The Simulation of the GSHCAL for CEPC

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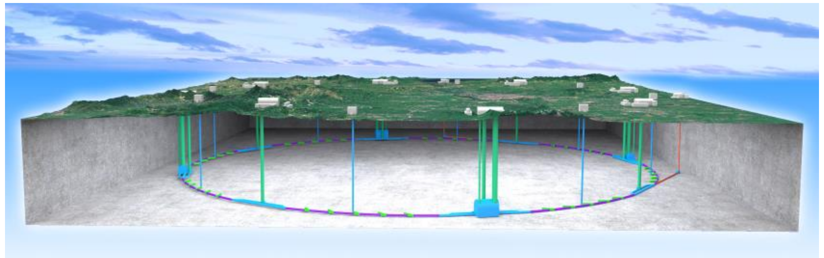
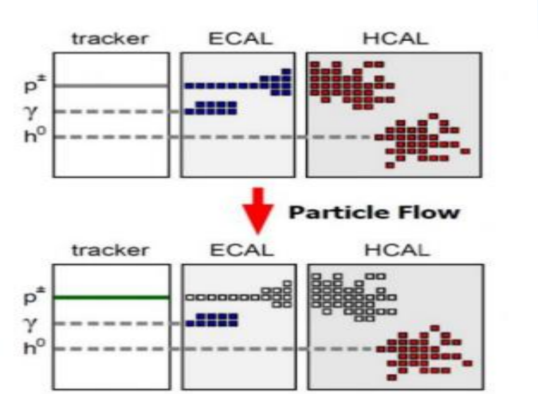
the Glass Scintillator Collaboration

Outline

1. Motivation and Introduction
2. GSHCAL intrinsic performance and PFA fast simulation
3. PFA full simulation based on the GSHCAL
4. Summary

1.1 Motivation



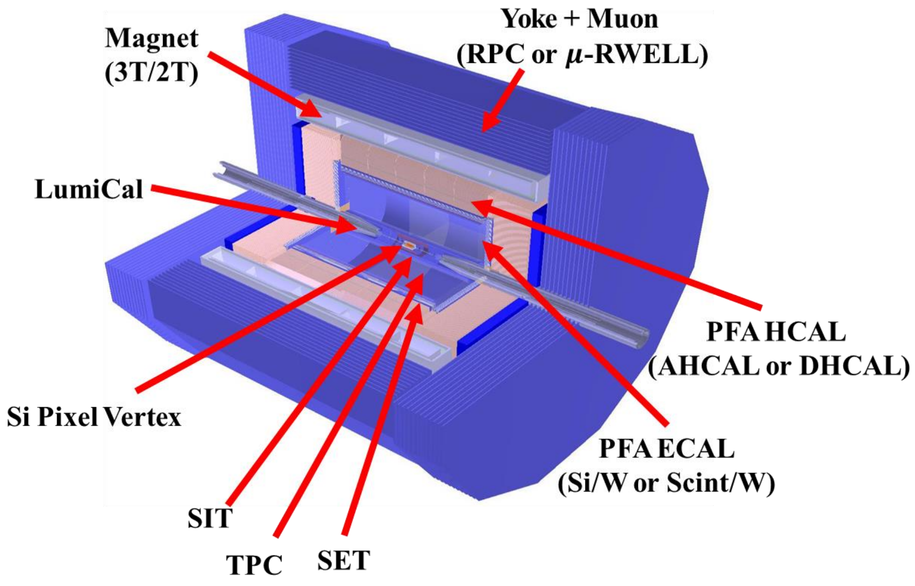


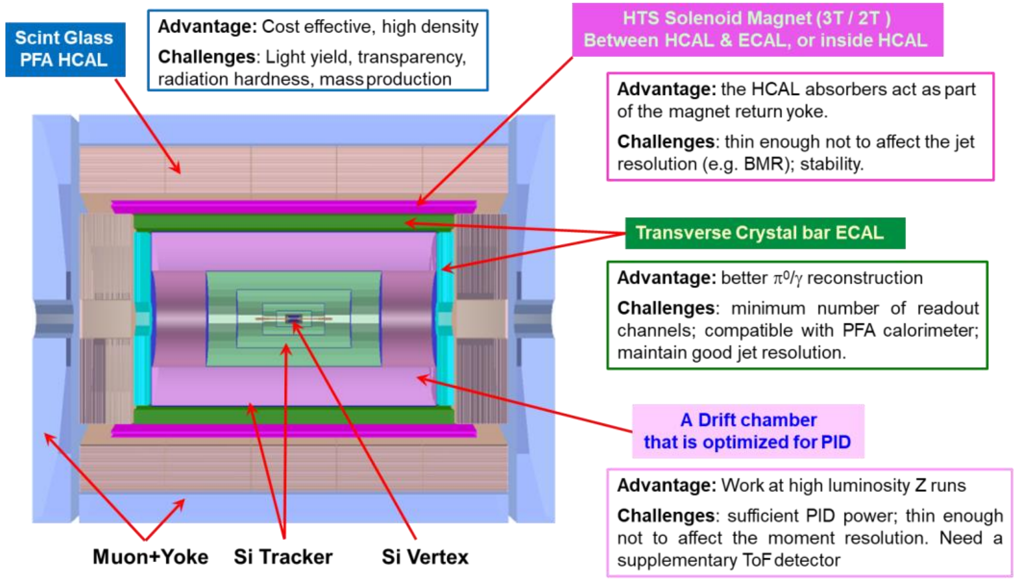
Future electron-position colliders (e.g. CEPC)

- precision measurements of the Higgs and Z/W bosons
- Challenge: jet energy resolution < $30\%/\sqrt{E(\mathrm{GeV})}$ &

  Boson Mass Resolution (BMR) < 4%

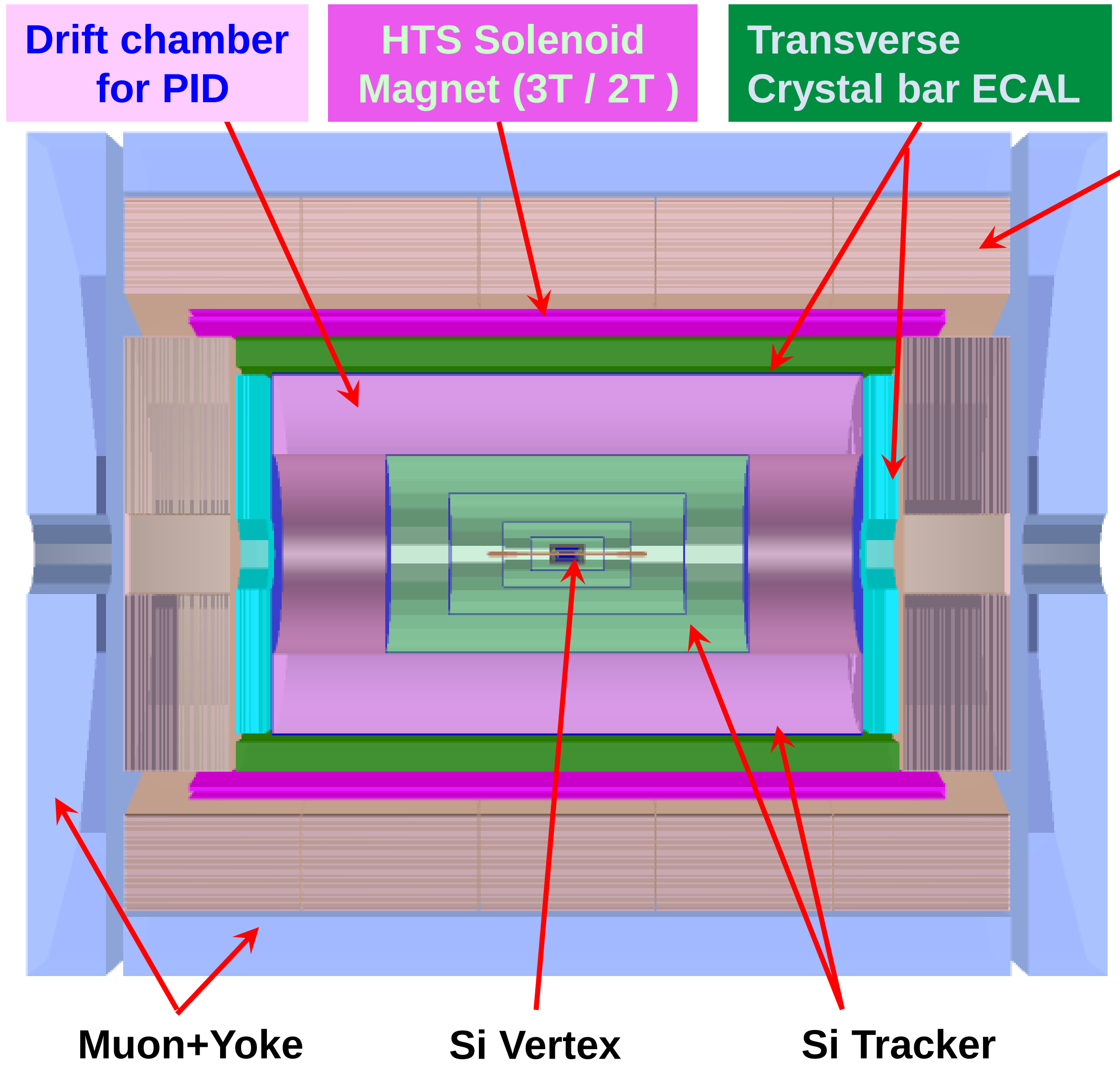
PFA-oriented detector: baseline design → the 4th conceptual design





