中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

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

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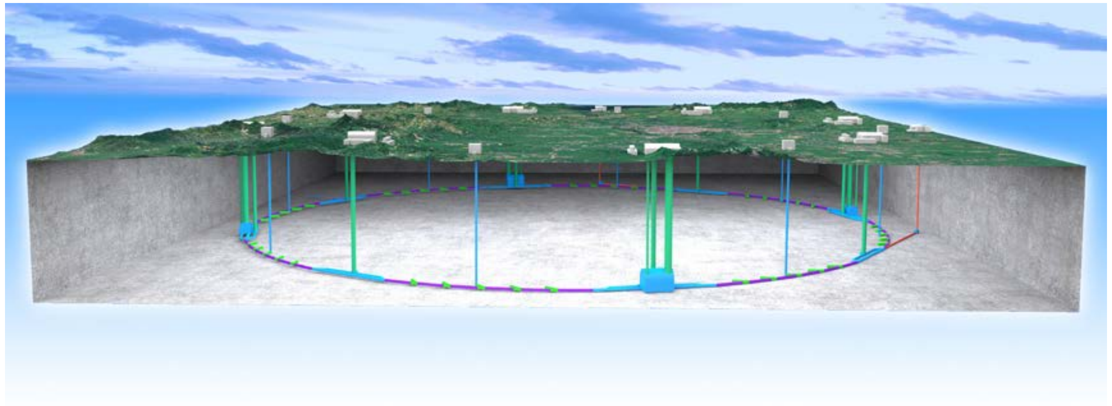
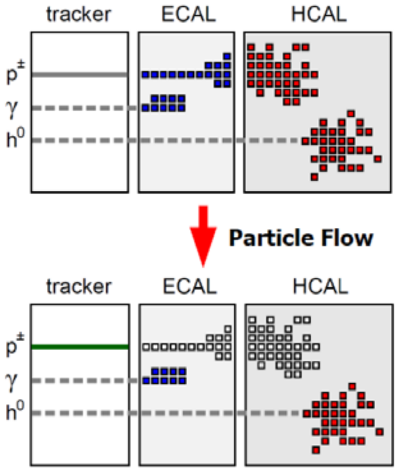
On behalf of CEPC Calorimeter Working Group

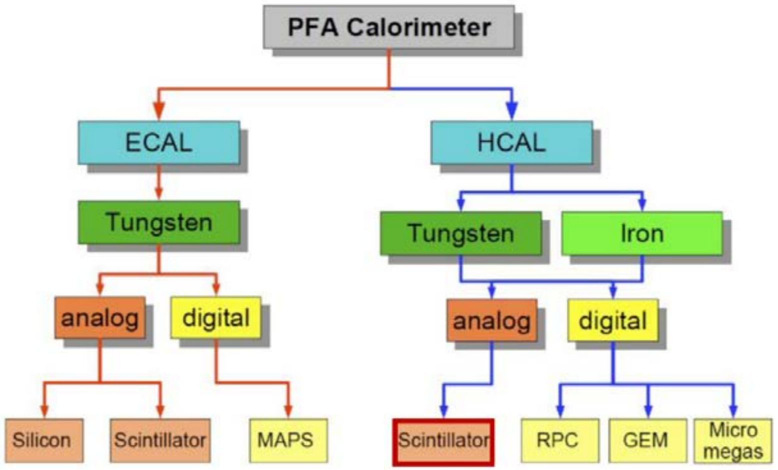
CALOR 2022 at University of Sussex, Brighton
May 20, 2022

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
  - Software challenge: complex reconstruction algorithms

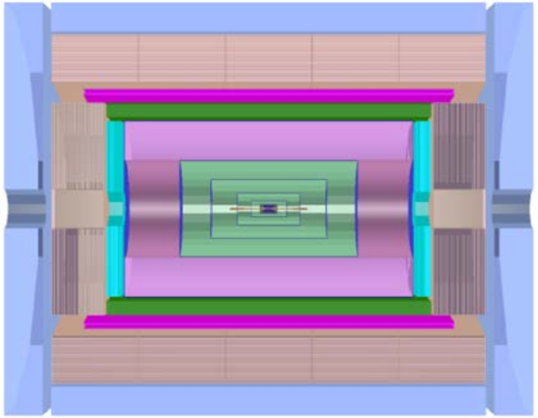




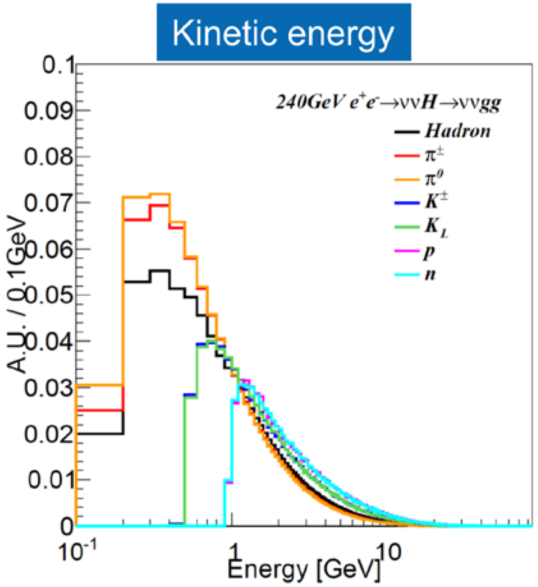


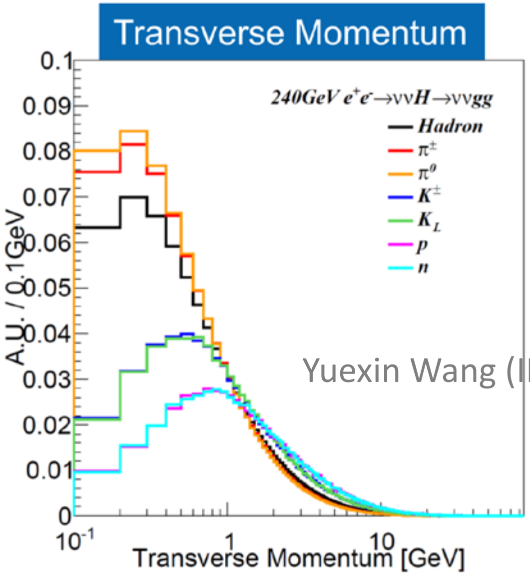
Motivations

- 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%



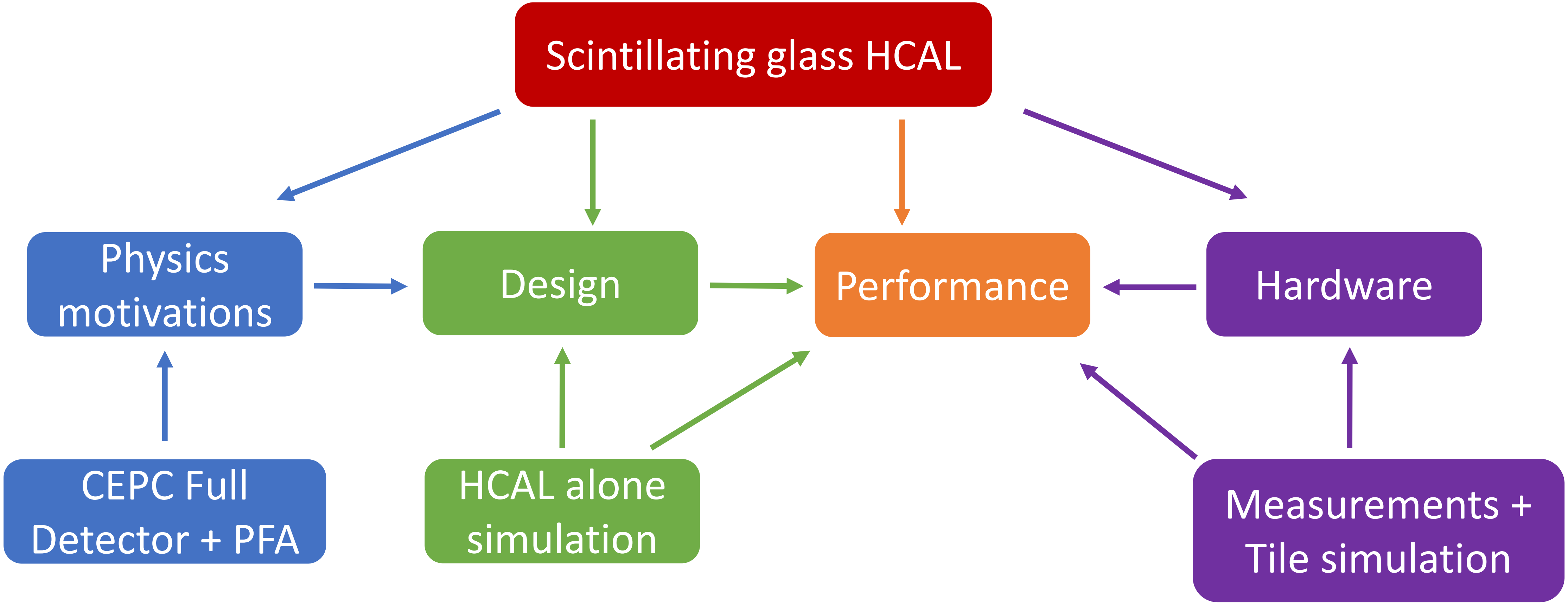
Calorimeters: crystal ECAL and Scintillating Glass HCAL





