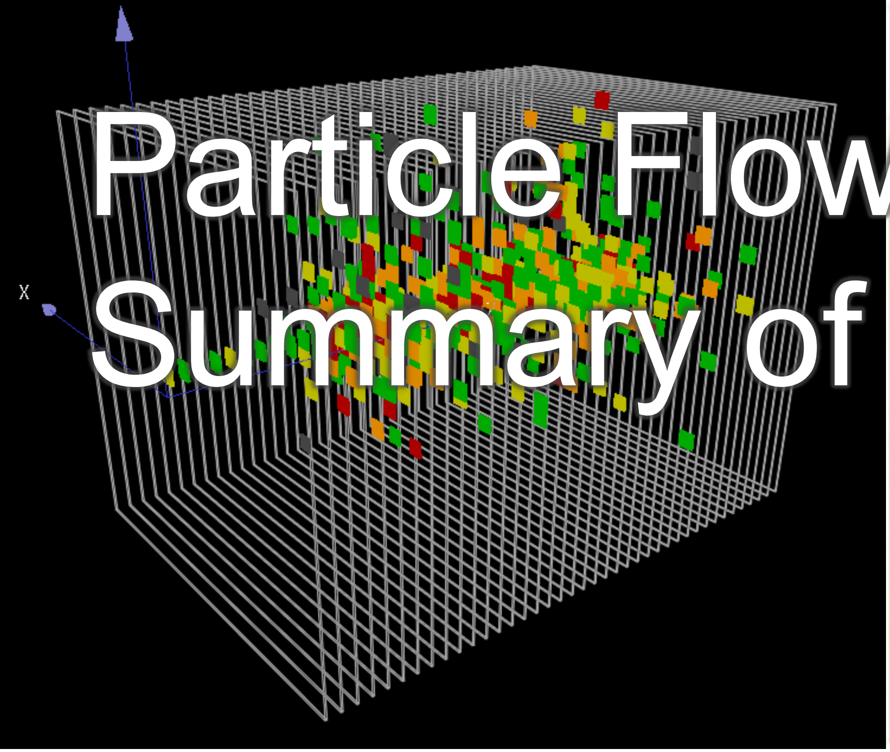
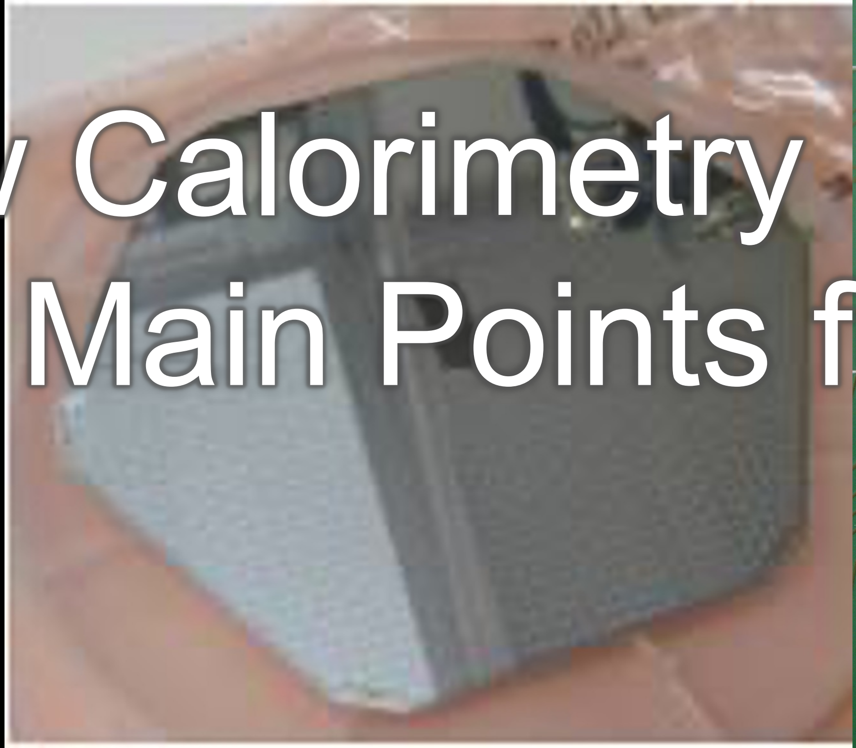
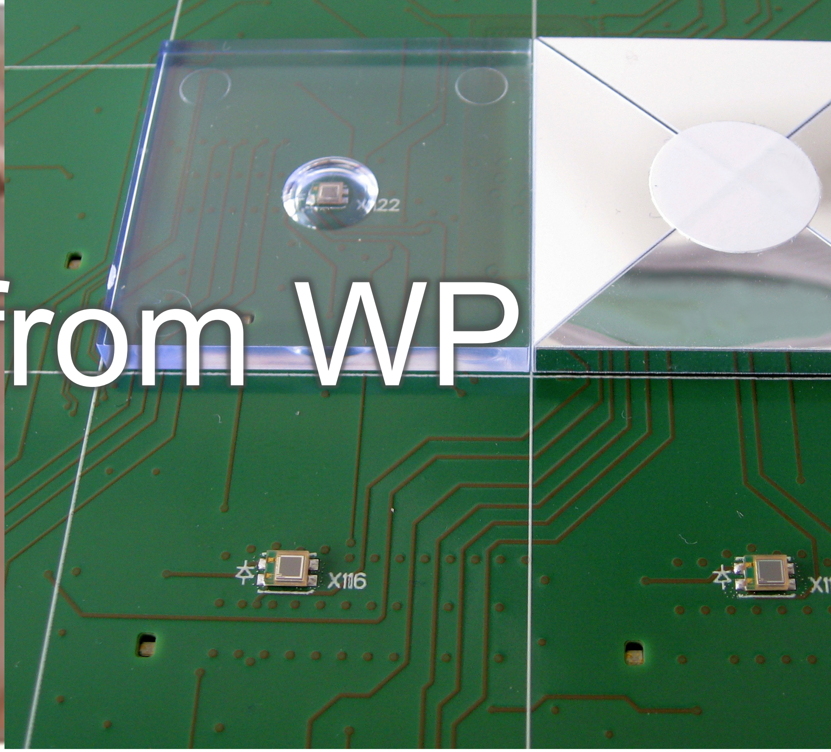
Particle Flow Calorimetry
Summary of Main Points from WP







