The R&D Progress of the GSHCAL

闪烁玻璃合作组
Glass Scintillator Collaboration

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The Institute of High Energy Physics, CAS

2024. Apr. 8th-11th, **The 2024 CEPC Workshop EU Edition (Marseille)**

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

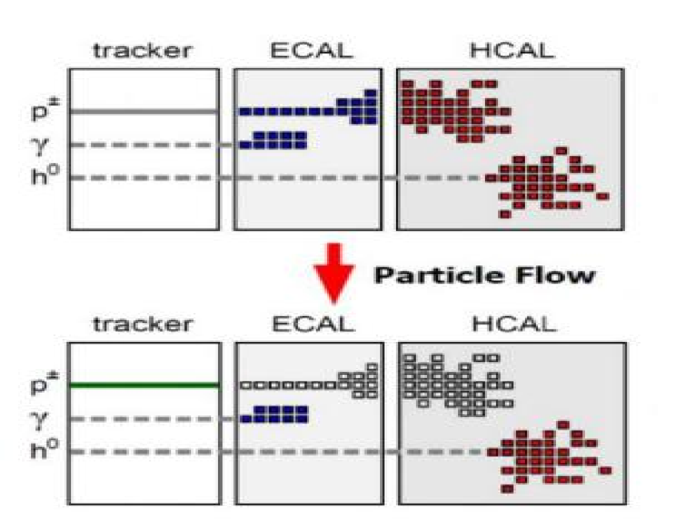
Baseline Design
***(For CDR)**

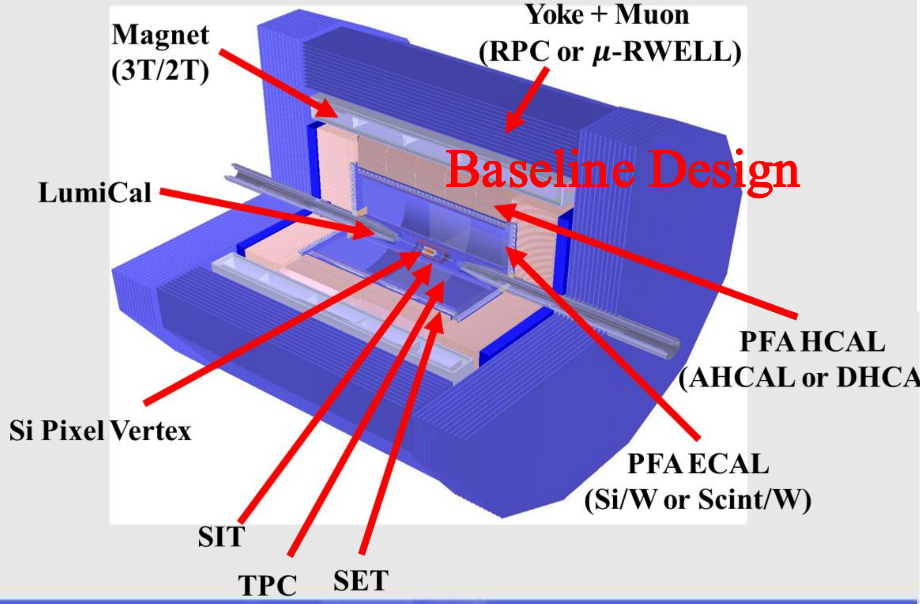
Evolution

The 4th Conceptual Design

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

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

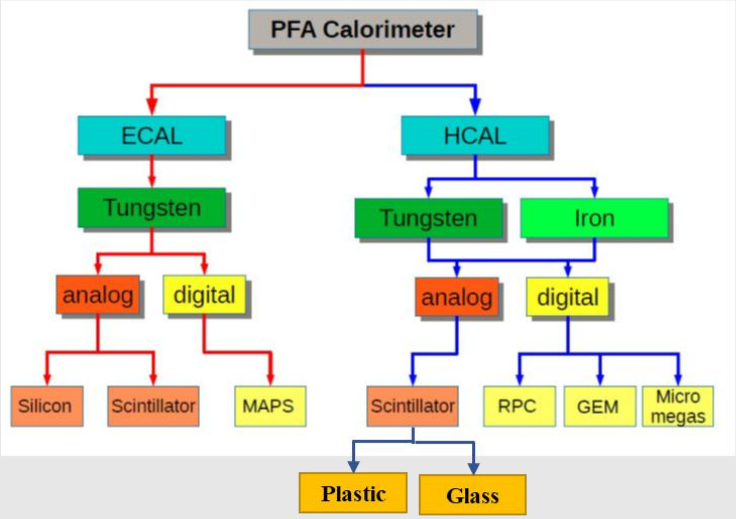


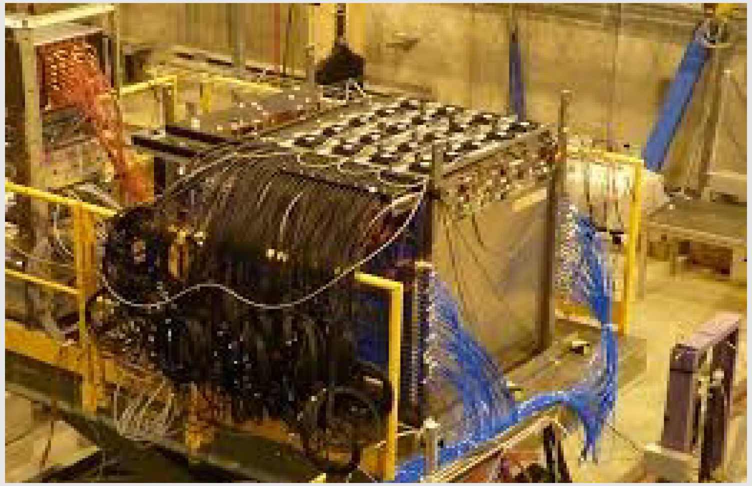


*CEPC Conceptual Design Report doi:10.48550/arXiv.1811.10545

HCAL Design Options

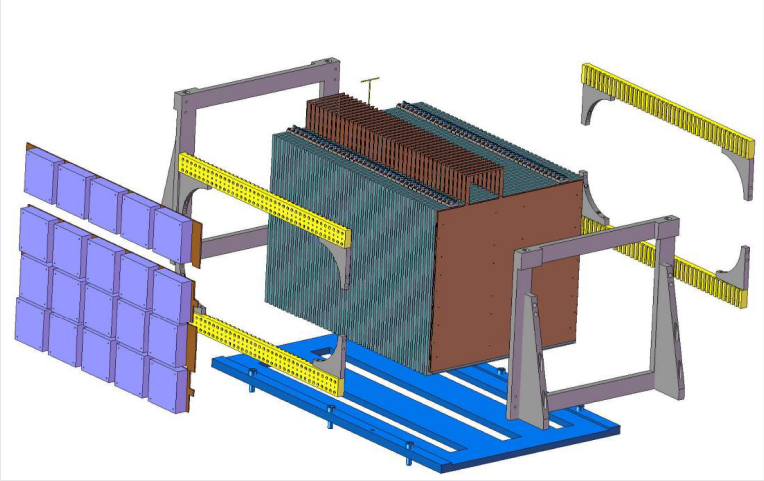
- Several HCAL design options have been proposed
  - Based on **Gaseous Detector**
    - e.g. CALICE SDHCAL doi:10.1088/1748-0221/11/04/P04001
  - Based on **Liquid Argon**
    - e.g. ATLAS LAr Endcap HCAL doi:10.1016/j.nuclphysbps.2011.03.150
  - AHCAL: **Plastic Scintillator** & SiPM readout
    - e.g. CEPC AHCAL doi:10.1088/1748-0221/17/11/P11034





➢ CALICE SDHCAL Prototype

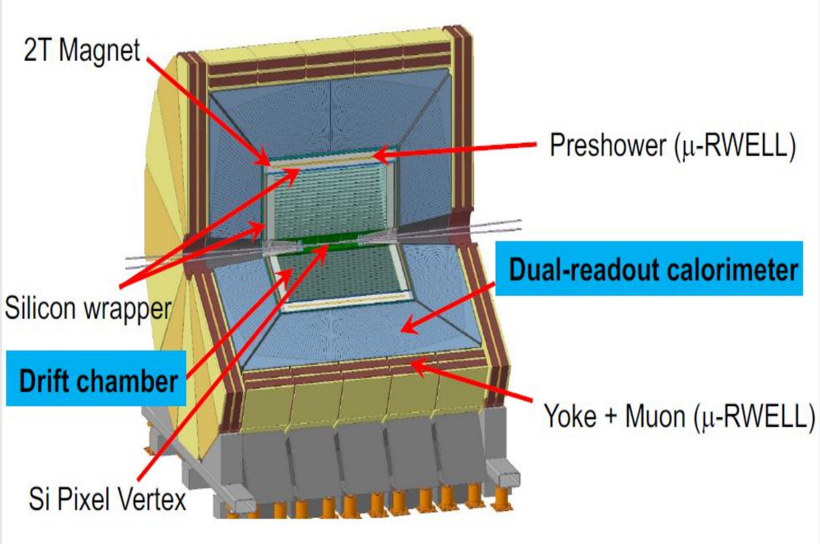
➢ ATLAS LAr Endcap HCAL



➢ CEPC AHCAL Prototype

CEPC Conceptual Detector Design

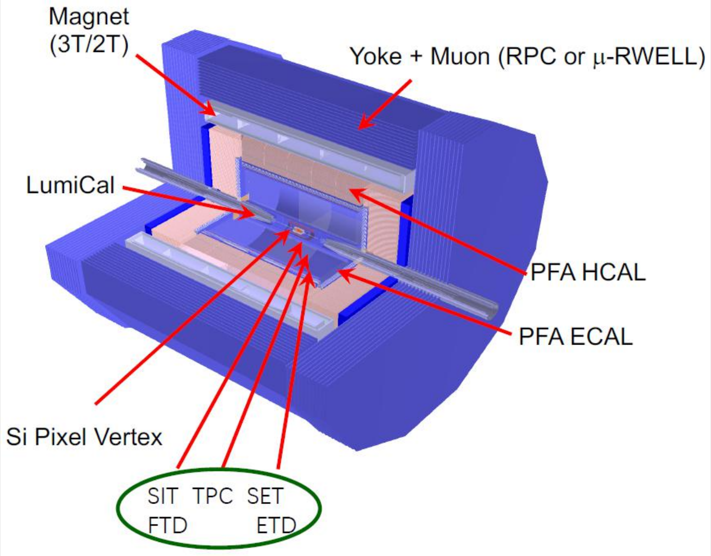
1st IDEA Concept
(also proposed for FCC-ee)



- **Dual-readout calorimeter (Cerenkov-Fiber & Scint-Fiber)**

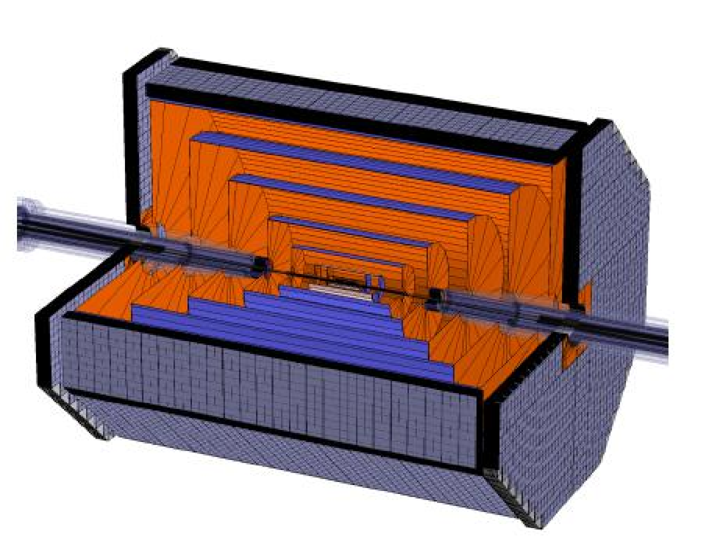
both for EM and Hadronic Shower

2nd CDR Baseline Design
(Particle Flow Approach)



