Study of SiW-ECAL and SDHCAL for CEPC

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On Behalf of CEPC Calorimeter Working Group

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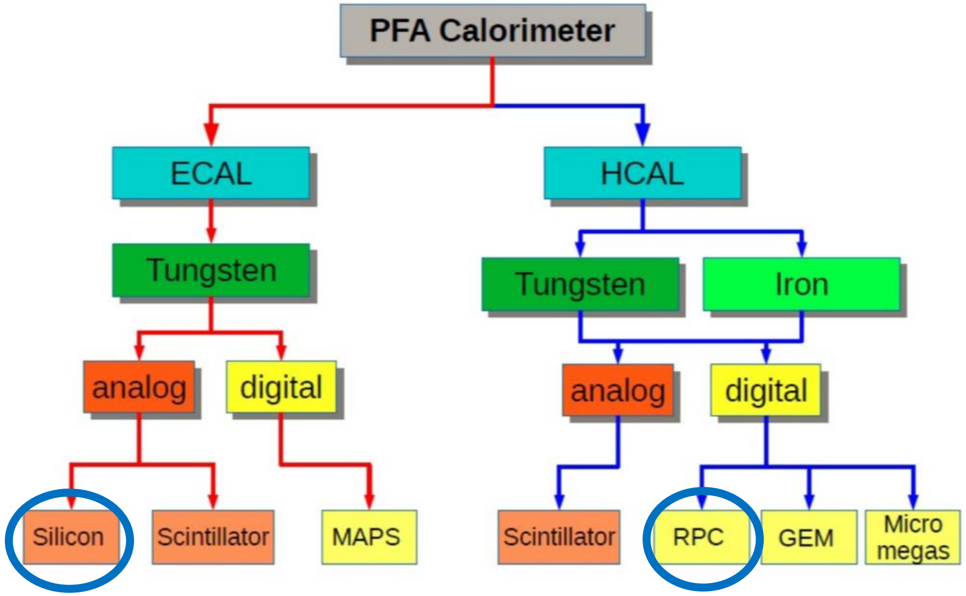
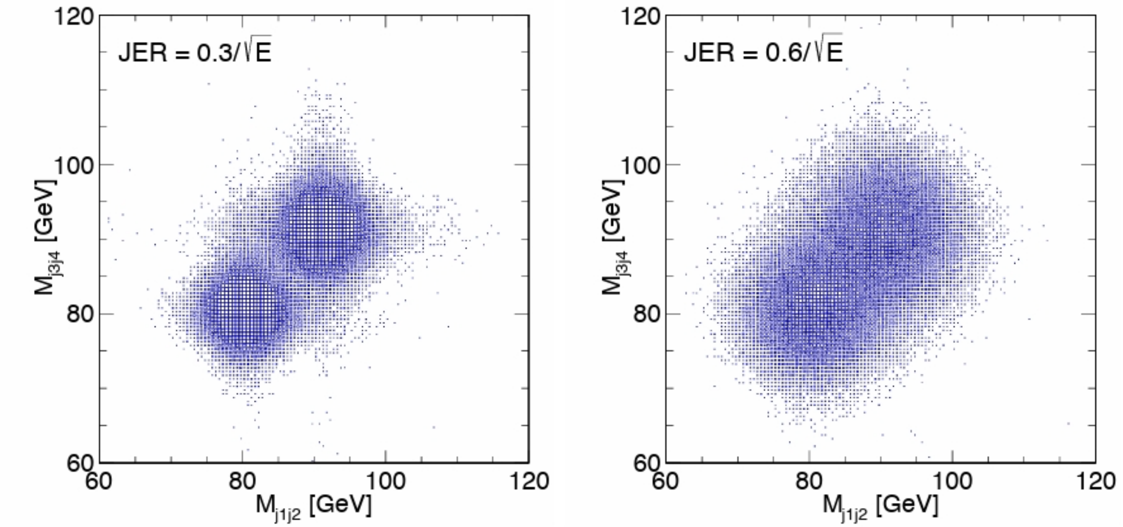
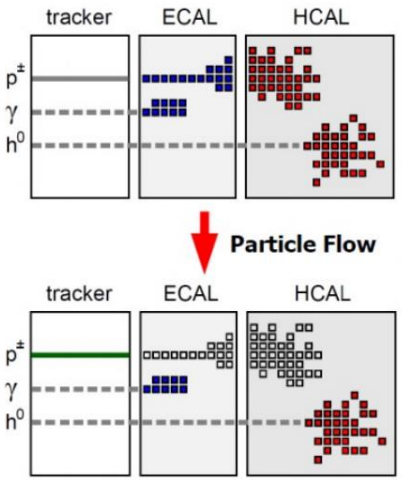
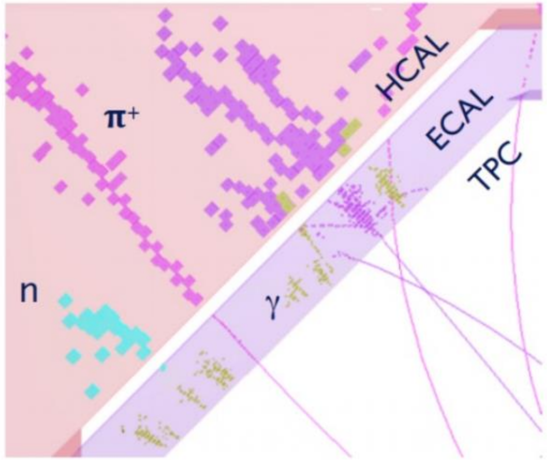
Introduction

- CEPC: future circular lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - PFA calorimeter: promising to achieve 3-4% jet resolution
- PFA Calorimeter





