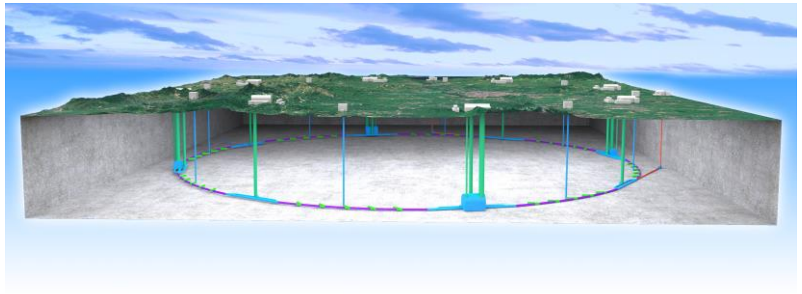
R&D Progress of AHCAL option with glass scintillator tiles

Dejing Du (Institute of High Energy Physics, CAS)
On behalf of CEPC Calorimeter Working Group

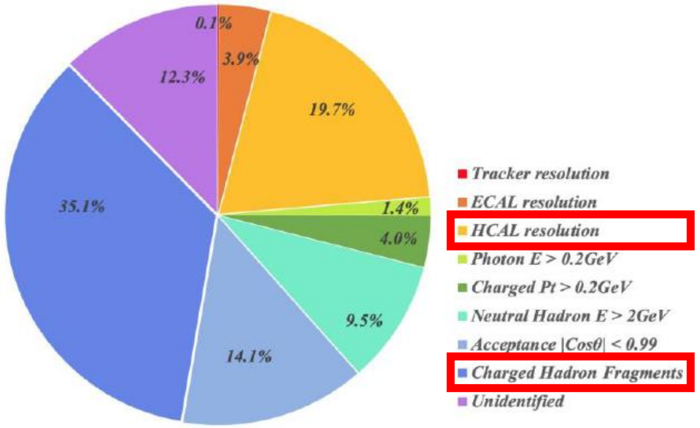
CALICE Collaboration Meeting
March 30, 2023

Motivations

- Future electron-position colliders (e.g. CEPC)
  - Main physical goals: precision measurements of Higgs/Z/W bosons
  - Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$
- CEPC detector: highly granular calorimeter (PFA-oriented)
  - Boson Mass Resolution (BMR) ~4% in baseline design
  - Further performance goal: BMR 4%→3%
  - Dominant factors in BMR: charged hadron fragments & HCAL resolution
- New option: glass scintillator HCAL (GS-HCAL)
  - Same as Scintillator-Steel AHCAL: replace plastic scintillator with glass scintillator
  - Higher density provides higher energy sampling fraction



All Factors in BMR based on PFA



By Yuexin Wang

Outline

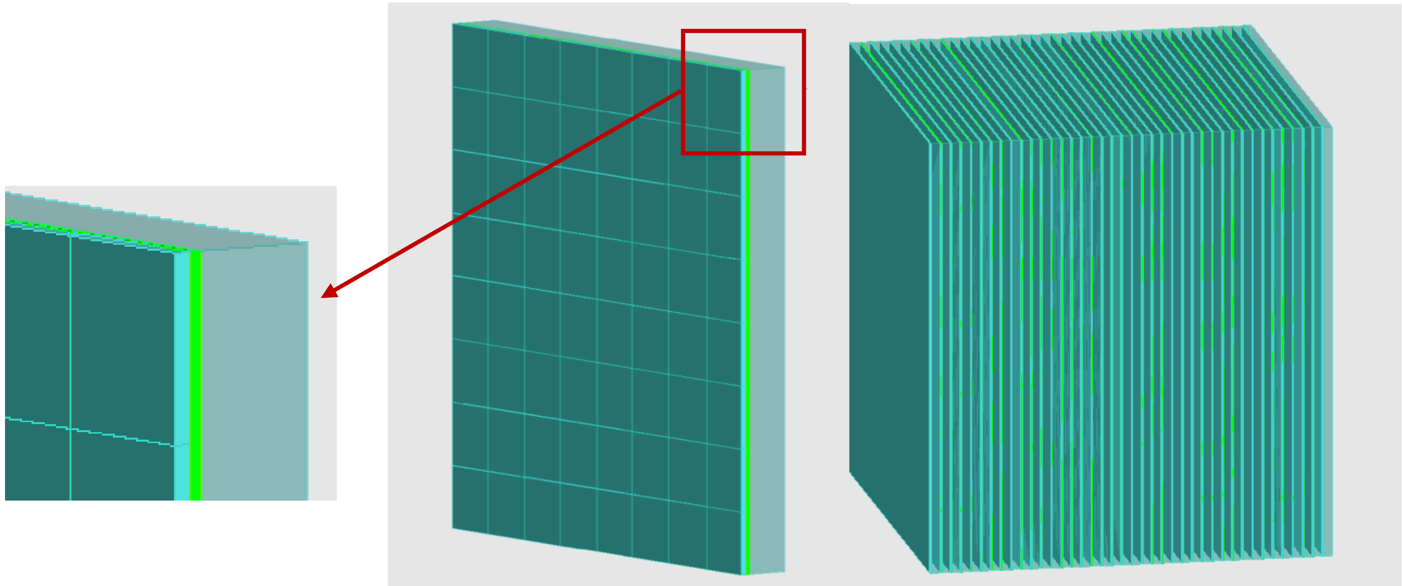
- Motivations
- Standalone simulation of GS-HCAL
  - Impact of sampling fraction and density
  - Energy linearity and resolution with single hadrons
- PFA performance with GS-HCAL
  - Key parameters: glass density and cell size
  - Optimized performance
- Glass scintillator material R&D
  - The improvement of key properties
  - The preparation of large-scale glass scintillator
- Summary

Outline

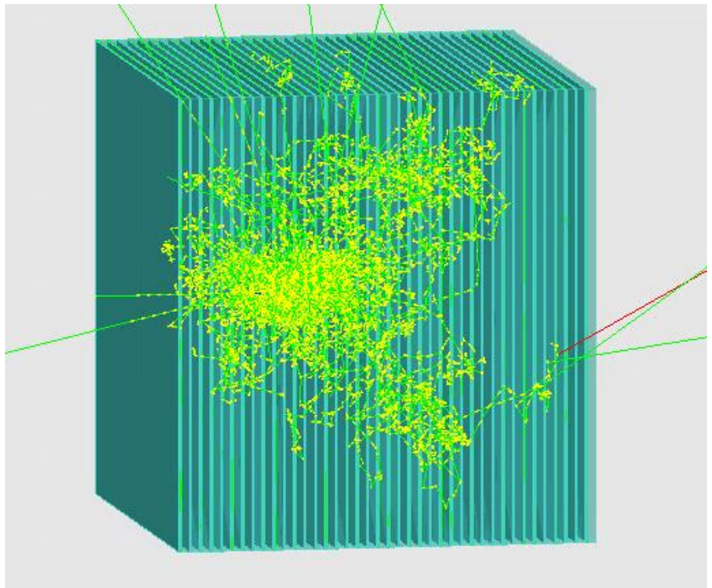
- Motivations
- Standalone simulation of GS-HCAL
  - Impact of sampling fraction and density
  - Energy linearity and resolution with single hadrons
- PFA performance with GS-HCAL
  - Key parameters: glass density and cell size
  - Optimized performance
- Glass scintillator material R&D
  - The improvement of key properties
  - The preparation of large-scale glass scintillator
- Summary

HCAL setup in standalone simulation

- Geometry: refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Replace plastic scintillator with glass scintillator
  - Steel absorber: ~13 mm
  - Scintillator tiles size: 30×30×10 mm^3
  - Glass density: 6 g/cm^3