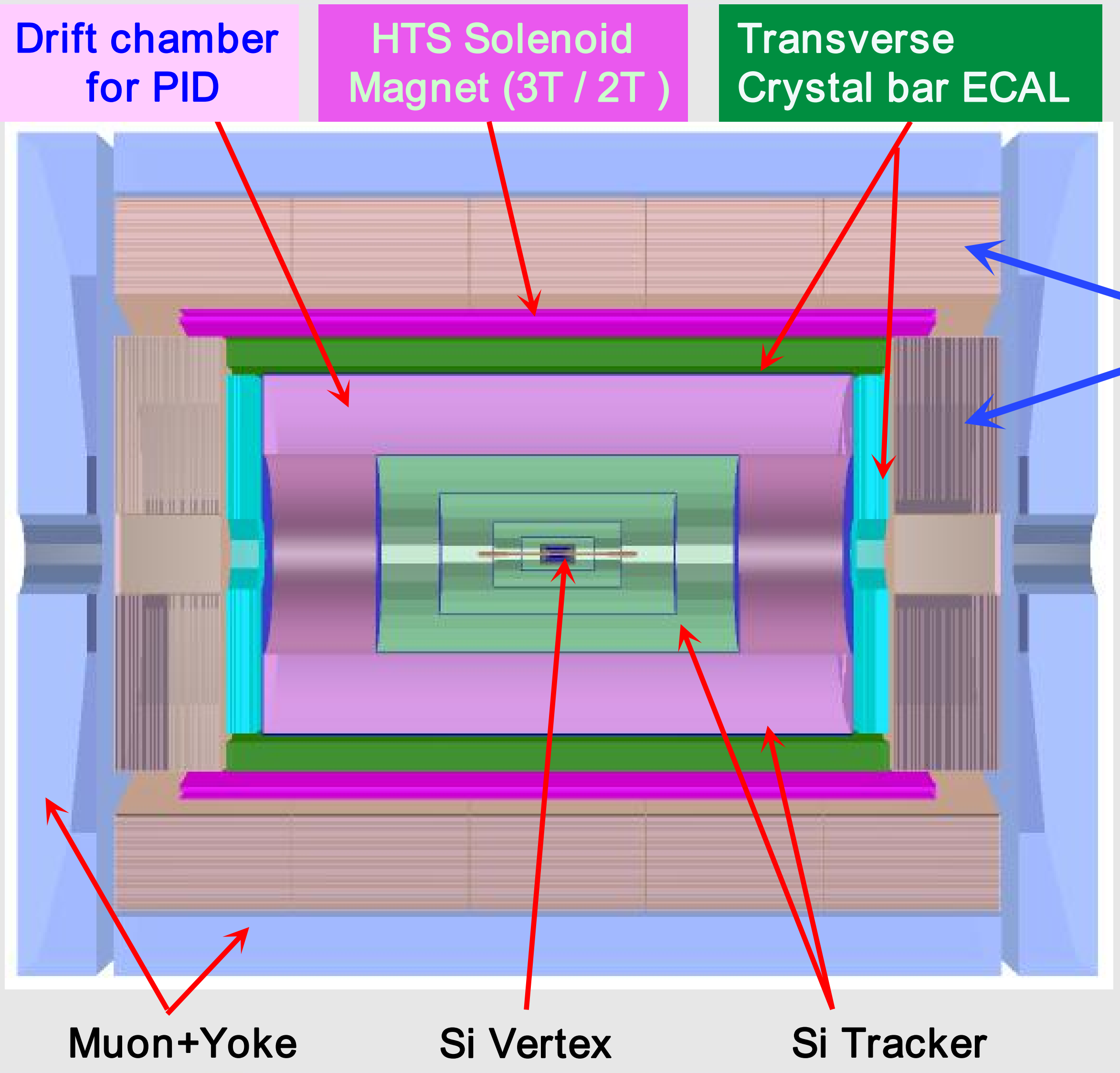
- **AHCAL (PS/Steel) or SDHCAL (Gas/Steel)**
- Si/W ECAL or PS/W ECAL

3rd FST concept
(Full Silicon Tracker)



- **AHCAL (PS/Steel) or SDHCAL (Gas/Steel)**
- Si/W ECAL or PS/W ECAL

The 4th Conceptual Detector Design



- Further performance goal: BMR 3.8% -> 3%
- Dominant factors on **BMR**: charged hadron fragments & **HCAL resolution**

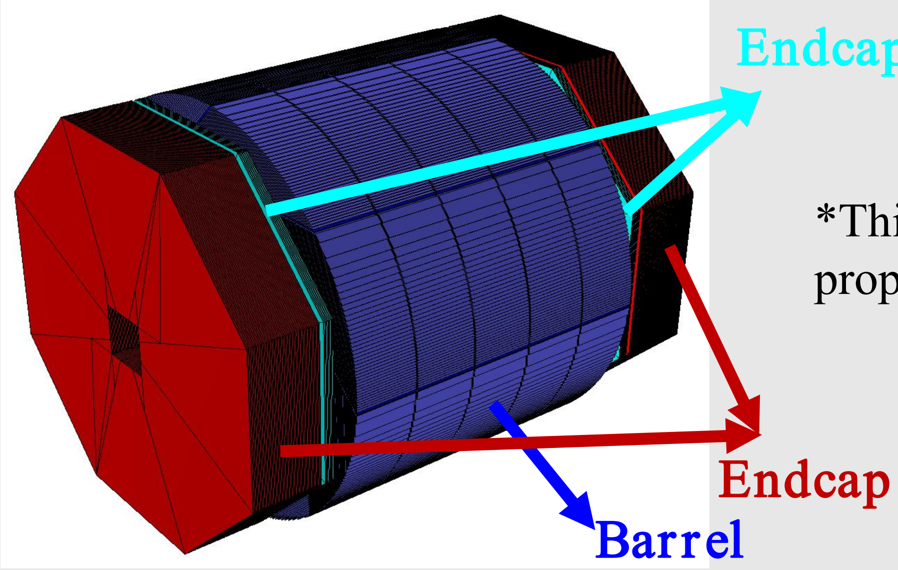
Glass Scintillator HCAL (GSHCAL)

- Glass Scintillator:
  - low cost
  - high density -> better ER/BMR & more compact
  - moderate light yield
  - short decay time
  - long absorption length
- Readout with SiPMs:
  - low cost & compact structure
  - immune to magnetic field
- To do: Simulation & offline calibration

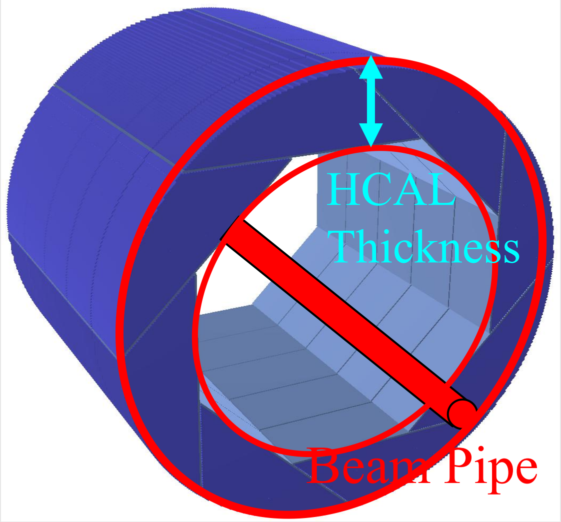
Outline

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

1.1 GSHCAL Overall Structure (2023 CDR)

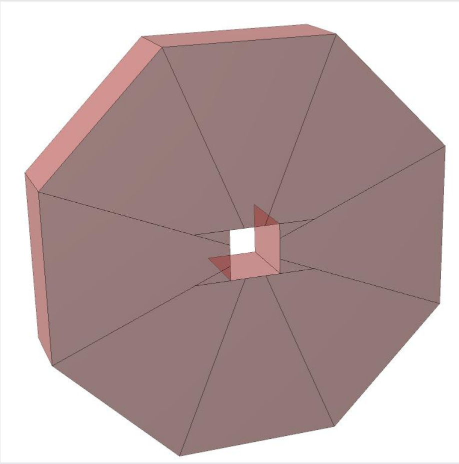


*This structure was also proposed for DHCAL

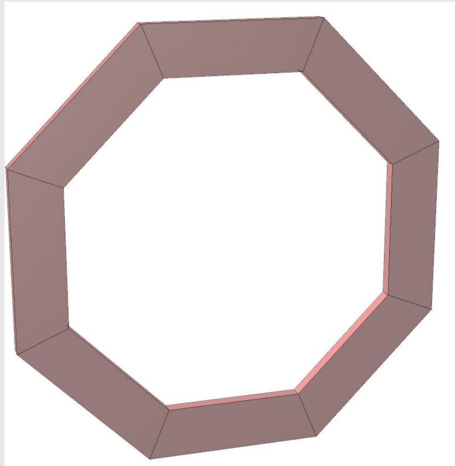


Barrel

Endcap

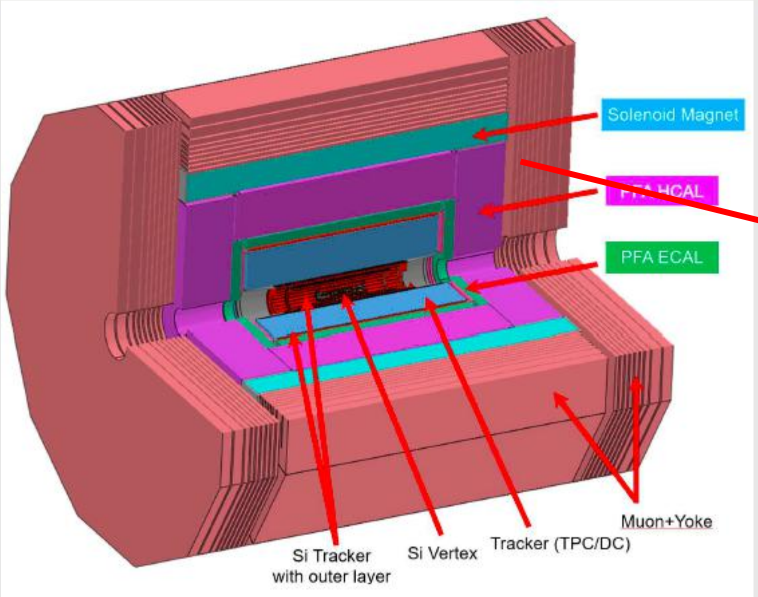


EndcapRing

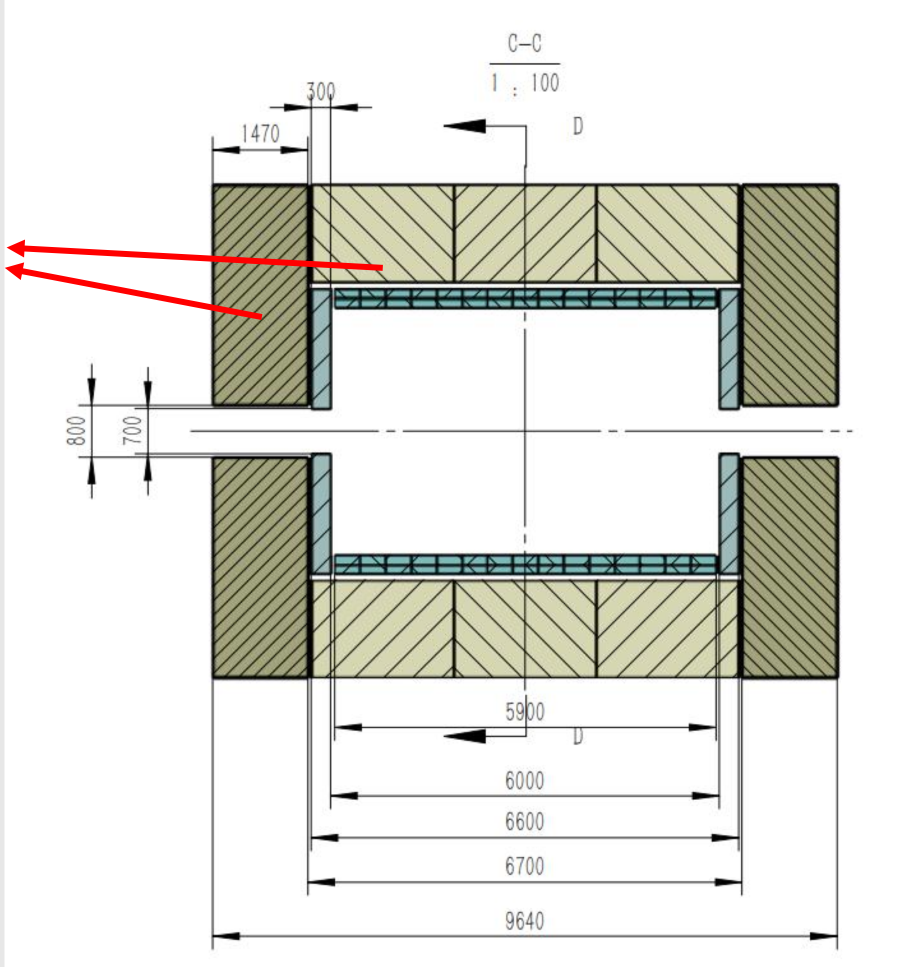


- The overall structure of the GSHCAL consists of three parts: the Barrel (8,Octagon), Endcap and EndCapRing
  - Thickness of the Barrel: ~1 m
  - Outer radius of the Barrel: ~3 m
  - Length along beam direction: ~7 m
  - **Number of Layers: ~40**
  - **GS/Steel Volume: ~46/64 m^3**
  - **Number of SiPM readout Channels: ~$3x10^6$**

1.2 GSHCAL Overall Structure (2024 pre-TDR)



GSHCAL



- The overall structure of the GSHCAL consists of two parts: the Barrel (16, Hexagon), Endcap
  - Thickness of the Barrel: 1470 mm
  - Inner radius of the Barrel: 2250 mm
  - Length along beam direction: 6700 mm
  - **Number of Layers: 48**
  - **GS/Steel Volume: ~104/143 m^3** （double size）
  - **Number of SiPM readout Channels: ~6.4x10^6** （double size）

