CEPC CDR Detector Concepts for Calorimetry

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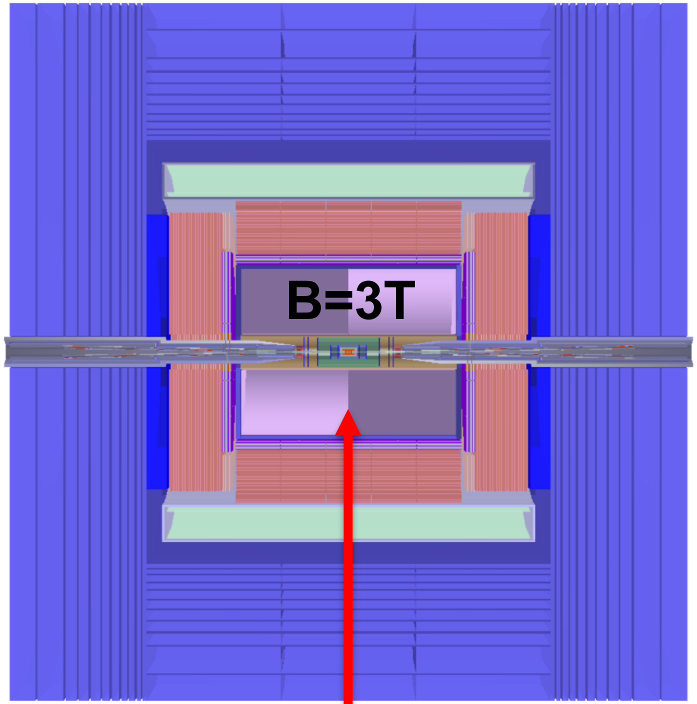
CEPC Detector Performance Requirements

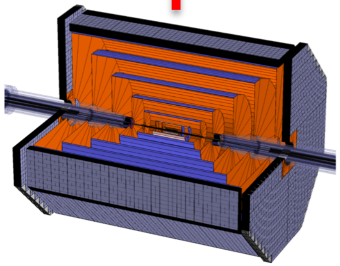
Primarily for the Higgs physics program at CEPC

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

CEPC Detector Concepts in CDR

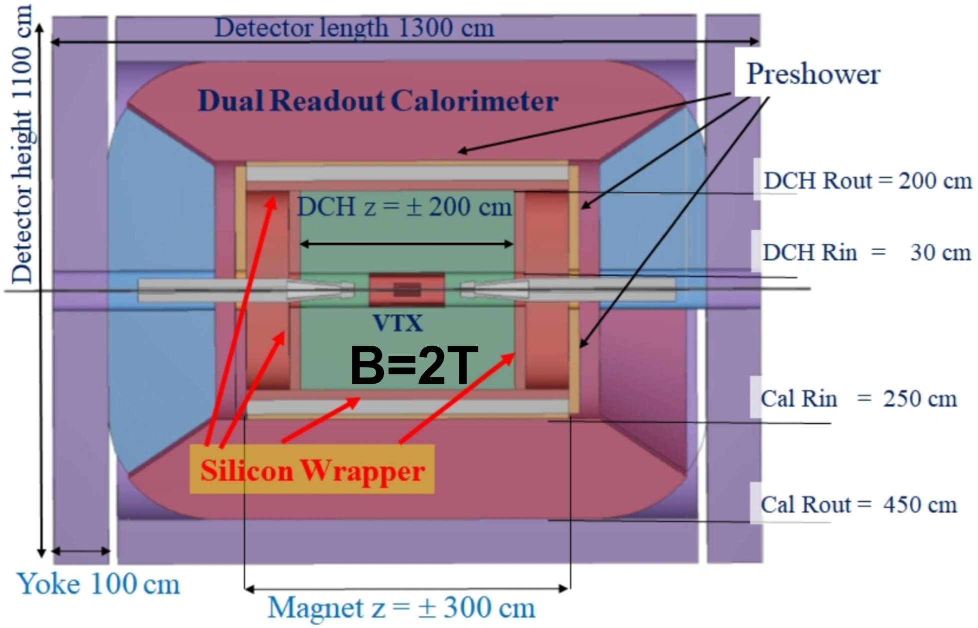
Baseline : PFA approach (derived from ILD)
Silicon + TPC
+ PFA-ECAL&HCAL + Muon





Another tracking option with full-silicon

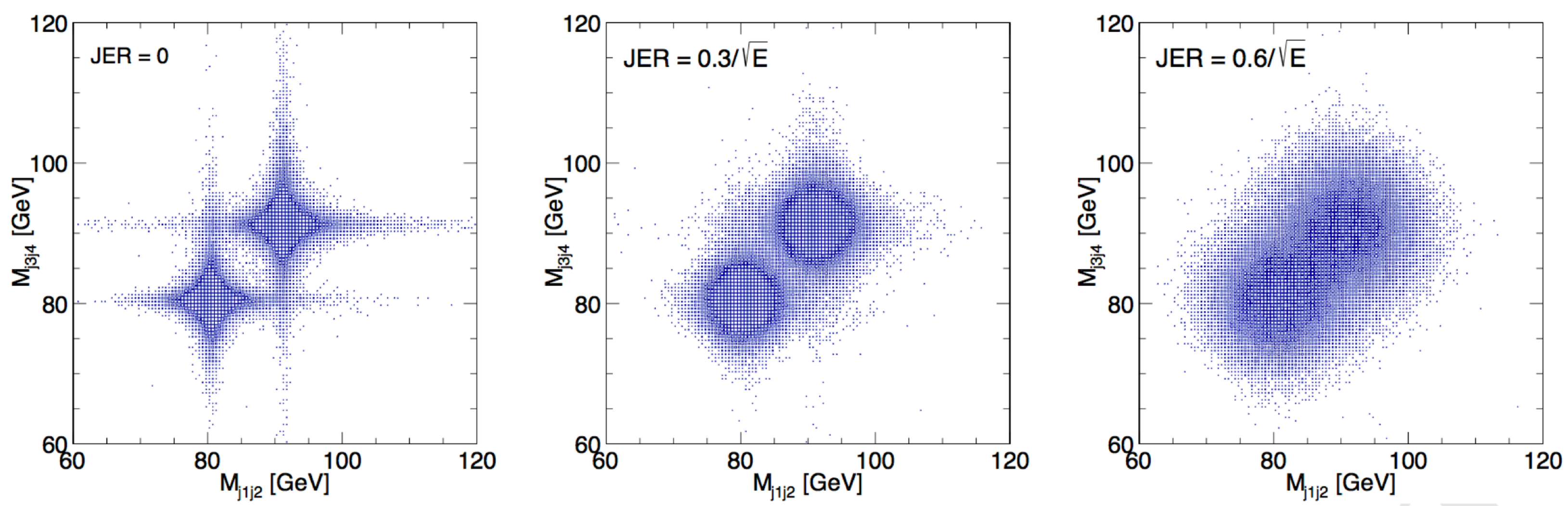
Alternative : IDEA
Silicon + Drift Chamber
+ Dual-readout calorimeter + Muon



Calorimeter outside the coil

Jet measurement at CEPC

- Separation of W/Z bosons in their hadronic decays translates into a jet energy resolution requirement of ~ 30% /√E (or 3-4% in the energy range of interest).
- The chief factor driving the design of the CEPC calorimetry system.



WW→4j and ZZ→4j

Other Drivers

- EWK physics
  - Precise e/γ measurement
  - γ/π^0 discrimination
  - …
- τ and heavy flavor physics
  - π^0 identification
  - …
- …

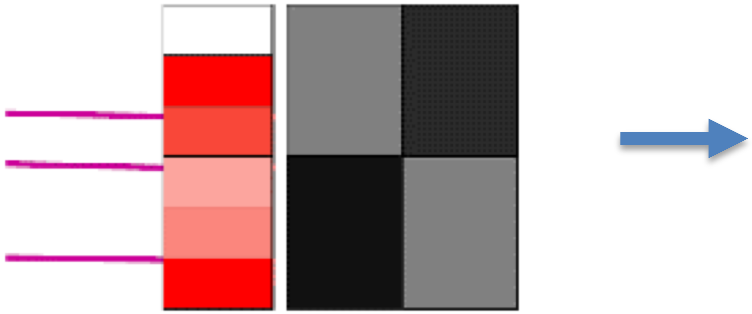
Mostly concerning ECAL

CDR Calorimeter Concepts

- Approach with Particle Flow Algorithm
  - Sampling electromagnetic and hadronic calorimeters with extremely high granularity
- A dual-readout calorimeter
  - A combined solution with good performance for both electromagnetic and hadronic particle showers.