1.2 The 4th Conceptual Detector Design

More details in This Talk



Glass Scintillator HCAL

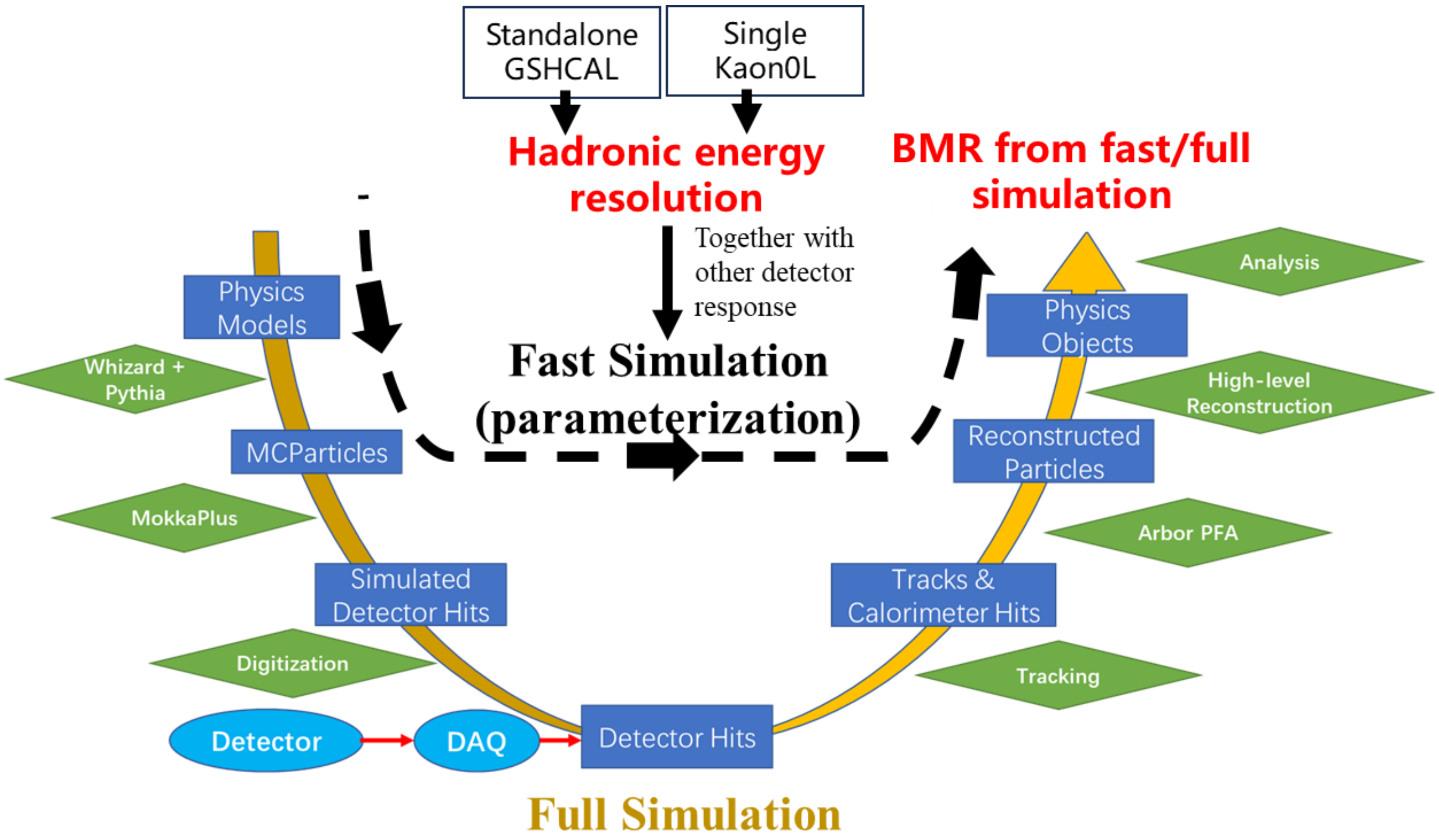
Advantage: Cost effective, high density

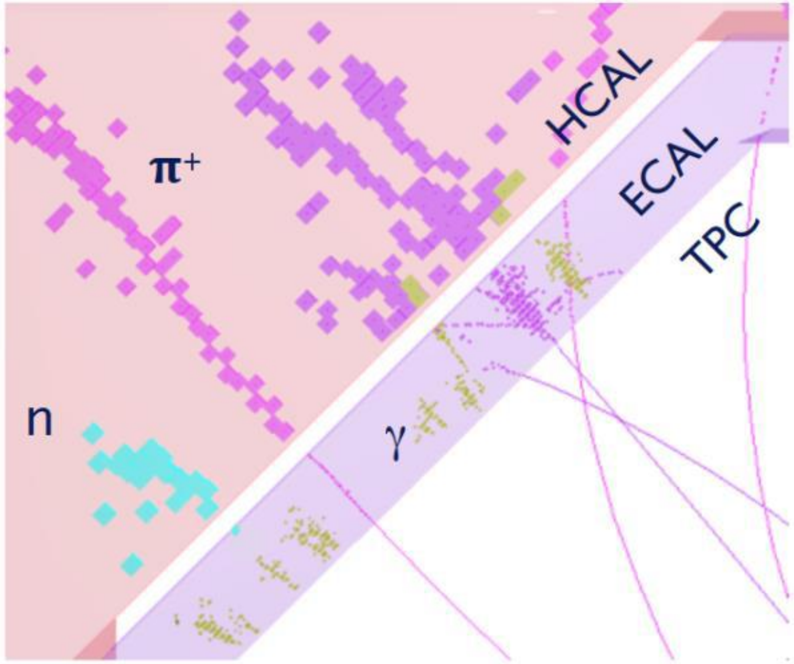
Challenges: Light yield, transparency, mass production

- Further performance goal: BMR 3.8%→3%
- Dominant factors in **BMR**: charged hadron fragments & HCAL resolution
  - Higher density provides higher energy sampling fraction
  - Doping with neutron-sensitive elements: improve hadronic response (Gd)
  - Large λ_I is beneficial for a relatively compact structure

1.3 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**

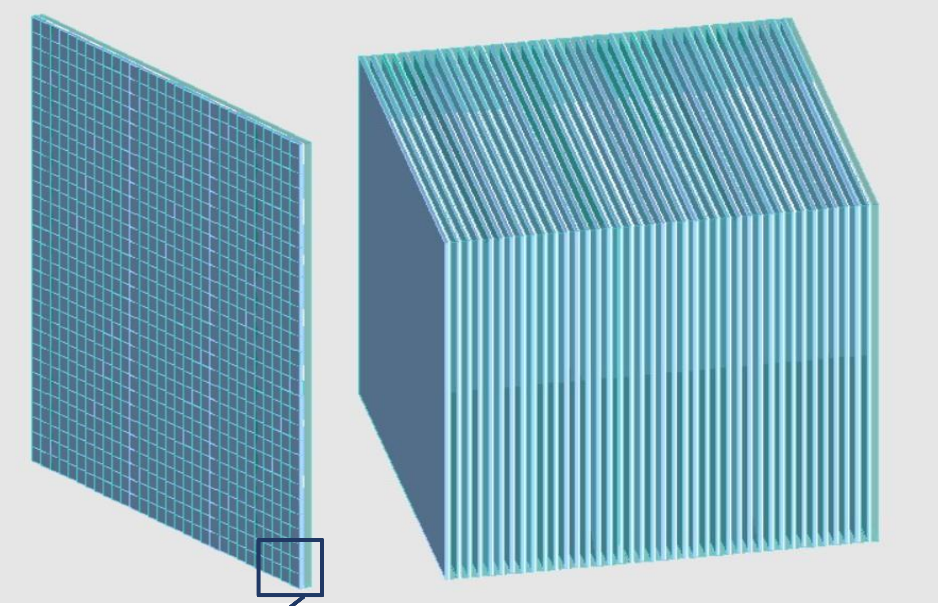


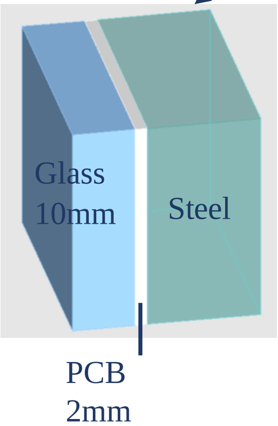


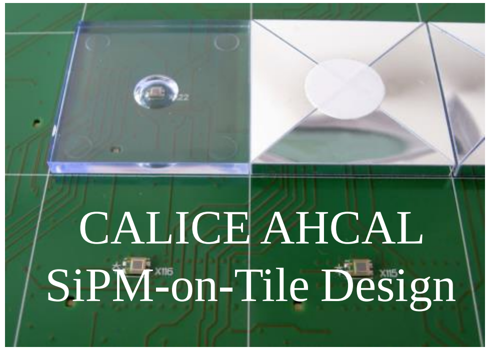
2.1 GSHCAL Intrinsic Performance Simulation

- Standalone GSHCAL module
  - Similar to the AHCAL in CEPC baseline design
  - 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	**5 λ**
Glass tile size	**40×40×10 mm³**
Glass density	**6 g/cm³**
Readout threshold	**0.1 MIP**

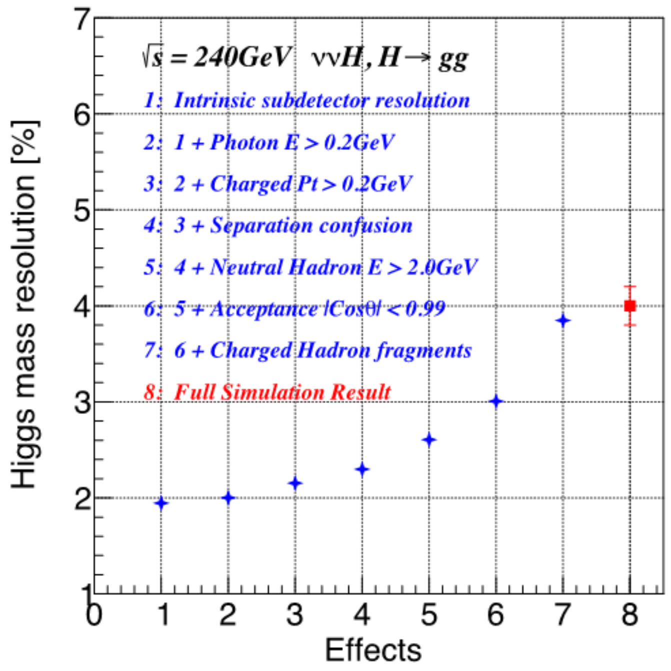




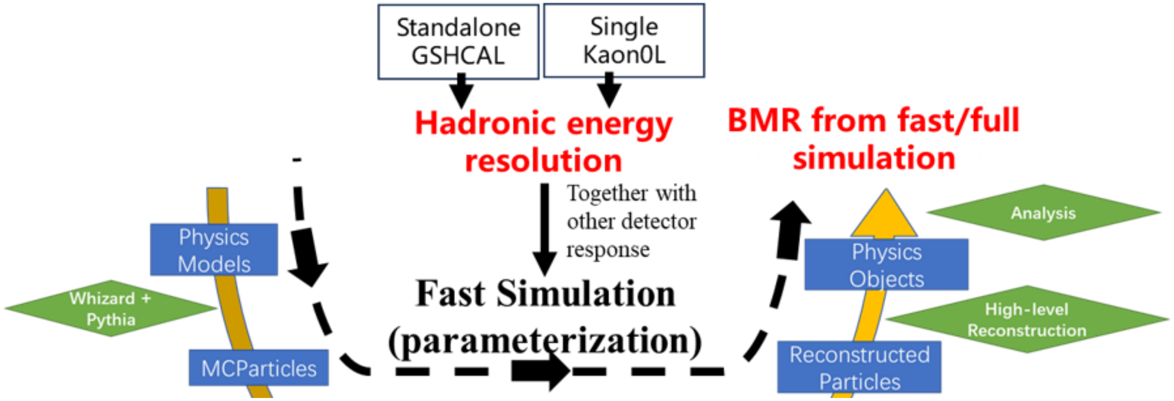


2.2 PFA Fast Simulation based on the GSHCAL

- **MCParticle input: 240 GeV e+e- → $\nu\bar{\nu}H$ (H → gg)**
- **Modeling (based on baseline results except for the GSHCAL)**
  - Energy/momentum resolution
    - Tracker ~0.1%
    - Si/W ECAL $17\%/\sqrt{E} \oplus 1\%$
    - GSHCAL Energy resolution based on intrinsic performance simulation
  - Energy/momentum threshold
    - Track P > 0.2 GeV
    - Photon E > 0.2 GeV
    - Neutral hadron E > 1 GeV
    - Acceptance |cosθ| < 0.99