Yuexin Wang (IHEP)

Outline



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

Outline

- Performance of scintillating glass HCAL
  - Geant4 simulation with single hadrons
    - Hadronic energy resolution: scintillating glass vs. plastic scintillator
    - Varying thickness of glass tiles and steel plates
  - Physical performance: BMR
- Scintillating glass material R&D
  - Measurements of scintillating glass samples
- Studies on the performance of basic detected unit
  - MIP response: optical simulation and cosmic ray test
  - Uniformity scan with varying tile thickness
  - Estimated performance
- Summary and prospects

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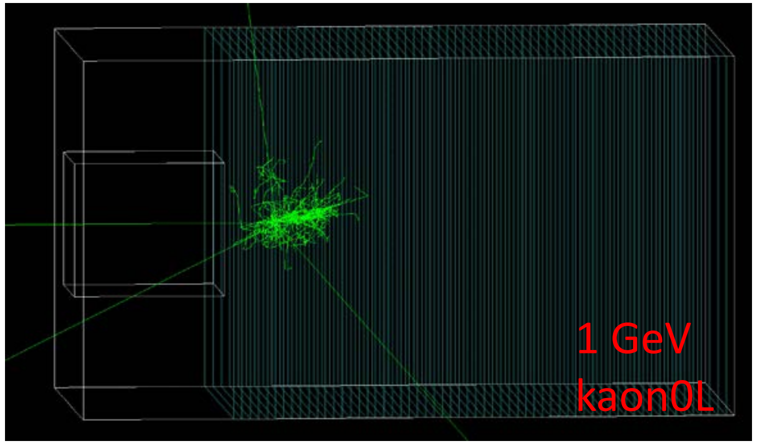
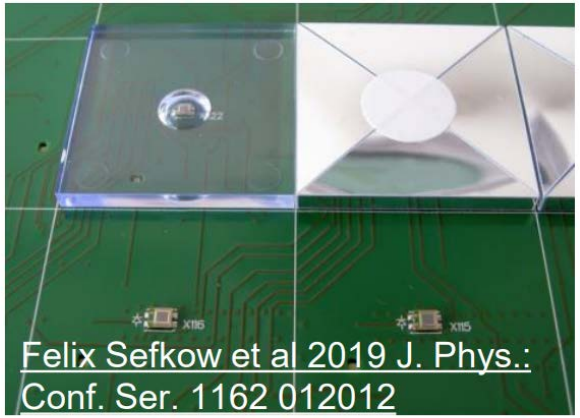
HCAL setup in Geant4 simulation

- Geometry: a la CALICE-AHCAL
  - Transverse plane: $108 \times 108cm^2$
    - Tile size: $3 \times 3\mathrm{cm}^2$
  - 60 longitudinal layers, each with
    - Scintillator: 3mm
    - PCB: 2mm
    - Absorber (steel): 20mm
- Scintillator materials
  - Plastic scintillator as baseline reference
  - Replace plastic scintillator with scintillating glass
    - 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)

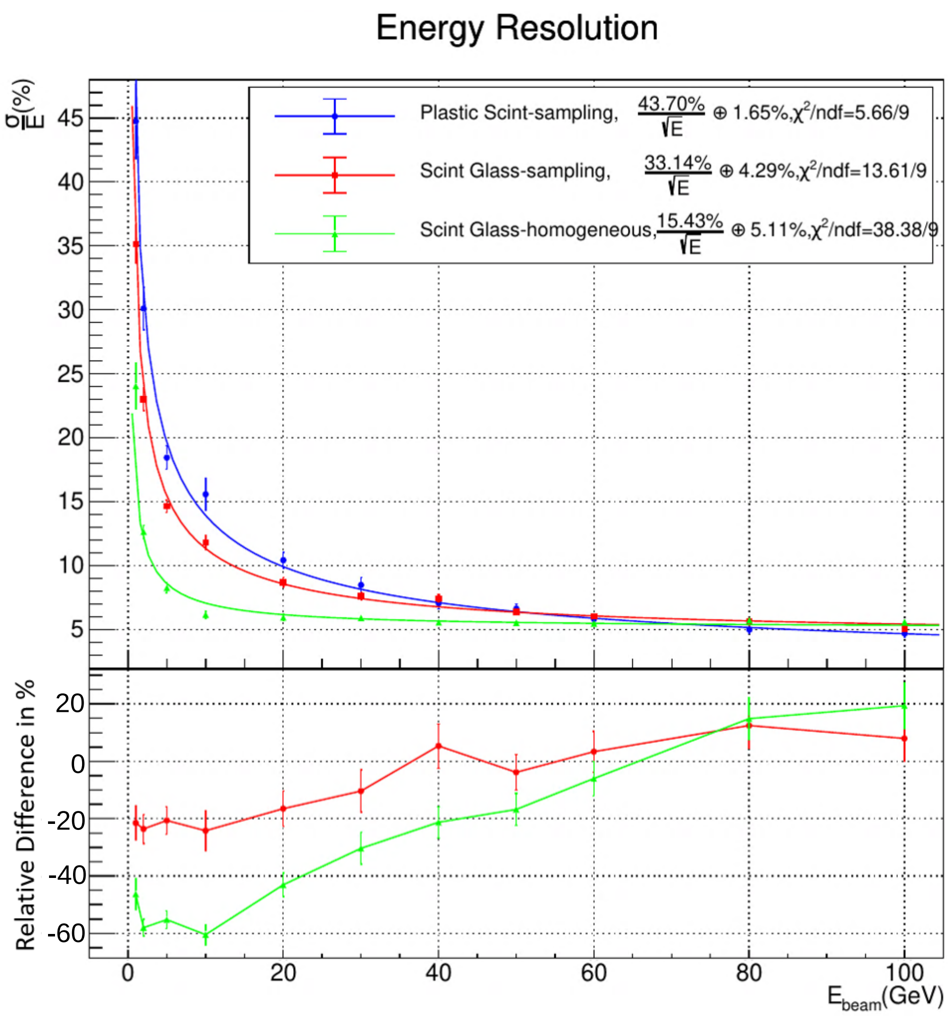


"SiPM-on-Tile" design for HCAL



Note: HCAL with 40 layers in CEPC CDR as baseline.
Hereby use 60 layers to evaluate leakage effects