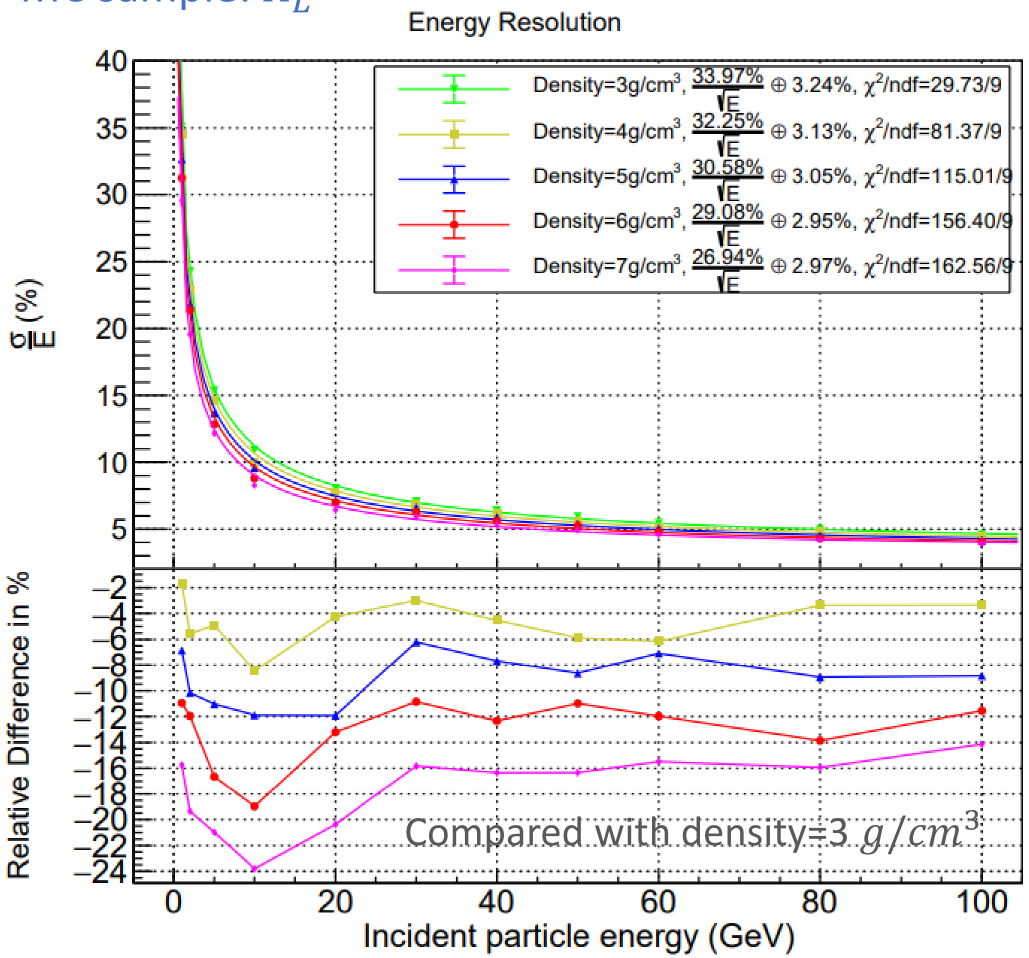
HCAL module and layer structure



Event display

Impact of glass density to energy resolution

MC sample: K_L^0



- Varying glass scintillator density: 3 to 7 g/cm^3
  - Each layer fixed with ~0.12 λ_I
  - Glass thickness: 10 mm
  - Energy threshold: 0.1 MIP
- Extraction of stochastic and constant terms in energy resolution

Density $[g/cm^3]$	3	4	5	6	7
Stochastic term [%]	33.97	32.25	30.58	29.08	26.94
Constant term [%]	3.24	3.13	3.05	2.95	2.97

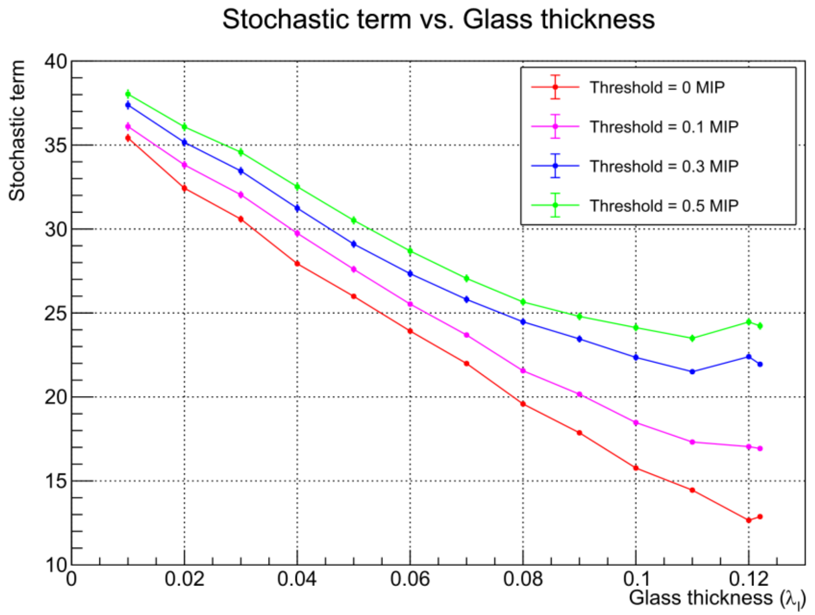
➢ Increasing density can improve hadronic energy resolution

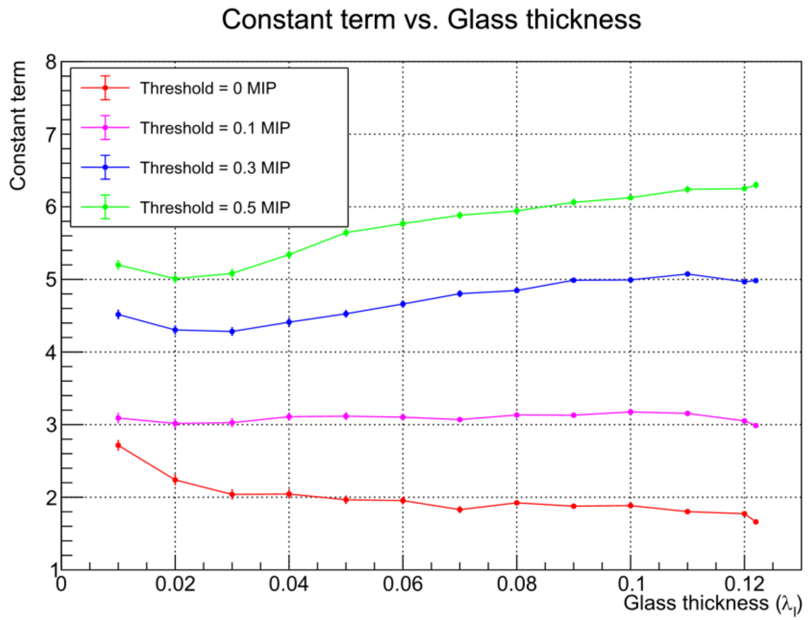
➢ Considering constraints of light yield in glass R&D, target density set as ~6 g/cm^3

Impact of sampling fraction to energy resolution

- Varying thickness: glass scintillator tiles and steel plates
  - Thicker glass → larger sampling fraction
  - Each layer fixed with ~0.12 λ_I
  - Glass density: 6 g/cm^3
- Extraction of stochastic and constant terms in energy resolution

