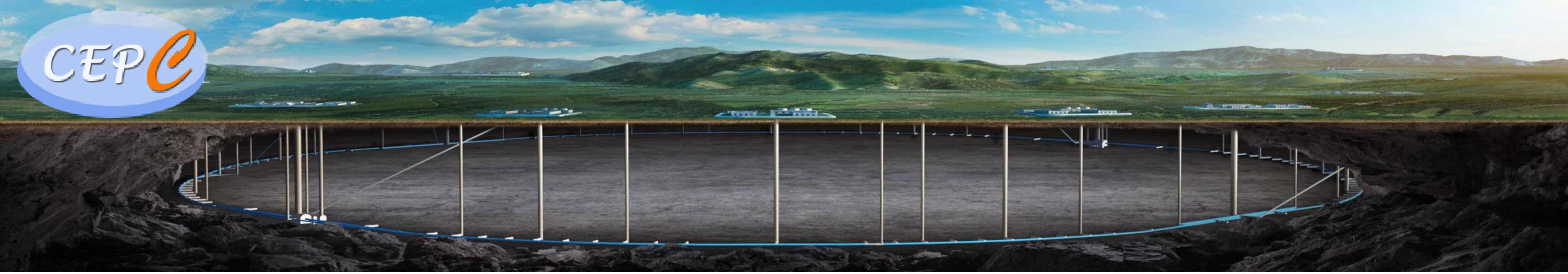

CEPC HCAL Detector

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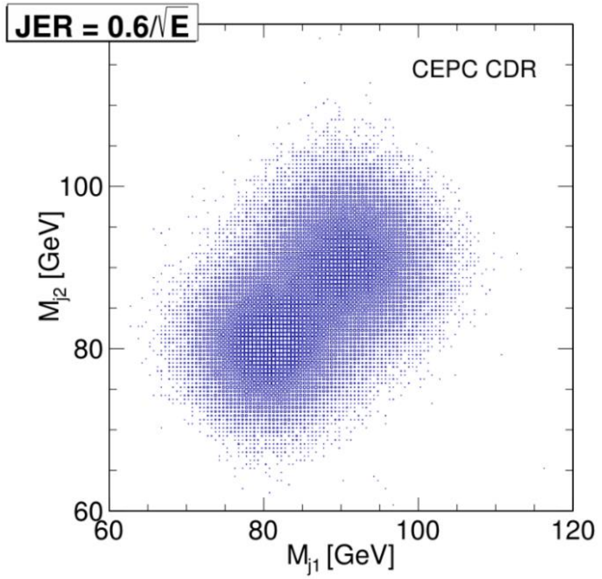
1. Introduction

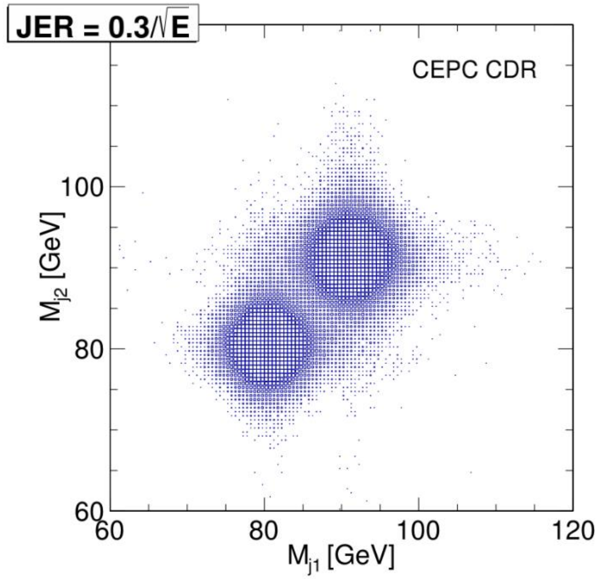
CEPC as Higgs/W/Z boson factories

- ❖ H/W/Z decay into hadronic final states are dominant, it is crucial to design high performance calorimetry system
- ❖ Required Jet Energy Resolution **σ/E ~ 3-4% at 100 GeV**

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 CDR, arXiv:1811.10545



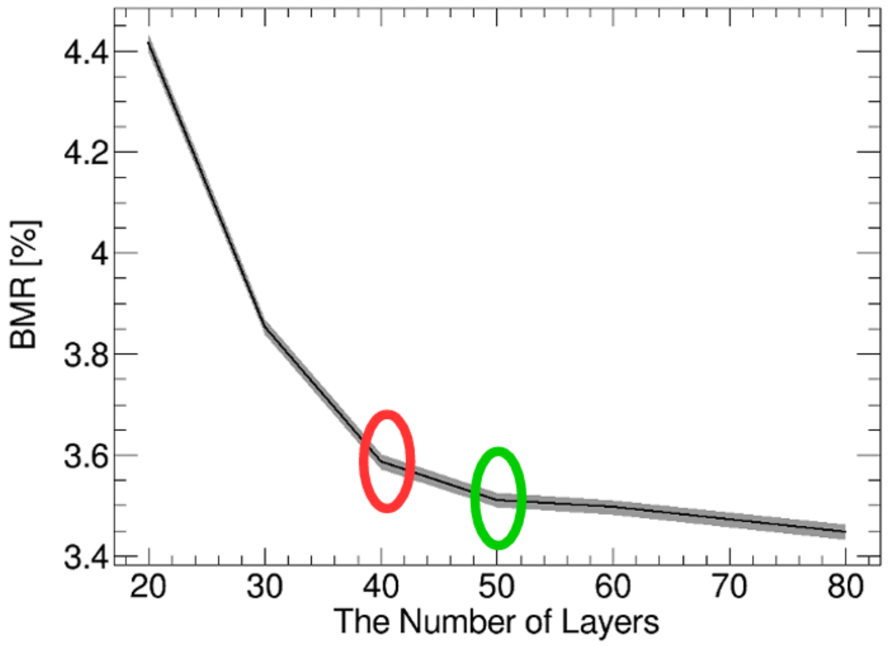


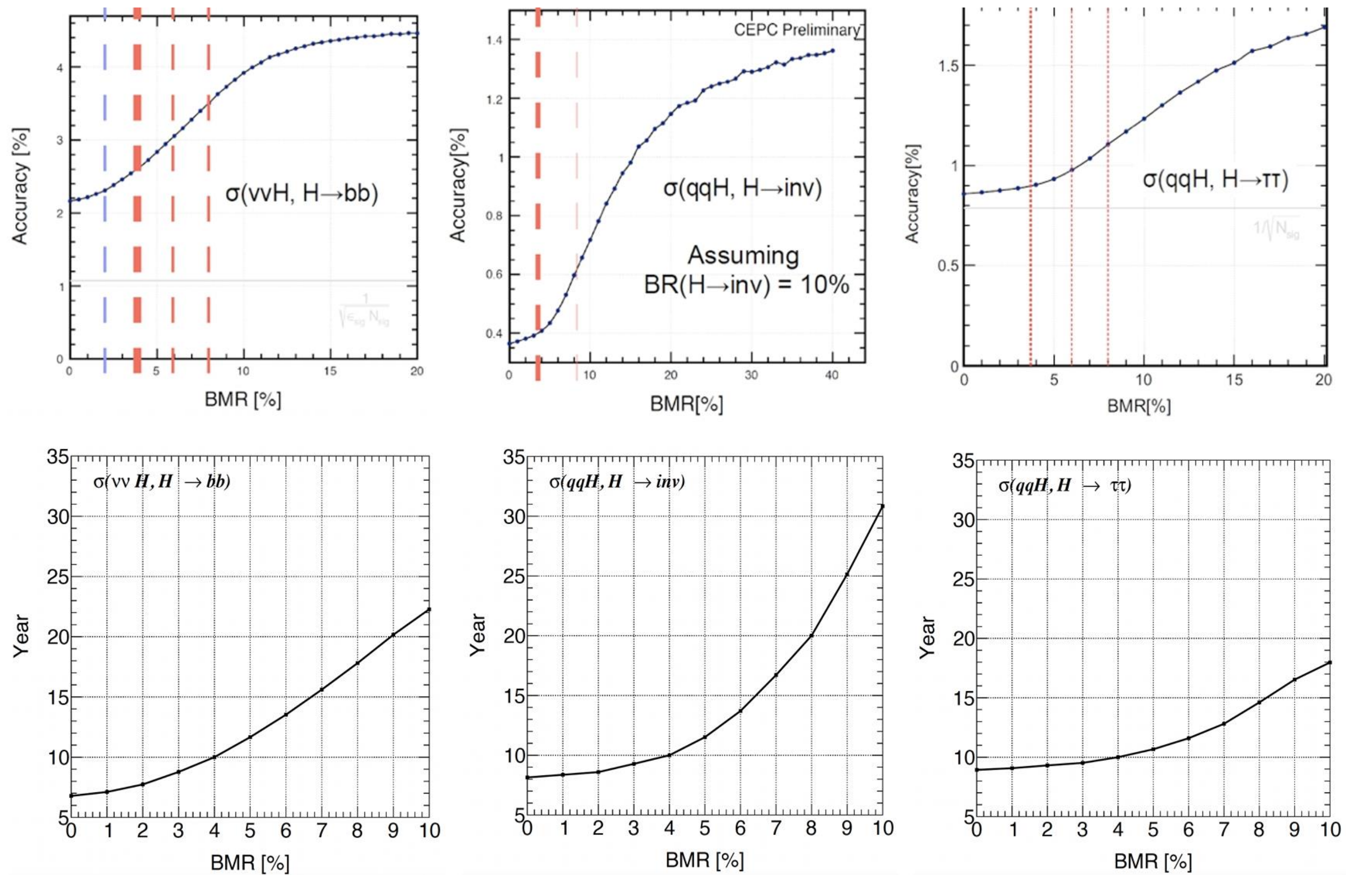
2. Requirement

Parameter	Conservative	Ambitious	Remarks
Hadron Energy Resolution	$60\%/\sqrt{E} \oplus 3\%$	$40\%/\sqrt{E} \oplus 5\%$	Jet performance flavor physics
Longitudinal Depth	48 layers, total depth of 6 λ_I		Containment most of jets
Transverse Granularity	40mm × 40 mm		H → gg (gluon jets)
Signal Dynamic Range	1 – 100 MIPs		0.1 MIP as trigger threshold
Time Resolution (1-MIP signal)	1 ns		Bunch crossing ID timing hadron performance
Power Consumption	15 mW/ch		O(5.6M) channels

2. Requirement

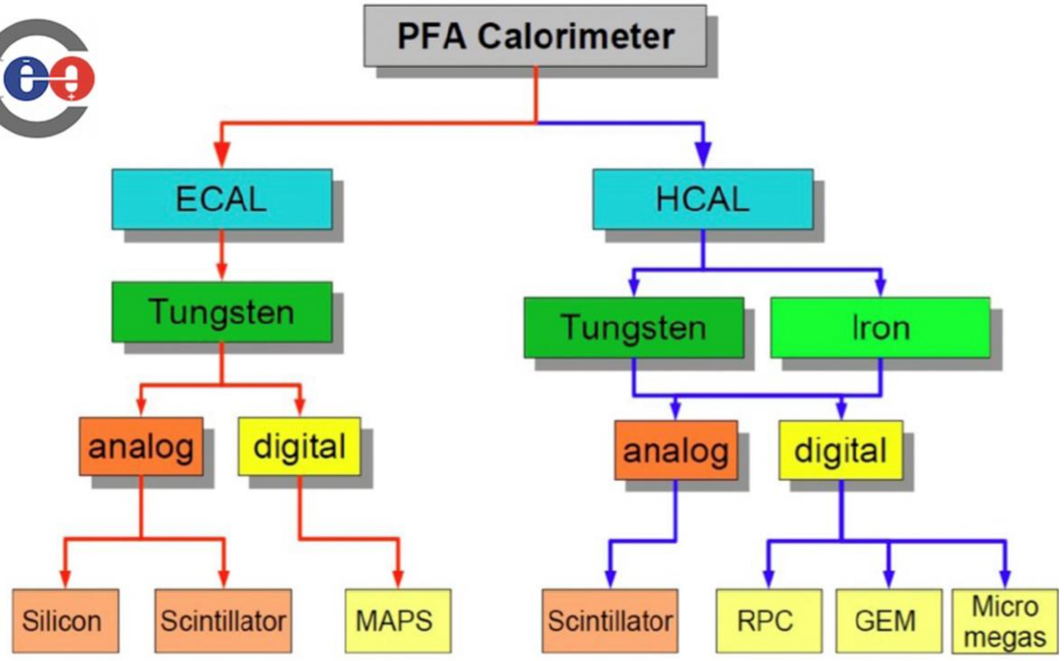
➔The increase of sampling layers (40 → 48 layers) will improve the total nuclear interaction length (~5λ → 6λ) and suppress hadronic shower leakage, which is beneficial to achieve better BMR and accuracy of benchmark physics processes.

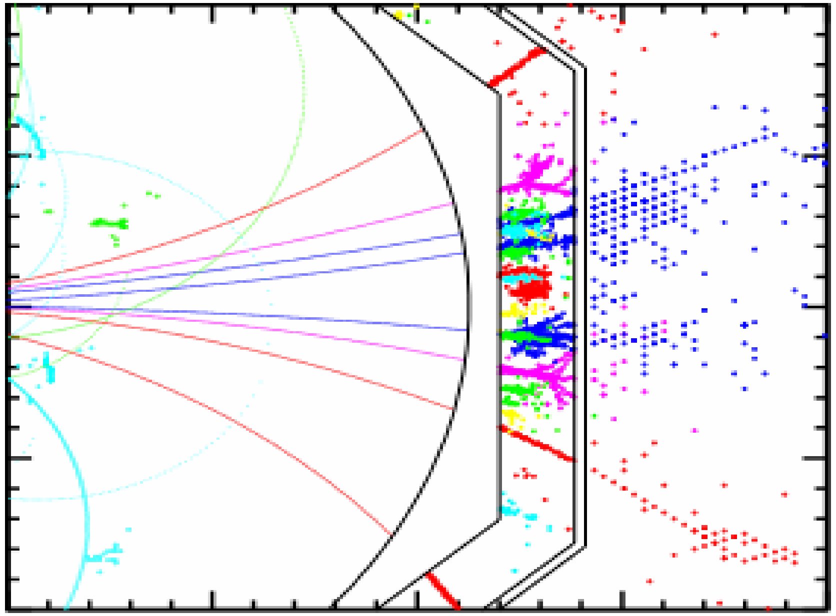




3. Technology Survey and Our Choice

- **Three major options for CEPC Hardronic Calorimeter**
  - – ① RPC-DHCAL (SDHCAL, prototype): 48-layer
  - – ② Plastic Scintillator-AHCAL (PS-HCAL, prototype): 40-layer
  - – ③ **Glass Scintillator-AHCAL (GS-HCAL):** (**new design** for CEPC Ref-TDR)

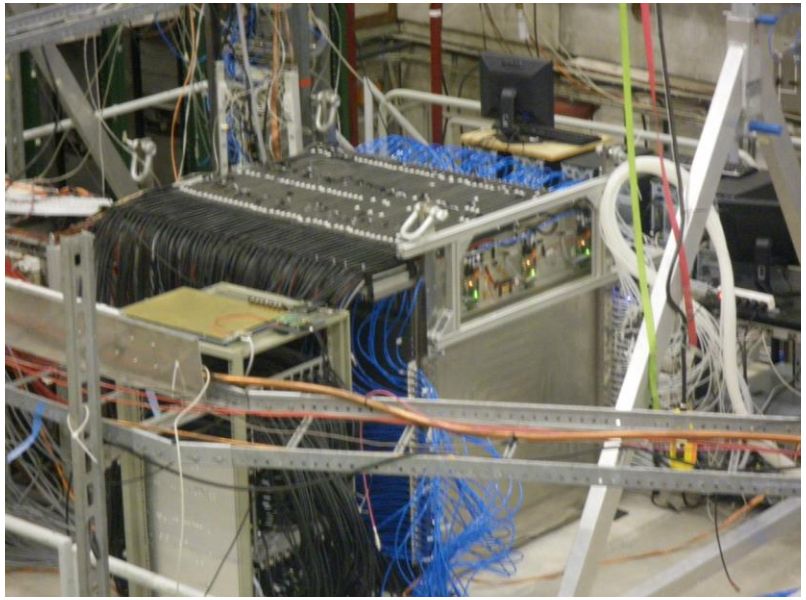


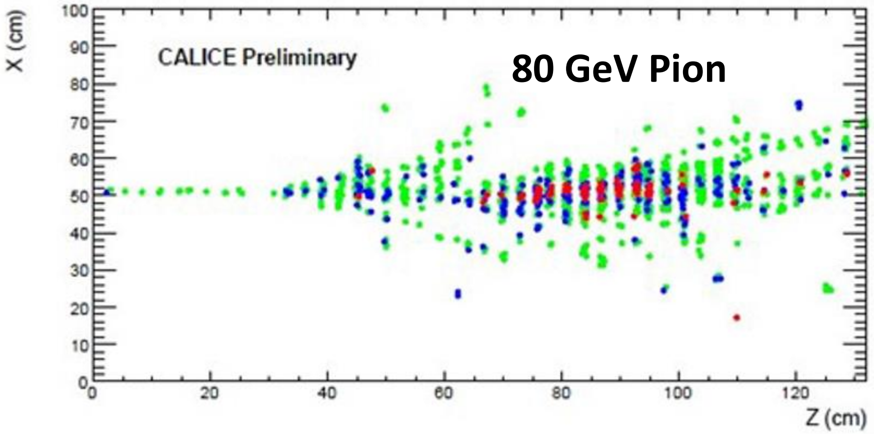


PFA calorimetry: extensively explored within the CALICE collab.

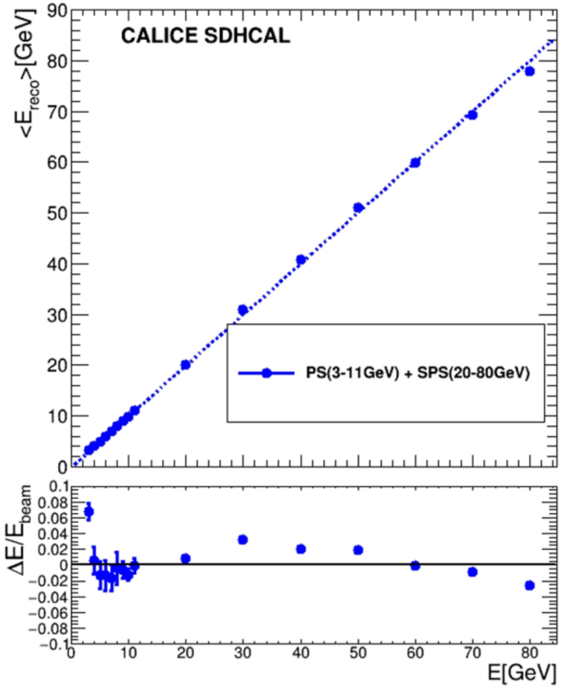
3.1 RPC based SDHCAL (Prototype)

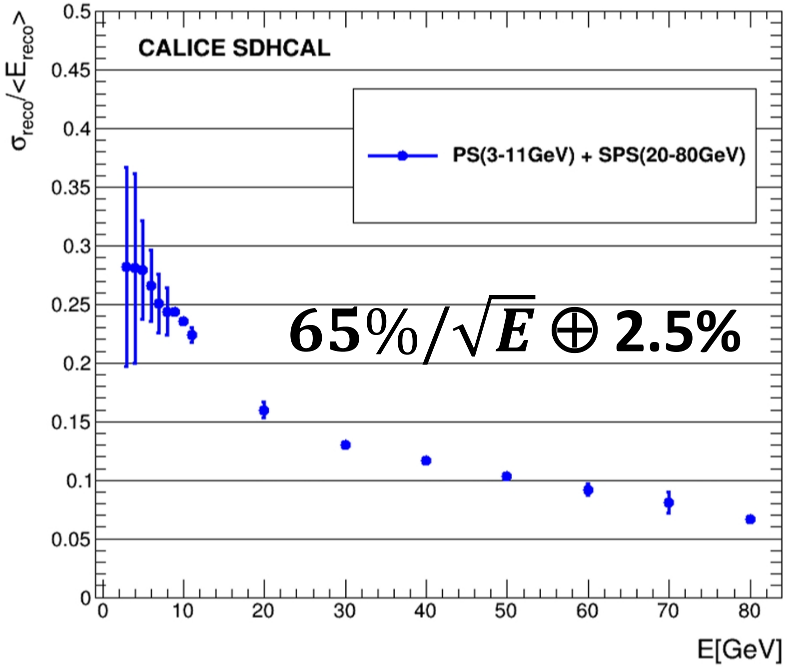
- **Semi-digital HCAL (SDHCAL)**
  - High granularity (1cm x1cm)
  - 48 layers (1m x 1m x 1.3m)
  - Three thresholds readout
  - Stainless-steel absorber with self-supporting mechanical structure





