Review of Silicon and SiPM-Scintillator Calorimeters

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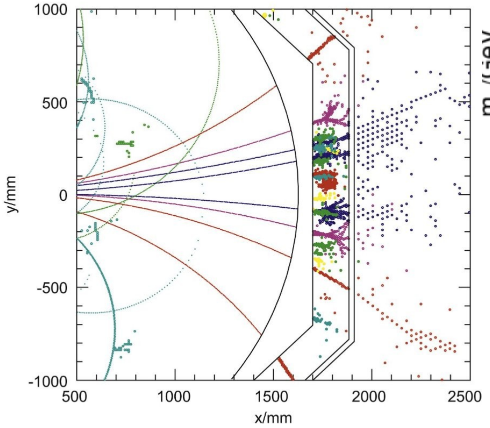
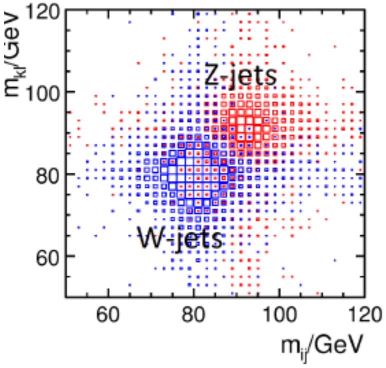
High-Granularity Strategy

The high-granularity-calorimetery strategy is to narrowly localize clusters from individual particles to allow particle-flow algorithms to optimize usage of tracking and calorimetry

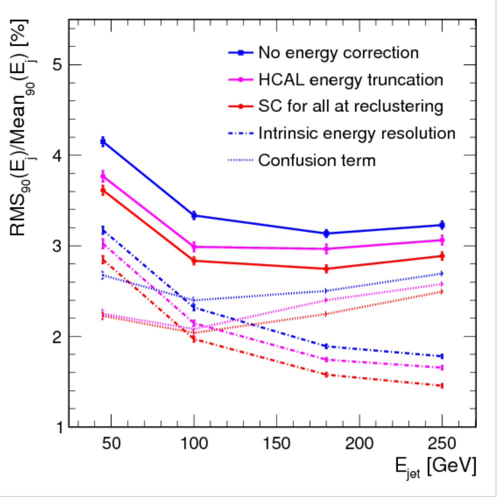
- Physics drivers include sufficient jet resolution to separate W, Z, and Higgs hadronic decays



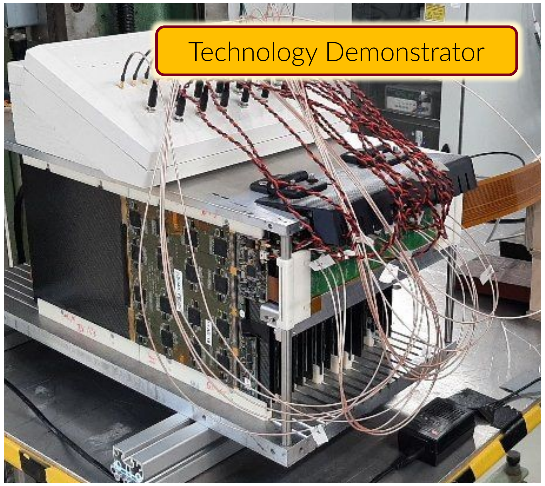


Silicon and SiPM-Scintillator calorimeters attack this problem with well-understood active materials, where the key challenges are in the integration of dense and cost-effective calorimeters

- Modern developments began with a focus on e+e- linear colliders and more recently included the HL-LHC CMS upgrade



What we have: CALICE SiW-ECAL



Fifteen-year program to develop and demonstrate technology for a dense, highly-segmented calorimeter for e+e- focusing on particle flow

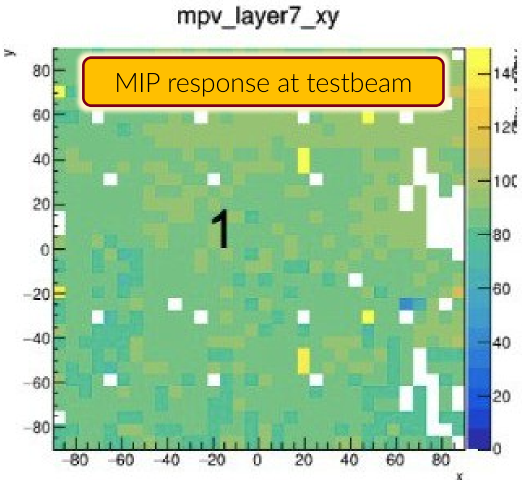
- Series of testbeam prototypes, demonstrating increasing sophistication and integration, original focus on linear collider operational parameters