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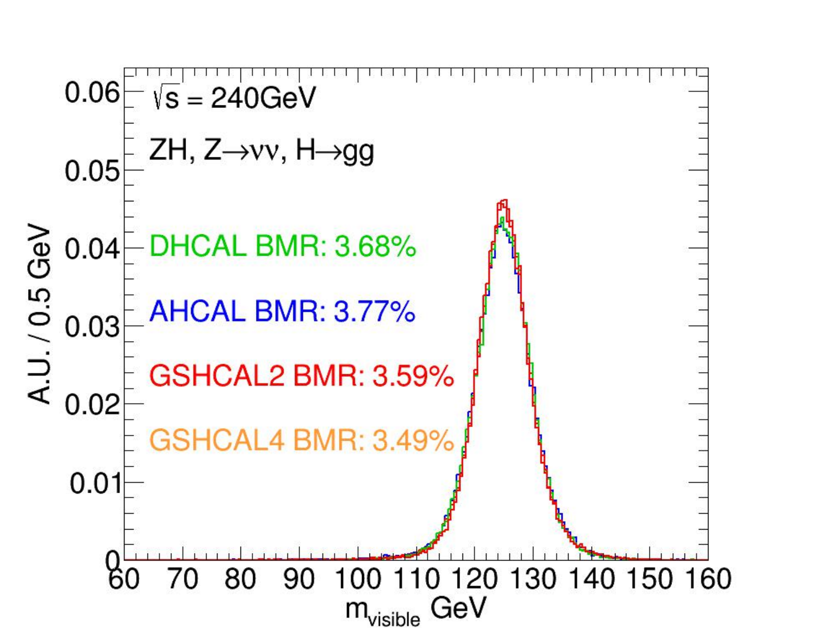
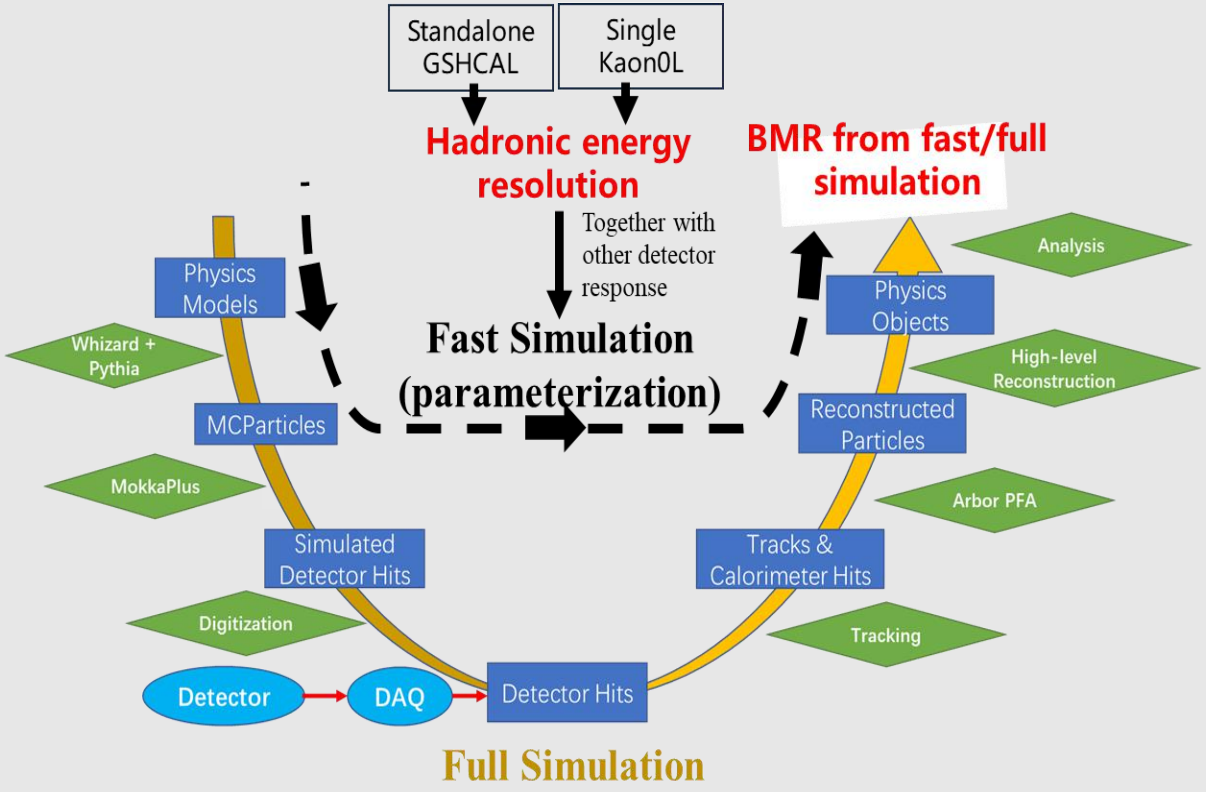
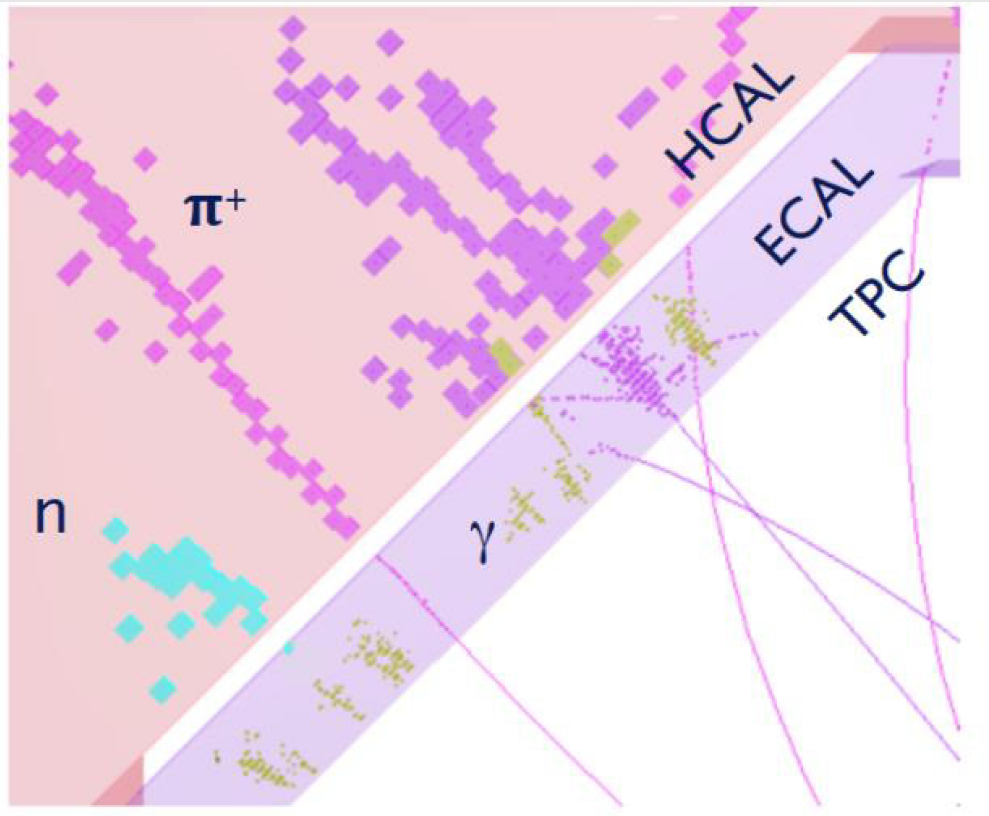


2.1 Simulation Studies of GSHCAL Performance

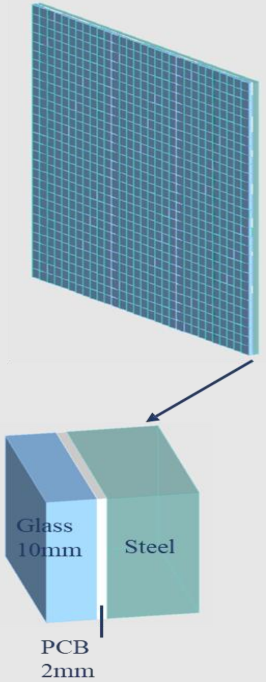
- Standalone module simulation -> Hadronic energy resolution -> Input for fast simulation
- Fast/Full simulation -> PFA performance (BMR) based on the GSHCAL
- The focus of this part is the PFA performance (BMR) obtained from the Full simulation

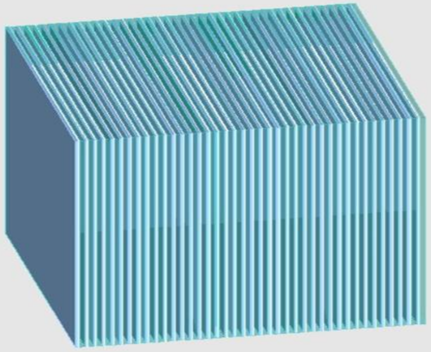




2.2 Full Simulation Setup

- Current full simulation is based on **CDR baseline design**, except for replacing the AHCAL with GS/steel HCAL
- Primaries input: 240 GeV e+e- -> nu_nu H (H -> gg)
- Glass components : Gd-B-Si-Ge-Ce^{3+}





GSHCAL Standalone Module

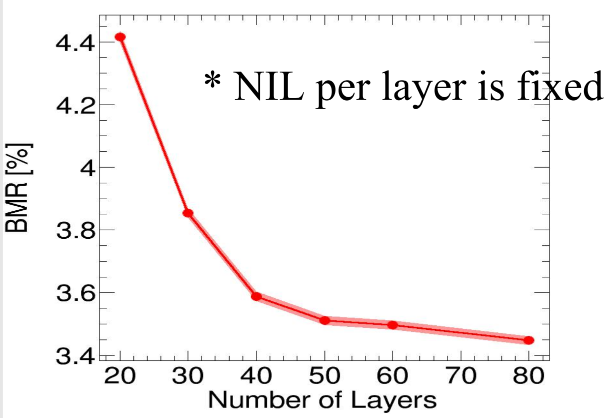
4x4x1 cm^2 GS readout with the SiPM

Nominal setup for the GSHCAL in full simulation:

	GSHCAL Structure (+ECAL option)	No. layer	Cell Size	Nucl. Inter. Length	Glass Density	Readout Threshold
Currently (at CDR)	Octagon GSHCAL (+Si/W ECAL)	40	40x40x10 mm^3	5 lambda	6 g/cm^3	0.1 MIP
To do (at pre-TDR)	Hexadecagon GSHCAL (+BGO Crystal ECAL)	48	40x40x10 mm^3	6 lambda	6 g/cm^3	0.1 MIP

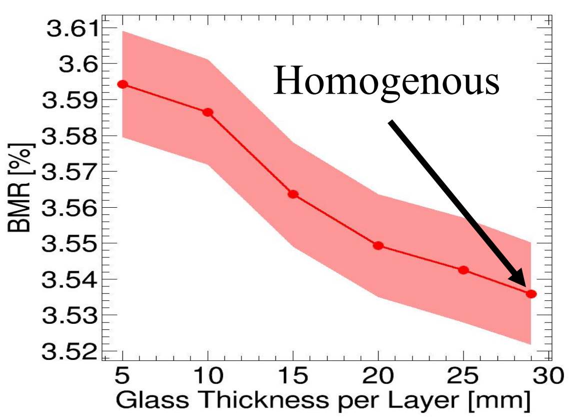
2.3 Impact of Some Key Parameters

Number of Layers



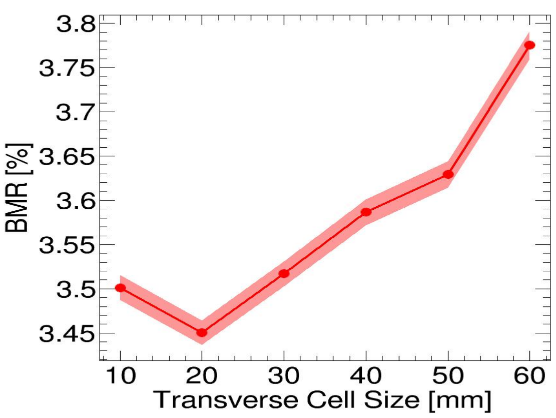
- More layers -> better BMR (pros)
- More layers -> thicker GSHCAL & more readout channels (cons)
- **Reasonable number of layers should be selected to balance the BMR & the cost**