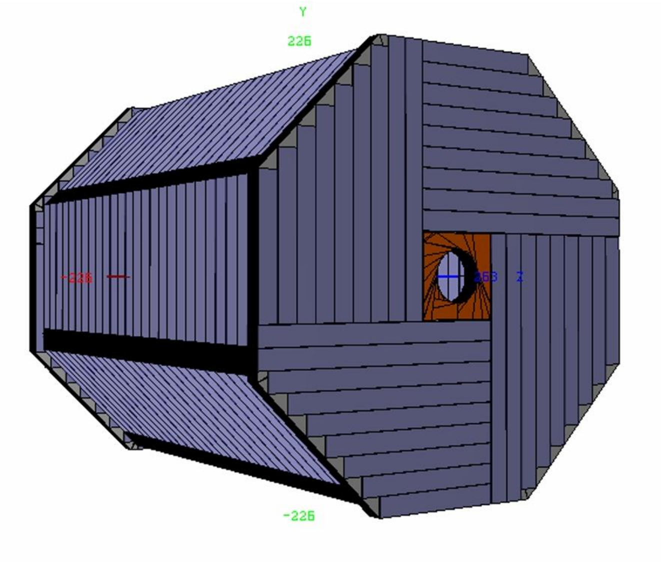


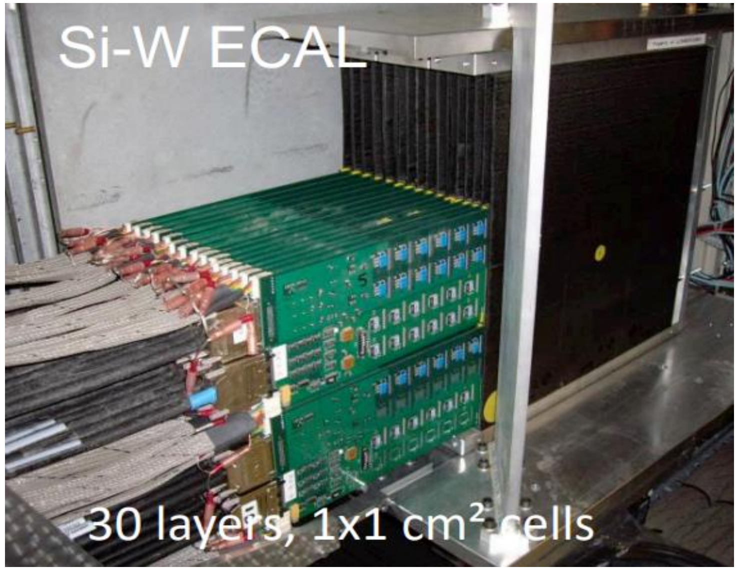


Calorimeters Designs for CEPC

Si-W ECAL

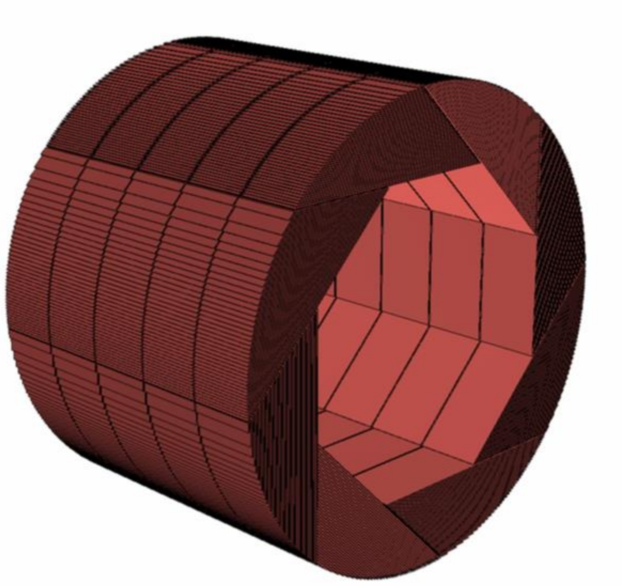
- Baseline design
- Sampling structure
- High granularity (1x1 cm^2)
- Strong shower separation

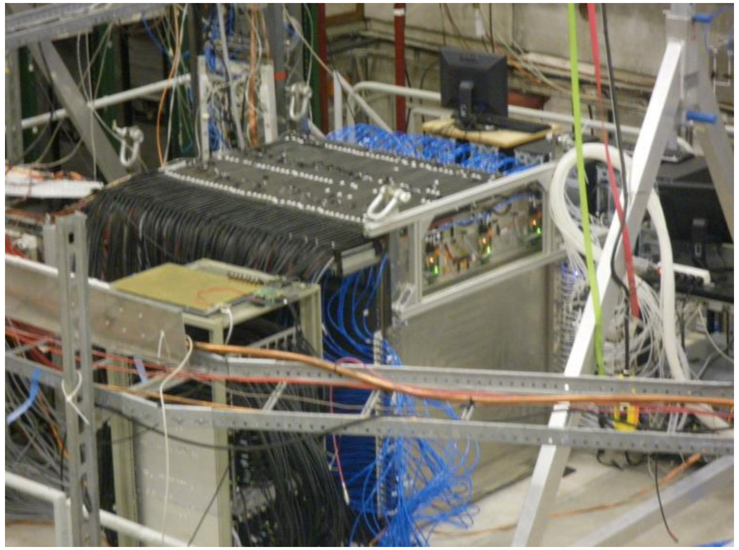




Semi-DHCAL (SDHCAL)

- High granularity (1x1 cm^2)
- Three thresholds readout
- Self-supporting mechanical structure as steel absorber