MC sample: K_L^0

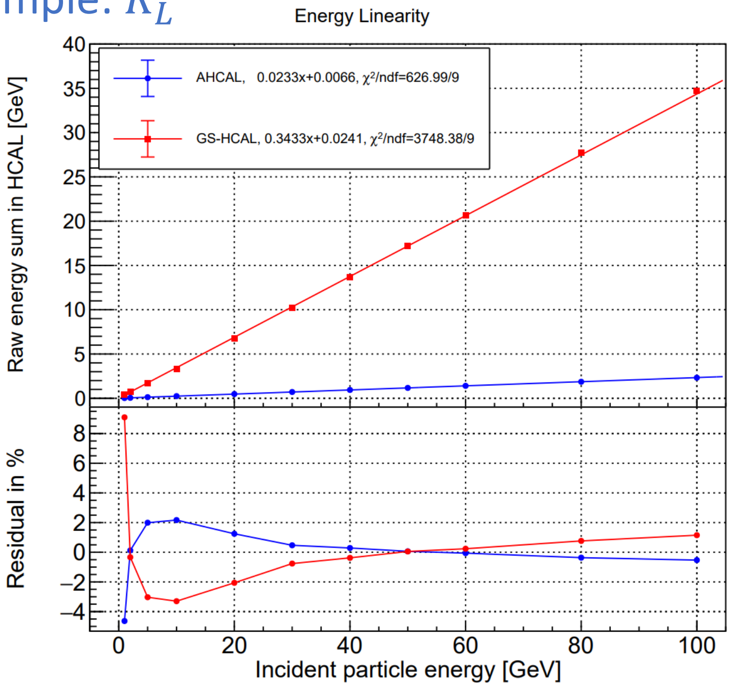


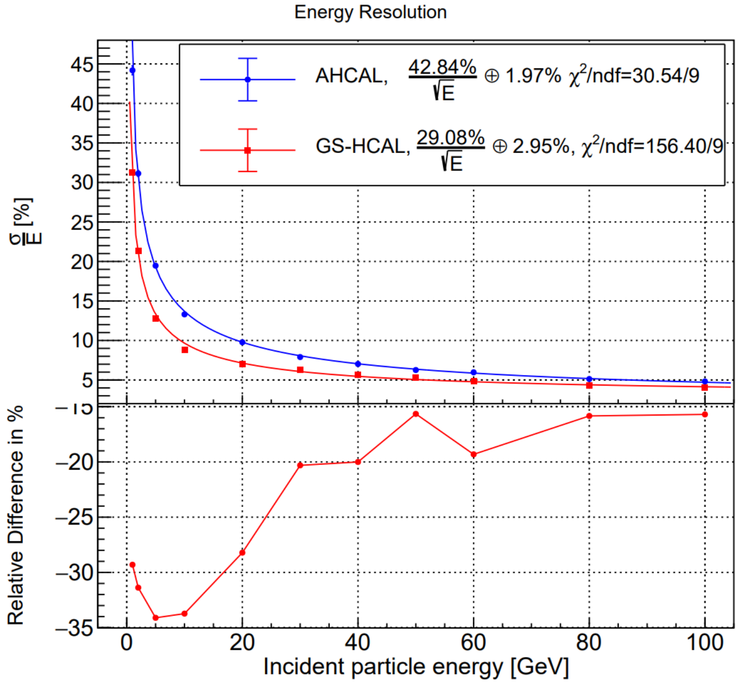


- ➢ Lower energy threshold would always be desirable for better resolution
- ➢ The stochastic term can be improved with thicker glass tiles
- ➢ The constant term is not significantly affected by the glass thickness for a given energy threshold

Energy linearity and resolution

MC sample: K_L^0





- Preliminary performance comparison: AHCAL vs. GS-HCAL
  - Same tile transverse size: $30\times30\ mm^3$
  - Glass thickness: 10 mm
  - Glass density: 6 g/cm^3
  - Energy threshold: 0.1 MIP

- Energy linearity:
  - Within ±3% range in 10-100 GeV, but with a relatively worse linearity in low energy range
  - GS-HCAL slightly worse than AHCAL
- Energy resolution:
  - GS-HCAL has a better hadronic energy resolution

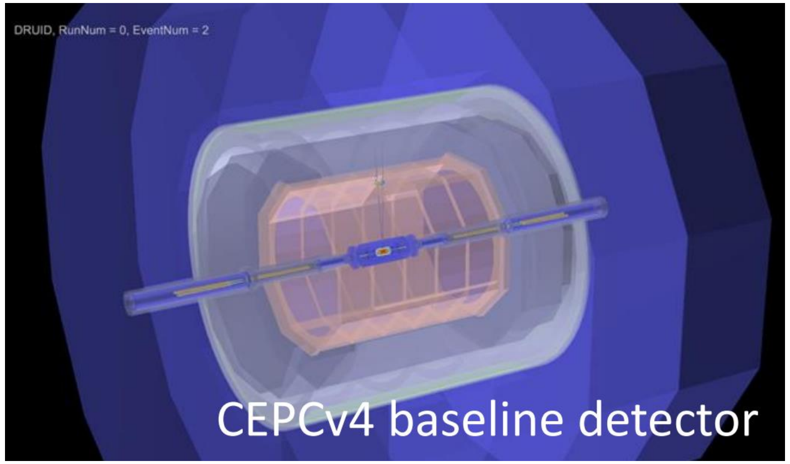
Outline

- Motivations
- Standalone simulation of GS-HCAL
  - Impact of sampling fraction and density
  - Energy linearity and resolution with single hadrons
- PFA performance with GS-HCAL
  - Key parameters: glass density and cell size
  - Optimized performance
- Glass scintillator material R&D
  - The improvement of key properties
  - The preparation of large-scale glass scintillator
- Summary

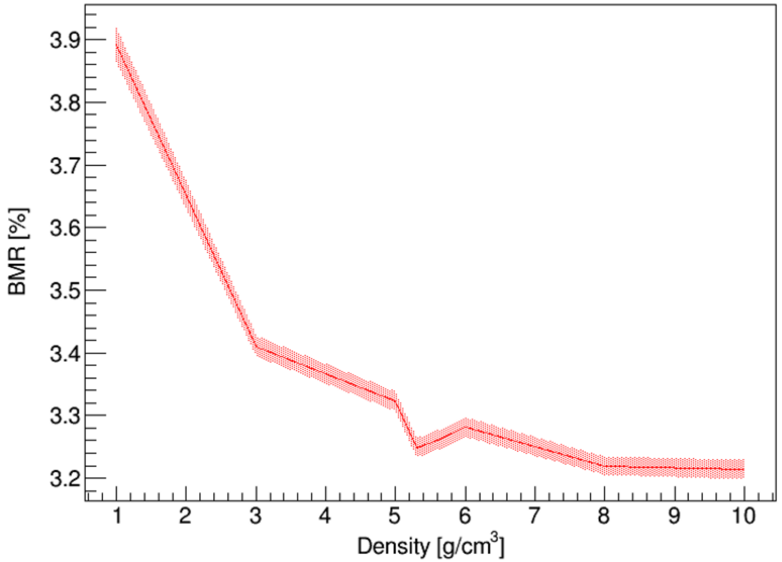
Impact of density to BMR

By Peng Hu

- Adapted from CEPCv4 baseline detector
  - SiW ECAL + GS-HCAL
  - Glass tile size: 30×30×10 mm^3
  - HCAL total layers: 40
- Physics performance:
  - Boson Mass Resolution (BMR): resolution of Higgs invariant mass
  - Reconstructed by Arbor-PFA



- Varying glass scintillator density: 1 to 10 g/cm^3
  - Physics events: $e^+e^- \to \upsilon\bar{\upsilon}$H (H → gg) at 240 GeV
  - Energy threshold: 0.1 MIP

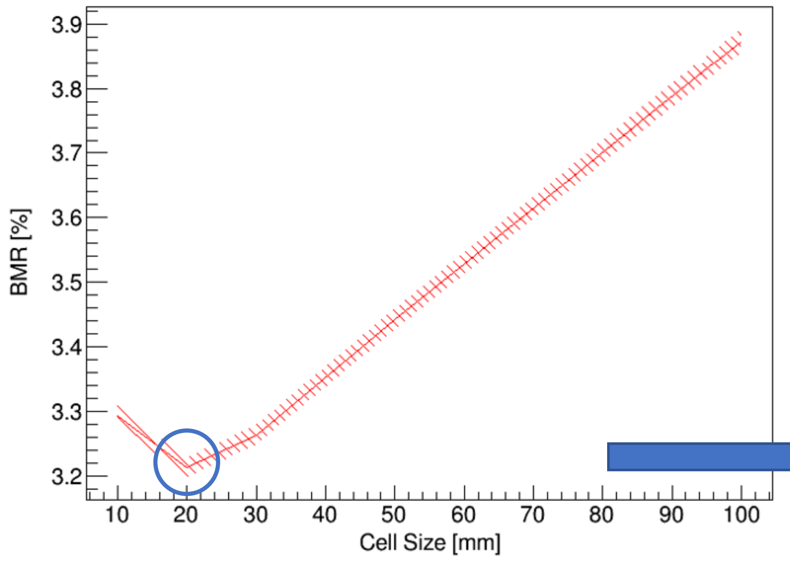


- ➢ BMR tended to improve with larger density
- ➢ Glass density ~6 g/cm^3 is a relatively reasonable target, which can guarantee a good BMR (~3.3%) and feasibility in R&D

