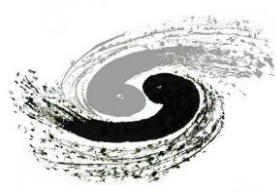
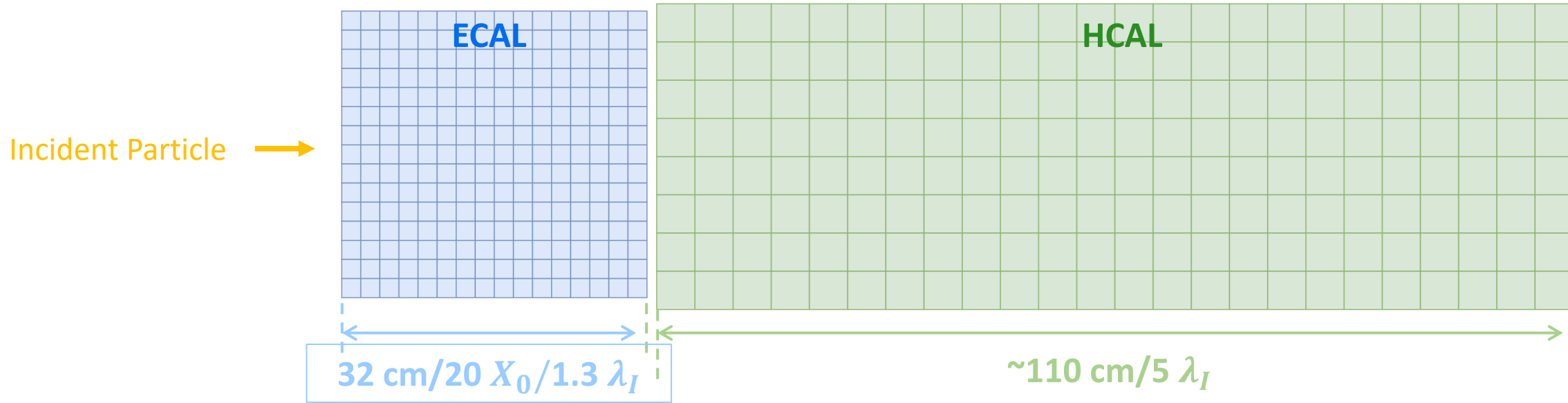


Scintillating Glass Calorimeters: status of R&D progress

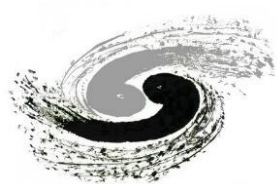
Yong Liu (IHEP), for the CEPC-calo team
CEPC Day
September 21, 2026



Scintillating Glass Calorimeters: a new design



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

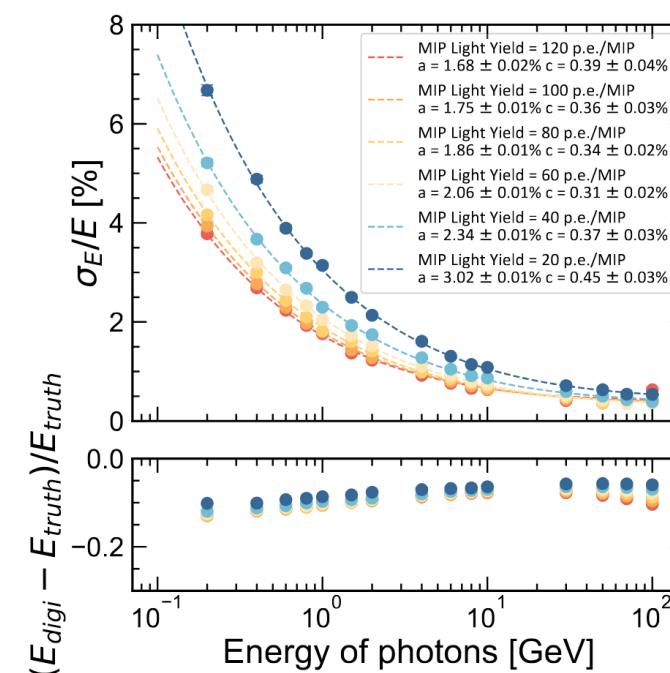


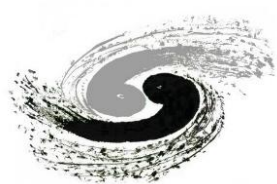
ScintGlass ECAL

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)





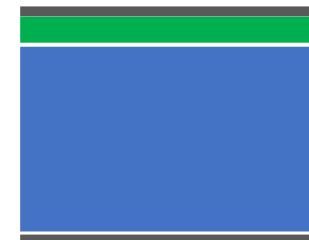
ScintGlass HCAL

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)

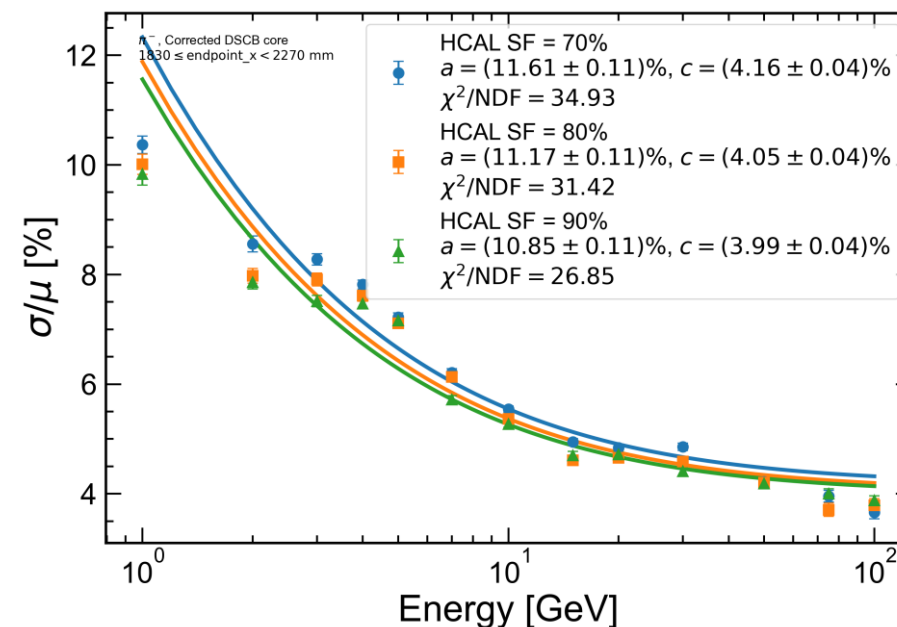
Sampling fraction 84.5%
HCAL depth $4.6\lambda_I$

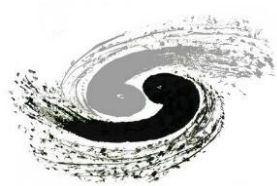


Cassette (1 mm)
Readout PCB (3.1 mm)
Glass Tile (23.8 mm)
Cassette (1 mm)

- 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: $\sim 500 \text{ ns}$

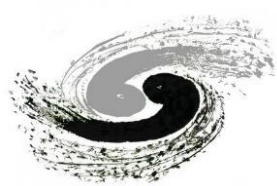
HCAL performance (simulation)





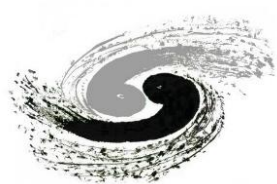
Goals and timeline: ScintGlass calorimeters

- 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 of detector units, modules/prototypes
 - Glass-SiPM unit testing: o(10-100) glass samples; QA/QC protocols; detector specs
 - ECAL prototype: **1024** ($8 \times 8 \times 16$) channels
 - HCAL prototype: **12960** ($18 \times 18 \times 40$) channels
- 2028-2029: beam tests of ECAL and HCAL prototypes for performance demonstration



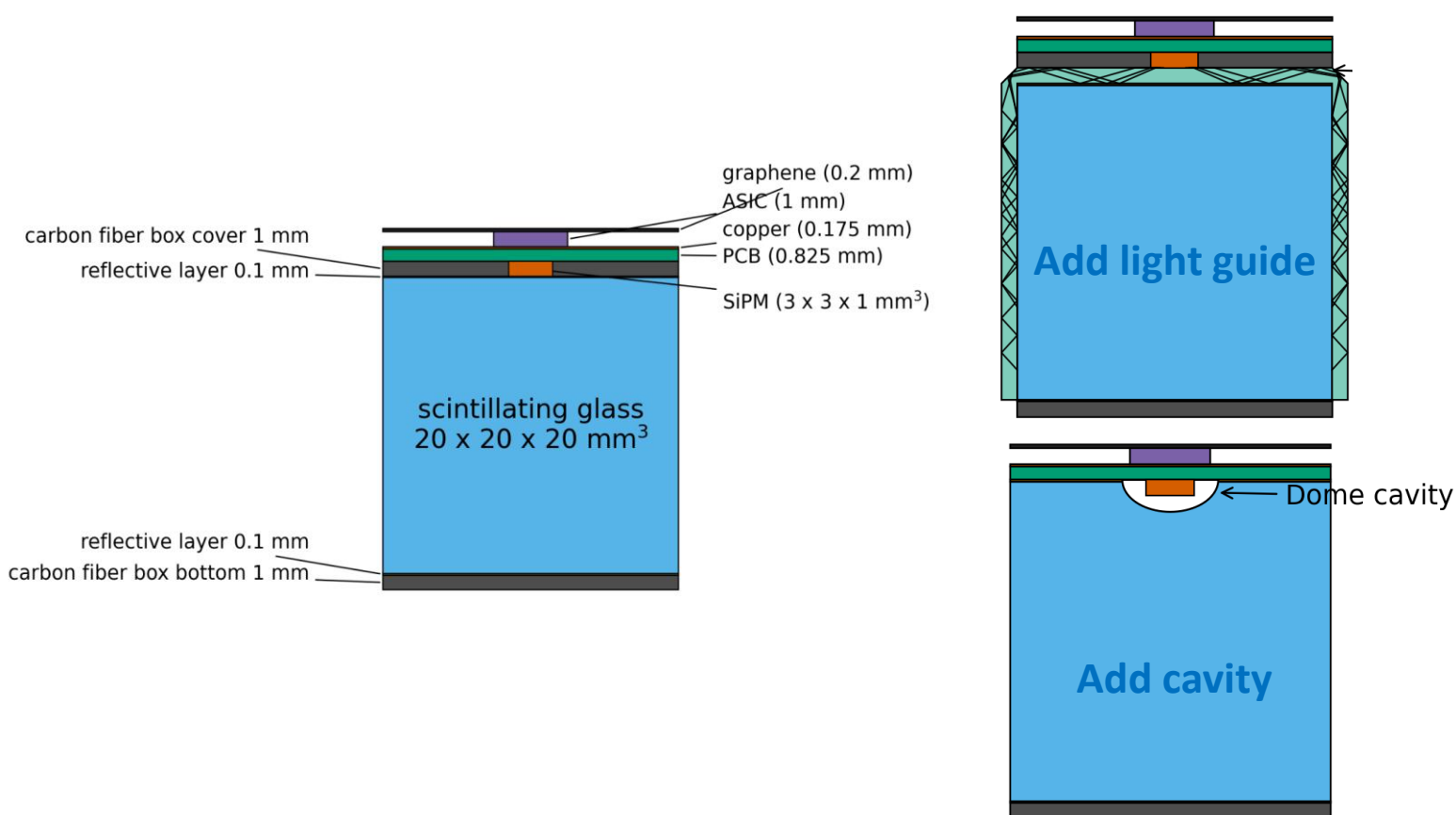
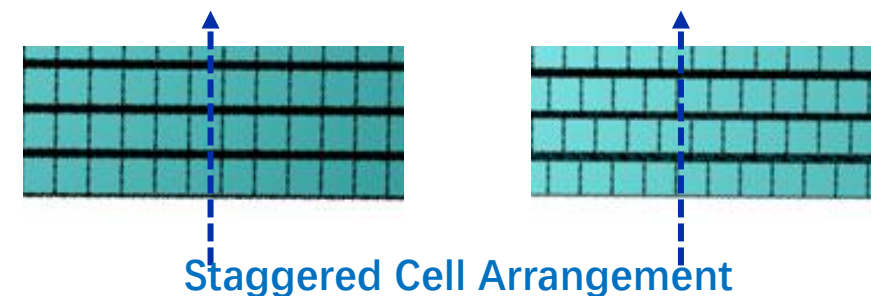
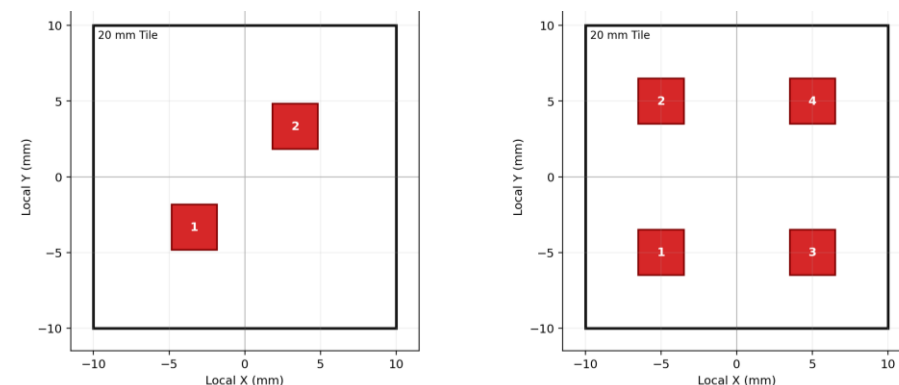
Outline: R&D progress