HCAL: plastic scintillator vs scintillating glass

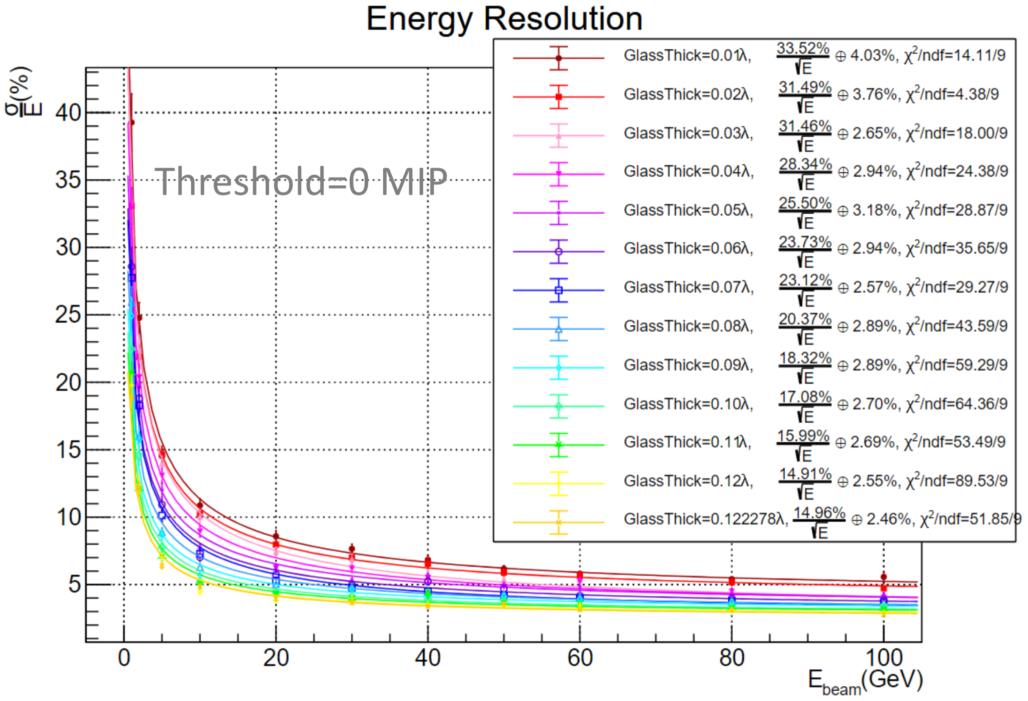


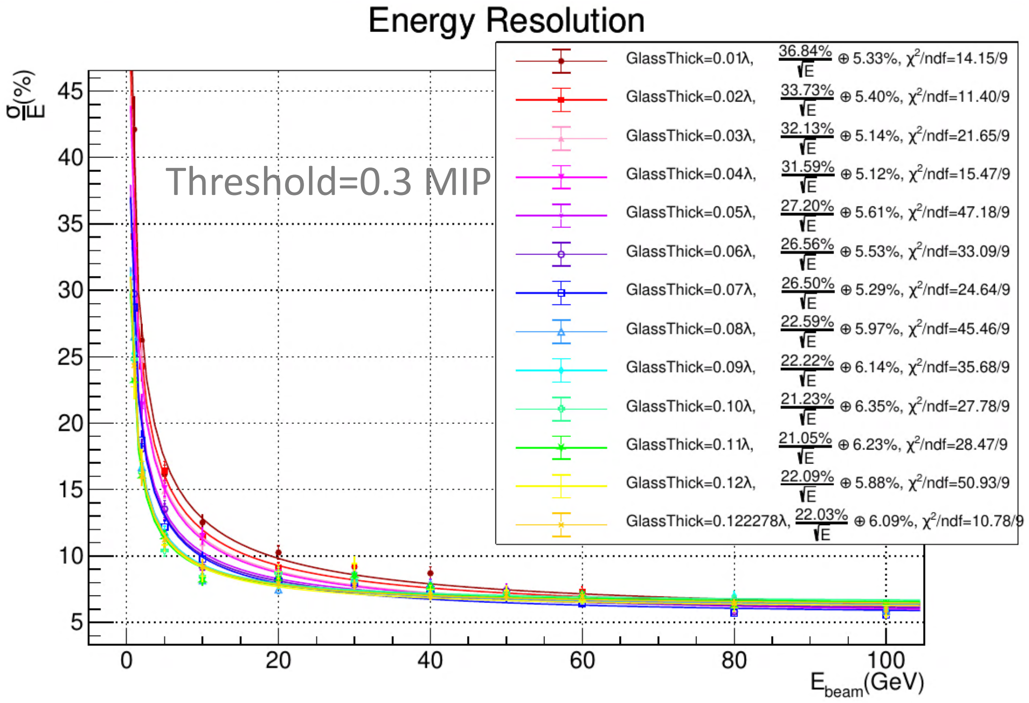
- Incident particle: K_L^0
- Preliminary performance comparison
  - Same thickness of sensitive materials: 3mm
  - No energy threshold applied
- Scintillating glass: better hadronic energy resolution in low energy region (<30GeV)
  - Note that majority of hadrons in jets at CEPC are with low energy
- More details in the next pages

Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
  - Each layer fixed with $\sim 0.12\lambda_I$: the same as AHCAL (3mm plastic tile, 20mm steel)
  - $\lambda_I = 22.4cm$

Incident particle: K_L^0





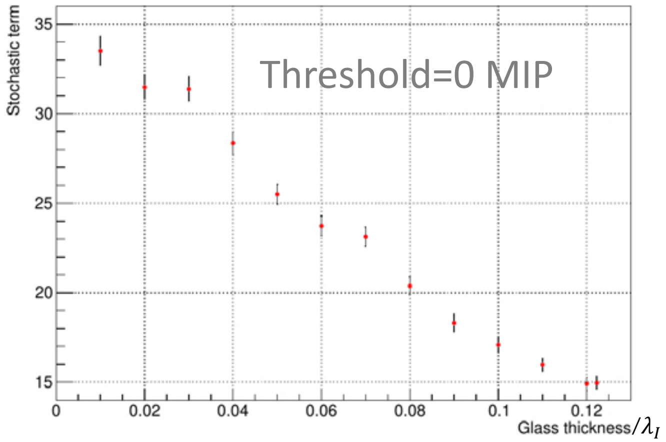
- Energy threshold significantly impacts hadronic energy resolution
- The empirical formula $(A/\sqrt{E(GeV)} \oplus C)$ can not well describe curves
  - (Note the χ^2/ndf values) Not fully follow the Poisson distribution

Orange curve corresponds to the homogeneous HCAL

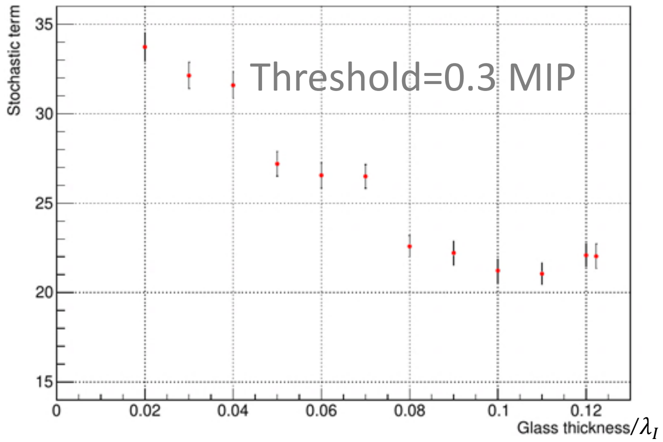
Impact of thickness to hadronic energy resolution

