



INSTR 2026

October 12-16, 2026 | Hefei, China

High-granularity calorimeters with scintillating glass for future Higgs factories

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INSTR 2026, Hefei

Oct. 14, 2026



中国科学院高能物理研究所

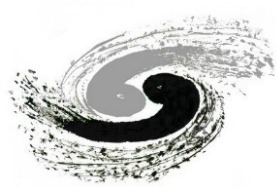
*Institute of High Energy Physics
Chinese Academy of Sciences*



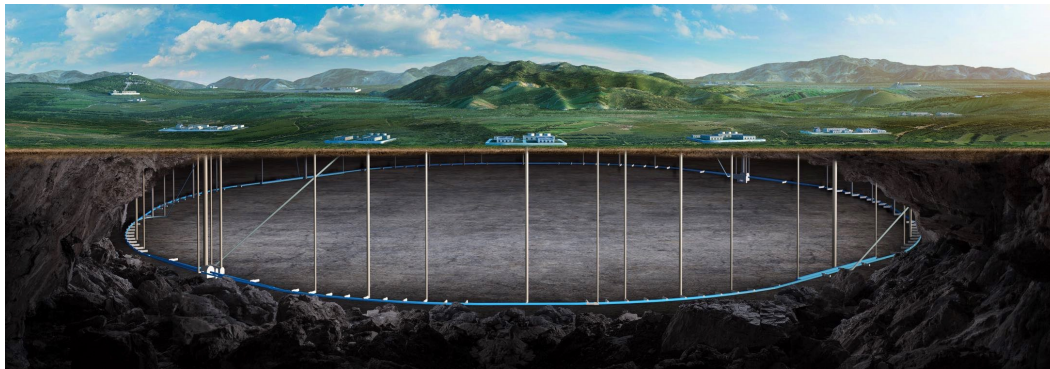
闪烁玻璃合作组
Glass Scintillator Collaboration



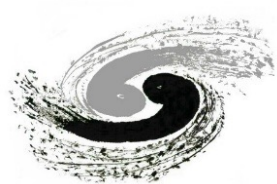
drdcalo



Motivations

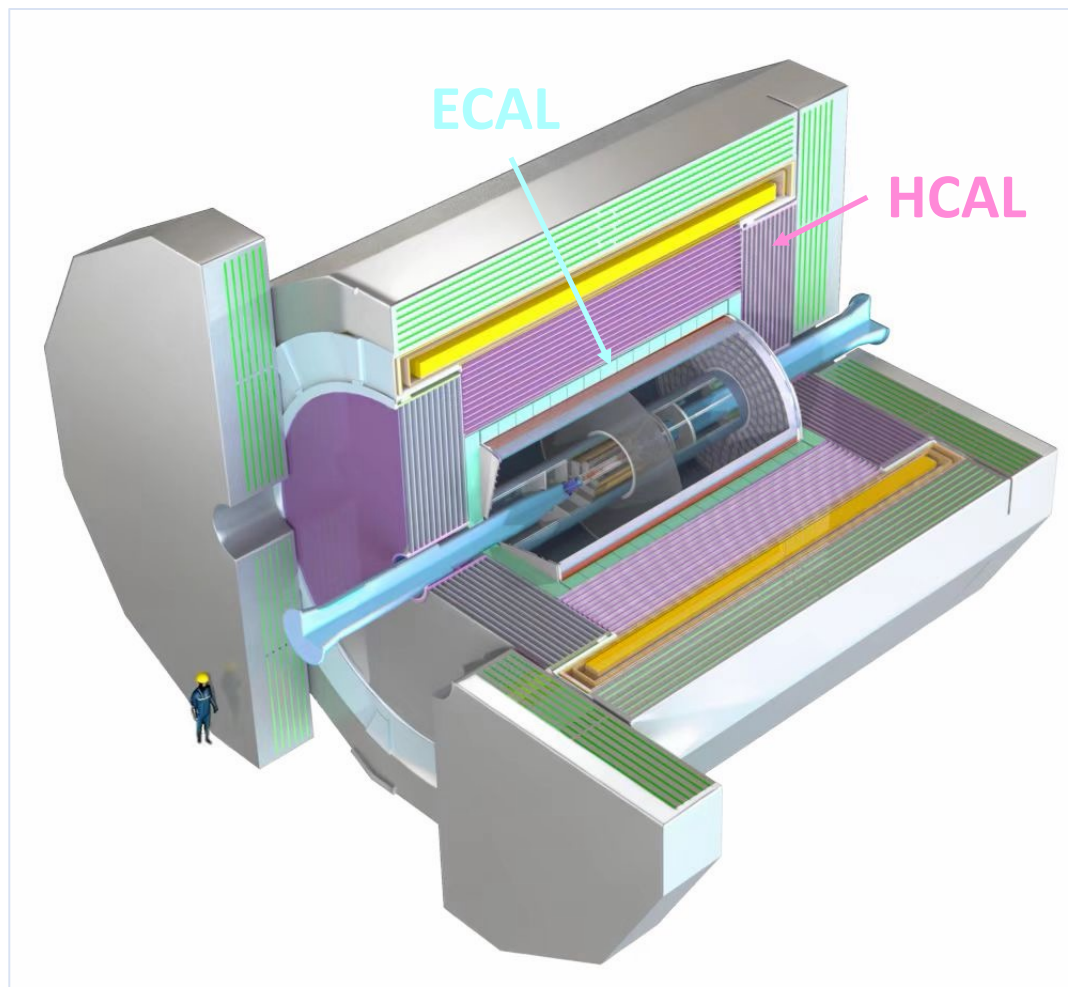


- Future electron-positron colliders: e.g. CEPC and FCC-ee
 - Challenge: jet energy resolution $\sim 30\%/\sqrt{E(\text{GeV})}$ for precision Higgs/Z/W measurements
- Detector with highly granular calorimeters: PFA-oriented
 - Dominant factors in JER: **charged hadron fragments & HCAL resolution**
- New detector concept: glass hadron calorimeter
 - Sampling HCAL: to use glass tiles as sensitive units, **featuring high granularity**
 - Higher energy sampling fraction → Glass is required for **high density** and **moderate light yield**
 - **Better hadronic energy resolution**



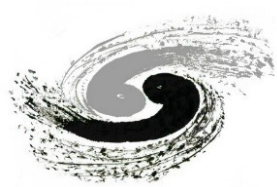
ScintGlass Hadron Calorimeter: overview

CEPC Reference Detector: <https://arxiv.org/abs/2510.05260>



Sub-system	Technologies
Beam pipe	Beryllium, ϕ 20 mm
LumiCal	Silicon tracker + LYSO crystals
Vertex	Si Pixels: CMOS MAPS+stitching
Inner tracker (ITK)	Si Pixels: CMOS MAPS 55-nm
Gas detector	TPC with high granularity
Outer tracker (OTK)	AC-LGAD $\rightarrow$ TOF
ECAL	4D transverse crystal bars
HCal	Glass scintillator, SiPM + Fe
Magnet	LTS Solenoid
Muon	Plastic scintillator bars, SiPM
TDAQ	Conventional
Back-end electronics	Common

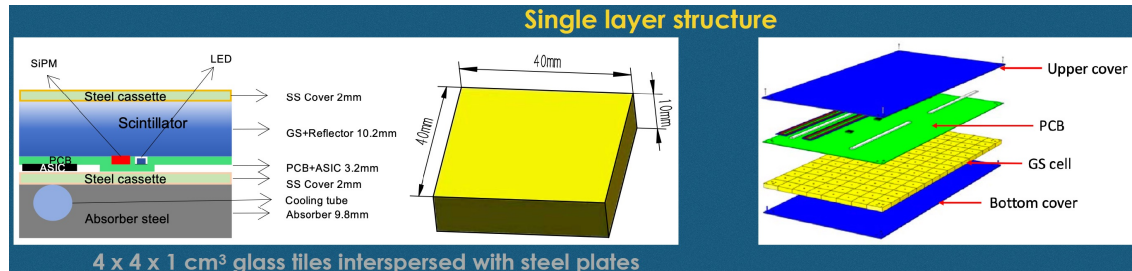
João Guimarães da Costa, CEPC Detector R&D, FCC Week, Helsinki, 8-12 June, 2026 ([link](#))



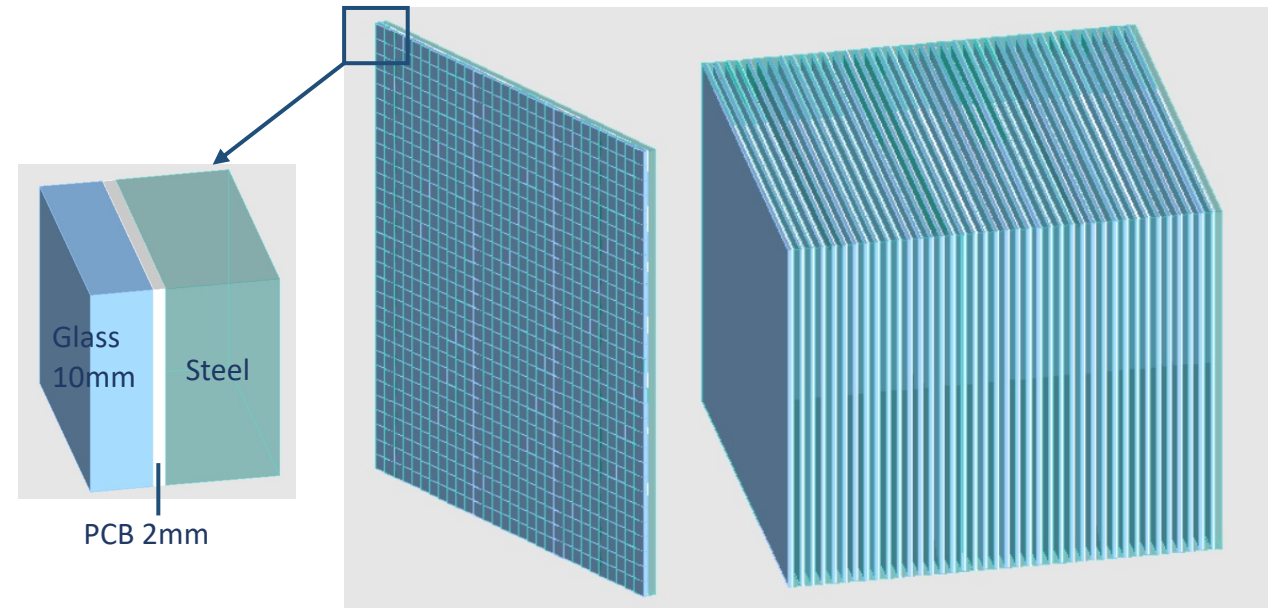
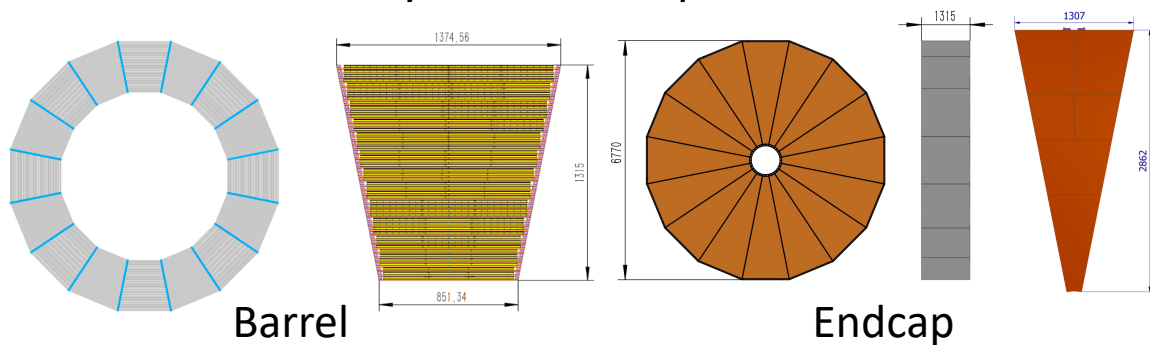
ScintGlass Hadron Calorimeter in CEPC Ref-TDR