JINST 11 (2016) P04001
JINST 17 P07017 (2022)



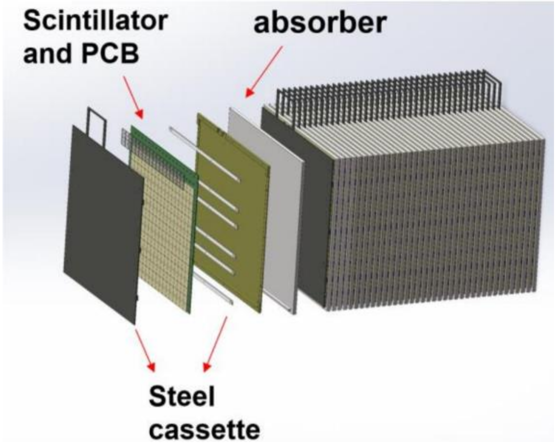


$65\%/\sqrt{E} \oplus 2.5\%$

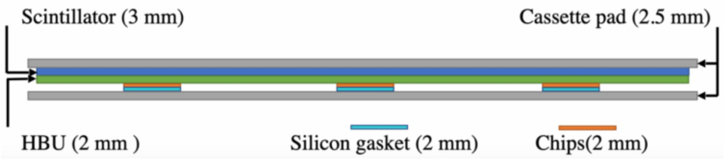
3.2 Plastic Scintillator HCAL (Prototype)

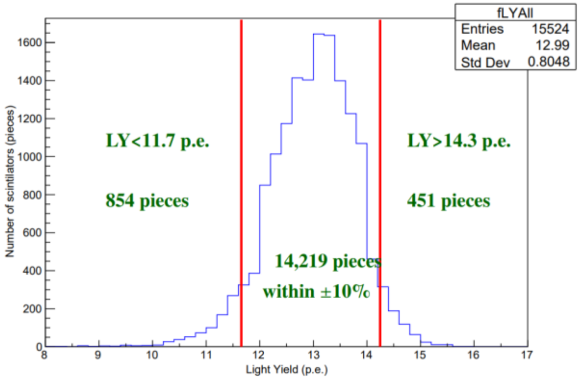
■ We have developed a PS-HCAL prototype in 2022 and TB at CERN

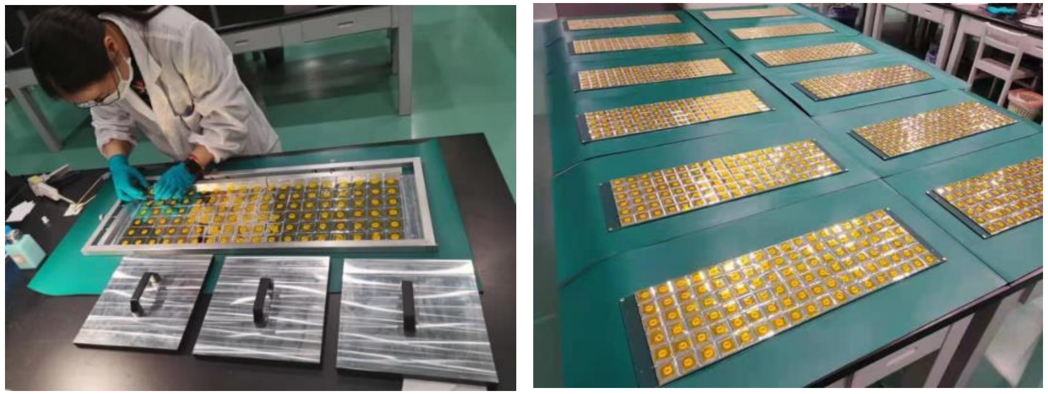
Calo	Layers	material	Absorber	Granularity	Electronics	Thickness	Resolution	Weight
PS-HCAL	40	PS+SiPM S14160-1315	Fe	$4\times4\ cm^2$	SPIROC-2E 12960-ch	$4.6\ \lambda_I$	$60\%/\sqrt{E}\oplus3\%$	5.0 T

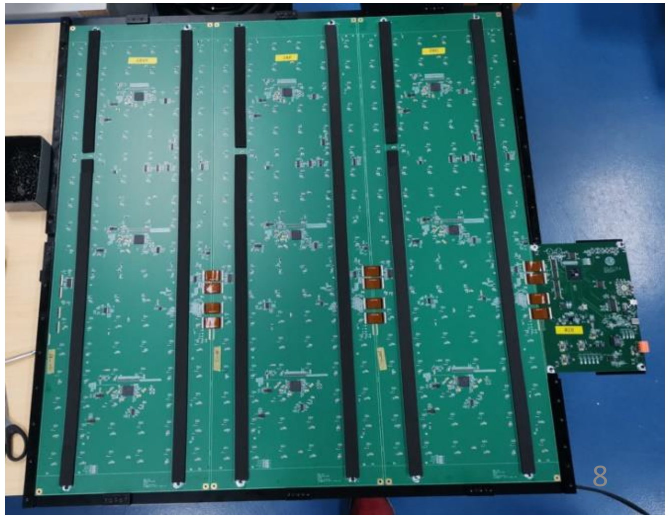


JINST 17 (2022) P05006

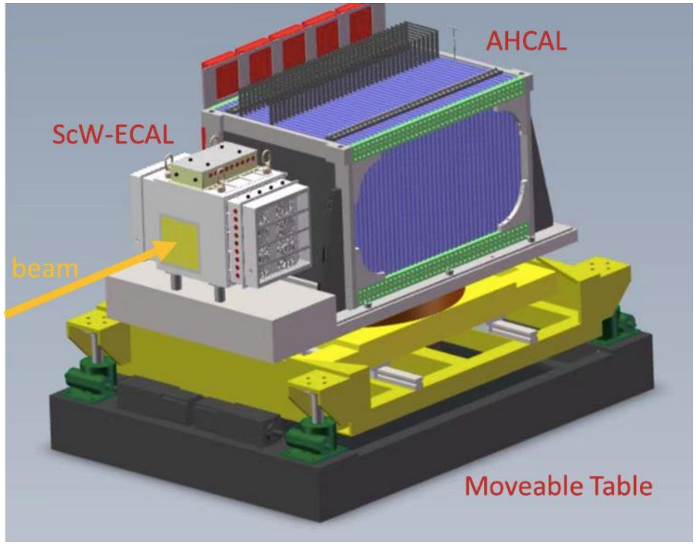


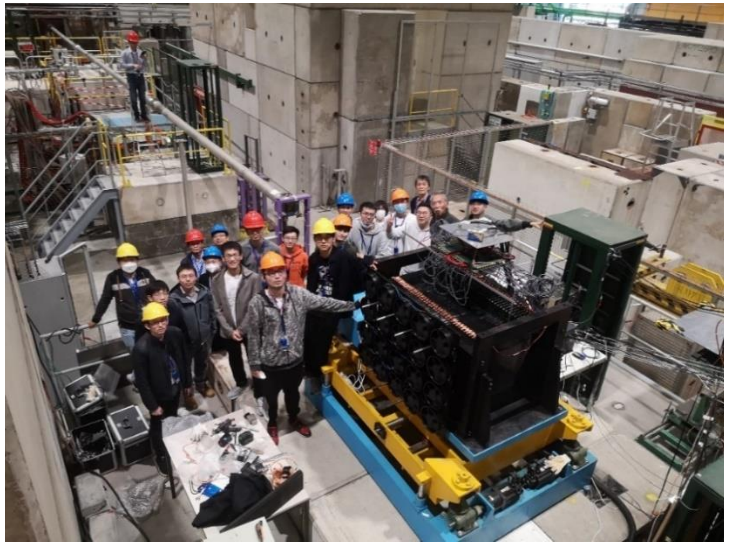






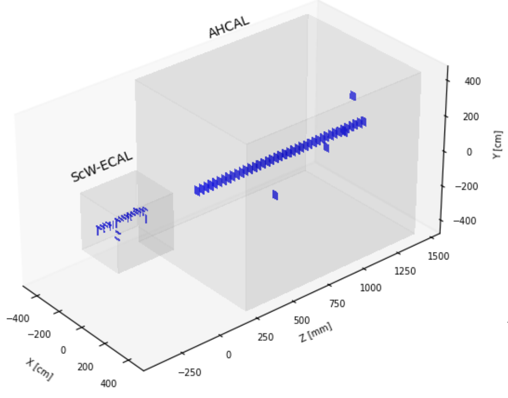
3.2 Plastic Scintillator HCAL (Prototype)



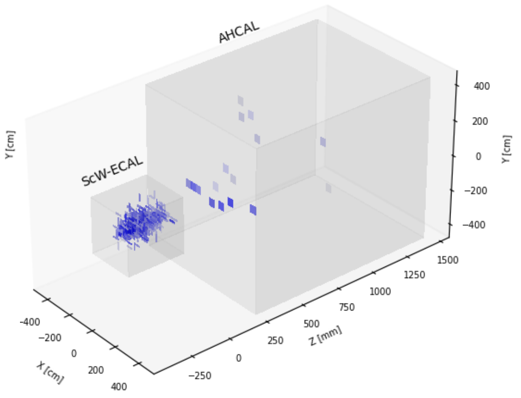


- ➔ **About 65 M test beam events collected**
- ➔ **AHCAL prototype pion TB data**
  - ➔ Energy linearity within $\pm 1.5\%$
  - ➔ Energy res. $56.2\%/\sqrt{E(GeV)} \oplus 2.9\%$

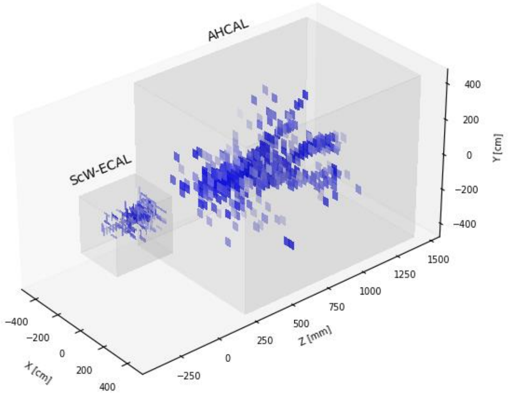
120 GeV mu-

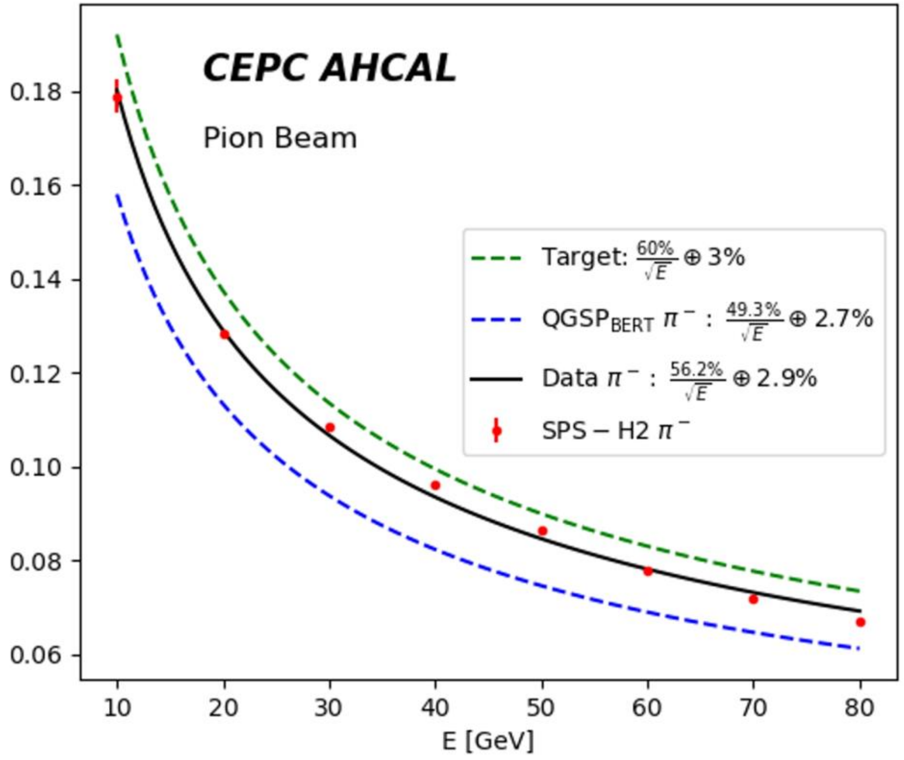


60 GeV electron



60 GeV pion (SPS)

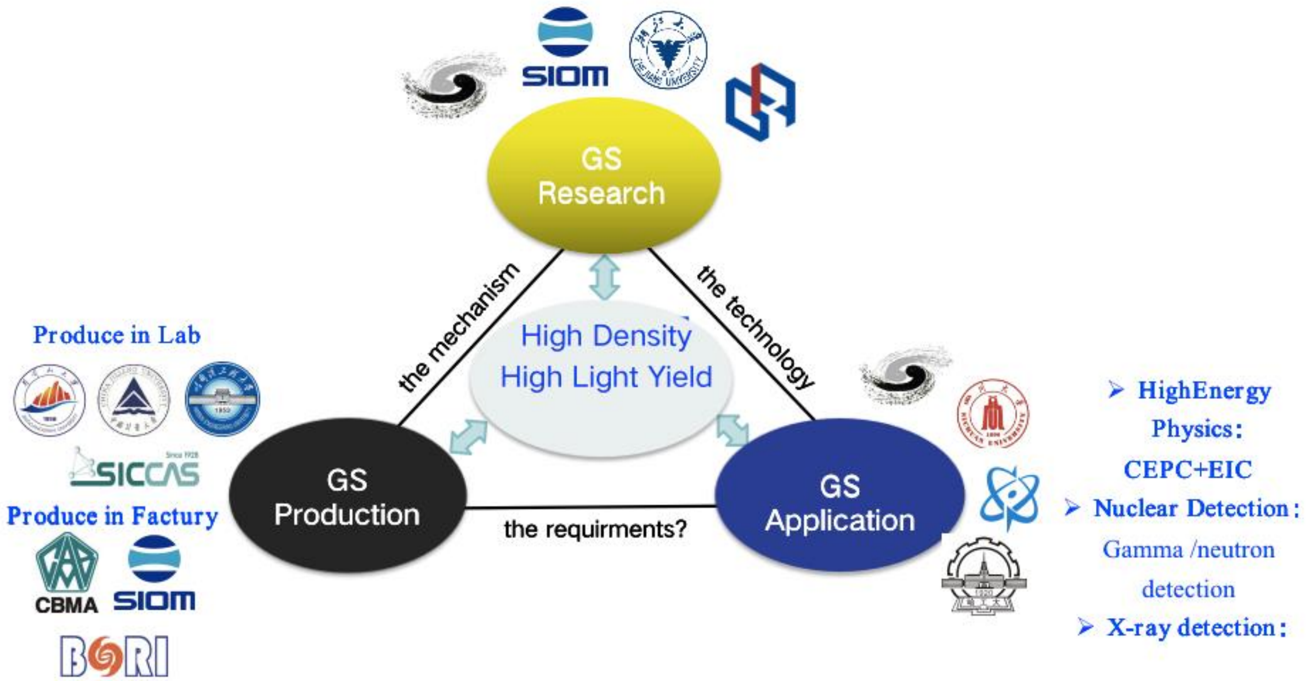




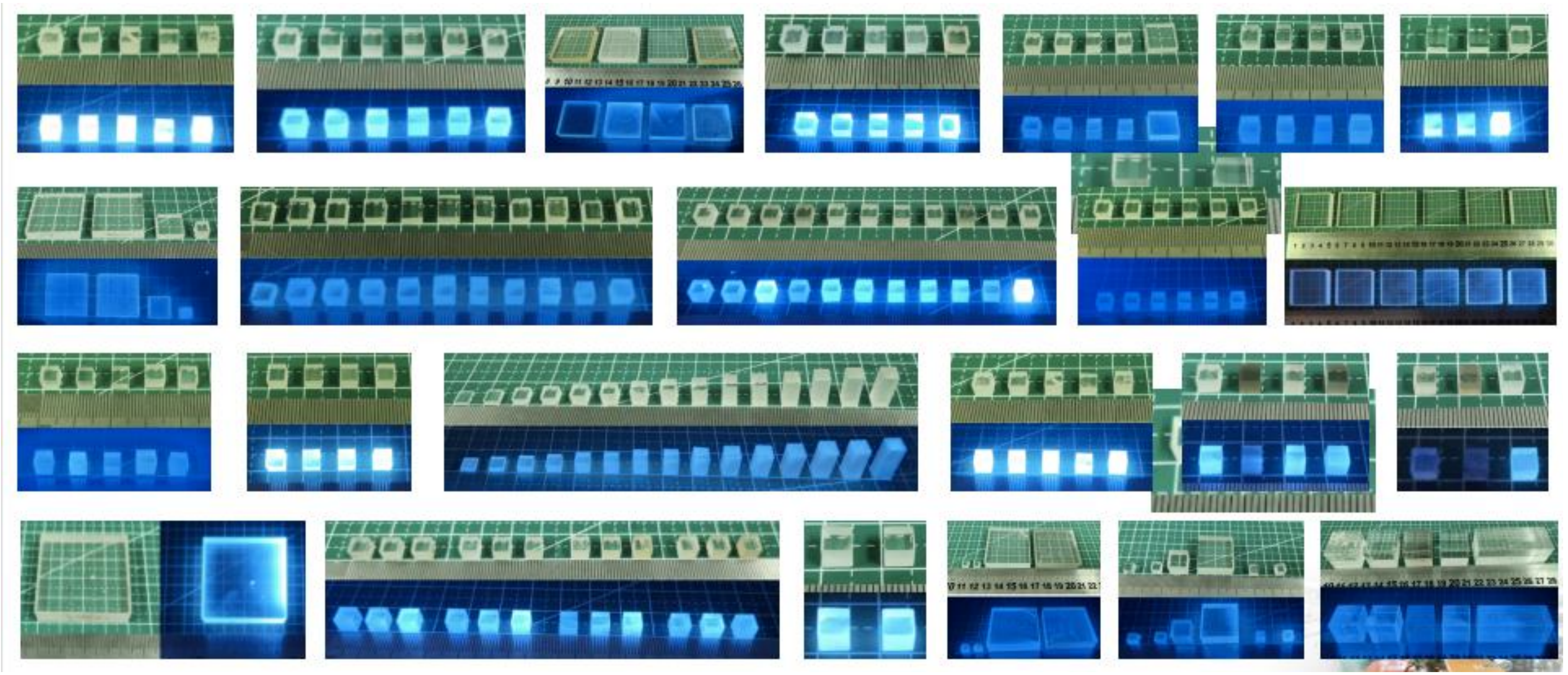
3.3 Glass Scintillator R&D

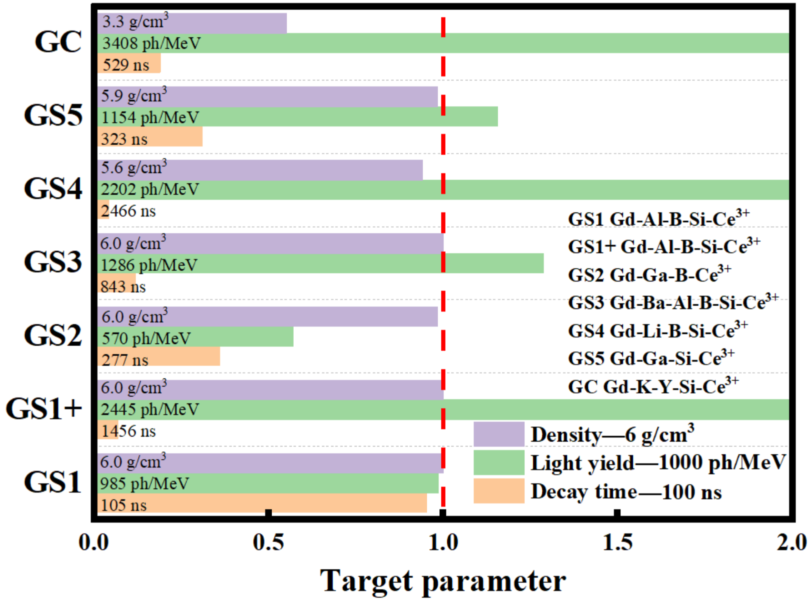
- The GS collaboration was established in 2021, it focuses on the large-area & high-performance glass scintillator for applications in nuclear and particle physics.
- The GS collaboration is organized by IHEP and the members include 4 Institutes of CAS, 6 Universities, 3 Factories currently.