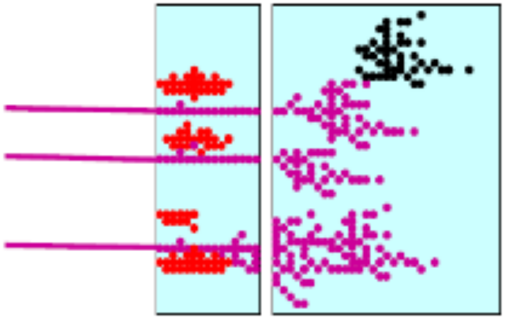
Particle Flow Algorithm

- Particle Flow Algorithm (PFA) : a very promising approach to achieving the unprecedented jet energy resolution of 3%-4%.



$E_{JET} = E_{ECAL} + E_{HCAL}$

Traditional jet measurement with calorimeters

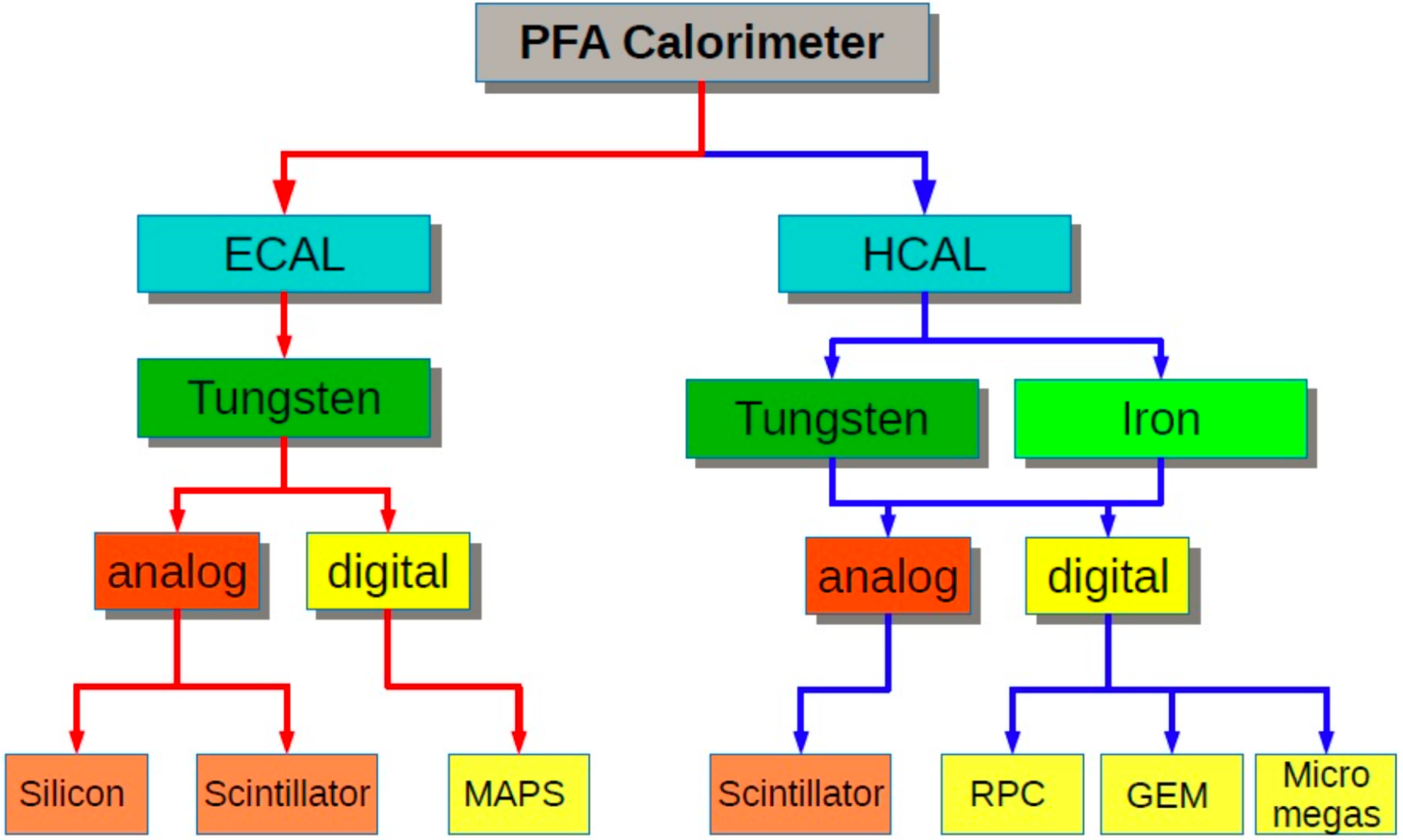


$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Jet measurement with PFA

- A highly segmented (both transversely and longitudinally) and fully-contained calorimetry system combined with a transparent and high-resolution tracking system.

PFA Calorimeter Technologies



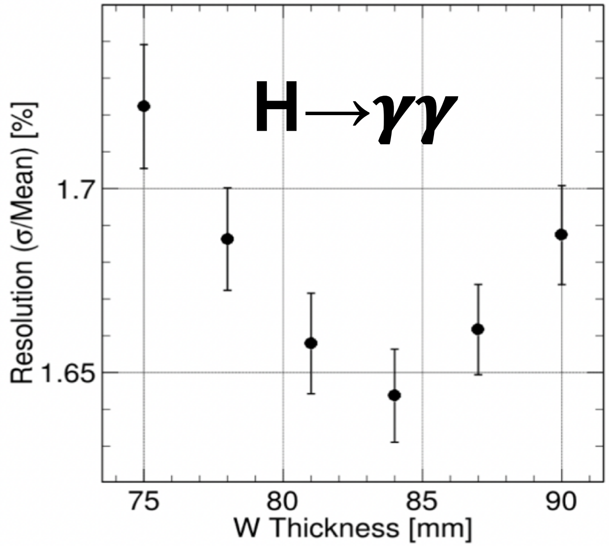
Granularity (3-d) is the key
Front-end electronics must be embedded in detectors

CEPC PFA-ECAL

- Tungsten as absorber
  - short radiation length, small Moliere radius, large X_0/λ
- Two types of sensitive layers
  - Silicon pads: stable, uniform, high S/N, large dynamic range, but costly.
  - Scintillator strips + SiPM
- So two options
  - Baseline: Si-W
  - Alternative: Sci-W

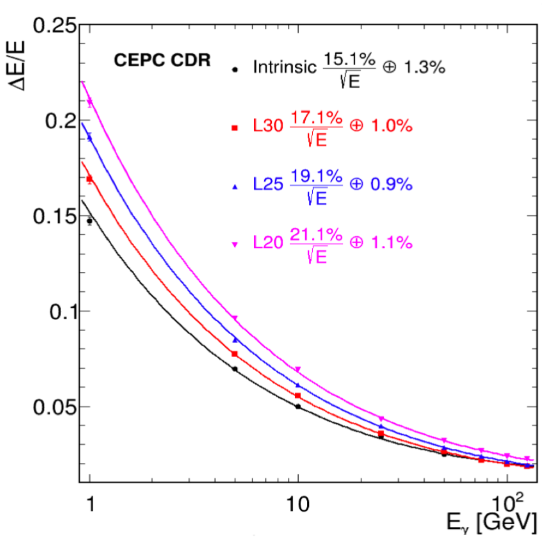
Design Optimization (I)

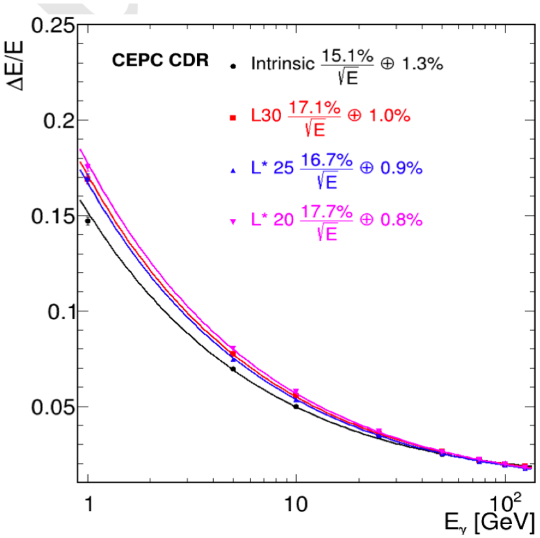
Total absorber thickness → 84 mm



σ(Higgs mass) vs. thickness

- 30 sampling layers
- 0.5mm silicon
- 2.1mm W for first 20 layers
- 4.2mm for last 10 layers