Features useful for circular Higgs factories:

- Extremely dense: ~6 mm total per sensitive layer including tungsten absorber
- Experience with long power chains, signal distribution, large circuit boards (FEVs)

Unlike circular Higgs factories:

- Linear collider developed concept of power pulsing to avoid need for integrated cooling loops. For a circular collider power pulsing is not possible, particularly at the Z pole



What we have: CMS Silicon HGCAL

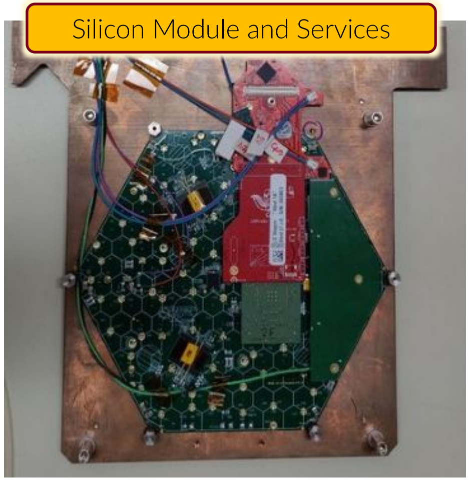
Large-scale (~25k 8" sensor) silicon calorimeter under construction for HL-LHC

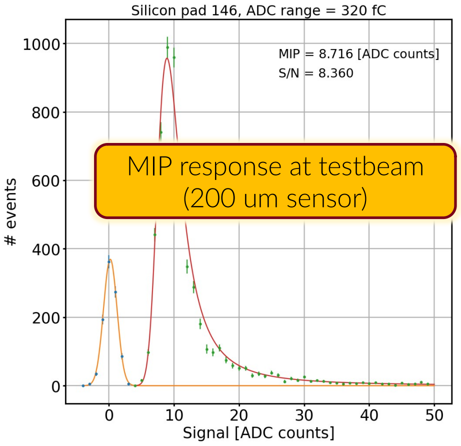
Features useful for circular Higgs factories:

- Precision shower timing (25-50 ps) integrated into low-power electronics
- Continuous operation including need for detector cooling
- Fully-integrated large-scale system with an experience of engineering and manufacturing trade-offs

Unlike circular Higgs factories:

- High radiation dose mandates cold operation, thin sensors, compromises to manage CTE effects, and a cooling strategy which affects absorber uniformity
- Occupancy is substantially higher than that expected for a circular e+e- collider, leading to different solutions for services and "large" gaps between absorbers