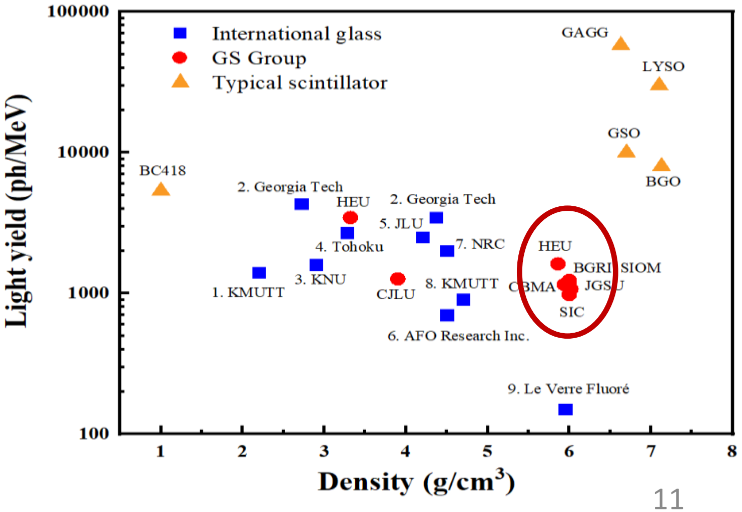
Glass Scintillator Collaboration
闪烁玻璃合作组
Glass Scintillator Collaboration



3.3 Glass Scintillator R&D





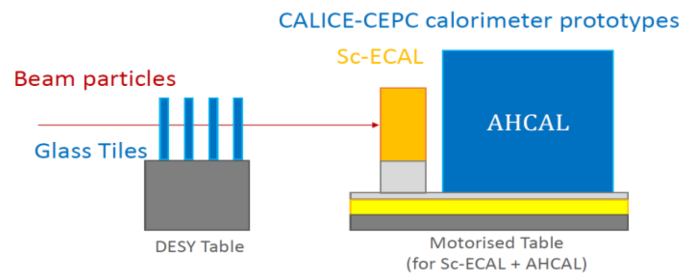


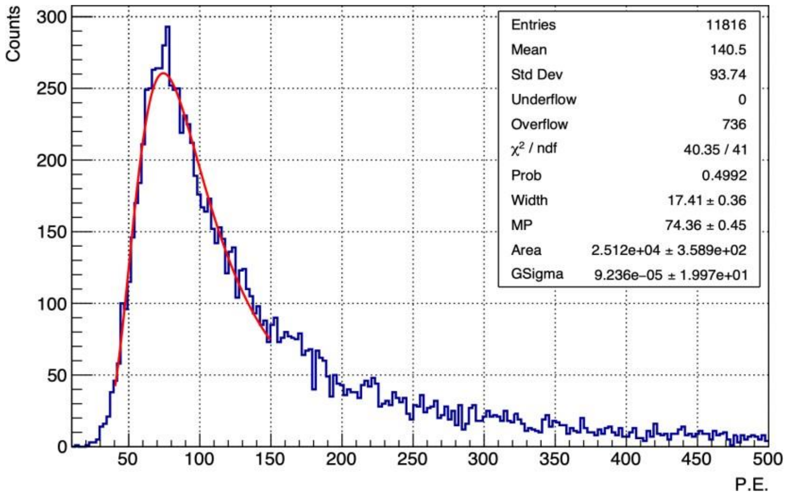
- ✓ The GS group did substantive research based on five glass scintillator types simultaneously and impressive progress has been achieved
- ✓ The performance of the best glass sample approach our initial goals, i.e. 6 g/cm^3 & 1000 ph/MeV & ~100 ns
- ✓ The GS group is leading R&D efforts on high density glass scintillator

3.3 Glass Scintillator (GS1) TB Performance

CERN Muon-beam (10 GeV muon)

11 glass tiles tested at CERN (2023/5)

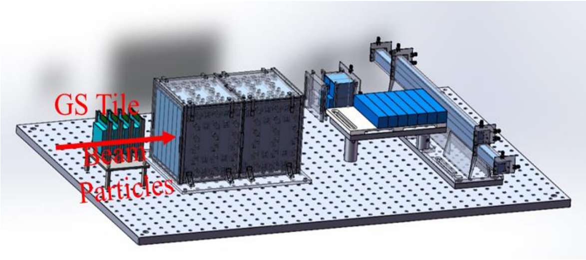


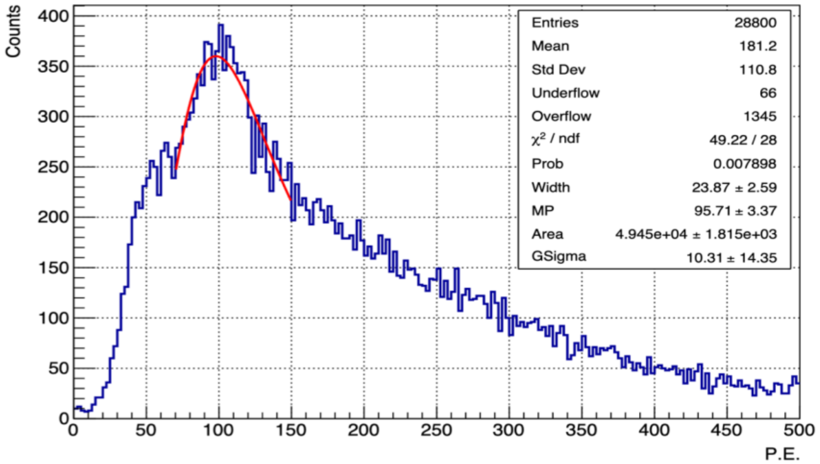


- **Typical Light Yield:**
  500 – 600 ph/MeV
- **Typical MIP response:**
  60 – 70 p.e./MIP

DESY Electron-beam (5 GeV electron)

9 glass tiles tested at DESY (2023/10)

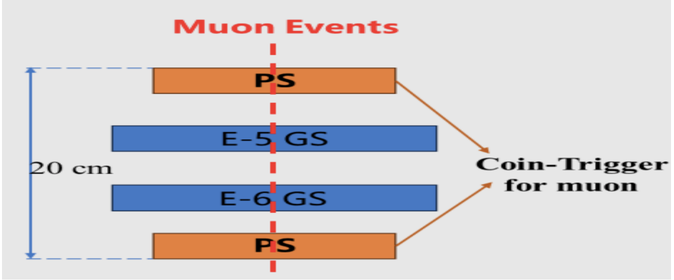


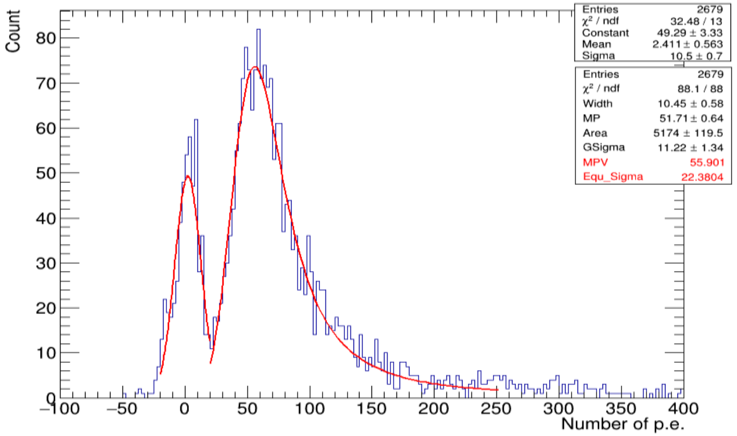


- **Typical Light Yield:**
  600 – 700 ph/MeV
- **Typical MIP response:**
  70 – 80 p.e./MIP

IHEP Cosmic Muon (3 GeV muon)

4 glass tiles tested at IHEP (2024/4)

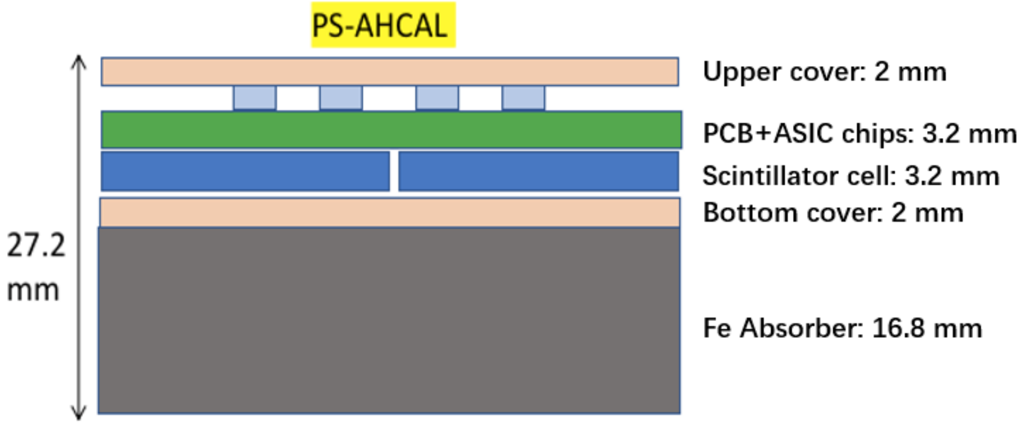




- **Typical Light Yield:**
  500 – 700 ph/MeV
- **Typical MIP response:**
  60 – 80 p.e./MIP

4.1 GS-HCAL vs PS-HCAL

- **Sampling fraction of PS-HCAL and GS-HCAL**



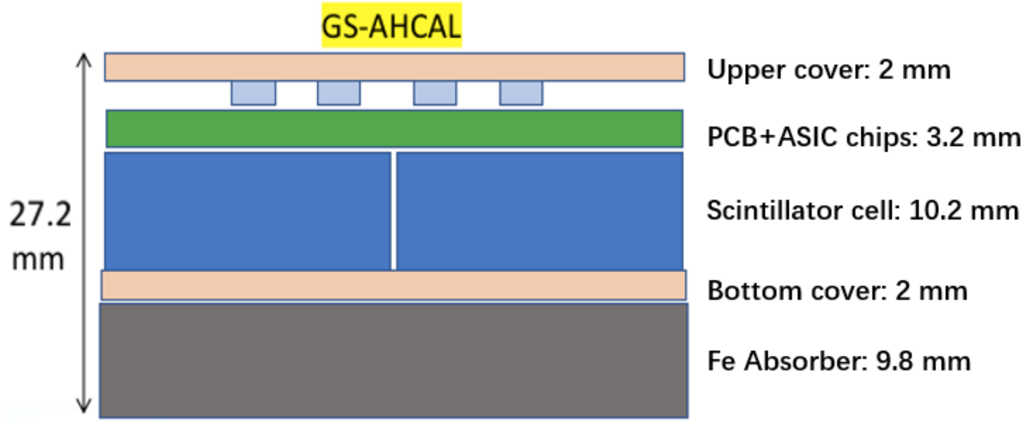
PS-HCAL (6.15 λ_I)

Fe: 20.8mm/171.5mm=0.1213 λ_I

PS: 3mm/688.7mm=0.0044 λ_I

PCB: 1.2mm/492.2mm=0.0024 λ_I

Sampling fraction ~ 1.6% (π^- TB, MC)



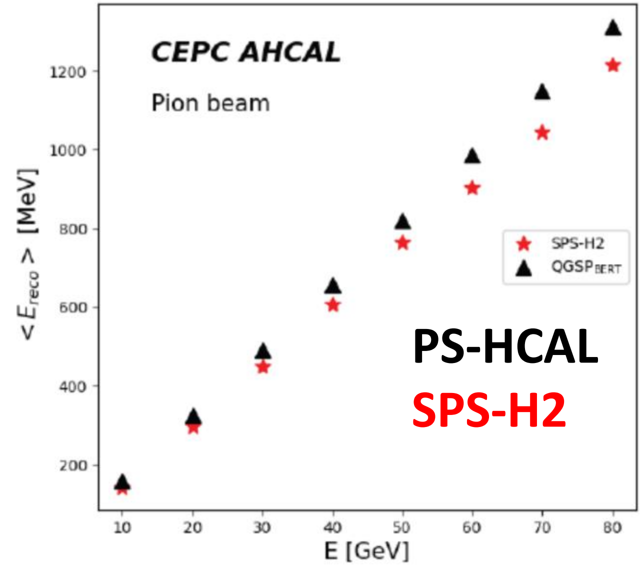
GS-HCAL (6.02λ_I)

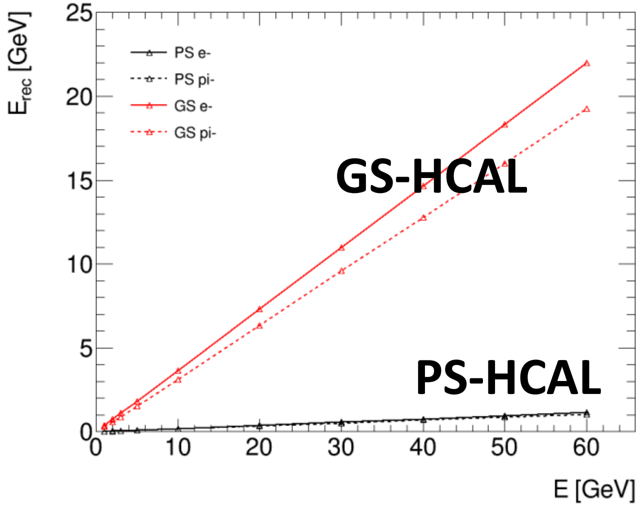
Fe: 13.8mm/171.5mm=0.0805 λ_I

GS: 10.2mm/242.8mm=0.0425 λ_I

PCB: 1.2mm/492.2mm=0.0024 λ_I

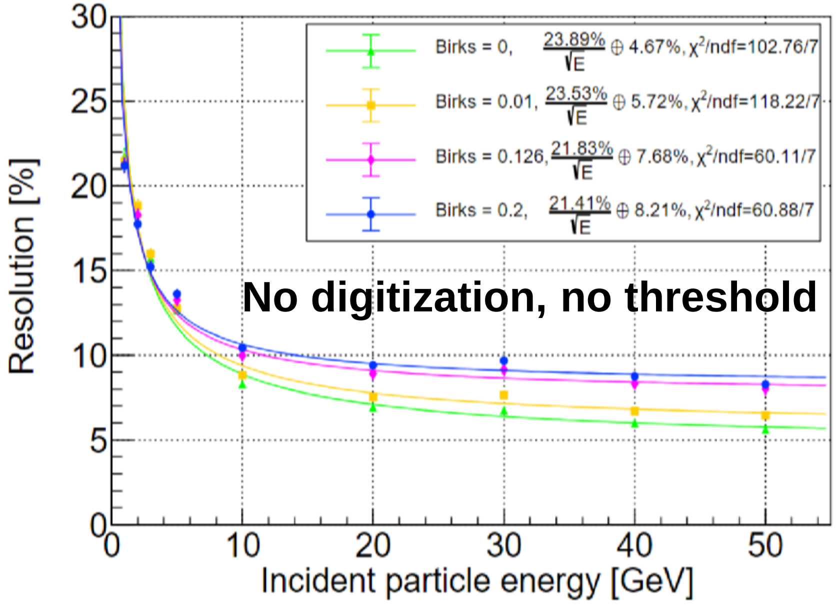
Sampling fraction ~ 31% (MC)



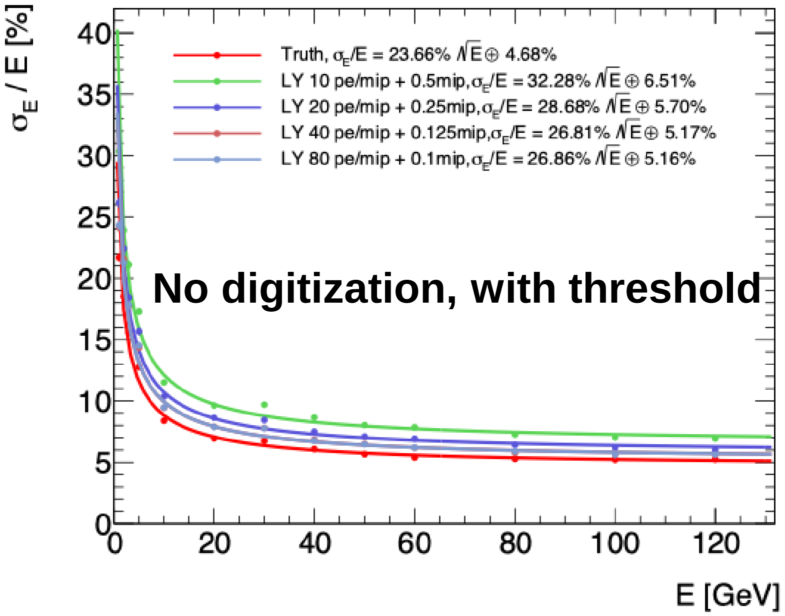


4.2 GS-HCAL Energy Resolution

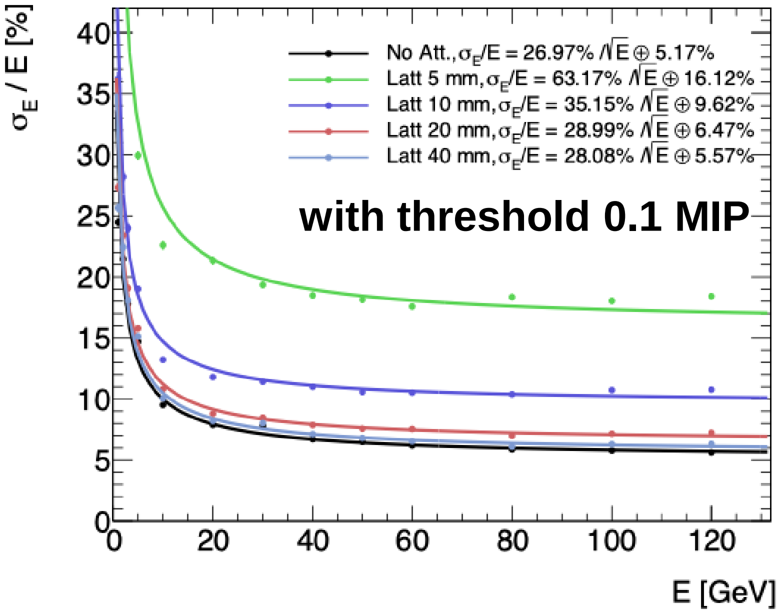
- **A full detector geometry constructed with DD4hep in CEPCSW**
  - GS1 (Gd-Al-B-Si-Cs): density 6 g/cm^3, $\lambda_I = $ 242.8 mm, attenuation length ~ 23mm
  - Geometry: follow the mechanics design, with simplified supporting structures.
  - GS cell size $4 \times 4 \times 1\ \mathrm{cm}^3$, 2.7cm / layer, 48 layers, $6\lambda_I$ in total



- Scintillator non-linearity in light output caused by quenching, Birks constant : C_{birks} ~0.01 (GS) vs ~0.008 (BGO)

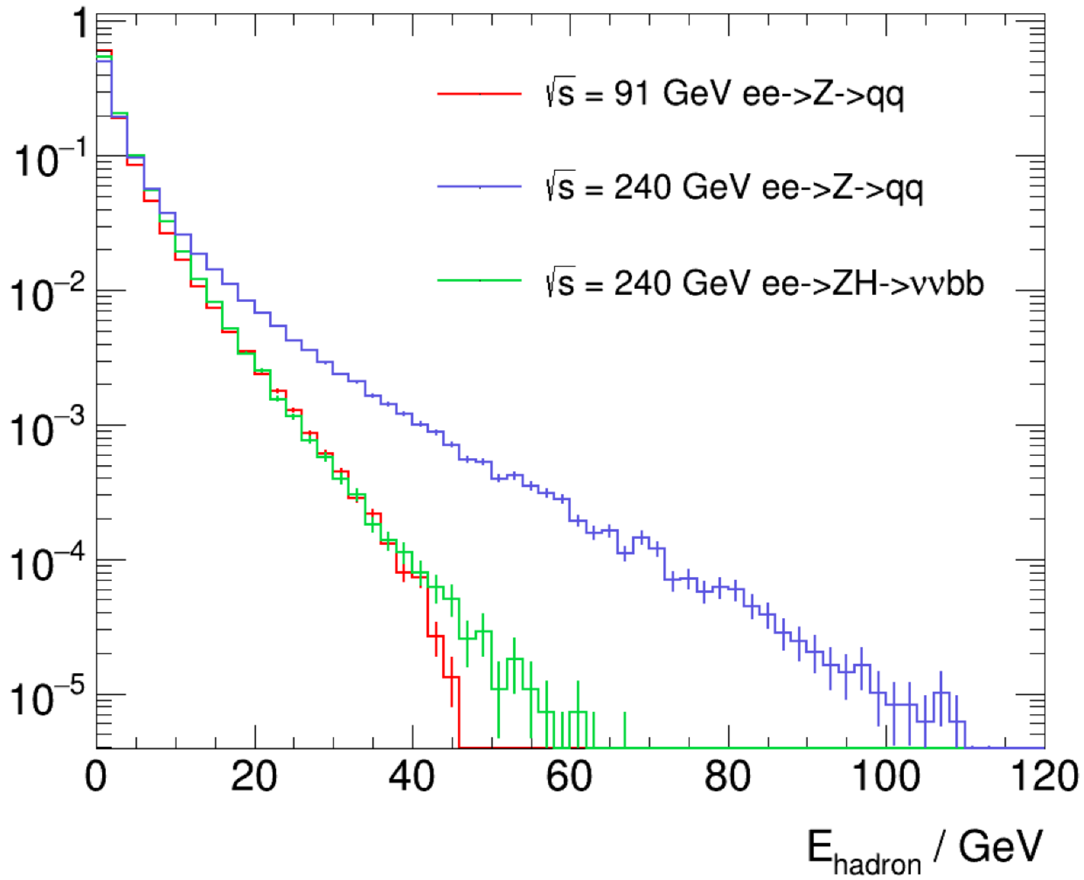


- GS light yield: > 50 p.e/MIP
- Threshold: 0.1 MIP (> 5 p.e)

