R&D of Glass Scintillator-HCAL

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

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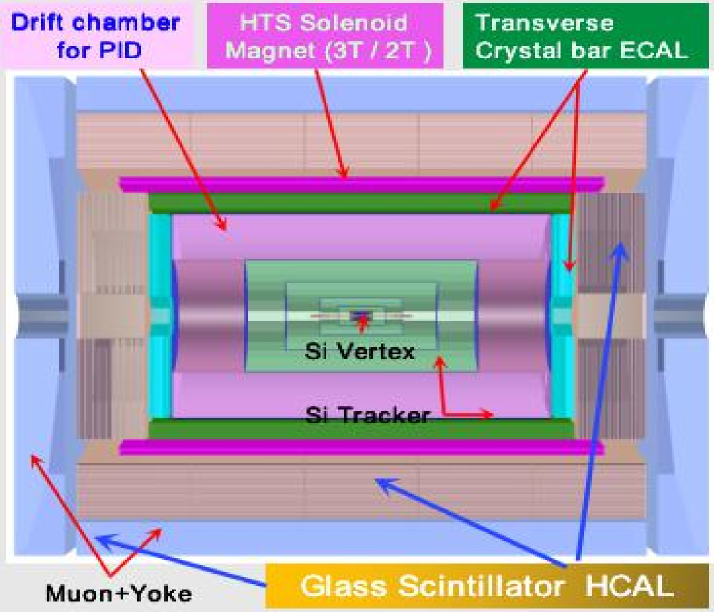
CLHCP2025 新乡
第十一届中国LHC物理会议
The 11th China LHC Physics Conference

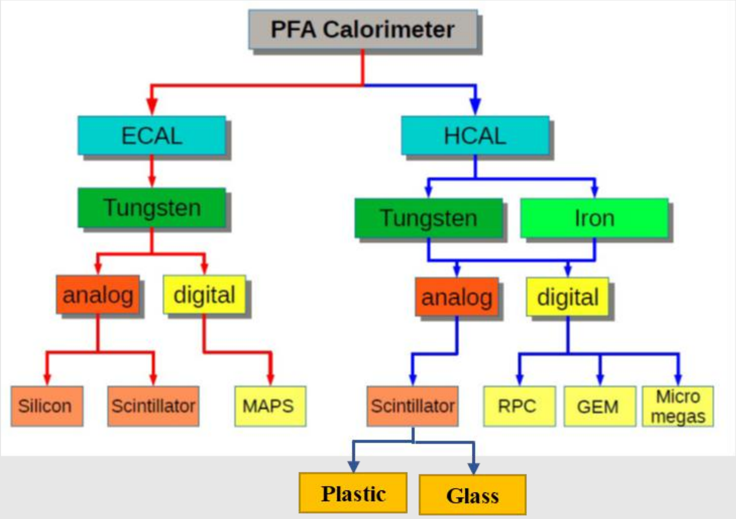
Outline

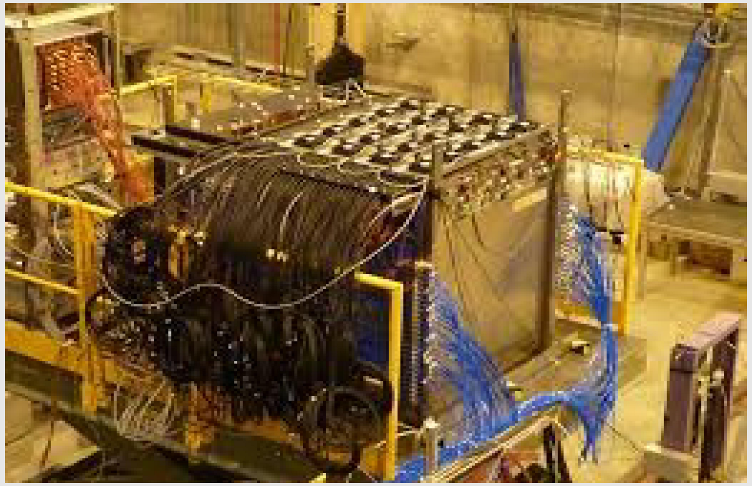
- 1. Motivation for GS-HCAL
- 2. R&D of the GS
- 3. Design of the GS-HCAL in CEPC
- 4. Summary and Next Plan



1.1 HCAL Design Options （The Past）

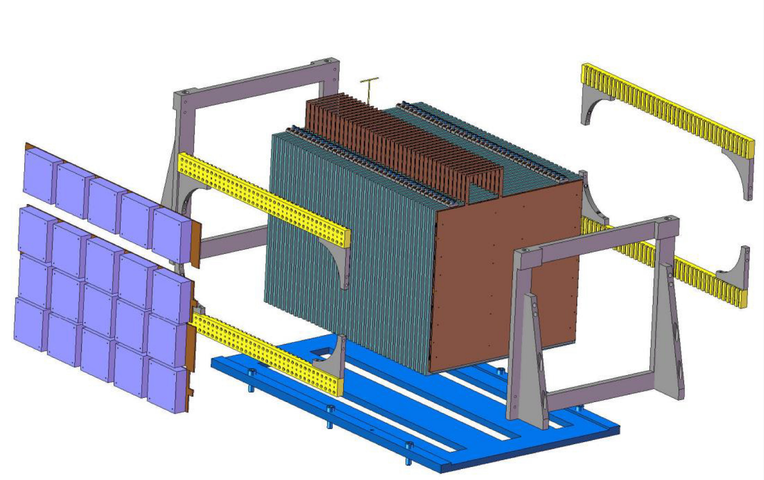
- Several HCAL design options have been proposed
  - Based on Gaseous Detector
    - e.g. CALICE SDHCAL doi:10.1088/1748-0221/11/04/P04001
  - Based on Liquid Argon
    - e.g. ATLAS LAr Endcap HCAL doi:10.1016/j.nuclphysbps.2011.03.150
  - AHCAL: Plastic Scintillator & SiPM readout
    - e.g. CEPC AHCAL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





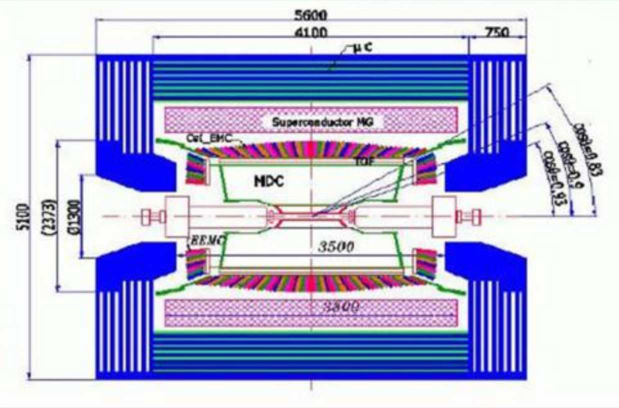
➢ CALICE SDHCAL Prototype

➢ ATLAS LAr Endcap HCAL

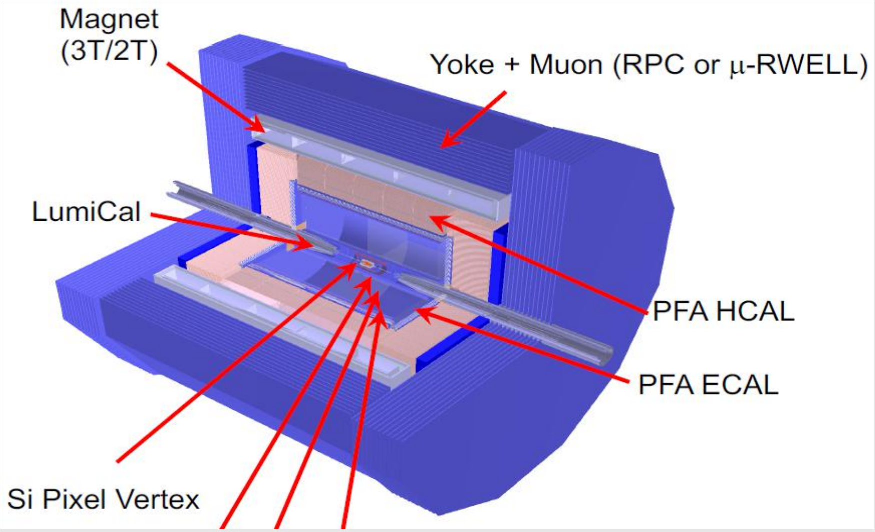


➢ CEPC AHCAL Prototype

1.2 Technologies uesd in Calorimeters



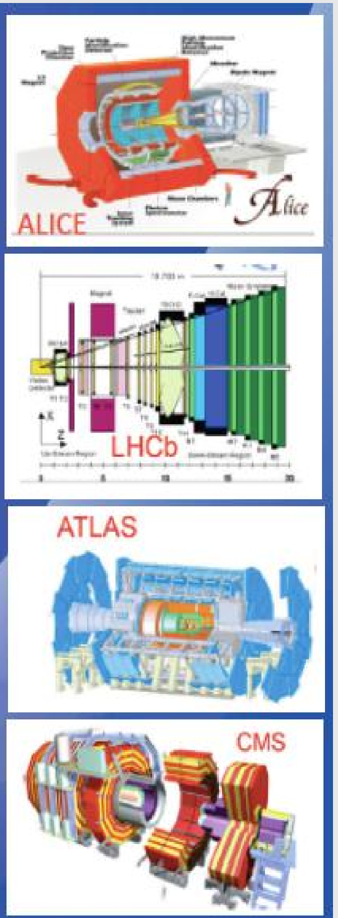
BEPC-BESIII-EMC： CsI + PD



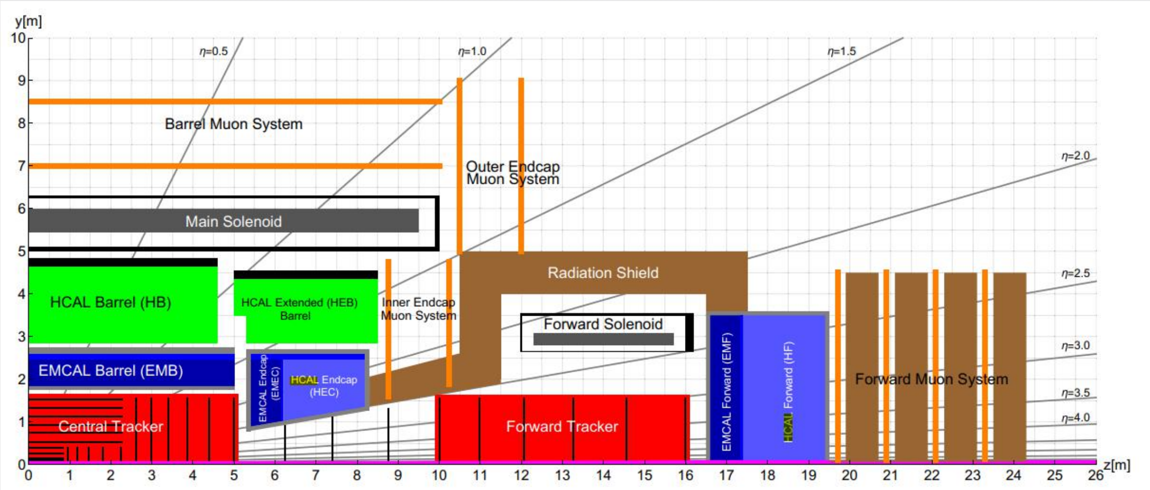
CEPC-CDR-ECAL： Scintillator tungsten

CEPC-CDR-HCAL： Plastic Scinillator + SiPM

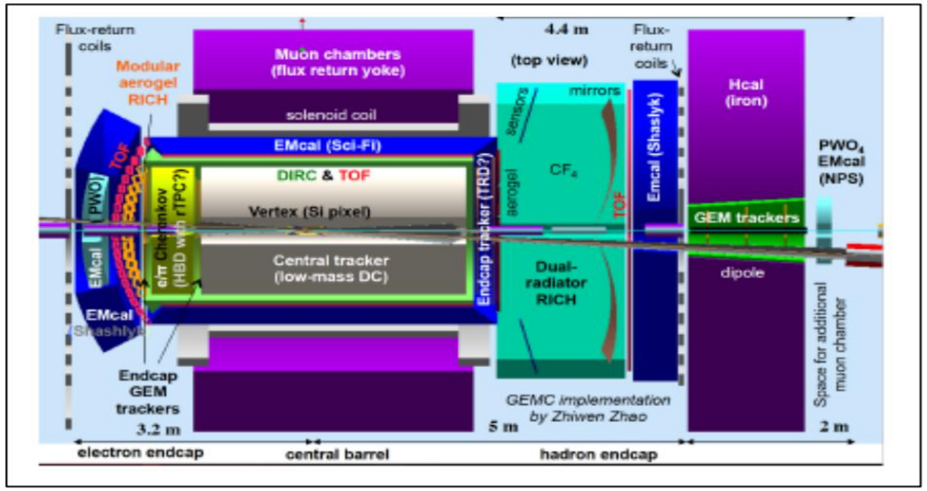
- $PbWO_4$ homogeneous calorimeter:
  - CMS ECAL, ALICE PHOS
- LAr sampling calorimeter:
  - ATLAS EM Barrel and Endcap, Hadronic Endcap, Forward calorimeters
- Scintillator/WLS fiber sampling calorimeters:
  - CMS HCAL Barrel and Endcap, ATLAS TileCal (barrel HCAL), LHCb HCAL
- Shashlik Pb/Scint sampling calorimeters:
  - ALICE EMCal/DCal, LHCb ECAL
- Quartz Fiber/Steel sampling calorimeter:
  - CMS HCAL Forward



Except **$PbWO_4$** or **Plastic Scinillator**, **Crystal can not used for the ECAL or HCAL, too expensive!**



■ Longitudinal cross-section of the FCC-hh reference detector



■ Example layout of the EIC detector base design

Task 1.2: Hadronic section with optical tiles	
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/Steel
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/Steel

Task 1.2
- AHCAL: Concept for continous readout
- **ScintGlass HCAL**: cm scale tiles

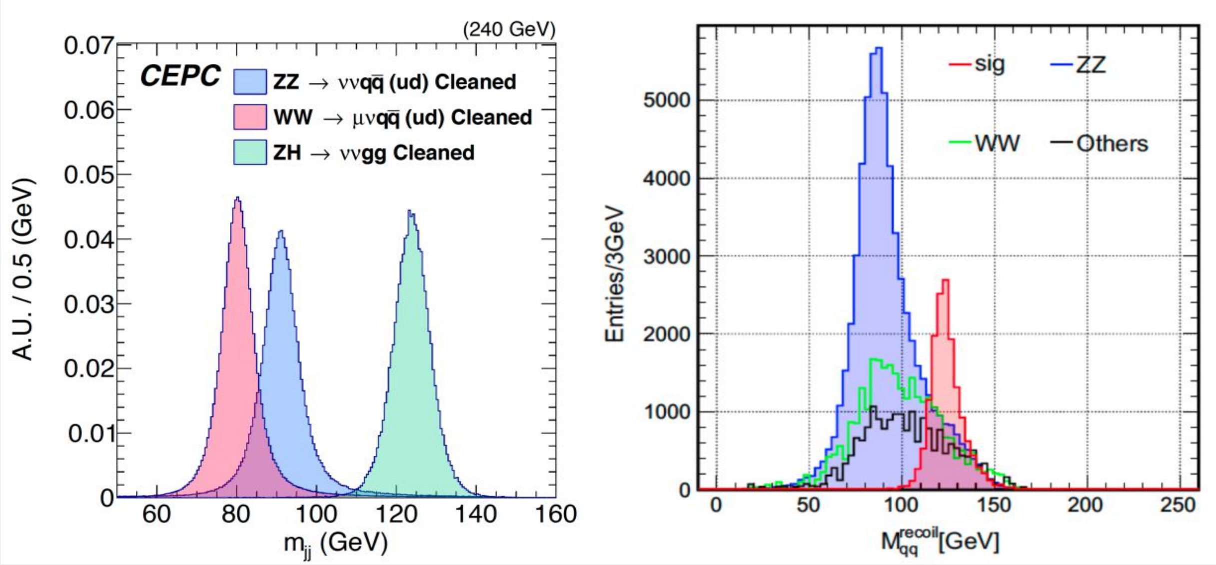
Glass for EIC:
- Sufficient resolution
- Fast response
- Radiation hardness

