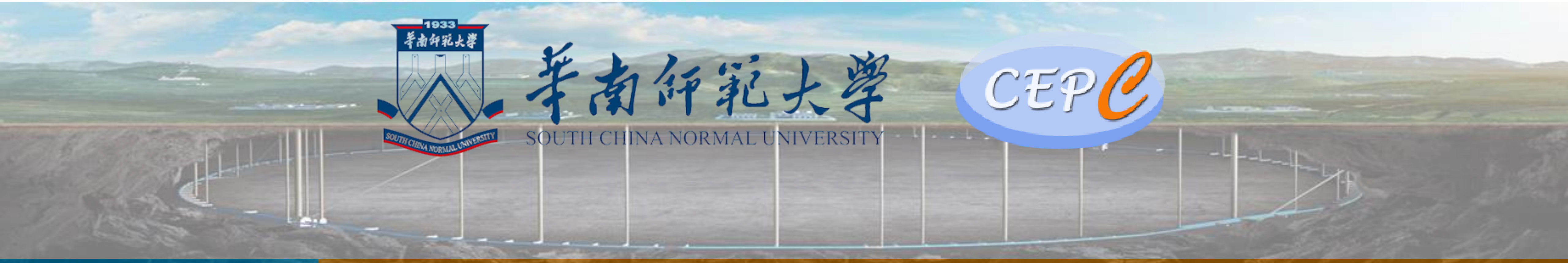
2025 European Edition of the International Workshop on the Circular Electron-Positron Collider (CEPC), Barcelona, Spain

16 Jun 2025, 08:00 → 19 Jun 2025, 14:10 UTC

# Status of the CEPC GS-HCAL

**Hengne Li (SCNU)**

**on behalf of the CEPC HCAL Group**



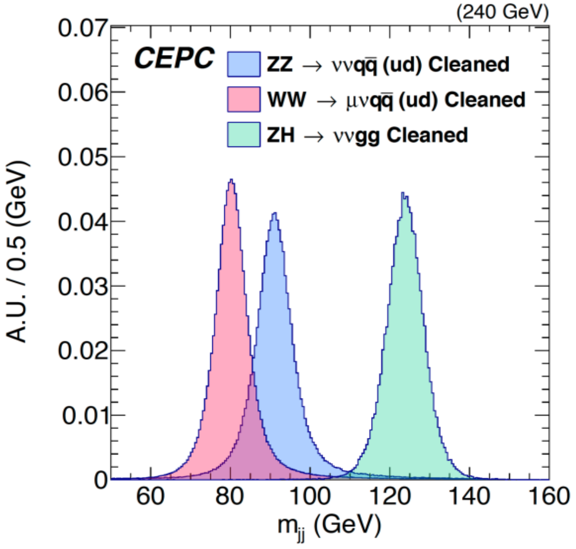
# Physics Requirements of HCAL

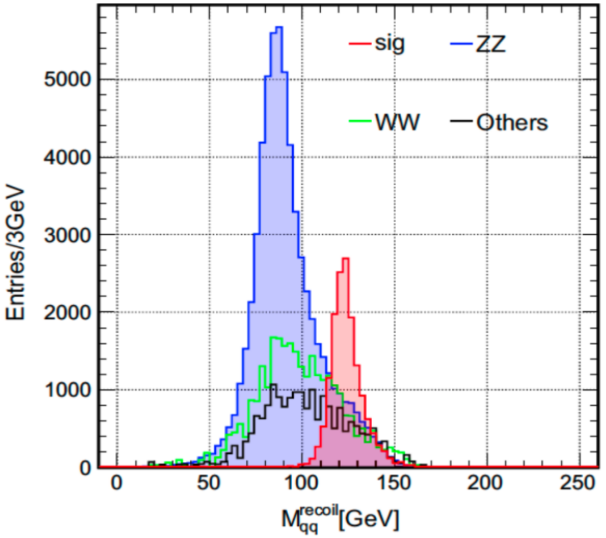
## CEPC HCAL Design requirements:

❖**Jet Energy Resolution $\Delta E/E < 30\%/\sqrt{E}$ GeV**

❖**Boson Mass Resolution (BMR) < 4% :**

it is strongly motivated by H/W/Z hadronic final states, BSM & Flavor Physics




CDR baseline (arXiv:1811.10545): BMR = 3.75%

## Leading contributions to BMR:

- ➢ HCAL resolution dominant the uncertainties from intrinsic detector resolution: **~19.7%**
- ➢ **Further improvement of HCAL is needed**

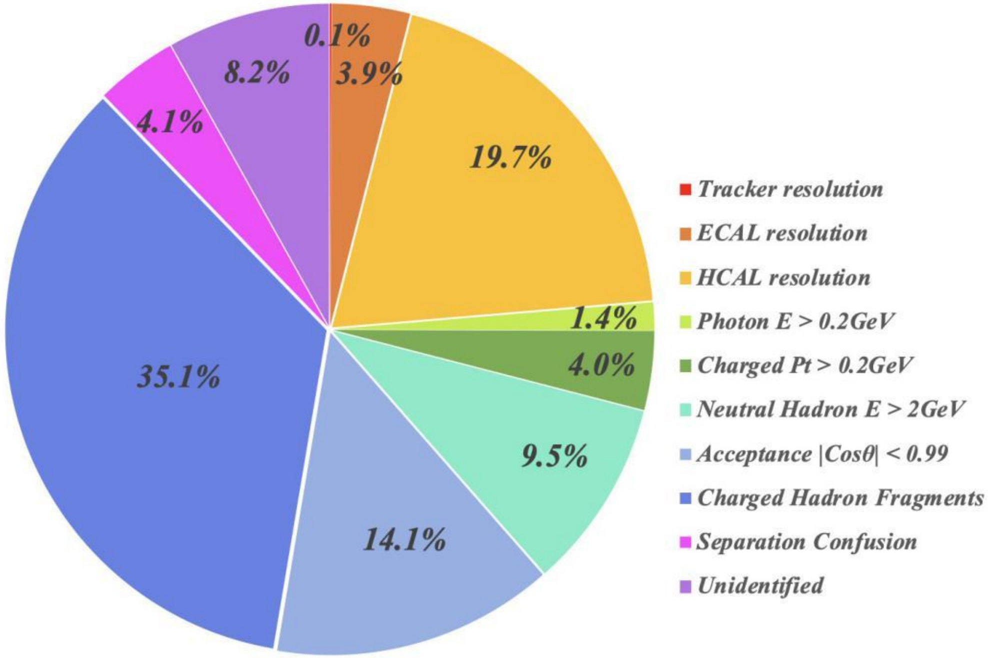
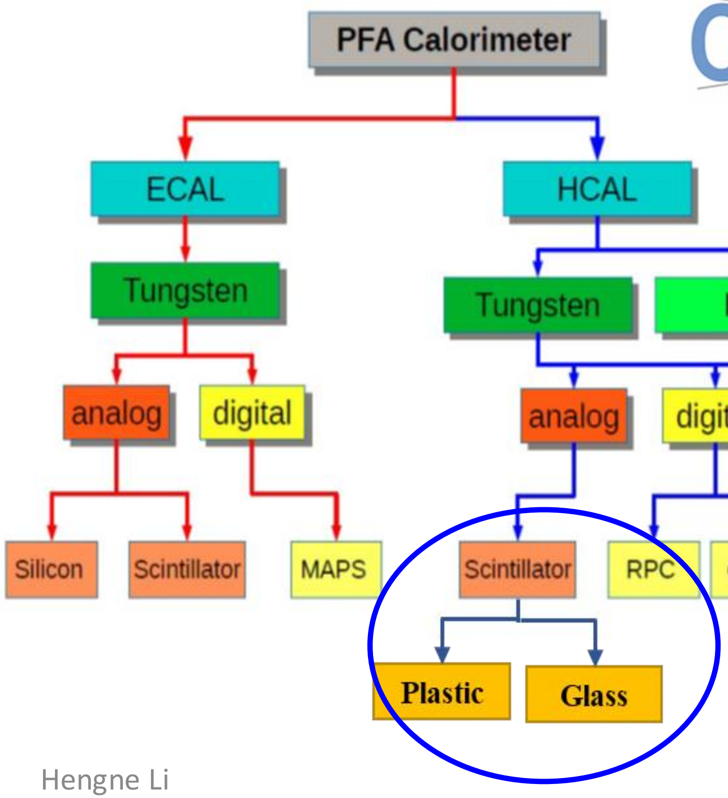
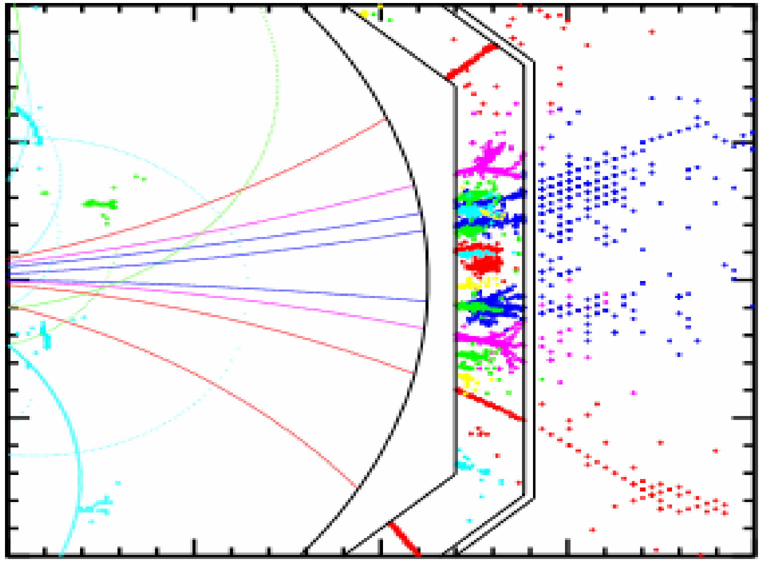


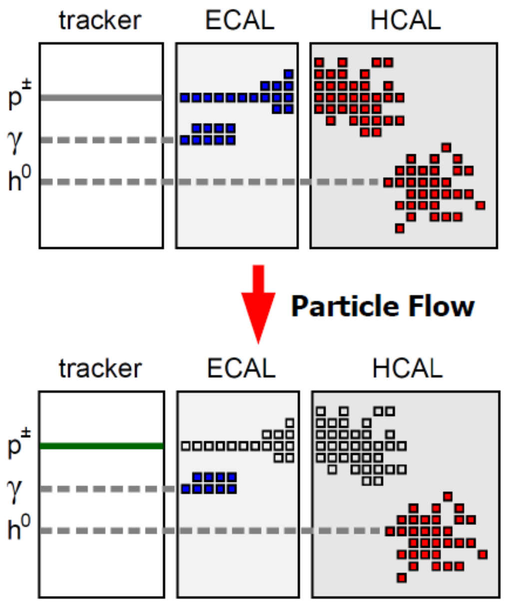

Fig8.18

# Technology Survey

- **PFA calorimetry: extensively explored within the CALICE collab.**
  - RPC-DHCAL (SDHCAL): 48-layer prototype
  - Plastic Scintillator-AHCAL (PS-HCAL): 40-layer prototype
  - Glass Scintillator-AHCAL (GS-HCAL): new design and baseline



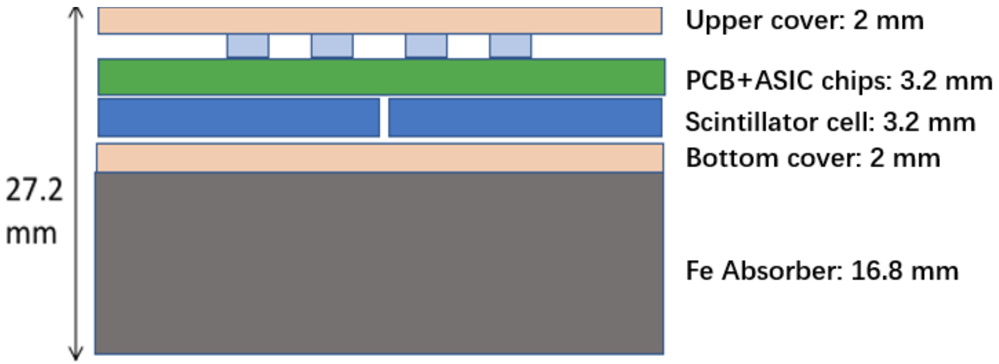





# Glass Scintillator HCAL

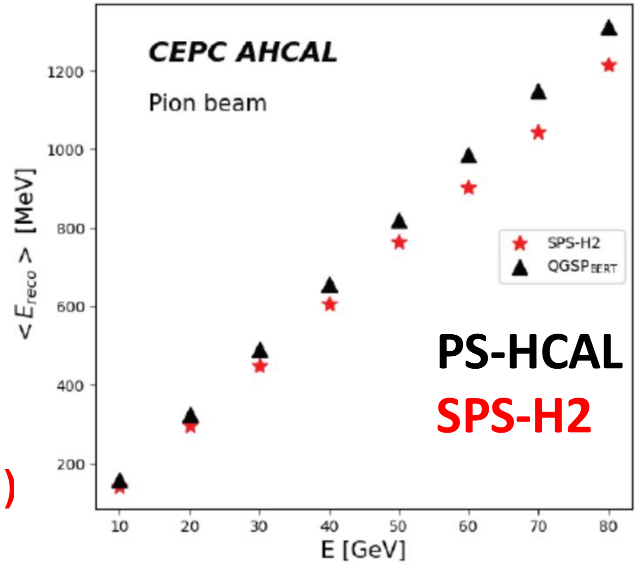
- **Basic idea:** to increase sampling fraction for better energy resolution
- With **high density and thick GS cell design**, the sampling fraction of GS-HCAL can be increased by **a factor of ~20** compared to that of PS-HCAL

**PS-HCAL**

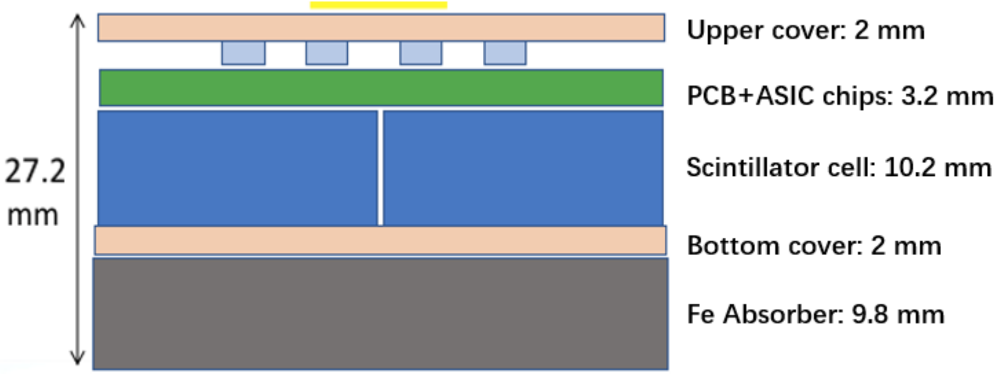



**PS-HCAL**

Fe: 20.8mm/171.5mm=0.1213 $\lambda_I$
PS: 3mm/688.7mm=0.0044 $\lambda_I$
PCB: 1.2mm/492.2mm=0.0024 $\lambda_I$
**Sampling fraction ~ 1.6% ($\pi^-$ TB, MC)**

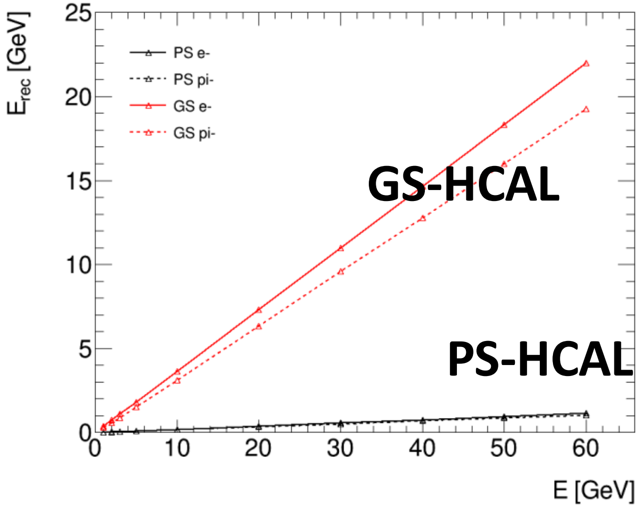



**GS-HCAL**




**GS-HCAL**

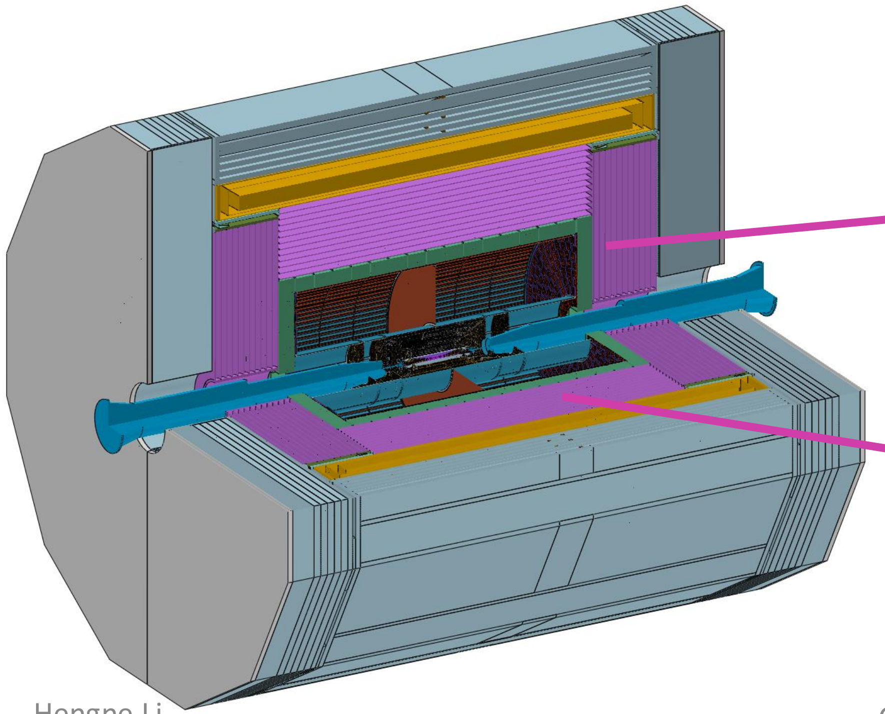
Fe: 13.8mm/171.5mm=0.0805 $\lambda_I$
GS: 10.2mm/242.8mm=0.0425 $\lambda_I$
PCB: 1.2mm/492.2mm=0.0024 $\lambda_I$
**Sampling fraction ~ 31% (MC)**

