Study of SiW-ECAL and SDHCAL for CEPC

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On Behalf of CEPC Calorimeter Working Group

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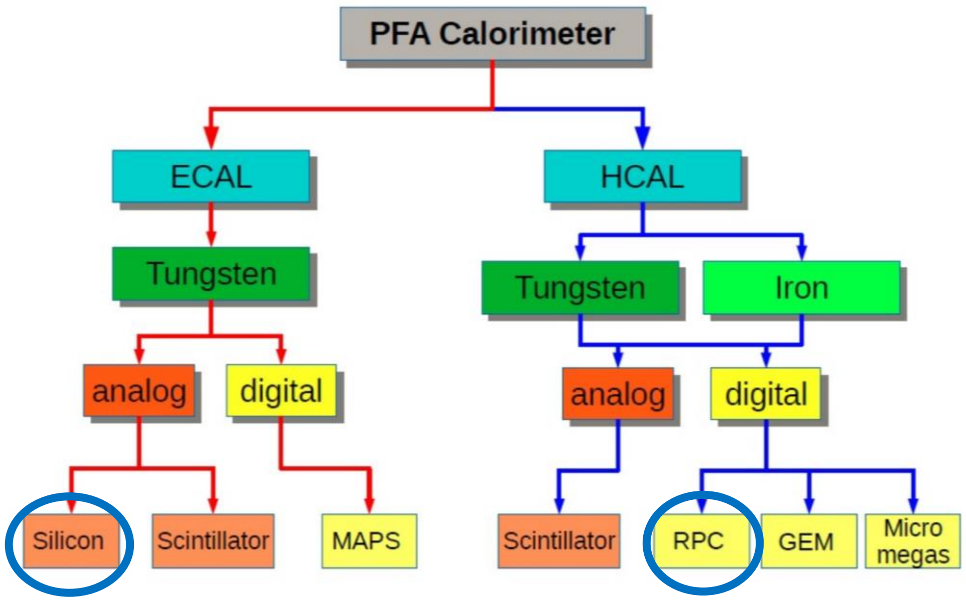
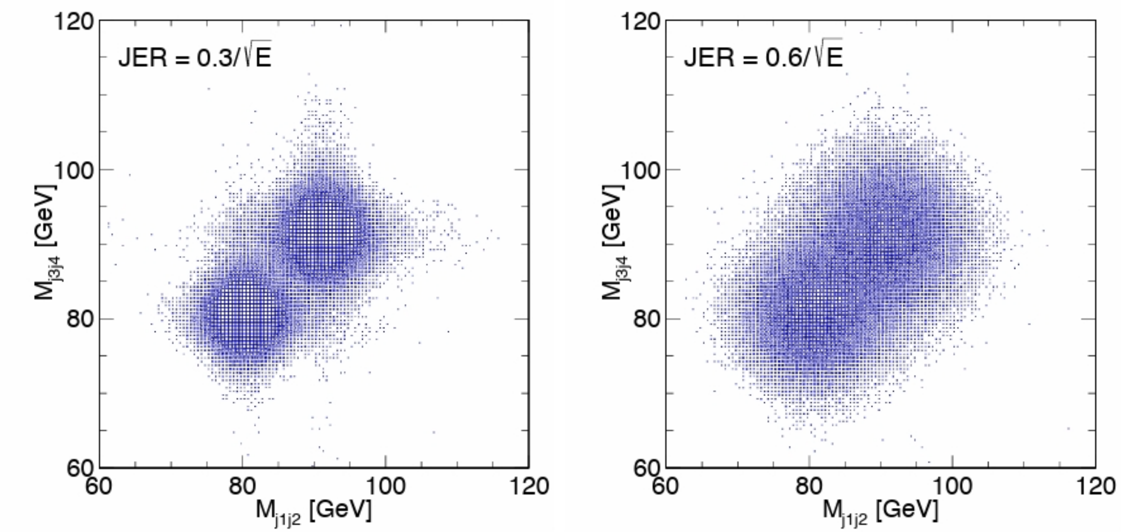
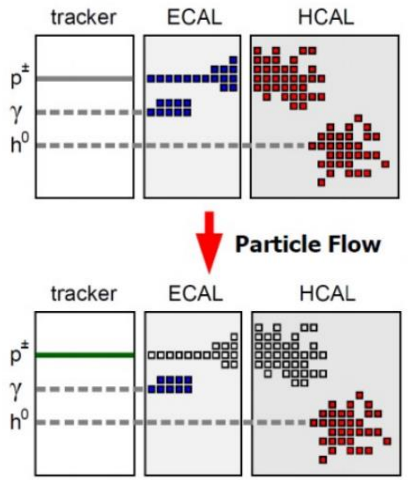
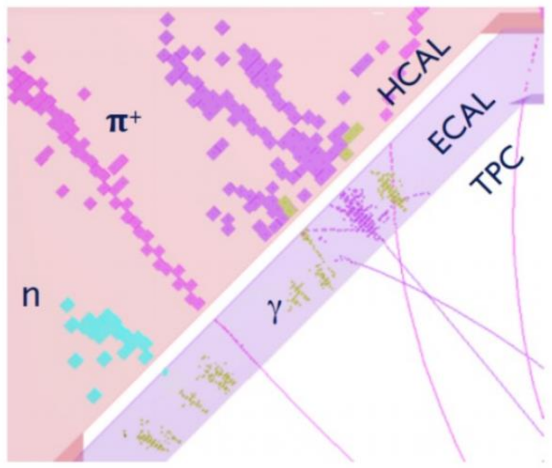
Introduction