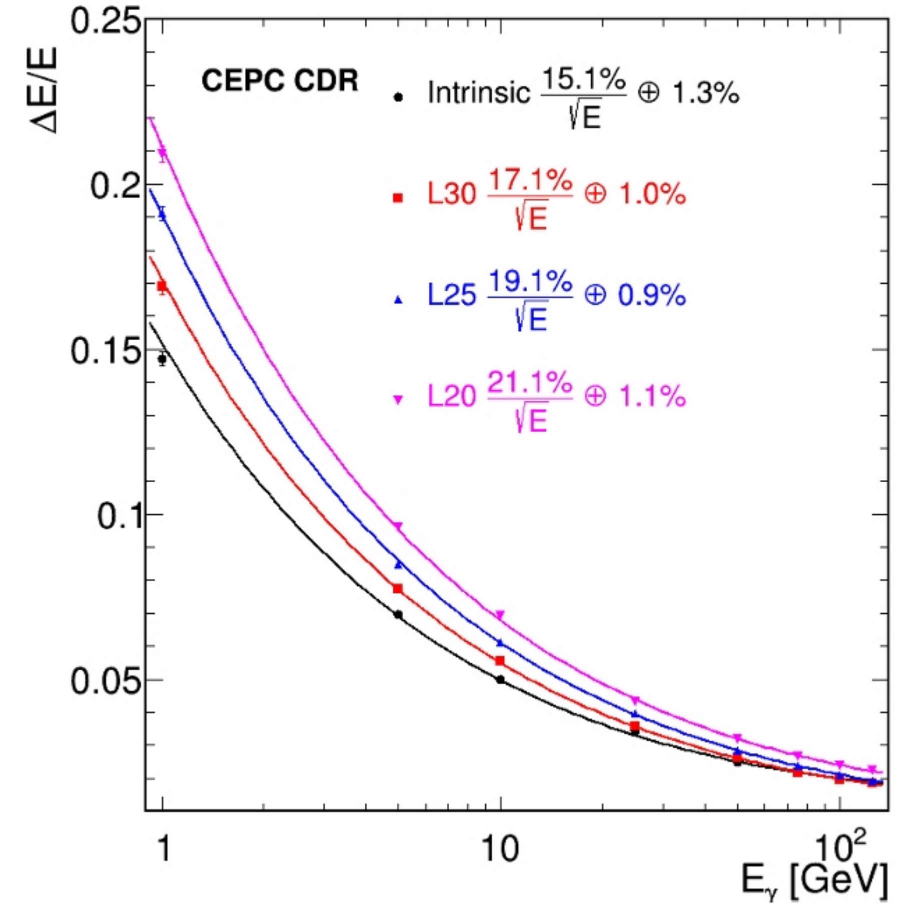


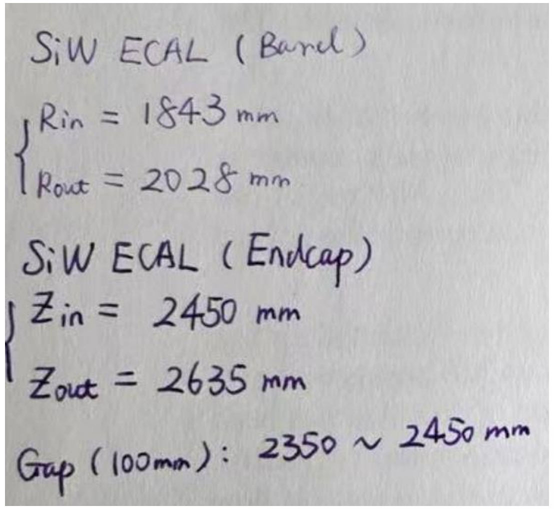


JINST 10 (2015) P10039, JINST 11 (2016) P06014
JINST 15 (2020) P10009, JINST 17 (2022) P07017

Performance of SiW-CAL

- Photon energy resolution vs sampling layers
- Silicon sensor thickness: 500 microns
- Dijet mass resolution: 3.75% for ννH→ννgg





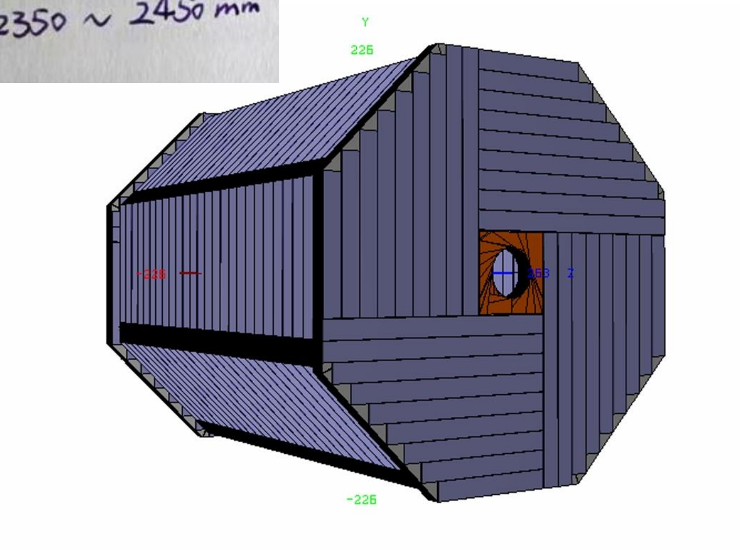


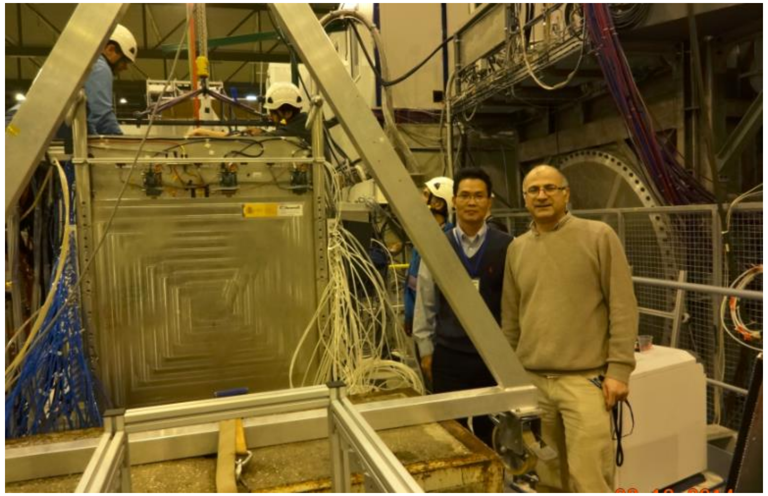
Figure 5.6: Schematic of the CEPC ECAL layout in its baseline design. The ECAL is organized into one cylindrical barrel and two disk-like endcap sections, with 30 layers in each section. The barrel section is arranged into 8 staves, each consisting of 5 trapezoidal modules. Each of the two endcap sections is made of four quadrants, each consisting of 2 modules. The ECAL barrel overall radius is 2028 mm in X-Y plane, the two endcaps are located at ±2635 mm.