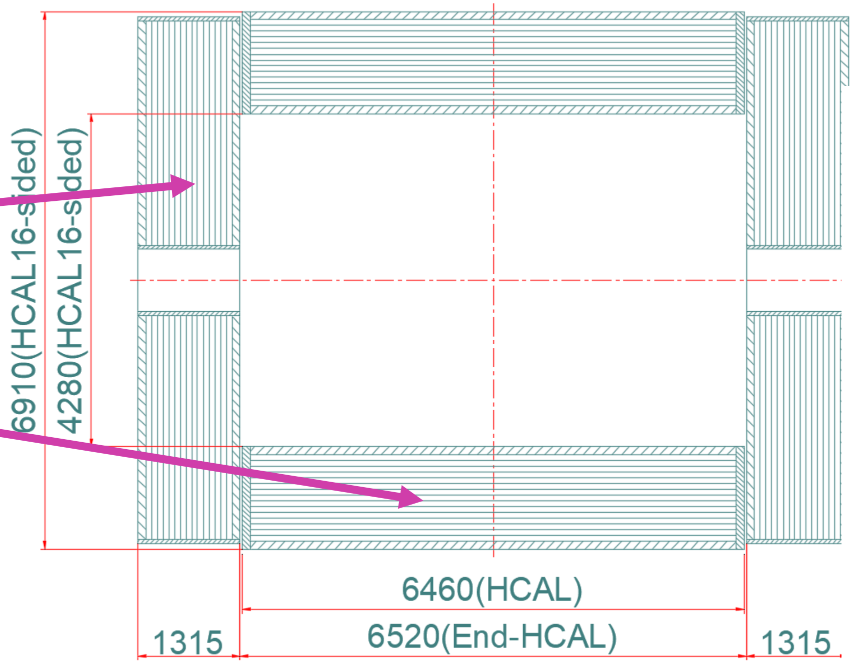


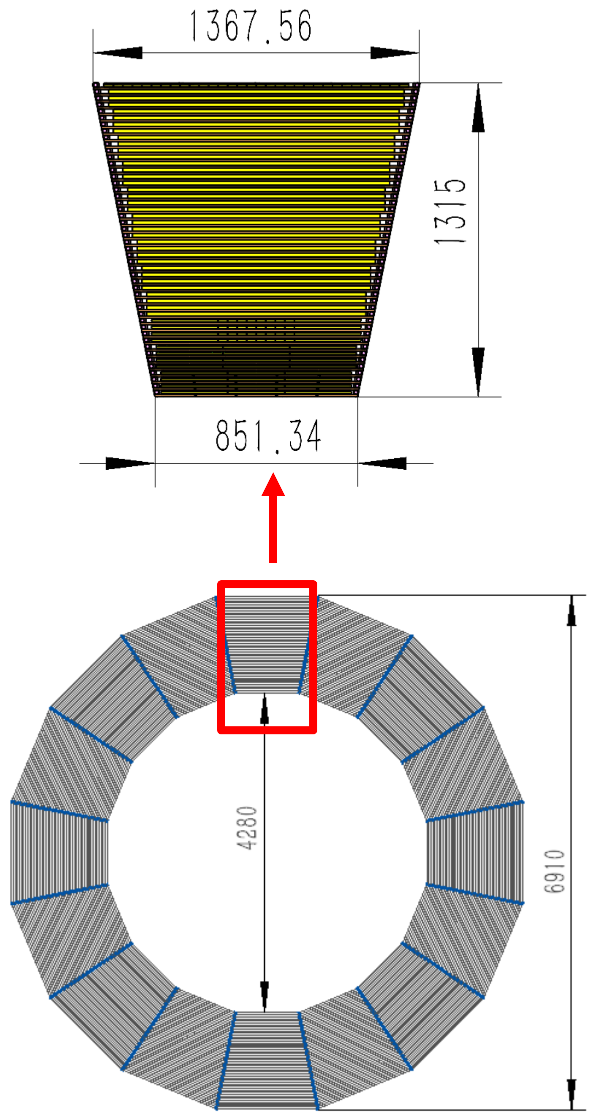
# GS-HCAL Mechanical Design

## ☐ GS-HCAL: One Barrel (16 wedges) 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 $\lambda_I$)

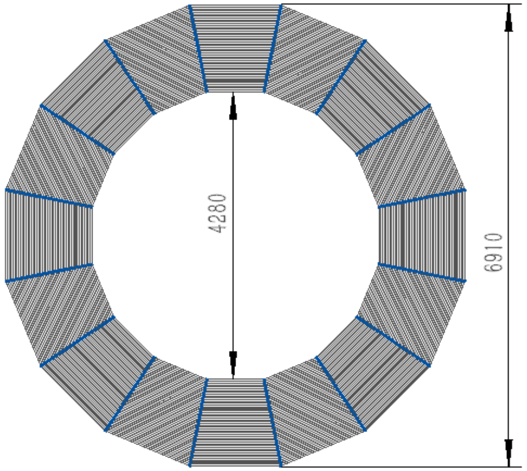


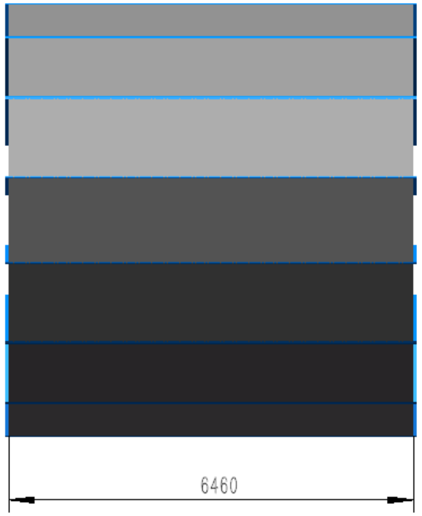


# Barrel HCAL Mechanics

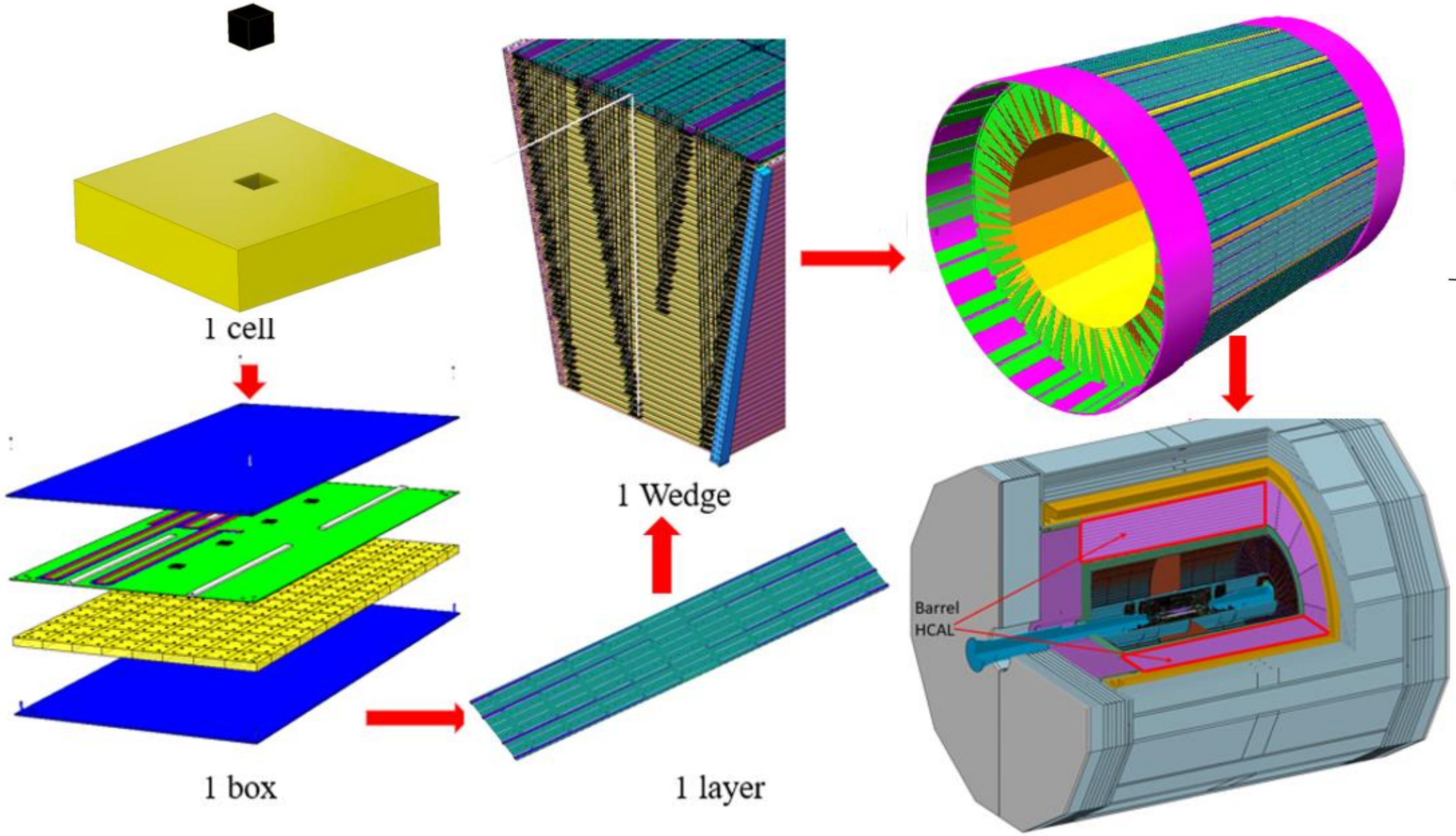
Main Structure




**Length: 6460mm**

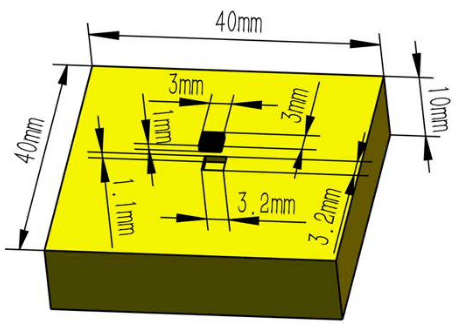
Integration of barrel HCAL structure



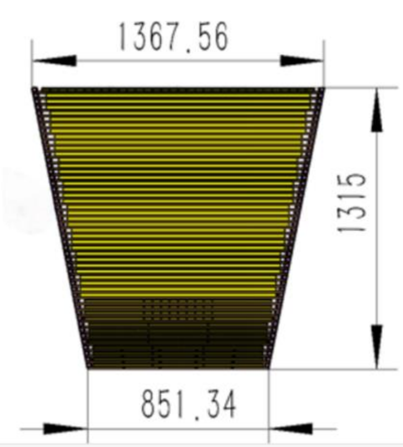

| | Cell | Box | Layer | Wedge |
|---|---|---|---|---|
| **Quantities** | 3212800 | 27840 | 48*16=768 | 16 |

**Total weight: 955 tons**

1 cell dimension

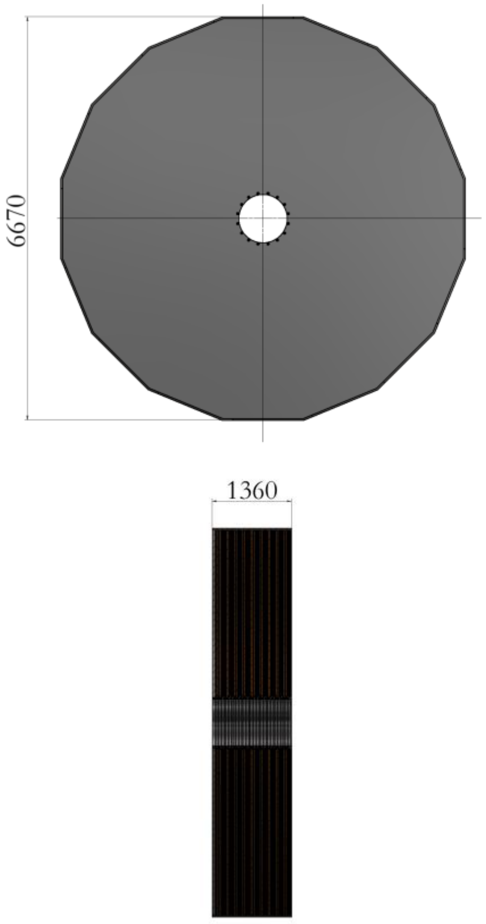



1 Wedge dimension



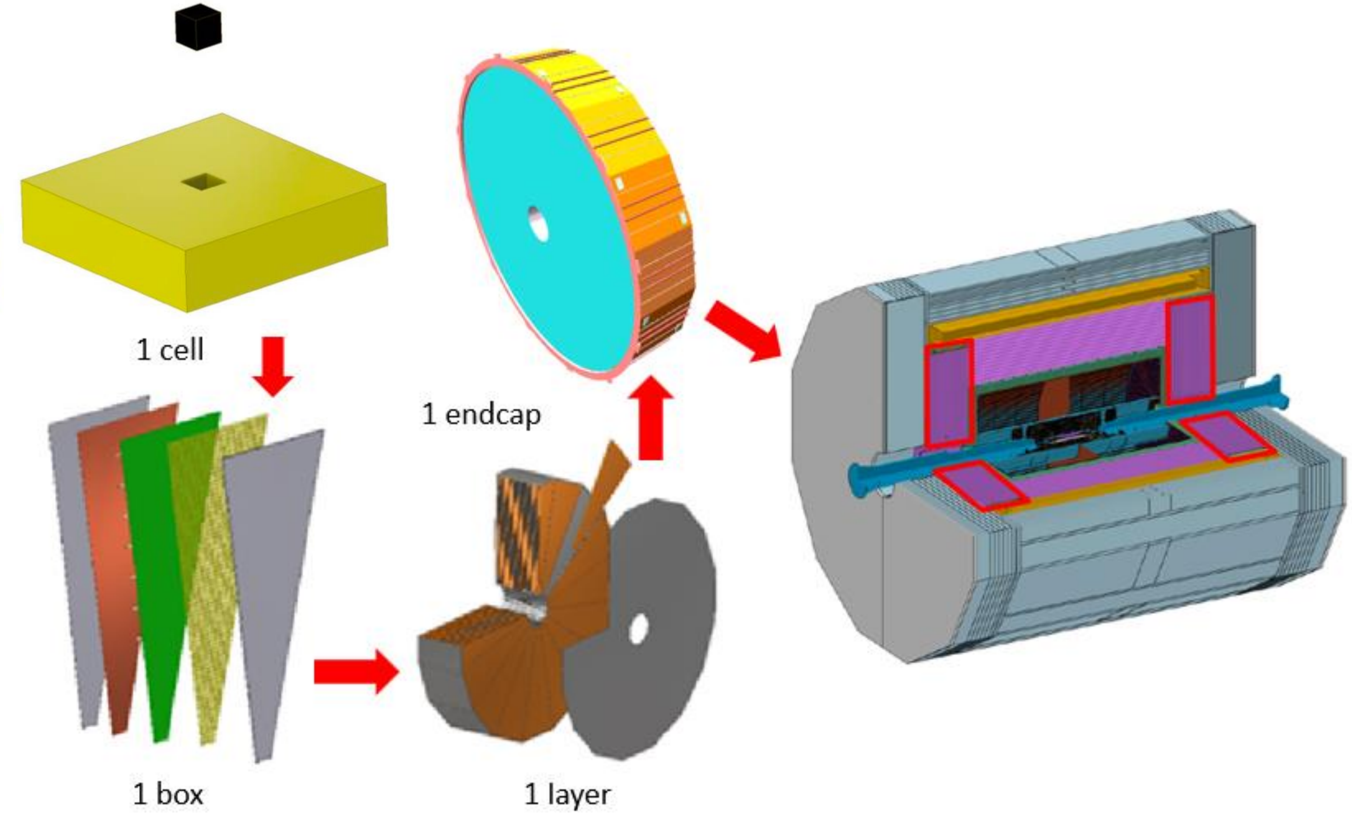
# Endcap HCAL Mechanics

Main Structure




Two endcap HCAL

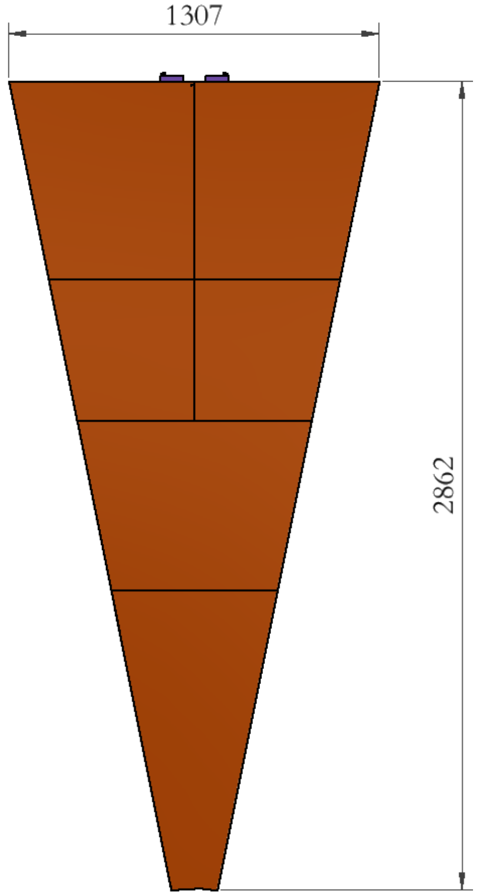
Integration of barrel HCAL structure




| | Cell | Box | Layer | Wedge |
|---|---|---|---|---|
| **Quantities** | 1006080*2 | 3072*2 | 48*16*2 | 16*2 |

**Total weight: 362 × 2 = 724 tons**

Boxes in one layer

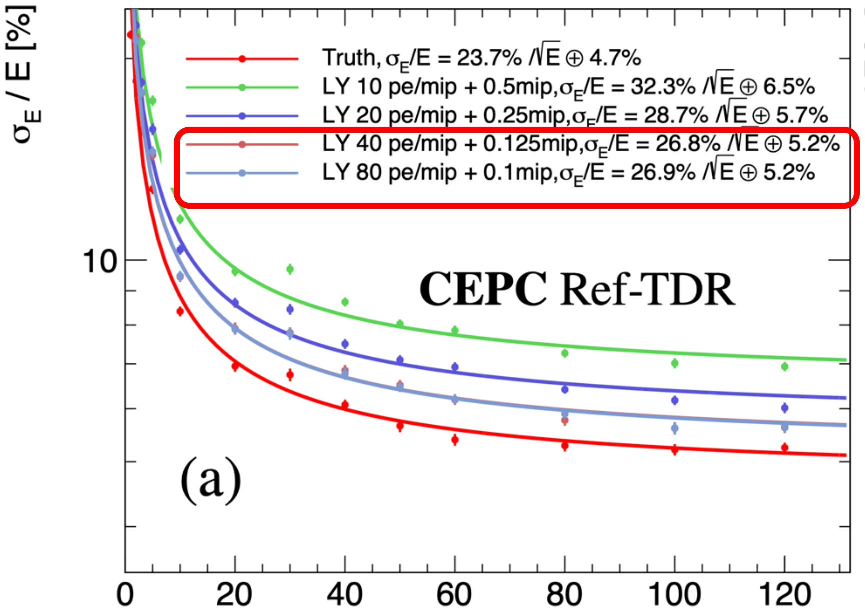


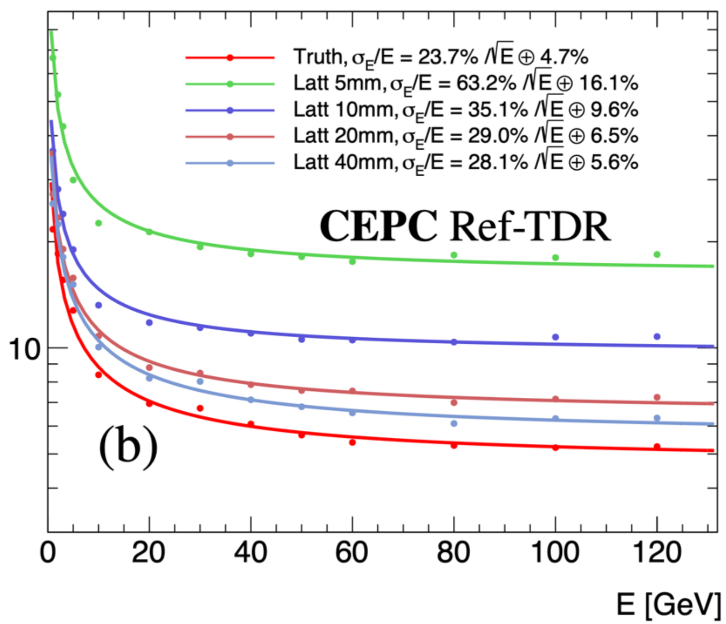

**4 types Box**

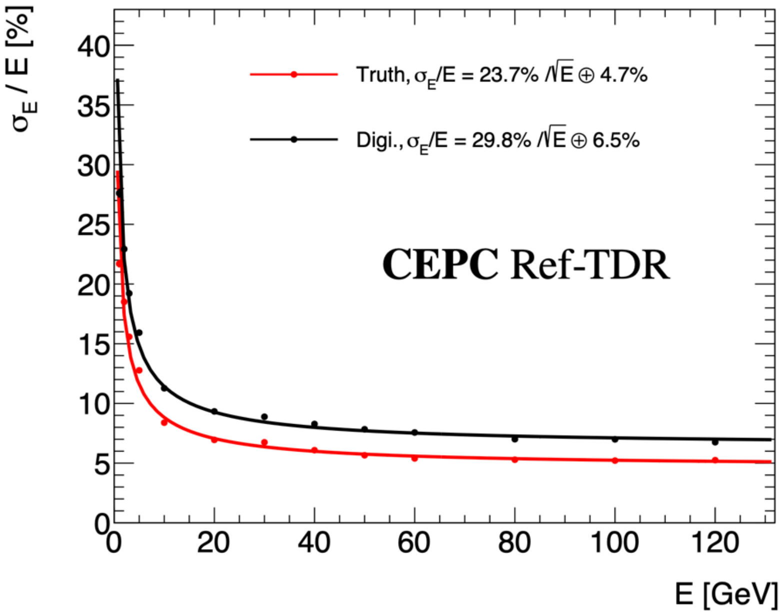
# GS-HCAL Energy Resolution

- **A full detector geometry constructed with DD4hep in CEPCSW**
  - GS density 6 $g/cm^3$, $\lambda_I = 242.8$ mm, attenuation length ~ 62 mm
  - GS cell size $4 \times 4 \times 1\ \mathrm{cm}^3$, 48 layers, $6\lambda_I$ in total
  - Geometry: follow the mechanics design with supporting structures.
  - **Light output: LO ~ 60 p.e./MIP can satisfy the design goal.**

**$\sigma_E/E = 29.8\%/\sqrt{E} \oplus 6.5\%$**




- GS light output: > 40 p.e/MIP
- Threshold: 0.1 MIP (> 5 p.e)

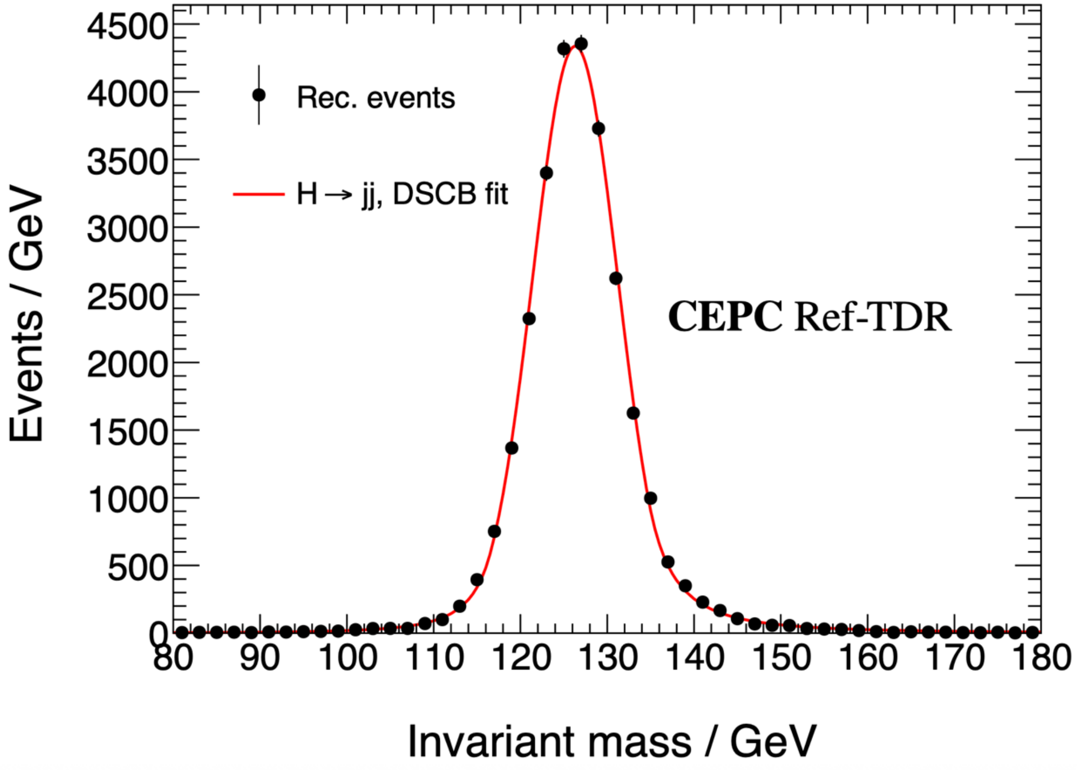
- GS attenuation length

- GS attenuation length: 62 mm

# GS-HCAL Physics Performance

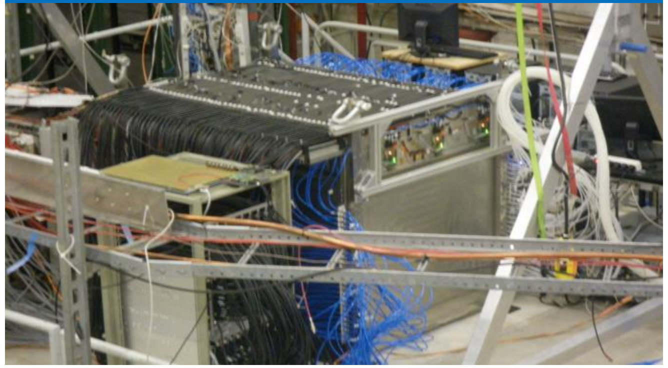
- **Hadron Energy Resolution (full simu. + digitization):**
  - MC Sample: $ee \rightarrow ZH \rightarrow \nu\nu gg$ @ 240GeV
  - Tracker (Si + TPC) + Crystal ECAL + GS-HCAL, Cyber PFA Reconstruction
- **BMR (H→gg) = 3.88%**

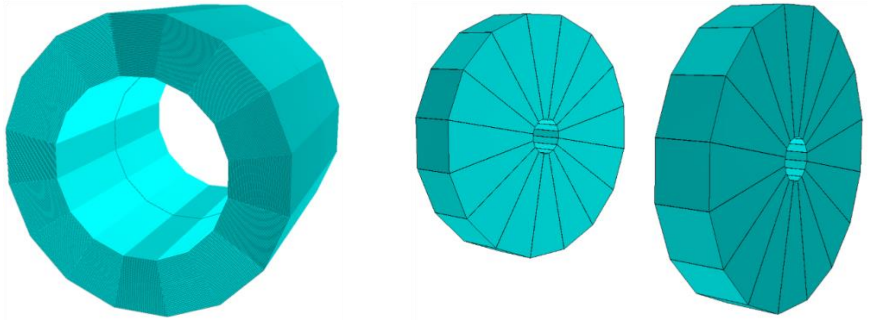
Fitted Higgs mass is 126.32 ±0.04 GeV,
σ(mjj ) = 4.90 ±0.04 GeV.



