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Development of highly granular hadronic calorimeter with glass scintillator tiles

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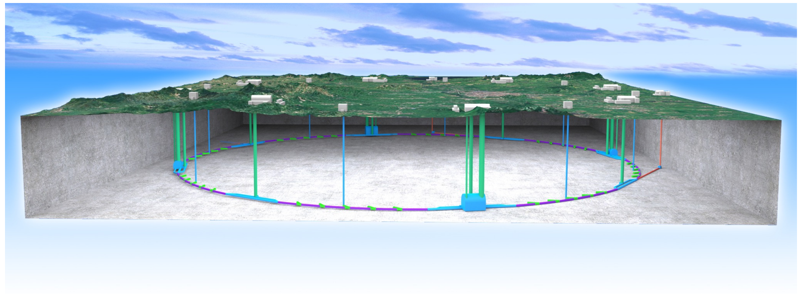
On behalf of CEPC Calorimeter Working Group

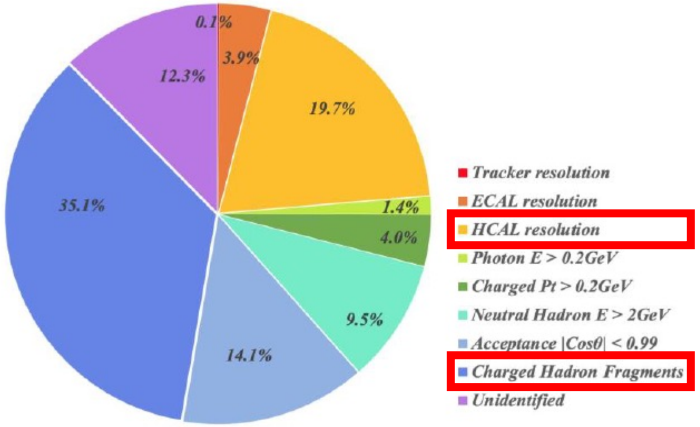
NED' 2023
August 10, 2023

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
  - Next performance goal: BMR 4%→3%
  - Dominant factors in BMR: charged hadron fragments & HCAL resolution
- New concept: glass scintillator HCAL (GS-HCAL)
  - Same as Scintillator-Steel HCAL (CDR baseline): replace plastic scintillator with glass scintillator
  - Higher density provides higher energy sampling fraction
  - Better hadronic energy resolution



All Factors in BMR based on PFA



By Yuexin Wang

Outline

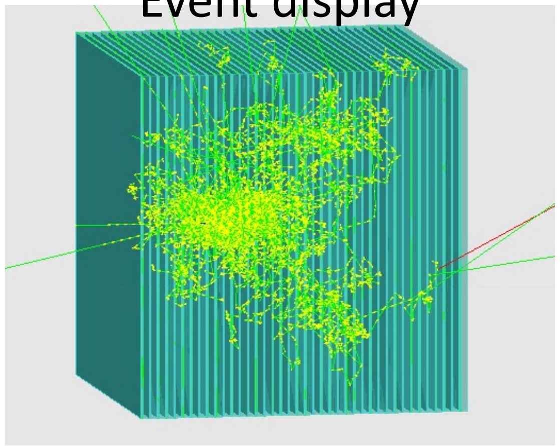
- Motivations
- Standalone simulation of GS-HCAL
  - Impact of key parameters
  - Optimize design
- PFA performance with GS-HCAL
  - Influence of key parameters on BMR
  - Optimized performance
- Glass scintillator material R&D
  - The improvement of key properties
  - Beamtest of large-scale glass scintillator tiles
- Summary

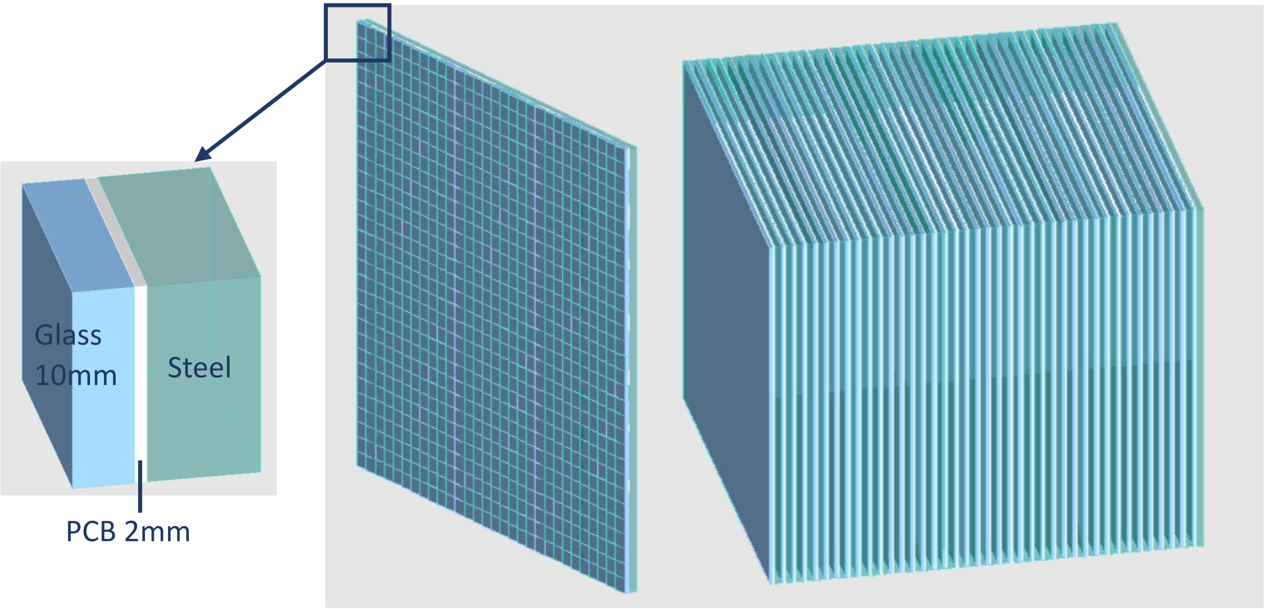
GS-HCAL simulation setup

- GS-HCAL geometry
  - Refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Replace plastic scintillator with glass scintillator
- Glass scintillator material
  - Composition: Gd-B-Si-Ge-F-Ce^{3+}
  - Nuclear interaction length: 23.83 cm
  - MIP response: 7 MeV/cm
- GS-HCAL nominal parameters

Total number of layers	**40**
Total nuclear interaction length	**6 λ**
Glass tile size	**40×40×10 mm³**
Glass density	**6 g/cm³**
Readout threshold	**0.1 MIP**