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





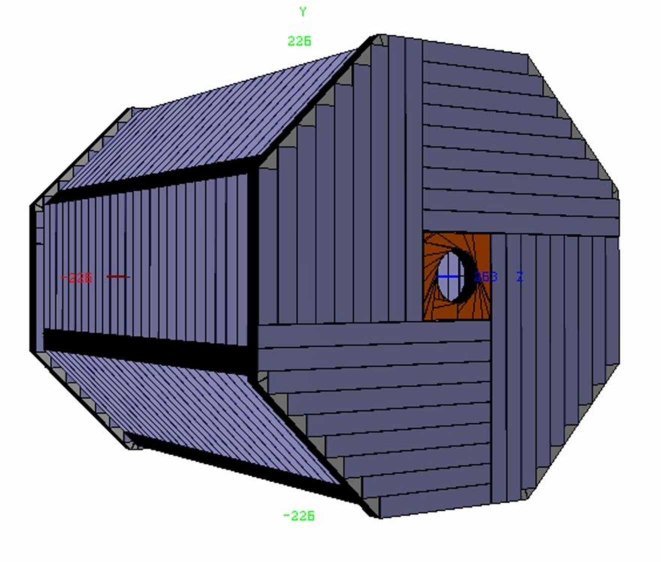


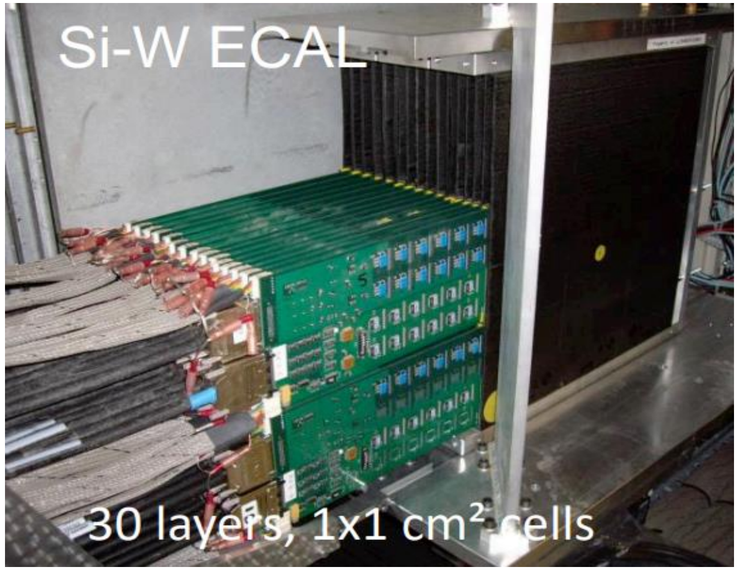


Calorimeters Designs for CEPC

Si-W ECAL

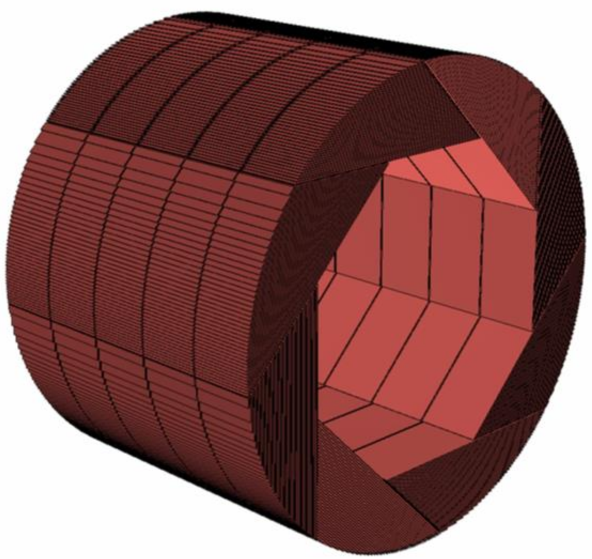
- Baseline design
- Sampling structure
- High granularity (1x1 cm^2)
- Strong shower separation

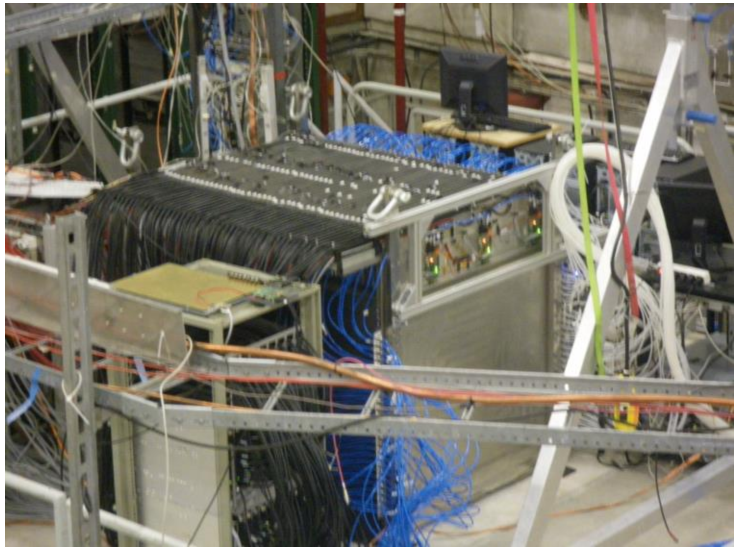




Semi-DHCAL (SDHCAL)