Glass Thickness per Layer



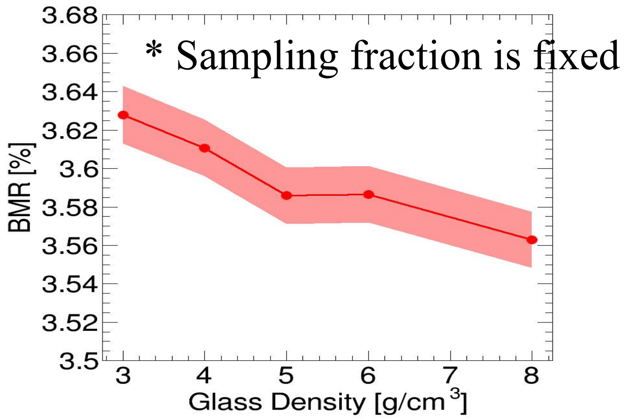
- Thicker glass -> better BMR (pros)
- Thicker glass -> thicker GSHCAL & worse optical performance (cons)
- **Reasonable glass thickness is necessary to balance the BMR & the optical performance & the cost**

Transverse Cell Size



- Smaller transverse cell -> better BMR (pros)
- Smaller transverse cell size -> more number of readout channels (cons)
- **Reasonable transverse cell size is necessary to balance the BMR & the cost of the readout channel**

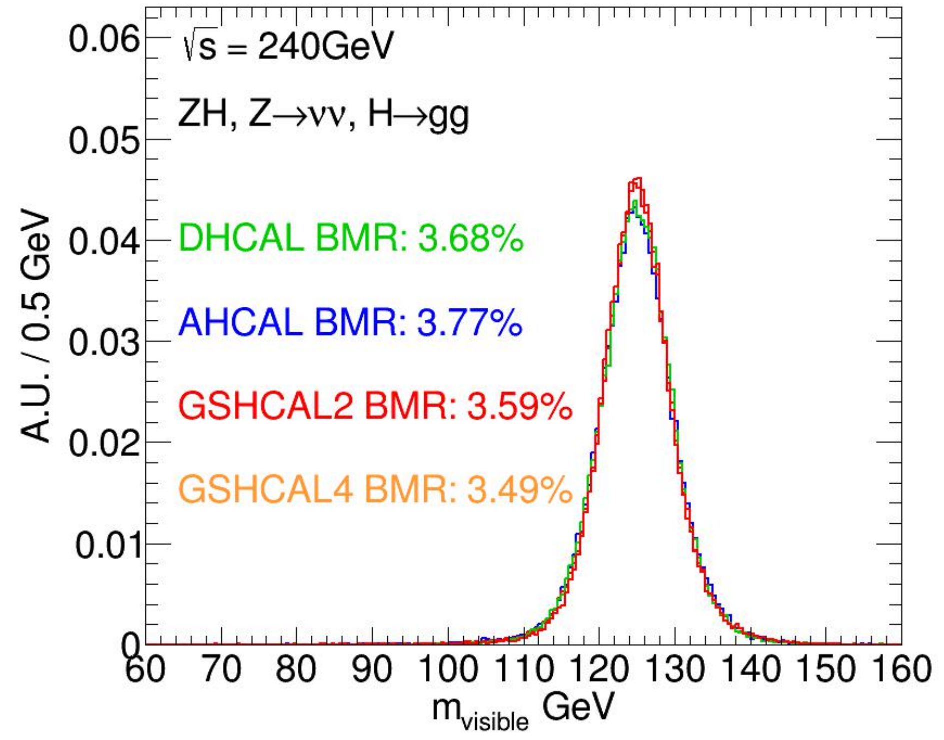
Glass Density



- Higher glass density -> lower cost & better BMR (pros)
- Higher glass density -> scintillation performance (BMR) degradation (cons)
- **Reasonable glass density should be selected to balance the BMR & the cost**

2.4 Different GSHCAL Designs

Status	CDR	CDR	CDR	Pre-TDR
Design Option	DHCAL	AHCAL	GSHCAL	GSHCAL
Material	RPC	PS	GS	GS
BMR	3.68%	3.77%	3.59%	3.49%
No. layers	40	40	40	48
Layer thickness (0.125 lambda)	3mm RPC+ 20mm Steel	3mm PS+ 20mm Steel	10mm GS+ 13.8mm Steel	10mm GS+ 13.8mm Steel
Inter. Length	4.8 lambda	5 lambda	5 lambda	6 lambda
Trans. Cell Size	10x10 mm^2	40x40 mm^2	40x40 mm^2	40x40 mm^2
Mat. Density	< 10^{-3} g/cm^3	1 g/cm^3	6 g/cm^3	6 g/cm^3
HCAL Thick.	931 mm	931 mm	962 mm	1170 mm
HCAL Volume	14 m^3(RPC) 91 m^3(Steel)	14 m^3(PS) 91 m^3(Steel)	46 m^3(GS) 64 m^3(Steel)	62 m^3(GS) 86 m^3(Steel)
No. Cells	4.5x10^7	2.8x10^6	2.9x10^6	3.9x10^6



- 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

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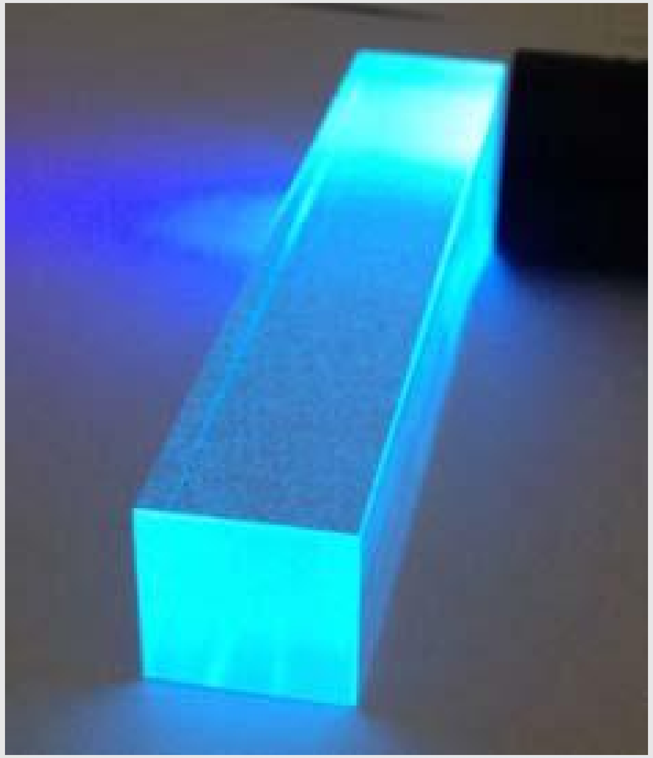
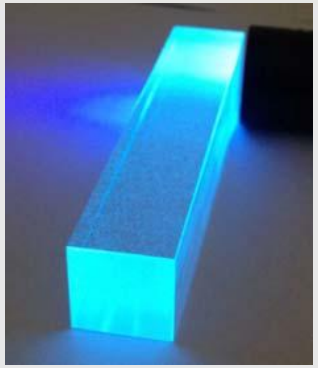


3.0 What is the Glass Scintillator？

Plastic Scintillator



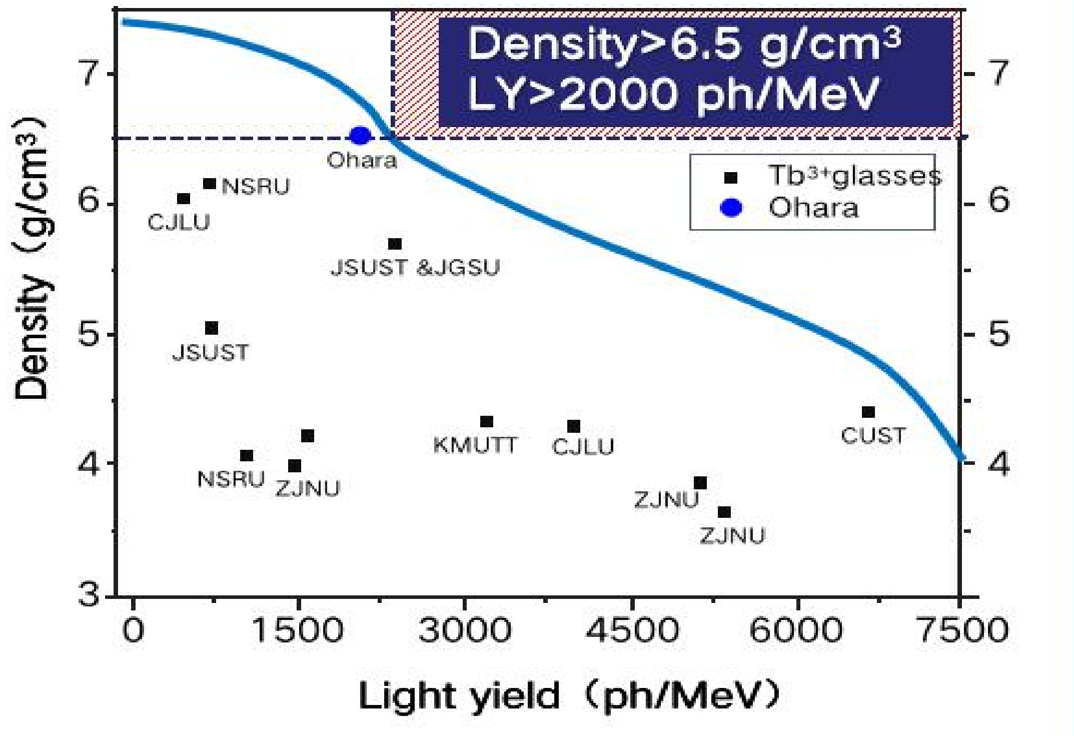
Glass Scintillator

Crystal Scintillator

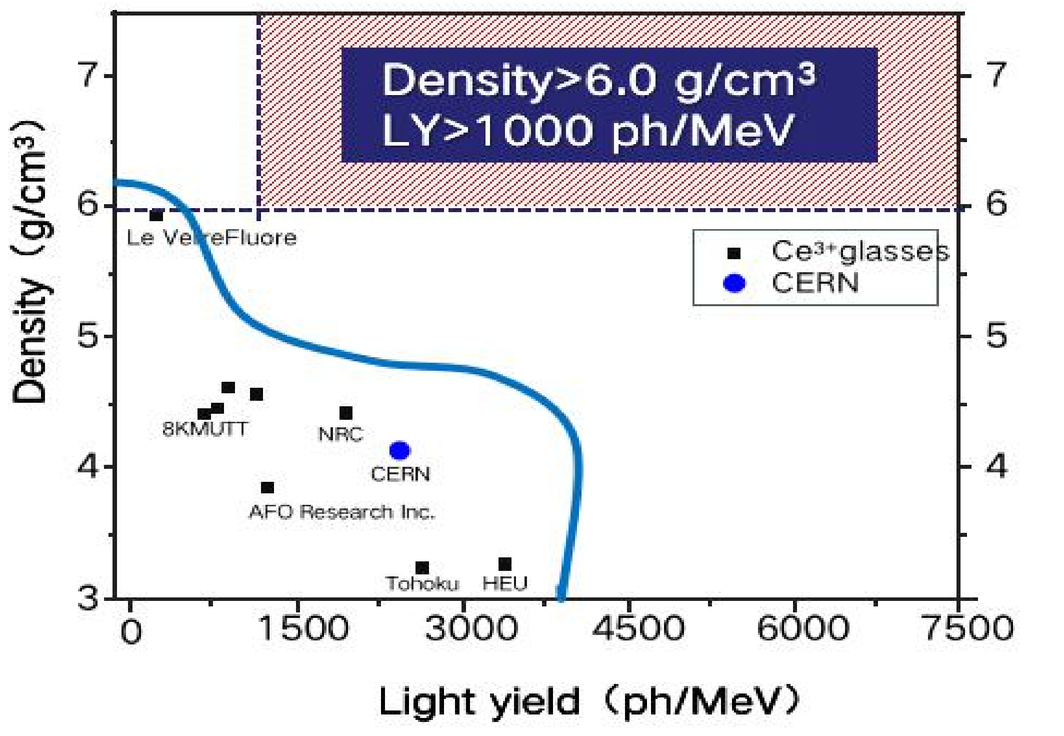
High light yield	★★★	High light yield	★	High light yield	★★★
Fast decay	★★★	Fast decay	★	Fast decay	★★
Low cost	★★★	Low cost	★★★	Low cost	★
Large Density	★	Large Density	★★	Large Density	★★★
Energy resolution	★★	Energy resolution	★	Energy resolution	★★★
Large size	★★★	Large size	★★	Large size	★

3.1 Current Research Status of the GS

- Before 2000, the high-density GS is mainly based on Pb (plumbum) or Bi (bismuth), with poor scintillation light;
- After 2000, GS with rare-earth elements （Tb,Terbium; Ce,**Cerium**） attract more attention for improved LY
- However, **it's a great challenge to realize a high density and high light yield at the same time**