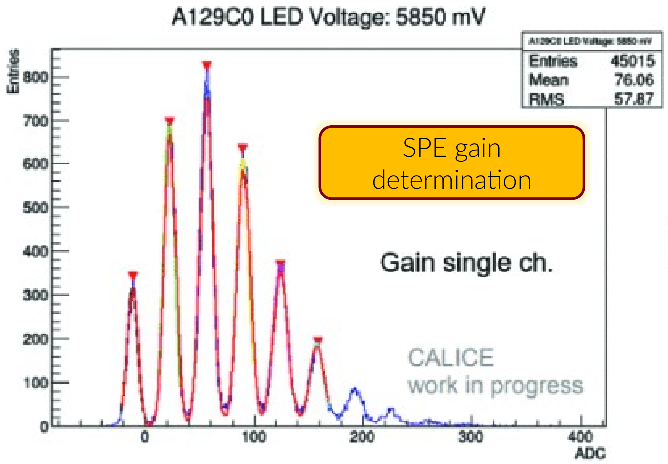


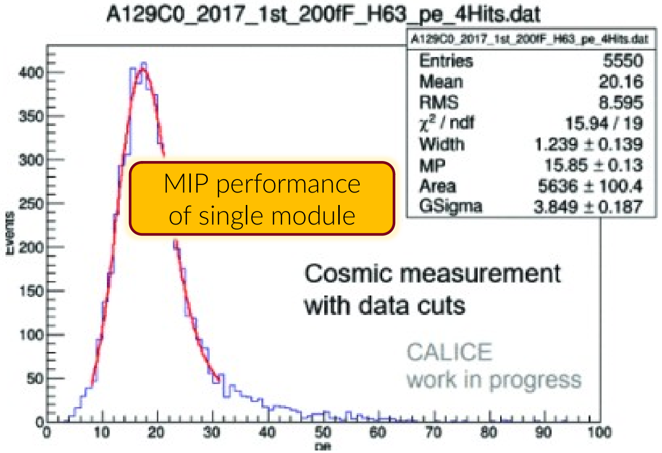


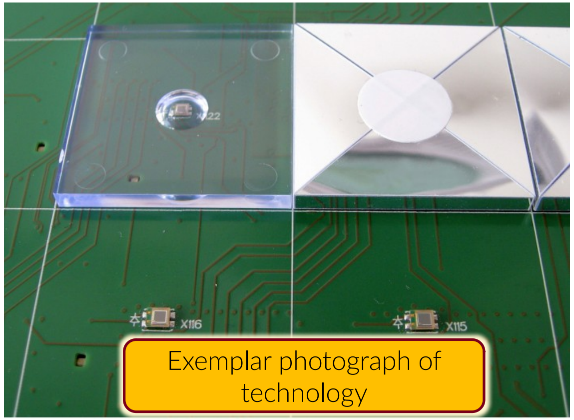
What we have: CALICE AHCAL

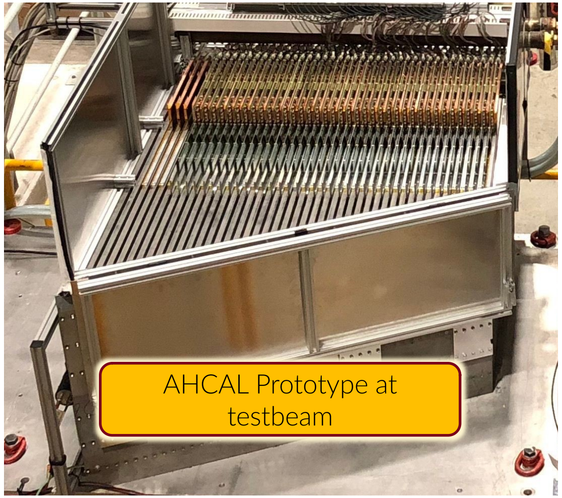
Hadron calorimeter readout technology based on direct readout of small (3 cm by 3 cm) plastic scintillator tiles either wrapped in reflective foil or constructed as larger structures with internal isolation

Well-demonstrated technology in testbeam with established construction techniques





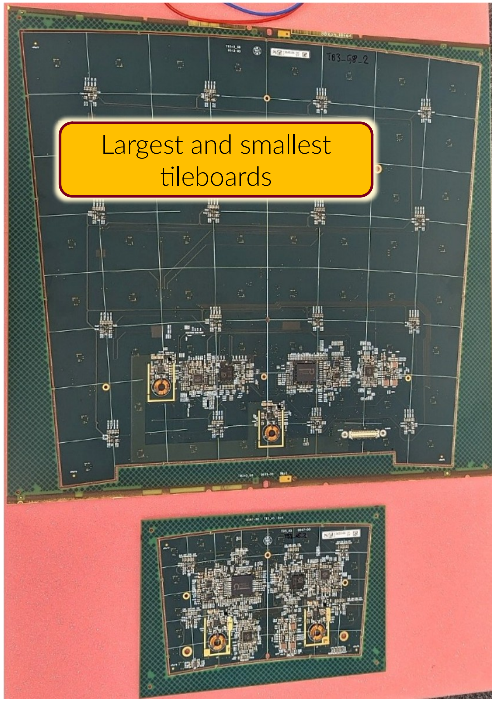


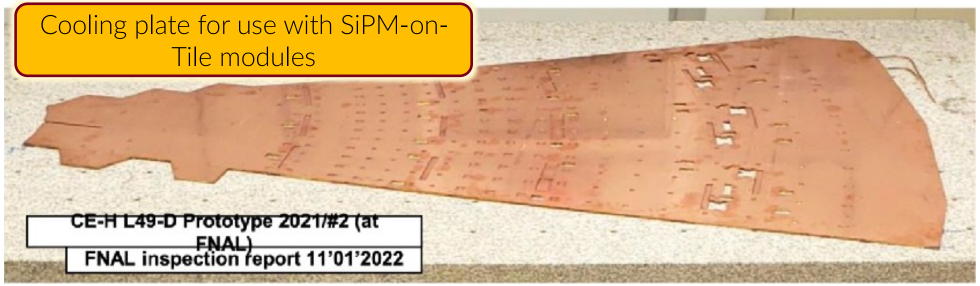


What we have: CMS SiPM-on-Tile HGCAL

The technology demonstrated by CALICE AHCAL was adopted for the rear (lower-radiation) portion of the CMS endcap calorimeter upgrade