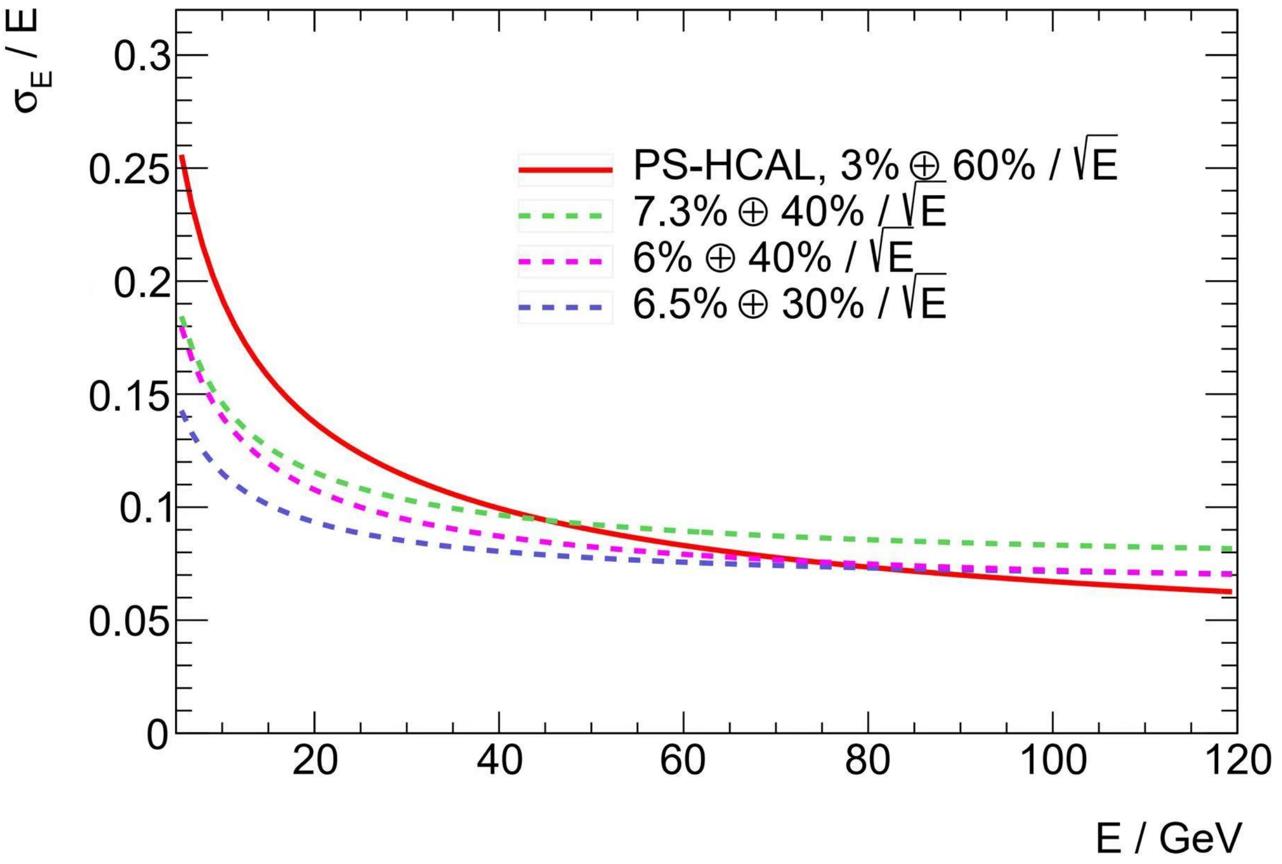


- GS attenuation length: ~23mm

4.2 GS-HCAL Energy Resolution



- E_{hadron} < ~ 100 GeV, typically < 60 GeV

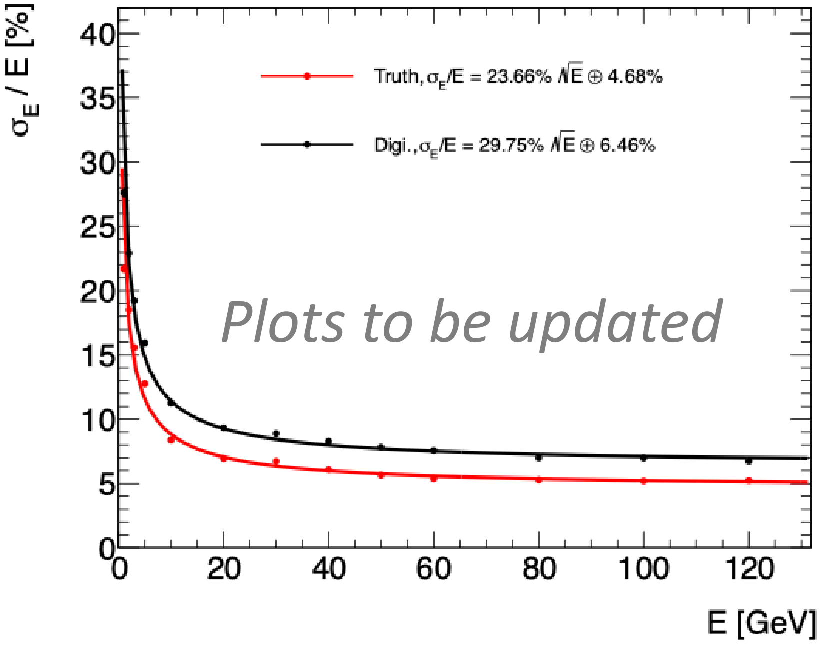


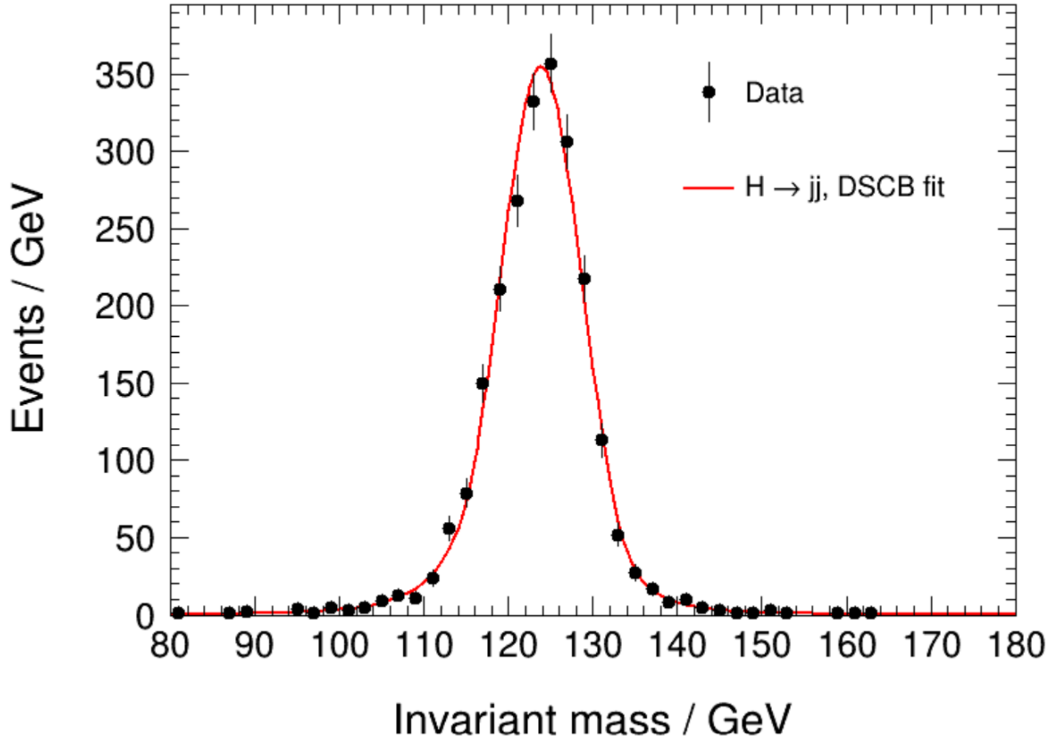
- Energy resolution of GS-HCAL is better than that of PS-HCAL for E < 80 GeV

4.3 GS-HCAL Physics Performance

- **Hadron Energy Resolution (full sim + digi) :**
- **PFA Reconstruction for $ee \rightarrow ZH \rightarrow \nu\nu gg$ events:**
  - Tracker + crystal bar ECAL + GS-HCAL (barrel only)
  - Improvements are expected with further optimizations (e.g. tracking, clustering, calibrations)
  - **BMR = 3.95±0.10% ($m_{jj} = 123.81 \pm 4.89$ GeV).**

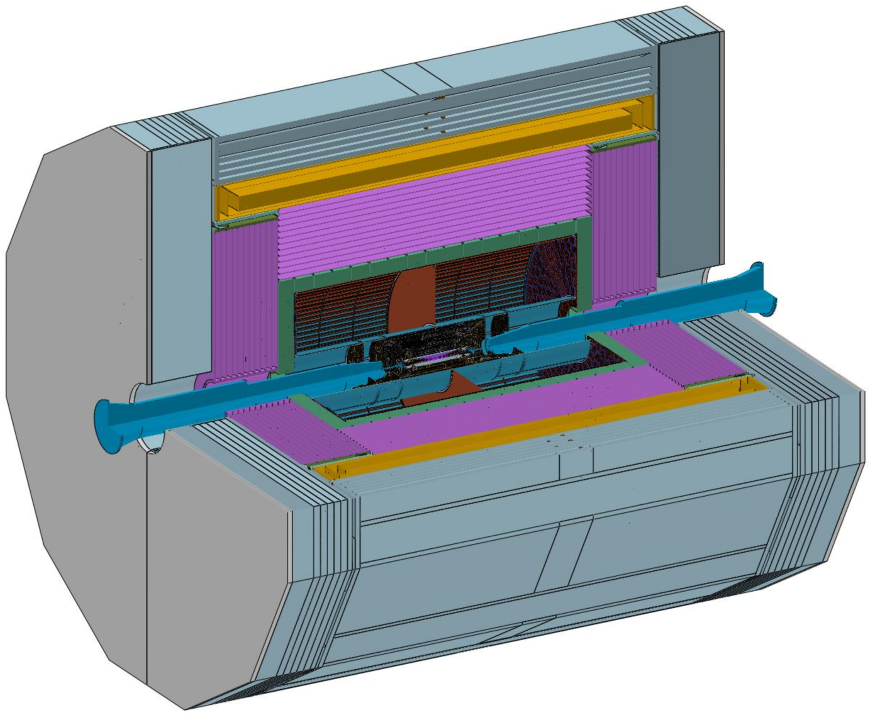
$$\sigma_E/E = \frac{29.75\%}{\sqrt{E}} \oplus 6.46\%$$

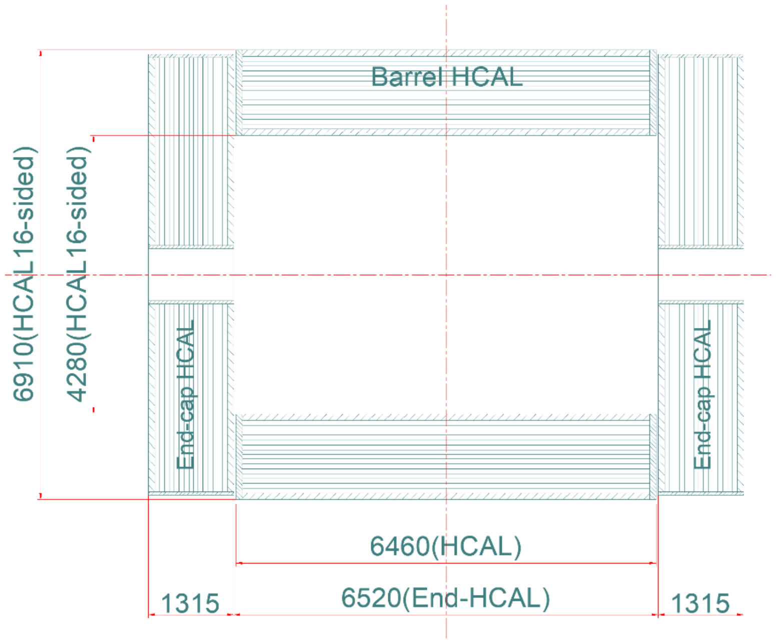


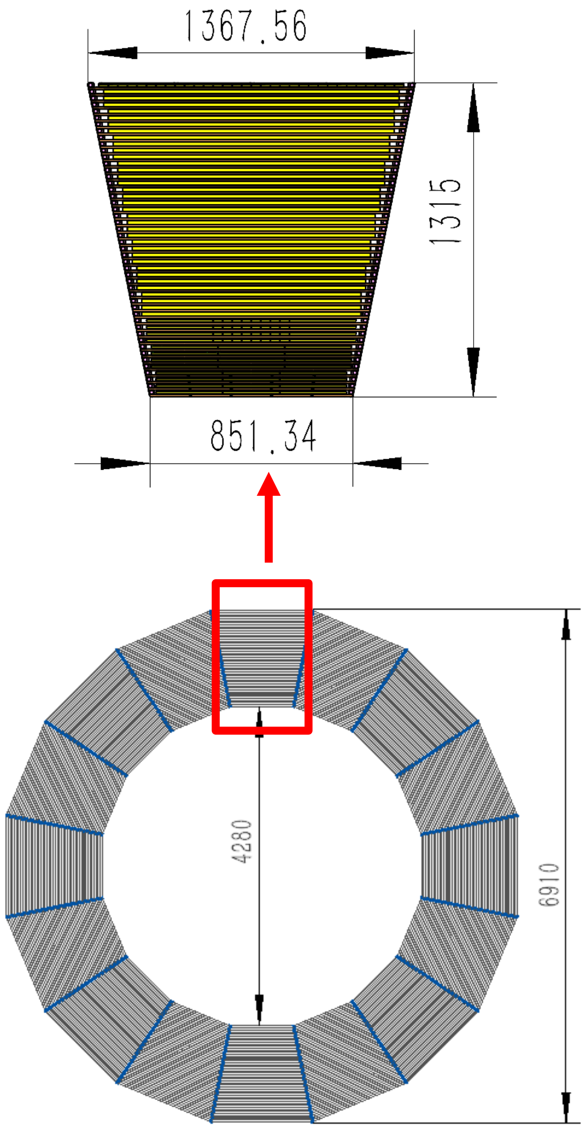


5. GS-HCAL Design

- **GS-HCAL: Barrel (16 sectors) and two Endcaps**
  - Thickness of the Barrel : 1315 mm
  - Inner radius of the Barrel : 2140mm (D_{in}=4280 mm)
  - Barrel Length along beam direction : 6460 mm
  - Number of Layers : 48 (~ 6 λ_I)

