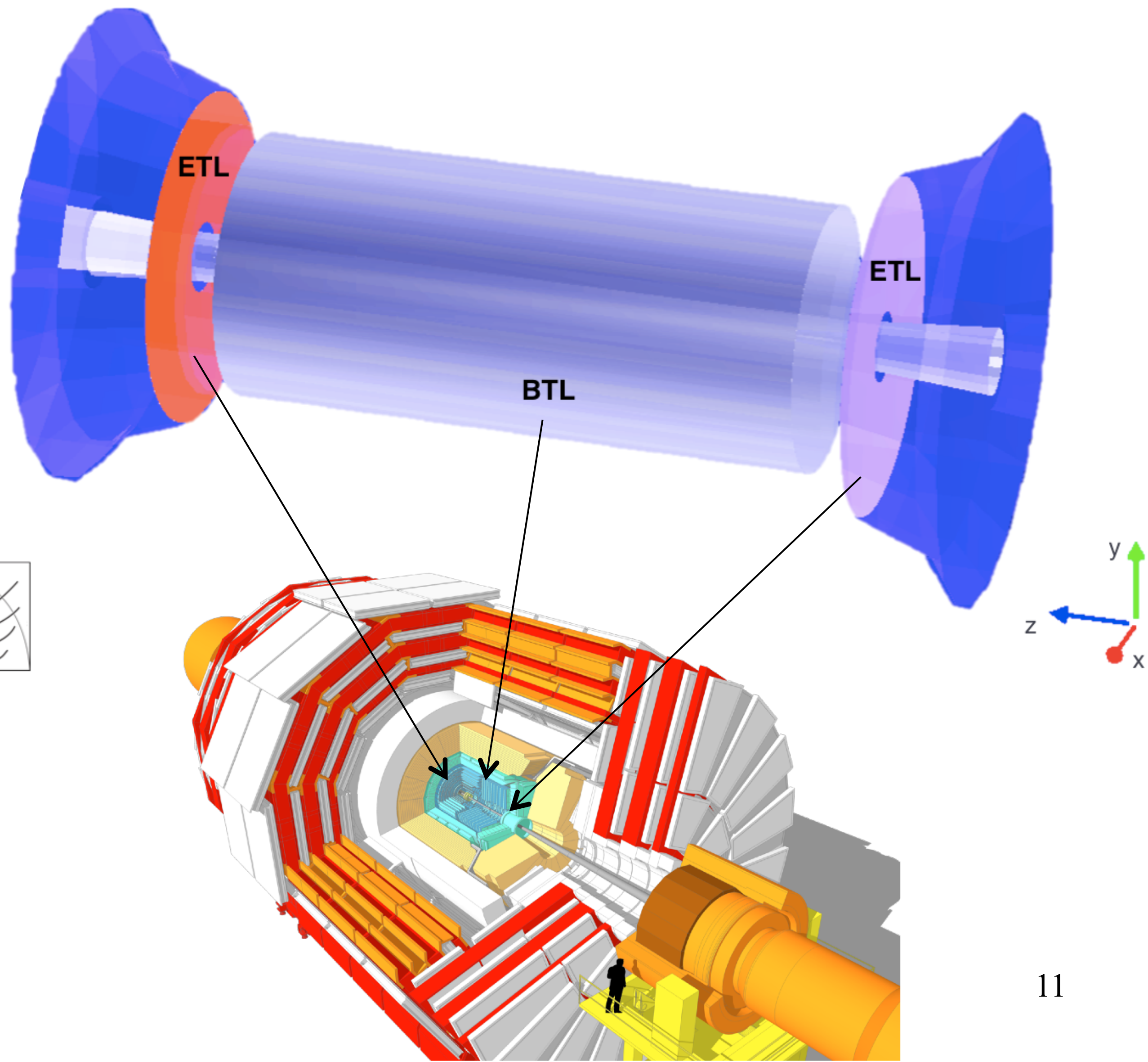


Coverage: $|\eta|<3.0$

Two detector technologies

Barrel Timing Layer: BTL
- LYSO crystals with SiPM

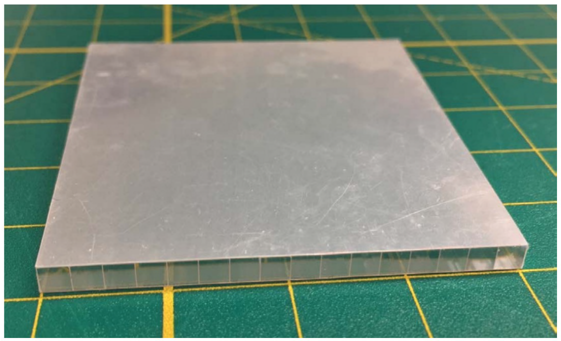
Endcap Timing Layer: ETL
- LGAD Ultrafast silicon detectors.