- ScintGlass HCAL: sampling structure

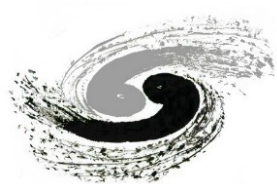
- $4 \times 4 \times 1 \text{ cm}^3$ glass tiles
- 83 m^3 : the total volume of glass
- $\sim 5.2\text{M}$ readout channels



48 layers stacked per module



[Poster](#) on Glass Tile Uniformity Optimisation (Yushan Liu)

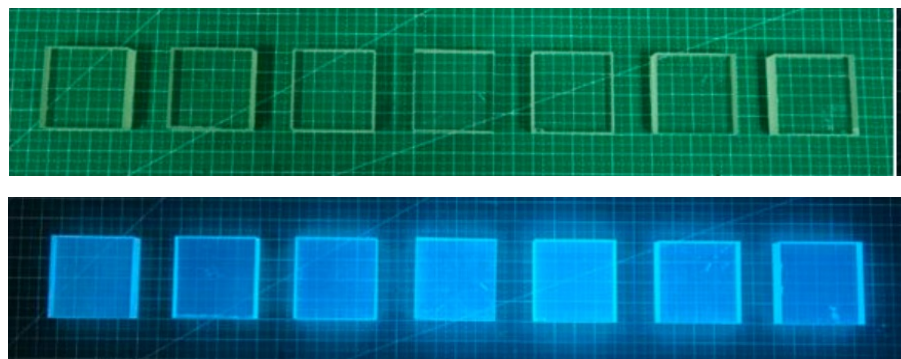


ScintGlass Hadron Calorimeter in CEPC Ref-TDR

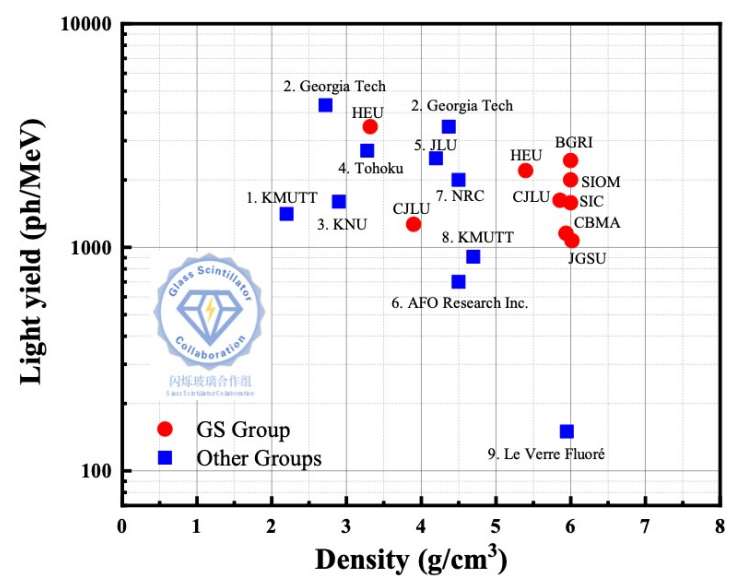
- Scintillating glass: aim for **high density** and **moderate light yield**

CEPC Reference Detector: <https://arxiv.org/abs/2510.05260>

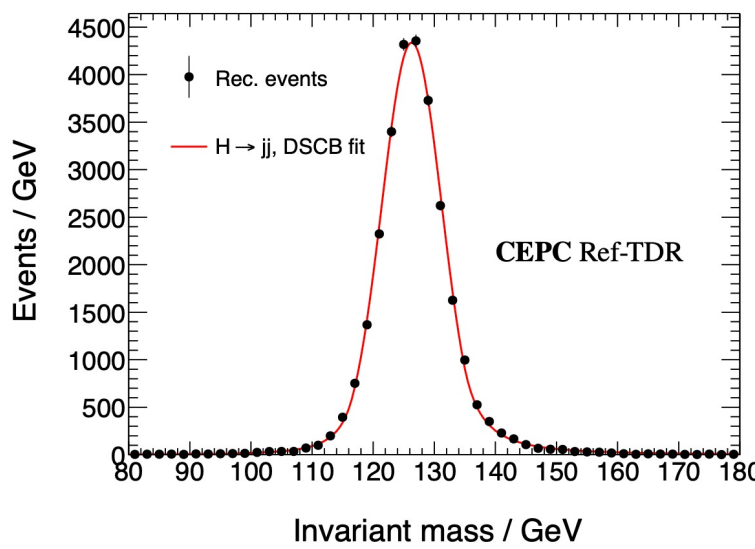
Key parameters	GFO glass	BGO	DSB Glass
Density (g/cm ³)	6.0	7.13	4.2
Melting point (°C)	1250	1050	1550
Radiation length (cm)	1.59	1.12	2.62
Molière radius (cm)	2.49	2.23	3.33
Nuclear interaction length (cm)	24.2	22.7	31.8
Z _{eff}	56.6	71.5	49.7
dE/dx (MeV/cm)	8.0	8.99	5.9
Emission peak (nm)	400	480	430
Refractive index	1.74	2.15	
Light yield (ph/MeV)	~ 1500	7500	2500
Energy resolution (% at 662 keV)	~ 23	9.5	
Scintillation decay time (ns)	~ 60, 500	60, 300	90, 400



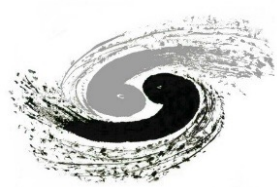
Optimisation on glass density and light yield



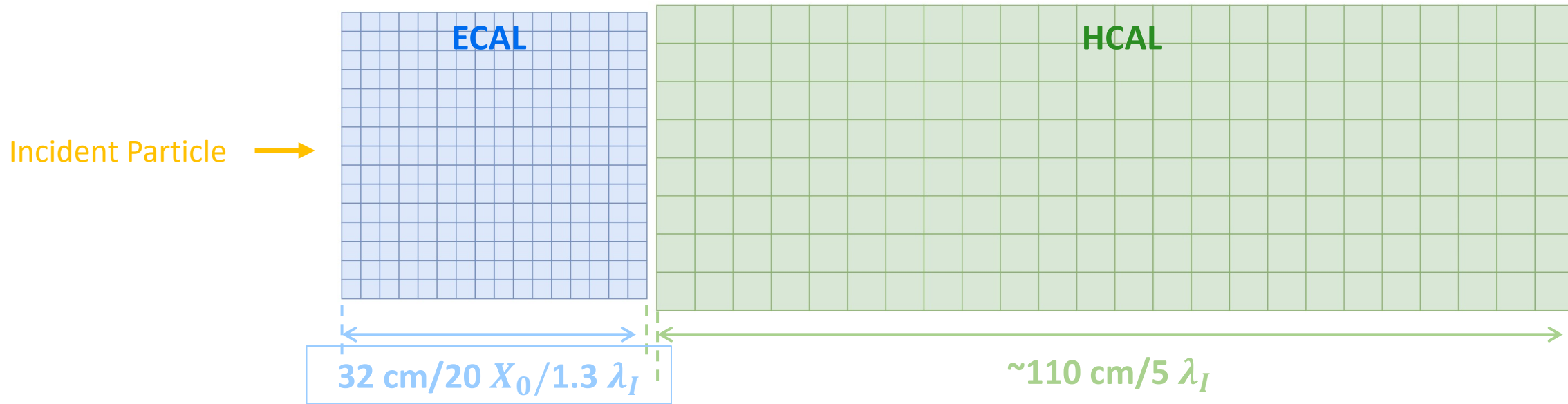
PFA performance on Higgs: including tracker, ECAL and HCAL



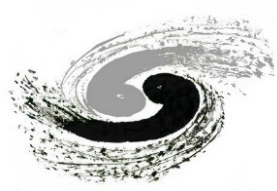
Higgs Boson Mass Resolution (BMR) = 3.88% (target <4%)



Scintillating Glass Calorimeters: a **new** design

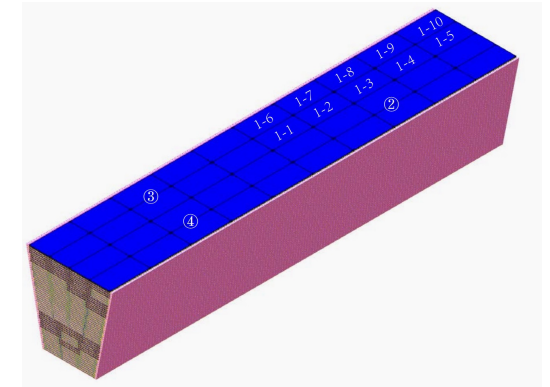
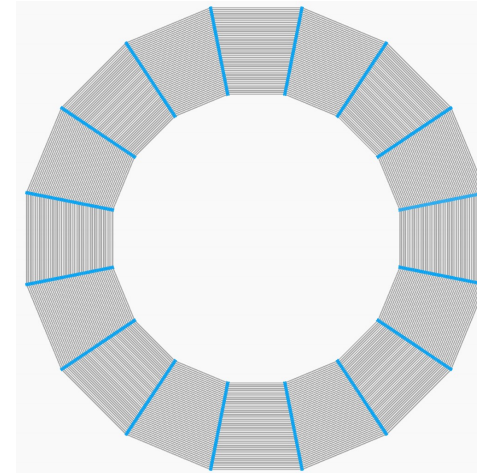


