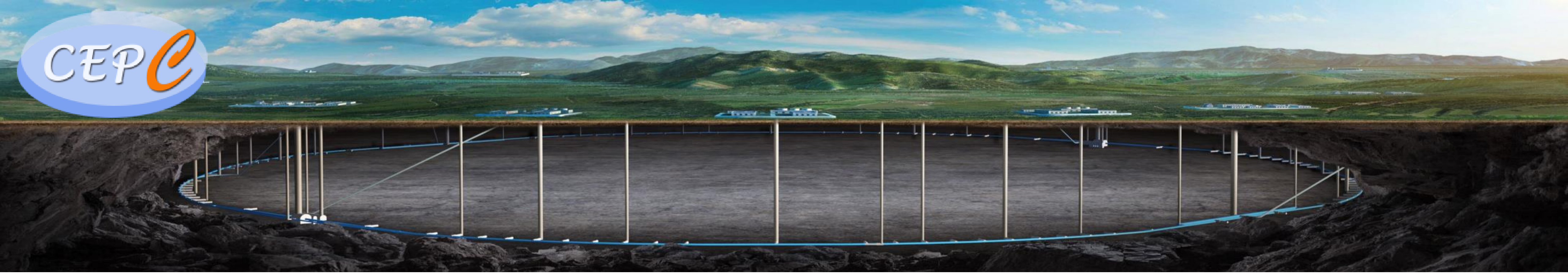

CEPC HCAL Detector

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Content

1. Introduction

- This talk focuses on the design and developments of the hadronic calorimetry system (HCAL) - related to the RefDet TDR Chapter 7
- General remarks: the calorimetry system is based on Particle-Flow Algorithm (PFA)
- Aim to achieve excellent Boson Mass Resolution (BMR) of 3~4%；

RefDet TDR Outline

Chapter 7 Hadron calorimeter

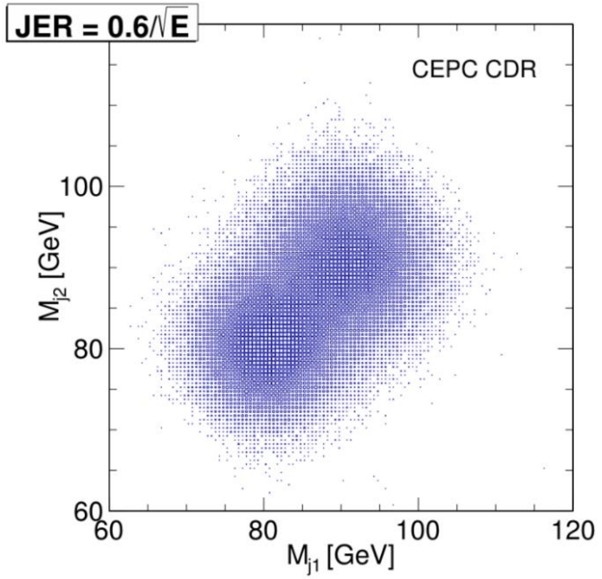
2. Motivation and Requirement

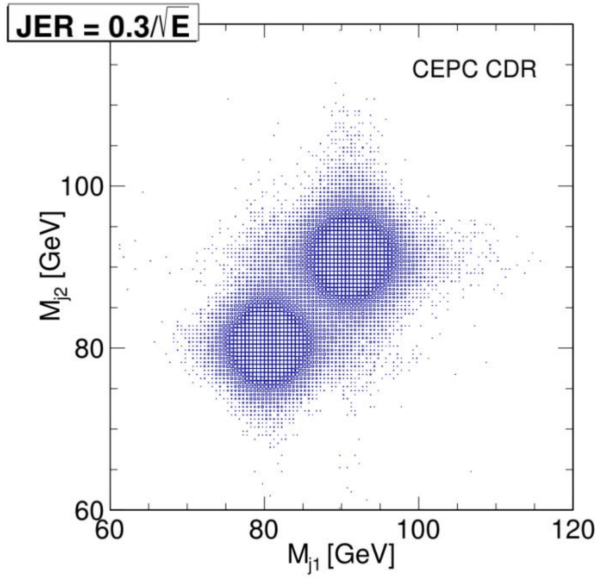
CEPC as Higgs/W/Z boson factories

- 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



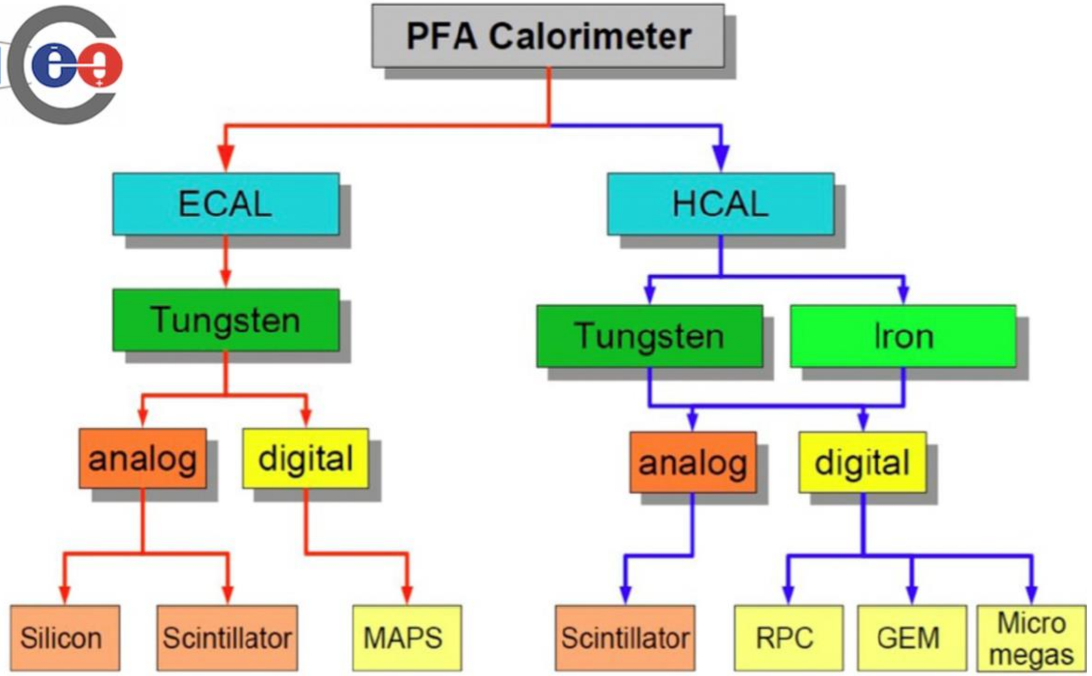


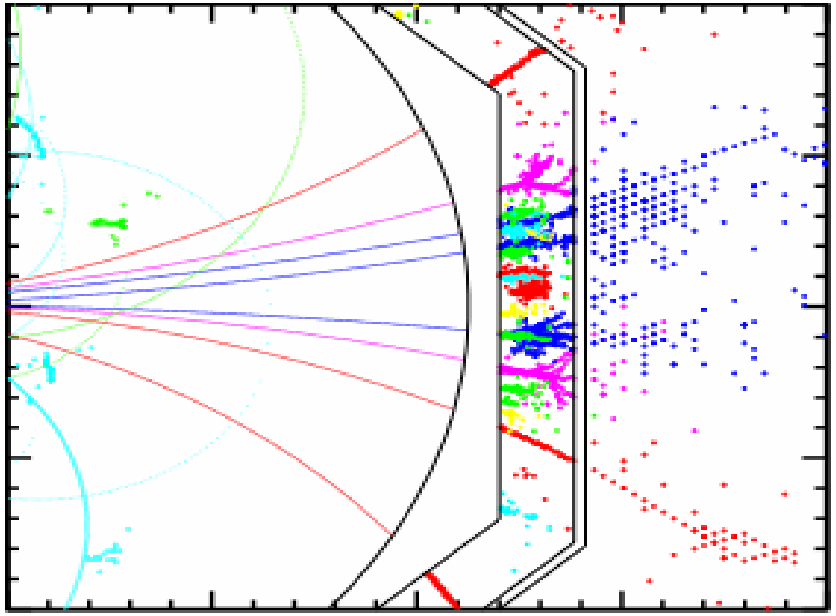
2. Motivation and Requirement

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 – 400 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

3. Technology Survey and Our Choice

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





PFA calorimetry: various options explored in the CALICE collaboration in past 20 years

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

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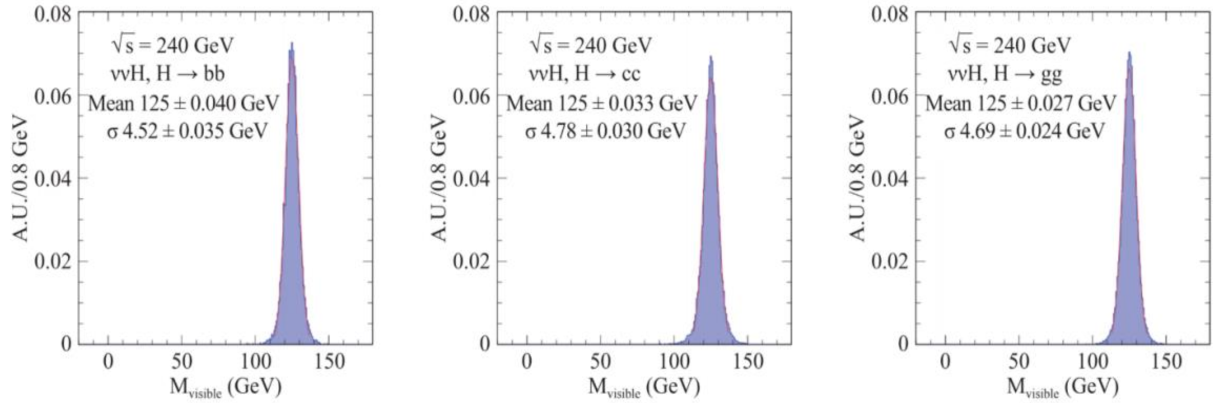
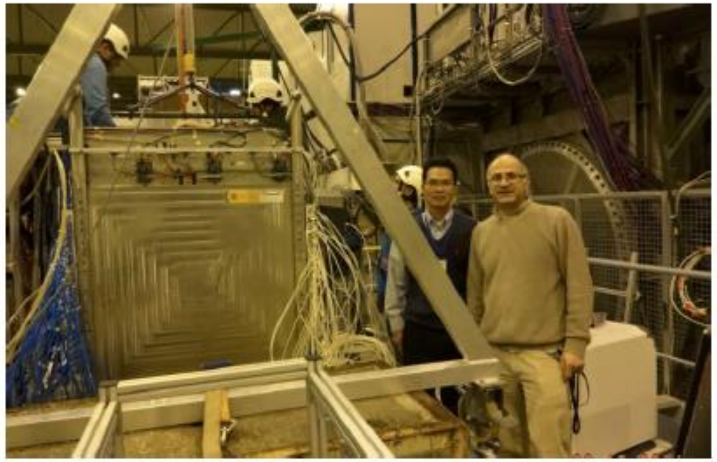
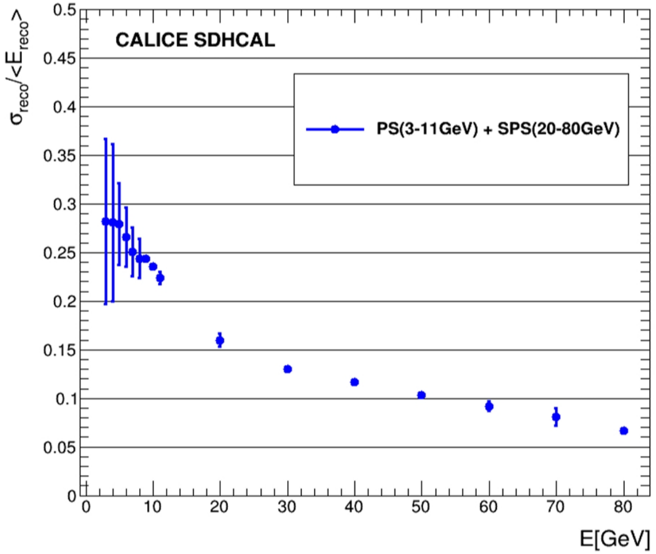


Fig. 8. (color online) Distributions of the reconstructed total visible invariant mass for $H \to bb, cc, gg$ events after event cleaning and fitted by Gaussian functions. The resolutions (sigma/mean) of the fitted results are 3.63% (bb), 3.82% (cc), and 3.75% (gg).

SDHCAL (1m³), 3 thresholds, TB at CERN





■ DHCAL performance (CDR)

$H \to gg$: 3.75%

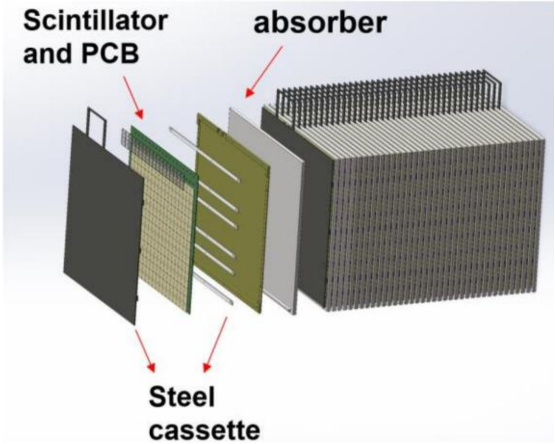
(Full Simu. + Arbor Rec.)

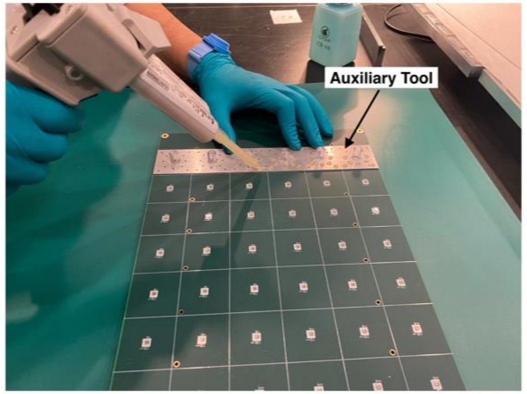
[*JINST* 17 P07017 (2022)]

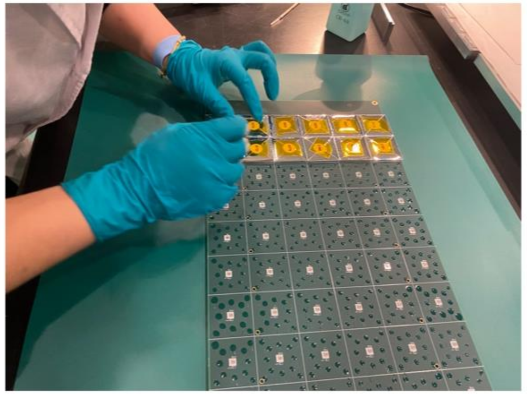
3.2 Plastic Scintillator HCAL (Prototype)

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

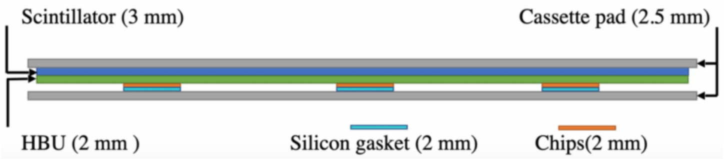
Calo	Layers	material	Absorber	Granularity	Electronics	Thickness	Resolution	Weight
PS-HCAL	40	PS+SiPM S14160-1315	Fe	$4\times4\ cm^2$	SPIROC-2E 12960-ch	$4.6\ \lambda_I$	$60\%/\sqrt{E}\oplus3\%$	5.0 T

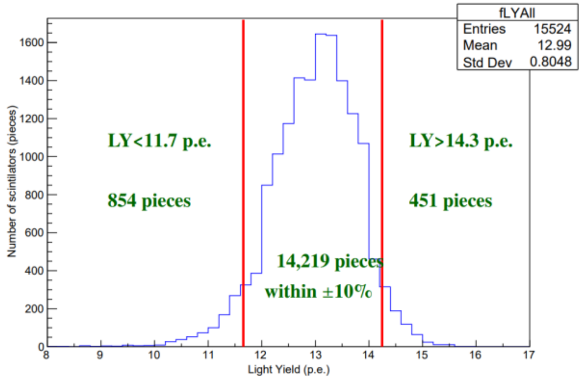


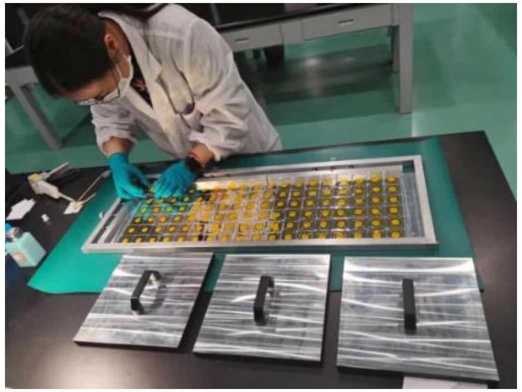


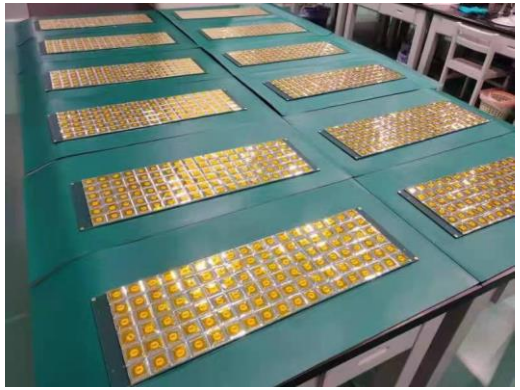


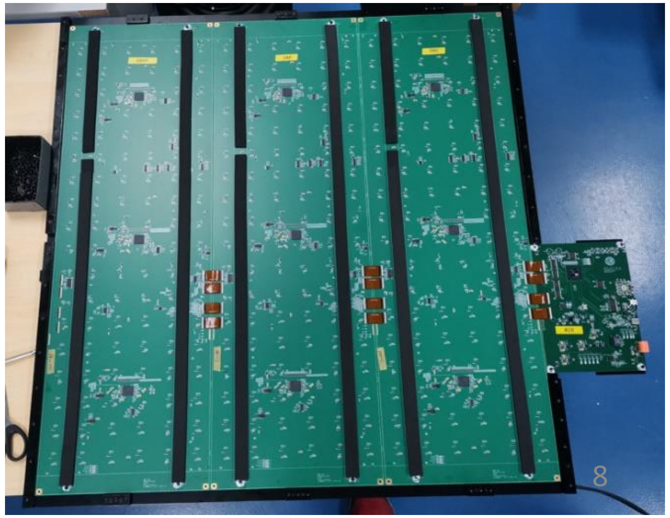
JINST 17 (2022) P05006





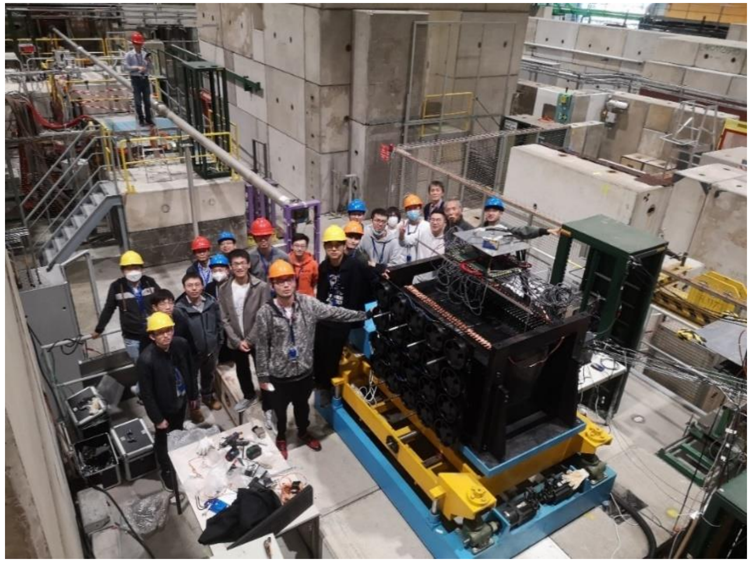






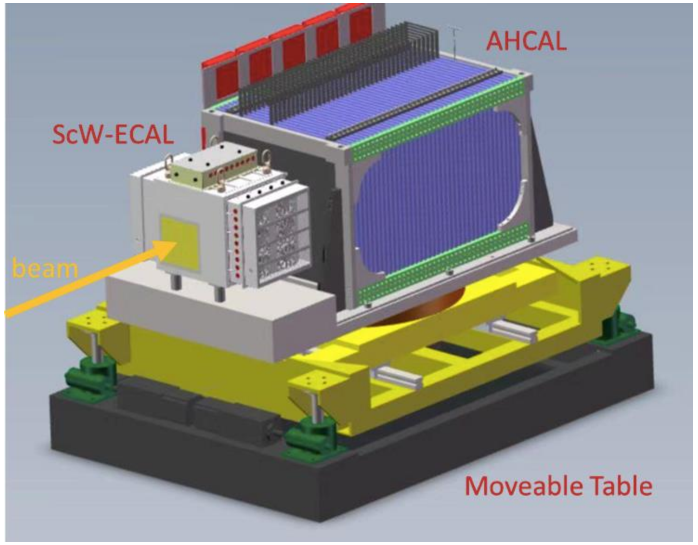
3.2 Plastic Scintillator HCAL (Prototype)

