The Simulation of the GSHCAL for CEPC

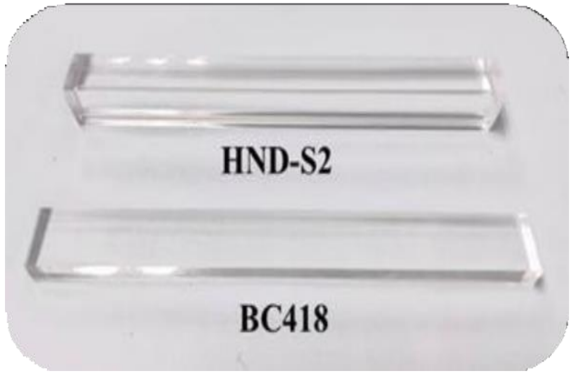
Peng Hu, **Dejing Du, Yuexin Wang, Yong Liu, Manqi Ruan, Sen Qian**

Institute of High Energy Physics, CAS
On behalf of the CEPC Calorimeter Working Group &
the Glass Scintillator Collaboration

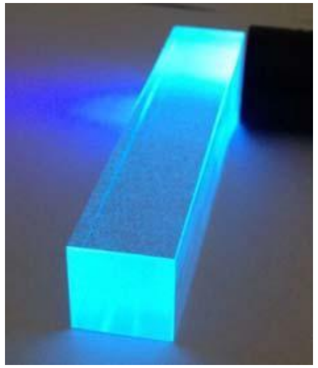
Outline

1. Introduction and Motivation
2. Intrinsic performance of the GSHCAL
3. PFA performance of the GSHCAL
4. Summary

1.1 The Glass Scintillator



Plastic Scintillator



Glass Scintillator

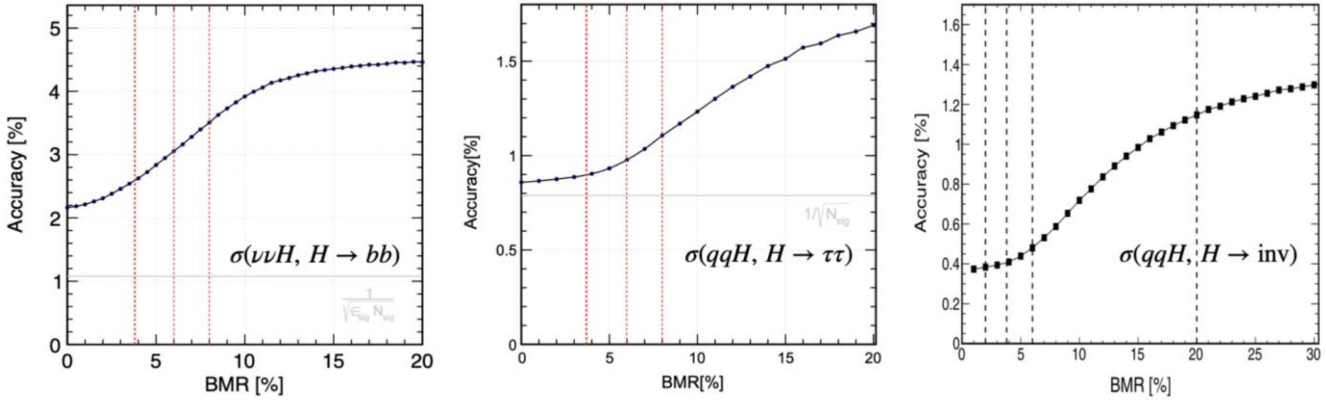
Crystal Scintillator

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**	★

1.2 The Boson Mass Resolution

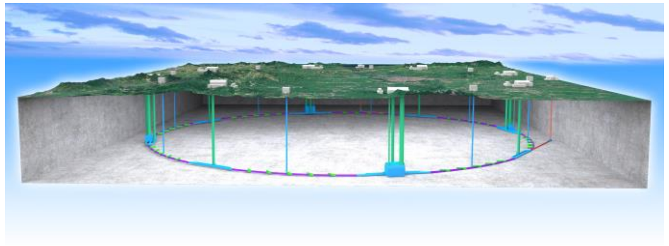
- In order to avoid the complexity induced by the jet clustering algorithm in events with hadronic final states, the **Boson Mass Resolution (BMR)** defined as the mass resolution of these hadronic systems is introduced to quantify the detector performance

- The BMR is a very important index for the achievement of the major scientific goals in the CEPC
  - BMR < 4% is necessary to achieve a separation larger than 2σ between W and Z bosons in their hadronic decays[1]
  - BMR < 4% is generally required in the Higgs width measurement via e+e- $\rightarrow \nu\bar{\nu}H(\rightarrow b\bar{b})$[2], the measurement $H \rightarrow \tau^+\tau^-$ via e+e- $\rightarrow Z(\rightarrow q\bar{q})H(\rightarrow \tau^+\tau^-)$[3], and the study of the Higgs invisible decay via e+e- $\rightarrow Z(\rightarrow q\bar{q})H(\rightarrow$ invisible)[1]



[1] CEPC Conceptual Design Report: Volume 2, arXiv:1811.10545.
[2] H. Zhao, arXiv:299 1806.04992
[3] D. Yu, doi:10.1140/epjc/s10052-019-7557-y

1.3 Motivation



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

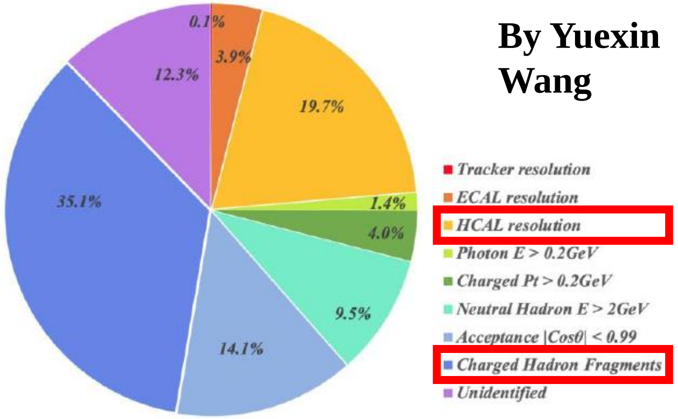
- Main physical goals: precision measurements of the Higgs and Z/W bosons
- Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$

CEPC detector: highly granular calorimeter + tracker

- Boson Mass Resolution (BMR) ~4% has been realized in baseline design
- Further performance goal: BMR 4%→3%
- Dominant factors in BMR: charged hadron fragments & HCAL resolution

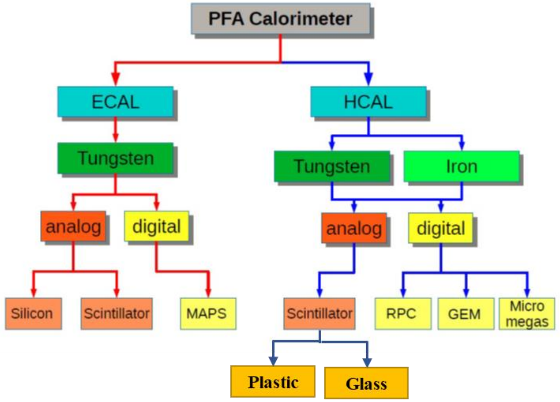
The Factors on BMR from Fast Simulation

By Yuexin Wang



New Option: Glass Scintillator HCAL (GS-HCAL)