- Constraints of an endcap geometry have required handling a wide range of components (>40 different tile sizes/shapes, seven basic PCB sizes with several varients of many of them)
  - Learning to automate with variants
- Radiation-tolerance has been a key design driver
  - Operation at cold to minimize SiPM noise
  - Use of small tiles to increase scintillation signal
- Power and readout components embedded into the cooling plate, requiring extensive co-design between circuit board and cooling plate teams





Developments: Ultrahigh granularity with MAPS

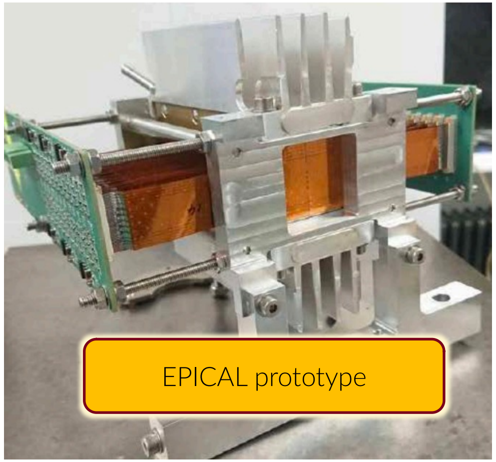
Integration of silicon sensor and electronics in CMOS (MAPS) has been successful for the ALICE inner tracker development

Two efforts ongoing to develop this concept for calorimetry purposes, with a goal to reach O(1 CHF/cm^2) for sensor and initial electronics

- Pixel dimensions in the range of 25 um –100 um
- In simulation, allows "easy" separation of showers as close as 5 mm

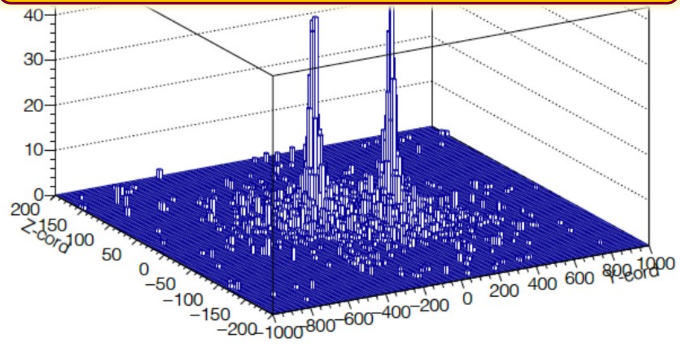
Challenges for the technology

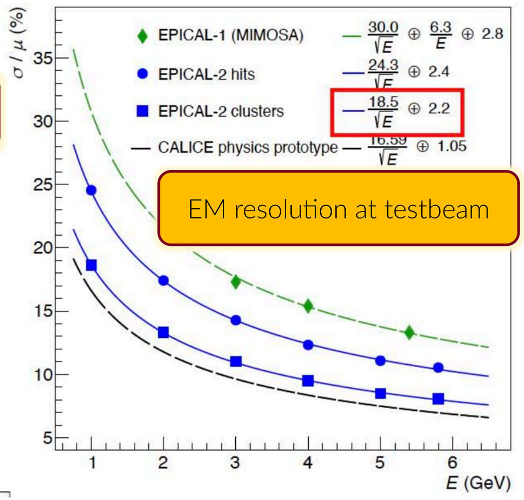
- Cost-effective scaling to large systems (stitching)
- Power utilization/cooling in the context of a circular collider environment → impact on density



EPICAL prototype

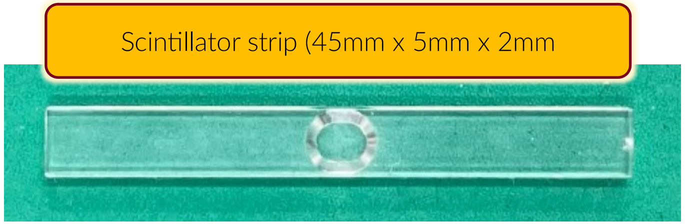
20 GeV showers separated by 1 cm (Oregon/SLAC)