- Simulation studies
 - EM/hadronic performance with single particles
 - Impact of bulk attenuation length of glass cubes
- Glass samples testing and simulation
 - Radioactive source tests: (sub-) MeV-scale energy spectrum
 - Cosmic-ray tests: MIP signals
 - Optical simulation: guidance of better understanding and design optimisation

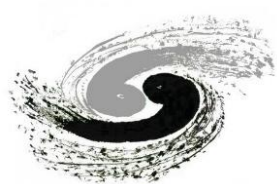


ECAL: Scintillating Glass Cube

- 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



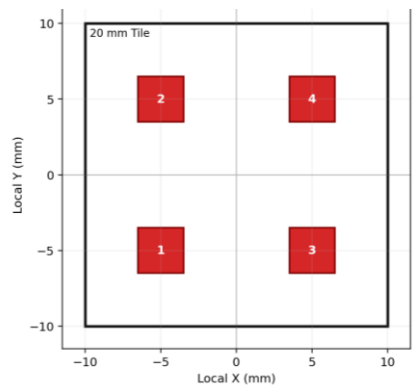
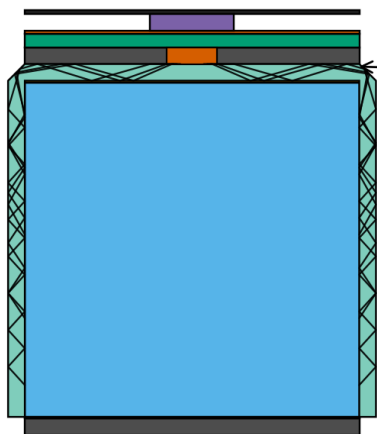
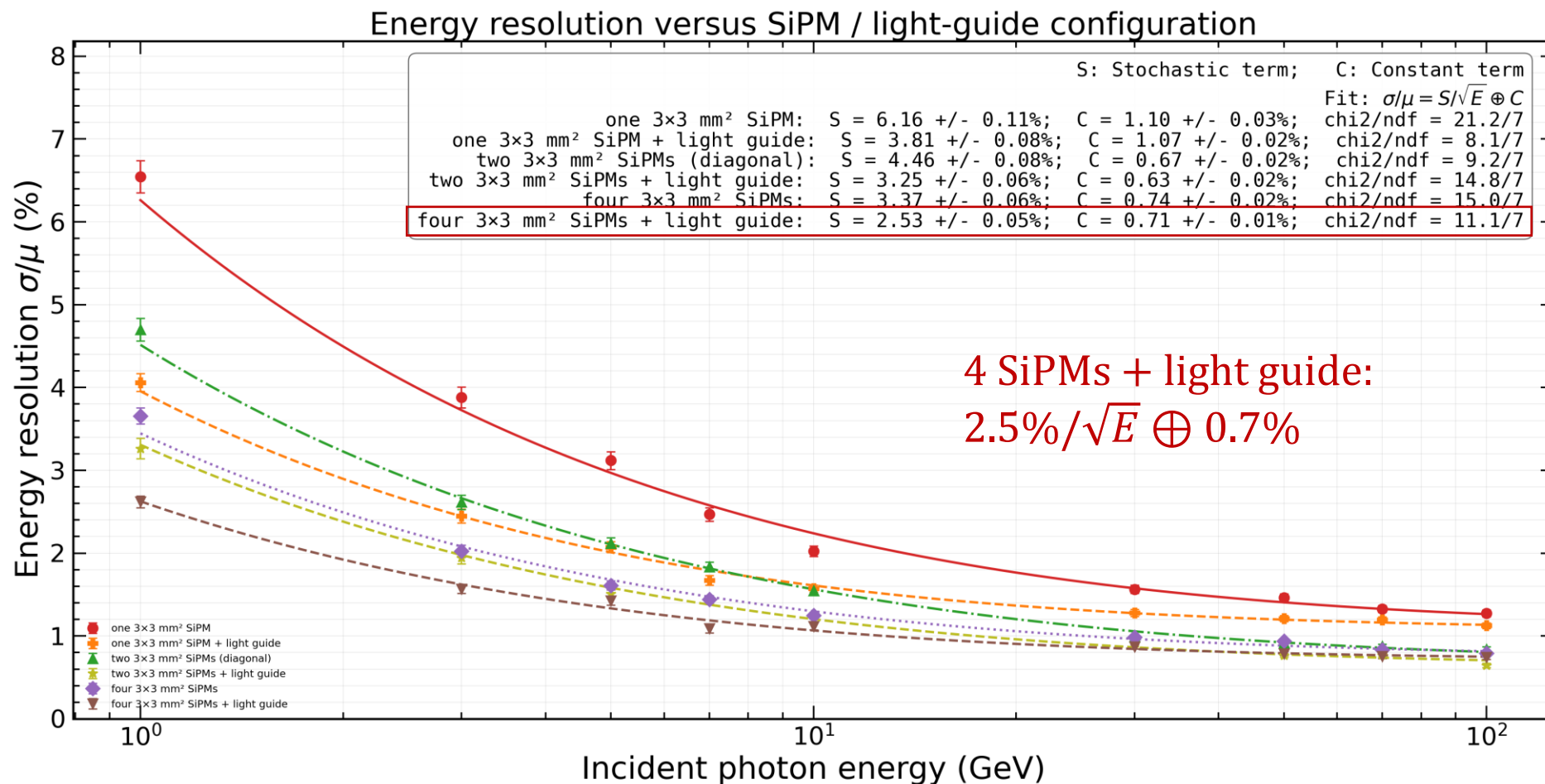
Multiple SiPMs per cell

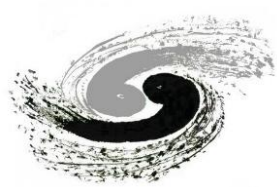


ECAL Performance from Simulation

- 1-100 GeV photons, entering near the centre of one module
- Energy sum of all cell above threshold, including digitisation per cell

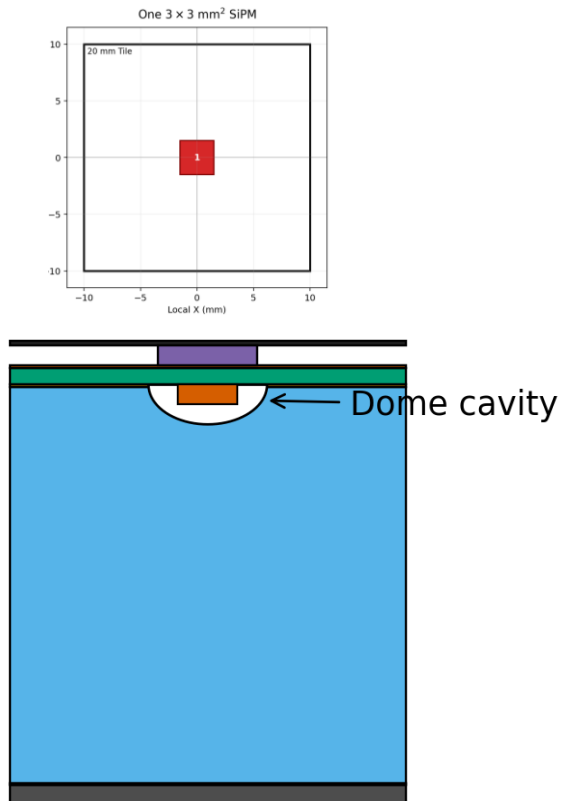
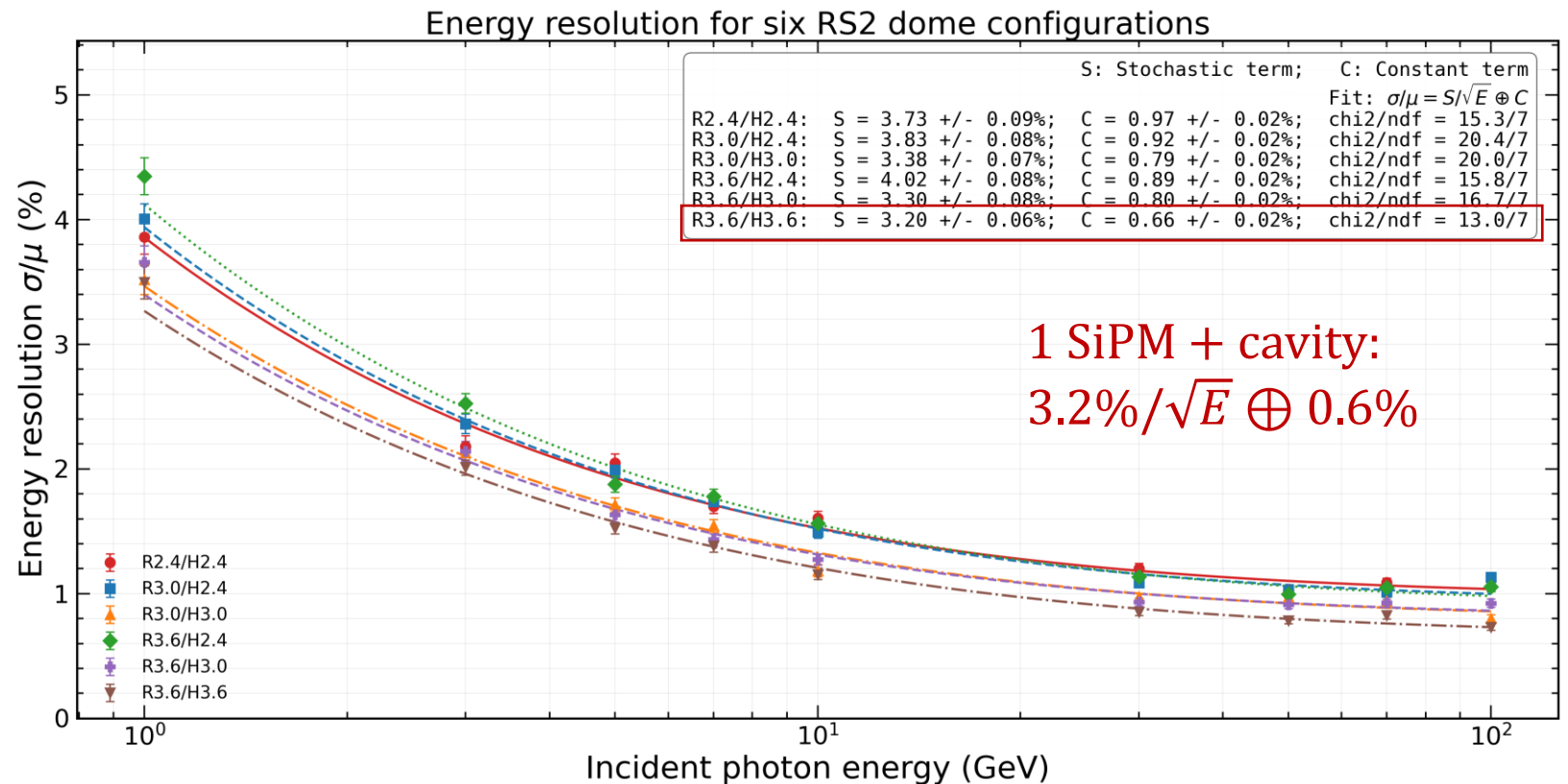
Assuming attenuation length of 10cm

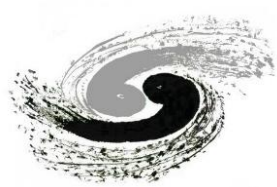




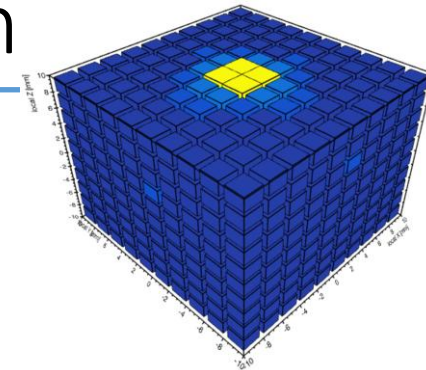
ECAL Performance from Simulation

- ECAL unit: a dome-shaped cavity in cube centre
 - To improve intra-cube uniformity and accommodate SMD-SiPM
 - Use **one 3x3 mm² SiPM**, assuming attenuation length of 10cm