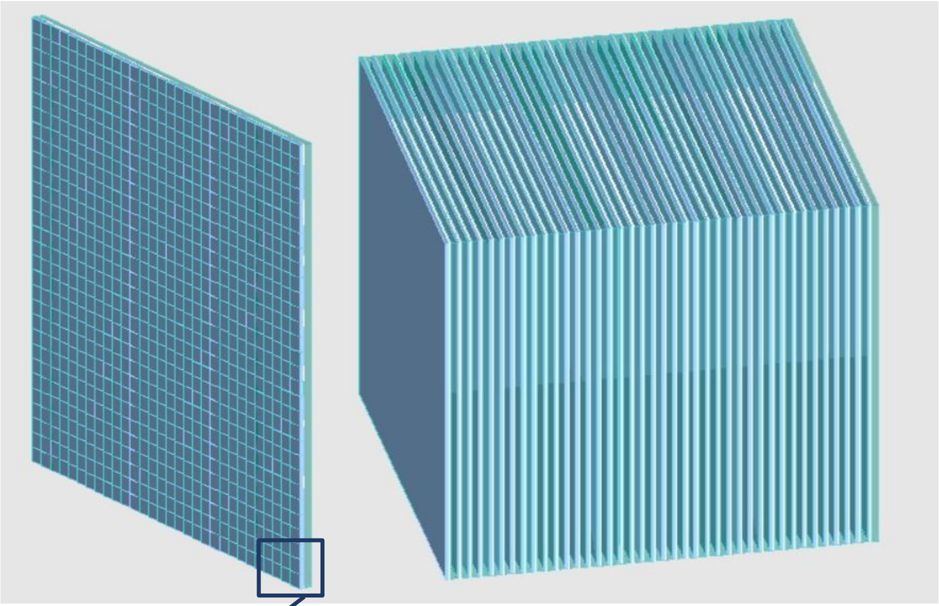
- Higher density provides higher sampling fraction
- Doping with neutron-sensitive elements: improve hadronic response (Gd)
- Advantages of low cost and easiness for mass production

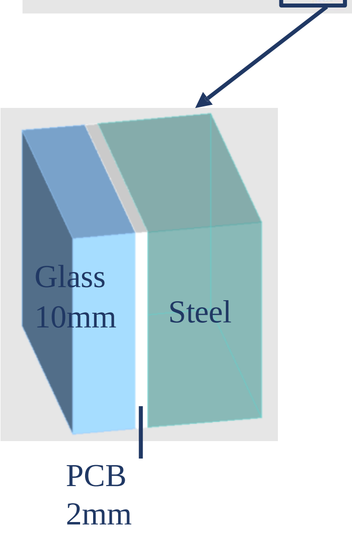


2.1 Intrinsic Performance Simulation of the GSHCAL

- GSHCAL geometry
  - Based on a standalone simulation in the Geant4
  - Refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Replace plastic scintillator with glass scintillator
- Glass scintillator material
  - Composition: Gd-B-Si-Ge-Ce^{3+}
- Primaries input: Single K_0^L
- GSHCAL 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**