Task 1 ： build a cost effective glass-ceramic calorimeter for the outer endcaps and central regions

Task 2： Push the performance of **glass ceramics** towards crystals

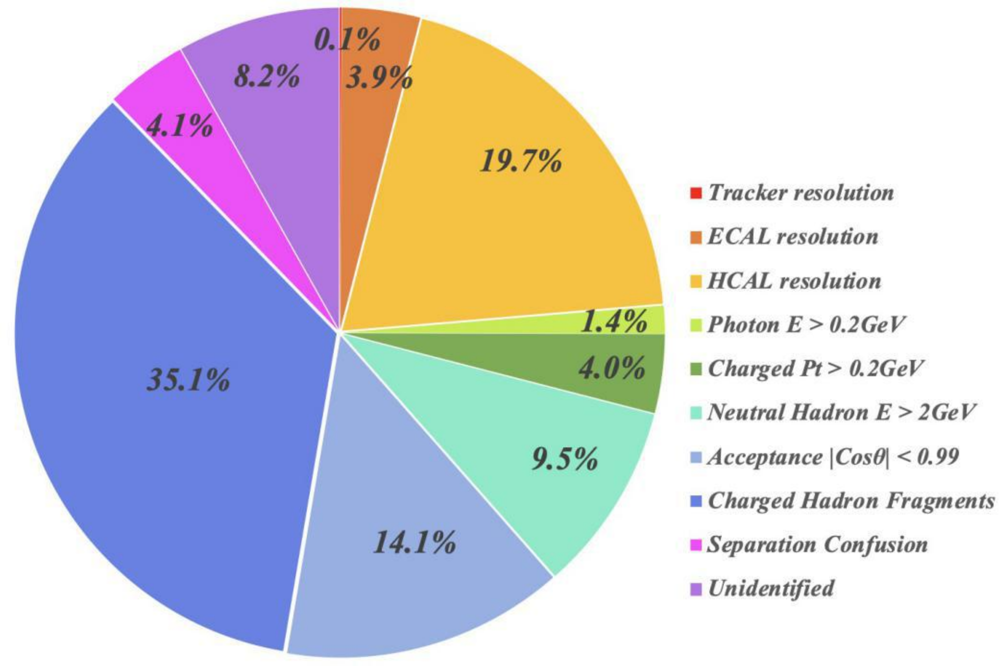
1.4 Physics Requirements of HCAL

- CEPC as Higgs/W/Z factories:
  - Jet Energy Resolution s/E ~ 5%
  - Boson Mass Resolution (BMR) < 4% :
    it is strongly motivated by H/W/Z hadronic final states, BSM & Flavor Physics



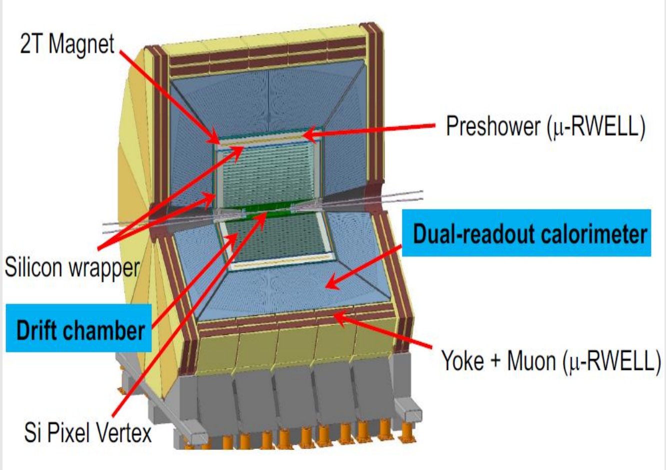
CDR baseline ([arXiv:1811.10545](https://arxiv.org/abs/1811.10545)): BMR = 3.75%

- Leading contributions to BMR:
  - HCAL resolution dominant the uncertainties from intrinsic detector resolution: **~19.7%**
  - Further improvement of HCAL is needed



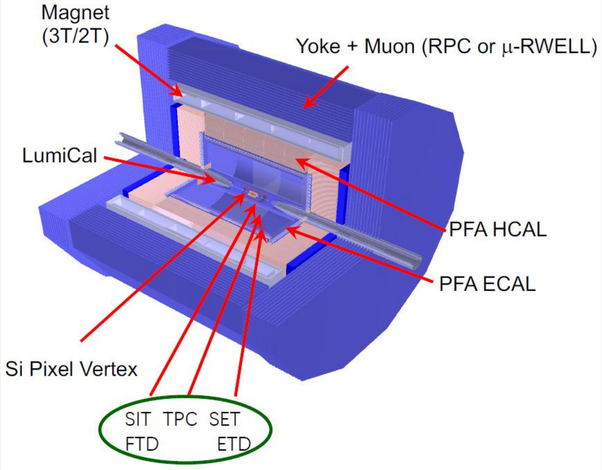
1.5 CEPC Conceptual Detector Design （The Future）

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



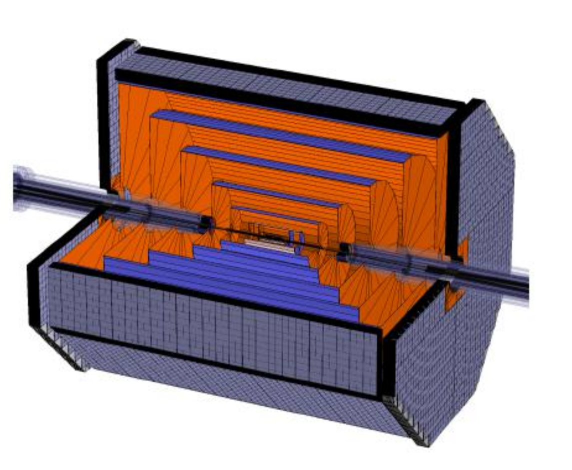
- **Dual-readout calorimeter (Cerenkov-Fiber & Scint-Fiber)**
- both for EM and Hadronic Shower

2nd CDR Baseline Design
(Particle Flow Approach)



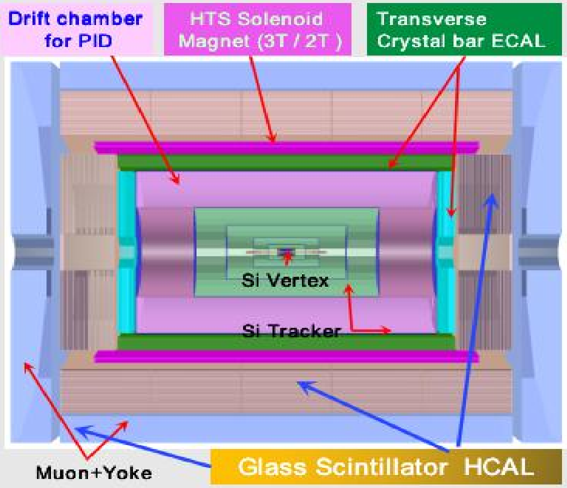
- **AHCAL (PS/Steel) or SDHCAL (Gas/Steel)**
- Si/W ECAL or PS/W ECAL

3rd FST concept
(Full Silicon Tracker)



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

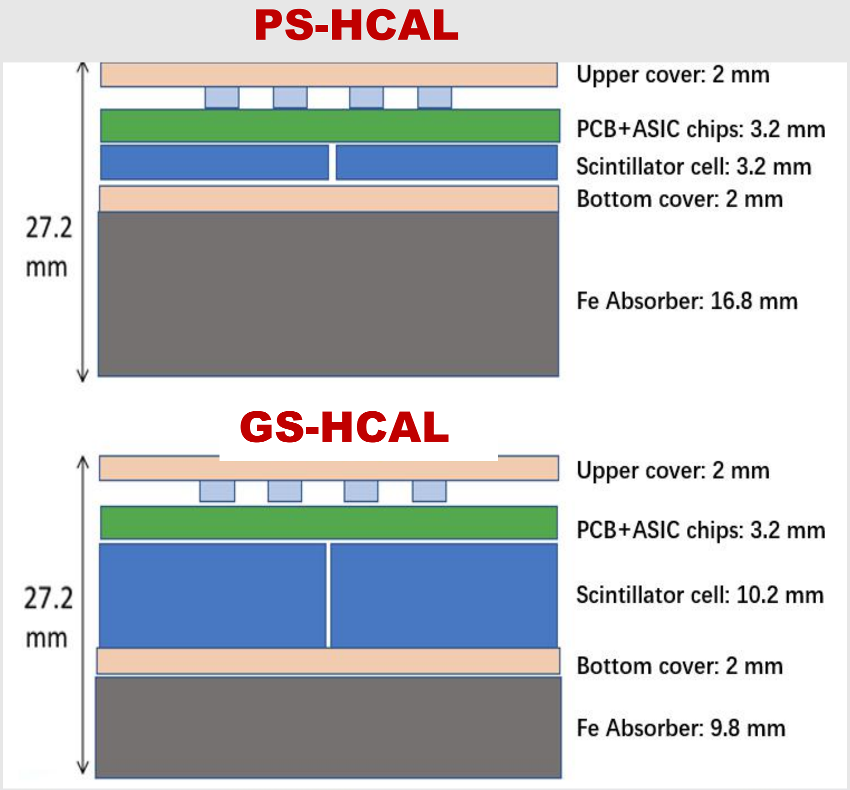
4th Conceptual Detector



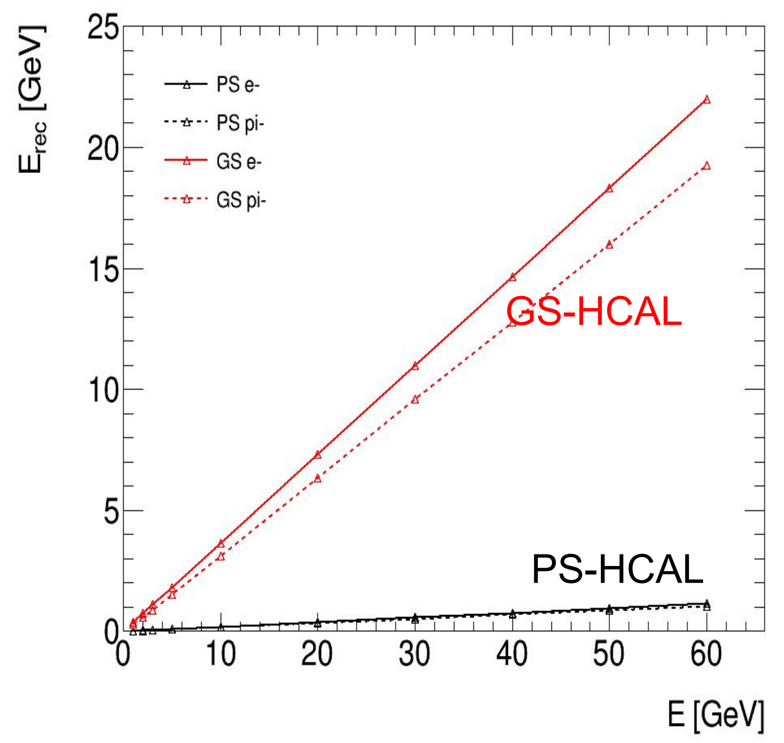
- **GSHCAL (GS/Steel)**
- BGO Crystal ECAL

1.6 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
  - Fe: 20.8mm/171.5mm=0.1213 λ_I
  - PS: 3mm/688.7mm=0.0044 λ_I
  - PCB: 1.2mm/492.2mm=0.0024 λ_I
  - Sampling fraction ~ 1.6% (π^- TB, MC)
- GS-HCAL
  - Fe: 13.8mm/171.5mm=0.0805 λ_I
  - GS: 10.2mm/242.8mm=0.0425 λ_I
  - PCB: 1.2mm/492.2mm=0.0024 λ_I
  - Sampling fraction ~ 31% (MC)



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2.0 Development of Glass Scintillator

1. Commercialization of glass scintillator

2. High density

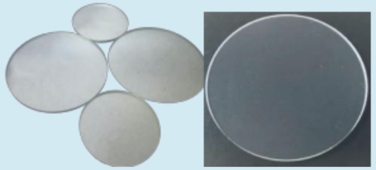
3. High LY

4. High density & LY

Glass Scintillators*

R. J. GINTHER† AND J. H. SCHULMAN†

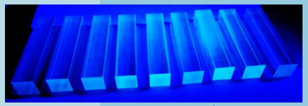
1958, Ce-doped high-silicon glass.
Under γ-ray excitation, the pulse height is 10% of NaI(TI).



1976, commercialized GS series glass scintillator (GS20 ρ=2.5 g/cm^3, LY=6000 ph/neutron

2015, DSB glasses for high energy physics experiments,
ρ= 3.8 g/cm^3,
LY= 1360 ph/MeV

1996, heavy metal fluoride glass EM calorimeter



2021, GS Group for R&D new glass scintillator
ρ= 6 g/cm^3 LY= **1000 ph/MeV**

1950 1960 1970 1980 1990 2000 2010 2020 2025

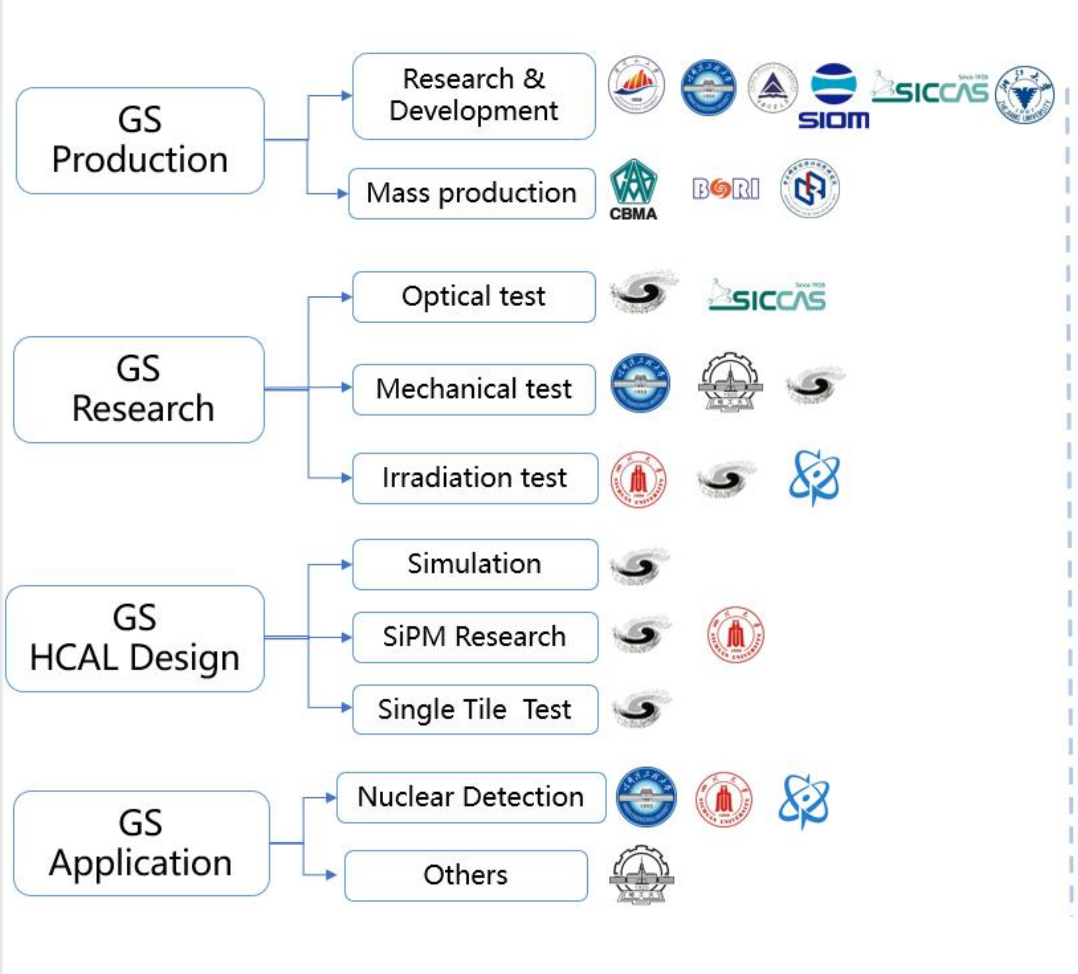
1962, glass for thermal neutron detection

