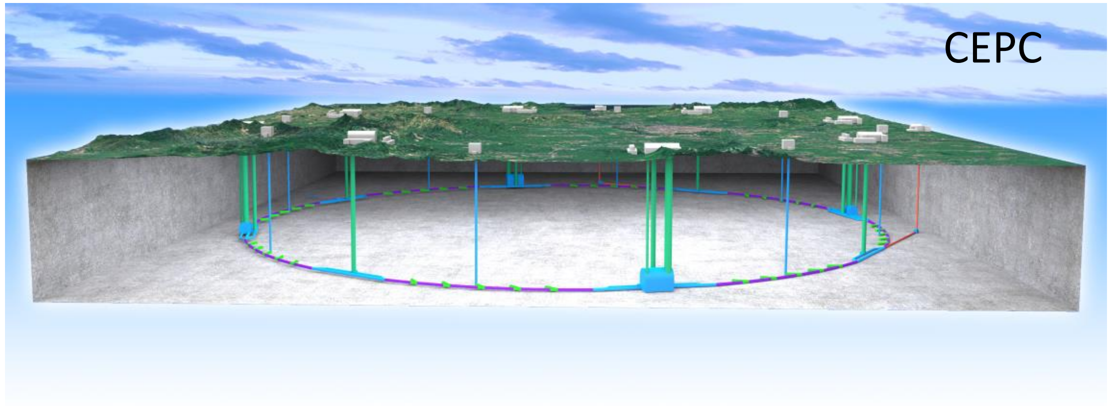
Development of a novel highly granular hadronic calorimeter with scintillating glass tiles

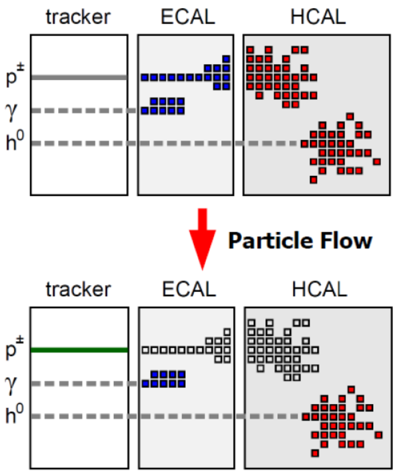
Dejing Du (Institute of High Energy Physics, CAS)
On behalf of CEPC Calorimeter Working Group

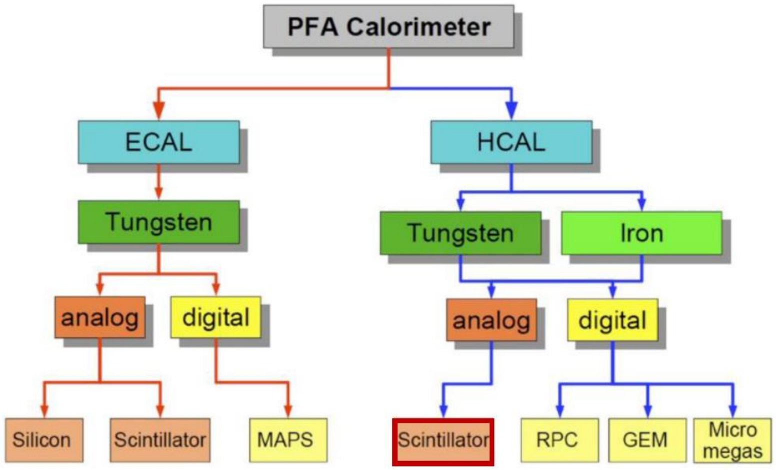
ICHEP 2022 at Bologna
July 8, 2022

Motivations

- Future electron-position colliders (e.g. CEPC)
  - Main physical goal: precision measurements of the Higgs and Z/W bosons
  - Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$
- Particle Flow Algorithm (PFA)
  - Choose sub-detector best suited for each particle type (charged, photons, neutral hadrons)
  - Require good separation power of close-by particles in calorimeters
- High granularity calorimetry for PFA
  - Hardware challenge: readout channels on the order of 1~10 million

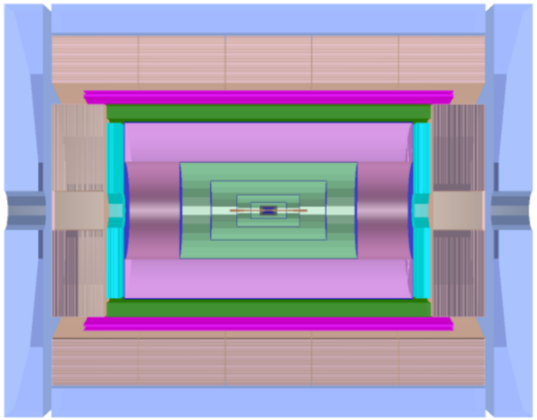






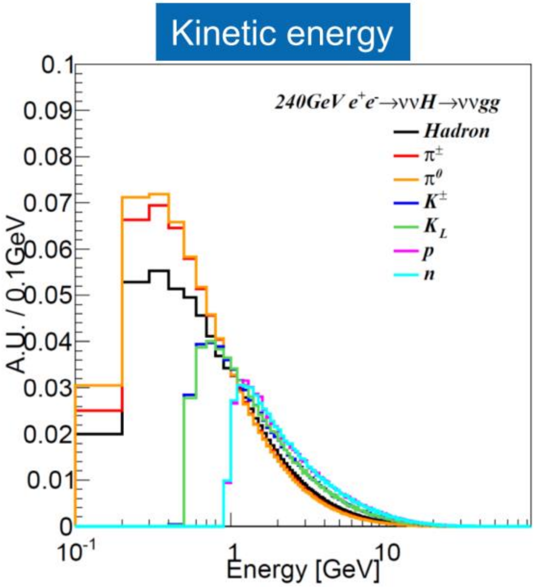
Motivations

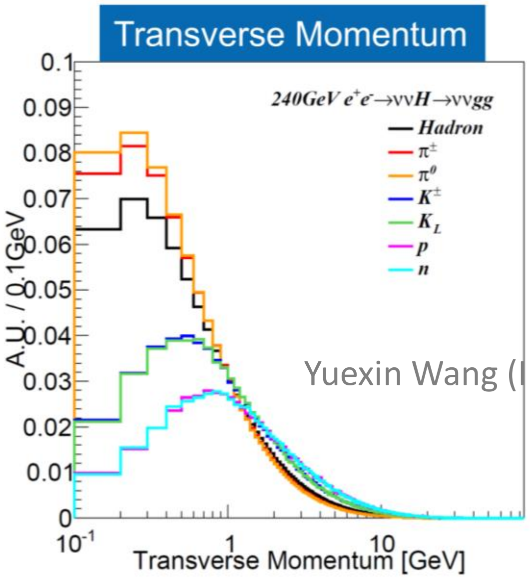
- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- <u>CEPC 4^{th} concept detector</u>: crystal ECAL + scintillating glass HCAL
  - A leap in terms of sampling fractions
  - Aim to improve the energy resolution: esp. the hadronic resolution
  - Physics performance goal: Boson Mass Resolution(BMR) 4%→3%



Calorimeters: crystal ECAL and Scintillating Glass HCAL

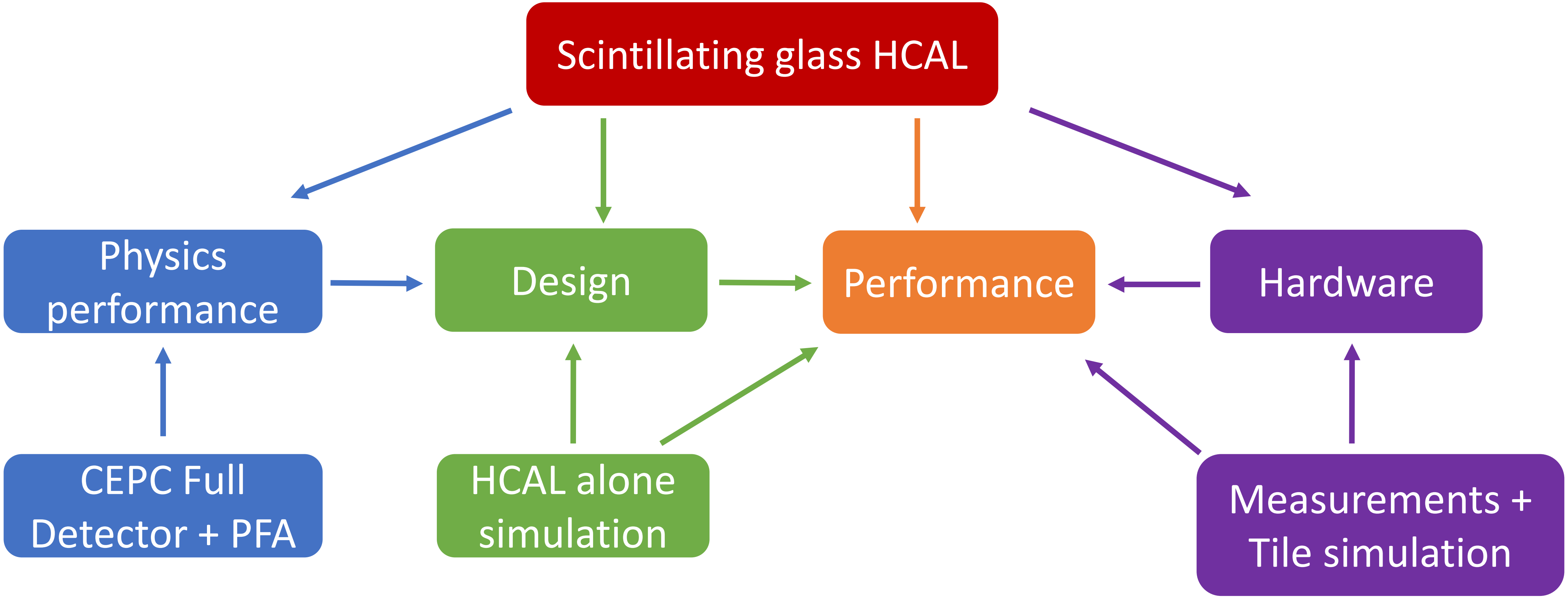
[Report on crystal ECAL]





Yuexin Wang (IHEP)

Outline


Scintillating glass HCAL
Physics performance
Design
Performance
Hardware
CEPC Full Detector + PFA
HCAL alone simulation
Measurements + Tile simulation