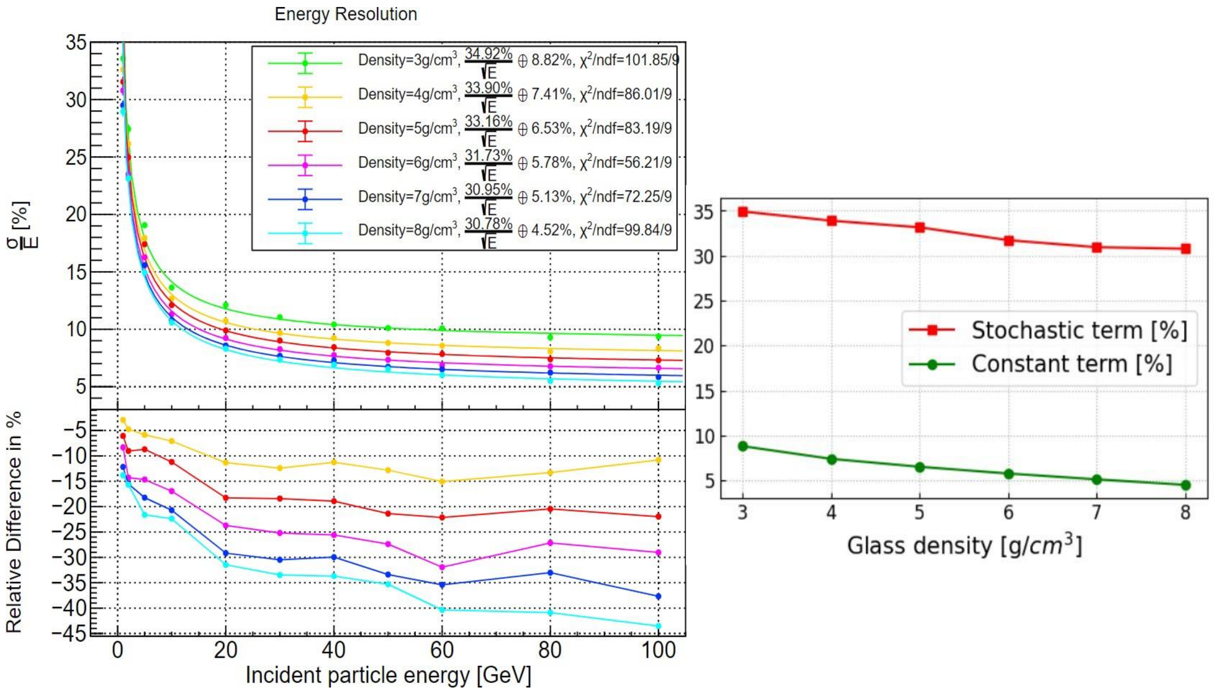




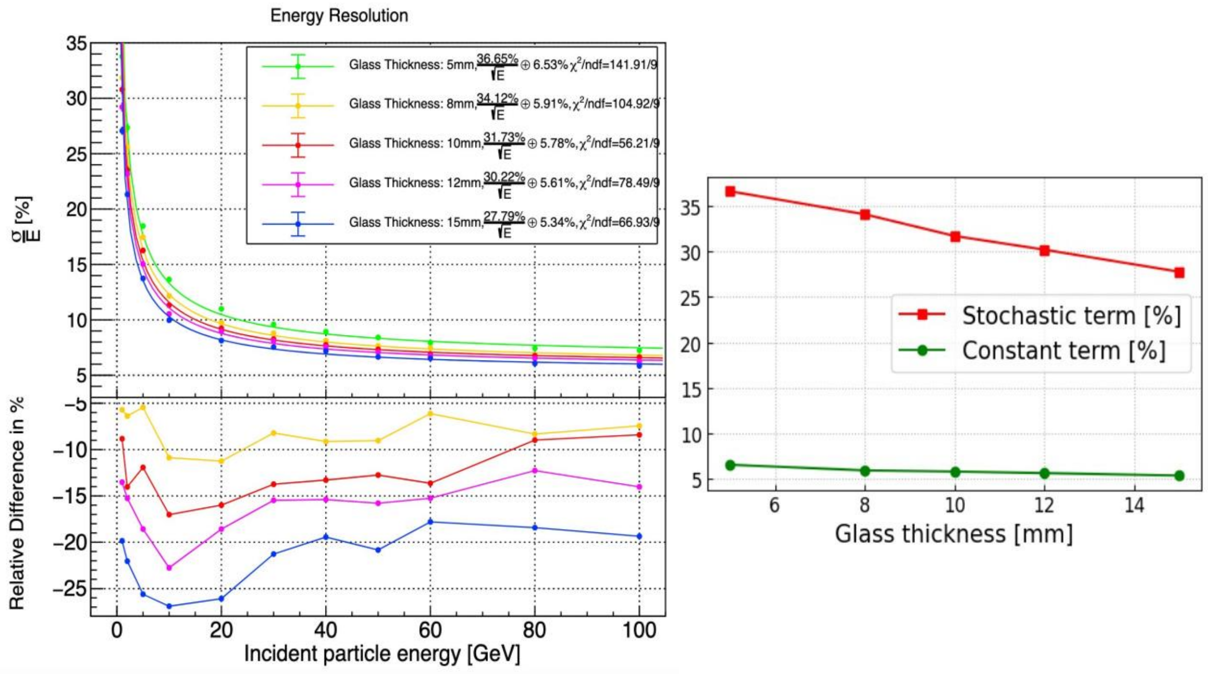
By Dejing Du

2.2 Impact of Density and Thickness

By Dejing Du



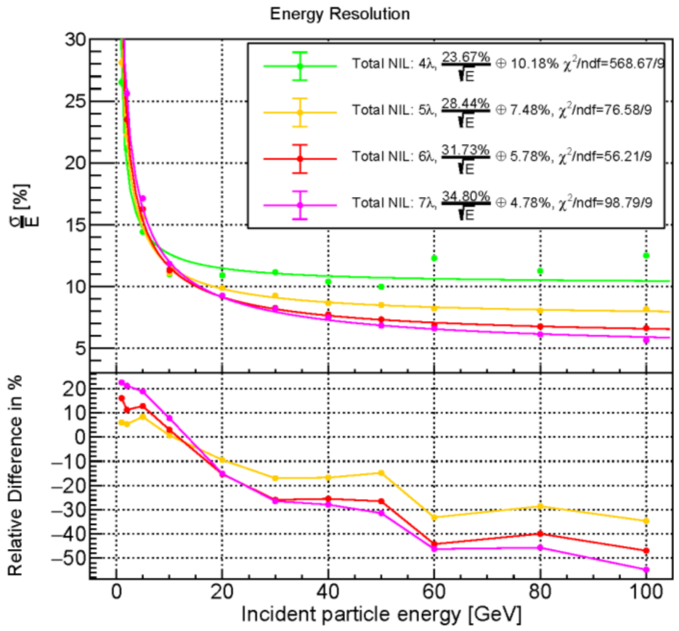
- Increasing glass density is a very effective way to improve the hadronic energy resolution due to a higher sampling fraction, but the light yield will suffer from degradation

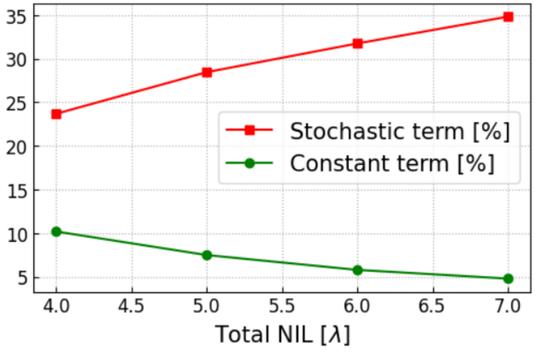


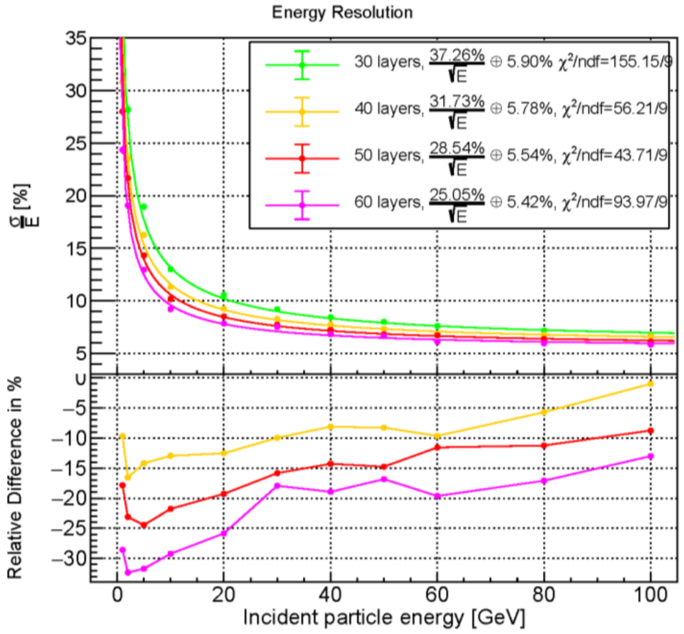
- Increasing glass thickness is another effective way to improve the hadronic energy resolution due to a higher sampling fraction, but the transmittance will suffer from degradation

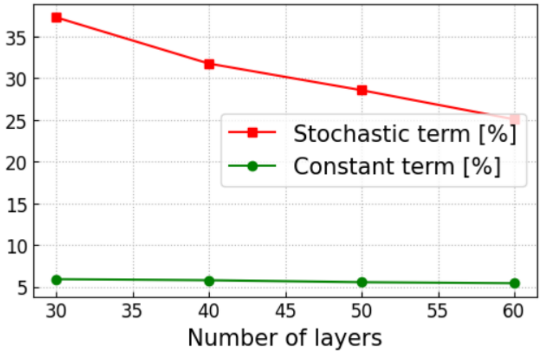
2.3 Impact of Total NIL and Number of Layers