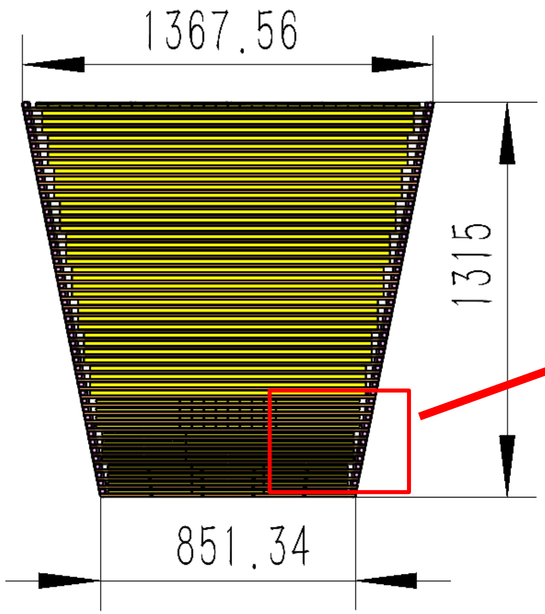




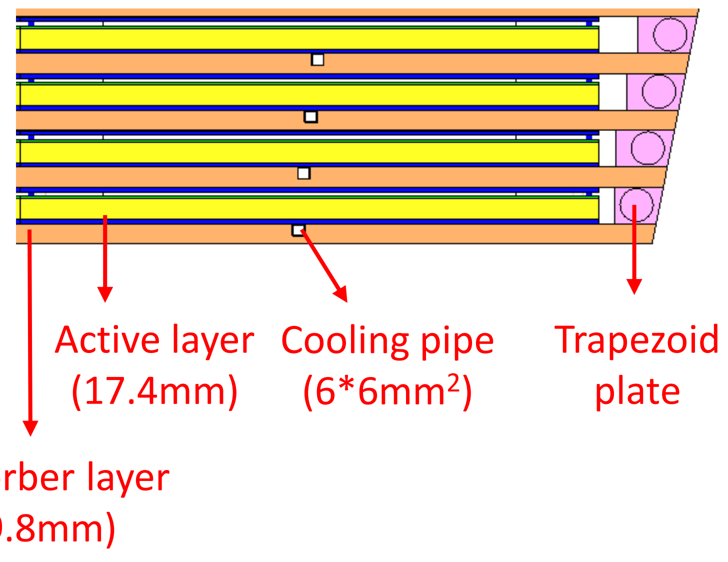


5.1 GS-HCAL Mechanical Design (Barrel)

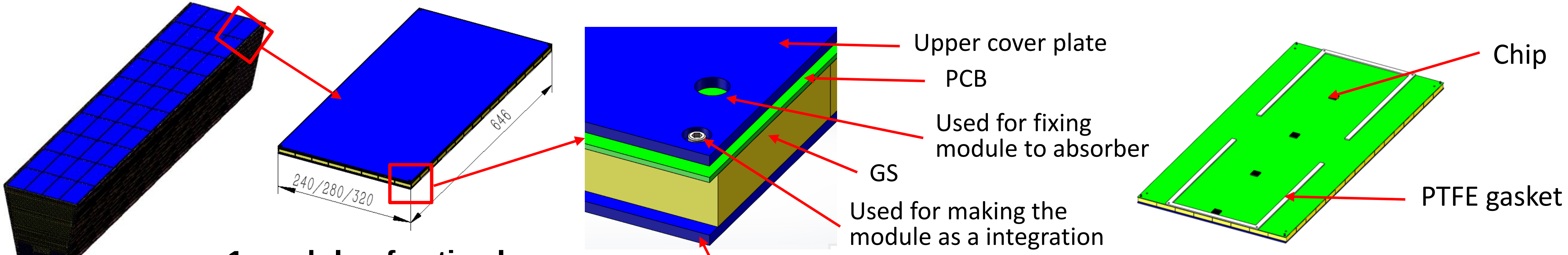
- **One Sector**



- **Several Layers**



- **Active layer structure**

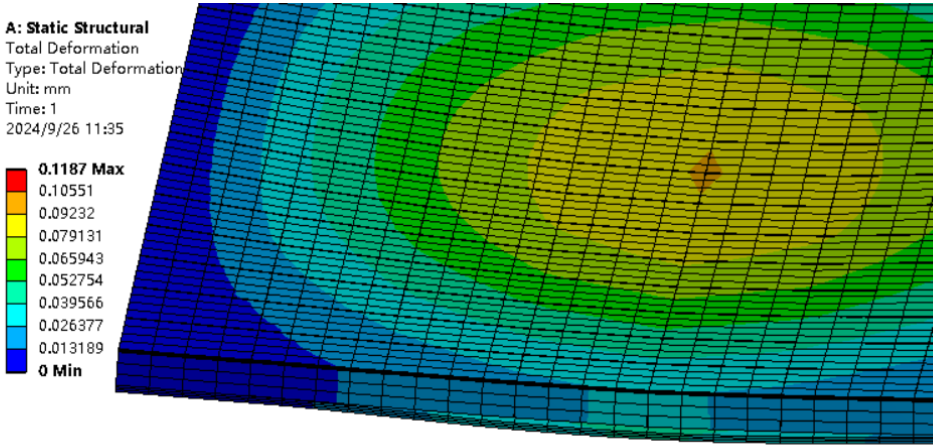


1 module of active layer

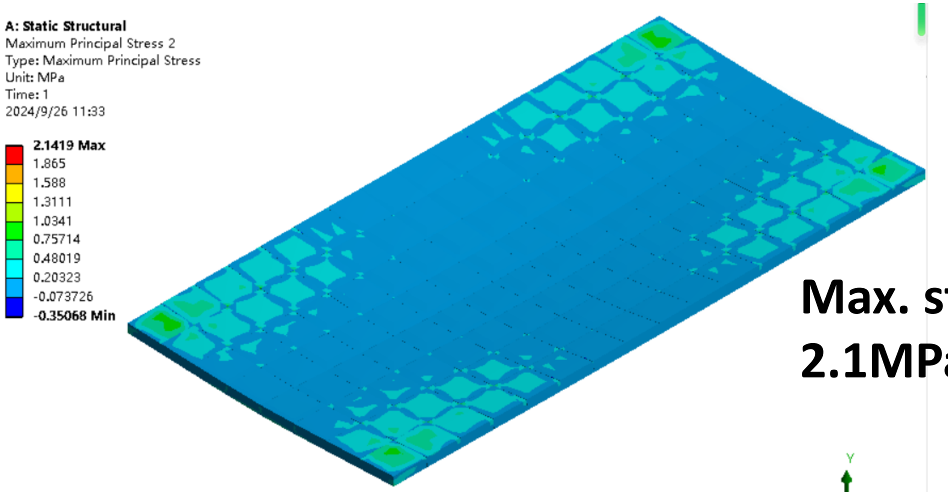
Removing the upper cover plate

5.1 GS-HCAL Mechanical Design (Barrel)

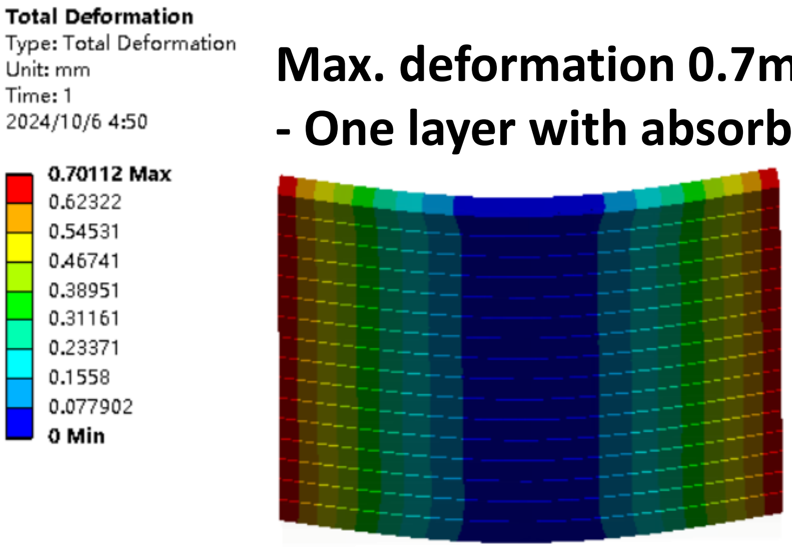
➢ Simulation of one active layer module (320mm × 646mm)



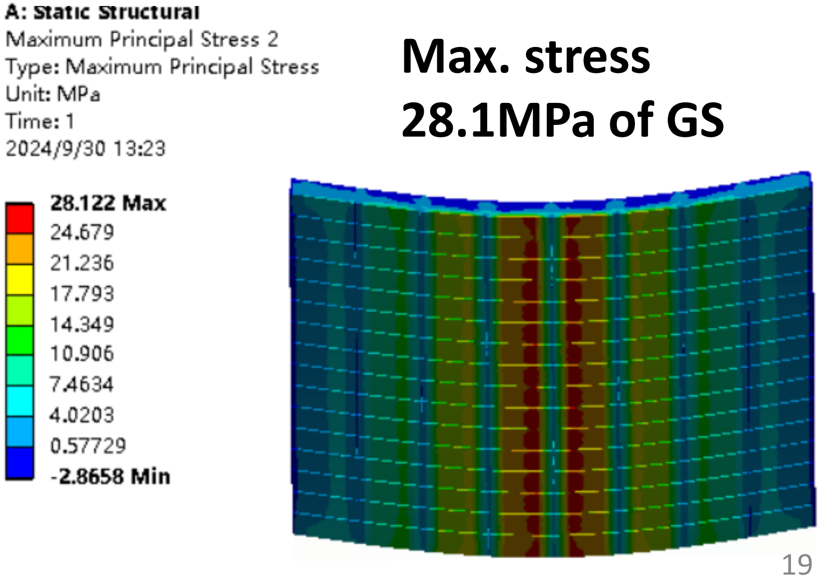
Max. deformation 0.11mm (single active layer)



Max. stress
2.1MPa of GS



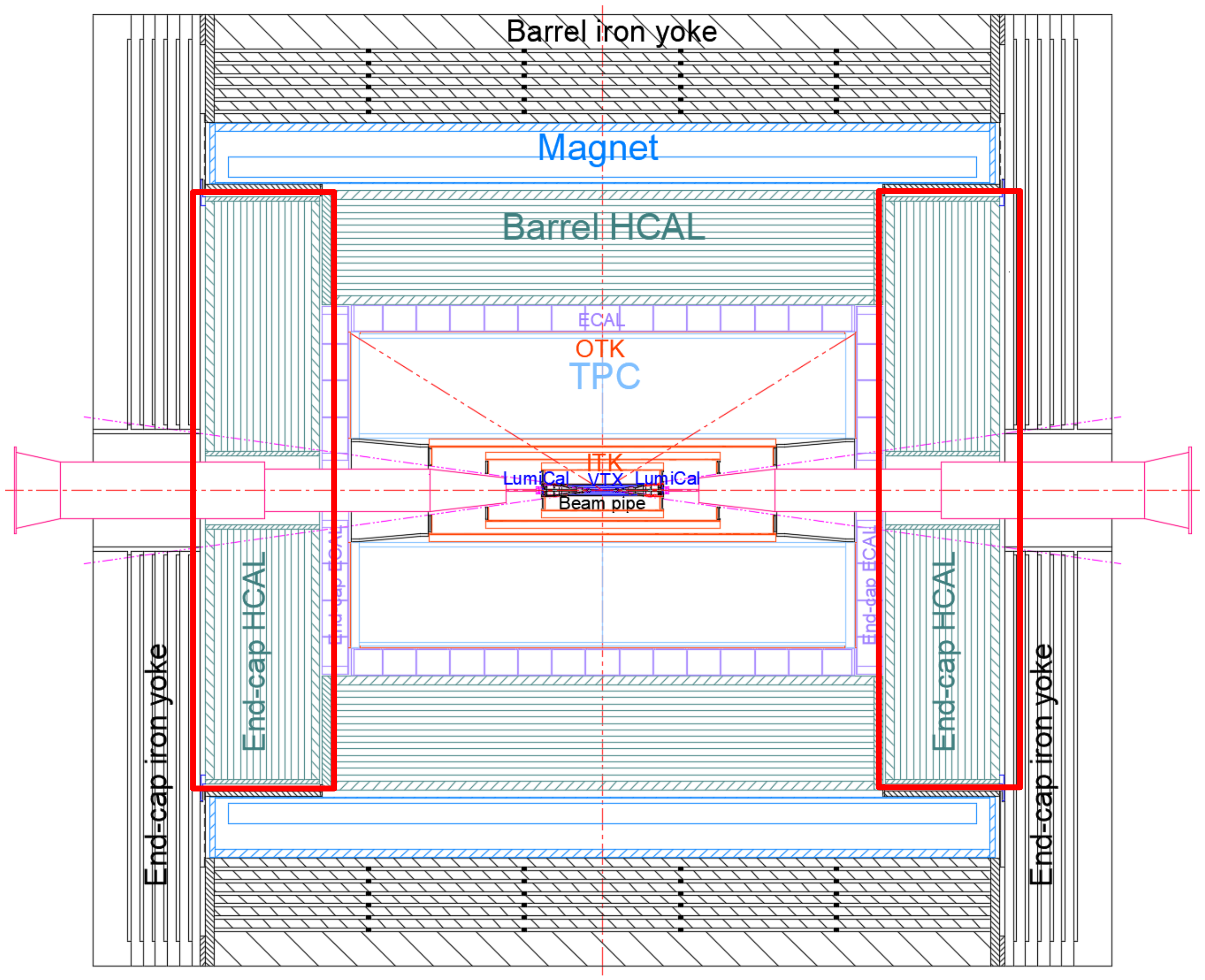
Max. deformation 0.7mm
- One layer with absorber



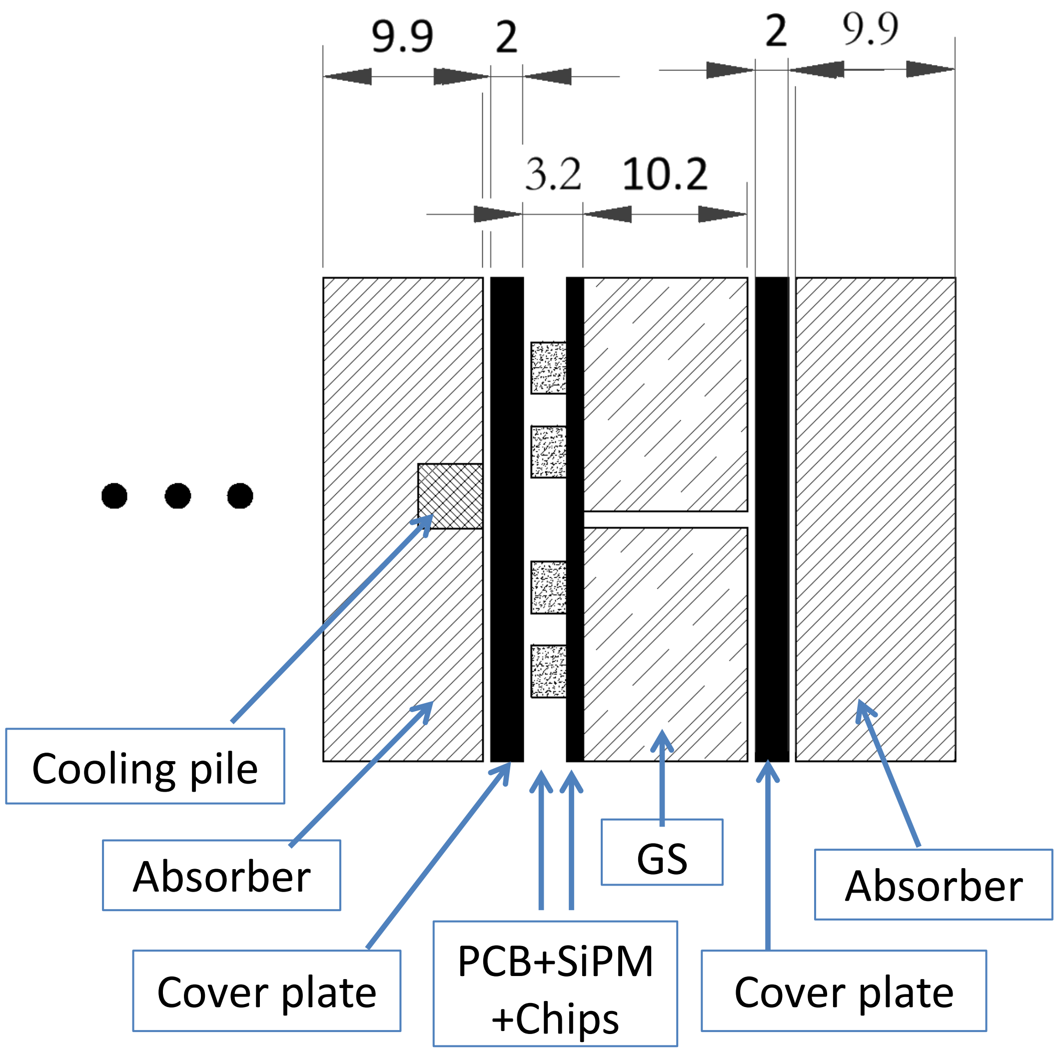
Max. stress
28.1MPa of GS

- The allowable max. stress of GS is about 50MPa

5.2 GS-HCAL Mechanical Design (Endcap)

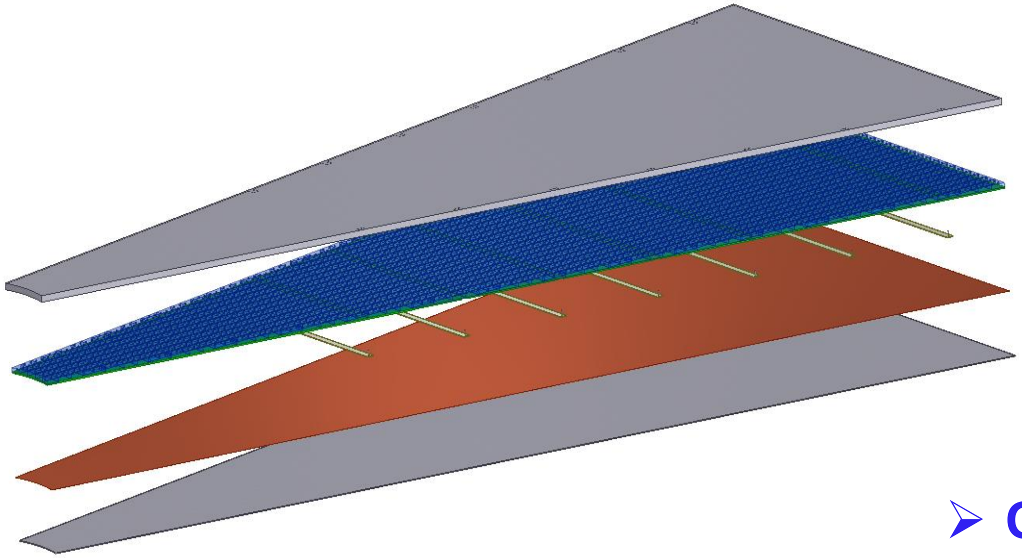


Two GS-HCAL endcap, 360 tons / each

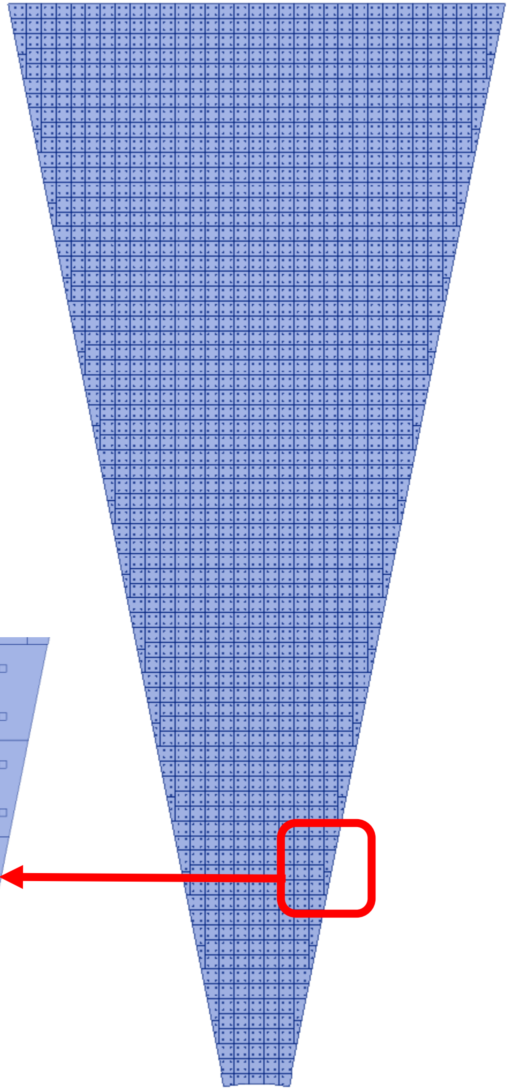


Schematic of one layer

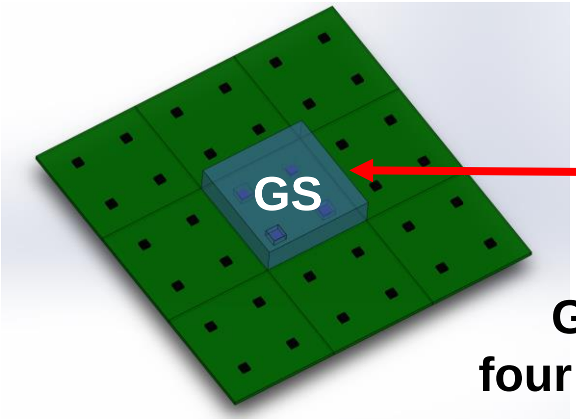
5.2 GS-HCAL Mechanical Design (Endcap)



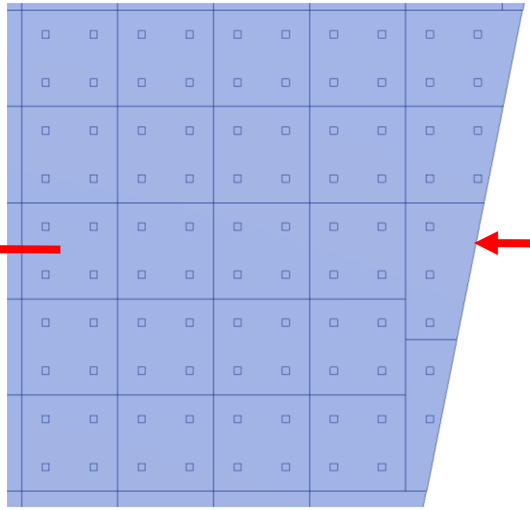
- Cover plate
- GS + PCB
- Tighten Strips
- Thermal Conductor
- Cover plate



- GS cell size: $40 \times 40 \times 10\ mm^3$
- Four special-shaped at edge



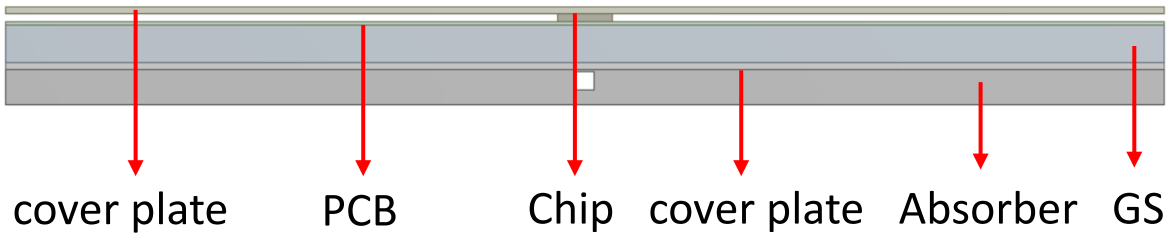
GS-SiPM-PCB
four SiPM ($3x3\ mm^2$)