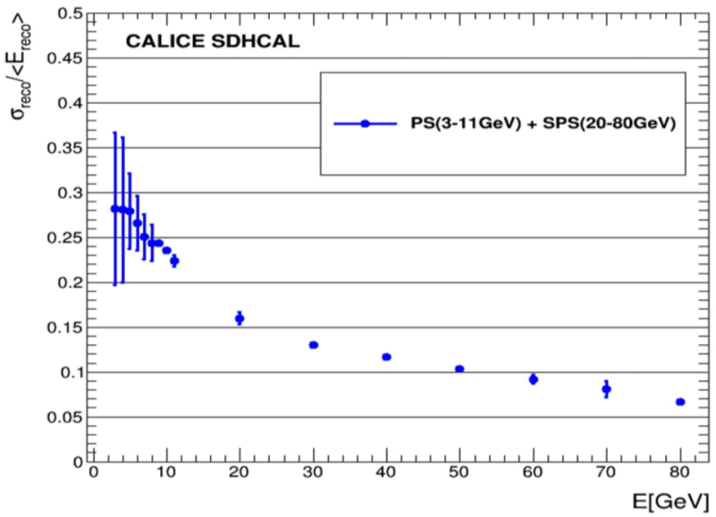
# Performance Comparison

| RPC-SDHCAL, 48-layer, 1x1 $cm^2$ | PS-HCAL, 40-layers, 4x4 $cm^2$ | GS-HCAL, 48 layers, 4x4 $cm^2$ |
| --- | --- | --- |



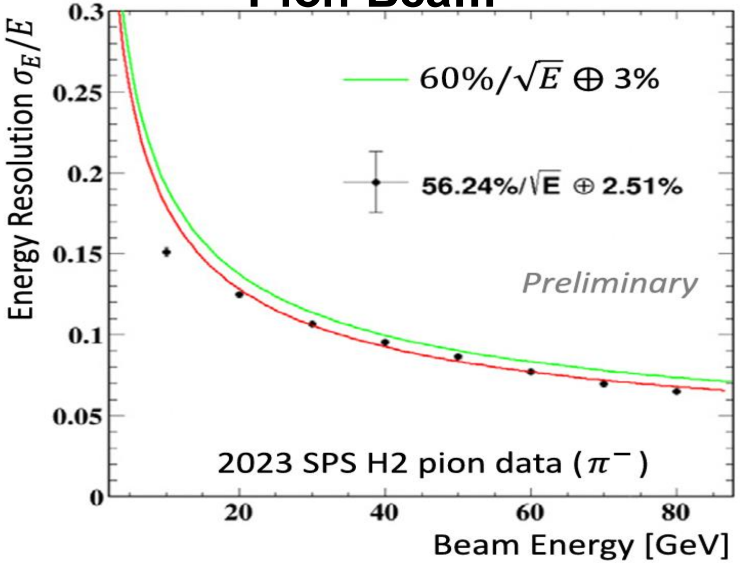


**Pion Beam**



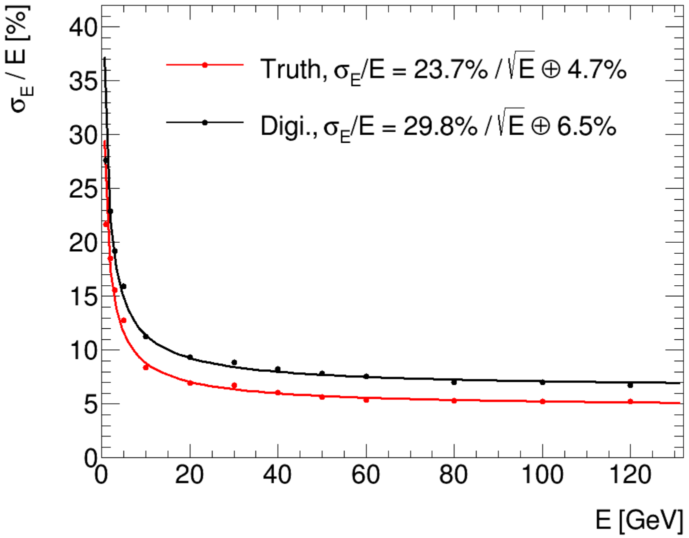

$$65\%/\sqrt{E} \oplus 2.5\%$$

**Pion Beam**




$$56.2\%/\sqrt{E} \oplus 2.5\%$$

**MC Simulation**



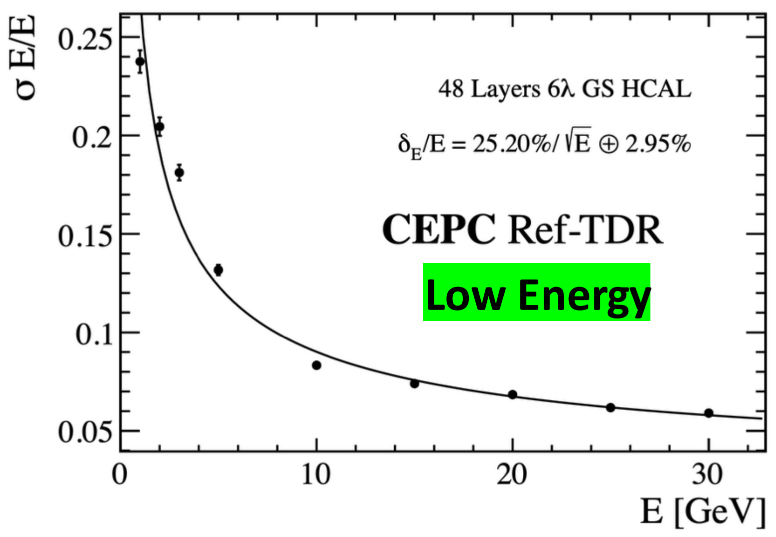

$$29.8\%/\sqrt{E} \oplus 6.5\%$$

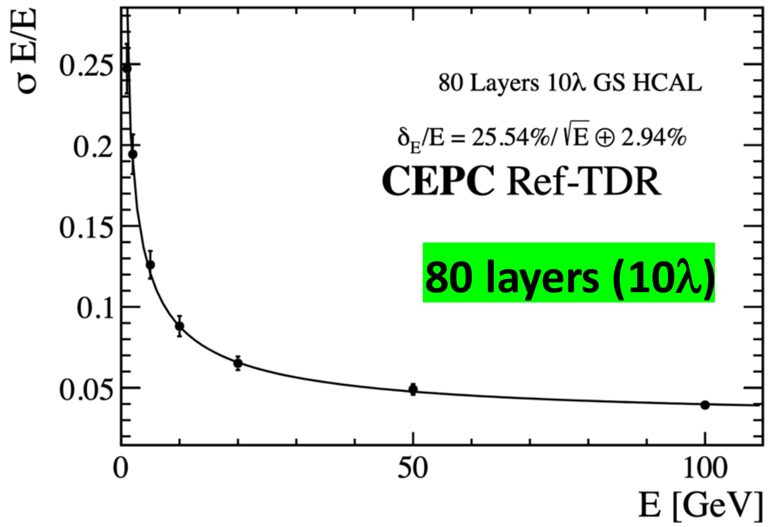
# GS-HCAL Constant Term

- **PS-HCAL prototype**: $5\lambda$, $\frac{\sigma_E}{E} = \frac{56.2\%}{\sqrt{E}} \oplus 2.5\%$, with shower start and end selection (require shower start at first 5 layers).
- **GS-HCAL in full sim+digi**: $6\lambda$, $\frac{\sigma_E}{E} = \frac{29.8\%}{\sqrt{E}} \oplus 6.5\%$ (all events)
  - All events at truth level: $\frac{\sigma_E}{E} = \frac{23.7\%}{\sqrt{E}} \oplus 4.7\%$
  - Shower starts at first 3 layers: $\frac{\sigma_E}{E} = \frac{25.9\%}{\sqrt{E}} \oplus 3.5\%$
  - Low energy beam ($E_{\pi^-} < 30$ GeV): $\frac{\sigma_E}{E} = \frac{25.2\%}{\sqrt{E}} \oplus 2.9\%$
  - Large HCAL (80 layers, $10\lambda$): $\frac{\sigma_E}{E} = \frac{24.7\%}{\sqrt{E}} \oplus 2.9\%$

➔ Large constant term in GS-HCAL is partly due to longitudinal leakage of the hadronic shower

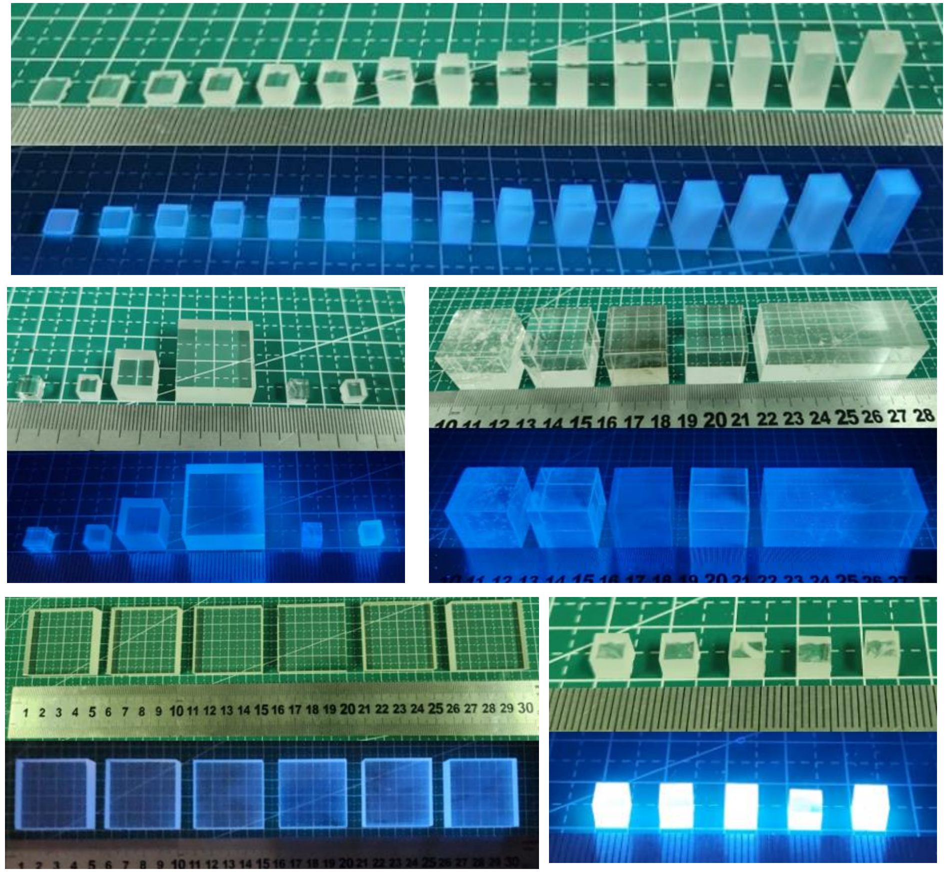
➔ Short attenuation length may also contribute



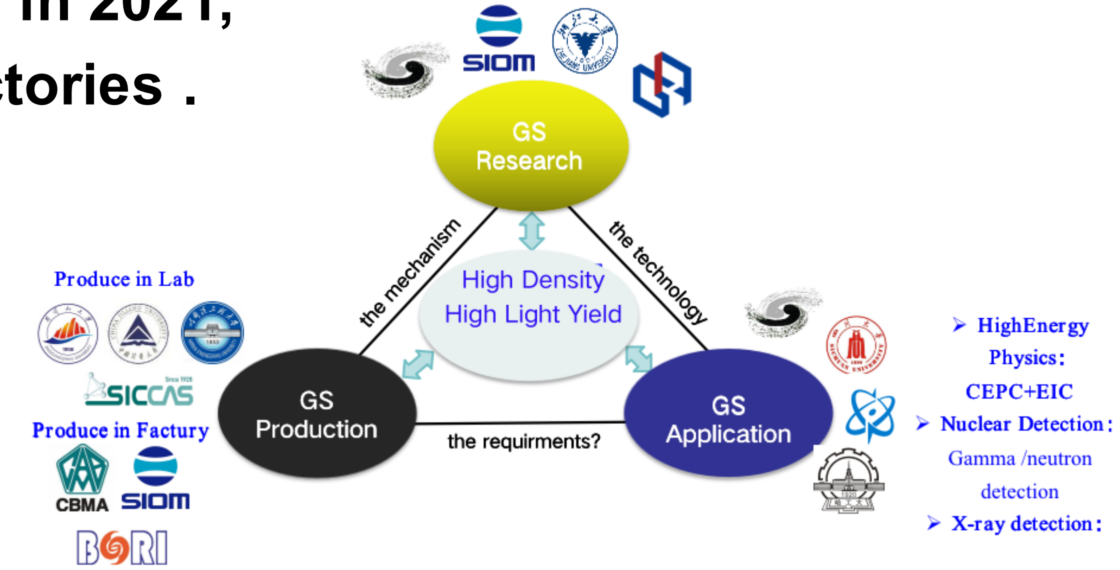
# GS Study

➢ The GS collaboration was organized by IHEP in 2021, it includes 4 Institutes of CAS, 6 Univ., 3 Factories .



Normal light

UV Light

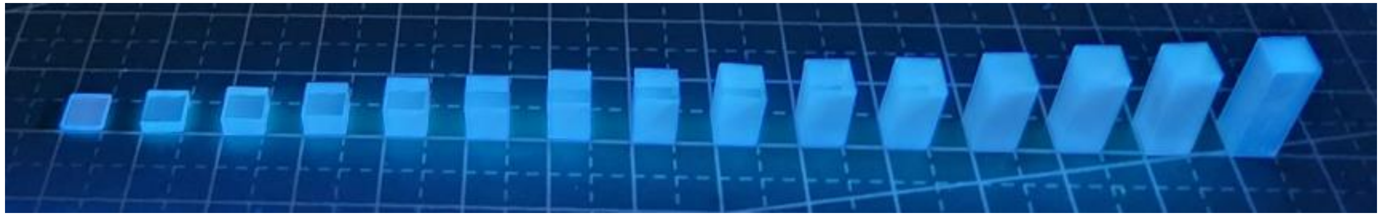



**Gadolinium Fluoro-Oxide (GFO)**

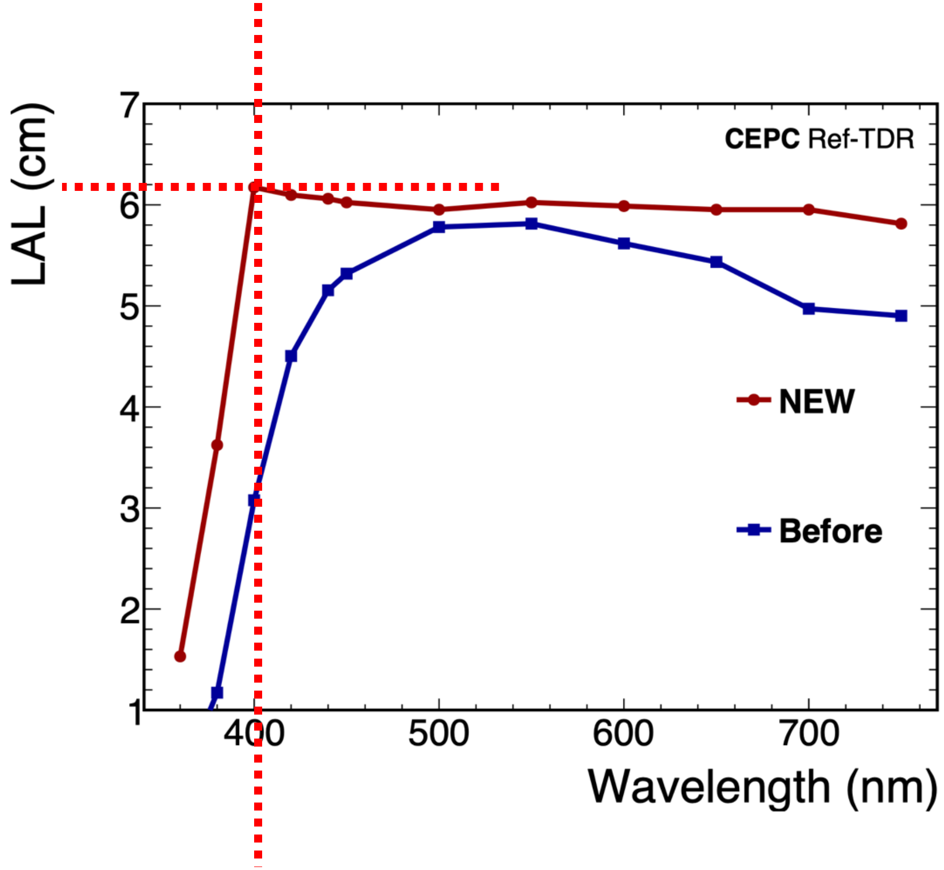
- Density~6.0 g/cm$^3$
- **LY ~ 1500 ph/MeV**
- **Emission peak: 400 nm**
- **Decay time: 60 and 500 ns**

# GS Study: Attenuation Length

- GFO samples with varying thicknesses were fabricated to measure the light attenuation length.
- Using energy spectra and light yield vs thickness of GFO to fit **attenuation length: 6.2 cm @ 400nm**

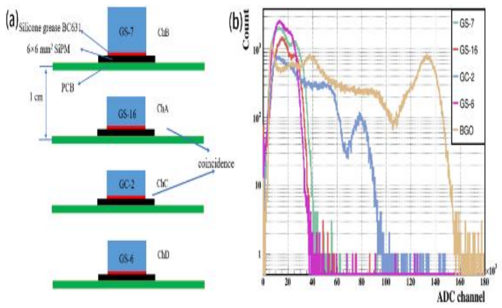


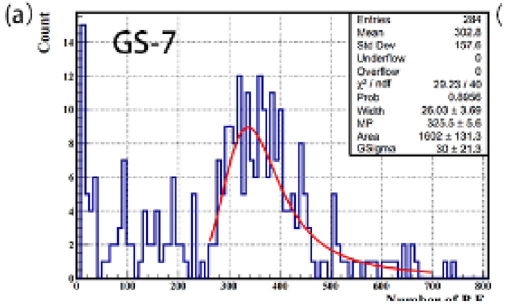
- New GFO samples from three vendors are under test, promising results will be available soon.



# GS Study: cosmic ray tests

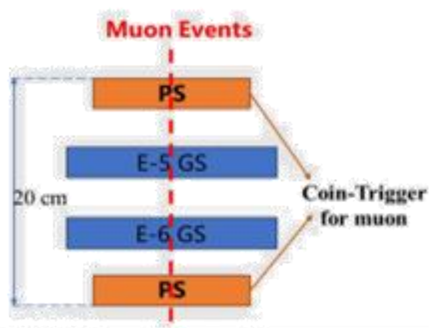
## 1st Cosmic ray (Integral gate=1 μs)

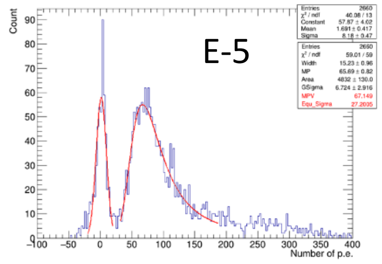



- **Lab grade GS (5mm cube)**
- Normalize the thickness and density of GS
- Prove consistency of LY and MIP responses

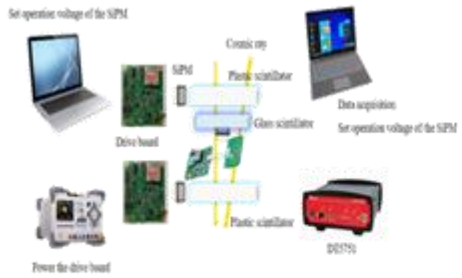
## 2nd Cosmic ray (Integral gate=4 μs)

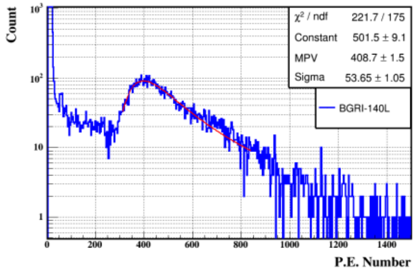



- **Size=40*40*10 mm$^3$**
- Light yield: ~750 ph/MeV
- MIP response: **~67 P.E./MIP**

## 3rd Cosmic ray (Integral gate=4 μs)

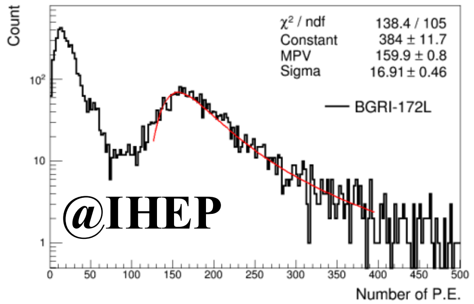




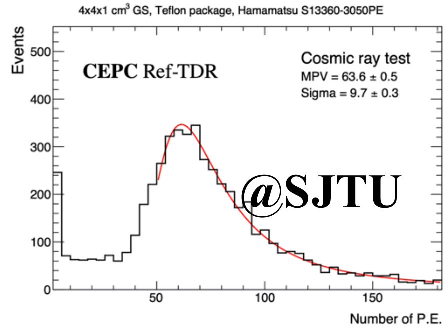

- **Size=20*20*10 mm$^3$**
- Light yield: ~1800 ph/MeV
- MIP response: **~400 P.E./MIP**

## New GS sample for Ref-TDR

- **Atten.leng. = 62mm**
- **Size=40*40*10 mm$^3$**
- **Teflon wrapped**
- Light yield ~1250 ph/MeV
- **Integral gate=1 μs**




- SiPM: 6*6 mm$^2$ HPK S13360-6025CS
- PDE: 0.221
- MIP response: **~159.9 p.e./MIP**




- SiPM: 3*3 mm$^2$ HPK S13360-3050PE
- PDE: 0.325
- MIP response:

**~63.6 p.e./MIP**

**V.S.**

**Convert to SiPM 3050 Result:**

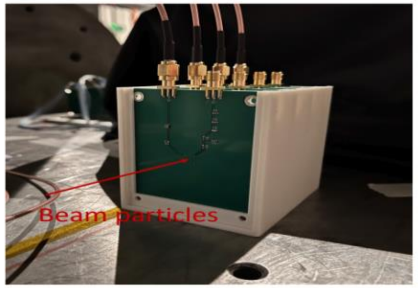
$$159.9 \cdot \underbrace{\frac{0.325}{0.221}}_{\text{PDE}} \cdot \underbrace{\frac{3*3}{6*6}}_{\text{Area}} = 58.8\ \text{p.e./MIP}$$

**Consistent results**

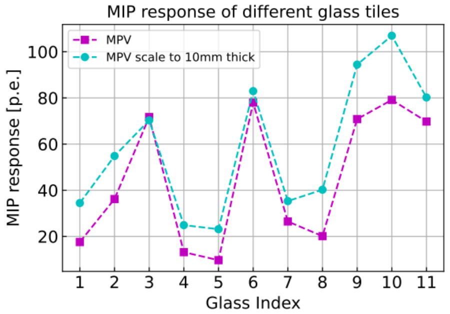
# GS Study: beam tests

**CERN Muon beam**

**(Integral gate=1 μs)**



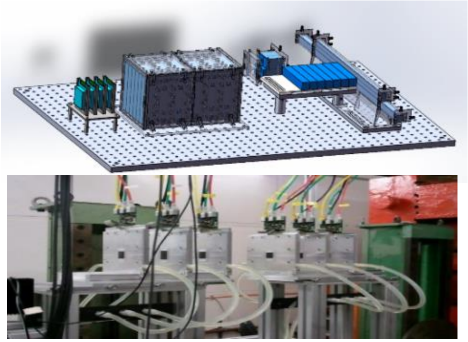

(a)

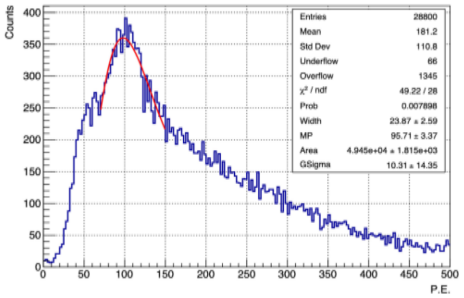



- **(25-40)*(25-35)*(4-10) $mm^3$**
- Typical light yield: 500-600 ph/MeV
- Typical MIP response: **60-100 P.E./MIP**

**DESY Electron beam**

**(Integral gate=1 μs)**





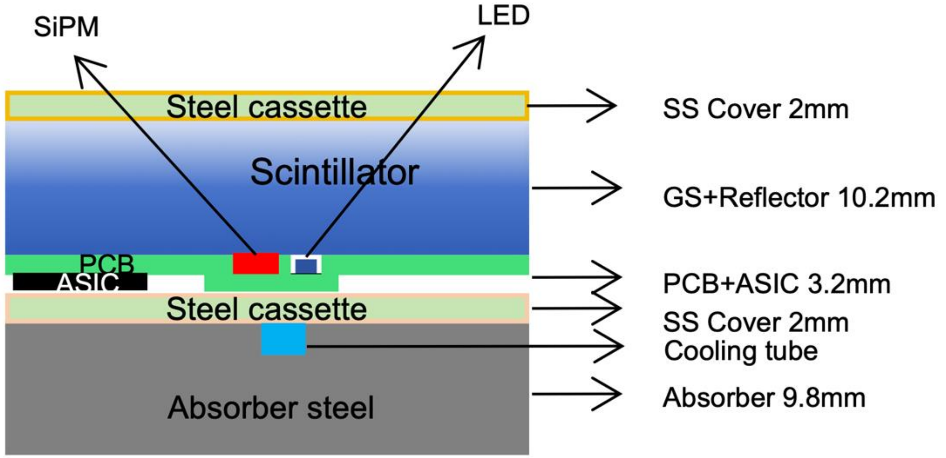

- **Size=40*40*10 $mm^3$**
- Typical light yield: 600-700 ph/MeV
- Typical MIP response: **80-90 P.E./MIP**