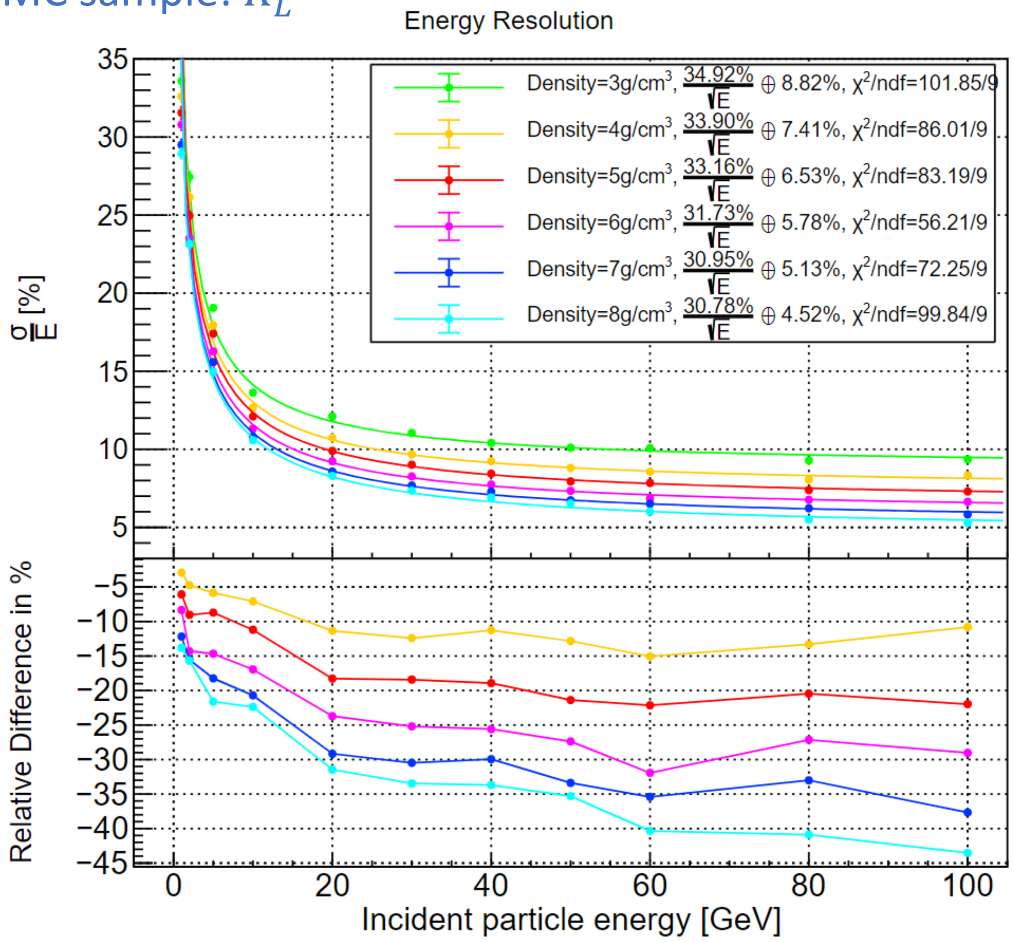
Event display



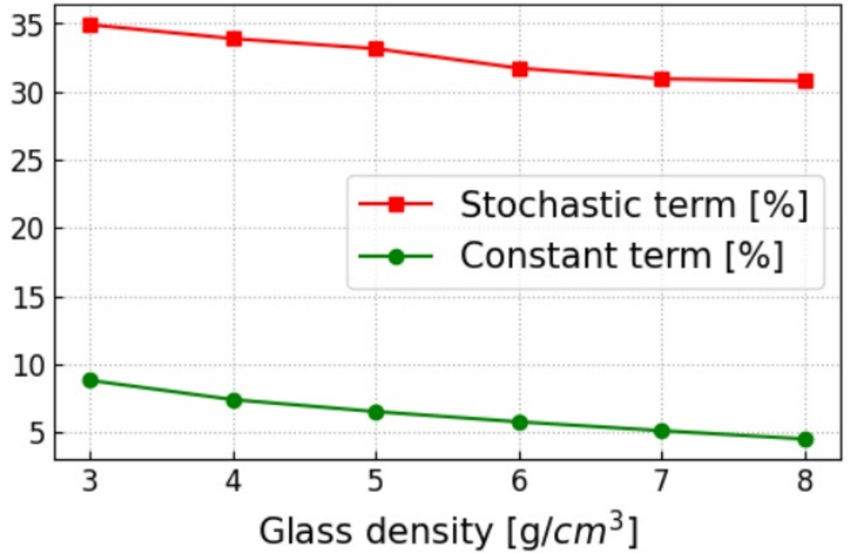


Impact of glass density to energy resolution

MC sample: K_L^0



- Varying glass scintillator density: 3 to 8 g/cm^3
- Extraction of stochastic and constant terms in energy resolution