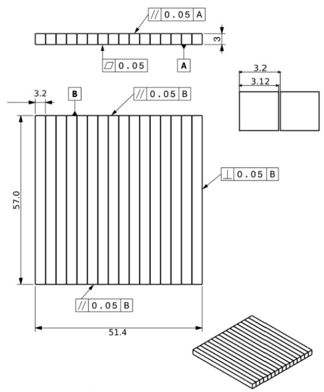


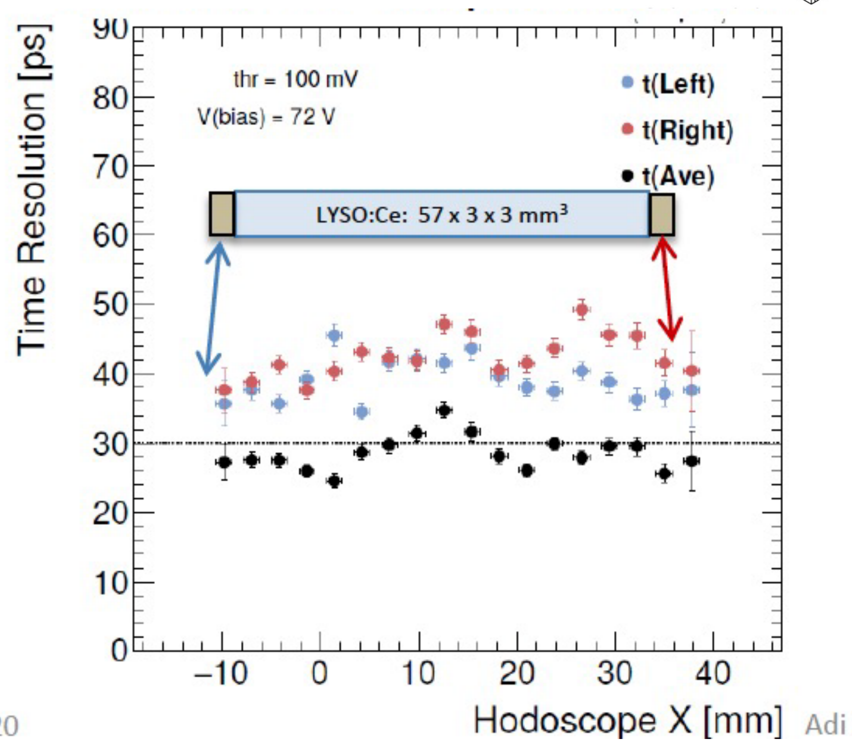
Detector Performance

BTL

Cerium doped LYSO readout by SiPMs





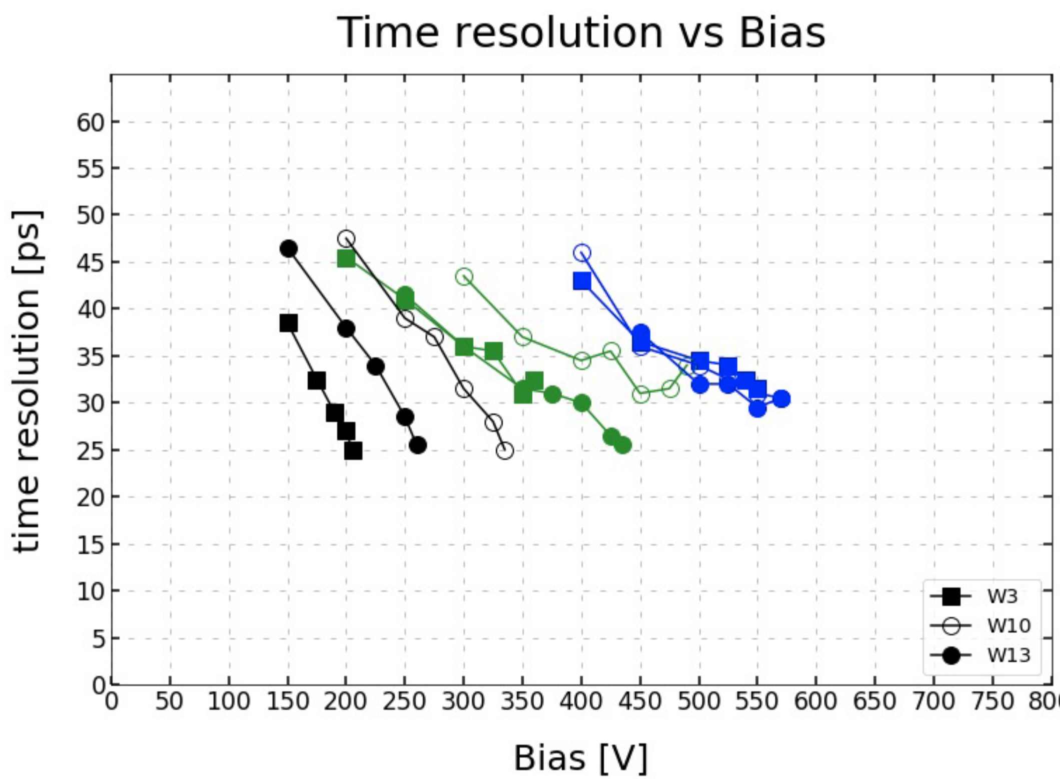


2020

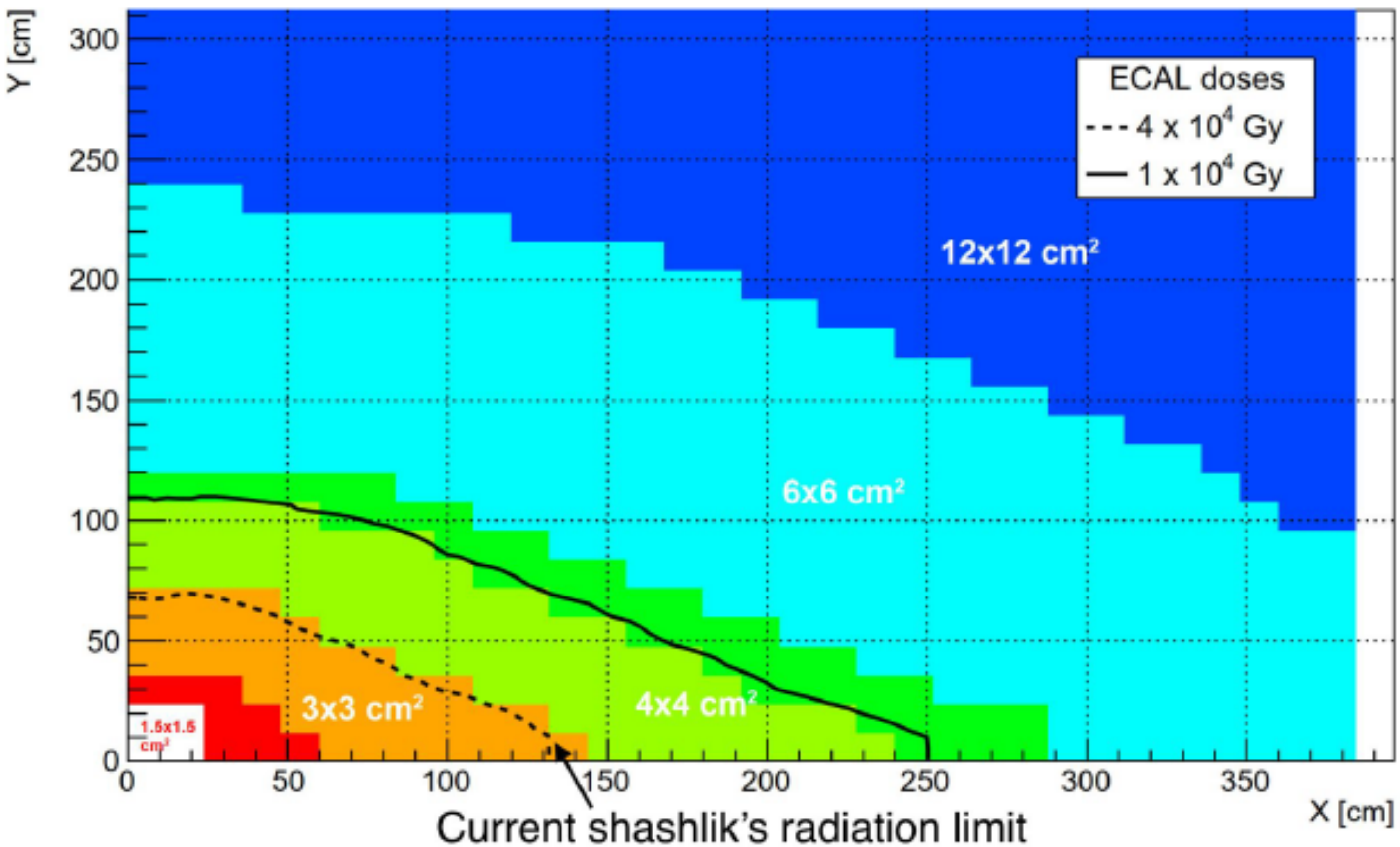
ETL

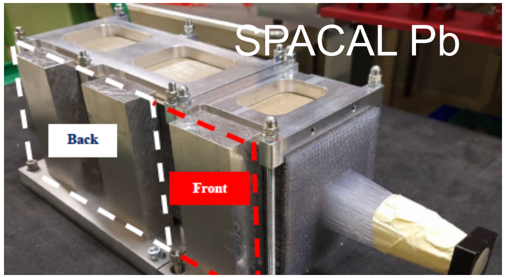
Low-gain avalanche detectors (LGADs)

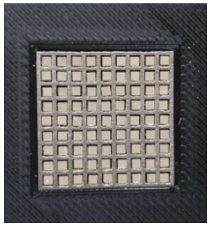
- Detector Intrinsic timing: 30ps
- 15×15 sensors now available from HPK (Japan), IME (China), FBK (Italy), NDL (China); CNM (Spain) expected.

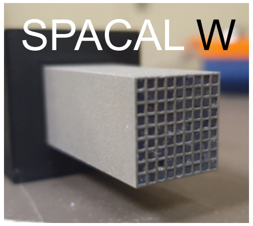


Scintillating ECAL for LHCb







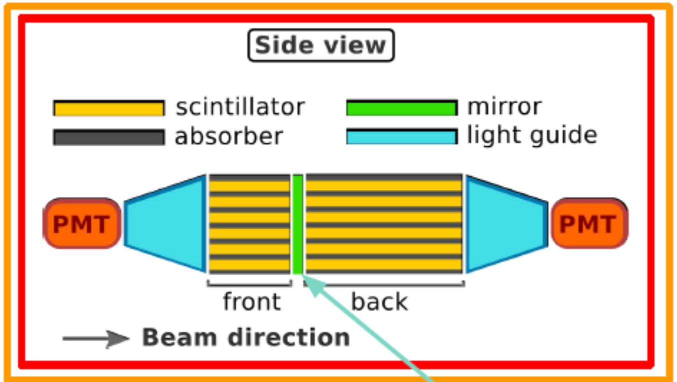


SPACAL W: 1.5x1.5 cm^2 32 new modules for extreme conditions up to 1 MGy
SPACAL Pb: 3x3 cm^2 144 new modules with moderate requirements up to 200 kGy

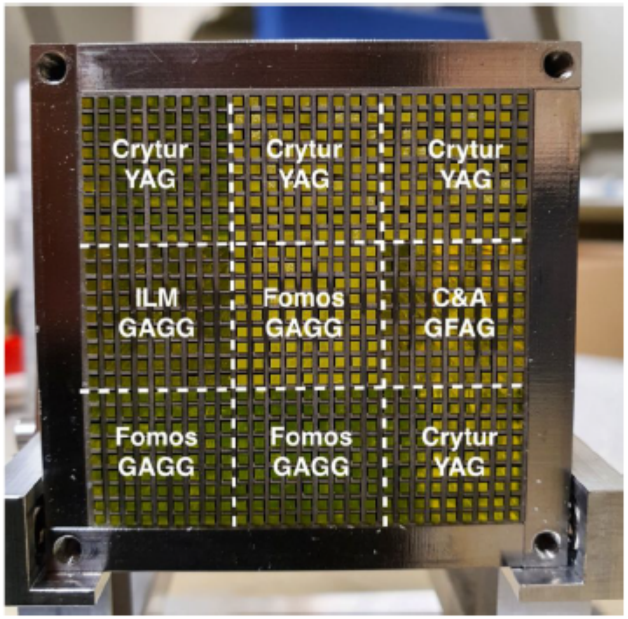
Shashlik:
- 4x4 cm^2, 272 new modules + 176 refurbished
- 6x6 cm^2, 896 rebuilt + 448 refurbished existing modules.
- 12x12 cm^2, 1344 refurbished existing modules.

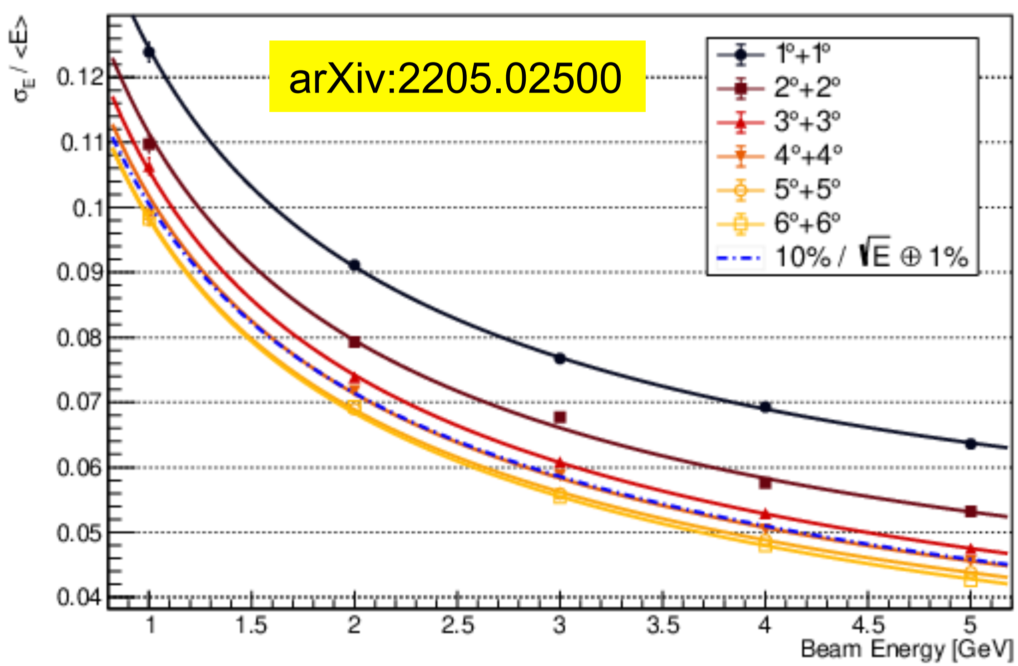
The LHCb SPACAL W

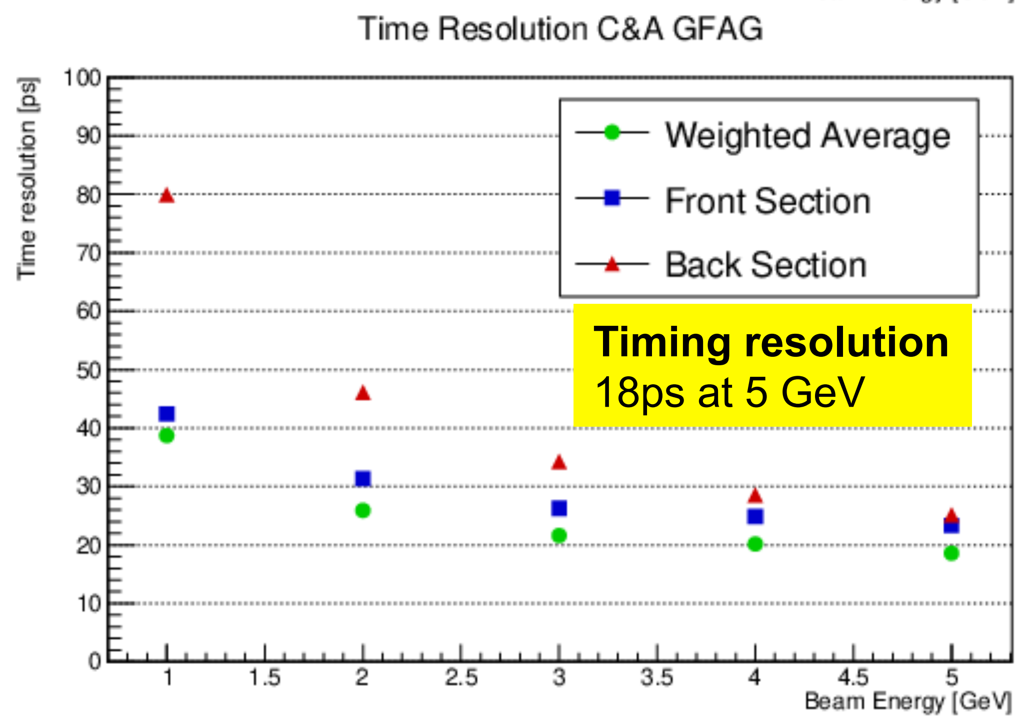
W Spaghetti Calorimeter
with Garnet fibers



Timing layer: MCP-PMT
Instruments 6 (1) (2022)