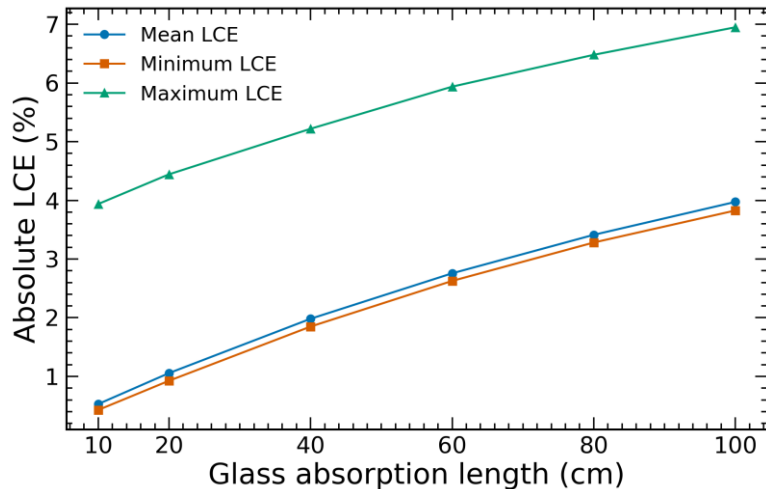
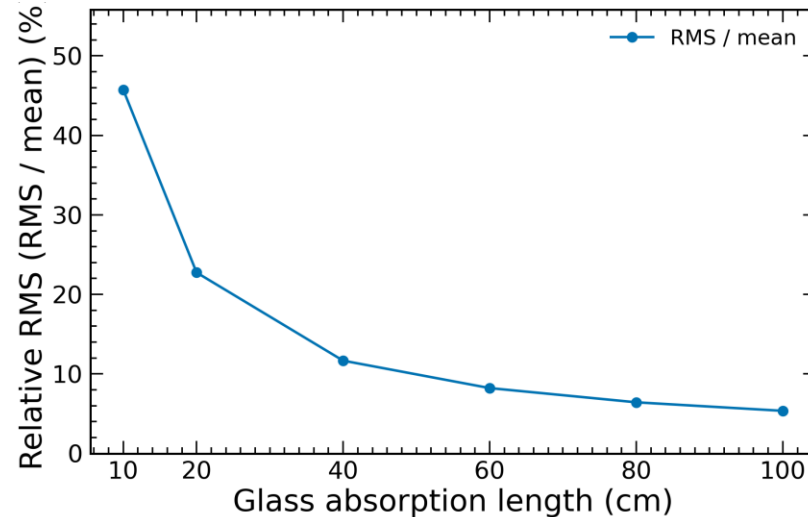
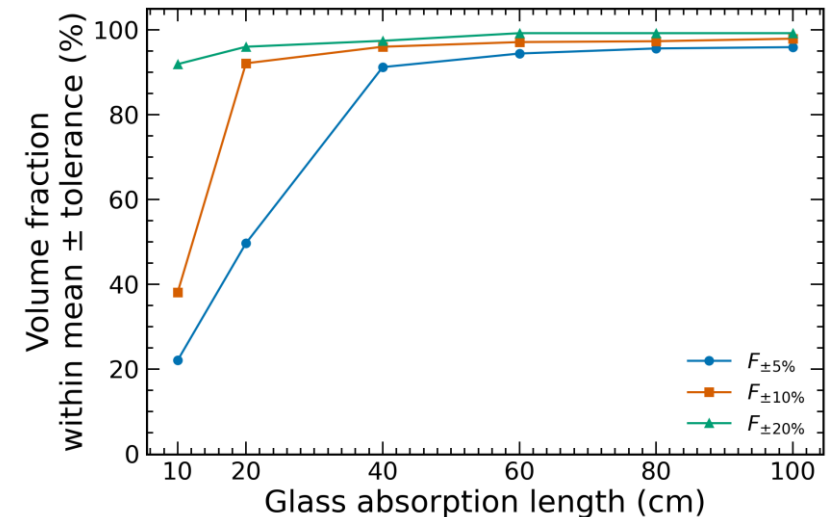




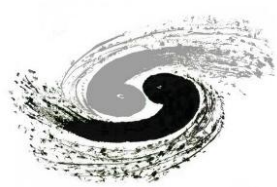
3D Light Collection Efficiency: optical simulation



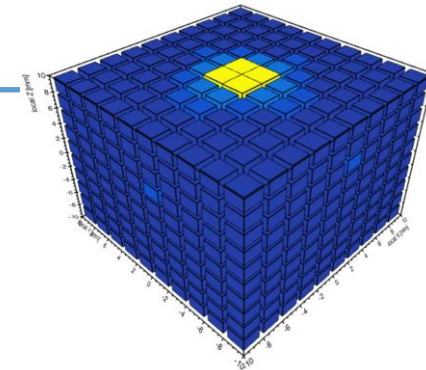
- LCE and uniformity dependency on glass bulk attenuation length
 - Attenuation length of 20 – 40 cm is expected to improve uniformity



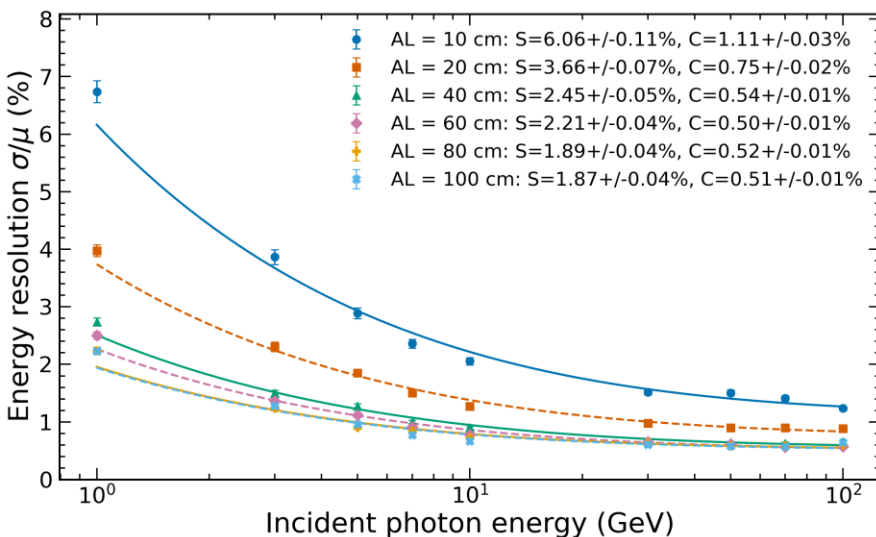
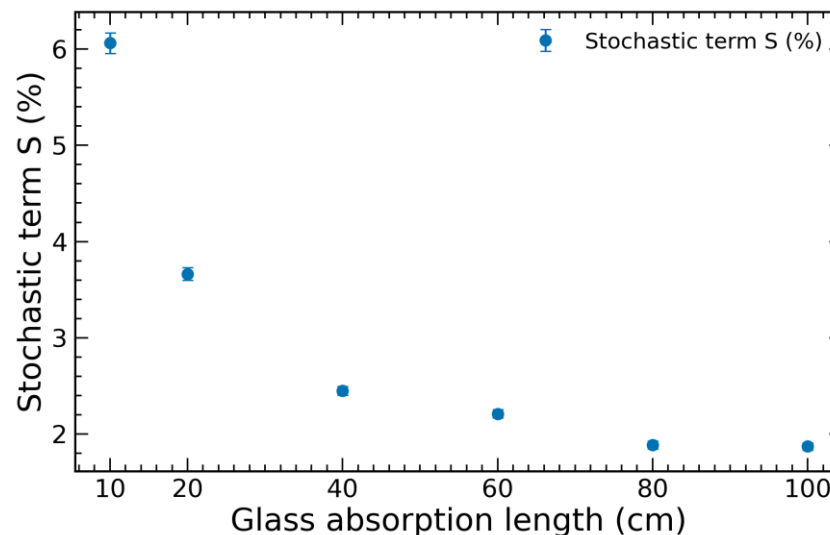
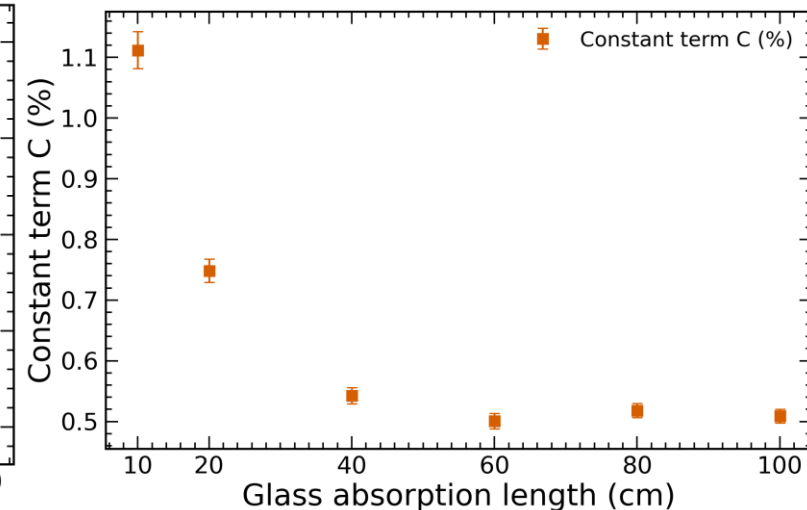
- Intra-cube response uniformity: to be validated via measurements
 - ScintGlass: intrinsic light yield, attenuation length, surface treatment
 - Glass-SiPM coupling, reflector

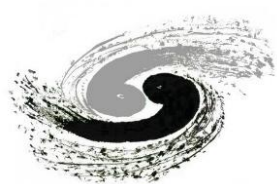


ECAL Performance from Simulation



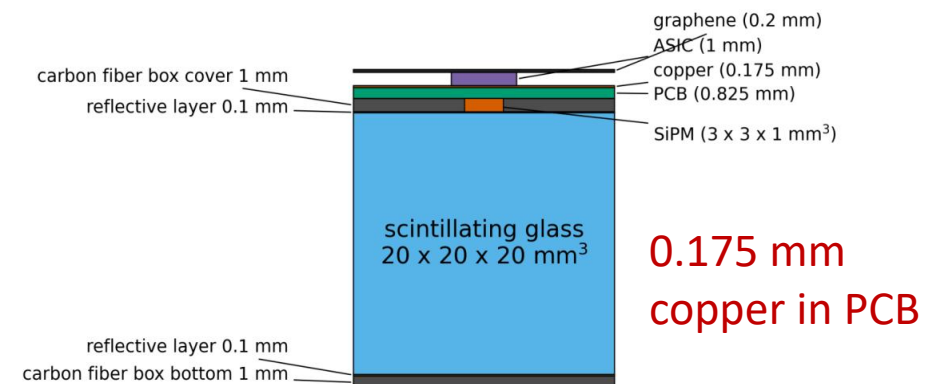
- EM performance: dependence on the glass attenuation length
 - Use one 3x3 mm² SiPM
 - No implementation of light guides or cavity (yet)
 - Attenuation length of 20 – 40 cm shows promising EM performance



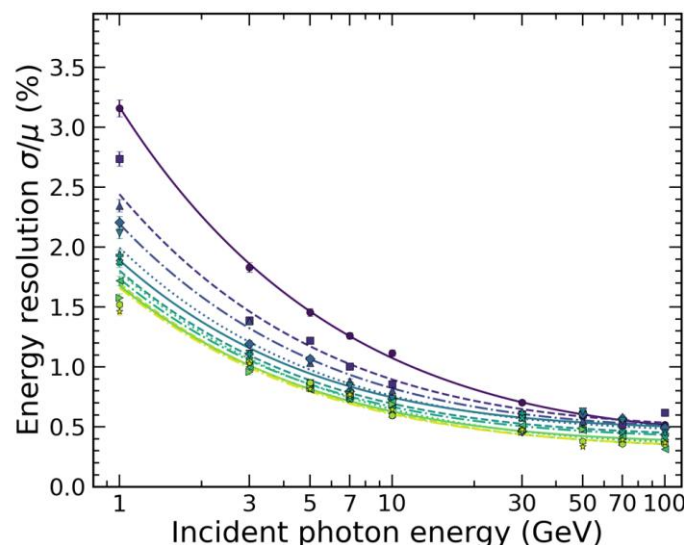
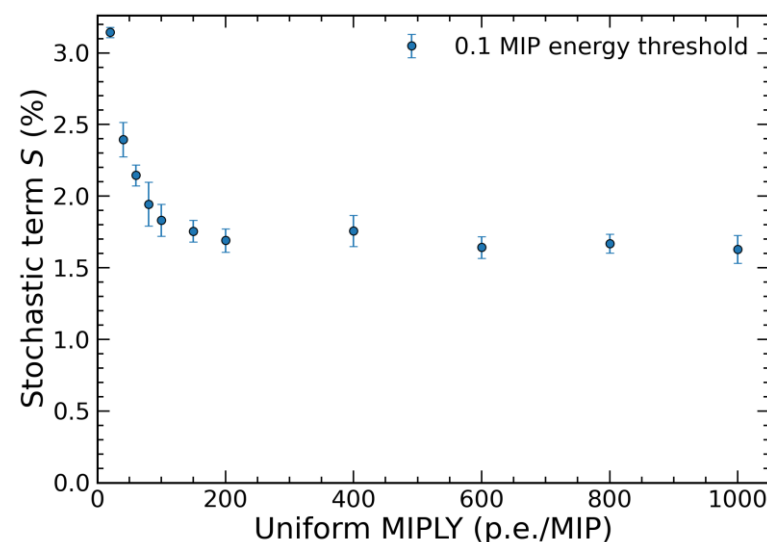