Oct 19 – Nov 2, 2022 — SPS H8 beamline
Apr 26 – May 10, 2023 — SPS H2 beamline
May 17 – 31, 2023 — PS T9 beamline

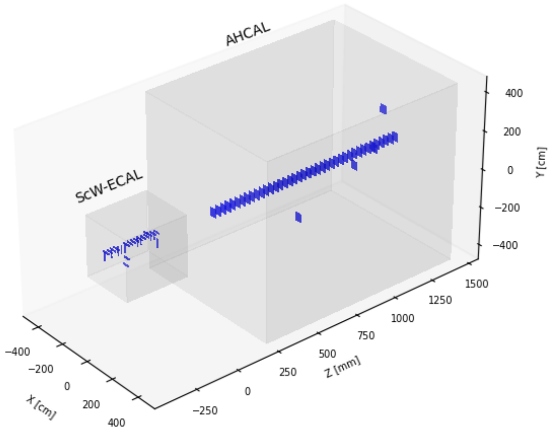


- **Collected large statistics of test beam data samples**
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 – 250 GeV at SPS
  - Pions: 1 – 15 GeV at PS, 10 – 120 – 150 – 350 GeV at SPS

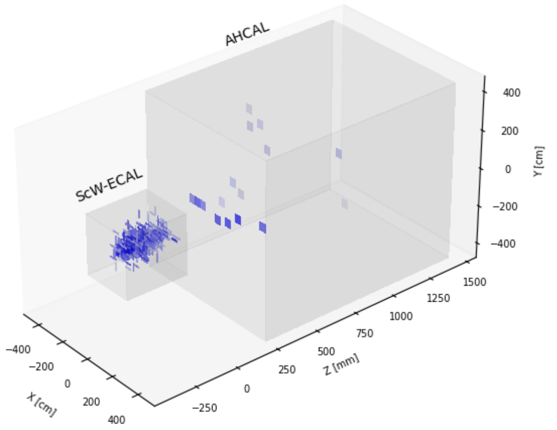
➔ About 65 M test beam events



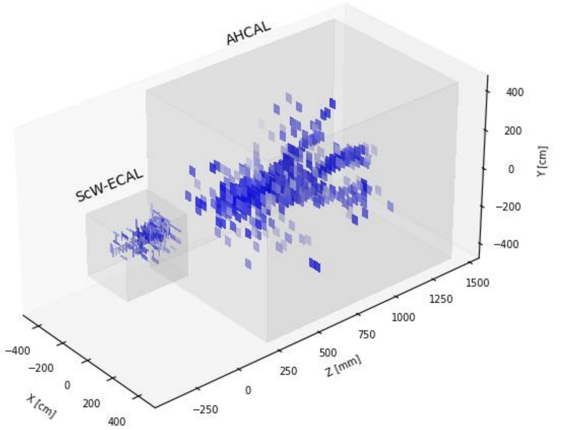
120 GeV mu-



60 GeV electron

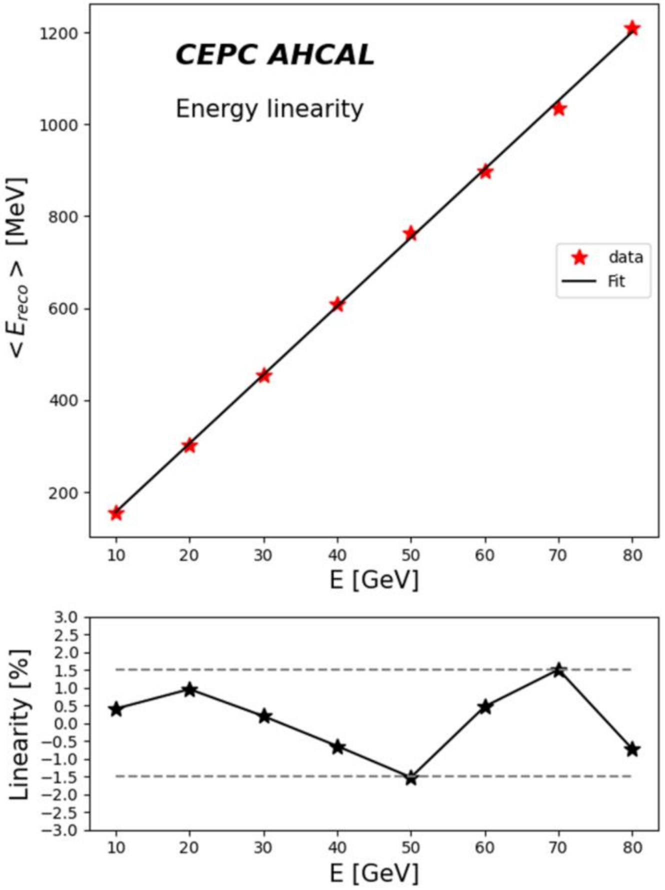


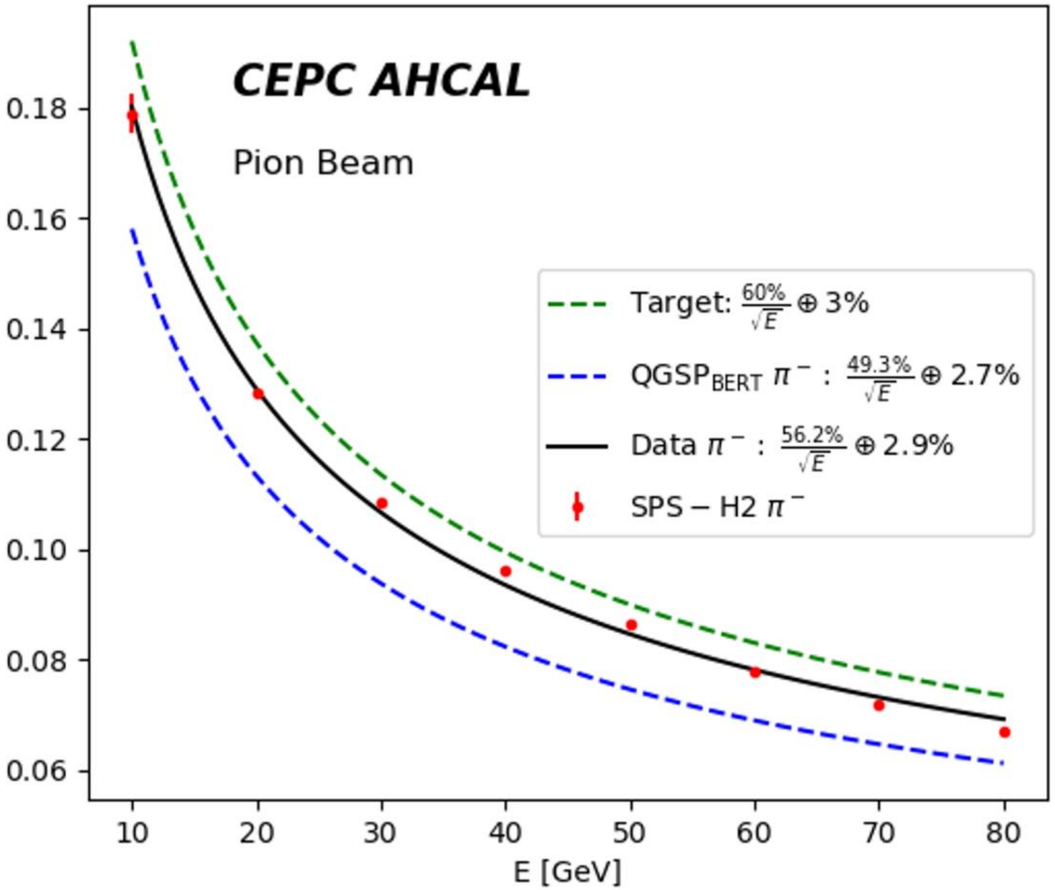
60 GeV negative pion (SPS)



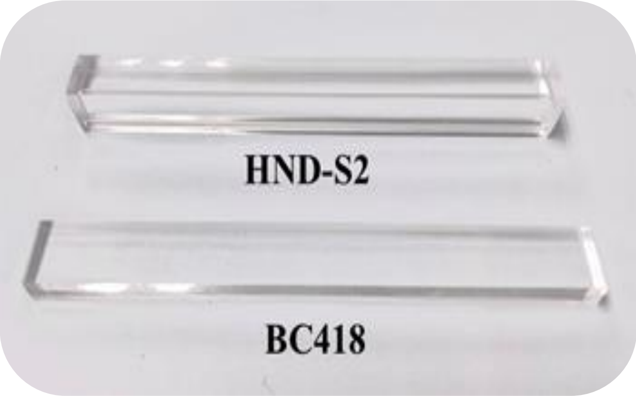
3.2 Plastic Scintillator HCAL (Prototype)

- **AHCAL prototype using pion TB data with ANN PID selection**
  - Energy linearity within $\pm 1.5\%$
  - Energy resolution $56.2\%/\sqrt{E(GeV)} \oplus 2.9\%$ (expected target $60\%/\sqrt{E(GeV)} \oplus 3\%$)

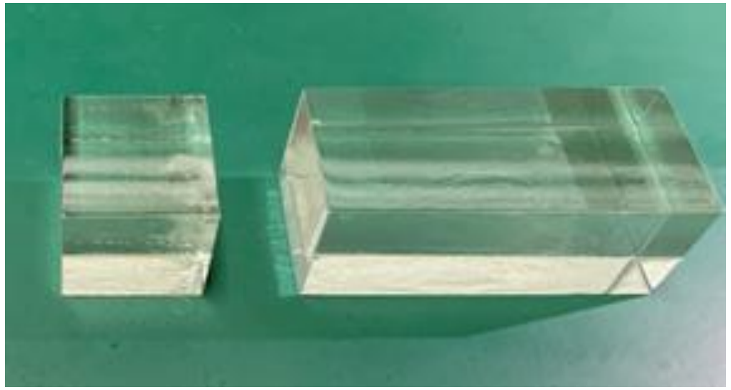




3.3 Comparison of Scintillators



Plastic Scintillator



Glass Scintillator

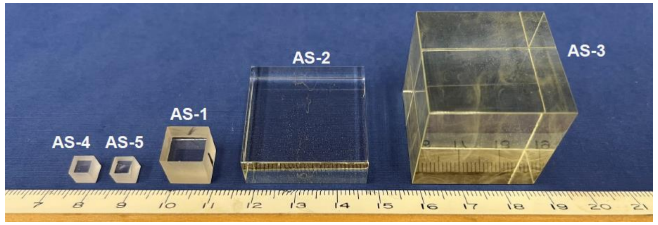
Crystal Scintillator

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

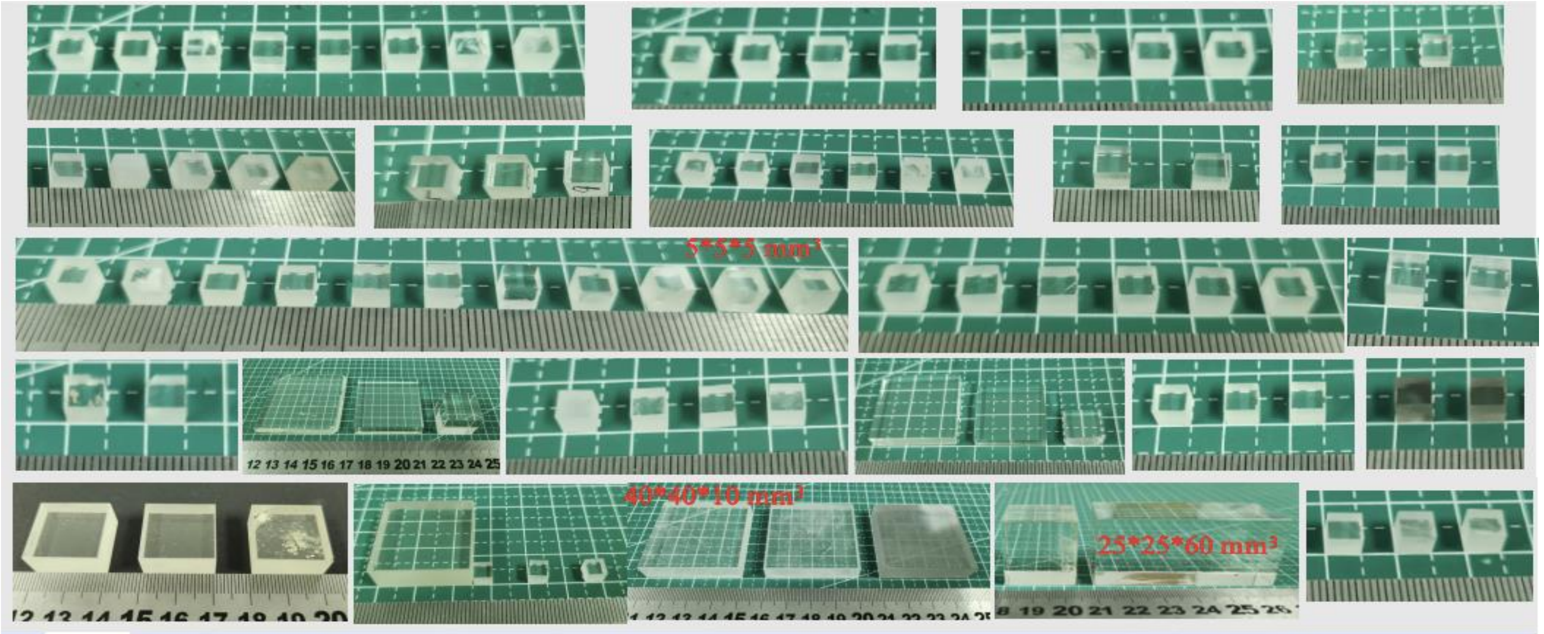
3.4 Glass Scintillator R&D

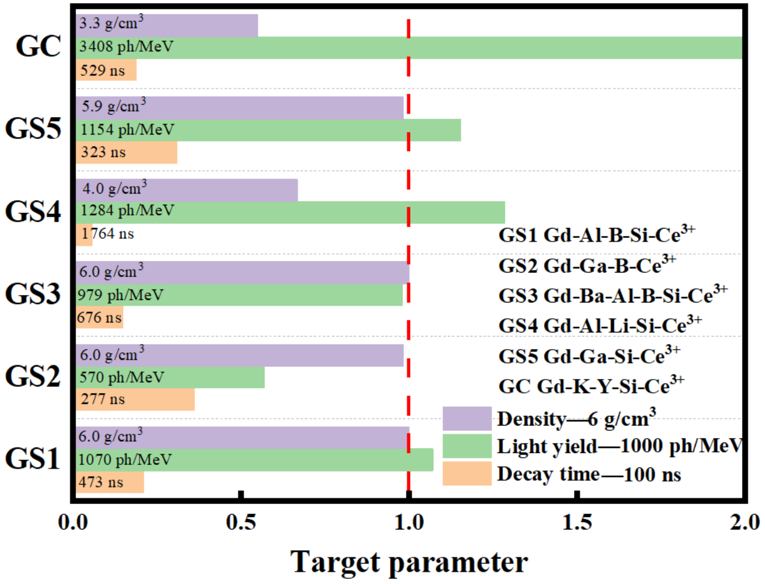
- The GS collaboration was established in 2021, it focuses on the large-area & high-performance glass scintillator for applications in nuclear and particle physics.
- The GS collaboration is organized by IHEP and the members include 3 Institutes of CAS, 5 Universities, 3 Factories currently.