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Seattle Snowmass Summer Meeting 2022
19 July 2022

Based on https://arxiv.org/pdf/2203.15138.pdf
All mistakes & omissions are my own

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

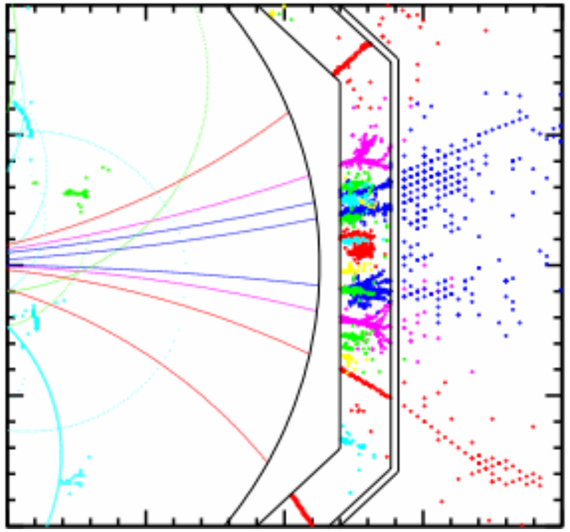
Overview

- Motivation
- Detector Upgrades/Concepts
- Technologies
- Challenges
- Future Directions

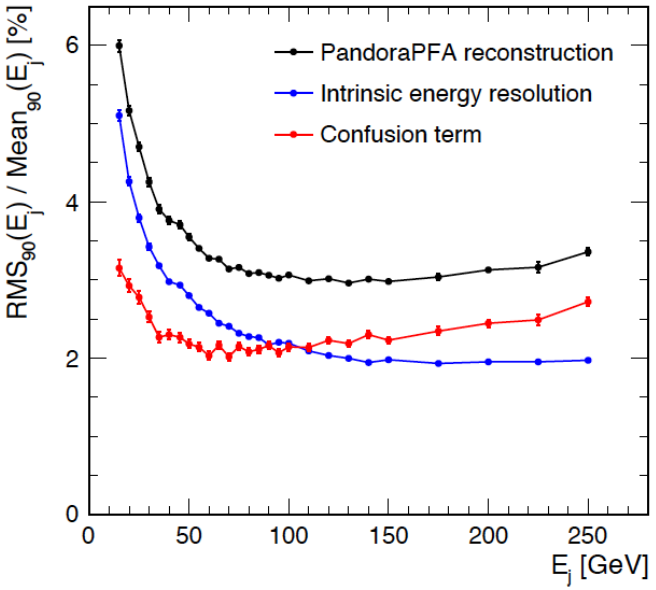
Motivation

Particle Flow Calorimetry

- main motivation: jet energy resolution
  - goal: want to distinguish Z → jet jet from W → jet jet
  - requires σ(E)/E ≈ 3-4%
- can be reached by particle flow algorithms (PFA)
  - for each particle within a jet: use the subdetector with optimal resolution
  - need to avoid double counting and wrong merging
- need an imaging calorimeter!



- requirements for the calorimeter:
  - highly granular
  - reconstruction of neutral particles: good energy resolution
  - calorimeter has to be within magnet coil: very compact



- more possible benefits of high granularity
  - background (pile up) rejection
  - particle identification (μ, τ, …)
  - reconstruction of long-lived particles