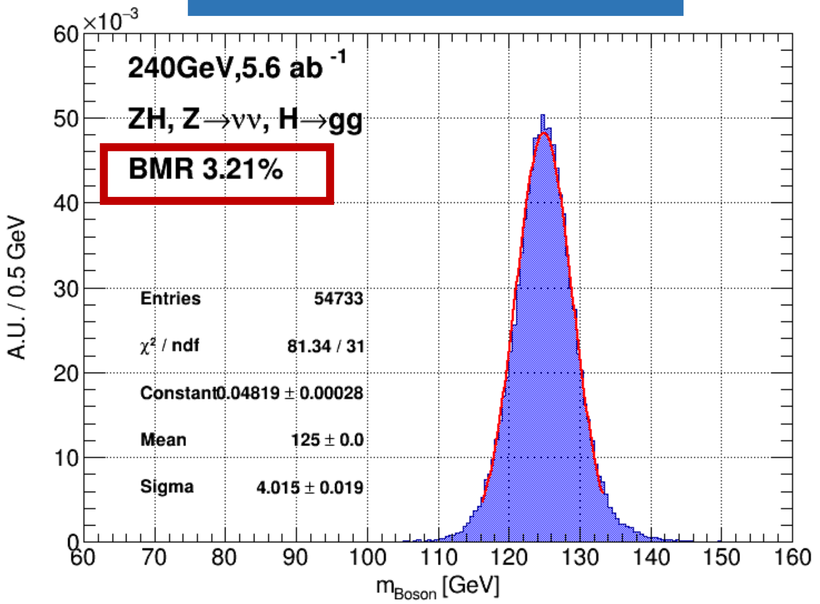
Impact of cell size to BMR

By Peng Hu

- Varying glass tile transverse size: 10×10 to 100×100 mm^2
  - Physics events: $e^+e^- \rightarrow \nu\bar{\nu}$H (H → gg) at 240 GeV
  - Glass thickness: 10 mm
  - Glass density: 6 g/cm^3
  - Energy threshold: 0.1 MIP



SiW ECAL + GS-HCAL



- ➢ BMR improved with smaller transverse size, when tile transverse size is larger than 20×20 mm^2
- ➢ Optimal BMR can reach 3.2%
- ➢ BMR can further improve by optimization of Arbor-PFA parameters

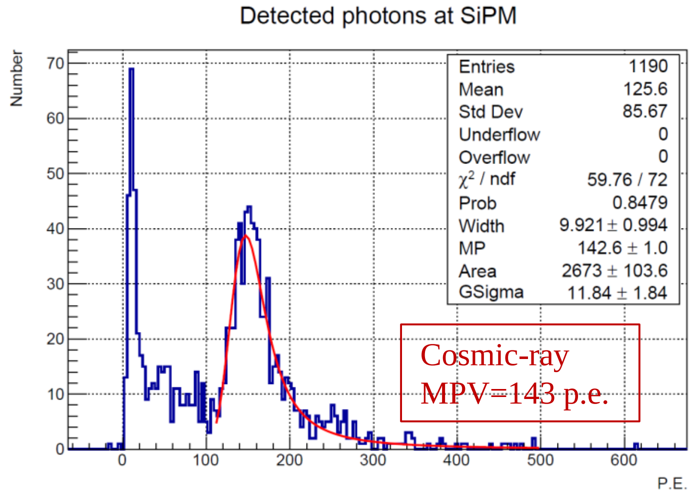
Outline

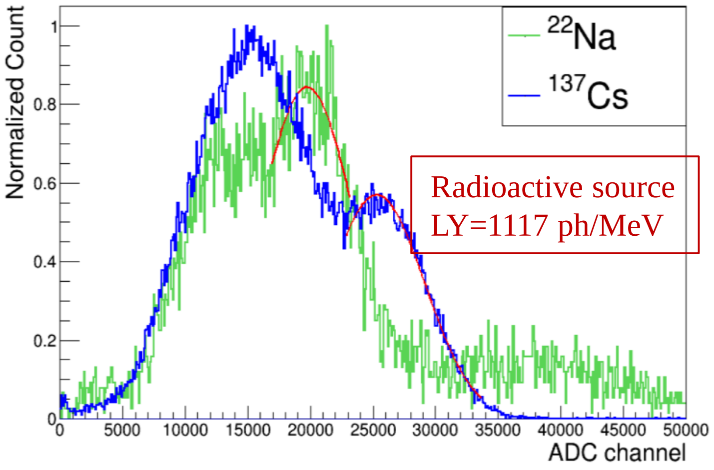
- Motivations
- Standalone simulation of GS-HCAL
  - Impact of sampling fraction and density
  - Energy linearity and resolution with single hadrons
- PFA performance with GS-HCAL
  - Key parameters: glass density and cell size
  - Optimized performance
- Glass scintillator material R&D
  - The improvement of key properties
  - The preparation of large-scale glass scintillator
- Summary

The light yield: radioactive source vs. cosmic-ray test

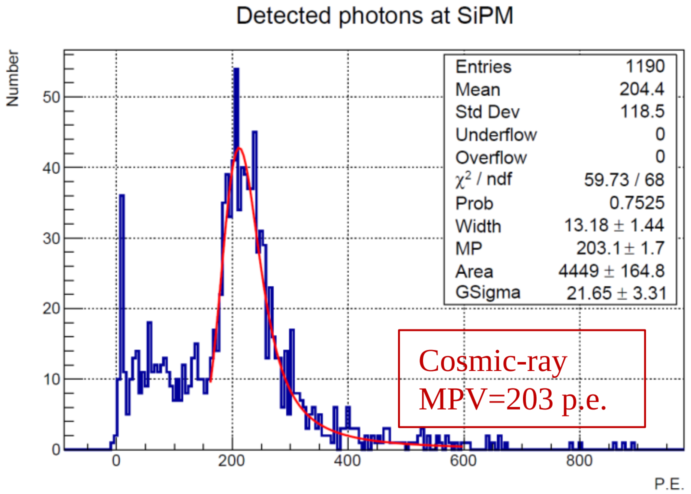
By Dejing Du, Zhehao Hua

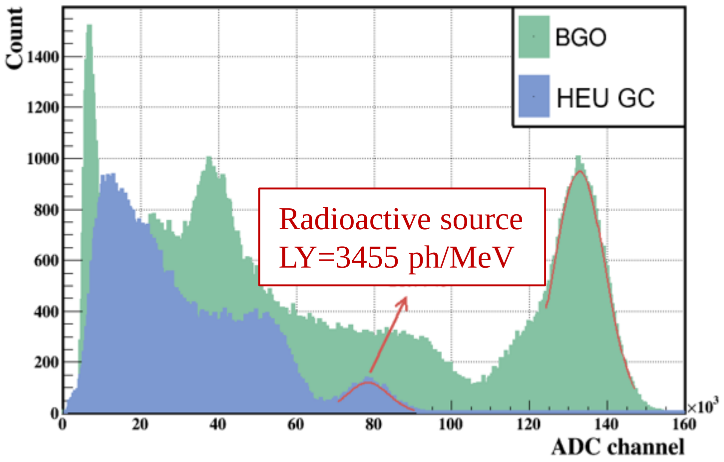
Borosilicate Glass (#1)





Glass Ceramic (#2)





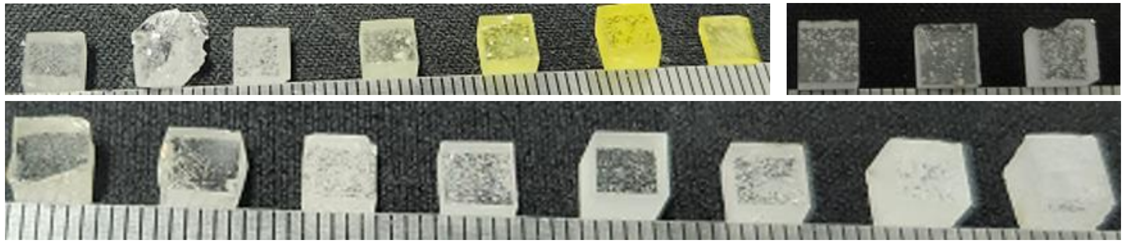
	#1	#2
Thickness(D) [mm]	2.6	2
Density(ρ) [g/cm^3]	5.44	3.3
Light yield(LY) [ph/MeV]	1117	3455
MIP [p.e.]	142.6	203.1
MIP/(D×ρ)	10.08	30.77
LY/MIP	110	113

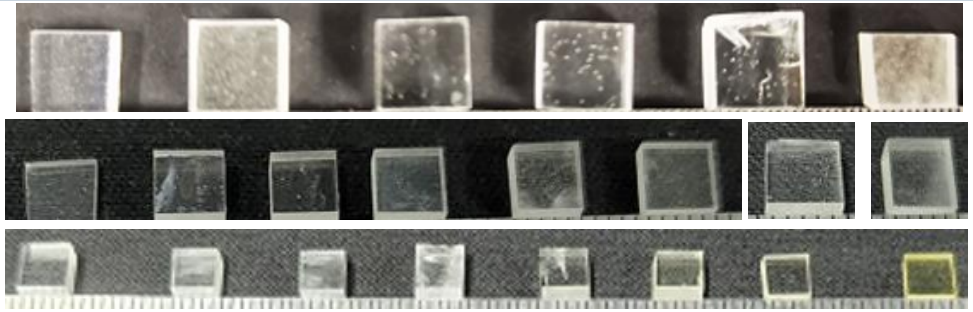
- Considering density and thickness, MIP response by cosmic-ray test is consistent with light yield by radioactive source test
- Verified the consistency of the test method for the light yield

