The R&D Progress of the GSHCAL

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

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The Institute of High Energy Physics, CAS

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Motivation

Future electron-position colliders (e.g. CEPC)

- precision measurements of the Higgs and Z/W bosons
- Challenge: jet energy resolution < 30%/sqrt(E[GeV]) & Boson Mass Resolution (BMR) < 4%

Solution

PFA-oriented Detector System

Derive — Derive

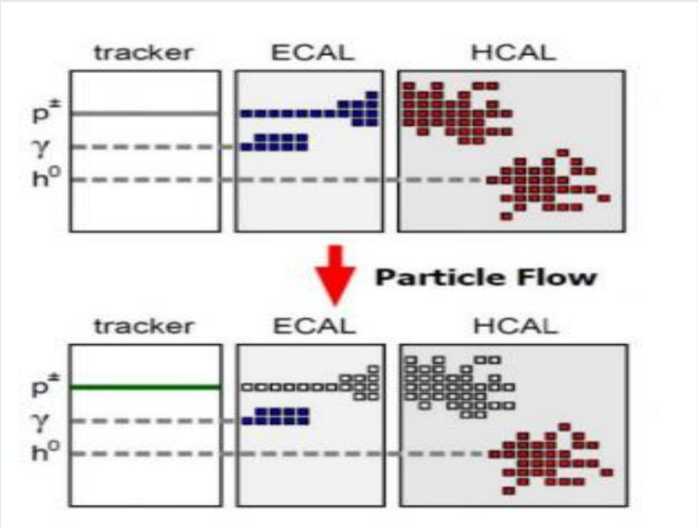
Baseline Design → Evolution → **The 4th Conceptual Design**

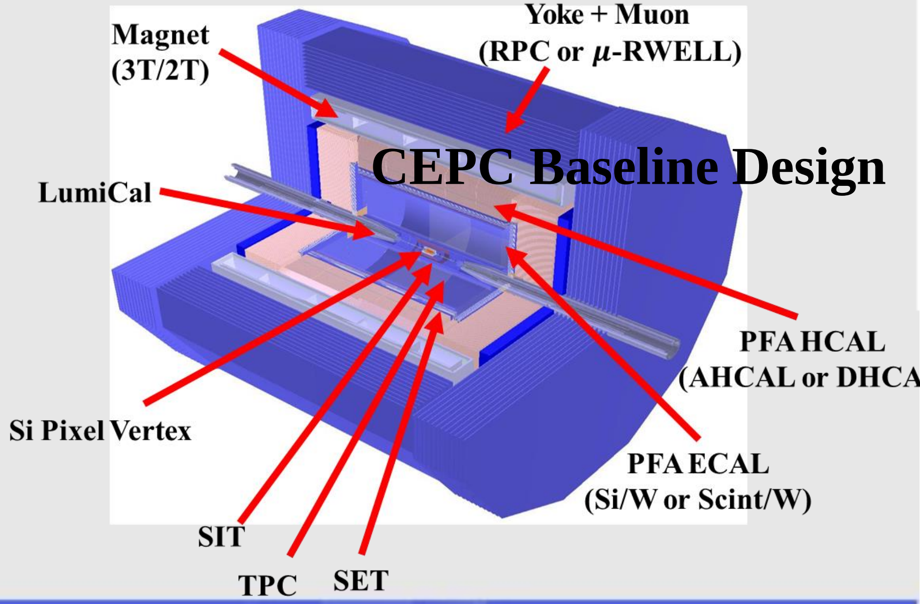
Baseline Design

- BMR ~3.8% Achieved
- Fulfill requirements of Higgs measurements

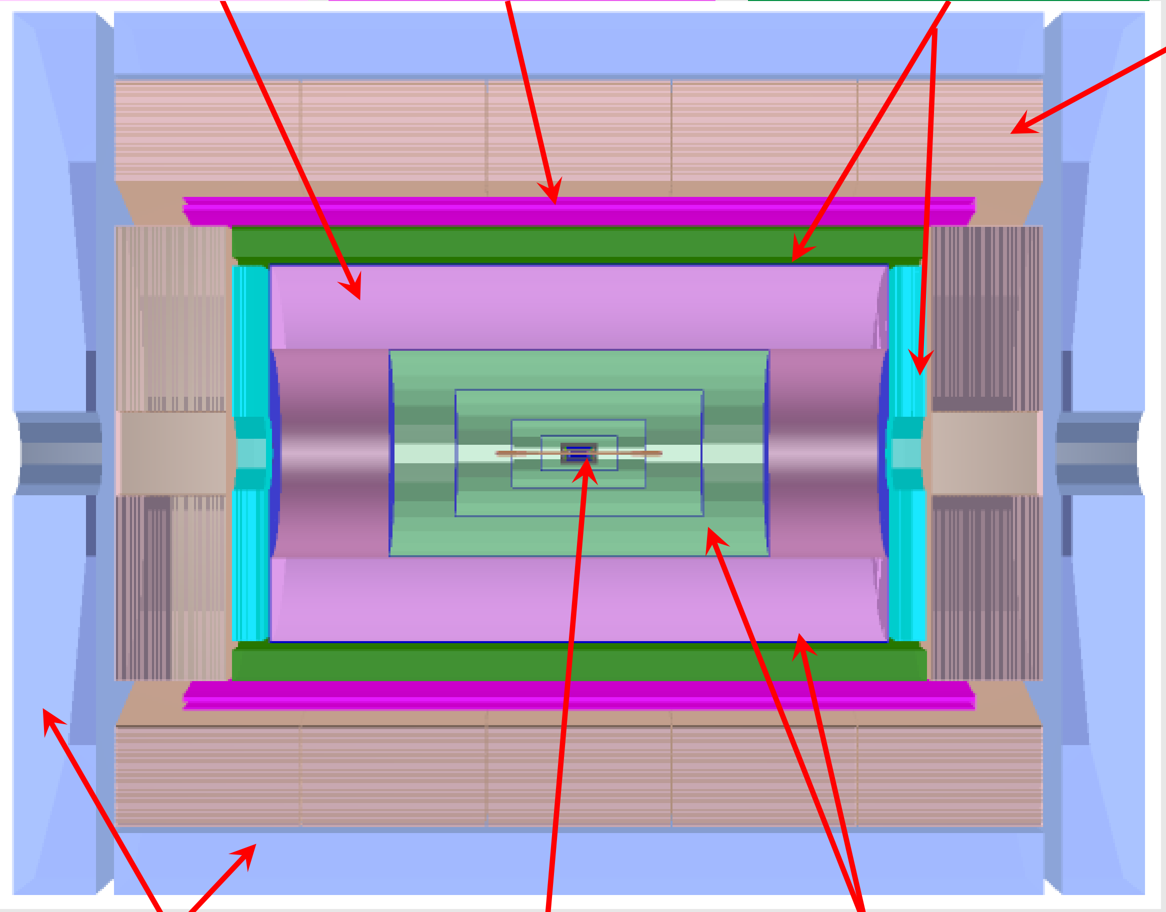
The 4th Conceptual Design

- Pursue BMR ~3.0%
- Requirements for NP tagging & Flavor Physics Measurements





The 4th Conceptual Detector Design



Glass Scintillator HCAL (GSHCAL)

Advantages: Cost effective, high density etc.

Challenges: Light yield, transparency, mass production

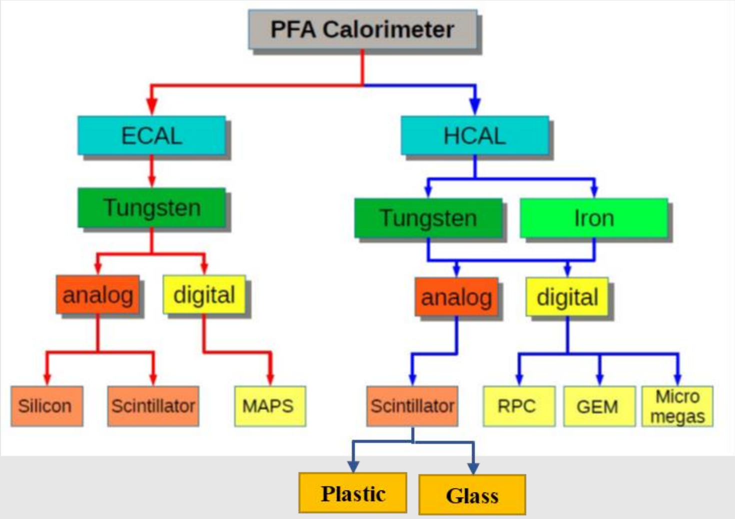
- Further performance goal: BMR 3.8% -> 3%
- Dominant factors on **BMR**: charged hadron fragments & HCAL resolution
  - Higher density provides higher energy sampling fraction
  - Doping with neutron-sensitive elements: improve hadronic response (Gd)
  - Large nuclear interaction length is beneficial for a relatively compact structure

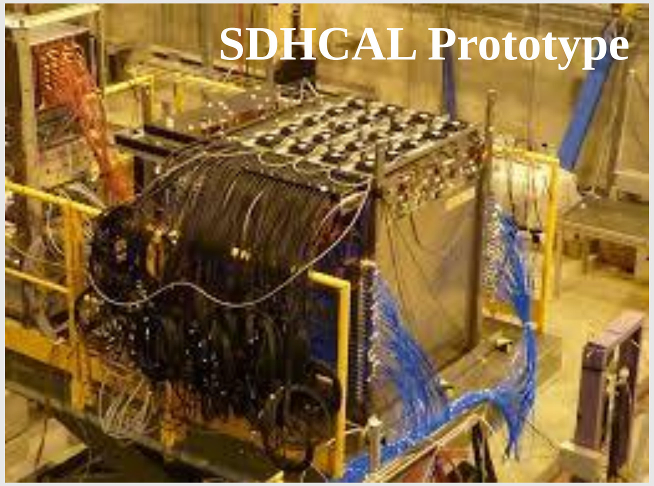
Outline

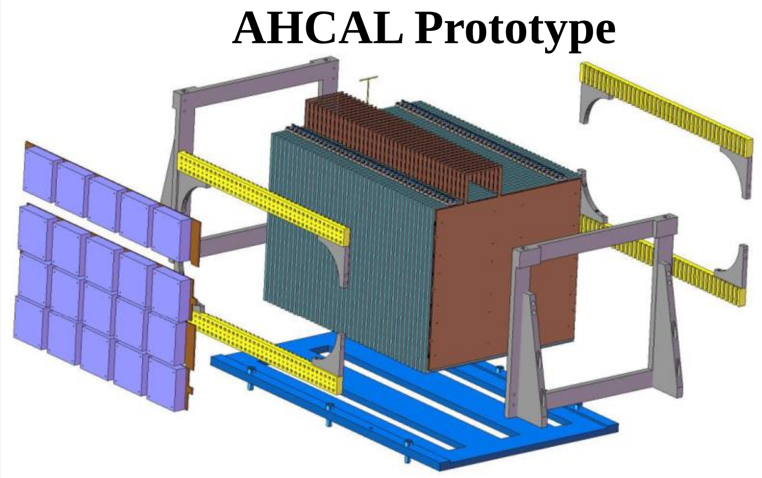
- **1. The HCAL Designs of the CEPC;**
- 2. PFA performance of the GSHCAL;
- 3. The Progress of the GS Production;
- 4. The Tests of GS Samples
- 5. Summary and Next Plan

1.1 HCAL Designs Proposed for the CEPC

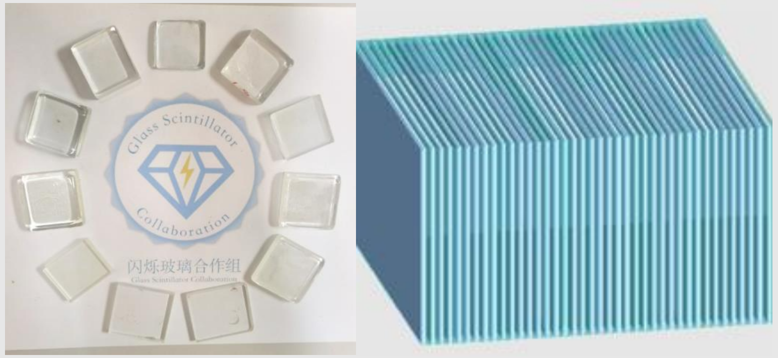
- **Several PFA-based HCAL designs were proposed for the CEPC**
  - DHCAL: baseline design, gaseous detector
    - CALICE SDHCAL group doi:10.1088/1748-0221/11/04/P04001
  - AHCAL: baseline design, plastic scintillator & SiPM readout
    - USTC doi:10.1088/1748-0221/17/11/P11034
  - GSHCAL: 4th conceptual design, glass scintillator & SiPM readout
    - IHEP & GS Collaboration doi:10.1016/j.nima.2023.168944