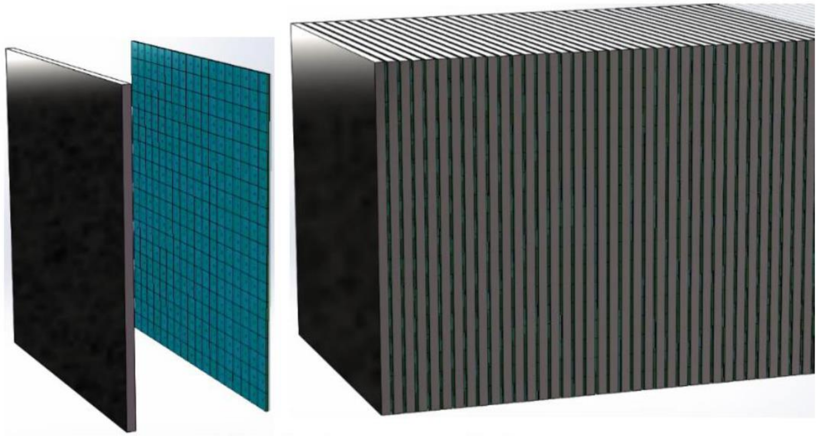
Outline

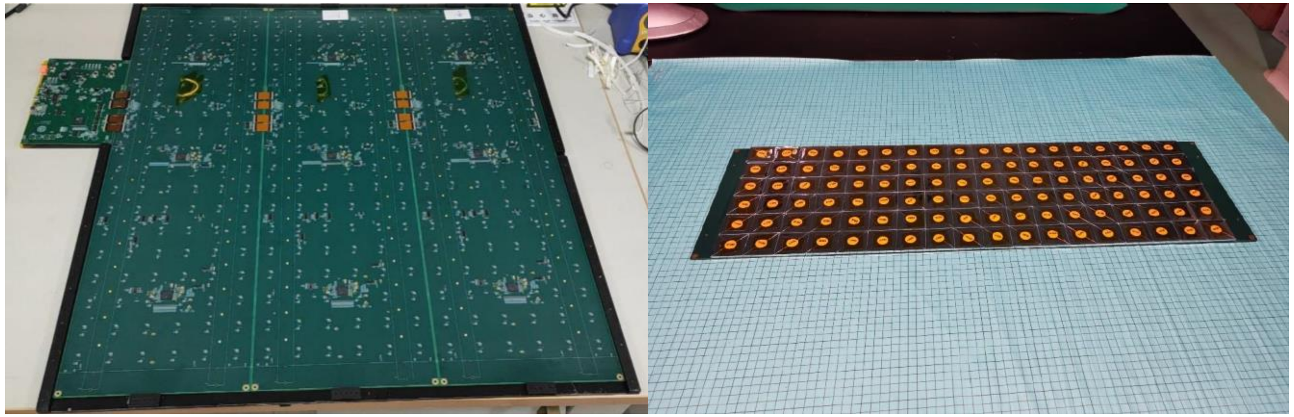
- Performance of scintillating glass HCAL
  - Geant4 simulation with single hadrons
  - Physical performance: BMR
- Scintillating glass material R&D
  - Measurements of scintillating glass samples
- Studies on the performance of HCAL detector unit
  - MIP response: experiment and simulation
  - Requirements on key parameters
- Summary and prospects

Hadronic calorimeter (HCAL) design: reminder

- CEPC CDR baseline: Scintillator-Steel AHCAL
  - 40 sampling layers
    - Plastic scintillator (sensitive): 3 mm thick
    - Steel (absorber): 20 mm thick
  - Tile size: $30 \times 30\ mm^2$
- Scintillating glass HCAL
  - Replace plastic scintillator with scintillating glass
  - Glass tile design: ongoing optimization

CEPC AHCAL prototype schematics



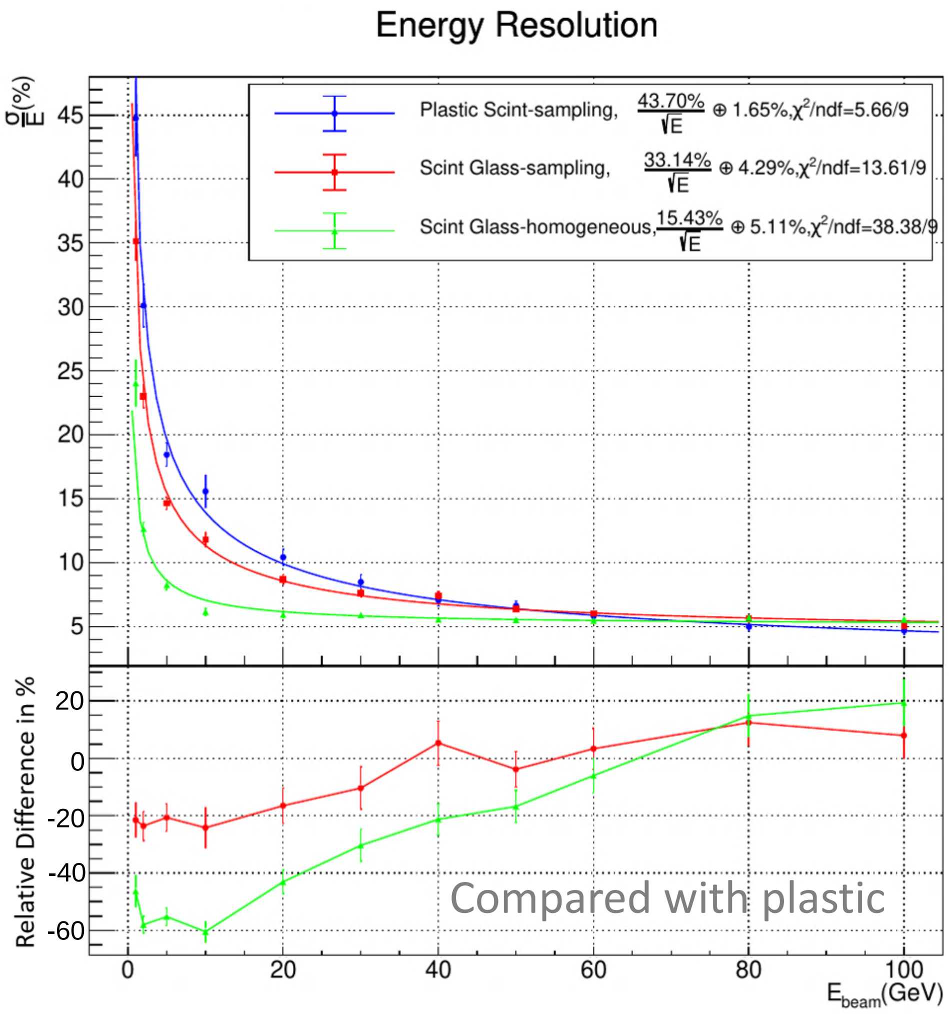


Single layer of CEPC AHCAL prototype

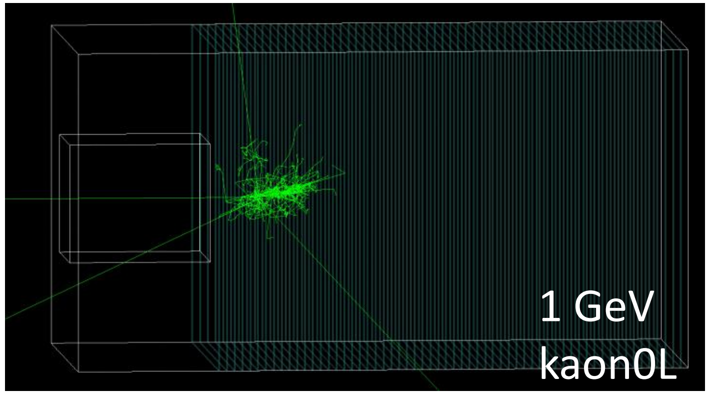
"SiPM-on-Tile" design

Felix Sefkow et al 2019 J. Phys.: Conf. Ser. 1162 012012

Performance of HCAL with scintillating glass



Incident particle: K_L^0 (1-100 GeV)
Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
Density: 4.94 g/cm^3 (goal: $> 6\ g/cm^3$)

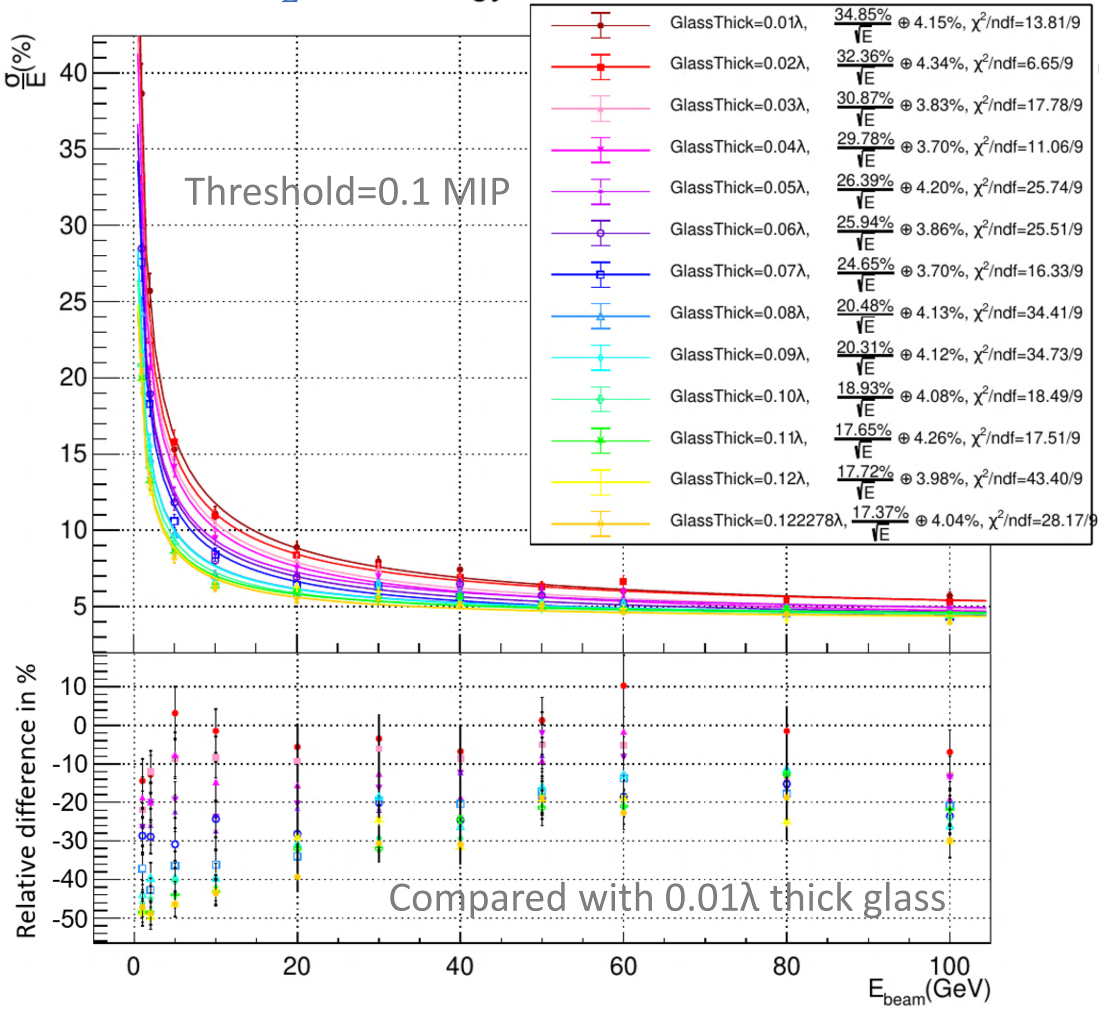


- Performance potentials: comparison
  - Followed by detailed studies (next pages)
- Scintillating glass: better hadronic energy resolution in low energy region (< 30 GeV)
  - Most hadrons at CEPC are with low energy