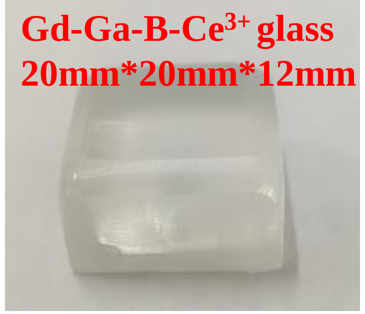
Overview of the Glass Scintillator R&D

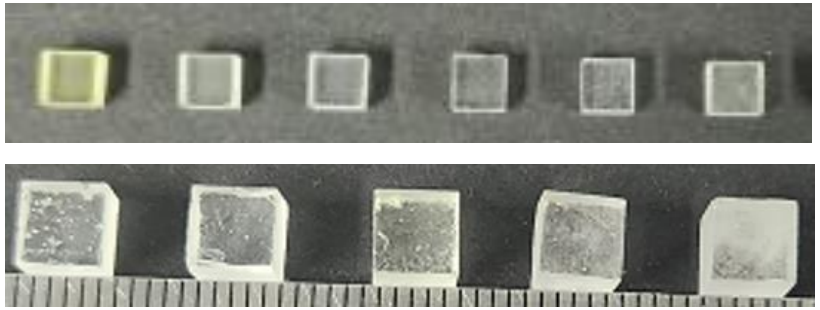
By the GS R&D collaboration group

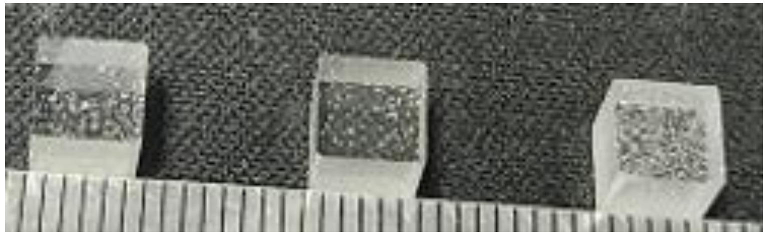
- Glass scintillator samples produced in the past year (>200)
- Different colored boxes correspond to samples from different institutes in collaboration







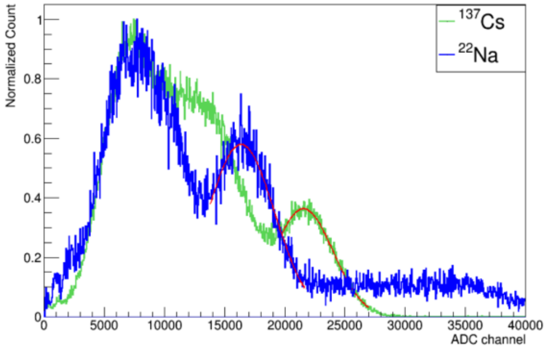




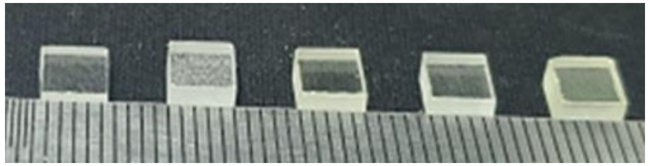
R&D: Borosilicate Glass (Gd-Al-B-Si-Ce^{3+})

By the GS R&D collaboration group

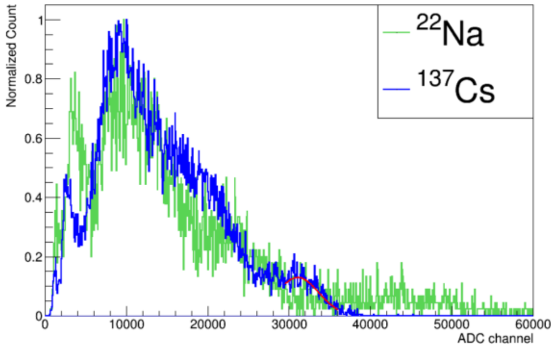
- Density ~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.77%



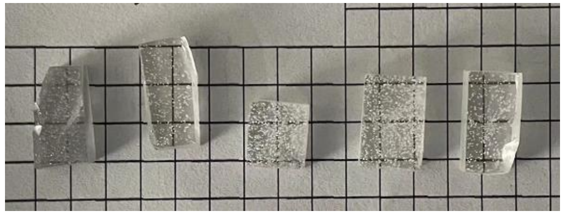
2021.11



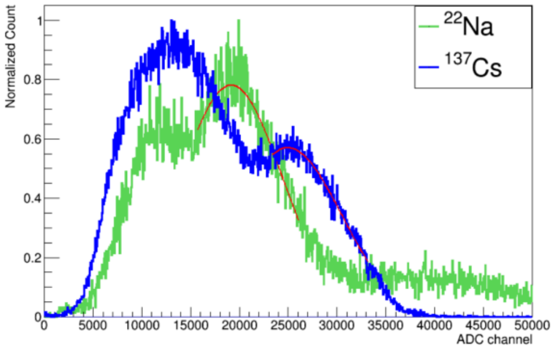
- Density ~4.0 g/cm^3
- LY>1200 ph/MeV
- ER=23.22%



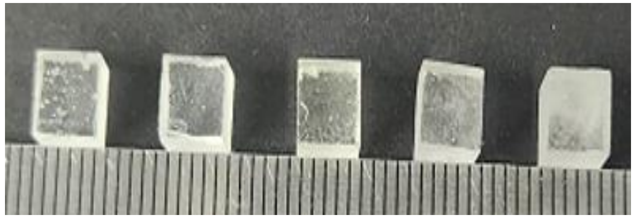
2022.06



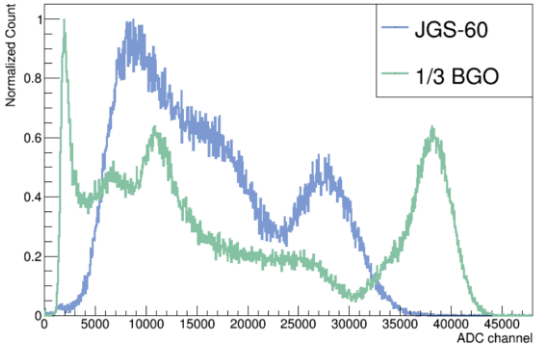
- Density ~6.0 g/cm^3
- LY>1000 ph/MeV
- ER=49.55%



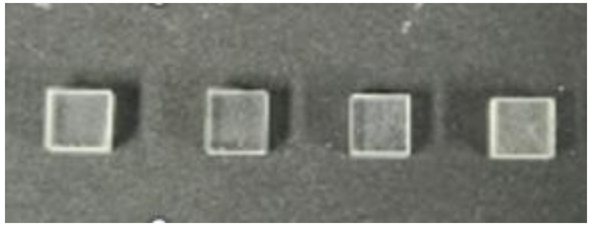
2022.11



- **Density ~6.0 g/cm^3**
- **LY>1200 ph/MeV**
- **ER=27.12%**



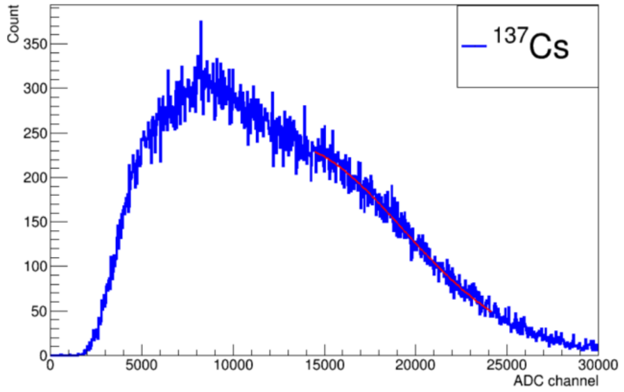
2023.02



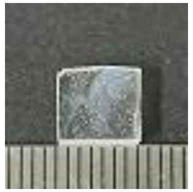
R&D: Glass Ceramic (Gd-Y-K-Si-Ce^{3+})