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

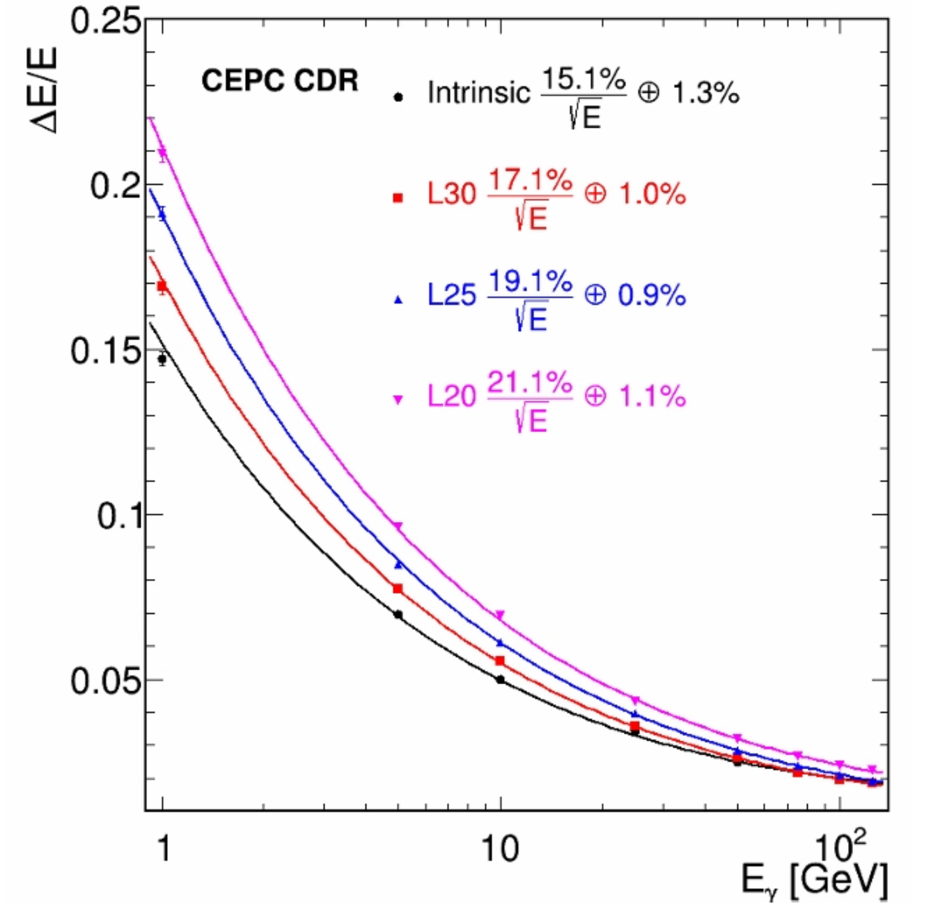


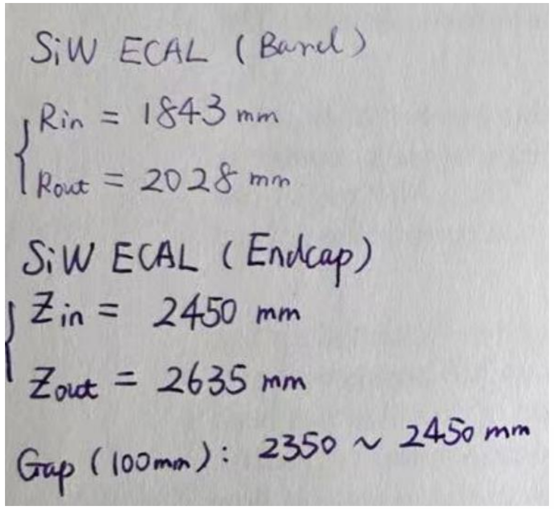


JINST 10 (2015) P10039, JINST 11 (2016) P06014
JINST 15 (2020) P10009, JINST 17 (2022) P07017

Performance of SiW-CAL

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





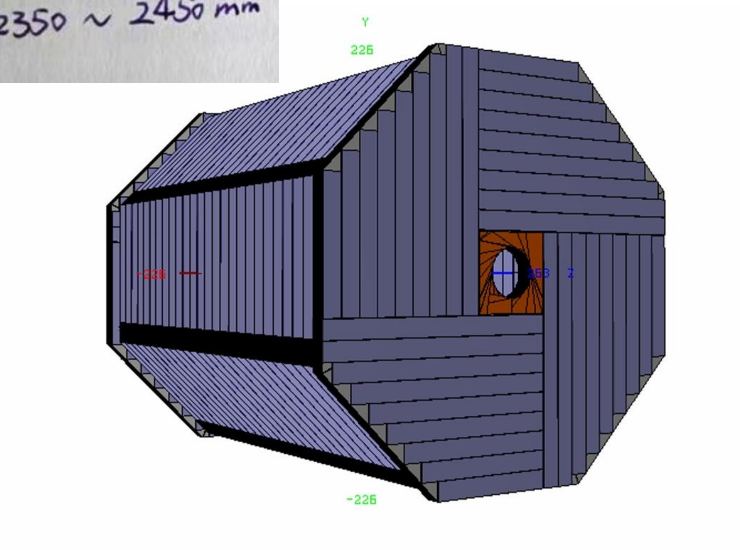


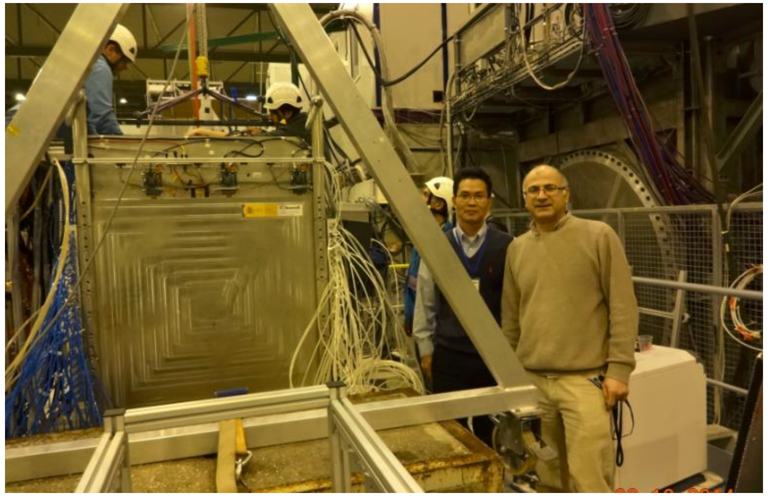
Figure 5.6: Schematic of the CEPC ECAL layout in its baseline design. The ECAL is organized into one cylindrical barrel and two disk-like endcap sections, with 30 layers in each section. The barrel section is arranged into 8 staves, each consisting of 5 trapezoidal modules. Each of the two endcap sections 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.