闪烁玻璃合作组
Glass Scintillator Collaboration

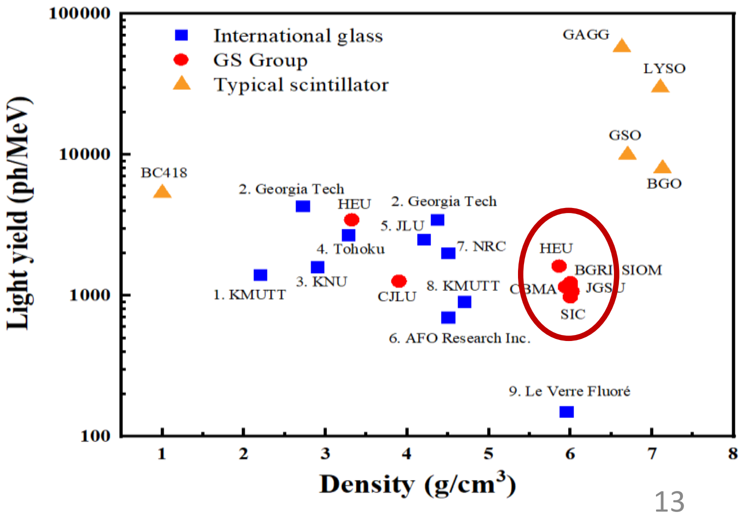


3.4 Glass Scintillator R&D





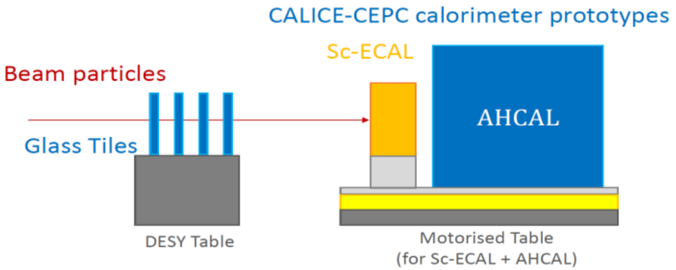
- ✓ The GS group did substantive research based on five glass scintillator types simultaneously and impressive progress has been achieved
- ✓ The performance of the best glass sample approach our initial goals, i.e. 6 g/cm³ & 1000 ph/MeV & ~100 ns
- ✓ The GS group is leading R&D efforts on high density glass scintillator

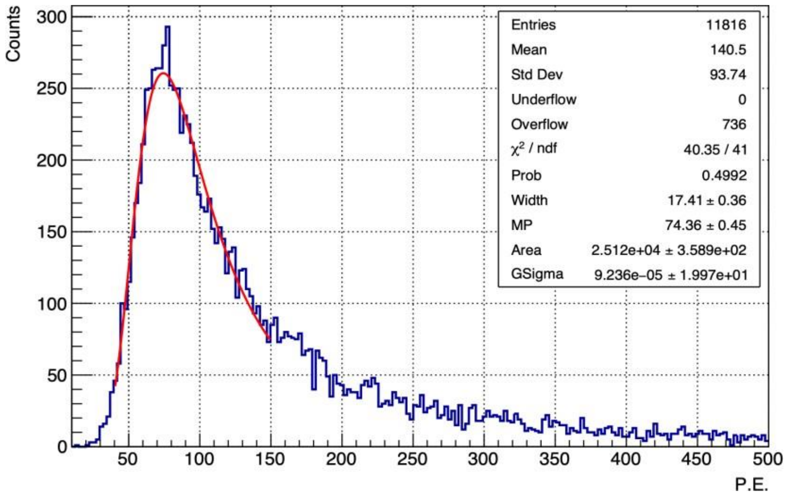


3.4 Glass Scintillator (GS1) TB Performance

CERN Muon-beam (10 GeV muon)

11 glass tiles tested at CERN (2023/5)

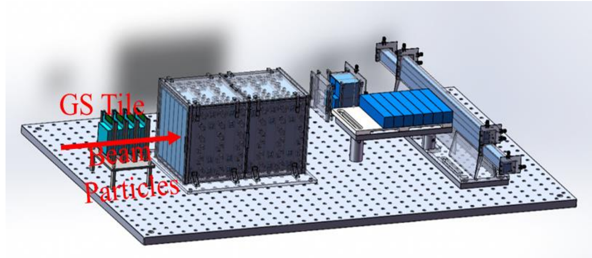


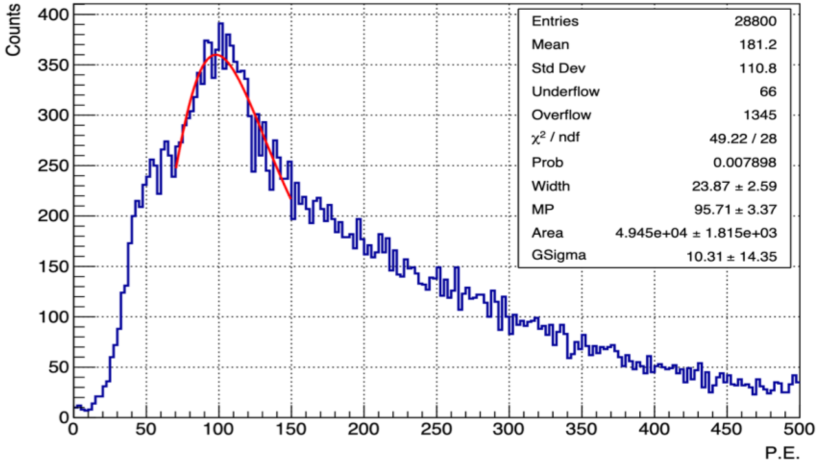


- **Typical Light Yield:**
  500 – 600 ph/MeV
- **Typical MIP response:**
  60 – 70 p.e./MIP

DESY Electron-beam (5 GeV electron)

9 glass tiles tested at DESY (2023/10)

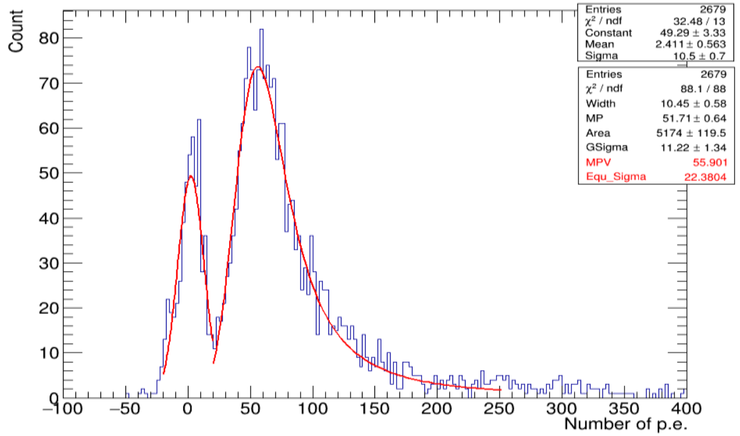




- **Typical Light Yield:**
  600 – 700 ph/MeV
- **Typical MIP response:**
  70 – 80 p.e./MIP

IHEP Cosmic Muon (3 GeV muon)

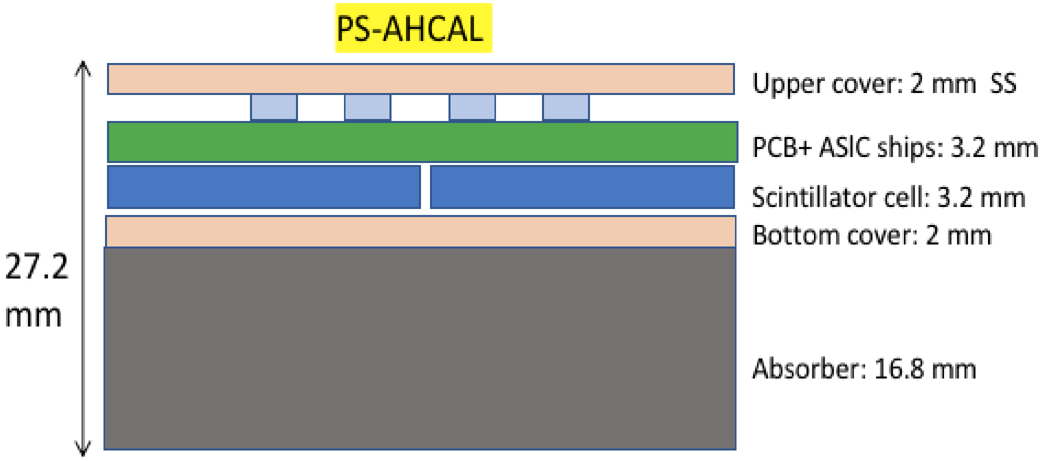
4 glass tiles tested at IHEP (2024/4)



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

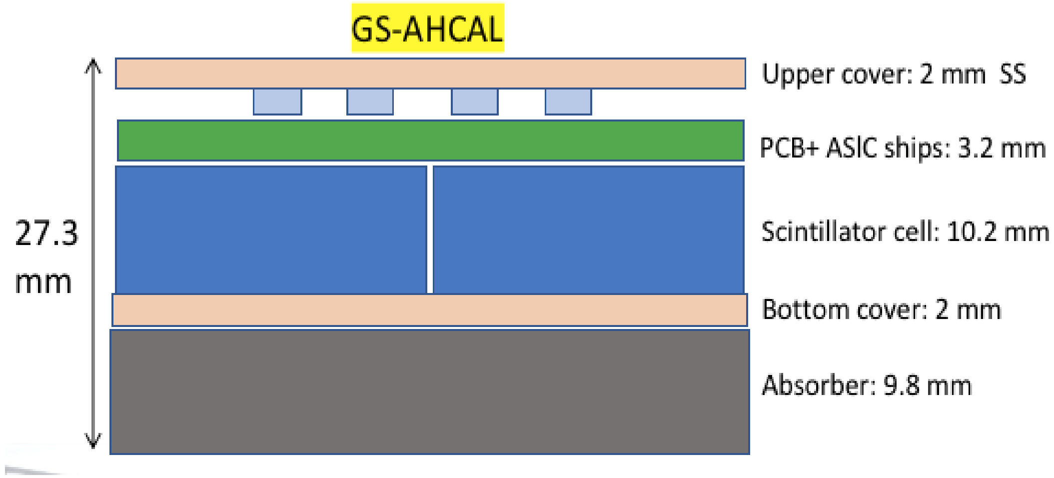
4.1 GS-HCAL vs PS-HCAL

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



PS-HCAL

$$f = \frac{\lambda_{PS}}{\lambda_{PS} + \lambda_{Steel} + \lambda_{PCB}} = 3.51\%$$

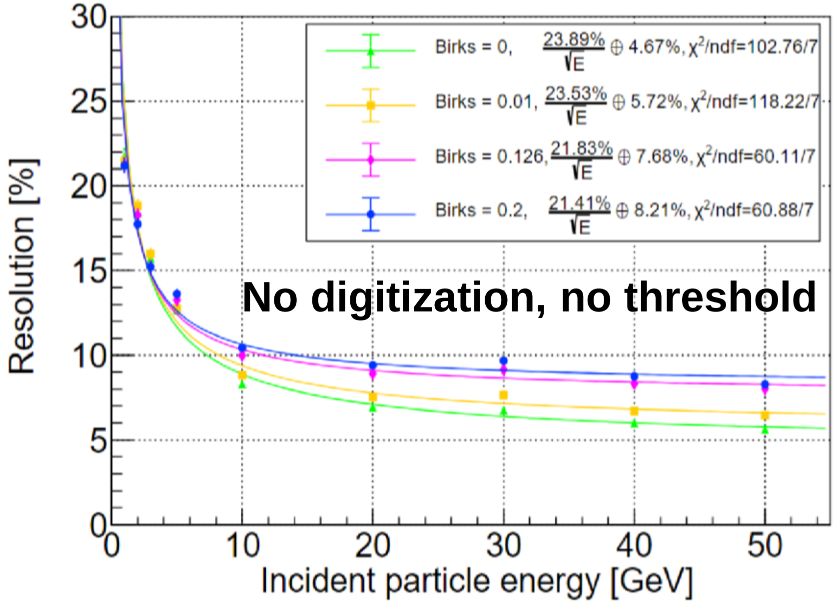


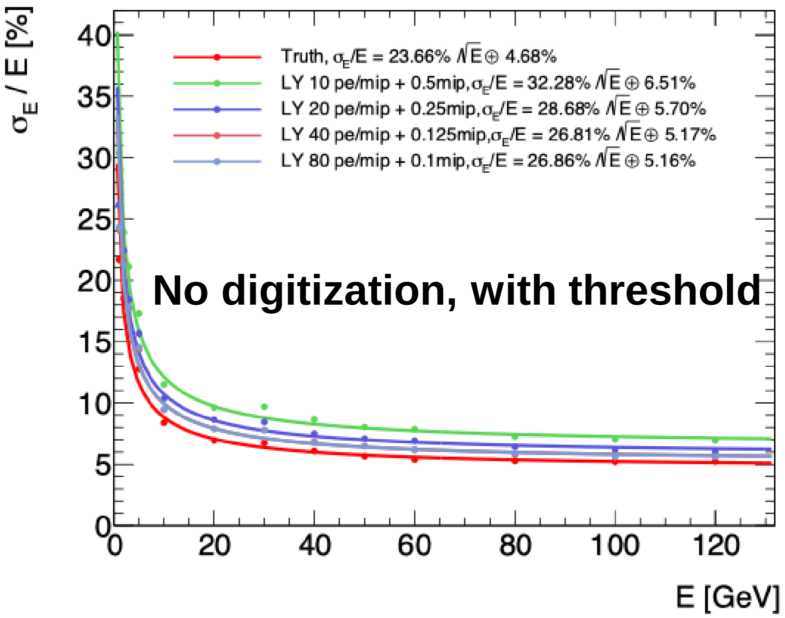
GS-HCAL

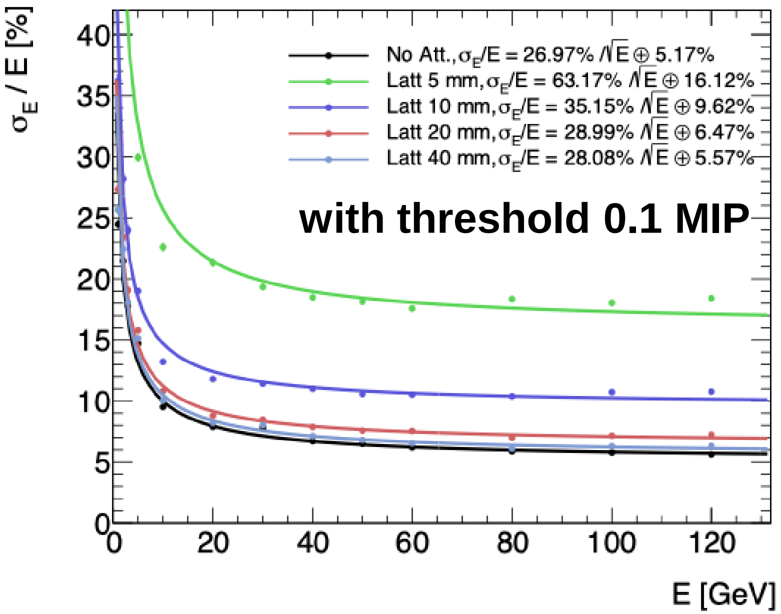
$$f = \frac{\lambda_{Glass}}{\lambda_{Glass} + \lambda_{Steel} + \lambda_{PCB}} = 32.57\%$$

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







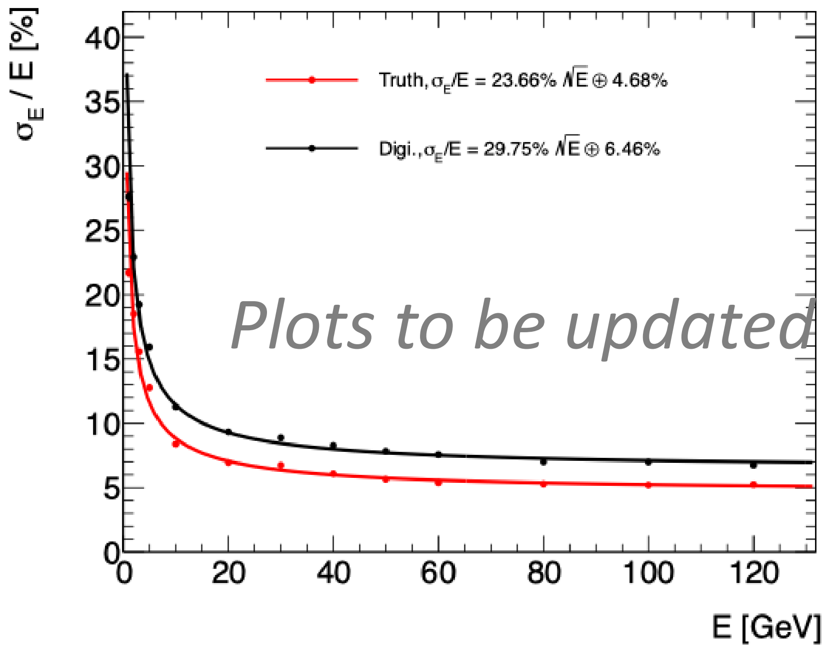
- Scintillator non-linearity in light output caused by quenching, Birks constant : $C_{birks} \sim 0.01\ (GS)$ vs $\sim 0.008\ (BGO)$

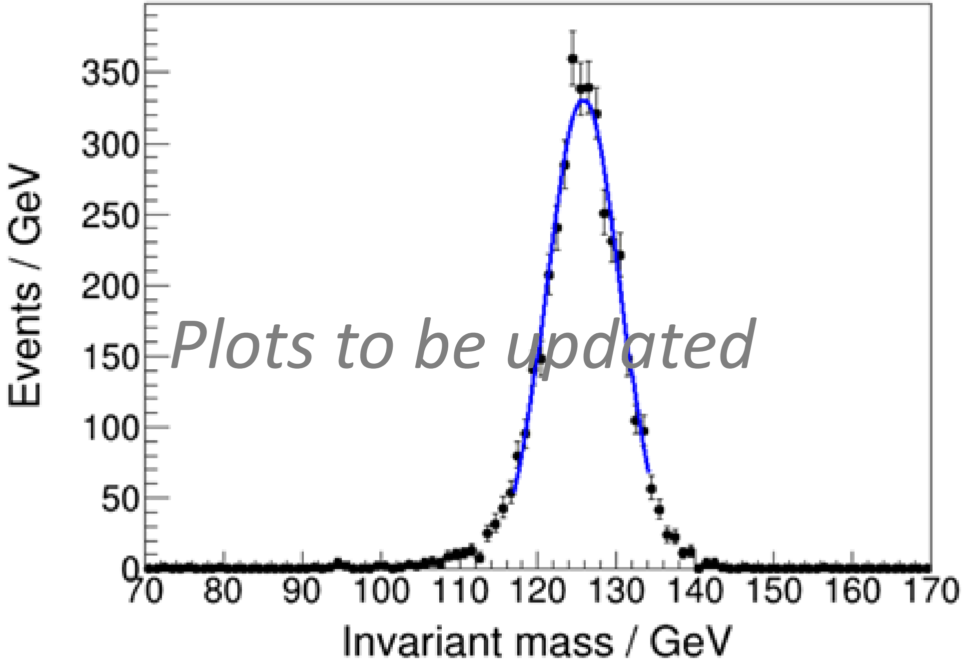
- GS light yield: > 50 p.e/MIP
- Threshold: 0.1 MIP (> 5 p.e)

- GS attenuation length: ~23mm

4.3 GS-HCAL Physics Performance

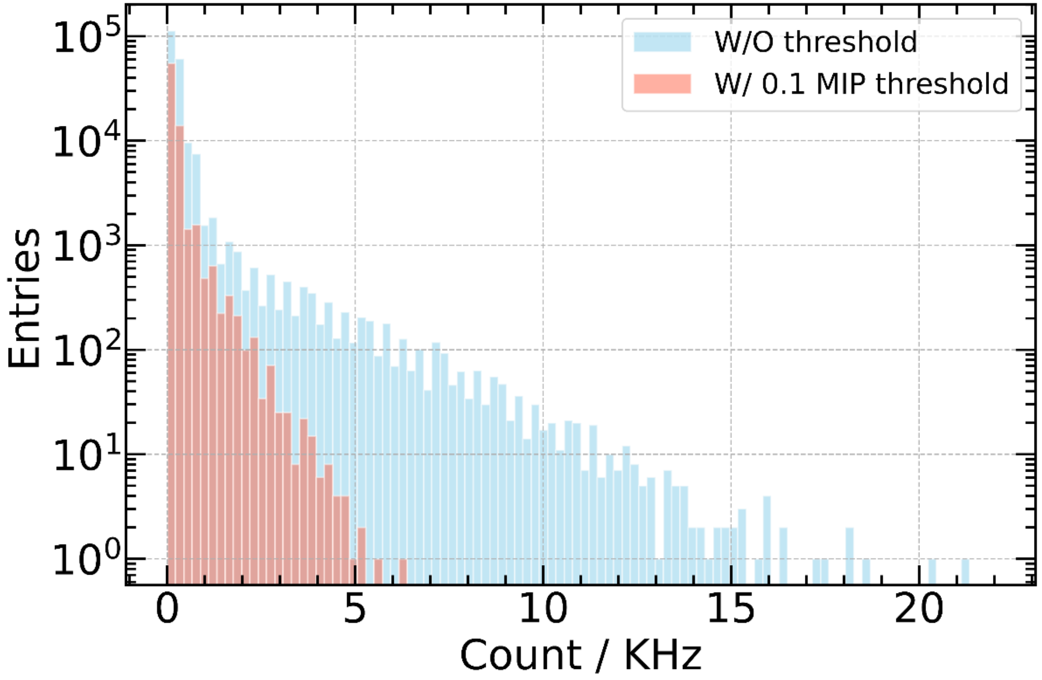
- **Hadron Energy Resolution (full sim + digi) :** $\sigma_E/E = \frac{29.75\%}{\sqrt{E}} \oplus 6.46\%$
- **PFA Reconstruction for $ee \rightarrow ZH \rightarrow \nu\nu gg$ events:**
  - Truth track + crystal bar ECAL + GS-HCAL (barrel only)
  - BMR = 3.70±0.08% ($m_{vis} = 125.79 \pm 4.66$ GeV).