**New results from KEK, CERN, and DESY are coming soon.**

# GS-HCAL Full-size Prototype (C3)

**Preparation of full-size GS-HCAL prototype (2025-2026)**

- Total: 48 layers
- Each layer: $13 \times 13$ GS cells ($52 \times 52$ cm$^2$)
- GS cell size: $4 \times 4 \times 1$ cm$^3$
- Total GS cells: $13 \times 13 \times 48 = 8112$
- 1 SiPM ($3\times3$ mm$^2$) for each GS cell
- 8112 NDL-SiPMs will be used
- ASIC Chip with power consumption of 15mW/ch
- Stainless steel as absorber and covers: 13.8mm




**Cooperation with DRD4 and DRD6**

- Sen Qian is deputy convener of WG4.1 in DRD4
- Contact person for GS-HCAL in WP6.1 in DRD6

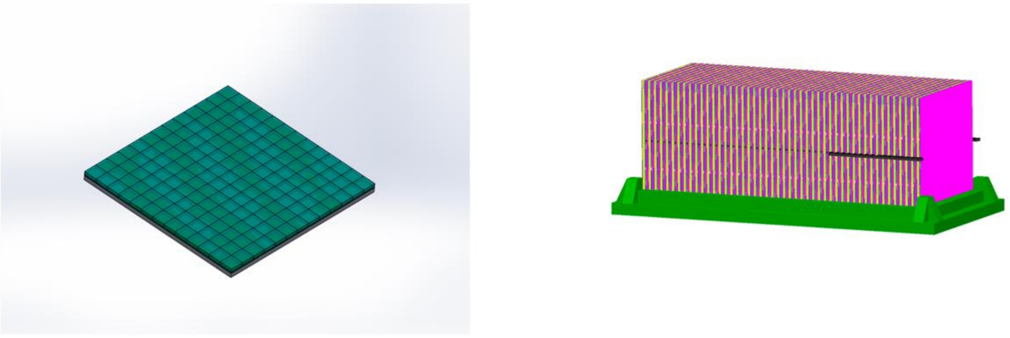


**Figure 8.24:** One layer and whole size of GS-HCAL prototype.

**TB plan (2027):**

- CERN: 2-180 GeV, e / $\mu$ / $\pi$ beams
- CSNS (China): 1.6 GeV proton beam

# 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.;

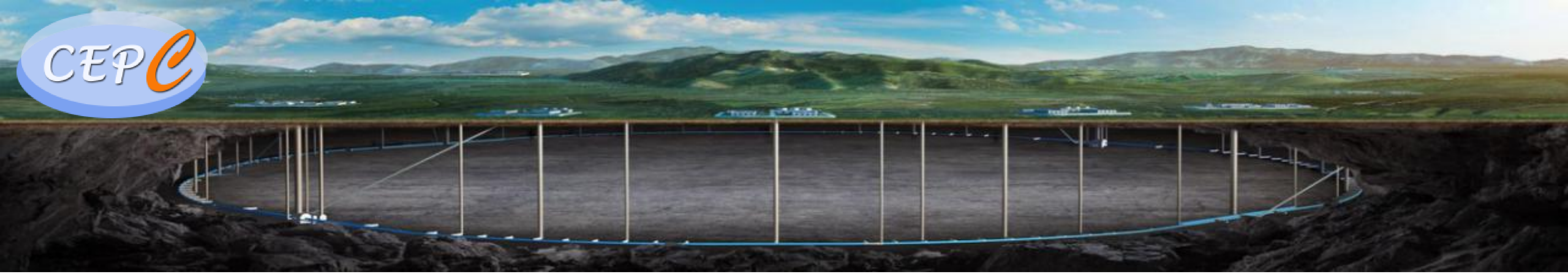
**DAQ:** Chen Boping(IHEP)

**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;

# Summary and Future Plans

- **Physics requirement for the design:**
  - Hadron energy resolution $< 30\%/\sqrt{E}$
  - Boson mass resolution (BMR) < 4%
- **GS-HCAL is selected as baseline based on its promising performance**
  - Intensive R&D on high quality GS (e.g. light yield, decay time, attenuation length)
  - Update design of GS-HCAL mechanics, cooling and readout electronics
  - Simulation studies with CEPCSW demonstrated: with a Light output of 60 p.e./MIP and attenuation length of 62 mm, can well satisfy the physics requirement.
- **Future R&D plans**
  - To develop techniques for mass production of GS, SiPM with low cost
  - To further optimize GS-SiPM coupling, cooling and readout electronics
  - To prepare full-size GS-HCAL prototype with integrated electronics for beam test




# Thanks for your attention!

# Mechanics

- FEA simulation study to evaluate key parameters: deformation and stress

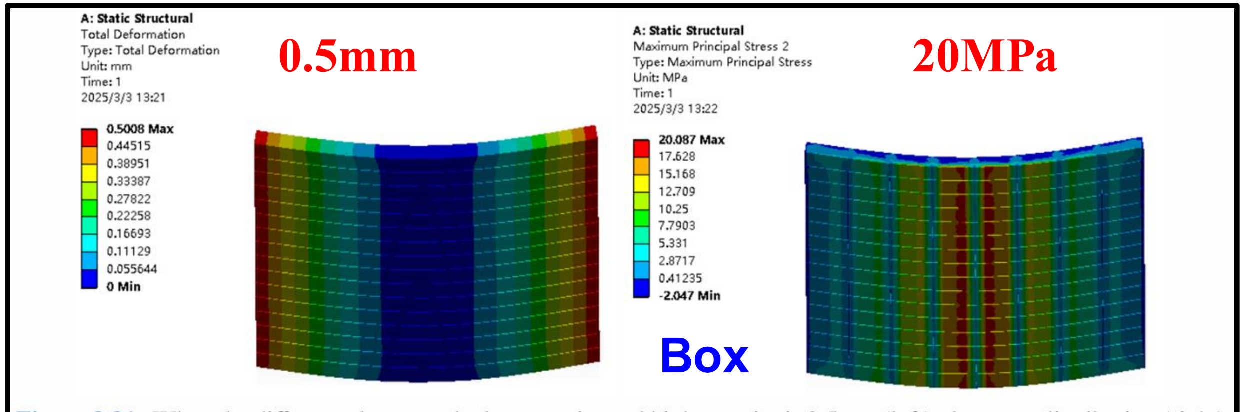



Figure 8.81: When the difference between the lowest point and highest point is 0.5mm (left), the stress distribution (right)

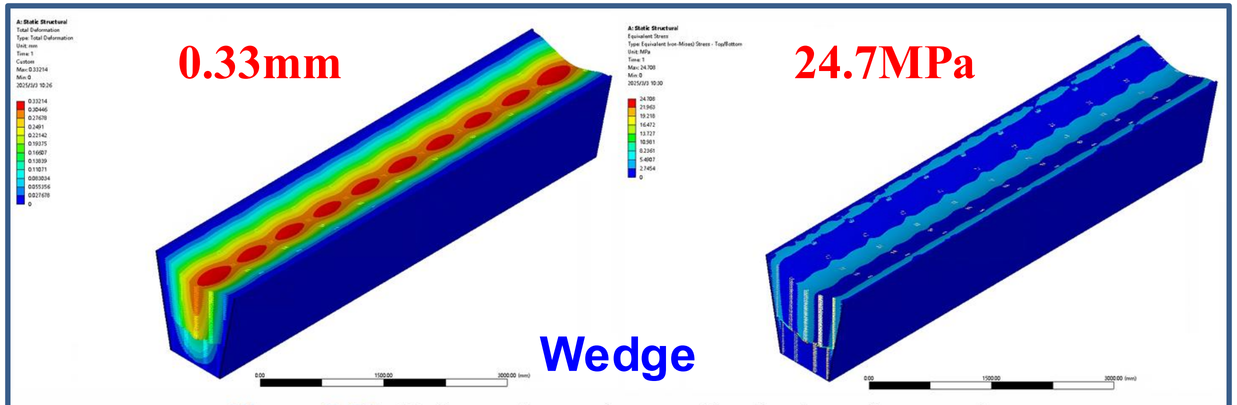



Figure 8.73: Deformation and stress distribution of one wedge

- Max deformation of GS box is 0.5mm, deformation of wedge is 0.33mm
- Max stress of GS is 20MPa (Box) and 37MPa (Endcap): less than allowable stress of GS (60MPa)

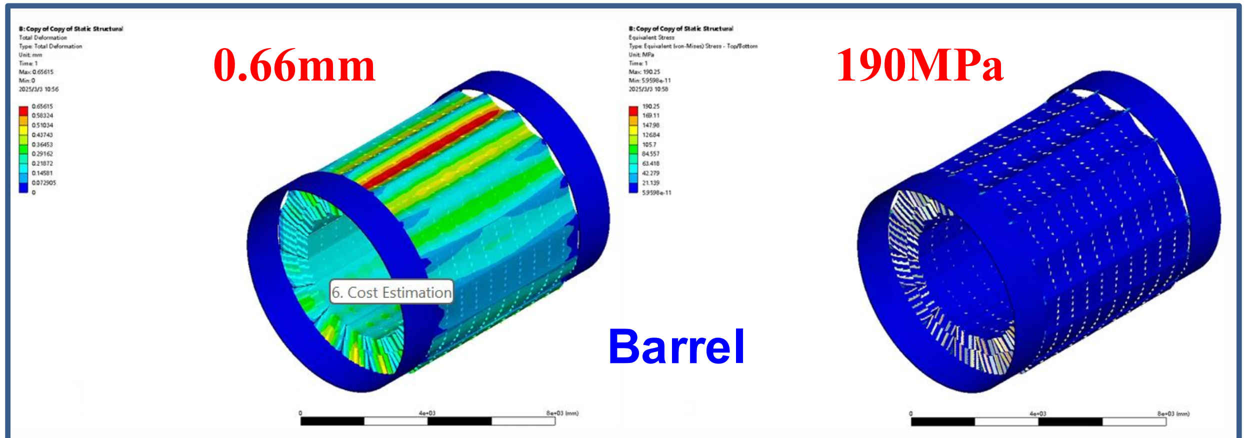
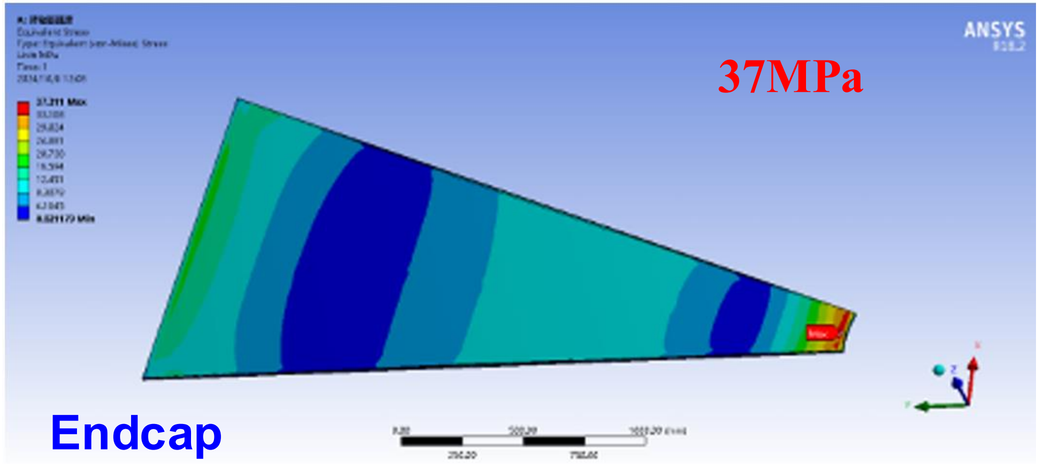
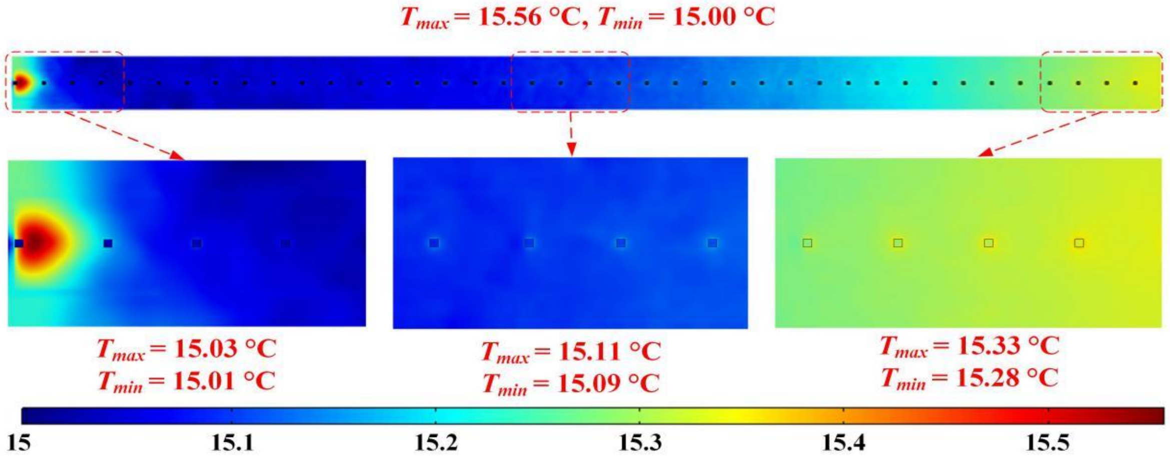



Figure 8.75: Deformation and stress distribution of berral HCAL



# Cooling

- ◆ Air cooling can not meet heat dissipation demands.
- ◆ **Liquid cooling technology is employed** to ensure efficient heat dissipation and temperature uniformity.




- ➢ **FEA simulation of liquid cooling system**

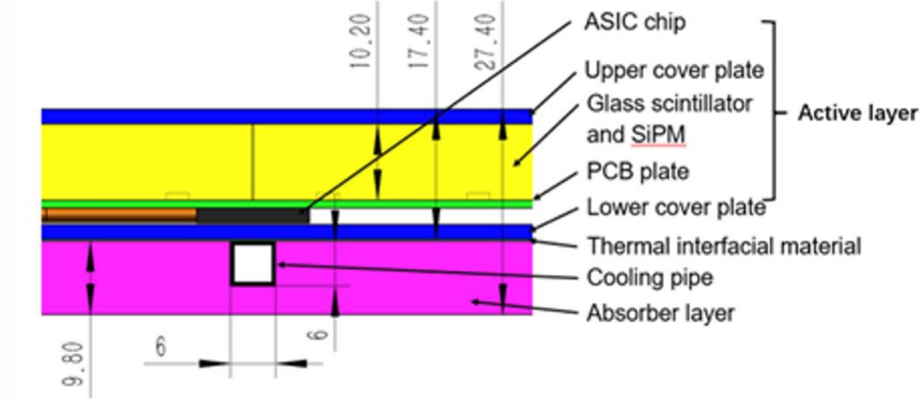



**Figure 8.65:** Cross section structure of each layer of detect module

- 4 pipes in each layer in parallel
- 8 layers gather in one pipe in parallel
- One end is inlet and another end is outlet

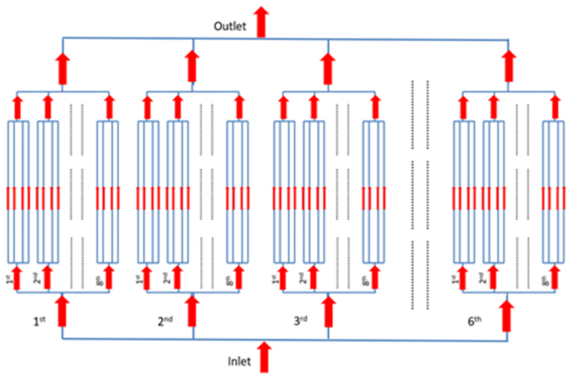
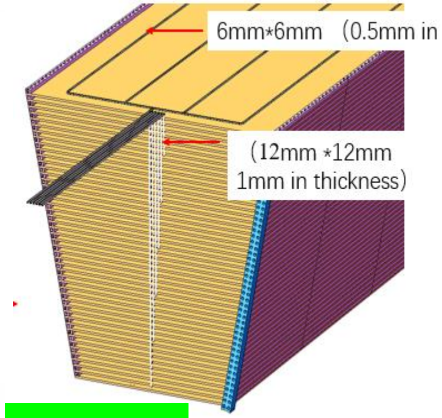



**Figure 8.100:** Cooling routing for each wedge

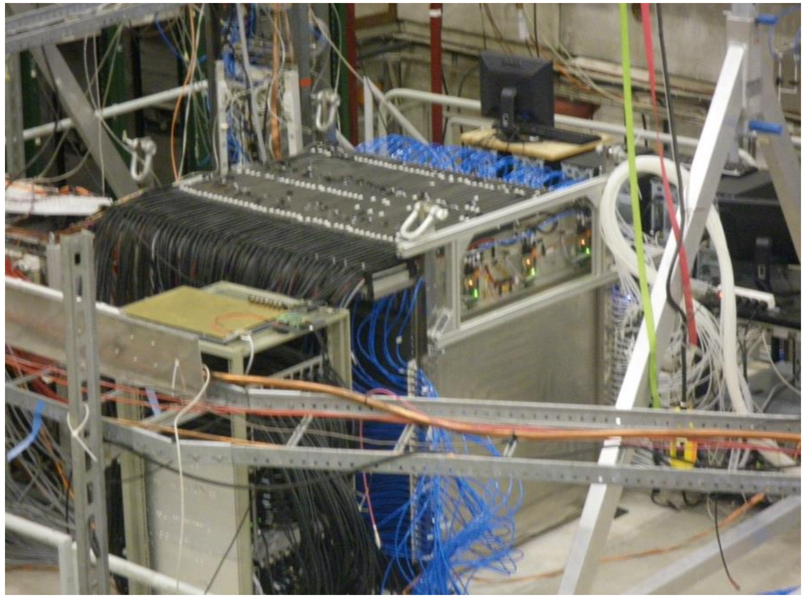


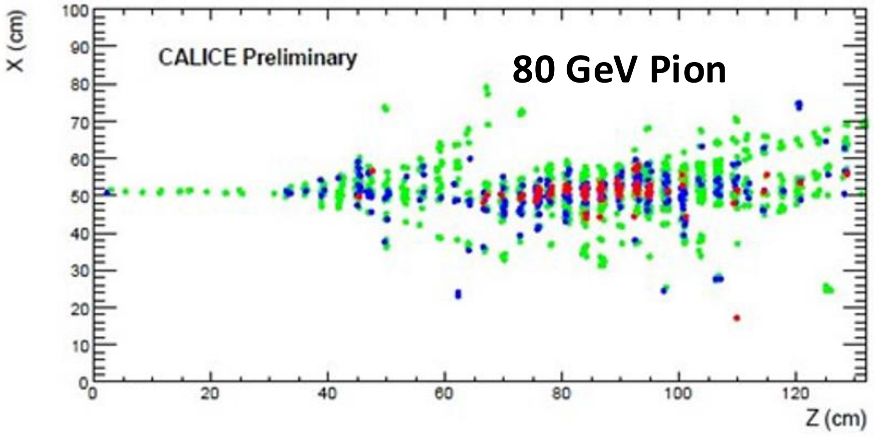

**Wedge**

- ◆ Inlet T=15 ℃, flow rate 0.005 kg/s (inlet velocity 0.1 m/s).
- ◆ **Temperature within same layer < 0.6 $^{0}$C**
- ◆ **Temp. variations of chips in same module < 0.1 $^{0}$C**

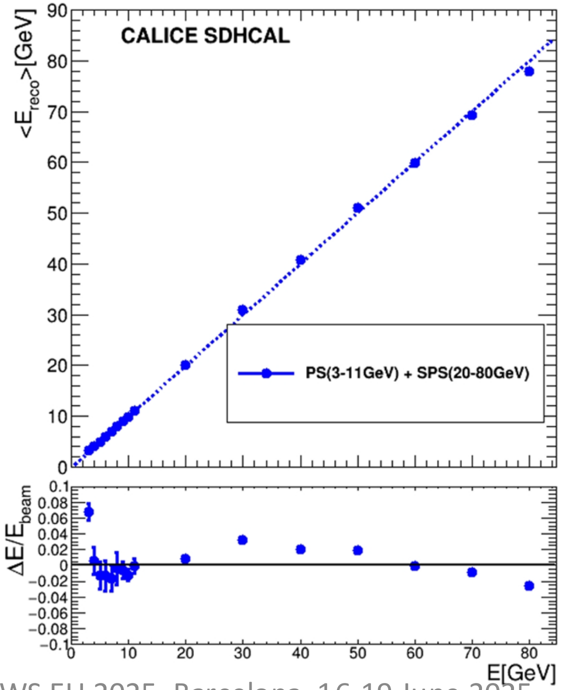
# 2.1 RPC based SDHCAL (Prototype)

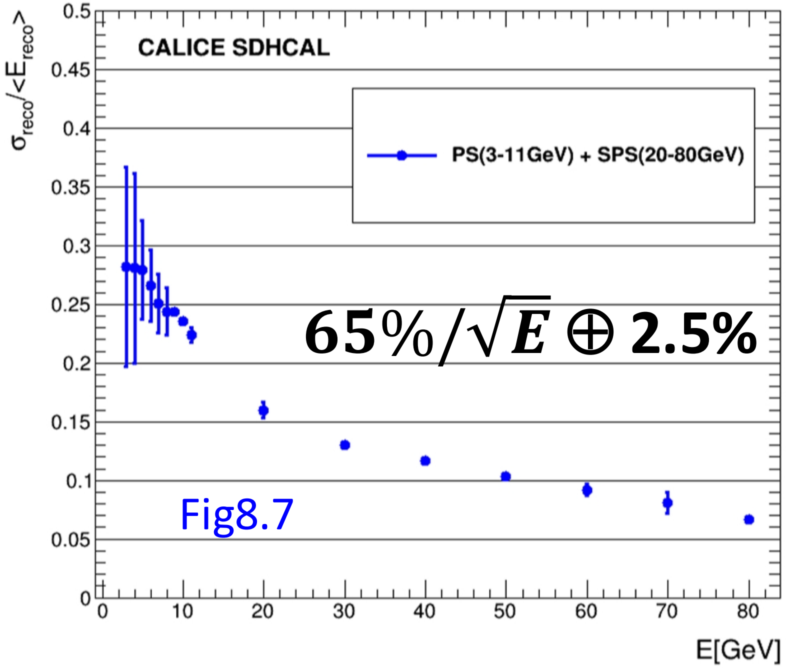
- **Semi-digital HCAL (SDHCAL)**
  - High granularity (1cm x1cm)
  - 48 layers (1m x 1m x 1.3m)
  - Three thresholds readout
  - Stainless-steel absorber with self-supporting mechanical structure