By the GS R&D collaboration group

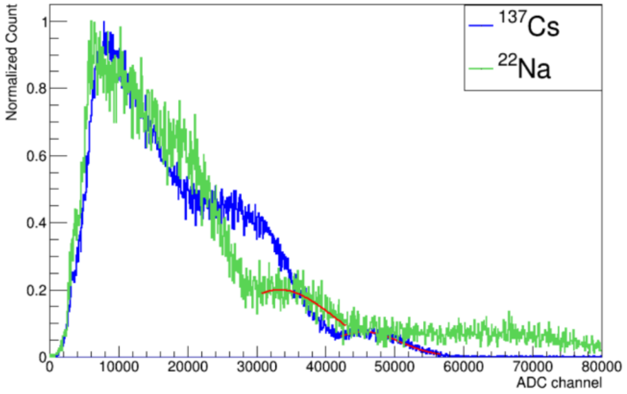
- Density ~3.3 g/cm^3
- LY=519 ph/MeV
- ER=None



2022.04

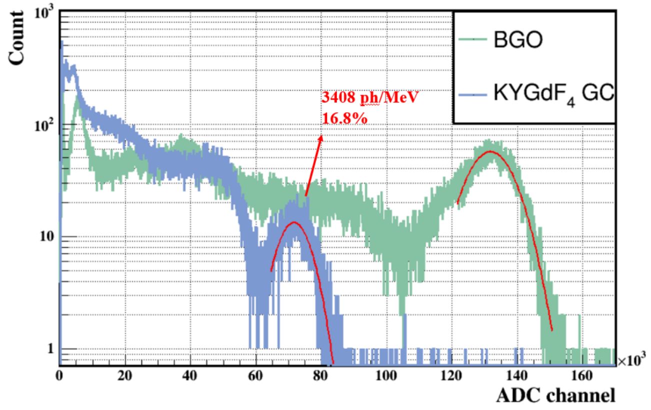


- Density ~3.3 g/cm^3
- LY>1600 ph/MeV
- ER=27.27%

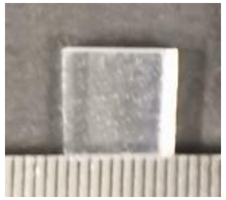


2022.10

- Density ~3.3 g/cm^3
- LY>3400 ph/MeV
- ER=16.77%



2022.11



Large-scale glass scintillator

By the GS R&D collaboration group

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

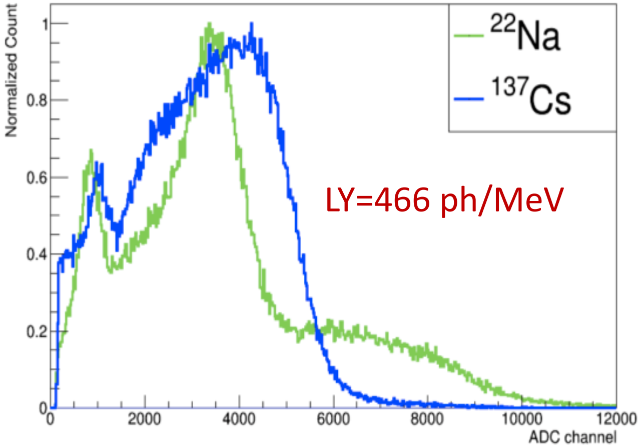
42mm×51mm×10mm

New system: Gd-Ga-B-Ce^{3+}

20mm×20mm×12mm

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

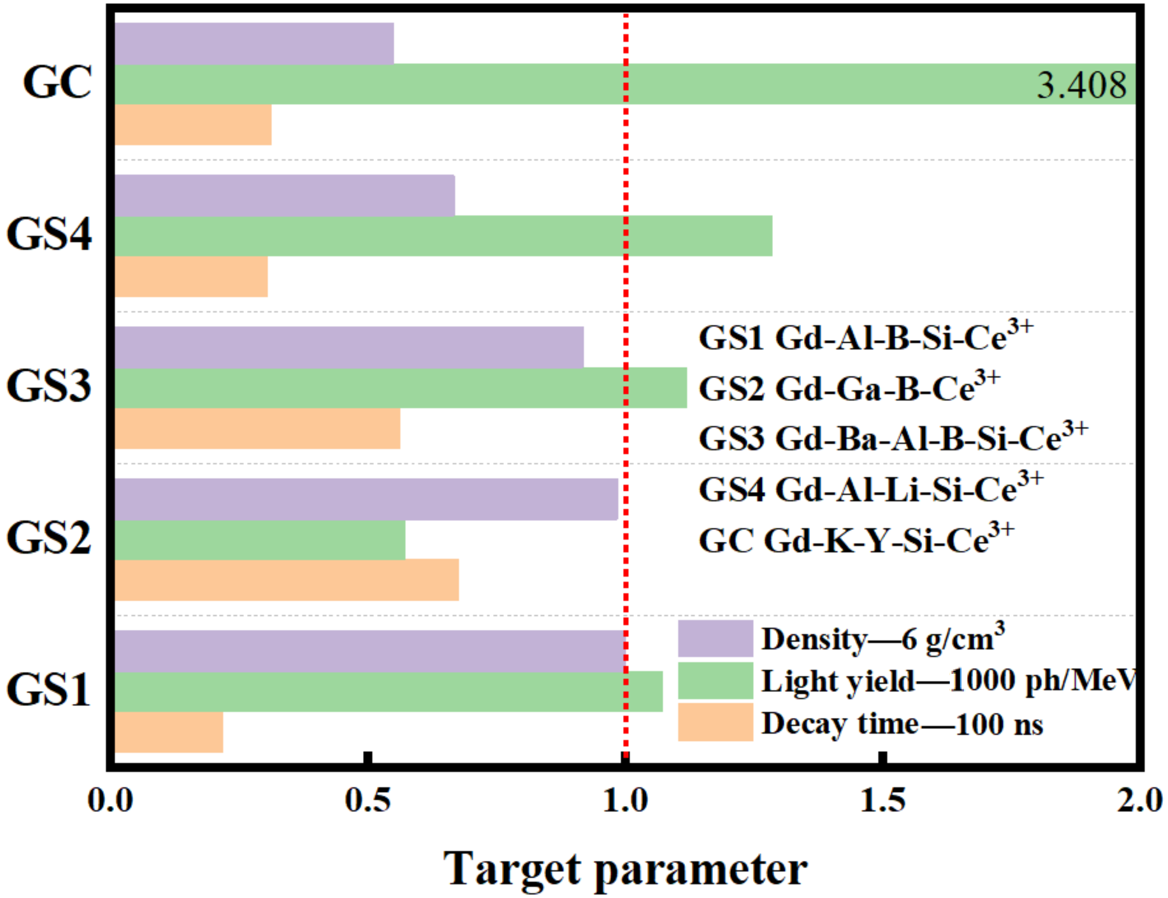
37mm×30mm×9mm



- Largest glass scintillator: 42×51×10 mm^3
- Properties of glass scintillator become worse after enlarging
  - Light yield, transmittance, uniformity
- Preparation technology of large size glass should be further optimized

Summary of Glass Scintillator R&D

By the GS R&D collaboration group



Glass scintillator with high density, light yield, good energy resolution and fast decay time

- Gd-Al-B-Si-Ce^{3+} glass: 6.0 g/cm^3, 1072 ph/MeV with 24.4%@662keV, 460 ns

- Ultra-high density tellurite glass—6.6 g/cm^3
- High light yield glass ceramic—3400 ph/MeV
- Large size glass—42mm×51mm×10mm

Summary and prospects

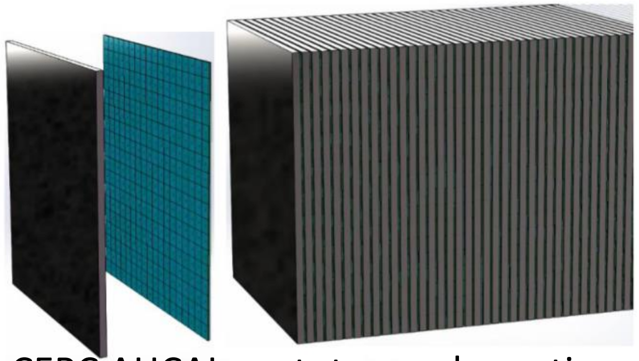
- Performance of GS-HCAL in standalone simulation
  - Key parameters: glass density and thickness
  - Better hadronic energy resolution
- PFA performance for GS-HCAL
  - Optimization of density and cell size
  - Preliminary result: BMR can reach 3.2%
- Ongoing glass scintillator R&D activities to address
  - High density, high light yield, fast decay time and large size

- Plans
  - To further improve the hadronic energy resolution: e.g. “Software compensation” technique
  - Some parameters of Arbor-PFA should be tuned for the glass scintillator HCAL
  - Enlarge glass size while keeping the same as properties of small size