ECAL Performance from Simulation

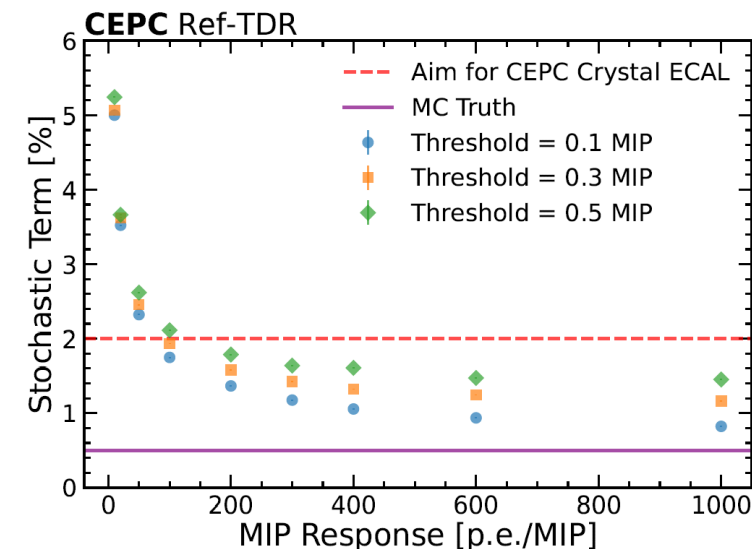
- Photon statistics: dominating the stochastic term
- Stochastic term (in EM resolution) vs. MIP response
 - ECAL design with embedding electronics/cooling in layers: with 20% X0 (2.8 mm Cu in 16 layers) → **a limiting factor**
 - **Hint: minimising dead materials in layers to pursue ~1% EM resolution (a la crystal ECAL in CEPC Ref-TDR)**

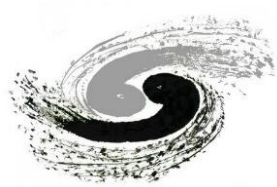


EM resolution with varying MIP response (p.e./MIP)



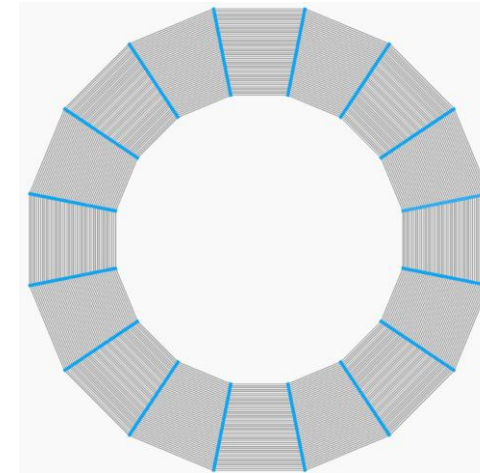
Crystal ECAL: EM performance



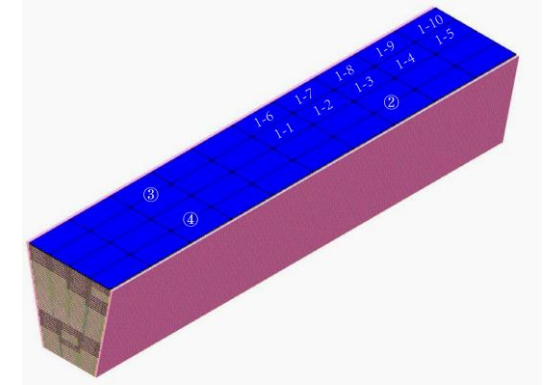
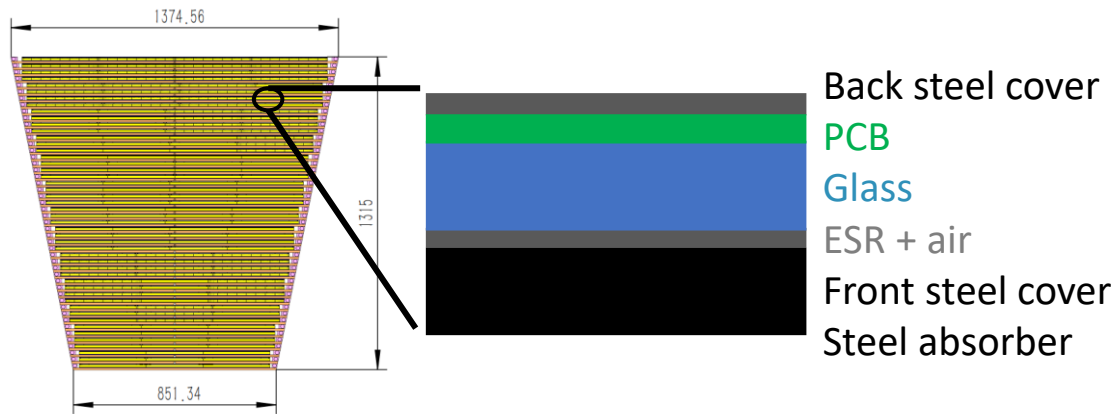


Homogeneous HCAL Design

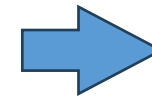
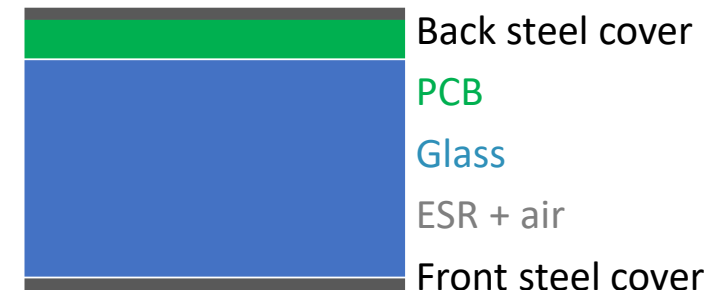
- Retain the steel for mechanical structure
- Replace the steel absorber by Glass
- Barrel HCAL
 - 16 sectors, supported by steel framework
 - Each layer composed of GS cells ($\sim 4 \times 4 \times 4 \text{ cm}^3$), ESR, PCB and steel covers
 - A total of $\sim 5\lambda$



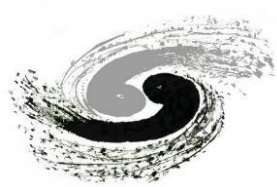
Barrel part of GS-HCAL in AGORA



sampling structure (30% sampling fraction)



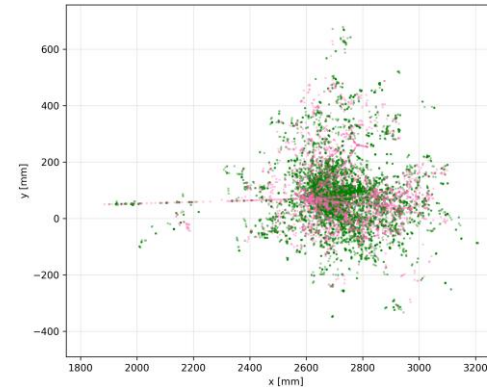
Homogeneous structure



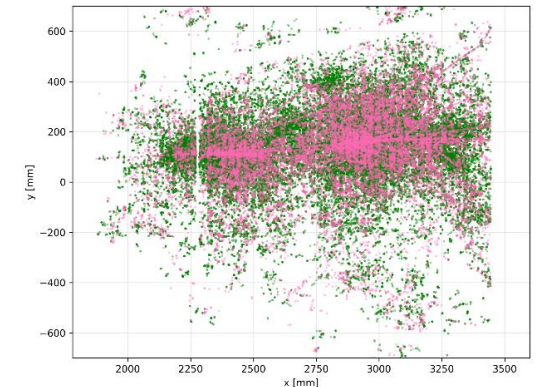
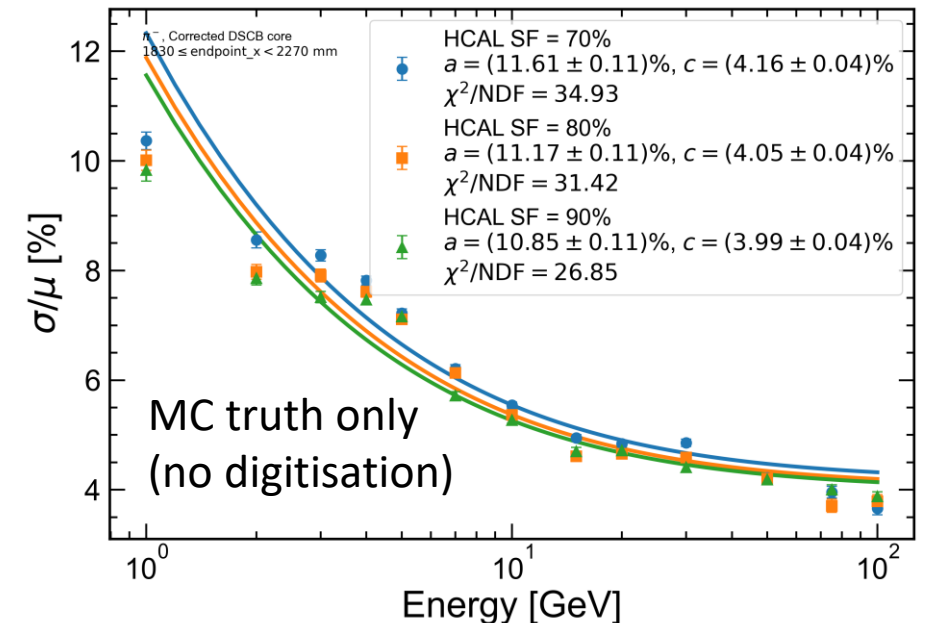
HCAL: Performance from Simulation

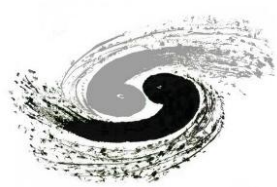
- Simulation configuration
 - Geometry: ECAL + HCAL with glass cubes
 - Three HCAL sampling fractions: 70%, 80%, 90%
 - Particles: single charged pions in 1 – 100 GeV
- Preliminary results
 - Hadronic energy resolution is $\sim 11\%/\sqrt{E} \oplus 4\%$ (based on MC truth only)
- Ongoing studies
 - Impact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

A single 10 GeV π^-



A single 100 GeV π^-

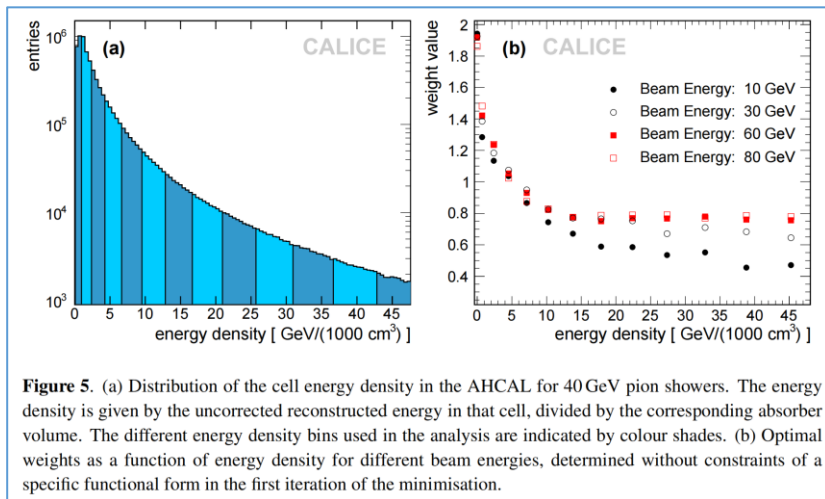




Software Compensation: ongoing studies

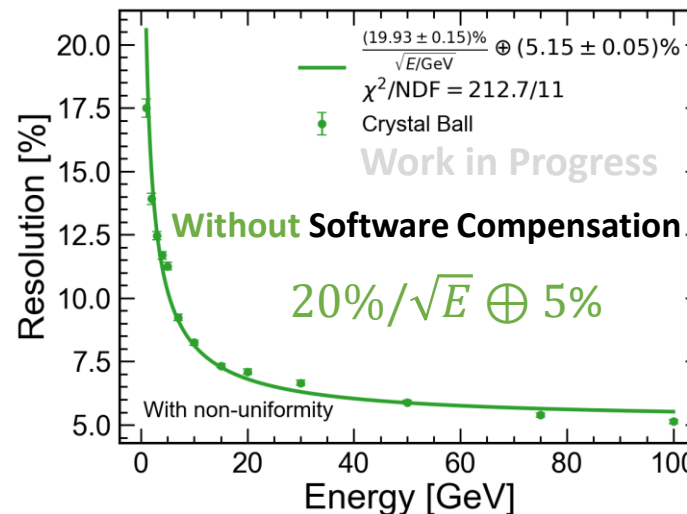
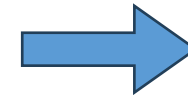
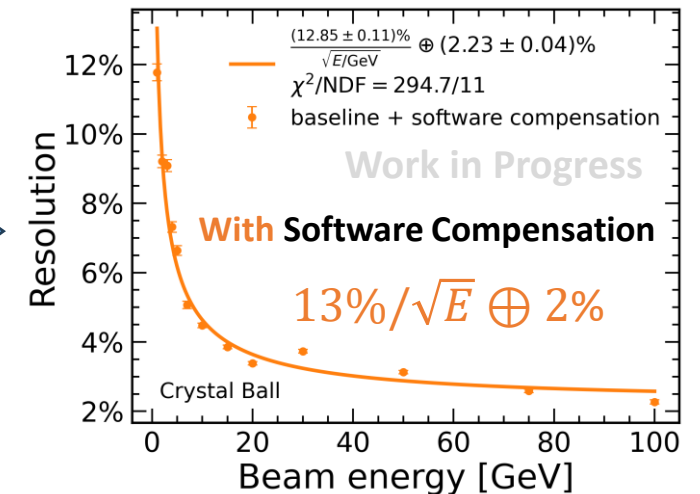
- Software compensation