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



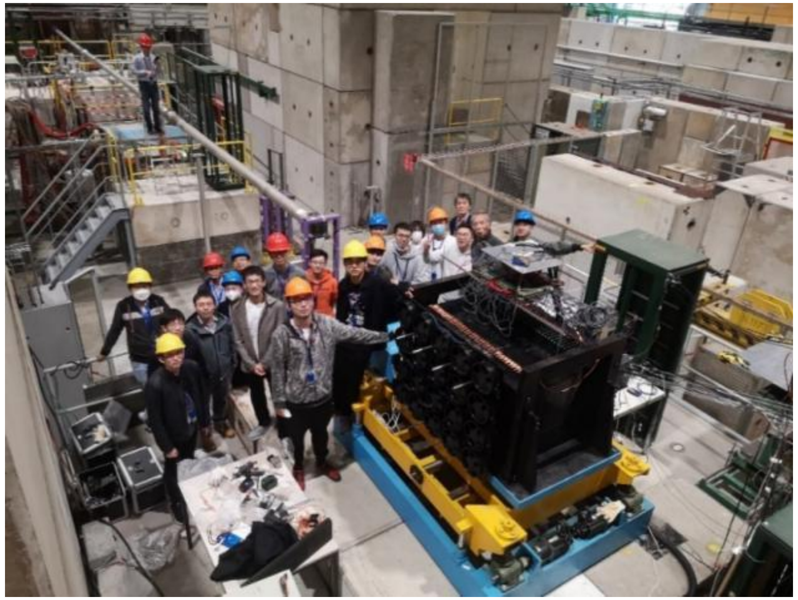

$65\%/\sqrt{E} \oplus 2.5\%$

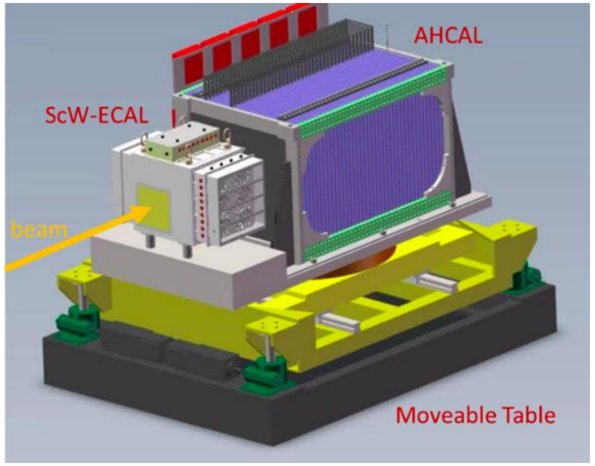
Fig8.7

# 2.2 Plastic Scintillator HCAL (Prototype)

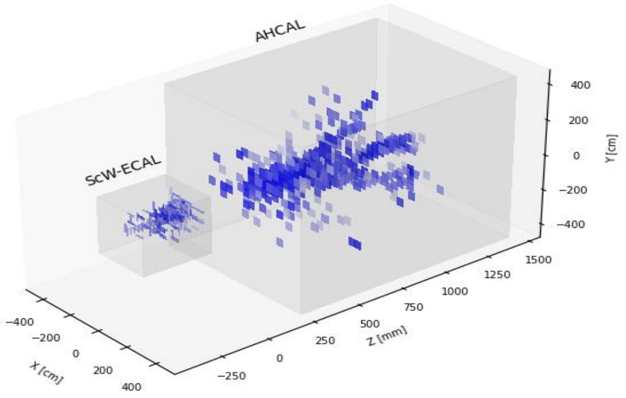
## ■ Plastic Scint. AHCAL (PSHCAL)

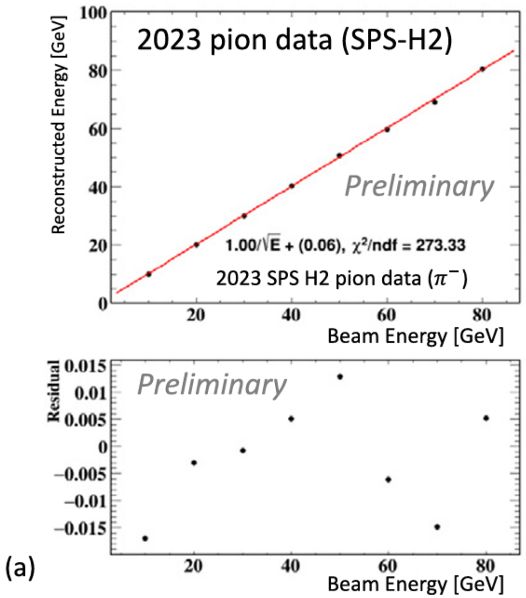
- High granularity (4cm x4cm)
- 40 layers (72 cm x 72cm x 1.1m)
- Plastic Scintillator + SiPM (12960)
- Stainless-steel absorber with self-supporting mechanical structure






60 GeV pion (SPS)



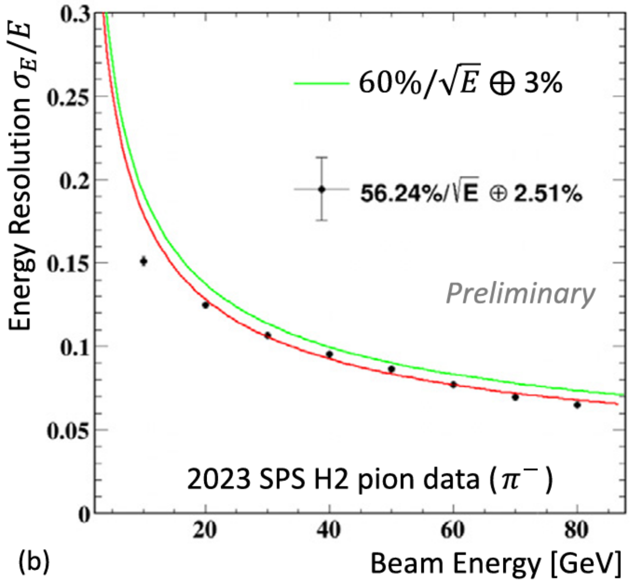



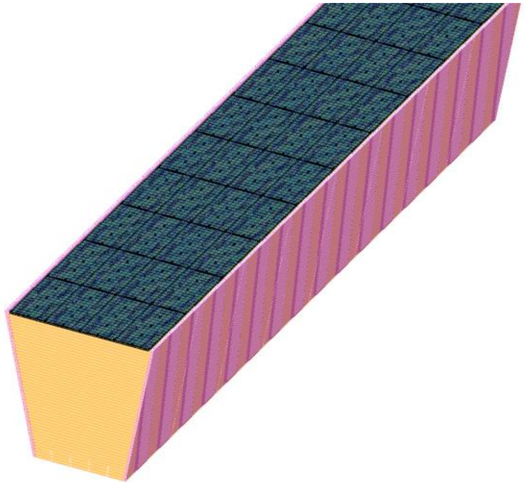

Fig8.14

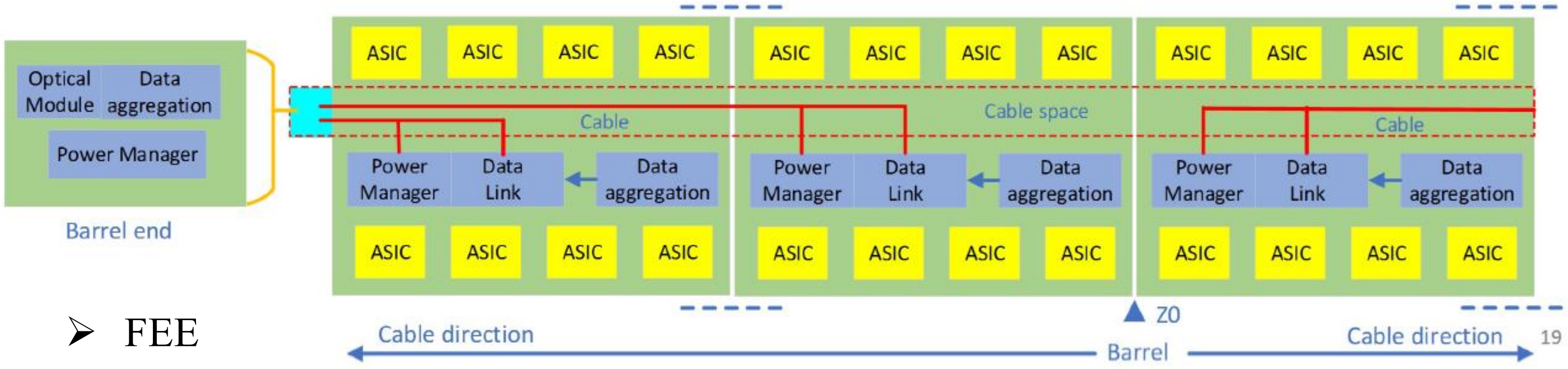
*NIMA 1072 (2025) 170191*

$56.2\%/\sqrt{E} \oplus 2.5\%$

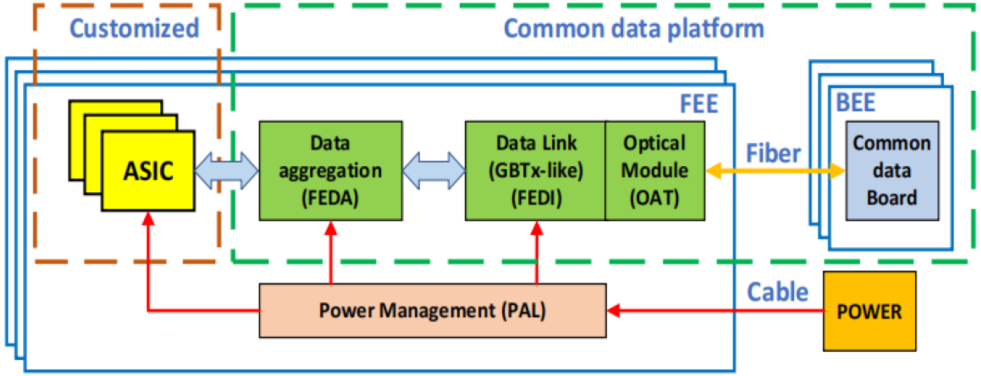
# 5.2 Readout Electronics (C2)

See Wei Wei's talk for details






- FEE




- **Front-End Electronics (FEE) readout boards in HCAL cell Box**
  - Thickness: 3.2mm = PCB 1.2mm + ASIC Chip 2mm
  - SiPMs, ASICs and Data Aggregation
  - PCB dimensions: flexible in different positions
- **SiPM-readout ASIC: under development**
  - Self-developed for CEPC calorimeter system
  - Functionality: energy and time measurements
  - Power consumption: target at 15mW/ch
- **Aggregation board at the end of barrel, cable connection**

- Energy Measurement: ASIC for ECAL & HCAL
- Data transmission: common data platform
- Trigger mode: FEE triggerless readout

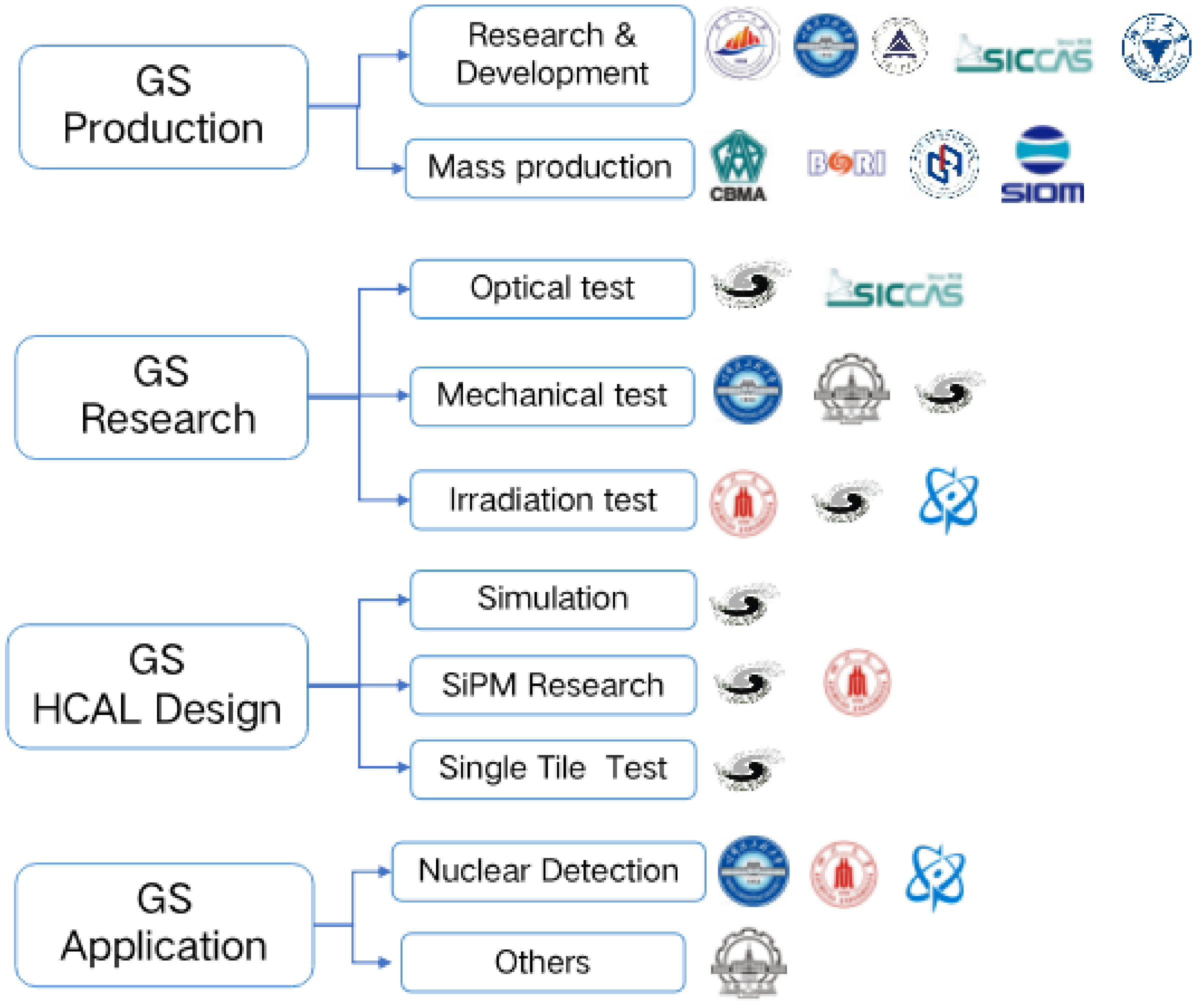
# 7.2 Research Team of GS-HCAL

- GS collaboration: 13 institutes, 26 faculty/staff, ~10 students
- HCAL working group: 8 institutes, 17 faculty/staff, ~10 students

- Physics of HCAL
- Technical Survey
- Design of the GSHCAL
- The Glass Scintillator
- The SiPM of HCAL
- Electronics & DAQ
- Mechanics of HCAL
- Calibration of HCAL
- The Mass Production
- Performance of HCAL
- The Outlook Study

| | |
|---|---|
| Institute of High Energy Physics, CAS<br>中国科学院高能物理研究所 | Sun Yat-sen University<br>中山大学 |
| Jinggangshan University<br>井冈山大学 | Zhejiang University<br>浙江大学 |
| Beijing Glass Research Institute<br>北京玻璃研究院 | Fudan University<br>复旦大学 |
| China Building Materials Academy<br>中国建筑材料研究院 | South China Normal University<br>华南师范大学 |
| China Jiliang University<br>中国计量大学 | Shanghai Jiao Tong University<br>上海交通大学 |
| Harbin Engineering University<br>哈尔滨工程大学 | University of Science and Technology of China<br>中国科学技术大学大学 |
| Harbin Institute of Technology<br>哈尔滨工业大学 | Zhengzhou University<br>郑州大学 |
| Sichuan University<br>四川大学 | Xi'an Jiaotong University<br>西安交通大学 |
| Shanghai Institute of Ceramics, CAS<br>中国科学院上海硅酸盐研究所 | Henan University<br>河南大学 |
| Shanghai Institute of Optics and Fine Mechanics, CAS<br>中国科学院上海光学精密机械研究所 | Beijing Normal University<br>北京师范大学 |
| Ganjiang Innovation Academy, CAS<br>中国科学院赣江创新研究院 | North China University of Technology<br>北方工业大学 |
| CNNC Beijing Nuclear Instrument Co.,<br>中核（北京）核仪器有限责任公司 | China General Nuclear Zhongjing Optoelectronic Co., Ltd.<br>中广核中京光电有限责任公司 |

# Research Team of GS




- Institute of High Energy Physics，CAS
  中国科学院高能物理研究所
- Jinggangshan University
  井冈山大学
- Beijing Glass Research Institute
  北京玻璃研究院
- China Building Materials Academy
  中国建筑材料研究院
- China Jiliang University
  中国计量大学
- Harbin Engineering University
  哈尔滨工程大学
- Harbin Institute of Technology
  哈尔滨工业大学
- Sichuan University
  四川大学
- Shanghai Institute of Ceramics，CAS
  中国科学院上海硅酸盐研究所
- Shanghai Institute of Optics and Fine Mechanics，
  中国科学院上海光学精密机械研究所
- CNNC Beijing Nuclear Instrument Co.,
  中核（北京）核仪器有限责任公司
- Zhejiang University
  浙江大学
- Ganjiang Innovation Academy, CAS
  中国科学院赣江创新研究院

# GS-HCAL Digitization Model

### 8.9.2.1 Energy linearity and resolution

The energy linearity and resolution are estimated with Geant4 simulation in CEPCSW. In order to study the intrinsic energy response in GS-HCAL, all inner sub-detectors are removed. A digitization model is constructed considering the following items:

- Birks constant. Currently a preliminary estimation of $C_{Birks} = 0.01$ is applied, considering the BGO has $C_{Birks} = 0.0086$. A measurement with heavy ion beam is being planned.
- Light yield. With the measurement from glass scintillator samples, the intrinsic MIP light yield can reach to $\tilde{2}000$ ph/MeV, thus the detected light yield is expected to be at least 100 p.e./MIP. This satisfies the requirement from noise and 0.1 MIP threshold.
- Attenuation length. 2.3 cm attenuation length is expected, based on current measurements. While more detailed studies of the glass scintillation properties need to be studied.
- Threshold. With the scanned impact on energy resolution, a 0.1 MIP threshold is expected.
- SiPM response.
- Electronic system.
- Other items are considered as negligible after the calibration.

This model gives an estimation of the energy resolution $\sigma_E/E = 29.8\%/\sqrt{E} \oplus 6.5\%$ and linearity within 2% before calibration in Figure 8.106 The physics list '*QGSP-BERT*' is used as default one. Other physics lists are also tested. The large constant term is contributed with the longitudinal leakage from this 6 $\lambda_I$ design, which is limited by the total detector volume and cost. This result is better than the traditional HCAL with typical energy resolution of $\sigma_E/E = 60\%/\sqrt{E} \oplus 3\%$.

# SiPM Dark Current Rate (DCR)

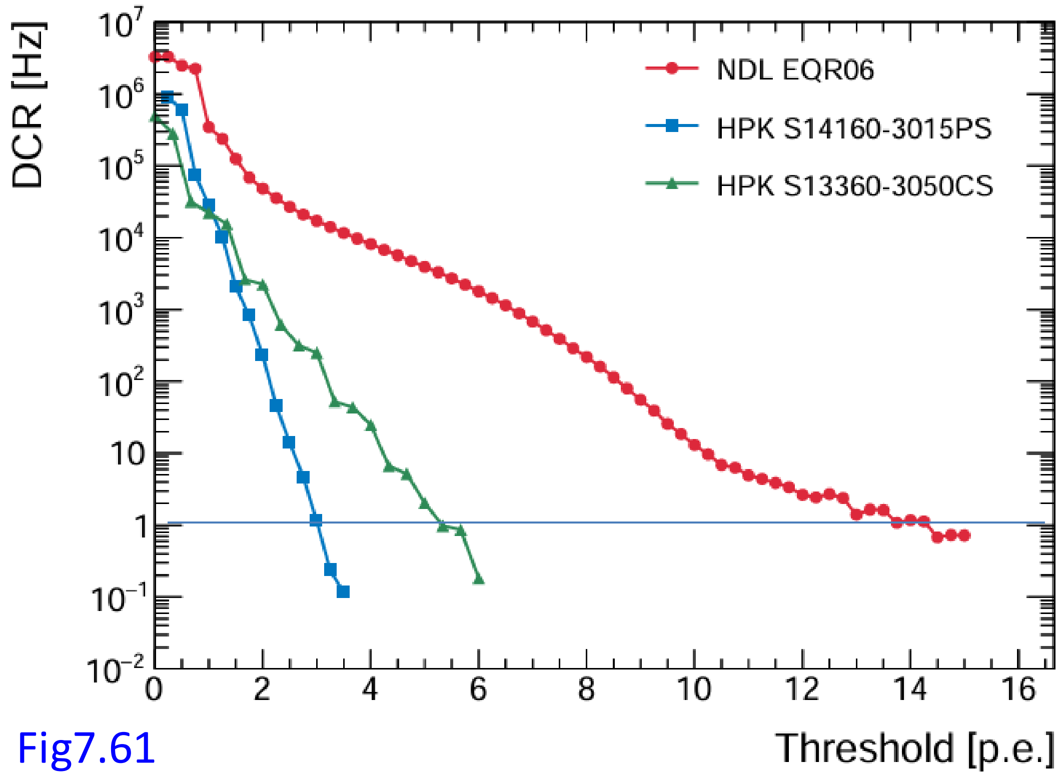



Fig7.61

The nominal dark count rate (DCR) of SiPMs, along with their testing temperature and bias voltage.

| SiPM | DCR (MHz) | Over votage (V) | Temperature (°C) |
|---|---|---|---|
| HPK S13360-3050CS | 0.5 | 3 | 25 |
| HPK S14160-3015PS | 0.7 | 4 | 25 |
| NDL EQR06 11-3030D-S | 2.5 | 8 | 20 |

**MPPC (multi-pixel photon counter)** | **S13360 series**

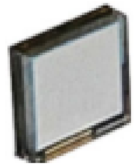
**Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)**

| Type no. | Measurement conditions | Spectral response range λ (nm) | Peak sensitivity wavelength λp (nm) | Photon detection efficiency PDE*4 λ=λp (%) | Dark count*5 Typ. (kcps) | Dark count*5 Max. (kcps) | Terminal capacitance Ct (pF) | Gain M | Breakdown voltage VBR (V) | Crosstalk probability (%) | Recommended operating voltage Vop (V) | Temperature coefficient at recommended operating voltage ΔTVop (mV/°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S13360-1325PE | | 320 to 900 | | | 70 | 210 | 60 | | | | | |
| S13360-3025CS | | 270 to 900 | | | 400 | 1200 | 320 | | | | | |
| S13360-3025PE | Vover =5 V | 320 to 900 | | 25 | | | | 7.0 × $10^5$ | | 1 | VBR + 5 | |
| S13360-6025CS | | 270 to 900 | | | 1600 | 5000 | 1280 | | | | | |
| S13360-6025PE | | 320 to 900 | | | | | | | | | | |
| S13360-1350PE | | 320 to 900 | | | 90 | 270 | 60 | | | | | |
| S13360-3050CS | | 270 to 900 | | | 500 | 1500 | 320 | | | | | |
| S13360-3050PE | Vover =3 V | 320 to 900 | 450 | 40 | | | | 1.7 × $10^6$ | 53 ± 5 | 3 | VBR + 3 | 54 |
| S13360-6050CS | | 270 to 900 | | | 2000 | 6000 | 1280 | | | | | |
| S13360-6050PE | | 320 to 900 | | | | | | | | | | |
| S13360-1375PE | | 320 to 900 | | | 90 | 270 | 60 | | | | | |
| S13360-3075CS | | 270 to 900 | | | 500 | 1500 | 320 | | | | | |
| S13360-3075PE | Vover =3 V | 320 to 900 | | 50 | | | | 4.0 × $10^6$ | | 7 | VBR + 3 | |
| S13360-6075CS | | 270 to 900 | | | 2000 | 6000 | 1280 | | | | | |
| S13360-6075PE | | 320 to 900 | | | | | | | | | | |

*4: Photon detection efficiency does not include crosstalk or afterpulses.
*5: Threshold=0.5 p.e.
Note: The above characteristics were measured at the operating voltage that yields the listed gain. (See the data attached to each product.)