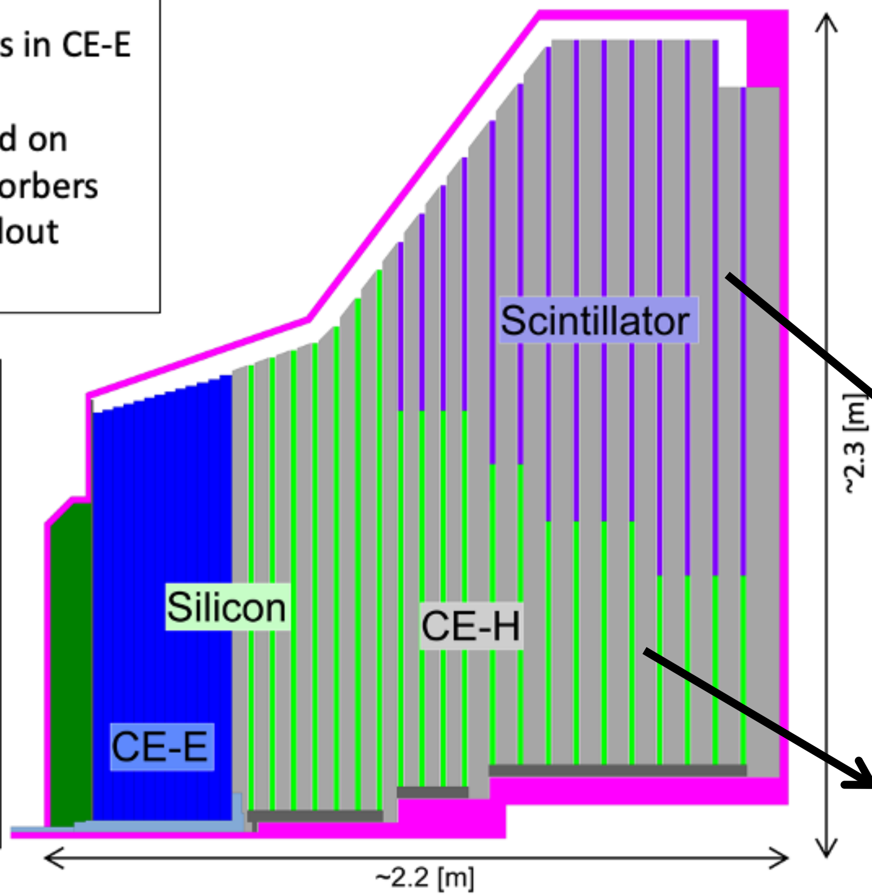


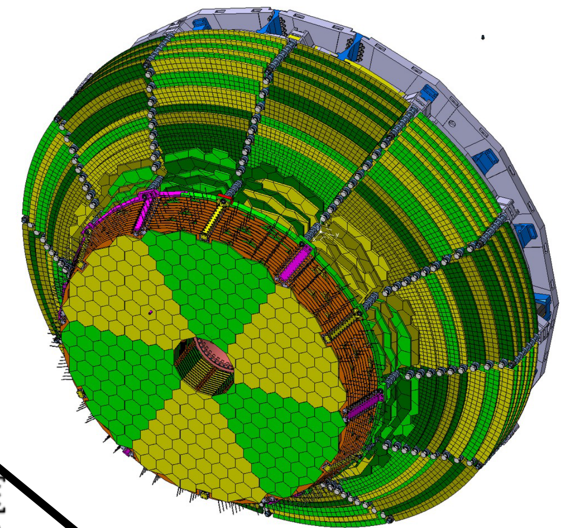


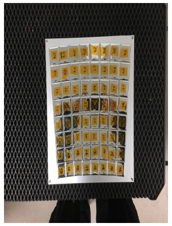
The CMS HGCAL

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

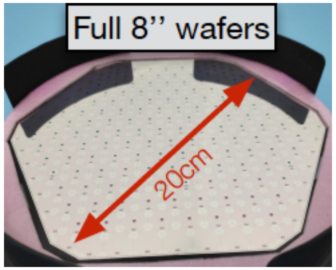
Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap







240,000 individual tiles

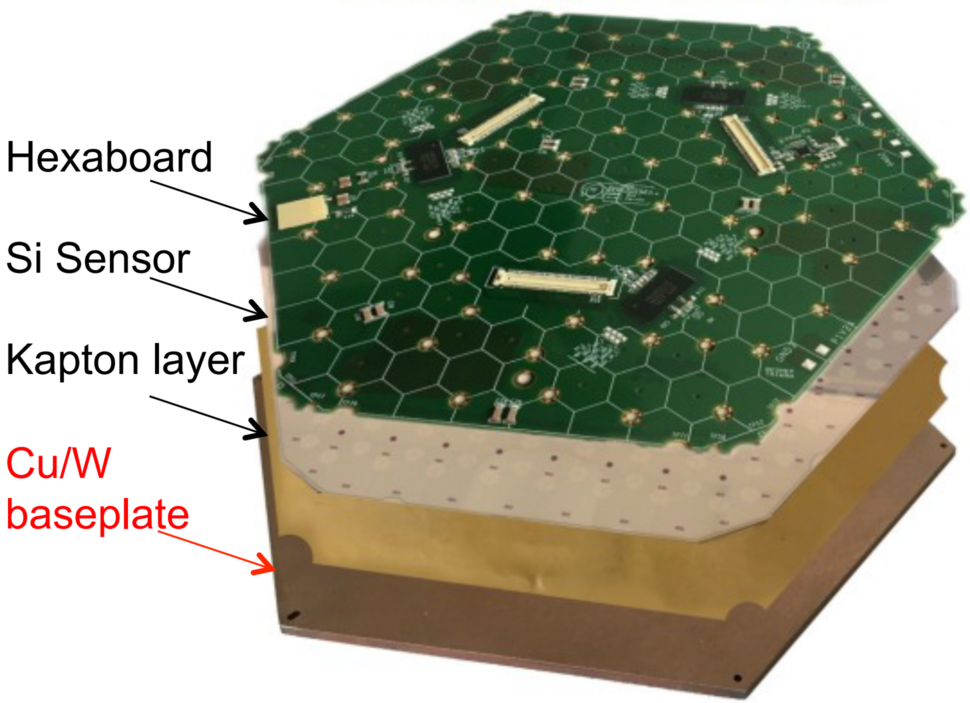


26,000 Sensors
6M Si Channels

Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Si modules: the heart of HGCAL

8-inch prototype module stack-up



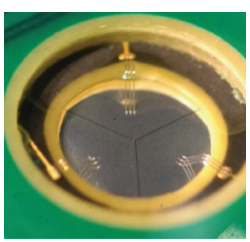
PCB ('Hexaboard') – Sensor
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

Silicon sensor

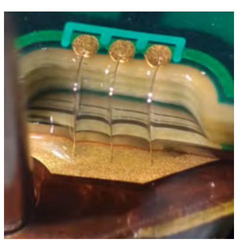
Kapton sheet
- Isolation to baseplate + bias supply to sensor back side

Baseplate
- Rigidity, contributes to absorber material

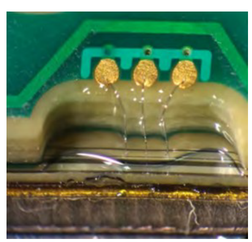
Si pads bonded to PCB



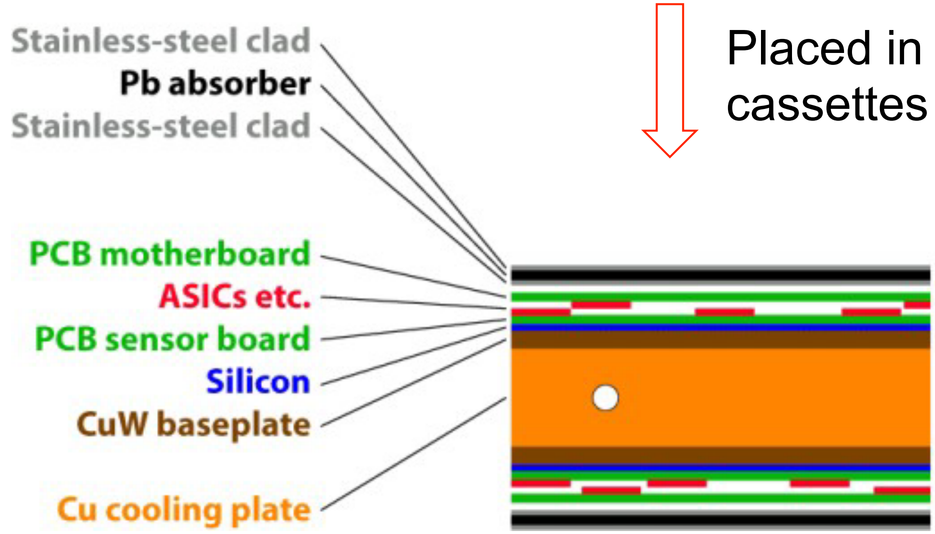
HV bias contacts



Guard ring contacts



Placed in cassettes

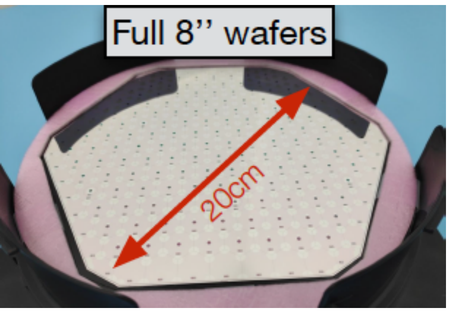


Module integration into cassettes

- Module is composed of the Si sensor and hexaboard PCB
- Passive wagon board is connected to one to three modules
- Engine board is connected to two wagon boards
- Data transmission via optical links to off-detector electronics

CE-E:
- Double-sided cassettes, self supporting, integrated absorber
(Cu cooling plate, Pb cover)

CE-H:
- Single-sided cassettes, mounted between steel absorbers
- All-Si and mixed cassettes (Si modules, SiPM-on-tile modules)