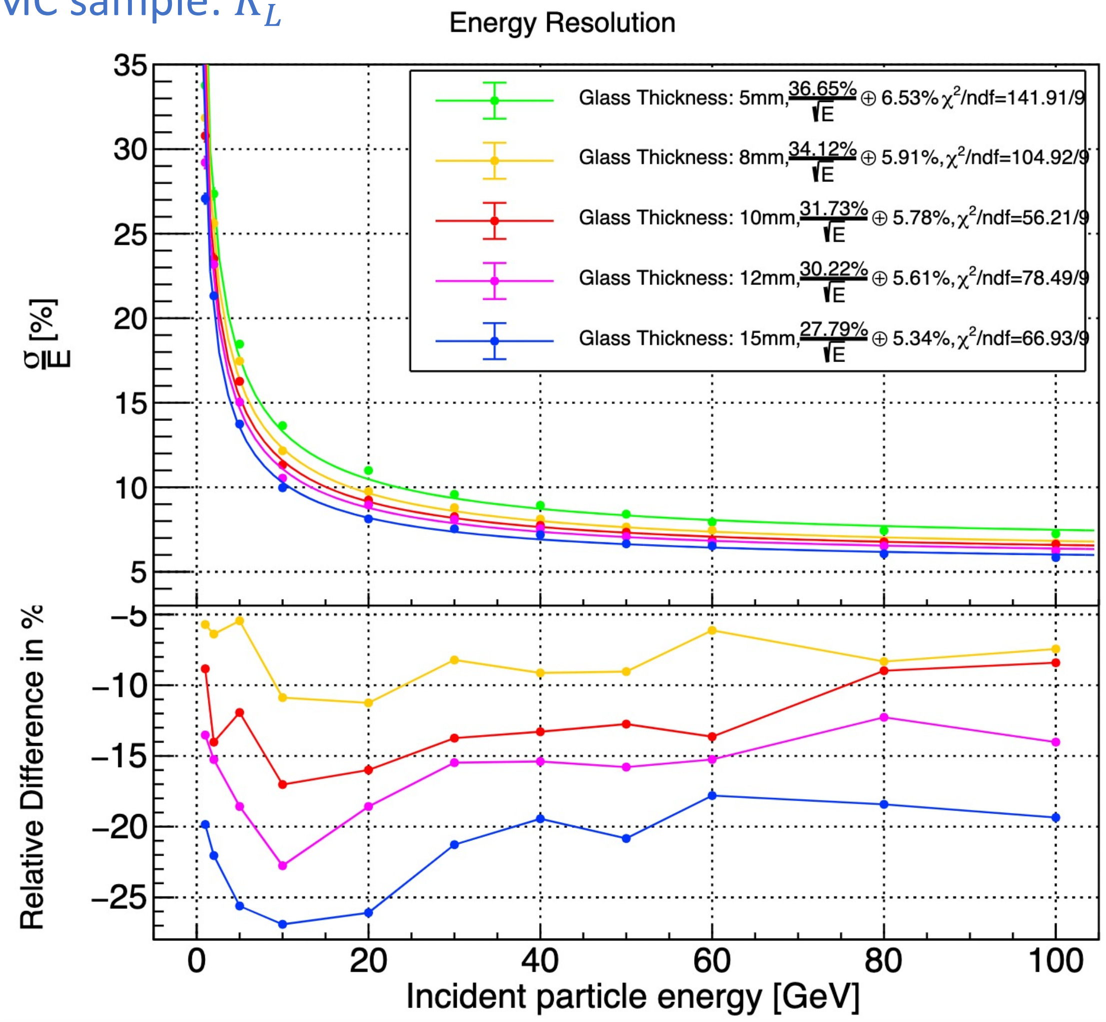


➢ Increasing density can improve hadronic energy resolution

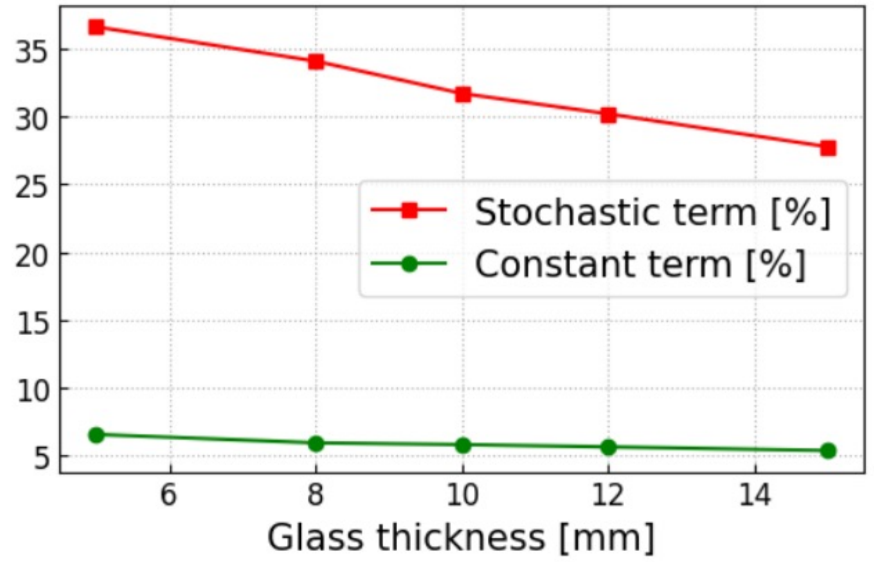
➢ Considering constraints of light yield in glass R&D, target density set as ~6 g/cm^3

Impact of glass thickness to energy resolution

MC sample: K_L^0



- Varying glass scintillator thickness: 5 to 15 mm
- Extraction of stochastic and constant terms in energy resolution



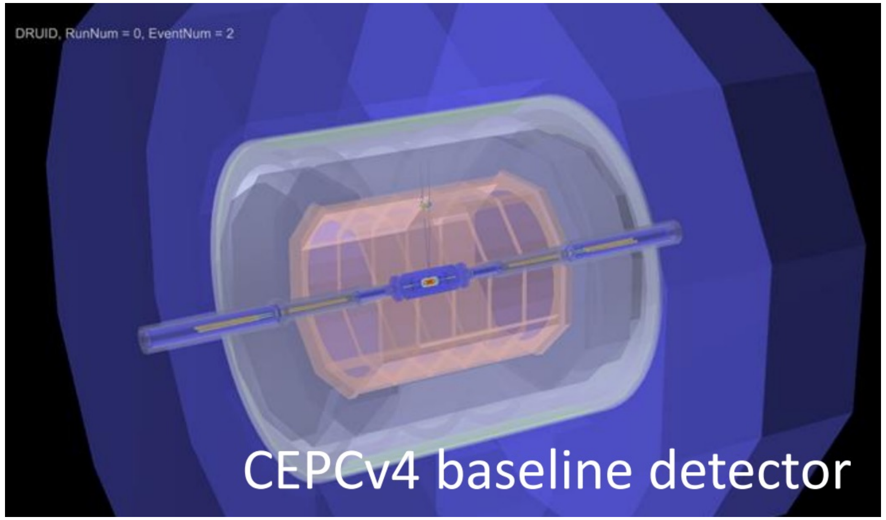
➢ The hadronic energy resolution can be improved with thicker glass tiles, especially the stochastic term

PFA performance simulation setup

By Peng Hu

- Adapted from CEPCv4 baseline detector: glass scintillator/steel HCAL + Si/W ECAL
- Primaries input: 240 GeV e+e- → $\upsilon\bar{\upsilon}$H (H → gg)
- Physics performance:
  - Boson Mass Resolution (BMR): resolution of Higgs invariant mass
  - Reconstructed by Arbor-PFA
- GS-HCAL nominal parameters

Total number of layers	**40**
Total nuclear interaction length	**6 λ**
Glass tile size	**20×20×10 mm^3**
Glass density	**6 g/cm^3**
Readout threshold	**0.1 MIP**



Impact of density and thickness to BMR

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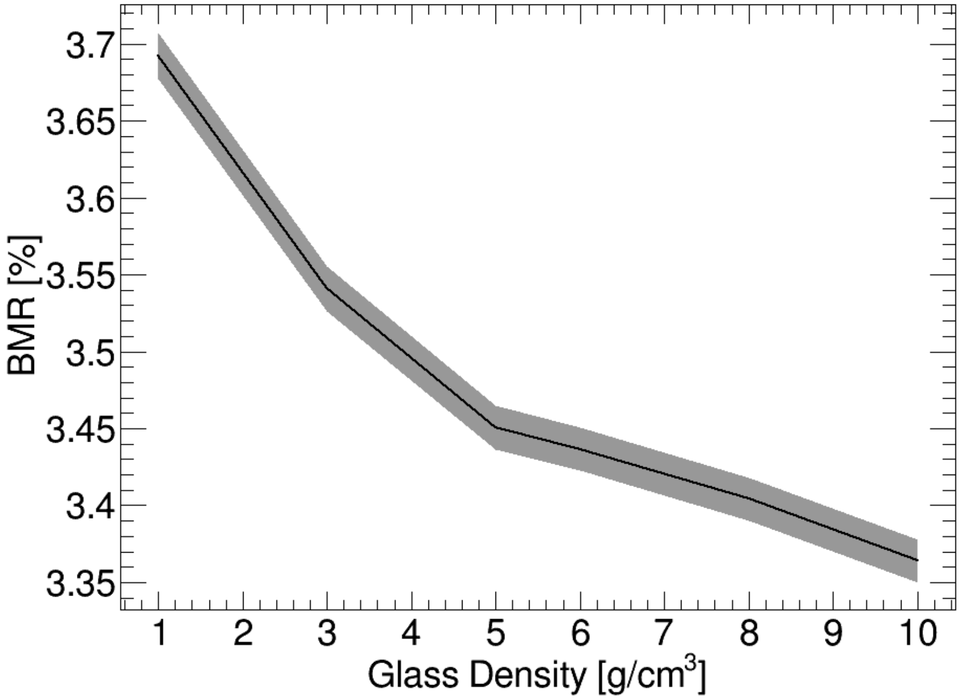
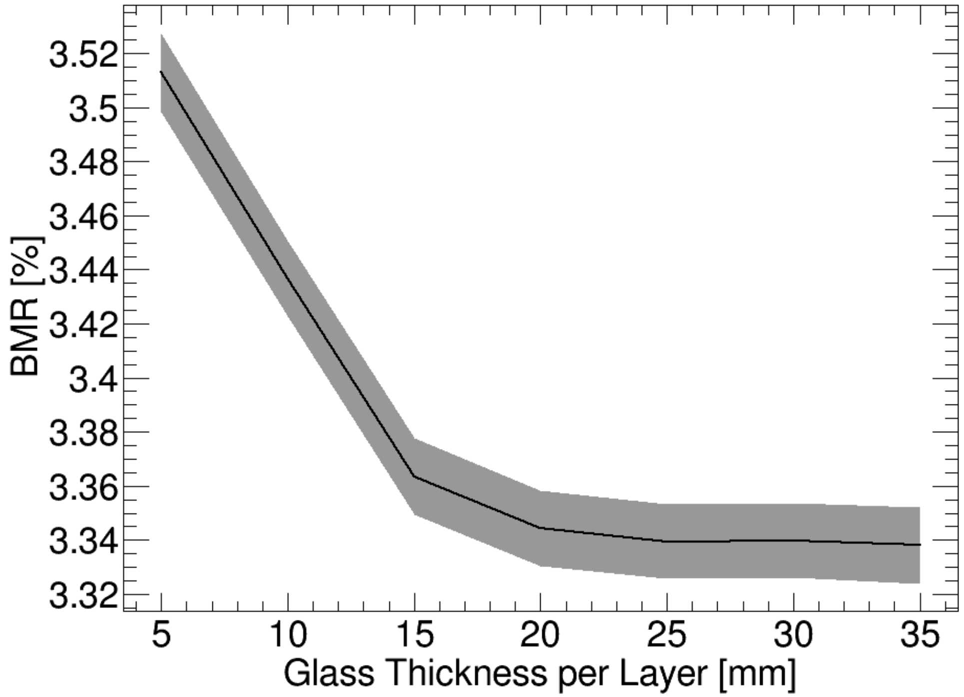