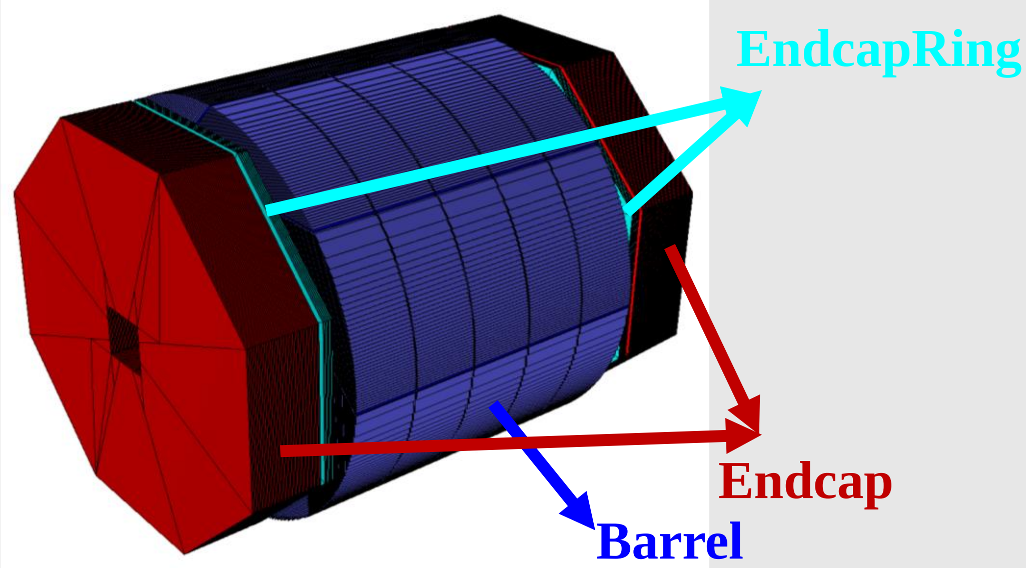

SDHCAL Prototype

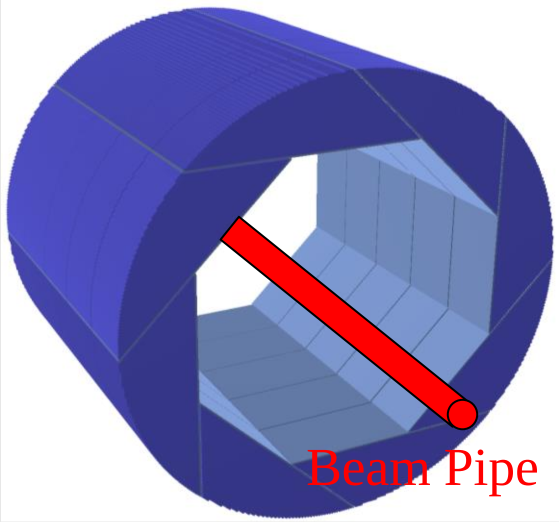

AHCAL Prototype

GSHCAL Prototype
To be designed in the next two years



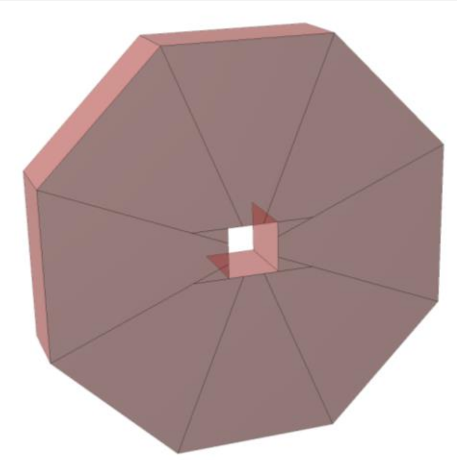
1.2 GSHCAL Overall Structure



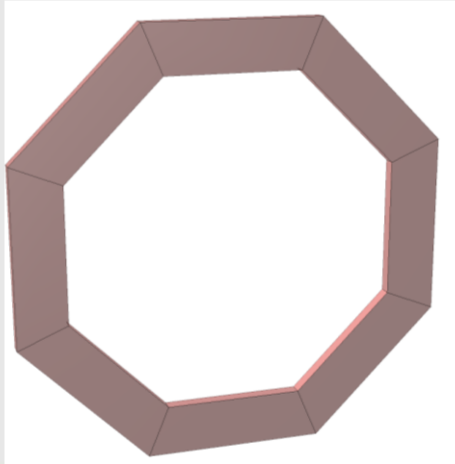


Barrel

Endcap



EndcapRing



- The overall structure of the GSHCAL consists of three parts: the Barrel, Endcap and EndCapRing
  - Thickness of the Barrel: ~1 m
  - Outer radius of the Barrel: ~3 m
  - Length along beam direction: ~7 m
  - **Number of Layers: ~40**
  - **GS/Steel Volume: ~46/64 m^3**
  - **Number of SiPM readout Channels: ~$3x10^6$**

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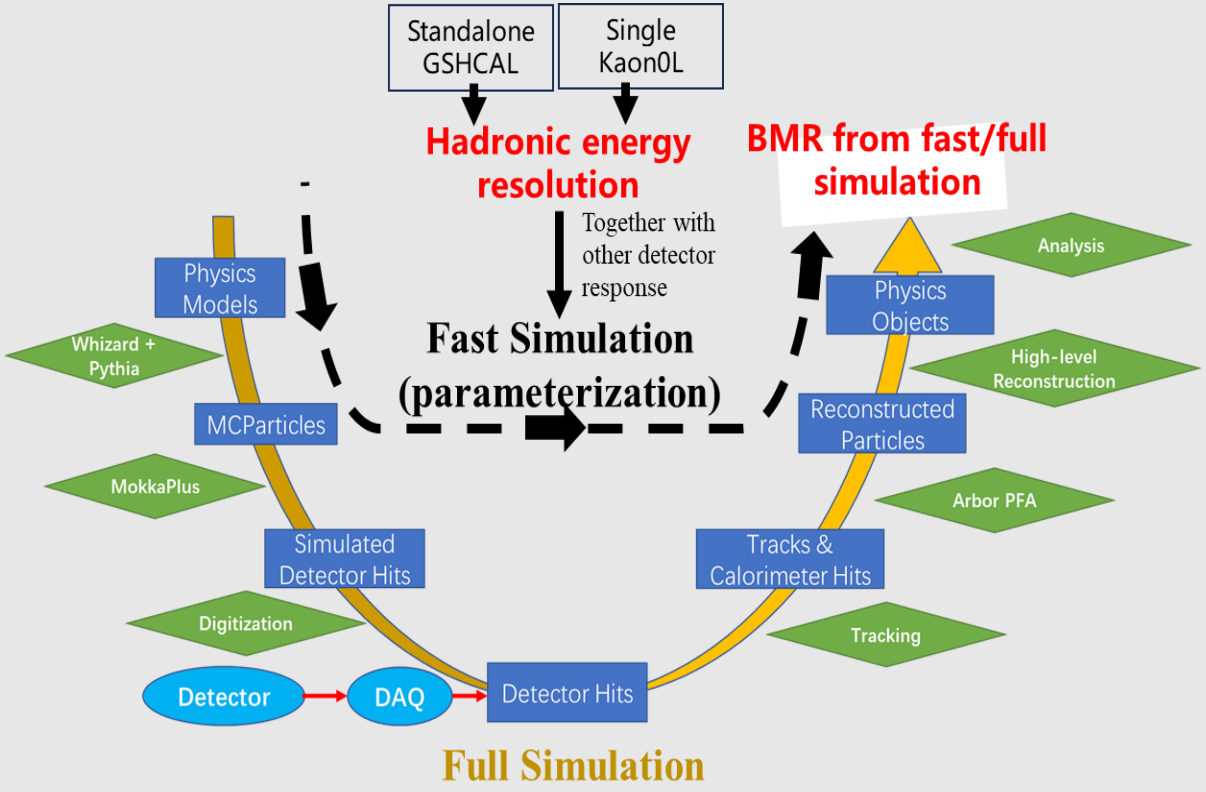
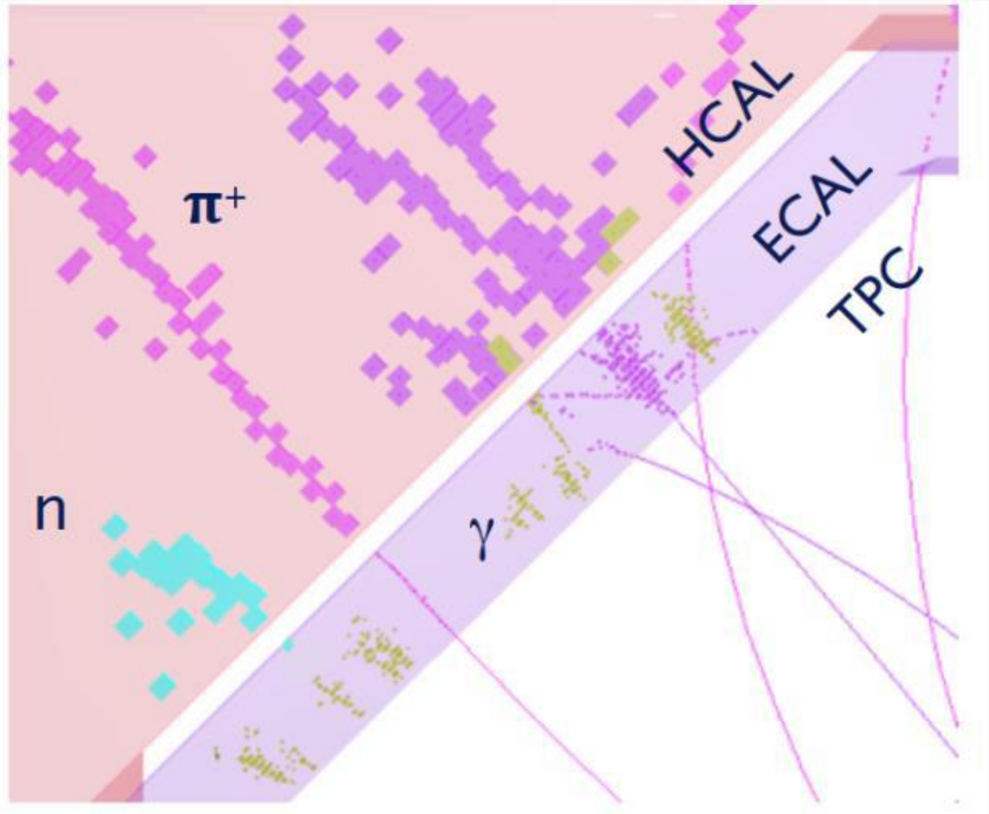
2.1 Simulation Studies of GSHCAL Performance

- **Standalone module simulation -> Hadronic energy resolution -> Input for fast simulation**
- **Fast/Full simulation -> PFA performance (BMR) based on the GSHCAL**
- **The focus of this part is the PFA performance (BMR) obtained from the Full simulation**



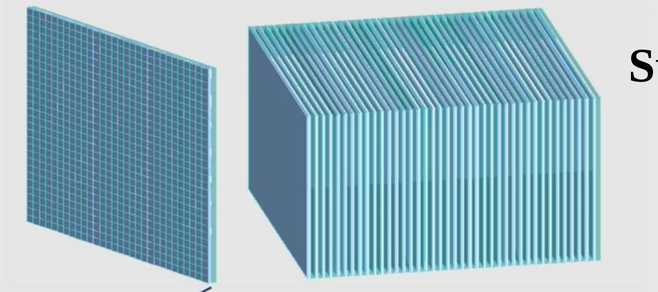


2.2 Simulation Setup

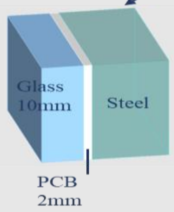
- Based on the CEPCSoft framework and CDR baseline design, but replacing the AHCAL with glass scintillator/steel HCAL
- Primaries input: 240 GeV e+e- -> nu_nu H (H -> gg)
- Glass components : Gd-B-Si-Ge-Ce^{3+}