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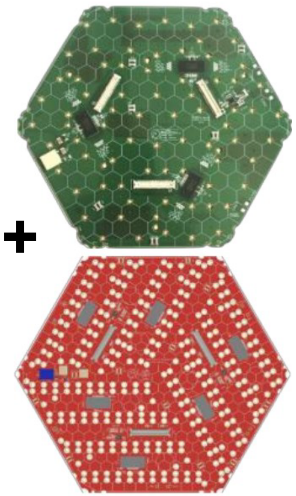
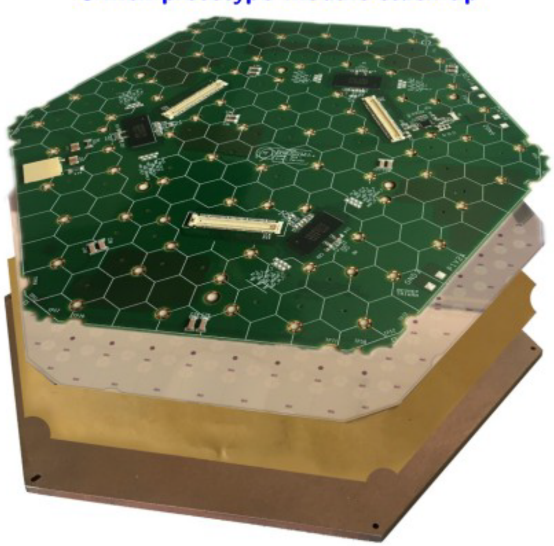
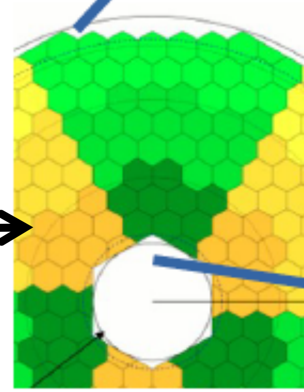
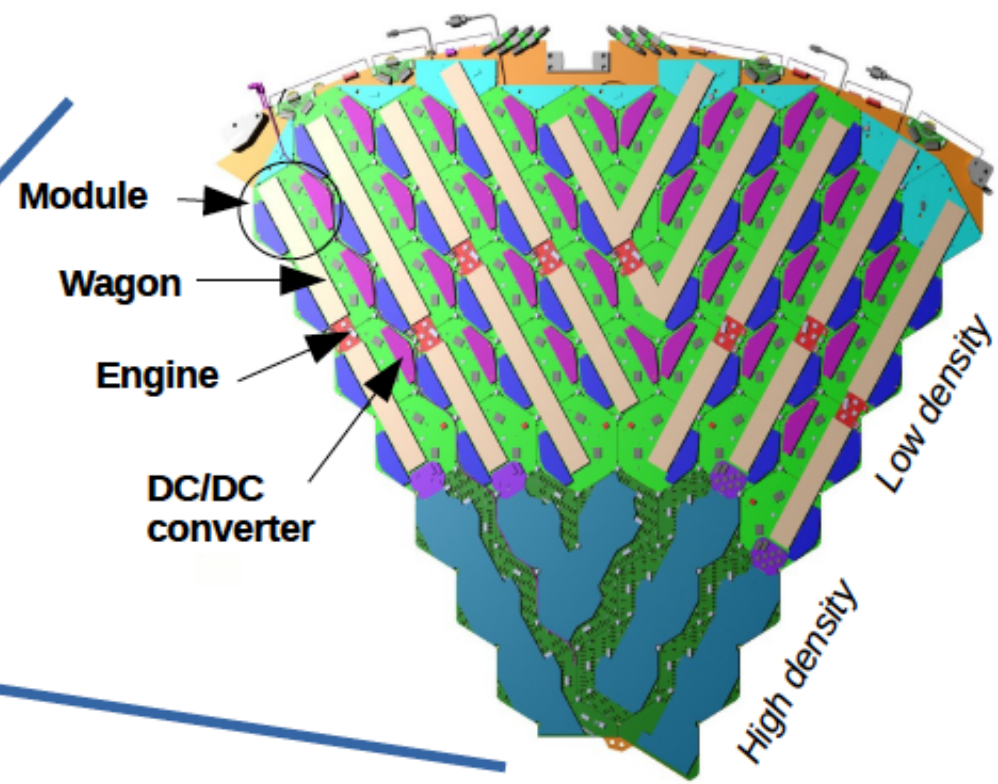


8-inch prototype module stack-up

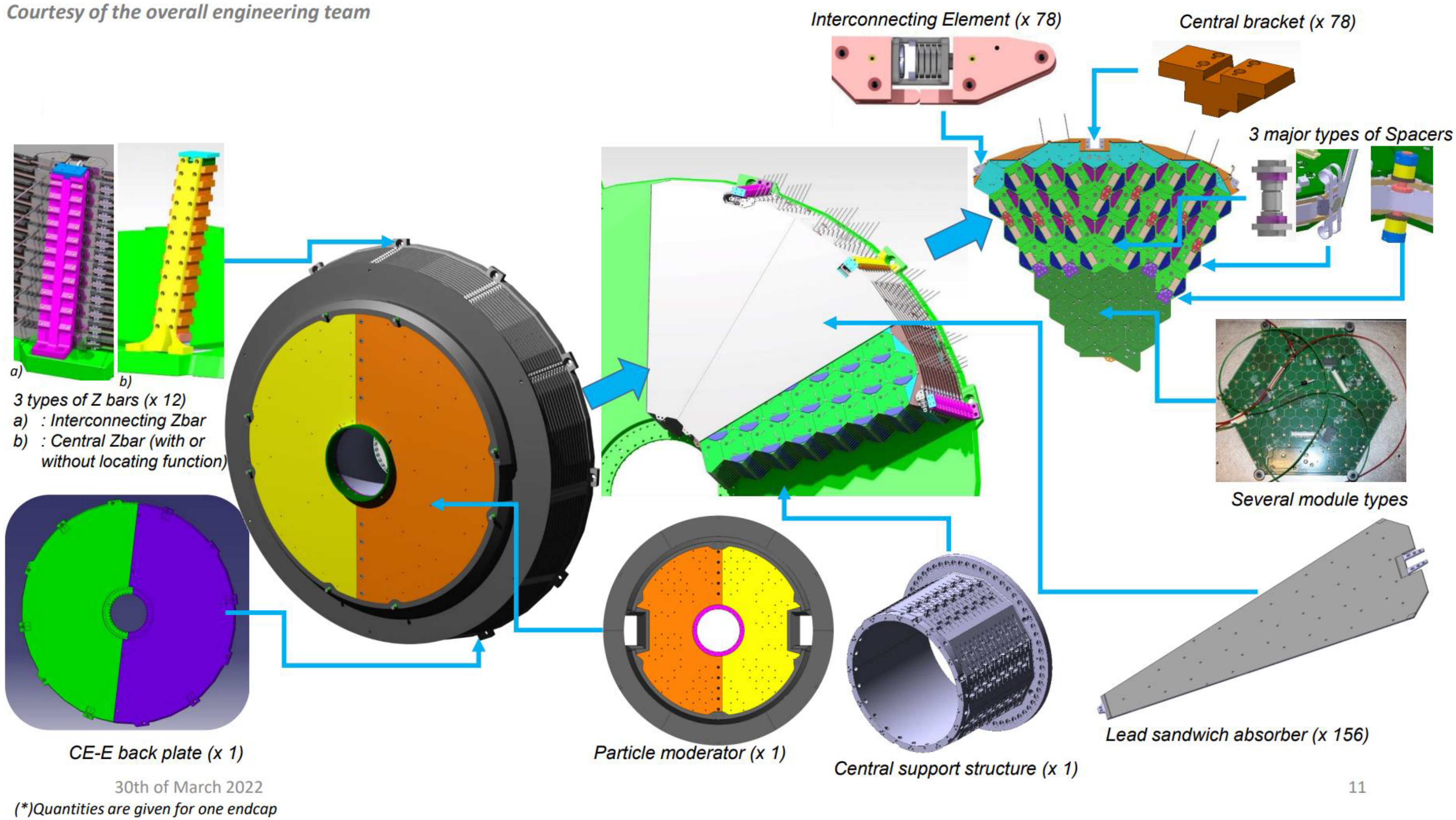






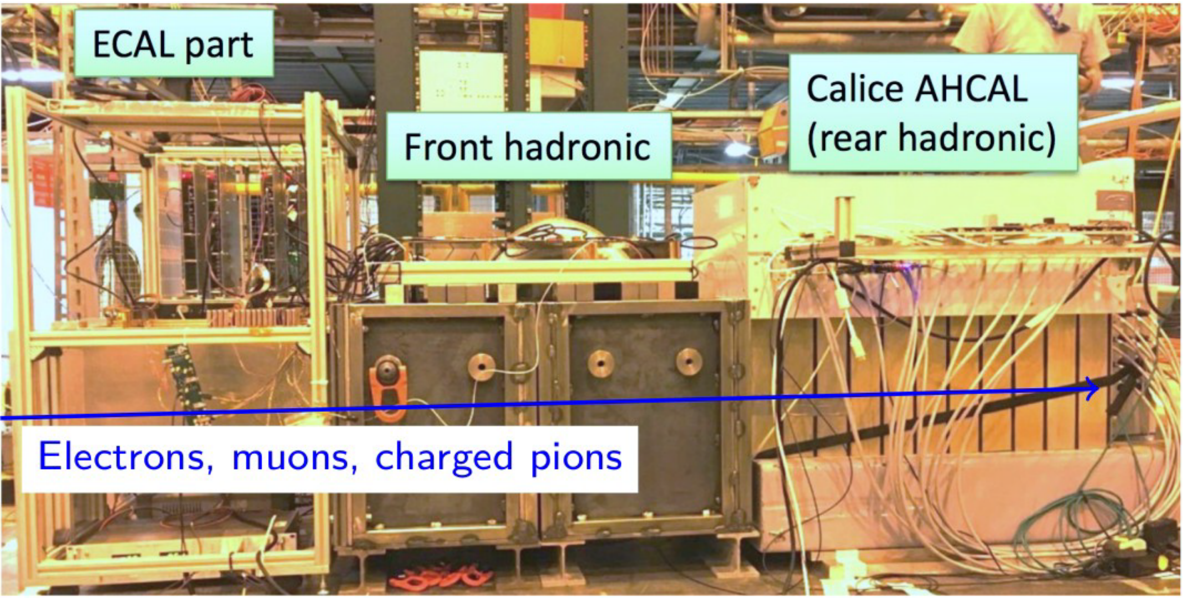
All-silicon cassette

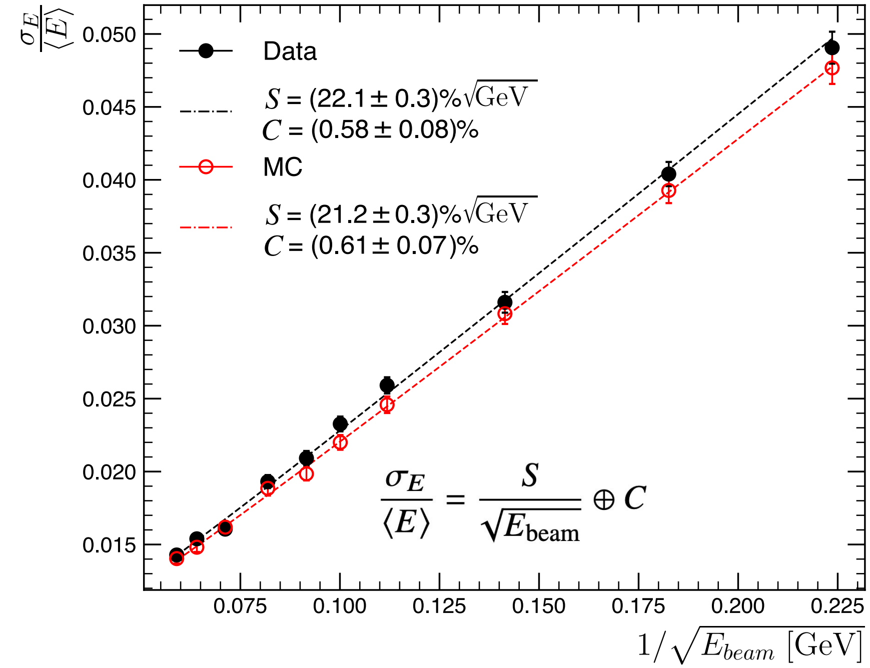
Integration into a full detector

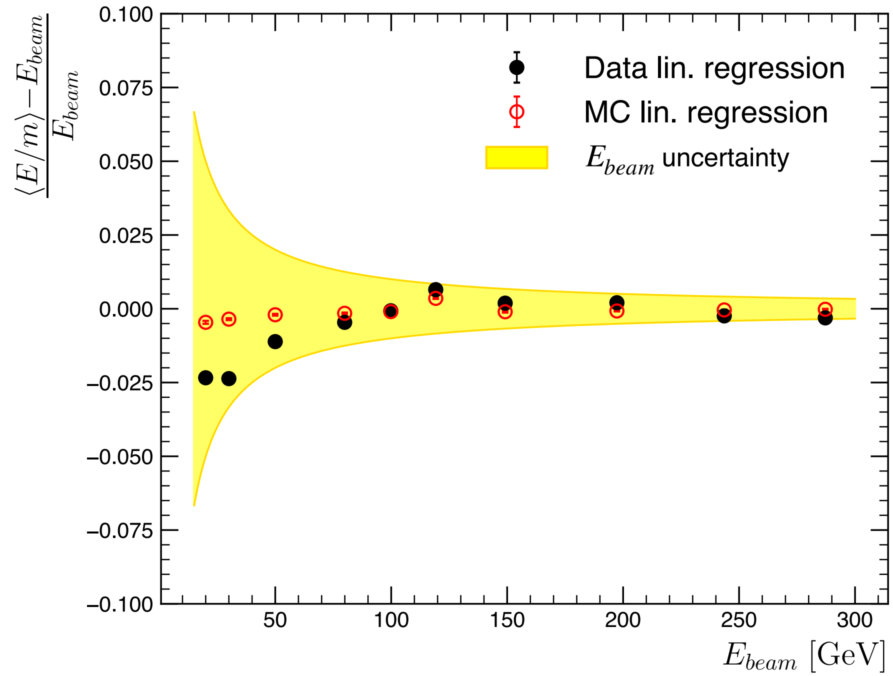


- Final integration into the full detector(s) is a **major challenge**.
- Mechanics, Interfaces, Services, Cooling, Thermal Screen, Tooling are some of the areas of intense activity by the HGCAL groups.