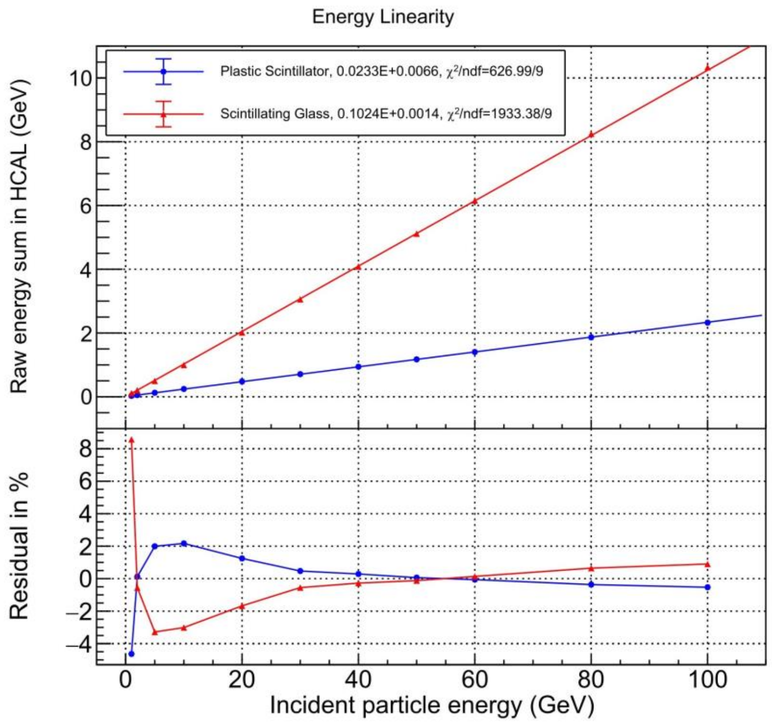
Backup

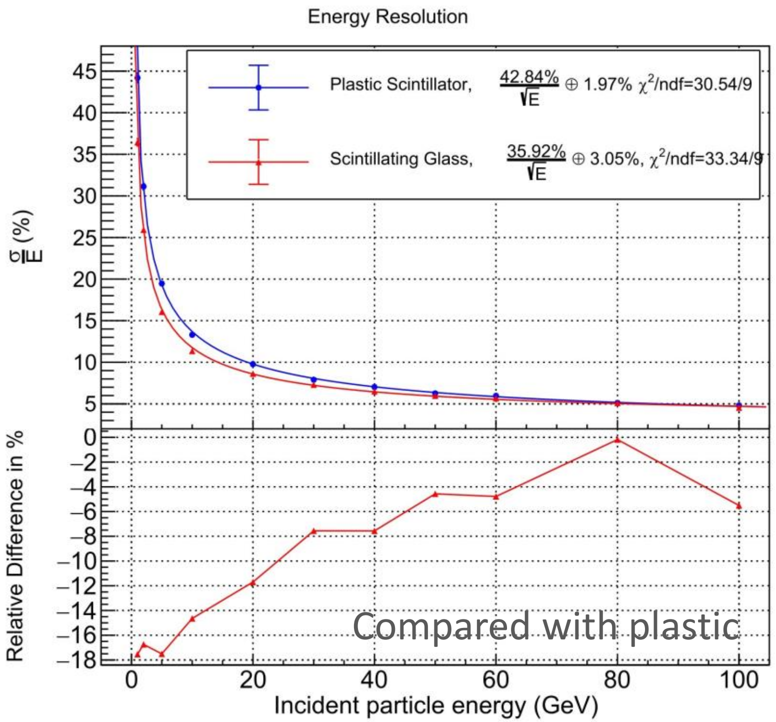
Energy linearity and resolution

- Geometry: refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Steel absorber: 20 mm
  - Scintillator size: 30×30×3 mm^3
  - Replace plastic scintillator with glass scintillator
- Glass density: 6 g/cm^3
- Energy threshold: 0.1 MIP
- Incident particle: 1-100 GeV K_L^0



CEPC AHCAL prototype schematics



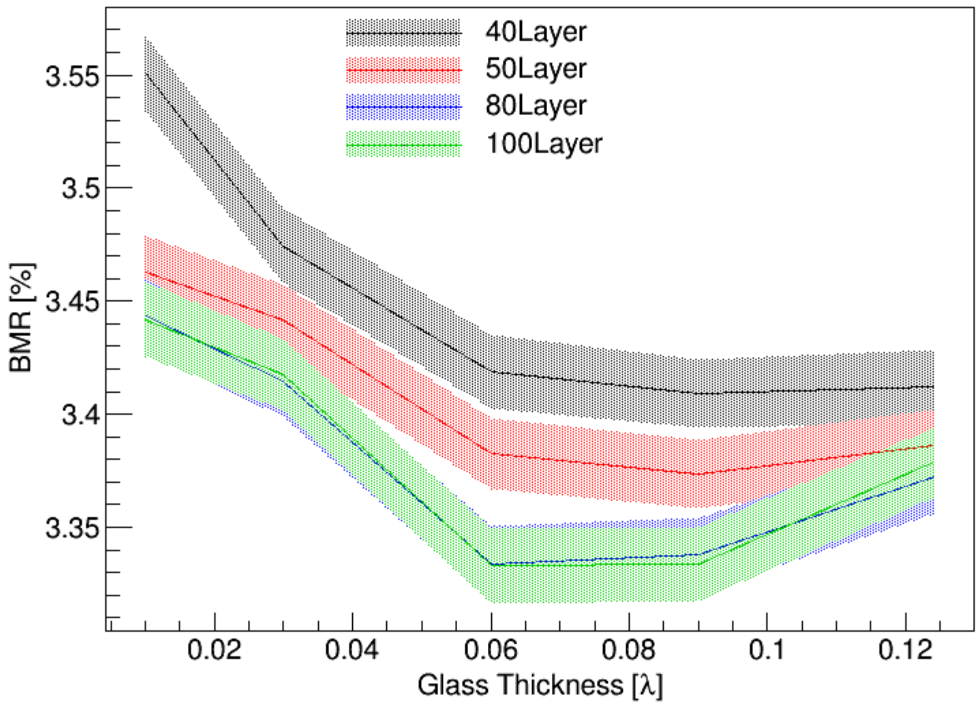


- Energy linearity:
  - Glass scintillator slightly worse than plastic scintillator
  - Within ±3% range in 10-100 GeV, but with a relatively worse linearity in low energy range
- GS-HCAL has a better hadronic energy resolution

Impact of thickness and #layers to BMR

By Peng Hu

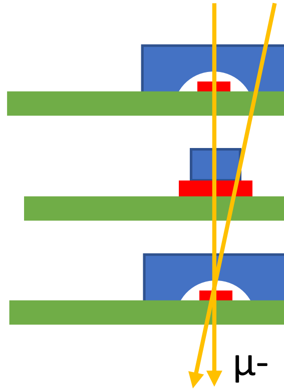
- Varying thickness: glass scintillator tiles and steel plates
  - Each layer fixed with ~0.12 λ_I
  - Glass density = 6
- e+e- → $\upsilon\bar{\upsilon}$H (H → gg) at 240 GeV
- Energy threshold = 0.1 MIP

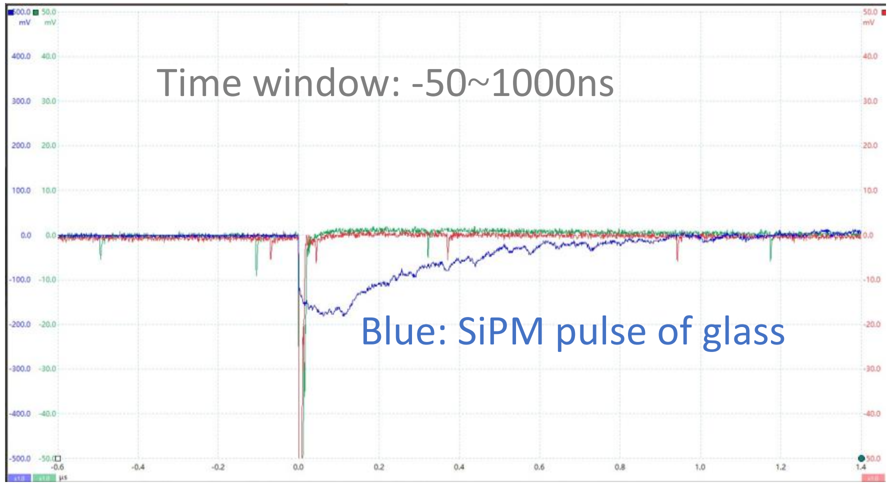


- BMR can be improved with the increasing of number of layers below 80 layers
- For GSHCAL of more than 80 layers, the effect of shower leakage on BMR can be ignored