* GSHCAL Nominal Parameters

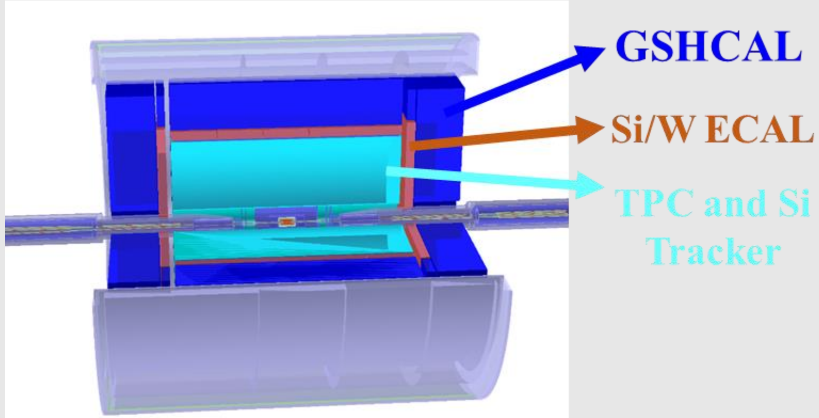
Total Number of Layers	**40**
Glass Cell Size	**40×40×10 mm^3**
Total Nuclear Interaction Length (NIL)	**5 λ**
Glass Density	**6 g/cm^3**
Readout Threshold	**0.1 MIP**



Standalone Module

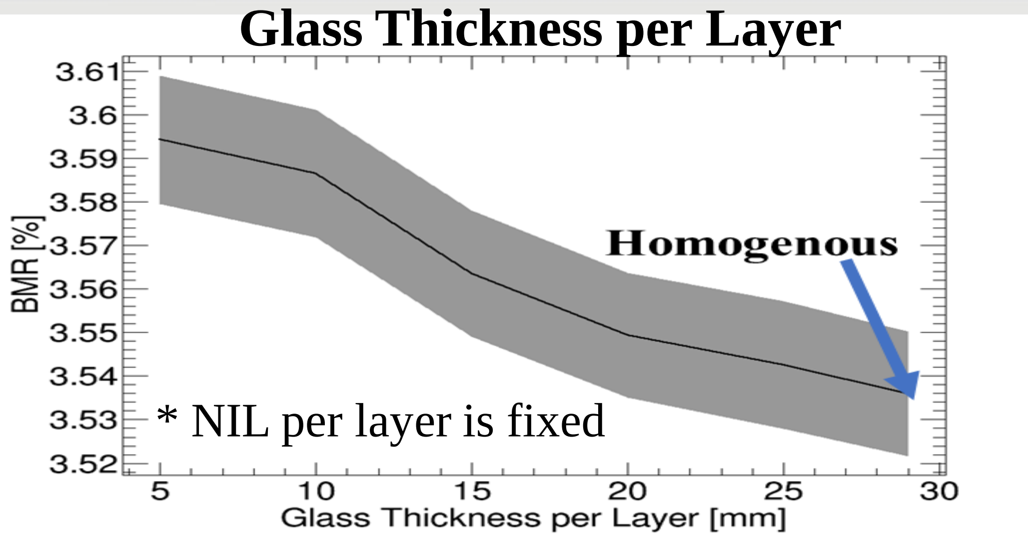


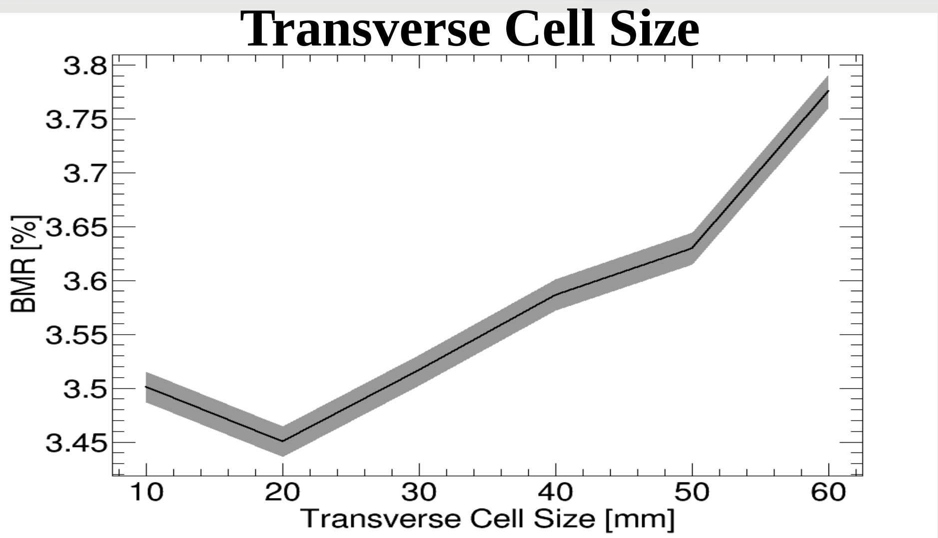
4x4x1 cm^2 GS readout with the SiPM



Baseline Design using GSHCAL

2.3 Impact of Some Key Parameters

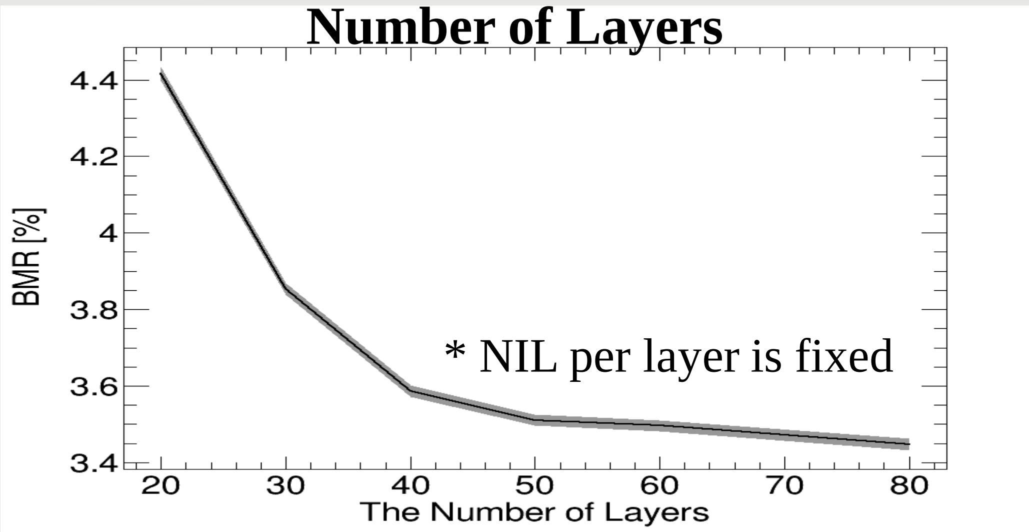


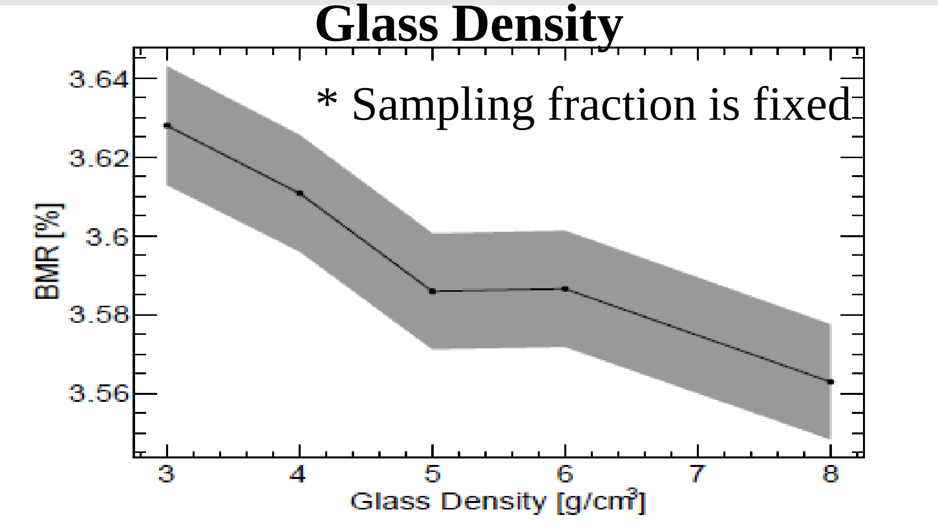


- Thicker glass -> higher sampling fraction -> better hadronic energy resolution & BMR (pros)
- Thicker glass -> thicker GSHCAL (higher cost) & worse optical performance of cells (cons)
- Reasonable glass thickness is necessary to balance the impact of sampling fraction and optical performance on the BMR, as well as the cost

- Smaller transverse cell size -> higher efficiency to separate close-by showers -> better BMR (pros)
- Smaller transverse cell size -> more number of readout channels -> higher cost (cons)
- Reasonable transverse cell size is necessary to balance the impact of transverse granularity on the BMR and the cost of the readout channel

2.3 Impact of Some Key Parameters



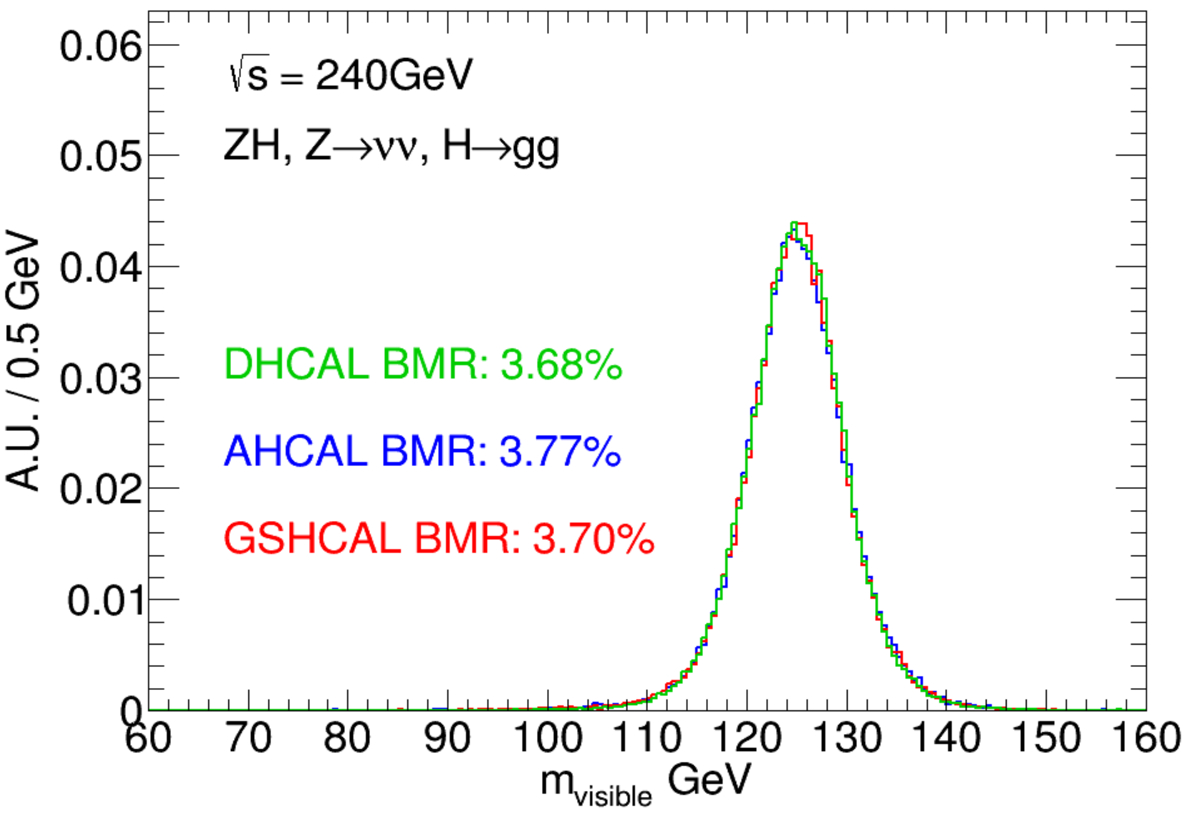


- More sampling layers -> greater total NIL and lower energy leakage -> better hadronic energy resolution and & BMR (pros)
- More sampling layers -> thicker GSHCAL & more readout channels -> higher cost (cons)
- Reasonable number of layers should be selected to balance the impact of energy leakage on the BMR and the cost

- Higher glass density -> more compact GSHCAL & lower confusion term in PFA -> lower cost & better BMR (pros)
- Higher glass density -> scintillation performance degradation -> BMR degradation (cons)
- Reasonable glass density should be selected to balance the BMR and the cost.