1988, glass scintillator calorimeter design

2000, the concept of energy transfer sensitization

2020, Ce^{3+} doped Gd-based glass

2.1 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

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

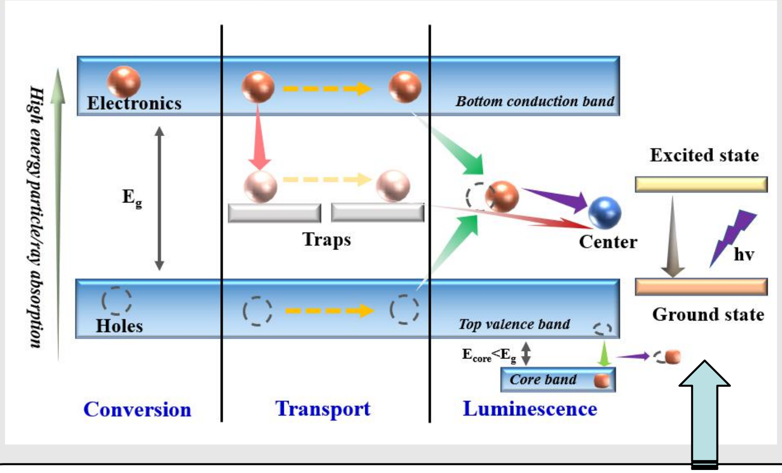
闪烁玻璃合作组
Glass Scintillator Collaboration

Spokesperson：Sen QIAN

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

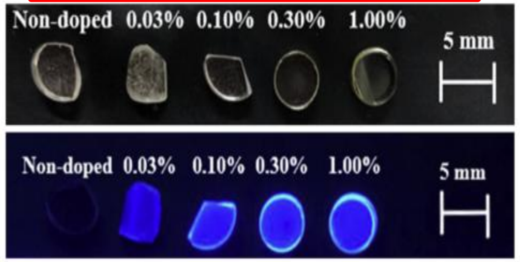
-- There are 4 Institutes from CAS, 6 Universitys, 3 Companies join us for the R&D of GS;

2.2 Design of the GS



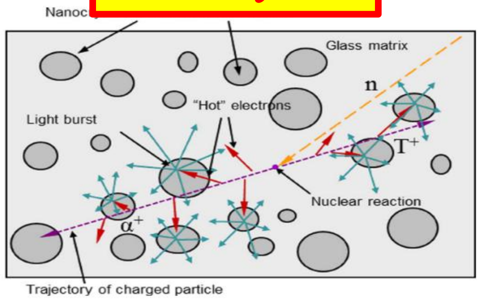
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



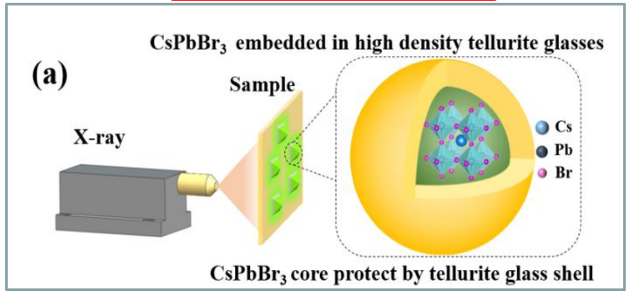
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



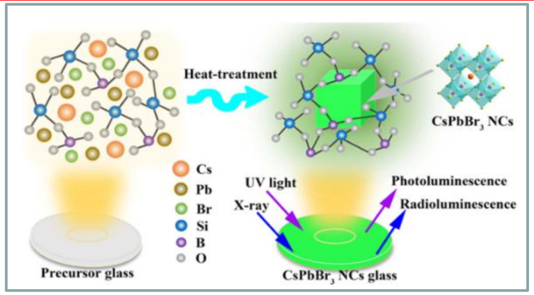
IEEE TNS 60 (2) 2013

Quantum Dots



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

Lanthanide + Quantum Dots



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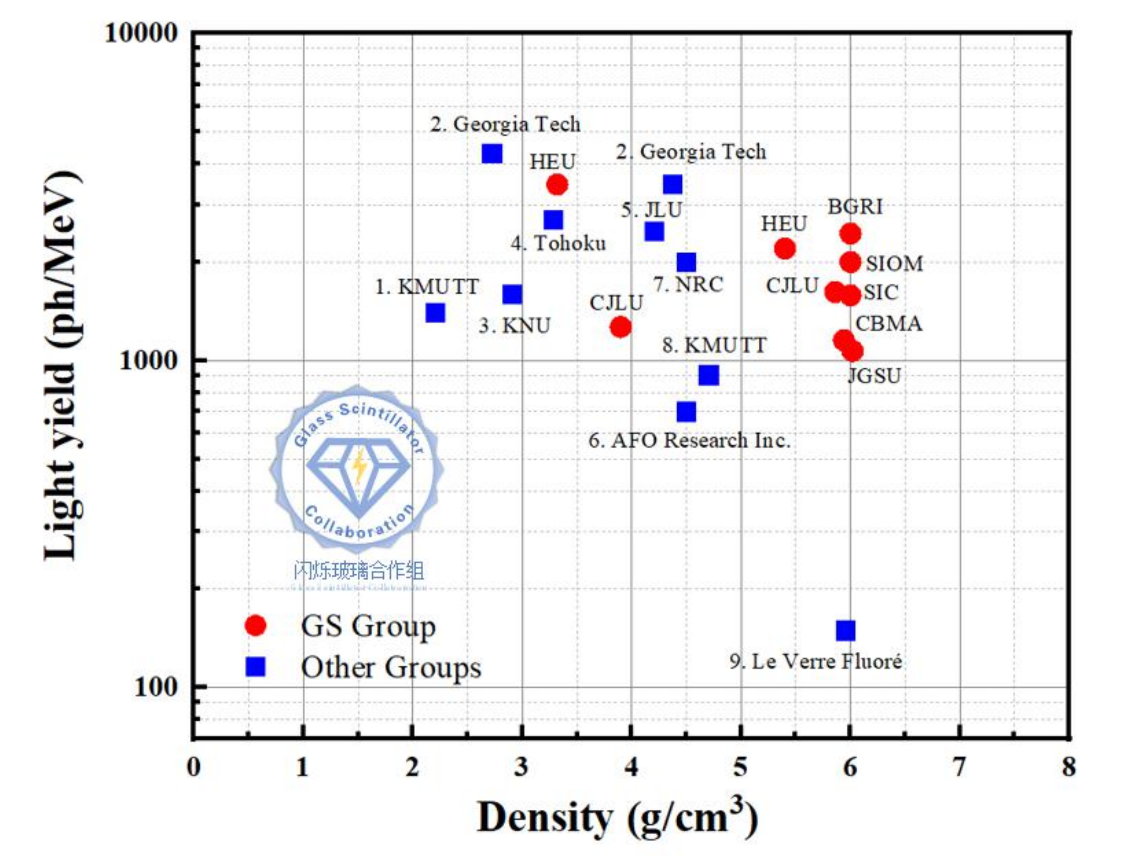
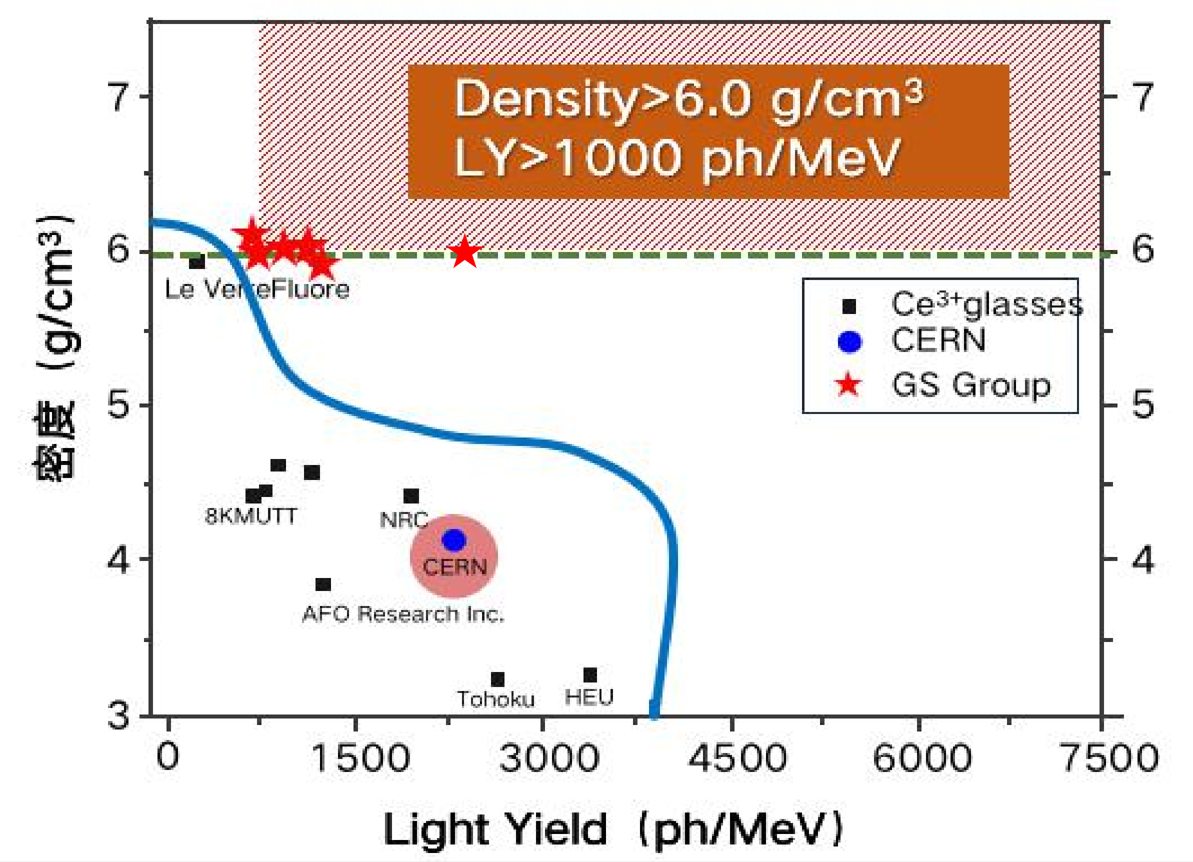
- High Light Yield (> 2000 ph/MeV): Lanthanide for the Luminescence Center: Cerium (Ce);
- High Density (> 6 g/cm^3) and Low radioactivity background: Gadolinium (Gd); ~~lutetium (Lu)~~

2.3 GS Group Samples



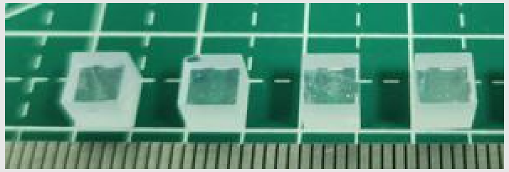


- The GS group has carried out a comprehensive and complete study;
- For high density glass scintillator, the light yield of GS group samples is in the absolute lead.

2.4 Small Size Sample

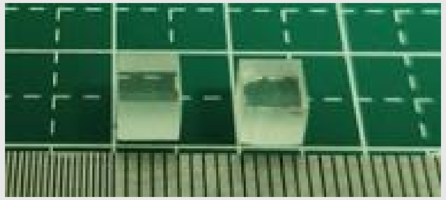
GFO & GFO+ （5mm×5mm×5mm）

GFO

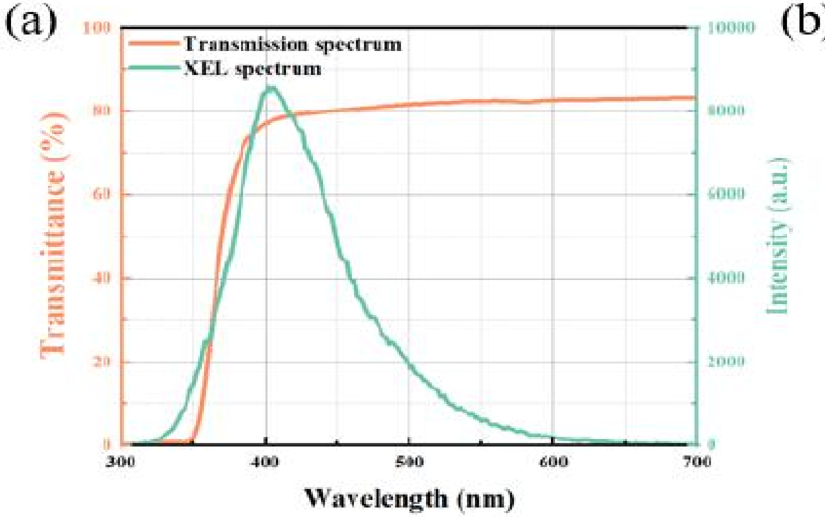


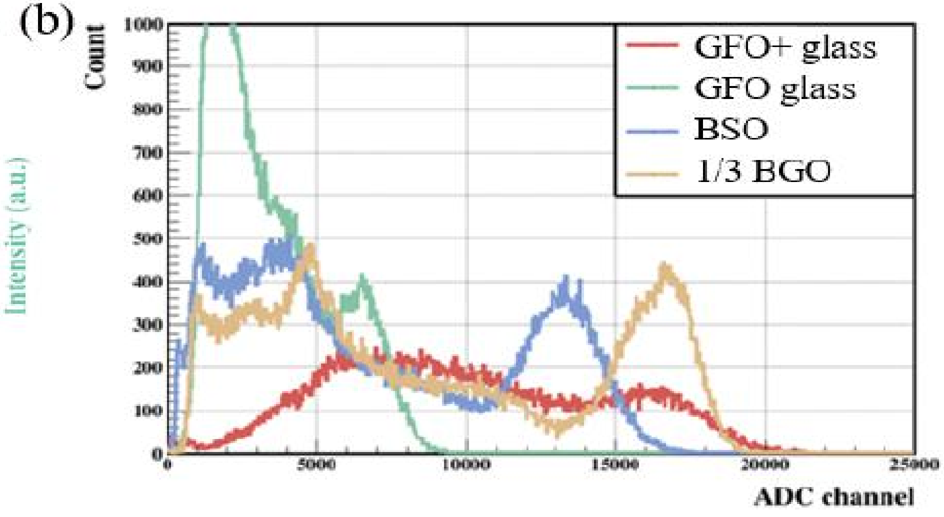
- Density~6.0 g/cm^3
- **LY=985 ph/MeV**
- ER=30.3%
- LO in 1μs=982 (99%)
- Decay=36 (8%), 105 ns

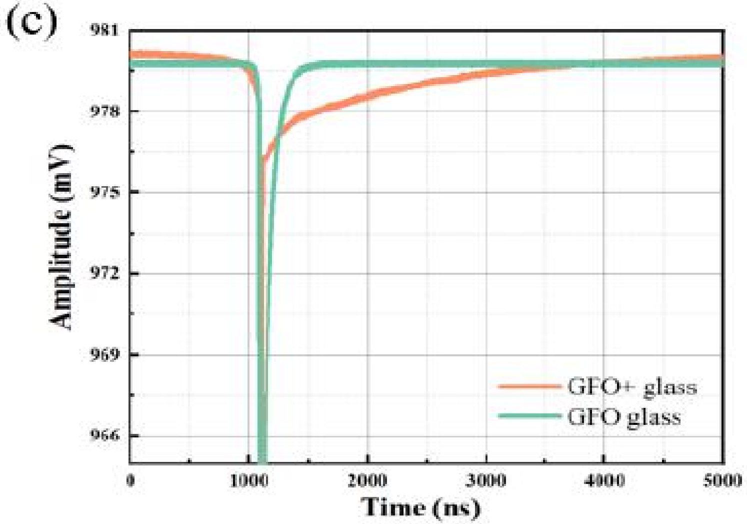
GFO+



- Density~6.0 g/cm^3
- LY=2445 ph/MeV
- ER=25.8%
- LO in 1μs=1074 (44%)
- Decay=101 (2%), 1456 ns