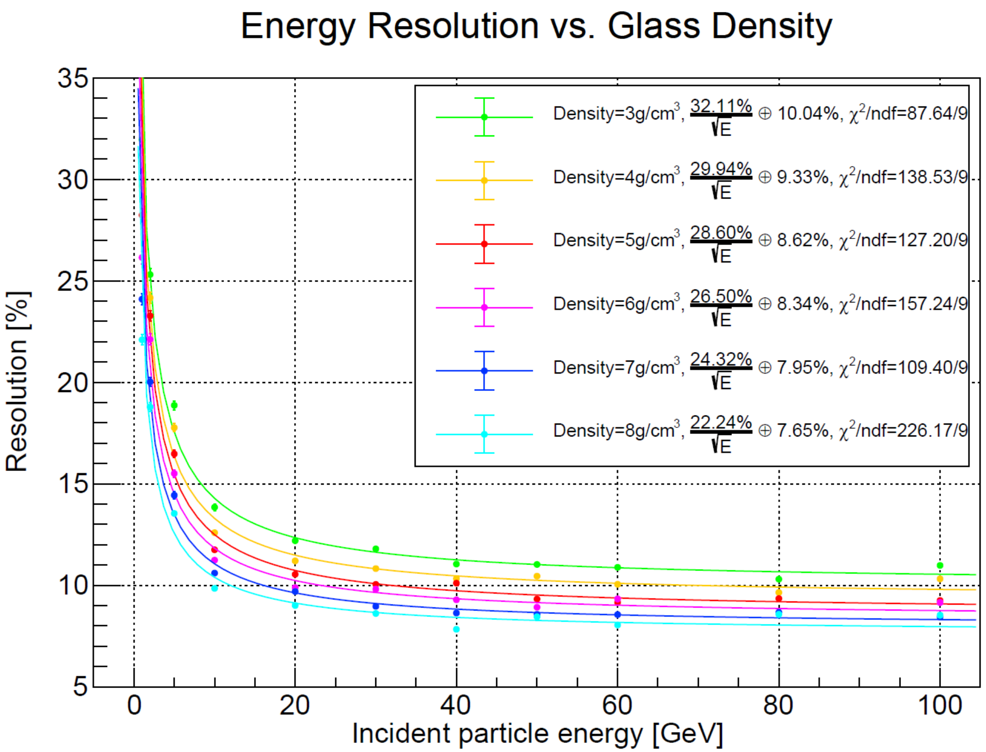


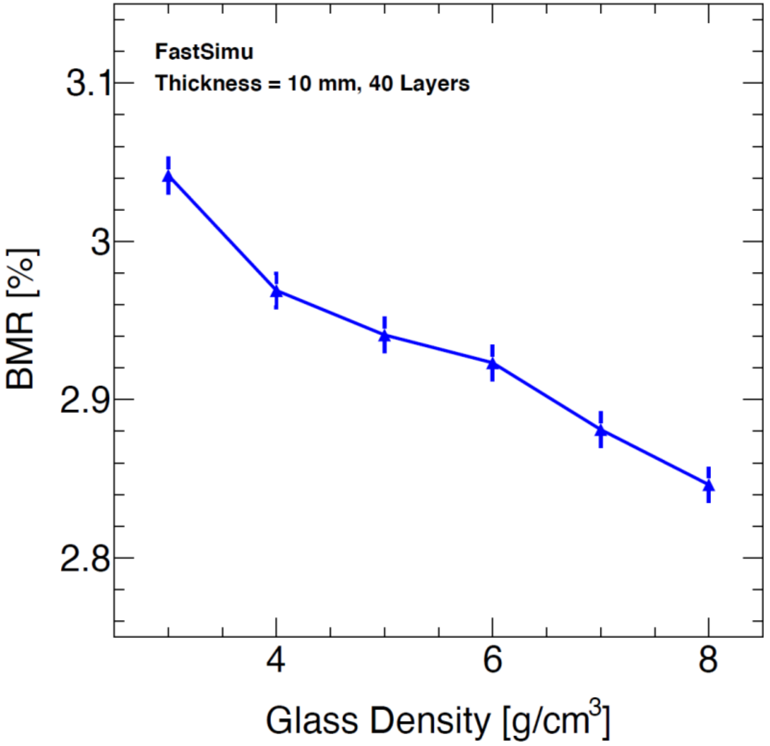
- Comparable results between the fast and full simulation for the baseline design



2.3 Impact of Density

Total Number of Layers	40
Glass Cell Size	$40\times40\times10$ mm^3
Total NIL	5 λ
Readout Threshold	0.1 MIP

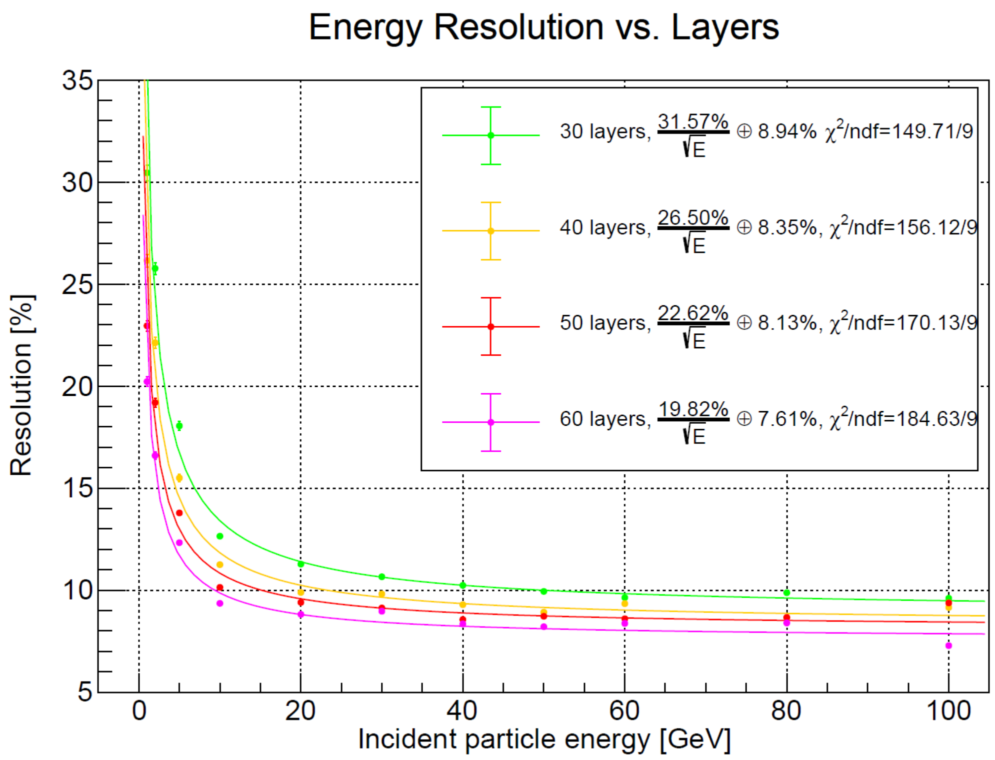


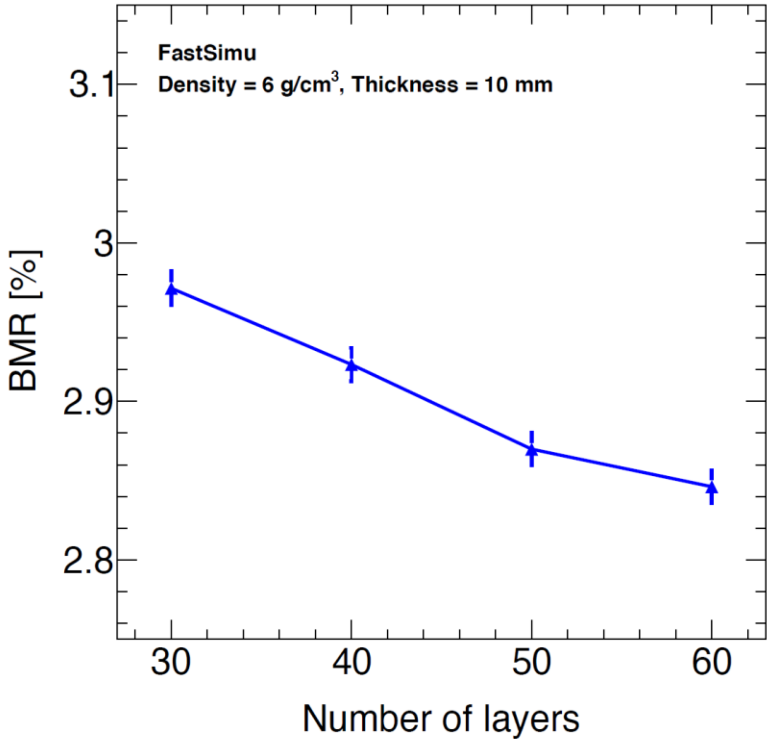


- ☐ **Higher density → higher hadronic energy resolution & better BMR**

2.4 Impact of Total Number of Layers

Glass Cell Size	$40\times40\times10\ mm^3$
NIL of Sampling Layer	$0.125\ \lambda$
Glass Density	$6\ g/cm^3$
Readout Threshold	0.1 MIP