By Dejing Du







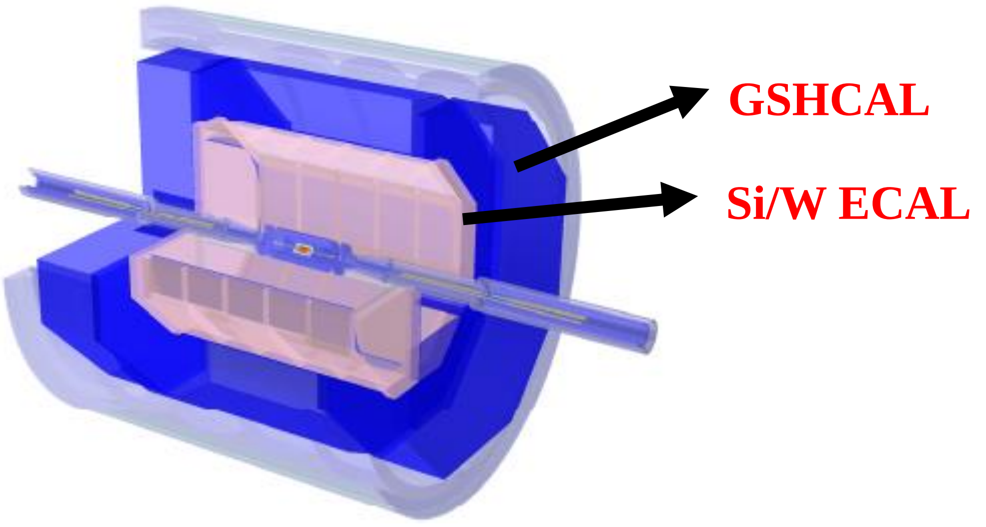


- Increasing the total nuclear interaction length can suppress the shower leakage, which gives a better constant term; the sampling fraction will decrease at the same time, thus a worse stochastic term is observed
- Increasing the number of layers will improve both the sampling fraction and the sampling frequency of the GSHCAL, but the readout channel will also increase rapidly

3.1 PFA Performance Simulation with the GSHCAL

- 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- → $\nu\bar{\nu}$H (H → gg)
- GS material parameters: as shown in right figure



⁕ GSHCAL Nominal Parameter

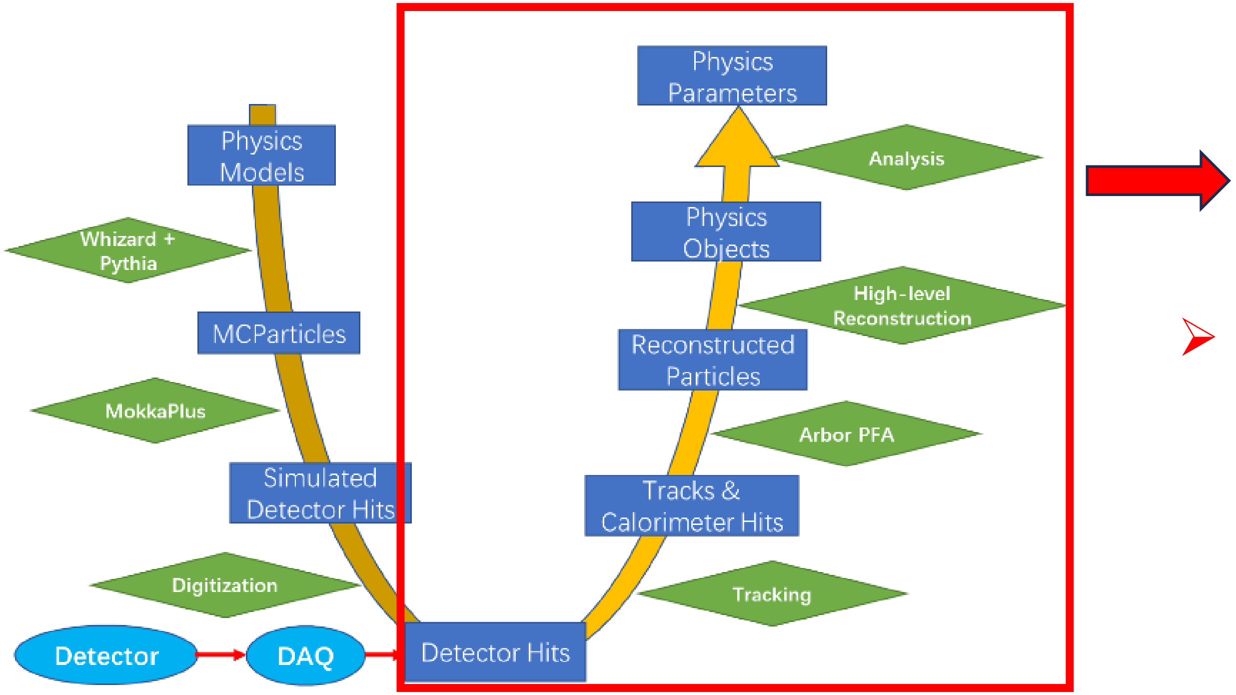
Total Number of Layers	**40**
Glass Cell Size	**20×20×10 mm³**
Total Nuclear Interaction Length	**6 λ**
Glass Density	**6 g/cm³**
Readout Threshold	**0.1 MIP**

	Composition	Density (g/cm³)	MIP Edep (MeV/mm)	NIL (mm/λ)
Simu-GS1	Gd-B-Si-Ge-Ce^{3+}	1	0.115	1226.5
Simu-GS2	Gd-B-Si-Ge-Ce^{3+}	3	0.331	476.6
Simu-GS3	Gd-B-Si-Ge-Ce^{3+}	5	0.573	286.0
Simu-GS4	Gd-B-Si-Ge-Ce^{3+}	6	0.695	238.3
Simu-GS5	Gd-B-Si-Ge-Ce^{3+}	8	0.94	178.7
Simu-GS6	Gd-B-Si-Ge-Ce^{3+}	10	1.188	143.0

3.2 Event Reconstruction and BMR Analysis

☐ Setup

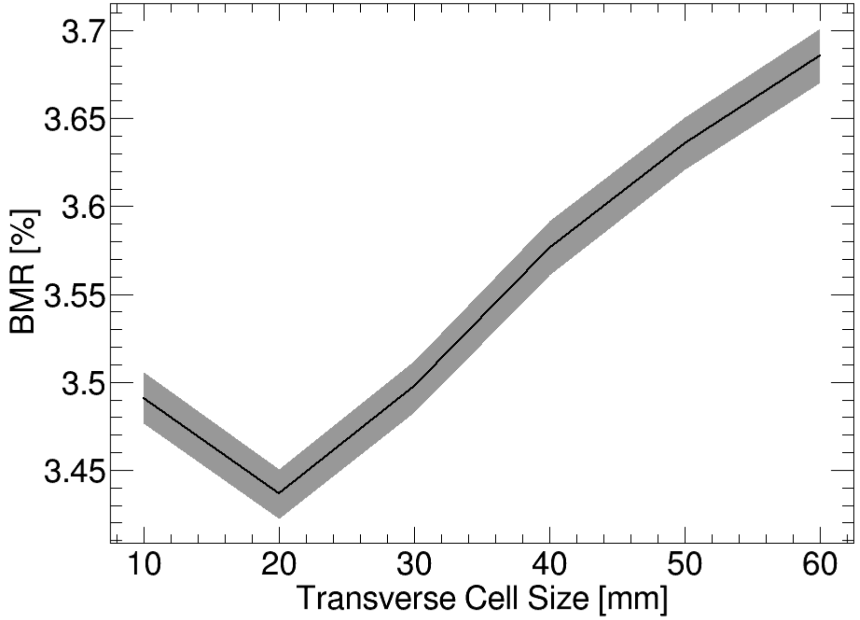
- Arbor PFA is applied
- The readout threshold in each glass cell was set to 0.1 MIP
- Event selection cut： Pt_ISR<1 GeV && Pt_neutrino<1 GeV && |Cos(Theta_Jet)|<0.8