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

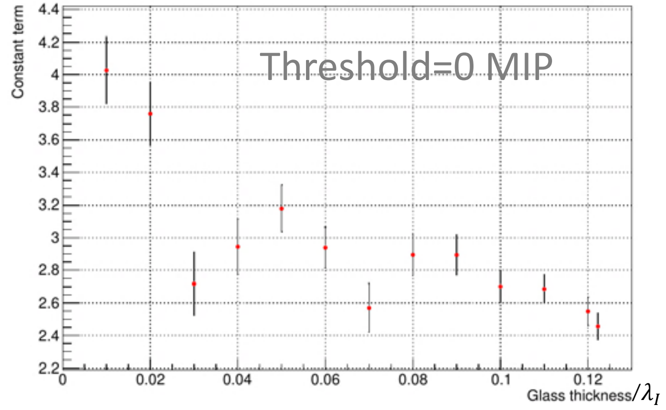
Stochastic term vs. glass thickness



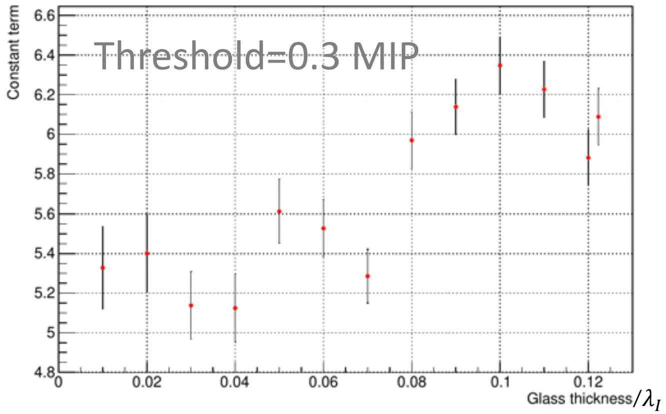
Stochastic term vs. glass thickness



Constant term vs. glass thickness



Constant term vs. glass thickness



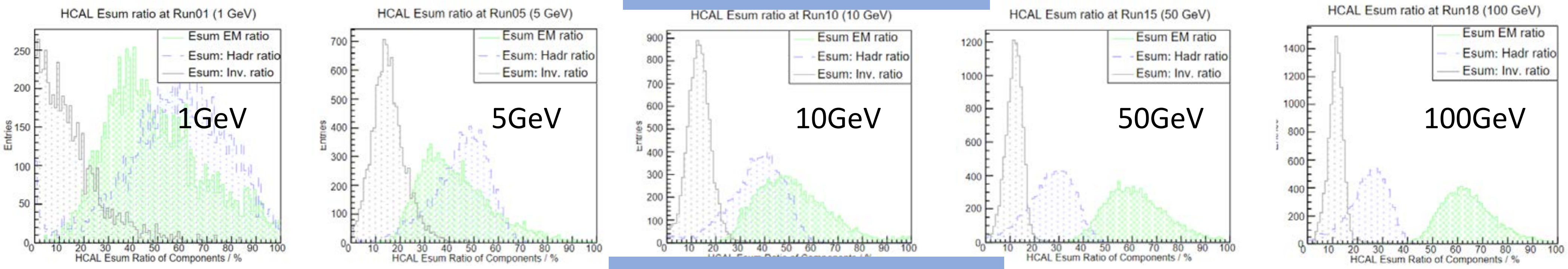
- Energy threshold has a significant impact on the energy resolution
- With the 0.3 MIP threshold, resolution will not be improved when glass thicker than ~0.08 λ_I (18mm)
- Higher threshold significantly degrades the constant term
- Lower threshold would always be desirable for better resolution

Categorize energy depositions

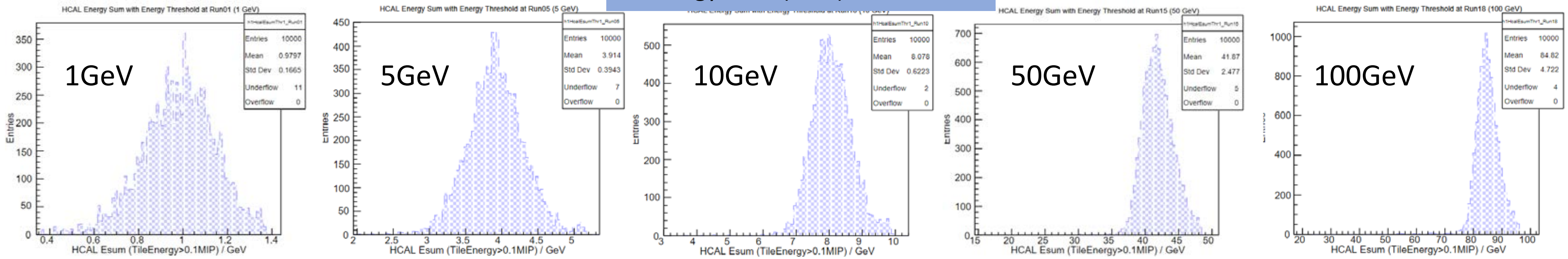
- Categorize energy depositions of hadronic showers: EM, hadronic, invisible

Incident particle: K_L^0
homogeneous HCAL

Component Energy Ratio



Energy Sum (Raw) of all tiles



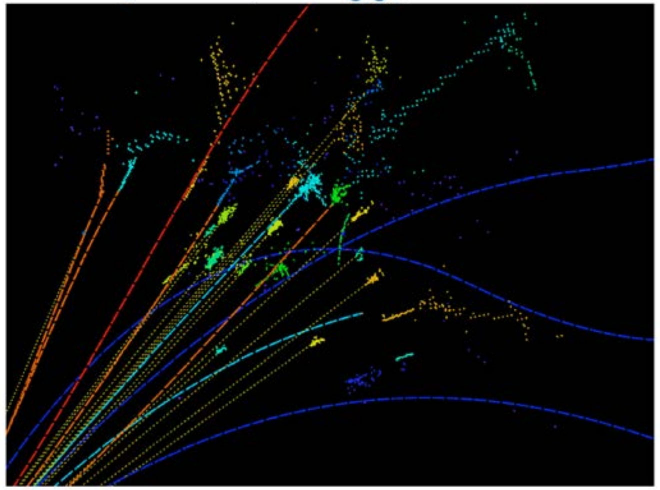
- EM energy deposition usually detected with higher efficiency
- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Yong Liu (IHEP)

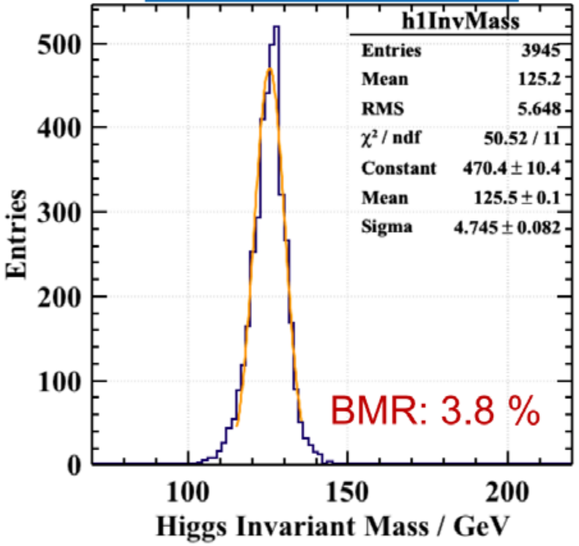
Physical performance: BMR

Dan Yu (IHEP)

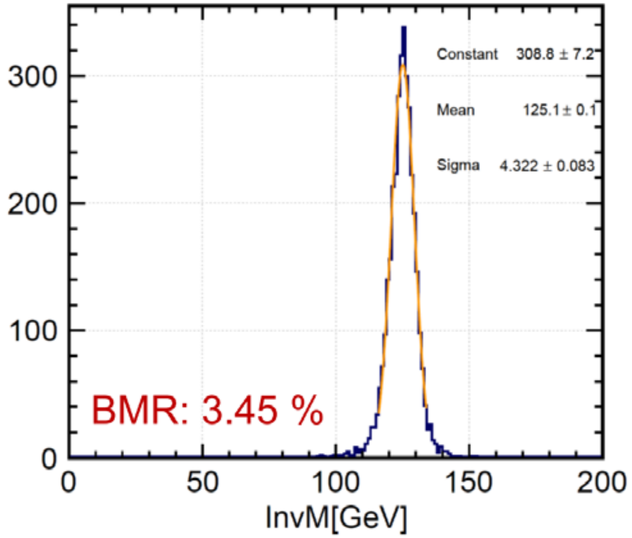
$ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV



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

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Glass Scintillators R&D Group

- GS Production
  - Development
  - Mass production
- GS Research
  - Optical test
  - Mechanical test
  - Irradiation test
- GS HCAL Design
  - Simulation
  - SiPM Research
  - Single Tile Test
- GS Application
  - Unclear Detection
  - Others

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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