Single photon measurement

Design Optimization (II)

H→gg

Higgs mass in H→gg vs. cell size

Silicon sensor size (mm)	Higgs boson mass resolution (with statistic error)
5	3.74 ± 0.02 %
10	3.75 ± 0.02 %
20	3.93 ± 0.02 %

Z→$\tau\tau$

Percentage of inseparable photons from τ decays in Z→$\tau\tau$ events

Cell size (mm)	Percentage of inseparable photons
1	0.07%
5	0.30%
10	1.70%
20	19.6%

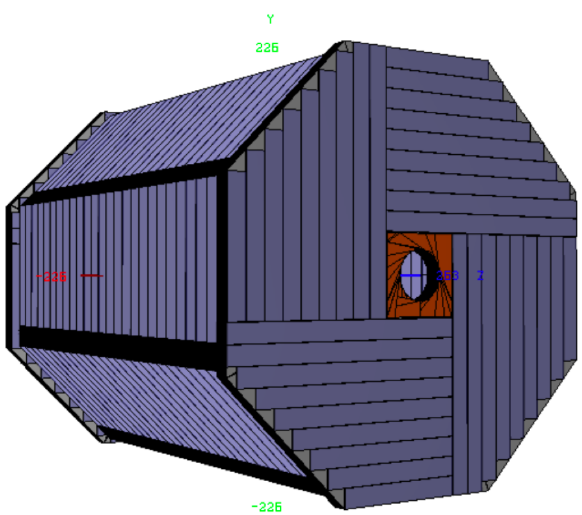
Cell size → 10×10 mm^2

ECAL Baseline Design

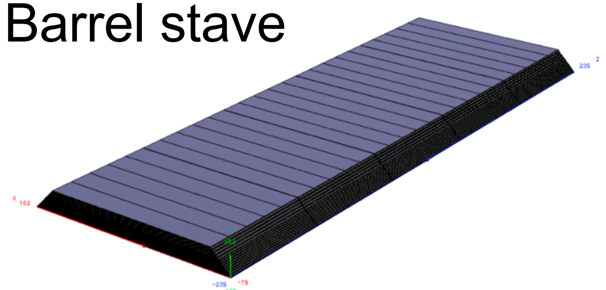
- A Si-W sandwich calorimeter
- Absorber
  - 30 layers of W plates
    - First 20 layers: 2.1mm thick each
    - Last 10 layers: 4.2mm thick each
  - 84 mm thick in total (24 X_0)
- Active medium
  - 30 layers of Si plates
  - 0.5 mm thick each
  - Cell size: 10*10 mm^2

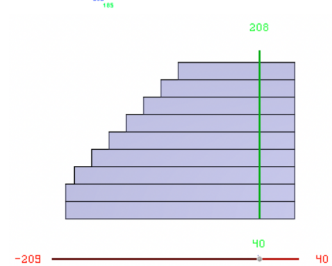
Layout and Structure

- One cylindrical barrel + two disk-like endcaps
- ~2 m in radius, and ~5.3 m long.
- 8 barrel sections: 1 section → 8 staves, 1 stave → 5 modules, 1 module → 5 columns
- Each endcap → 4 quadrants, 1 quadrant → 9 columns
- Column: slabs integrated into supporting structures
- Best possible hermeticity and minimum crack regions



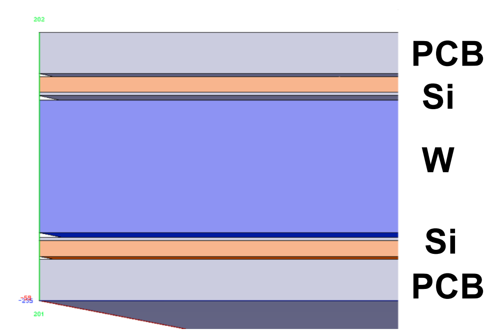
Barrel stave





Endcap quadrant

Slab

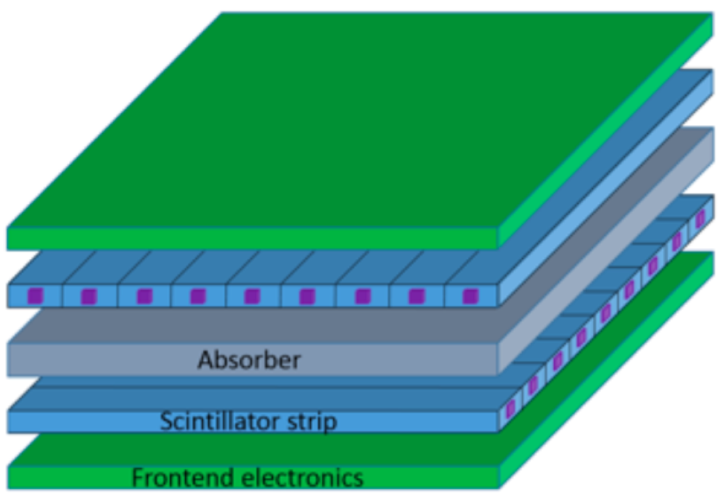


Channel Count, Power Consumption

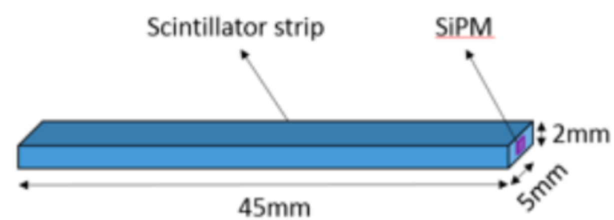
- Numbers of channels
  - 17.3 M for barrel, 7.43 M for endcaps
- Total power consumption
  - 124 kW (SKIROC) + 22 kW (DIF) ~ 146 kW
- Active cooling is likely required. Passive cooling might be possible with a reduced density of channels.
  - For example, with a cell-size of 20mm*20mm?

An Alternative ECAL: Sci-W

- Big advantage is in cost
- The primary difference is in active layer thickness
  - 2 mm thick scintillator
- Scintillator read out with SiPM
- SiPM monitoring and calibration is required



"Crossing" configuration of strips to get a high effective granularity

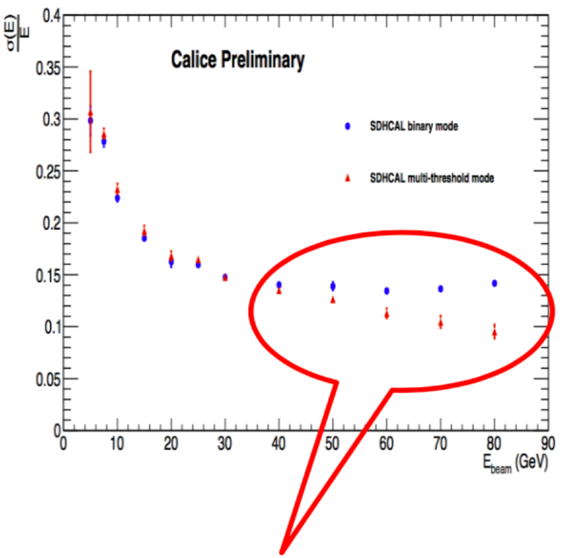


Cell-size: 45mm*5mm

CEPC PFA-HCAL Options

- HCAL technology options in CDR
  - SDHCAL with RPC (baseline)
  - SDHCAL with THGEM
  - AHCAL with scintillator + SiPM
- Fe as absorber in all options
- Digital HCAL requires a higher readout granularity than analogue HCAL to avoid saturation for high energy showers
  - More channels with digital HCAL