Impact of thickness to hadronic energy resolution

Incident particle: K_L^0

Energy Resolution



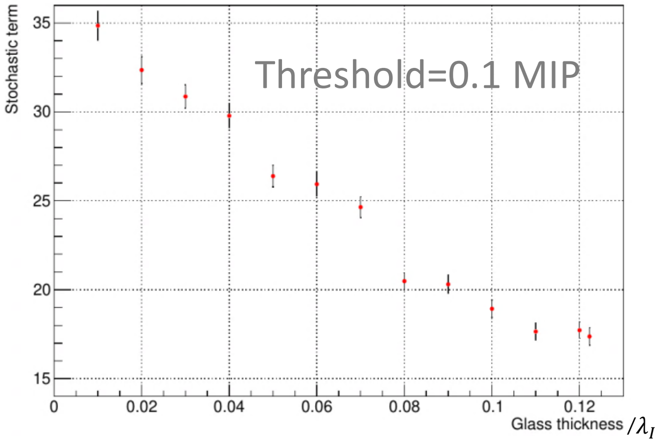
Orange curve corresponds to the homogeneous HCAL

- Varying thickness: glass and steel
  - Each layer fixed with ~$0.12\lambda_I$
  - Total depth ~$4.8\lambda_I$ with 40 layers
  - Nuclear interaction length λ_I
    - Glass $= 22.4\ cm$
    - Steel $= 16.8\ cm$
- Better energy resolution with thicker scintillating glass

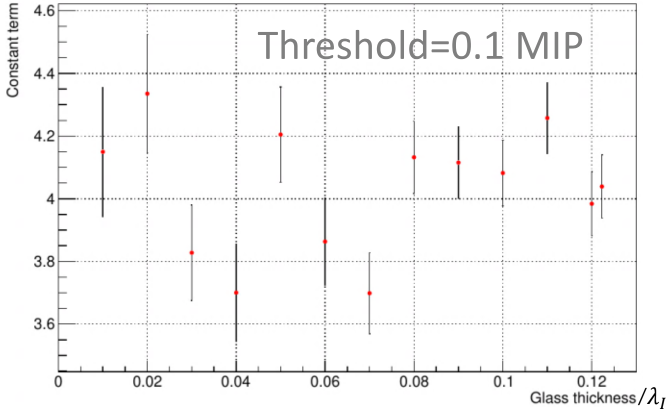
Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
- Extraction of stochastic and constant terms in energy resolution

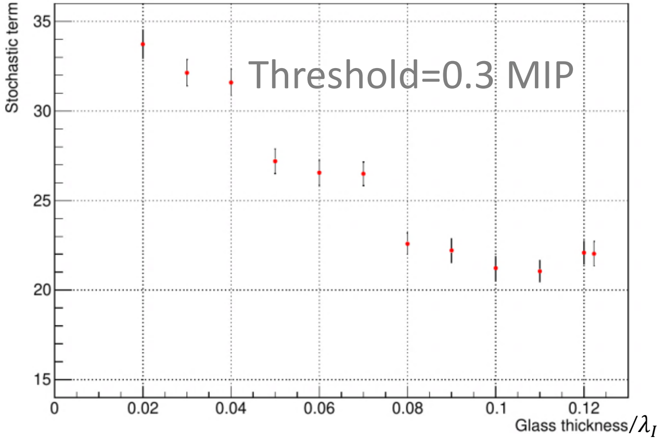
Stochastic term vs. glass thickness



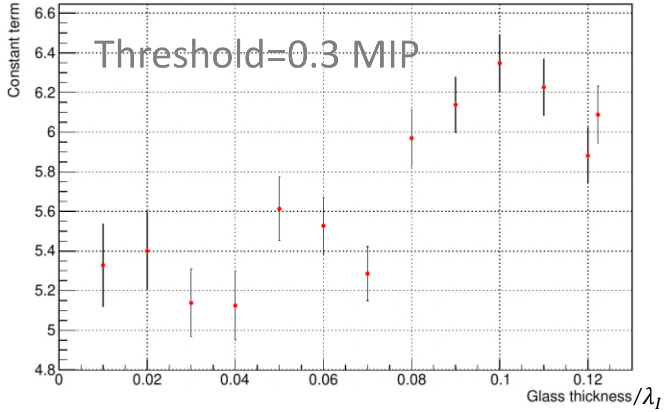
Constant term vs. glass thickness



Stochastic term vs. glass thickness



Constant term vs. glass thickness

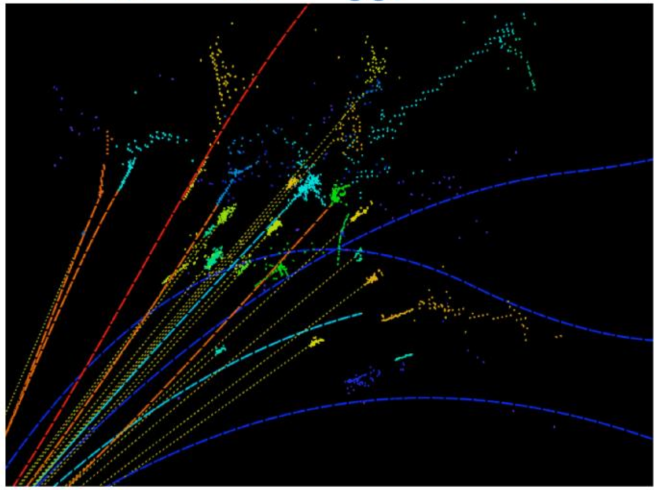


- Energy threshold has a significant impact on the energy resolution
- Resolution will not be improved when glass gets thicker for a given threshold
- Higher threshold significantly degrades the constant term
- Lower threshold would always be desirable for better resolution

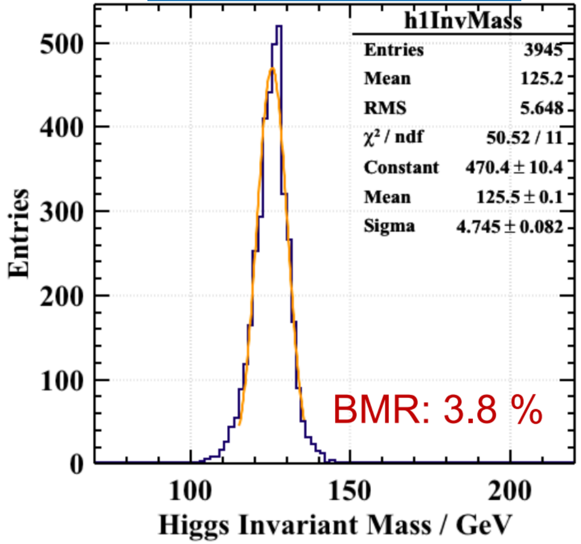
Physical performance: BMR

Dan Yu (IHEP)

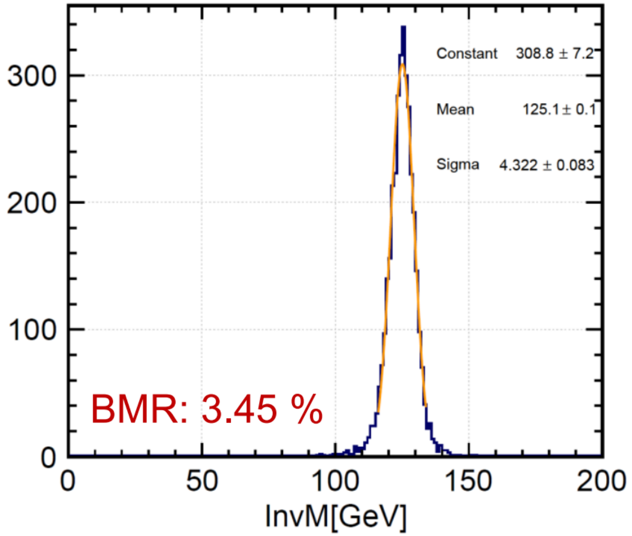
$ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV



CEPC CDR Baseline:
SiW ECAL + DHCAL



SiW ECAL + Homogeneous
Tile-HCAL with ScintGlass

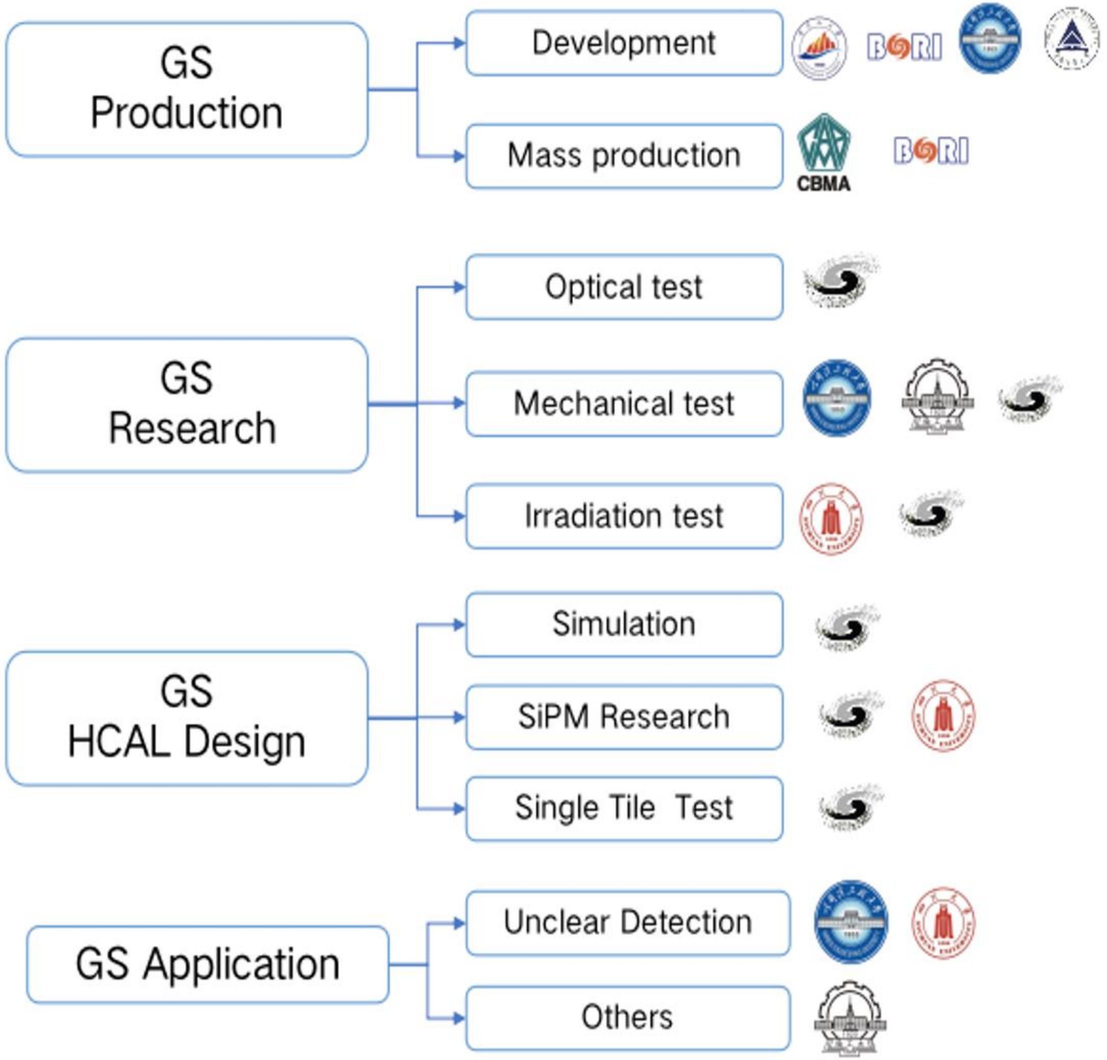


- Ideal homogenous scintillating glass HCAL
  - Preliminary results: ~10% improvement in BMR
  - Expect further improvements: e.g. optimization of PFA