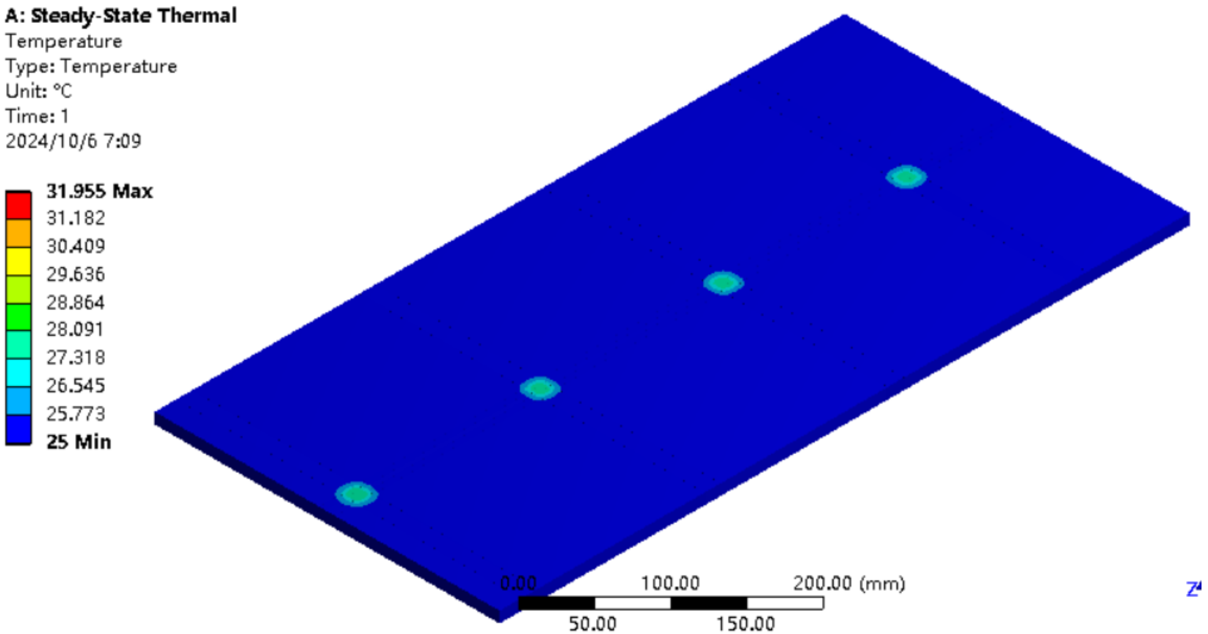


5.3 GS-HCAL Cooling Simulation

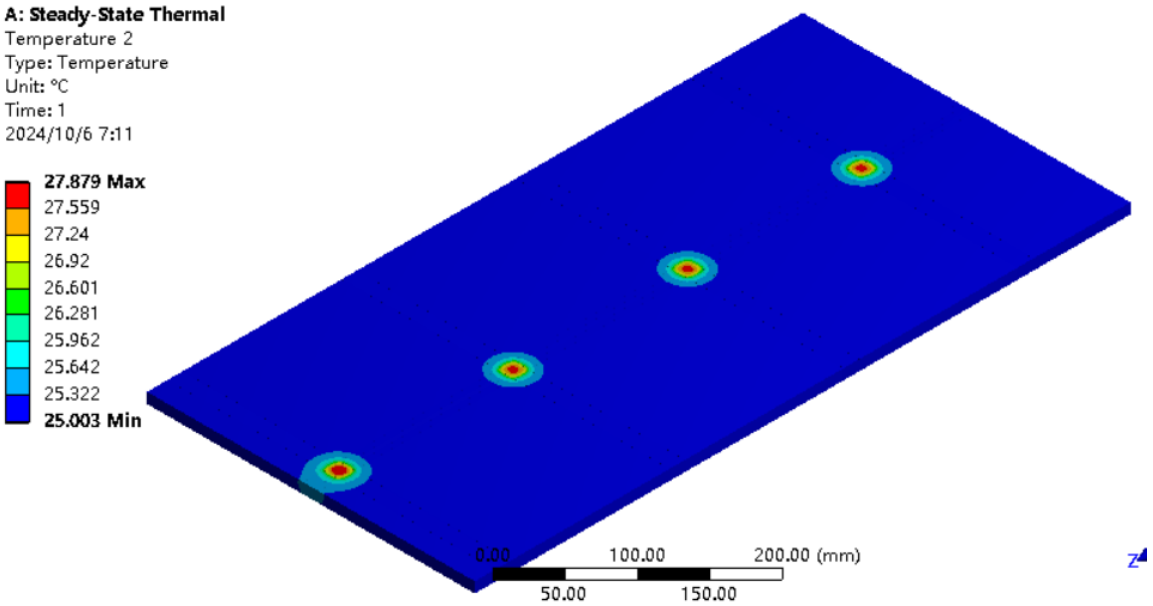
➢ **Cooling simulation of 1 active layer module (320mm × 646mm)**

- Heat source (chip): 15 mW/ch
- coefficient of heat conduction: 5000W/m^2 K;
- Inlet water 25°C, environment temperature is 25°C
- Thermal contact resistance: 500W/m^2





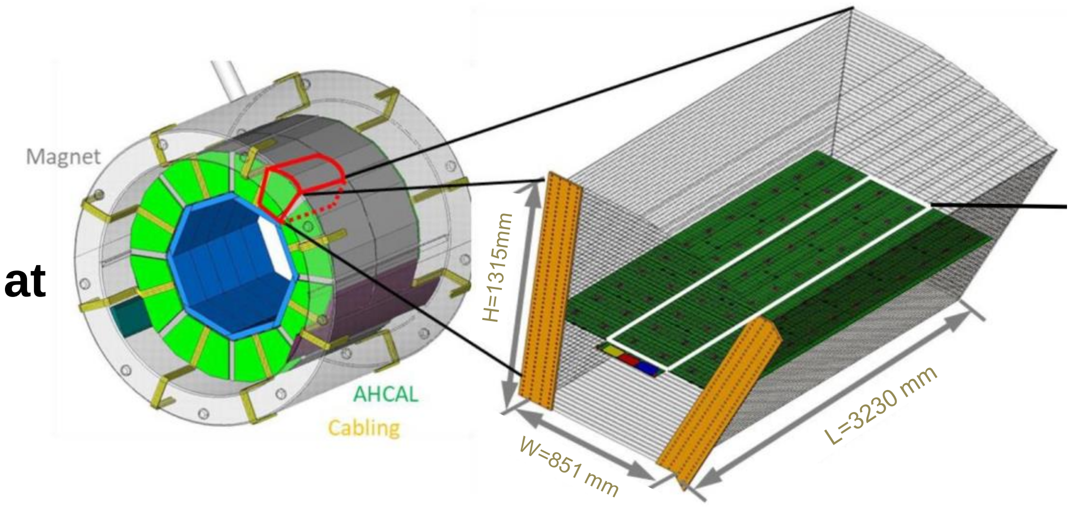
Temperature distribution: 25 ℃ ~ 32 ℃

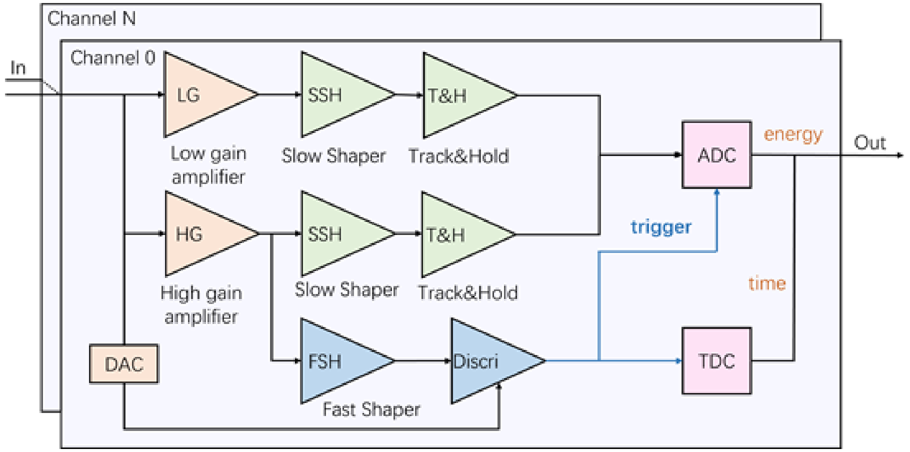


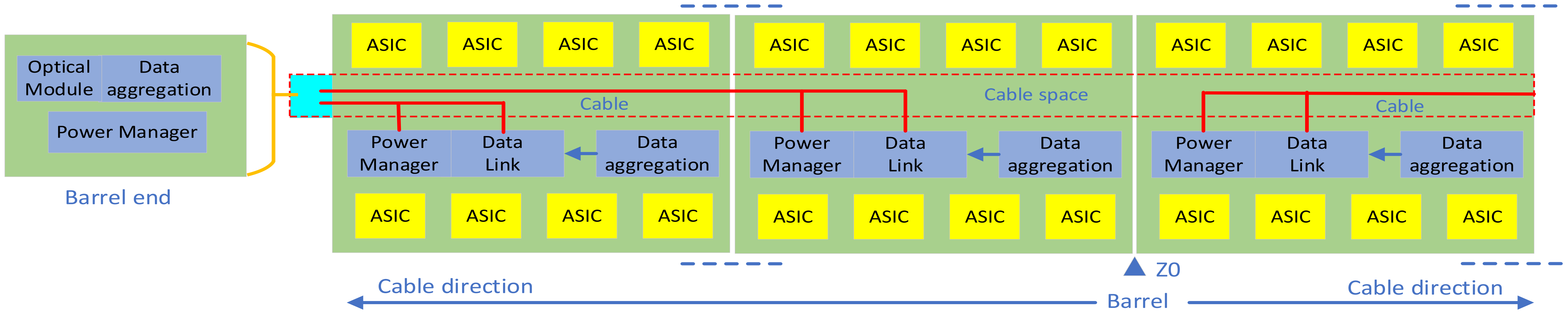
Temperature difference (GS vs SiPM): 2.8 ℃

6. GS-HCAL Readout Electronics

- **Thickness: 3.2mm**
  - PCB 1.2mm
  - ASIC Chip 2mm
- **Aggregation board at the end of barrel**







Aggregation board at the end of barrel, cable connection

7. Cost Estimation: GS-HCAL vs PS-HCAL

Parameter Name	Barrel	Endcaps (x2)	GS-HCAL	PS-HCAL
Inner Radius for HCAL	2140 mm	400 mm	-	-
Length for barrel or Radius	6460 mm	3455 mm (R_{out})	-	-
Longitudinal Depth	$1315\ mm\ (6\lambda_I)$		-	-
Glass Scintillator ($1/cc) Granularity 4cm x 4cm	54.6 m^3	35.6 m^3	GS (90.2 m^3) **$1/cc, $90.2M**	Plastic Scintillator **$1.5/ch, $8.4M**
Material Volume (m^3) Fe (tons, $8/kg)	75.3 m^3	49.2 m^3	124.5 983.6 t ($7.9M)	188.3 m^3 1488 t ($11.9M)
Readout channels	3.4M (5450m^2)	2.2M (3552m^2)	5.6M	5.6M
Power (15mW/ch)	51 kW	33 kW	84 kW	84 kW
SiPM ($1.5/ch)	$5.1M	$3.3M	$33.6M	$8.4M
Electronics: $2.5/ch	$8.5M	$5.5M	$14M	$14M
Total			**$145.7M (x7) ~1020M RMB**	**$42.7M (x7) ~ 299M RMB**

8. Technical Challenges

- **The main technical challenges**
  - R&D of the **high performance Glass Scintillator**
    - e.g. high density, high light yield, large attenuation length, short decay time;
  - **Mass production of high quality GS title and SiPM** in cost effective way；
    - Cost of GS title (40x40x10 mm^3) ~ \$1/cc → further cost reduction ?
    - Hamamatsu HPK / NDL SiPM (3x3 mm^2) ~ \$1.5/ch with O(5M) pieces
    - Optimizing granularity, GS and SiPM couplings to reduce cost
  - Highly integrated, **fully embedded and scalable electronics** with a parallel readout;
  - Design and installation of the **big size and heavy weight** detector structure.

9. HCAL Research Group

- **CEPC-HCAL team：IHEP, USTC, SJTU, XJTU, SCNU, SCU, HEU, ZZU**
  - **Detector for PS/GS-HCAL：** Staff(**9**) + Student(**5**)
  - **Electronics:** Staff(**5**)
  - **Mechanics:** Staff(**3**)
  - **GS Collaboration：** 13 institutes, Staffs (26) + Students (10)

Convener: Sen Qian (IHEP), Jianbei Liu (USTC)

Physics： Manqi Ruan(IHEP)， Haijun Yang (SJTU)

Software: Sengsen Sun(IHEP)

Design: Fangyi Guo(IHEP), Hengne Li(SCNU), Qingming Zhang(XJTU), Weizheng Song(IHEP), Peng Hu(261)
Dejing Du(IHEP), Hongbing Diao(SUTC), Jiyuan Chen(SJTU), to design the GS-HCAL based on CEPCSW;

Glass Scintillator: Sen Qian(IHEP), Jing Ren(HEU)， the GS collaboration (13 institutes, 26 staffs +10 students);

SiPM: Yuguang Xie(IHEP), Jifeng Han(SCU), Guang Luo(SYSU), SiPM and electronics for the GS performance test;

Electronics: Jingfan Chang(IHEP), to design the ASIC and FEE, power supply, cables etc.;

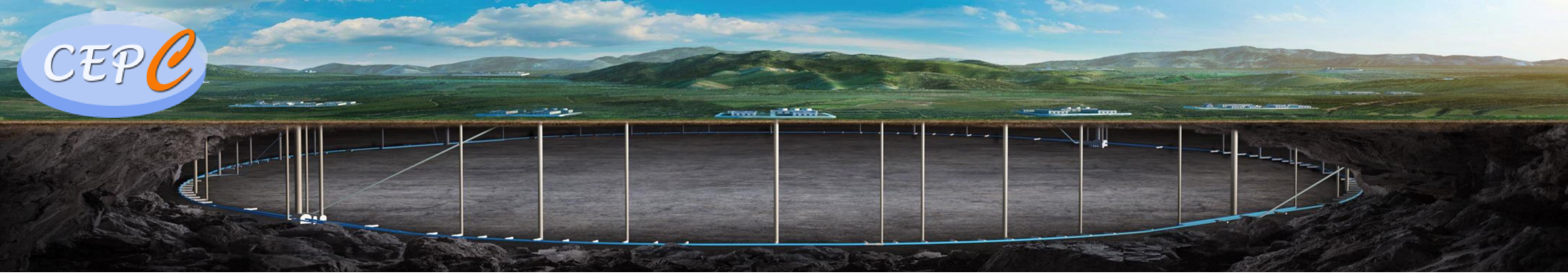
DAQ: Chen Boping(IHEP)

Mechanics and cooling system: Yatian Pei(IHEP), Junsong Zhang(IHEP), Shang Bofeng(ZZU)

Detector： Boxiang Yu(IHEP), Yunlong Zhang (USTC), Yong Liu (IHEP), GS-HCAL module, TB and cosmic test;

10. Summary and Plan

- **Detector**
  - R&D of high quality GS and develop technique for mass production
  - Optimize GS title granularity (cell size), GS and SiPM coupling
  - GS-HCAL prototype for beam test
- **Electronics**
  - Optimization of readout electronics design
- **Mechanics**
  - Optimization of the mechanic design
  - Optimization of the cooling design
- **Simulation and Performance with CEPCSW**
  - Optimization of GS-HCAL design
  - GS-HCAL full simulation and reconstruction for benchmark physics



Thanks for your attention !

7. Cost Estimation: PS-HCAL

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for HCAL	2140 mm	400 mm	NA
Length for barrel; Outer radius for endcap*	6460 mm	3455 mm	NA
Longitudinal Depth	$1315\ mm\ (6\lambda_I)$		NA
Plastic Scint. ($1.5/ch) Granularity 4cm x 4cm	5450 m^2	3552 m^2	9002 m^2 ($8.4M)
Material Volume (m^3) Fe (tons, $8/kg)	114 m^3	74.3 m^3	188.3 m^3 1488 t ($11.9M)
Readout channels	3.4M (5450m^2)	2.2M (3552m^2)	5.6M
Power (15mW/ch)	51 kW	33 kW	84 kW
SiPM ($1.5/ch)	$5.1M	$3.3M	$8.4M
Electronics: $2.5/ch	$8.5M	$5.5M	$14M
Total	**$42.7M (x 7) ~ 299M (RMB)**		

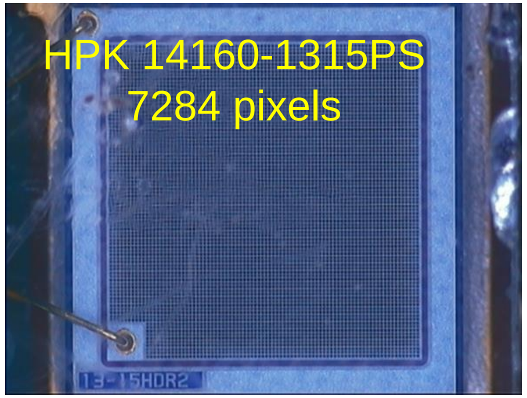
7. Cost Estimation: RPC-SDHCAL

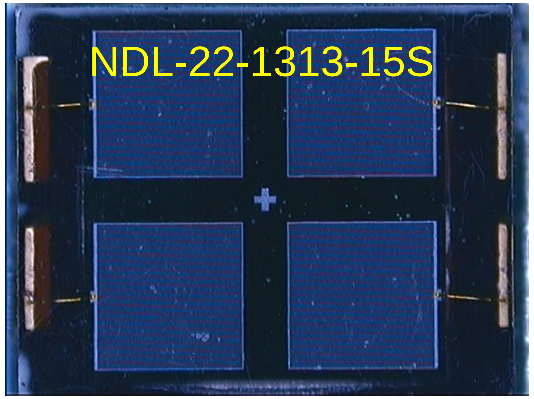
Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for HCAL	2140 mm	400 mm	NA
Length for barrel; Outer radius for endcap*	6460 mm	3455 mm	NA
Longitudinal Depth	$6\lambda_I$ (Thickness depends on each option)		NA
RPC + Casette (\$1425/m^2) Granularity 2cm x 2cm	5450 m^2	3552 m^2	9002 m^2 (\$12.9M)
Material Volume (m^3) Fe (tons, \$8/kg)	86 m^3	56 m^3	142 m^3 1122 t (\$9M)
Readout channels	13.6M (5450m^2)	8.9M (3552m^2)	22.5M
Power (kW) 1.4mW/ch, 5.4W/DIF/m^2	48.5 kW	31.6 kW	80.1 kW
Electronics: \$1/ch	\$13.6M	\$8.9M	\$22.5M
Total	**\$44.4M (x 7) ~ 311M (RMB)**		

SiPM

NIMA 980 (2020) 164481

- **HPK-SiPM**
  - Low PDE, dark rate and crosstalk
  - High breakdown voltage
  - Better quality control
- **NDL-SiPM**
  - High PDE, dark rate and crosstalk
  - Low breakdown voltage
  - Low price

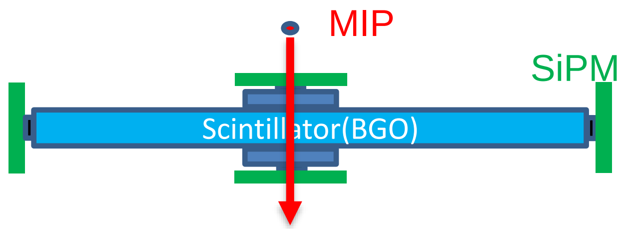


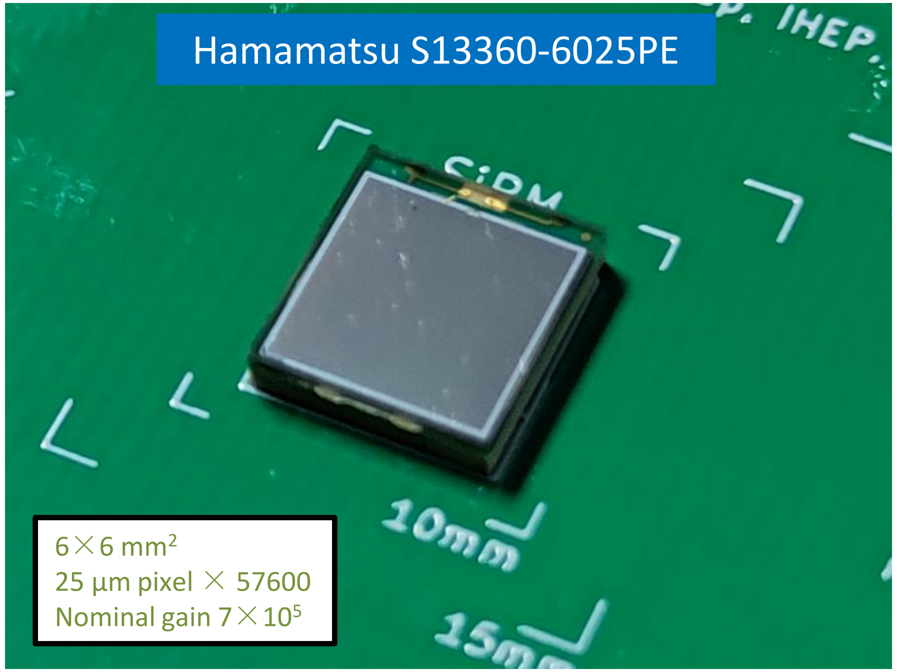


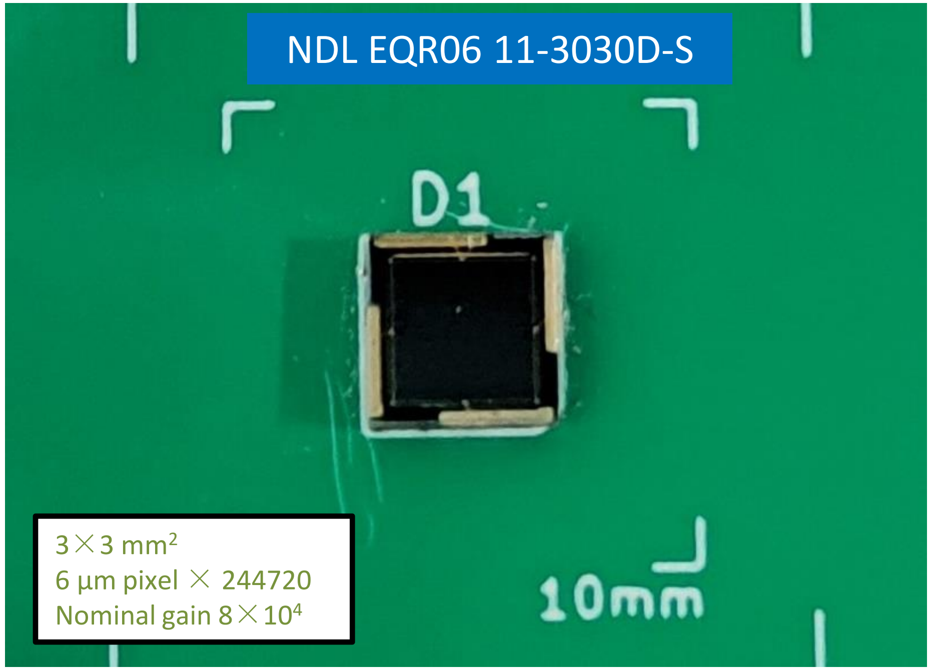
Company	HPK			NDL
Type	13360-1325PE	14160-1315PS	14160-3015PS	22-1313-15S
Light output [p.e.]	13	17		20
Crosstalk[%]	1.59	1.17		4.4
Dark Counts [kHz]	120	290	700	550
Breakdown[V]	53	38	38	27.5