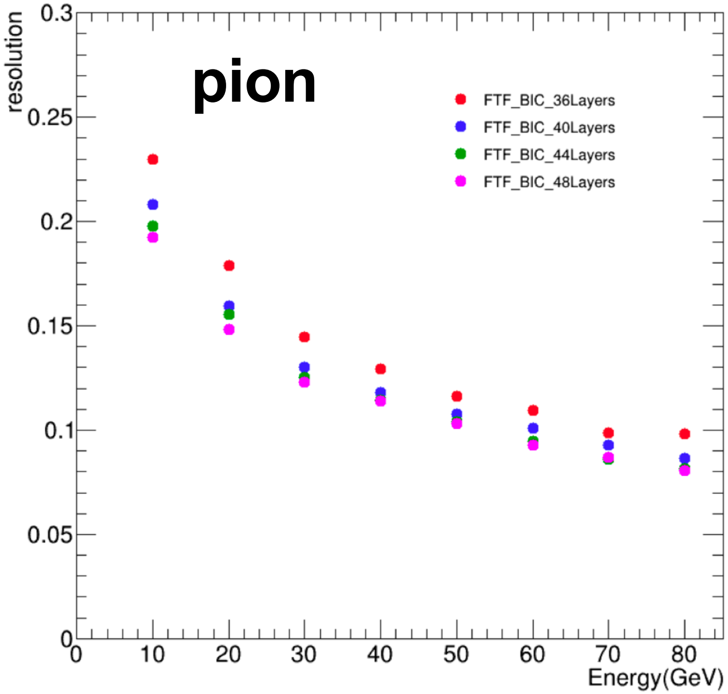
Read out with multiple thresholds: Semi-digital HCAL → SDHCAL

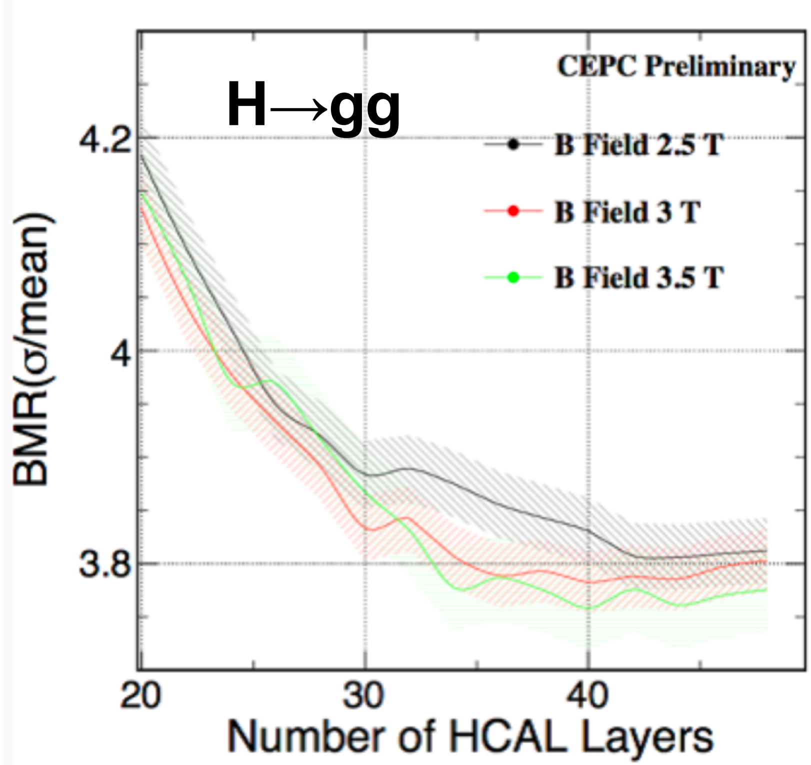


SDHCAL with 3-threshold results in better energy resolution than binary mode for E_{beam} > 40 GeV

HCAL Optimization (I)

- SDHCAL resolution with different numbers of sampling layers.

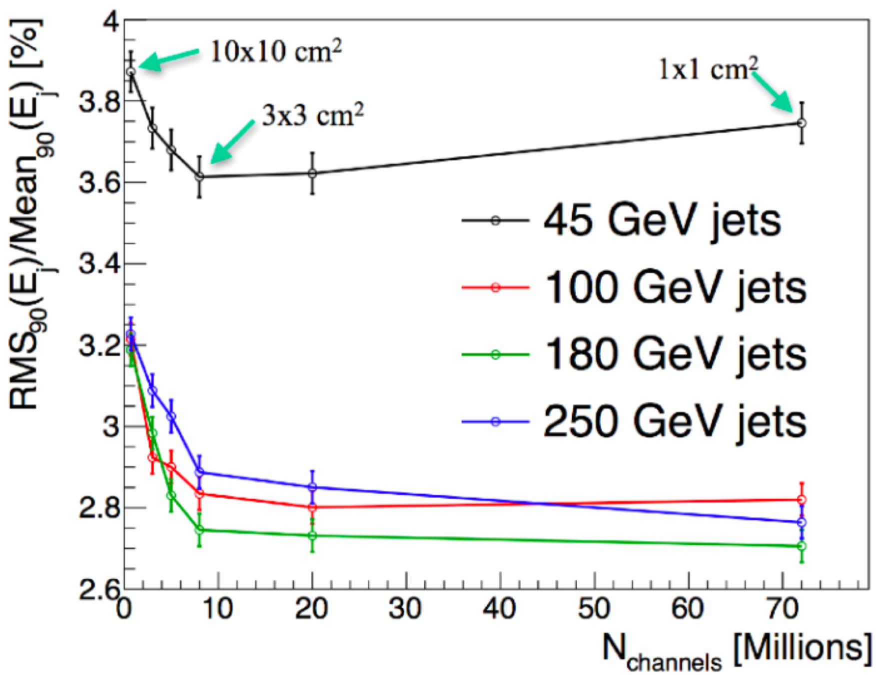


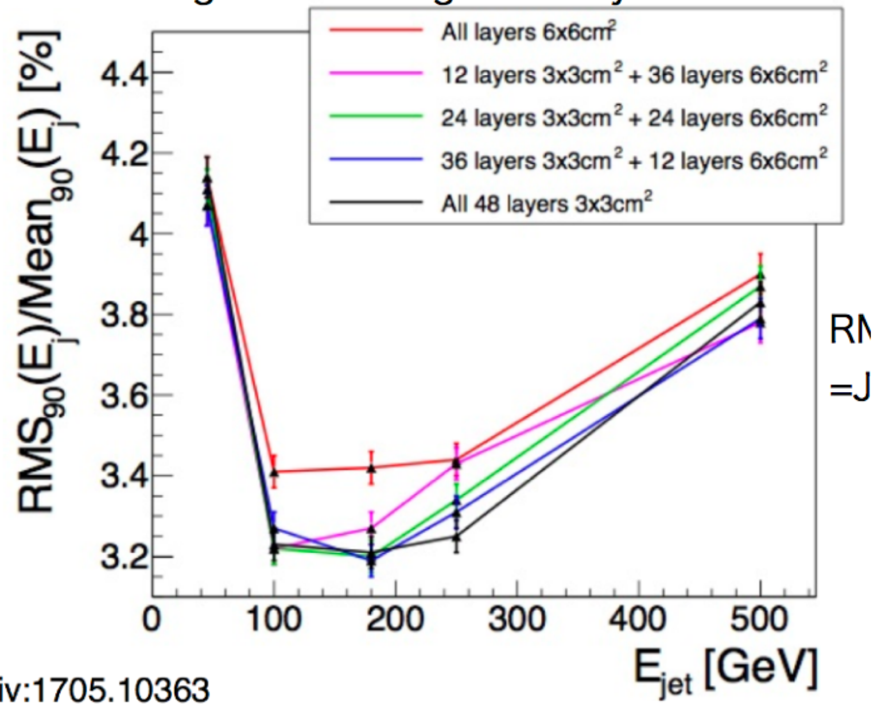


HCAL Optimization (II)

- AHCAL with various cell sizes and in non-uniform cell-size configurations.

Jet energy resolutions expected for different configurations of granularity





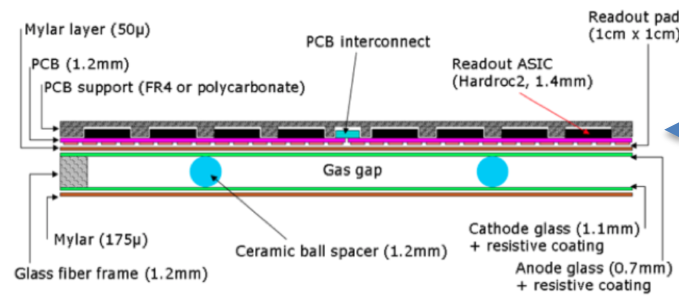
arXiv:1705.10363

By Huong Lan Tran etc.