- **Integrated** calorimetry design
 - Scintillating glass in **homogeneous** structure, featuring **high granularity and cost effectiveness**
- Hadronic Calorimeter (HCAL)
 - Aim and key feature: **significantly improved hadronic resolution**
 - Glass tile dimensions (typical): 3-4 cm thick, transverse $4 \times 4 \text{ cm}^2$
- Electromagnetic Calorimeter (ECAL)
 - Aim and key feature: **excellent EM resolution** (similar to crystal)
 - Glass cube dimensions (typical): $2 \times 2 \times 2 \text{ cm}^3$



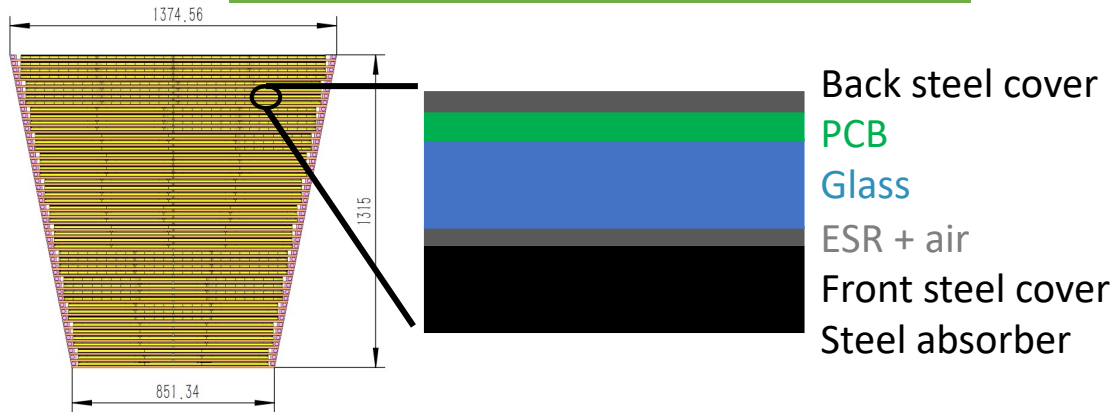
Scintillating Glass HCAL: a new design

- Retain the major mechanical structure
- Replace the steel absorber by glass
- Barrel HCAL
 - 16 sectors, supported by steel framework
 - Each layer: glass tiles/cubes, reflector, PCB, mechanics
 - A total depth of $\sim 5\lambda$



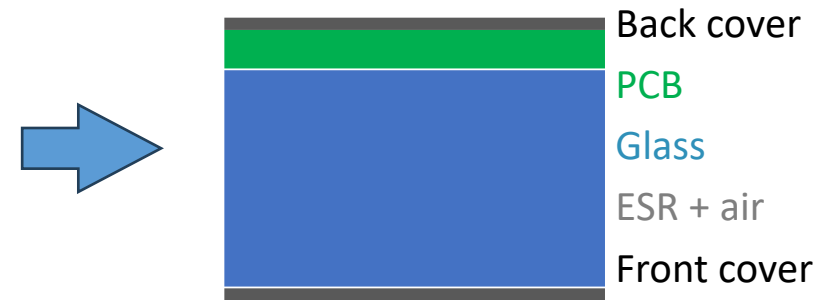
Barrel part of HCAL in AGORA

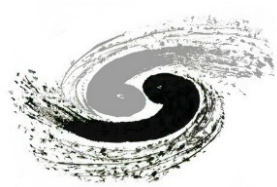
HCAL design in CEPC Reference TDR



Sampling structure (30% sampling fraction)

A new HCAL design in homogeneous structure





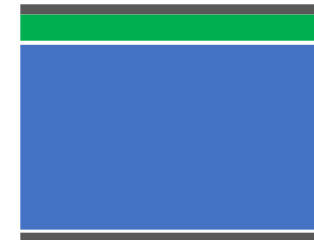
Scintillating Glass for homogeneous HCAL

Sampling fraction 60.0%
HCAL depth $5.0\lambda_I$



Cassette (1 mm)
Readout PCB (3.1 mm)
Glass Tile (18.3 mm)
Cassette (1 mm)

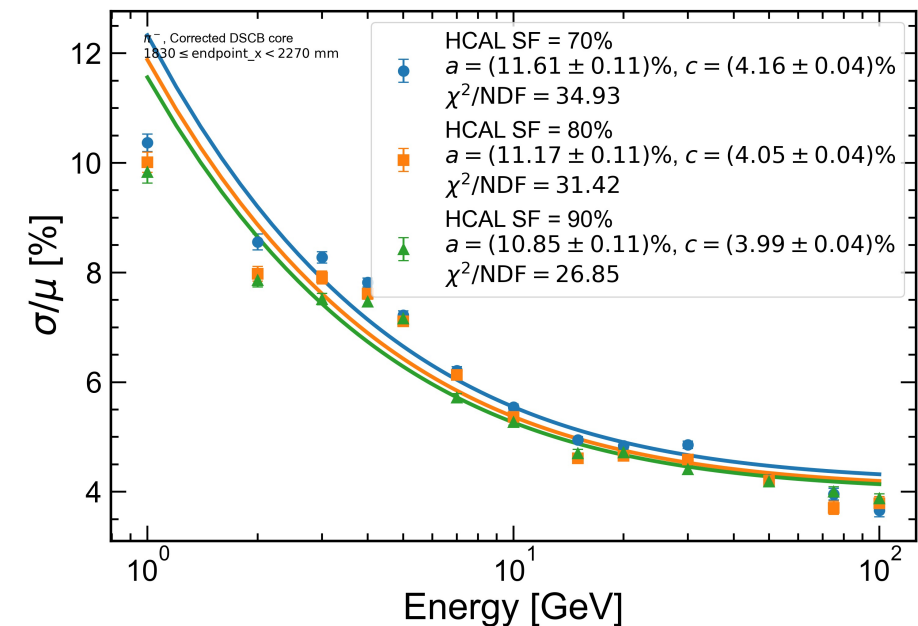
Sampling fraction 84.5%
HCAL depth $4.6\lambda_I$

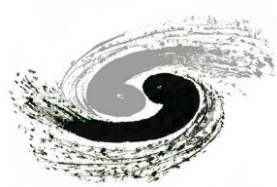


Cassette (1 mm)
Readout PCB (3.1 mm)
Glass Tile (23.8 mm)
Cassette (1 mm)

- HCAL: pursuing highest possible sampling fraction
 - Boundary condition: **total thickness unchanged** (the same as HCAL design in *CEPC Ref-TDR*)
- Glass requirements for HCAL
 - Density: 6.0 g/cm^3
 - Transverse Dimensions: $4 \times 4 \text{ cm}^2$, Thickness: $3\text{-}4 \text{ cm}^3$
 - Intrinsic Light Yield: **$\geq 1000 \text{ ph/MeV}$**
 - **Attenuation Length: $\geq 10 \text{ cm}$**
 - **Scintillation Time: $\sim 500 \text{ ns}$**

HCAL performance (simulation)

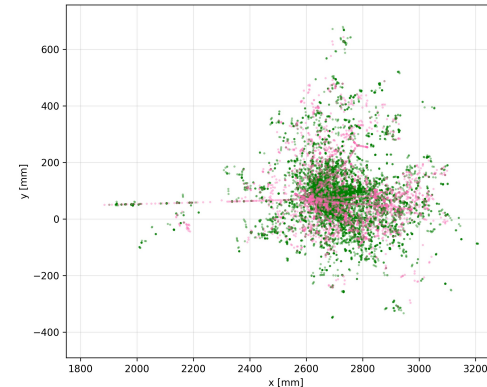




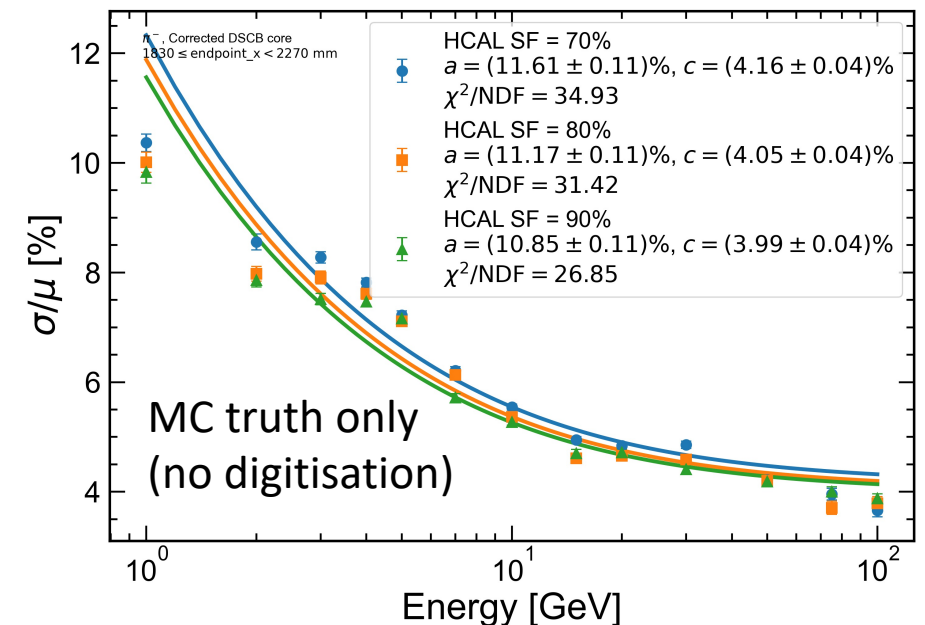
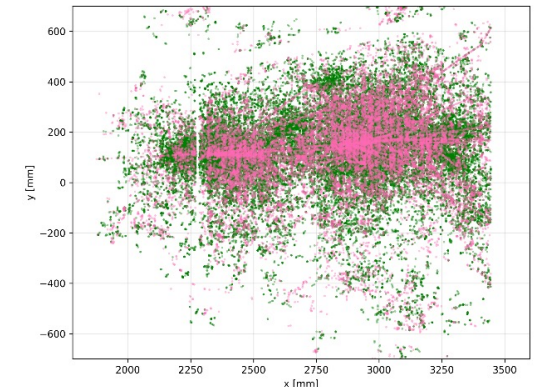
HCAL: Performance from Simulation