SiPM

- **SiPM Options：**
  - **HPK S13360-6025PE，57600 pixels**
  - **NDL EQR06 11-3030D-S，244760 pixels**
  - **HPK S14160-3015PS，39984 pixels**
  - **HPK S14160-3025PS, 14440 pixels**

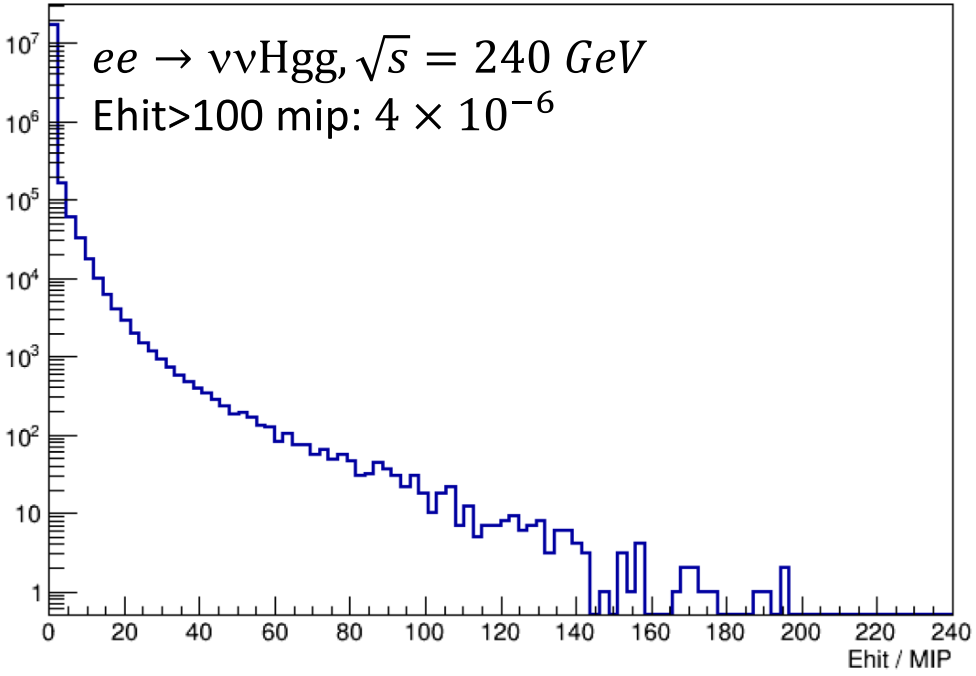


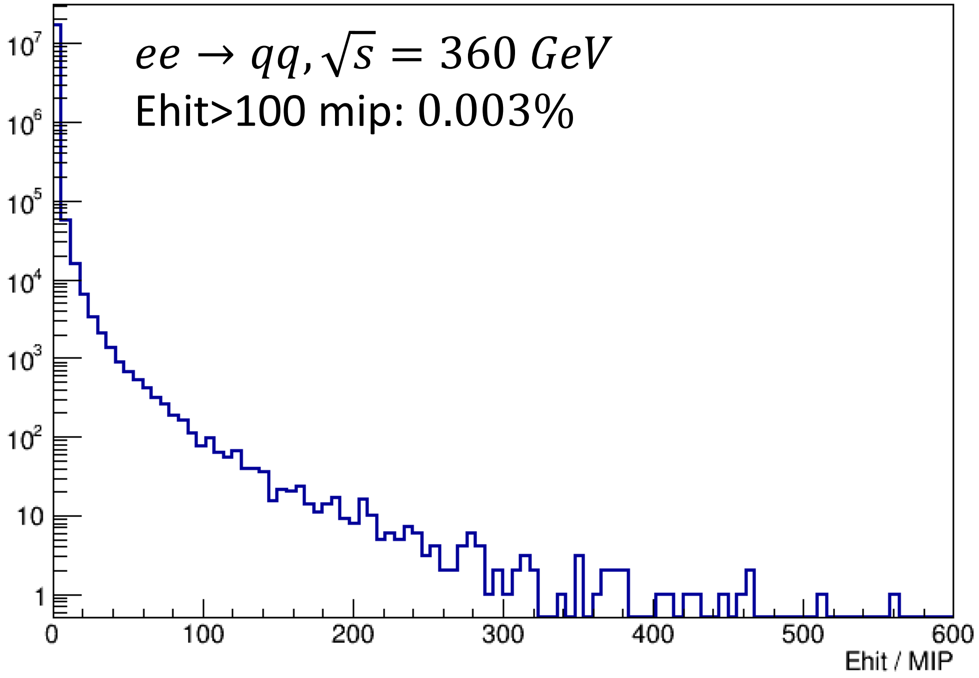




Key parameters to energy resolution

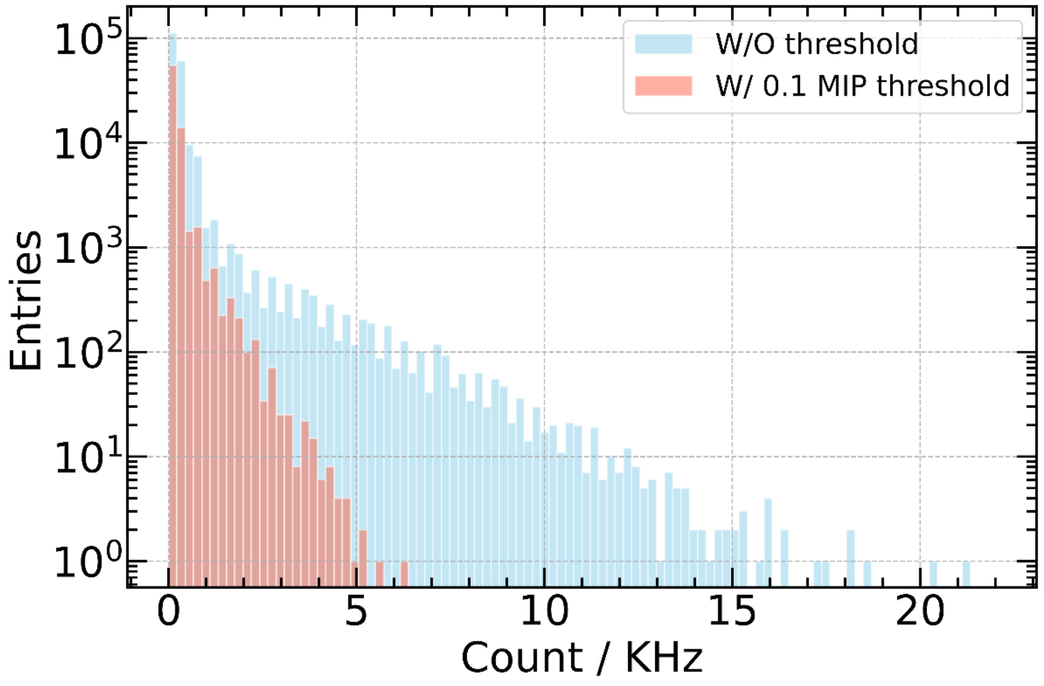
- **Dynamic range: 0 ~ 100 MIP can cover >99.99% cases**
  - For SiPM: 8000 p.e. can be controlled in linear range (suppose LY ~ 80 p.e./MIP).
  - For electronics: 1~1k can be achieved.
  - Considering the common electronics design for ECAL, HCAL and Muon, HCAL's demands can be covered by ECAL.

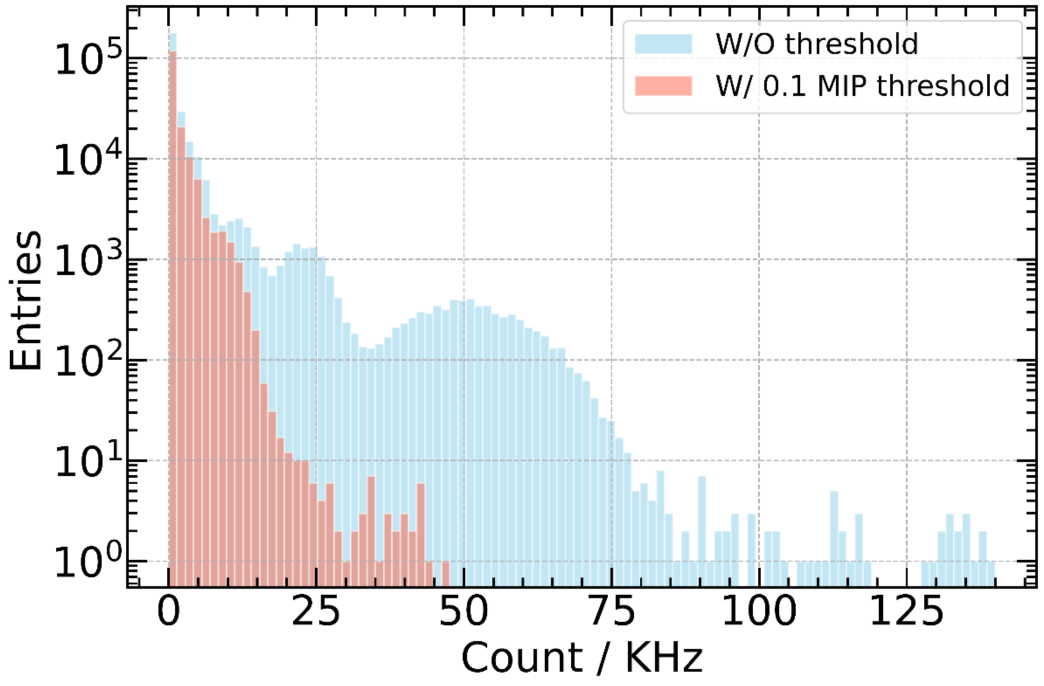




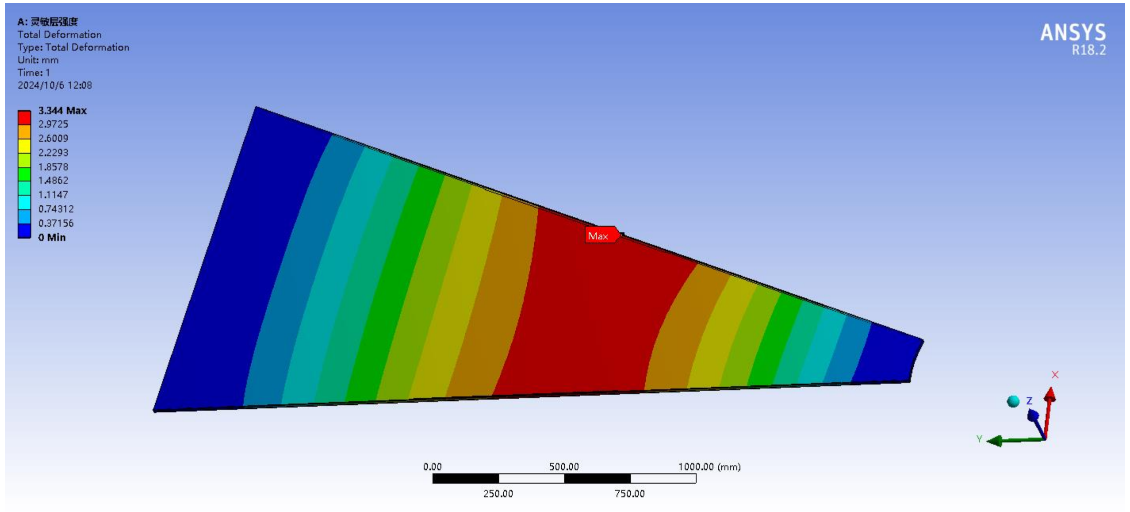
4.4 GS-HCAL Background Estimation

- **Simulation of beam background processes:**
  - 50 MW(H), bunch spacing 355 ns, with pair production, single beam processes
  - Event rate with 0.1 MIP threshold: barrel < 5 kHz, endcap < 50 kHz

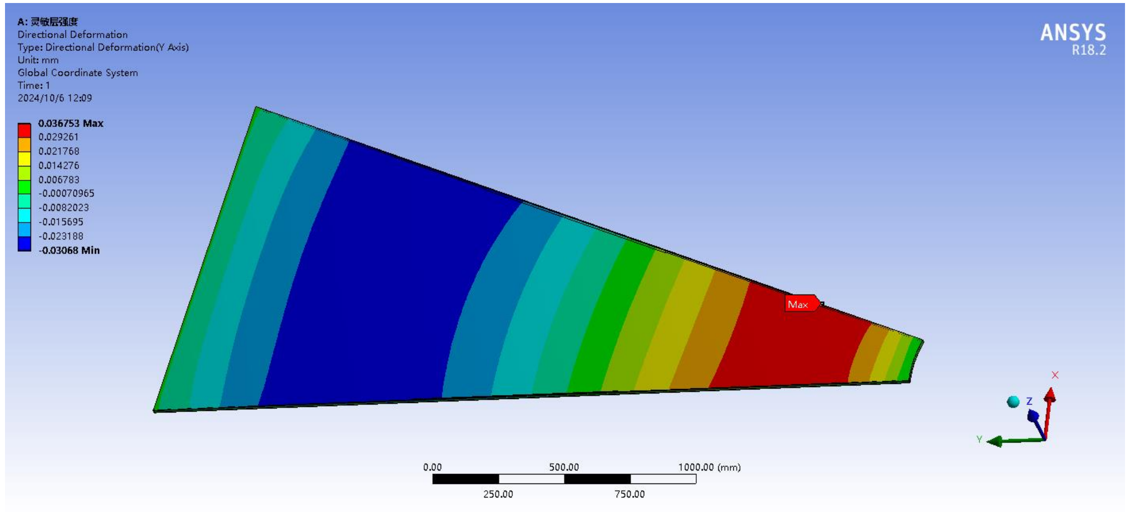


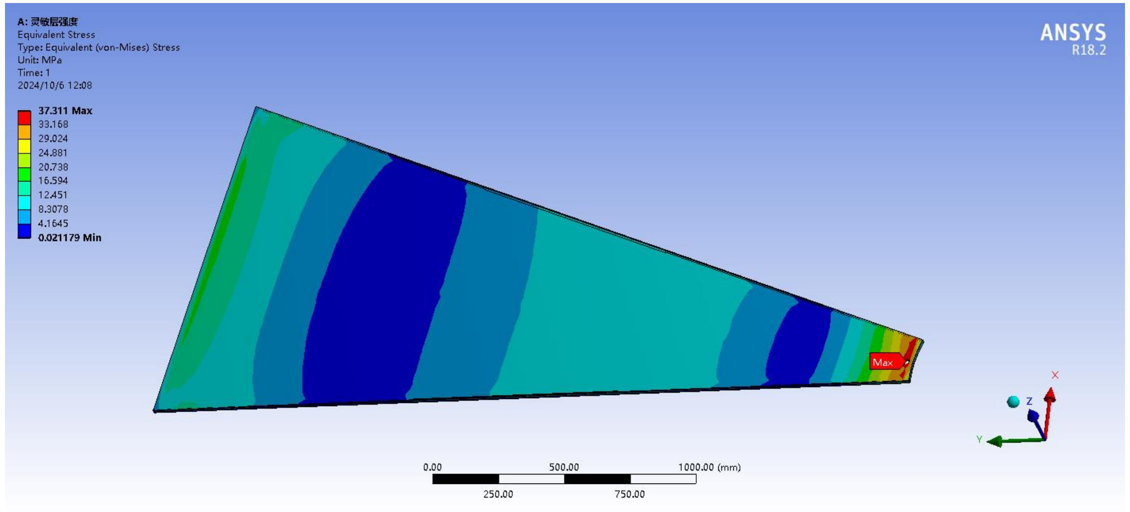


5.2 GS-HCAL Mechanical Design (Endcap)

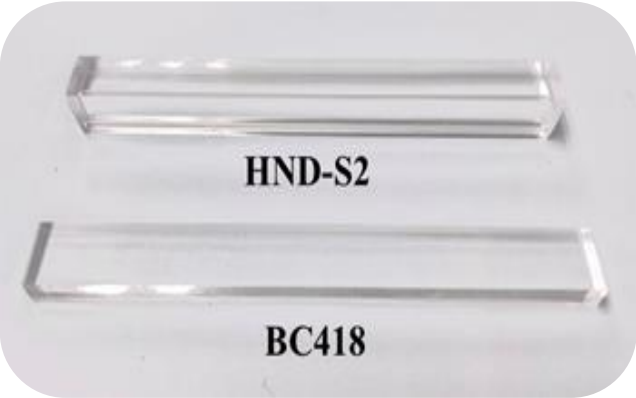


- Max. deformation in one active layer: 3mm (due to gravity)
- Horizontal extrusion deformation: 0.037mm
- Max. principal stress at narrow end: 37MPa

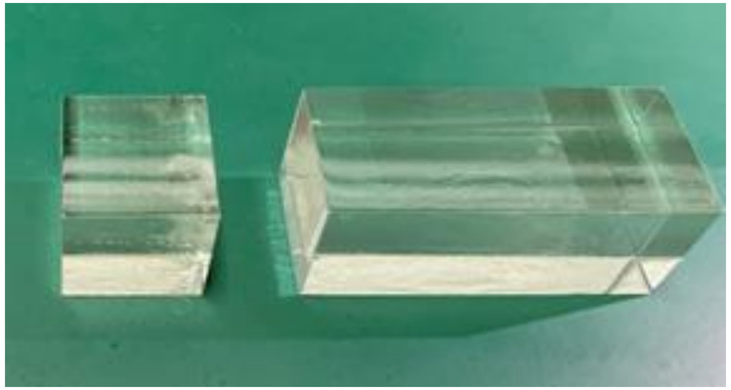




3.3 Comparison of Scintillators



Plastic Scintillator



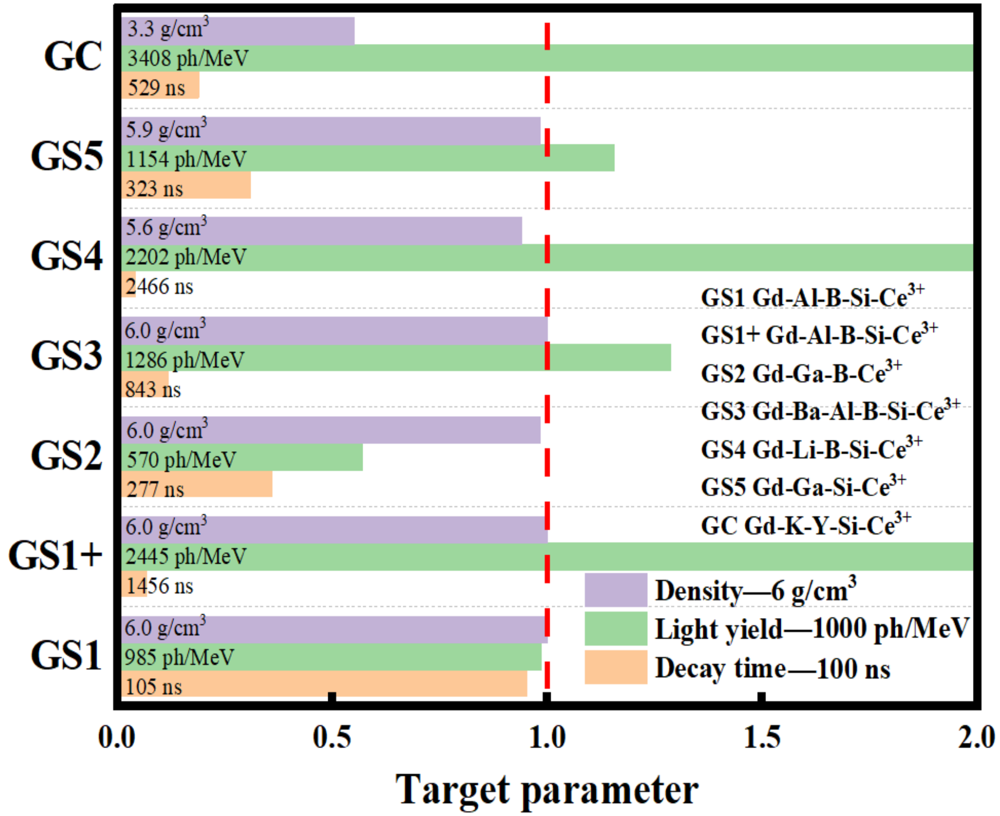
Glass Scintillator

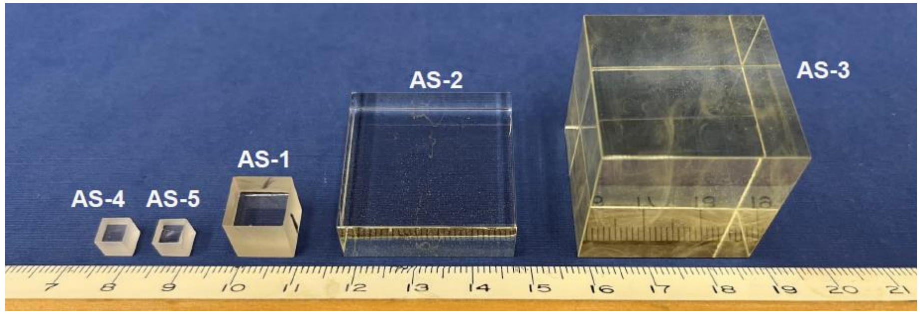
Crystal Scintillator

	Plastic Scintillator	Glass Scintillator	Crystal Scintillator
Large density	★	★★	★★★
High light yield	★★	★★	★★★
Energy resolution	★	★★	★★★
Low cost	★★★	★★	★
Fast decay	★★★	★★	★★
Large size	★★★	★★	★★