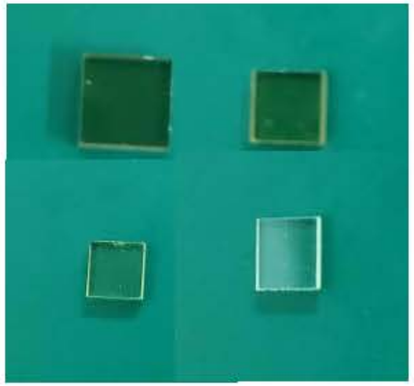
Harbin Engineering University
哈尔滨工程大学

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



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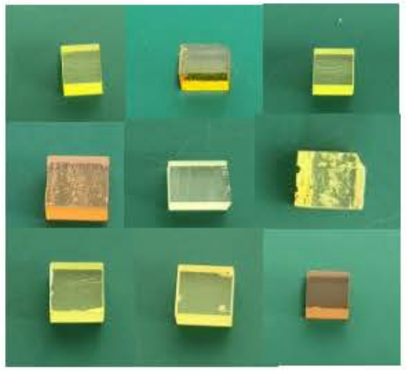

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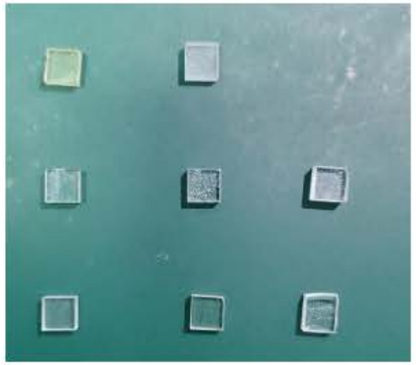

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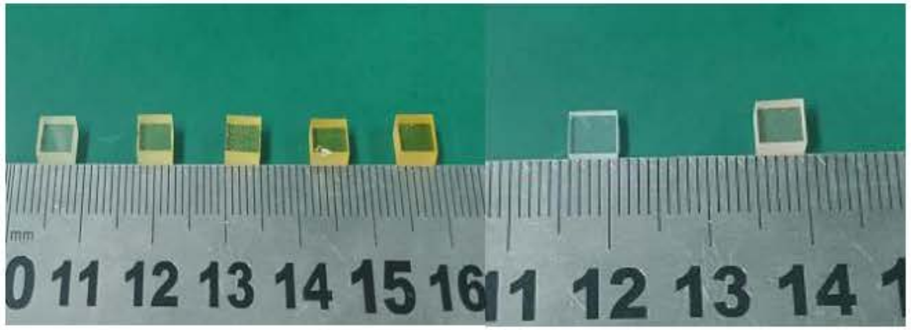

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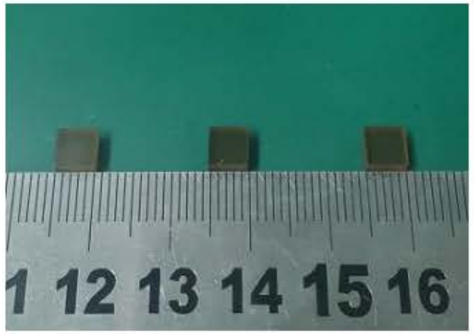
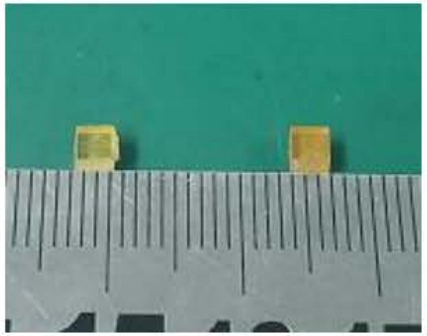


2021.11.22



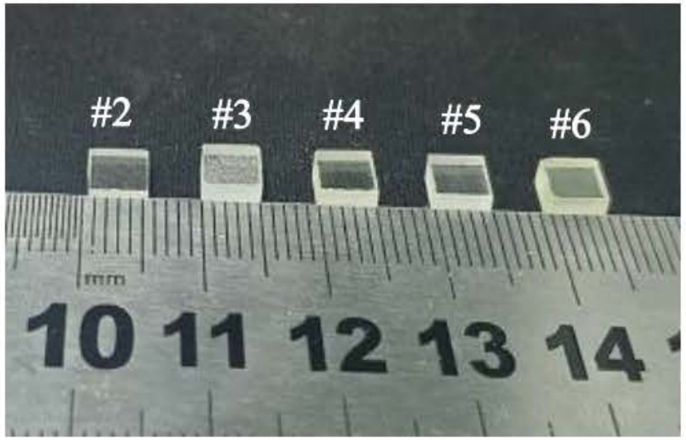
2021.11.23

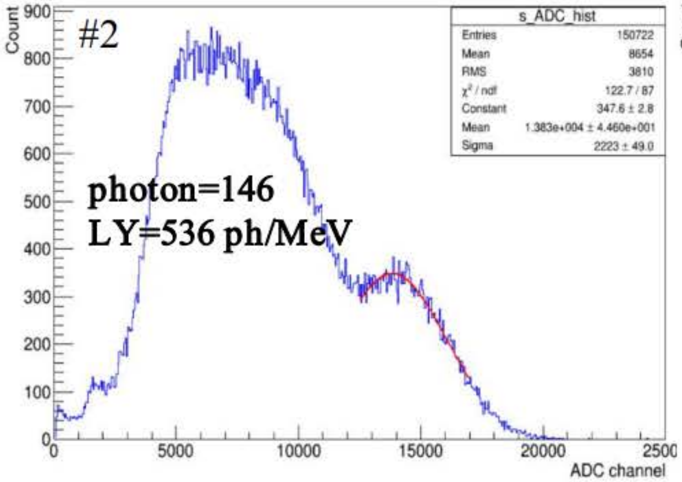
- Comprehensive measurements of key properties
  - Transmission/emission spectra, light yield and decay time
- Over 30 pieces of scintillating glass have been tested, most of which have poor performance
- The best performance glass with the composition: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$

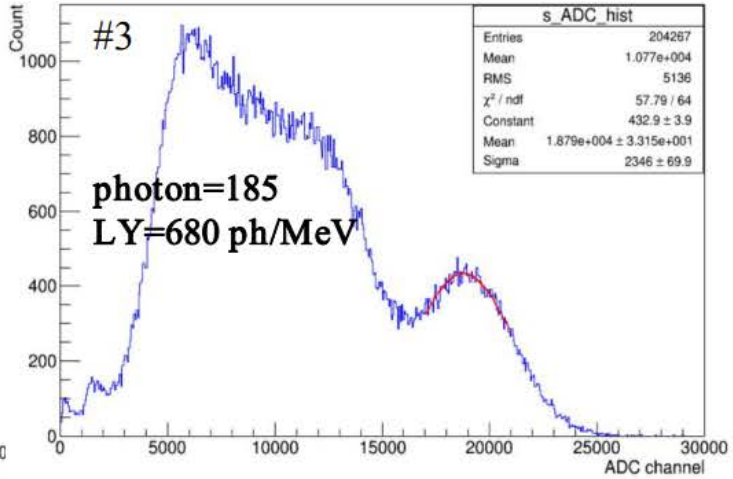
Zhehao Hua (IHEP)