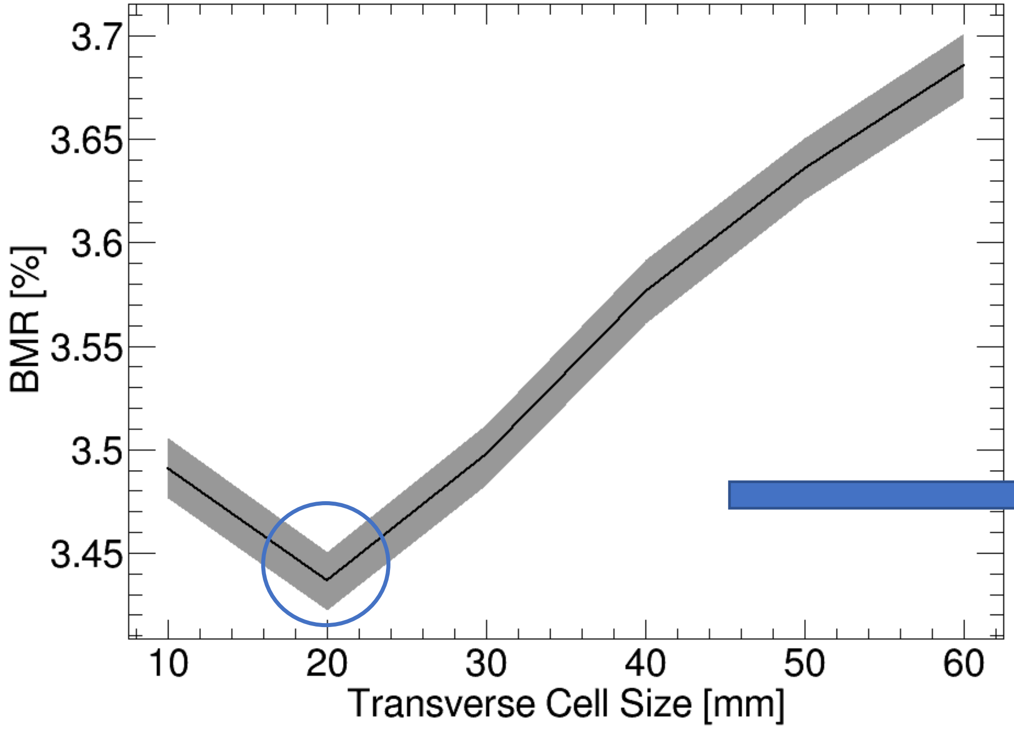


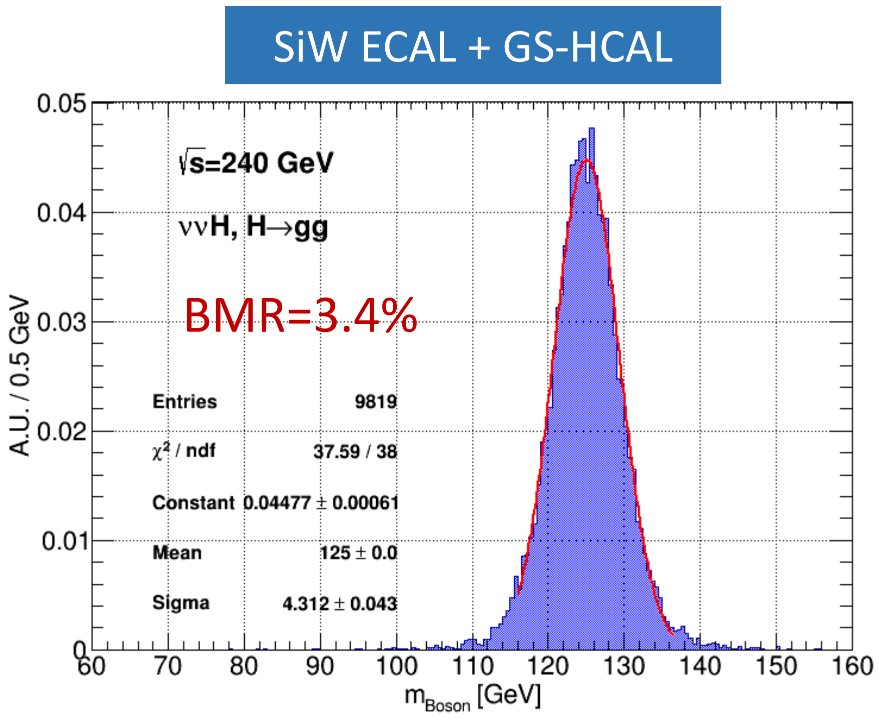
- BMR tended to improve with larger density
- Glass scintillator density ~6 g/cm^3 is a relatively reasonable target

- Thicker glass tile is conducive to higher sampling fraction and better BMR
- Glass thickness of 10 mm will be chosen for current design

Impact of tile size to BMR

By Peng Hu



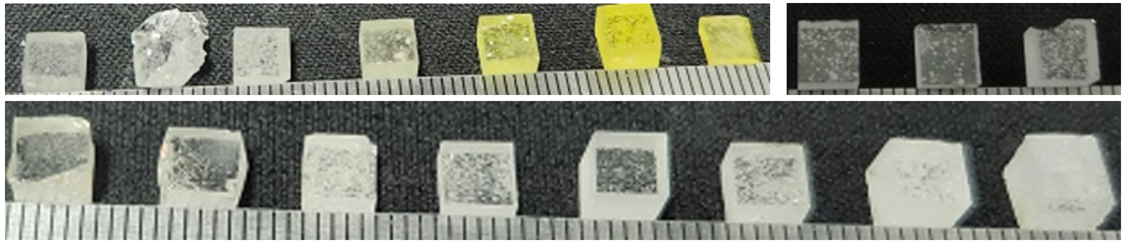


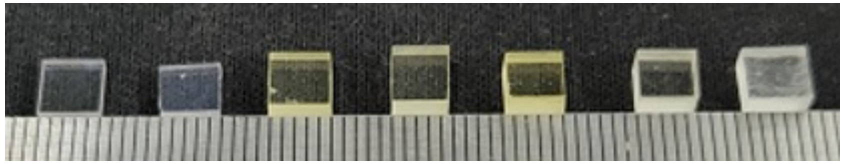
- ➢ BMR improved with smaller transverse size, when tile transverse size is larger than 20×20 mm^2
- ➢ Optimal BMR can reach 3.4%, it can further improve by optimization of Arbor-PFA parameters
- ➢ Next goal: BMR ~3%