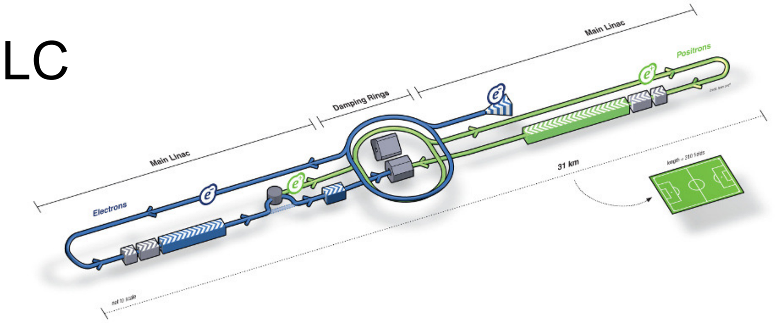
Detector Upgrades/Concepts

CALICE

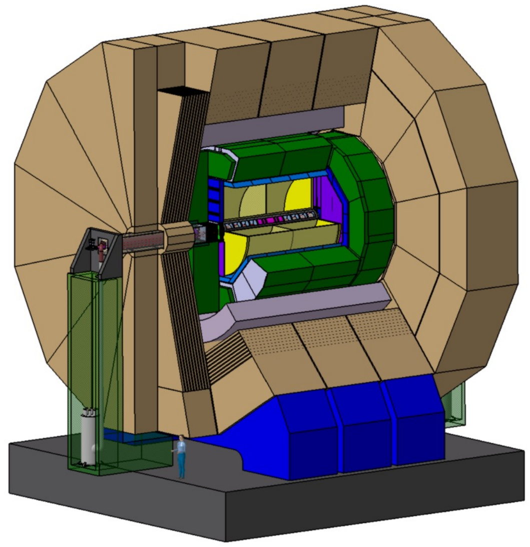
- **Dedicated detector R&D collaboration** focusing on the development of **highly granular calorimeters optimized for the application of particle flow algorithms**
- Originally founded for calorimeter development for the International Linear Collider (ILC)
- Scope now widened to integrate applications of highly granular calorimeters in other environments
- Provides **framework for the R&D activities**, ensuring **common standards for beam tests and data analysis**, as well as organizing **combined beam tests of full calorimeter systems**
- ECAL technologies for active material:
  - small scintillator strips
  - silicon sensors
- HCAL technologies for active material:
  - scintillator tiles
  - gaseous detectors (RPCs, GEMs and MicroMegas)
- Various readout concepts:
  - Analog
  - Digital
  - Semi-digital

Detector Concepts

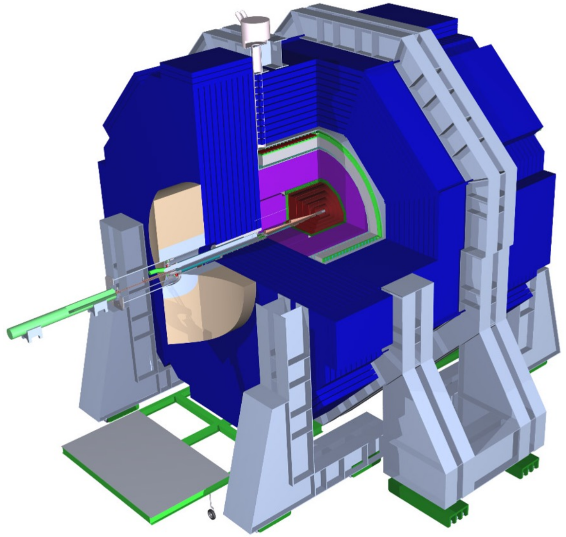
ILC



- Particle Flow calorimeters are essential ingredients in many detector concepts for future Higgs factories



ILD



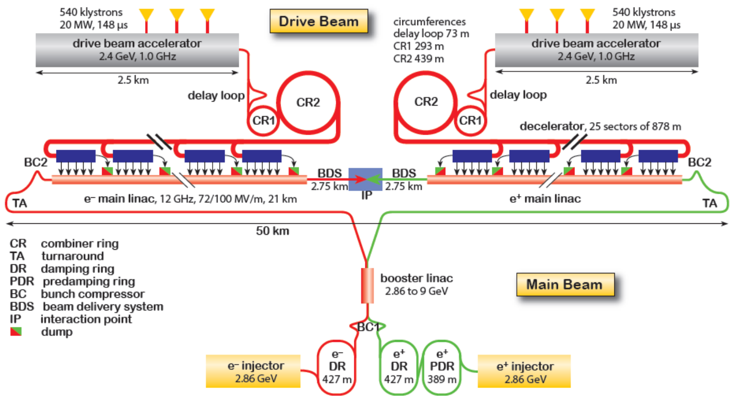
SiD

ECAL: silicon/tungsten or
 scintillator-strip/tungsten
HCAL: RPC/steel or
 scintillator-tiles/steel