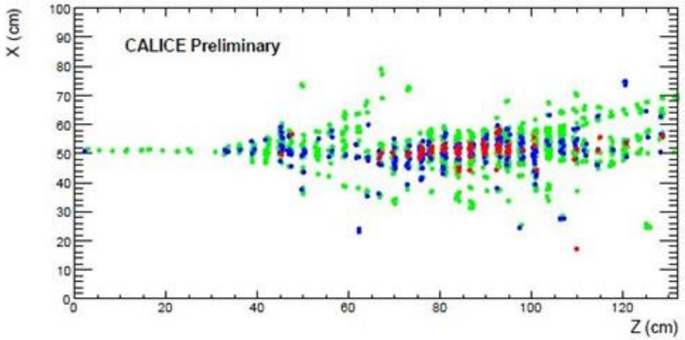
Performance of SDHCAL

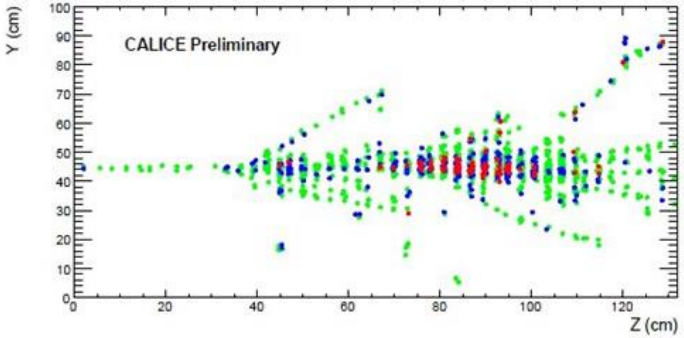
JINST 11 (2016) P04001

- DHCAL ($1m^3$), TB at FNAL/CERN

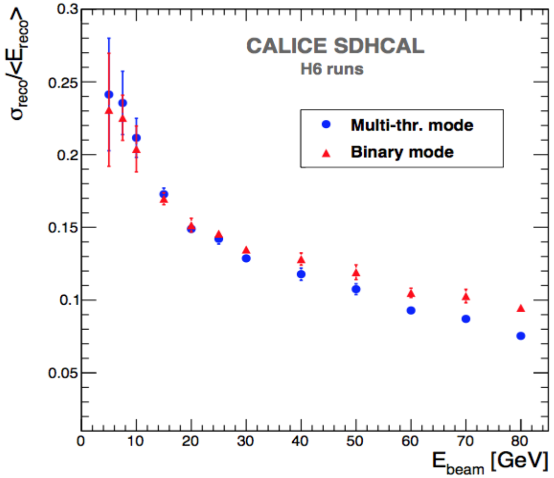
- SDHCAL ($1m^3$), 3 thresholds, TB at CERN