Outline

- Performance of scintillating glass HCAL
  - Geant4 simulation with single hadrons
  - Physical performance: BMR
- Scintillating glass material R&D
  - Measurements of scintillating glass samples
- Studies on the performance of HCAL detector unit
  - MIP response: experiment and simulation
  - Requirements on key parameters
- Summary and prospects

Glass Scintillators R&D Group



中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Jinggangshan University
井冈山大学

Beijing Glass Research Institute
北京玻璃研究院

China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

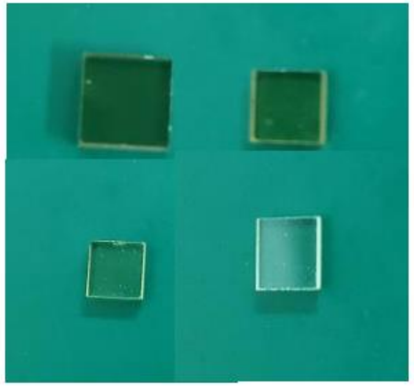
Harbin Engineering University
哈尔滨工程大学

Harbin Institute of Technology
哈尔滨工业大学

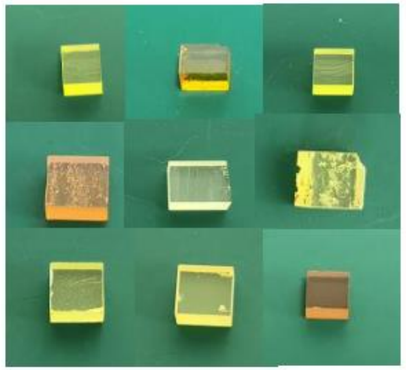
Sichuan University
四川大学

Measurements of scintillating glass samples

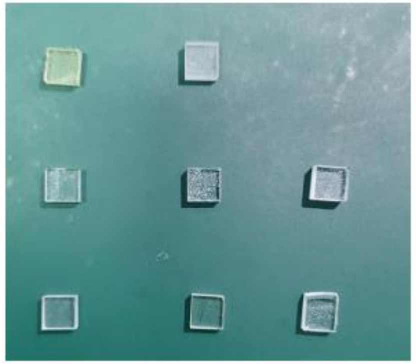
2021.8.12



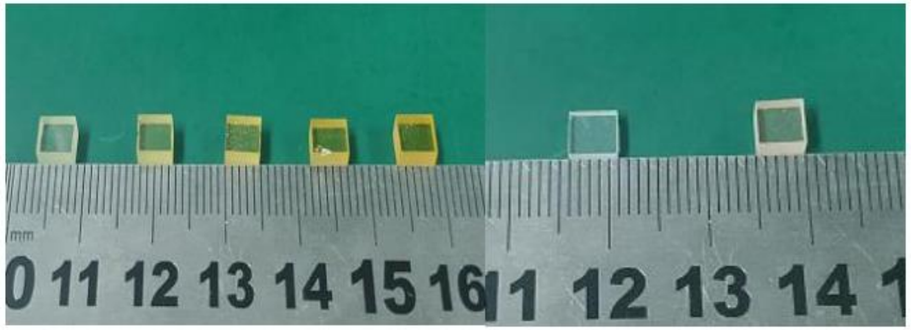
2021.10.11



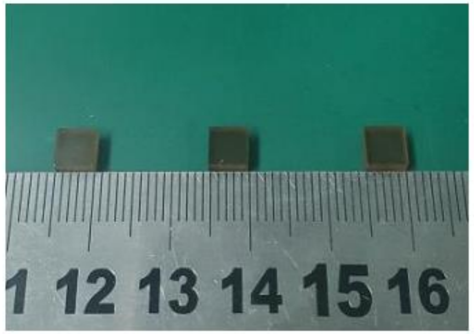
2021.10.31



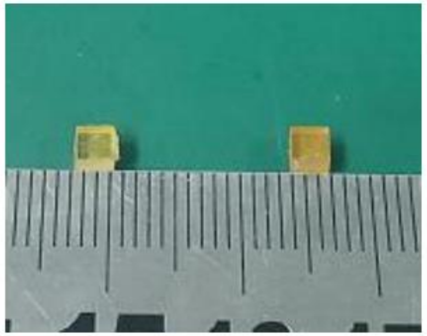
2021.11.8



2021.11.13



2021.11.22



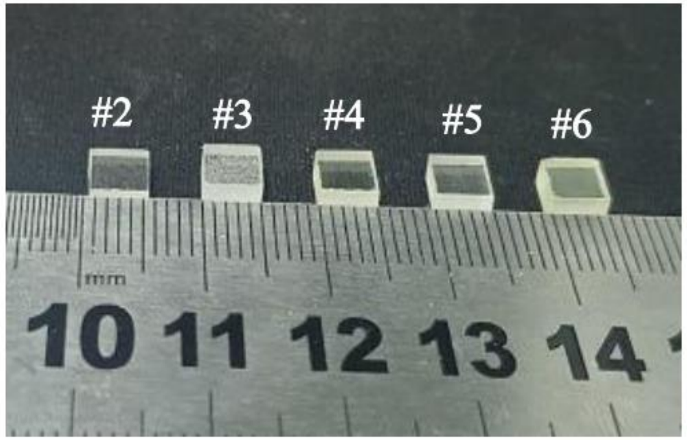
2021.11.23

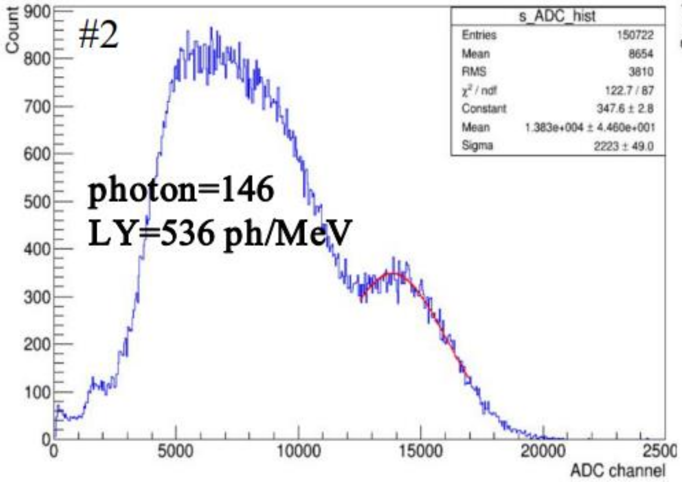
- Comprehensive measurements of key properties
    - Transmission/emission spectra, light yield and decay time
- Over 30 pieces of scintillating glass have been tested, most of which have poor performance
- The best performance glass with the composition: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$

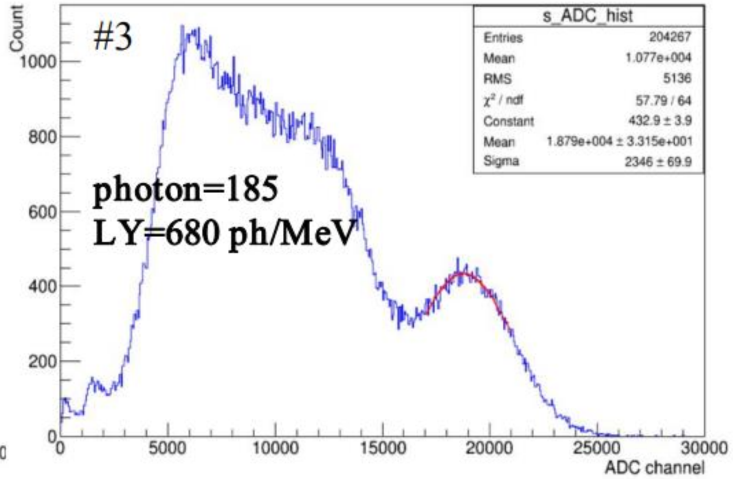
Zhehao Hua (IHEP)

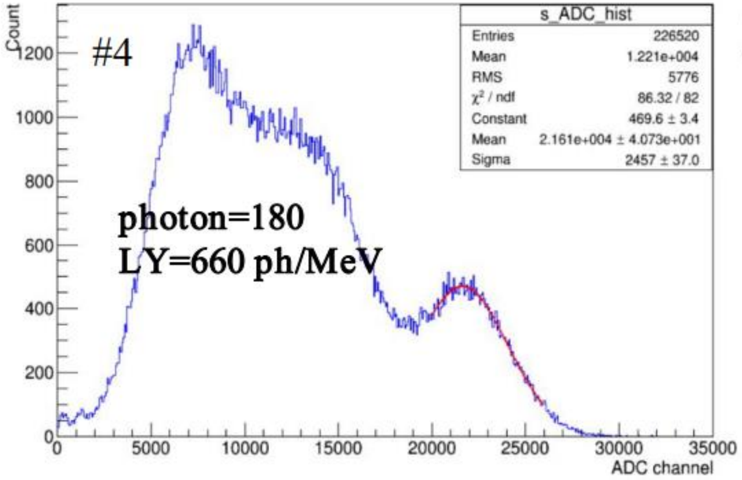
Measurements of light yield

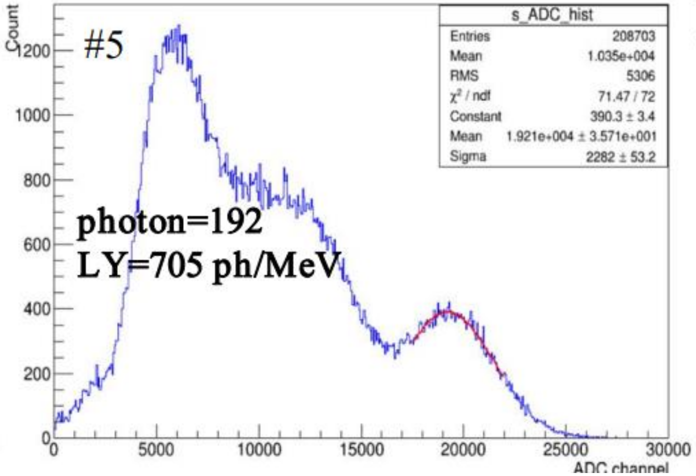
$$LY_s = \frac{Mean_{energy} * 1000\text{keV}}{Mean_s * PDE_w * PCE * Energy}$$