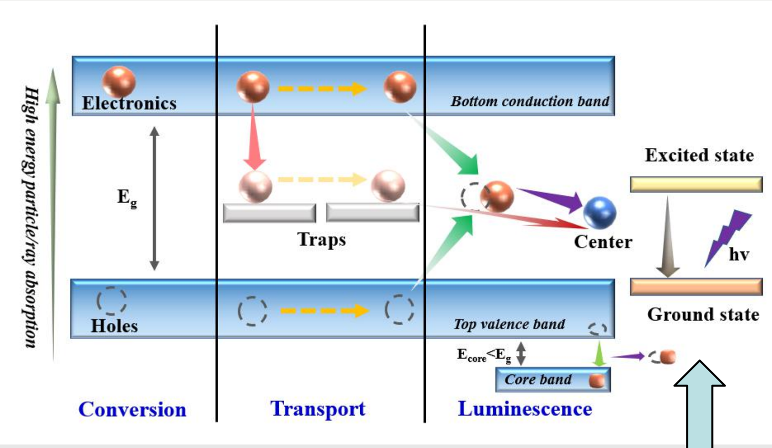


Tb^{3+} doped glass with high light yield



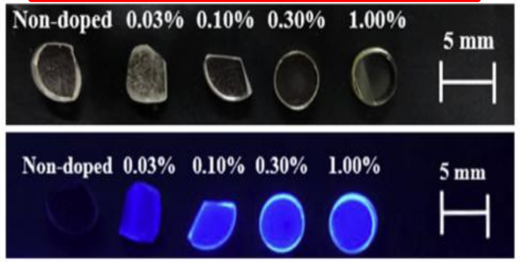
Ce^{3+} doped glass with short decay time

3.2 The Design of the GS



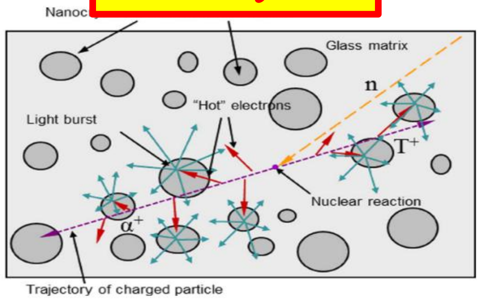
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



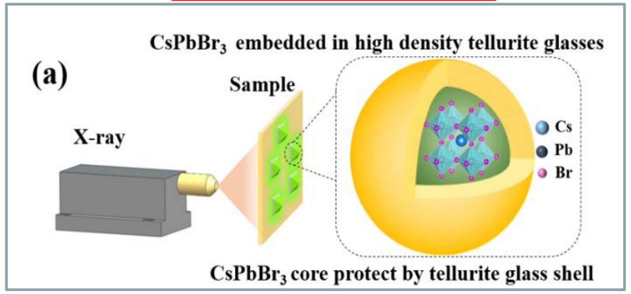
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



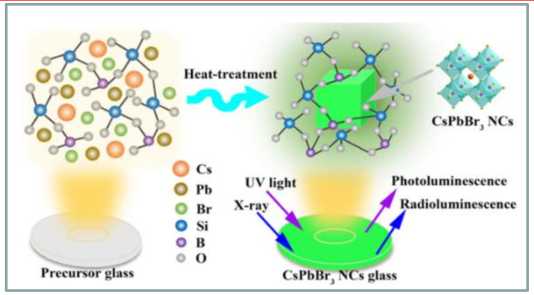
IEEE TNS 60 (2) 2013

Quantum Dots



Optics Letters 46(14) 3448-3451 (2021)

Lanthanide + Quantum Dots



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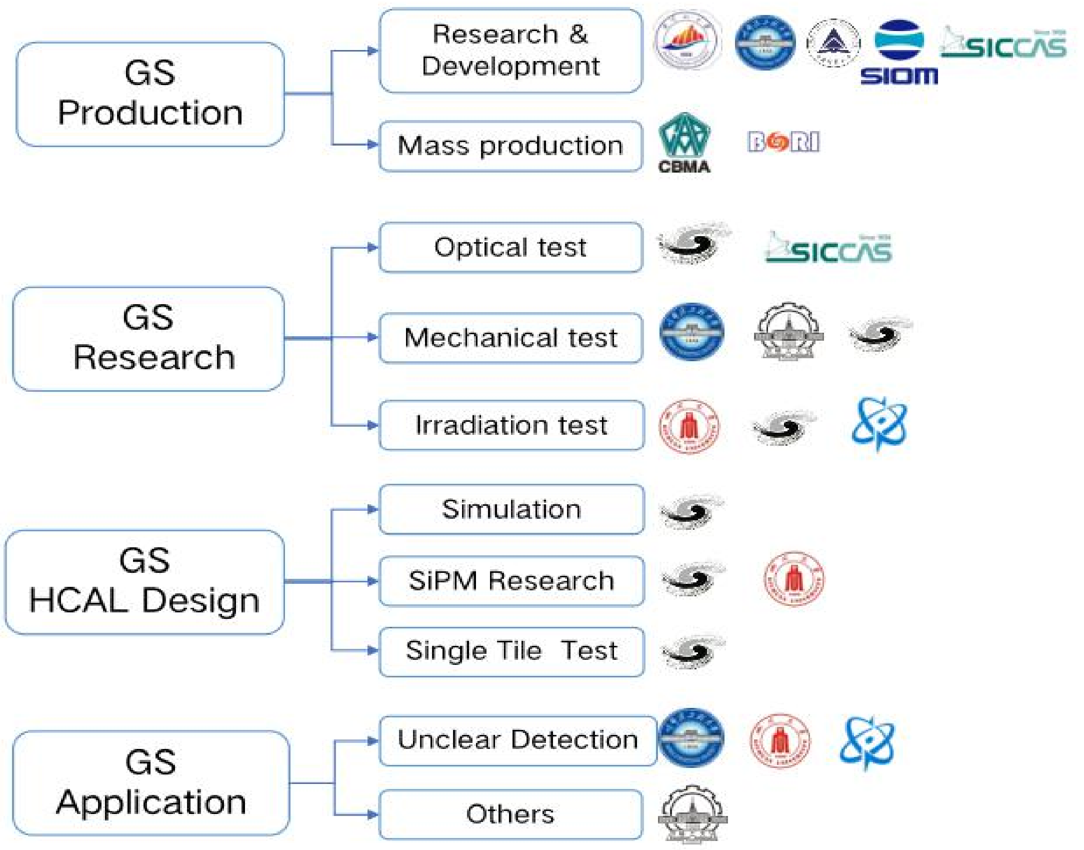
- High Light Yield (> 2000 ph/MeV): Lanthanide for the Luminescence Center: Cerium (Ce);
- High Density (> 6 g/cm³) and Low radioactivity background: Gadolinium (Gd); ~~lutetium (Lu)~~

3.3 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

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 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

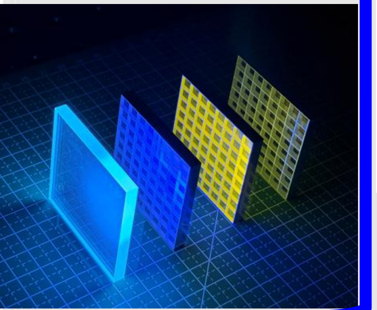
Spokesperson：Sen QIAN

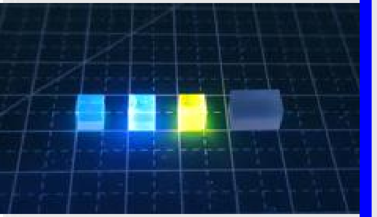
-- The Glass Scintillator Collaboration Group established in Oct.2021；

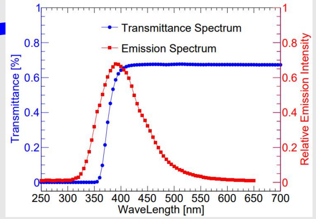
-- There are 3 Institutes of CAS, 5 Universitys, 3 Factorys join us for the R&D of GS;

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

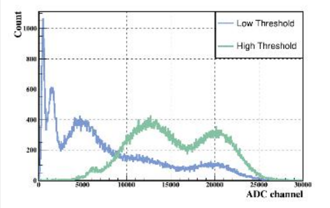
3.4 The Scintillator Test Facilities for GS



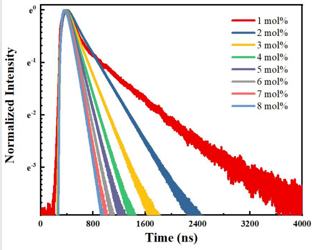




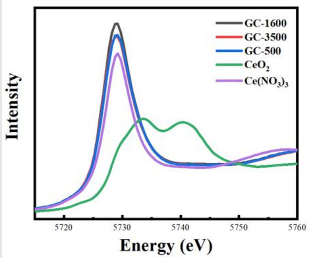
- Transmittance
- Absorbance
- Refractive index
- Emission peak



- Light yield
- Energy resolution
- MIP response
- Neutron discrimination



- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time



- Valence state
- Coordination
- Elemental analysis
- Structural analysis

Others

……

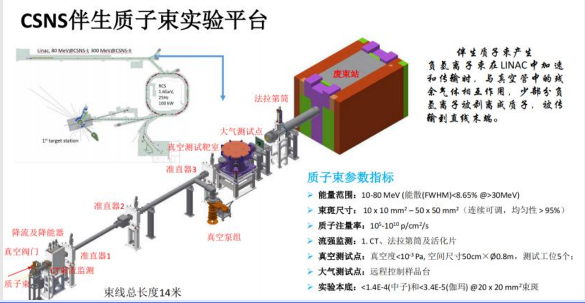
- Faraday effect
- Radiation resistance
- Homogeneity

- IHEP--PMT Lab for Scintillator Test

- IHEP--Radioactive Test

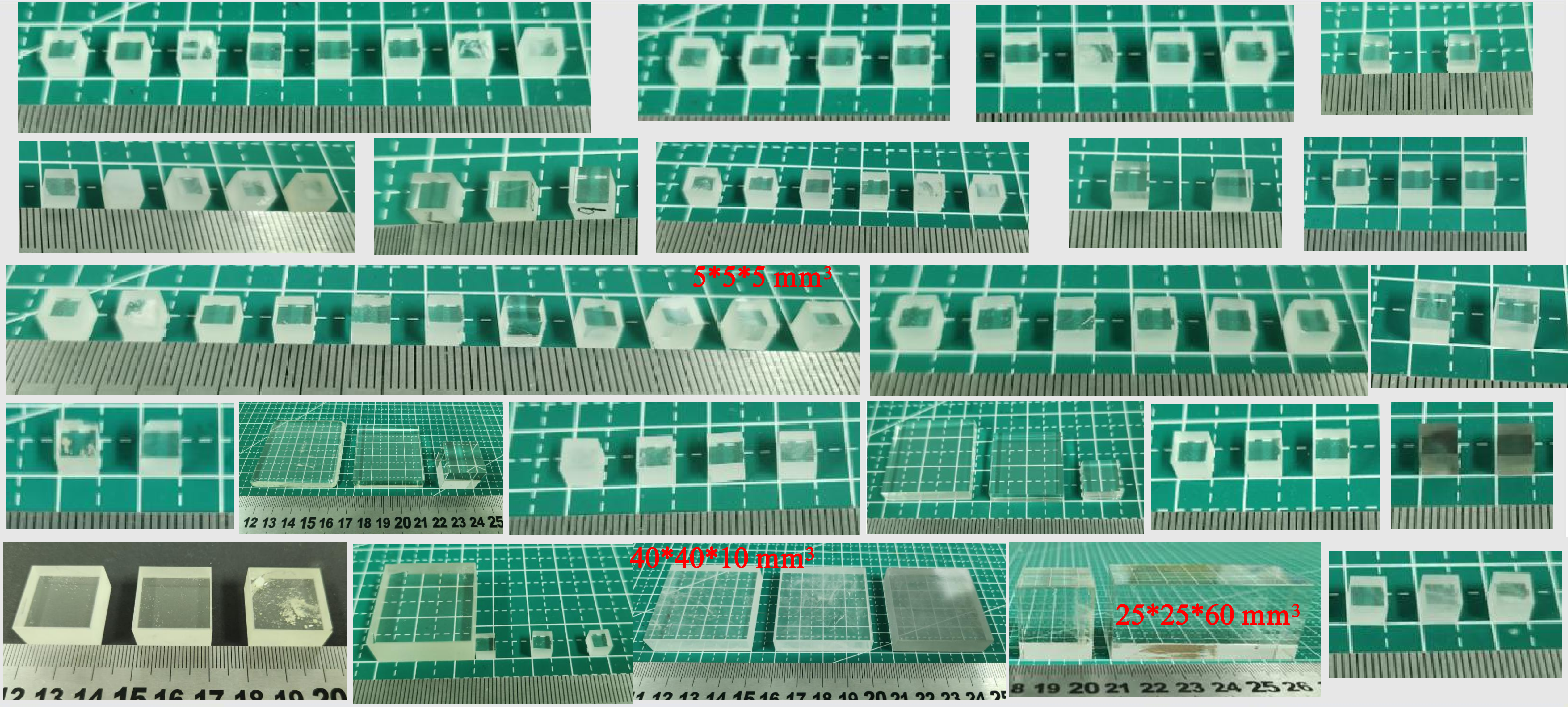
- IHEP--XAFS

- IHEP-CSN-- P Beam



- CERN-MUON Beam

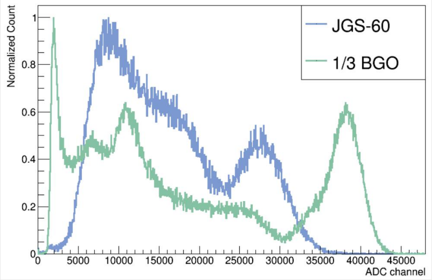
3.5 The GS Samples produced （>700）



3.6 The R&D efforts from GS Collaboration

Gd-Al-B-Si-Ce^{3+}

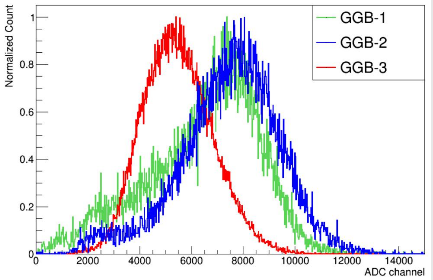
- 2021.11
- Density ~4.5 g/cm^3
- LY~800 ph/MeV
- ER=26.8%
- Decay=262 (18%) 1235 ns