- HPK 13160: DCR ~ 0.5MHz,
- Threshold >5 pe (0.1 MIP), DCR rate ~ 1Hz
- integral time ~1us,
- ➔ SiPM noise rate ~ 5.3M*$10^{-6}$ ~ 5.3

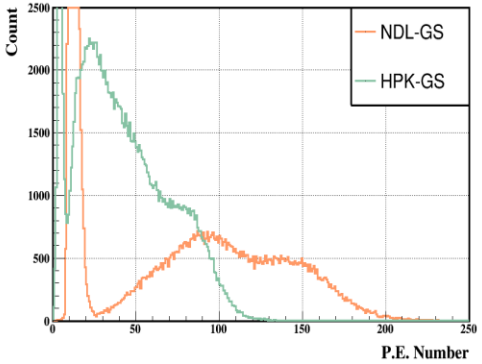
# GS+SiPM

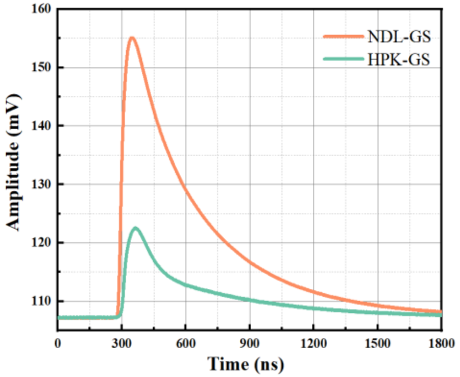


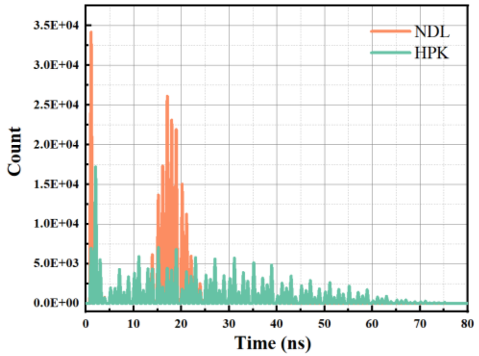
NDL EQR20 HPK S13360-3025CS

| | NDL | HPK |
|---|---|---|
| Photosensitive area (mm) | 3×3 | 3×3 |
| Operation Voltage (V) | 32.3 | 56.64 |
| Gain | $8\times10^5$ | $7\times10^5$ |
| SPE channel | 99 | 61 |
| PDE @390nm (%) | 42 | 22 |
| P.E. Number | 138 | 75 |
| Energy resolution (%@662keV) | 40.9 | 44.2 |
| Scintillation decay (ns) | 487.6 | 594.4 |

- **Mass production of high quality SiPM;**
  - HPK S13360 series (3x3 mm$^2$) ~ 20% Detection efficiency.
  - HPK S14160 series have about 43% PDE @390nm, more suitable for HCAL, will be tested soon.
  - NDL (3x3 mm$^2$) ~ 40% DE， could be improved to 60% in the future
  - IHEP will cooperation with NDL for the performance test
- **Mass production of low cost SiPM；**
  - Hamamatsu HPK / NDL SiPM (3x3 mm$^2$) ~ \$1.5/ch with O(5M) pieces
  - Optimizing granularity, GS and SiPM couplings to reduce cost



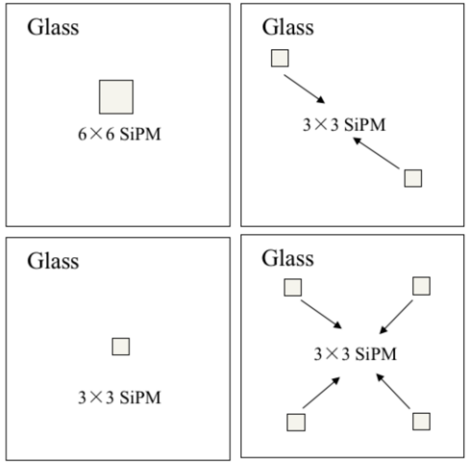



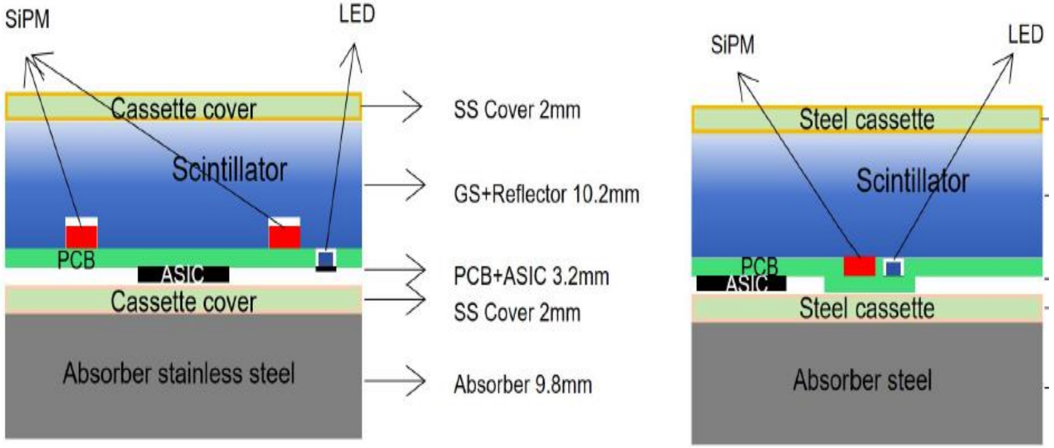




- 137Cs Energy spectra
- Average waveform
- Glass+137Cs Energy spectra

# SiPM+GS Coupling

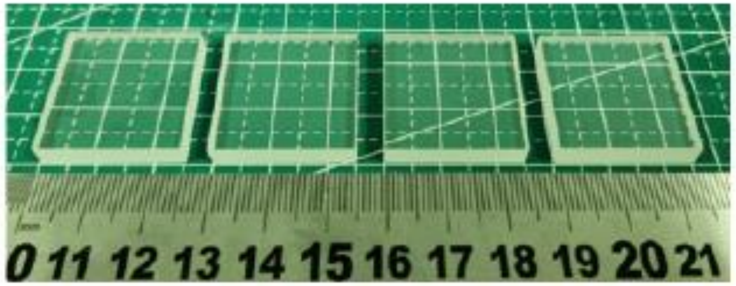
| SiPM coupled glass | Relative detection efficiency | |
|---|---|---|
| | $TiO_2$ | Teflon |
| Reflectivity (%@400 nm) | ~70 | ~86 |
| Single 3×3 mm | 0.7 | / |
| **Single 6×6 mm** | **1** | **1.43** |
| **Four 3×3 mm** | **2.08** | **2.4** |
| Four 6×6 mm | 2.98 | 4.2 |

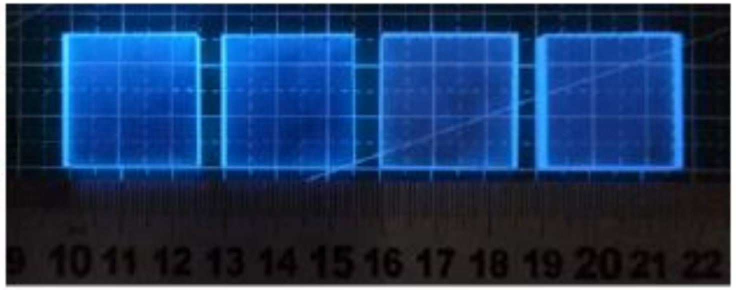



- Because the light attenuation length is only ~23 mm, more SiPMs are needed to collect sufficient light.
- One scintillator is coupled with either 1, 2, or 4 SiPMs (3 mm × 3 mm SiPMs).
- In the future, the performance of GS is expected to improve, potentially allowing the use of fewer SiPMs — possibly even just one.
- Glass scintillators bonded to the PCB with optical glue were tested. The results show that the glue is sufficiently strong for this purpose.
- There is a gap to hold the SiPM either in the GS or in the PCB. More tests are needed to determine the optimal position of this gap (in the glass or PCB) and to identify a low-cost and practical method for implementation.

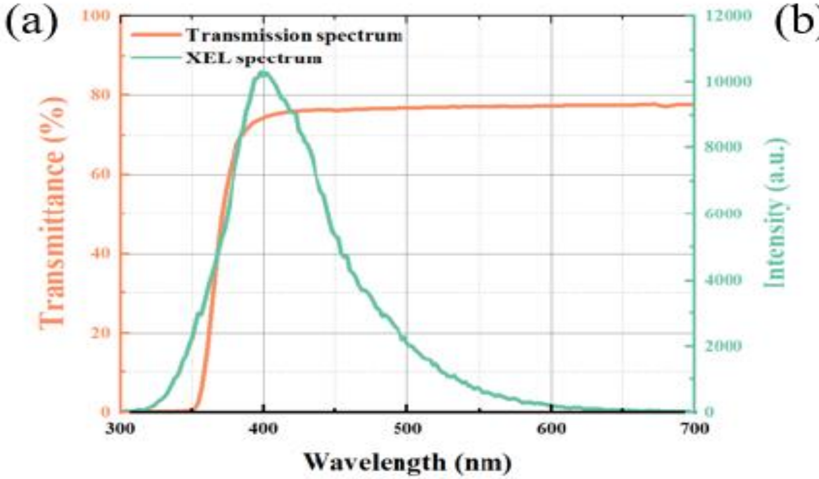
# 5.1 GS Study: large size (4×4×1cm$^3$)

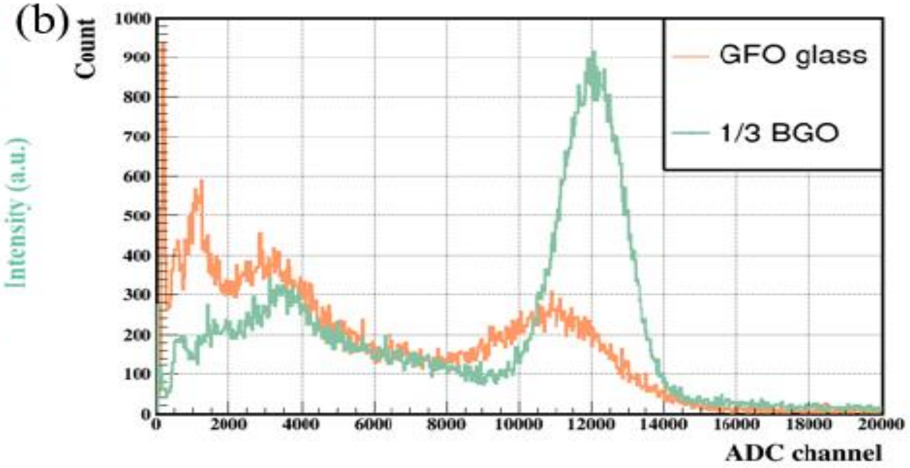


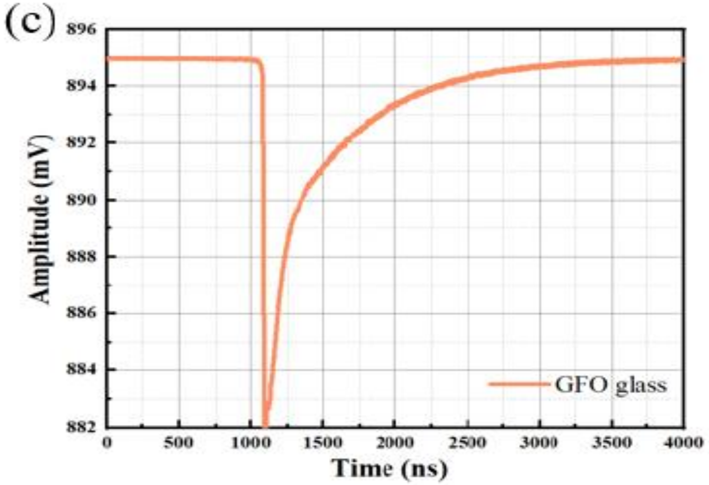




- Density=6.0 g/cm$^3$
- LY=1506 ph/MeV
- ER=41.2%
- LO in 1μs=1129 (75%)
- Decay=53 (3%), 655 ns

- Three company/institutes are capable to produce larger size GS with mass production;
- For GS-HCAL prototype: **Size = 40*40*10 mm$^3$ ; Density = 6.0 g/cm$^3$;**
- Light yield could > 1000 ph/MeV, **but typical decay time > 100 ns**;



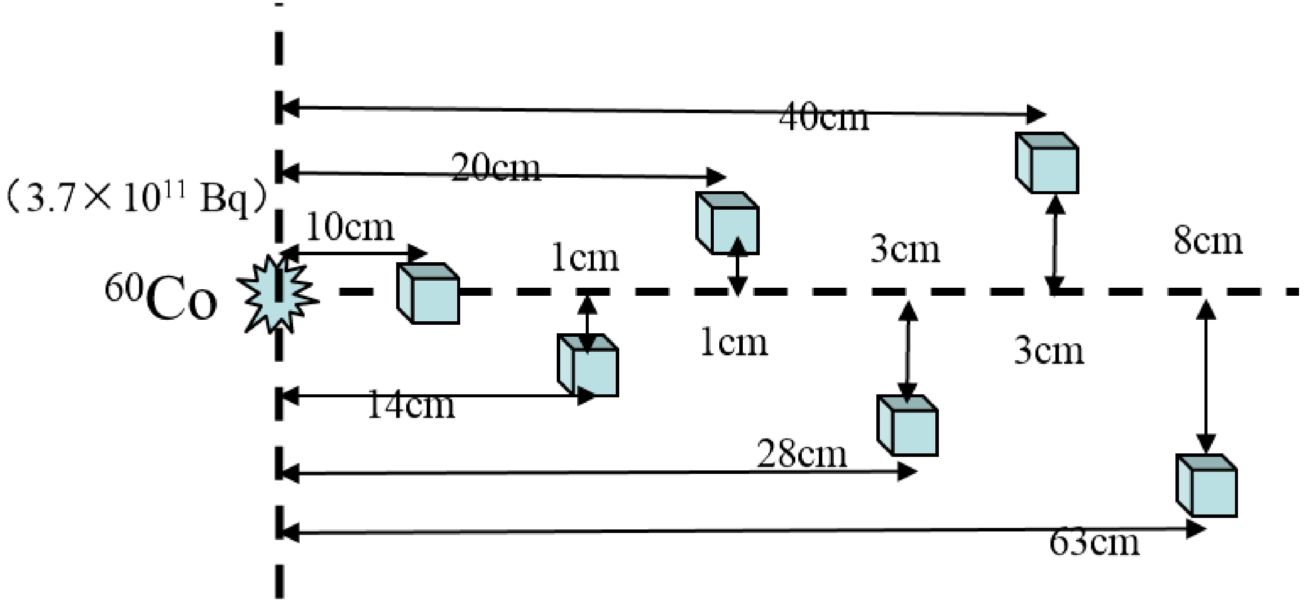



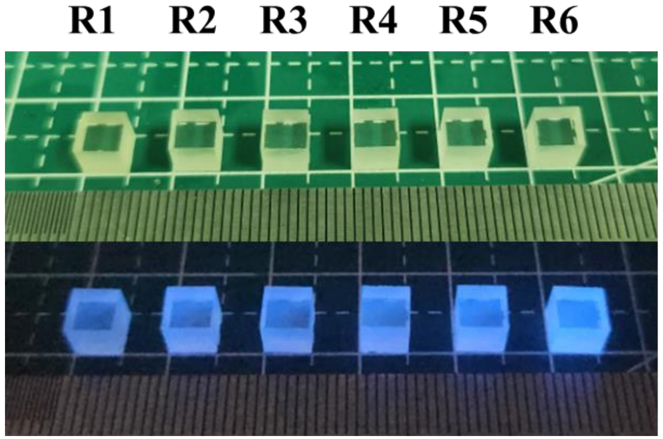



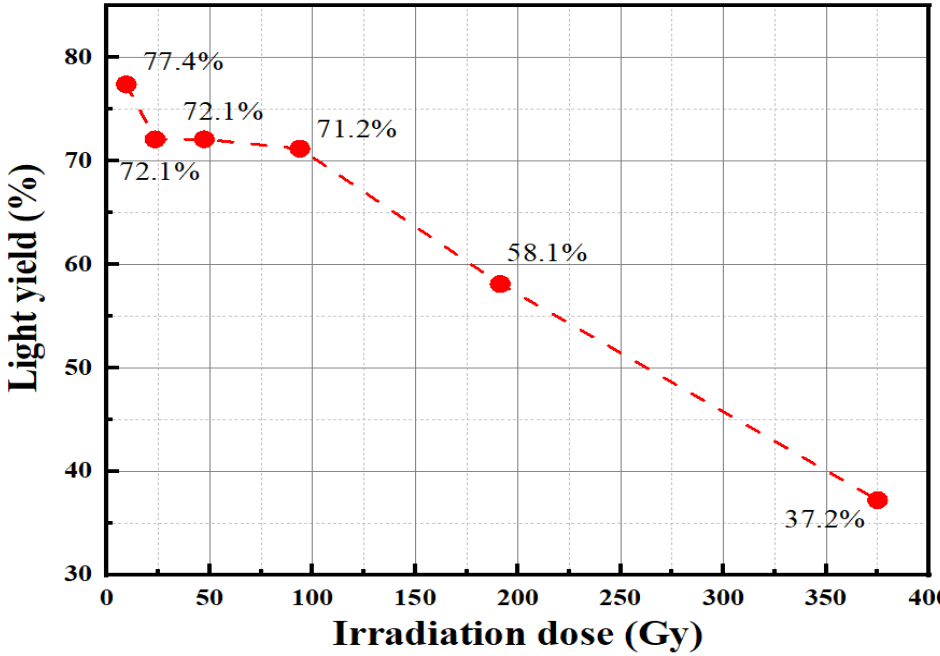

- (a) Transmission and XEL spectra
- (b) Energy spectra
- (c) Scintillation decay curves

# 5.1 GS Study: Irradiation Test

- **6 GS samples** (5×5×5 mm³) were irradiated with a **⁶⁰Co source of 3.656×10¹¹ Bq**
- GS samples were placed with different distances

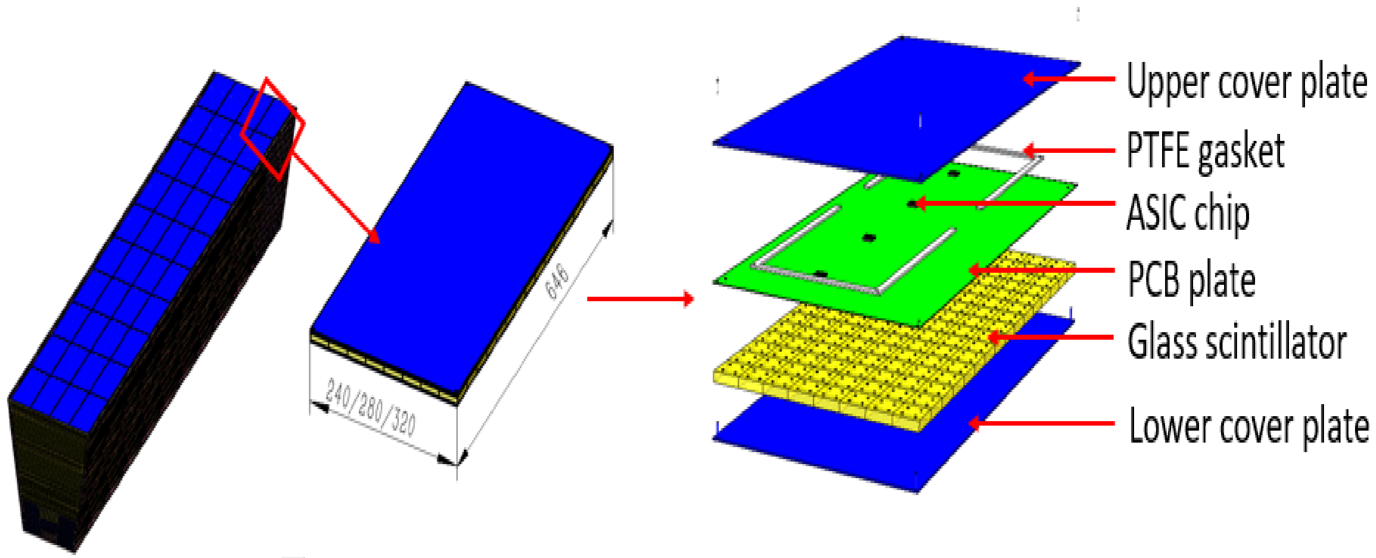


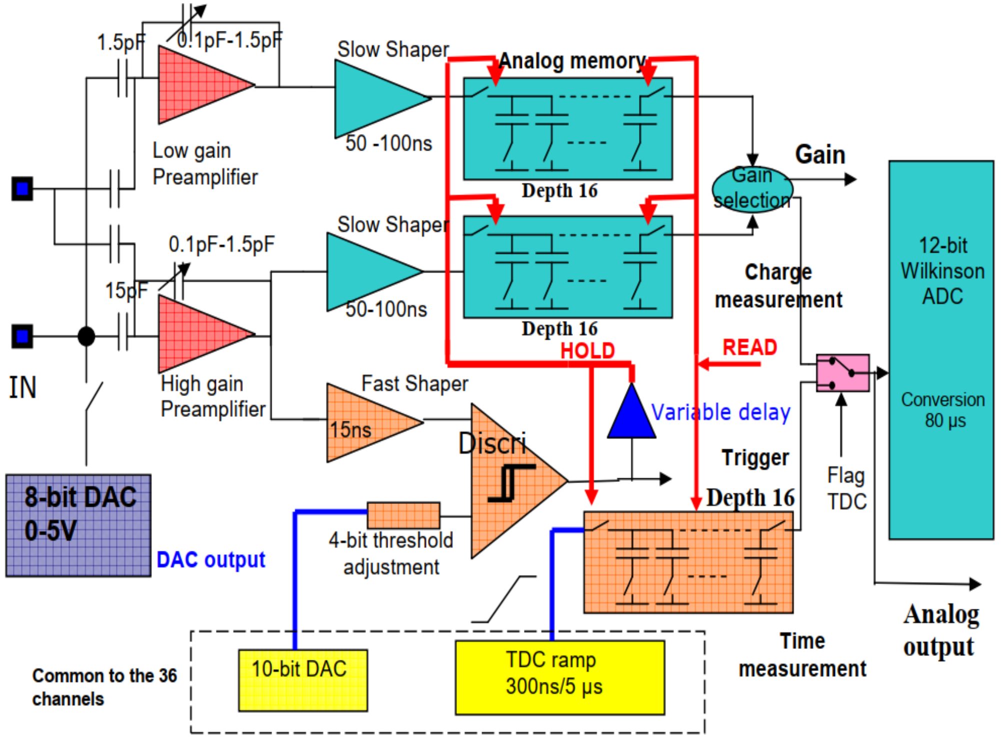




- **Light output** of GS samples are reduced to **58%** of its original level after **~200 Gy** dose exposure which is consistent with proton irradiation in 20 years (~200 Gy)

# Power Supply for SiPM




➢ The Box Design for the GS-HCAL in the Prototype

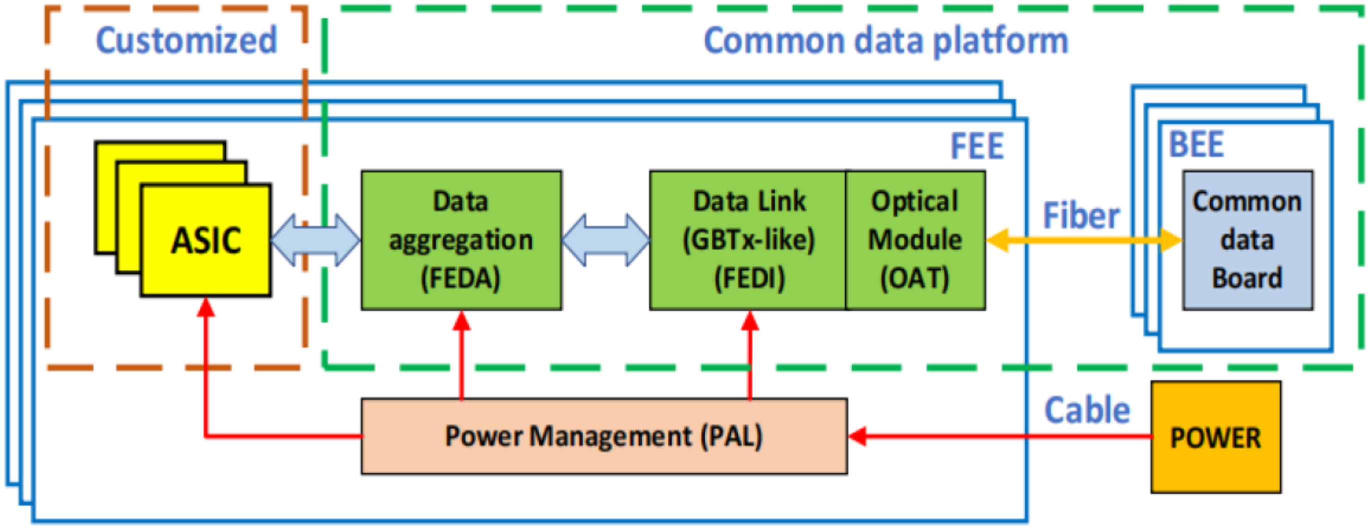



- SiPMs in the GS-AHCAL receive a uniform bias voltage via a PCB box.
- SiPMs will be categorized, and those with similar operating voltages will be grouped in one box, sharing the same power supply.
- ASIC chip can regulate the bias voltage within ±0.5 V, which is narrower than the ±5 V range of SPIROC2E. Tests have confirmed that ±0.5 V regulation is sufficient for SiPM operation.