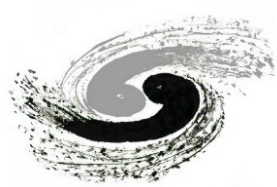
- Simulation configuration
 - Geometry: ECAL + HCAL with glass cubes
 - Three HCAL sampling fractions: 70%, 80%, 90%
 - Particles: single charged pions in 1 – 100 GeV
- Preliminary results: MC-truth hits
 - Hadronic energy resolution is $\sim 11\%/\sqrt{E} \oplus 4\%$
- Ongoing studies
 - Impact of response non-uniformity
 - Software compensation for better hadronic energy resolution (next page)

A single 10 GeV π^-



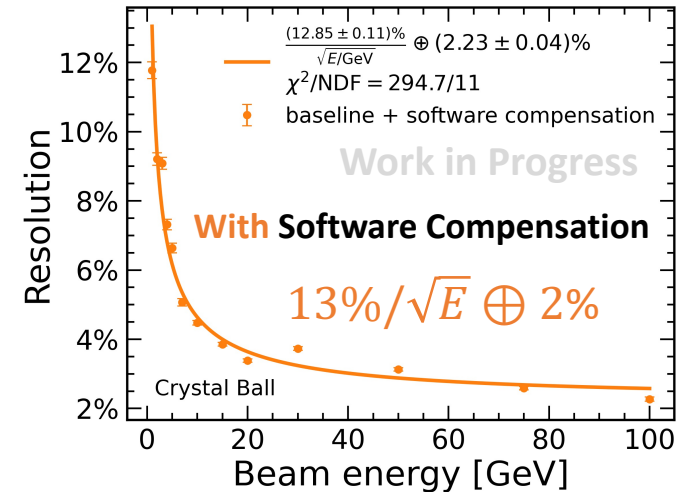
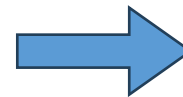
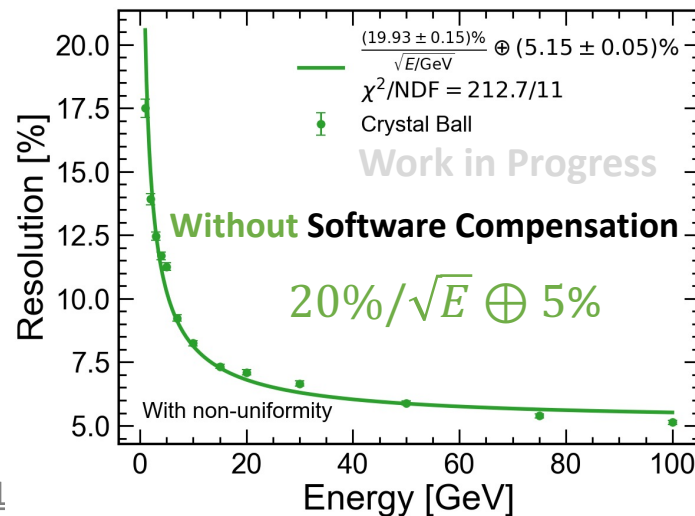
A single 100 GeV π^-





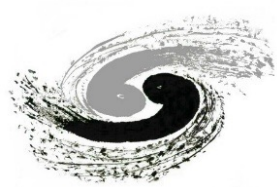
Software Compensation: hadron performance

- Software compensation (SC)
 - SC technique applied in many detectors or experiments: WA1/CDHS, H1, ATLAS, CALICE, CMS-HGCAL, etc. (different naming in literature)
 - Local SC: to assign weights based on measured energy density (enabled by high granularity) to hits corresponding to EM and purely hadronic components for $e/h \sim 1$
 - Significant improvement in hadronic energy resolution for ScintGlass ECAL+HCAL

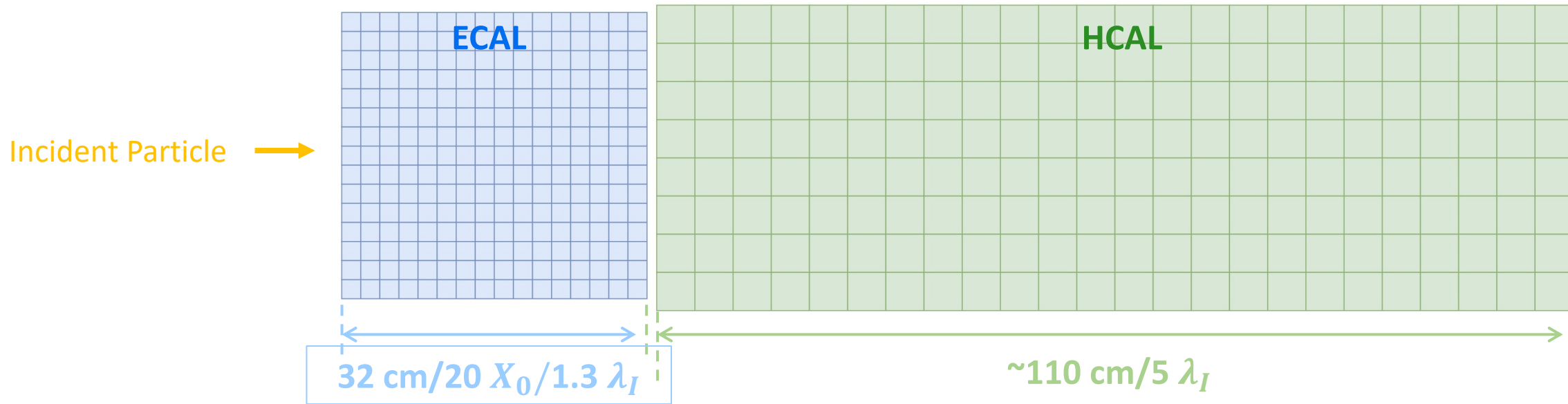


C Adloff et al 2012 JINST 7 P0901
Eur. Phys. J. C (2017) 77:698

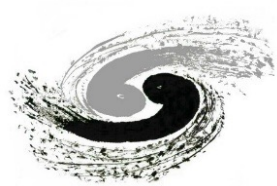
Including digitisation, especially intra-cube non-uniformity of both ECAL and HCAL



Scintillating Glass Calorimeters: a new design



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 - Aim and key feature: significantly improved hadronic resolution
 - Glass tile dimensions (typical): 3-4 cm thick, transverse $4 \times 4 \text{ cm}^2$
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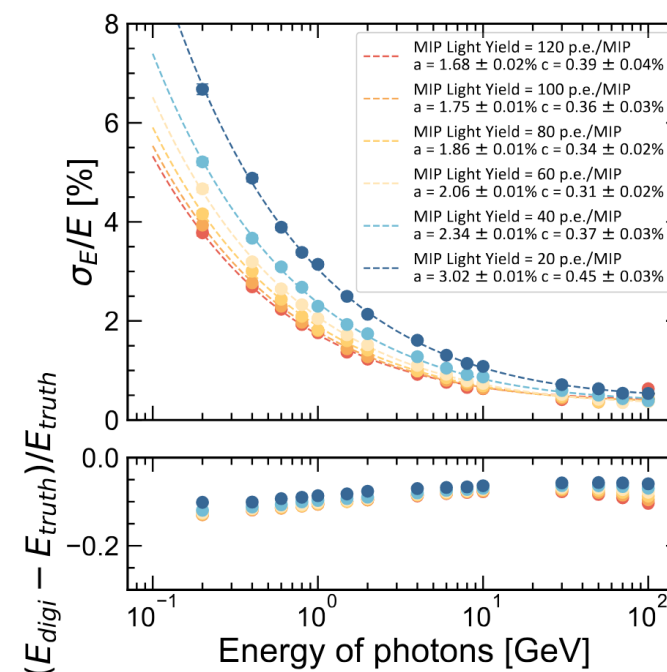


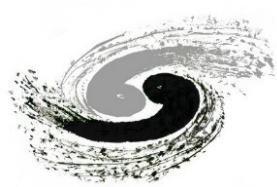
Scintillating Glass for homogeneous ECAL

Scintillator	Density (g/cm ³)	Radiation Length (mm)	Scintillation Time (ns)	Emission Peak (nm)	Refractive Index	Light Yield (ph/MeV)
BGO crystal	7.1	11.2	~300	480	2.15	8,000-10,000
BSO crystal	6.8	11.5	~100	480	2.06	~2,000
GFO glass	6.0	15.9	~500	400	1.74	1,000-2,000

- ECAL with finely-segmented glass: the first of this kind
- Glass requirements for ECAL
 - Density : 6.0 g/cm³
 - Dimensions : 2×2×2 cm³
 - Intrinsic Light Yield: **2000 ph/MeV**
 - **Attenuation Length: ≥10 cm**
 - **Scintillation Time: ~500 ns**