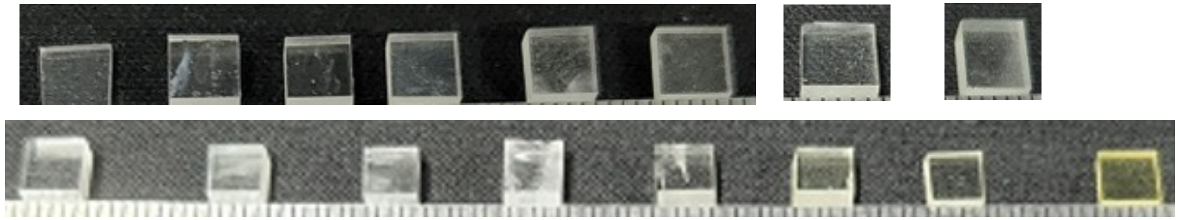
Overview of the Glass Scintillator R&D

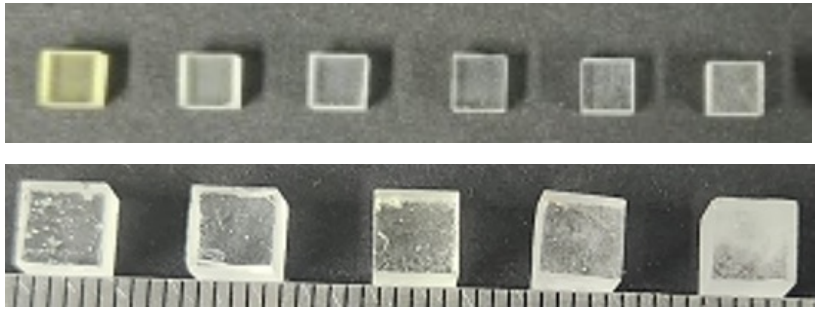
By the GS R&D collaboration group

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

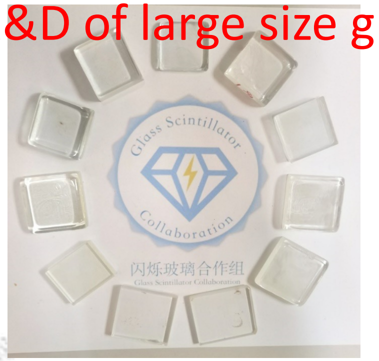


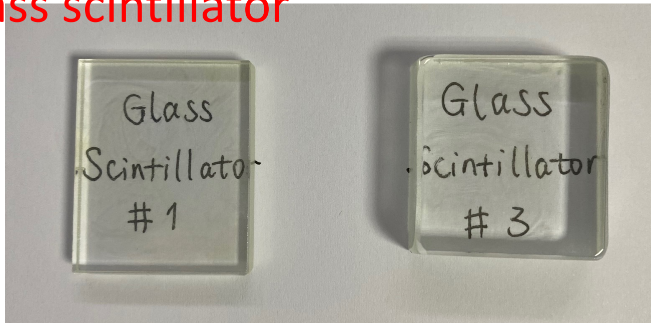


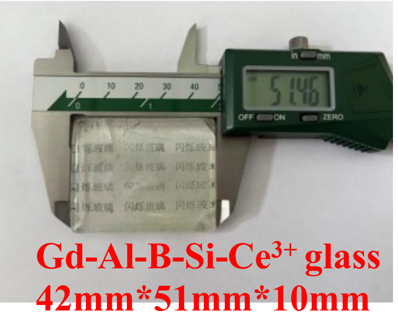


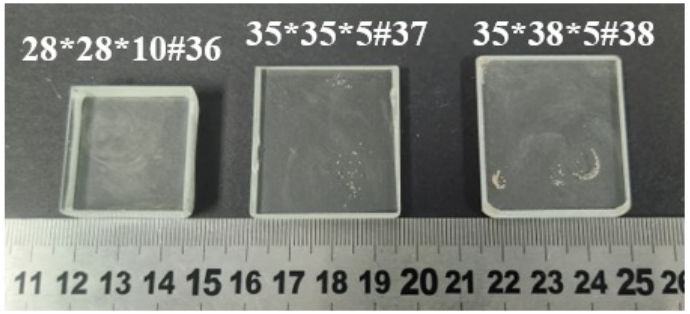


R&D of large size glass scintillator



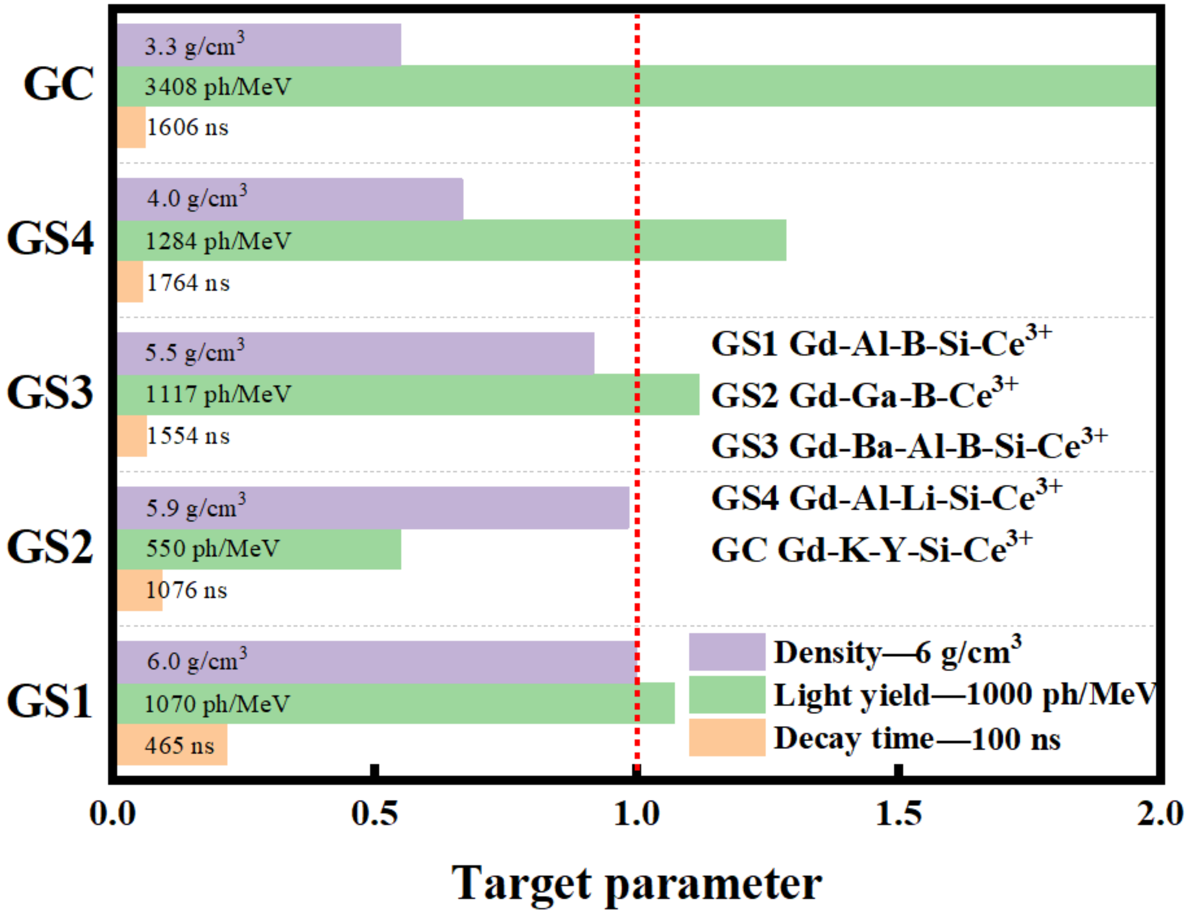






Summary of Glass Scintillator R&D

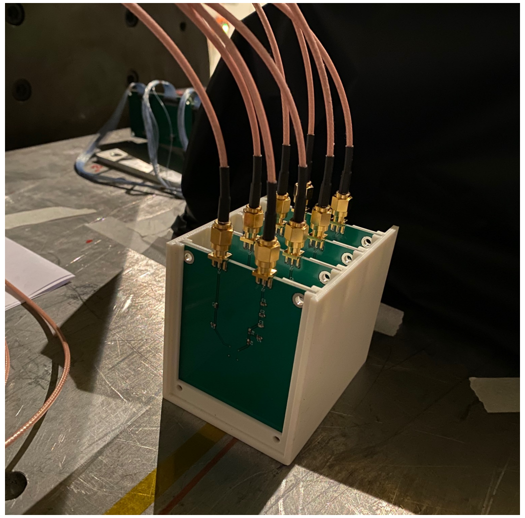
By the GS R&D collaboration group

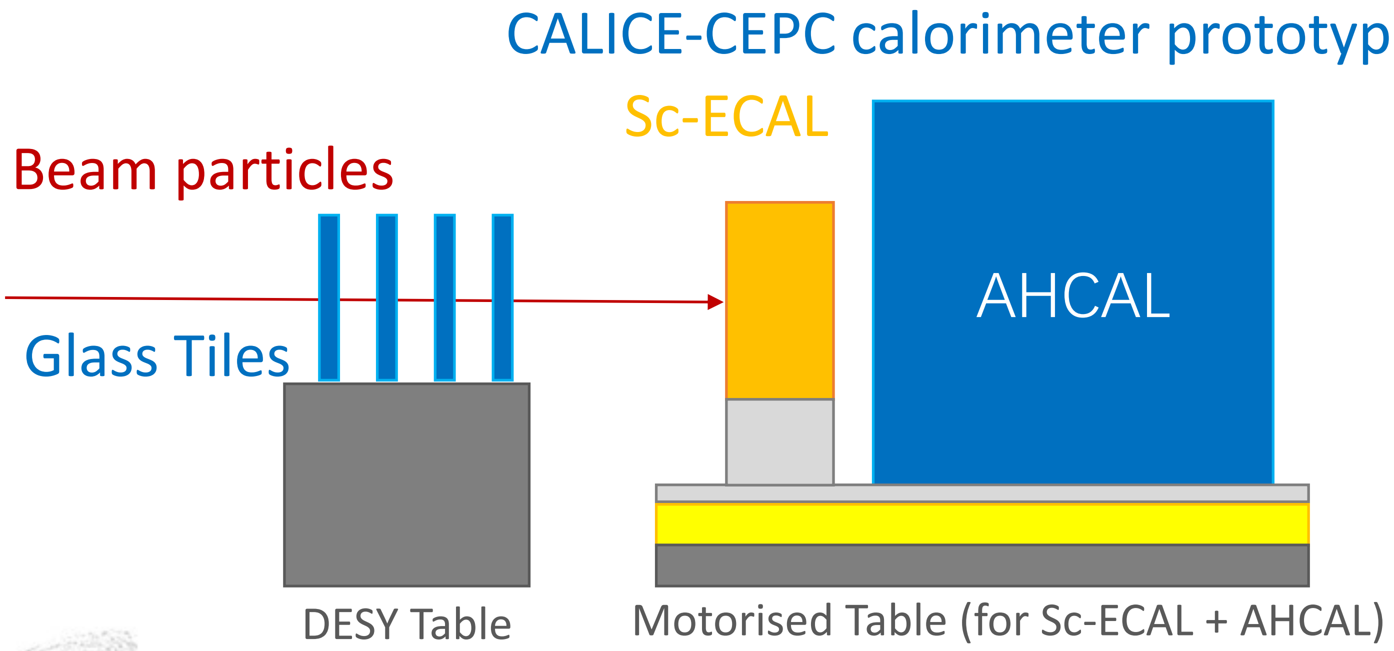


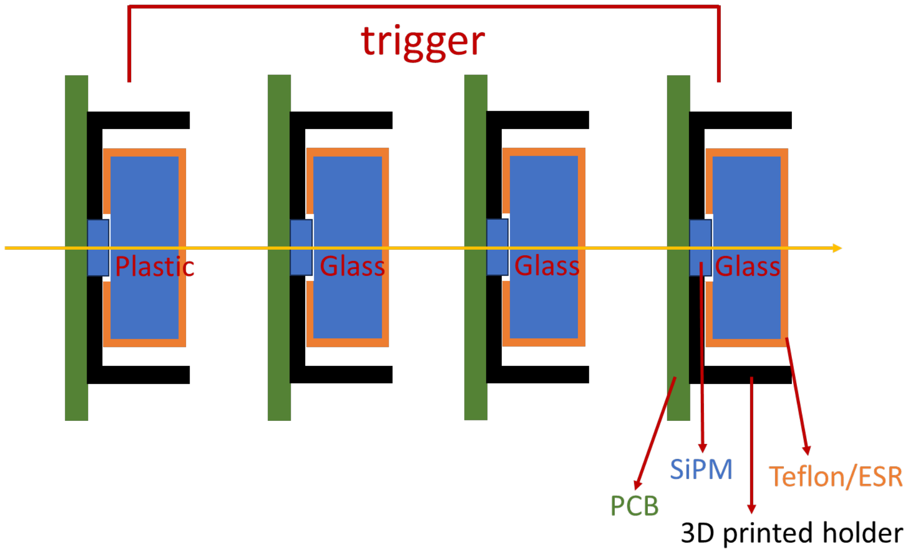
- Gd-Al-B-Si-Ce^{3+} glass: 6 g/cm^3, 1072 ph/MeV, 460 ns
- Target: 6 g/cm^3, 1000-1500 ph/MeV, 100 ns
- Challenge
  - Improve density while keeping light yield and transmittance
  - Properties of glass scintillator become worse after enlarging
- Optimal single properties
  - Ultra-high density tellurite glass—6.6 g/cm^3
  - High light yield glass ceramic—3400 ph/MeV
  - Fast decay time glass doped Pr^{3+}—100 ns
  - Large size glass—50mm×50mm×12mm