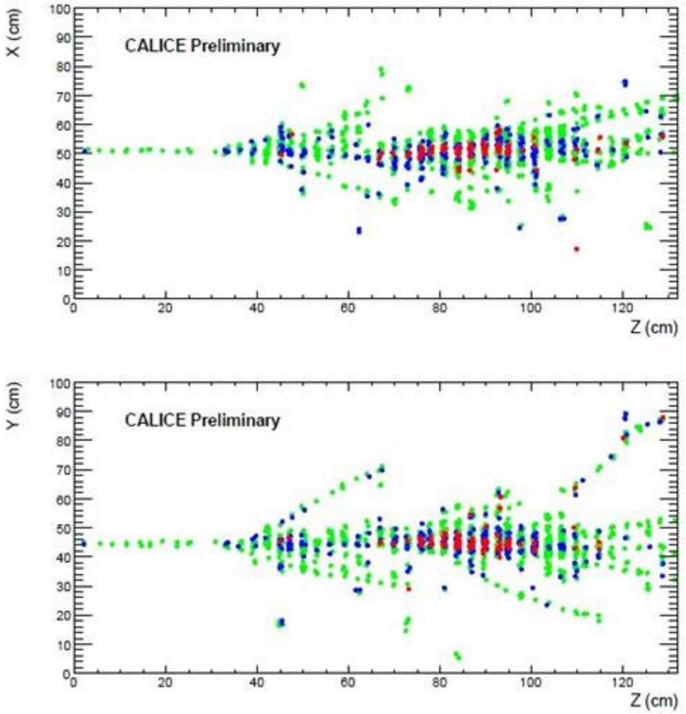
Performance of SDHCAL

JINST 11 (2016) P04001

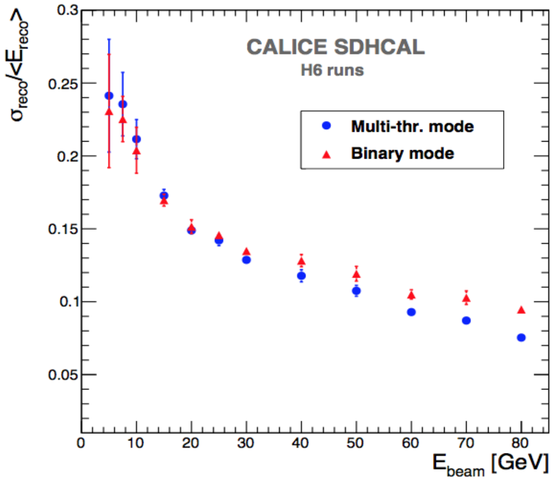
- DHCAL ($1m^3$), TB at FNAL/CERN

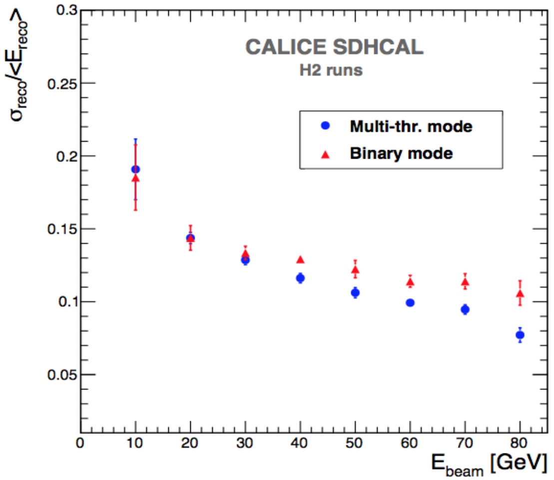
- SDHCAL ($1m^3$), 3 thresholds, TB at CERN