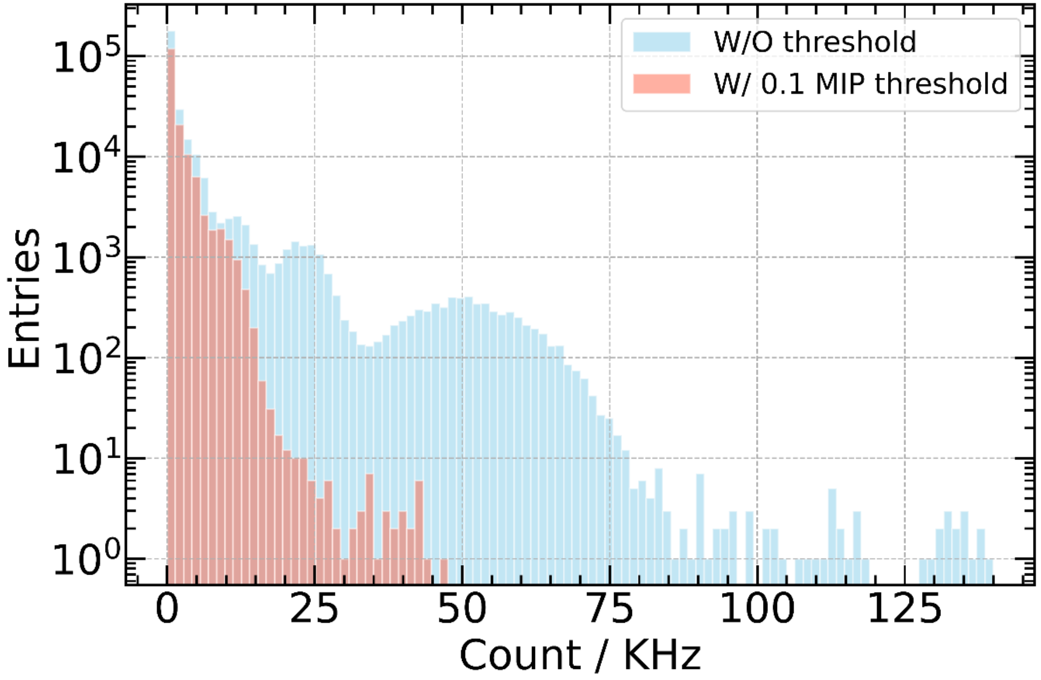




4.4 GS-HCAL Background Estimation

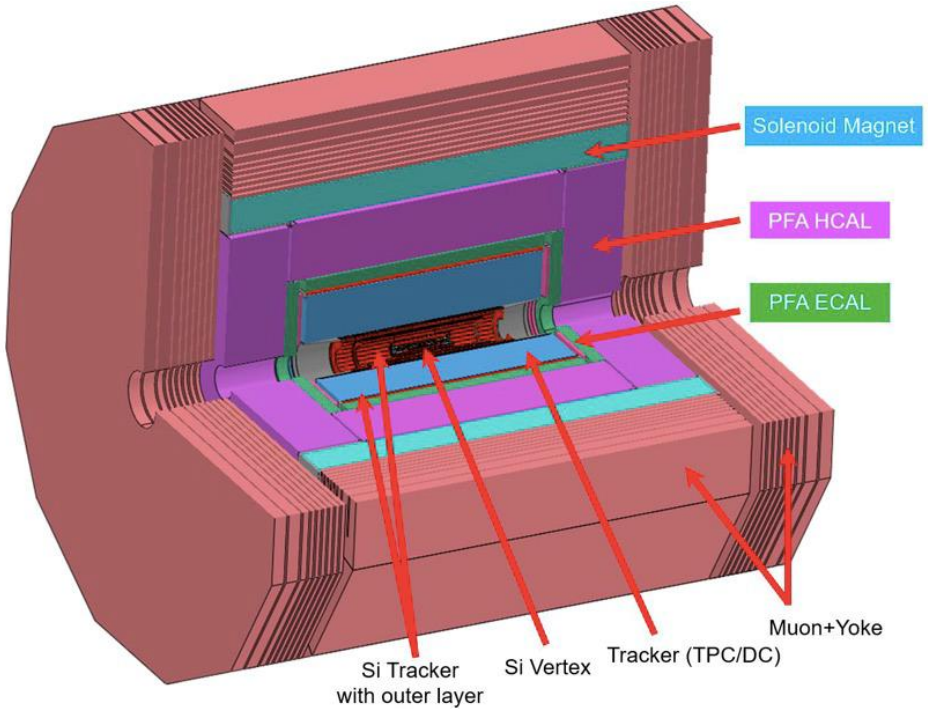
- **Simulation of beam background processes:**
  - 50 MW(H), bunch spacing 355 ns, with pair production, single beam processes
  - Event rate with 0.1 MIP threshold: barrel < 5 kHz, endcap < 50 kHz
  - Need further investigation of pile-up effect

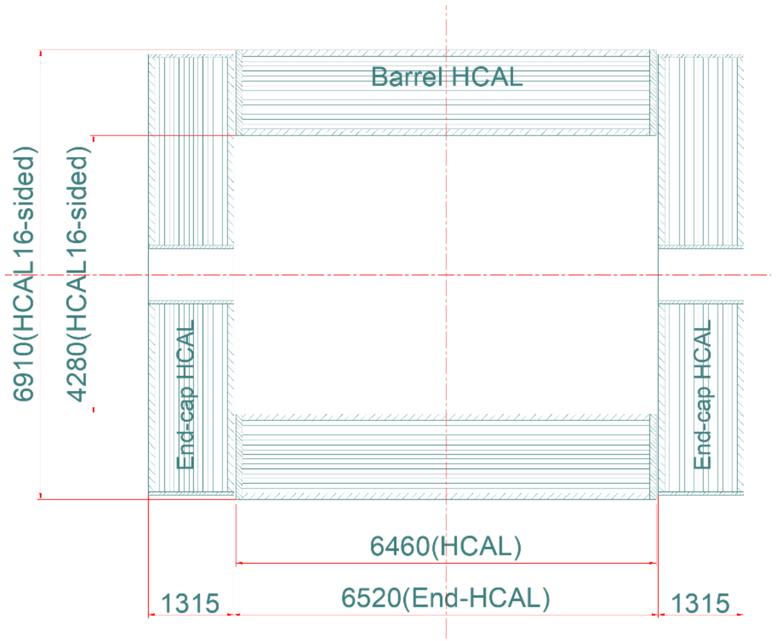


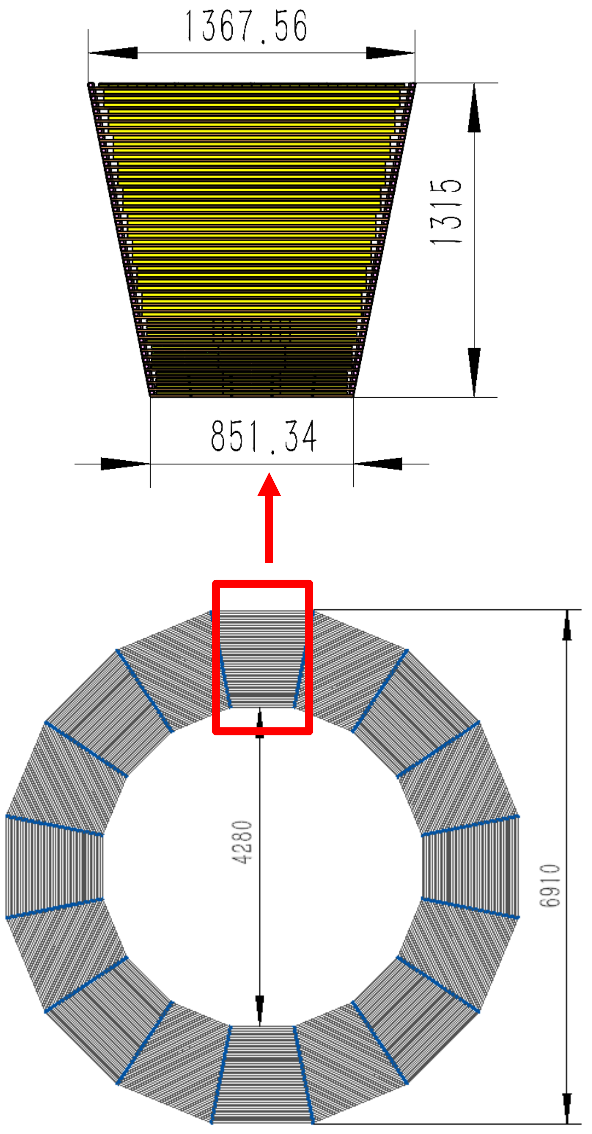


5. GS-HCAL Design

- **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)

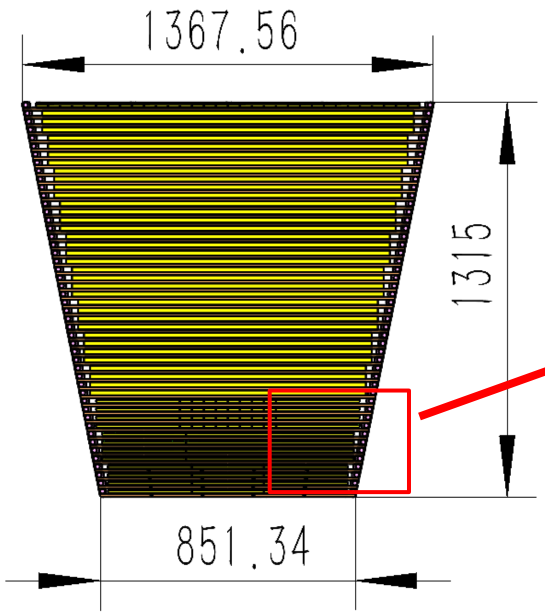




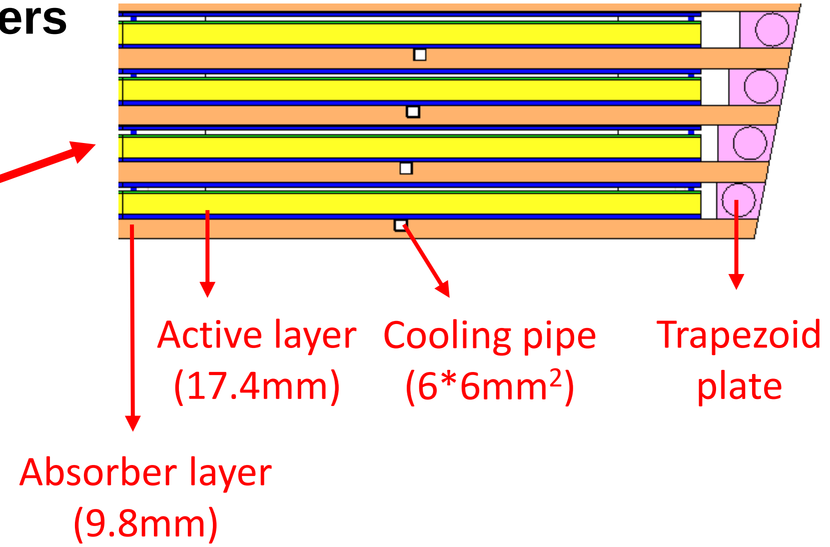


5.1 GS-HCAL Mechanical Design (Barrel)

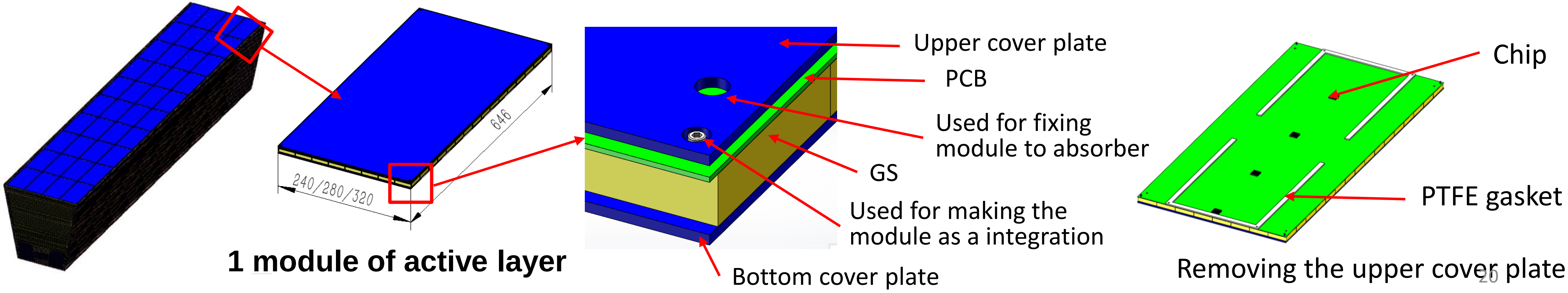
- **One Sector**



- **Several Layers**

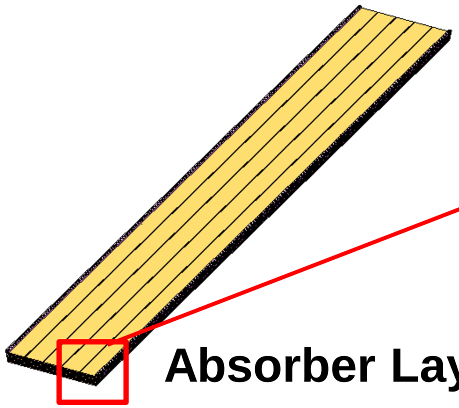


- **Active layer structure**

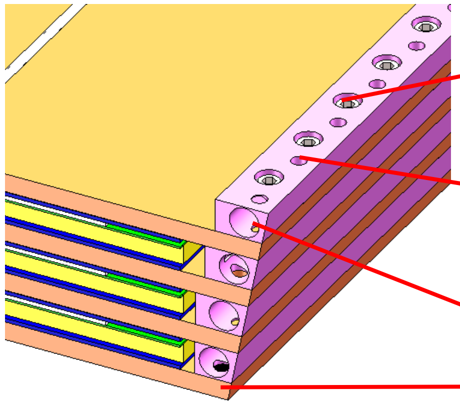


5.1 GS-HCAL Mechanical Design (Barrel)

- **Absorber layer structure**



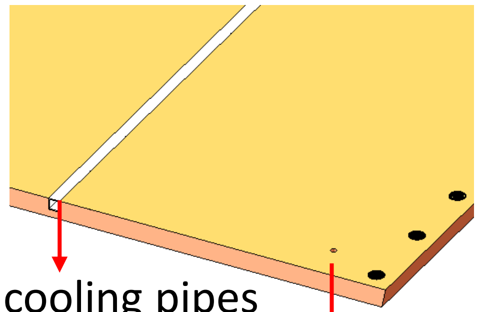
Absorber Layers



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

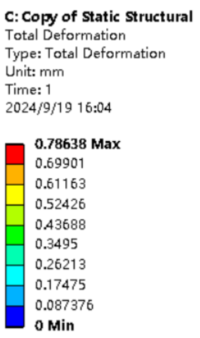


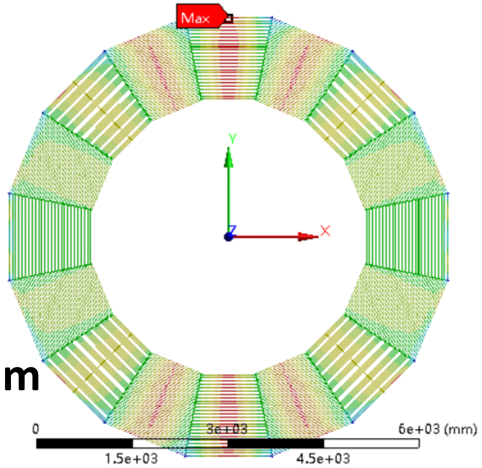
4 cooling pipes for each layer

Screw for fixing active layer module

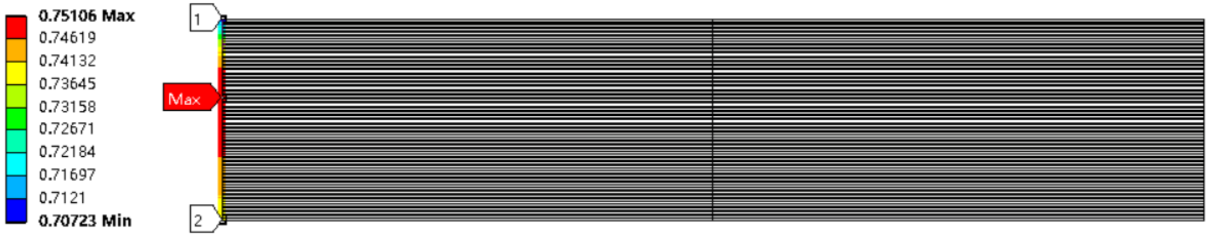
module (320mm × 646mm)