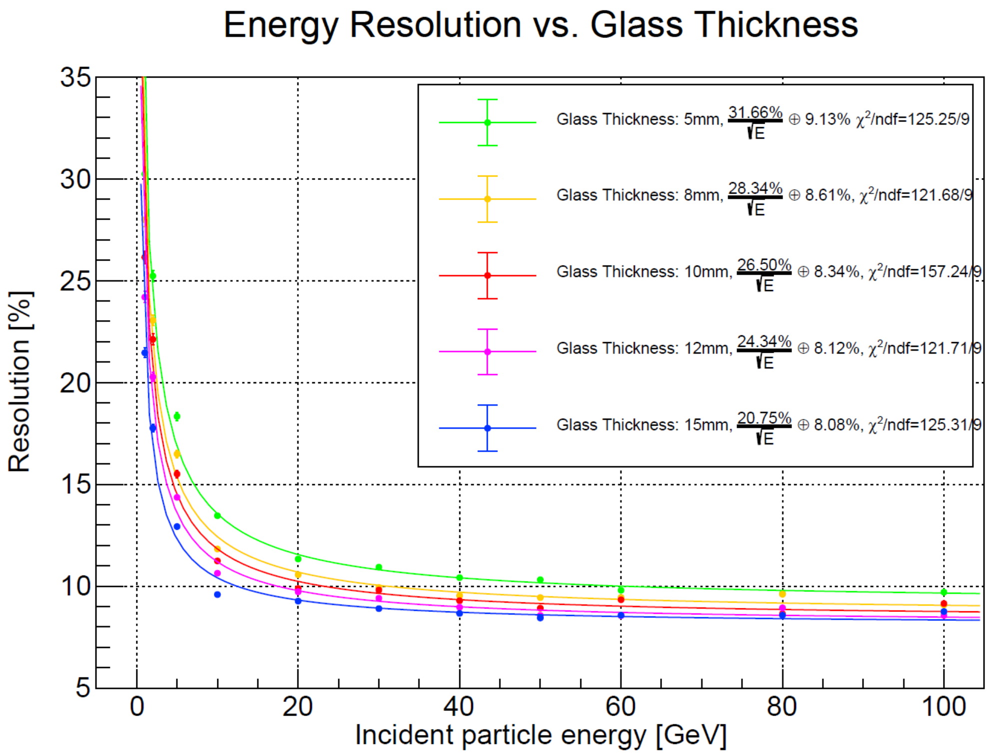


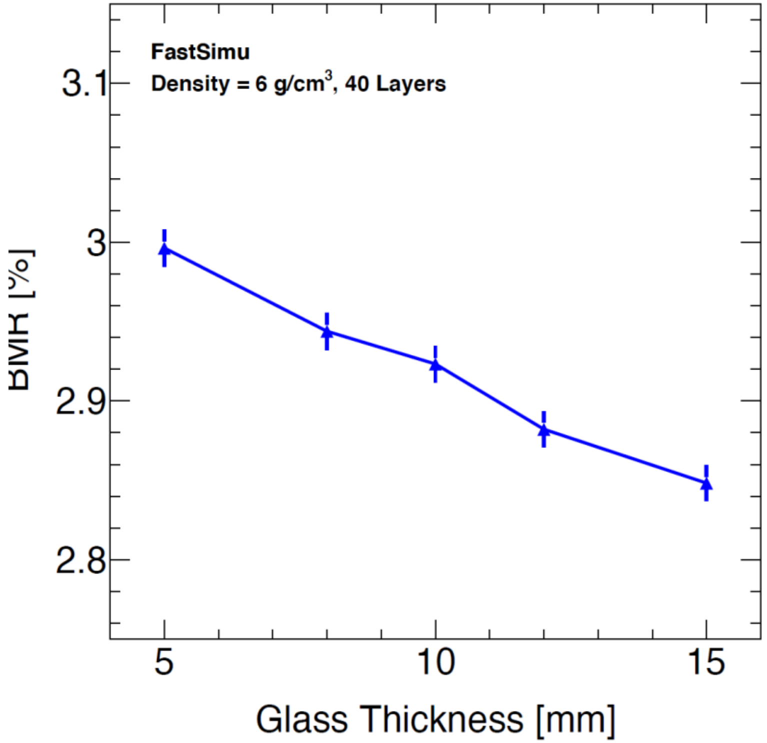


- Increasing number of layers → higher hadronic energy resolution & better BMR

2.5 Impact of Glass Thickness

Total Number of Layers	40
Transverse Cell Size	40×40 mm^2
Total NIL	5 λ
Glass Density	6 g/cm^3
Readout Threshold	0.1 MIP



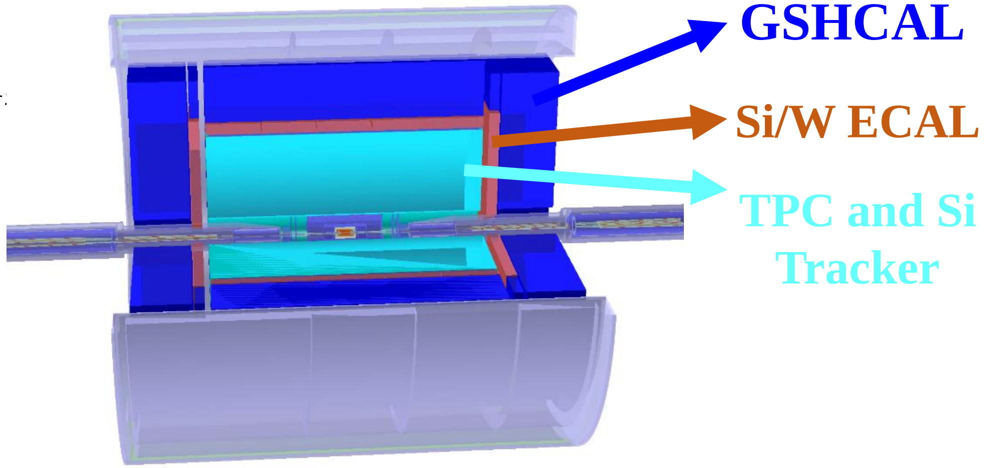


- ☐ **Thicker glass → higher hadronic energy resolution & better BMR**

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

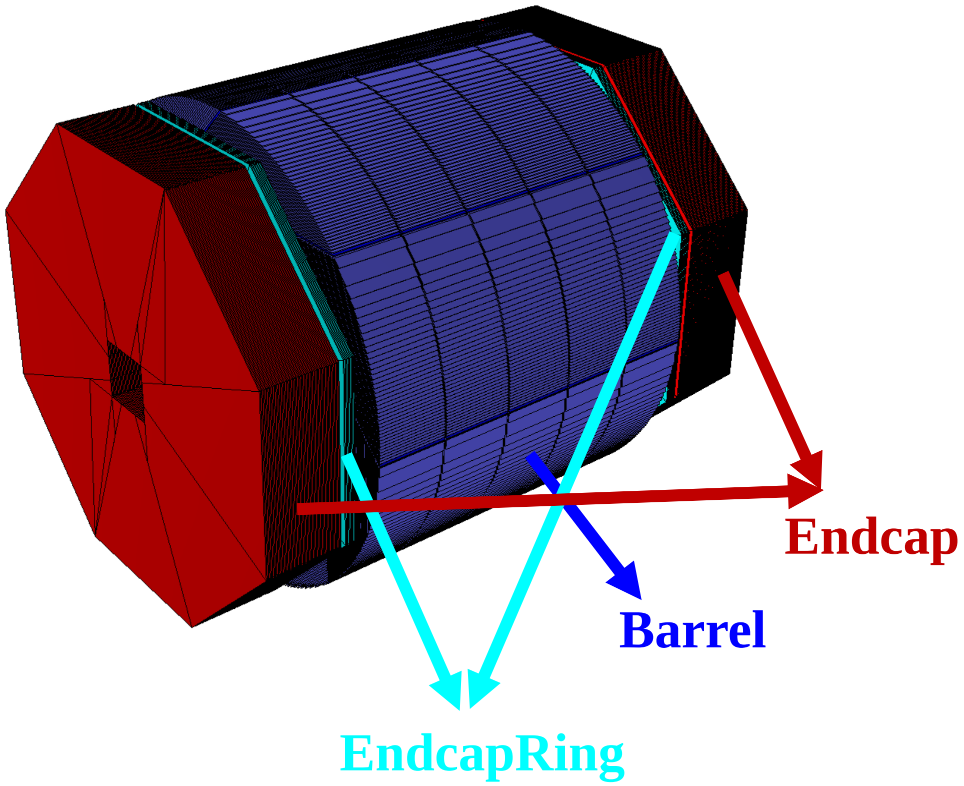


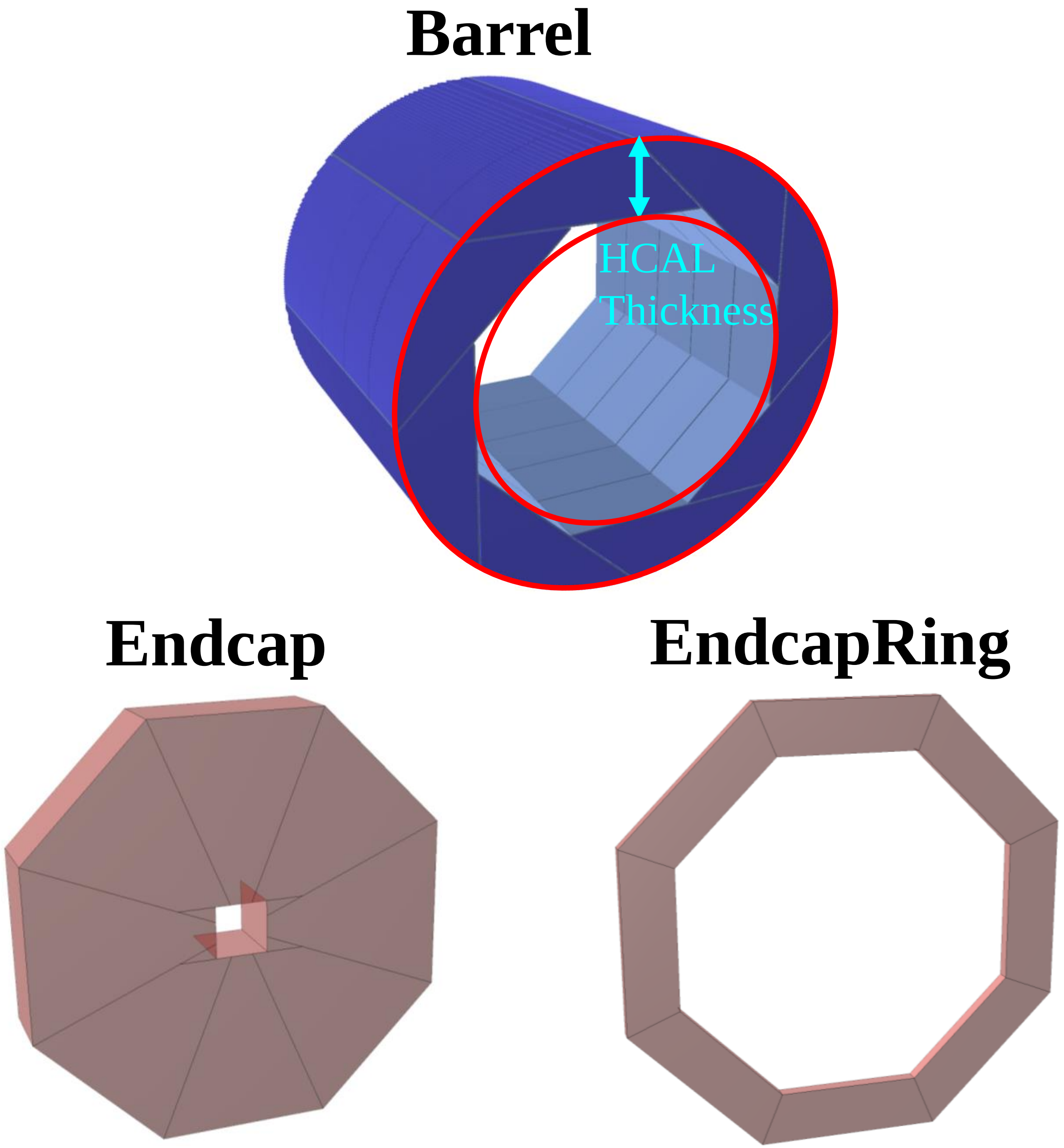
❋ GSHCAL Nominal Parameter

Total Number of Layers	**40**
Glass Cell Size	**40×40×10 mm^3**
Total Nuclear Interaction Length (NIL)	**5 λ**
Glass Density	**6 g/cm^3**
Readout Threshold	**0.1 MIP**