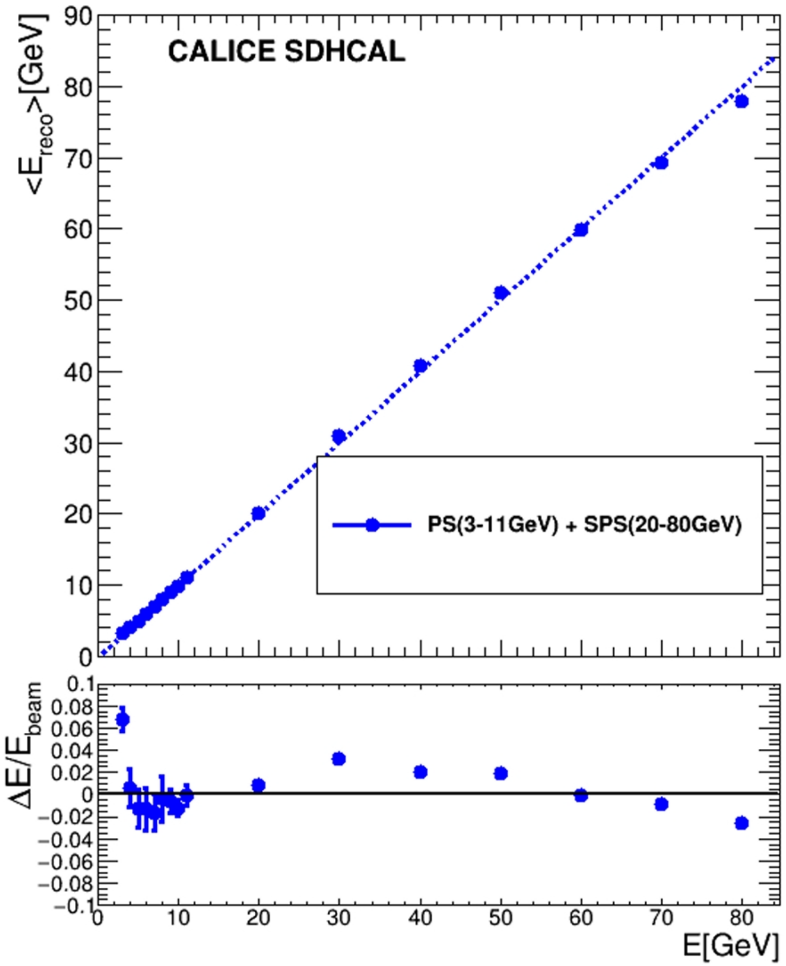
80 GeV Pion

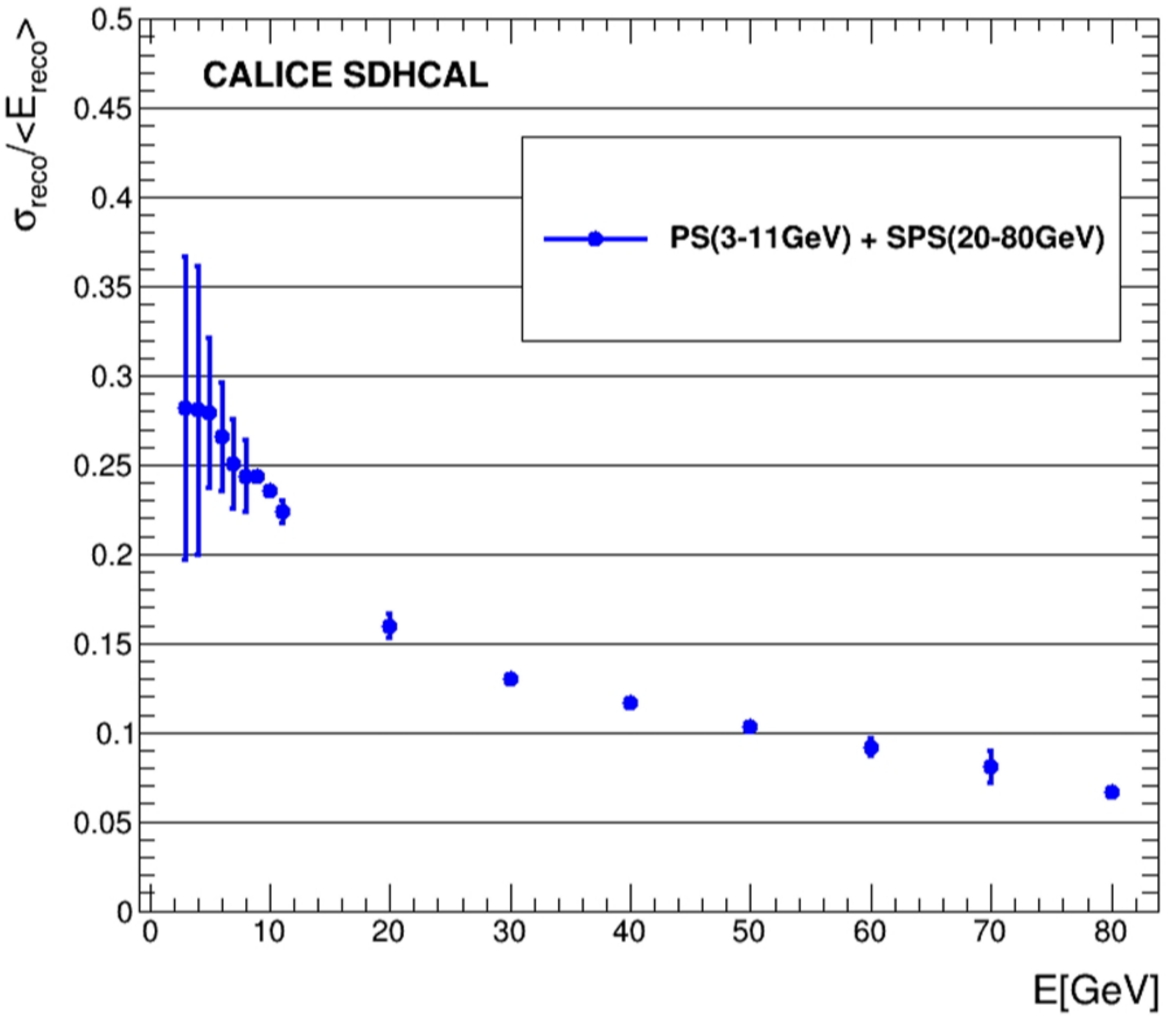




Performance of SDHCAL

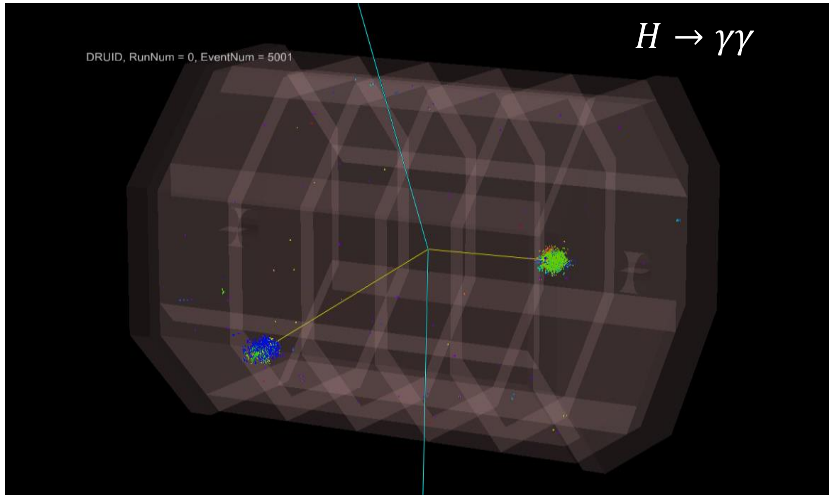
JINST 17 (2022) P07017





Performance Comparison: BMR

- Higgs boson mass resolution(BMR) improvement:
  - $H \rightarrow gg$: 4.5% → 3.6% (full sim + Arbor rec.)
  - $H \rightarrow \gamma\gamma$: 2.1% → 1.2% (fast sim.)
- Better BMR with crystal ECAL