2.4 GSHCAL vs. Baseline Design

Parameter	GSHCAL	AHCAL	DHCAL
Readout	Analog	Analog	Digital
Number of layers	40	40	40
Layer thickness	0.125 lambda (3mm GS +18.8mm Steel)	0.125 lambda (3mm PS +20mm Steel)	0.12 lambda (3mm RPC +20mm Steel
Total Nuclear Interaction Length	5 lambda	5 lambda	4.8 lambda
Transverse Cell Size	40x40 mm^2	40x40 mm^2	**10x10 mm^2**
Sensitive Material Density	6 g/cm^3	1 g/cm^3	< 10^{-3} g/cm^3
HCAL Thickness	**873 mm**	931 mm	931 mm
HCAL Volume	**13 m^3(GS) 81 m^3(Steel)**	14 m^3(PS) 91 m^3(Steel)	14 m^3(RPC) 91 m^3(Steel)
Number of Cells	**2.7×10^6**	2.8×10^6	4.5×10^7



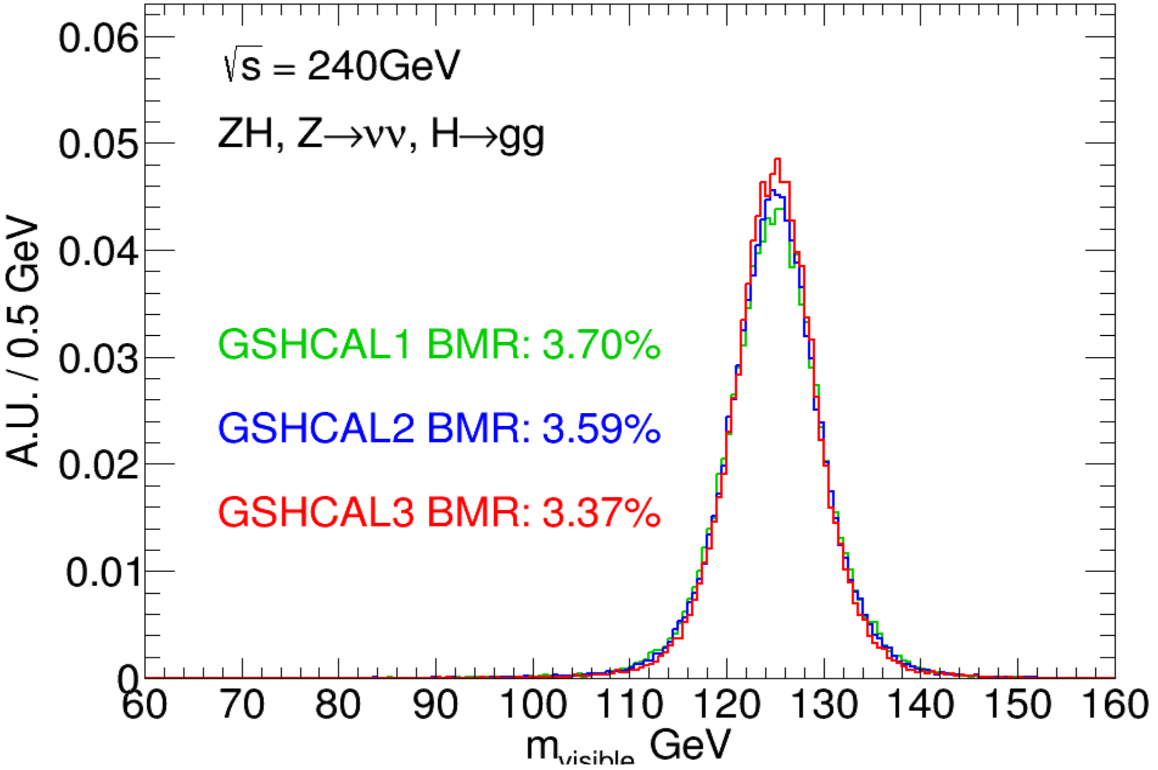
*Gaussian fitting range: Mean +/- 2 RMS

- By using a similar setup with the AHCAL, the GSHCAL can achieve a more compact structure and less readout channels, as well as a comparable PFA performance with the DHCAL

2.5 Different GSHCAL Designs

Nominal Setup

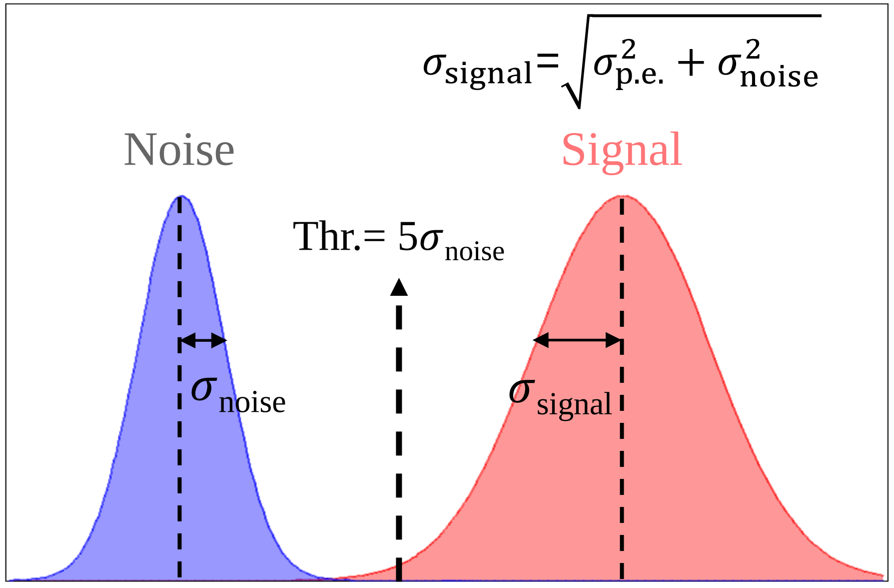
Parameter	GSHCAL1	GSHCAL2	GSHCAL3
Readout	Analog	Analog	Analog
Number of layers	40	40	40
Layer thickness	0.125 lambda (3mm GS +18.8mm Steel)	0.125 lambda (10mm GS +13.9mm Steel)	0.125 lambda (29.7 mm GS)
Total Nuclear Interaction Length	5 lambda	5 lambda	5 lambda
Transverse Cell Size	40x40 mm^2	40x40 mm^2	20x20 mm^2
Sensitive Material Density	6 g/cm^3	6 g/cm^3	6 g/cm^3
HCAL Thickness	873 mm	962 mm	1218 mm
HCAL Volume	13 m^3(GS) 81 m^3(Steel)	46 m^3(GS) 64 m^3(Steel)	159 m^3(GS)
Number of Cells	2.7×10^6	$\mathbf{2.9\times10^6}$	5.4×10^7

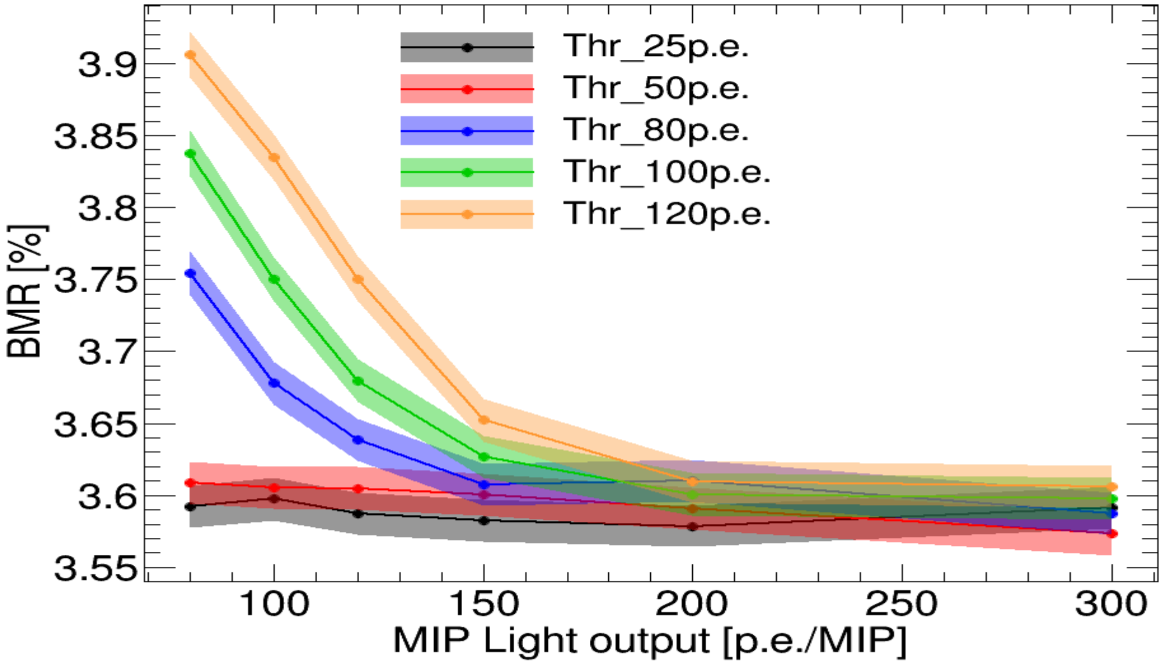


*Gaussian fitting range: Mean +/- 2 RMS

- ➢ The GSHCAL2 design is slightly thicker (+30 mm) than the AHCAL, BMR can reach ~3.6% （improved ~5%）
- ➢ The GSHCAL3 is a homogenous design, with which the BMR can reach ~3.4% and show ~10% improvement, but the total volume and readout channel will also increase significantly

2.6 Preliminary Digitization for Deposited Energy





- The deposited energy is digitized based on the fluctuation from the p.e. number and the noise
- Readout threshold was set to 5*Sigma$_{noise}$
- The noise, readout threshold and MIP light output are three correlated factors that impact the BMR; when the noise fluctuation is better than ~10 p.e. (i.e. Thr. less than 50 p.e.) and the MIP light output > 80 p.e./MIP, the impact of MIP light output on the BMR is not significant

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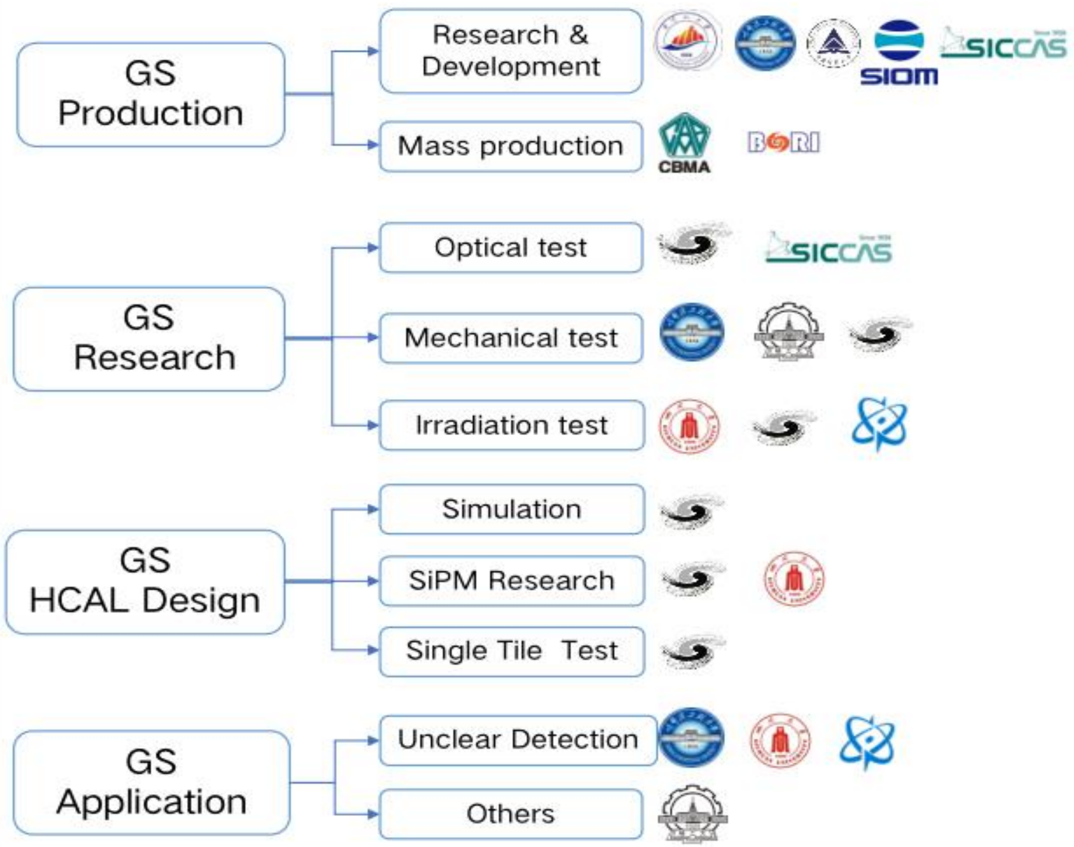
3.1 Large Area Glass Scintillator Collaboration