- **Simulation of absorber structure**

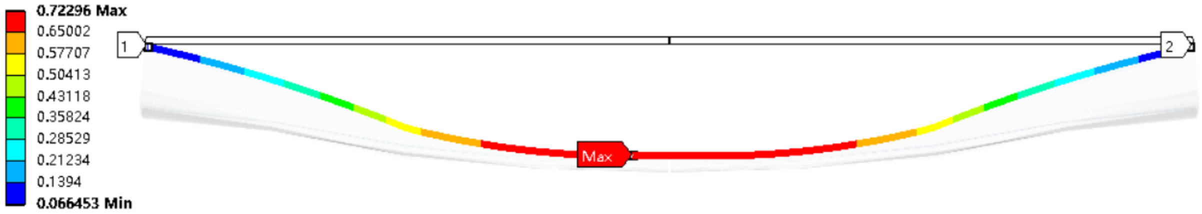




Deformation:0.786mm
Due to gravity



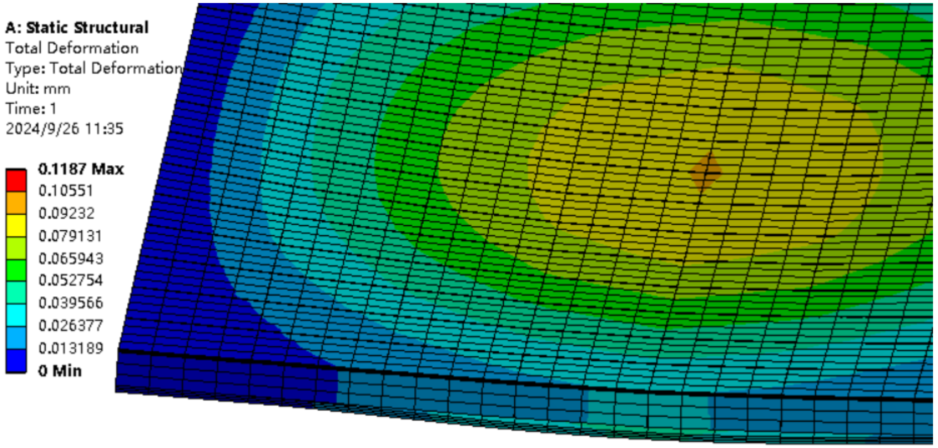
Deformation difference between 48 layers is lower than 0.05mm



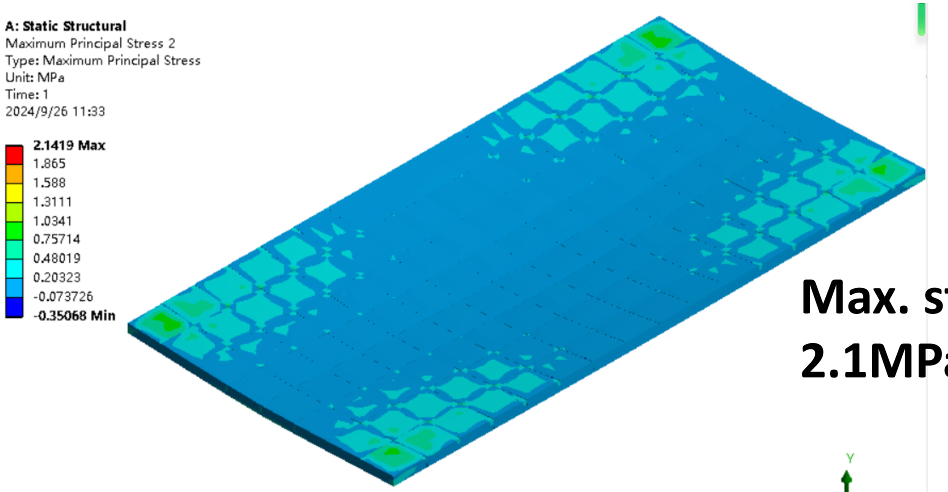
Deformation difference within 1 layer is lower than 0.7mm

5.1 GS-HCAL Mechanical Design (Barrel)

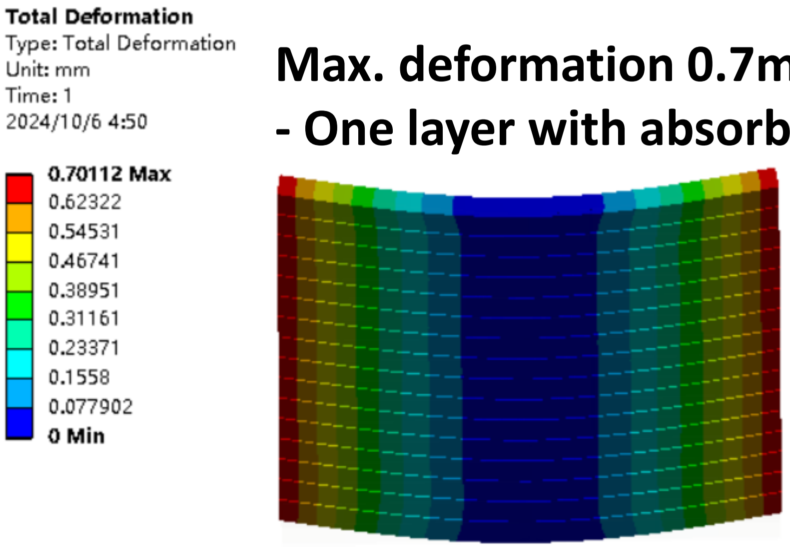
➢ **Simulation of one active layer module (320mm × 646mm)**



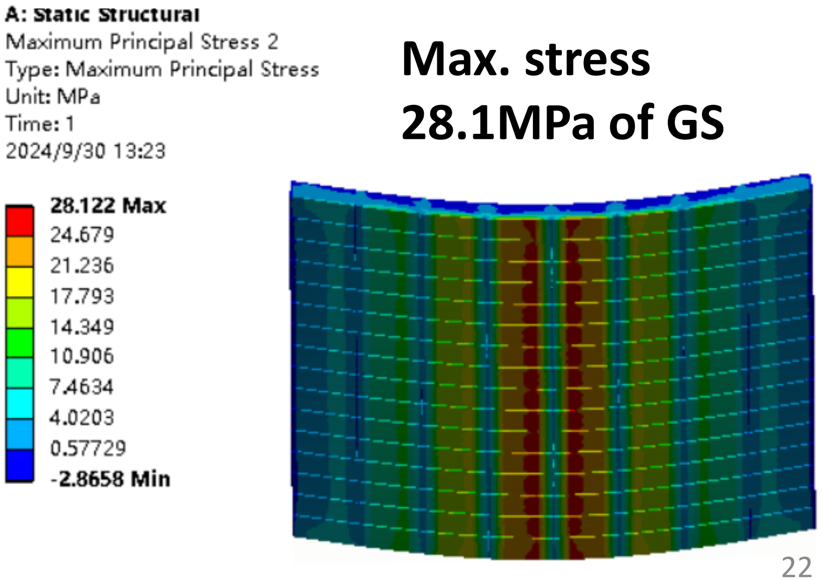
Max. deformation 0.11mm (single active layer)



Max. stress 2.1MPa of GS



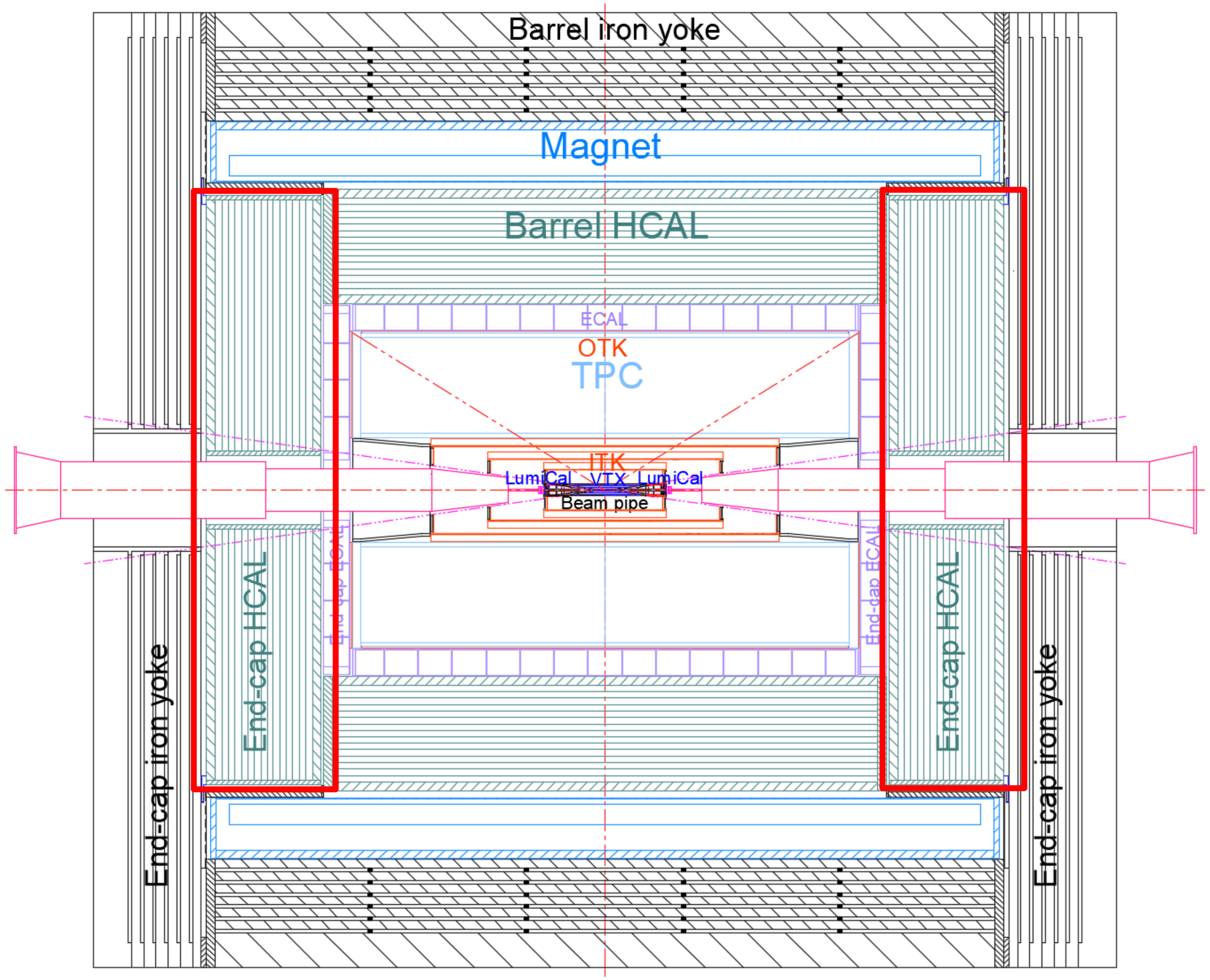
Max. deformation 0.7mm
- One layer with absorber



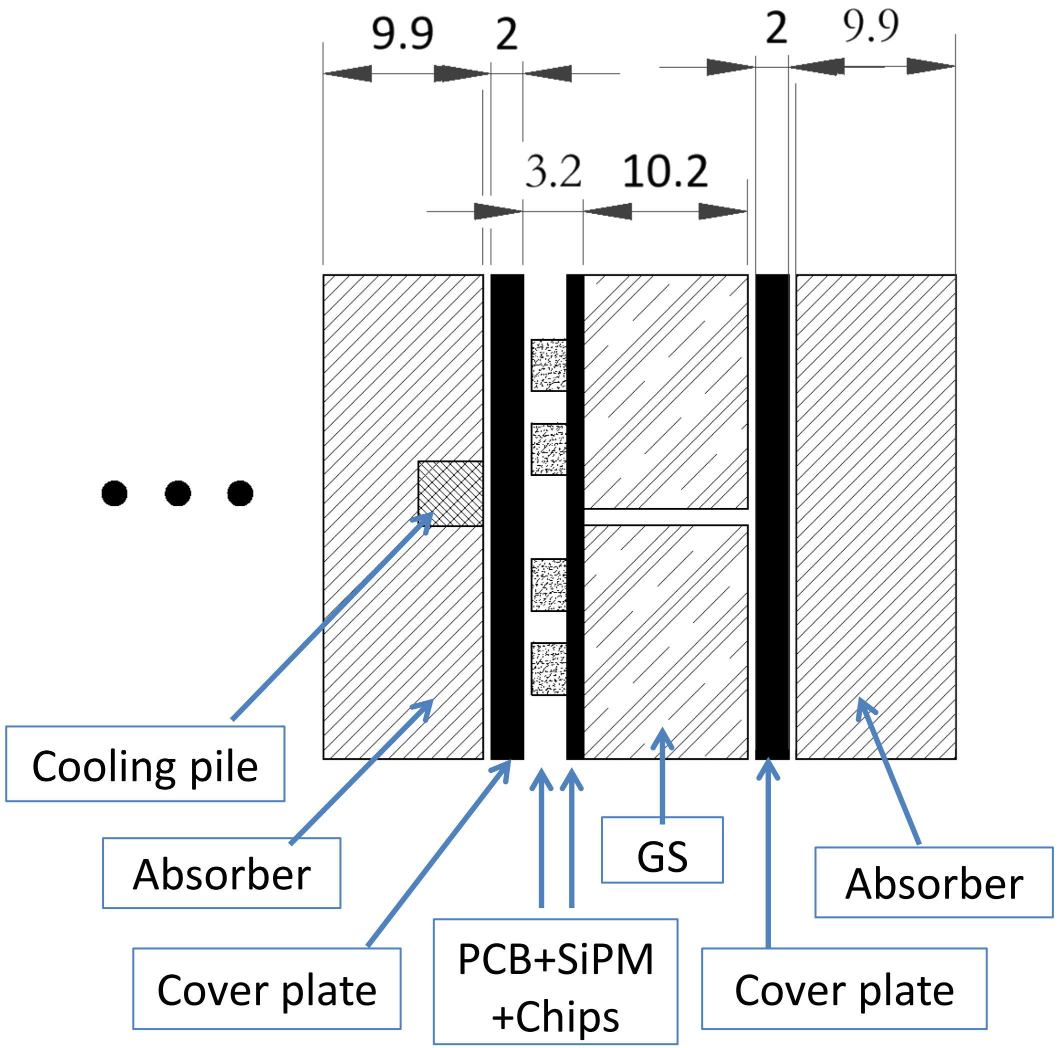
Max. stress
28.1MPa of GS

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

5.2 GS-HCAL Mechanical Design (Endcap)

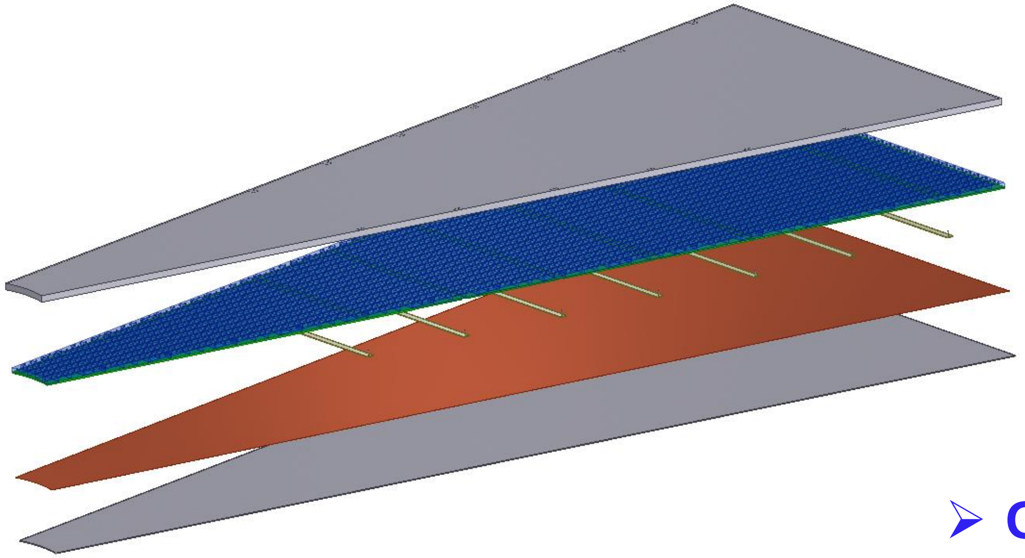


Two GS-HCAL endcap, 360 tons / each

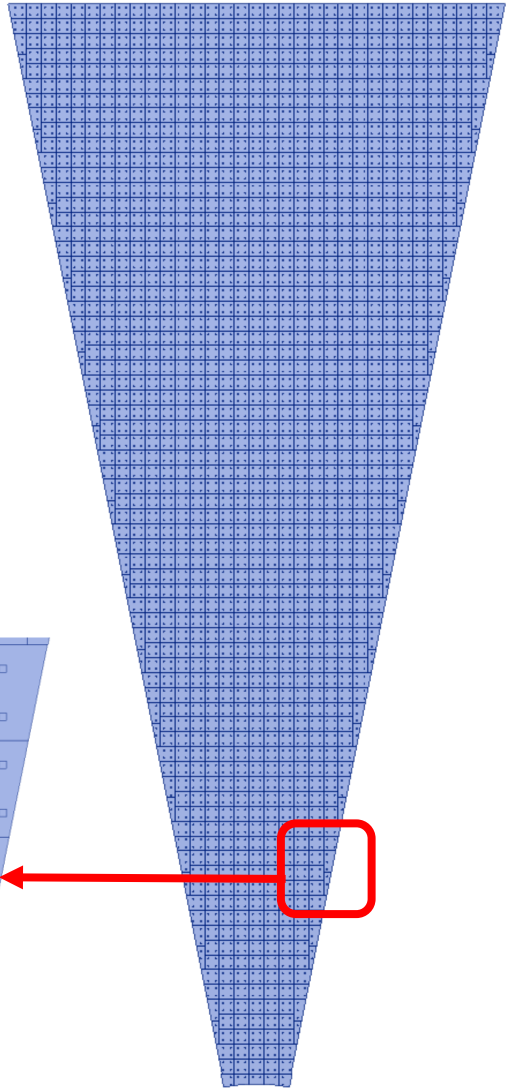


Schematic of one layer

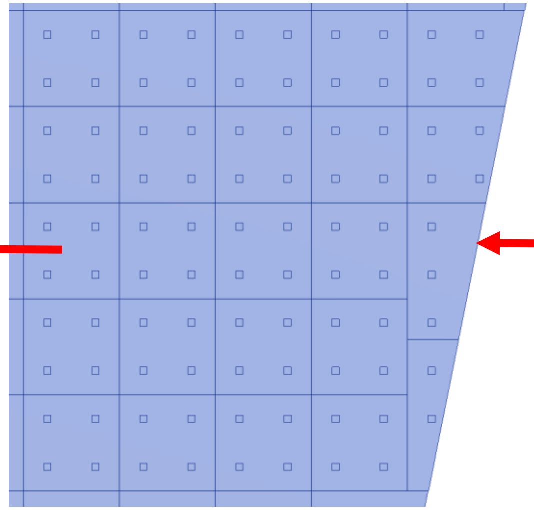
5.2 GS-HCAL Mechanical Design (Endcap)