- To assigns weights based on measured energy density (enabled by high granularity) to calorimeter hits corresponding to EM and purely hadronic components for $e/h \sim 1$

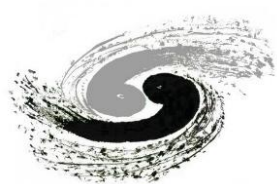


C Adloff *et al* 2012 JINST 7 P09017
Eur. Phys. J. C (2017) 77:698

Software compensation technique applied in many detectors or experiments: WA1/CDHS, H1, ATLAS, CALICE, CMS-HGCAL (different naming in literature)



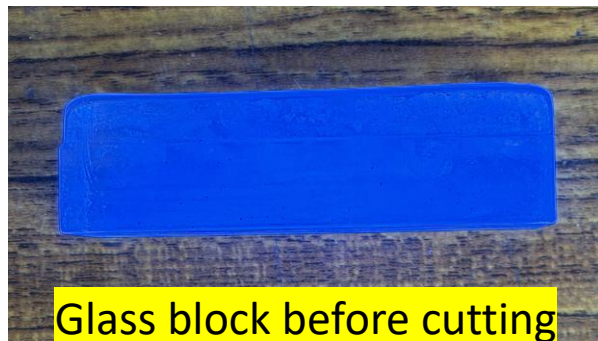
Including digitisation, especially intra-cube non-uniformity of both ECAL and HCAL



Latest status: ScintGlass samples from BGRI (1)

- Glass samples ready at BGRI in late August
- Batch 1: four samples in total
 - $5 \times 5 \times 5 \text{ mm}^3$ cubes ($\times 2$): one with all six sides polished, the other with four
 - $20 \times 20 \times 20 \text{ mm}^3$ cube ($\times 1$); $40 \times 40 \times 20 \text{ mm}^3$ tile ($\times 1$)

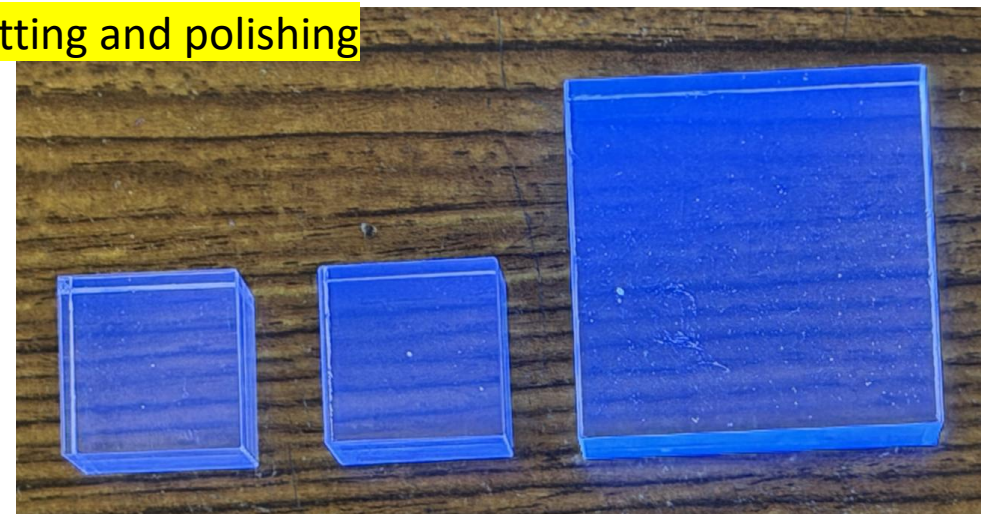
Photos from
Dong Yang (BGRI)



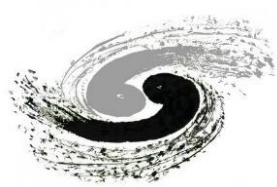
Glass block before cutting



Glass samples after cutting and polishing



All samples were cut from the same large glass block

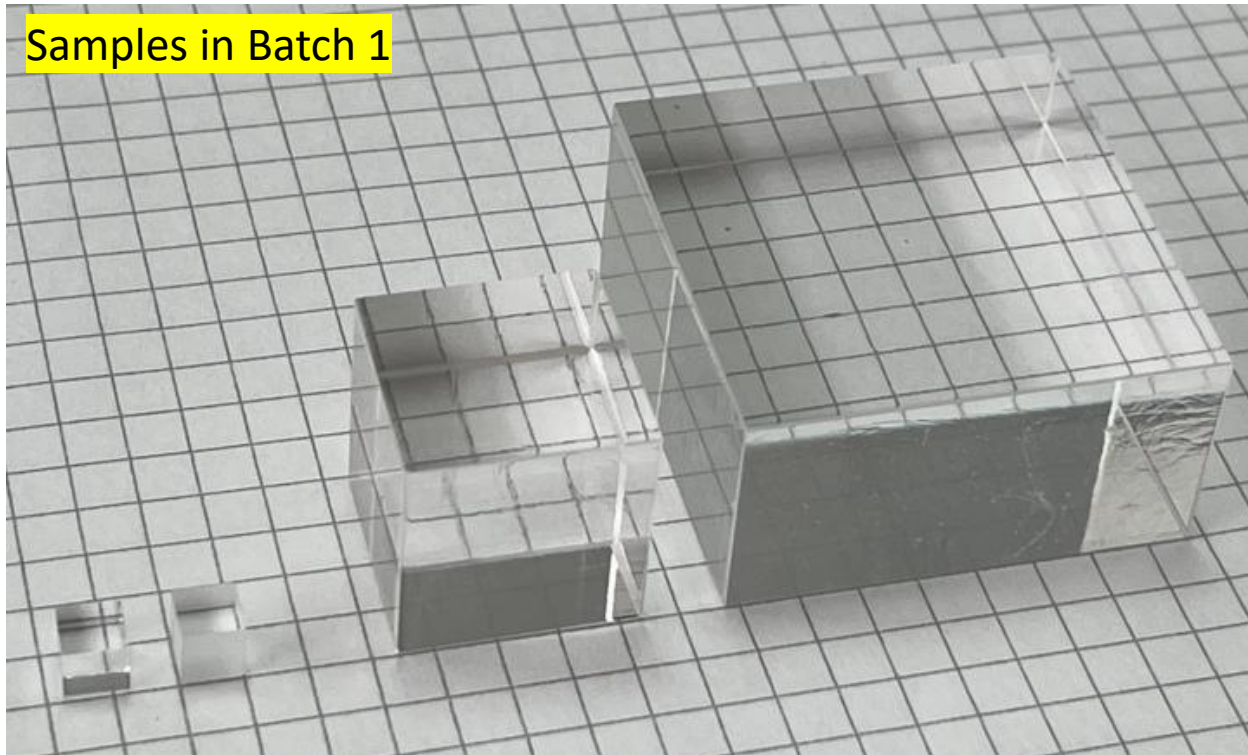


Latest status: ScintGlass samples from BGRI (2)

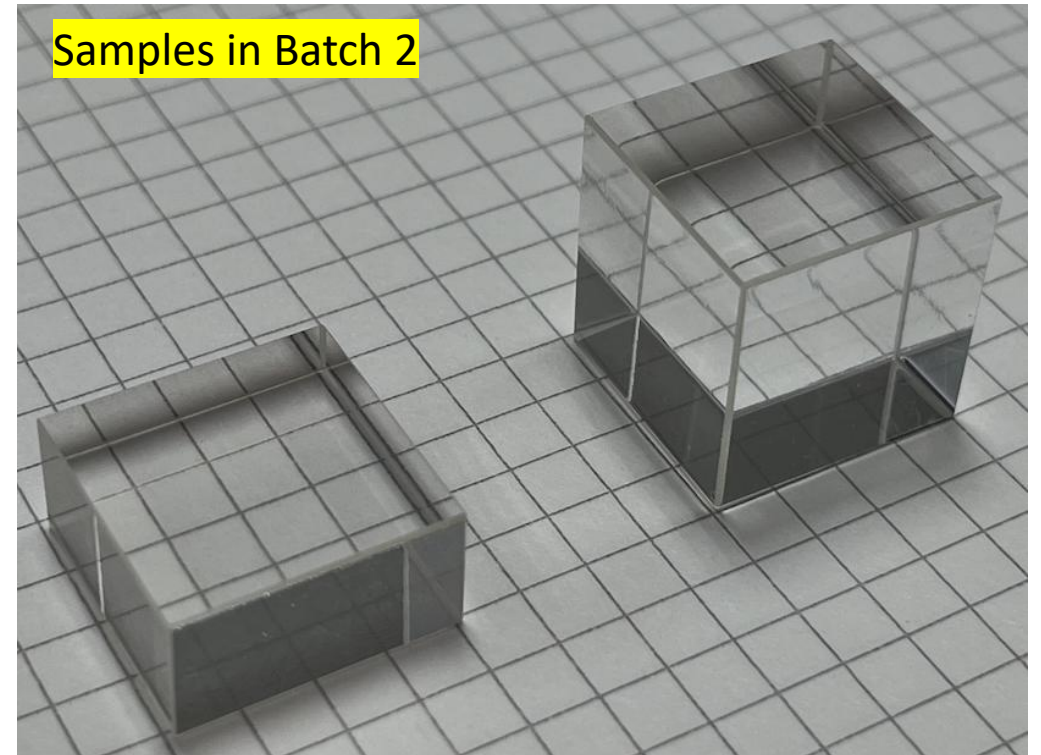
- Batch 1: four samples
- Batch 2: two samples
 - $20 \times 20 \times 10 \text{ mm}^3$ tile ($\times 1$)
 - $20 \times 20 \times 20 \text{ mm}^3$ cube ($\times 1$)

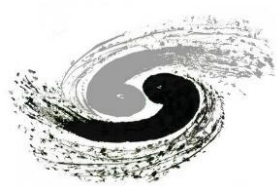
Photos were taken upon receipt at IHEP

Samples in Batch 1



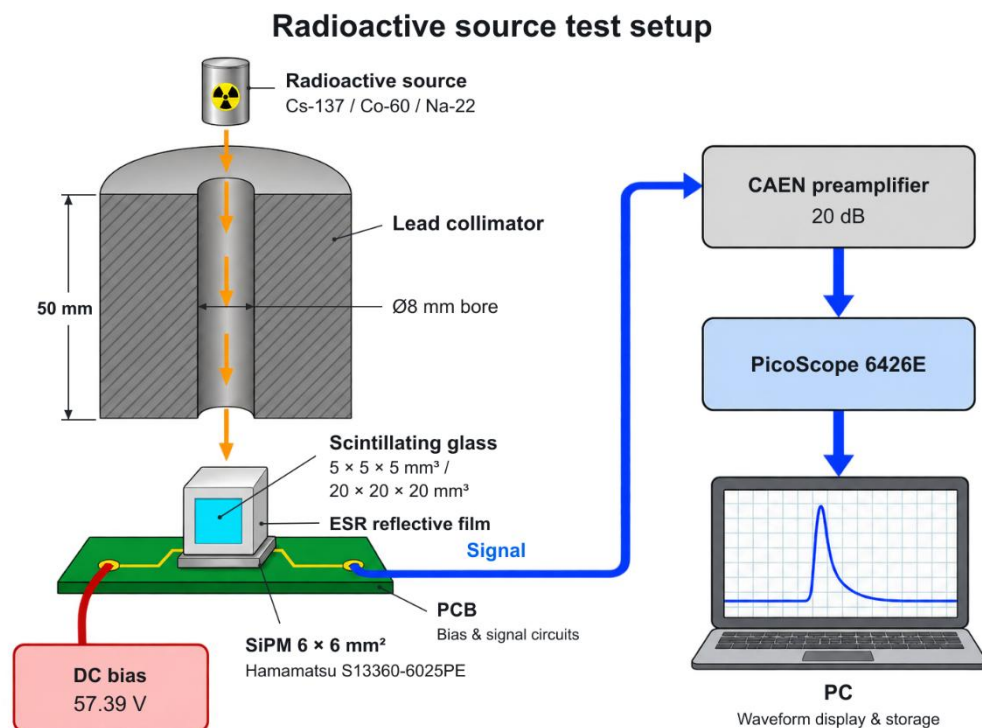
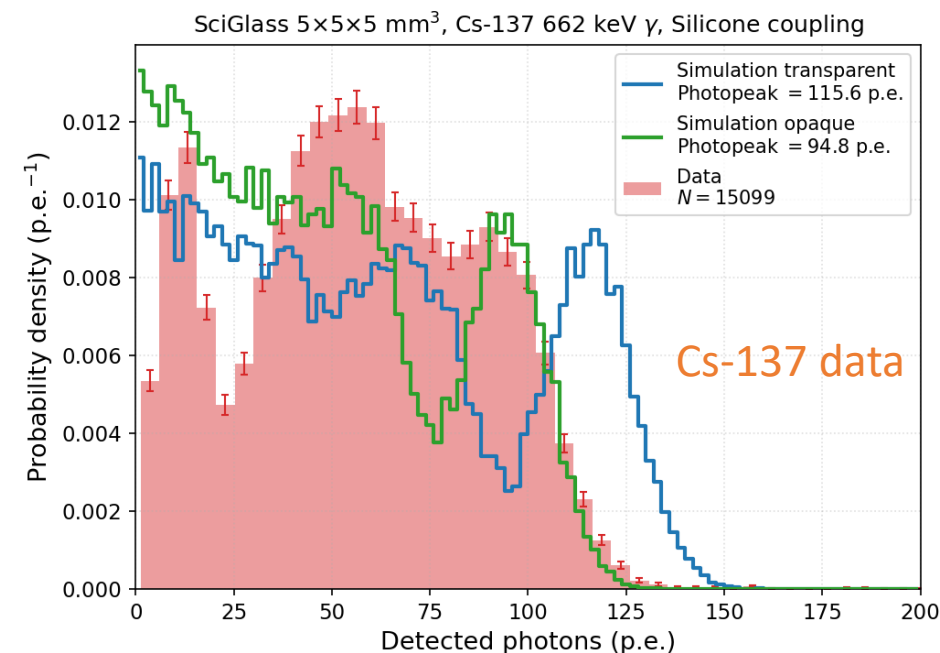
Samples in Batch 2