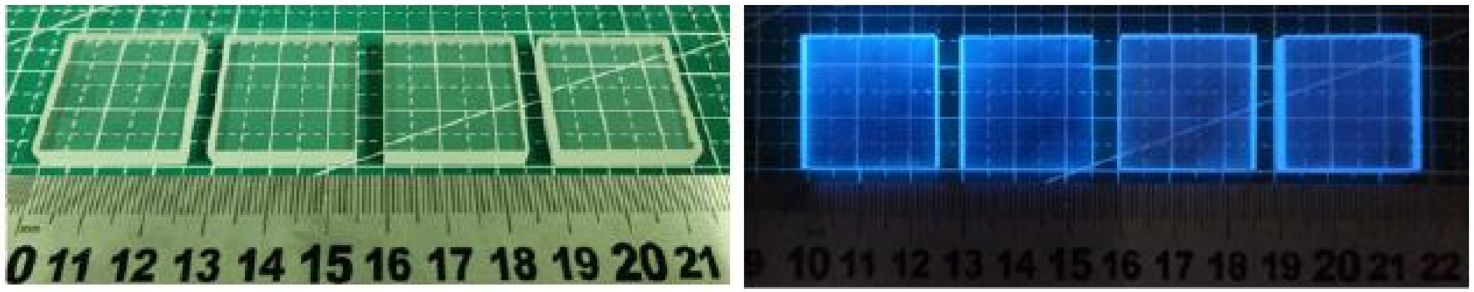


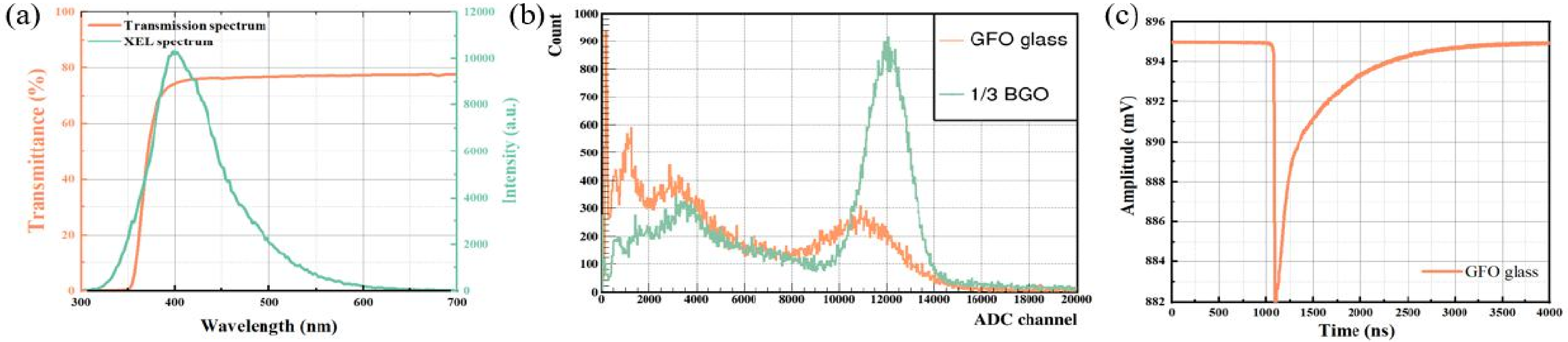
- (a) Transmission and XEL spectra
- (b) Energy spectra
- (c) Scintillation decay curves

2.5 Large Size Sample

GFO （40mm×40mm×10mm）

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





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

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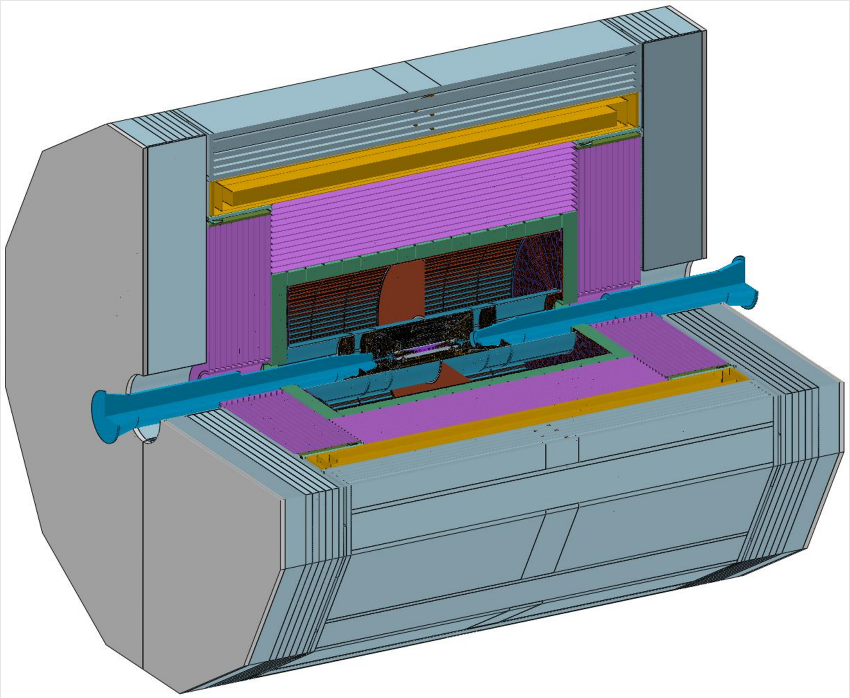
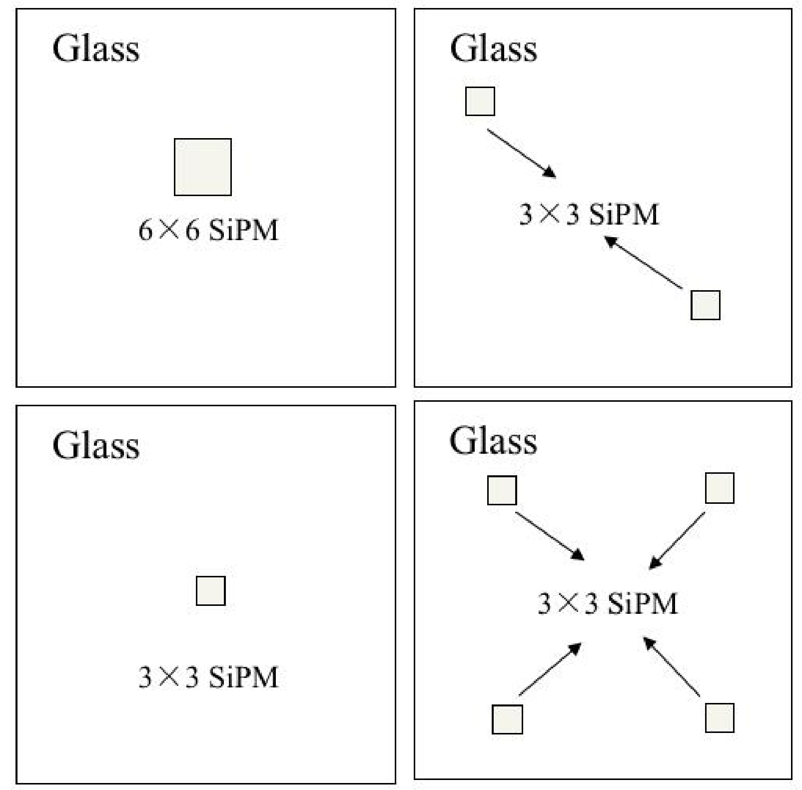
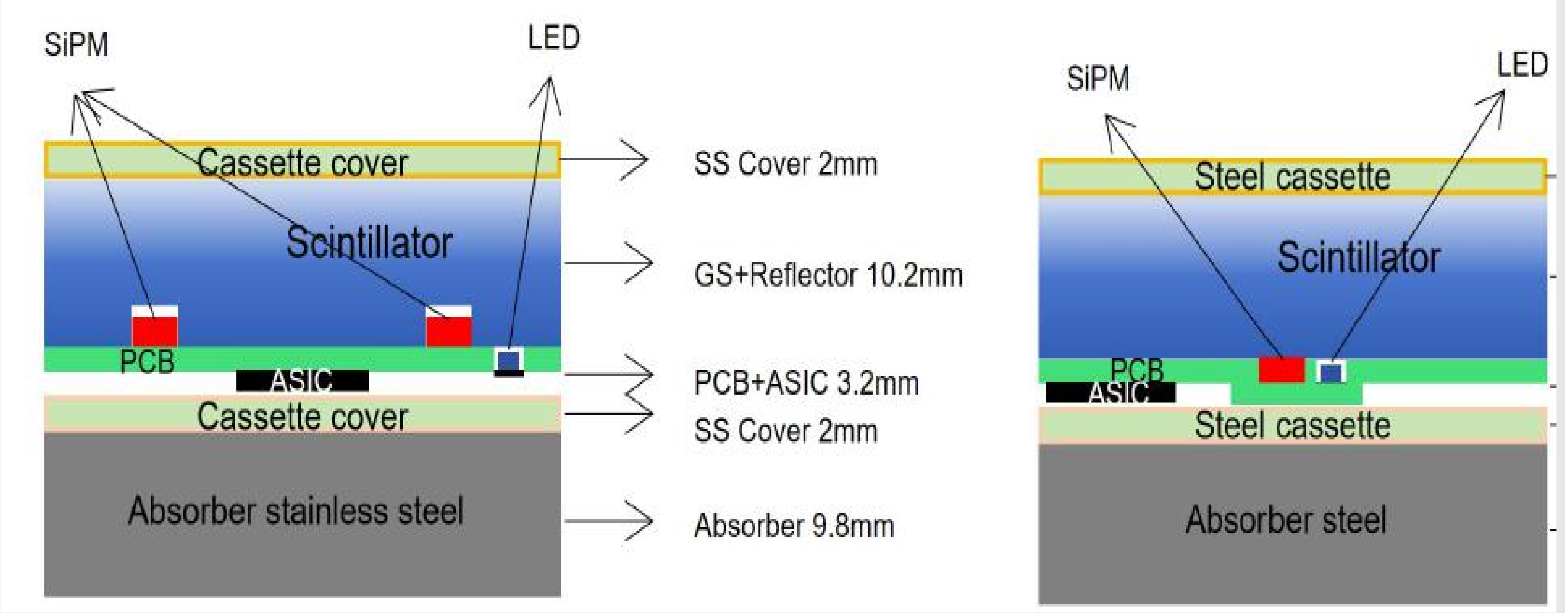


3.1 Detector Cell = GS +SiPM

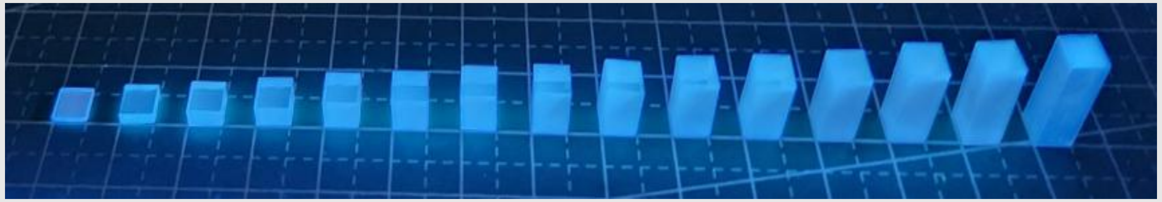


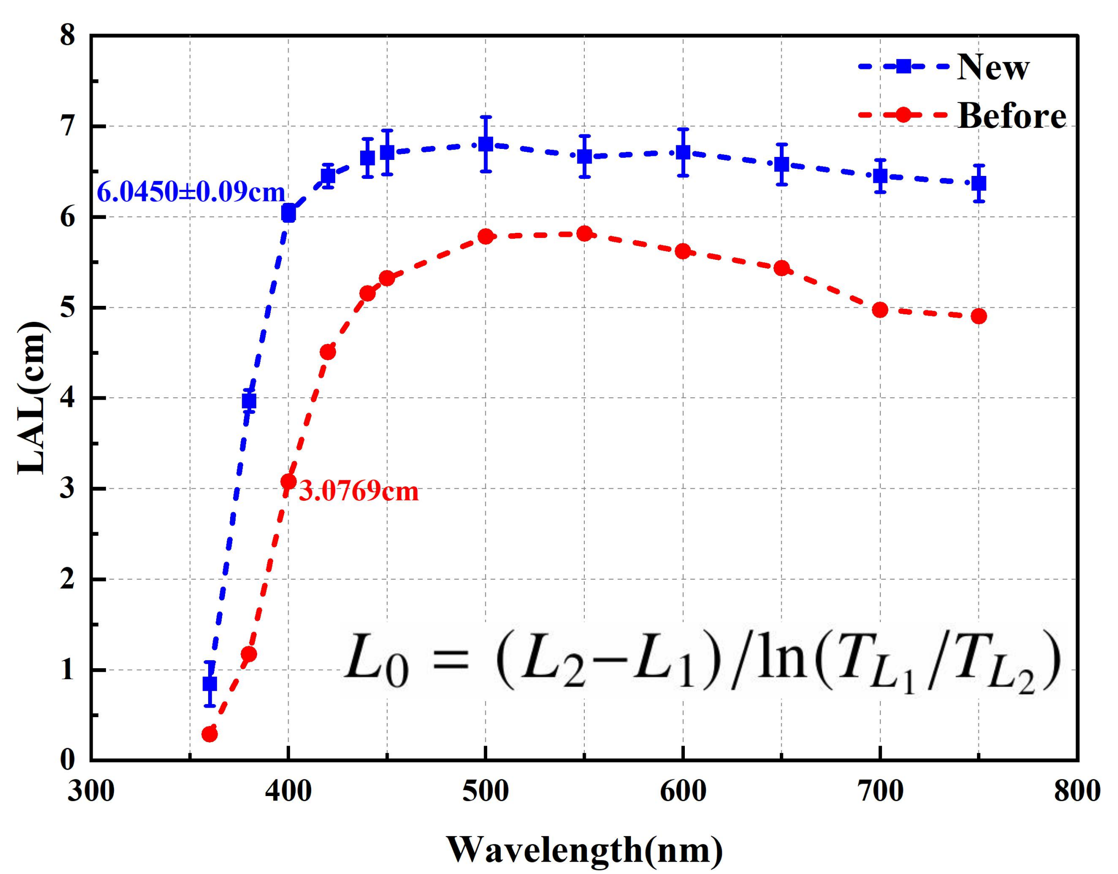


- at the beginning, light attenuation length is only ~23 mm, more SiPMs are needed to collect sufficient light.
- One scintillator is coupled with either 1, 2, or 4 SiPMs (3 mm × 3 mm SiPMs).
- There is a gap to hold the SiPM either in the GS or in the PCB. More tests are needed to determine the optimal position of this gap (in the glass or PCB) and to identify a low-cost and practical method for implementation.