CERN Beamtest of large-scale glass tiles

- Beamtest along with [CALICE-CEPC calorimeter prototypes]
- Major motivation: to measure the MIP response of each glass tile
- 11 glass tiles successfully measured using 10GeV mu- beams
- 1 plastic scintillator tile (reference) and 3 scintillator glass tiles in the beamline, use the first and last tile as triggers







Beamtest results of all glass tiles

	Size (mm^3)	Density (g/cm^3)	T (%)	Decay time (ns)	MIP response (p.e./MIP)	Scale to 10mm thickness (p.e/MIP)
#1	33.5×27.6×5.1	~5.1	69	300 (19%), 881	15	29.4
#1 (ESR)					42	82.4
#2	30.2×29.5×6.6	~5.1	61	114 (11%), 770	35	53.0
#3	29.9×28.1×10.2	~5.1	70	90 (6%), 754	66	64.7
#3 (ESR)					69	67.6
#4	37.2×35.1×5.3	~5.1	80	96 (6%), 1024	31	58.5
#5	40.0×35.1×4.2	~5.1	78	335 (26%), 1068	38	90.5
#6	30.3×29.8×9.4	~5.1	55	134 (5%), 1132	67	71.3
#7	34.8×34.8×7.5	~5.1	65	113 (27%), 394	60	80.0
#8	27.8×25.6×5.0	~5.1	81	136 (23%), 933	41	82.0
#9	34.6×34.7×7.5	~5.1	49	141 (12%), 771	69	92.0
#10	34.7×35.2×7.4	~5.1	64	129 (10%), 819	74	100.0
#11	30.5×30.0×8.7	~5.1	81	153 (12%), 1085	73	83.9