# Readout Electronics

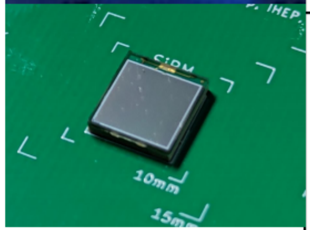
Details in "Electronics" talk

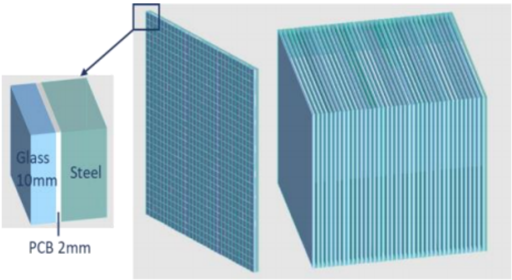
- Dynamic range of charge measurement:
  - **0.1MIPs (800fC) – 100MIPs (800 pC);**
- Charge resolution: 10% at 1 MIP;
- Integral non-linearity (INL): < 1%
- SiPM Terminal Capacitance : **<100pF**;
- Single channel average event rate :
  1.5kHz/ch at Higgs;
- Single channel maximum event rate :
  **42.33kHz at Higgs.**




- Energy Measurement: ASIC for ECAL & HCAL
- Data transmission: common data platform
- Trigger mode: FEE triggerless readout

# 5.3 GS-HCAL Full-size Prototype (C3)



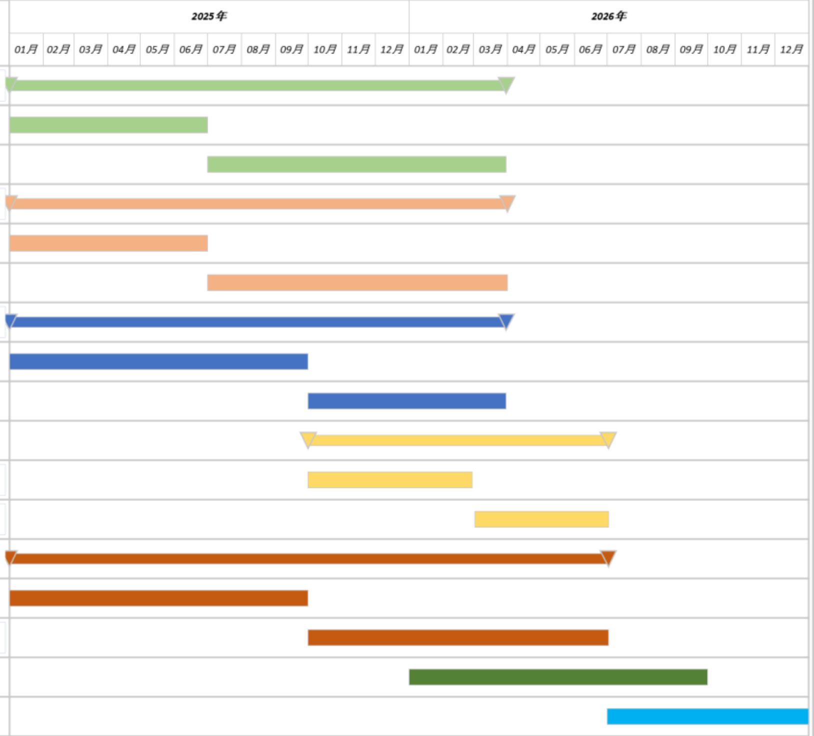

| | 2021-2023 | 2024-2025 | 2026 | 2027 |
|---|---|---|---|---|
| **Physics+<br>Software+<br>Design+<br>Mechanics** | Design<br>TDR | Optimization<br>calibration | new Design；<br>calibration；<br>beam test | <br> |
| **Glass Scintillator** | R&D<br>5X5X5 mm³ | R&D<br>40X40X10 mm³ | 10K pieces<br>mass production<br>batch test | Assembly the cell； |
| **SiPM** | test samples | performance<br>test, choice | 40K pieces<br>batch test | FInish the Module for<br>performance test； |
| **Electronics** | the design of<br>ASIC and FEE,<br>power supply | V1，V2<br>performance<br>test | V2<br>mass production<br>batch test | the cosmic ray test;<br>the beam test; |

25

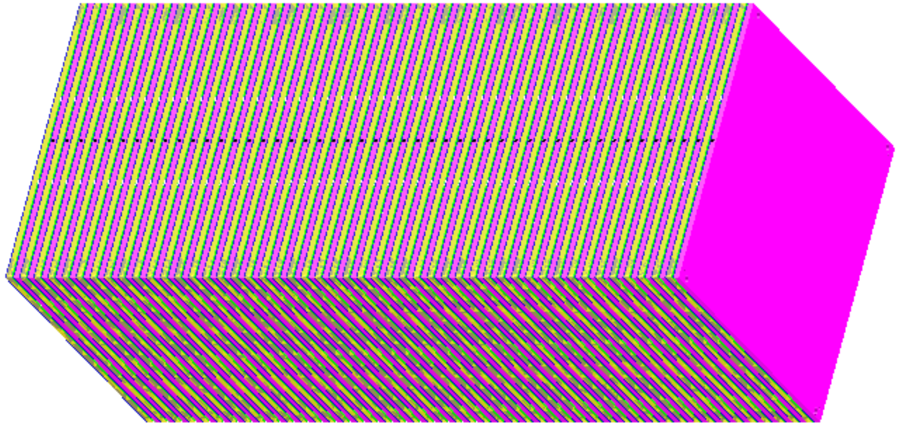
# Working Plan

- Plan of the Prototype of GS-HCAL in the next two years (2025-2026).
- Prototype of the HCAL was designed right now.

| ID | Item | Start time | Compeleted | Duration |
|---|---|---|---|---|
| 1 | **GS tiles production** | **1/1/2025** | **30/3/2026** | **64.8周** |
| 2 | GS and R&D | 1/1/2025 | 30/6/2025 | 25.8周 |
| 3 | GS mass production and QC | 1/7/2025 | 30/3/2026 | 39周 |
| 4 | **SiPM purchase and QC** | **1/1/2025** | **1/1/2025** | **0周** |
| 5 | SiPM selection | 1/1/2025 | 30/6/2025 | 25.8周 |
| 6 | SiPM purchase and QC | 1/7/2025 | 31/3/2026 | 39.2周 |
| 7 | **ASIC chips research and production** | **1/1/2025** | **30/3/2026** | **64.8周** |
| 8 | ASIC chips design | 1/1/2025 | 30/9/2025 | 39周 |
| 9 | ASIC chips production | 1/10/2025 | 30/3/2026 | 25.8周 |
| 10 | **Electronics design and production** | **1/10/2025** | **1/7/2026** | **39.2周** |
| 11 | PCB design | 1/10/2025 | 27/2/2026 | 21.6周 |
| 12 | PCB production | 2/3/2026 | 1/7/2026 | 17.6周 |
| 13 | **Machine and cooling** | **1/1/2025** | **1/7/2026** | **78.2周** |
| 14 | Machine and cooling design | 1/1/2025 | 30/9/2025 | 39周 |
| 15 | Machine and cooling installation | 1/10/2025 | 1/7/2026 | 39.2周 |
| 16 | **Integration of Sensitive Layers and test** | 1/1/2026 | 30/9/2026 | 39周 |
| 17 | **GS-prototype integration and test** | 1/7/2026 | 30/11/2027 | 74周 |




**Prototype design**

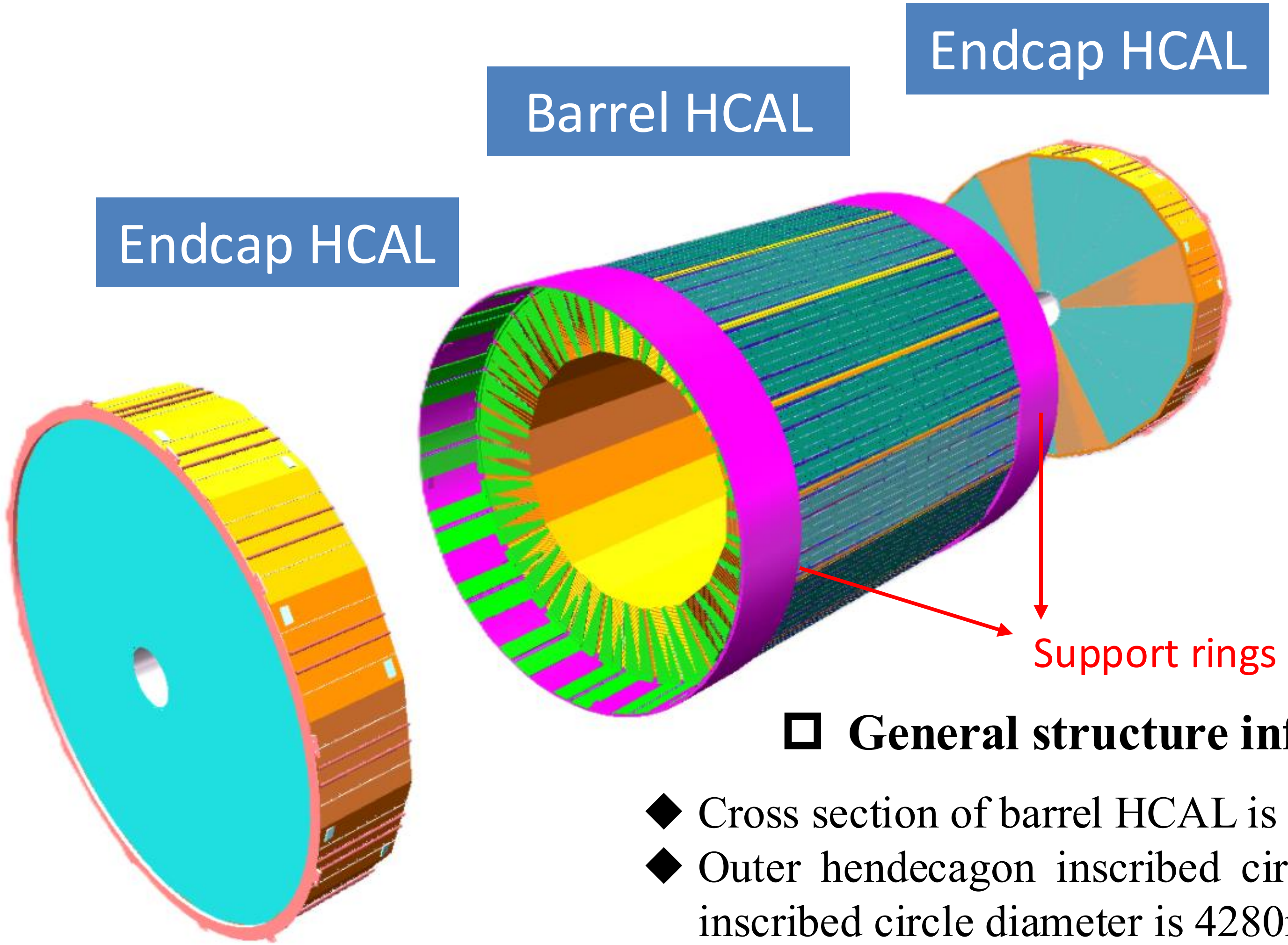


- Total: 48 layers
- Each layer: 13*13 glasses

- This study is to address the IDRC **Comment ③:**
- Preparation and beam testing of full-size HCal prototype;

# HCAL Mechanics Design

- Layout for all HCAL components




**☐ Requirements:**

- ◆ Support structure zone is as lower as possible.
- ◆ Maximum stress of different materials need to be lower than their allowable stress level.
- ◆ Deformation of different materials need to be controlled so that there will be no broken parts under different conditions.
- ◆ Outer contour dimension tolerance need to be 0mm to -5mm ;
- ◆ Inner contour dimension tolerance need to be 0mm to +5mm.

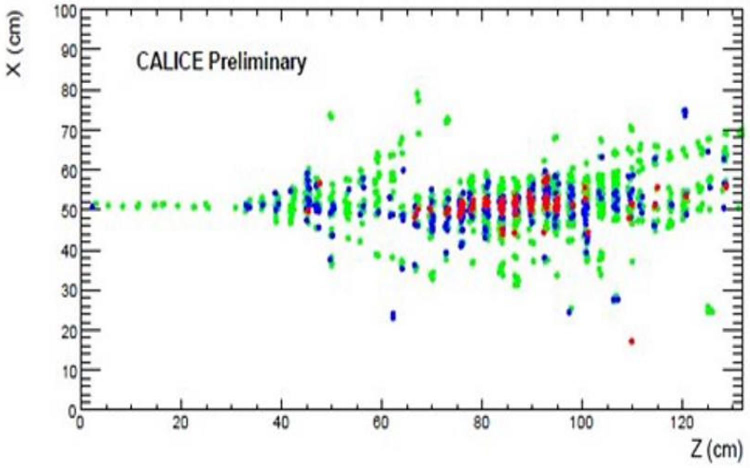
**☐ General structure information:**

- ◆ Cross section of barrel HCAL is a regular hendecagon
- ◆ Outer hendecagon inscribed circle diameter is 6910mm and the inner hendecagon inscribed circle diameter is 4280mm.
- ◆ Total weight is **1679 tons** and there are totally **5224960 (~530M) glass scintillator**

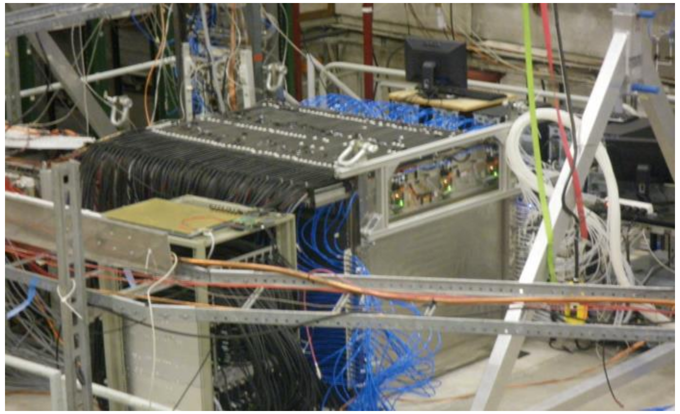
# 2.1 RPC-DHCAL （Gas Detector）

- **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

➢ **80 GeV Pion beam test in CERN**

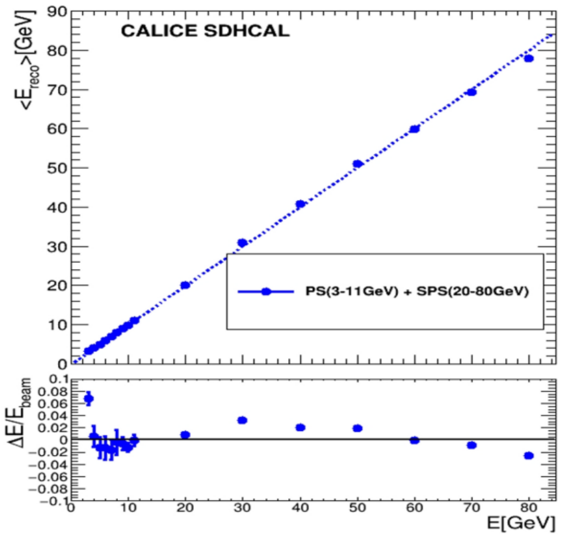


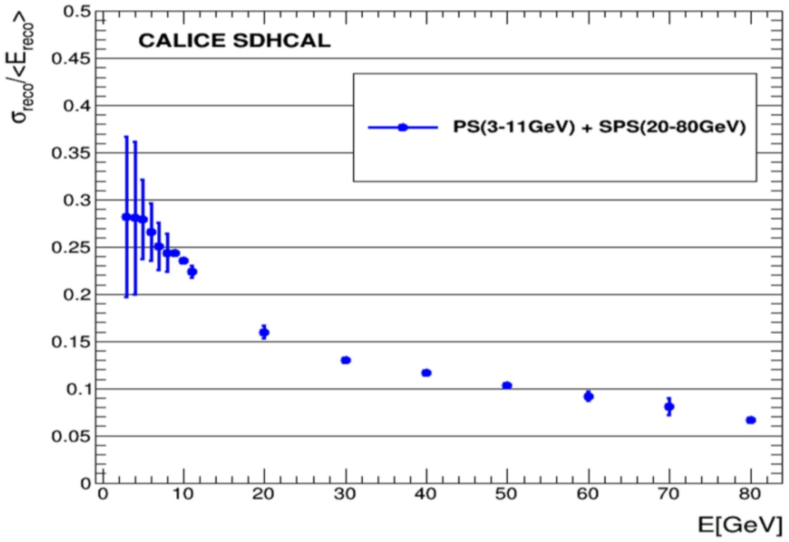

➢ **The prototype of the DHCAL**



- **DHCAL performance：**
  - Higgs boson mass resolution(BMR):
  - $H \to gg$: 3.68% (full sim + Arbor rec.)
  - Energy Linearity within ±1.5%?
  - Energy Resolution:

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




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

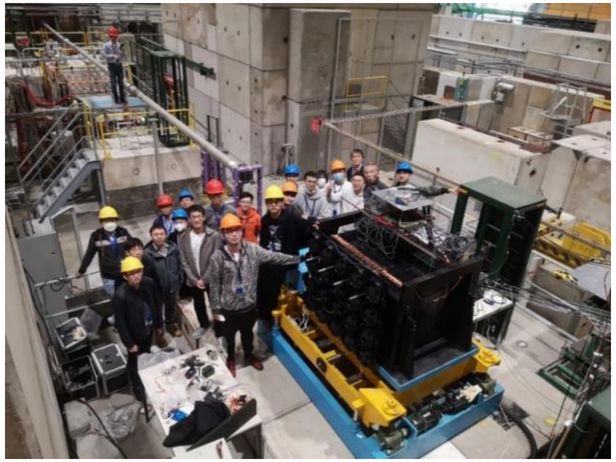
# 2.2 PS-HCAL

- Plastic Scintillator-AHCAL **(PSHCAL)**
  - High granularity (4cm x4cm)
  - 40 layers Three thresholds readout
  - Plastic Scintillator + SiPM
  - Stainless-steel absorber with self-supporting mechanical structure

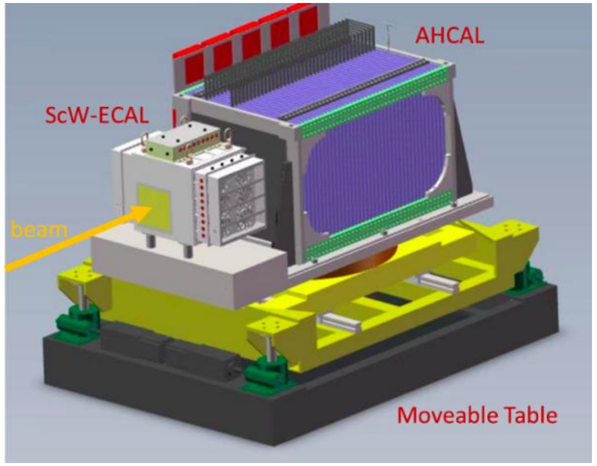
- **PS-HCAL performance：**
  - Higgs Boson Mass Resolution (BMR):
  - $H \rightarrow gg$: 3.77% (full sim + Arbor rec.)
  - Energy Linearity within ±1.5%
  - Energy Resolution:

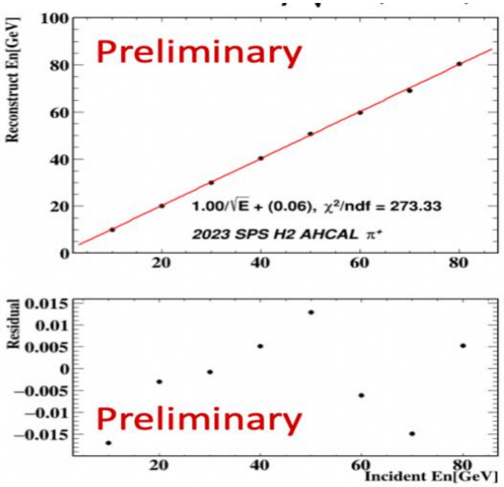
$$60\%/\sqrt{E} \oplus 3\%$$

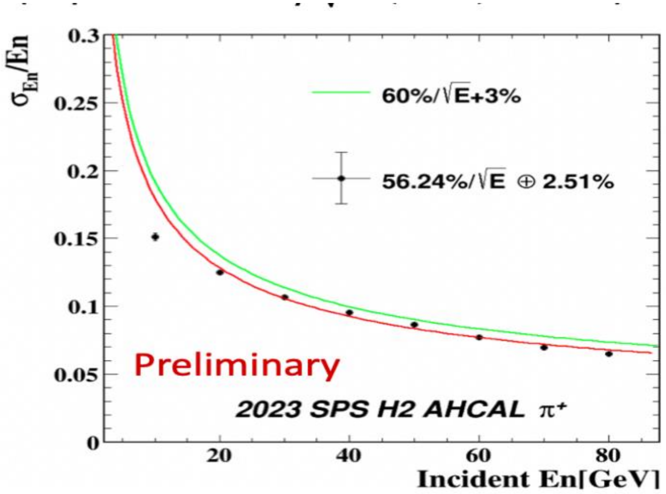
➢ **80 GeV Pion beam test in CERN**



➢ **The prototype of the DHCAL**



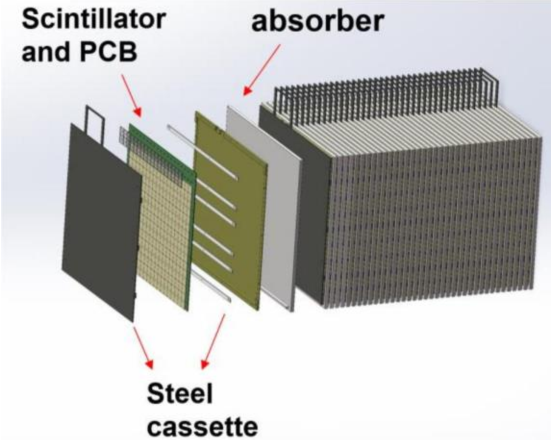



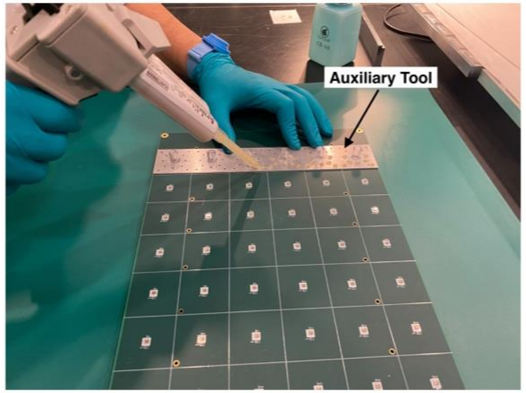

JINST 17 (2022) P05006

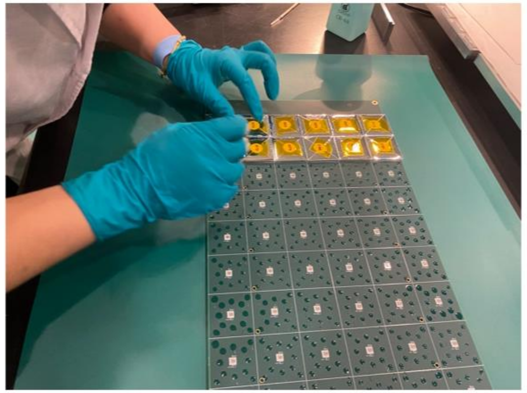
# 2.2 Plastic Scintillator HCAL (Prototype)