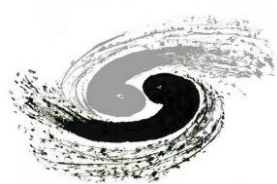


Latest status: testing ScintGlass samples

- Glass samples were extensively tested at IHEP
 - $5 \times 5 \times 5 \text{ mm}^3$ cube: tested with radioactive sources (Na-22, Cs-137, Co-60)
 - $20 \times 20 \times 20$ (10) mm^3 cubes: tested with radioactive sources and cosmic muons



- Source tests could not achieve good S/N at full energy peak
- Geant4 optical simulation provides guidance

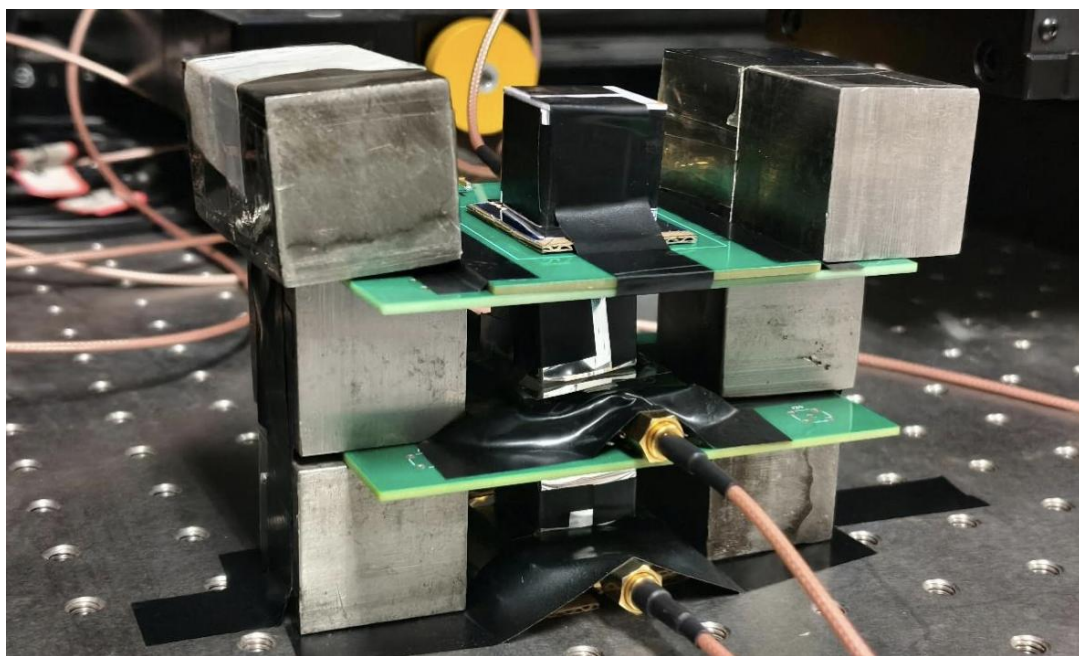
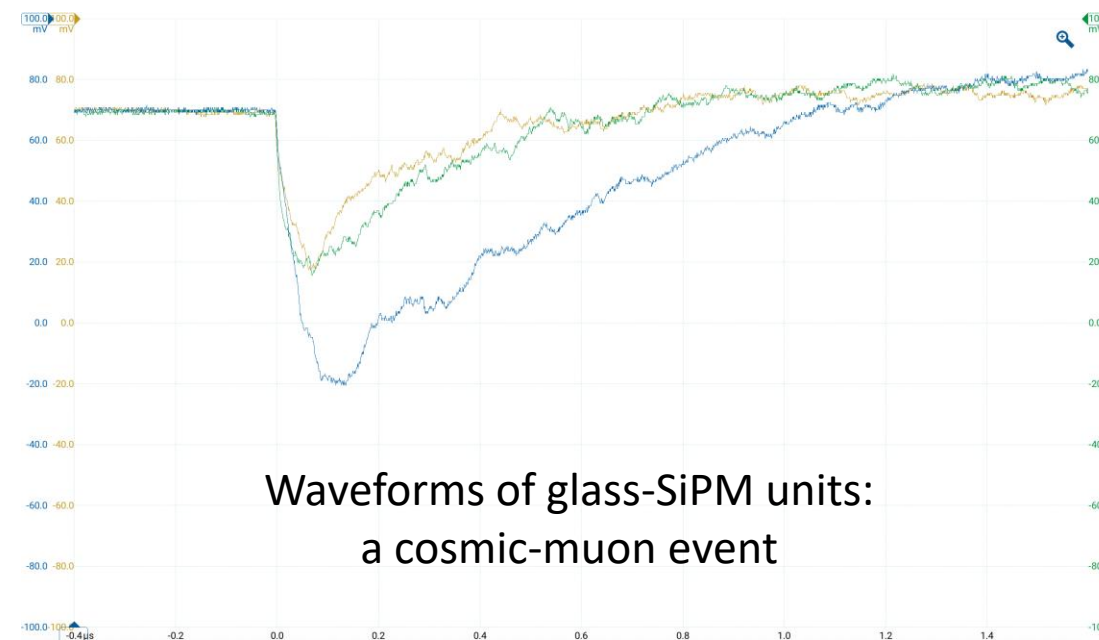


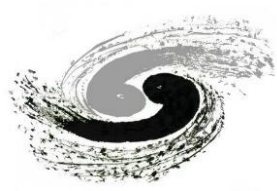
Glass samples: cosmic-ray tests

- Cosmic-ray setup with three glass samples
 - $20 \times 20 \times 20 \text{ mm}^3$ cube (Batch 1, top trigger)
 - $20 \times 20 \times 20 \text{ mm}^3$ cube (Batch 2, DUT)
 - $20 \times 20 \times 10 \text{ mm}^3$ tile (Batch 2, bottom trigger)
- DUT will be swapped with other trigger cubes

Setup configurations

- HPK S13360-6025PE at 57.39V
- ESR foil wrapping
- Glass-SiPM: air-coupling
- Pre-amplifier (20dB) for each SiPM



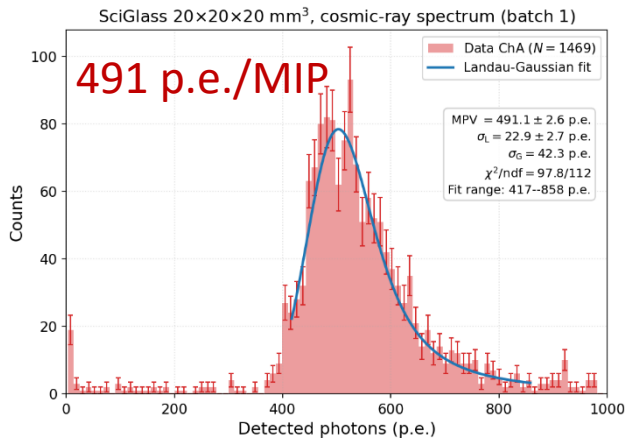


Cosmic-ray test results

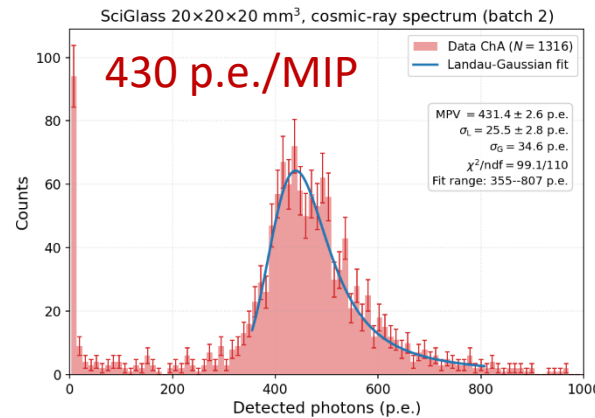
Event Rate: on average 20 events per hour

- Glass samples were extensively tested with cosmic muons
 - Measurement results: 430-490 p.e./MIP for 20mm thick cube, 230 p.e./MIP for 10mm thick
 - **Using one 6x6 mm² SiPM**, a factor of two less for two 3x3 mm² SiPMs (to be validated by more tests)
 - Very promising to meet the ECAL requirement
 - Also indication that the attenuation length is much longer than 6 cm

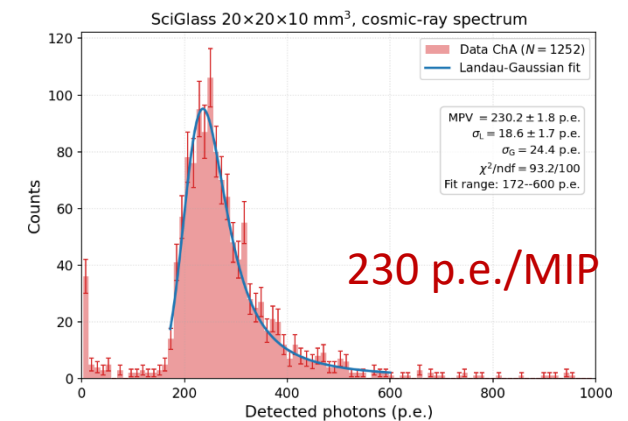
$20 \times 20 \times 20 \text{ mm}^3$ (Batch 1)



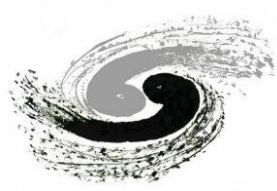
$20 \times 20 \times 20 \text{ mm}^3$ (Batch 2)



$20 \times 20 \times 10 \text{ mm}^3$ (Batch 2)



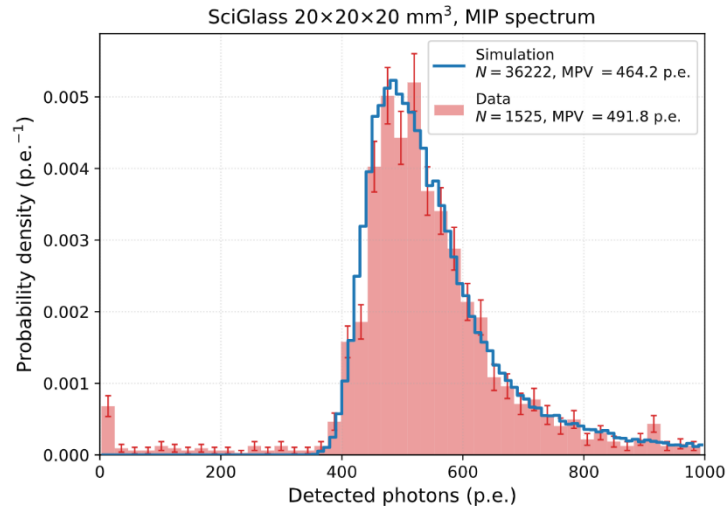
- Trigger data can also be useful
 - MIP response ratio between DUT/trigger for a given sample is 1.6 – 1.7 (due to acceptance)
 - Testing three samples simultaneously: promising to save time in future



Geant4 optical simulation

Adapted version of the G4 model
validated by 2023 DESY beamtest

- Optical simulation for glass
 - Aims: better understanding of glass properties, detector unit design/optimisation
 - (Key) Inputs: *intrinsic light yield*, *bulk attenuation length*



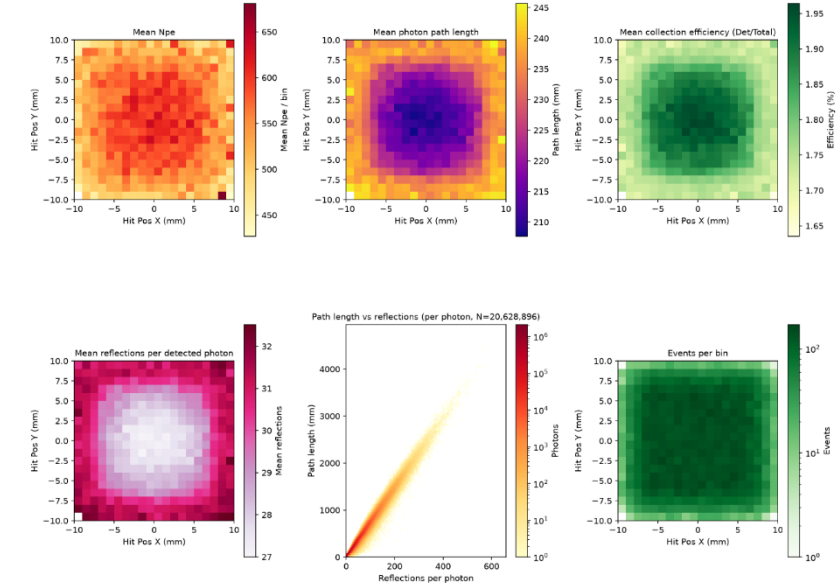
G4 optical simulation setting:

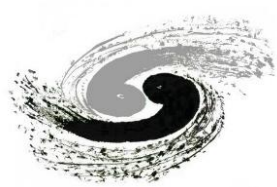
- Light yield = 1500 ph/MeV,
- Bulk attenuation length ~ 20 cm

(Ongoing validation with more tests)

- Ongoing studies to further improve uniformity
 - Light collection efficiency (LCE)
 - #(reflections) and light path lengths: comparison of reflectors and surface roughness

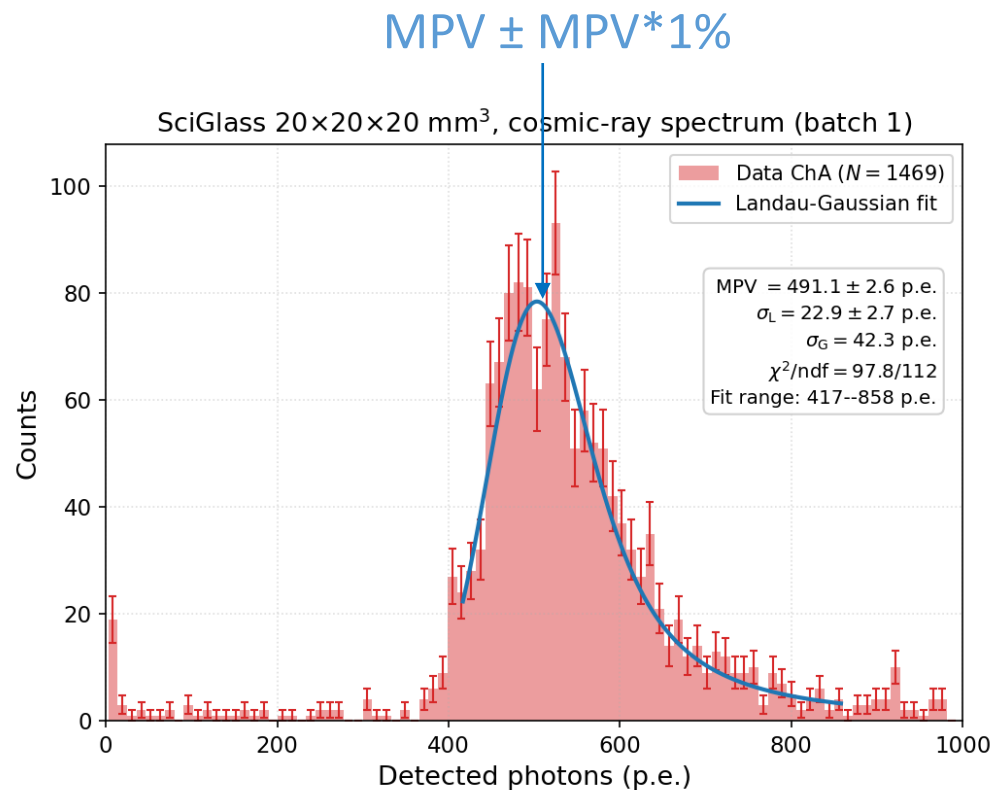
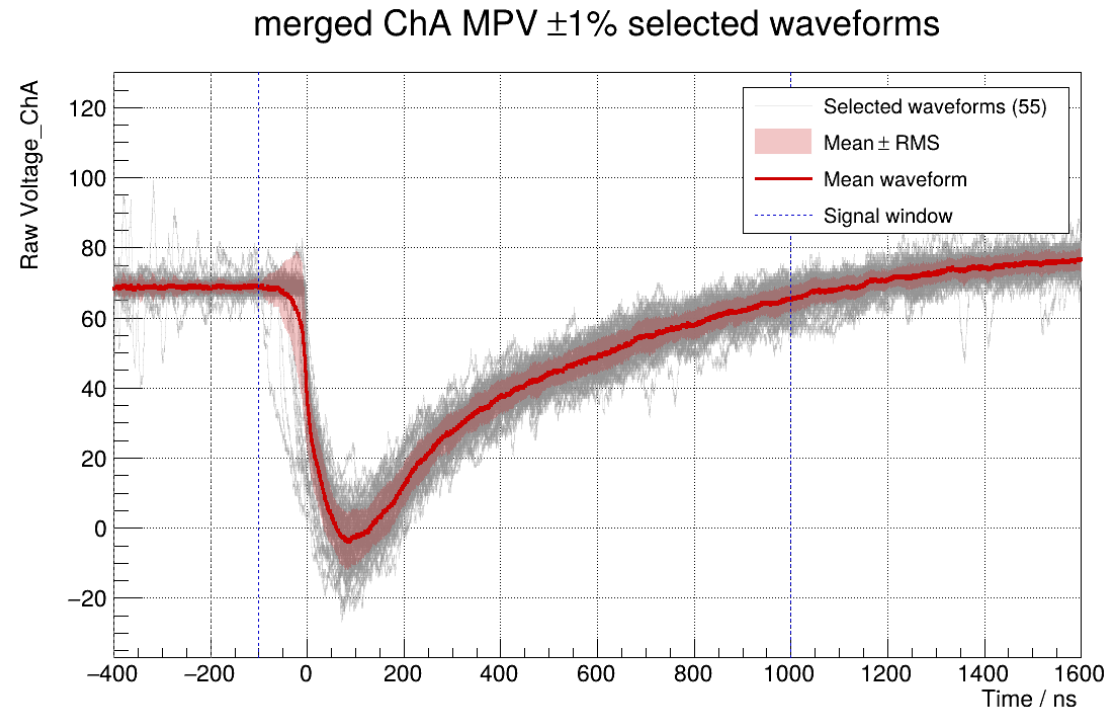
SciGlass 20×20×20 mm³ | MIP (μ^- 4 GeV) | Air coupling (Mid, $\alpha=0.75$) | Trigger coincidence (0° - 30°)
Events with Edep > 0: 36,222 — 1×1 mm² grid

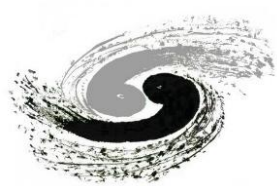




Typical waveform for 1-MIP signals

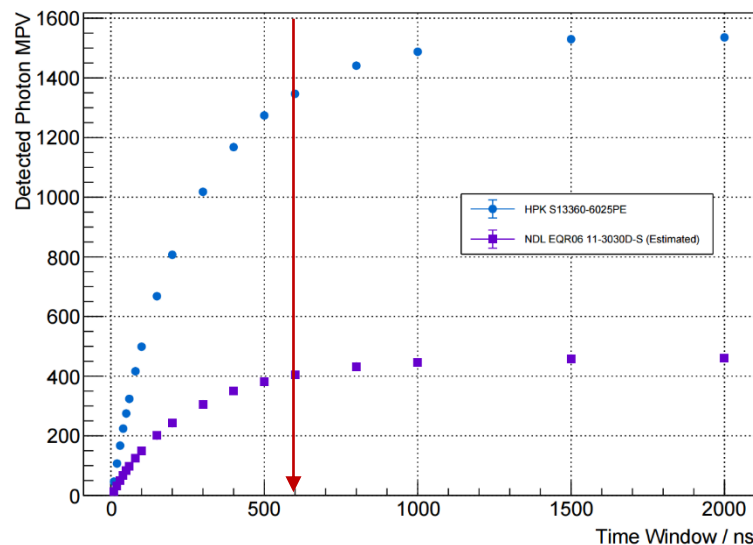
- Typical MIP signals of SiPM-glass as DUT (in the cosmic setup centre)
 - Averaged waveform in the energy range of MPV (Most Probable Value) $\pm$ MPV*1%
 - Input to readout electronics and signal integration time



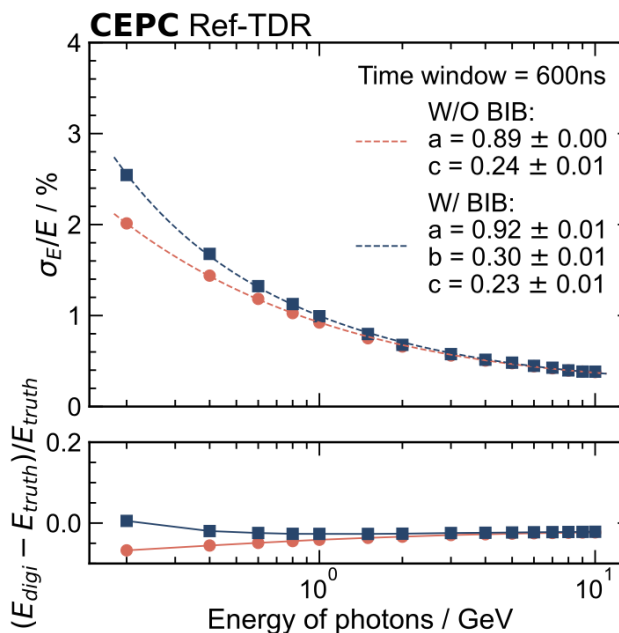


Effective light output: BGO crystal ECAL (reminder)

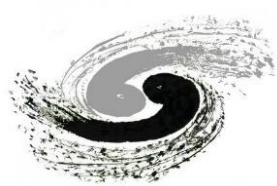
BGO-SiPM Response vs Gated Time



Beam-induced backgrounds in ECAL



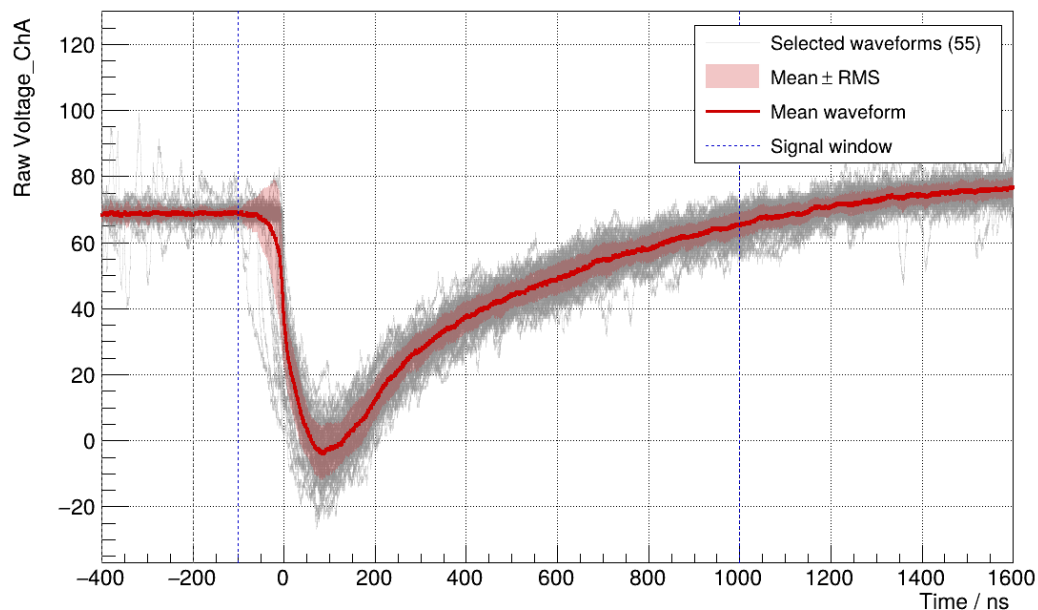
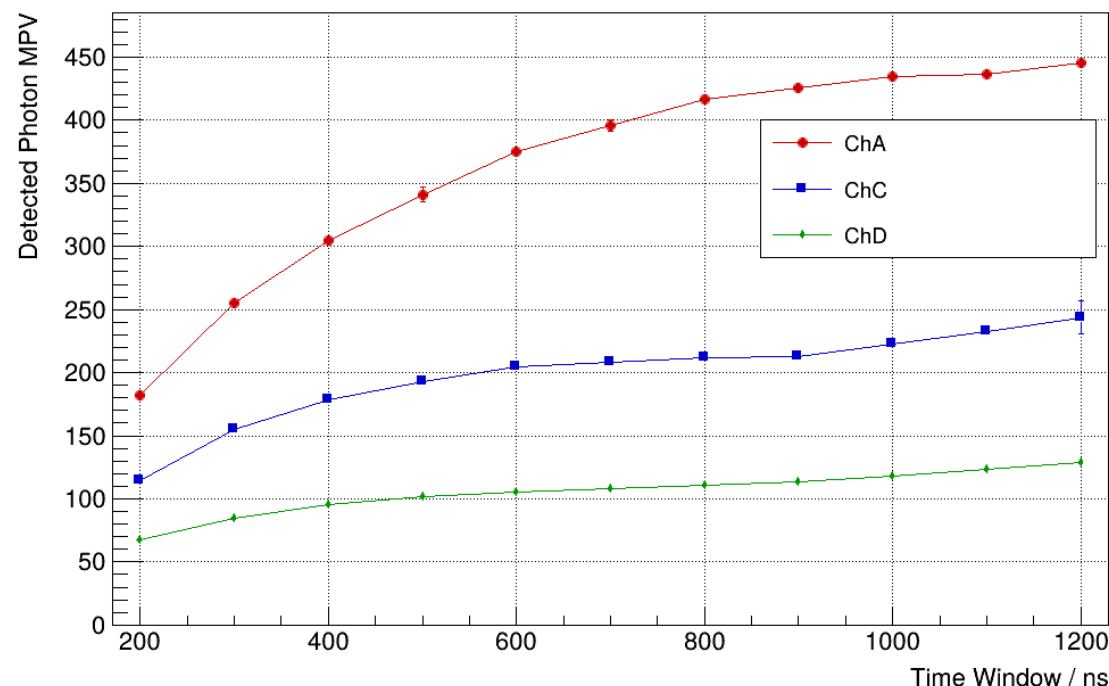
- **Intrinsic light yield of scintillating glass**
 - Using a time window that is as long as possible
- **Collision environment at CEPC/FCC-ee:** beam-induced backgrounds
 - The calorimeter signal time window cannot be too long → effective light output
 - For CEPC crystal ECAL with a time window ≤ 600 ns, the energy resolution will not be significantly affected
- **Proposal:** define the effective light output of scintillating glass within a specified time range