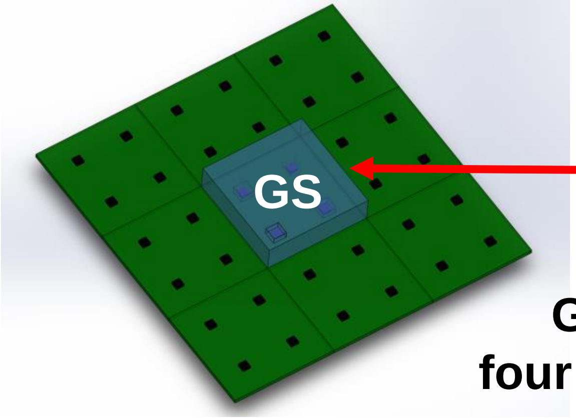


- Cover plate
- GS + PCB
- Tighten Strips
- Thermal Conductor
- Cover plate



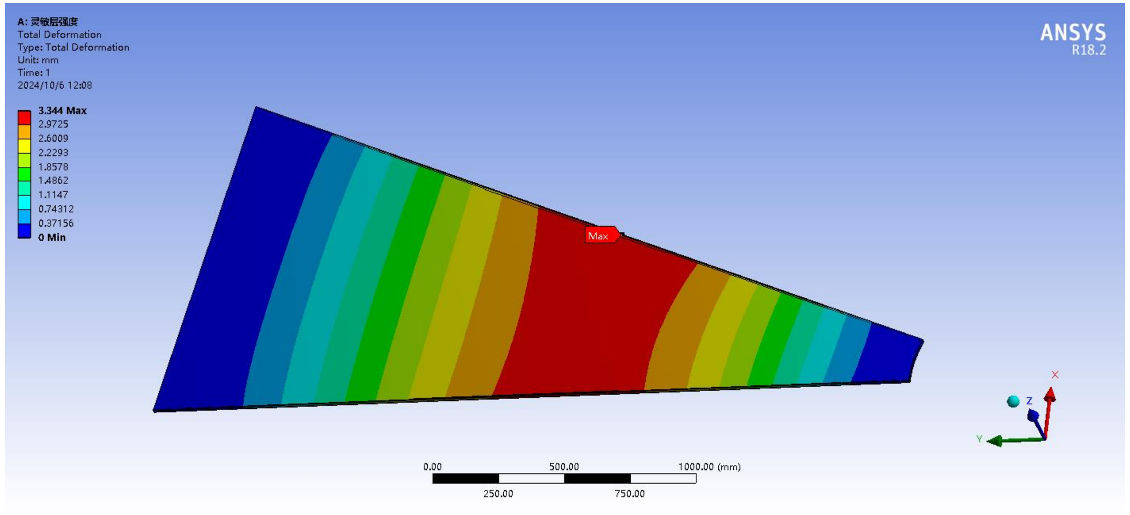
- GS cell size: $40 \times 40 \times 10\ mm^3$
- Four special-shaped at edge



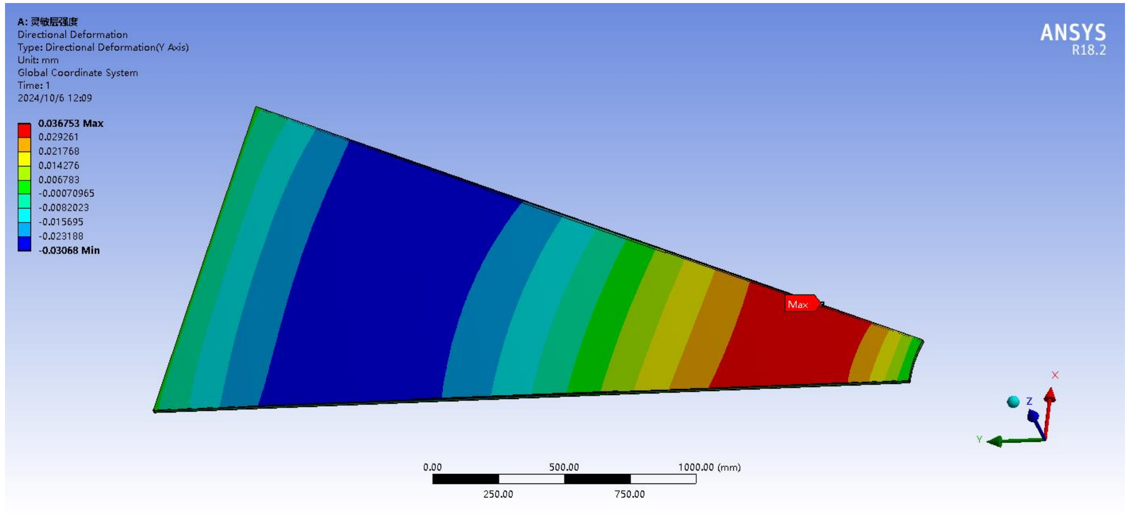


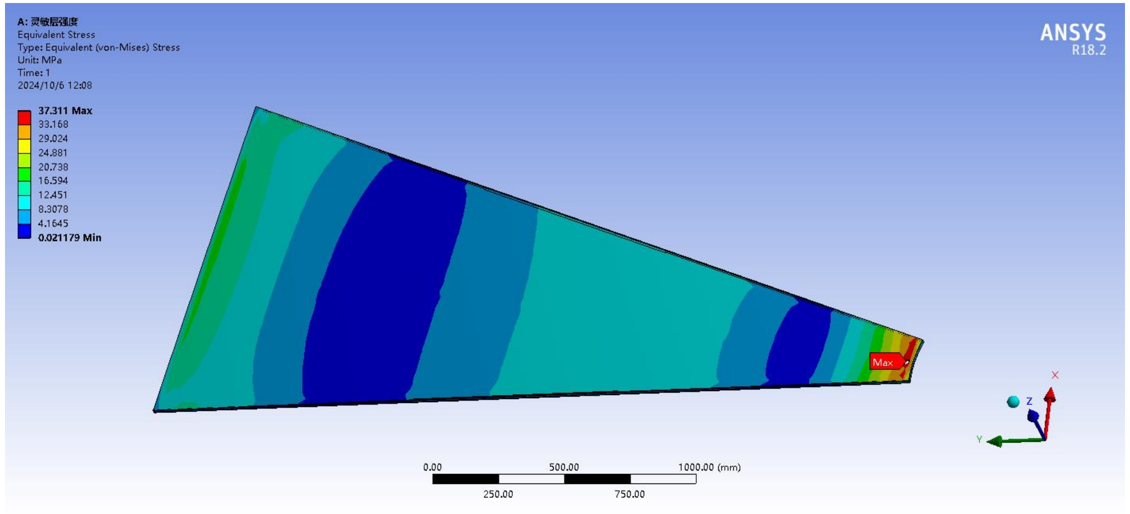
GS-SiPM-PCB
four SiPM ($3x3\ mm^2$)

5.2 GS-HCAL Mechanical Design (Endcap)



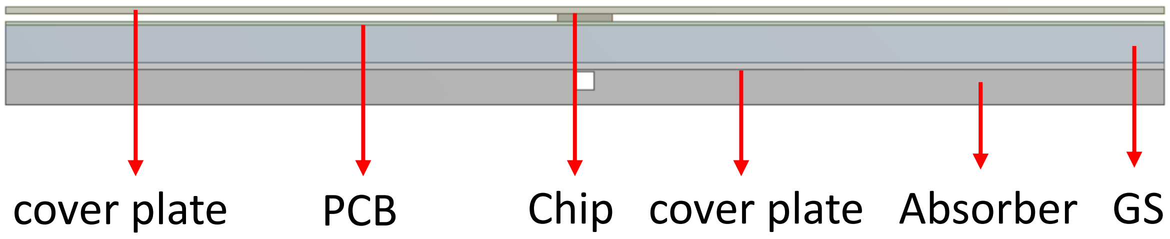
- Max. deformation in one active layer: 3mm (due to gravity)
- Horizontal extrusion deformation: 0.037mm
- Max. principal stress at narrow end: 37MPa

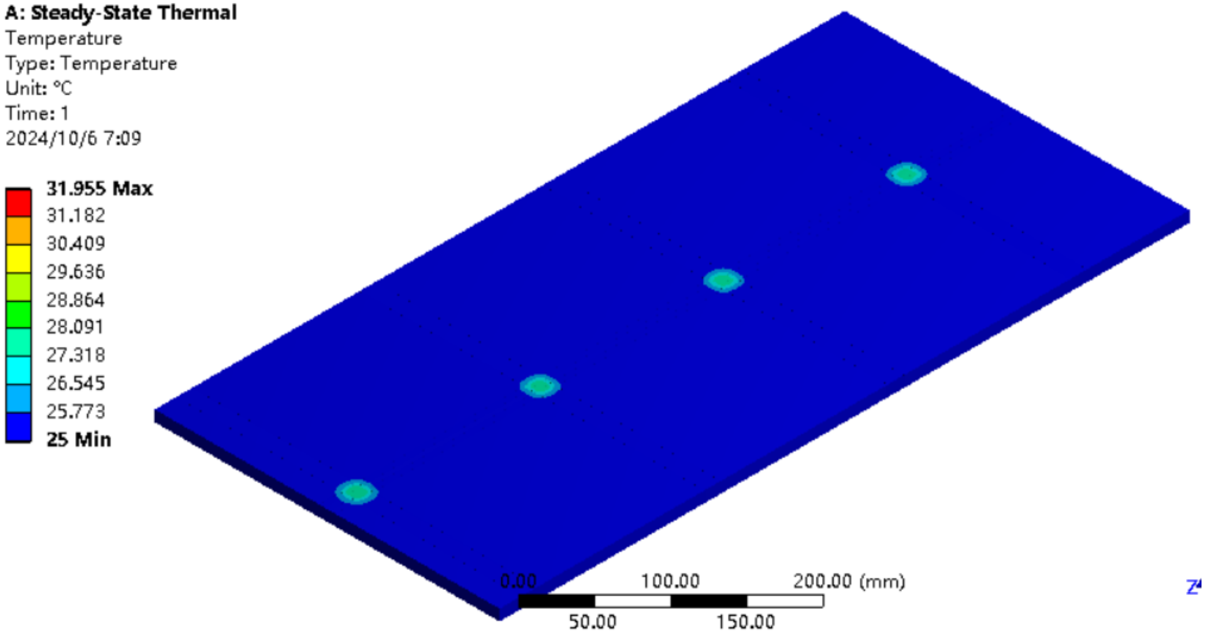




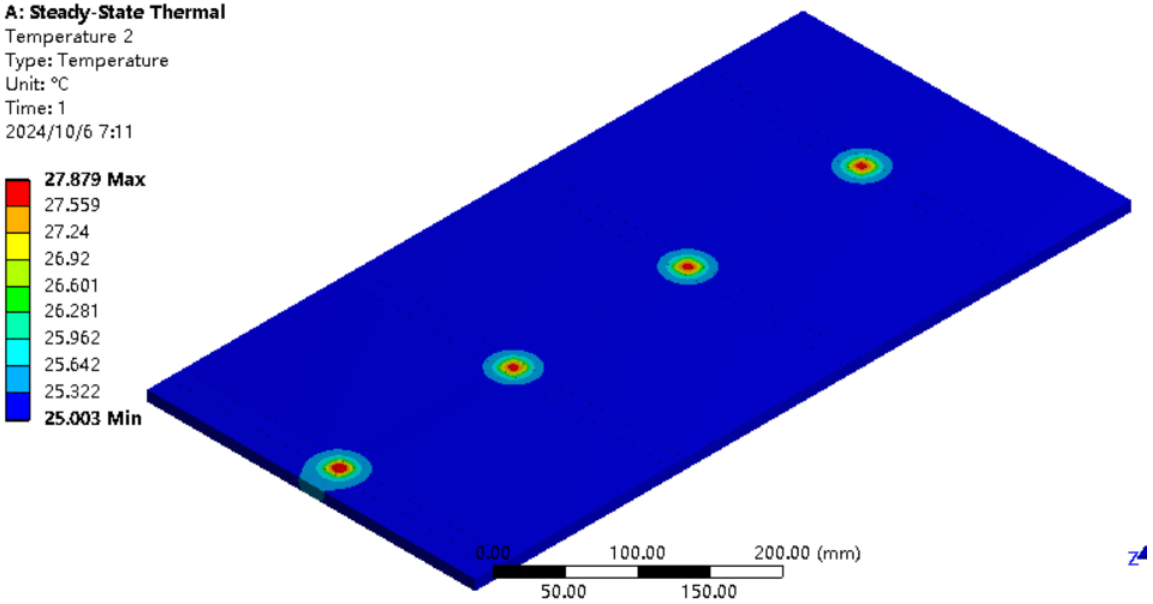
5.3 GS-HCAL Cooling Simulation

- **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 ℃

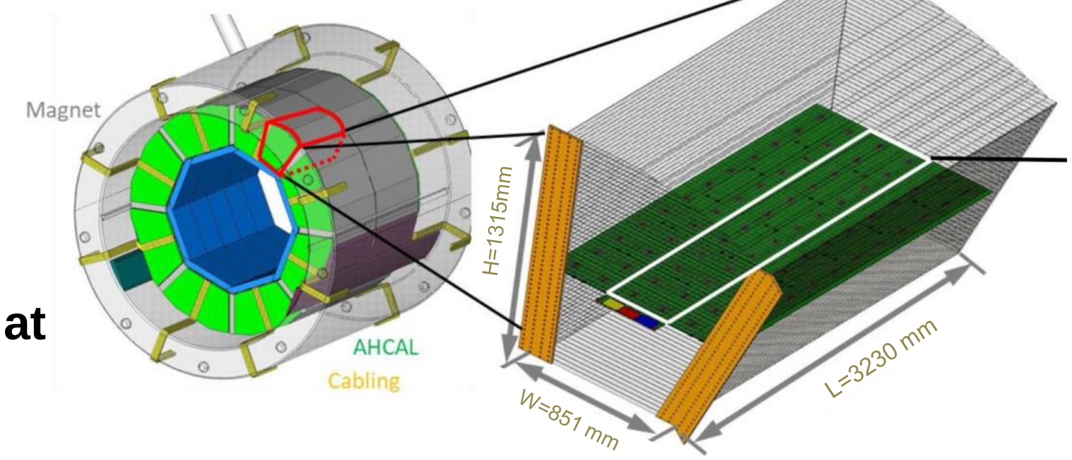


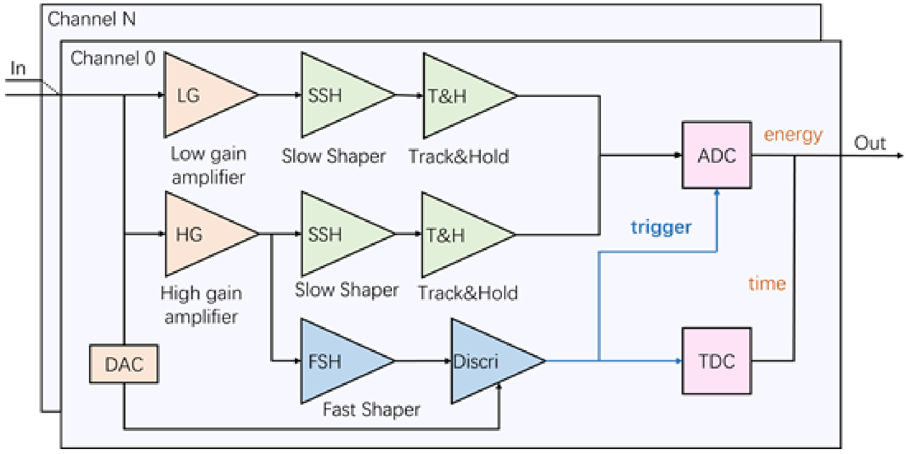
Temperature difference (GS vs SiPM): 2.8 ℃

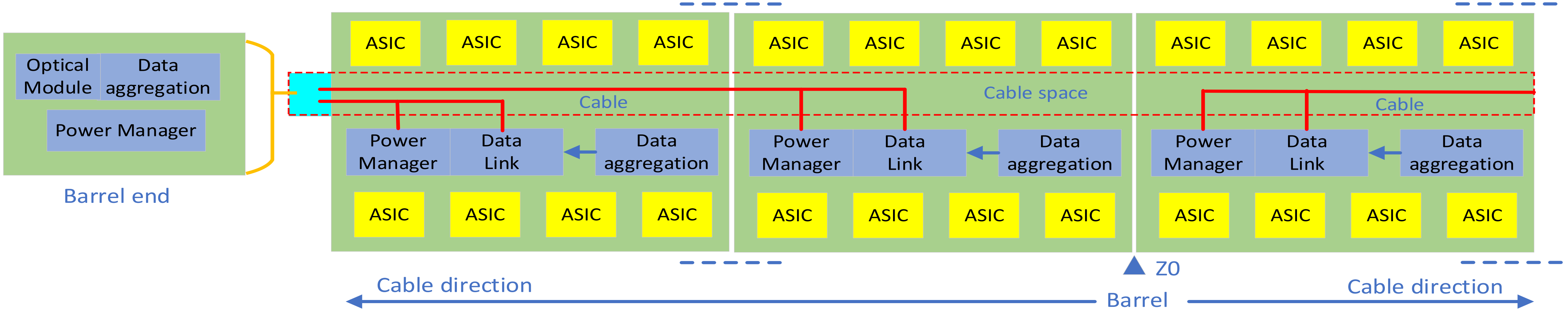
6. GS-HCAL Readout Electronics

- **Thickness: 3.2mm**
  - PCB 1.2mm
  - ASIC Chip 2mm
- **Power: 15 mW/ch**
- **Aggregation board at the end of barrel**

To be updated

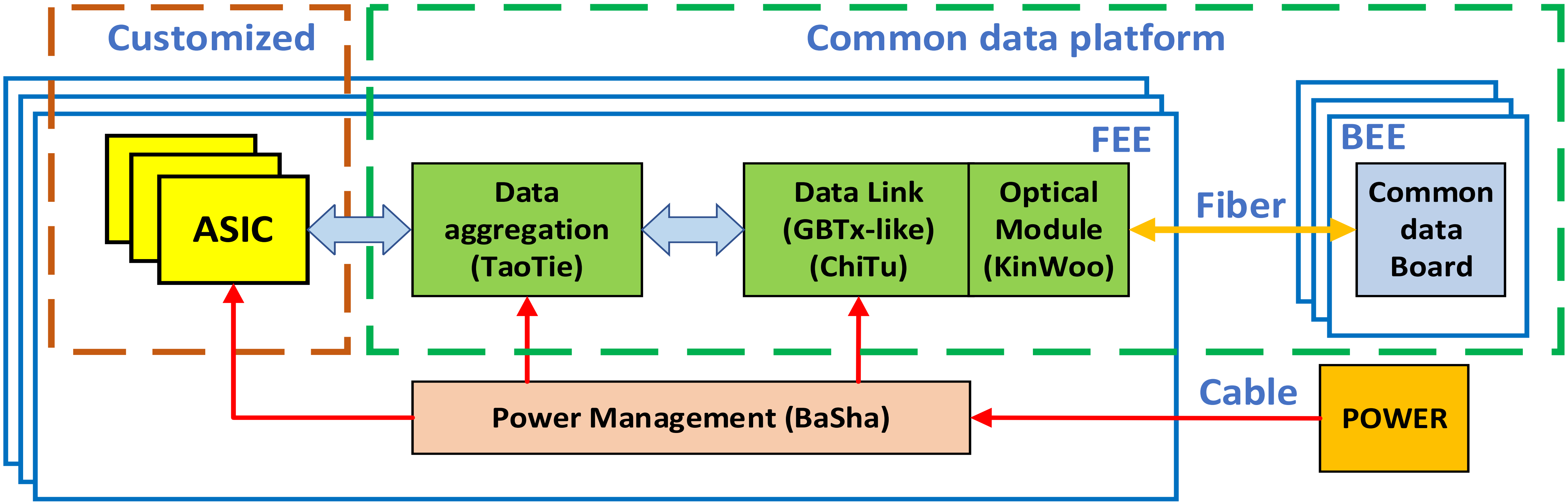






Aggregation board at the end of barrel, cable connection

6. GS-HCAL Readout Electronics



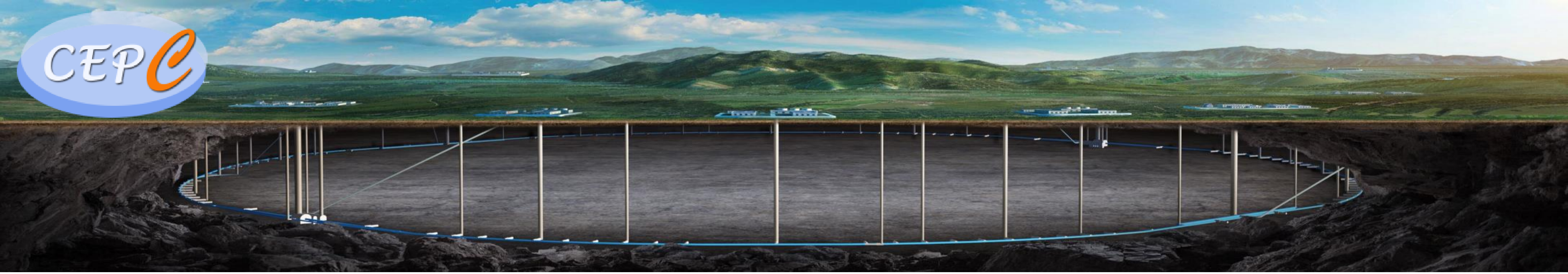
- **Energy Measurement:** ASIC for ECAL & HCAL
- **Data transmission:** common data platform (see electronics report)
- **Trigger mode:** FEE trigger-less readout

7. HCAL Research Group

- **CEPC-HCAL team：IHEP, USTC, SJTU, HNNU**
  - **Detector for RPC-DHCAL：** Staff(**2**) + Student(**1**)
  - **Detector for PS/GS-AHCAL：** Staff(**9**) + Student(**5**)
  - **Electronics:** Staff(**5**)
  - **Mechanics:** Staff(**3**)
- **The Glass Scintillator Collaboration**
  - Institute (11) + Staff (20)+ Student (10)
- **Join the DRD6 - WP1 for the GS study and HCAL study**

8. Summary and Plan

- **Detector**
  - R&D of high denisty and high light yield glass scintillator
  - Small prototype of GS-HCAL for beam test
  - Test special shape plastic/glass scintillator
- **Electronics**
  - ASIC chips R&D
  - Readout electronics design
- **Mechanics**
  - Optimization of the mechanic design
  - Optimization of the cooling design
- **Simulation and Performance**
  - Optimization of GS-HCAL geometry in CEPCSW
  - GS-HCAL full simulation and reconstruction in CEPCSW



Thanks for your attention !