■ **We have developed a PS-HCAL prototype and TB at CERN in 2022-2023**

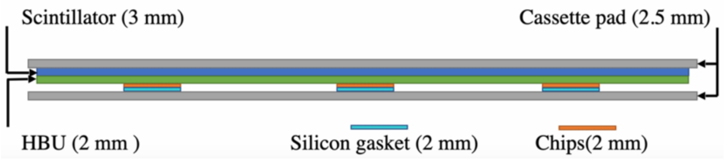
| Calo | Layers | material | Absorber | Granularity | Electronics | Thickness | Resolution | Weight |
|---|---|---|---|---|---|---|---|---|
| PS-HCAL | 40 | PS+SiPM S14160-1315 | Fe | $4\times4\ cm^2$ | SPIROC-2E 12960-ch | $4.6\ \lambda_I$ | $60\%/\sqrt{E}\oplus3\%$ | 5.0 T |

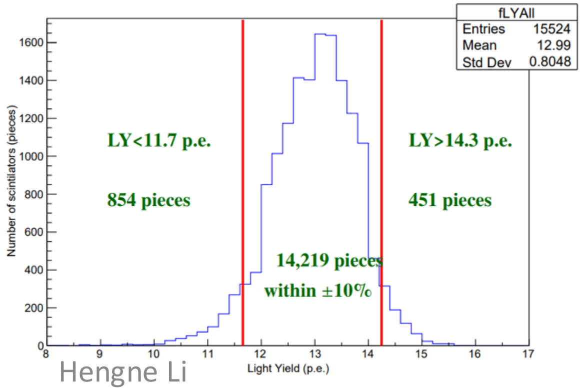


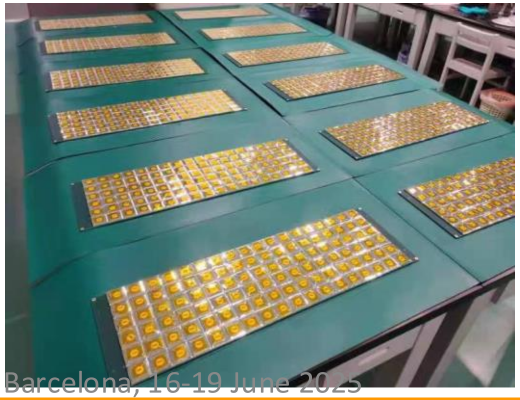



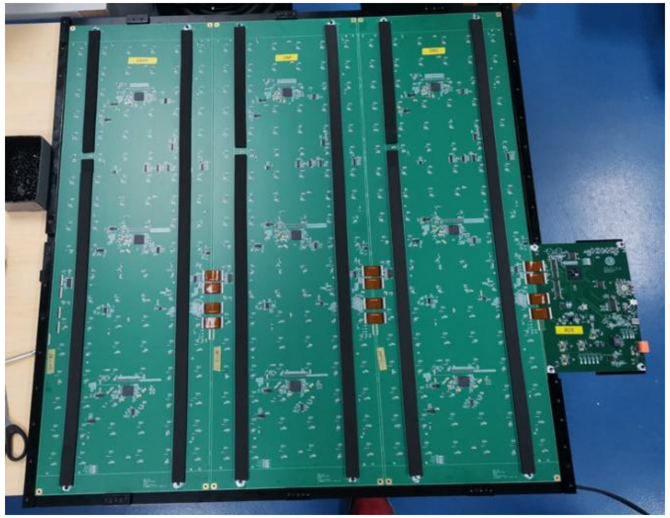



JINST 17 (2022) P05006





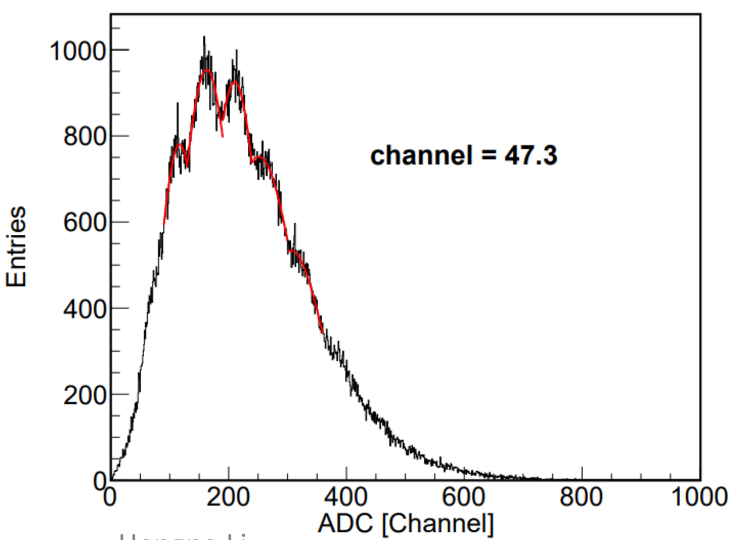
# Light Yield

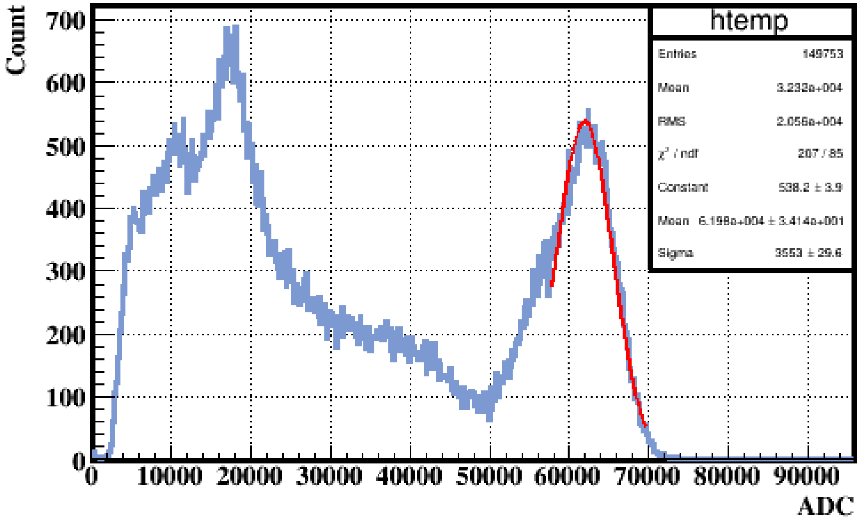
- **Light yield/ Light output:**

The efficiency of converting particle deposition energy into photons; photons/MeV, requires the device to be able to distinguish a single photoelectron signal. The results are obtained by comparing a single photoelectron signal with a test sample to the full-energy peak.

- **Intrinsic light yield:**

The light yield without any light loss inside the scintillator.




BGO:

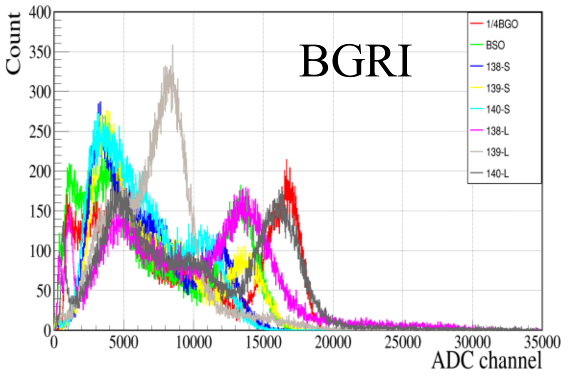
$$LY = \frac{M \times 1000\ keV}{S \times \varepsilon_{PDE} \times E\ keV} =$$

7917 ph/MeV (5*5*5 mm$^3$)

# Progress of large size GS

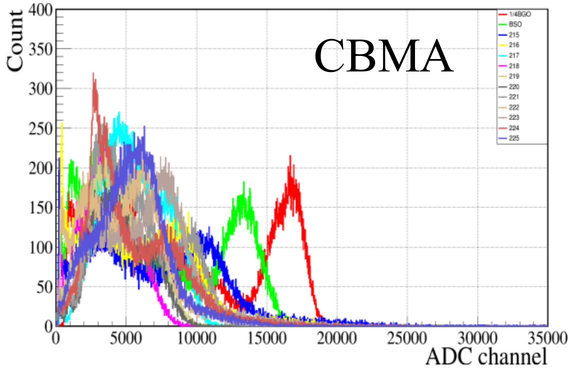
## BGRI

- Size=40*40*10 mm$^3$
- Density=6.0 g/cm$^3$
- LY=1506 ph/MeV
- ER=41.2%
- LO in 1μs=1129 (75%)
- Decay=53 (3%), 655 ns



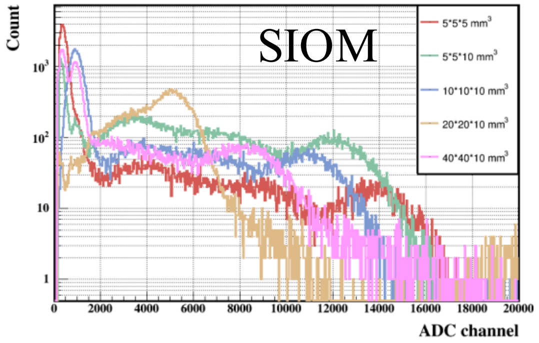

## CBMA

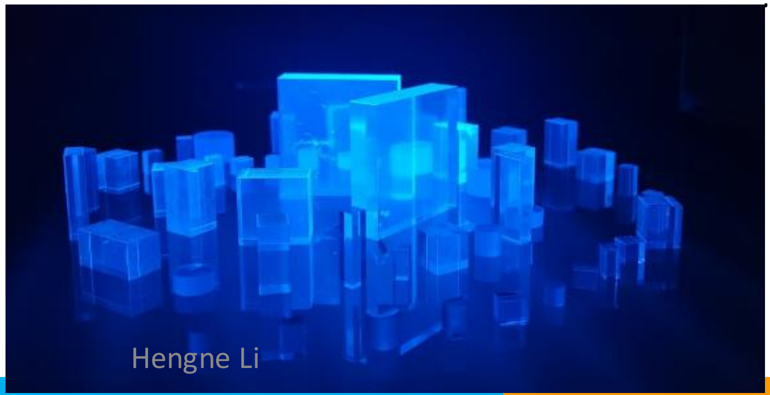
- Size=40*40*10 mm$^3$
- Density=6.0 g/cm$^3$
- LY=1119 ph/MeV
- ER=57.1%
- LO in 1μs=616 (55%)
- Decay=80 (4%), 1167 ns

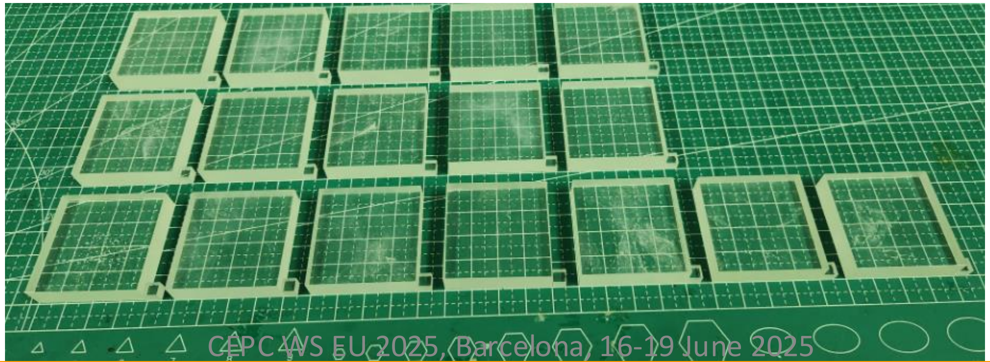


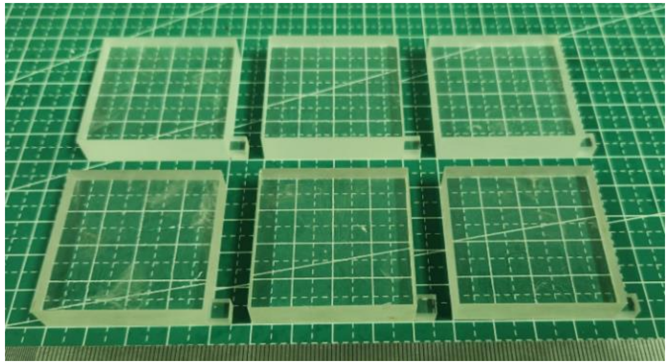

## SIOM

- Size=40*40*10 mm$^3$
- Density=6.0 g/cm$^3$
- LY=861 ph/MeV
- ER=41.7%
- LO in 1μs=697 (81%)
- Decay=114 (11%), 516 ns

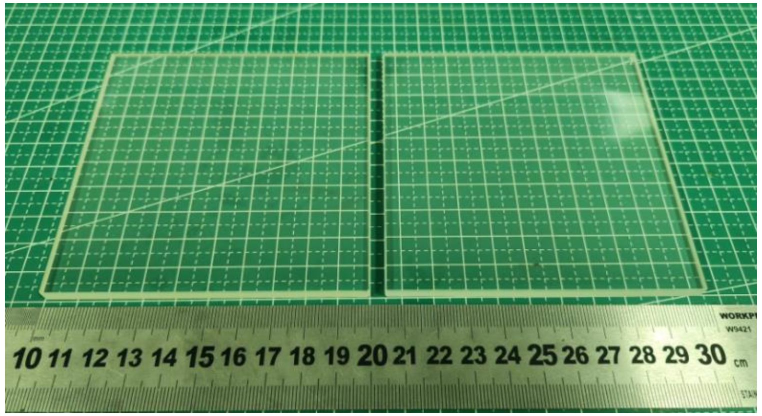


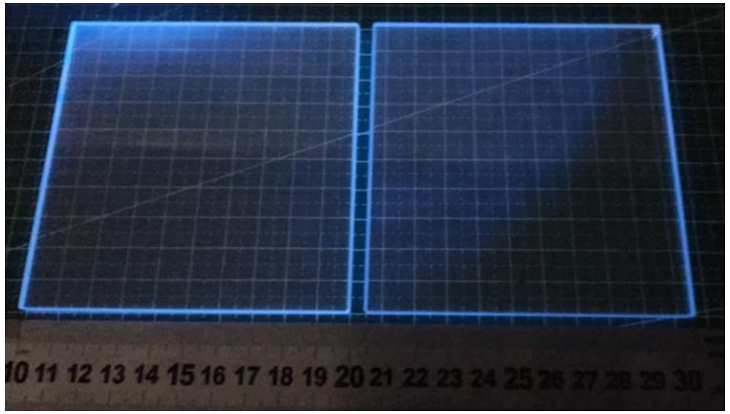



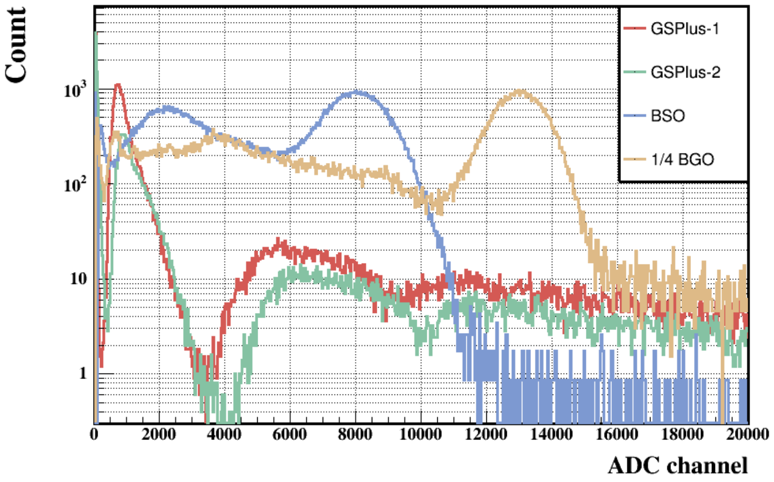


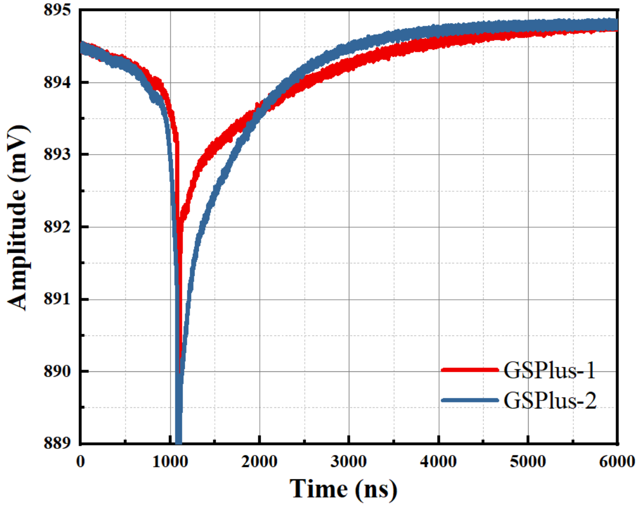


# Ultra-Large GS（10cm X 10cm）

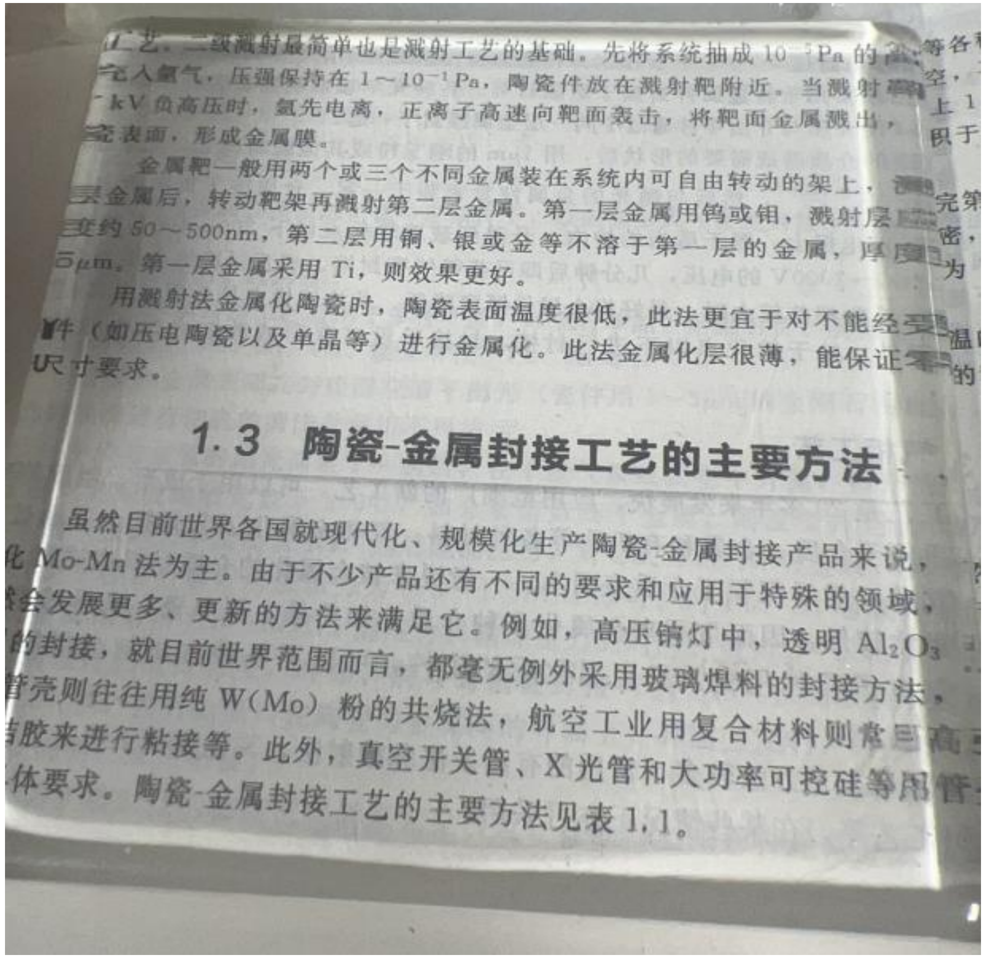


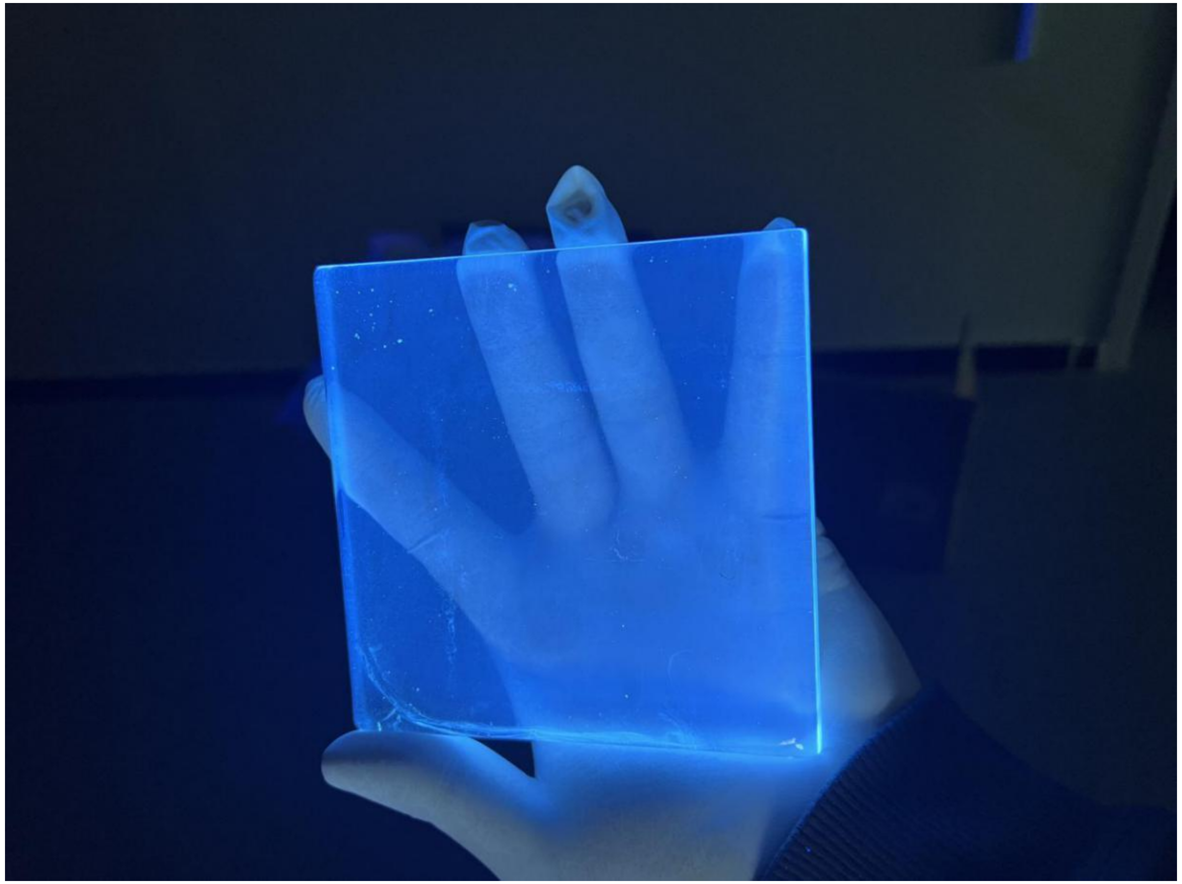




| | LY (ph/MeV) | Decay time (ns) |
|---|---|---|
| GSPlus-1 | 732 | 101.9 (1.0%), 1456.5 |
| GSPlus-2 | 795 | 72.1 (3.3%), 783.0 |

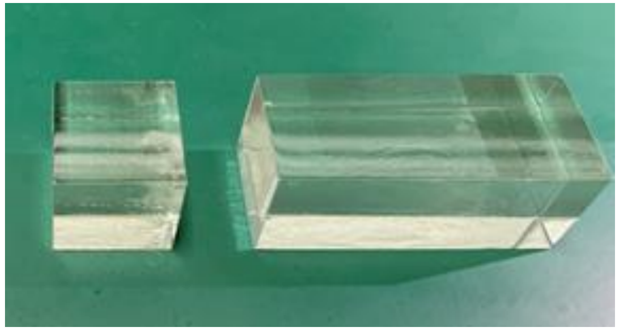
| | 5*5*5 mm³ | 5*5*10 mm³ | 10*10*10 mm³ | 20*20*10 mm³ | 40*40*10 mm³ |
|---|---|---|---|---|---|
| LY from PMT (ph/MeV) | 1464 | 1273 | 1155 | 941 | 861 |

# Ultra-Large GS（12.5cm X 122cm）



# Scintillator-AHCAL: Materials

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