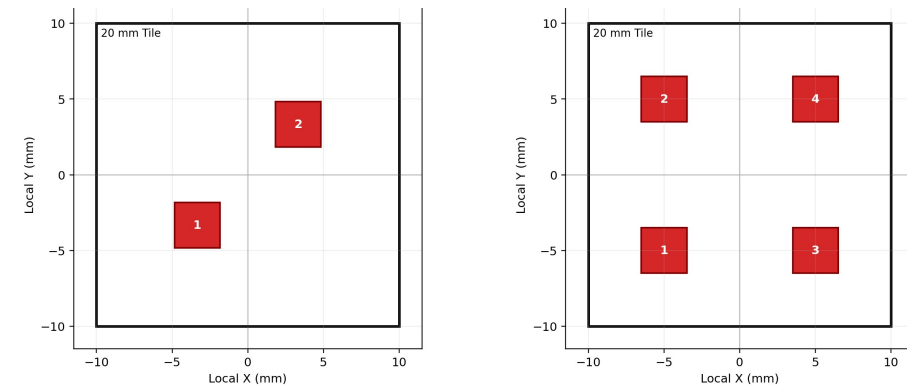
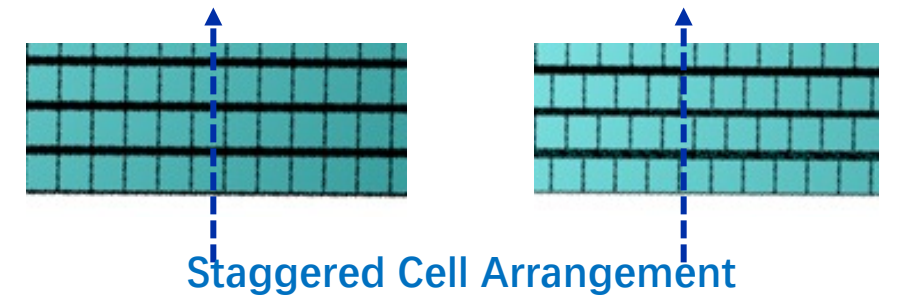
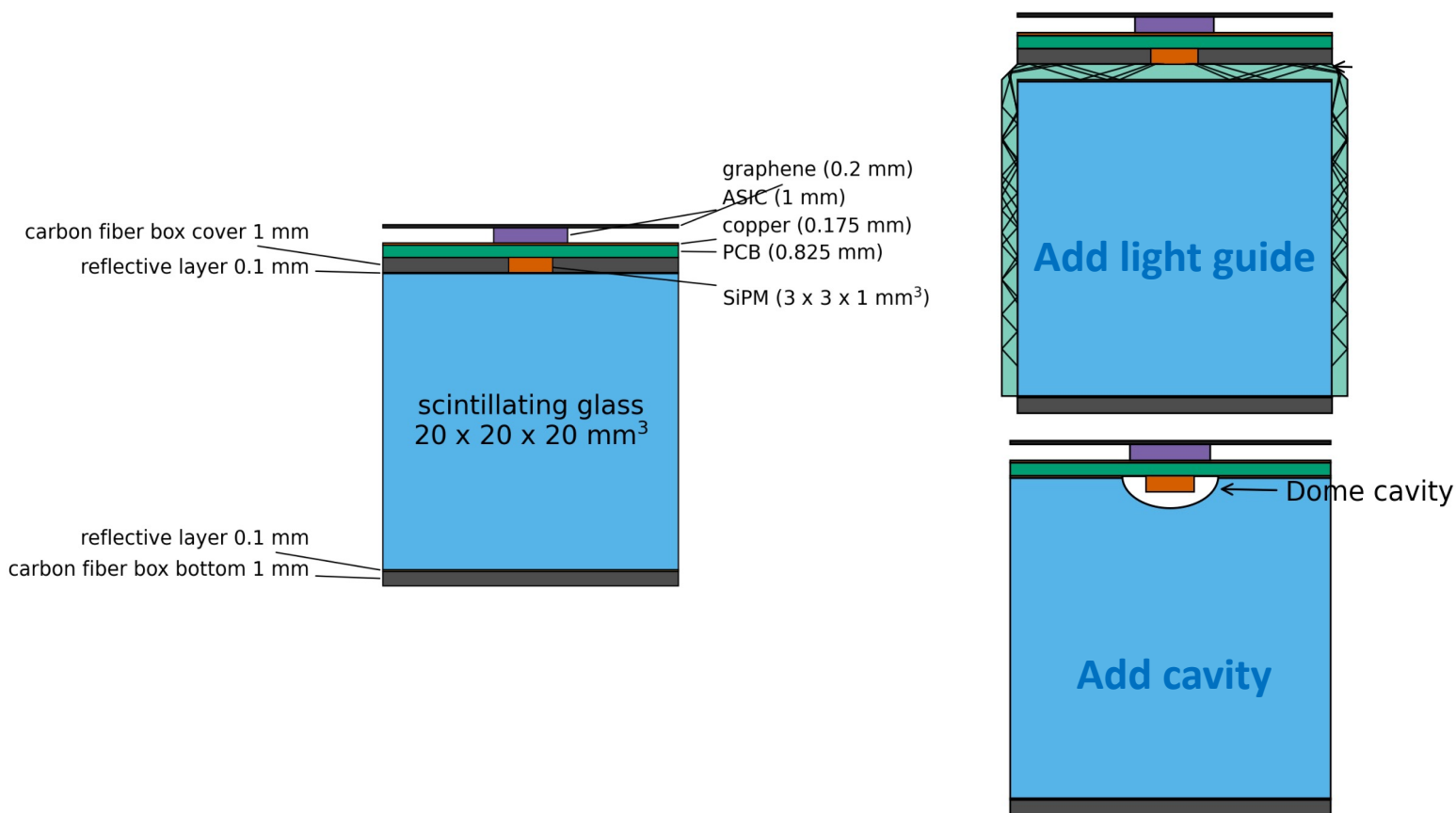
ECAL performance (simulation)



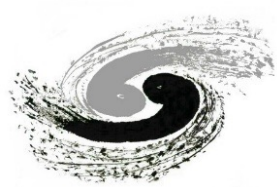


ECAL: Scintillating Glass Cube

- Light collection uniformity within a cube: **critical to achieve the target EM performance**
- Solutions: add light guide, add cavity, staggered cells, multiple SiPMs per cell

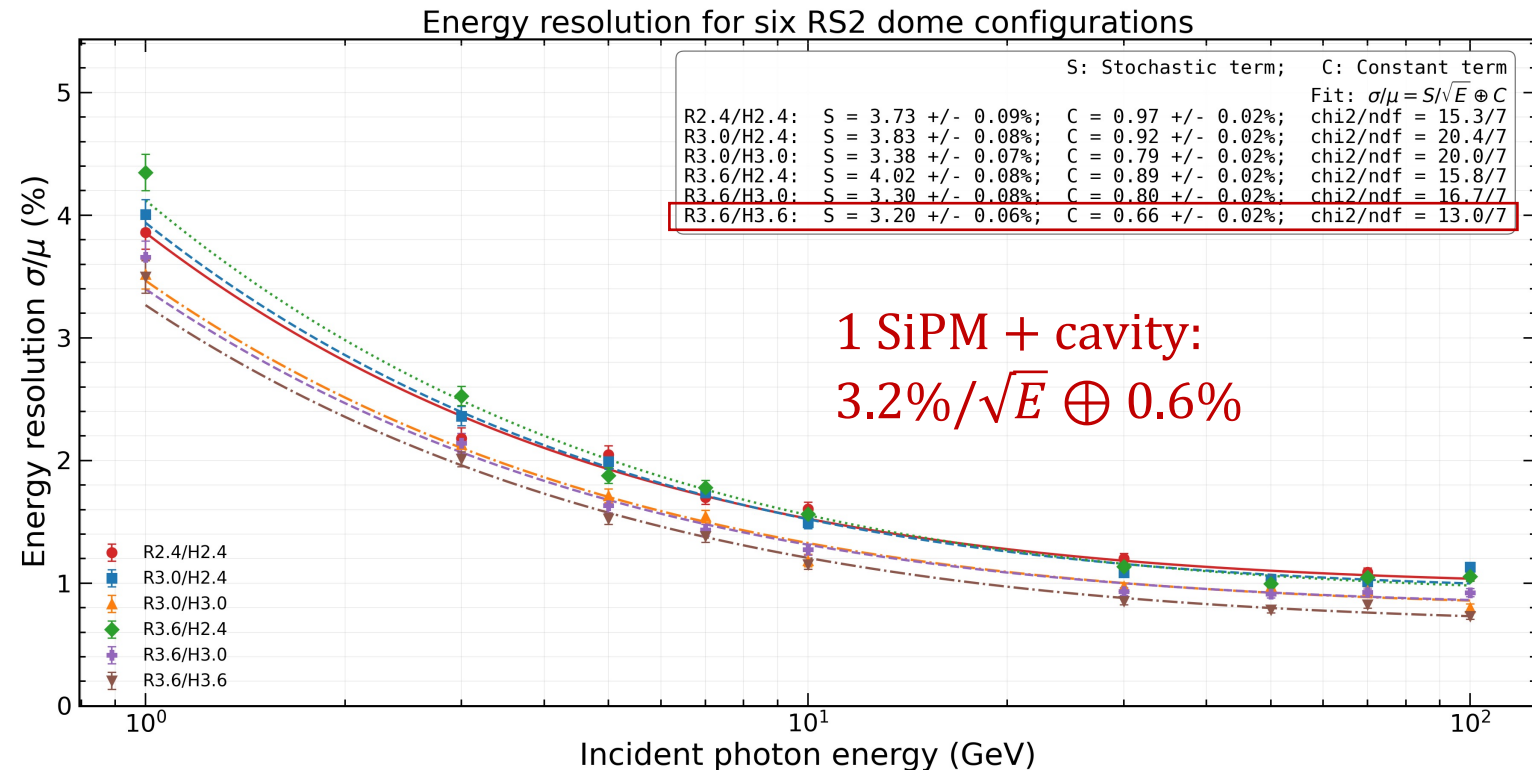
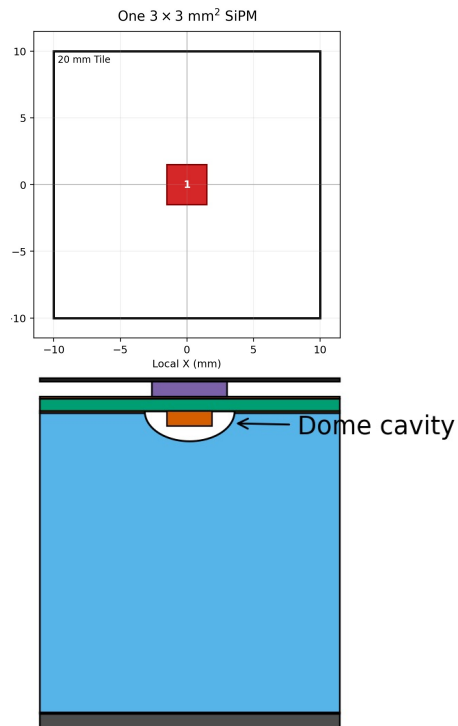


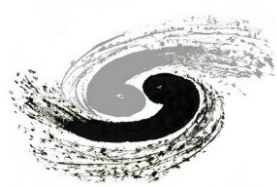
Multiple SiPMs per cell



ECAL Performance from Simulation

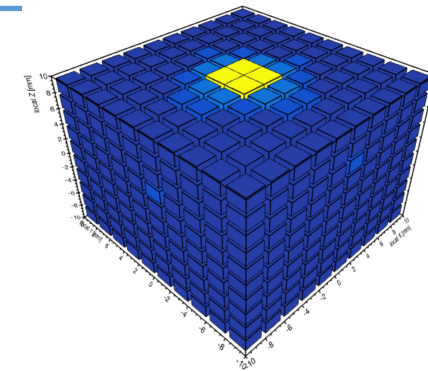
- A dome-shaped cavity in cube centre
 - A la “SiPM-on-Tile” design for CALICE-AHCAL and CMS-HGCAL
 - To improve intra-cube **uniformity** and to **accommodate SMD-SiPM**
 - Use **one 3x3 mm² SiPM**, assuming bulk attenuation length of 10cm (to be validated)