3.2 Attenuation Length of new GS

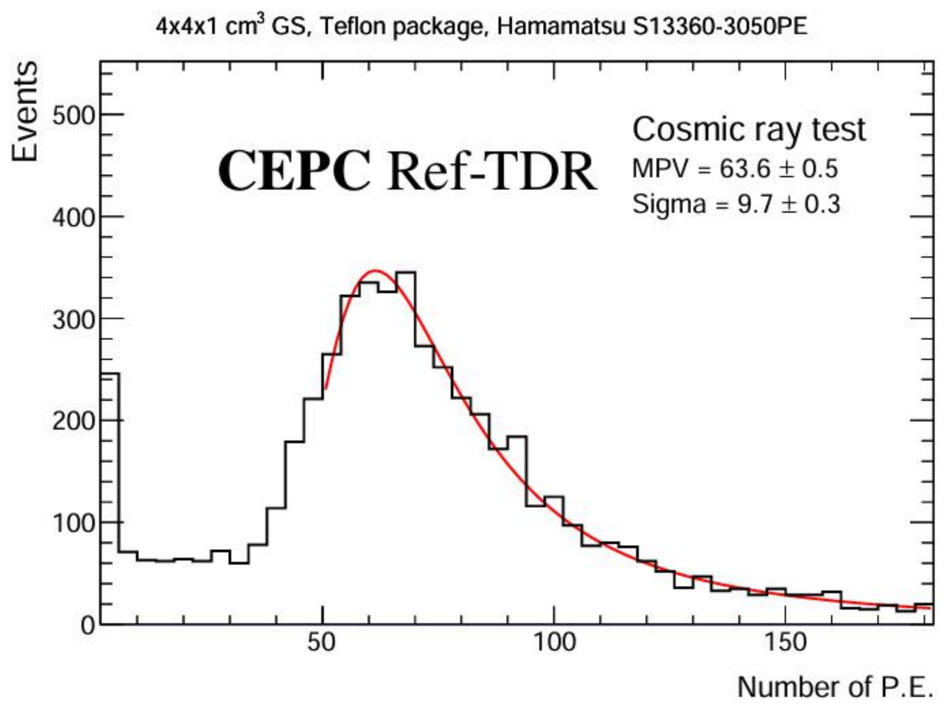
- GS samples before IDRC review
  - attenuation length: 3.1 cm @ 400nm
- NEW GS samples after IDRC review
  - attenuation length: 6.1 cm @ 400nm
- Feasible to use one SiPM per GS tile



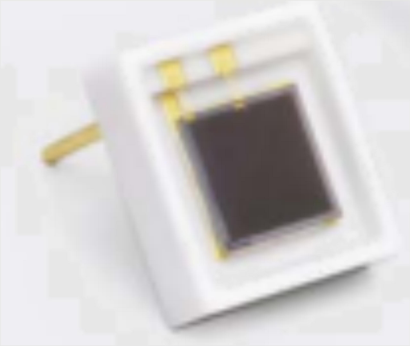


3.3 Performance of GS-SiPM coupling

- Cosmic ray test of GS-SiPM coupling
- Light output is ~ 64 pe/MIP



NDL EQR20

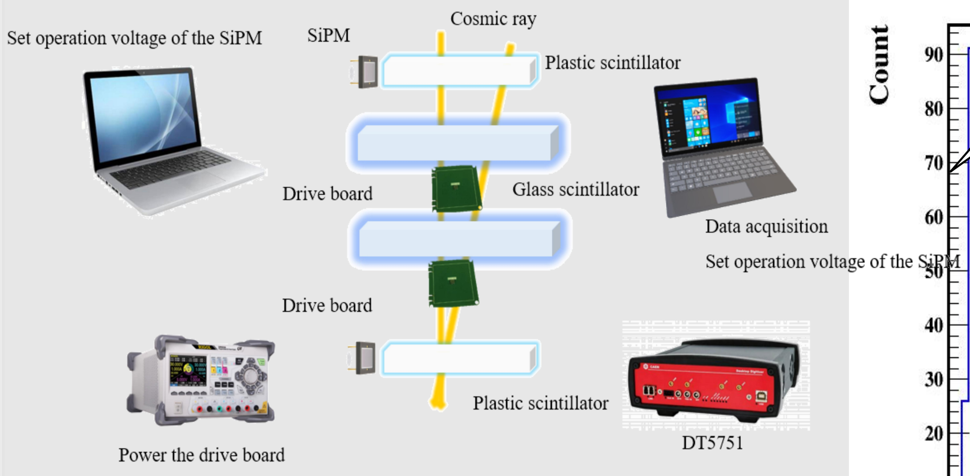


HPK S13360

- Mass production of high quality SiPM;
  - HPK S13360 ~22% PDE ➔ HPK S14160 ~43%
  - NDL EQR20 ~42% PDE ➔ NDL ~50%
- Cost of mass production (~5.3M)
  - GS: ~ 0.5 CHF/cc, SiPM: ~ 1.25 CHF/pcs

- Further Optimization of GS size, thickness, GS-SiPM couplings (air vs optical glue).

3.4 Cosmic Ray test result



1.BGRI-146L 40×40×10 mm³

2.BGRI-4# 40×40×20 mm³

•Detector:

1. NDL EQR20 11-3030 3×3 mm²,

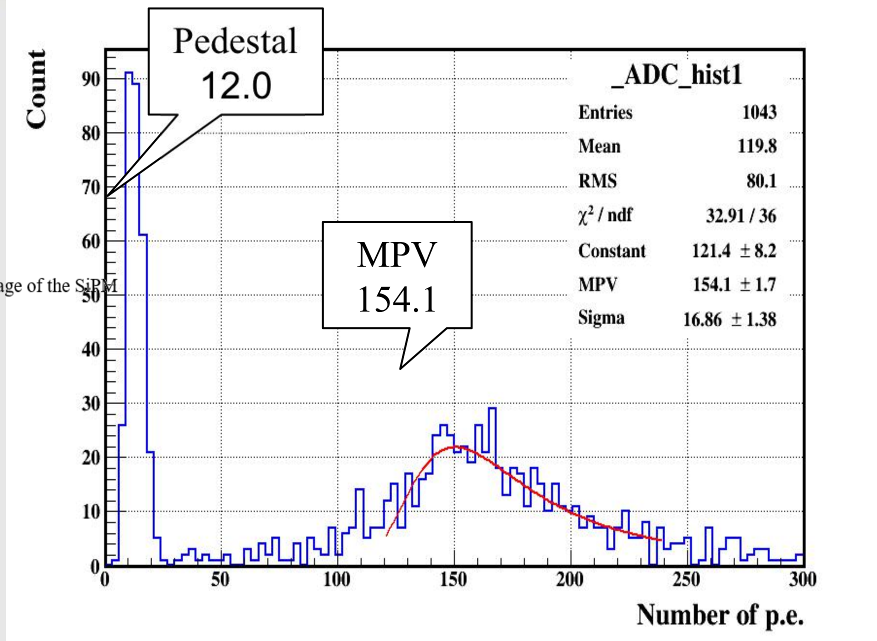
Weighted PDE=42.5%

•Reflector: Teflon

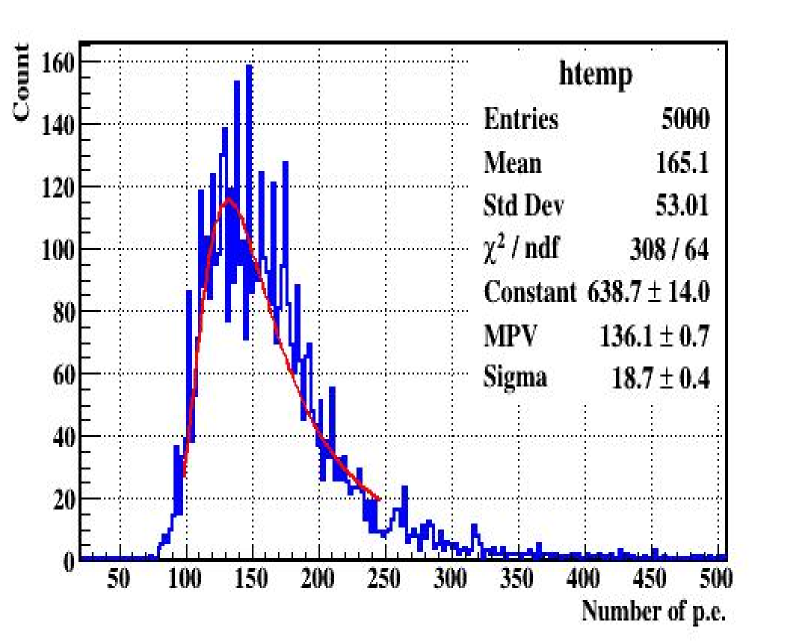
•DAQ: DT5751 Integral time=1000 ns

•Trigger: PS 30*30*10 mm³×2

•Distance: 5 cm



Cosmic ray test (ADC pedestal deducted)



MIP response simulation for Muon

MIP Response (p.e./MIP)	
Cosmic ray experiment	G4 Muon simulation
142.1±1.7	136.1±0.7

3.5 GS Beam Test at KEK

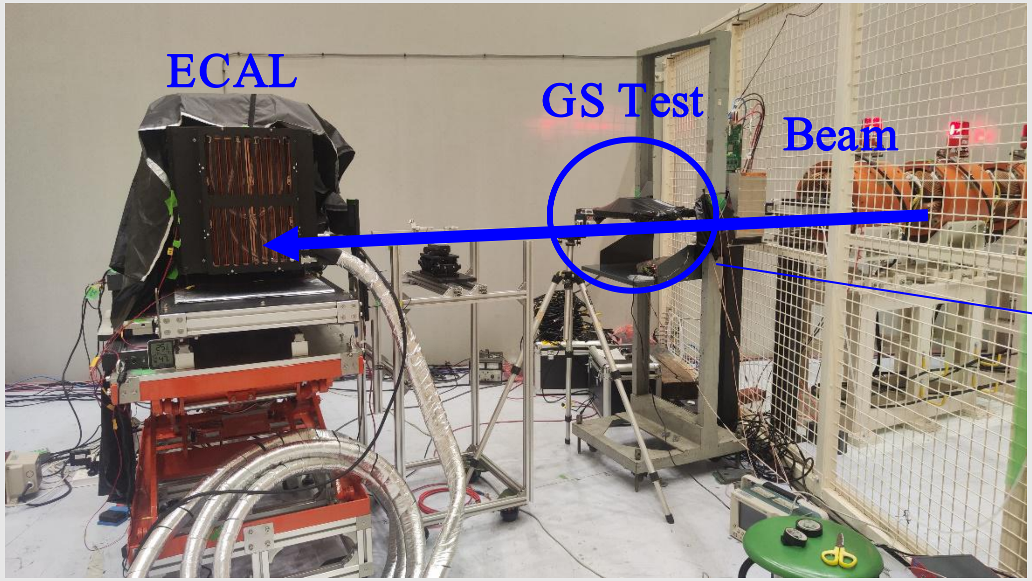
- GS tile size: 4 × 4 × 1 cm^3 & 1 SiPM (3×3 mm2) for each GS tile

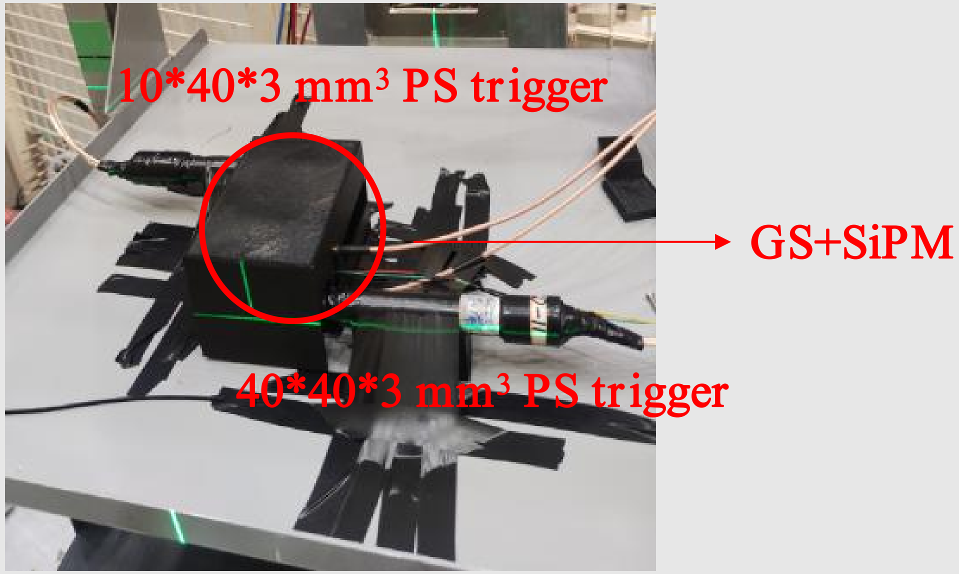
KEK test beam in 2025.6

- 5 GeV electron
- 1.6 kHz (from beam line)

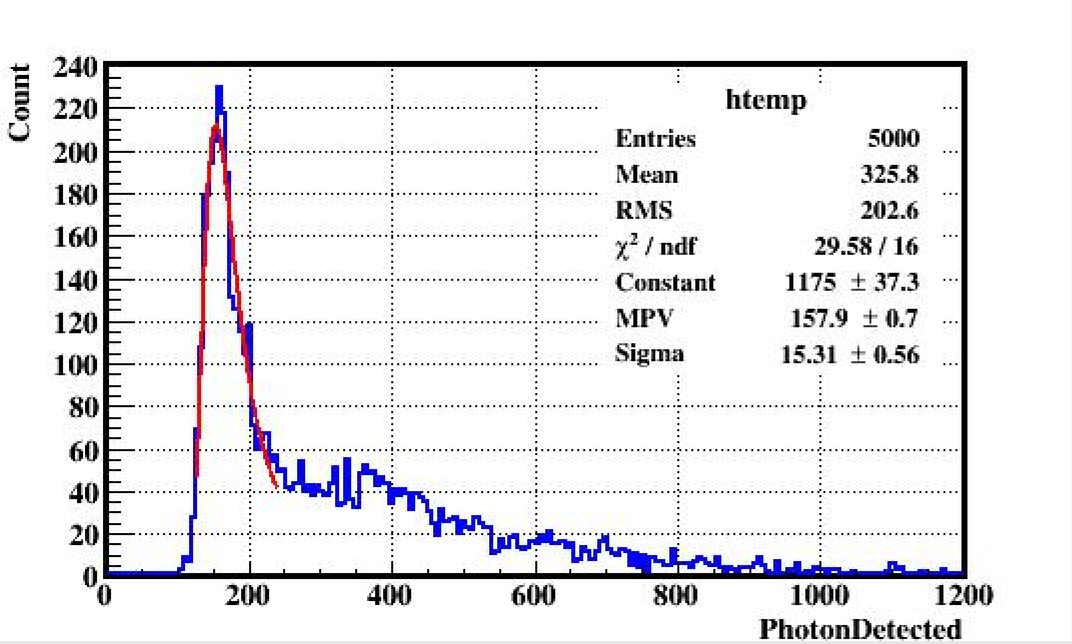
Experimental goals for GS-HCAL

- MIP response calibration with low-energy electron for GFO glass
- Compare light output with previous samples measured by DESY
- Compare wrapping effects of different reflectors (Teflon, Tyvek, TiO2)
- Compare performance of various SiPMs from different manufacturers

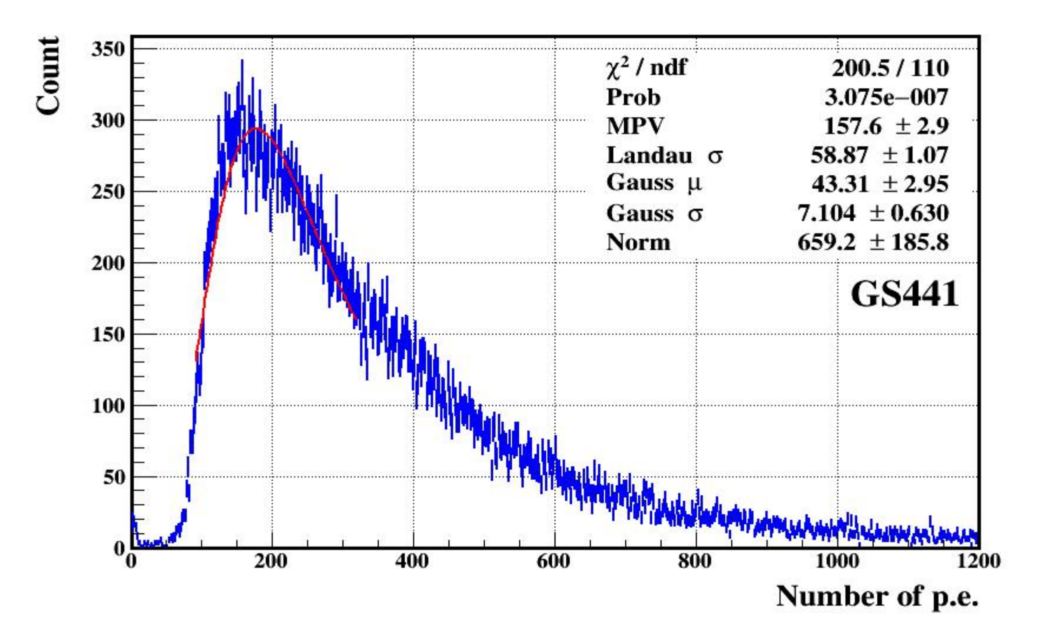




Electron beam test result



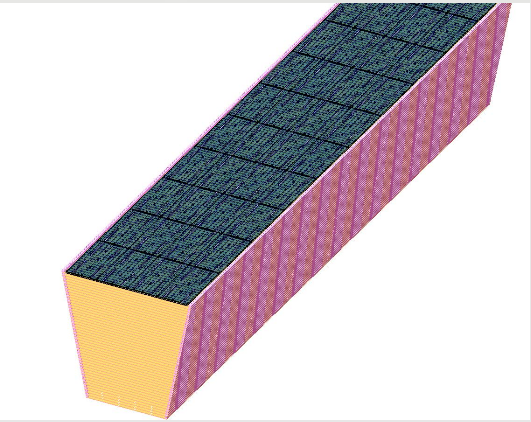
MIP response simulation for electron beam