HCAL Conceptual Designs

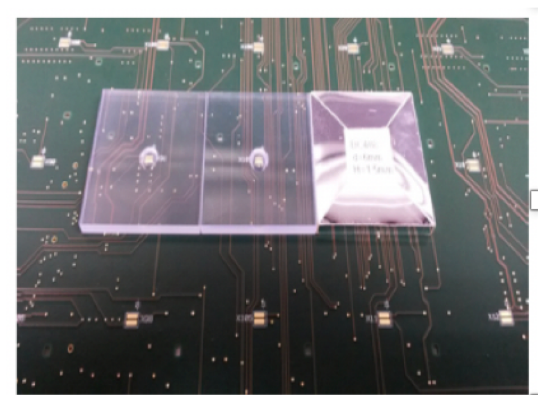
- 40 layers
- Absorber: Fe (steel)
  - 40 layers × 2cm, $5\lambda_I$
- Active layers
  - SDHCAL
    - glassRPC, 6mm thick
    - cell-size: 1cm×1cm
  - AHCAL
    - Sci (3mm) + SiPM, ~5mm thick
    - cell-size: 3cm×3cm

Very compact glass RPC unit



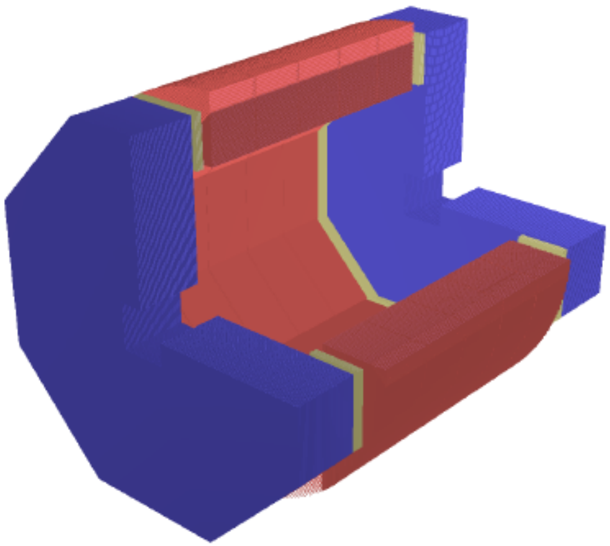
Embedded readout electronics

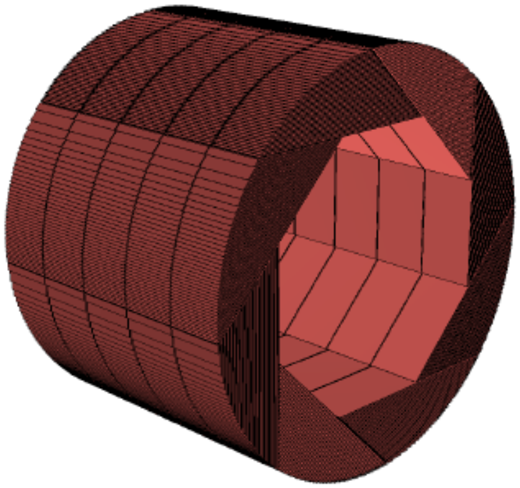
SiPM-on-Tile

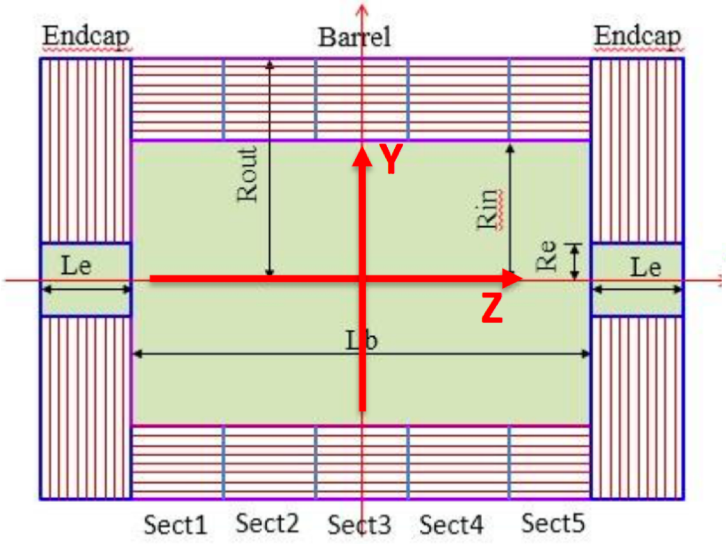


Geometry and Layout

SDHCAL

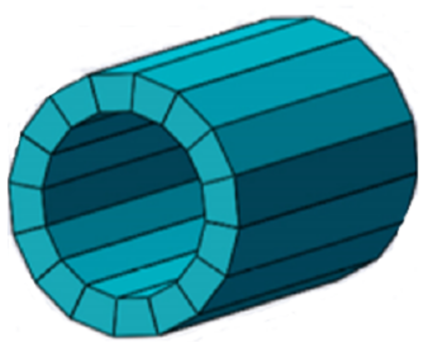




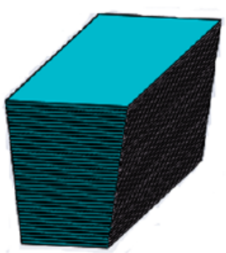


AHCAL

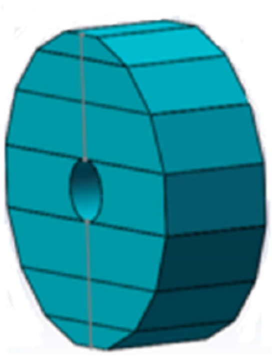
AHCAL barrel



AHCAL super module



AHCAL endcap



- Inner radius in X-Y plane R_{in} = 2300mm
- Outer radius R_{out} = 3340mm
- Inner & outer of HCAL endcap in Z-axis are 2670mm and 3710mm

Channel Counts, Power Consumption

- **HCAL Barrel, R_{in} = 2.3m, R_{out} = 3.34m, length = 2.67*2=5.34m, N_{layer}=40**
  Area of HCAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 3782 m^2
- **HCAL Endcap (2), R_{in} = 0.35m, R_{out} = 3.34m, N_{layer}=40**
  Area of HCAL endcap = $2*PI*(R_{out}*R_{out} - R_{in}*R_{in})*N_{layer}$ = 2772 m^2

Cell Size \ channels	HCAL Barrel	HCAL Endcap	Channels (N_{ch})	Power AHCAL	Power SDHCAL
1cm x 1cm	37.82M	27.72M	65.5M		110 kW
2cm x 2cm	9.455M	6.93M	16.4M		52 kW
3cm x 3cm	4.2M	3.08M	7.3M	110 kW	43 kW
4cm x 4cm	2.36M	1.73M	4.1M	88 kW	
5cm x 5cm	1.51M	1.11M	2.6M	77 kW	

Power Consumption (rough estimation):

AHCAL: 7mW/ch * N_{ch3} + 9W/DIF/m^2 * 6554 (59kW)

SDHCAL: 1mW/ch * N_{ch1} + 5.4W/DIF/m^2 * 6554 (35.4kW)

Active cooling is likely needed.
Water cooling should be sufficient.