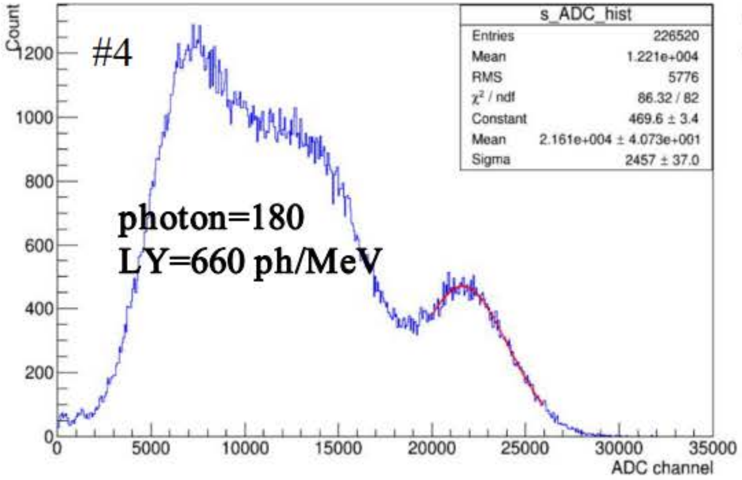
Measurements of light yield

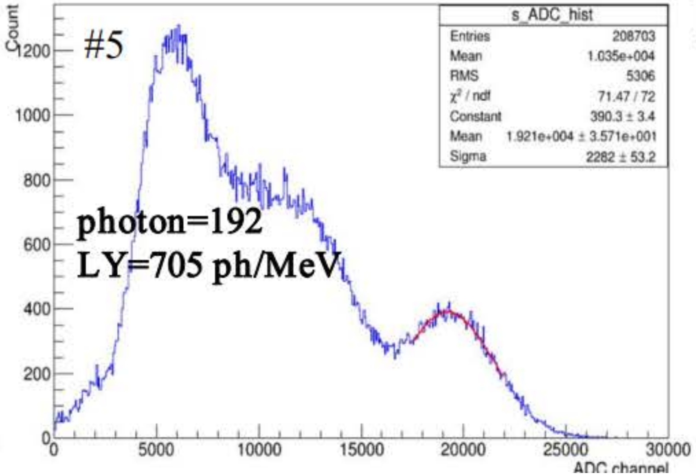
$$LY_S = \frac{Mean_{energy} * 1000\text{keV}}{Mean_S * PDE_W * PCE * Energy}$$

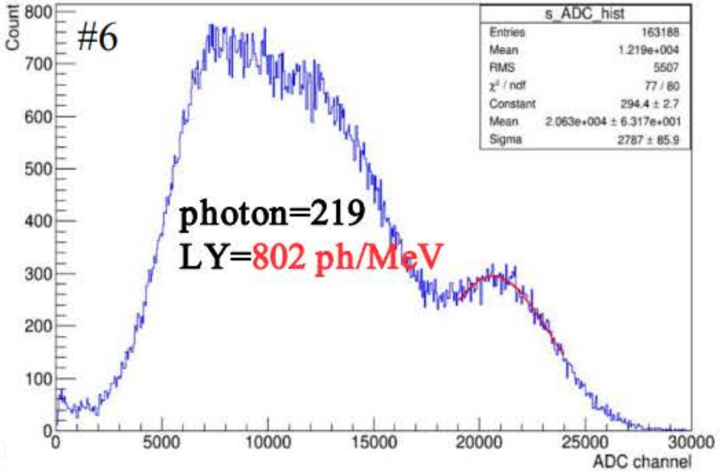












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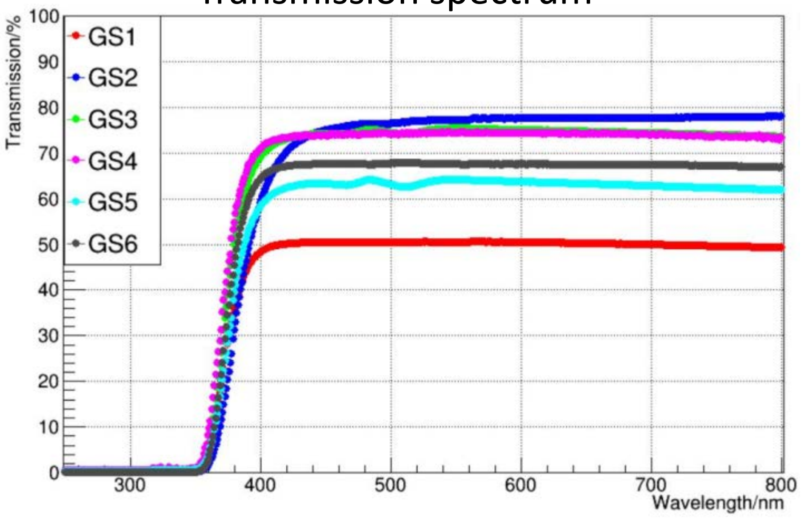
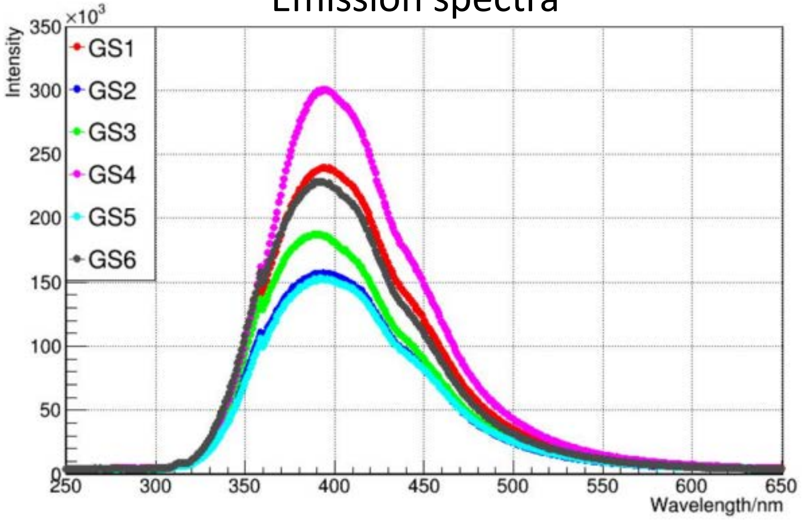
Transmission spectrum, emission spectra and decay time

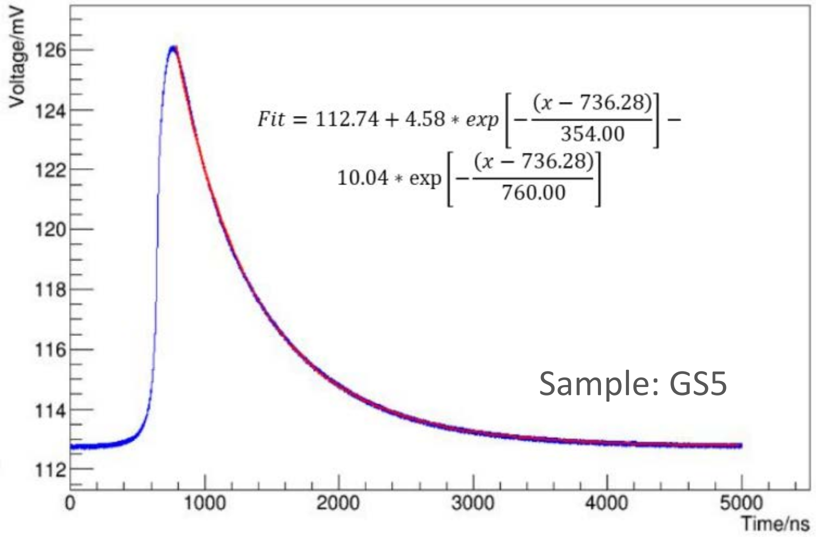
Transmission spectrum



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)

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 could reach 800 ph/MeV (until December 2021)
- Latest sample measurement result: light yield reached 1600 ph/MeV, but density < 4 g/cm^3
- Next plans
  - Improve both light yield (2000 ph/MeV) and density (6 g/cm^3)
  - develop large-sized samples

Zhehao Hua (IHEP)