Chinese Physics C Vol. 43, No. 2 (2019) 023001

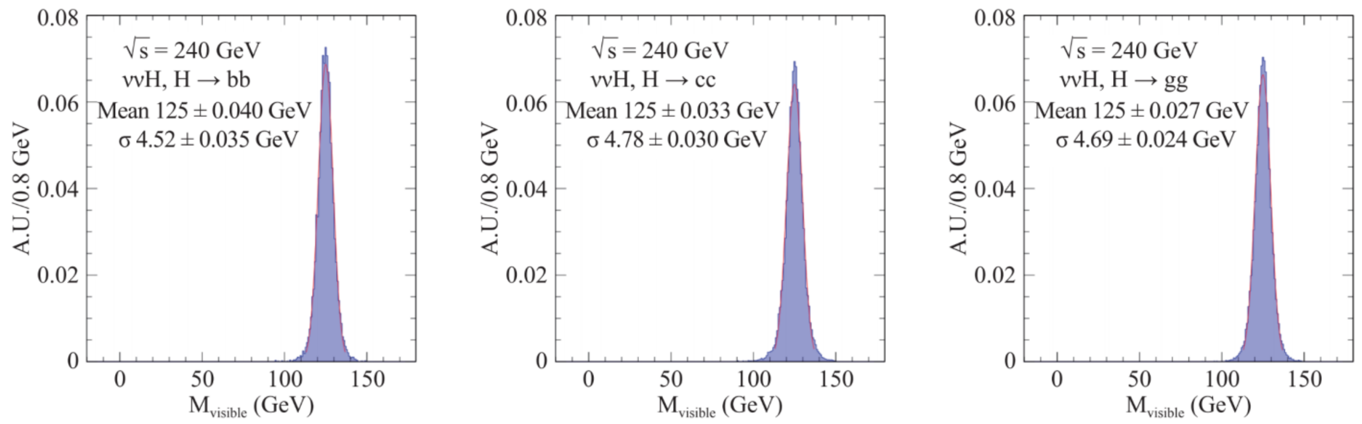
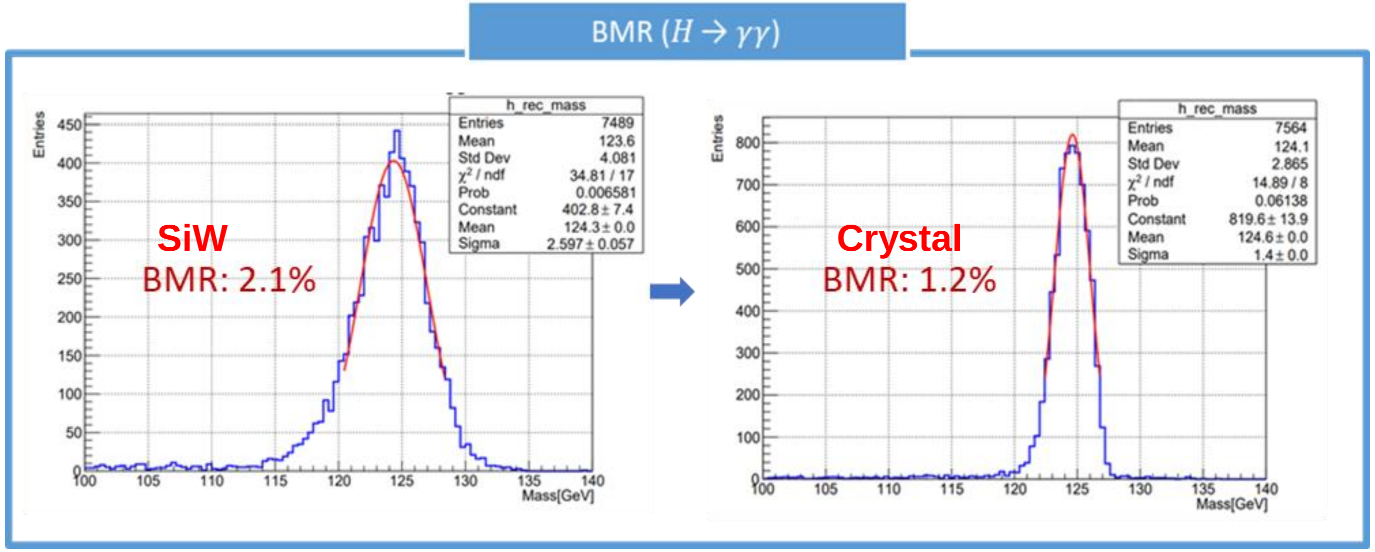


Fig. 8. (color online) Distributions of the reconstructed total visible invariant mass for $H \rightarrow bb, cc, gg$ events after event cleaning and fitted by Gaussian functions. The resolutions (sigma/mean) of the fitted results are 3.63% (bb), 3.82% (cc), and 3.75% (gg).

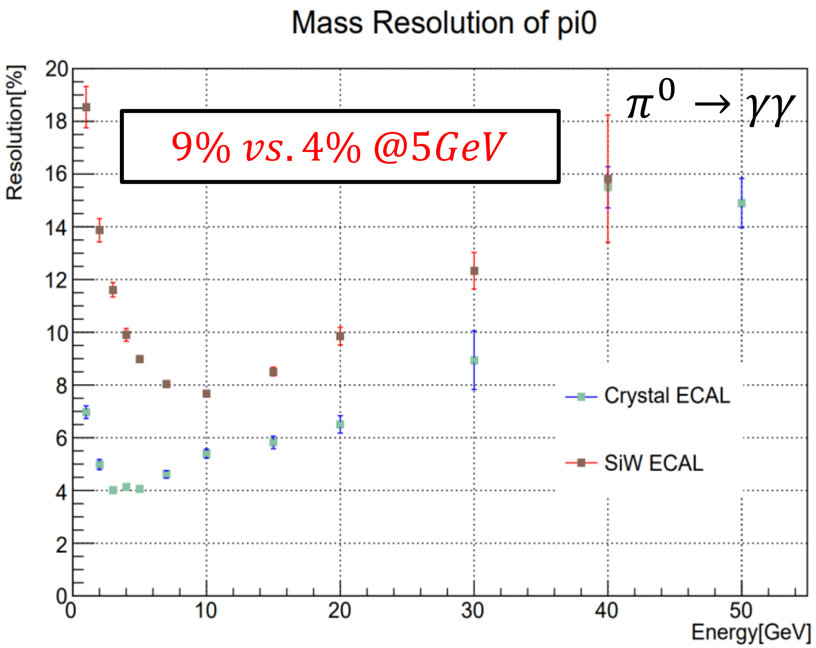


ECAL Performance Comparison : π^0/γ Reconstruction

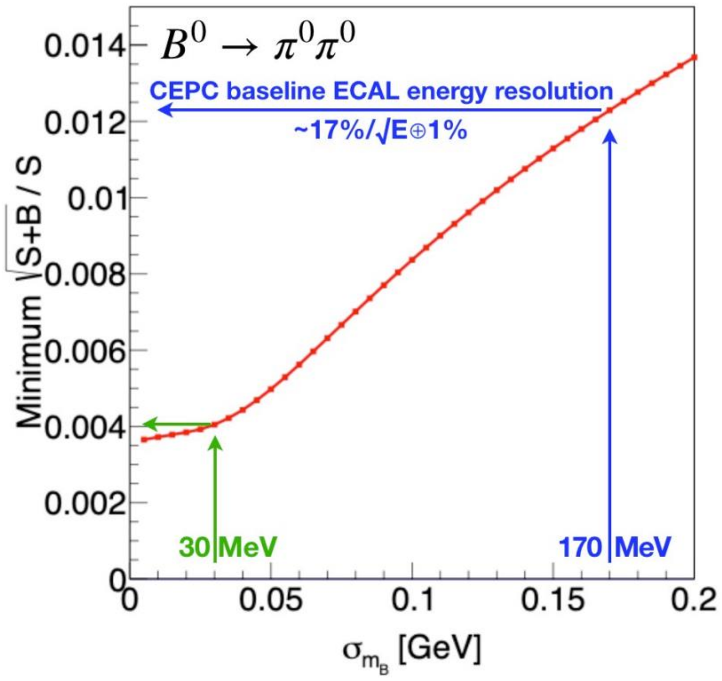
- $B^0 \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ measurement
  - Necessary channel to determine CKM angle α
  - ECAL performance can be characterized by σ_{m_B}
- Crystal ECAL: more potentials for π^0/γ reconstruction (flavor physics)