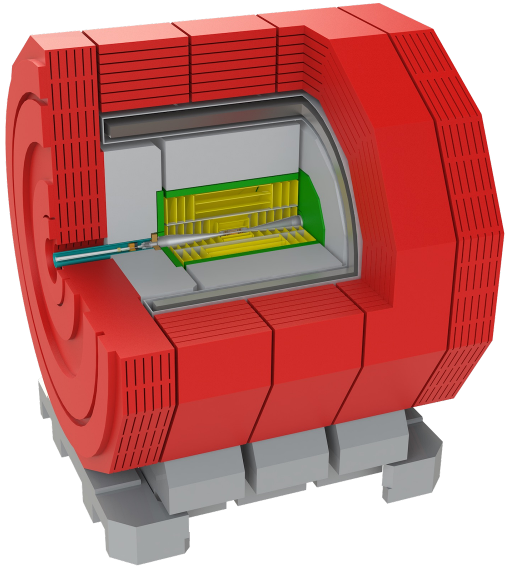
ECAL: silicon/tungsten

HCAL: scintillator-tiles/steel

Detector Concepts

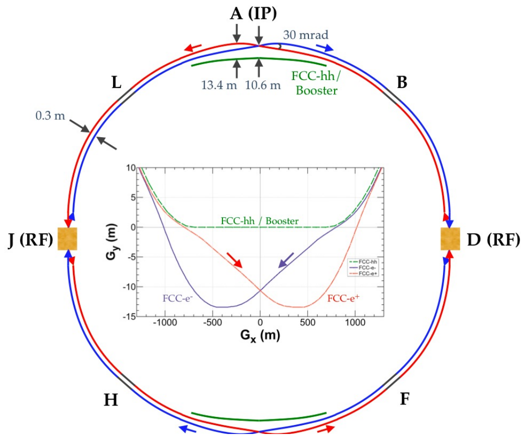


CLIC

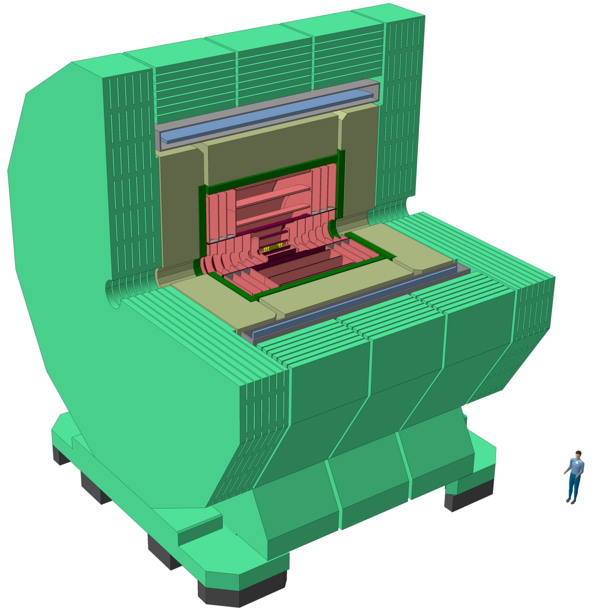


CLICdet

ECAL: silicon/tungsten
HCAL: scintillator-tiles/steel



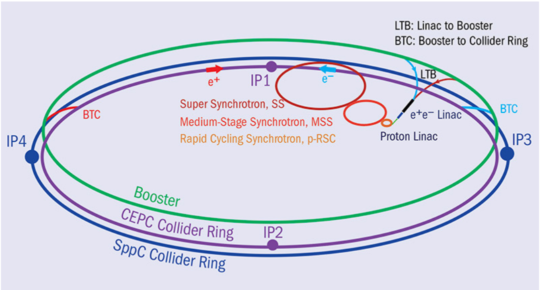
FCC-ee



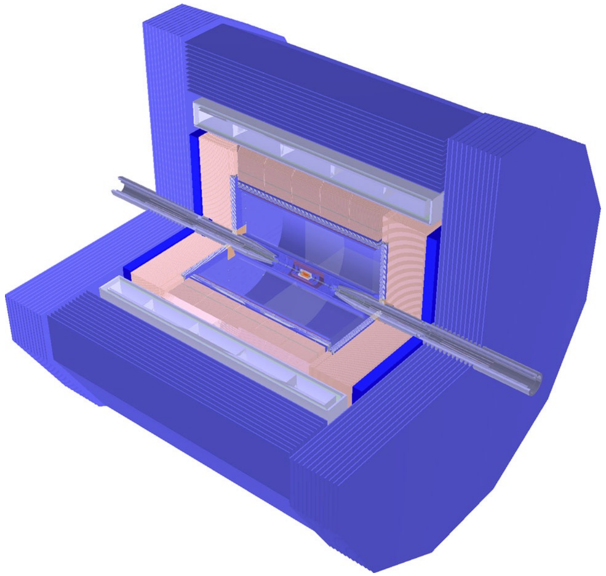
CLD

ECAL: silicon/tungsten
HCAL: scintillator-tiles/steel

Detector Concepts



CEPC

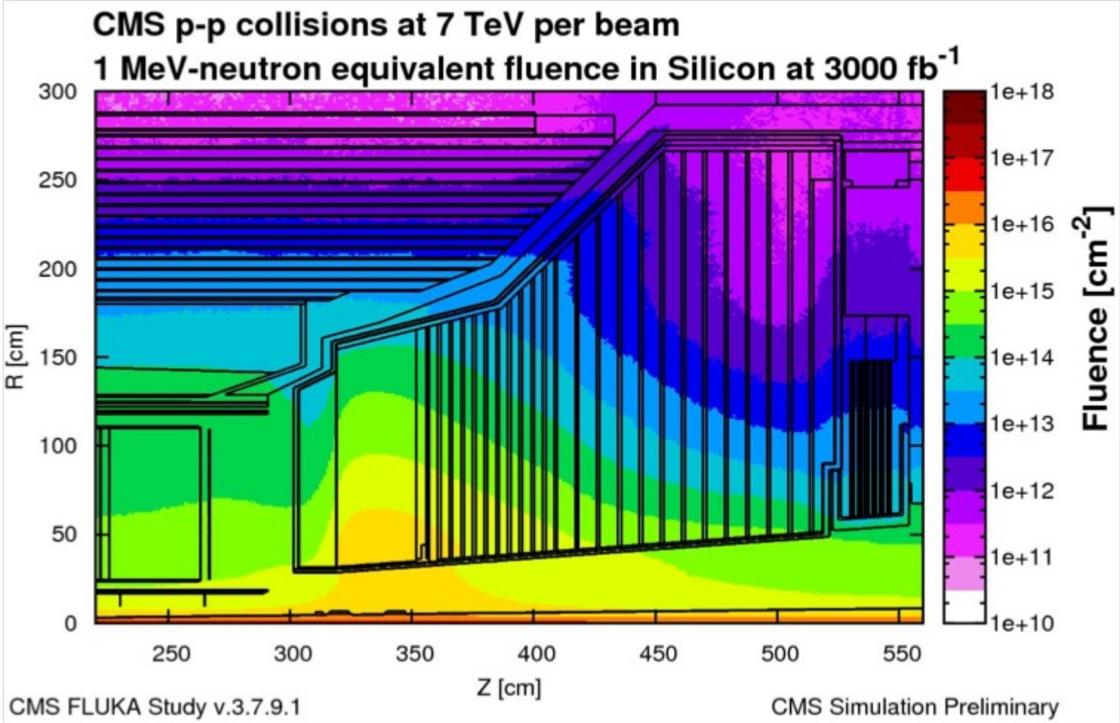