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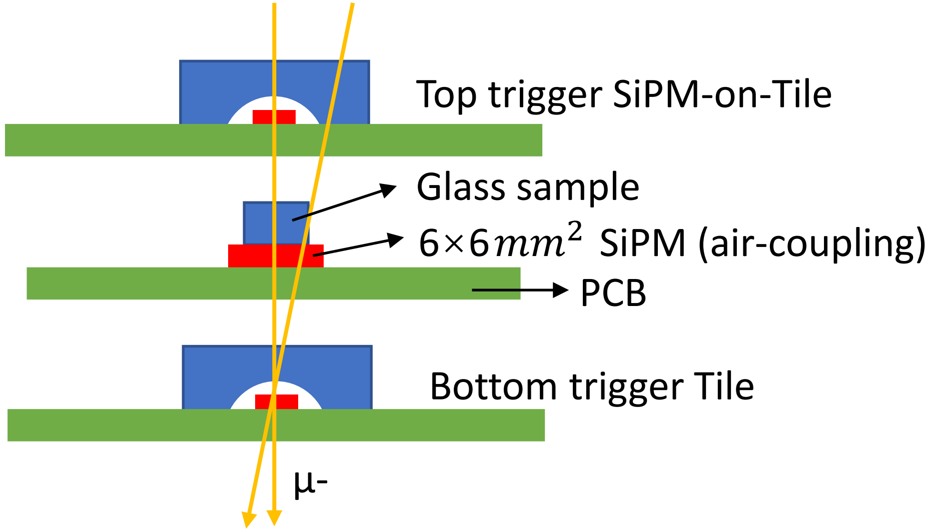
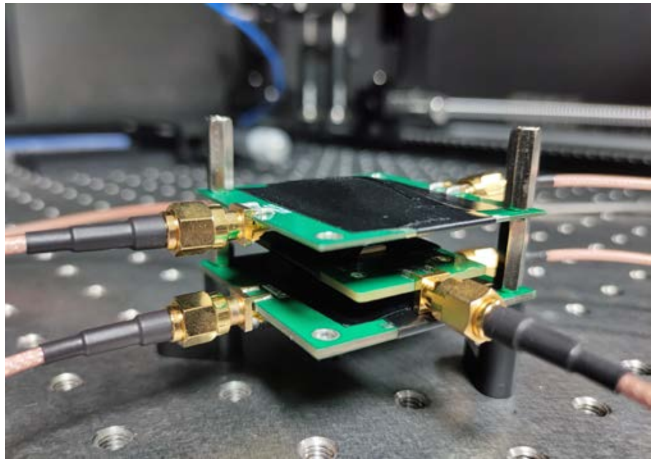
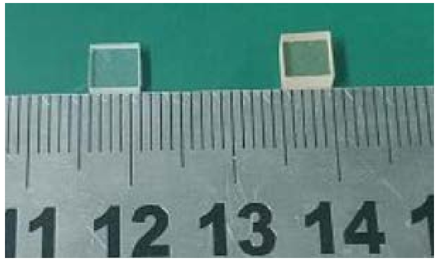
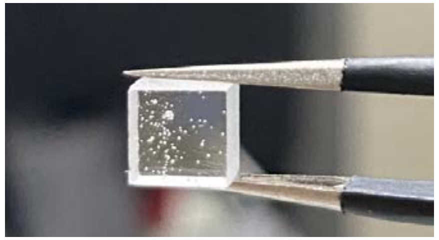
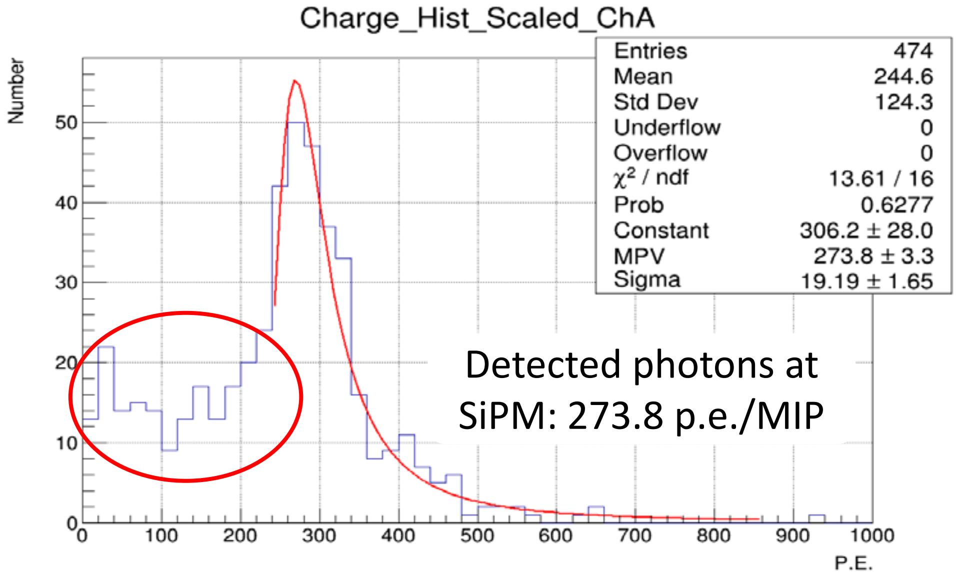
MIP response: cosmic-ray test







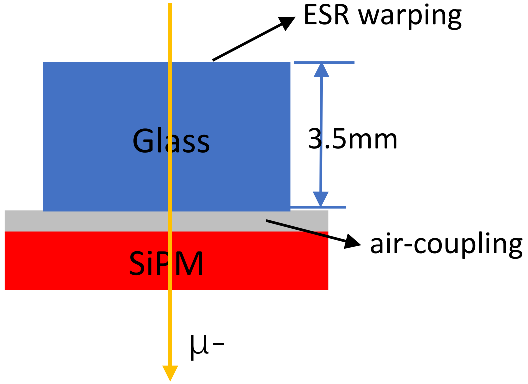


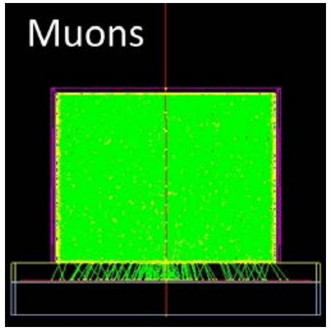


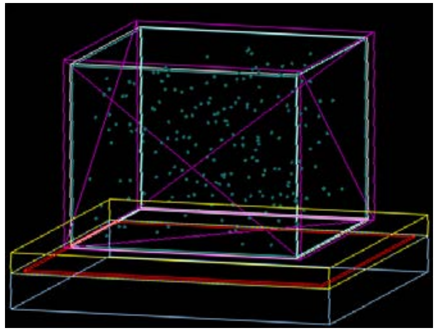
- Glass sample size: 4.5×4.5×3.5mm^3
- MIP response: 274 p.e./MIP
- Plastic scintillator triggers cover larger area than sample does, some comic rays cross part of the sample

MIP response: optical simulation

- Simulation setup
  - Scintillating glass ($4.5 \times 4.5 \times 3.5 mm^3$)
  - $6 \times 6\ mm^2$ SiPM
  - Small air bubbles are included
- 1 GeV mu- (regard as MIP particle)
- Vertical incidence in tile center

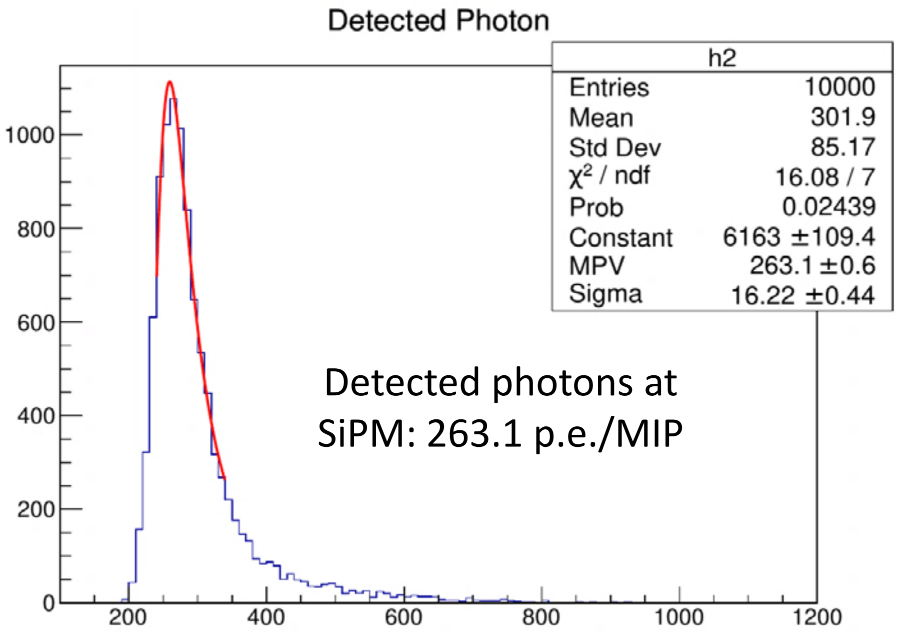






Properties of scintillating glass
- Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
- Density: 4.94 g/cm^3
- Refractive index: 1.67
- Transmittance: 64%
- Emission peak: 394 nm
- Light yield: 881 ph/MeV