Simulated Performance of PFA ECAL+HCAL

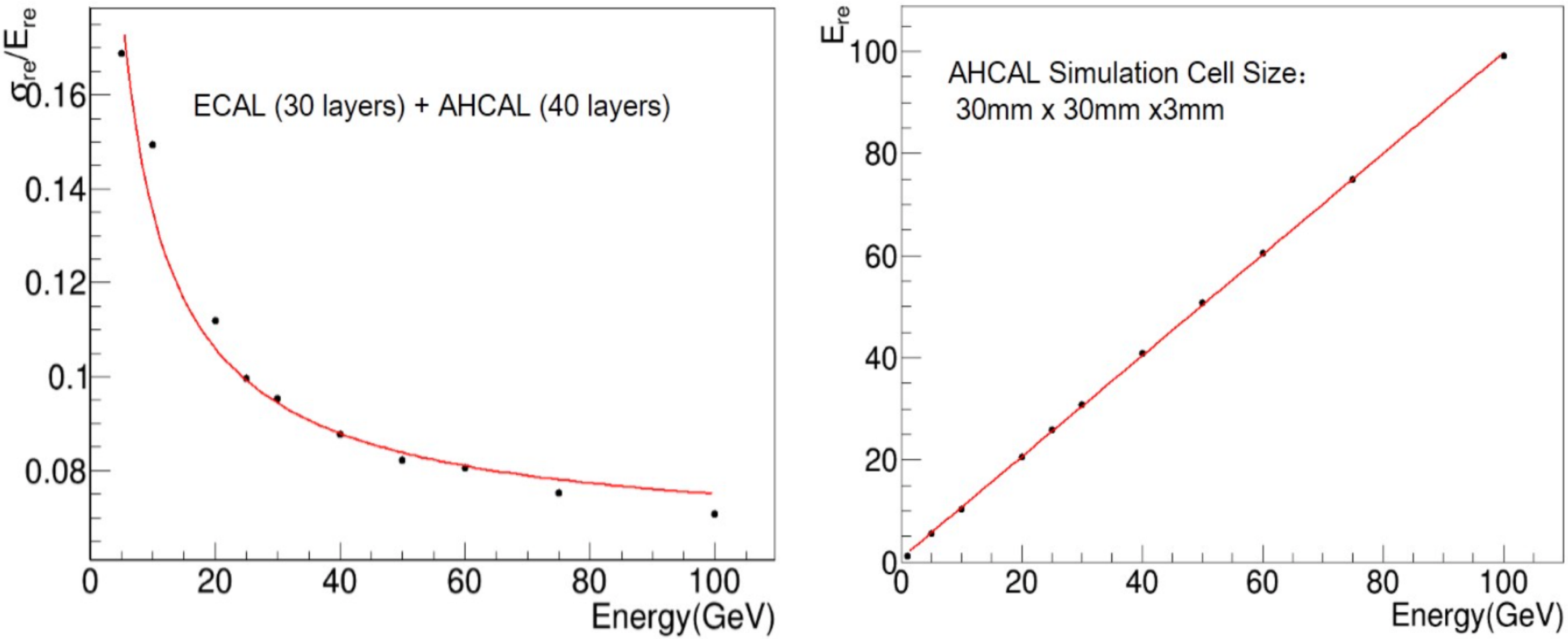
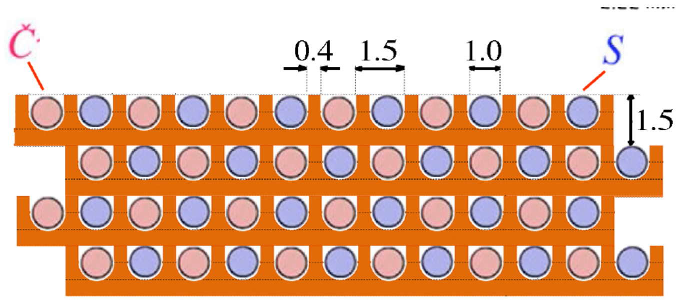


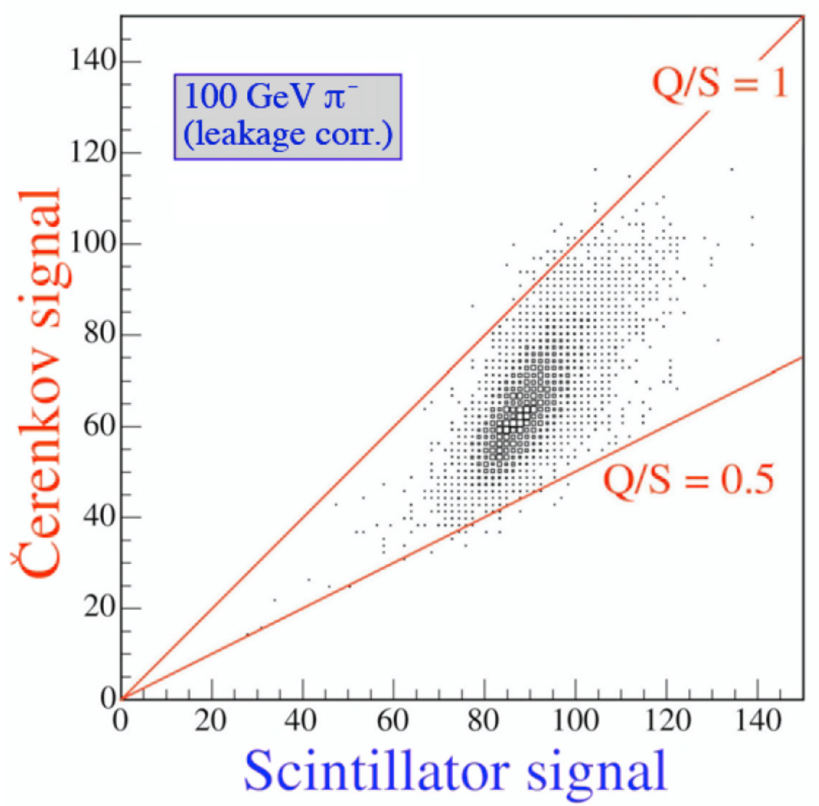
Figure 5.32: The left plot is the energy resolution from the SiW-ECAL and AHCAL for pions. The right plot is the corresponding results of reconstruction energy linearity. The energy resolution is 11% and 8% for energy at 20 GeV and 80 GeV, respectively.

Dual-Readout Calorimeter



Fiber pattern RD52

Reconstruct f_{EM} on an event basis → Alternating quartz and and scintillating fibers in metal matrix.



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

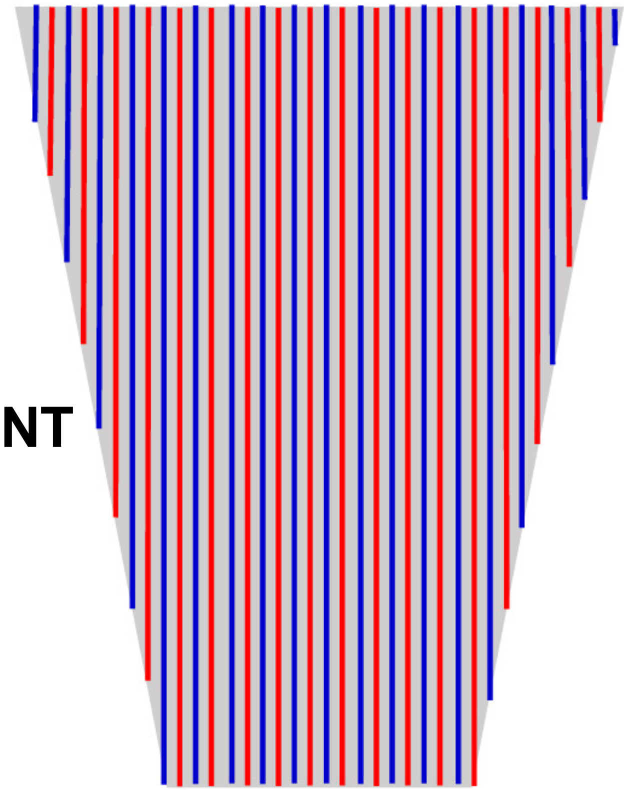
with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

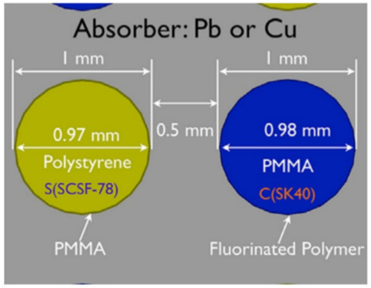
Geometry and Layout

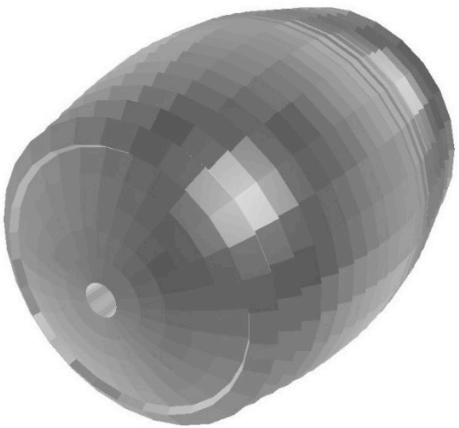
- Projective layout
- Wedge geometry
- Full coverage