Beam-Test Campaigns







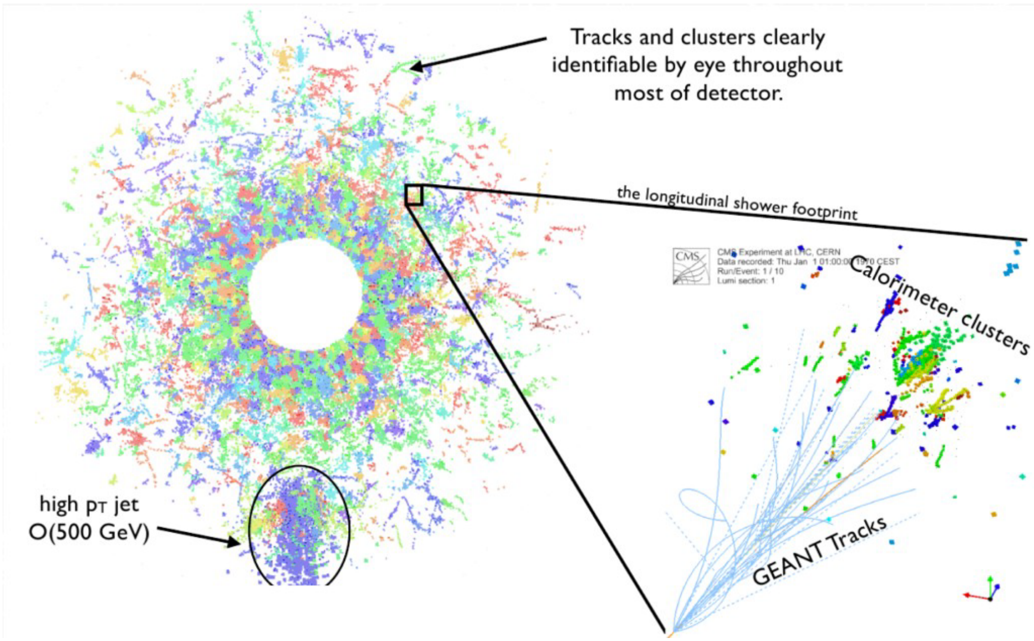
JINST **17** P05022
arXiv:2111.06855

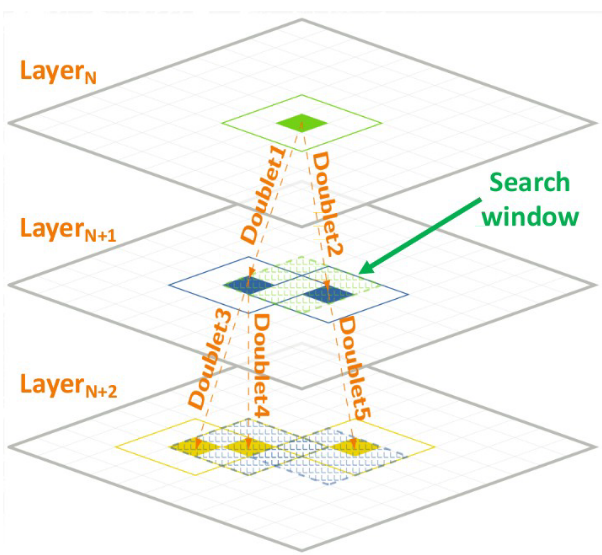
EM performance:

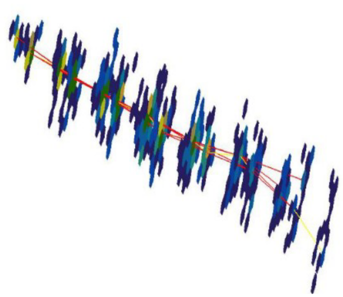
- 0.6% local constant term
- 22% stochastic term
- Good linearity for relevant energies > ~50GeV

Physics object reconstruction

Novel reconstruction algorithms are employed, including machine learning for PID



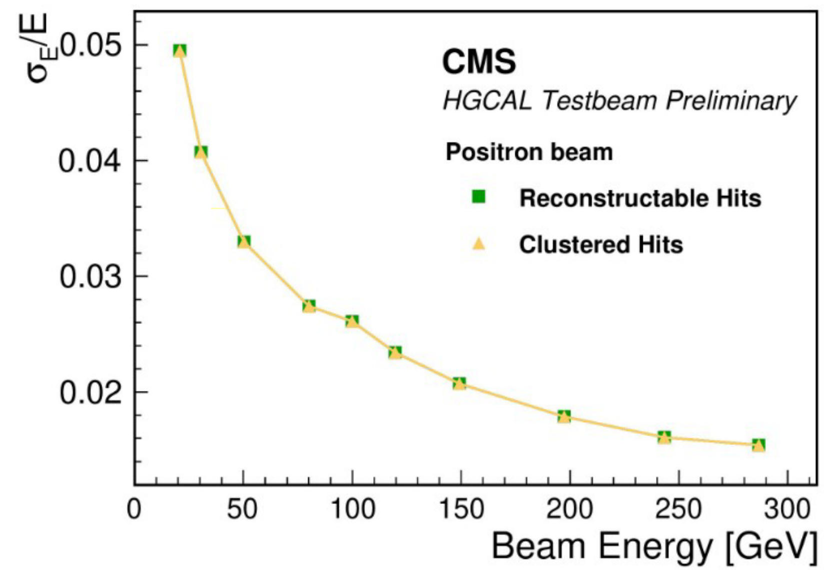




Trackster connecting several 2D LayerClusters

CLUE: algorithm for energy clustering:

- Reduces the number of hit objects by building clusters of energy
- Can be parallelized and runs on GPUs
- tested with beam-test data



TICL: The Iterative Clustering

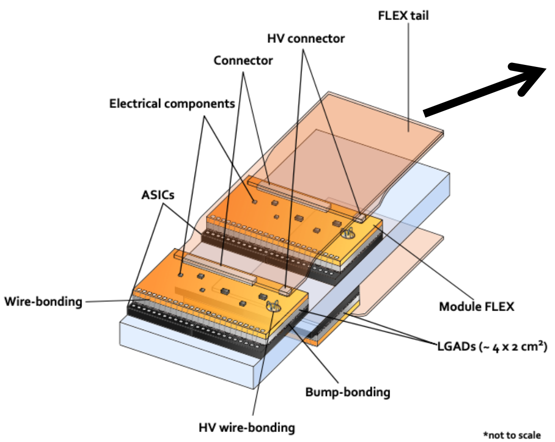
- Impinging particles create ‘Rechits’
- Rechits are clustered together to form 2D LayerClusters (CLUE algorithm)
- Clusters on different layers are linked together to form Tracksters (showers)

Summary

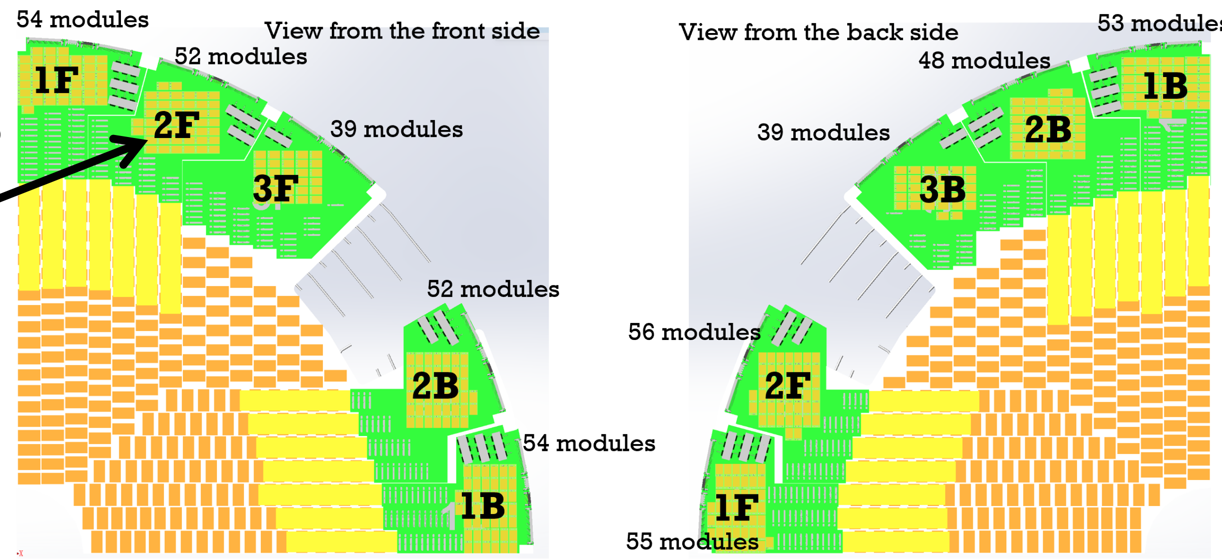
- High Granularity Calorimetry seems to be the choice for ALICE, ATLAS, CMS and LHCb phase-2 upgrades.
- All projects have been successful in building working prototypes and testing them in beam-test facilities.
- Detector integration will be one of the biggest challenges, and in all projects a **significant progress on how to get to the complete detector** is observed.
- Exciting times: **we are entering a new era in HEP calorimetry.**