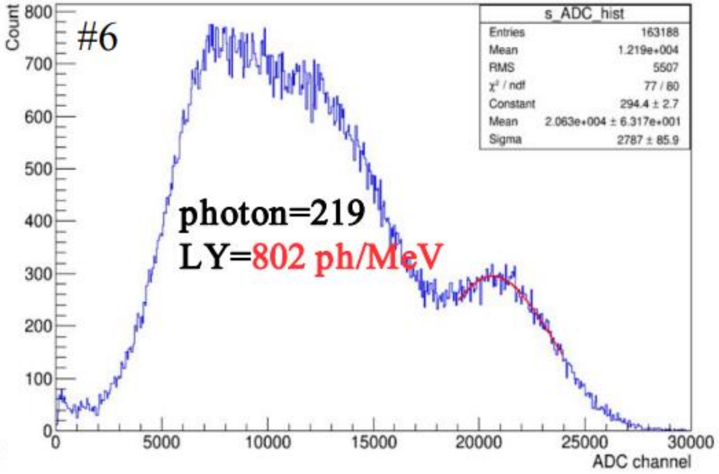












Zhehao Hua (IHEP)

Measurement results of scintillating glass samples

Number	Density (g/cm³)	Transmittance (%)	Light yield (ph/MeV)	Energy Resolution (%)	Decay time (ns)	Emission peak (nm)
#1	~4.5	50	546	30.84	273,1004	394
#2	~4.5	78	536	37.87	334,939	392
#3	~4.5	75	680	29.41	351,1123	393
#4	4.65	74	660	31.82	308,1363	396
#5	**4.94**	64	705	27.97	**354,760**	392
#6	4.53	67	**802**	**26.77**	318,1380	393

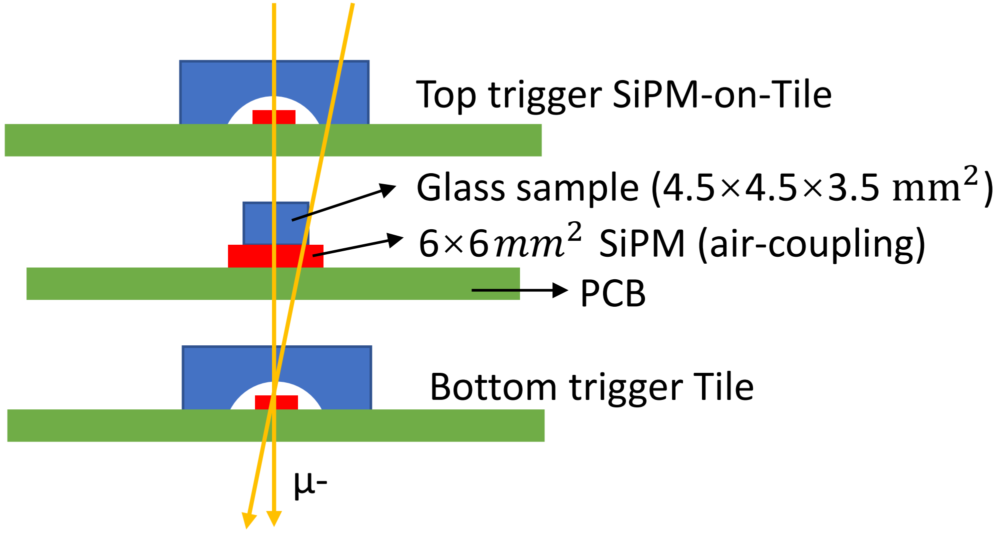
- The light yield of scintillating glass sample reached 800 ph/MeV (until December 2021)
- Latest sample measurement result: light yield reached 1600 ph/MeV, but density < 4 g/cm^3
- Next steps
  - Increase density (6 g/cm^3) while keeping light yield (1000-2000 ph/MeV)
  - Develop cm-scale samples

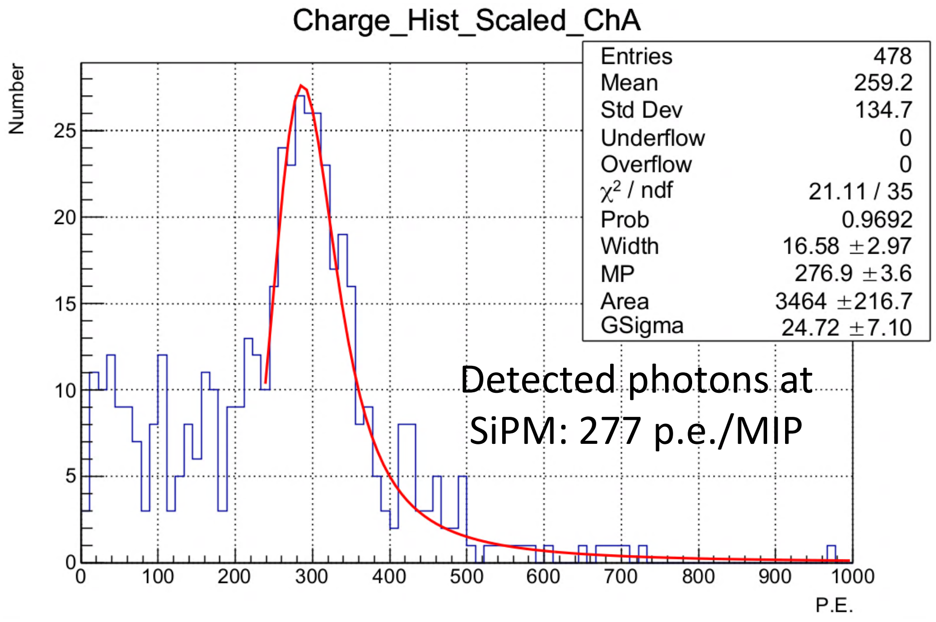
Zhehao Hua (IHEP)

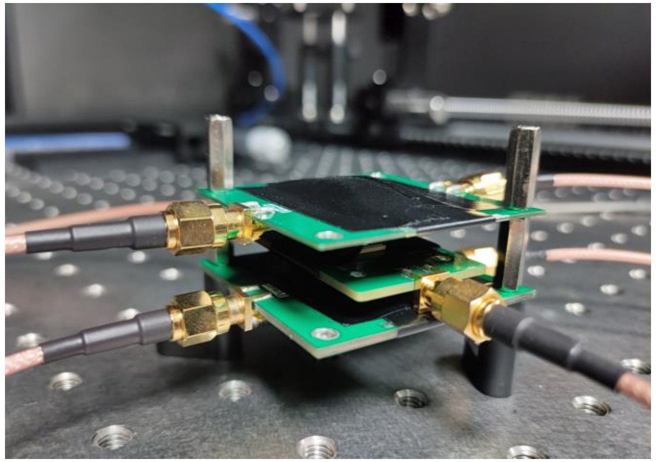
Outline

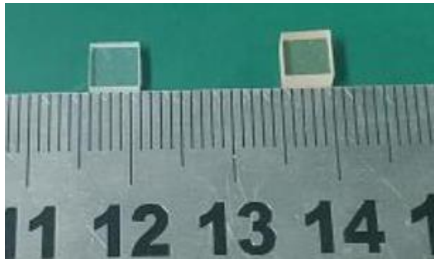
- Performance of scintillating glass HCAL
  - Geant4 simulation with single hadrons
  - Physical performance: BMR
- Scintillating glass material R&D
  - Measurements of scintillating glass samples
- Studies on the performance of HCAL detector unit
  - MIP response: experiment and simulation
  - Requirements on key parameters
- Summary and prospects

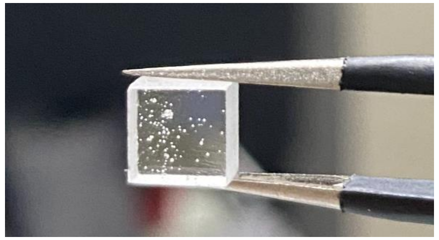
MIP response: cosmic-ray test







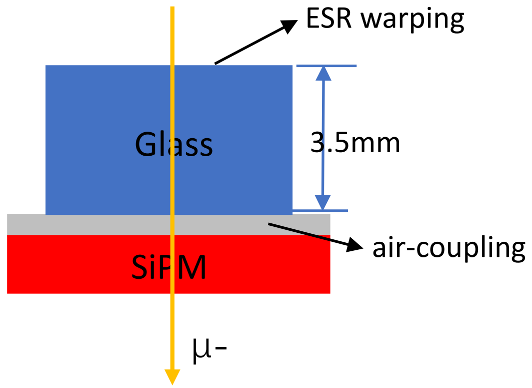


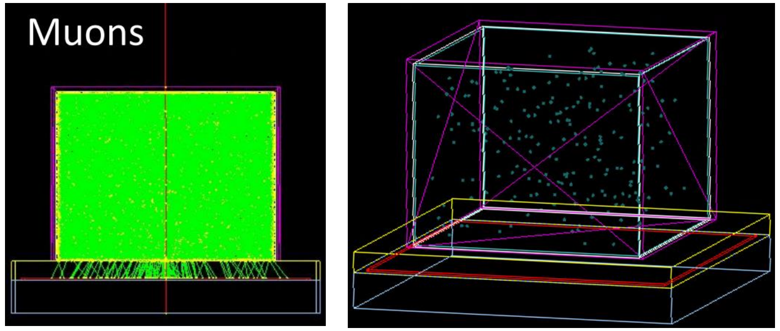


- MIP (minimum-ionization particle) response
  - Basis for energy reconstruction
  - Muon is a good MIP candidate
  - Cosmic muons used for MIP calibration
- Glass sample with highest light yield
  - MIP response: 277 p.e./MIP

Geant4 full simulation and validation

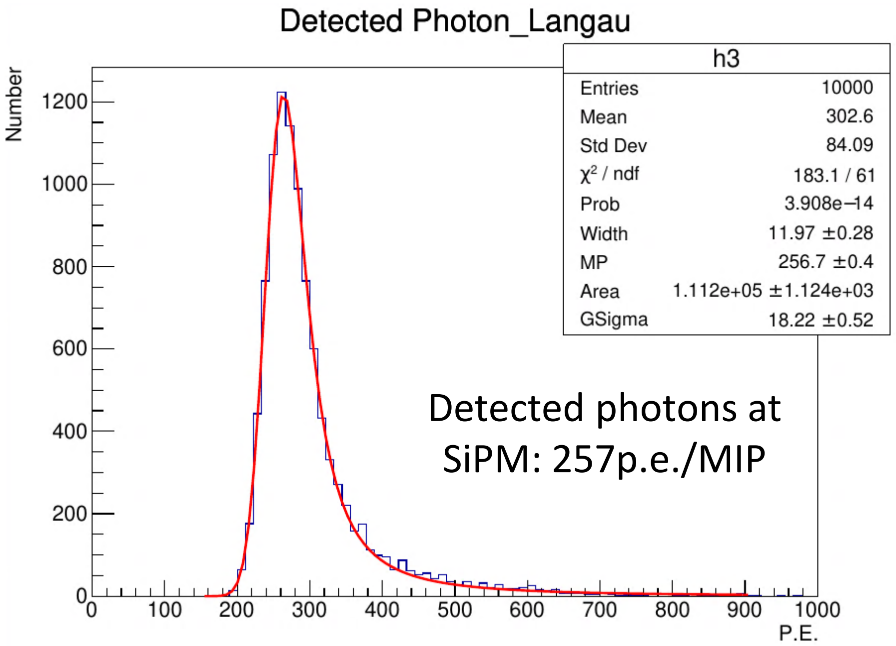
- Simulation setup
  - Scintillating glass ($4.5\times4.5\times3.5mm^3$)
  - $6\times6\ mm^2$ SiPM
  - Small air bubbles are included
- 1 GeV mu- (regard as MIP particle)