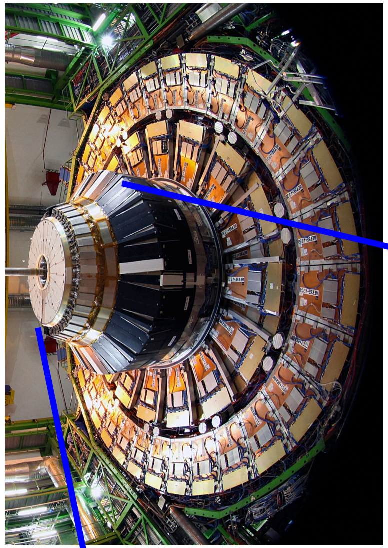
baseline
detector
concept

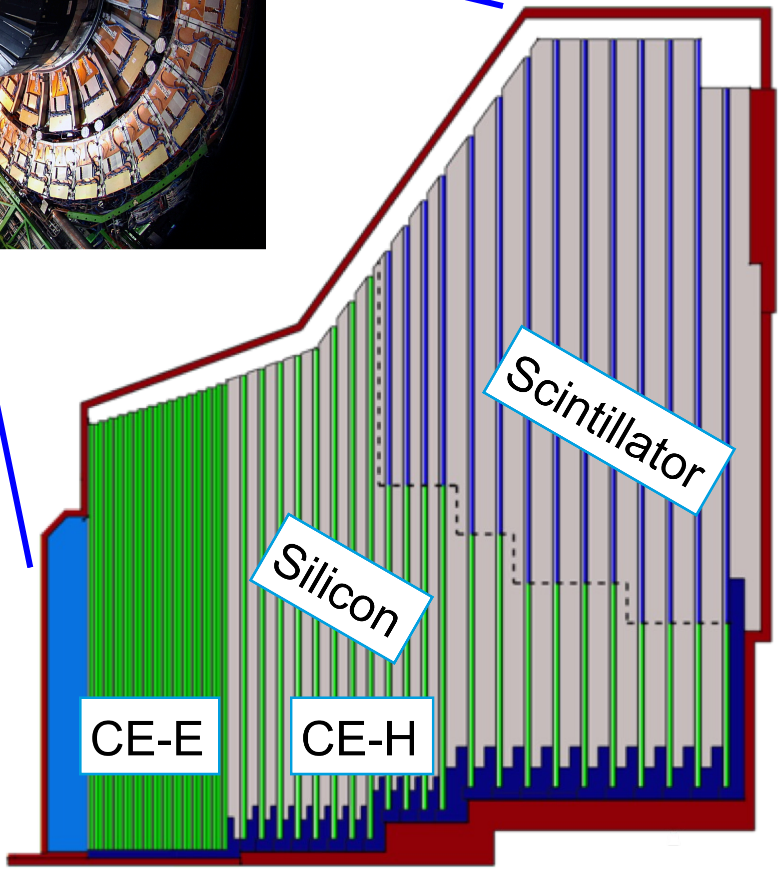
ECAL: scintillator-strip/tungsten
HCAL: RPC/steel or
scintillator-tiles/steel

CMS HGCAL

- CMS calorimeter endcap will be replaced for HL-LHC by **H**igh-**G**ranularity **cal**orimeter
- synergy with high granularity calorimeter concepts developed for electron-positron colliders
  - silicon in the front and close to the beam pipe
  - scintillator tiles wherever radiation levels allow