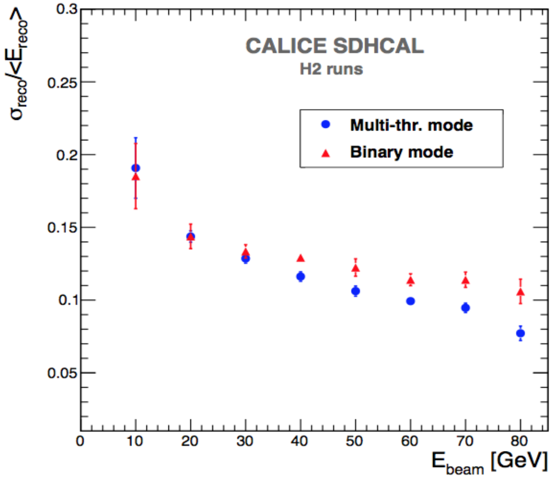






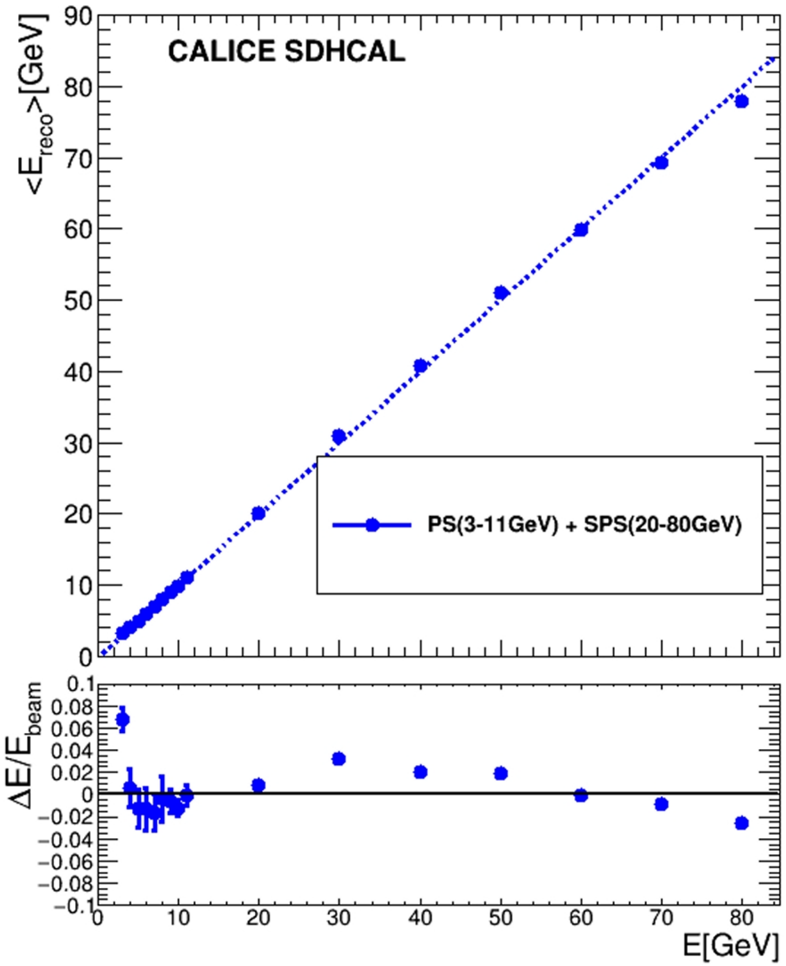
80 GeV Pion

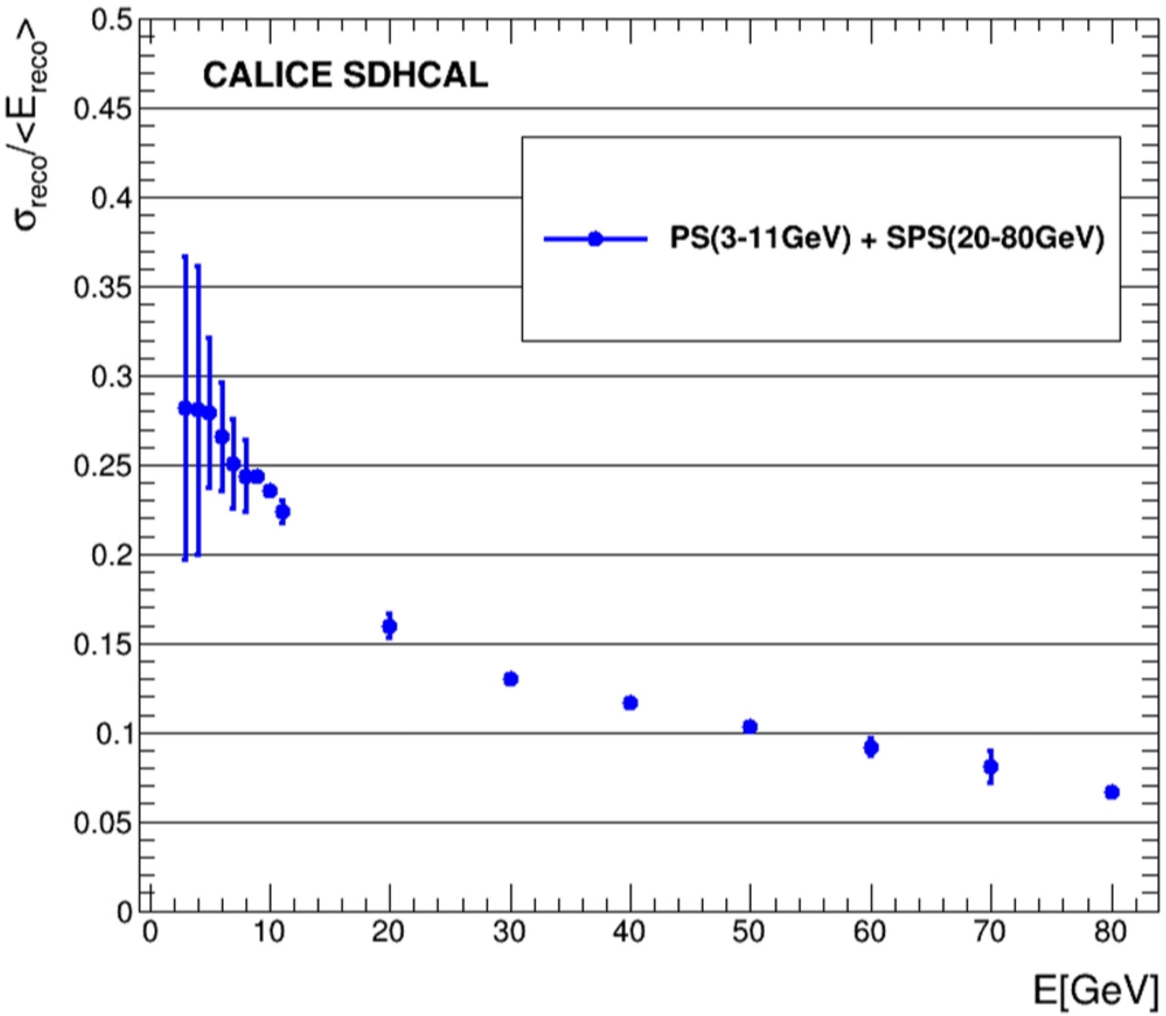




Performance of SDHCAL

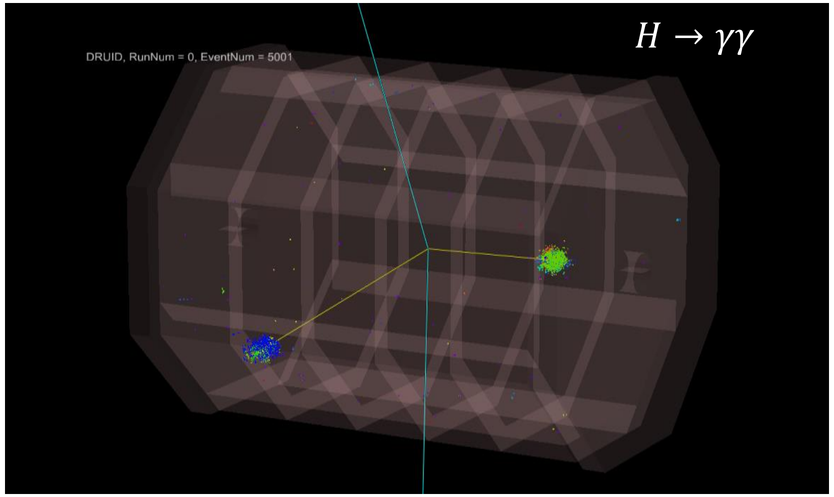
JINST 17 (2022) P07017



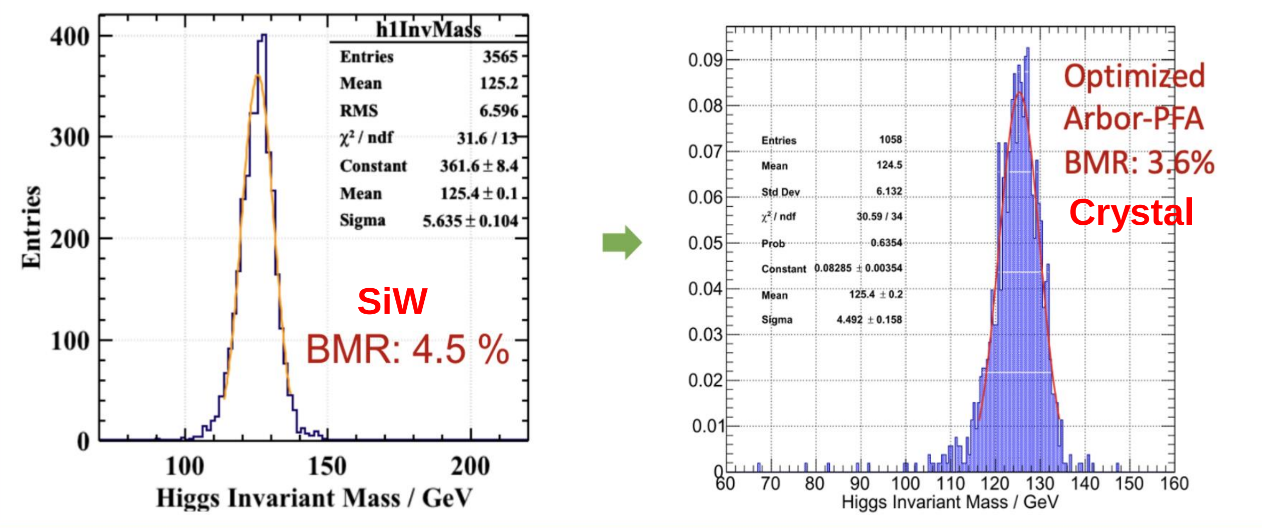


Performance Comparison: BMR

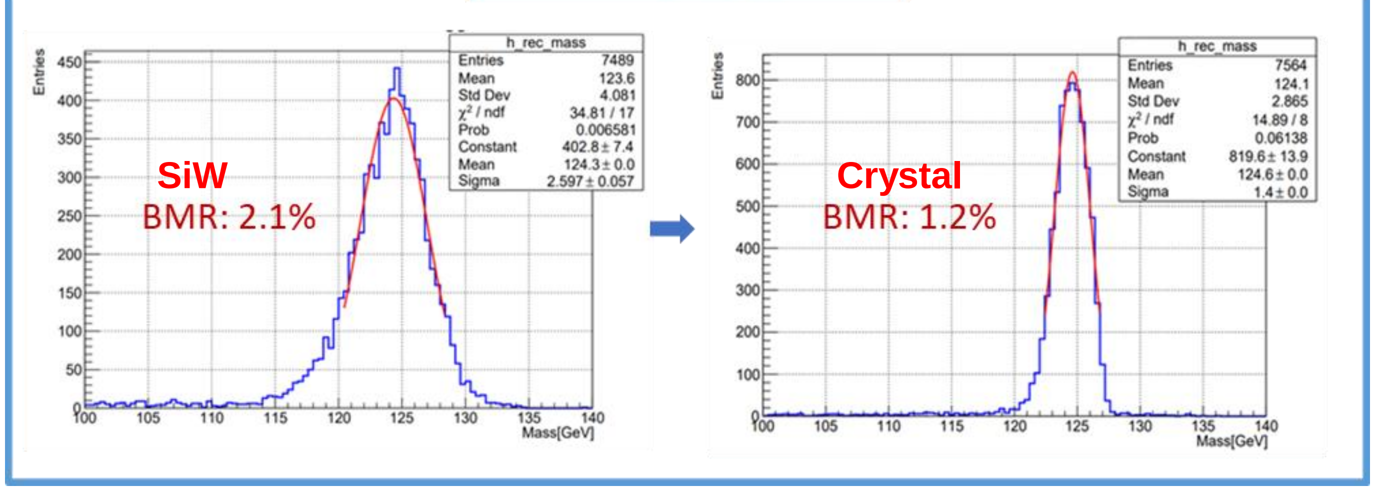
- Higgs boson mass resolution(BMR) improvement:
  - $H \rightarrow gg$: 4.5% → 3.6%
  - $H \rightarrow \gamma\gamma$: 2.1% → 1.2%
- Better BMR with crystal ECAL



BMR ($H \rightarrow gg$)



BMR ($H \rightarrow \gamma\gamma$)

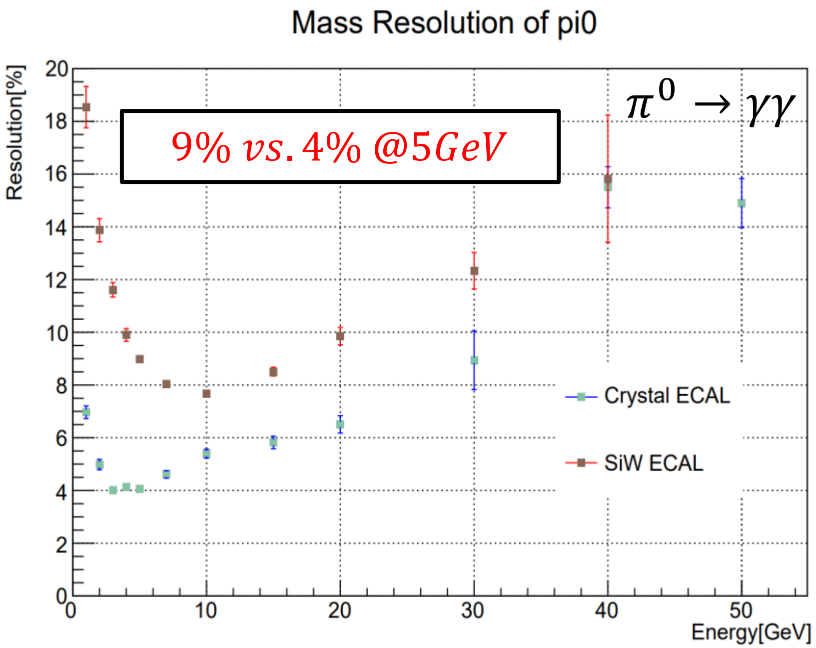


ECAL Performance Comparison : π^0/γ Reconstruction