Properties of scintillating glass
- Component: $B_2O_3-SiO_2-Al_2O_3-Gd_2O_3-Ce_2O_3$
- Density: 4.94 g/cm^3
- Refractive index: 1.67
- Transmittance: 64%
- Emission peak: 394 nm
- Light yield: 881 ph/MeV

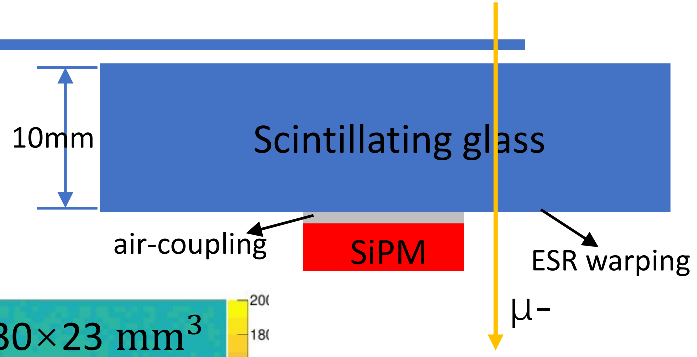
(All data based on measurements)

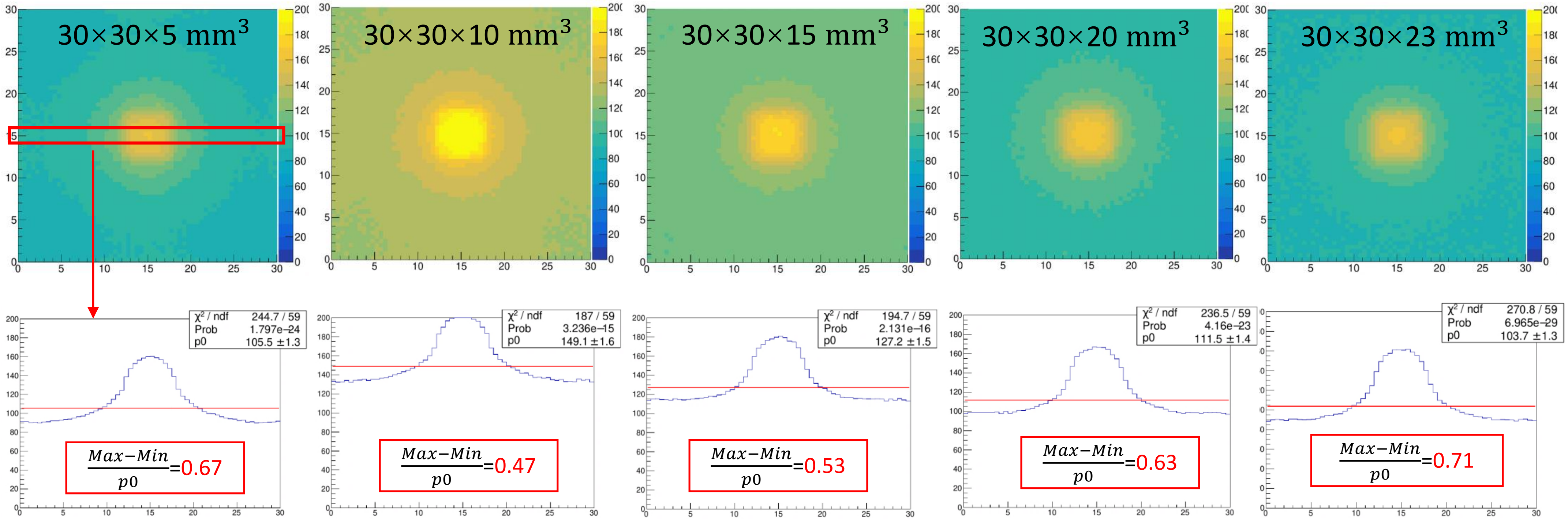


- MIP response in simulation
  - Perpendicular incidence (ideal)
  - Energy deposition: 2.0 MeV/MIP
  - #detected photons: 257 p.e./MIP
- Simulation validated by measurements
  - Reasonable consistency achieved

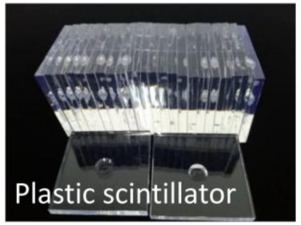
Uniformity scan: impact of tile thickness

- Performance projection with realistic tile size ($30\times30\ mm^2$)
  - Using validated Geant4 simulation
  - Assumption: larger tile properties remain the same as small samples

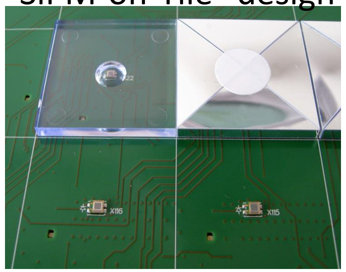




Tiles for AHCAL (30x30x3mm)



“SiPM-on-Tile” design



Felix Sefkow et al 2019 J. Phys.: Conf. Ser. 1162 012012

- Considering response and uniformity, the optimal thickness is ~10mm
- Plan to develop scintillating glass with thickness ~10mm, transmittance is an important parameter
- Uniformity can be further optimized with new glass tile designs

Requirements for key parameters

Key parameters	Value	Remarks
Tile size	~30×30 mm^2	Reference CALICE-AHCAL, granularity, number of channels
Tile thickness	~10 mm	energy resolution, uniformity and MIP response
Density	6-7 $\mathrm{g/cm}^3$	More compact HCAL structure with higher density
Intrinsic light yield	1000-2000 p.e./MeV	Higher intrinsic LY can tolerate lower transmittance
Transmittance	~75%	
MIP light yield	~150 p.e./MIP	Needs further optimizations: e.g. SiPM type, SiPM-glass coupling
Energy threshold	~0.1 MIP	Higher light yield would help to achieve a lower threshold
Scintillation times	~100 ns	Mitigation pile-up effects at CEPC Z-pole (91 GeV)
Scintillation spectrum	Typically 350-600 nm	To match SiPM PDE and transmittance spectra

- Ongoing R&D activities focus on these key parameters

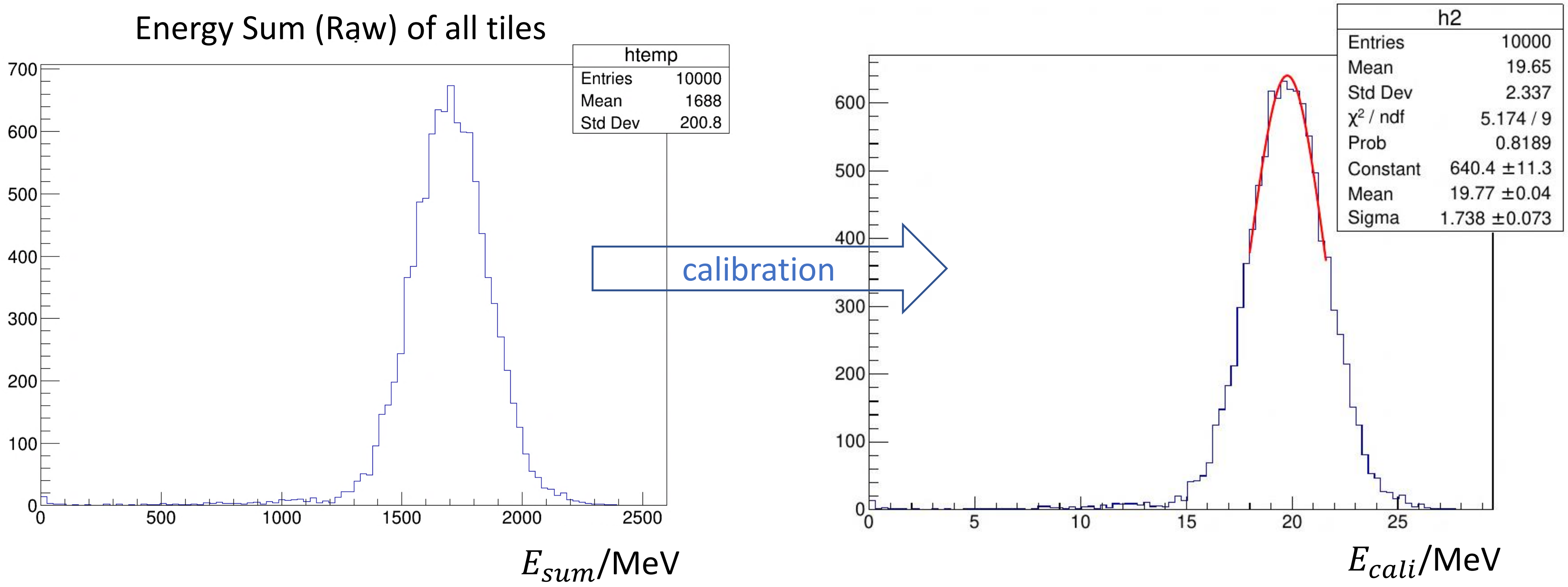
Summary and prospects

- A novel HCAL concept with high-density scintillating glass
  - High granularity for PFA
  - Performance of scintillating glass HCAL: better energy resolution in low energy region
  - Scintillating glass R&D and characterization of glass samples
  - Studies on the performance of HCAL detector unit
- Prospects
  - To further improve the energy resolution: e.g. “Software compensation” technique
  - Improve uniformity of a scintillating glass tile through tile-designs
  - Scintillating glass R&D: improve density while keeping light yield, develop large-sized samples

Thank you!