Technologies

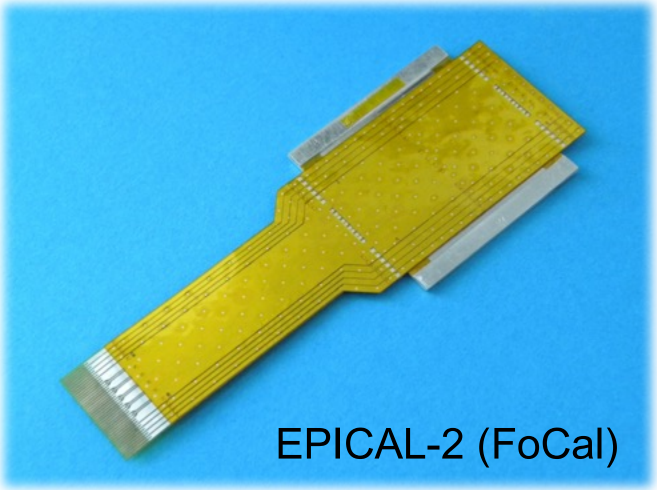
Technologies: Overview

name	purpose	project	active material	channel size	readout (A/D/SD)	# of layers (depth)
CALICE SiW ECAL	ECAL	ILC [a]	silicon	$5 \times 5\,\mathrm{mm}^2$	analog	30 ($24X_0$)
SiD ECAL	ECAL	ILC	silicon	$13\,\mathrm{mm}^2$	analog	30 ($26X_0$)
HGCAL Si	ECAL [b]	HL-LHC	silicon	$52 - 118\,\mathrm{mm}^2$	analog	28 ($25X_0$)
FoCal	ECAL	HL-LHC	silicon	$30 \times 30\,\mu\mathrm{m}^2$	digital	28 ($25X_0$)
CALICE Sci-ECAL	ECAL	ILC [c]	SiPM-on-tile	$5 \times 5\,\mathrm{mm}^2$ [d]	analog	30 ($24X_0$)
RADiCAL	ECAL	FCC-hh	crystal + WLS	$4 \times 4\,\mathrm{mm}^2$ [e]	analog	29 ($25X_0$)
CALICE AHCAL	HCAL	ILC [f]	SiPM-on-tile	$3 \times 3\,\mathrm{cm}^2$	analog	40 ($4\lambda_I$)
HGCAL Scint	HCAL	HL-LHC	SiPM-on-tile	$6 - 30\,\mathrm{cm}^2$	analog	22 ($7.8\lambda_I$) [g]
CALICE DHCAL	HCAL	ILC	RPC	$1 \times 1\,\mathrm{cm}^2$	digital	40 ($4\lambda_I$)
CALICE SDHCAL	HCAL	ILC	RPC	$1 \times 1\,\mathrm{cm}^2$	semi-digital	40 ($4\lambda_I$)

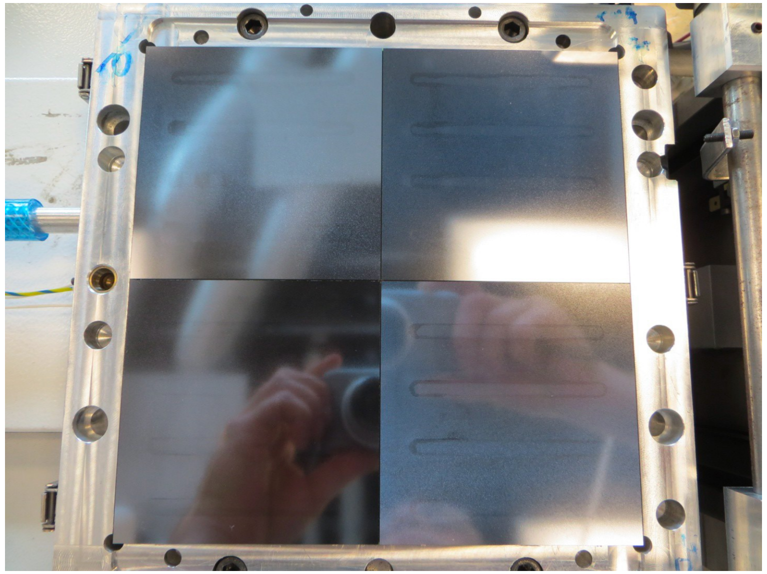
[a] also for CLIC & FCC-ee
[b] silicon also used in HCAL part
[c] also for CEPC
[d] effective size, strips have $5 \times 45\,\mathrm{mm}^2$
[e] effective shower size at shower max; module cross section is $14 \times 14\,\mathrm{mm}^2$
[f] also for CEPC, CLIC & FCC-ee
[g] contains also pure silicon and mixed layers