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China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

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Harbin Institute of Technology
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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 Unclear Instrument Factory
中核（北京）核仪器有限责任公司

闪烁玻璃合作组
Glass Scintillator Collaboration

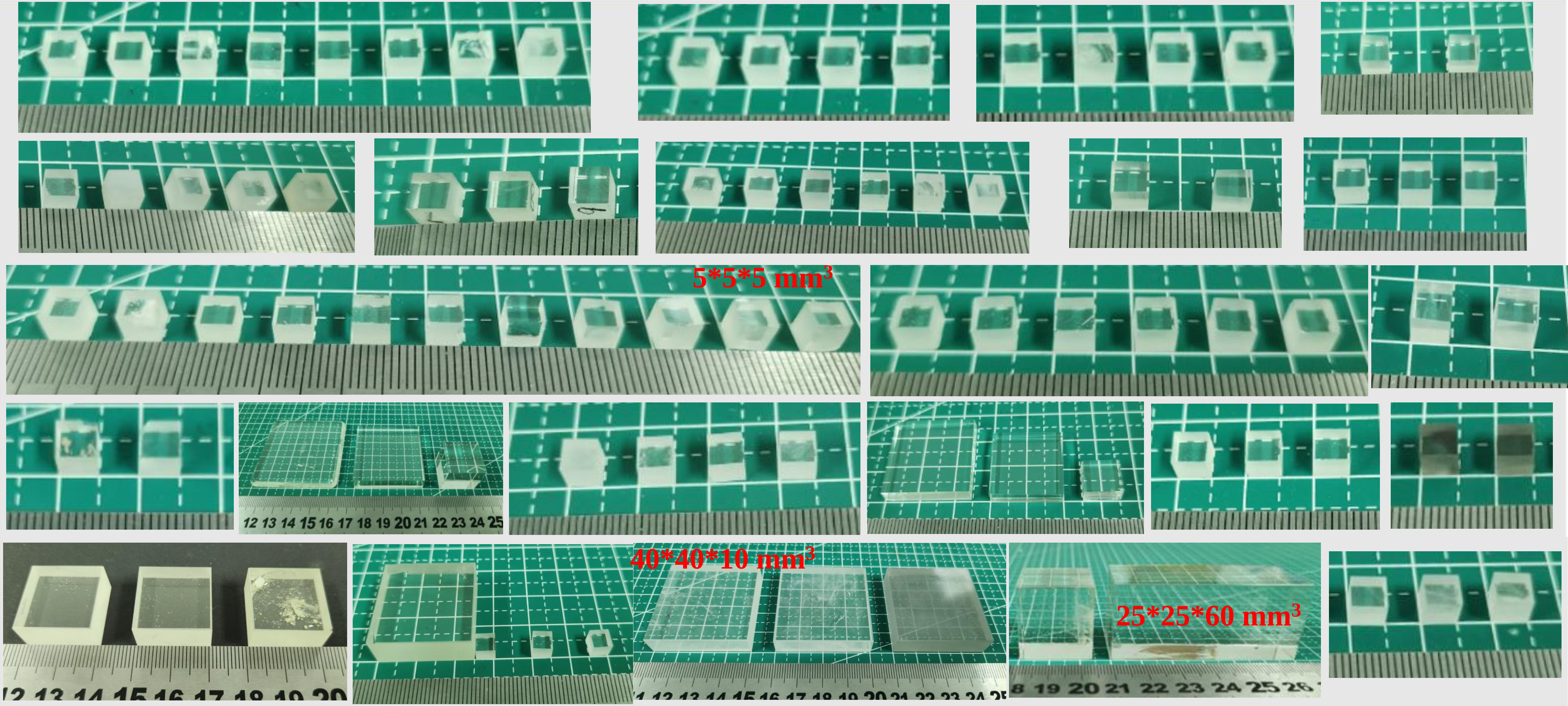
Spokesperson：QIAN Sen

-- The Glass Scintillator Collaboration Group established in Oct.2021；

-- There are 3 Institutes of CAS, 5 Universitys, 3 Factorys join us for the R&D of GS;

-- The Experts of the GS in the University, Institute and Industry are still welcomed to join us **(qians@ihep.ac.cn)**.

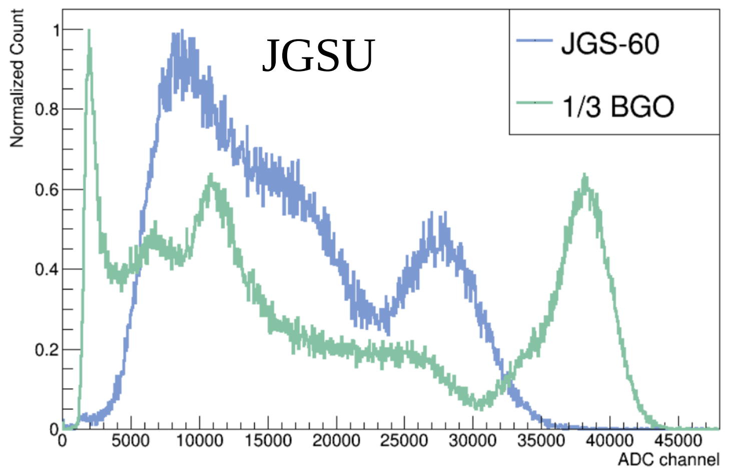
3.2 The GS Samples produced （>600）



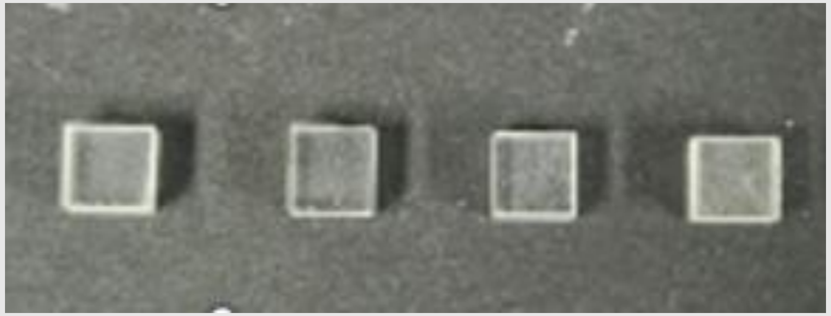
3.3 The Best Performance Achieved Currently

Small-Size

- **Size=5*5*5 mm^3**
- Density~6.0 g/cm^3
- LY~1100 ph/MeV
- ER=24.4%
- LO in 1μs=899 ph/MeV
- Decay=92 (8%), 473 ns

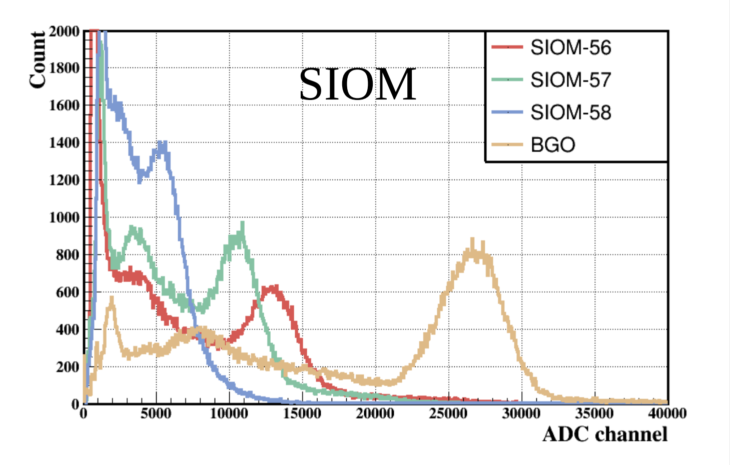


2023.02



Large-Size

- **Size=40*40*10 mm^3**
- Density=6.0 g/cm^3
- LY=1198 ph/MeV
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns



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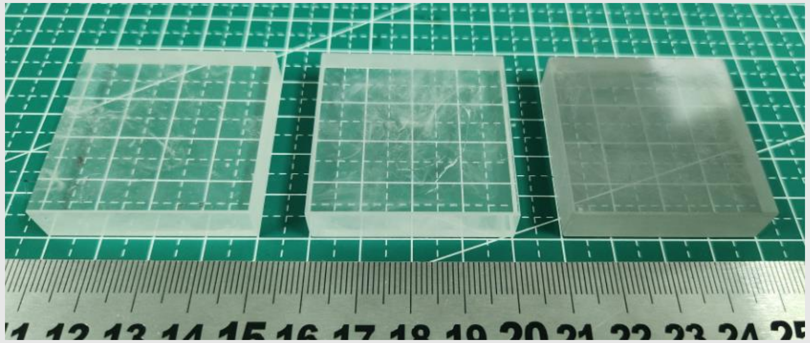
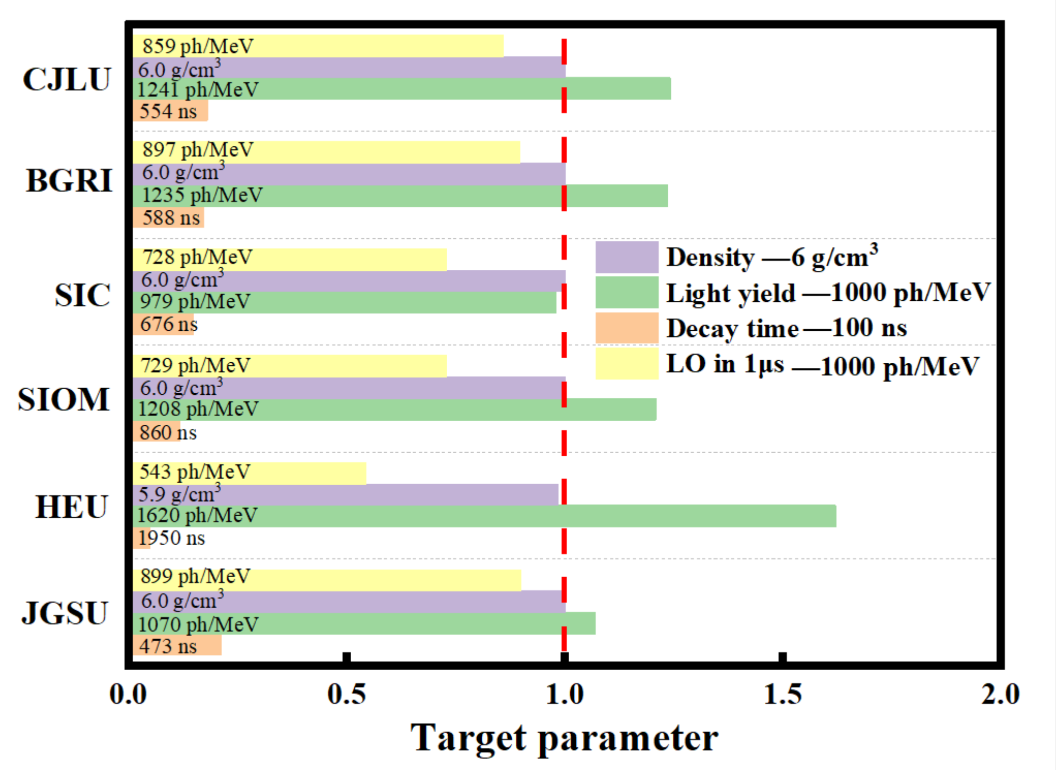
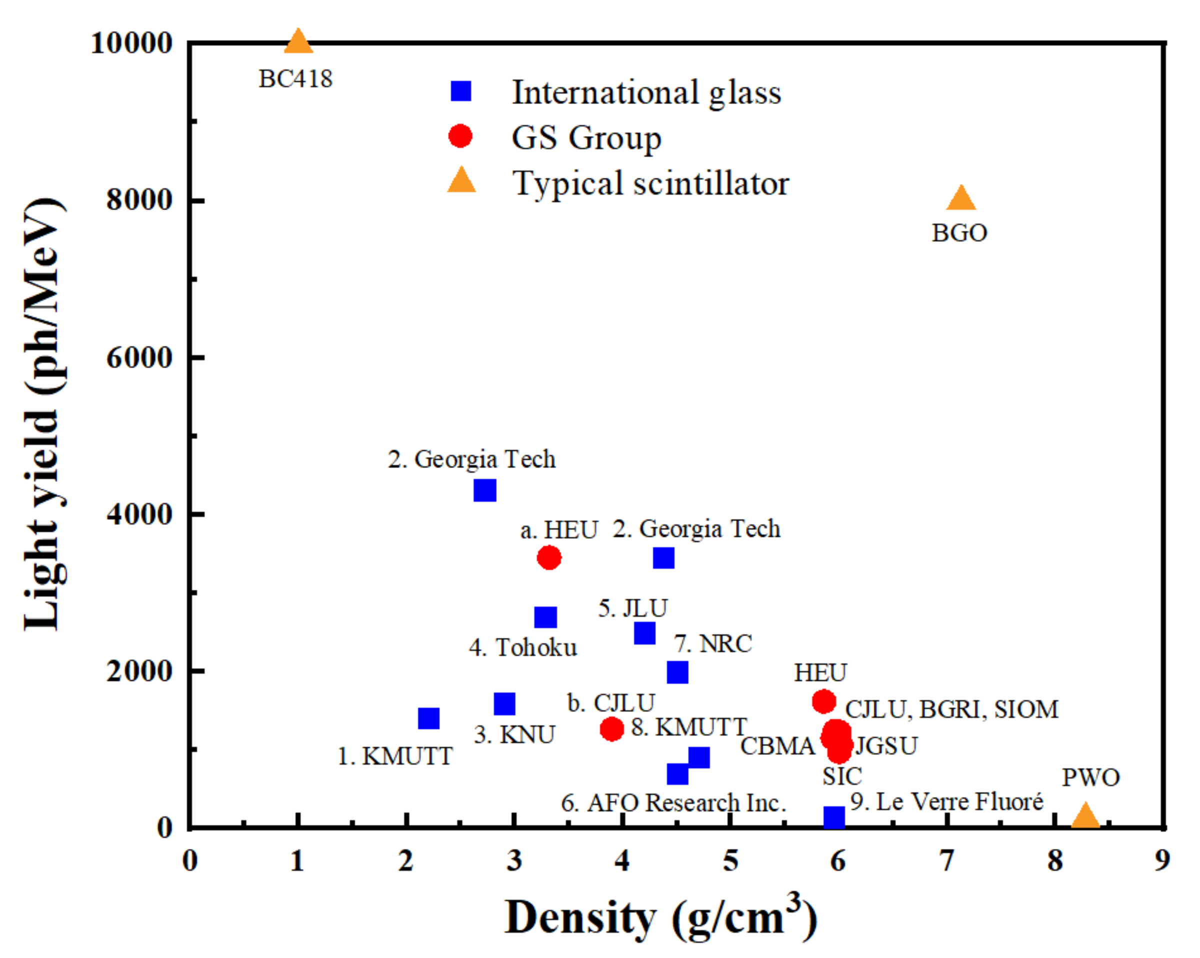