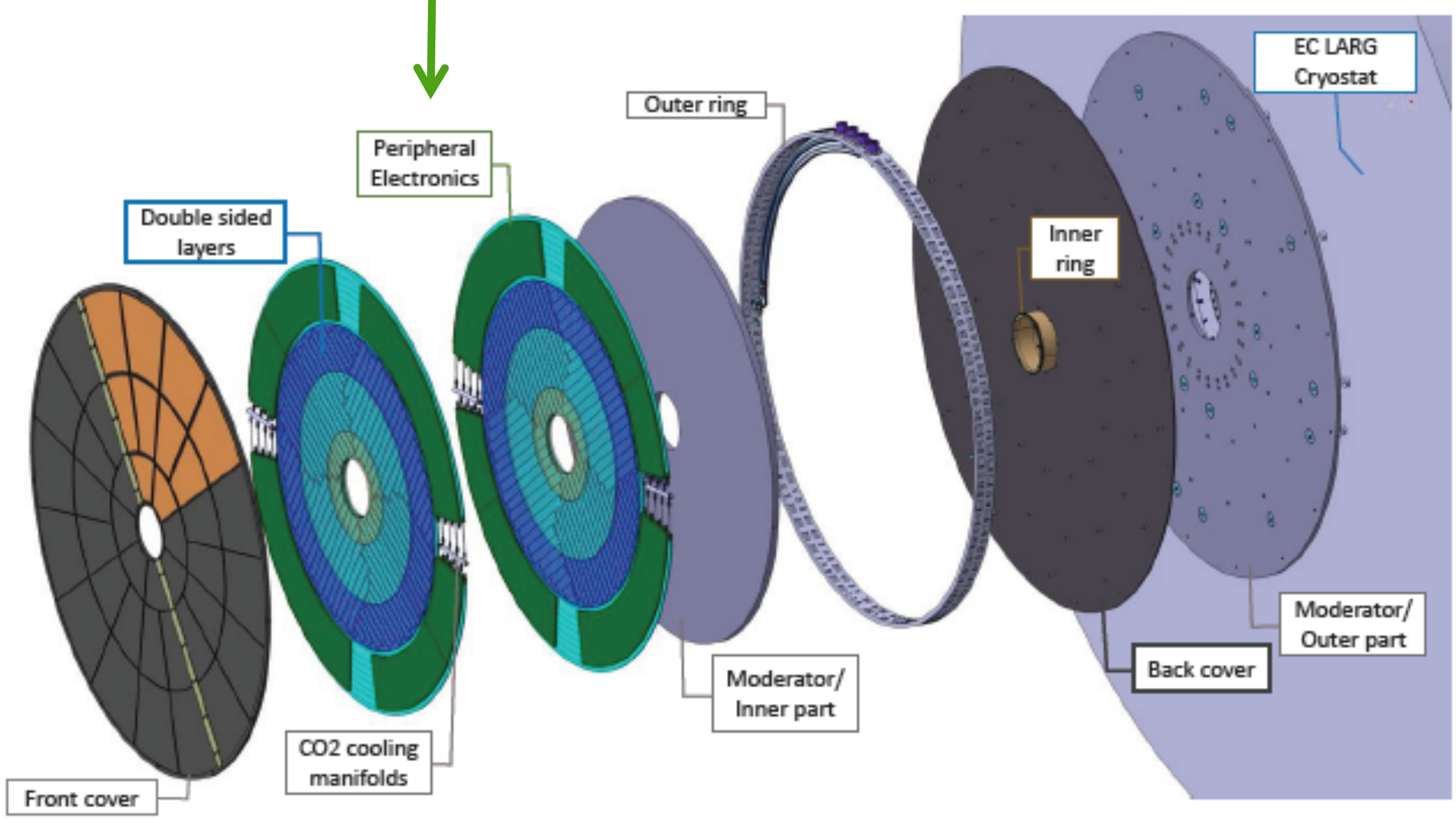
Extra Slides

HGTD Integration



Modules connected to 6 different types of PEB





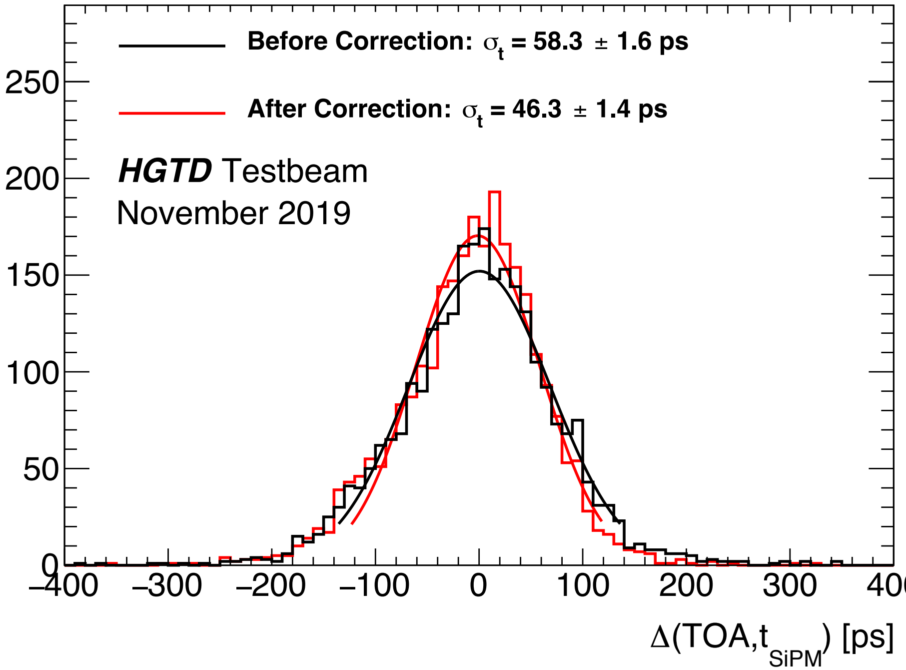
ATLAS LGAD Timing Integrated ROC

ALTIROC asic (TSMC 130 nm CMOS)

- time-of-arrival (TOA) + time-over-threshold (TOT) data per channel, transmitted upon L1 trigger
- Vernier delay line TOA TDC
- TOT for time-walk correction
- requirement for jitter to : < 25 ps
- <300 mW cm^{-2} (+ sensor: < 100 mW cm^{-2}) to satisfy cooling power budget (20 kW/side)

ALTIROC v2 diced in Q4 of 2021

- presently under test
- addition of full digital electronics functionality



Design of final ALTIROC v3

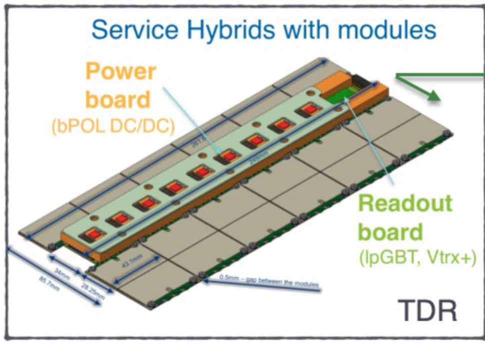
- radiation-hard version
- expected this summer

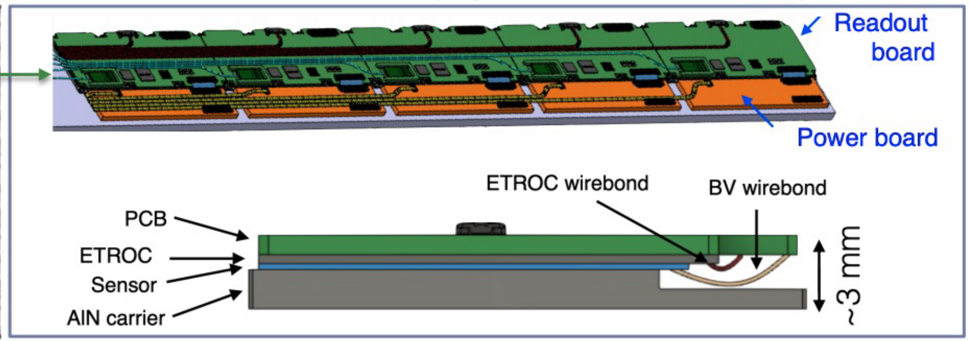
ETL design overview

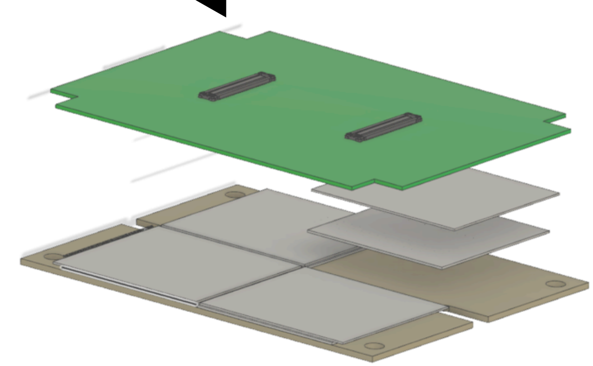
- LGAD sensors bump-bonded to ASICs
- Interspersed with readout boards
- Two layers of Si sensors covering $1.6 < |\eta| < 3.0$

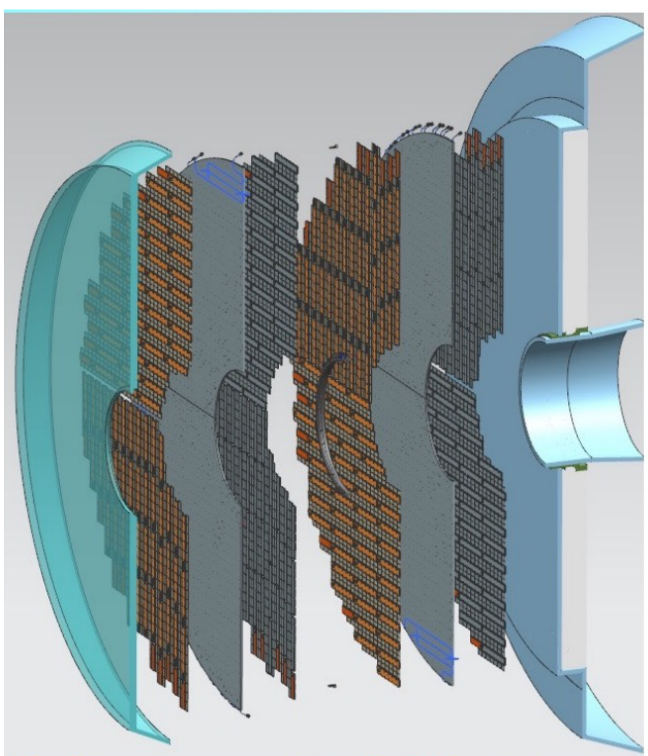
Module: 4 16x16 pixel LGADs each bump bonded to one ETROC

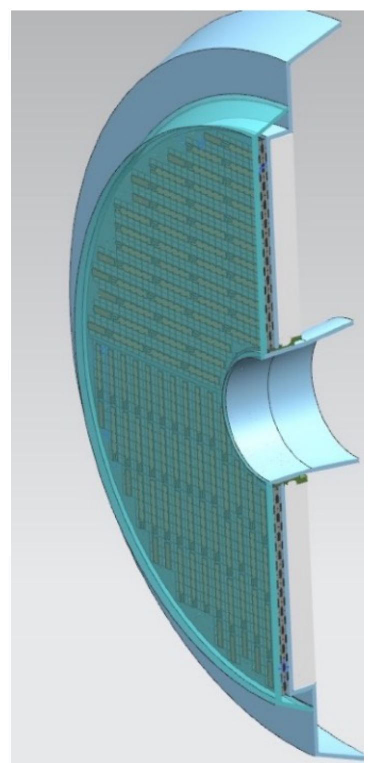
Readout boards moved to atop the modules; save z thickness and simplify construction.