	Composition	Density (g/cm^3)	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 GSHCAL Geometry





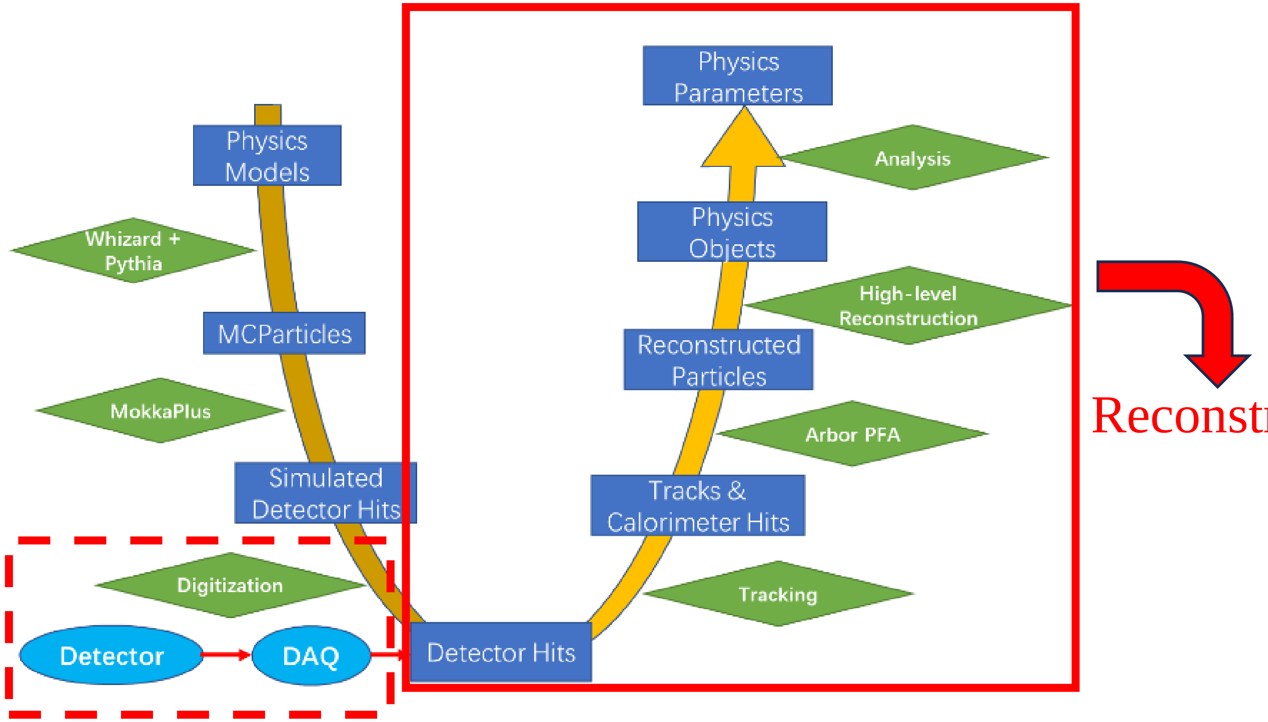
- In following slides, the volume of HCAL will be calculated from the volume sum of Barrel, Endcap and EndcapRing according to their geometry parameters

3.3 Event Reconstruction and BMR Analysis

☐ Setup

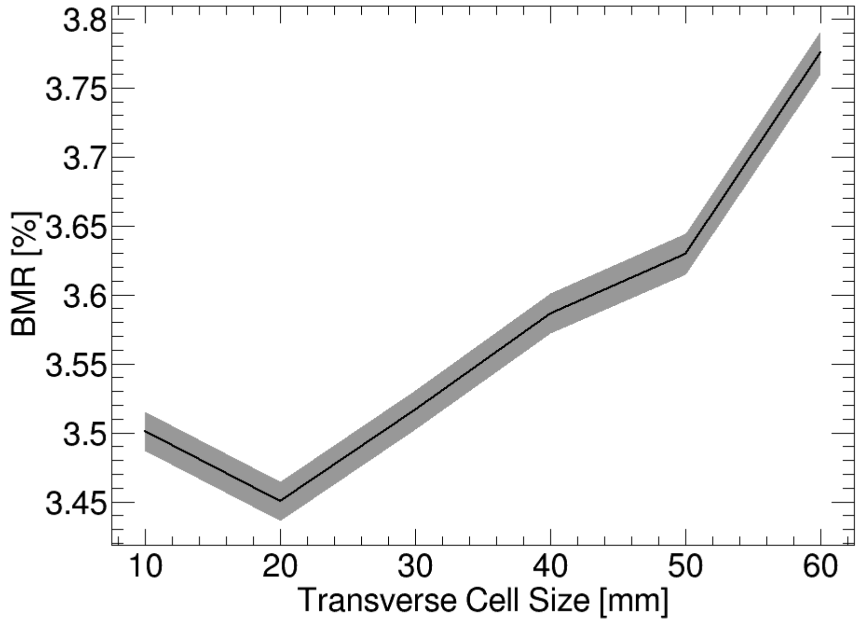
- Arbor PFA is applied
- The readout threshold in each glass cell was set to 0.1 MIP
- Event selection cut： Pt_ISR<1 GeV && Pt_neutrino<1 GeV && |Cos(Theta_Jet)|<0.8
- The BMR will be obtained from the total invariant mass distribution of all reconstructed final-state particles

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

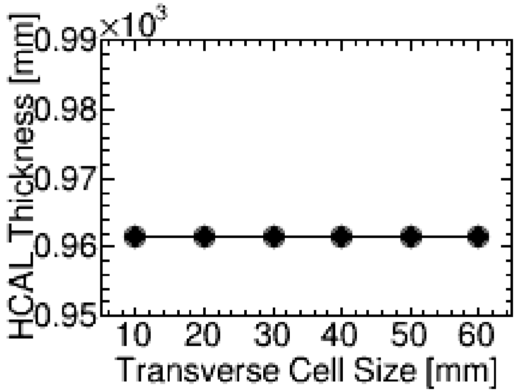


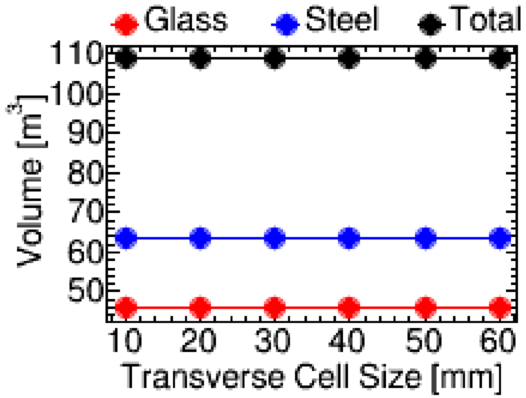
Reconstruction Pipeline

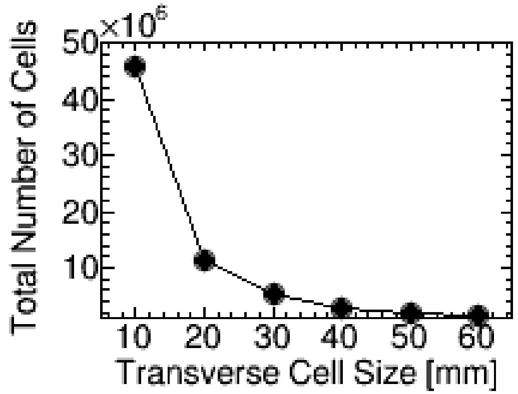
3.4 Impact of Transverse Size



Total Number of Layers	**40**
Glass Thickness	**10 mm**
Total NIL	**5 λ**
Glass Density	**6 g/cm^3**
Readout Threshold	**0.1 MIP**

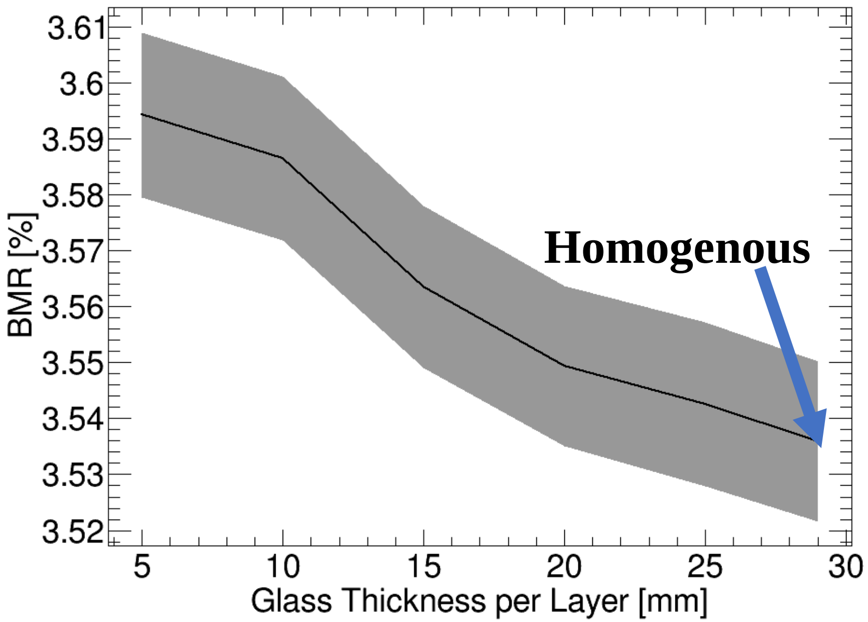




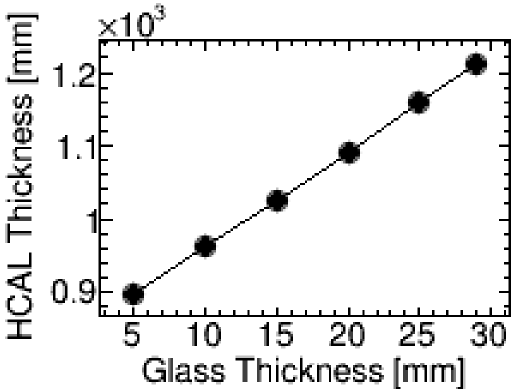


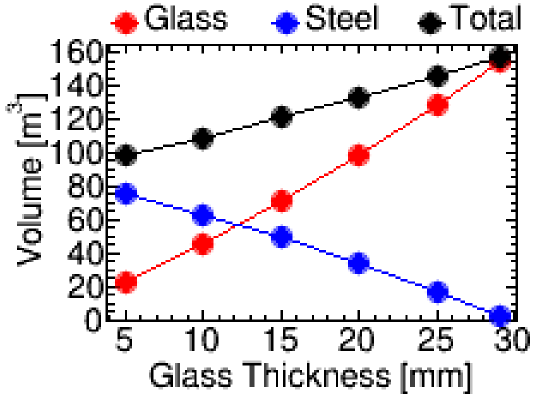
- The transverse size of the glass cell is a very important factor for the granularity and total number of readout channels of the GSHCAL
- Considering the PFA performance and total number of readout channels, a transverse size of 40 mm will be chosen for current design