3.4 Summary of the GS Samples



* The sample size is 5x5x5 mm^3, except for **BGRI** (10x10x5 mm^3)



- The GS group has carried out a comprehensive and complete study;
- For high density glass scintillator, the glass light yield of GS group is in the absolute lead.

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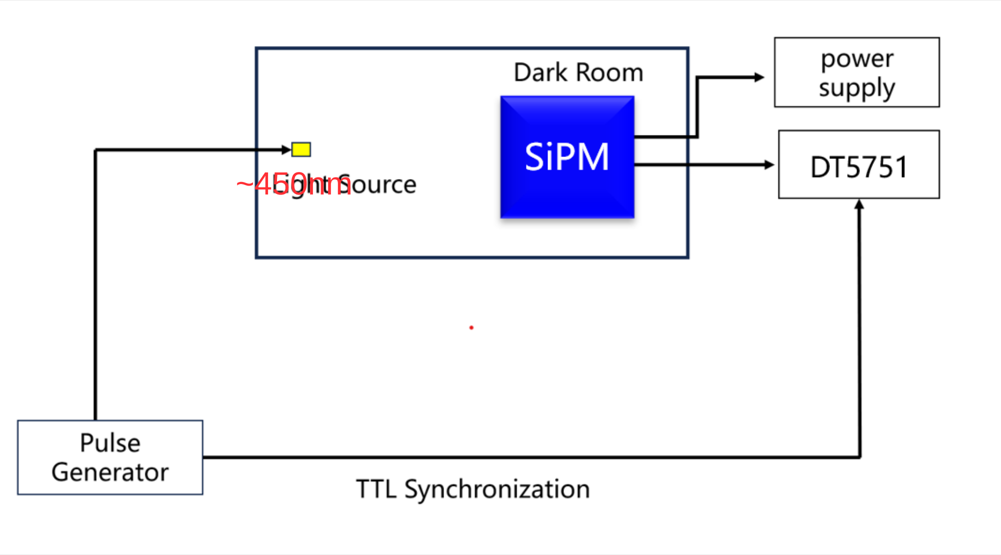
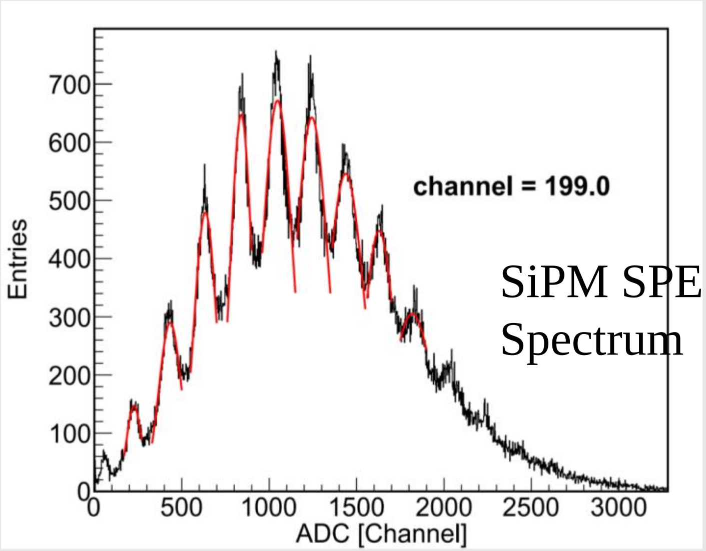
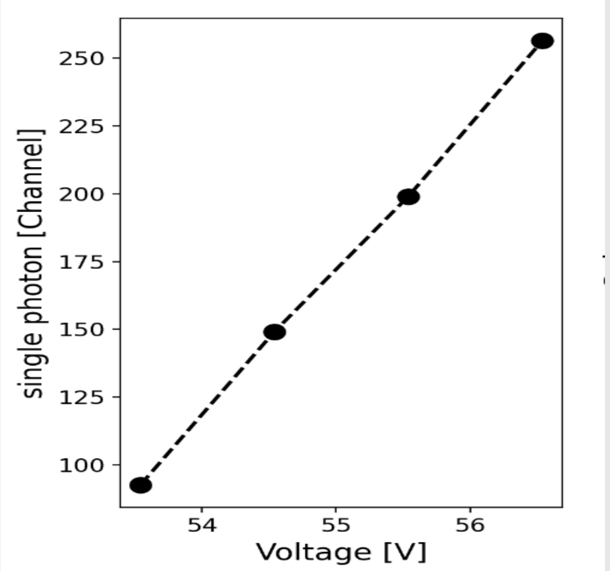
4.1 Study on the SiPM readout for GS



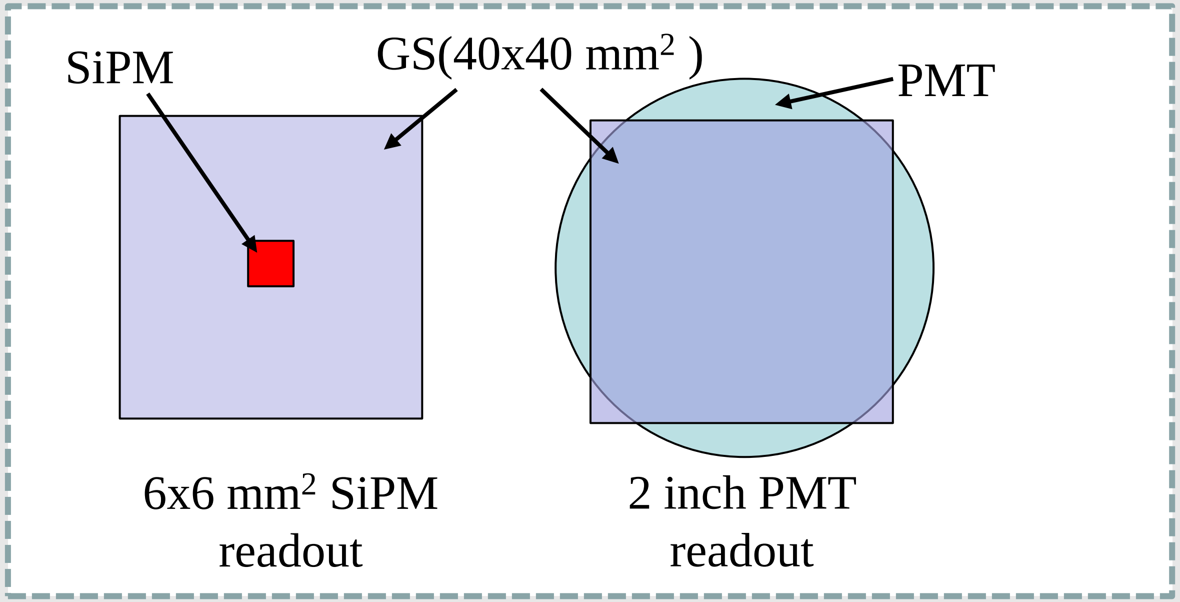




- The SiPM readout design is being studied from different aspects:

- **Intrinsic performance studies on different SiPMs** -> select a proper SiPM type
- **The coupling design study of the SiPM and GS** -> achieve good light output and response uniformity
- **R&D of low cost and large-area SiPMs (localized)** -> reduce the GSHCAL cost

4.2 SiPM vs. PMT Readout for GS



GS	SiPM_LO (ph/MeV)	PMT_LO (ph/MeV)	CE（%）
5*5*5	1029	911	113
20*20*10	193	673	28.7
40*40*10	180	513	35

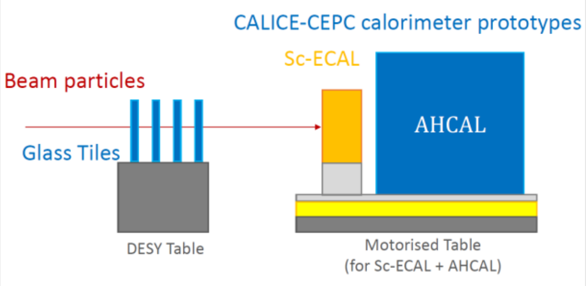
BGO	SiPM_LO (ph/MeV)	PMT_LO (ph/MeV)	CE（%）
5*5*5	6500	5976	109
10*10*10	2259	6233	43.2
20*20*10	2803	6495	36.2
30*30*10	1210	6114	19.8
40*40*10	953	5023	19.0

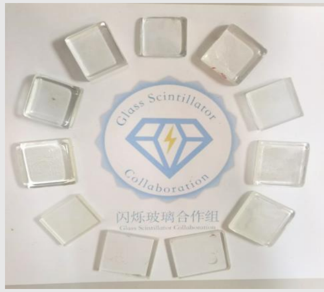
- GS and BGO samples of different sizes were coupled with the SiPM and PMT to study the CE (SiPM_LO/PMT_LO) ;
- The CE for the GS tends to increase with cell size, which is inconsistent with the trend for the BGO ;
- More GS samples of different sizes are needed to test to understand the result;