4. Main Technical Challenges

■The main challenge

- R&D of the high denisity and high light yield glass scintillation;
- Mass production and quality / cost control;

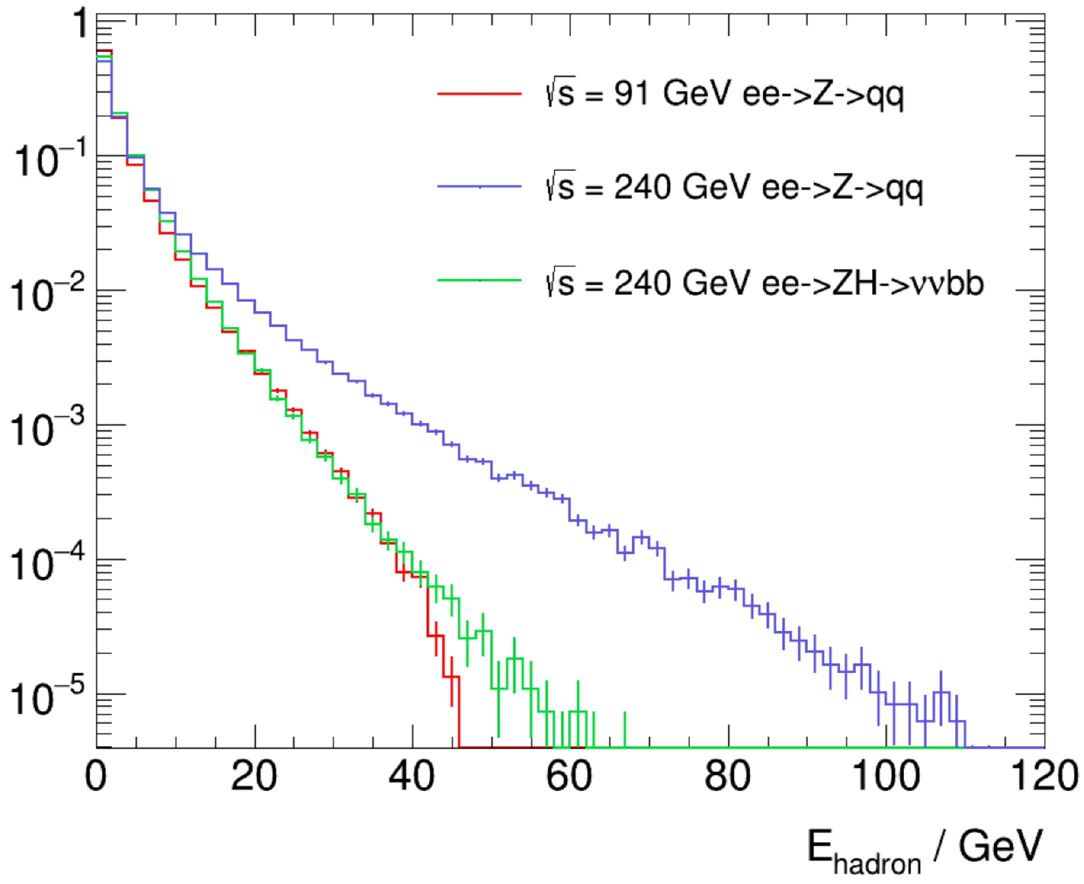
■Technical innovations needed to meet the challenge

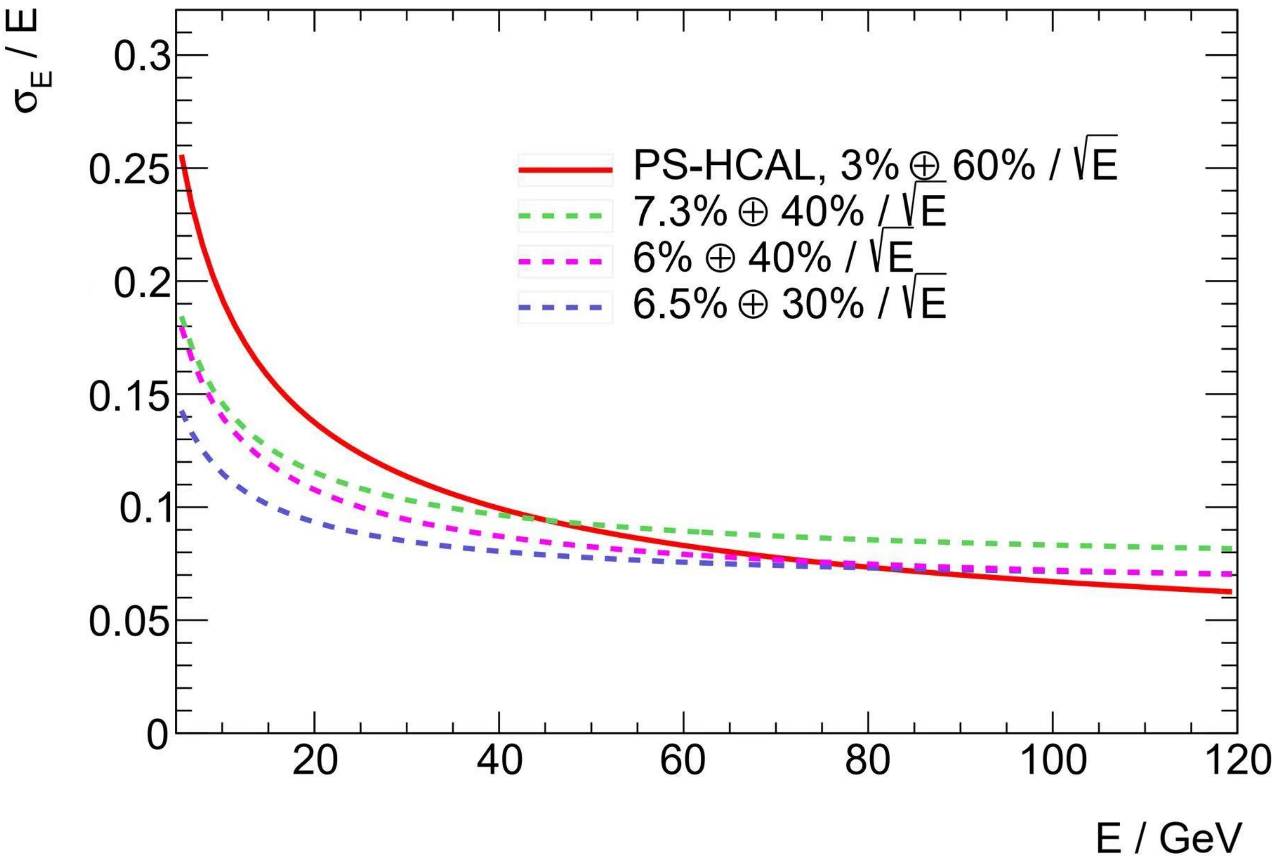
– Technique for **large scale production of high quality scintillator tiles** in a low-cost way

– Highly integrated, **fully embedded and scalable electronics** with a parallel readout design for high rate application

– The **design and installation** of the **big size and heavy weight** detector structure.

Backup slides

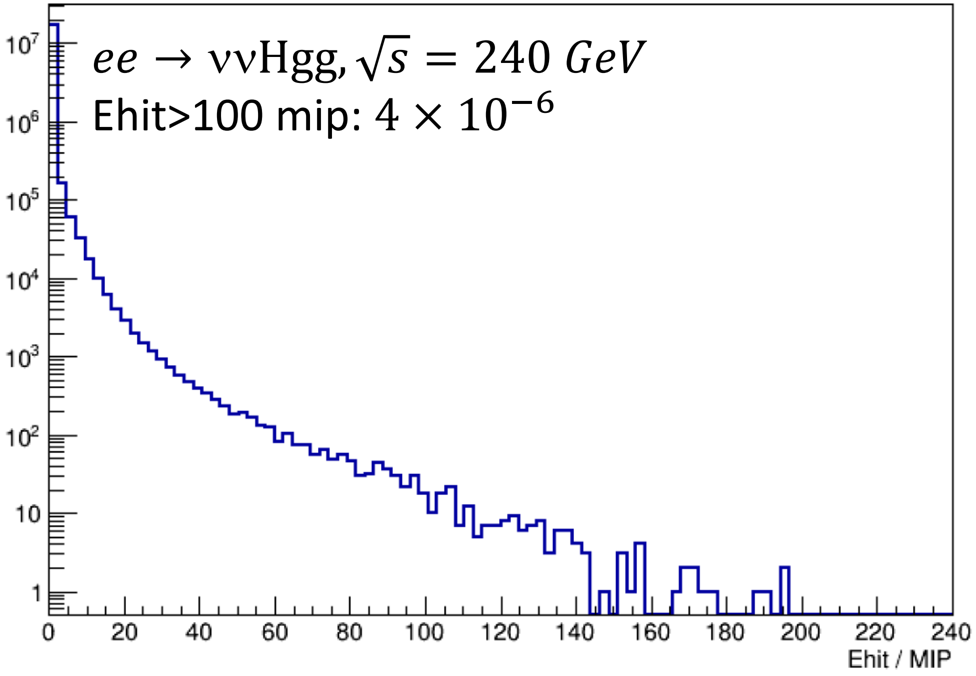


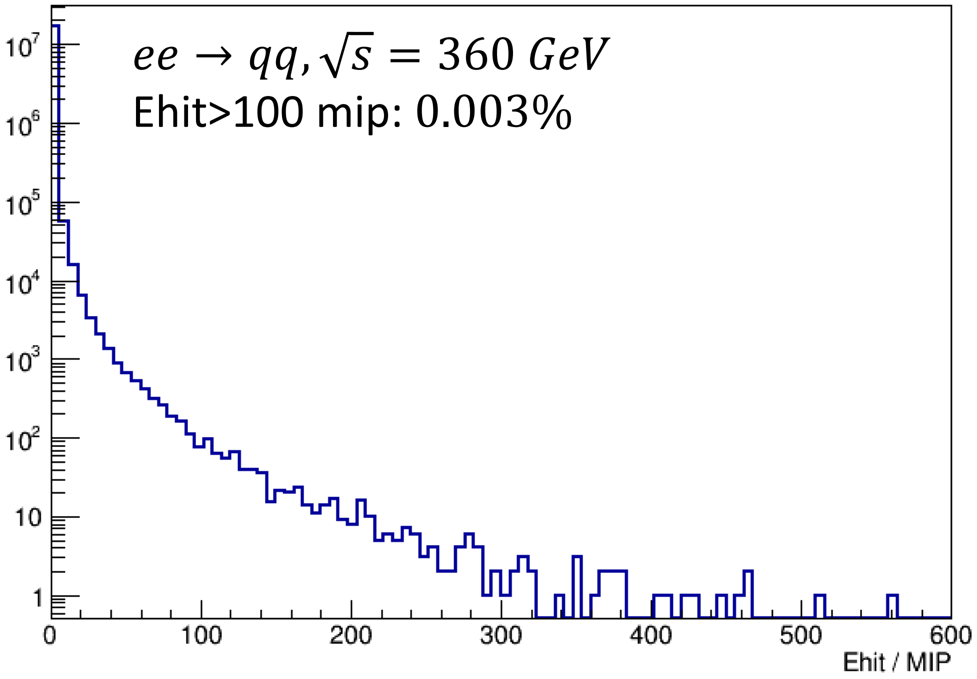


- E_{hadron} < ~ 100 GeV, typically < 60 GeV
- Energy resolution of GS-HCAL is better than that of PS-HCAL for E < 80 GeV

Key parameters to energy resolution

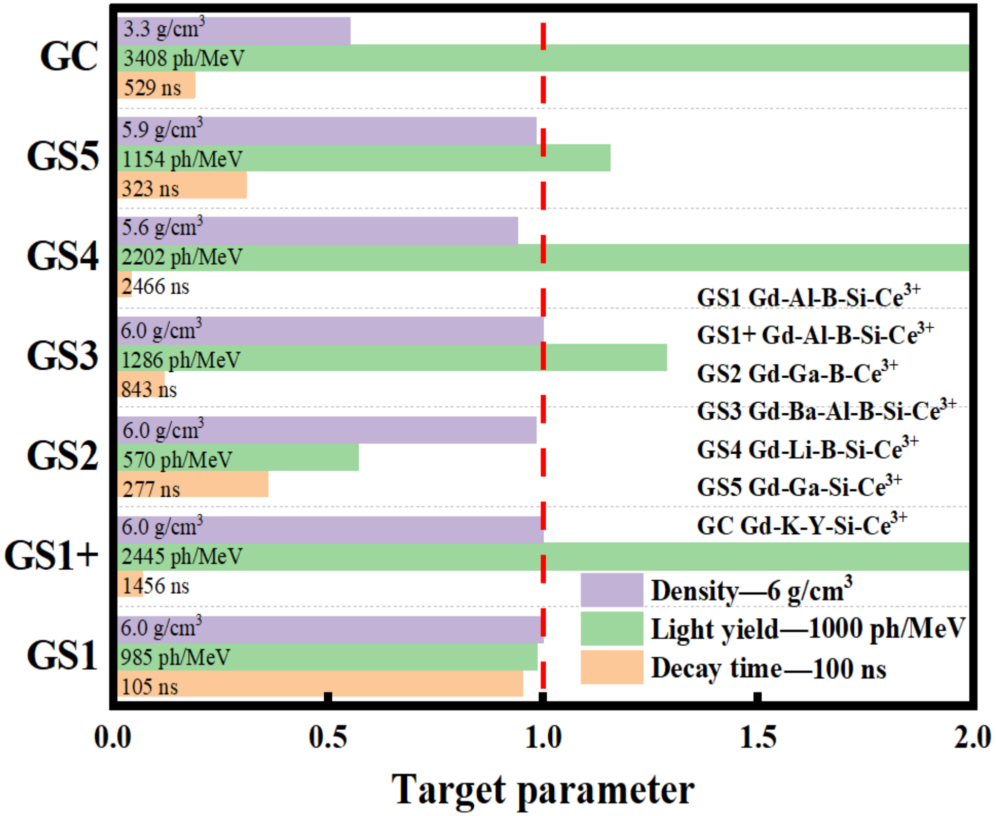
- **Dynamic range: 0 ~ 100 MIP can cover >99.99% cases**
  - For SiPM: 8000 p.e. can be controlled in linear range (suppose LY ~ 80 p.e./MIP).
  - For electronics: 1~1k can be achieved.
  - Considering the common electronics design for ECAL, HCAL and Muon, HCAL's demands can be covered by ECAL.

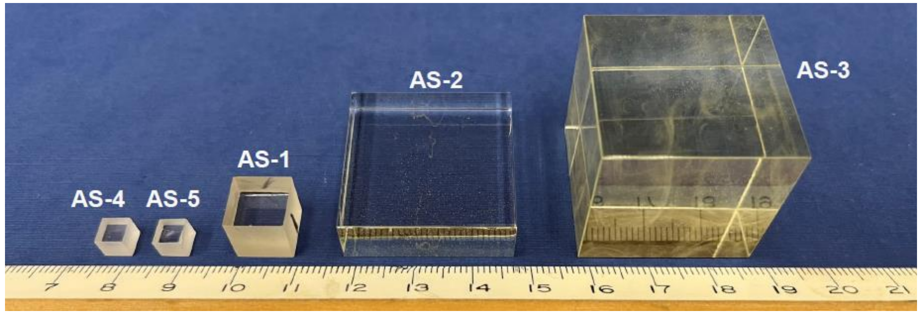




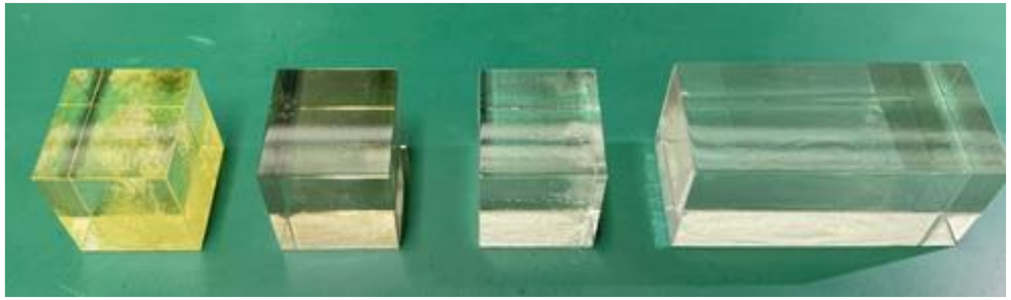
1. GS-HCAL: Sample test

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





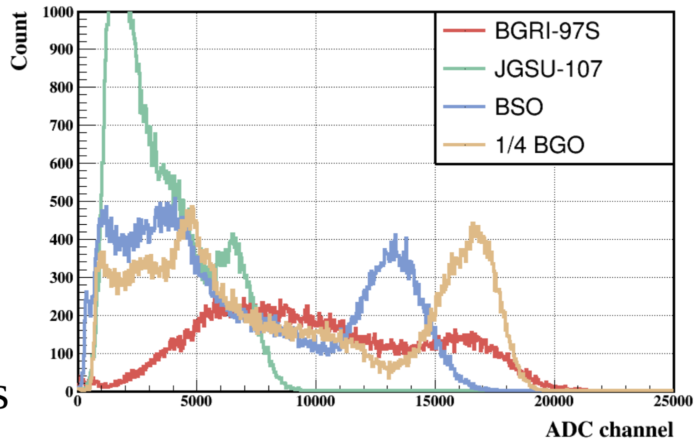
The samples (called AS glass) post to EIC for the test.