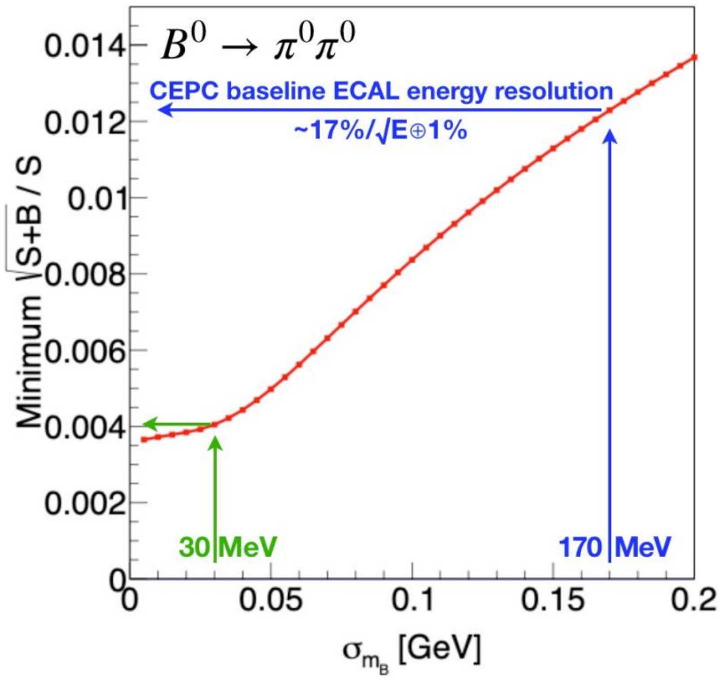
- $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ measurement
  - Necessary channel to determine CKM angle α
  - ECAL performance can be characterized by σ_{m_B}
- Crystal ECAL: more potentials for π^0/γ reconstruction (flavor physics)

	ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
SiW	$17\%/\sqrt{E}\oplus 1\%$	170	~ 1.2%	~ 21%
Crystal	$3\%/\sqrt{E}\oplus 0.3\%$	30	~ 0.4%	~ 4%

3 ~ 5 times improvement



$$\frac{\delta m_0}{m_0} = \frac{\delta E_1}{2E_1} \oplus \frac{\delta E_2}{2E_2} \oplus \cot\frac{\alpha}{2}\frac{\delta\alpha}{2}$$



B0 to pipi @CEPC(CEPC Flavor Physics/New Physics/Detector Technology Workshop, Fudan, 2023), Yuexin Wang