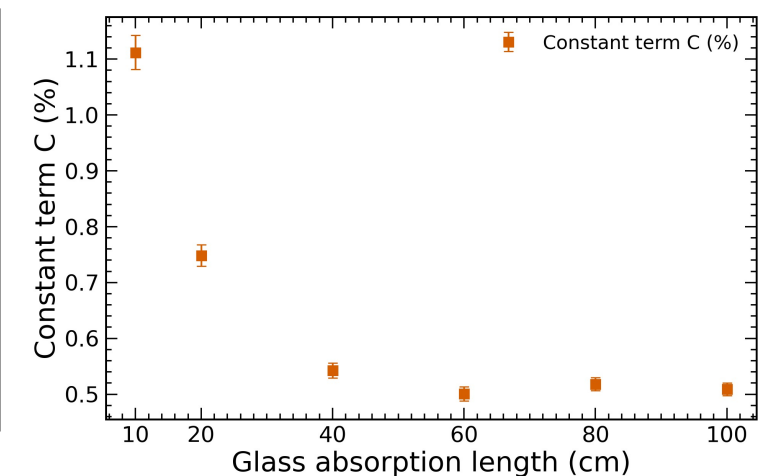
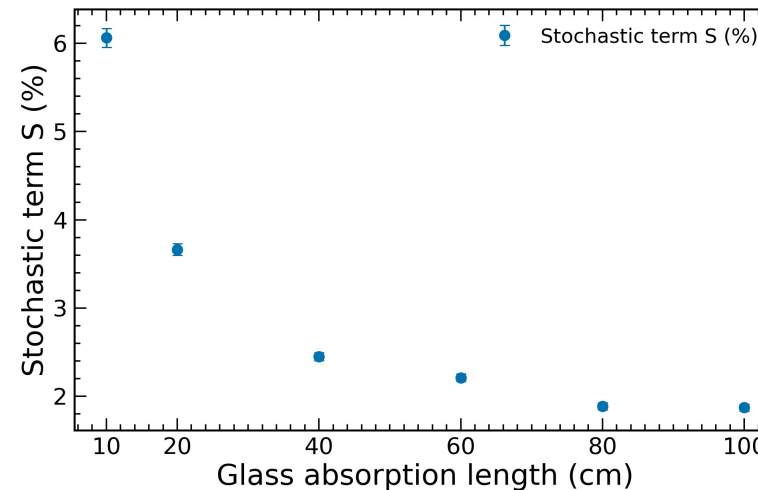
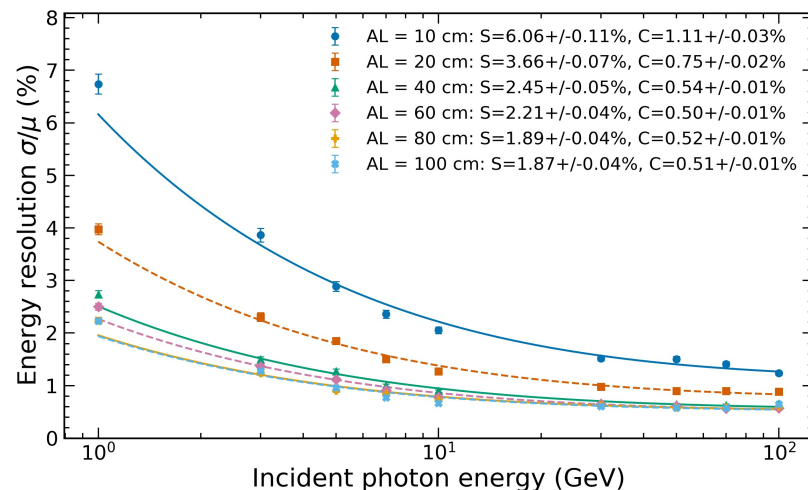
ECAL Performance from Simulation

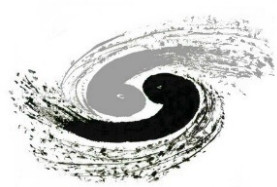
$\varepsilon(x, y, z)$: LCE mapping
in 3D (per cell)



- Geant4 simulation configurations
 - Energy deposition $E_{dep}(x, y, z)$ from Geant4 simulation for EM showers
 - Light Collection Efficiency (LCE) $\varepsilon(x, y, z)$ from optical simulation
 - Detected signal per cell $S_{cell} = \sum_{cell} E_{dep}(x, y, z) \cdot \varepsilon(x, y, z) \cdot PDE(\text{SiPM})$
 - Clustering of all cells (above auto-trigger threshold, nominal as 0.1 MIP)
- EM performance: dependence on the glass attenuation length
 - Attenuation length of 20 – 40 cm shows promising EM performance
(i.e. the stochastic term close to or less than 3%, the constant term <1%)

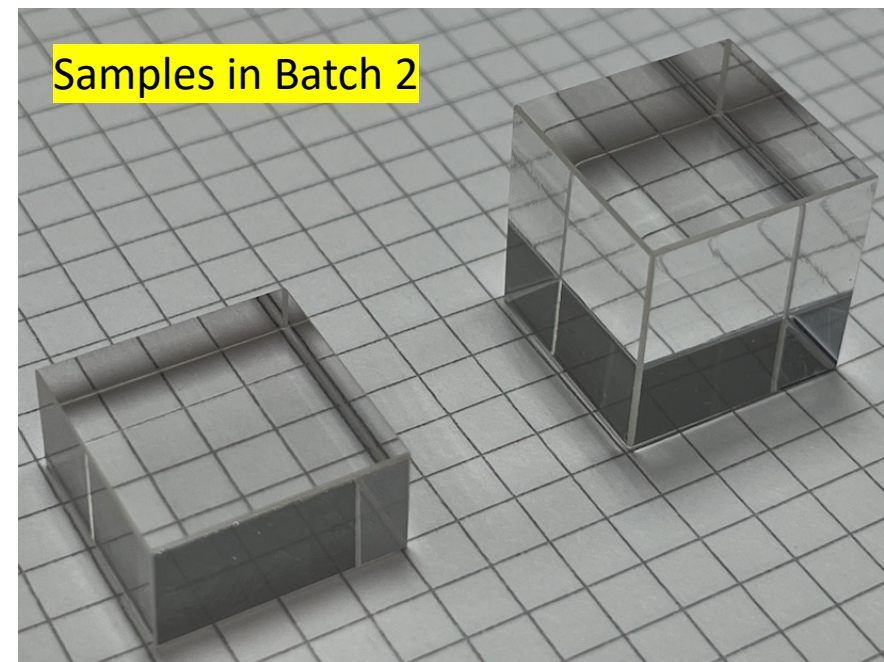
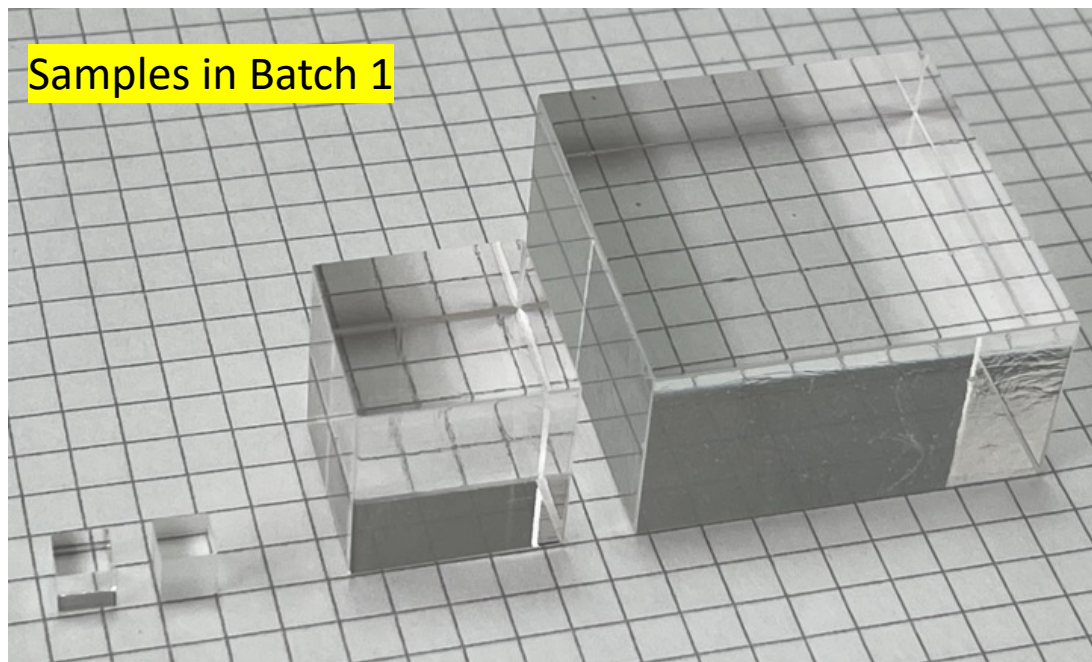
- Each glass cube uses only one 3x3 mm² SiPM
- Dome-shaped cavity was not implemented yet