Summary and prospects

- GS-HCAL in standalone simulation
  - Quantify hadronic performance with single hadrons and optimize key parameters
  - Better intrinsic hadronic energy resolution
- PFA performance in full detector simulation
  - Optimization of density and cell size
  - Preliminary result: BMR can reach 3.4%
- Ongoing glass scintillator R&D activities
  - To address high density, high light yield, fast decay time and large size
  - Large-scale glass tiles of MIP response can reach 100 p.e/MIP

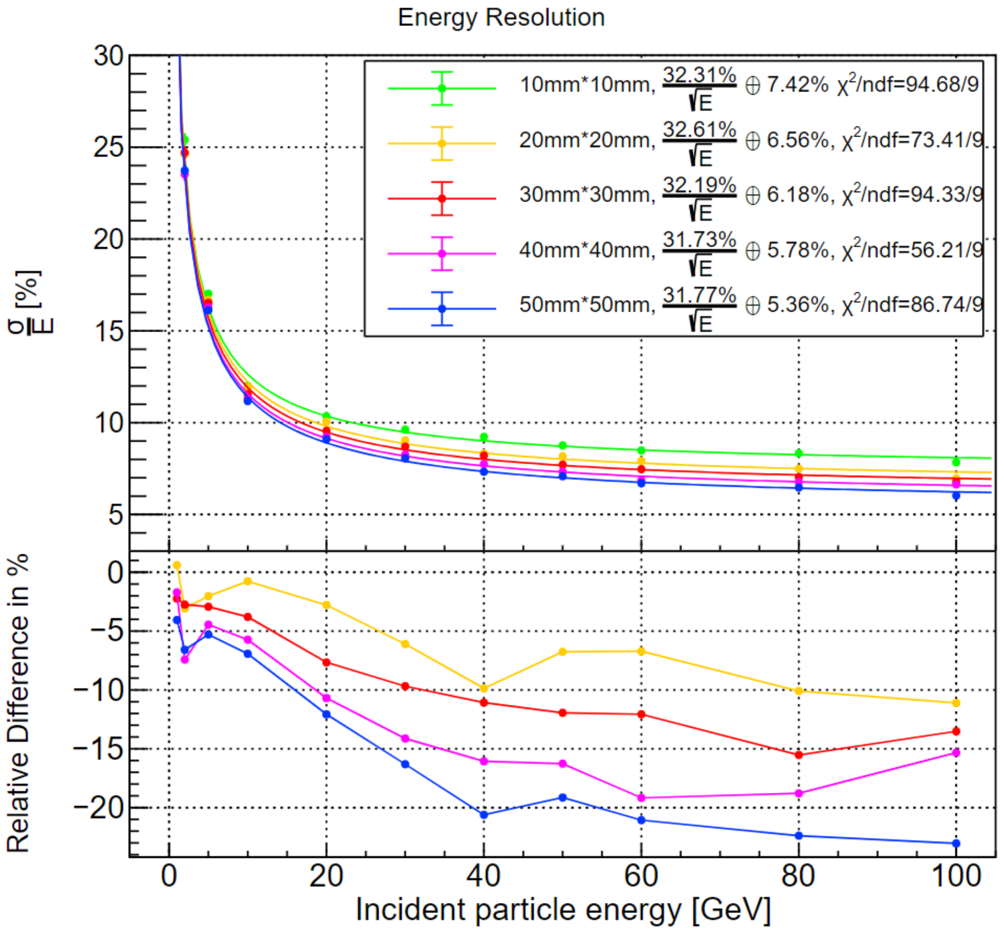
- Plans
  - To further improve the hadronic energy resolution: e.g. “Software compensation” technique
  - Some parameters of Arbor-PFA should be tuned for the glass scintillator HCAL
  - Scintillation process and readout digitization should be considered in simulation

Thanks！

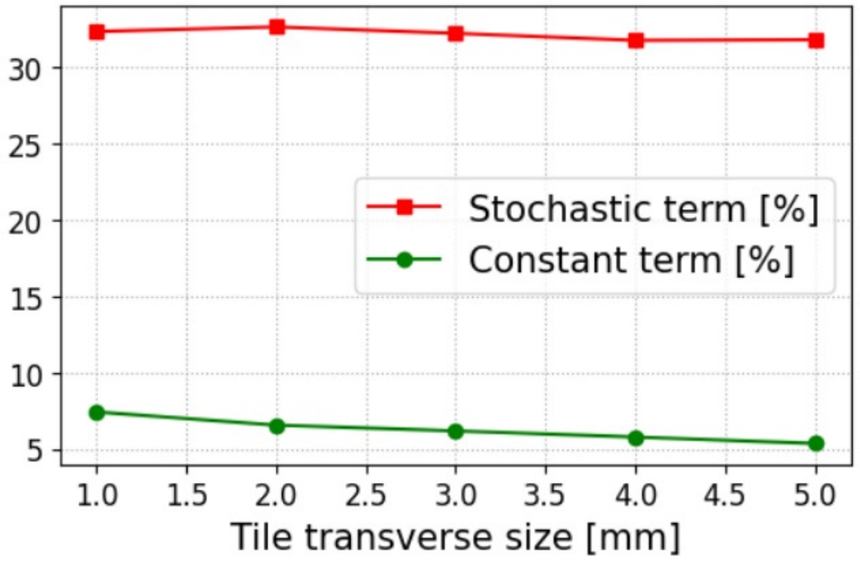
Backup

Impact of tile size to energy resolution

MC sample: K_L^0



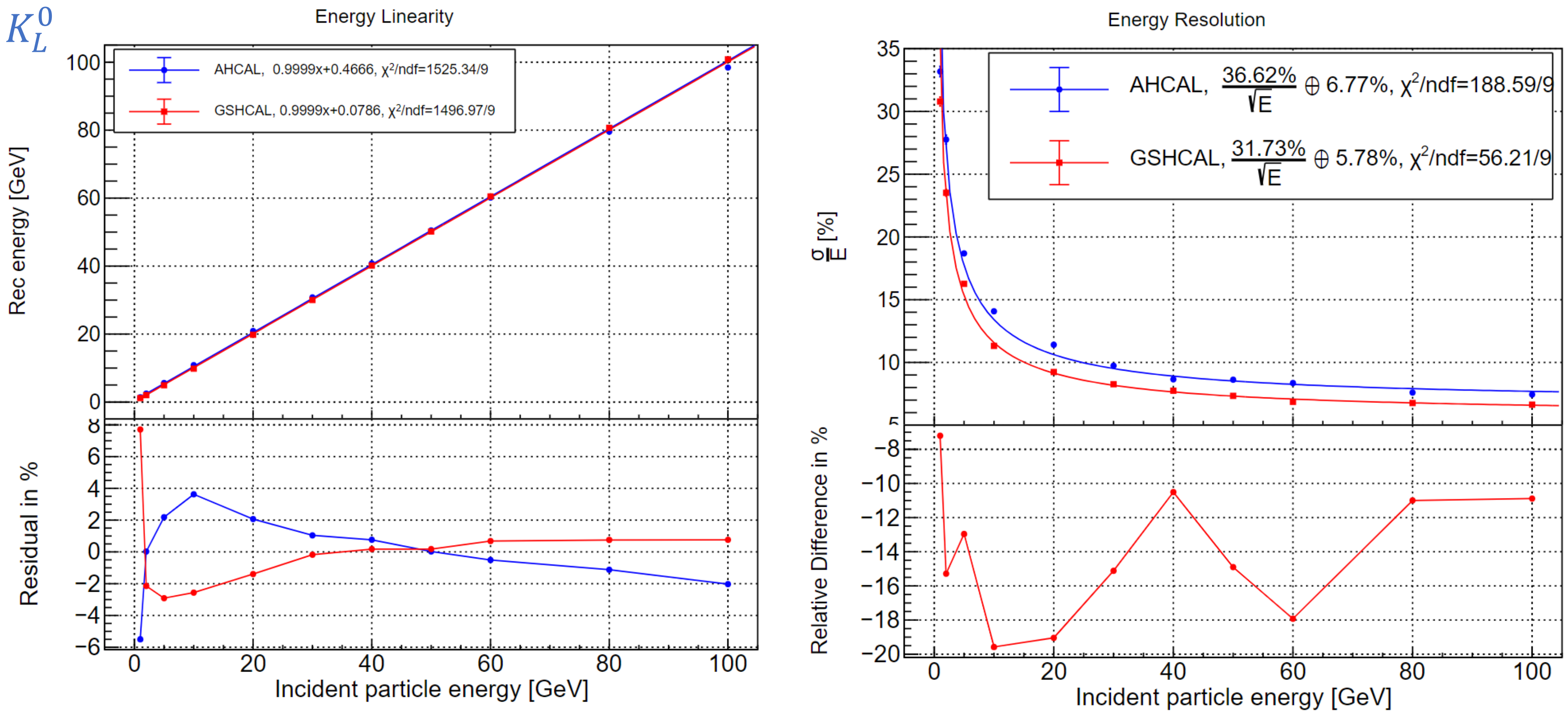
- Varying transverse size of glass scintillator tiles: 10×10 to 50×50 mm^2
- Extraction of stochastic and constant terms in energy resolution