Backups

Definition of energy resolution



Incident particle: 20GeV K_L^0

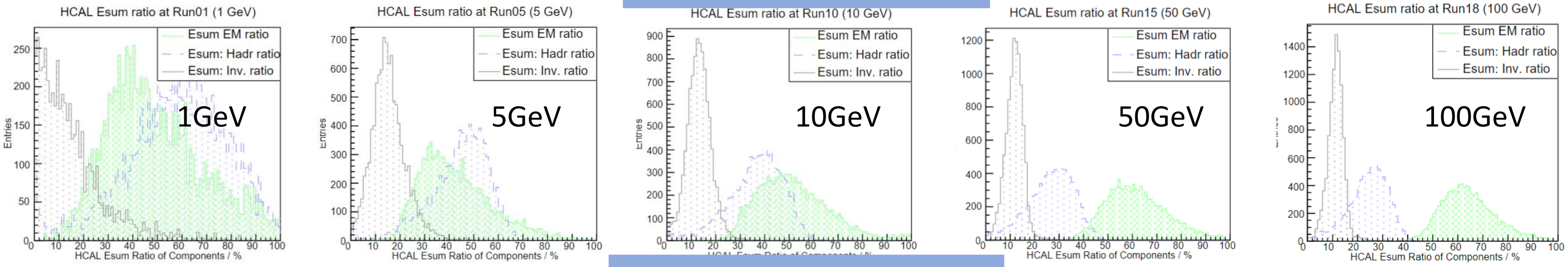
- Calibration constant: 0.086
- Fit range: (- 1σ, +1σ)
- Energy resolution: $\frac{\sigma}{E_{beam}}$

Categorize energy depositions

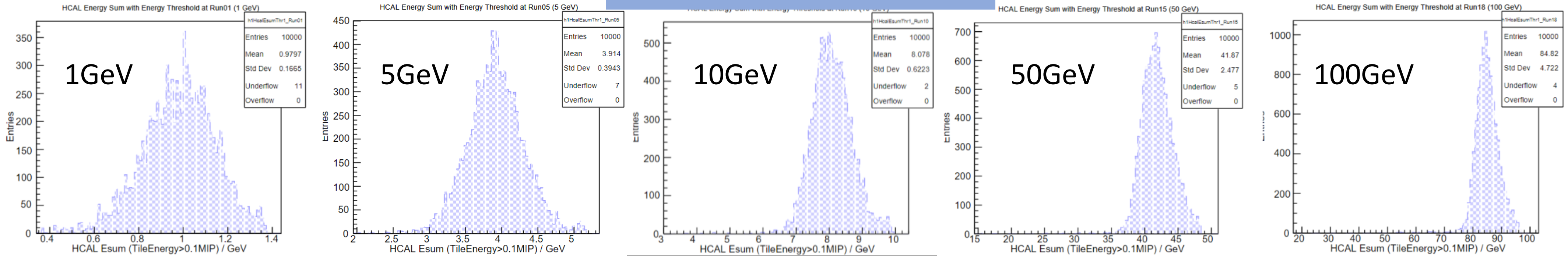
- Categorize energy depositions of hadronic showers: EM, hadronic, invisible

Incident particle: K_L^0
homogeneous HCAL

Component Energy Ratio



Energy Sum (Raw) of all tiles



- EM energy deposition usually detected with higher efficiency
- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Yong Liu (IHEP)

Calculation of light yield

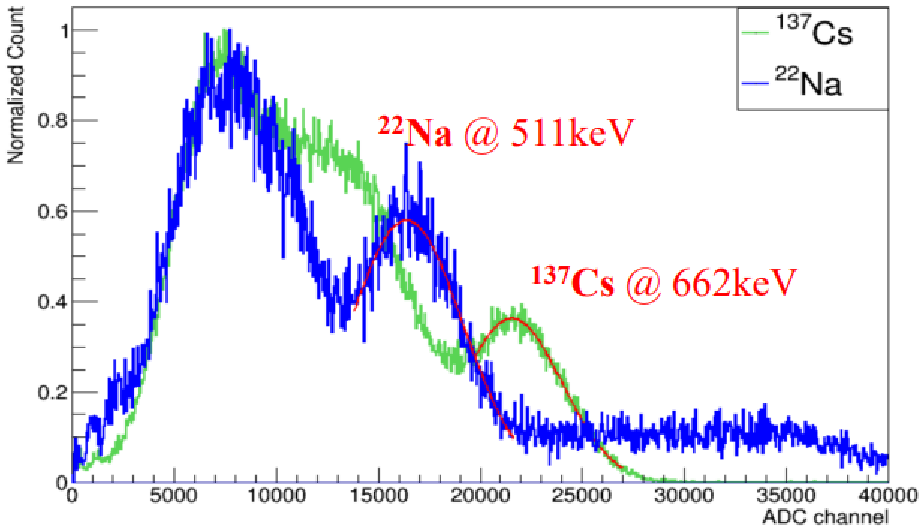
--Absolute light yield: The formula of the light yield： $LY_s = \frac{Mean_{energy} * 1000\text{keV}}{Mean_s * PDE_w * PCE * Energy}$

Calculated by different Almighty peak of radioactive source, the light yield of #6 glass is **802 ph/MeV;**

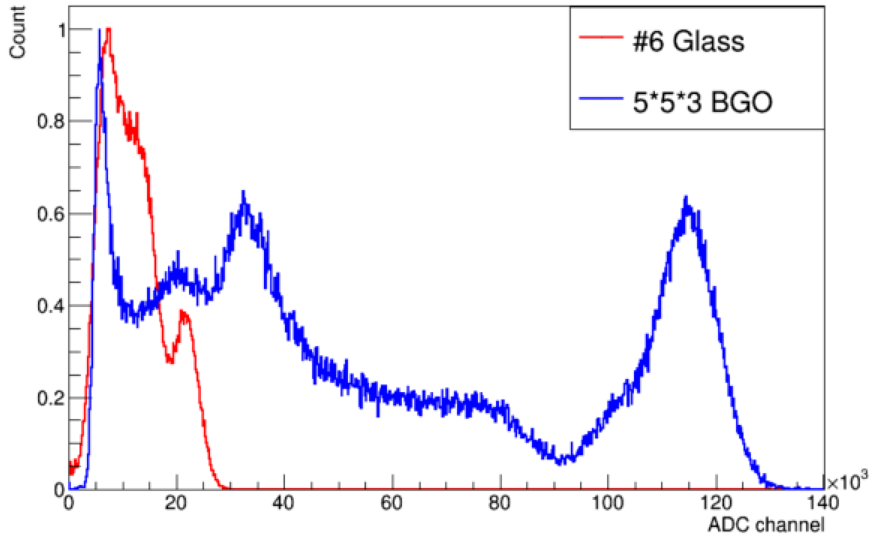
--Relative light yield: Calculate the relative light yield of glass through BGO standard crystal,

the light yield of #6 glass is **845 ph/MeV**;

--The light yield of the glass calculated by the two methods is the same.