- Currently
- Density ~6 g/cm^3
- LY~1070 ph/MeV
- ER=24.4%
- Decay=92 (8%) 1235 ns

Gd-Ga-B-Ce^{3+}

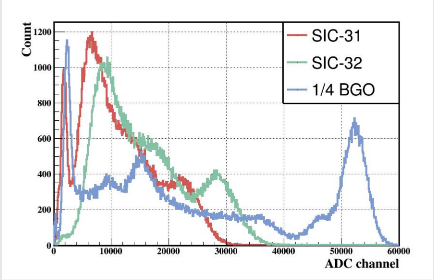
- 2022.07
- Density ~5.9 g/cm^3
- LY~550 ph/MeV
- ER= None
- Decay=148 (16%) 1076 ns



- Currently
- Density ~6.0 g/cm^3
- LY~570 ph/MeV
- ER= None
- Decay=277 ns

Gd-R-Al-B-Si-Ce^{3+}

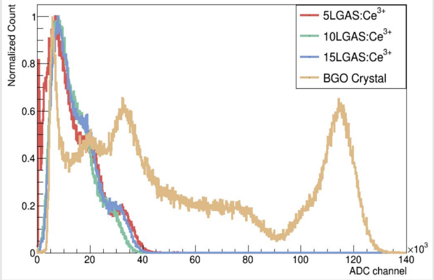
- 2022.12
- Density ~5.5 g/cm^3
- LY~1100 ph/MeV
- ER= 35.8%
- Decay=178 (4%) 1554 ns



- Currently
- Density ~6.0 g/cm^3
- LY~980 ph/MeV
- ER= 28.5%
- Decay=150 (10%) 676 ns

Gd-Al-Si-Ce^{3+}

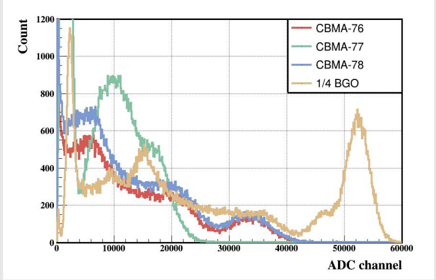
- 2022.03
- Density ~4.0 g/cm^3
- LY~810 ph/MeV
- ER= 29.3%
- Decay=267 (41%) 1232 ns



- Currently
- Density ~4.0 g/cm^3
- LY~1300 ph/MeV
- ER= 23.2%
- Decay=329 (20%) 1764 ns

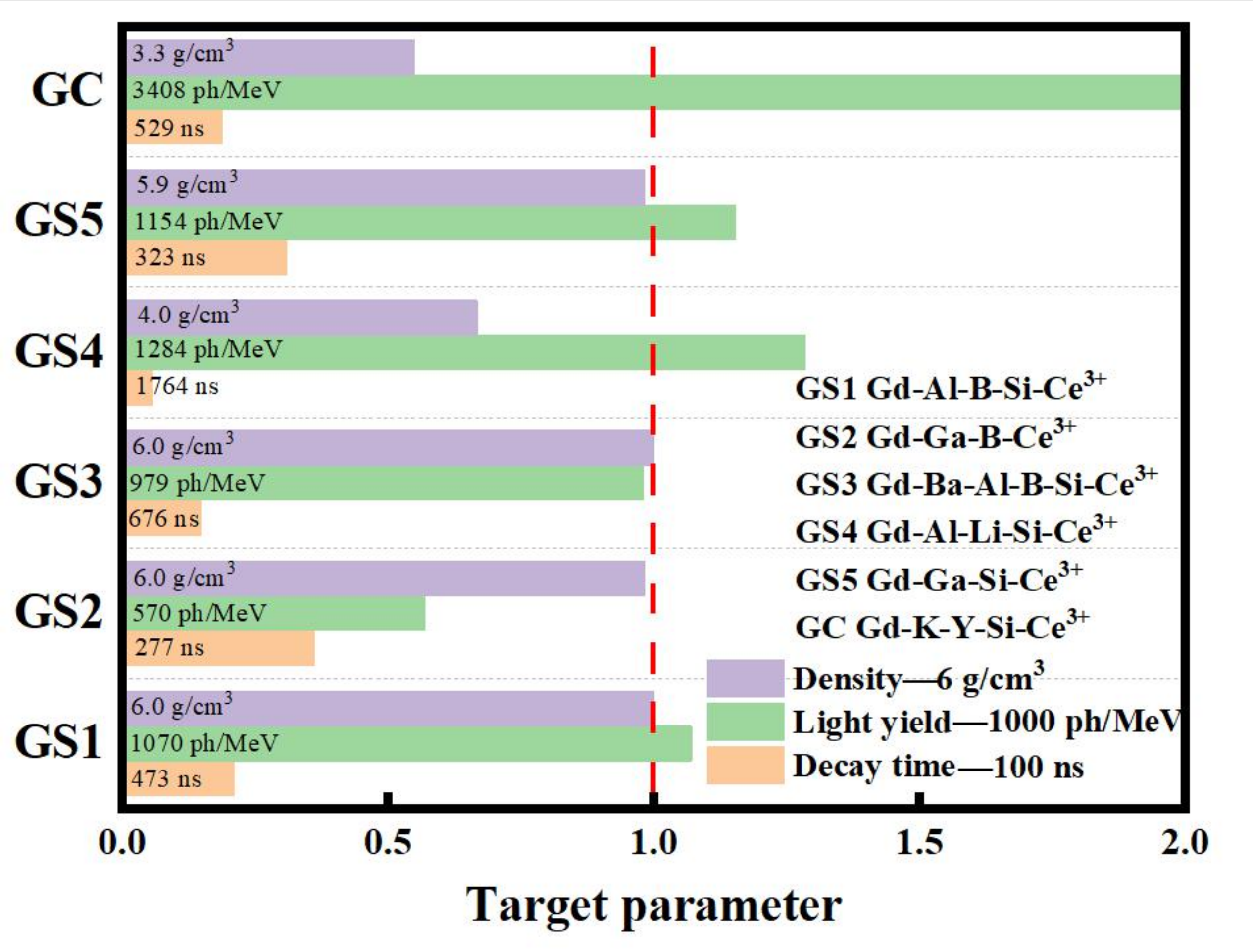
Gd-Ga-Si-Ce^{3+}

- 2023.07
- Density ~5.0 g/cm^3
- LY<400 ph/MeV
- ER= None
- Decay=287 ns



- Currently
- Density ~5.9 g/cm^3
- LY~1150 ph/MeV
- ER= 25.4%
- Decay=92 (39%) 323 ns

3.7 Performance of Small-size Samples



* The sample size is 5x5x5 mm³, except for **GC** (5x5x2 mm³)

Glass scintillator of high density and high light yield

◆ GS1: Gd-Al-B-Si-Ce^{3+} glasses: (Borosilicate Glass)

6.0 g/cm³ & 1235 ph/MeV with 24.0% @662keV & 588 ns

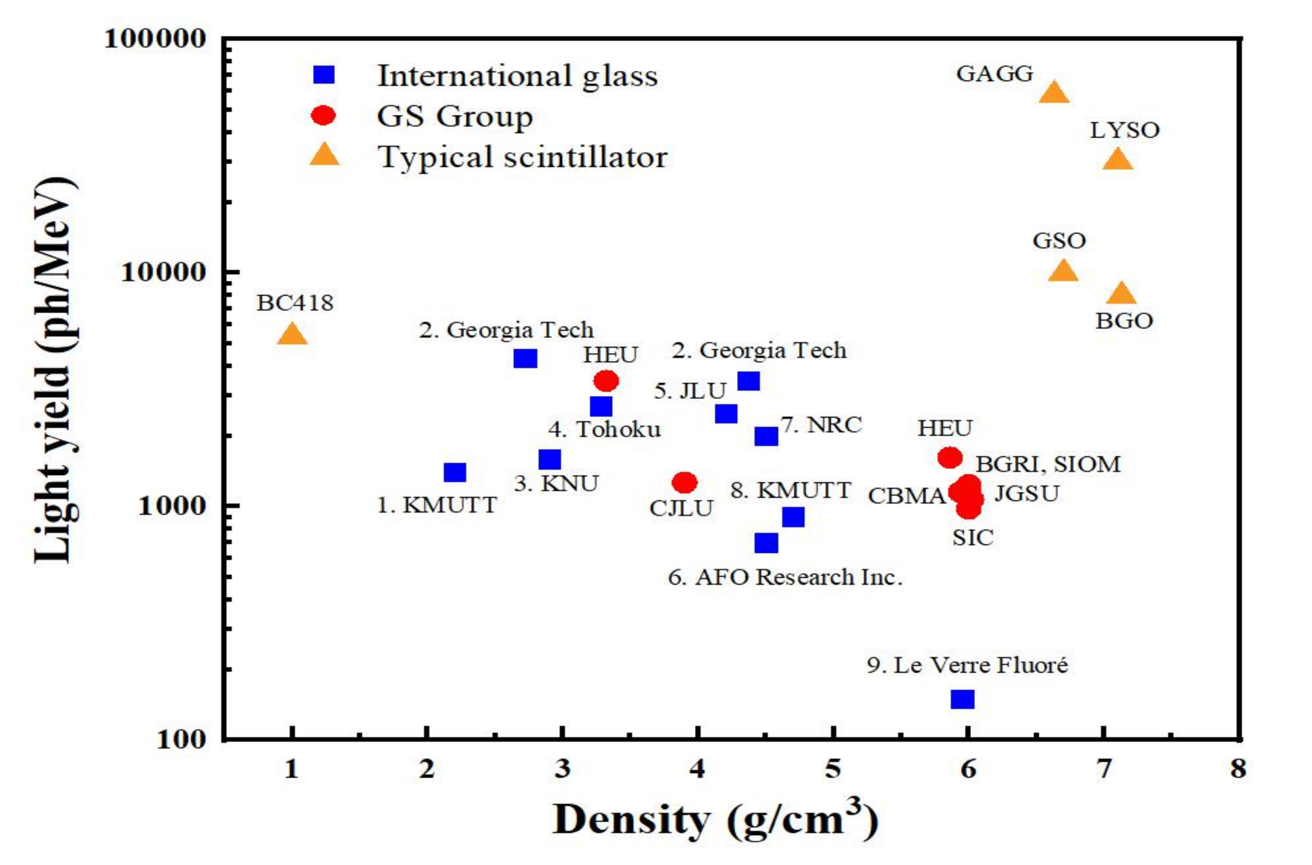
◆ GS5: Gd-Ga-Si-Ce^{3+} glasses: (Silicate glass)