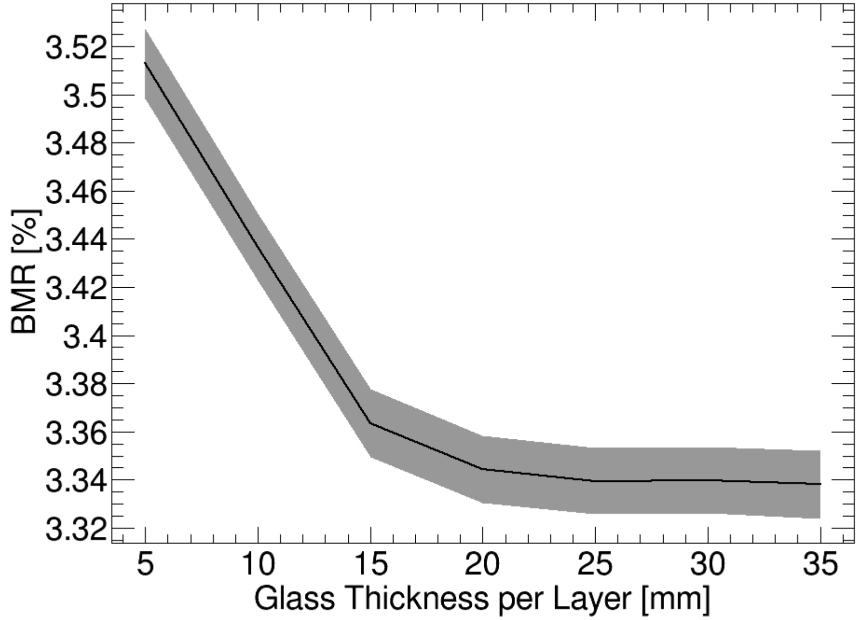


Reconstruction Pipeline

➢ The CaloHit digitization, including the scintillation process and readout time window were not considered in the following results

3.3 Impact of Transverse Size and Thickness

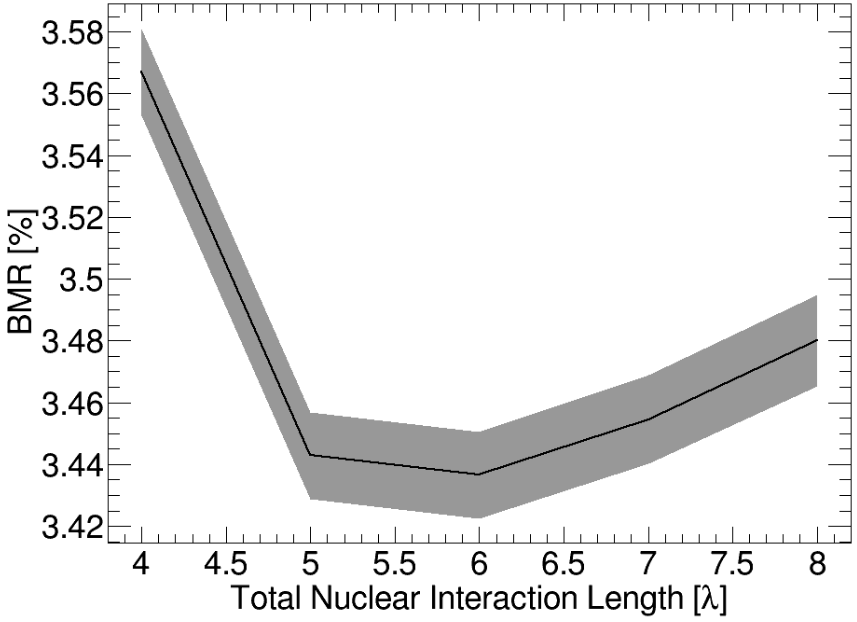


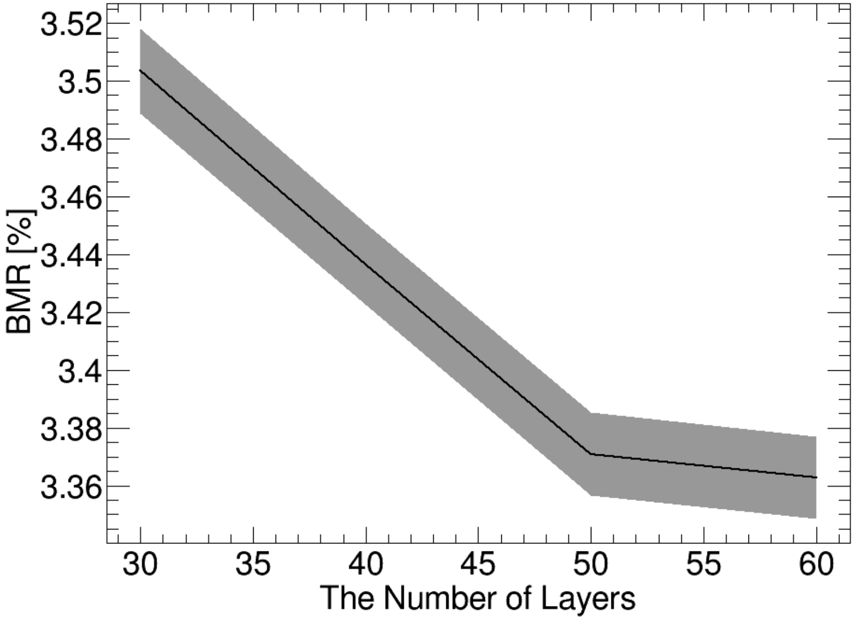


- The transverse size of the glass cell is a very important factor for the granularity and total number of readout channels of the GSHCAL
- Considering the PFA performance and total number of readout channels, a transverse size of 20 mm will be chosen for current design (though the behavior with cell size lower than 20 mm needs a further study)

- A thicker glass cell is conducive to a higher sampling fraction and a better BMR, though the transmittance and the position response non-uniformity will become worse; besides, the glass thickness will be also limited by the total thickness of the GSHCAL
- A glass thickness of 10 mm will be chosen for current design, considering the BMR improvement provided by a thicker glass cell is not significant and meet the requirement from other aspects