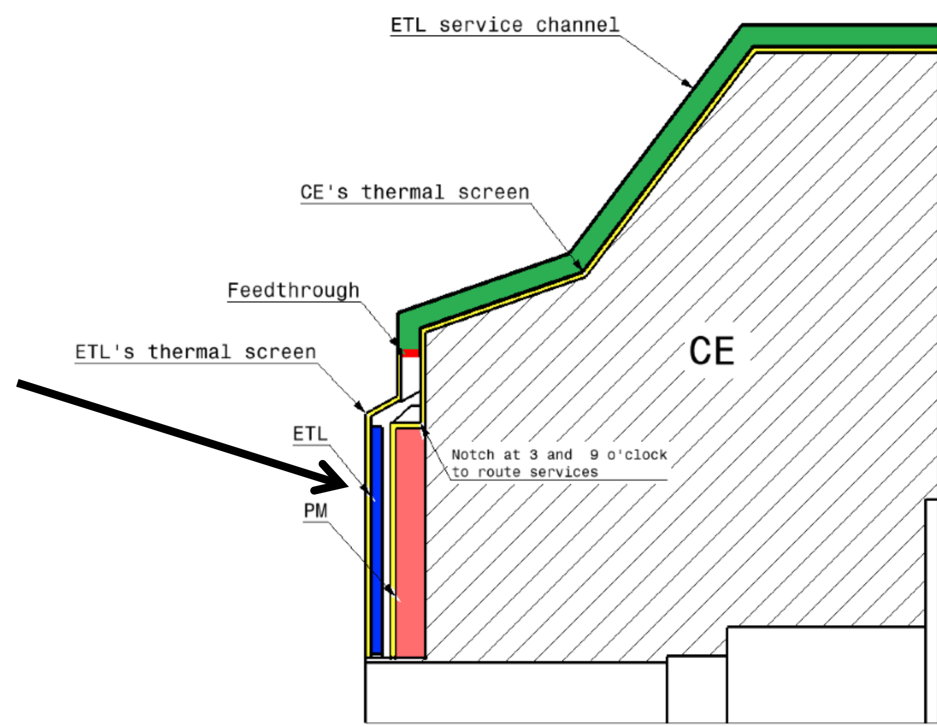






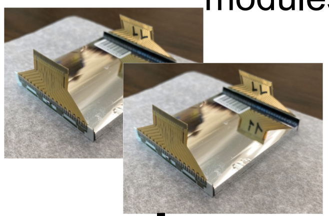






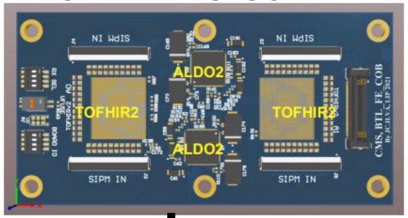
BTL design overview

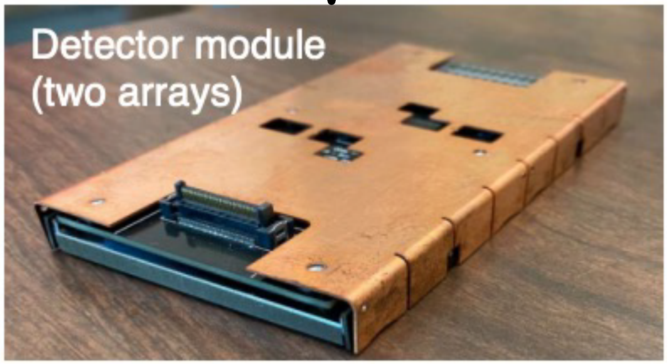
LYSO+SiPM sensor modules

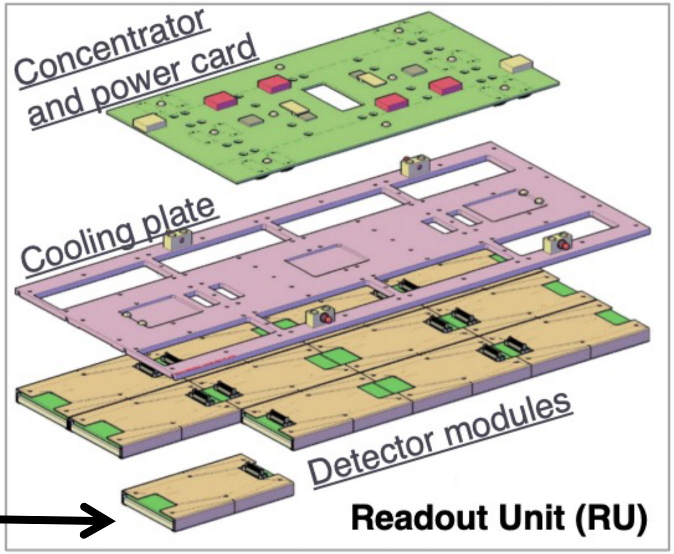


+

FE boards housing TOFHIR ASICs

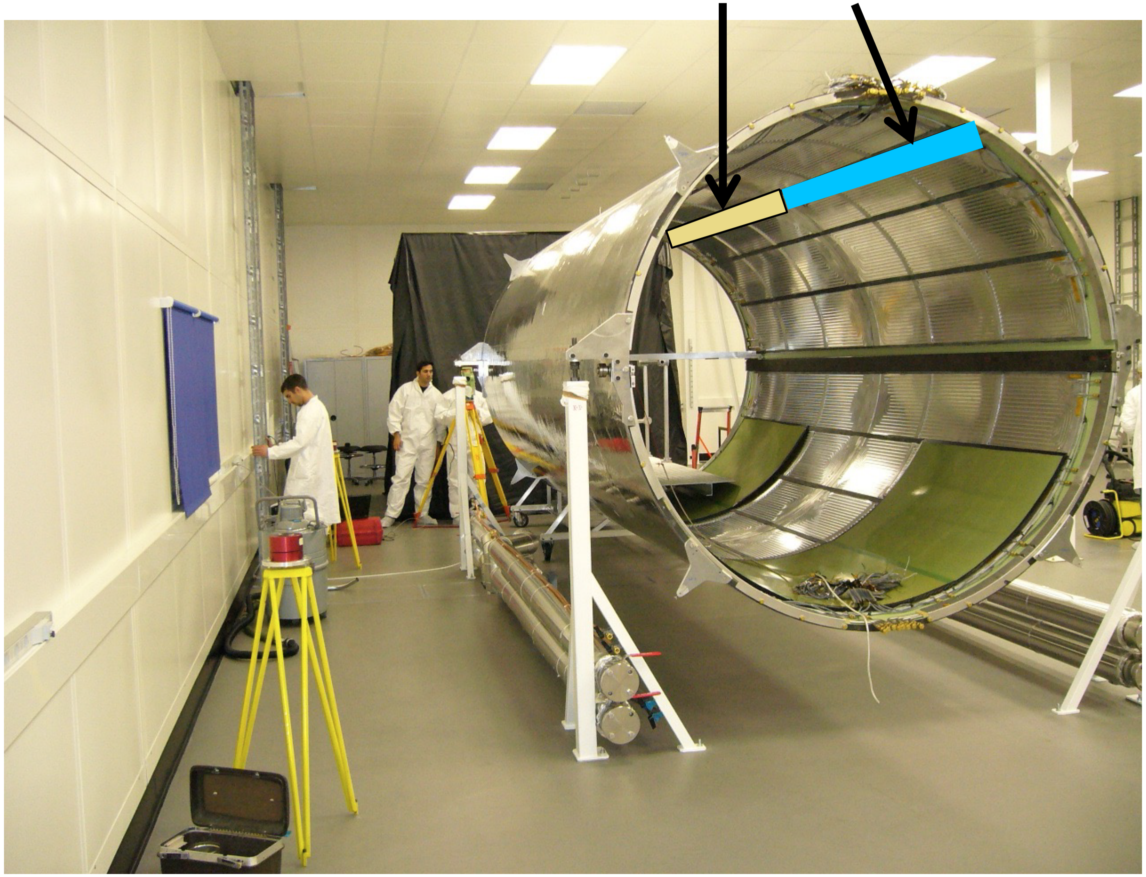




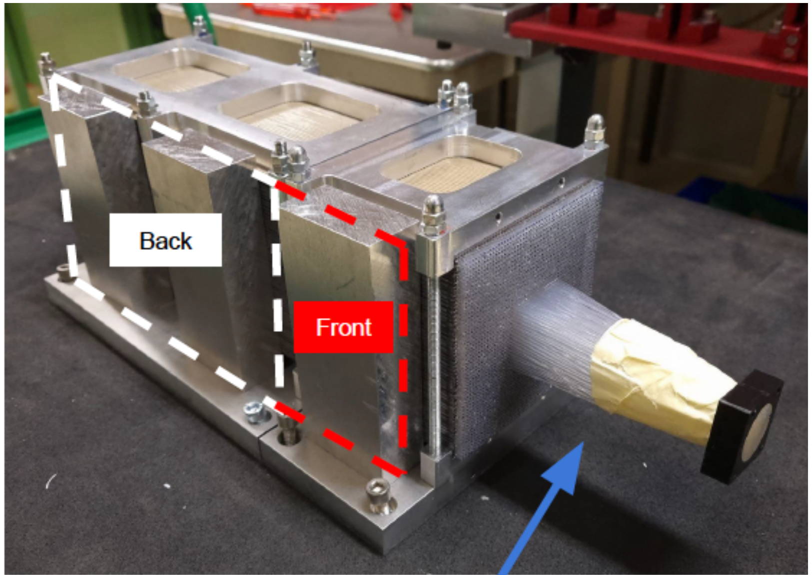


- 331k channels, 165k LYSO bars
- LYSO, SiPMs, FE boards comprise **Detector Modules**
- Detector modules placed in Readout Units
- 72 trays each carrying 6 RU's