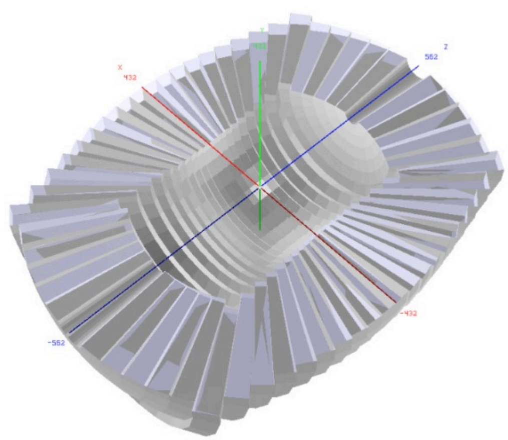
Wedge module

$\Delta\theta \times \Delta\phi = 1.27^\circ \times 1.27^\circ$



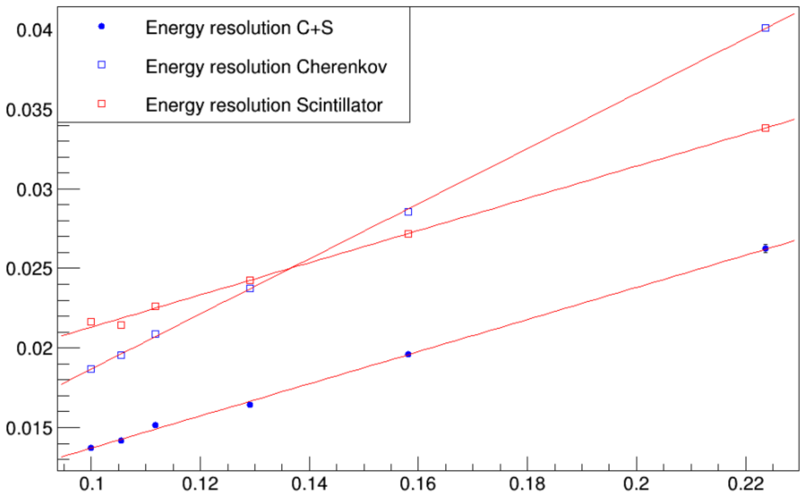


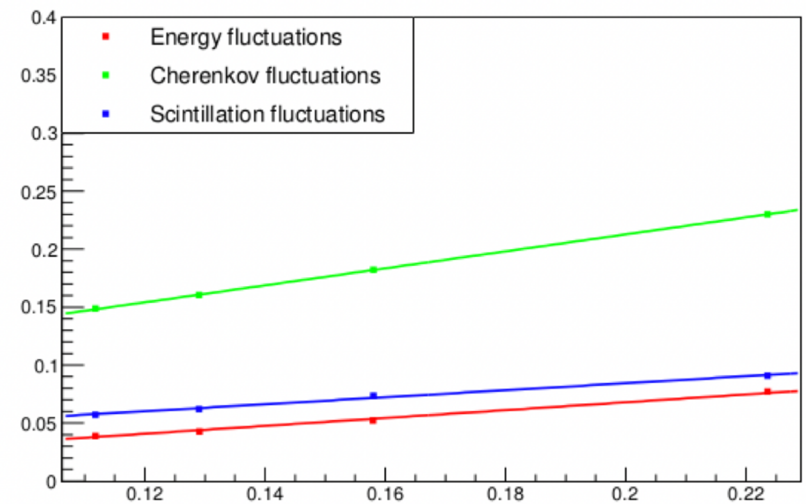




Simulated Performance

With copper as absorber





$1/\sqrt{E}$(GeV)

EM resolution

Hadronic resolution

fibers used	Fitted Gaussian *em* energy resolution
S-fibers only	$\sigma/E = 10.1\%/\sqrt{E} \oplus 1.1\%$
C-fibers only	$\sigma/E = 17.3\%/\sqrt{E} \oplus 0.1\%$
S-fibers and C-fibers	$\sigma/E = 10.1\%/\sqrt{E} \oplus 0.4\%$

fibers used	Fitted Gaussian hadronic energy resolution
S-fibers only	$\sigma/E = 30\%/\sqrt{E} \oplus 2.4\%$
C-fibers only	$\sigma/E = 73\%/\sqrt{E} \oplus 6.6\%$
Dual-readout S-fibers and C-fibers	$\sigma/E = 34\%/\sqrt{E} \oplus (\text{negligible})\%$

PID Capability

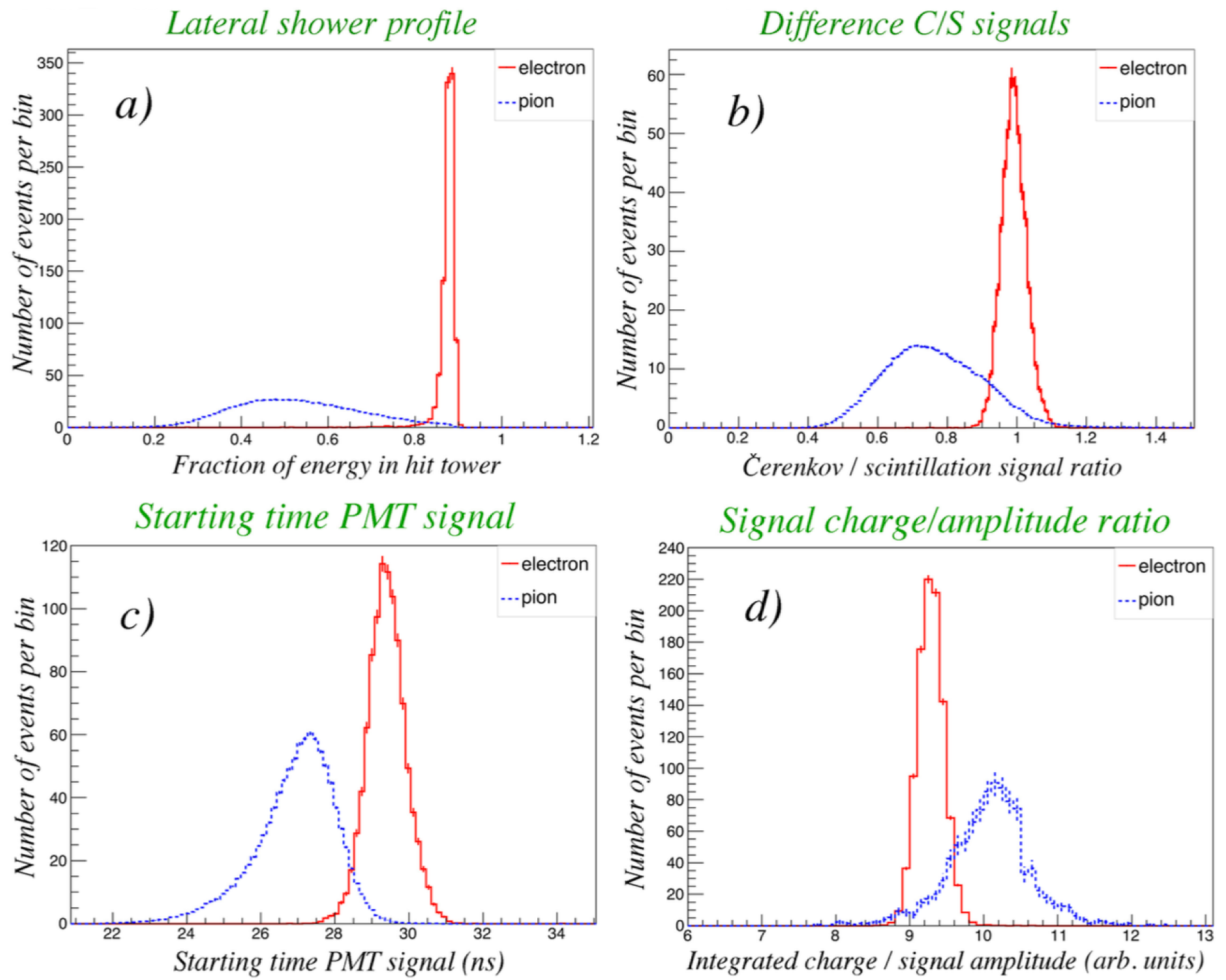


Figure 5.44: Distribution of four discriminating variables for 60 or 80 GeV electrons and pions, as measured with the RD52 lead-fiber prototype [33]: (a) energy fraction deposited in the hit tower; (b) C/S signal ratio in the hit tower; (c) starting time of the PM signal; (d) ratio of the integrated charge and the amplitude of the signals.