Summary

➢ Down-select criteria for calorimetry system: performance

Category	Items	SiW ECAL + SDHCAL
Performance	Boson Mass Resolution (BMR) < 4%	BMR ~ 3.75% (ννH→ννgg) BMR ~ 2.1% (H → γγ)
	PID in jets: lepton ID and precision	Lepton ID: TBD;
	Timing Resolution	~ ns (SKIROC2A, 5mW/ch) ~ ns (HARDROC2, 1.4mW/ch) 20-30ps (HGCROC, CMS) 40-50ps (PETIROC with MRPC)
	EM energy resolution	~17%/ √ E ⊕ 1% (SiW ECAL)
	Hadron energy resolution	~ 68% / √ E ⊕ 1% (SDHCAL)
	π^0 → γγ reconstruction	Simulation studies
	Granularity	1 x 1 cm^2; 1 x 1 cm^2
	Pile-up at Z-pole	TBD

No. of Channels of SiW ECAL and SDHCAL

- ECAL Barrel, R_{in} = 1.9m, R_{out} = 2.1m, Length = 6.1m, N_{layer}=30
  Active Area of ECAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 2300 m^2
- ECAL Endcap (2), R_{in} = 0.35m, R_{out} = 2.1m, N_{layer}=30
  Area of HCAL endcap = $2*PI*(R_{out}*R_{out} – R_{in}*R_{in})*N_{layer}$ = 808 m^2

- HCAL Barrel, R_{in} = 2.15m, R_{out} = 3.45m, Length =6.3m, N_{layer}=40
  Area of HCAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 4433 m^2
- HCAL Endcap (2), R_{in} = 0.35m, R_{out} = 3.45m, N_{layer}=40
  Area of HCAL endcap = $2*PI*(R_{out}*R_{out} – R_{in}*R_{in})*N_{layer}$ = 2961 m^2

ECAL Active Area: 3108 m2 → 31.1 M (1x1 cm^2 cell)
HCAL Active Area: 7394 m2 → 73.9 M (1x1 cm^2 cell)

Cost Estimation

- Reference of ILD cost estimation (TDR, V4, P306)

Item		Unit cost	Cost ($)
Tungsten	168 tons	$123/kg	20.7M
Carbon fiber			2.1M
Silicon sensor	3110 m^2	$3/$cm^2$	93.3M
Readout ASIC			16.5M
Readout Board			21.0M
Materials, Cables, connectors			3.5M
Tooling			9.3M
Assembly			13.5M
Integration			0.5M
Sum			180.4M

Material	Cost [ILCU]	System	Comment
Tungsten	123/kg	SiECAL, ScECAL, AHCAL, FCAL	quote from manufacturer (130 EUR/kg)
Stainless Steel	5/kg	AHCAL, SDHCAL	processing costs to be added (1-4 EUR/ kg)
Si sensors	3/cm^2	SiECAL	based on extrapolation of current quotation of 5 EUR/ cm^2
SiPM	1/pc	ScECAL, AHCAL, muon	based on manufacturer extrapolation, current price 7-10 EUR/piece
ASIC	0.22-0.25/ch	SiECAL, ScECAL, AHCAL	current price 0.5 EUR/ch
ASIC	0.1/ch	SDHCAL	current price of 0.18 EUR/ch
PCB	7900/m^2	SiECAL	prototype
PCB	2600/m^2	ScECAL	extrapolated from prototype price of 10800/m^2
PCB	1800/m^2	SDHCAL, AHCAL	for AHCAL extrapolated from prototype price of 10800/m^2

SiECAL		ScECAL	
Item	Cost [kILCU]	Item	Cost [kILCU]
Tungsten	16310	Tungsten + carbon parts	18500
Carbon fiber structure	2130	Module realisation	1700
Silicon sensors	75000	Scintillators	1030
Readout ASIC	16500	Photo Detectors	10200
Readout Board	21000	Readout ASIC	2500
Materials	1300	Readout Board	25000
Cables, connectors	2220	Readout System	6200
Tooling	9300	Cables, connectors	1000
Assembly	13500	Power supplies	4100
Integration	500	Tooling	3800
Sum SiECAL	157760	Sum ScECAL	74000

Cost of SDHCAL (Active layers)

Unit Cost: ~ 42K RMB/m^2 (for 1x1 cm^2)
~ 30K RMB/m^2 (for 3x3 cm^2)

SDHCAL: 7394 m^2 ➔ 310M RMB
➔ 222M RMB

Absorber (148 m^3) ➔ 74M RMB

Total Cost (RMB): 384M vs 296M

Parts	Unit Price (RMB)	Quantity	Total (RMB)
Glass	150 / m^2	2	300
Resistive Paint	1 / g	100	100
Frame	10 / m	4	40
Spacers	1	81	81
Spacer Glue	3.3 / g	30	100
Gas Connector	20	2	40
HV contacts	80 / m	0.1	8
HV connectors	50	2	100
Total cost of 1m^2 GRPC			769

Parts	Unit Price (Euro)	Quantity	Total(Euro)
Cassette plates	8 /kg	50	400
Plate machining	200	1	200
Cassette walls	8 / kg	0.8	6.4
Mylar foils	15 / m^2	2	30
Silicone glue	0.3 / ml	60	18
Bolts M2	0.02	60	1.2
Total cost of 1m^2 cassette			655.6
Readout Electronics	Unit Price (Euro)	Quantity	Total (Euro)
ASIC (64 channels)	11.5	144 (9216)	1656
ASU:PCB (8-layer)	300	6	1800
DIF (detector interface DAQ card)	285	3	855
ASU-ASU connector	11	6	66
DIF-ASU	40	3	120
Total cost for readout electronics			4497

Backup

No. of Channels of HCAL

Cell Size \ channels	HCAL Barrel	HCAL Endcap	Channels (N_{ch})	Power AHCAL	Power SDHCAL
1cm x 1cm	43.3M	33.48M	76.78M		
2cm x 2cm	1.157M	8.37M	19.19M		
3cm x 3cm	4.2M	3.08M	7.3M		
4cm x 4cm	2.36M	1.73M	4.1M		

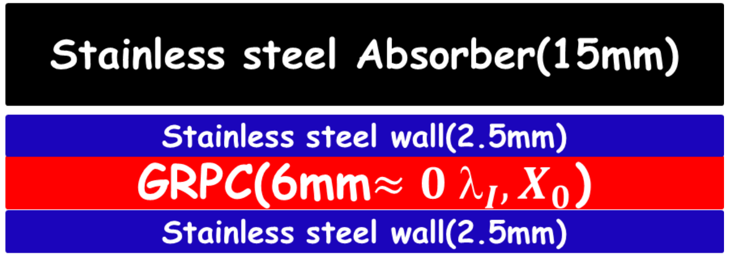
Power Consumption (rough estimation):