3.4 Impact of Total NIL and Number of Layers

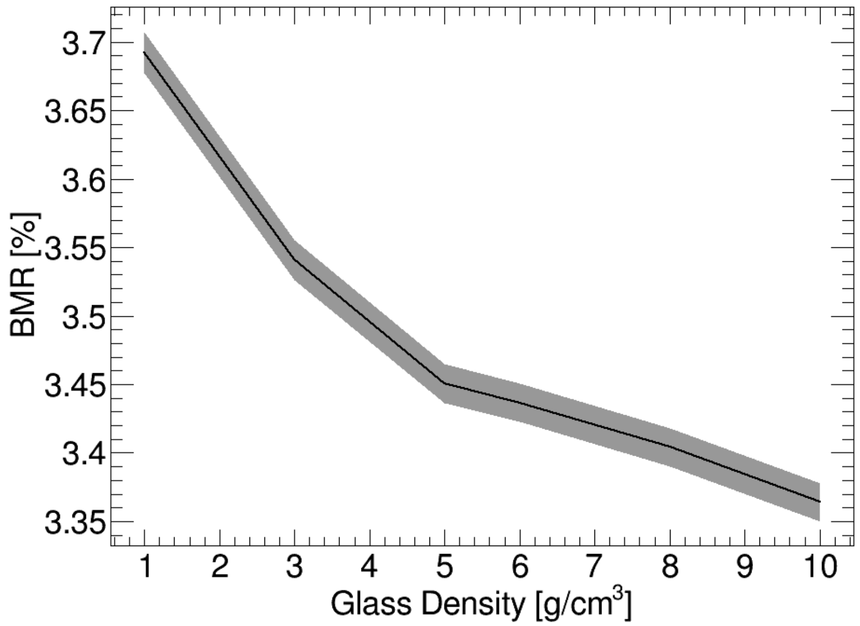


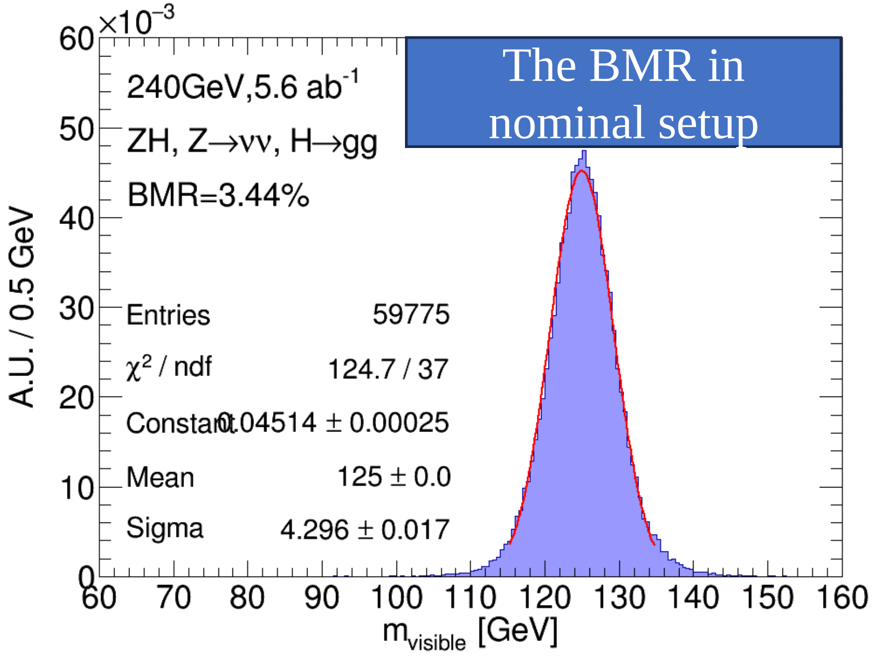


- The BMR is subjected to shower leakage and sampling fraction when varying the total nuclear interaction length of the GSHCAL
- The BMR is dominated separately by shower leakage ($< 6\ \lambda$) and sampling fraction ($> 6\ \lambda$);
- A total NIL of $6\ \lambda$ will be chosen for current design to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

- 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

3.5 Impact of Density

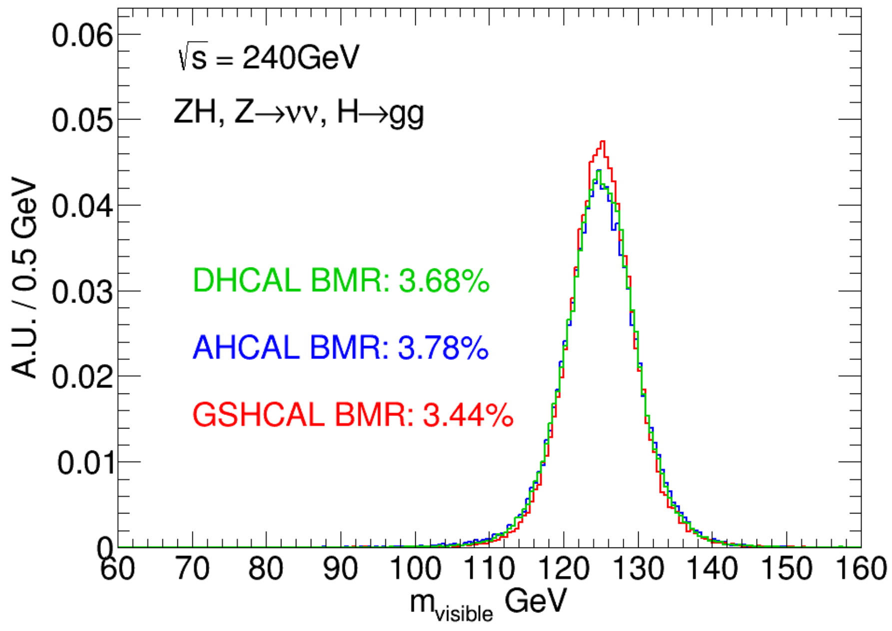




- The high-density glass scintillator is beneficial to a better BMR and more compact design, but the scintillation performance (light output, transmittance and etc.) usually decrease with increasing glass density
- A glass density of 6 g/cm^3 will be chosen for current design, since the BMR improvement provided by a higher density is not significant and the degradation of scintillation performance is acceptable

3.6 Baseline Design vs. GSHCAL

Parameter (nominal)	GSHCAL	AHCAL	DHCAL
Readout	Analog	Anlog	Digital
Number of layers	40	40	40
Layer thickness	0.15 lambda (10 mm GS +Steel)	0.124 lambda (3 mm PS +20 mm Steel)	0.12 lambda (3 mm RPC +20 mm Steel)
Total Nuclear Interaction Length	6 lambda	~5 lambda	~4.8 lambda
Transverse Cell Size	20x20 mm^2	30x30 mm^2	10x10 mm^2
Sensitive Material Density	~6 g/cm^3	~1 g/cm^3	\
Sensitive Material Light Yield	~1e3 ph/MeV	~1e4 ph/MeV	\
Sensitive Material Decay Time	~100 ns	~ 2 ns	\



- Comparing nominal GSHCAL with DHCAL and AHCAL
- Gaussian Fitting Range: Mean ± 2 RMS

➢ In the CDR baseline design, the BMR of DHCAL ~3.7%, and of AHCAL ~3.8%;

➢ By replacing the CEPC_v4 baseline HCAL with the GSHCAL , the BMR can reach ~3.4% in the nominal setup and show ~10% improvement with. the AHCAL baseline design (~3.8%)