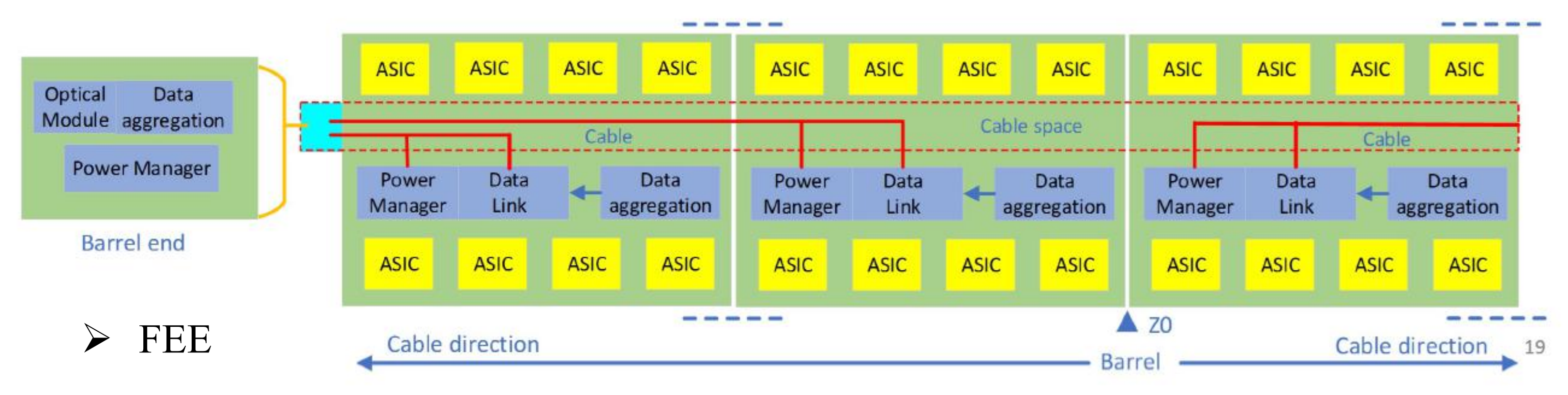


KEK electron beam test

GS	Reflector	MIP Response (p.e./MIP)	
		NDL 3030 (Weighted PDE=42.5%)	
		Simulation for Electron	Electron Beam Test
BGRI-146	Teflon	157.9±0.7	157.6±2.9

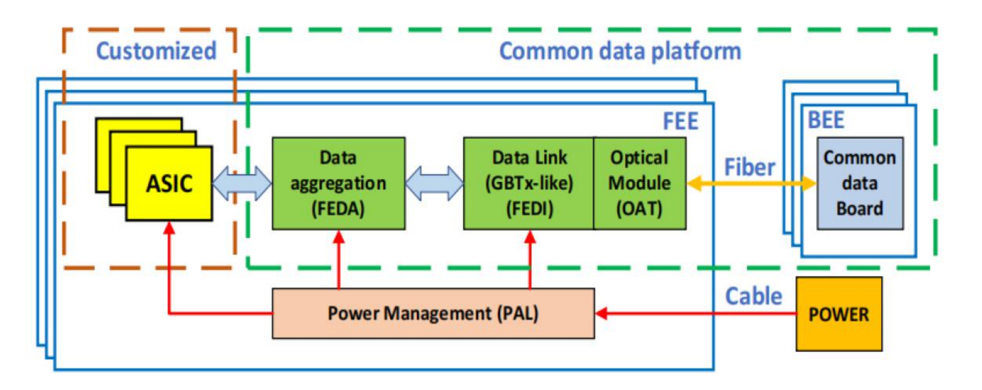
3.6 Readout Electronics





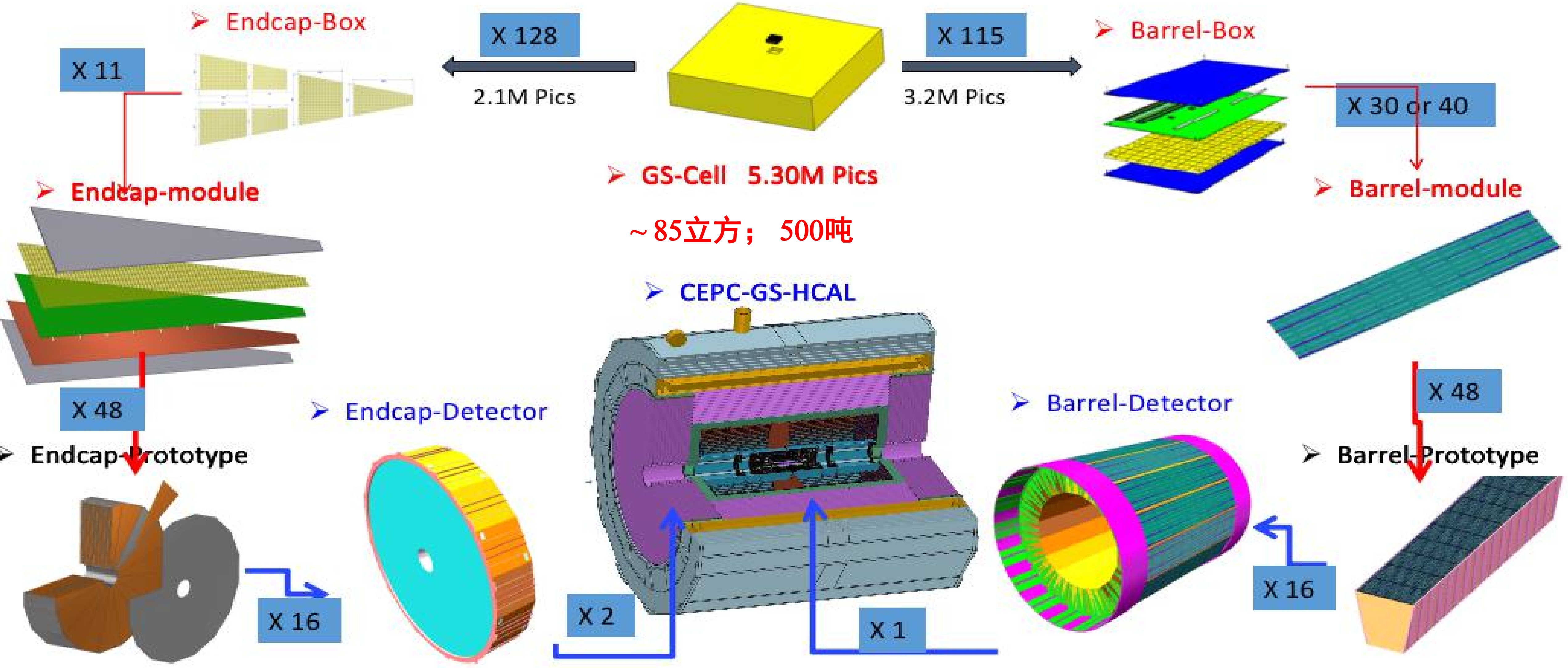
➢ FEE

- 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

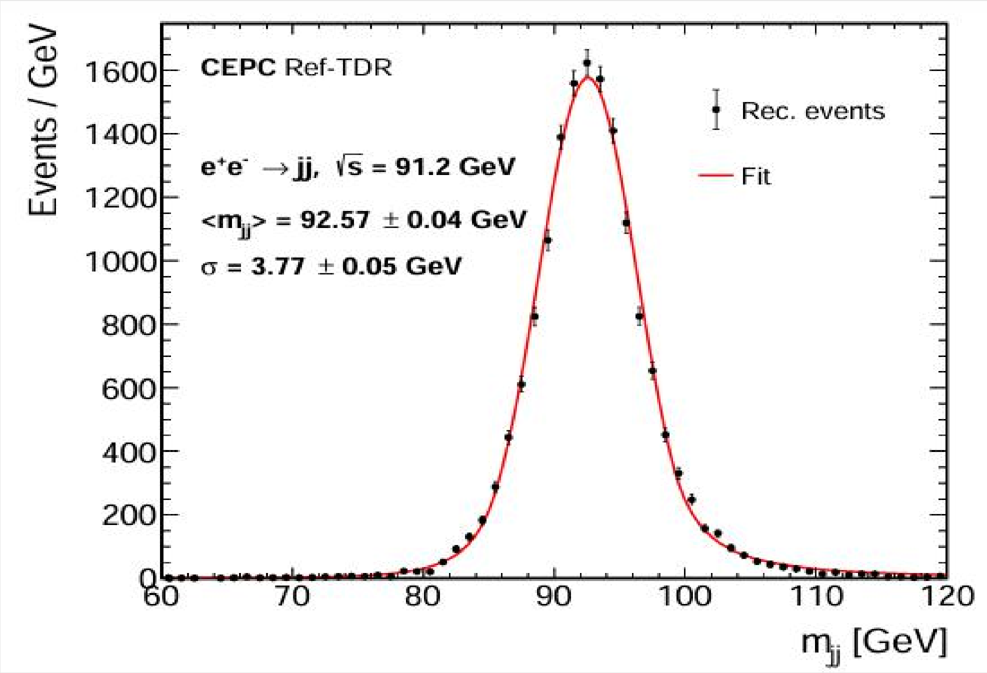
3.7 Overview of the Mechanics



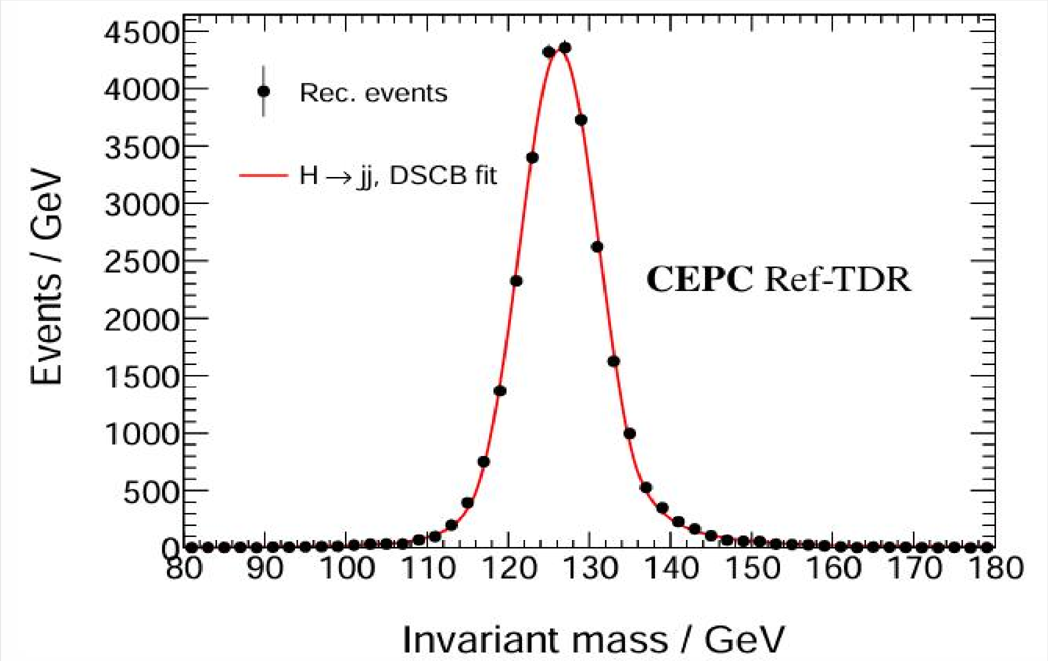
3.8 GS-HCAL Physics Performance simulation

- **Hadron Energy Resolution (full simu. + digitization):**
  - MC Sample: ee→Z→jj @ 91.2 GeV, ee→ZH→ nngg @ 240 GeV
  - Tracker (Si + TPC) + Crystal ECAL + GS-HCAL, Cyber PFA Reconstruction

BMR (Z→jj) = 4.0%



BMR (H→gg) = 3.87%



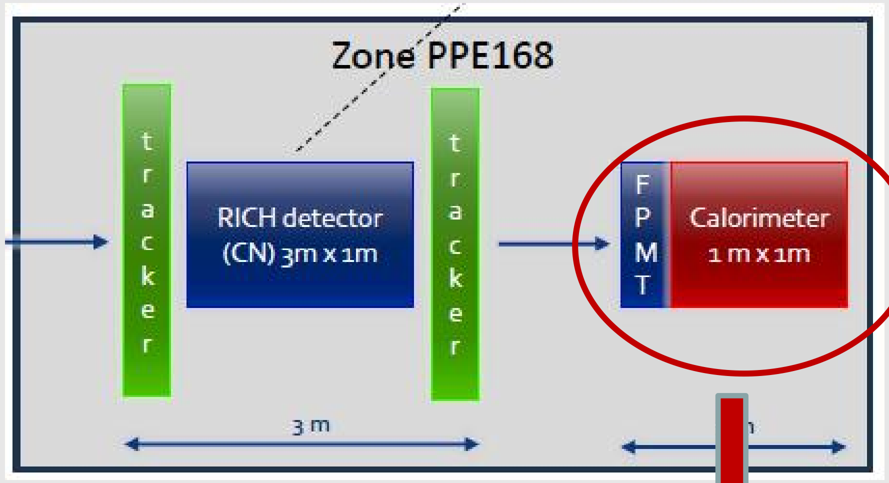
Outline

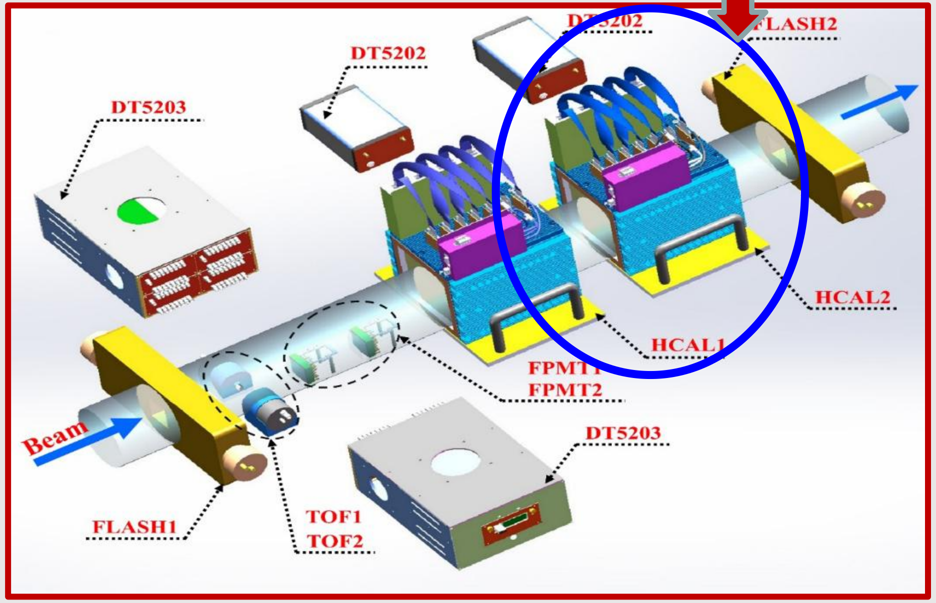
- 1. Motivation for GS-HCAL
- 2. R&D of the GS
- 3. Design of the GS-HCAL in CEPC
- 4. Summary and Next Plan