Silicon

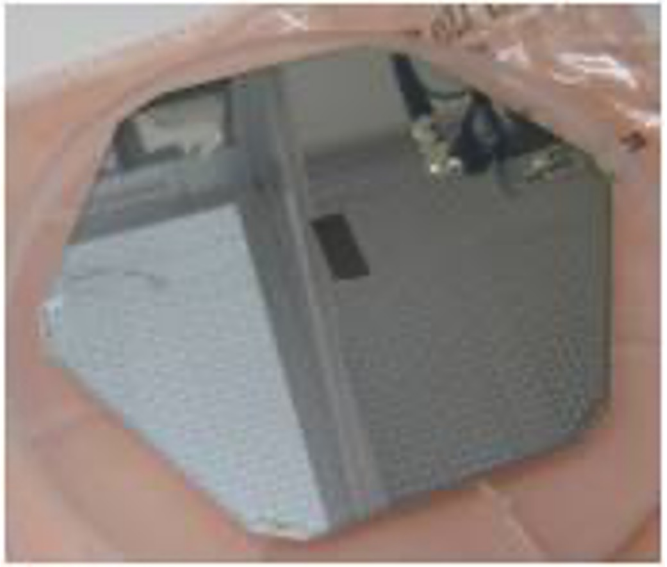
- Most common: silicon sensors with analog readout
  - Typical pad size of ~10 to ~100 mm^2
  - Examples: CALICE SiW ECAL, SiD ECAL, HGCAL Si
- Alternative: silicon sensor with digital readout
  - Based on MAPS, ~30*30 μm^2 pixels
  - Example: EPICAL (R&D for ALICE FoCal)



EPICAL-2 (FoCal)



CALICE SiW ECAL



SiD ECAL

HGCAL Si

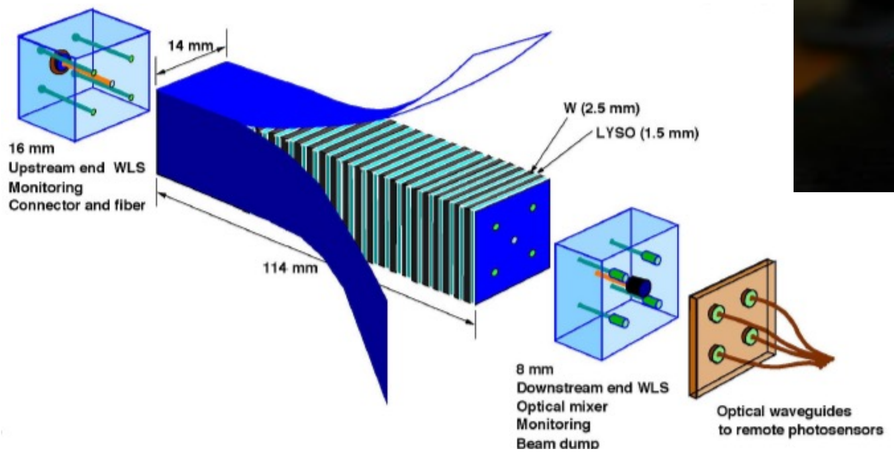
Crystal

High-Granularity Crystal Calorimetry

- Homogeneous ECAL made from small scintillation crystals
- Could reach very good intrinsic energy resolution
- Dual readout of Cerenkov and scintillation photons could potentially improve hadron energy resolution

RADiCAL

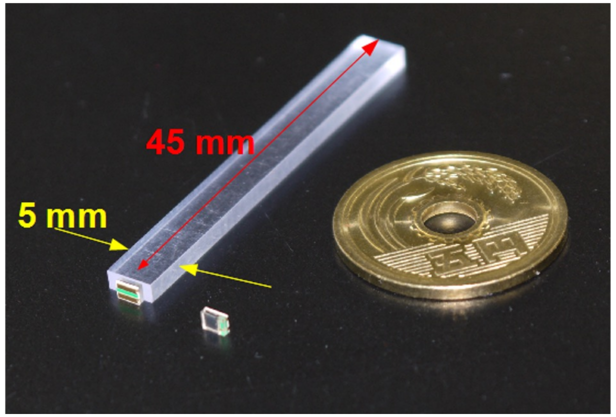
- LYSO/tungsten sampling ECAL read out by rad-hard WLS fibres at both ends
- Aim: identify technology that can withstand conditions of FCC-hh endcaps
  - 500 Grad ionization dose
  - 5 x 10^18 1MeV n_{eq} fluence

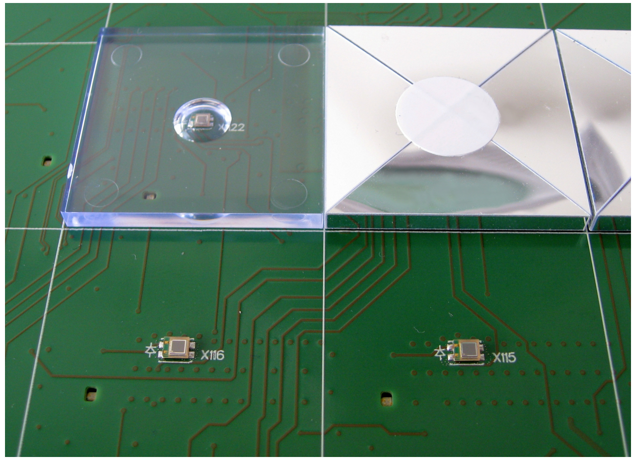


Scintillator Strips & Tiles (SiPM-on-Tile)

- High granularity possible due to individual direct readout by SiPMs
- ECAL
  - scintillator strips, size ~5*45 mm², alternating orientation
  - Example: CALICE SciW ECAL
- HCAL
  - Scintillator tiles, size ~5 to ~30 cm²
  - Examples: CALICE AHCAL, HGCAL Sci