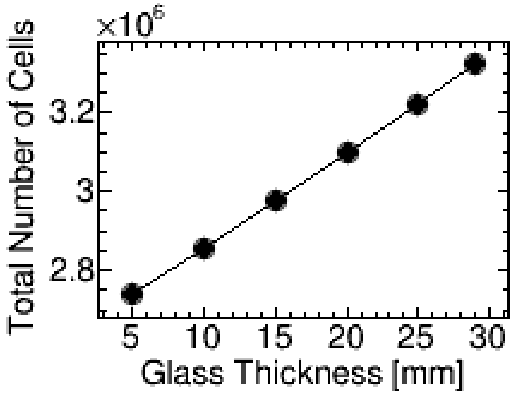
3.5 Impact of Glass Thickness



Total Number of Layers	40
Transverse Cell Size	40×40 mm^2
Total NIL	5 λ
Glass Density	6 g/cm^3
Readout Threshold	0.1 MIP



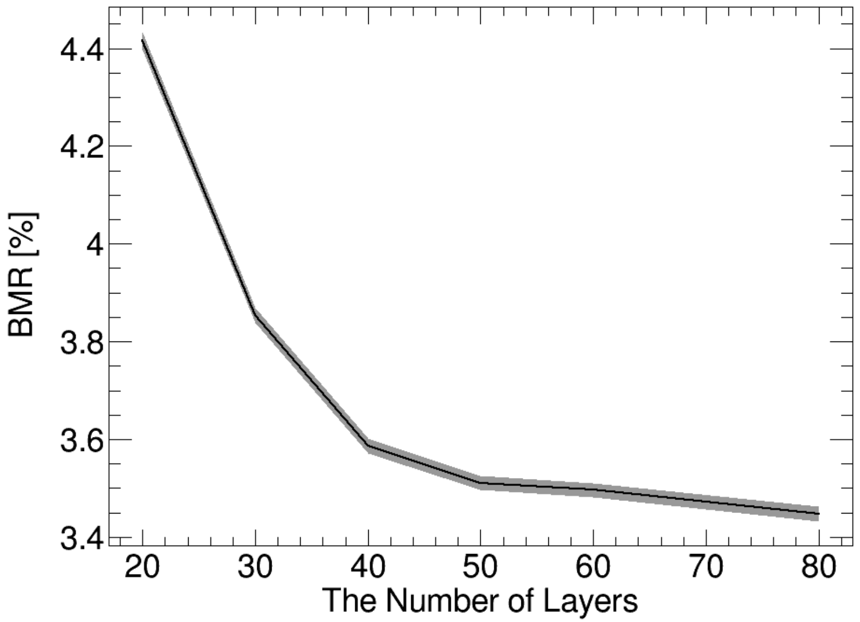




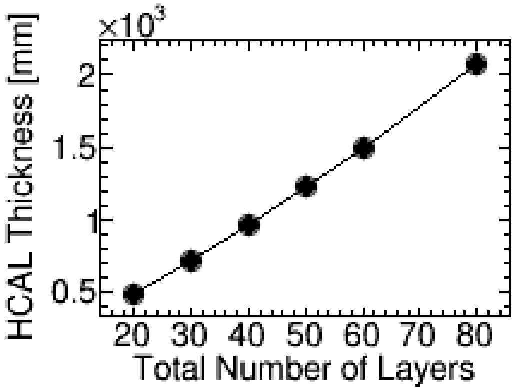
- A thicker glass cell is conducive to a higher sampling fraction and a better BMR, though the transmittance and the position response non-uniformity will become worse; besides, the glass thickness will be also limited by the total thickness of the GSHCAL

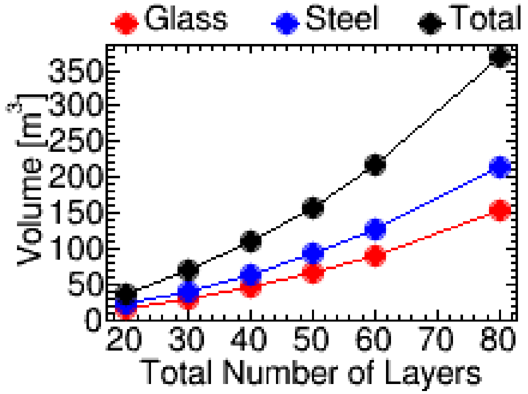
- A glass thickness of 10 mm will be chosen for current design, considering the BMR improvement provided by a thicker glass cell is not significant and the GSHCAL thickness is within a reasonable range

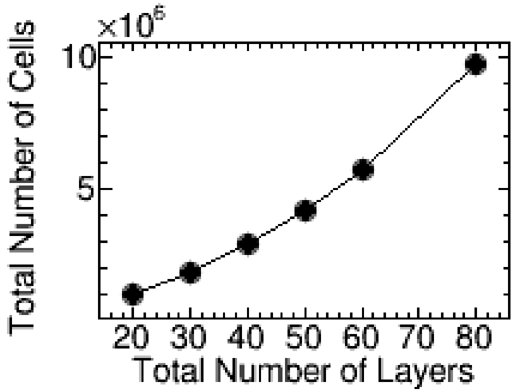
3.6 Impact of Number of Layers



Glass Cell Size	40×40×10 mm^3
NIL of Sampling Layer	0.125 λ
Glass Density	6 g/cm^3
Readout Threshold	0.1 MIP

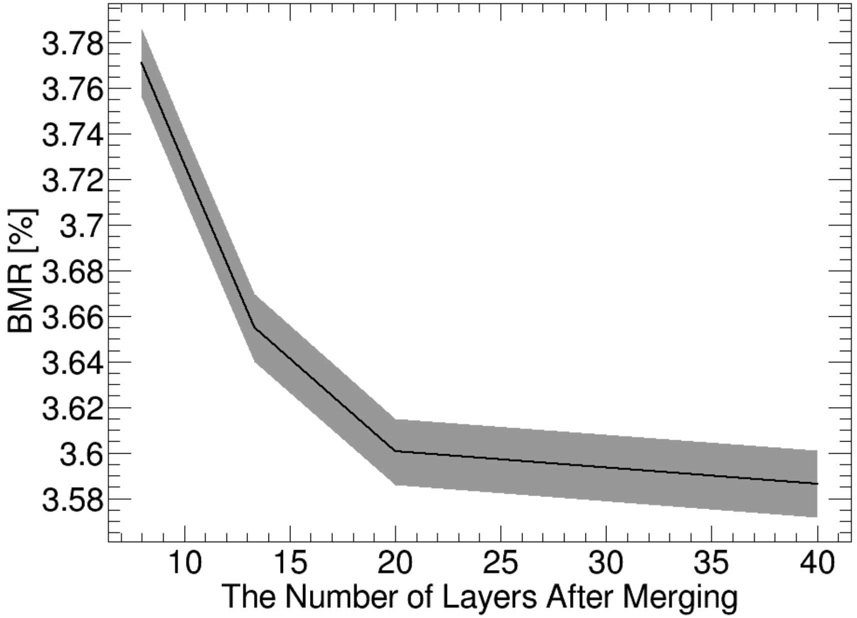




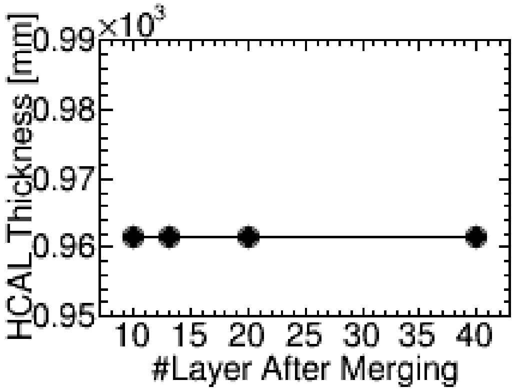


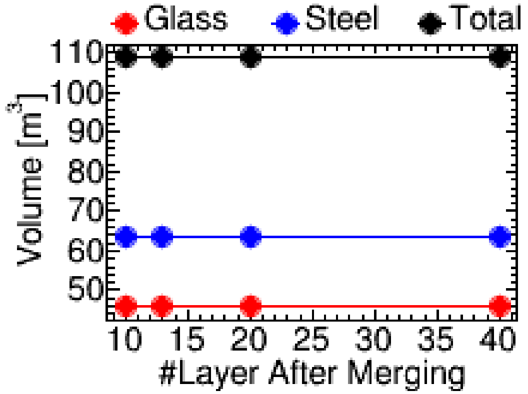
- The increase of sampling layers will improve the total nuclear interaction length and suppress shower leakage, which is beneficial to achieve a better BMR
- 40 sampling layers will be chosen for current design, considering the BMR improvement provided by more sampling layers is not significant and the GSHCAL thickness is within a reasonable range

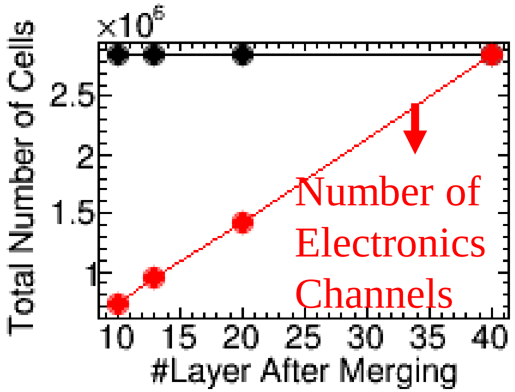
3.7 Impact of Number of Layers After Merging



Total Number of Layers	**40**
Glass Cell Size	**40×40×10 mm^3**
Total NIL	**5 λ**
Glass Density	**6 g/cm^3**
Readout Threshold	**0.1 MIP**



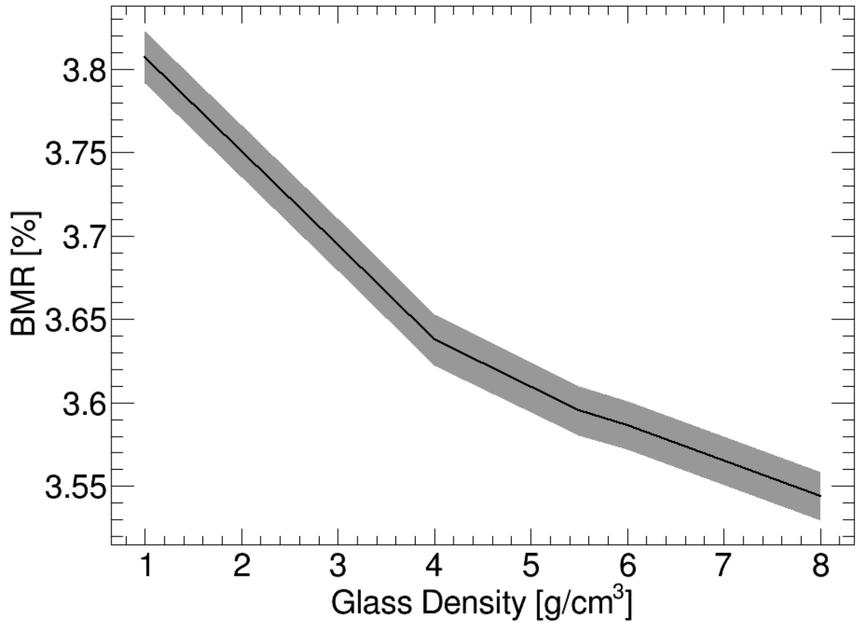




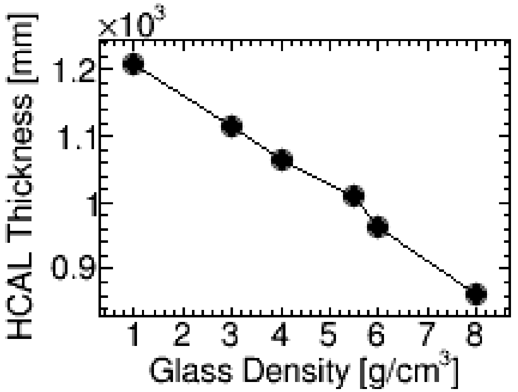
- By merging the signal in the cells from adjacent layers into one channel, the BMR will suffer from degradation to some degree but the number of electronics channels can be saved