Summary

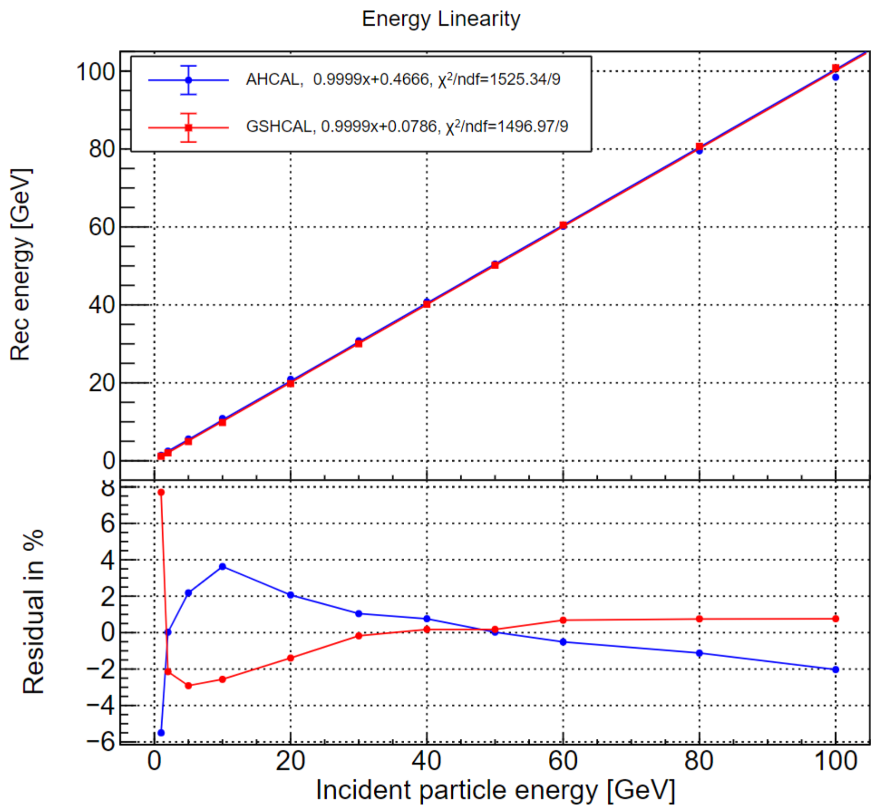
- The performance of the GSHCAL in a nominal setup was studied both in a standalone simulation and in the CEPCSoft framework

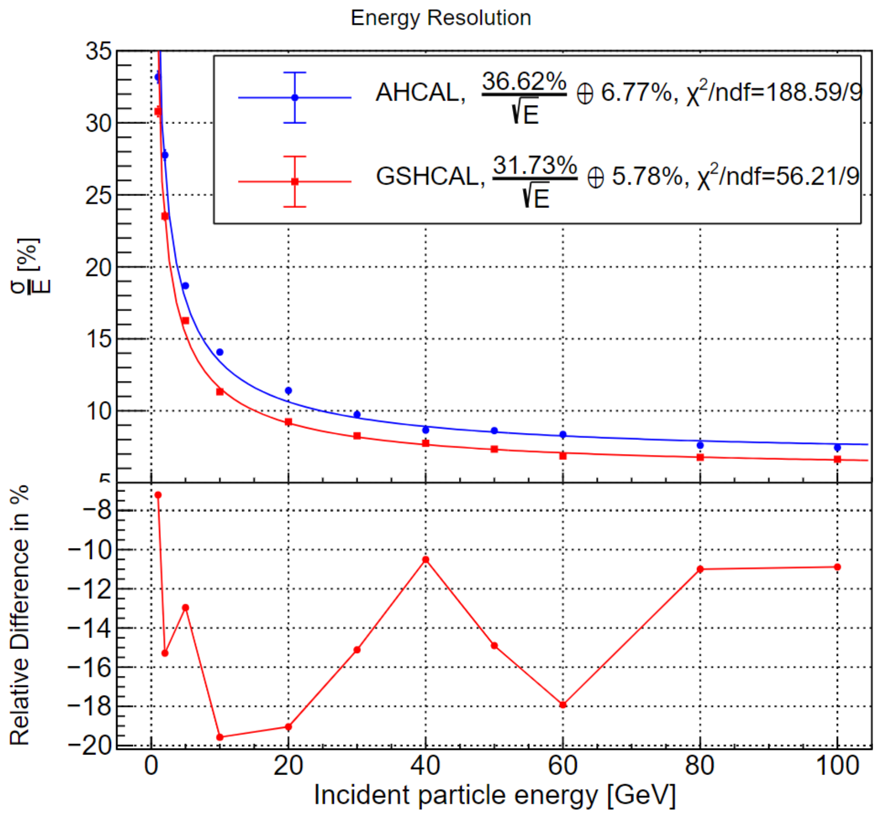
- In terms of the PFA performance, the BMR with GSHCAL of nominal setup can reach ~3.44% and show ~10% improvement with respect to the baseline AHCAL design (~3.8%), which is a very promising alternative design

- Fine tuning of the PFA parameters is needed and will be further studied; the implementation of digitization process is still ongoing

Thank you!

Intrinsic performance (GSHCAL vs. AHCAL)

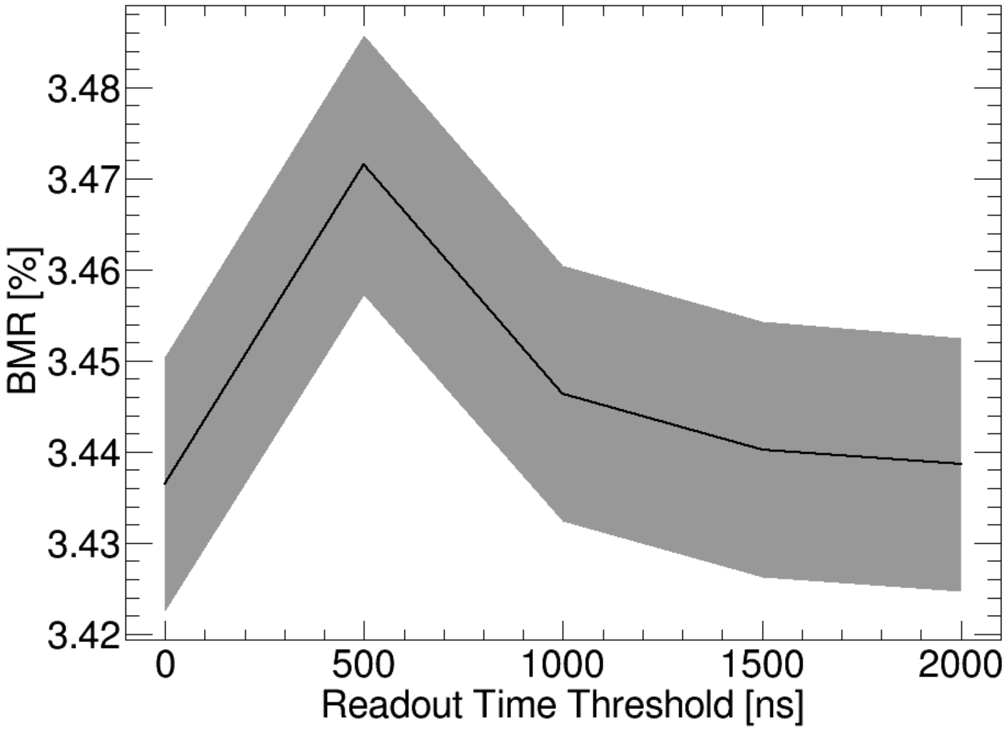




- Intrinsic performance comparison: CDR baseline AHCAL vs. nominal GSHCAL
- Energy linearity: GSHCAL slightly worse than AHCAL
  - Within ±3% range in 10-100 GeV, but with a relatively worse linearity in lower energy range
- Energy resolution: GSHCAL has a better hadronic energy resolution and improves by around 15%