AHCAL: 7mW/ch $*$ N_{ch3} + 9W/DIF/m^2 $*$ 7678 (69.1kW)

SDHCAL: 1.4mW/ch $*$ N_{ch1} + 5.4W/DIF/m^2 $*$ 7678 (41.5kW)

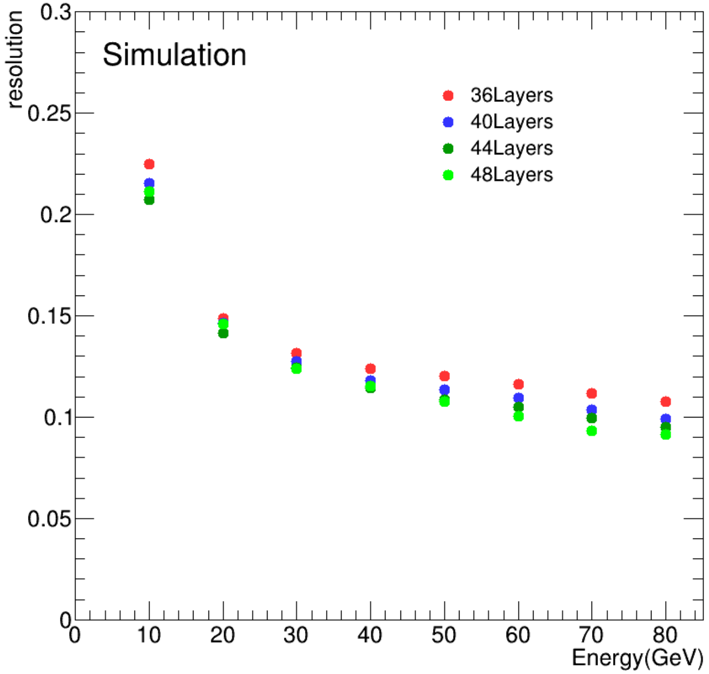
Electronics Channels and Power

$(0.12\lambda_I, 1.14X_0)$



➔SDHCAL has 48 layers which aims for ILC Detector
each layer: 6mm gRPC + 20mm absorber

➔48-layer ~ 5.76 λ_I

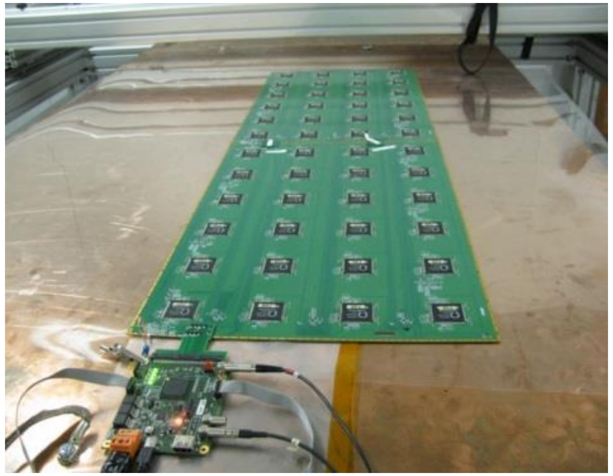


➔ $1m^2$ RPC needs 6 PCBs, each PCB has 1536 ch (24 ASIC chips)

➔ Each ASIC chip (Hardroc) has 64 channels, size 4.3mm*4.7mm

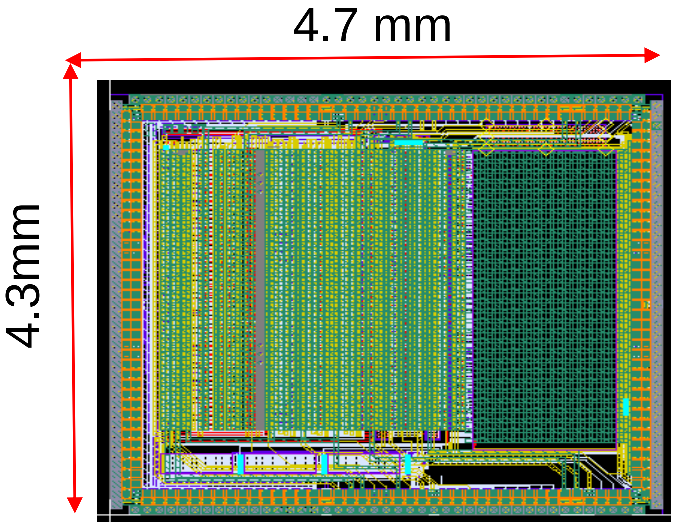
➔ ASIC Power: 1.4mW/ch * 64 ch = 90 mW/Chip

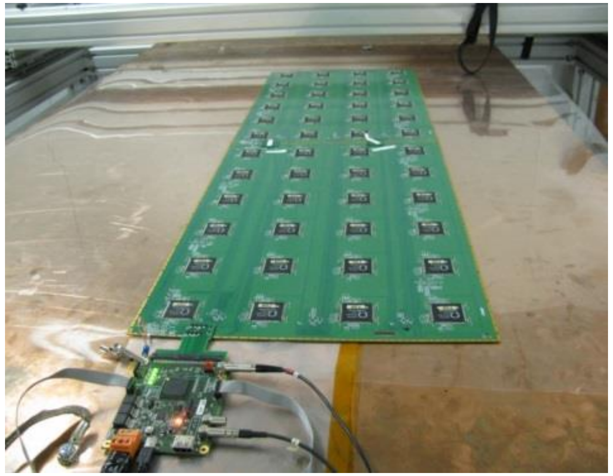
➔ Power: 1.4mW/ch * 9216 ch (6*24*64) = 13 W/m^2



Readout Electronics for RPC

ASICs : HARDROC2
64 channels
Trigger less mode
Memory depth : 127 events
3 thresholds
Range: 10 fC-15 pC
110fC, 5pC, 15pC
Gain correction → uniformity





Printed Circuit Boards (PCB) were designed to reduce the cross-talk with 8-layer structure and buried vias.

Tiny connectors were used to connect the PCB two by two so the 24X2 ASICs are daisy-chained. $1\times1m^2$ has 6 PCBs and 9216 pads.

DAQ board (DIF) was developed to transmit fast commands and data to/from ASICs.