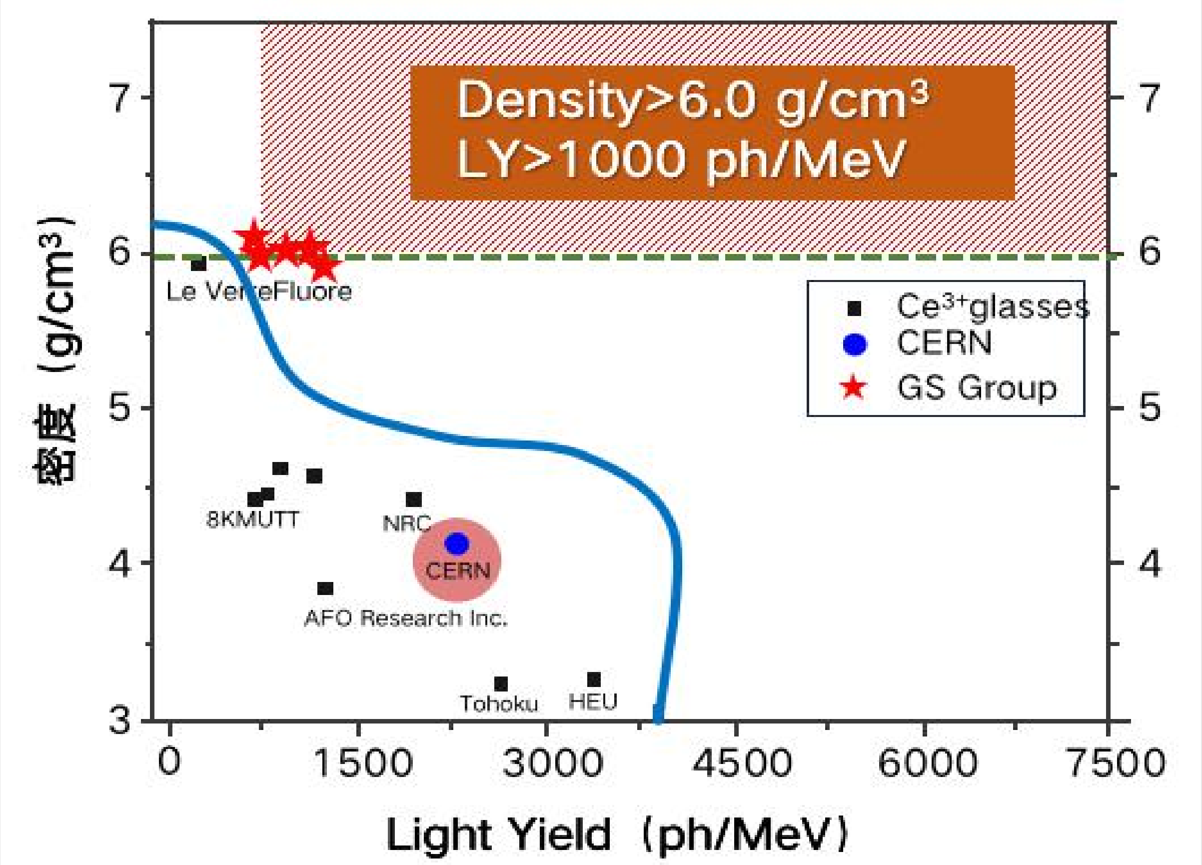
5.9 g/cm³ & 1154 ph/MeV with 25.4% @662keV & 323 ns

Other Highlights:

- Ultra-high density **Tellurite Glass**—6.6 g/cm³
- High light yield **Glass Ceramic**—3500 ph/MeV
- Fast Decay Time **Pr^{3+}-doped Glass**—100 ns
- Large size Glass—51mm*51mm*10mm

3.8 GS Group Samples vs International Samples



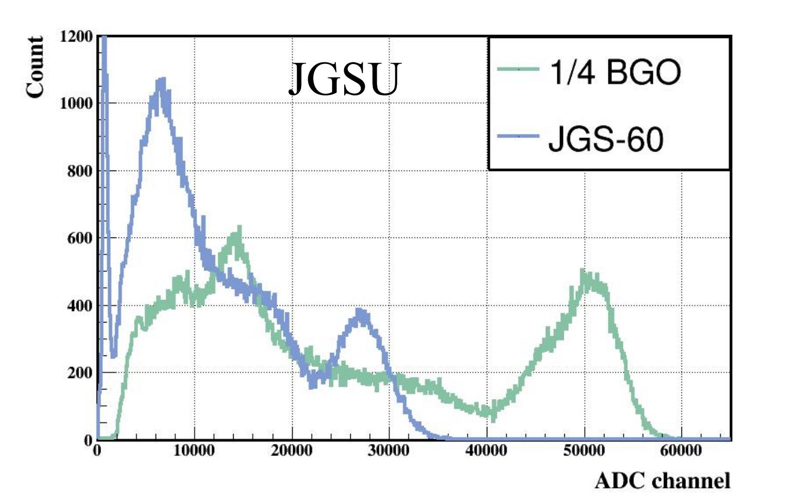


- The GS group has carried out a comprehensive and complete study;
- For high density glass scintillator, the light yield of GS group samples is in the absolute lead.

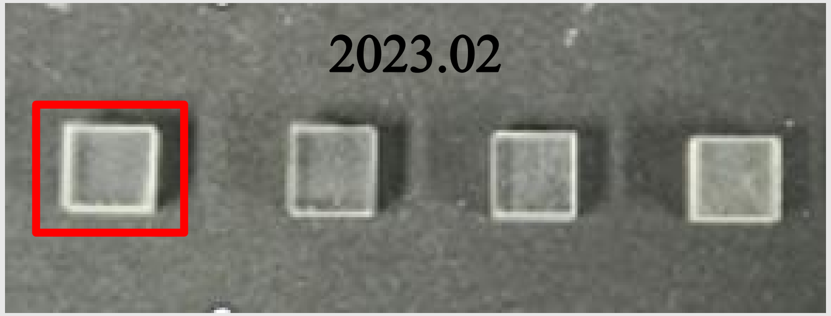
3.9 The Best Performance Achieved Currently

Small-Size

- **Size=5*5*5 mm³**
- Density~5.9 g/cm³
- LY~1070 ph/MeV
- ER=24.4%
- LO in 1μs=899 ph/MeV
- Decay=92 (8%), 473 ns

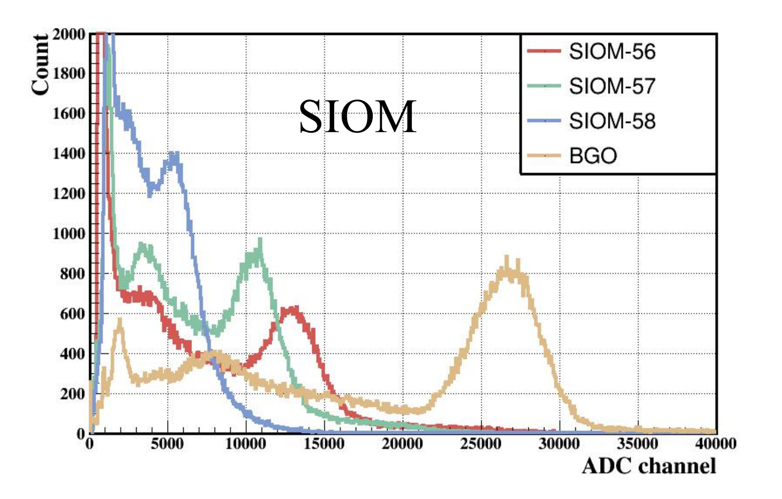


2023.02

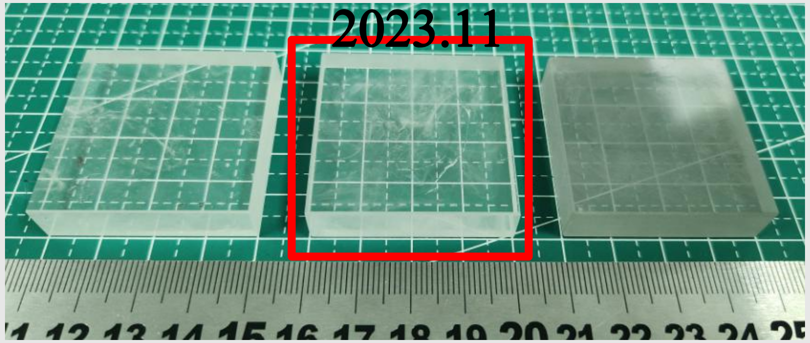


Large-Size

- **Size=40*40*10 mm³**
- Density=6.0 g/cm³
- LY ~1200 ph/MeV
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns



2023.11



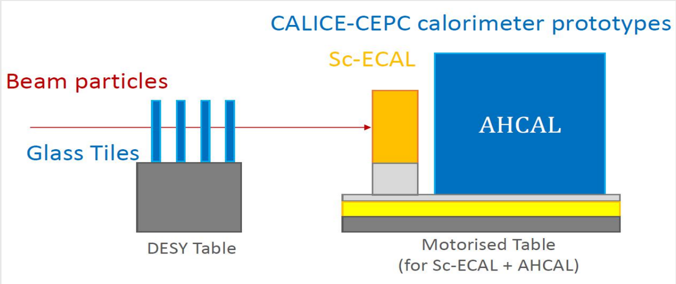
Outline

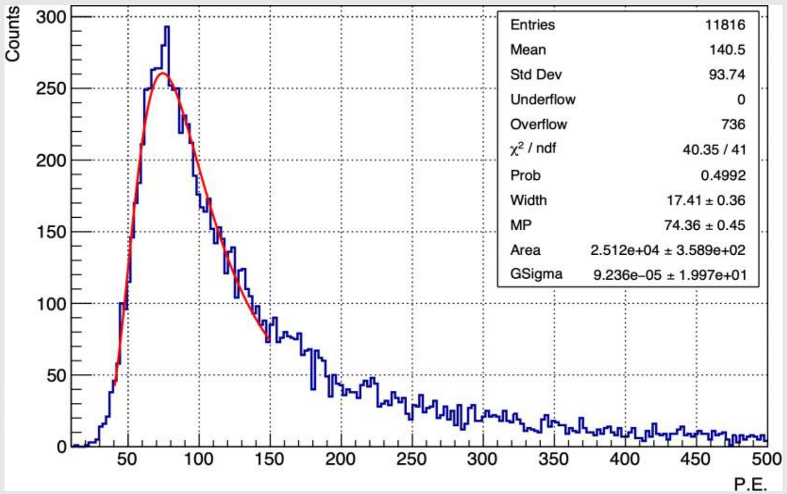
- 1. The Structure Design of the GSHCAL;
- 2. PFA performance of the GSHCAL;
- 3. The Progress of the GS Production;
- **4. The Tests of GS Samples of HCAL**
- 5. Summary and Next Plan

4.1 The MIP response of GS Samples

CERN Muon-beam (10 GeV muon)

11 glass tiles tested at CERN (2023/5)

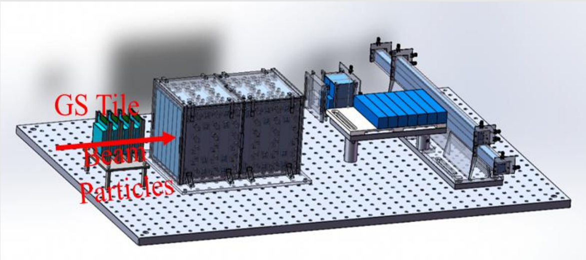


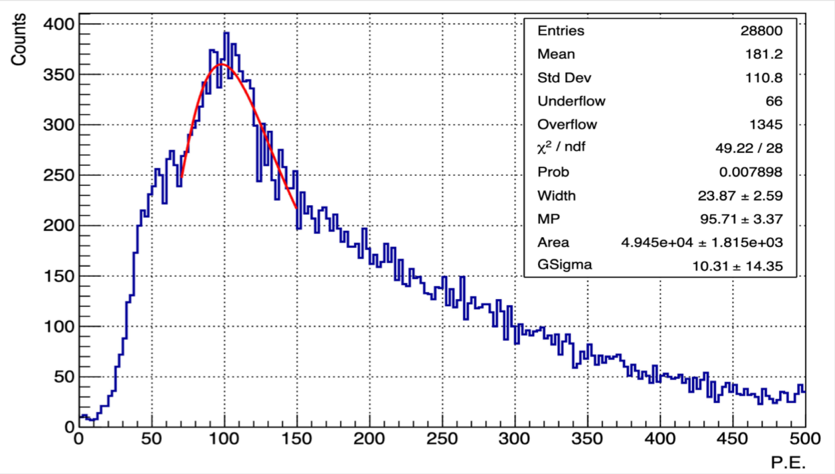


- Typical Light Yield: 500 – 600 ph/MeV
- Typical MIP response: 60 – 100 p.e./MIP

DESY Electron-beam (5 GeV electron)

9 glass tiles tested at DESY (2023/10)

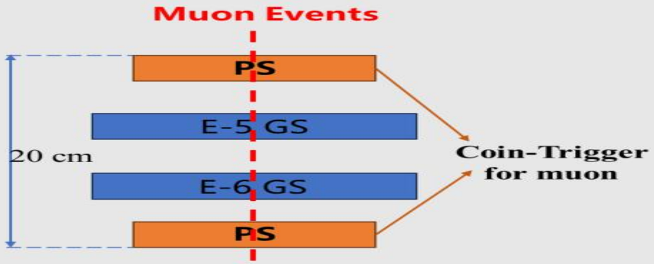


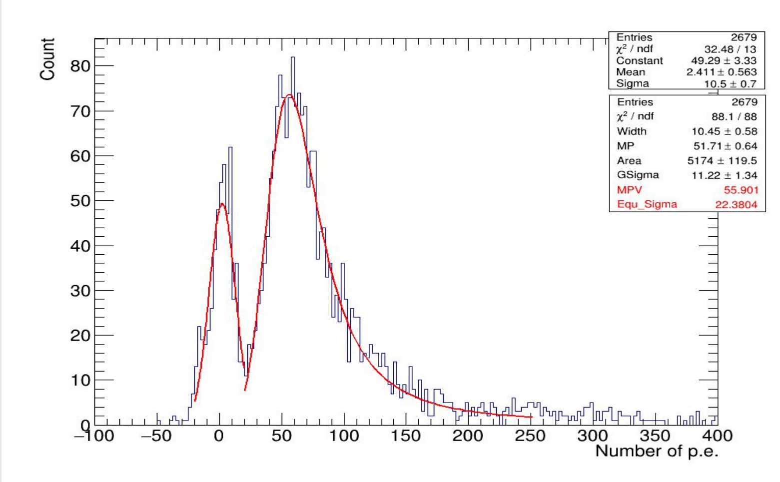


- Typical Light Yield: 600 – 700 ph/MeV
- Typical MIP response: 80 – 90 p.e./MIP

IHEP Cosmic-Muon- (3GeV muon)