CALICE SciW ECAL





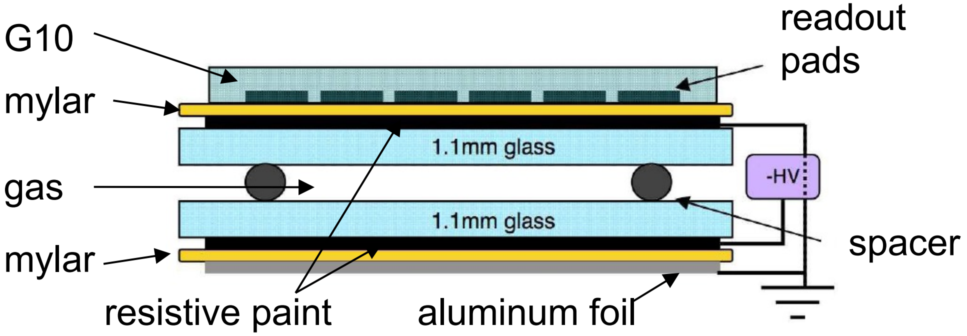
CALICE AHCAL

HGCAL Sci

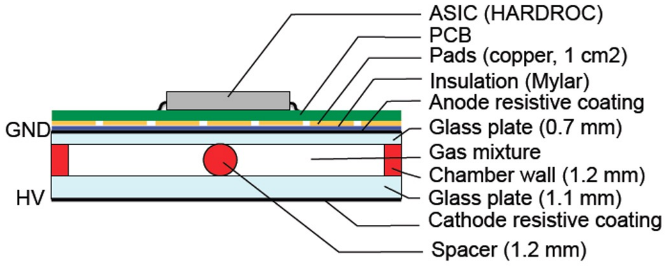
Gaseous Detectors (RPCs, GEMs, …)

- gaseous detectors operated in avalanche mode: measured charge only weakly correlated with primary deposited energy
  - Dedicated readout schemes: digital, semi-digital
- Typical pad size of 1 cm^2
- RPCs
  - Examples: CALICE DHCAL, CALICE SDHCAL
- Advanced GEMs
  - Could sustain higher particle rates and provide better time resolution

CALICE DHCAL



CALICE SDHCAL



Challenges

Distinguishing characteristics

- Silicon:
  - + Very stable signals with very small channel-to-channel variations; Radiation hardness
  - – Expensive; Very small signals
- Crystals and Ceramics:
  - + High density; Radiation hardness; Intrinsic brightness; Can be used also in homogeneous ECAL
  - – Expensive
- Gaseous:
  - + Cost effective
  - – Sensitive to gas flow and to environmental conditions (temperature, humidity); Possibly: green house effects
- SiPM-on-tile:
  - + Cost effective
  - – Sensitive to temperature effects; SiPM saturation effects

Common Aspects and Challenges

- **Embedded electronics**: usually necessary due to large channel densities and difficulties to bring analog signals of all cells outside
  - electronics not accessible for repair -> strong requirements on **quality tests** before assembly and on **longevity**
  - **complex readout elements** such as ASICs situated **in positions of vulnerability** to radiation and environmental issues
  - large area covered by PCB on the active area can contribute significantly to the cost especially for HCALs

- **Power Management:** amount of heat produced by the electronics needs to be minimized or removed
  - Linear electron-positron colliders: power pulsing
  - Hadron colliders: need dedicated cooling system with cooling inside the active layers

Common Aspects and Challenges

- **Industrialisation:** overall channel counts are hundred-thousands to millions, covered areas in the active layers are hundreds of square meters
  - Nevertheless, a niche for most industry areas
  - Usually, only the components and some of the first assembly steps can be done by companies

- **Data Analysis:** large number of channels is also challenging for several analysis aspects
  - **Simulation**: new ideas based on machine learning
  - **Calibration**: fluctuations not so important, main challenge is to avoid syst. bias and monitor stability
  - **Reconstruction**: “classical” Particle Flow Algorithms like PandoraPFA and ARBOR (and algorithms used in ATLAS and CMS), new ideas inspired by computer vision

Future Directions & Assessment of long-term Importance

Future Directions & Long-term Importance

- Many of the developments for PFA calos so far focused on high precision jet measurements for linear electron-positron colliders
- For circular machines (especially hadron colliders), event pile-up and radiation are much more important
  - Radiation hardness of materials
  - Hit time measurements for improved association of hits to particles and particles to interaction vertices
- So far, experimental results mainly from beam tests
  - CALICE, SiD ECAL, FoCal, HGCAL prototype
  - In general demonstrated viability of the concepts (in testbeam environment)
  - Important cross check with GEANT simulation
- First full demonstration of the technique will be the CMS HGCAL, which will be the first to break ground in this new technological territory

- The impact of the Particle Flow Calorimetry Technique rests on demonstrations of its successful experimental application

Thank you!

Common Aspects and Challenges

- Cell size optimization driven by several factors
  - ECAL cells should be small enough to allow the separation of close-by showers and a reliable assignment of showers to corresponding tracks
  - in order to distinguish electromagnetic and hadronic showers as well as to identify electromagnetic sub-showers within hadron showers, the cell size should be of the order of the Moliere radius and the radiation length X0,
  - very small cell size especially in the ECAL beneficial for τ reconstruction
  - especially at hadron colliders, a small cell size allows better rejection of energy depositions from pile-up events