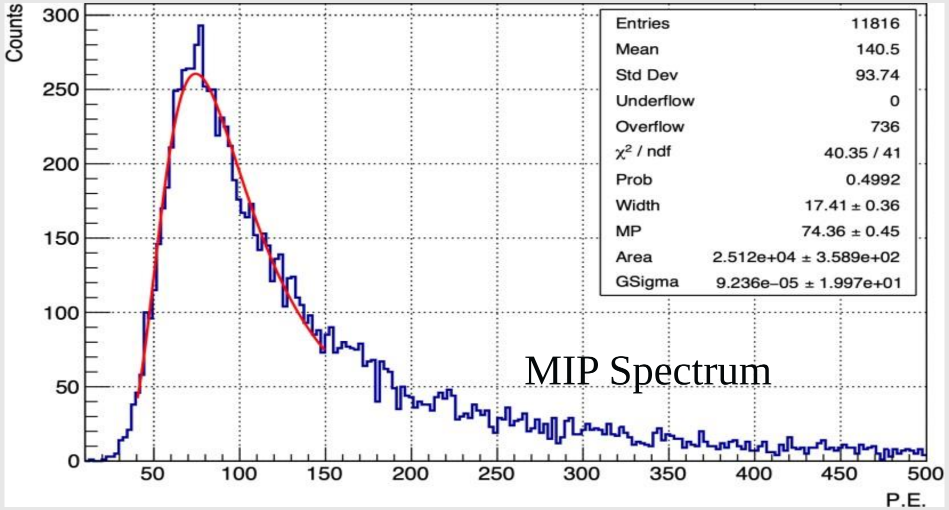
4.3 Beam Test of GS Samples

CERN Muon-beam (10 GeV muon)

- 11 glass tiles tested at CERN PS (2023, May 16)



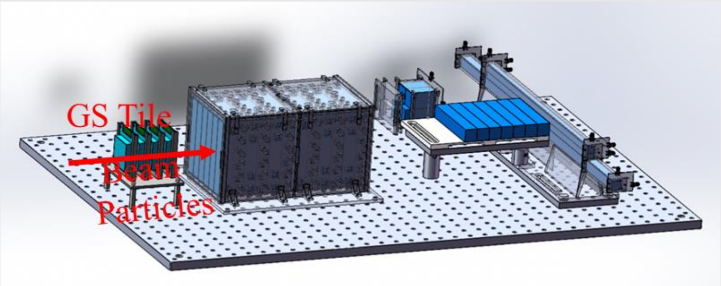


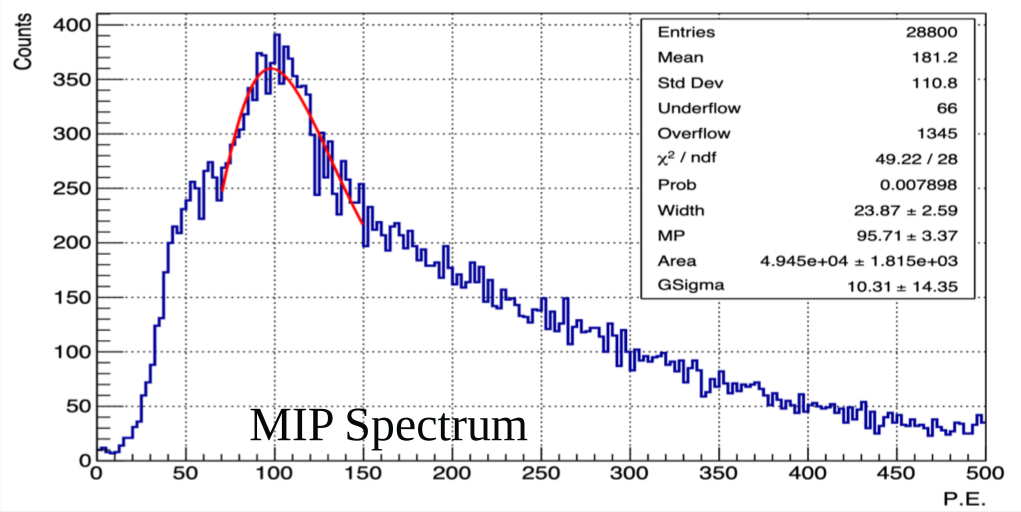


- ➢ Preliminary results look promising:
- ➢ **Typical MIP response is 60 – 100 p.e./MIP**

DESY Electron-beam (5 GeV electron)

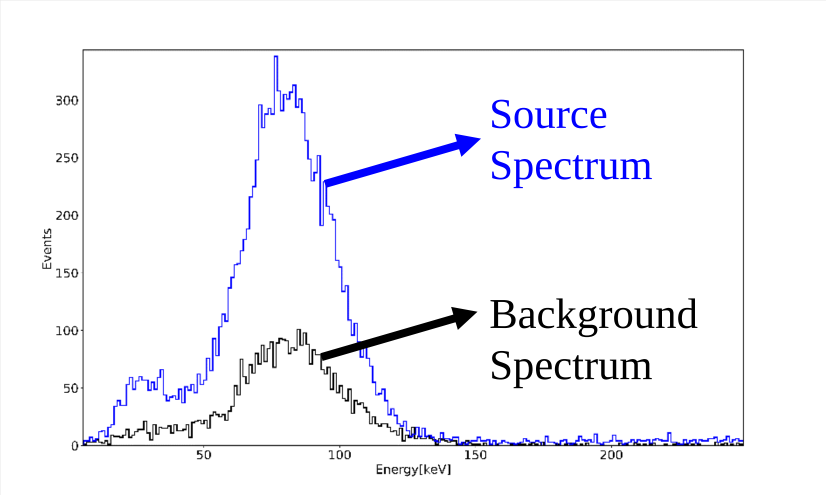
- 9 glass tiles tested at DESY II Electron Synchrotron (2023, Oct 2)





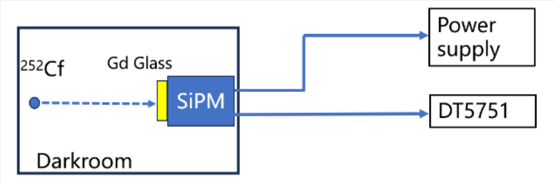
- ➢ **Typical MIP response is 80 – 90 p.e./MIP,**
- ➢ **The average ratio between the LY and MIP is ~ 7.4**

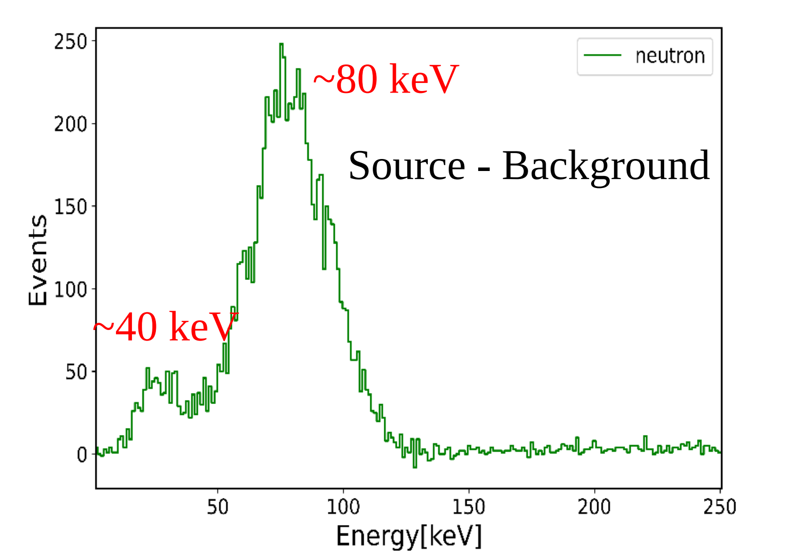
4.4 Neutron Detection by GS



$$n + {}^{155}Gd \rightarrow {}^{156}Gd^{*} \rightarrow {}^{156}Gd + \gamma(8.5MeV) + e^{-}_{IC}(0.039-0.19MeV) + X$$

$$n + {}^{157}Gd \rightarrow {}^{158}Gd^{*} \rightarrow {}^{158}Gd + \gamma(7.9MeV) + e^{-}_{IC}(0.029-0.20MeV) + X$$





- The neutron response of the Gd-doped glass sample was study by using Cf^{252} neutron source;
- The source and background spectra were measured and **clear neutron signal can be detected;**
- The peak of ~40 keV is due to the Kalpha line of Gd, and the peak of ~80 keV is due to the deexcitation of Gd^{156} and Gd^{158} ;
- **This Type of GS could detect the neutron with the Gd.**

Outline

- 1. The Status of the HCAL for CEPC;
- 2. PFA performance of the GSHCAL;
- 3. The Progress of the GS Production;
- 4. The Tests of GS Samples
- **5. Summary and Next Plan**

5.1 Summary of GSHCAL Simulation and Design;

- Overall 4th conceptual detector design has not been implemented in the software framework yet, we first study the PFA performance of the GSHCAL in the baseline design by replacing the AHCAL with the GSHCAL, and the impact of some key GSHCAL parameters on BMR was obtained.
- The GSHCAL of **nominal setup** is a cost-effective design with a **BMR of ~3.6% (**~5% improvement w.r.t the AHCAL), which is a very promising alternative design.
- Overall PFA performance of the 4th conceptual detector design and the design implementation in the software framework is ongoing; Fine tuning of the PFA parameters for this design is also needed.
- The study of digitization process considering more parameters (transmittance, decay time and non-uniformity etc.) is also ongoing and should be validated on test data.
- Study of the overall PFA performance combining the GS-HCAL & GS-ECAL will be considered in next step.

5.2 Summary of GS Production and Test

- Two batches of large-size glass samples have been studied with the beam test; the **MIP light output** of the two batches can **reach above 60 p.e./MIP and 80 p.e./MIP**, respectively

- The R&D of large-size glass tiles featuring **high density, high light yield and short decay time** is the main focus of next stage for the Glass Scintillator R&D collaboration

- More detailed studies like **SiPM performances**, coupling designs with the glass cell and the photon collection efficiency will be done to give advice for glass tile design

- The mechanical and **modular design** of the GSHCAL will be studied later

Welcome colleagues who are interested in our work to discussed with us and join us

Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS

The Scintillator data

Typy	Composition	Density (g/cm^3)	Light yield (ph/MeV)	Decay time (ns)	Emission peak(nm)	Price/1 c.c (RMB)
Glass Scintillator in Paper	Ce-doped high Gadolinium glass[1]	4.37	3460	522	431	~10
	Ce-doped fluoride hafnium glass[2]	6.0	2400	23.4	348	**150**
Plastic Scintillator	BC408[3]	~1.0	5120	2.1	425	60
	BC418[3]	~1.0	5360	1.4	391	80
Crystal	GAGG:Ce[4]	6.6	50000	50	560	2400
	LYSO:Ce[5]	7.1	30000	40	420	1200
	BGO[6]	7.3	8000	300	480	**800**
Glass Scintillator for CEPC (preliminaryl target)	**?**	**>7**	**>1000**	**< 100**	**350-500**	**~1**
Stuaus of Glass Scintillator	?	**>6**	**>1000**	< 200	350-500	**~?**

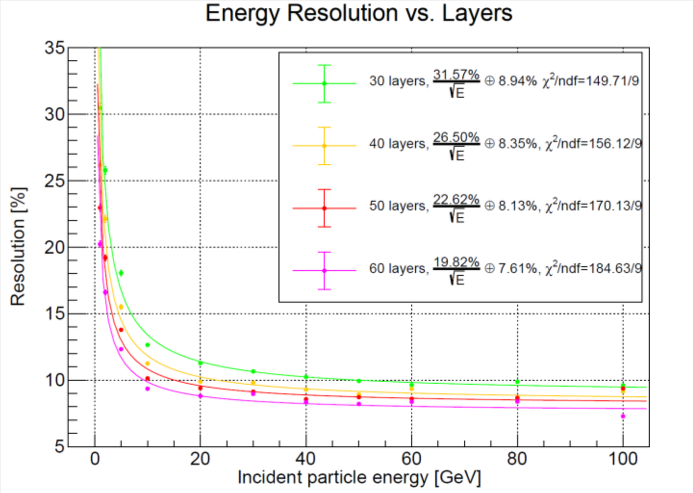
[1] Struebing, C . Journal of the American Ceramic Society, 101(3). [2] Zou, W. Journal of Non-Crystalline Solids, 184(1), 84-92 . [3] Plastic Scintillators | Saint-Gobain Crystals. [4] Zhu, Y. Qian, S. Optical Materials, 105, 109964. [5] Ioannis, G. Nuclear Instruments & Methods in Physics Research. [6]Akapong Phunpueok, et al. Applied Mechanics and Materials, 2020,901:89-94.