LY of the GS =802ph/MeV

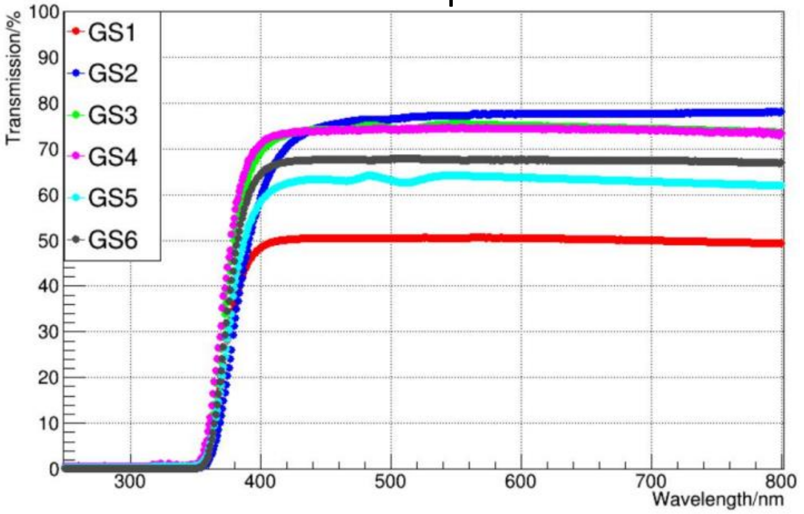


LY of BGO=8800 ph/MeV
LY of the GS =845ph/MeV

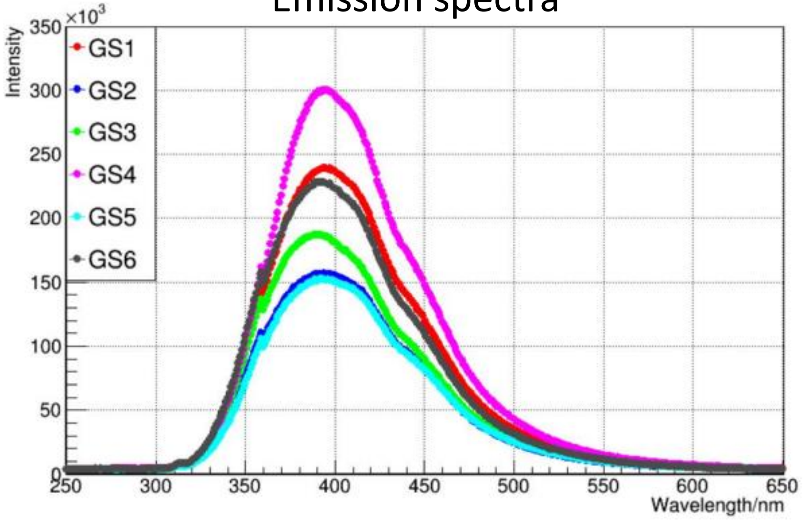
By Zehao Hua

Transmission spectrum, emission spectra and decay time

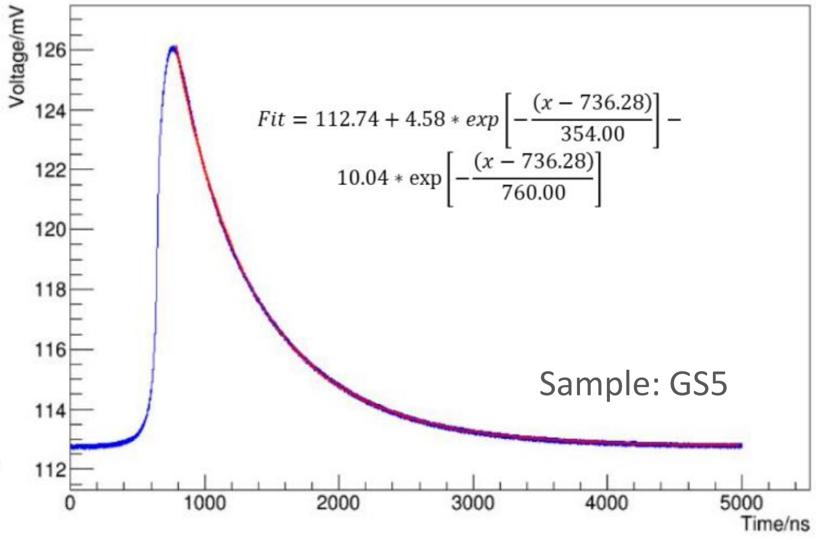
Transmission spectrum



Emission spectra



Decay time

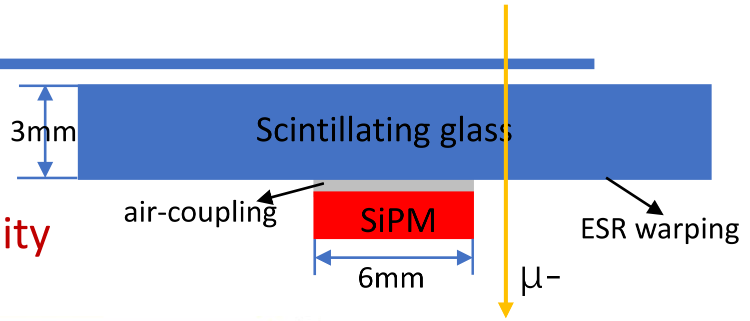


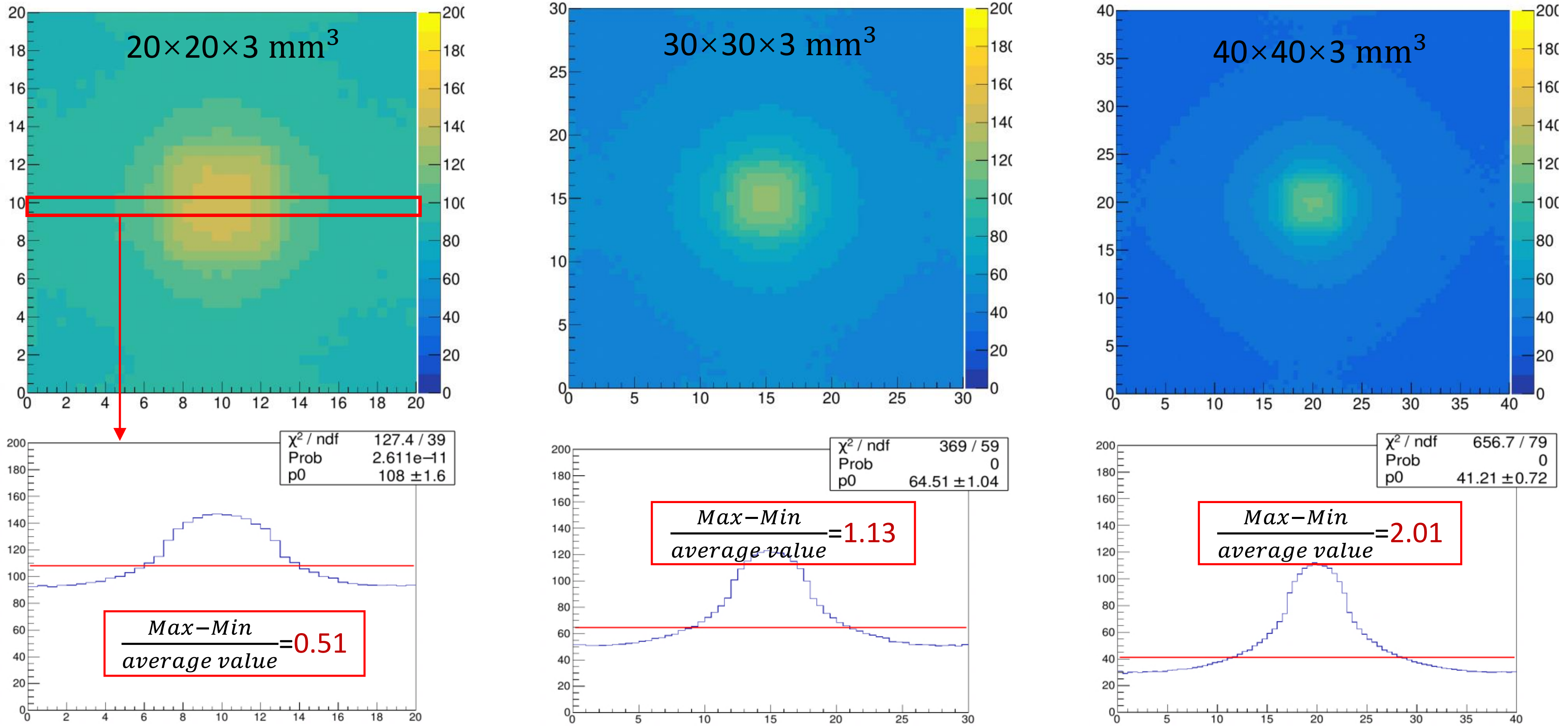
- Transmittance of samples can reach up to 78%
  - air bubbles, heavy metal ratio will affect its transmittance
- Emission peak is around 393 nm
  - can be matched with the detector band by adjusting the composition
- The decay time of GS5 is 354 ns (18%), 760 ns (82%)

Zhehao Hua (IHEP)

Uniformity scan: impact of tile size

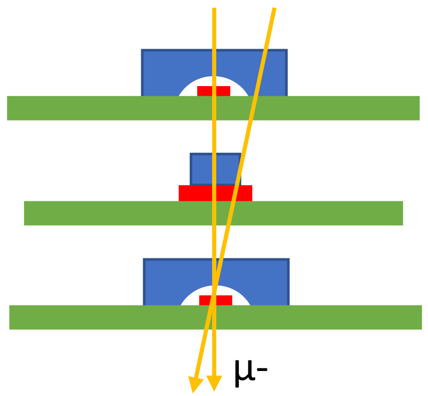
- Projected performance of a realistic AHCAL tile size
- Assumption: larger tile properties remain the same as small glass samples
- Larger tile size leads to less detected photons and more significant non-uniformity

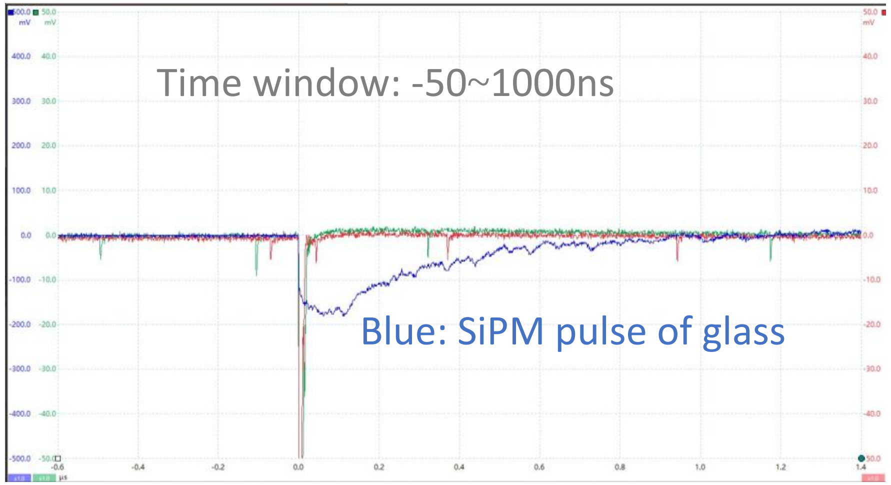




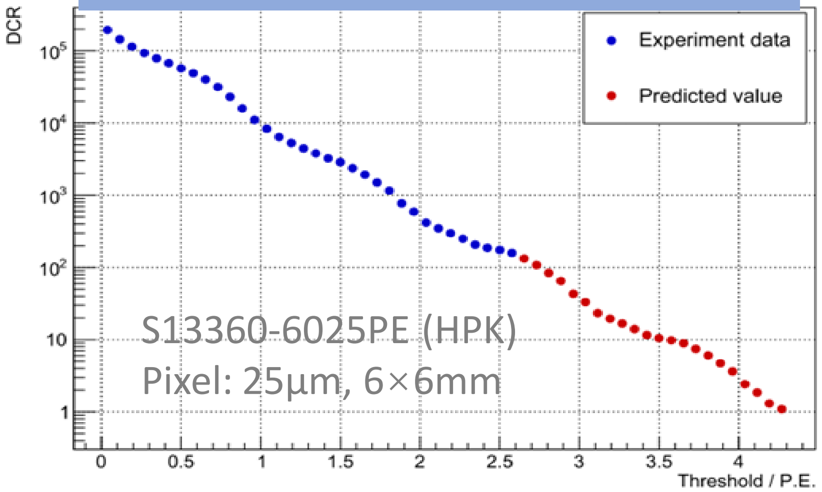
Incident particle: mu-
change hit position
(0.5mm step)

Threshold impacts

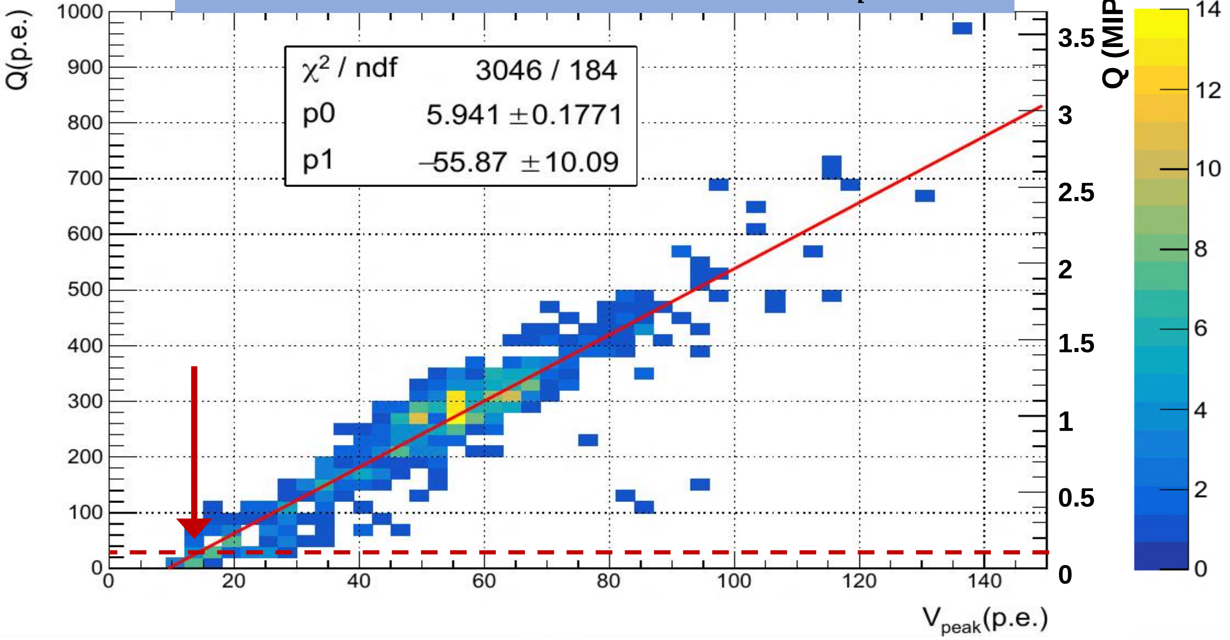




Dark count rate vs. voltage threshold



Cosmic muon data: Charge vs. V_{peak}



- Higher threshold can suppress noise impacts
  - SiPM dark noise is negligible (< 1 Hz) when threshold > 4.5 p.e.
- **Electronics threshold** vs. **energy threshold** (HCAL reconstruction)
  - 0.1 MIP (energy) ⟶ 14 p.e (voltage)
- Energy threshold of 0.1 MIP is feasible