test beam data

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

NIM A 735 (2014) 120

Choice of Absorber Material

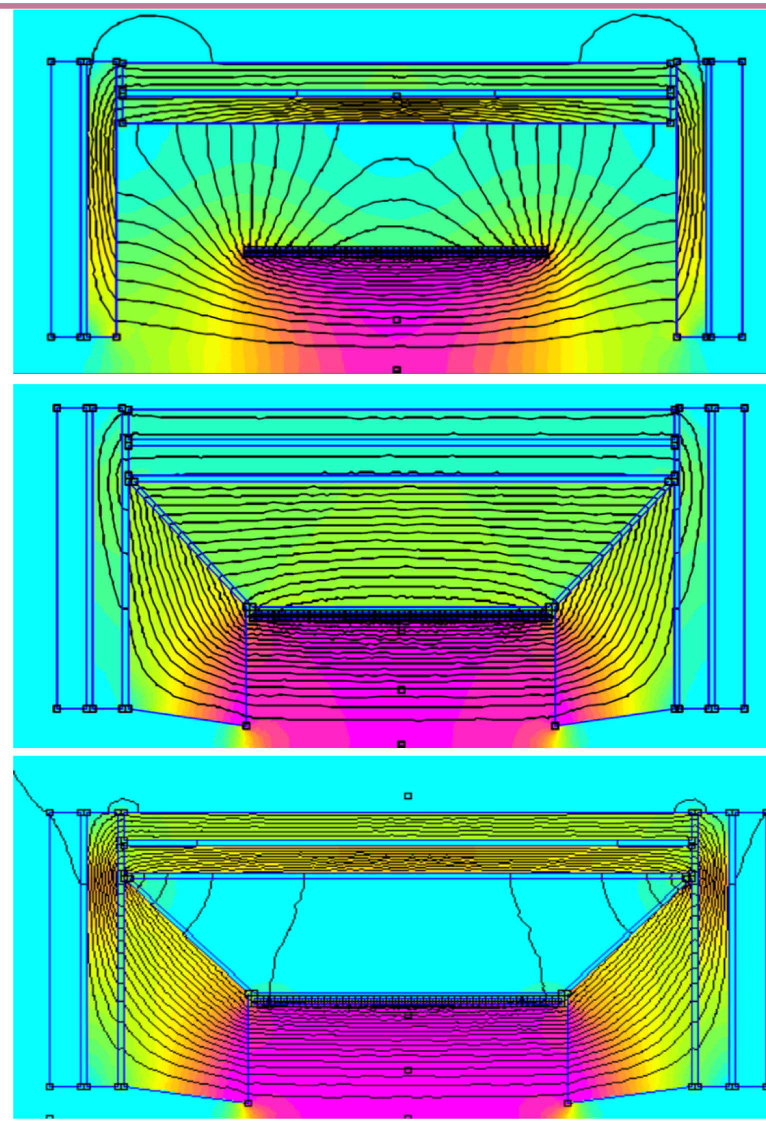
Effect on magnetic field

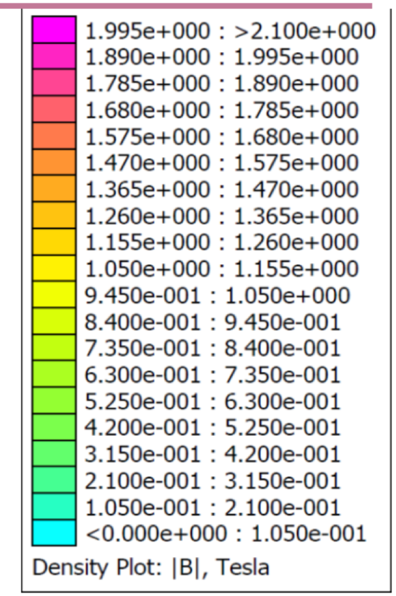
INFN
Istituto Nazionale di Fisica Nucleare

Copper absorber

Iron absorber

Iron absorber in endcap
Copper absorber in barrel

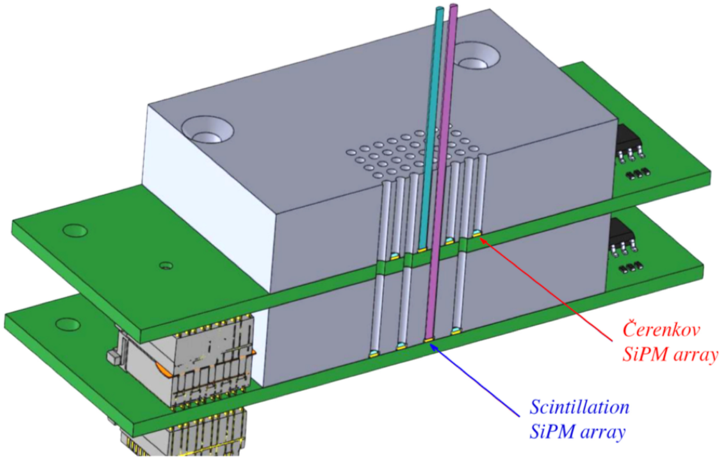


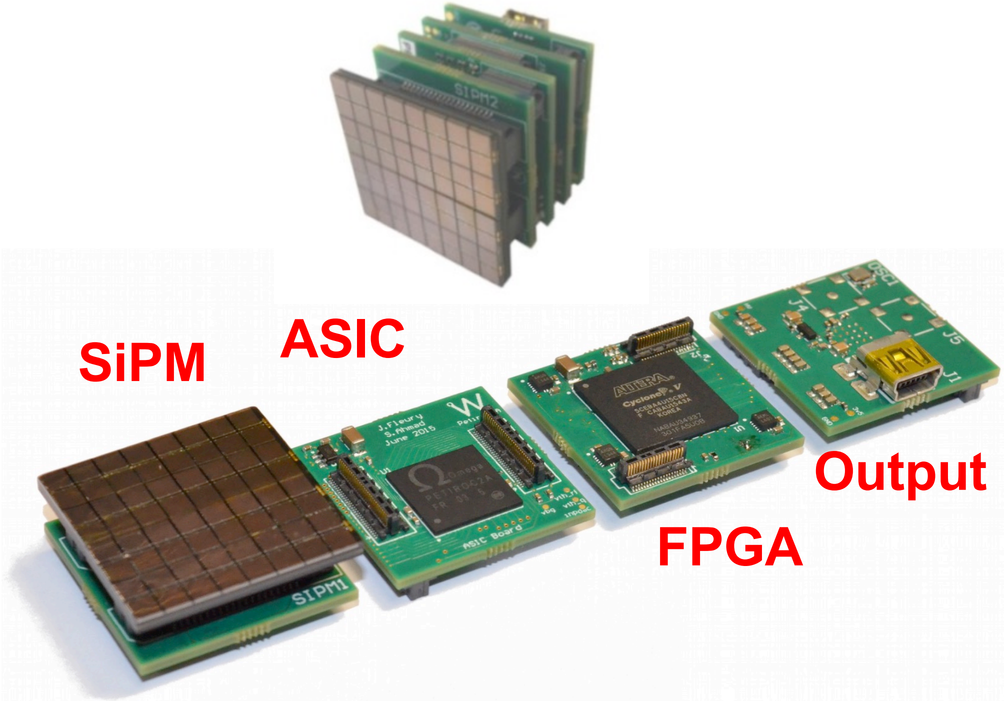


Femm study

Photon Detection and Readout

- Staggered SiPM readout to avoid cross-talk
- Small-pitch SiPM needed for scintillation light
- Compact readout electronics with stacked structure
- 8 fibers/channel → 5.6 mm granularity, 25 M channels





Summary

- PFA Concept
  - ECAL: 30 layers, W, 24 X_0
    - 10mm*10mm Si pads; 5mm*45mm scintillator strips
  - HCAL: 40 layers, Fe, 5 λ_I
    - SDHCAL: 1cm*1cm;   gRPC, THGEM
    - AHCAL: 3cm*3cm;   scintillator tiles + SiPM
- Dual readout concept
  - Cu/Fe, 10 λ_I
  - Scintillation fibers + quartz fibers