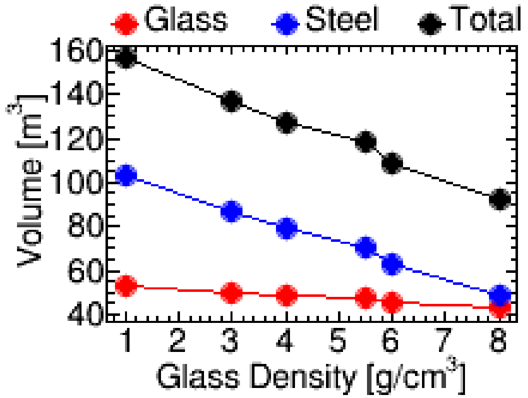
- Merging two layers are found to be a effective way to save the number of electronics channels and has little influence on the BMR

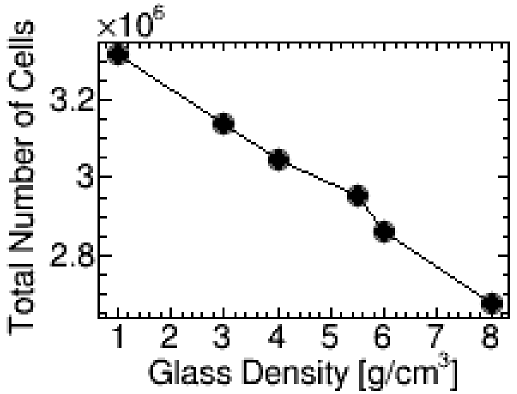
3.8 Impact of Glass Density



Total Number of Layers	40
Glass Cell Size	40×40×10 mm^3
Total NIL	5 λ
Readout Threshold	0.1 MIP





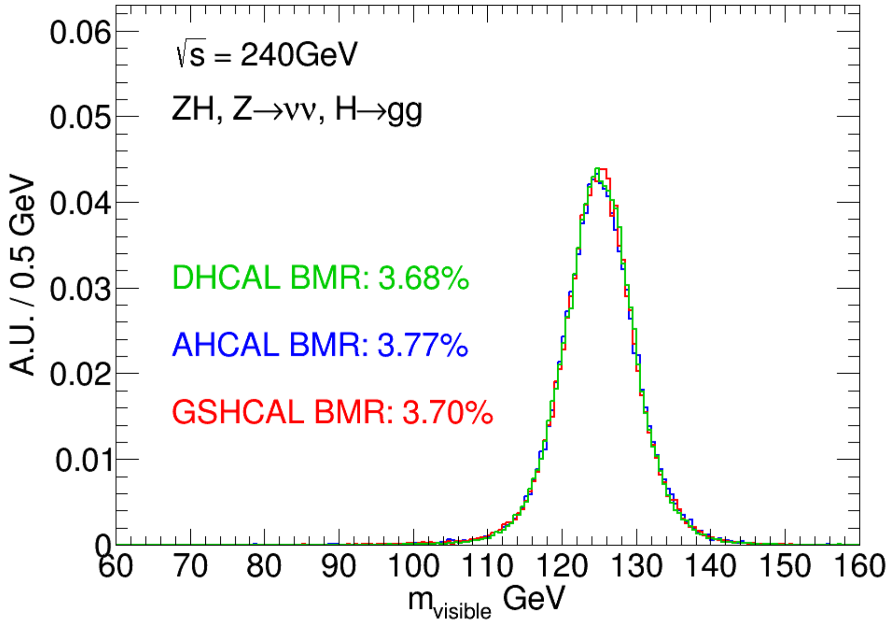


- The glass scintillator with a higher density is beneficial to a better BMR and more compact design, but the scintillation performance will also degrade to some extent

- glass density of 6 g/cm^3 will be chosen for current design, considering a balance between the scintillation performance and the BMR

3.9 Baseline Design vs. GSHCAL

Parameter	GSHCAL	AHCAL	DHCAL
Readout	Analog	Analog	Digital
Number of layers	40	40	40
Layer thickness	0.125 lambda (3mm GS +18.8mm Steel)	0.125 lambda (3mm PS +20mm Steel)	0.12 lambda (3mm RPC +20mm Steel
Total Nuclear Interaction Length	5 lambda	5 lambda	4.8 lambda
Transverse Cell Size	40x40 mm^2	40x40 mm^2	10x10 mm^2
Sensitive Material Density	6 g/cm^3	1 g/cm^3	\
HCAL Thickness	873 mm	931 mm	931 mm
HCAL Volume	13 m^3(GS) 81 m^3(Steel)	14 m^3(PS) 91 m^3(Steel)	14 m^3(RPC) 91 m^3(Steel)
Number of Cells	2.7×10^6	2.8×10^6	4.5×10^7

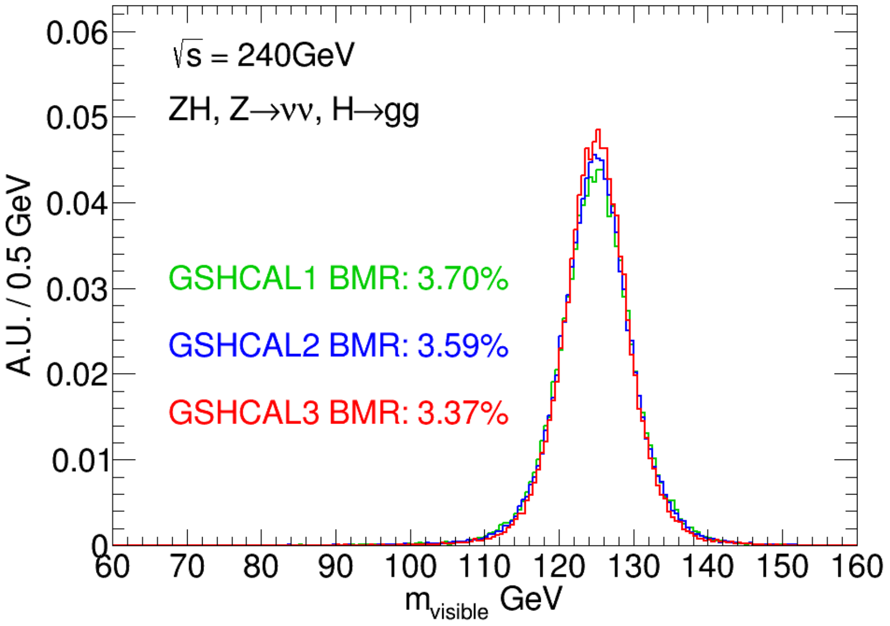


- Comparing GSHCAL design with DHCAL and AHCAL
- Gaussian fitting range: Mean $\pm$ 2 RMS

➢ 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

3.10 Different GSHCAL Design

Parameter	GSHCAL1	GSHCAL2	GSHCAL3
Readout	Analog	Analog	Analog
Number of layers	40	40	40
Layer thickness	0.125 lambda (3mm GS +18.8mm Steel)	0.125 lambda (10mm GS +13.9mm Steel)	0.125 lambda (29.7 mm GS)
Total Nuclear Interaction Length	5 lambda	5 lambda	5 lambda
Transverse Cell Size	40x40 mm^2	40x40 mm^2	20x20 mm^2
Sensitive Material Density	6 g/cm^3	6 g/cm^3	6 g/cm^3
HCAL Thickness	873 mm	962 mm	1218 mm
HCAL Volume	13 m^3(GS) 81 m^3(Steel)	46 m^3(GS) 64 m^3(Steel)	159 m^3(GS)
Number of Cells	2.7×10^6	2.9×10^6	5.4×10^7



- Comparing different GSHCAL design option
- Gaussian fitting range: Mean ± 2 RMS

- The GSHCAL2 design is slightly thicker (+30 mm) than the AHCAL, but the BMR can reach ~3.6% and be improved by ~5%
- The GSHCAL3 is a homogenous design, with which the BMR can reach ~3.4% and show ~10% improvement, but the total volume and readout channel will also increase significantly

Summary

- The PFA fast and full simulation based on the GSHCAL with different setup was studied, together with its intrinsic performance; significant discrepancy between the fast and full simulation needs further study

- The GSHCAL of nominal setup will slightly increase the thickness, but the BMR can reach ~3.6% and show ~5% improvement w.r.t 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 study of digitization process is still ongoing

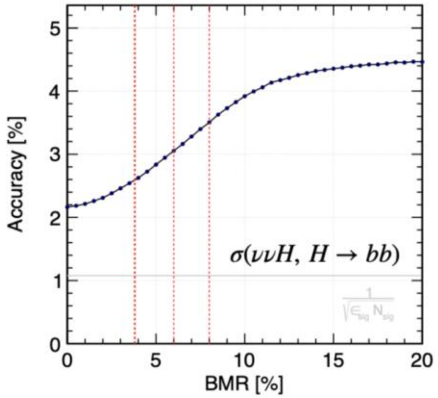
- Investigate the overall PFA performance combining the GSHCAL and crystal bar ECAL will be considered in next step

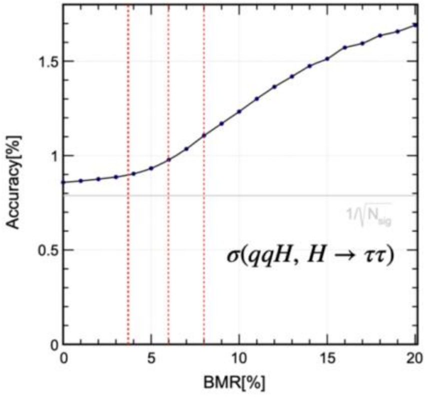
Backup

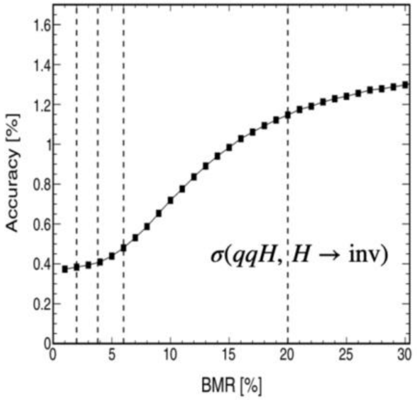
The Boson Mass Resolution

- 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 $e{+}e{-} \to \nu\bar{\nu}H(\to b\bar{b})$[2], the measurement $H \to \tau^+\tau^-$ via $e{+}e{-} \to Z(\to q\bar{q})H(\to \tau^+\tau^-)$[3], and the study of the Higgs invisible decay via $e{+}e{-} \to Z(\to q\bar{q})H(\to \text{invisible})$[1]