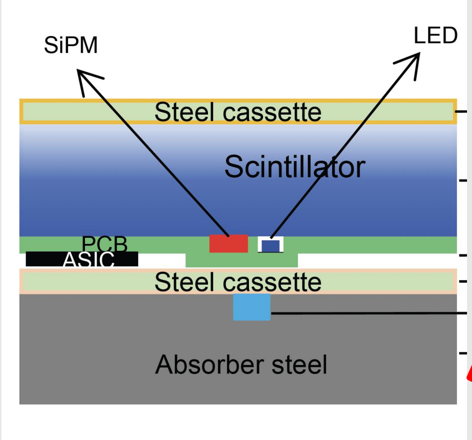
Summary and Future Plans

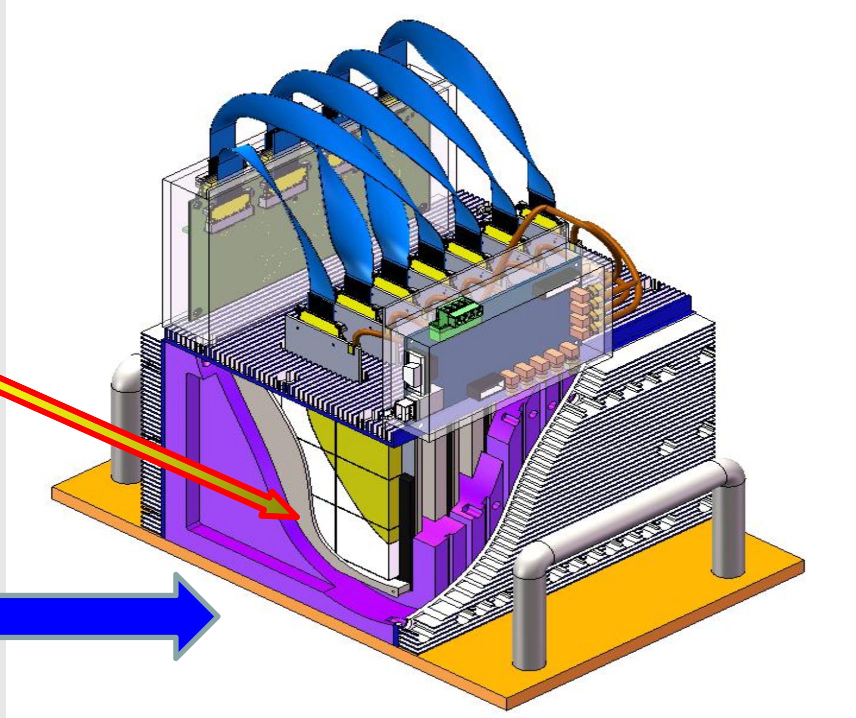
- **Physics requirement for the design:**
  - Hadron energy resolution < 5 %
  - Boson mass resolution (BMR) < 4%
- **GS-HCAL is selected as baseline based on its promising performance**
  - Intensive R&D on high quality GS (e.g. light yield, decay time, attenuation length)
  - Update design of GS-HCAL mechanics, cooling and readout electronics
  - Preliminary study with CEPCSW shows promising result which is feasible for Ref-TDR
- **Future R&D plans**
  - To further optimize GS size, GS-SiPM coupling, cooling and readout electronics
  - To optimize simulation, digitization, reconstruction and analysis chain
  - To develop techniques for mass production of GS, SiPM with low cost
  - To prepare full-size GS-HCAL prototype with integrated electronics for beam test

GS-HCAL Mini-prototype







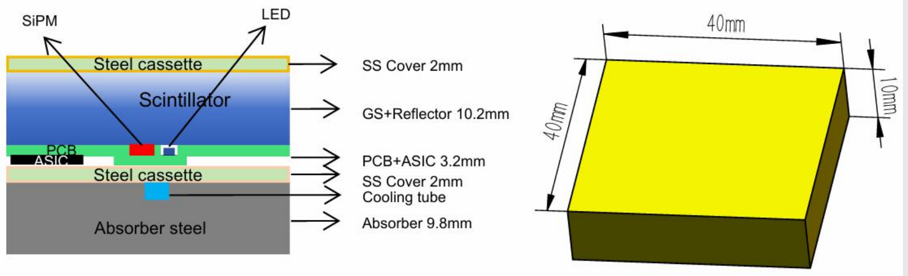


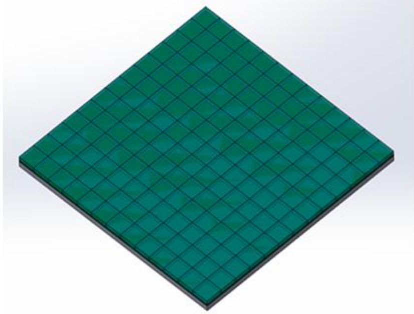
- **Mini-Prototype:** 7 layers, each layer has 3×3=9 GS tiles, 63 GS tiles in total, each GS size of 4×4×1 cm^3
- **Two mini-prototypes** using HPK & NDL, respectively
- **CERN beam tests** (Pion / Muon) **in October 2025**

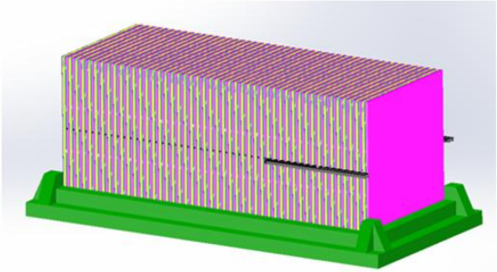
GS-HCAL Full-size Prototype

- Plan towards a full-scale prototype
  - Step 1: test beam of new GS tiles at KEK (2025.6)
  - Step 2: test beam of mini-prototype at CERN (2025.10)
  - Step 3: batch production & test of ~10k GS (2025-2026)
  - Step 4: build full-scale prototype with ~8k GS tiles (2026)
  - Step 5: test beam of full-scale prototype (2027)
- Full-scale GS-HCAL prototype (2025-2026)
  - Total: 48 layers, Total GS tiles: 13 × 13 × 48 = 8112
  - Each layer: 13 × 13 GS tiles (52 × 52 cm2)
  - GS tile size: 4 × 4 × 1 cm^3
  - 1 SiPMs (3×3 mm2) for each GS tile
  - ASIC Chip with power consumption of 15mW/ch
  - Stainless steel as absorber and covers: 13.8mm

- Test beam plan (2027)
  - CERN: PS or SPS
  - KEK (Japan): 5 GeV electron
  - HEPS (China): 6 GeV electron







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REVIEW

OPEN ACCESS

Glass scintillator: A window to future high-energy radiation detection

Zexuan Sui,[1,2] Sen Qian,[1,2,*] Luyue Niu,[1] Peng Hu,[3] Zhehao Hua,[2] Xiaoxin Zheng,[1] Xinyuan Sun,[4] Gao Tang,[5] Hua Cai,[6] Dong Yang,[7] Weichang Li,[8] Minghui Zhang,[9] Jifeng Han,[10] and Jing Ren[1,*]
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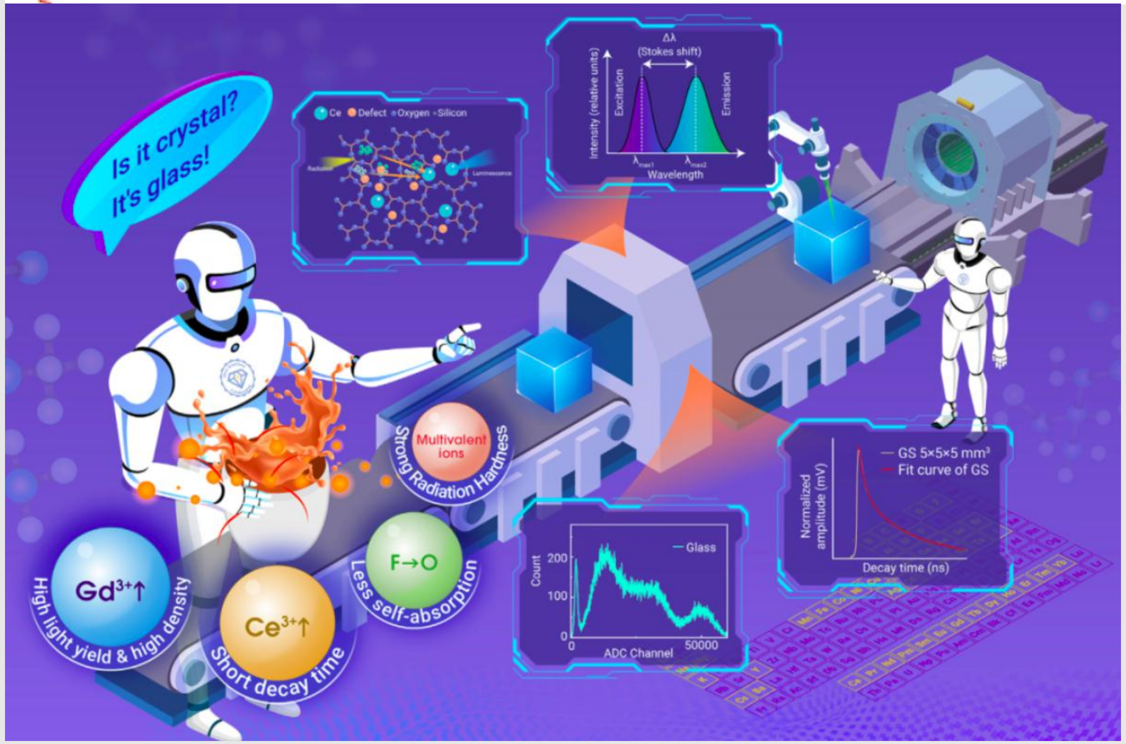
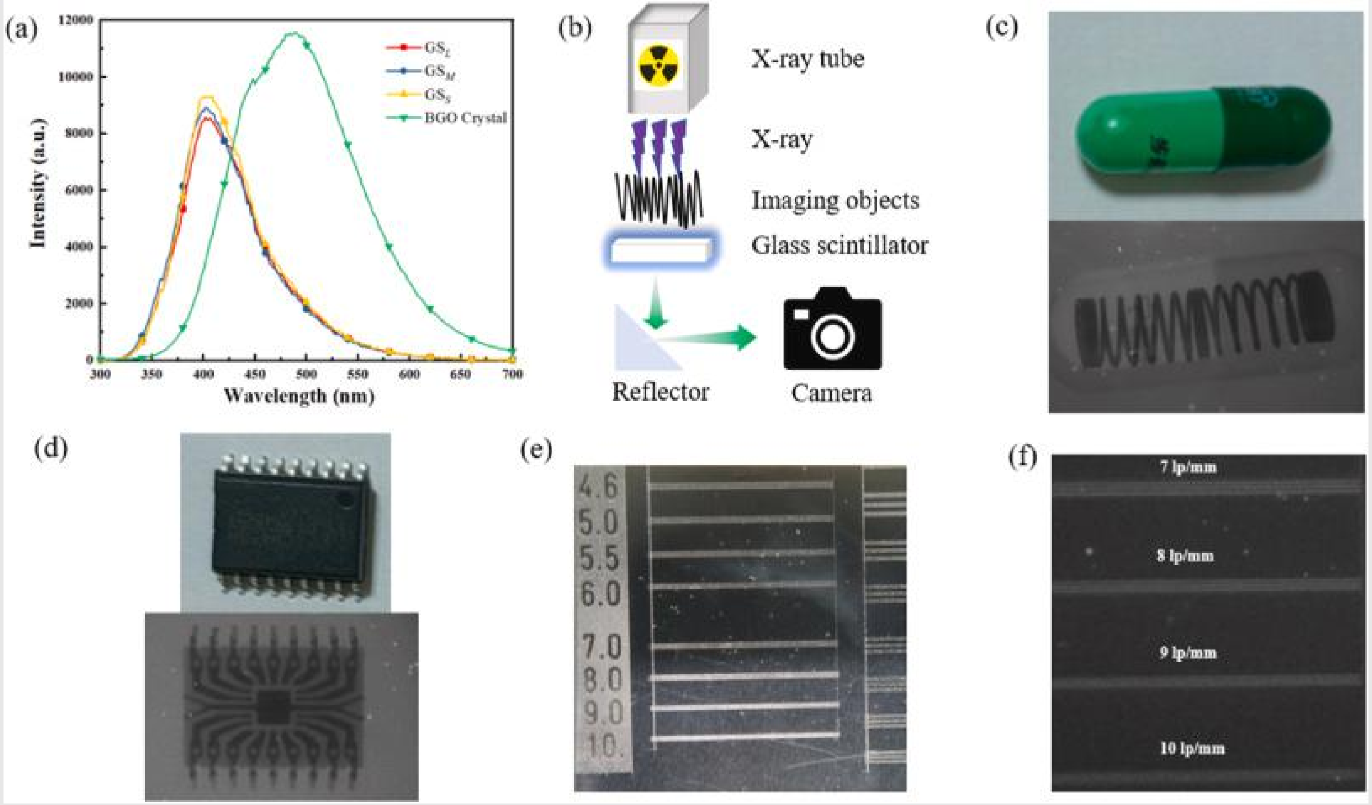


Glass Scintillator Collaboration

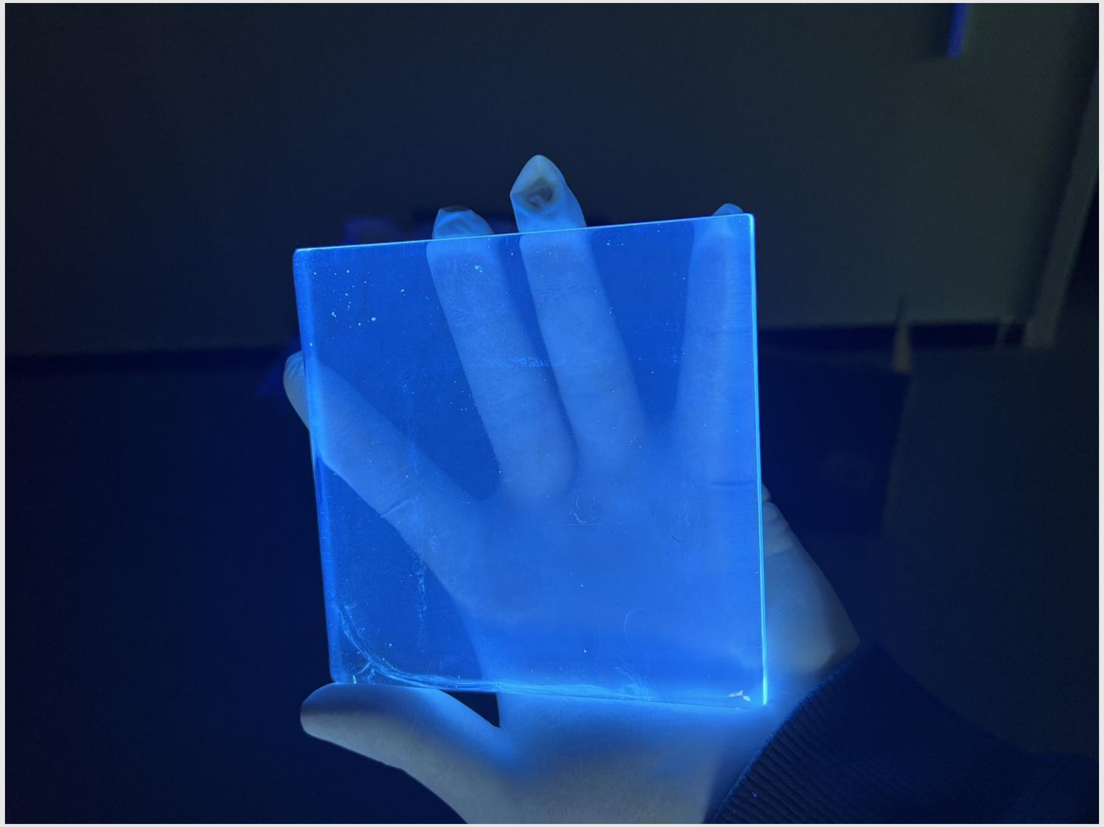
闪烁玻璃合作组
Glass Scintillator Collaboration

DOI:10.1016/j.xinn.2025.100878；
Sui Z., Qian S., Niu L., et al. (2025). Glass scintillator: A window to future high-energy radiation detection. The Innovation 6:100878.