	ECAL Resolution	σ_{m_B} (MeV)	$B^0 \rightarrow \pi^0\pi^0$	$B^0_s \rightarrow \pi^0\pi^0$
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

No. of Channels of SiW ECAL and SDHCAL

- ECAL Barrel, R_{in} = 1.9m, R_{out} = 2.15m, Length = 5.9m, N_{layer}=30
  Active Area of ECAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 2252 m^2
- ECAL Endcap (2), R_{in} = 0.35m, R_{out} = 2.15m, N_{layer}=30
  Area of ECAL endcap = $2*PI*(R_{out}*R_{out} - R_{in}*R_{in})*N_{layer}$ = 848 m^2

- HCAL Barrel, R_{in} = 2.2m, R_{out} = 3.55m, Length =6.5m, N_{layer}=48
  Area of HCAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 5440 m^2
- HCAL Endcap (2), R_{in} = 0.4m, R_{out} = 3.55m, N_{layer}=48
  Area of HCAL endcap = $2*PI*(R_{out}*R_{out} - R_{in}*R_{in})*N_{layer}$ = 3753 m^2

ECAL Active Area: 3100 m2 → 31.0 M (1x1 cm^2 cell)
HCAL Active Area: 9193 m2 → 91.93 M (1x1 cm^2 cell)
→ 23M (2x2 cm^2) or 10.2M (3x3 cm^2)

Performance

Items	Priority	Results / Status	Remarks
Boson Mass Resolution	A	3.75% (ννH → ννgg) 2.1% (H→ γγ)	BMR < 4%
Intrinsic EM/hadronic energy resolution	A	SiW-ECAL: 17%/√E ⊕ 1% SDHCAL: 68%/√E ⊕ 1%	Test beam
Separation power		-	gamma/gamma, gamma/hadron, hadron/hadron
Lepton ID in jets		-	
Timing capability		~ ns	~ ns (SKIROC2A, 5mW/ch) ~ ns (HARDROC2, 1.4mW/ch)
π^0 reconstruction		14% @ 2 GeV 9.0% @ 5 GeV 7.5% @ 10 GeV	simulation
Pile-up at Z-pole			Granularity:1cm x 1cm

Cost (SiW-ECAL)

ILD TDR, V4, P306

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	350 mm	NA
Length for barrel	5900 mm	1900 mm + $24X_0$	NA
Longitudinal Depth	$24X_0$ (Thickness depends on each option)		NA
Modularity	#modules in phi, #rings along Z	Assuming ideal geometry if no design?	NA
Material Volume (m^3) Tungsten (2.8mm/layer, $123/kg)	6.3	2.4	8.7 m^3 168 t ($20.7M)
Cooper (1mm/layer, $10/kg)	2.25	0.85	3.1 m^3 ($0.3M)
Readout channels	22.5M (2252m2)	8.5M (848m2)	31.0M
Power dissipation (kW) 5mW/ch	112.6	42.4	155
Cost: sensitive materials Silicon sensor CHF3.5/cm2	78.82M	29.68	CHF 108.5M
Cost: electronics RMB15/ch	337.8M	127.2M	RMB 465
Subtotal	21M*7.2 + 108.5M*8 +465M = RMB 1484M		

Performance

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for HCAL	1900 mm + $24X_0$	400 mm	NA
Length for barrel; Outer radius for endcap*	6500 mm	1900 mm + $24X_0 + 6\lambda_I$	NA
Longitudinal Depth	$6\lambda_I$ (Thickness depends on each option)		NA
Modularity	#modules in phi, #rings along Z	Assuming any ideal geometry if no design?	NA
Material Volume (m^3) Fe (tons, $8/kg)	108.8	75.1	183.9 (1448 t) (no cassette $8.7M)
Readout channels (2x2 cm^2)	54.4M (13.6M)	37.53M (9.4M)	94.76M (23M)
Power dissipation (kW) 1.4mW/ch, 5.4W/DIF/m^2	105.5 48.4	72.8 33.4	178.3 (81.8)
Cost: sensitive materials RPC + cassette: $1425/$m^2$	$7.7M	$5.3M	$13M
Cost: electronics: $4500/$m^2$ → $3000/$m^2$	$27.2M ($16.3M)	$18.8M ($11.3M)	$46M ($27.6M)
Subtotal	67.7M (49.3) *7.2 = 487M (354M) RMB		

Technical Readiness

Category	Status	Design 1	Other Alternative Design (if any)
Technical Readiness Level	Full Simulation (system level)	Yes	
	Full Simulation (module level)	Yes	
	Prototyping R&D (common)		
	Prototyping R&D (modules, units)	Yes	

Backup

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	$\sim 17\%/\sqrt{E} \oplus 1\%$ (SiW ECAL)
	Hadron energy resolution	$\sim 68\% / \sqrt{E} \oplus 1\%$ (SDHCAL)
	$\pi^0 \rightarrow \gamma\gamma$ reconstruction	Simulation studies
	Granularity	1 x 1 cm^2; 1 x 1 cm^2
	Pile-up at Z-pole	TBD

Cost Estimation (SiW ECAL)

- Reference of ILD cost estimation (TDR, V4, P306)
- CEPC SiW ECAL cost: $180.4M ~ 1.3B RMB

Item		Unit cost	Cost ($)
Tungsten	168 tons	$123/kg	20.7M
Carbon fiber			2.1M
Silicon sensor	3100 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 Item	Cost [kILCU]	ScECAL 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 Estimation (SDHCAL)

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

Unit Cost: ~ 42K RMB/m^2 (for 1x1 cm^2)
~ 30K RMB/m^2 (for 3x3 cm^2)
SDHCAL: 7394 m^2 ➔ 310M vs 222M RMB
Absorber (148 m^3) ➔ 74M RMB
Total Cost (RMB): 384M vs 296M