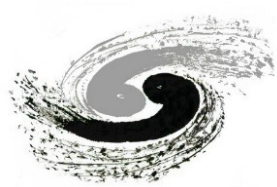




Latest ScintGlass samples

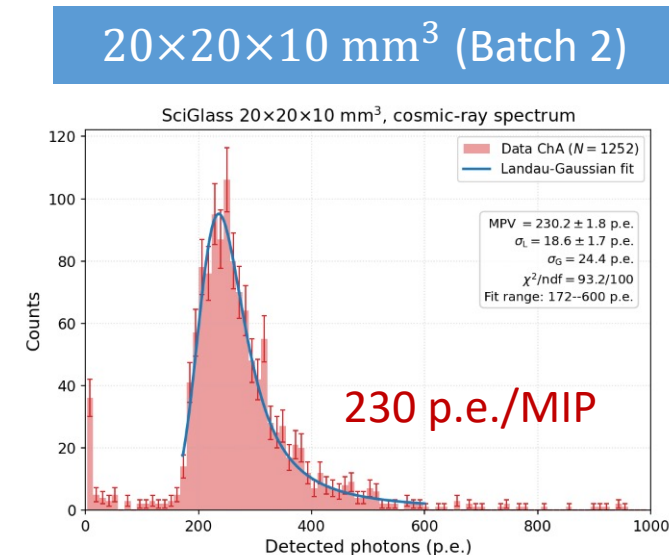
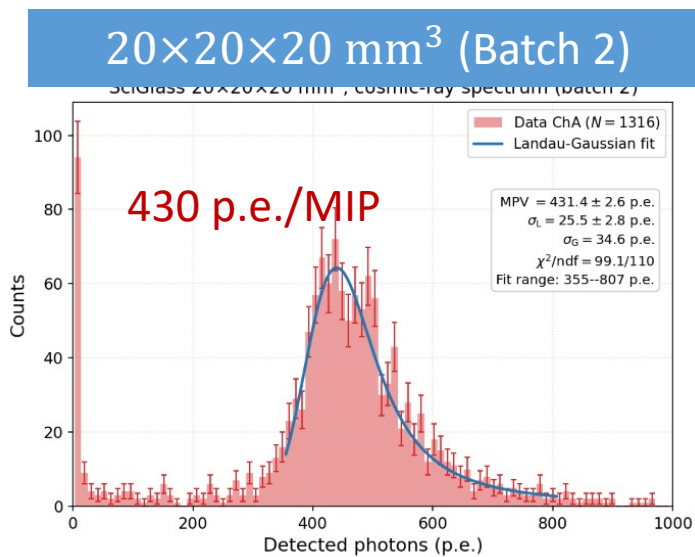
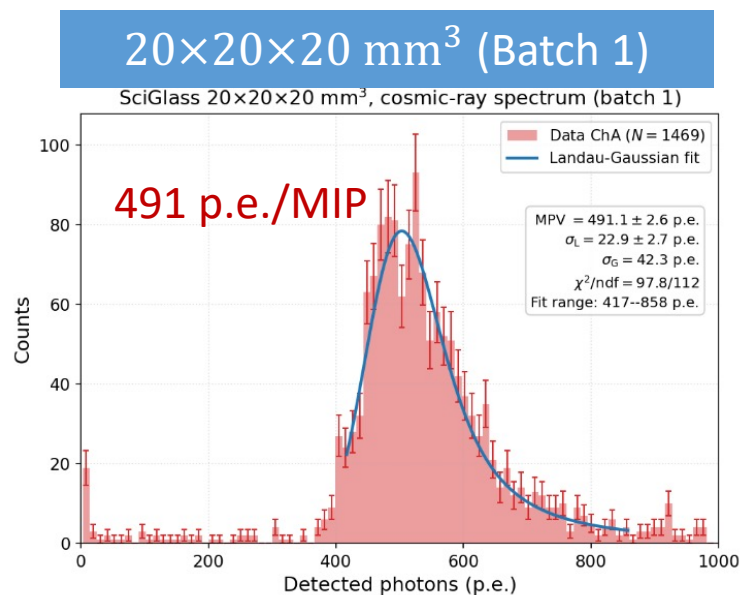
- Batch 1: four samples
 - $5 \times 5 \times 5 \text{ mm}^3$ cubes ($\times 2$): one with all sides polished, the other with two rough sides
 - $20 \times 20 \times 20 \text{ mm}^3$ cube ($\times 1$); $40 \times 40 \times 20 \text{ mm}^3$ tile ($\times 1$)
- Batch 2: two samples
 - $20 \times 20 \times 10 \text{ mm}^3$ tile ($\times 1$), $20 \times 20 \times 20 \text{ mm}^3$ cube ($\times 1$)

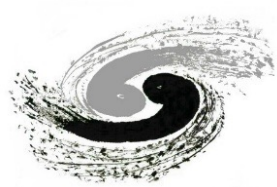




Cosmic-ray test results (1)

- Glass samples were tested with cosmic muons
 - MIP response: 431 - 491 p.e./MIP for 20mm thick glass, 230 p.e./MIP for 10mm thick
 - **Using one 6x6 mm² SiPM**
 - **Very promising to meet the ECAL requirement**
 - Also indication that the attenuation length is **significantly longer than 6 cm**

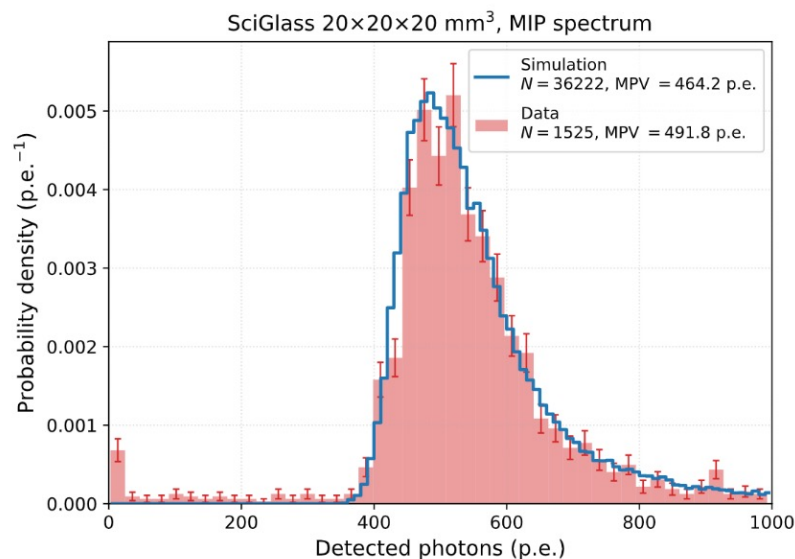




Geant4 optical simulation

Adapted version of the G4 model
validated by 2023 DESY beamtest

- Optical simulation for scintillating glass
 - Aims: better understanding of glass properties, detector unit design optimisation
 - Key input parameters: ***intrinsic light yield***, ***bulk attenuation length***

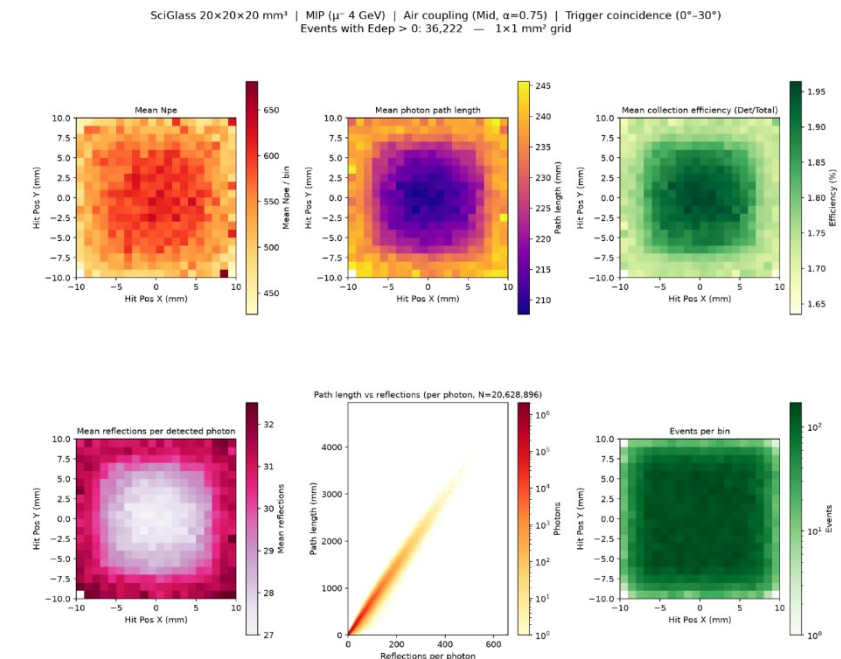


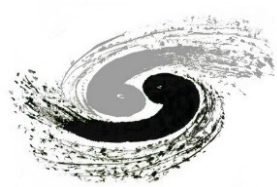
G4 optical simulation setting:

- Light yield = 1500 ph/MeV
- Bulk attenuation length ~20 cm

(Ongoing validation with more tests)

- (Ongoing) Studies to further improve uniformity
 - Light collection efficiency (LCE)
 - No. of reflections and light path lengths: comparison of reflectors and surface roughness

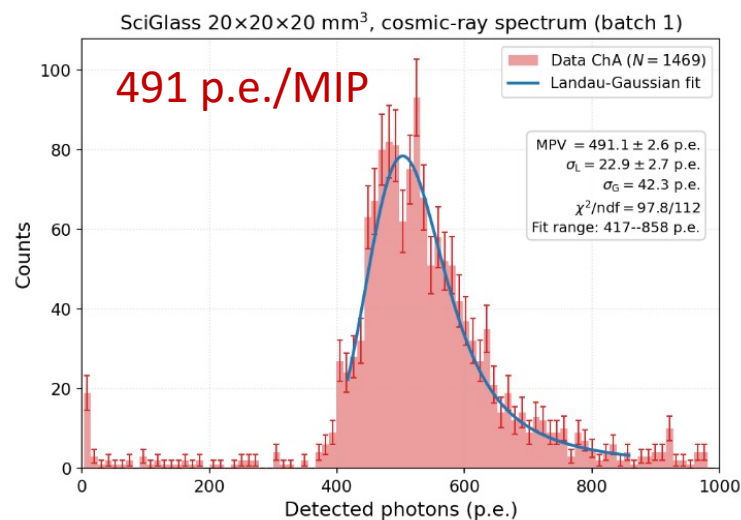




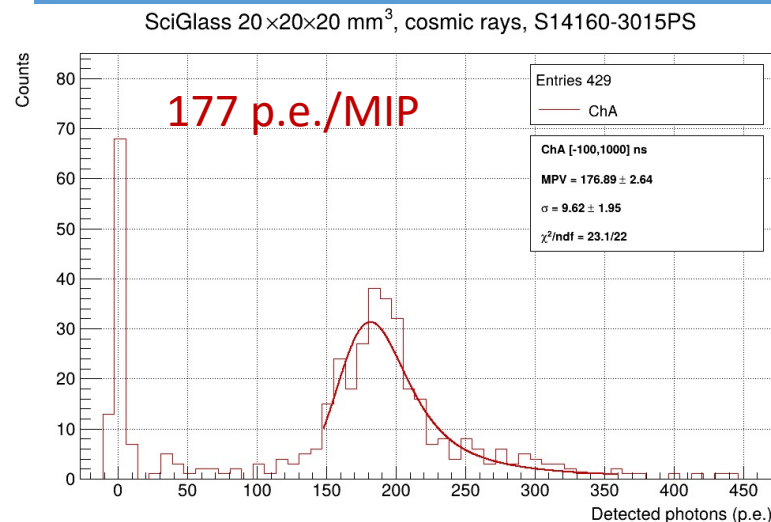
Cosmic-ray test results (2)