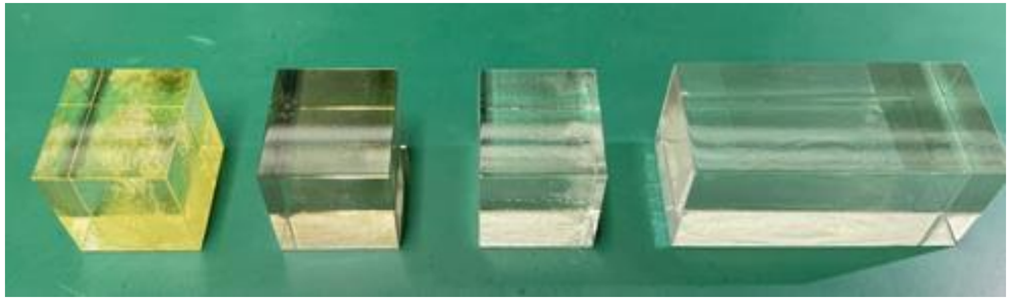
1. GS-HCAL: Sample test

Parameters	Unit	BGO	GS1	GS1+	GS5
Cost		1	0.1 ?		
Density	g/cm^3	7.13	6.0	6.0	5.9
Transmittance	%	82	70	80	80
Refractive Index	--	2.1	1.74	1.71	1.75
Emission peak	nm	480	400	390	390
Light yield, LY	ph/MeV	8000	985	2445	1154
Energy resolution, ER	%	9.5	30.3	25.8	25.4
Decay time	ns	60, 300	36, 105	101,1456	90, 300





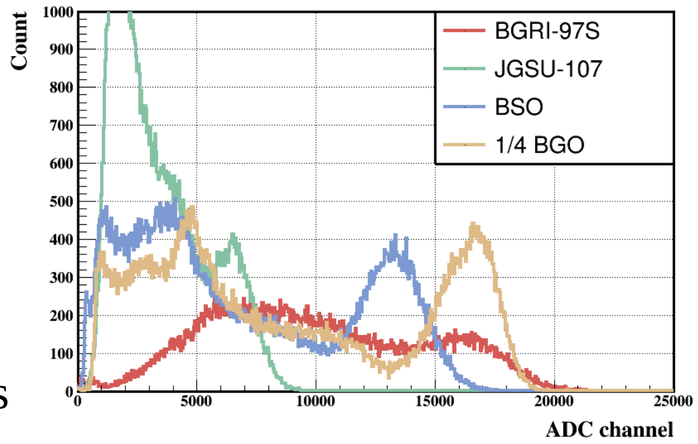
The samples (called AS glass) post to EIC for the test.



1. GS-HCAL: Sample test

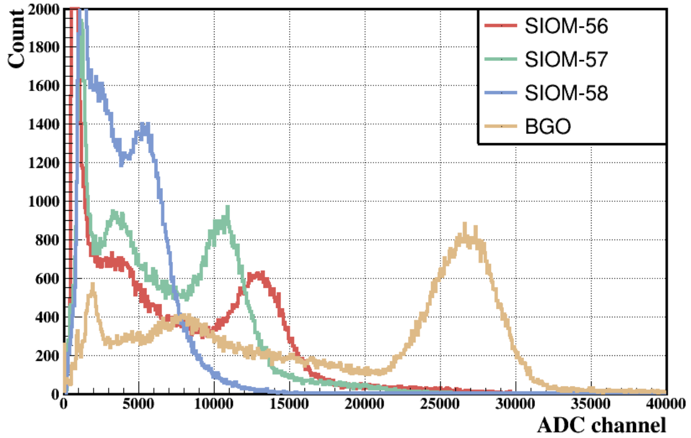
Small-Size Sample

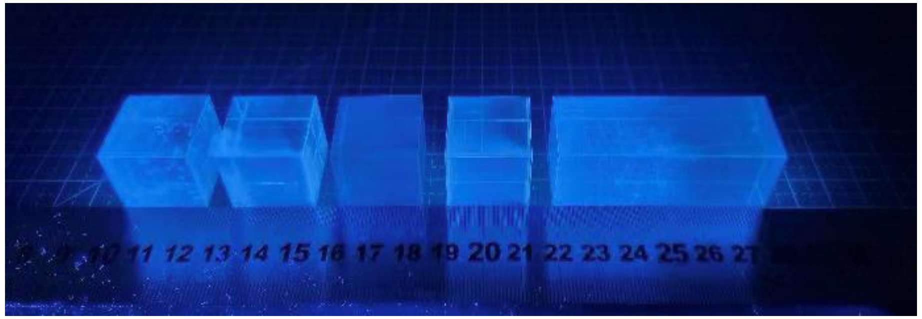
- **Size=5*5*5 mm^3**
- Density~6.0 g/cm^3
- **LY~2445 ph/MeV**
- ER=25.8%
- LO in 1μs=1074 ph/MeV
- Decay=**101** (2%), 1456 ns

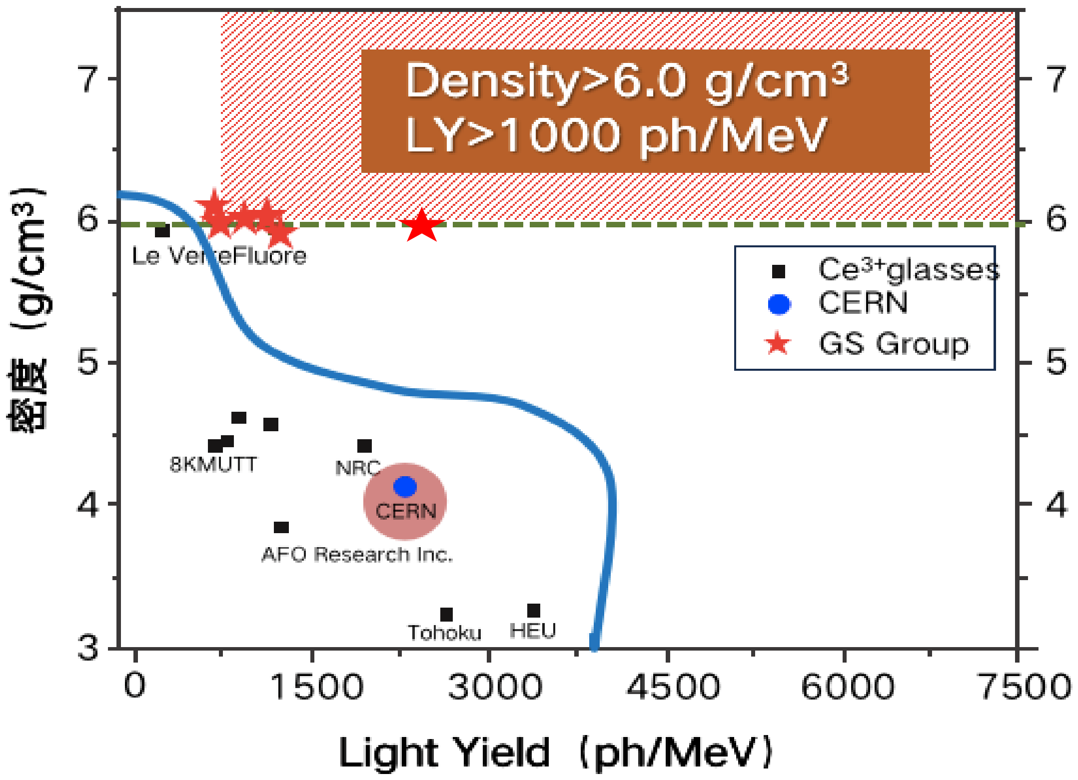


Large-Size Sample

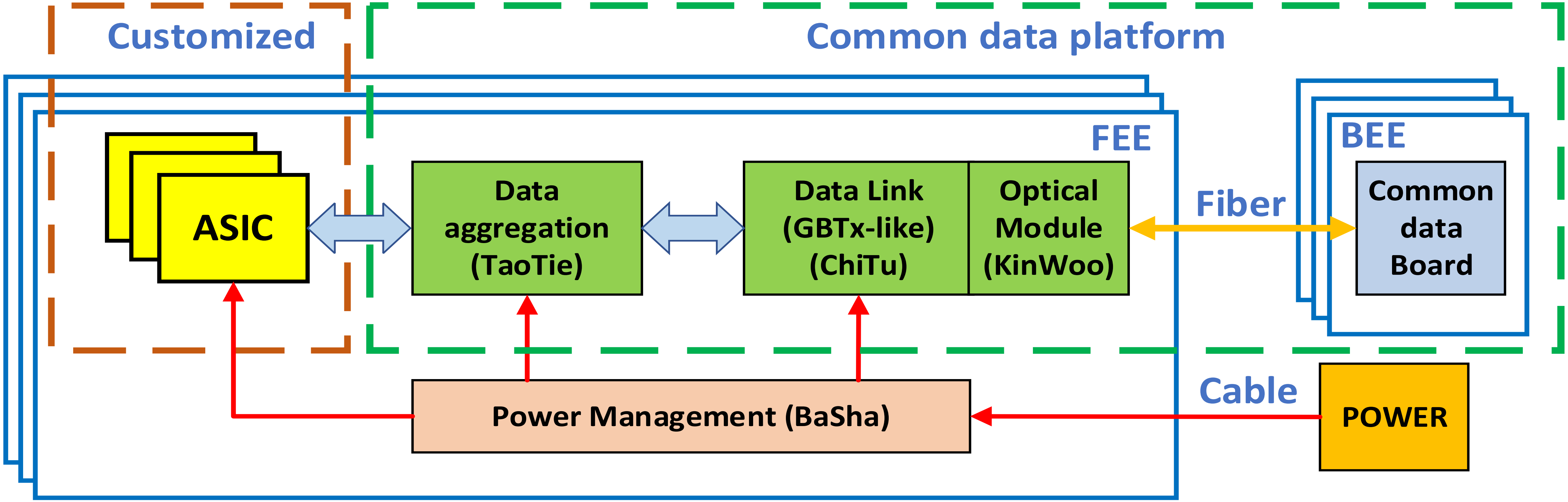
- **Size=40*40*10 mm^3**
- Density=6.0 g/cm^3
- **LY ~1200 ph/MeV**
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns







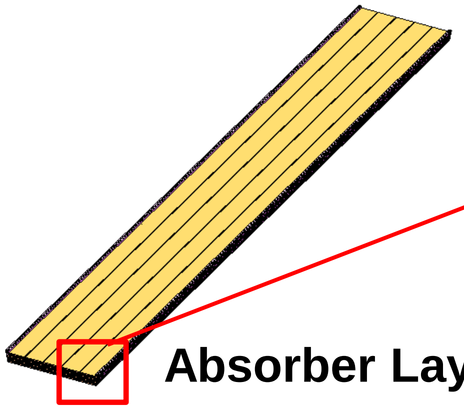
6. GS-HCAL Readout Electronics



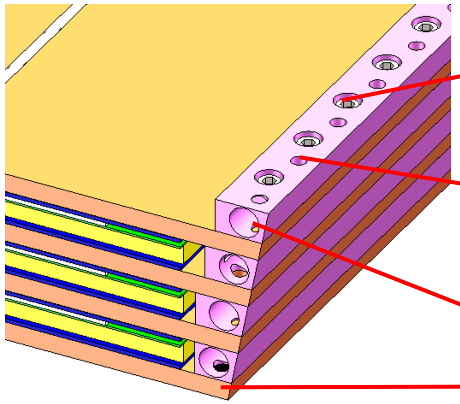
- **Energy Measurement:** ASIC for ECAL & HCAL
- **Data transmission:** common data platform (see electronics report)
- **Trigger mode:** FEE trigger-less readout

5.1 GS-HCAL Mechanical Design (Barrel)

- **Absorber layer structure**



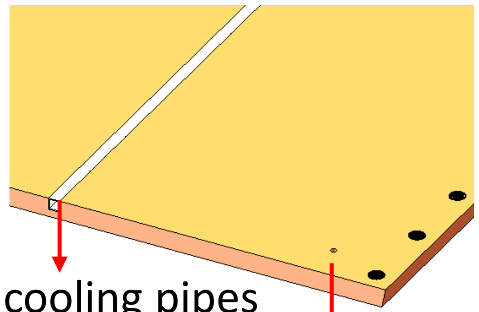
Absorber Layers



The bolts go through the upper trapezoid plate, the lower absorber layer and fix it with the lower trapezoid plate

Screws used for fix the upper absorber plate and upper trapezoid plate

Screws used for fix the edge sealing

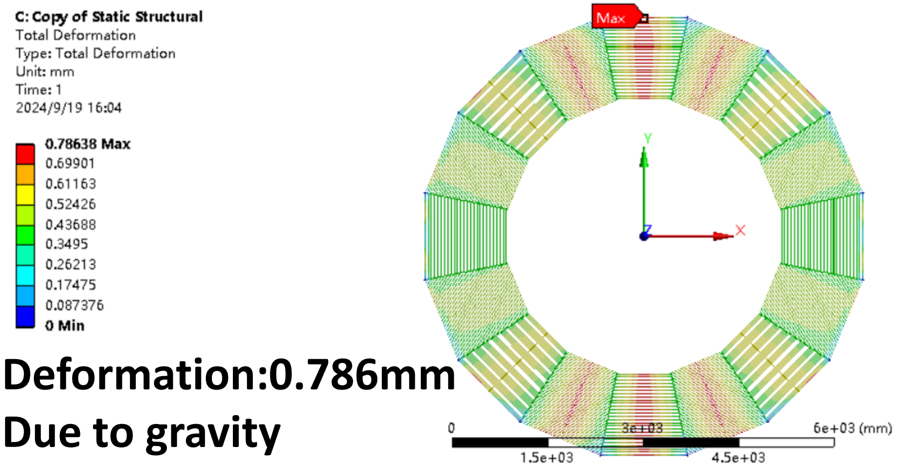


4 cooling pipes for each layer

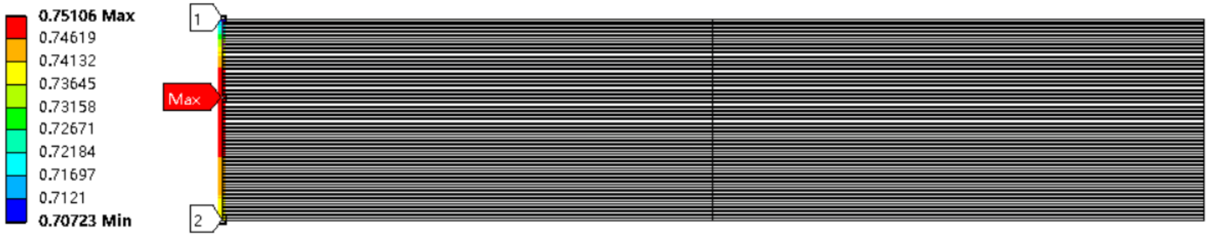
Screw for fixing active layer module

module (320mm × 646mm)

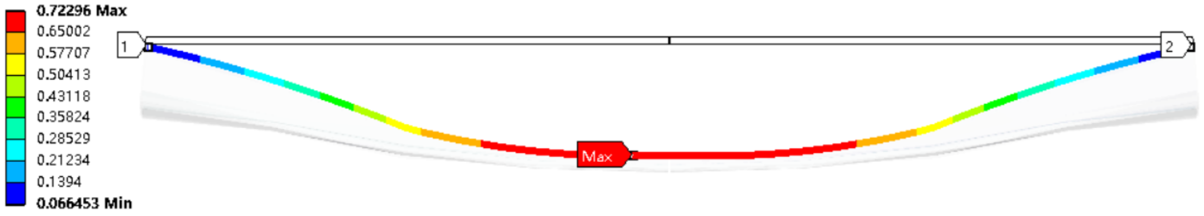
- **Simulation of absorber structure**



Deformation:0.786mm
Due to gravity



Deformation difference between 48 layers is lower than 0.05mm



Deformation difference within 1 layer is lower than 0.7mm

3. GS-HCAL Mechanical Design

- Assembling of one division

①

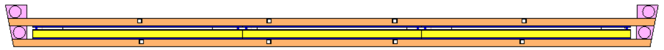
First absorber

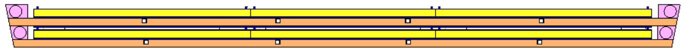
②

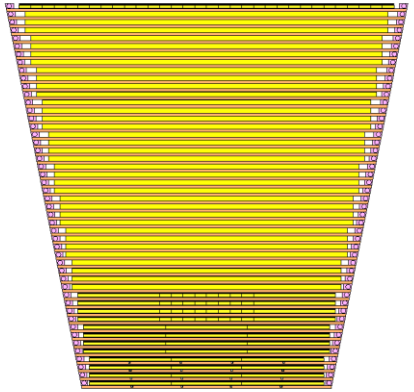
First trapezoid plate

③

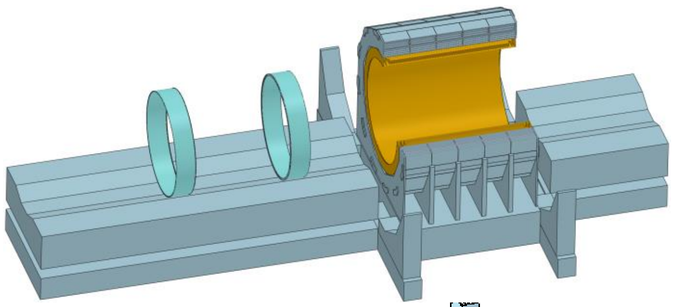
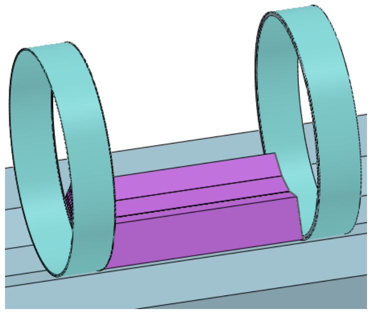
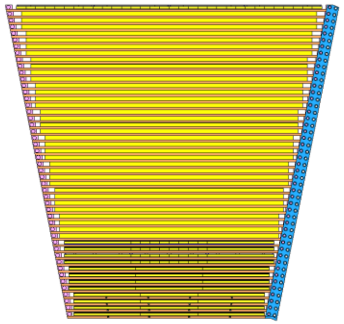
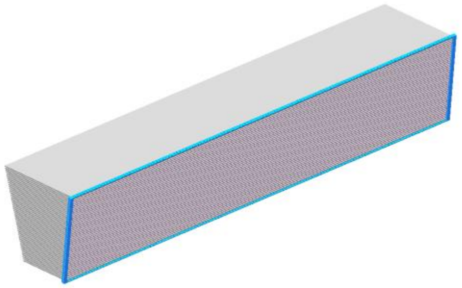
First active layer

④

Second absorber and trapezoid plate

⑤

Second active layer

⑥

One division

- Installation





Using edge sealing to connect two division