1. GS-HCAL: Sample test

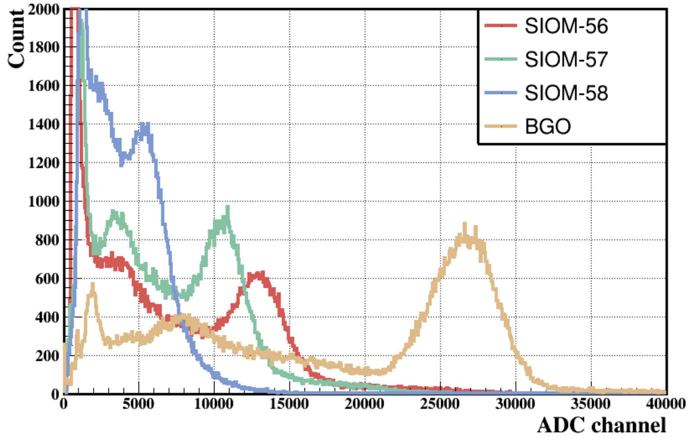
Small-Size Sample

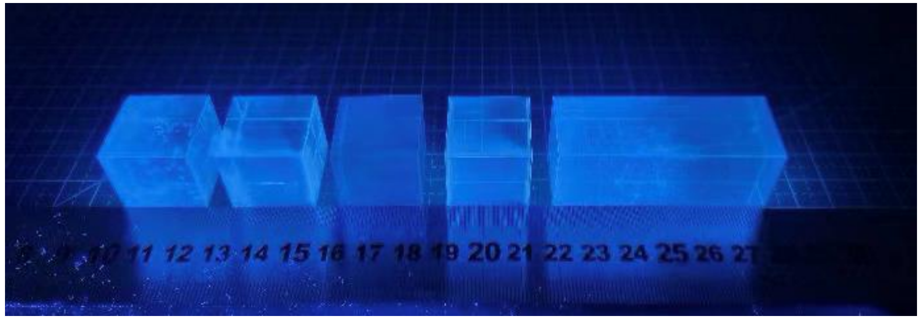
- **Size=5*5*5 mm^3**
- Density~6.0 g/cm^3
- **LY~2445 ph/MeV**
- ER=25.8%
- LO in 1μs=1074 ph/MeV
- Decay=**101** (2%), 1456 ns

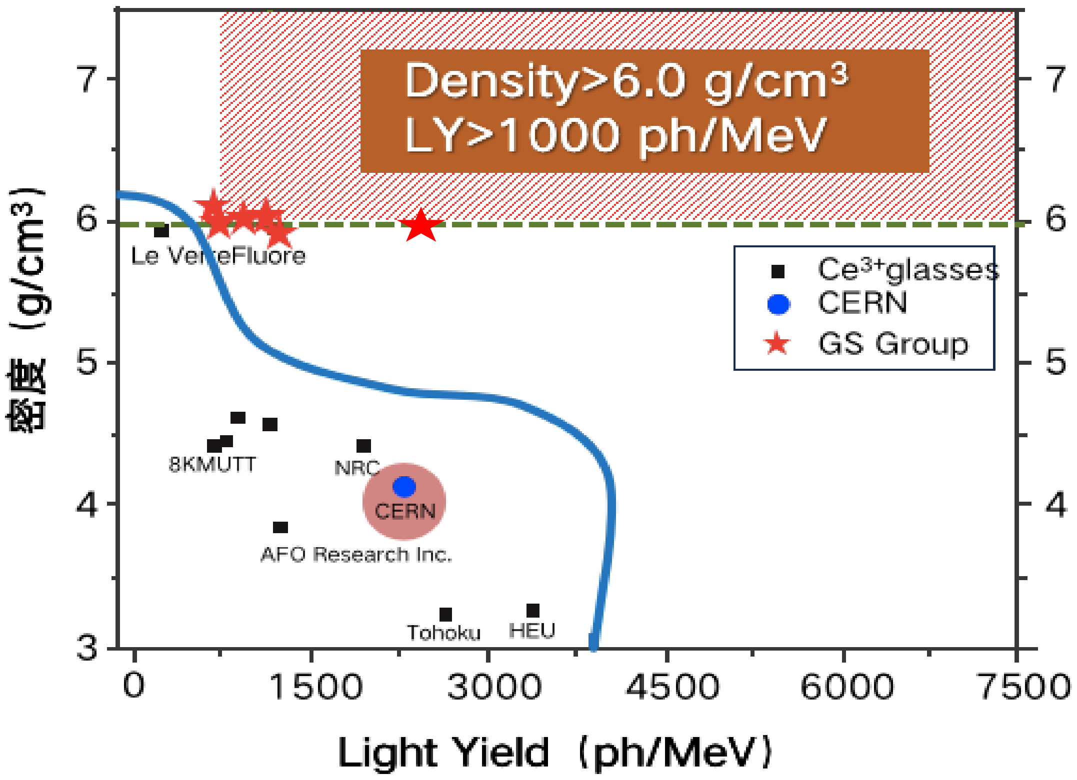


Large-Size Sample

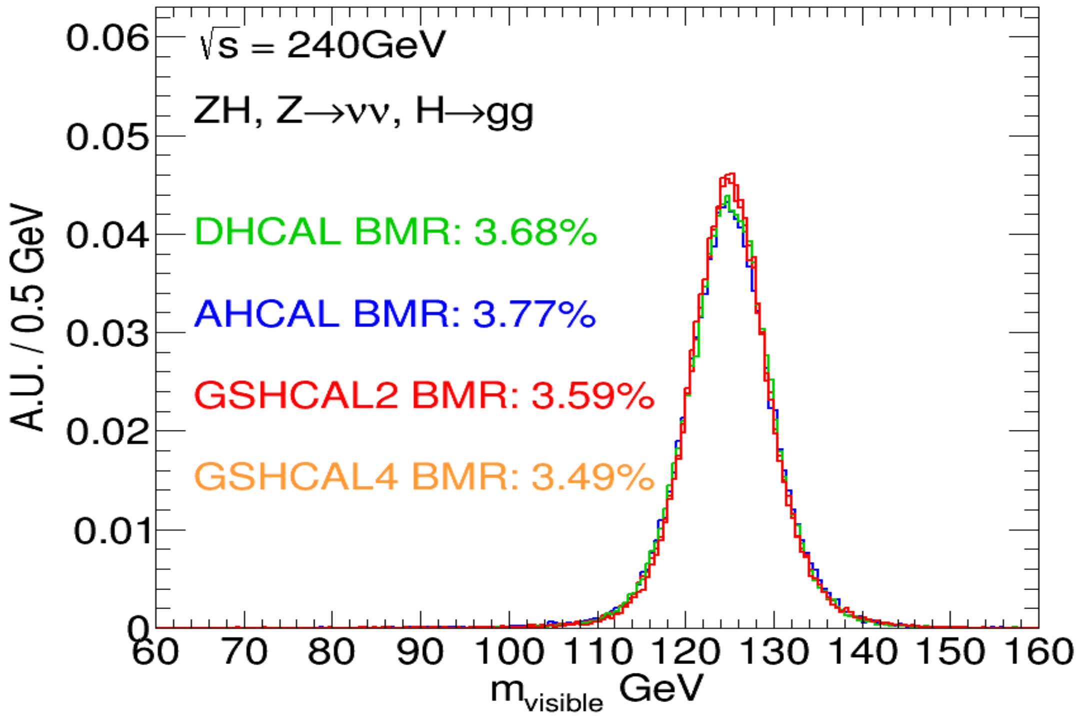
- **Size=40*40*10 mm^3**
- Density=6.0 g/cm^3
- **LY ~1200 ph/MeV**
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns

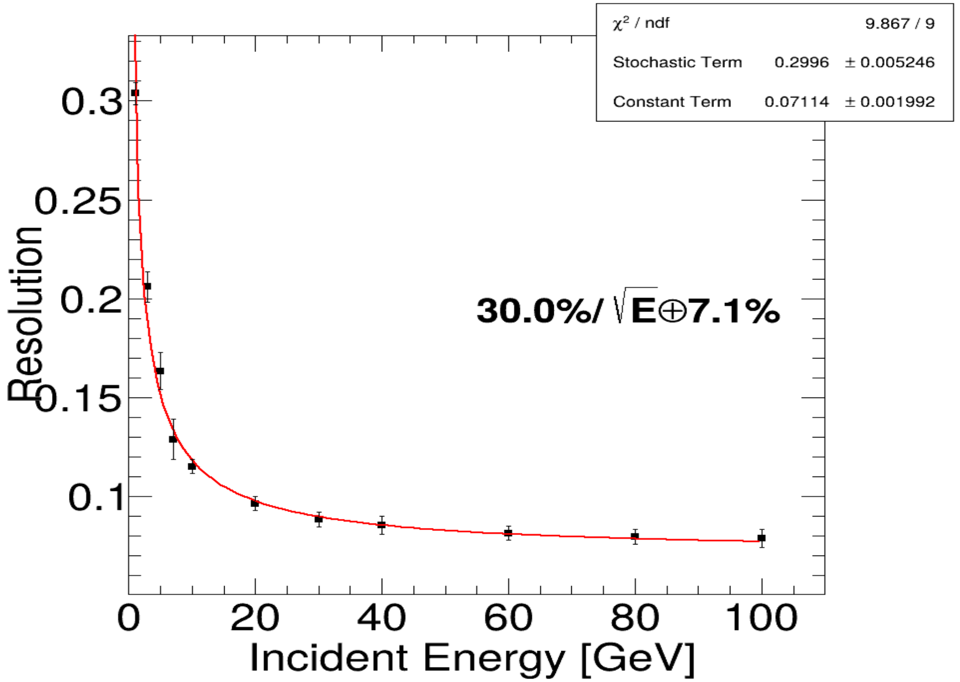






2. GS-HCAL Performance (MC)



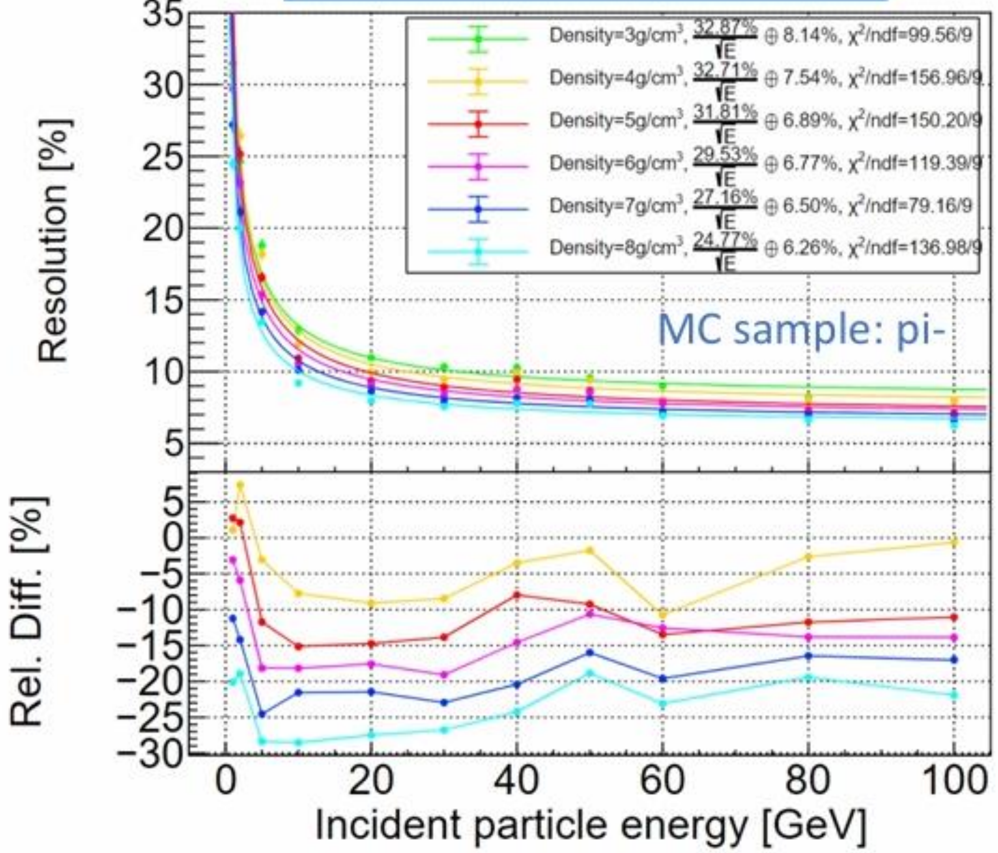


Status	CDR	CDR	R&D	Ref-TDR
Design Option	SDHCAL	AHCAL	GSHCAL	GSHCAL
Active Material	RPC	PS	GS	GS
Boson Mass Res.	3.7%	3.8%	**3.6%**	**3.5%**
No. of Layers	40	40	40	48
Nucl. Inter. Length	$4.8\lambda_I$	$5\lambda_I$	$5\lambda_I$	$6\lambda_I$

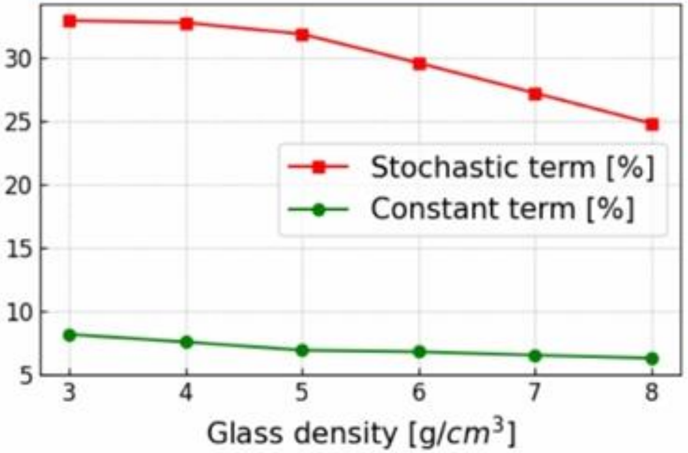
- Using similar setup as PS-HCAL, GS-HCAL can achieve a **more compact structure and less readout channels**, as well as a comparable PFA performance with the DHCAL;
- The energy resolution is about 30% by simulation with the construction of Ref-TDR design.

2. GS-HCAL Performance (MC)

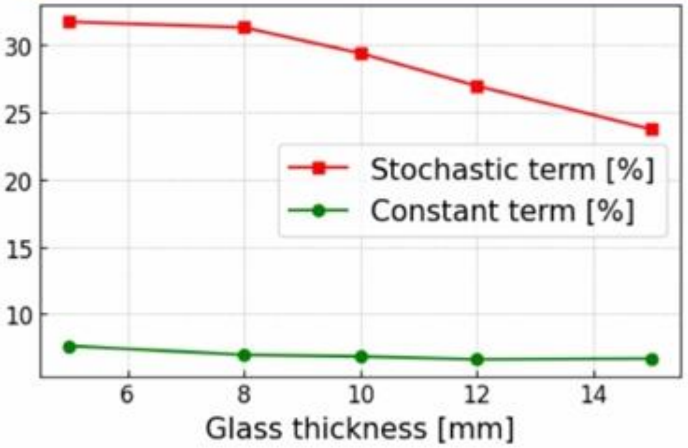
Hadronic energy resolution



Energy resolution vs. glass density



Energy resolution vs. glass thickness



- Improvements of hadronic energy resolution
  - Glass density and thickness, energy threshold
- Targets for scintillating glass R&D
  - Density: 6 g/cc
  - Thickness: 10mm
  - Intrinsic light yield: 1000 photons/MeV

3. GS-HCAL Mechanical Design

- Assembling of one division

① 

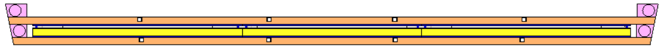
First absorber

② 

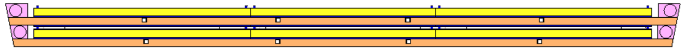
First trapezoid plate

③ 

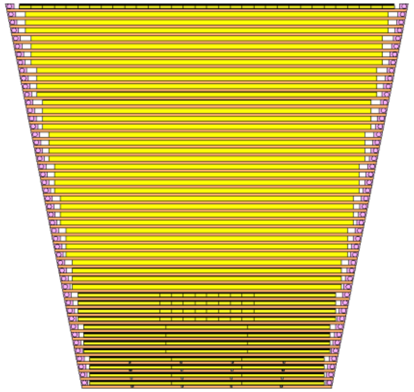
First active layer

④ 

Second absorber and trapezoid plate

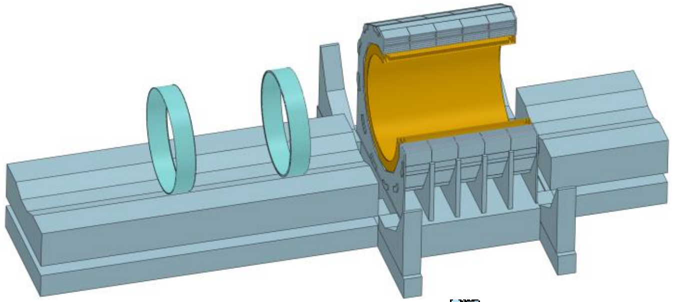
⑤ 

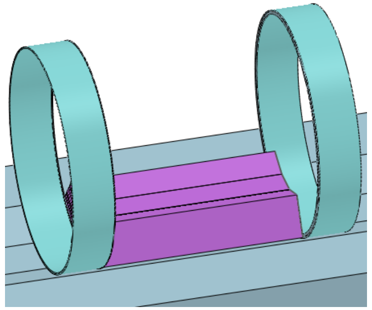
Second active layer

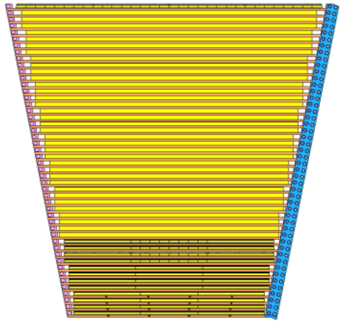
⑥ 

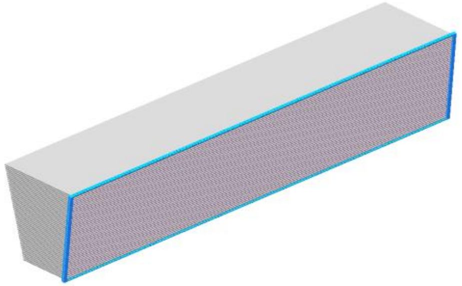
One division

- Installation









Using edge sealing to connect two division