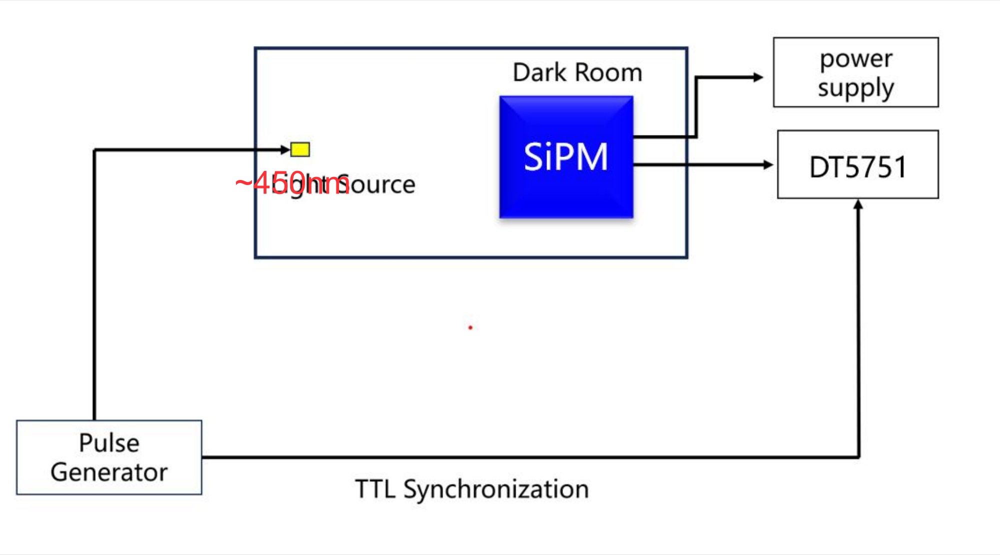
4 glass tiles tested at IHEP (2024/4)

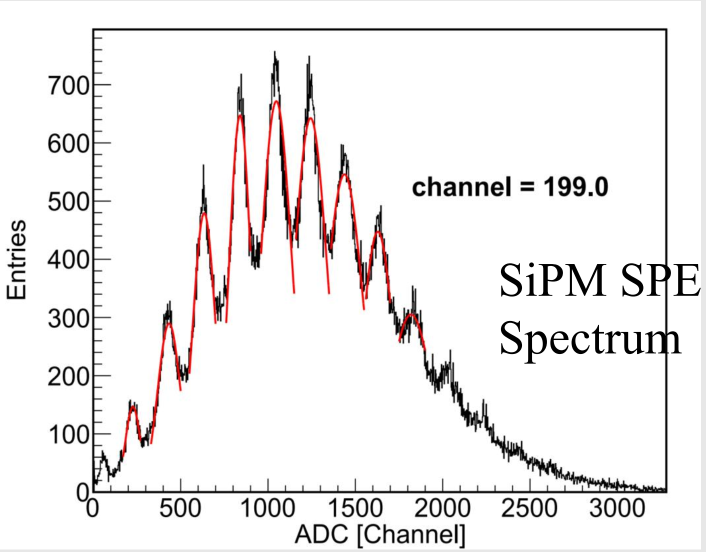


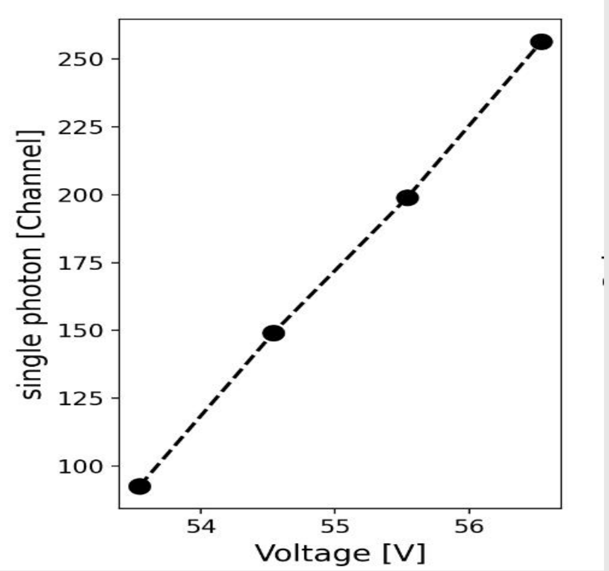


- Typical Light Yield: 600 – 700 ph/MeV
- Typical MIP response: 50 – 60 p.e./MIP

4.3 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

Outline

- 1. The Structure Design of the GSHCAL;
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5.1 Summary of GSHCAH R&D and Next Plan

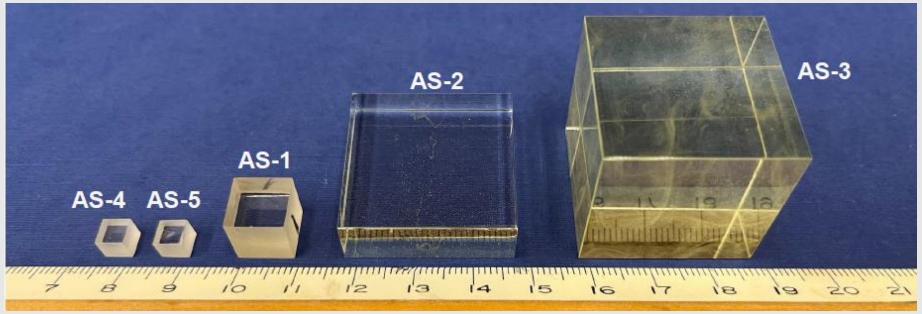
- We have studied the PFA performance of the GSHCAL in the CDR baseline design, and the impact of some key GSHCAL parameters on BMR was obtained.
- GSHCAL of **nominal setup at CDR** can achieve a **BMR of ~3.6%** (~5% improvement w.r.t the AHCAL), which is a very promising alternative design.
- Design optimization of the GSHCAL at **TDR** is ongoing, in which the 4th Conceptual Detector Design will be adopted

Next Plan

- To **optimize the GSHCAL design for the TDR** (currently the 4th Conceptual Detector Design is not ready in the simulation and reconstruction framework)
- 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.
- PFA performance combining the **GS-HCAL & GS-ECAL** will also be considered in next step.

5.2 Summary of GS R&D

Parameters	Unit	BGO	LYSO	GAGG	GS1	GS5	Current goals	TDR goals
Cost							!!!	!!!
Density	g/cm³	7.13	7.5	6.6	6.0	5.9	6	?
Hygroscopicity	--	No	No	No	No	No	No	No
Radiation Length, X_0	cm	1.12	1.14	1.63	1.59	1.61	?	?
Transmittance	%	82	83	80	80	80	80	?
Refractive Index	--	2.1	1.82	1.91	1.74	1.75	?	?
Emission peak	nm	480	420	520	390	390	?	?
Light yield, LY	ph/MeV	8000	3000	54000	1347	1154	1000	2000
Energy resolution, ER	%	9.5	7.5	5.0	25.3	25.4	25	?
Decay time	ns	60, 300	40	100	80, 600	90, 300	100	300?



- We need the **truth requirment** of the GS from the CEPC-HCAL to control the **real cost** of the GS.

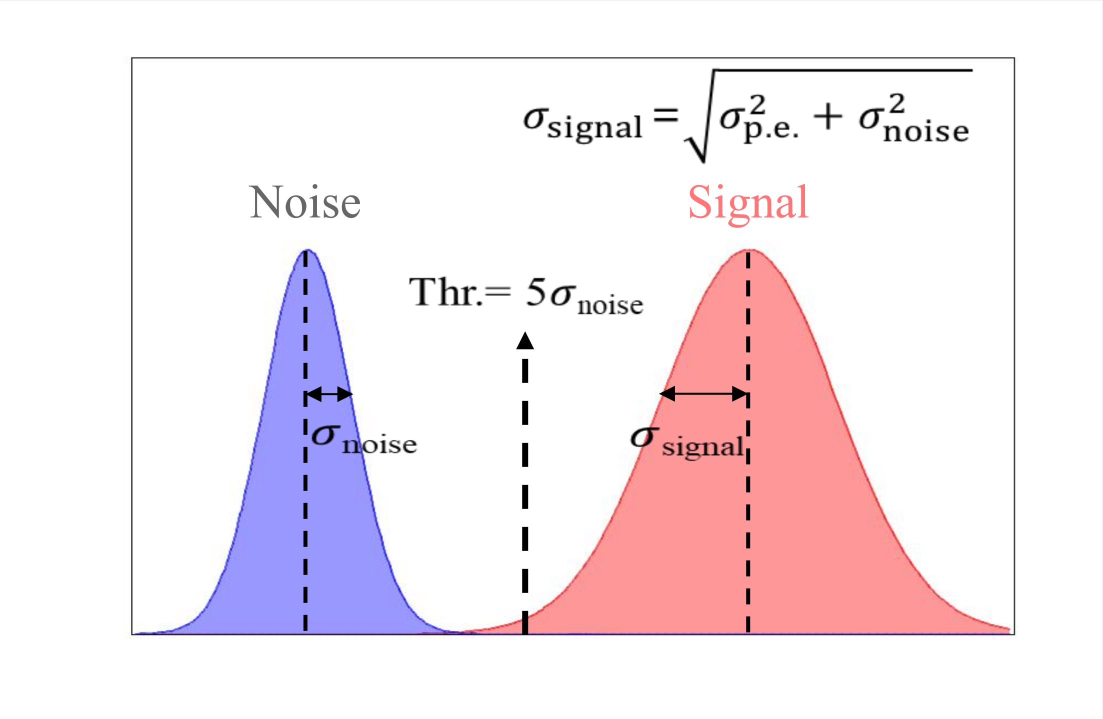
Glass Scintillator Collaboration

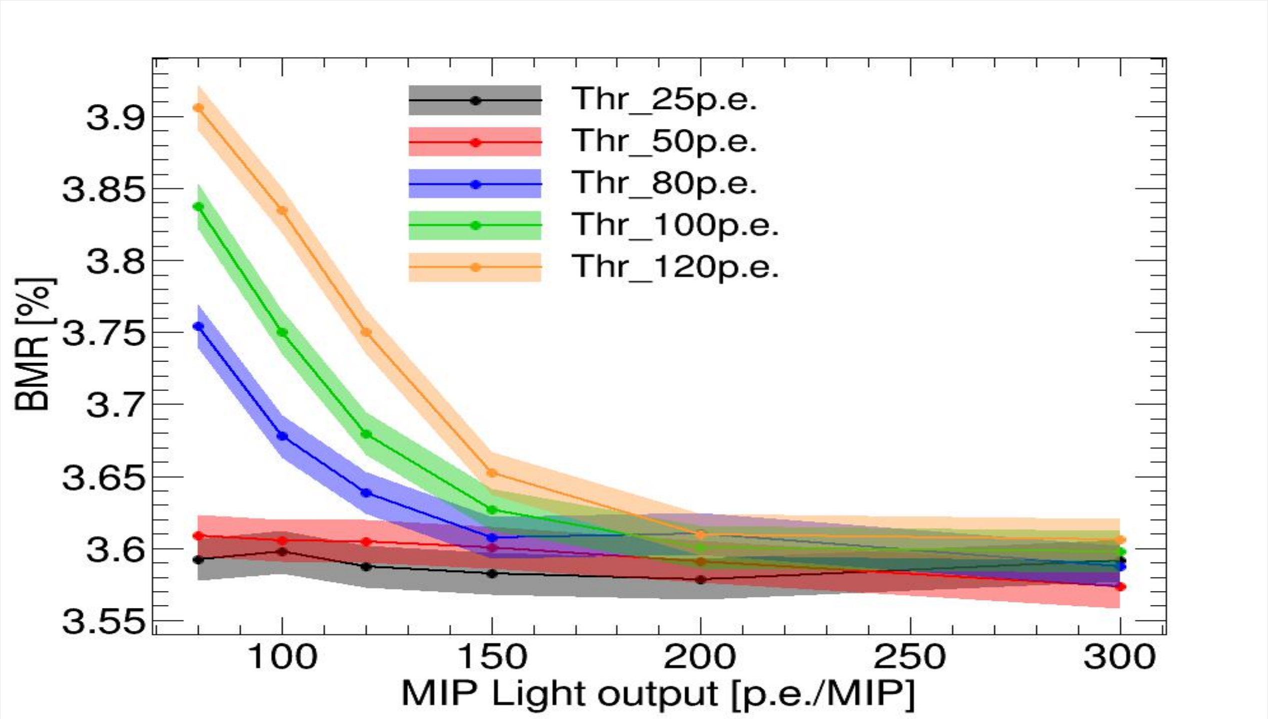
See the unseen
change the unchanged

The Innovation

THANKS

2.5 Preliminary Digitization Studies





- 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