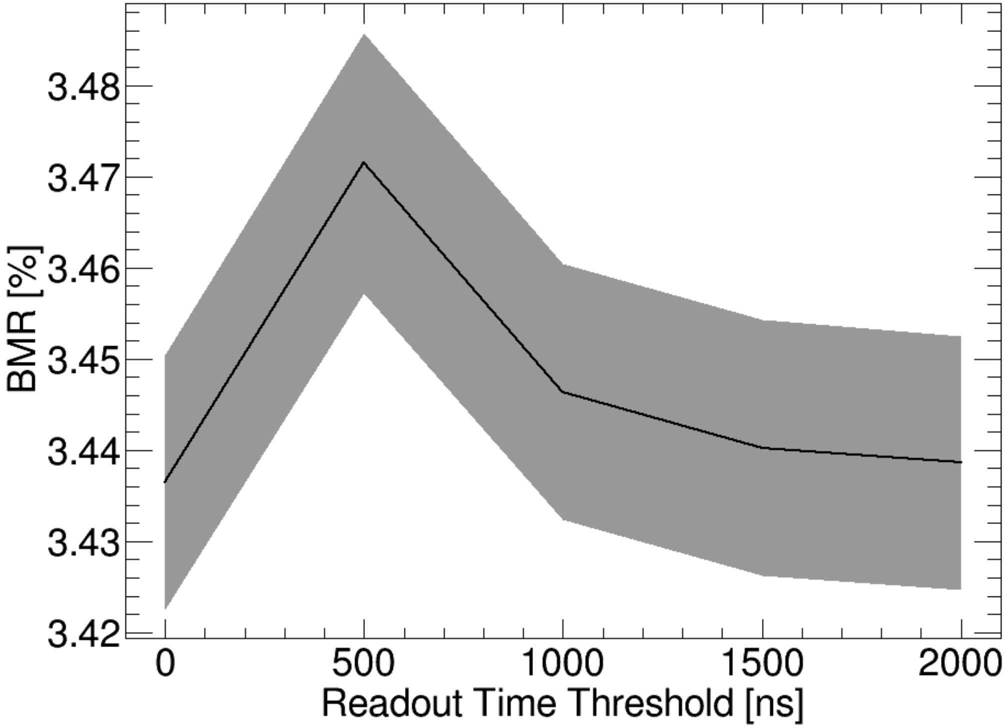




[1] CEPC Conceptual Design Report: Volume 2, arXiv:1811.10545.
[2] H. Zhao, arXiv:299 1806.04992
[3] D. Yu, doi:10.1140/epjc/s10052-019-7557-y

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

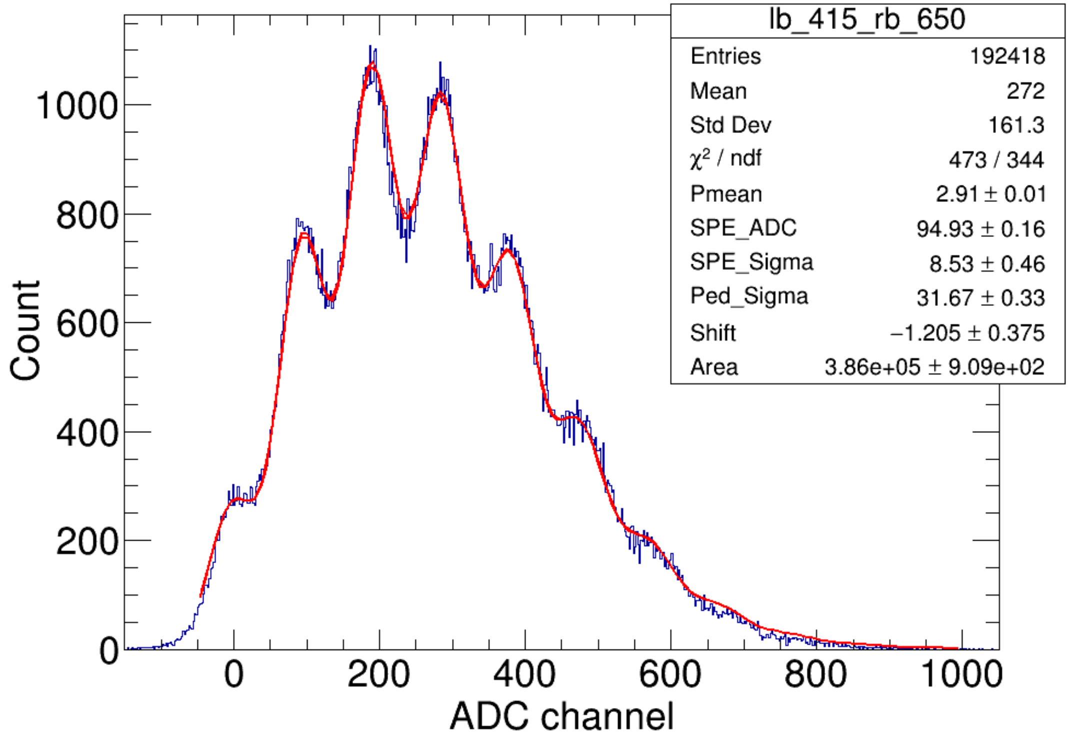
a) $PE_{detected} = \boxed{Gaus(\boxed{Poisson(Mean\_pe)}, Sigma)}$

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

- Simga = Sqrt(Poisson(Mean_pe)*SPE_Sigma²+Ped_Sigma²)

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)

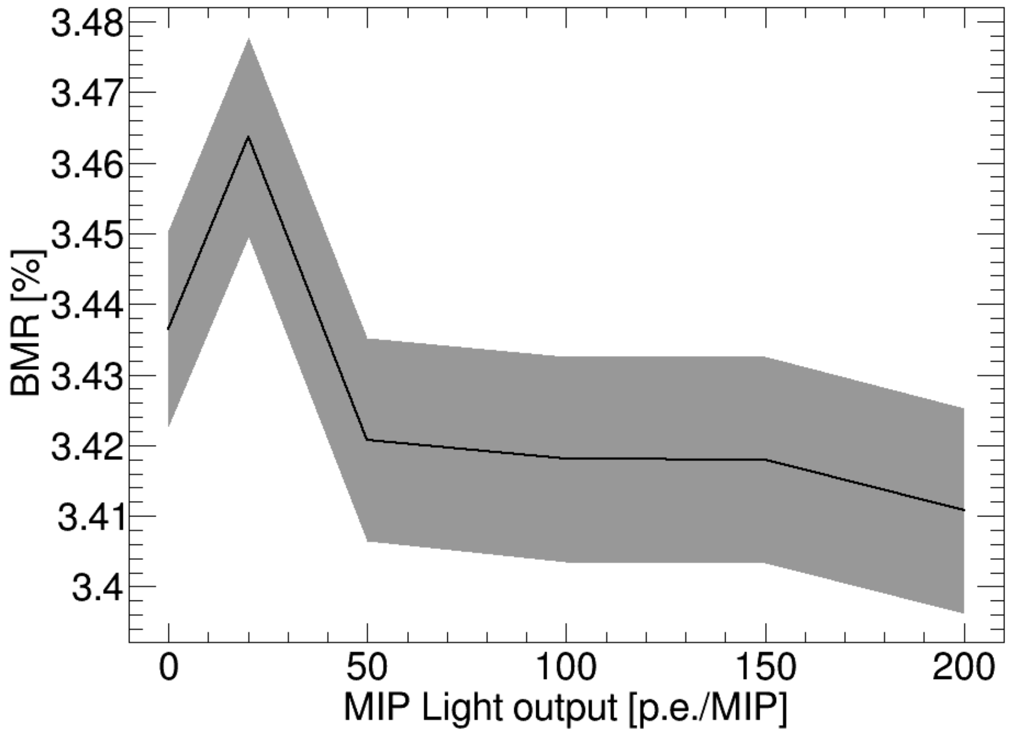
Gaussian sampling with consideration of the fluctuation of a given photoelectron signal, which is caused by the fluctuation of the pedestal (the electronics noise, denoted as **Ped_Sigma**) and the single photoelectron signal (from the gain and the amplifier, etc, denoted as **SPE_Sigma**)



- 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)

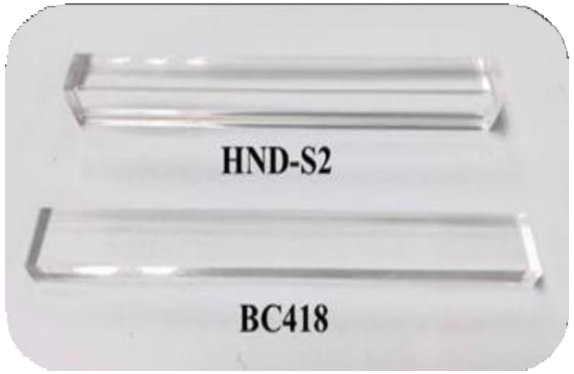


- The MIP Light output will have a significant impact on the fluctuation of electronics signal and thus a very important factor to the BMR
- MIP response of 50 p.e./MIP is enough to obtain a optimized BMR based on this preliminary simulation

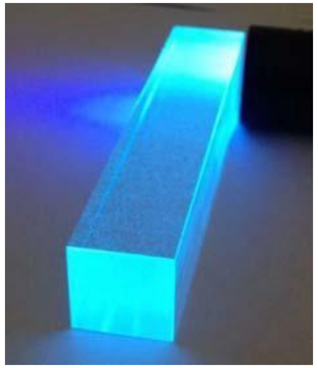
Requirements of Detector for the CEPC

Sub-detector	Key Specifications	Key technology
Silicon vertex detector	$\sigma_{r\phi} \sim 3$ µm, $X/X_0 < 0.15\%$ (per layer)	Spatial resolution and material
Silicon tracker	$\sigma\left(\frac{1}{p_T}\right) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}$ GeV^{-1}	Large-area silicon detector
TPC/Drift Chamber	Relative uncertainty 2%	Precise dE/dx (dN/dx) measurement
Time of Flight detector	$\sigma(t) \sim 30$ ps	Large-area silicon timing detector
Electromagnetic Calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ Granularity $\sim 2 \times 2 \times 2$ cm^3	High granularity 4D crystal calorimeter
Hadronic Calorimeter	Single hadron $\sigma_E^{\mathrm{had}} \sim 40\%/\sqrt{E(\mathrm{GeV})}$ Jet $\sigma_E^{\mathrm{jet}} \sim 30\%/\sqrt{E(\mathrm{GeV})}$ Support PFA reconstruction	Glass scintillator HCAL
Magnet system	Ultra thin High temperature Superconducting magnet	Magnet field 2−3 T Material budget < 1.5 X_0 Thickness < 150 mm

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**	★