➢ Transverse size of glass scintillator tiles is not the dominant factor affecting the energy resolution

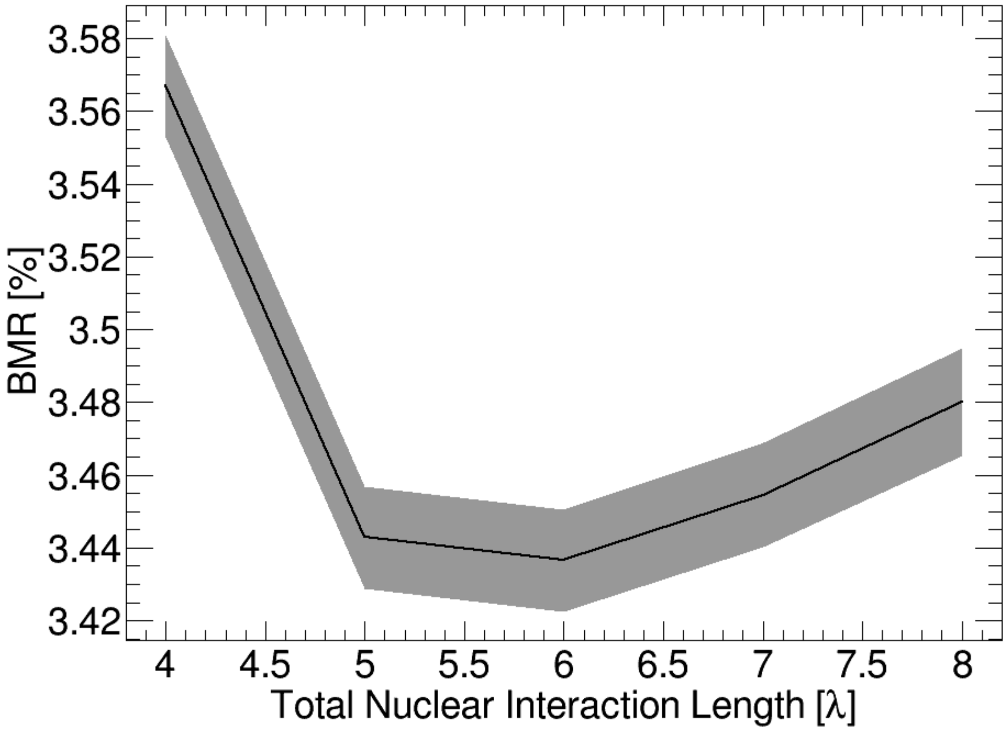
Energy linearity and resolution

MC sample: K_L^0



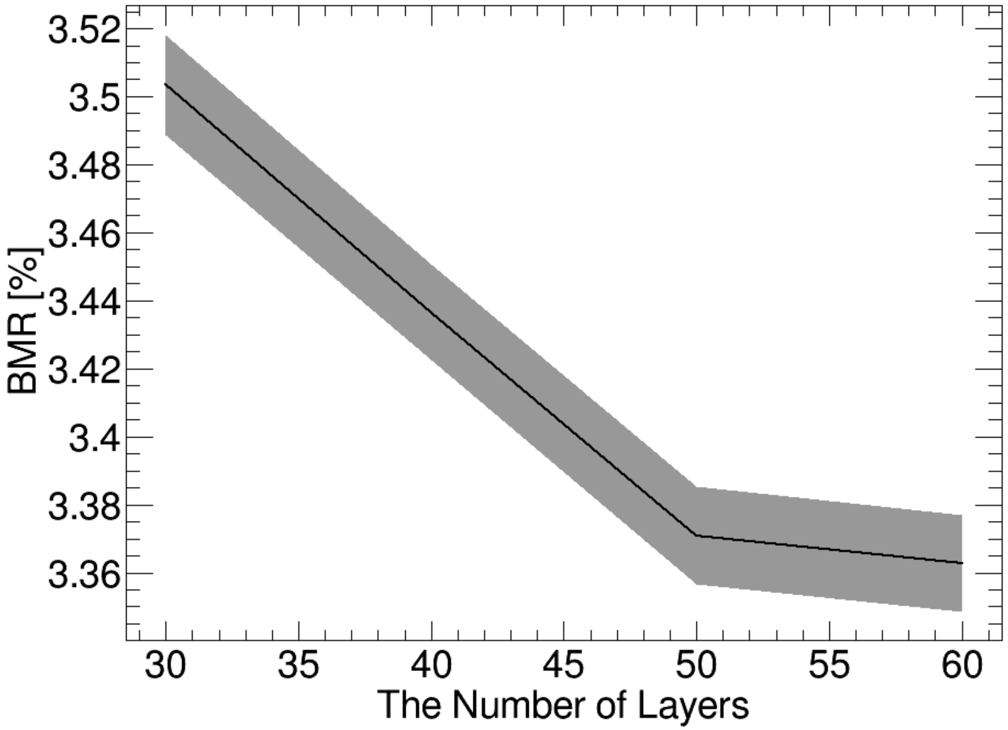
- Preliminary performance comparison: AHCAL vs. GS-HCAL
- Energy linearity: GS-HCAL slightly worse than AHCAL
  - Within ±3% range in 10-100 GeV, but with a relatively worse linearity in low energy range
- Energy resolution: GS-HCAL has a better hadronic energy resolution

Study on the Total NIL



- The BMR is subjected to shower leakage and sampling fraction when varying the total nuclear interaction length of the GSHCAL
- The BMR is dominated separately by shower leakage (< 6 λ) and sampling fraction (> 6 λ);
- A total NIL of 6 λ will be chosen for current design to obtain a optimal BMR

Study on the Number of Layers



- The increase of sampling layers will improve the sampling frequency and sampling fraction, which is beneficial to achieve a better BMR

- 40 sampling layers will be chosen for current design, considering the BMR improvement provided by more sampling layers is not significant and the number of readout channels is in a reasonable level