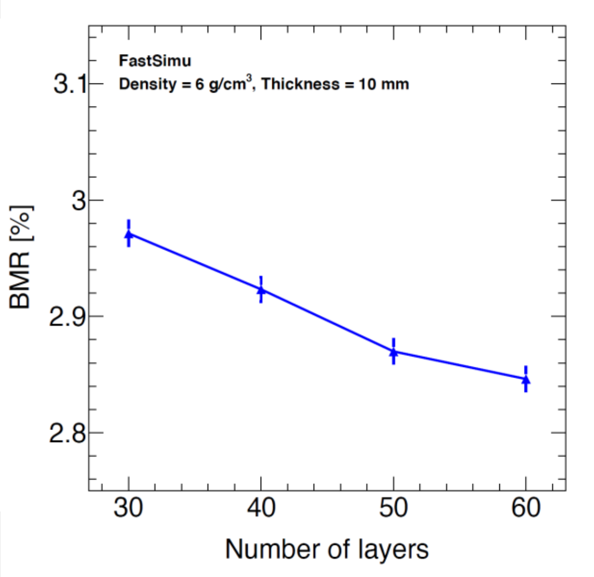
Impact of Number of Layers

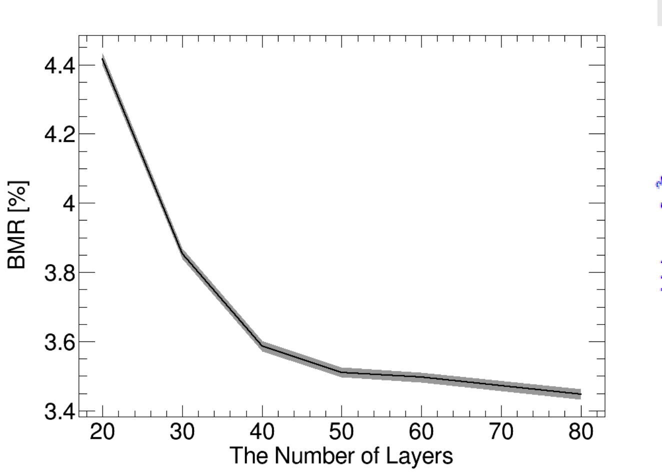
Glass Cell Size	$40\times40\times10\,mm^3$
NIL of Sampling Layer	$0.125\,\lambda$
Glass Density	6 g/cm^3
Readout Threshold	0.1 MIP

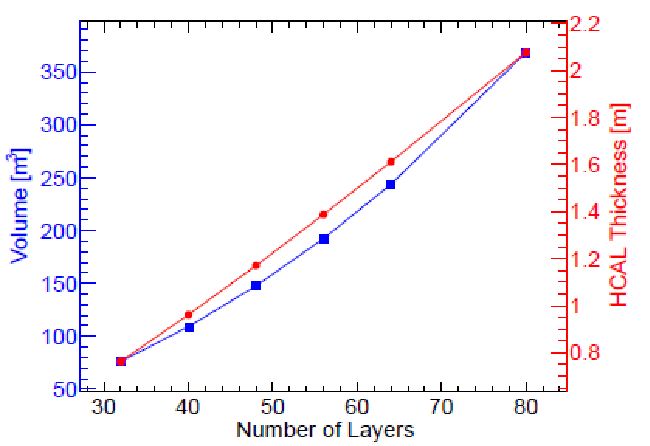
- The number of layers will only have an impact on the total nuclear interaction length (NIL), more sampling layers can increase the total NIL and suppress the energy leakage, which improve the hadronic energy resolution and the BMR.

- However, the volume of the GSHCAL itself and the outer solenoid and yoke, will increase significantly with the number of layers, which also means a higher cost. Therefore, a reasonable number of layers should be selected to balance the impact of energy leakage on the BMR and the cost.





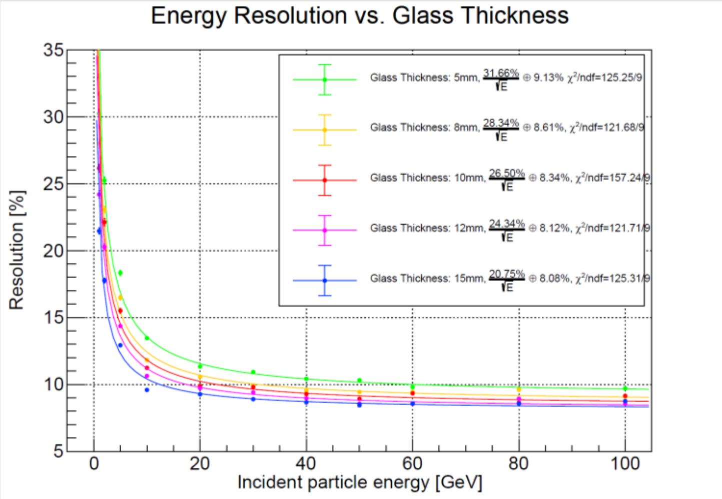


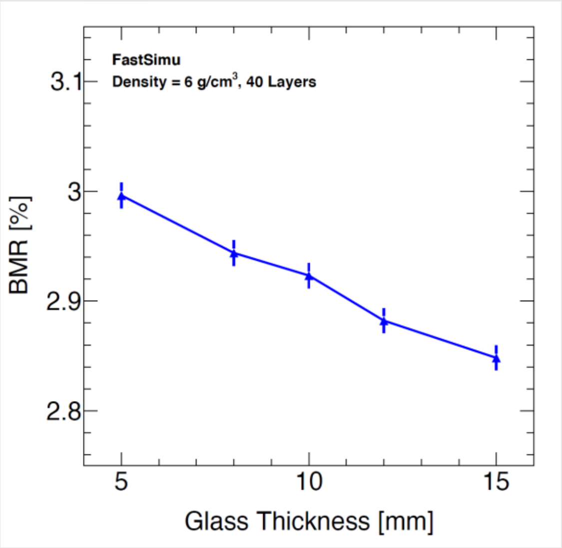


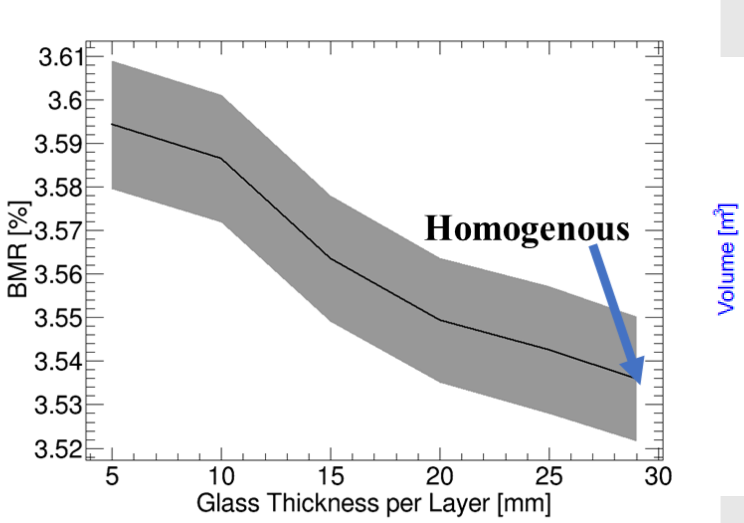
Impact of Glass Thickness

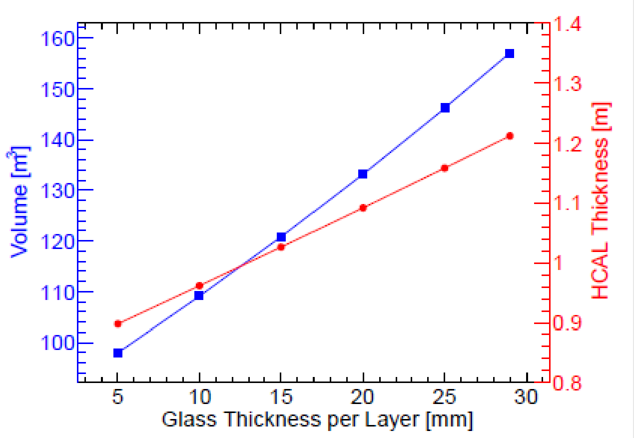
Total Number of Layers	**40**
Transverse Cell Size	**$40\times40\,\mathrm{mm}^2$**
Total NIL	**$5\,\lambda$**
Glass Density	**6 g/cm^3**
Readout Threshold	**0.1 MIP**

- A thicker glass cell is conducive to a higher sampling fraction, which can improve the hadronic energy resolution and the BMR.
- However, the increase of glass thickness will lead to a thicker GSHCAL (significantly increasing the cost) and poor optical performance
- Hence, a reasonable glass thickness is necessary to balance the impact of sampling fraction and optical performance on the BMR, as well as the cost.







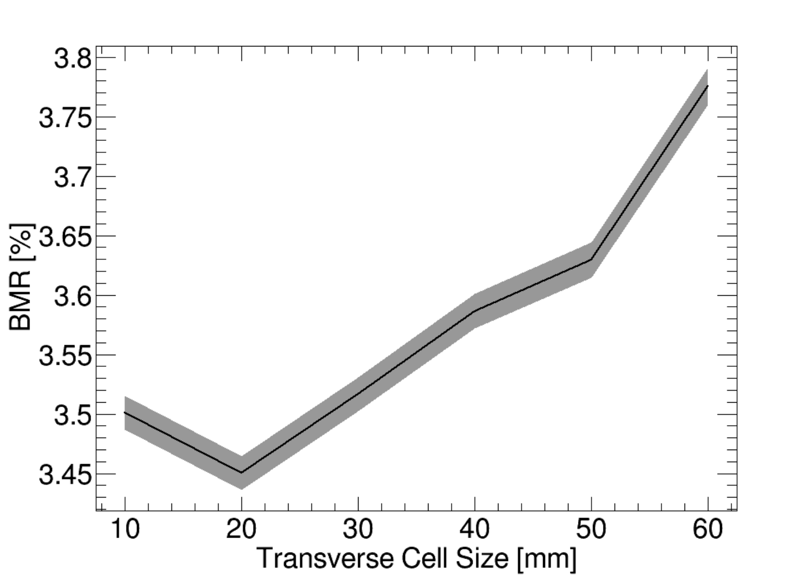


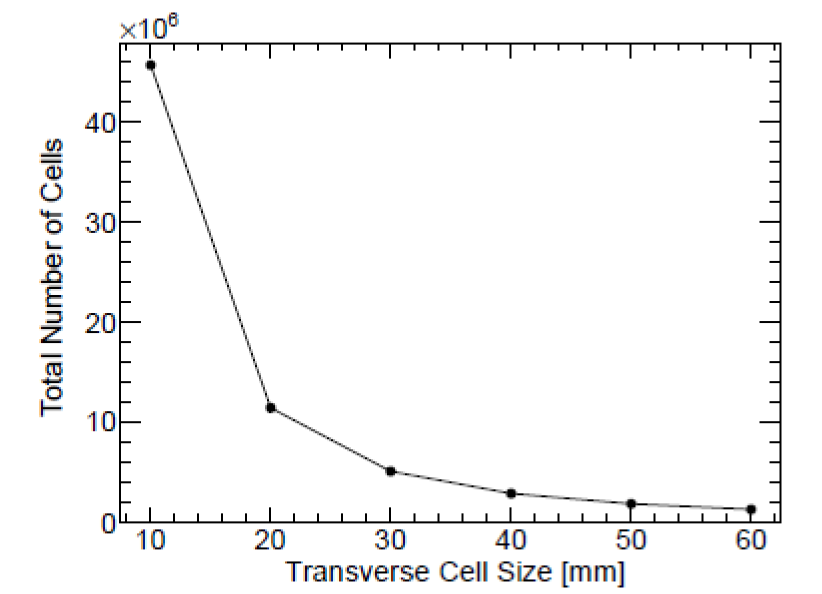
Impact of Transverse Size

Total Number of Layers	40
Glass Thickness	10 mm
Total NIL	5 λ
Glass Density	6 g/cm^3
Readout Threshold	0.1 MIP

- Both the high granularity and the excellent energy resolution are the key factors to achieve a good PFA performance and the BMR; A smaller transverse cell size will improve the efficiency to separate close-by showers and is beneficial for a better BMR.

- But the number of readout channels will also increase dramatically, thus a reasonable transverse cell size is necessary to balance the impact of transverse granularity on the BMR and the cost of the readout channel





Impact of Glass Density

Total Number of Layers	40
Glass Cell Size	40×40×10 mm^3
Total NIL	5 λ
Readout Threshold	0.1 MIP

- The glass density is an very important factor to achieve a good BMR and compact detector design ; the glass thickness will decrease with increasing glass density, thus the GSHCAL will be significantly more compact and significantly reduce the cost. Meanwhile, a more compact GSHCAL can reduce the impact of the confusion term and improve the BMR.

- Nevertheless, the increase of the glass density can degrade the scintillation performance, which will worsen the BMR. Therefore, a reasonable glass density should be selected to balance the BMR and the cost.