The Application of the Glass Scintillator



Ultra-Large size glass （12.5cm X 122cm）

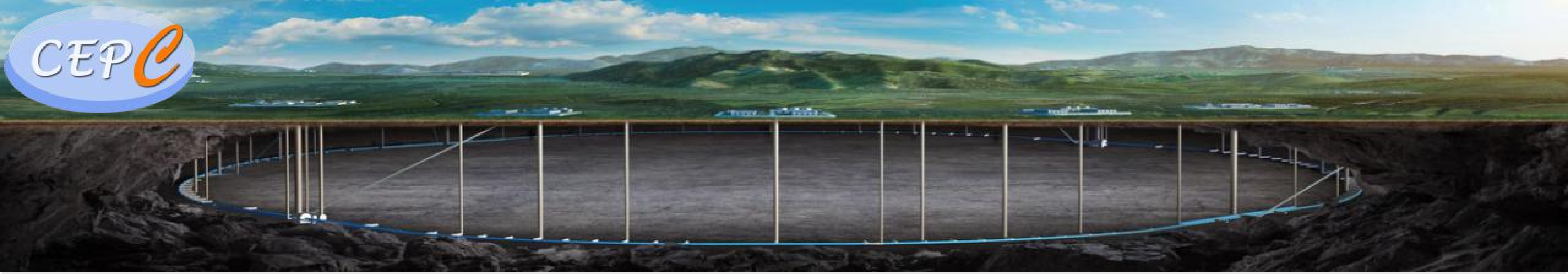


From: Adv. Opt. Mater. 2025, 2403243

From: Ceram. Int., 50 (2024) 47253–47258

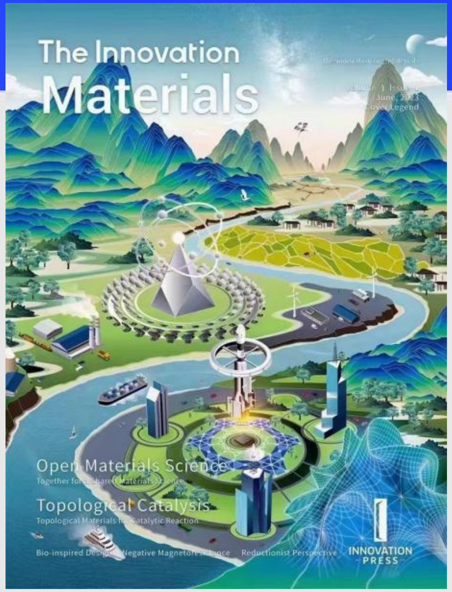
From: Ceram. Int., 2025.02.151

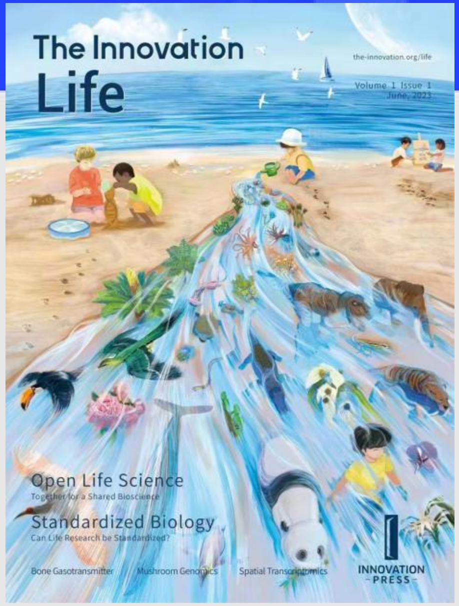
Thanks for your attention!

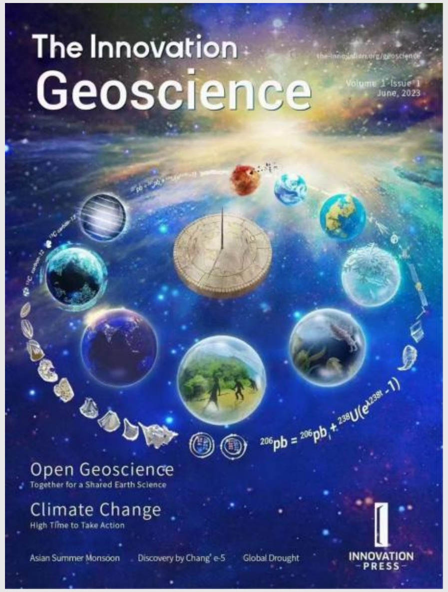


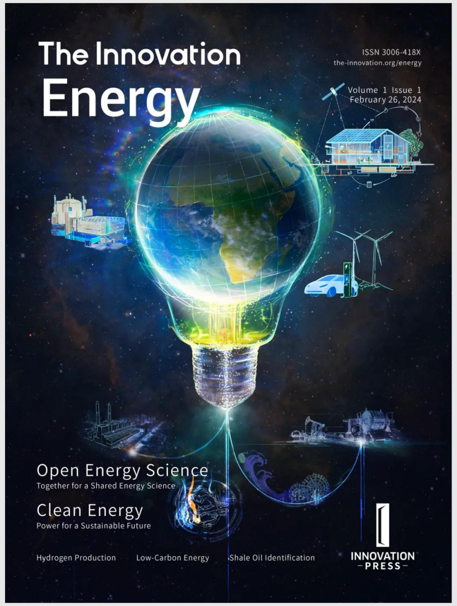
Backup slides

Impact Factor=33.1

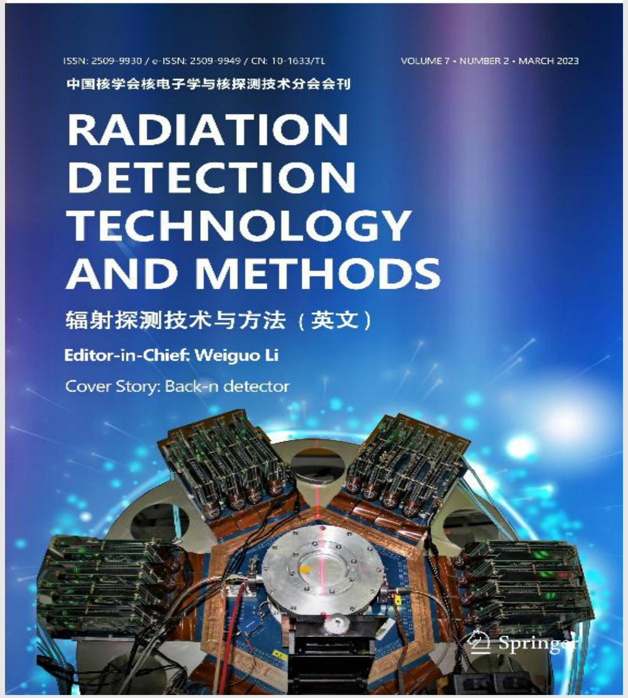


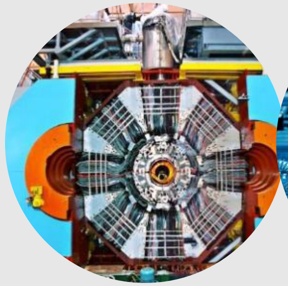




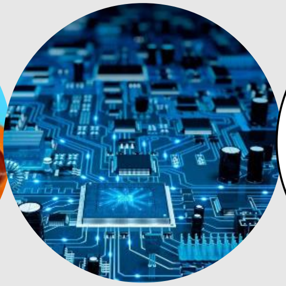


核电子学与核探测技术 & Radiation Detection Technology and Methods

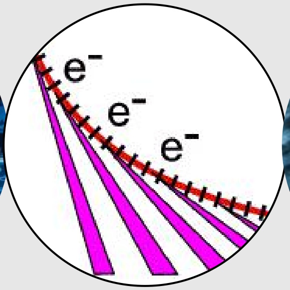




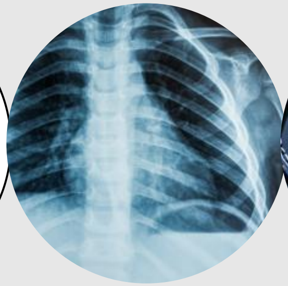
核探测
技术



核电子学
技术



加速器
技术



核医学
技术

同步辐射
技术

计算机
技术

天体粒子
技术

HCAL Research Group

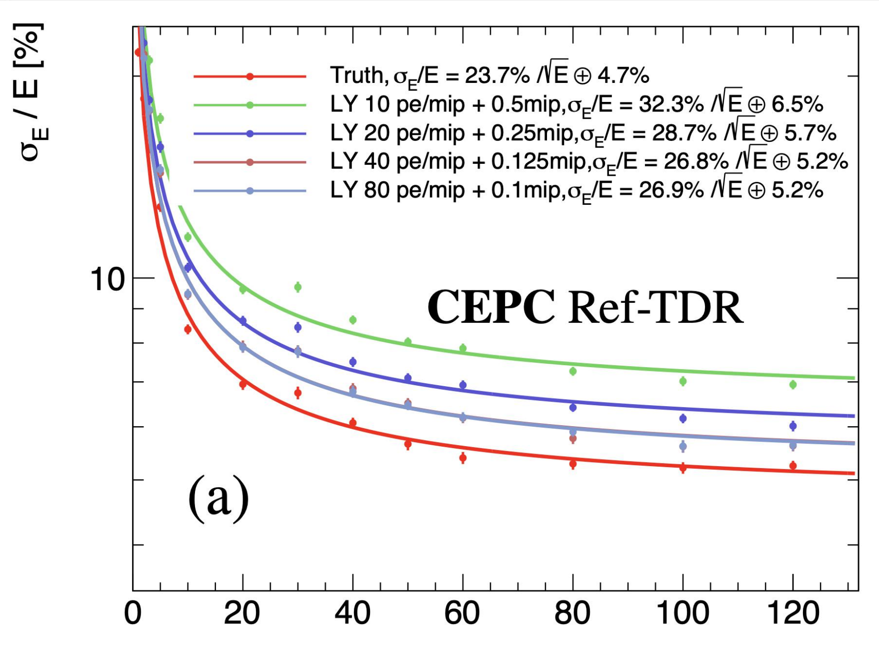
- Actively involve in DRD-Calo Collaboration
- CEPC-HCAL team: IHEP, USTC, SJTU, XJTU, SCNU, SCU, HEU, ZZU
  - Detector for PS/GS-HCAL: Staff(9) + Student(10)
  - Electronics: Staff(5), Mechanics: Staff(3)
  - GS Collaboration: 13 institutes, Staffs (26) + Students (10)

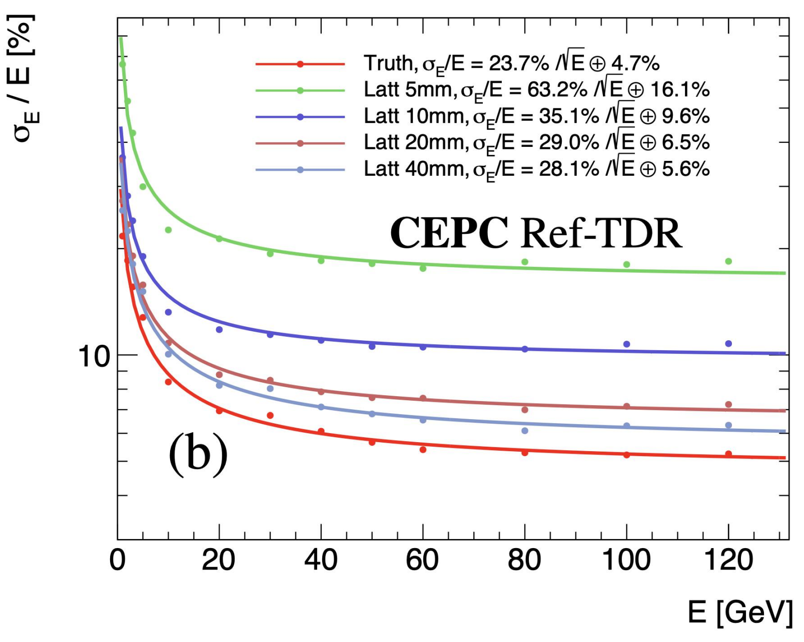
Convener: Sen Qian (IHEP), Jianbei Liu (USTC)
Physics: Manqi Ruan(IHEP), Haijun Yang (SJTU)
Software: Sengsen Sun(IHEP)
Design: Fangyi Guo(IHEP), Hengne Li(SCNU), Qingming Zhang(XJTU), Weizheng Song(IHEP), Peng Hu(261)
Dejing Du(IHEP), Hongbing Diao(USTC), Jiyuan Chen(SJTU), to design the GS-HCAL based 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;

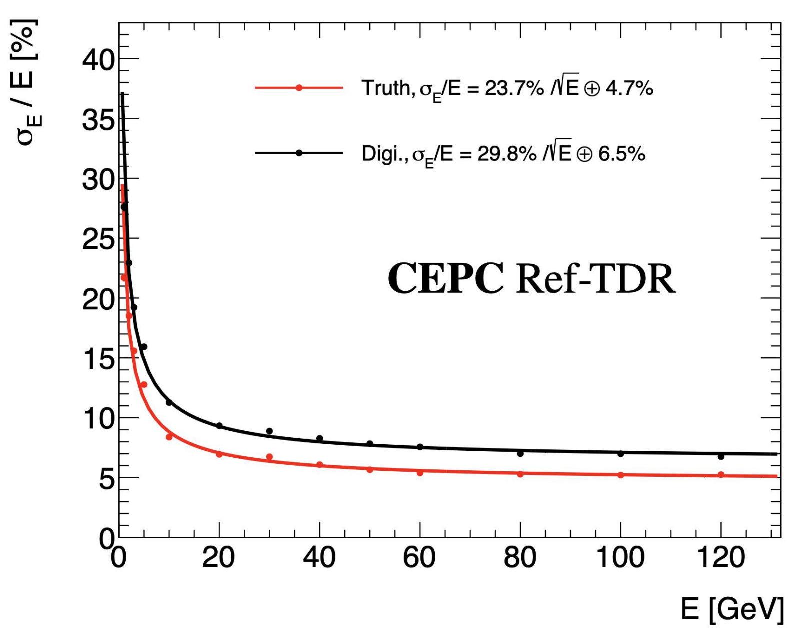
GS-HCAL Energy Resolution

- **A full detector geometry constructed with DD4hep in CEPCSW**
  - GS density 6 g/cm^3, λ_I = 242.8 mm, attenuation length ~ 60 mm
  - GS cell size $4\times4\times1$ cm^3, 48 layers, $6\lambda_I$ in total
  - Geometry: follow the mechanics design with supporting structures.

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







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

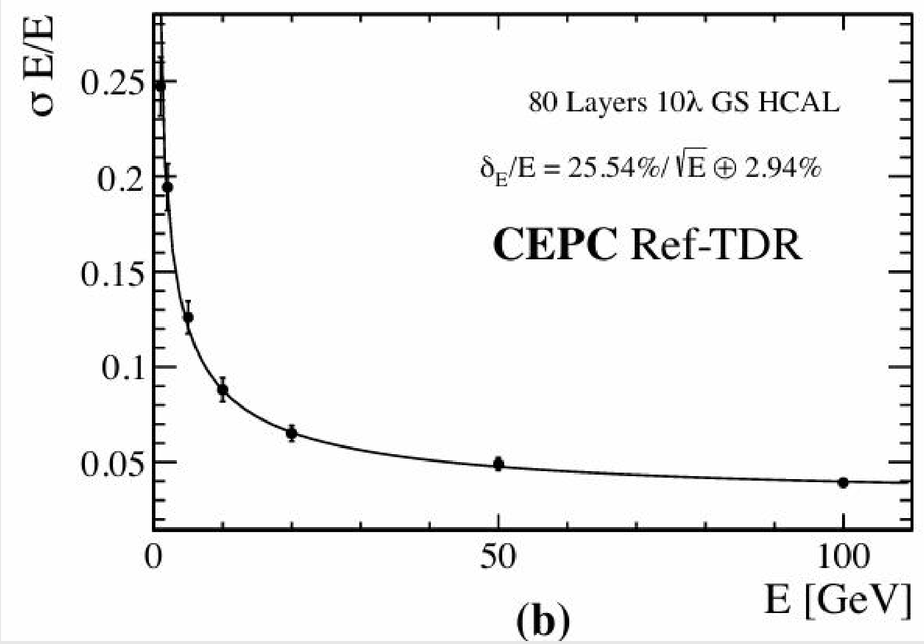
- GS attenuation length

- GS attenuation length: ~60 mm

GS-HCAL Constant Term

- **GS-HCAL in full simu+digi:** 6λ, $\frac{\sigma_E}{E} = \frac{29.8\%}{\sqrt{E}} \oplus 6.5\%$ (**all events**)
  - Large HCAL (80 layers, 10λ): $\frac{\sigma_E}{E} = \frac{24.7\%}{\sqrt{E}} \oplus 2.9\%$
  - Shower starts at the first 2 layers: $\frac{\sigma_E}{E} = \frac{25.9\%}{\sqrt{E}} \oplus 3.5\%$

80 layers (10λ)



- Large constant term in GS-HCAL is mainly due to longitudinal shower leakage, combining ECAL(1.2 λ_I) and HCAL(6 λ_I) helps to reduce leakage
- Software compensation is expected to reduce constant term