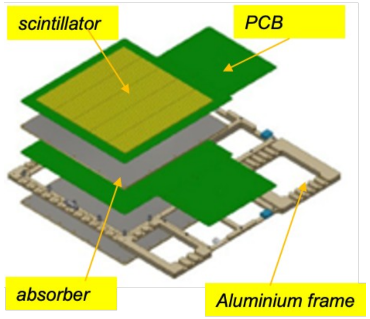
EM resolution at testbeam

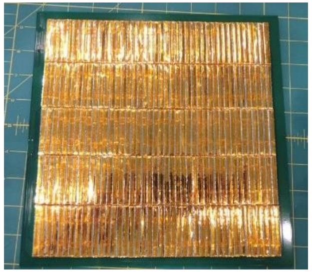
Developments: Scintillator Strip ECAL



Design for an ECAL using narrow strips of scintillator oriented in orthogonal directions on subsequent layers, read out by SiPMs similarly to AHCAL concept

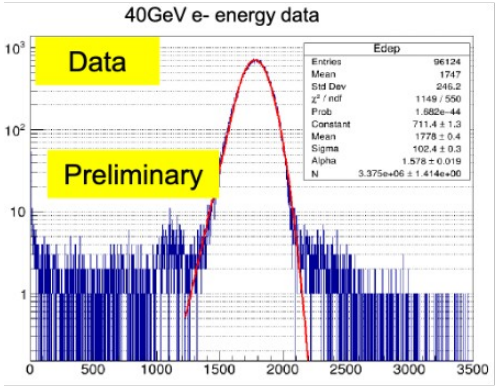
- Goal is to reduce channel count and cost relative to silicon sensors while retaining same position resolution and achieving an energy resolution of O(2%) for 40 GeV electrons





Challenges

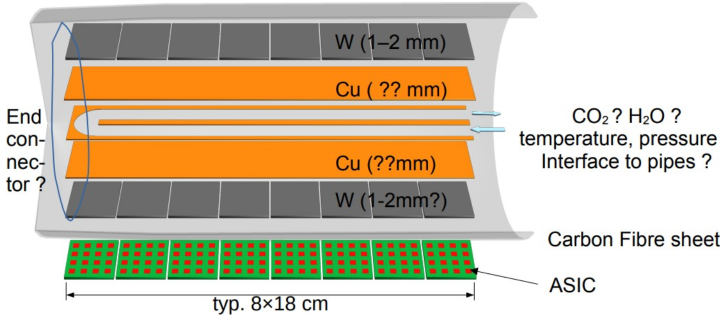
- Improving timing resolution and hit position determination
  - Ideas include read out on both ends of the bar, possibly by doubling length of bar or increasing channel count
- Automation of production and QC for large number of scintillator bars

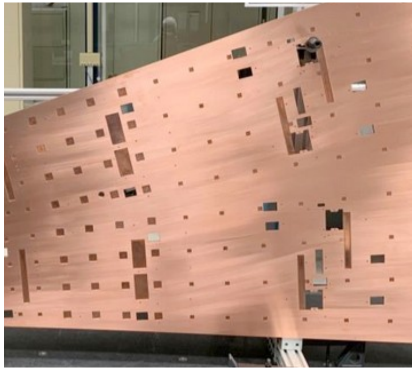


What we need: Services

Service integration is a major challenge for a 4π detector

- Cooling: a circular Higgs factory detector is unlikely to be able to depend on power-pulsing (which is a good solution for LC detectors) to avoid cooling, particularly with an increasing demand for precision timing which has a power cost
  - Solutions are needed which achieve the necessary cooling without unnecessarily compromising detector compactness or uniformity
- Powering: modern electronics wants high current at low voltage – hard!
  - Solutions used in CMS HGCAL (DC/DC conversion) are bulky and produce absorber non-uniformities
  - Consider shift to serial powering? Such a change requires both new ASICs (shunt regulators) and disciplined approaches to readout and electronics





Compromises made for services can significantly affect constant terms

What we need: Electronics

Electronics is a key piece of the puzzle for calorimetry

- Requirement for high dynamic range and emerging expectation for precision hit timing drive development of new chips
- System integration is heavily affected by decisions which are sometimes considered minor – e.g. configuration, monitoring, and reset systems