AHCAL		SDHCAL	
Item	Cost [kILCU]	Item	Cost [kILCU]
Absorber	5200	Absorber	6500
Module production	3400	Module mechanics	2300
Cassettes	2100		
Scintillators	1500	RPC incl cassettes	6800
Reflective Foil	1200		
Photo sensors	7700		
ASIC	1800	ASIC	6600
Readout Board	13200	Readout Board	13000
Readout	2300	Readout	2000
Cabling, connections	1000	Elec Integration	1600
HV/ LV supplies	1000	Services incl. HV/ LV	200
Cooling system	1000	Cooling System	1000
		Gas System	900
Tooling, testing	500	Testing	200
Assembly, installation	2800	Assembly, tooling	3900
DAQ	200		incl.
Sum AHCAL	44900	Sum SDHCAL	44800

Electronics Channels and Power

$(0.12\lambda_I, 1.14X_0)$

Stainless steel Absorber(15mm)

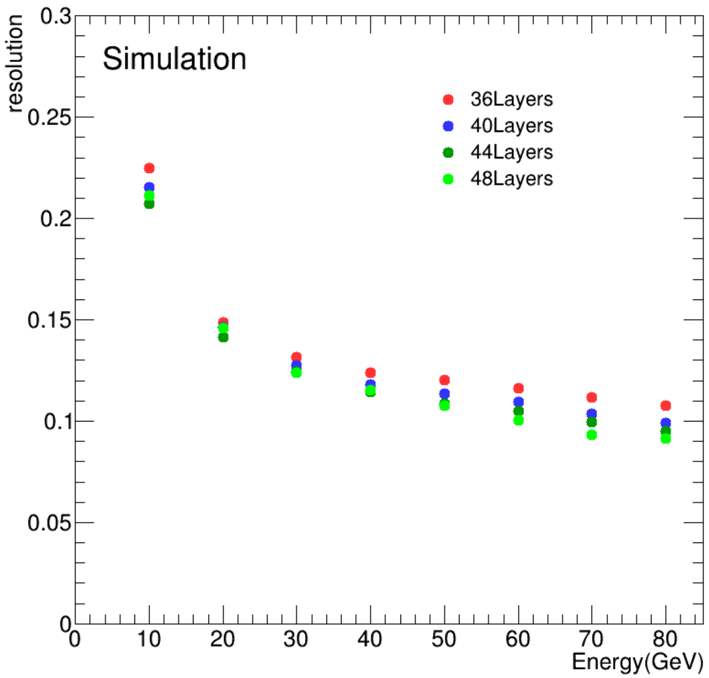
Stainless steel wall(2.5mm)

GRPC(6mm≈ $0\ \lambda_I, X_0$)

Stainless steel wall(2.5mm)

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

➔48-layer ~ 5.76 λ_I

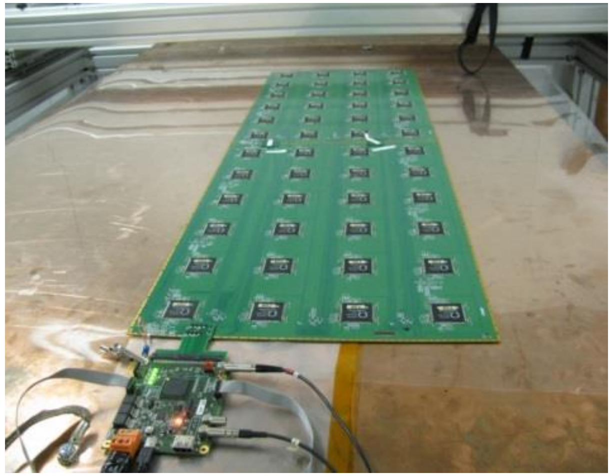


➔ 1m^2 RPC needs 6 PCBs, each PCB has 1536 ch (24 ASIC chips)

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

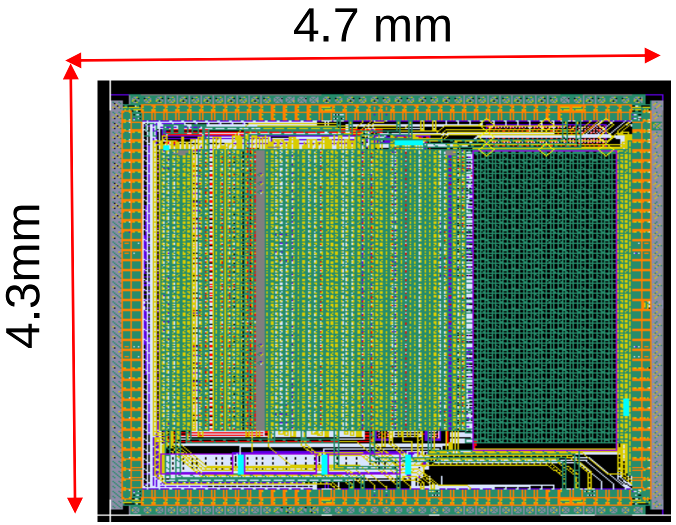
➔ ASIC Power: 1.4mW/ch * 64 ch = 90 mW/Chip

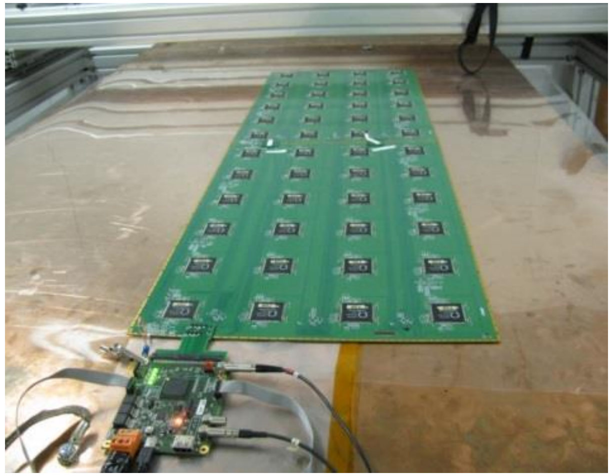
➔ Power: 1.4mW/ch * 9216 ch (6*24*64) = 13 W/m^2



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. $1 \times 1 m^2$ has 6 PCBs and 9216 pads.

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