- One glass sample tested with different SiPMs with cosmic muons
 - MIP response in the range of 95 - 491 p.e./MIP
 - Differences can be reasonably explained by contributions from LCE and SiPM PDE
 - Very promising to meet the ScintGlass ECAL requirement

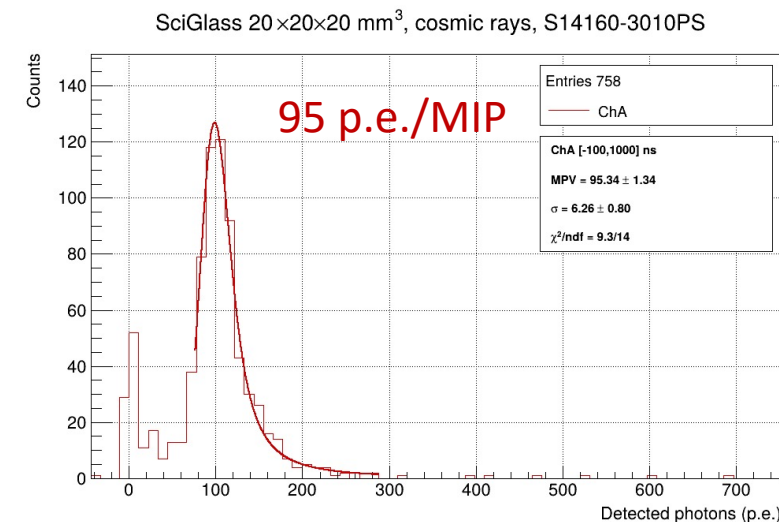
6×6 mm² SiPM (25 μm pixel pitch)



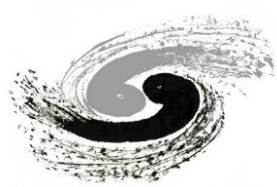
3×3 mm² SiPM (15 μm pixel pitch)



3×3 mm² SiPM (10 μm pixel pitch)

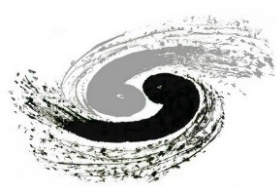


Tests with the same glass 20×20×20 mm³ (Batch 1)



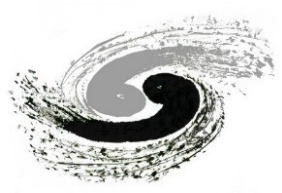
Summary and planning

- A new design: integrated ECAL and HCAL based scintillating glass
 - (Starting from ScintGlass sampling HCAL in CEPC Ref-TDR)
 - Featuring best in both worlds: maximum possible sampling fraction, high granularity
- Steady progress: simulation studies and tests
 - Simulation on ECAL and HCAL: key parameters and design specifications
 - Measurements with latest glass samples, guided by Geant4 optical simulation
- Preliminary conclusions
 - **Using one SiPM:** achieved 95 - 491 p.e./MIP with cosmic muons (using different SiPM types)
 - Tests indicate that the glass bulk attenuation length is significantly larger than 6 cm
 - Promising to meet the glass requirement for photon statistics
- Planning for near future
 - Continue to optimise detector design (esp. intra-cube/tile uniformity) and EM/hadronic performance
 - Further study response uniformity with cosmic muons (limited by low rate)
 - Prototype design and studies on system integration (mechanics, cooling, FEA, cabling, etc.)

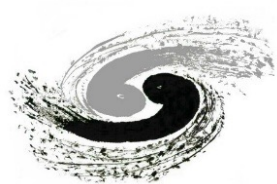


Prospects

- 2026: design optimisation and definition of specifications
 - Integrated design of ECAL-HCAL based on ScintGlass
 - SiPM candidates, readout electronics, system integration (mechanics and cooling)
 - Longitudinal/transverse granularity: HCAL sampling fraction, separation power, cost estimates
 - **Critical issue: intra-cube/tile response uniformity**
 - Requirements for scintillating glass materials
- 2026-2028: developments from detector units to modules/prototypes
 - 2026-2027: testing of glass samples; QA/QC protocols; specifications
 - 2027-2028: ECAL prototype
 - 2027-2029: HCAL prototype
- 2028-2029: beam tests of ECAL and HCAL prototypes for performance evaluation



Backup



(Tentative) Requirements for SiPM-readout ASIC

- MIP response: based on the latest tests of glass-SiPM detector units
 - SiPM option: HPK S14160-3015PS for balance of S/N ratio and dynamic range
 - MIP response: 177 p.e./MIP in cosmic-ray tests
- Dynamic range: Geant4 simulation of Bhabha and $ee \rightarrow q\bar{q}$ events at 360 GeV

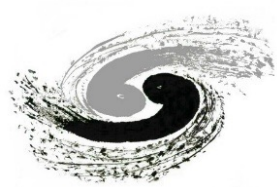
Table 1: Verified SiPM parameters from Hamamatsu datasheets [2–4].

Parameter	S13360-6025PE	S14160-3010PS	S14160-3015PS
Active area	$6 \times 6 \text{ mm}^2$	$3 \times 3 \text{ mm}^2$	$3 \times 3 \text{ mm}^2$
Pixel pitch	$25 \mu\text{m}$	$10 \mu\text{m}$	$15 \mu\text{m}$
Pixel count	57,600	89,984	39,984
PDE at 400 nm	$\sim 23\%$	$\sim 15\%$	$\sim 27\%$
PDE (peak)	25% @ 450 nm	18% @ 460 nm	32% @ 460 nm
Gain	7.0×10^5	1.8×10^5	3.6×10^5
Terminal capacitance	1280 pF	530 pF	530 pF
Dark count rate	1600 kcps	700 kcps	700 kcps
Breakdown voltage	53 V	38 V	38 V

Table 3: Summary of detector-driven requirements for the SiPM-readout ASIC, using the S14160-3015PS as reference.

Parameter	Requirement
Reference SiPM	S14160-3015PS
SiPM gain	3.6×10^5
Single-p.e. charge $Q_{\text{p.e.}}$	57.7 fC
MIP response (DUT cube)	177 p.e.
MIP charge	10.2 pC
Dynamic range	0.1–1400 MIPs
0.1 MIP charge	1.02 pC
1400 MIP charge	14.3 nC
LSB per channel	0.03 MIP ($\approx 0.306 \text{ pC}$)
Equivalent noise per channel	0.01 MIP ($\approx 0.102 \text{ pC}$)
Number of LSB steps	$\sim 46,667$ (~ 15.5 bits)

The selected SiPM (S14160-3015PS) may not cover the required dynamic range → still need to continue the work on SiPM



ScintGlass calorimeter prototypes: scale (tentative)

- ECAL prototype:

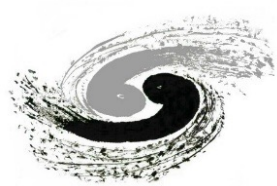
- Dimension: $16 \times 16 \times 32 \text{ cm}^3$
- Glass cubes: $2 \times 2 \times 2 \text{ cm}^3$
- 2 SiPMs per glass cube (tentative)
- Weight: $\sim 50 \text{ kg}$

Component	Quantity (Unit)
Glass Cubes	1,024 (pcs)
SiPMs	2,048 (pcs)
Electronics	1,024 (channels)

- HCAL prototype

- Transverse area: $72 \times 72 \text{ cm}^2$
- Longitudinal depth $\sim 5\lambda_I$ (1.0-1.2m)
- Longitudinal 40 layers
- Glass tiles (transverse): $4 \times 4 \text{ cm}^2$
- 1 SiPM per glass tile
- Weight: $\sim 5 \text{ ton}$

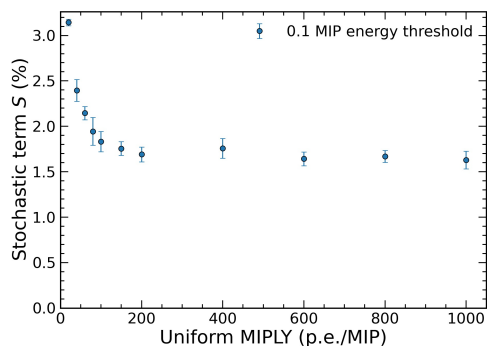
Component	Quantity (Unit)
Glass Tiles	12,960 (pcs)
SiPMs	12,960 (pcs)
Electronics	12,960 (channels)



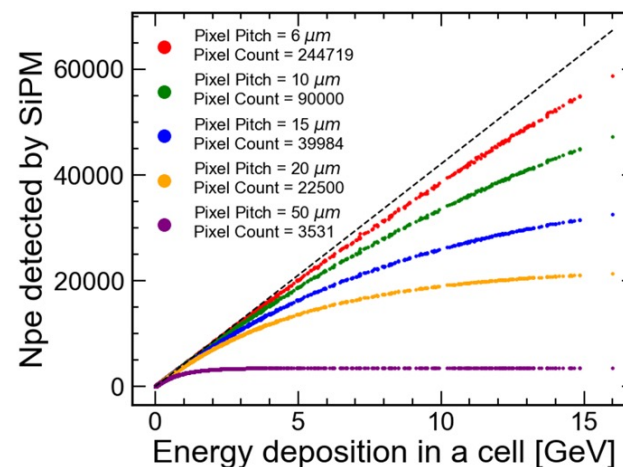
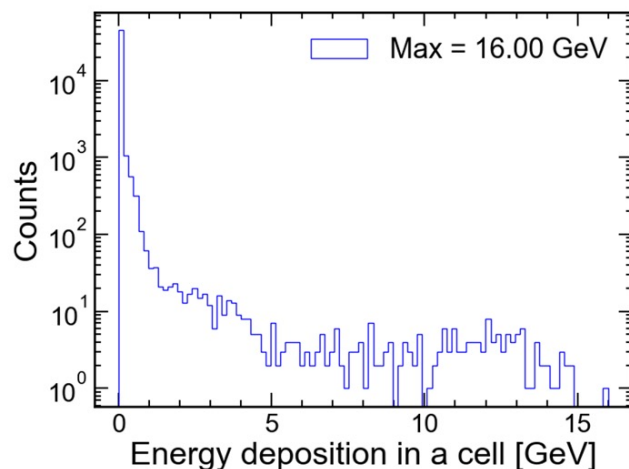
Design specifications: ongoing studies

- Preliminary results from simulation
 - MIP response: dominating photon statistics
 - Dynamic range: requirements from physics, glass-SiPM non-linearity

ECAL: EM resolution with varying MIP response



ECAL dynamic range



HCAL dynamic range