Tensions in the system

- Efficient designs (e.g. combining many functions into a single electrical link) are often hard to work with for users (not compatible with standard tools, requiring special hardware or firmware)
  - Similarly, a shift to serial powering will imply all links must move to a DC-balanced form, which moves out of simple conventional technologies
- Chip cost and technology evolution – as chip technology advances, the stakes rise with each new chip
  - Limiting the ability to develop moderate-scale prototypes
  - Longer convergence time to meet requirements of all users
  - Correlated/combined risk if an issue is discovered

Overall, the calorimeter community needs to work together to understand needs including as much “long perspective” input on system integration impacts as possible, as well as the analog side desires

What we need: Construction

"Industrial scale" construction techniques are important for detectors on this scale

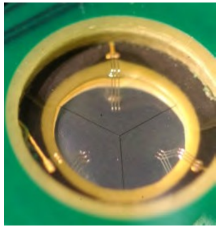
- It is well-known that minor irritants in prototyping can become blockers when scaled to production

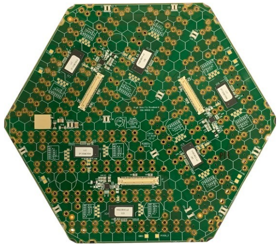
On the other hand, "learning by doing" is expensive when the necessary scale is 10% of a Higgs factory detector

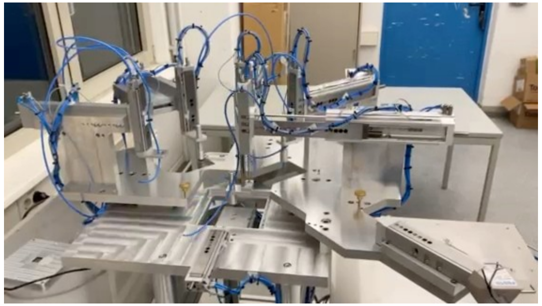
- Critical to learn from ongoing CMS HGCAL efforts (what would have been done differently…)

Example comparison points:

- Connection of readout PCBs to sensors: glued (CALICE) versus wire-bonded through distributed holes (HGCAL)
- Scintillator wrapping materials and techniques : cost/performance balances
- Optimization of "unit size" taking sensors and realistic PCB requirements into account – must connect to electronics early!







Opportunities

Opportunities may be available to improve performance from improvements to detector materials or strategies

- Classic silicon sensor technology appears solid, but some R&D may be valuable on design details and possible integration of interconnects or metal layers on the sensors
  - MAPS technologies have potential but may be challenging for very large areas
- SiPM-on-tile technologies are relatively mature, but the surface treatment of the tiles remains an area of possible R&D (e.g. wrapping)
  - Efforts to look at alternative dense scintillator materials (e.g. dense scintillating glass)
  - Material adjustments to optimize timing performance if it is shown to be valuable
- Detector enhancement for particle identification
  - Possibilities from detector timing – realistic achievable system performance, inclusion of high-gain layers and impact on calorimetry
  - Possible options to help dE/dx strategies

Key R&D Areas in the Next Years

Adaptations to circular collider case

- Cooling, readout strategies, serial power (?)

Consolidating experience for manufacturing

- Collect experience from CALICE, HGCAL, and other relevant efforts to understand what has worked well and what has not
  - Have we reached a practical limit in single-unit size? (e.g. multiple sensors from one 8" wafer would be better than the HGCAL solution)
  - Cost/signal optimization for scintillator systems

Endcap calorimeter optimization

- Physics goals and detector constraints are different than for barrel, which has been the major focus to date for CALICE.

Evaluate opportunities for use of commercial electronics or common building blocks within the detector

- Common building-block chips (e.g. lpGBT) will be extremely important for the prototyping and eventual construction of the detector

Conclusion

The particle-flow calorimetry concepts using silicon and scintillator active materials, developed for LC particularly by the CALICE collaboration, has shown strong promise which led to its adoption for the CMS HGCAL Endcap Calorimeter Upgrade

A Higgs factory remains the target for these technologies, where the goal of separating hadronic decays of massive bosons by mass is a key physics driver

To realize these concepts in the context of a circular collider detector, the experiences from the CALICE prototypes and the HGCAL construction and operation must be synthesized to retain the best elements and focus R&D on the aspects which have not worked as well as originally envisioned, to enable the full physics potential of a Higgs factory collider