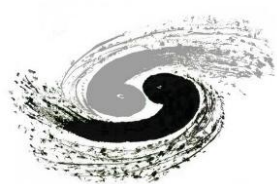


Effective light output: Glass-SiPM unit

- Based on the latest cosmic-ray data
 - Varying gated time window for signal integration: in p.e./MIP with single photon calibration
 - Will choose an appropriated time window: S/N ratio, beam backgrounds

merged ChA MPV $\pm 1\%$ selected waveforms





ScintGlass calorimeter prototypes: timeline

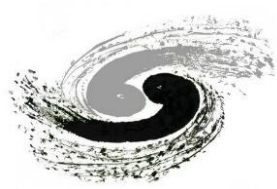
ScintGlass ECAL



- Address critical issues
- ScintGlass samples
- Simulation
- Detector specifications
- Mechanics + cooling
- Prototype design



ScintGlass HCAL



ScintGlass calorimeter prototypes: scale

- 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: $\sim 50 \text{ kg}$

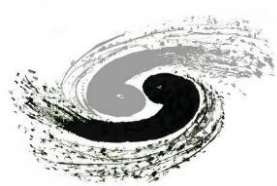


Component	Quantity (Unit)
Glass Cubes	1,024 (pcs)
SiPMs	2,048 (pcs)
Electronics	1,024 (channels)

- HCAL prototype

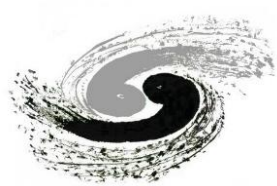
- Transverse area: $72 \times 72 \text{ cm}^2$
- Longitudinal depth $\sim 5\lambda_I$ (1.0-1.2m)
- Longitudinal 40 layers
- Glass tiles (transverse): $4 \times 4 \text{ cm}^2$
- 1 SiPM per glass tile

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



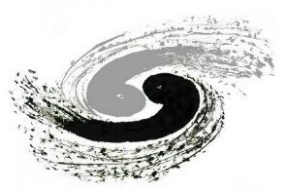
Considerations on Beam-induced backgrounds

- ScintGlass ECAL
 - Finer granularity leads to lower levels of BIB rates, TID and NIEL **per channel**
 - With **a factor of ~10** more channels
 - Assuming ScintGlass ECAL granularity is $2 \times 2 \times 2 \text{ cm}^3$
 - AGORA Crystal ECAL granularity is $1.5 \times 1.5 \times \sim 40 \text{ cm}^3$
- Beam-induced backgrounds
 - (To first order) Expect **~10 times lower** occupancy/TID/NIEL **per channel** on average
 - This would imply ScintGlass ECAL is promising to cope with the High-Lumi Z mode?
 - High-Lumi Z mode: **a factor of ~10** higher luminosity than Low-Lumi Z in *CEPC Ref-TDR*
 - (Hereby not considering radiation damages in glass/SiPM)
- Considerations on future planning
 - Quantitative evaluation of BIB at High-Lumi Z
 - BIB simulation samples $\rightarrow$ new geometry of ScintGlass ECAL in CEPCSW

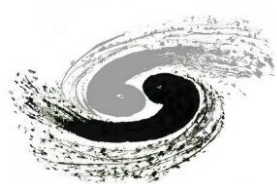


Summary and prospects

- A new design: integrated ECAL and HCAL based scintillating glass
 - Featuring best in both worlds: maximum sampling fraction, high granularity
- Steady progress made: extensive studies
 - Simulation on ECAL and HCAL: key parameters and design specifications
 - Measurements with latest glass samples, guided by Geant4 optical simulation
- Preliminary conclusions
 - **Using one 6×6 mm² SiPM**: achieved over 400 p.e./MIP with cosmic muons
 - Attenuation length appears much larger than 6 cm
 - Promising to meet the ECAL requirement on photon statistics
- Prospects
 - Final design aims to use **one 3×3 mm² SiPM** for readout
 - Continued on the planned activities to optimise detector design and performance
 - Will further study response uniformity with cosmic muons, but will be limited by low rate
 - Testbeam facility: high-energy beam would be very helpful (much more efficient data taking)



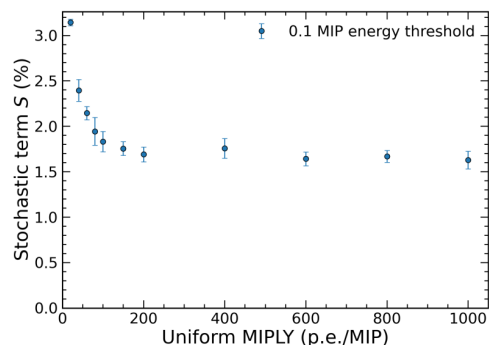
Backup



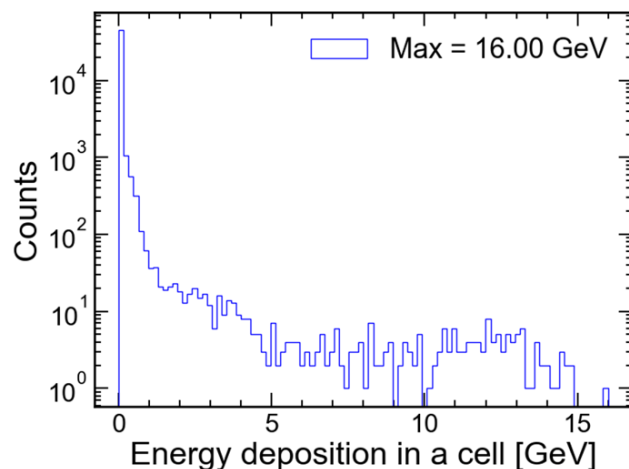
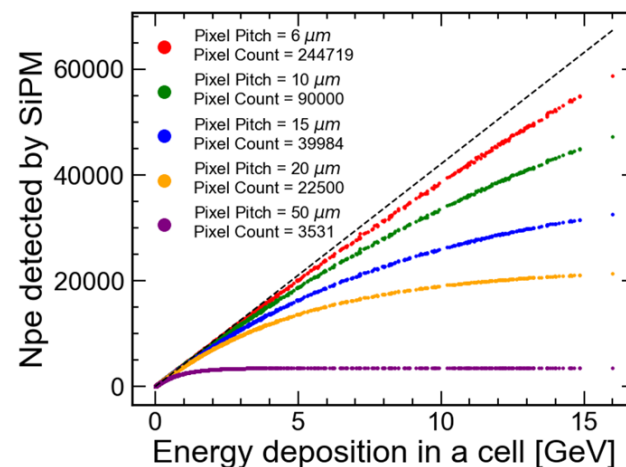
Design specifications: ongoing studies

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

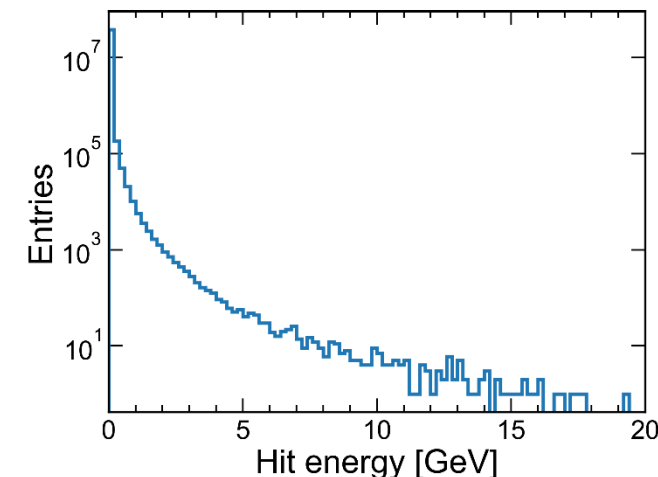
ECAL: EM resolution with varying MIP response

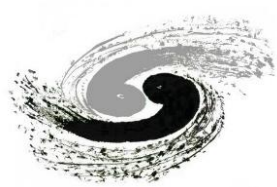


ECAL dynamic range

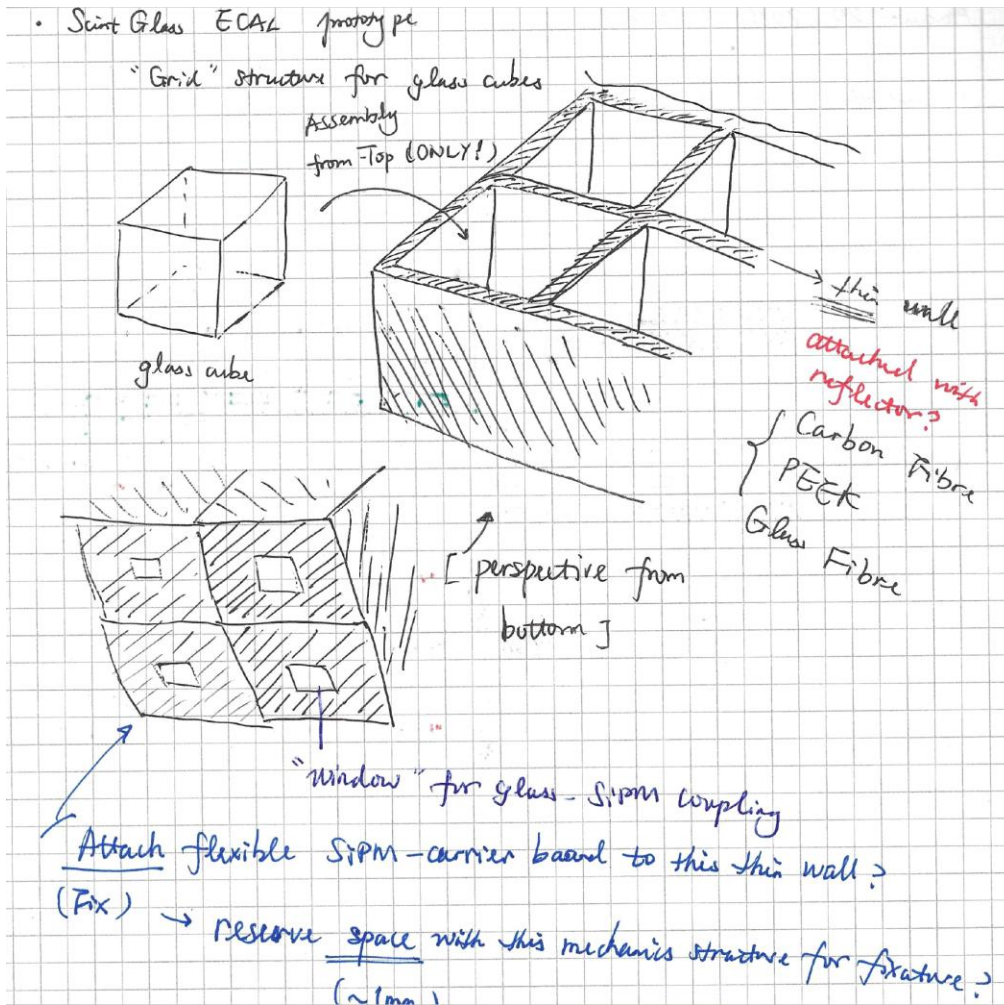


HCAL dynamic range





Considerations on ScintGlass ECAL design/prototyping



- Grid structure for glass cube arrays
 - Options: Carbon-Fibre, Glass-Fibre, PEEK, etc.
 - **Material selection**: *mechanical strength/stability (FEA)* vs. *cost-effectiveness (market survey)*
- Reflector for glass cubes
 - Options: (1) individual wrapping, (2) attach reflector to grid structure (facilitating mass assembly)
 - Considerations: (1) *assembly feasibility, efficiency, reliability*; (2) *light collection efficiency, uniformity*
- SiPM carrier board
 - Options: (1) normal PCB as in HGCCAL prototype, (2) flexible PCB
 - Considerations: (1) *Material budget and its impact/requirement*, (2) *cost*, (3) *performance*