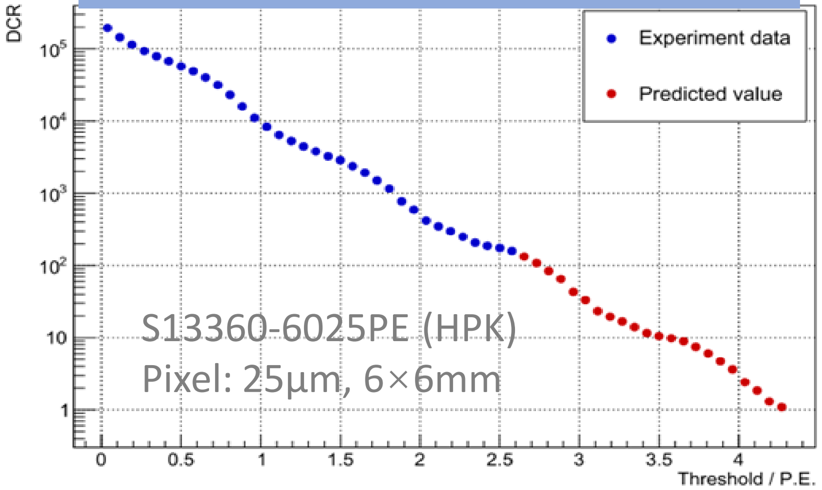
- The BMR of 40-layers can reach 3.42%
- For ideal setup of more than 80 layers, BMR can be further improved to 3.33%

Threshold impacts

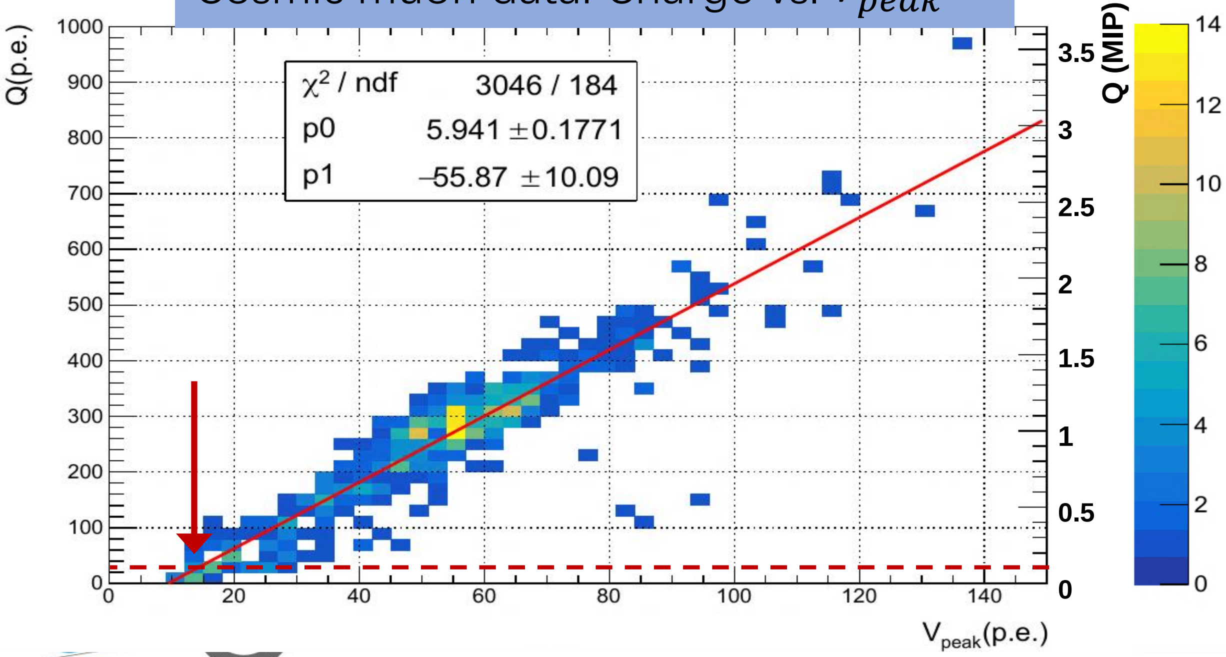




Dark count rate vs. voltage threshold



Cosmic muon data: Charge vs. V_{peak}

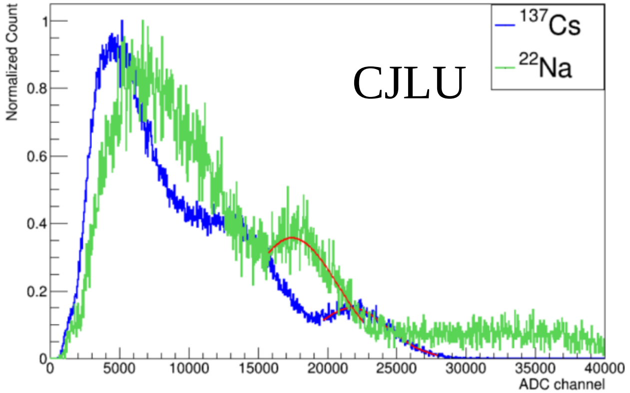


- Higher threshold can suppress noise impacts
  - SiPM dark noise is negligible (< 1 Hz) when threshold > 4.5 p.e.
- **Electronics threshold** vs. **energy threshold** (HCAL reconstruction)
  - 0.1 MIP (energy) ⟶ 14 p.e (voltage)
- Energy threshold of 0.1 MIP is feasible

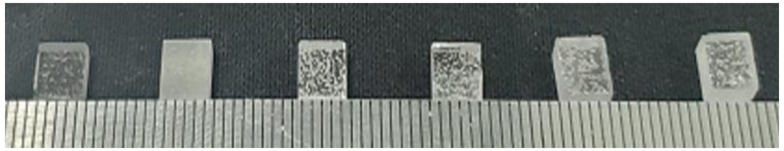
R&D: Silicate Glass (Gd-Al-Si-Ce^{3+})

By the GS R&D collaboration group

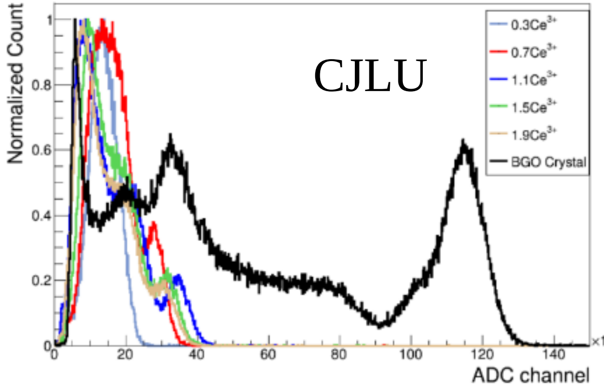
- Density ~4.0 g/cm^3
- LY=807 ph/MeV
- ER=29.29%



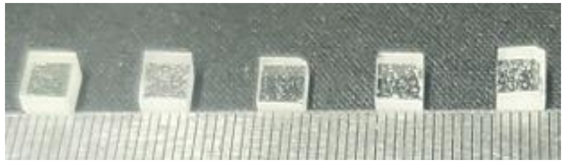
2022.03



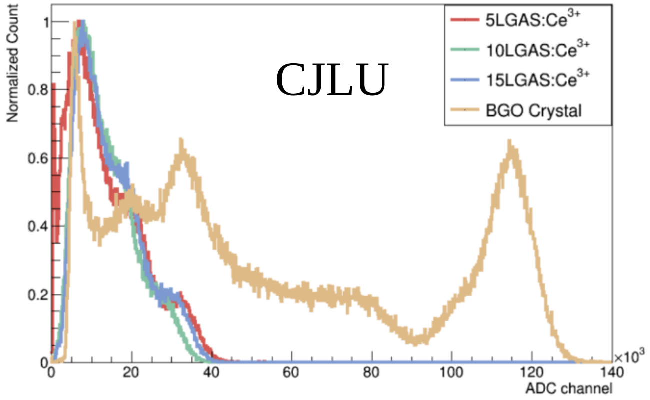
- Density ~4.2 g/cm^3
- LY>1200 ph/MeV
- ER=22.98%



2022.05



- Density ~4.2 g/cm^3
- LY>1300 ph/MeV
- ER=23.22%



2022.10