Digitization for Readout Time

- ➢ Only the (G4)step whose time is within the time threshold will be considered
- ➢ Threshold 0 means no time digitization (i.e. all steps will be used)



- The readout time threshold has an important impact on the slow signal (mainly caused by neutrons); more slow signals will be rejected as the time threshold decreases, thus the energy resolution and the BMR also become worse
- A higher readout time threshold is beneficial to obtain a better BMR but the improvement is not significant, thus 1 us is considered to be enough

Digitization for Detected Photoelectrons

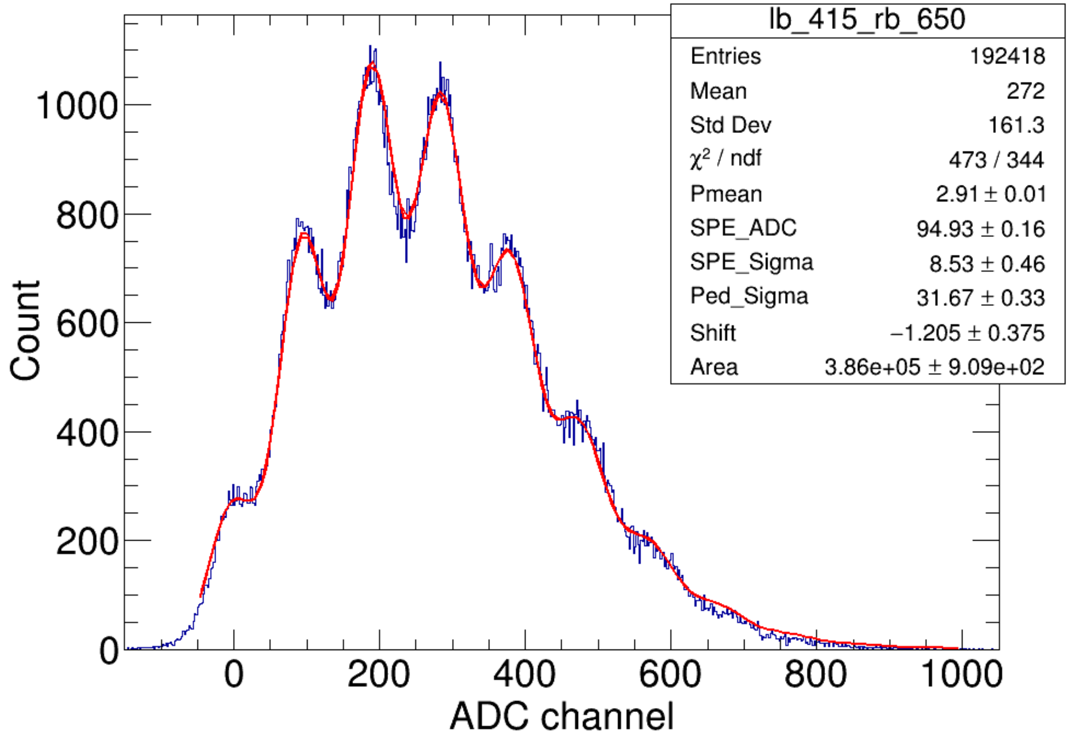
a) $PE_{detected} = Gaus(Poisson(Mean\_pe), Sigma)$

b) $Edep_{detected} = PE_{detected}/MIPLO$

- Simga = $Sqrt(Poisson(Mean\_pe)*SPE\_Sigma^2+Ped\_Sigma^2)$

Poisson sampling with consideration of the scintillation process and the photon detection efficiency of the SiPM; the **Mean_pe** is the mean detected p.e. for MIP (p.e./MIP)

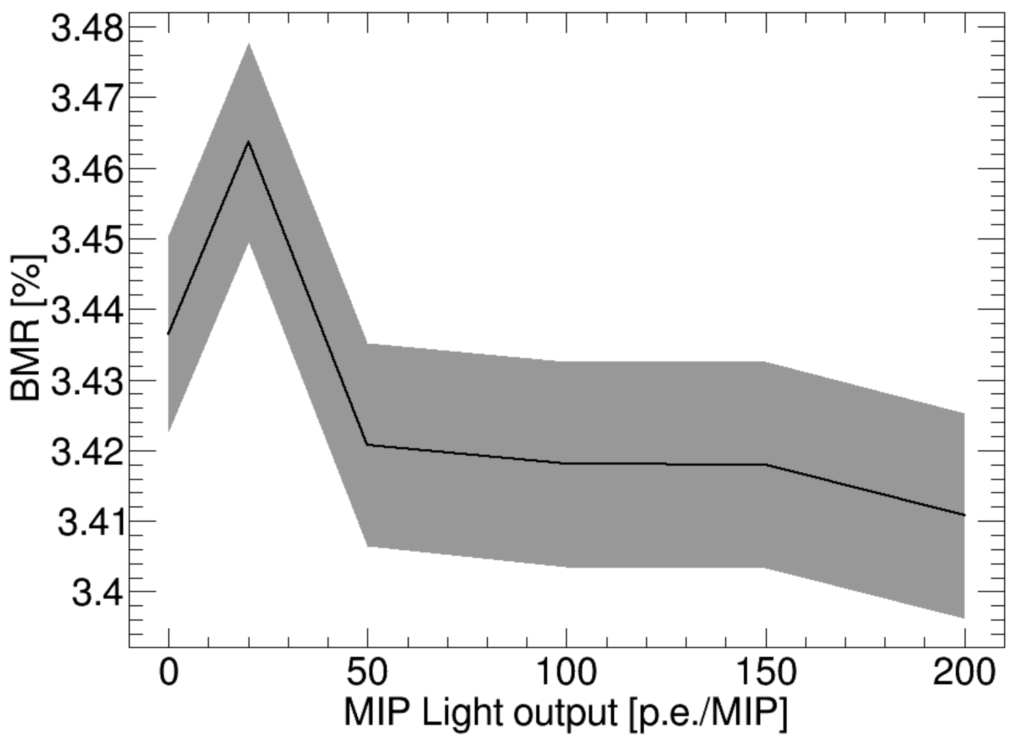
Gaussian sampling with consideration of the fluctuation of a given photoelectron signal, which is caused by the fluctuation of the pedestal (the electronics noise, denoted as **Ped_Sigma**) and the single photoelectron signal (from the gain and the amplifier, etc, denoted as **SPE_Sigma**)



- Measured SPE spectrum of Hamamatsu S13360-6050CS, fitted with convoluted Poisson and Gaussian function mentioned above to obtain **SPE_Sigma** and **Ped_Sigma**

Digitization for Detected Photoelectrons

- The energy deposition is sampled based on the method mentioned in last slide
- Readout threshold was set to 5 p.e.
- 0 p.e./MIP means no digitization for detected photoelectrons (i.e. the energy threshold of 0.1 MIP is used)



- The MIP Light output will have a significant impact on the fluctuation of electronics signal and thus a very important factor to the BMR
- MIP response of 50 p.e./MIP is enough to obtain a optimized BMR based on this preliminary simulation