Two 250cm trays in eta

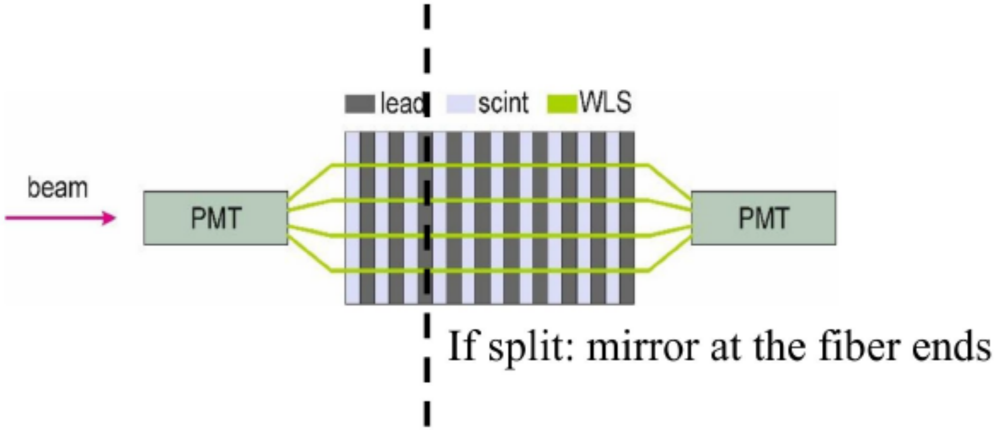


SPACAL-Pb and Shashlik



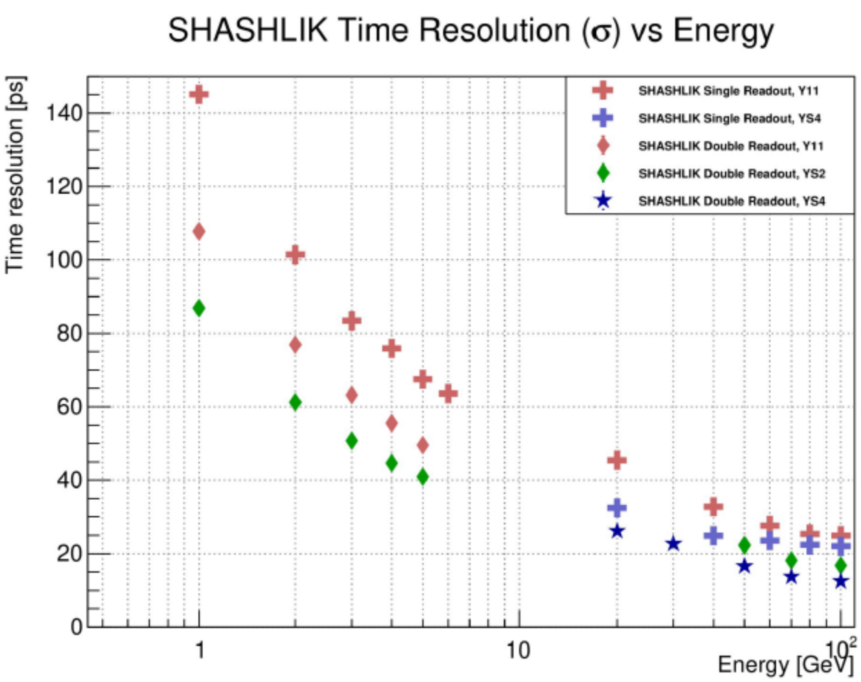
Fiber bundle, 1 cell

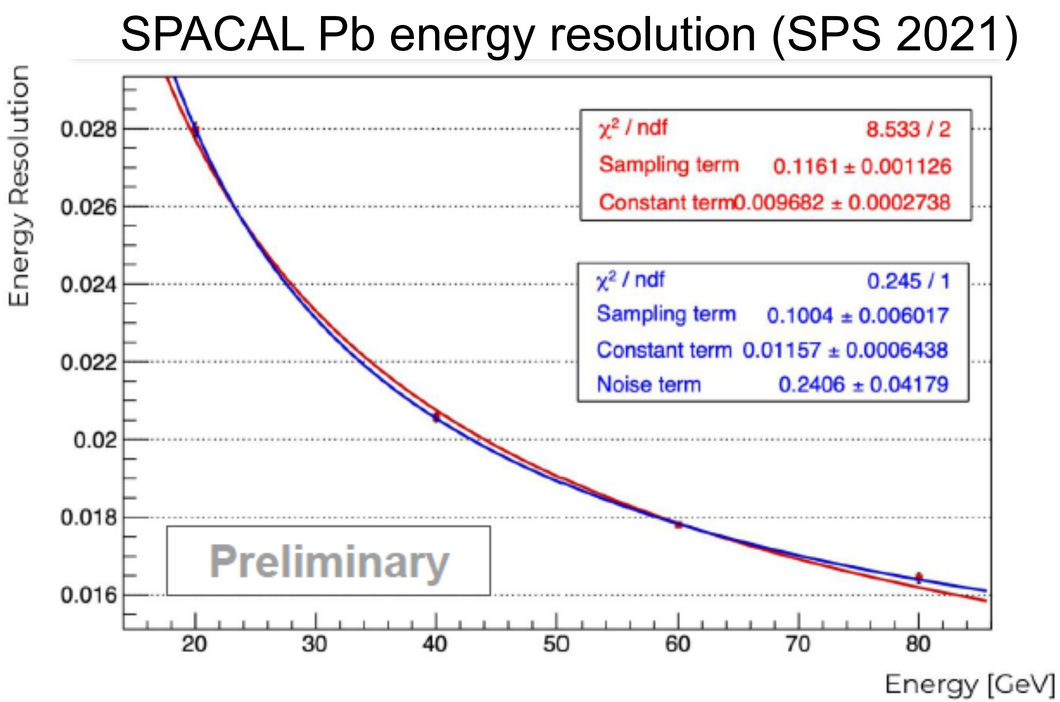
- **Lead** absorber with **polystyrene** fibers
- 9 cells, each 3 x 3 cm^2 (RM ≈ 3 cm)
- Length: 8 + 21 cm (7 + 18 X0)
- Reflective mirror between sections
- HPK R7899 for energy resolution
- HPK R7600U-20 metal channel dynode (MCD) PMT for timing
- Different readout configurations:
  - Direct contact
  - 10 cm long PMMA light guide
  - Bundle of fibers coupled directly to MCD



- 4 mm thick scintillating tiles and 2 mm thick lead tiles with wavelength shifting (WLS) fibers
- Radiation hardness limit at 40-50 kGy suitable for non-central part of ECAL
- R&D to improve intrinsic time resolution
- Main focus on double-sided readout to mitigate the effect of longitudinal shower fluctuations
  - With continuous WLS fibers
  - With split fibers at shower max (≈7X0)

Test-Beam measurements





Time resolution above 5 GeV

- SPACAL W+GAGG < 20 ps
- SPACAL W+Polystyrene < 20 ps
- SPACAL Pb+Polystyrene < 25 ps
- SHASHLIK < 40 ps

		Measurements on TB modules [%]	MC simulations on TB modules [%]	MC simulations on optimized modules [%]
SPACAL-W	*Sampling term*	10.6 ± 0.1	10.4 ± 0.1	9.1 ± 0.1
	Constant term	1.9 ± 0.5	2.27 ± 0.04	1.38 ± 0.03
SPACAL-Pb	*Sampling term*	10.0 ± 0.6	10.4 ± 0.1	10.4 ± 0.1
	Constant term	1.16 ± 0.06	1.09 ± 0.04	0.62 ± 0.06

Timing measurement

$$\sigma_{tot}^2 = \sigma_{Landau}^2 + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + \sigma_{clock}^2$$

Jitter

Time walk

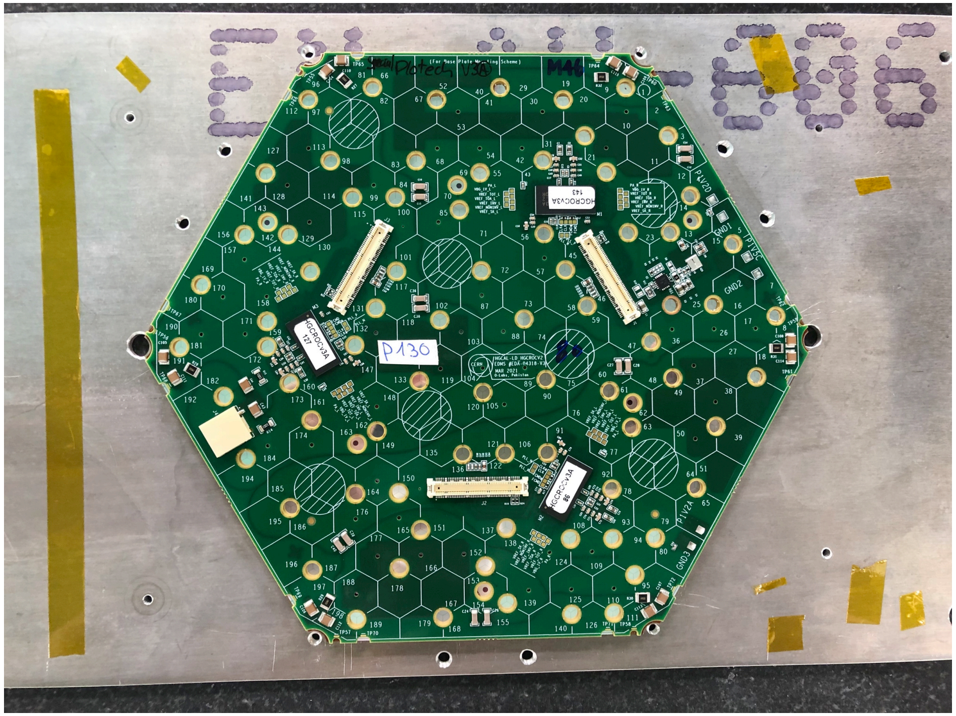
TDC bin width

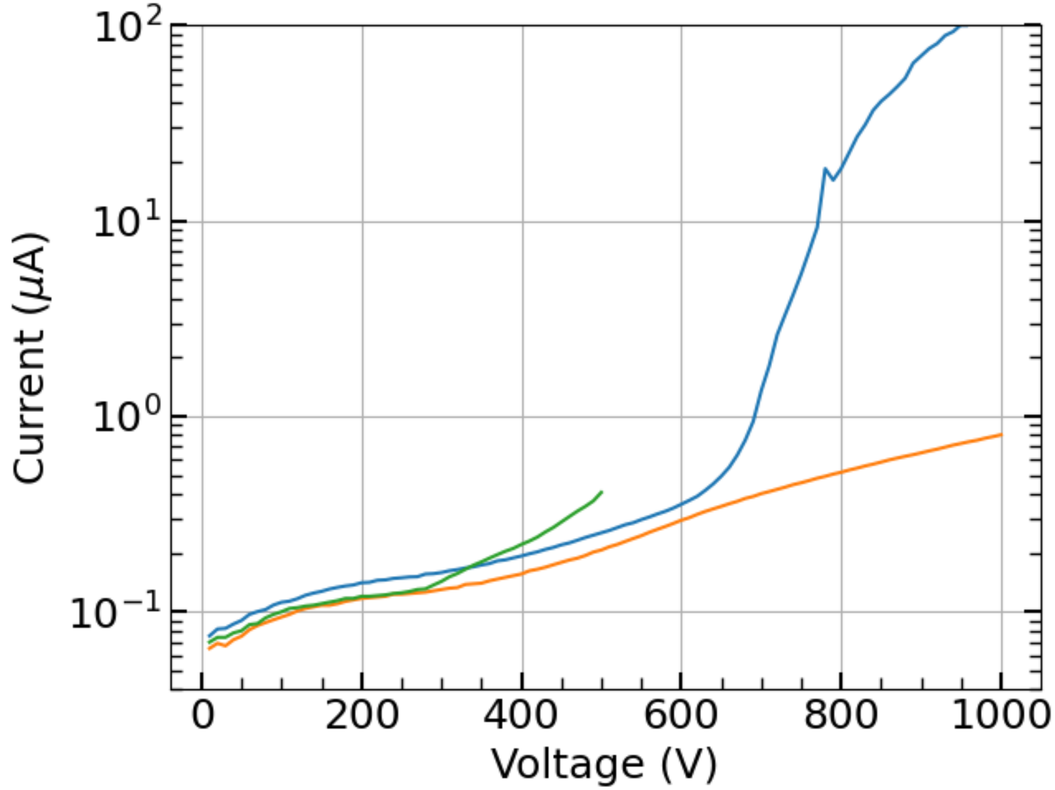
<15ps

Intrinsic Landau contribution for 50μm Si σ_L<25ps

Dominant at high S/N

HGCAL 8" modules (spring/2022)





300μm 8" Low Density HGCROCV3 complete modules, assembled and tested in 2022

- Well behaved IV curves and low measured noise.
- Alignment, thickness and flatness within specs.
- Modules will be used in cassette assembly, beam tests and further measurements.