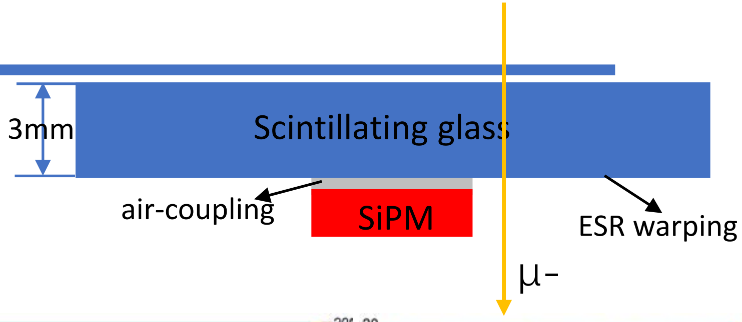
(All data based on measurements)

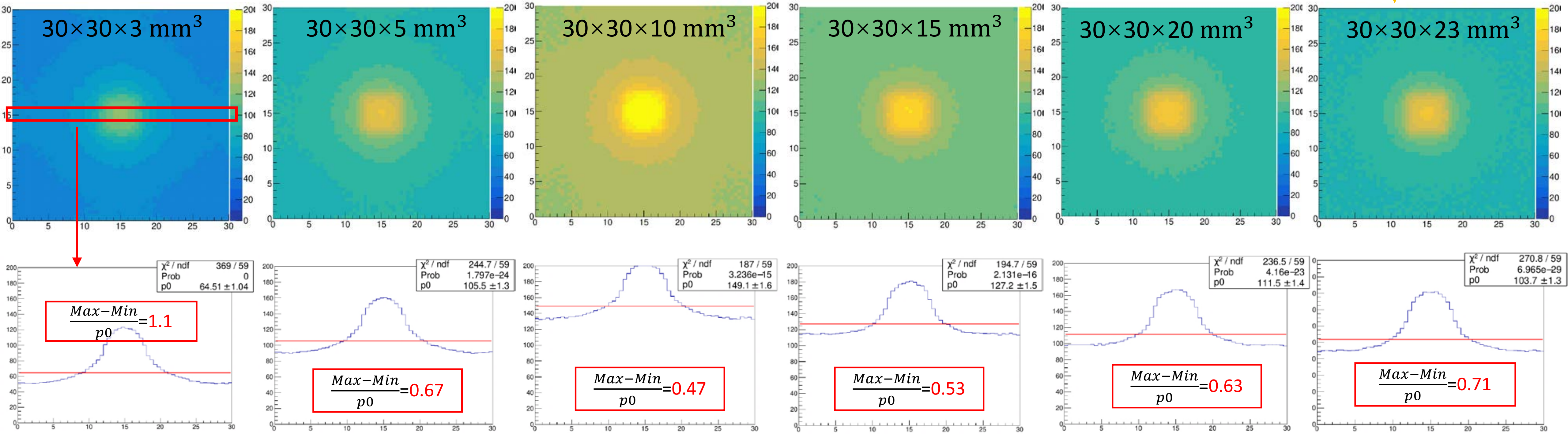


- MIP response
  - Energy deposition: 2.0 MeV/MIP
  - Detected photons: 263 p.e./MIP
- The difference between simulation and experiment result: ~4%

Uniformity scan: impact of tile thickness

- Projected performance of a realistic AHCAL tile size
- Assumption: larger tile properties remain the same as small glass samples (transmittance: 86%)

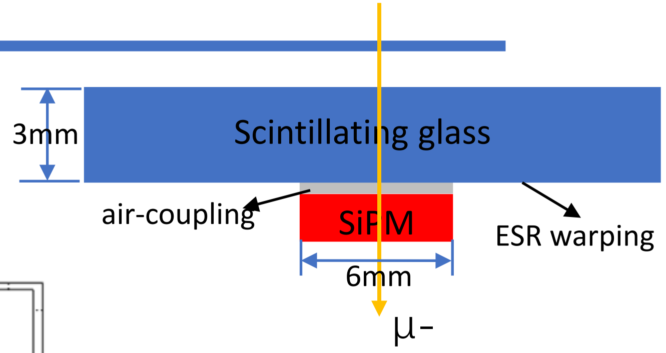




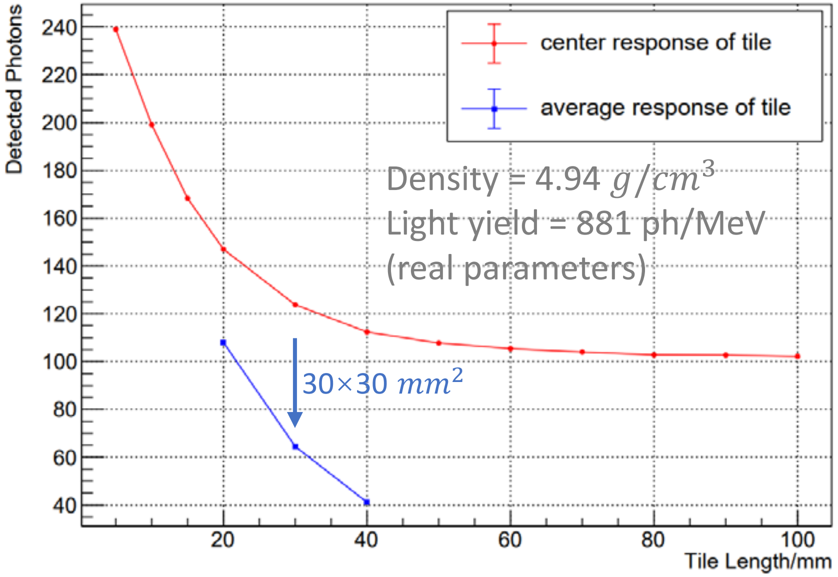
- When the thickness is 10mm, the detected photons is the largest and the uniformity is the best.
- Plan to develop scintillating glass with thickness >10mm, transmittance is an important parameter

Impact of scintillating glass tile size

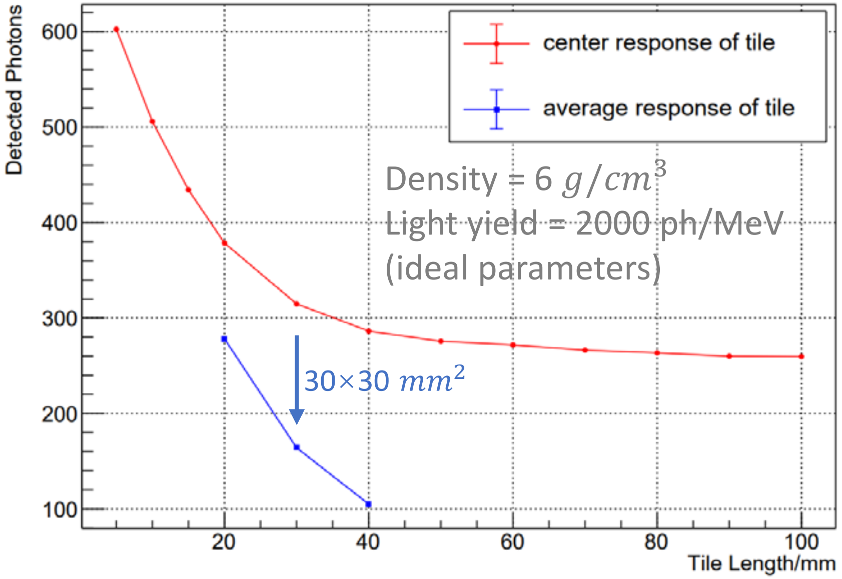
- Assumption: larger tile properties remain the same as small glass samples
- Vary transverse size, fixed tile thickness at 3 mm (AHCAL baseline design)



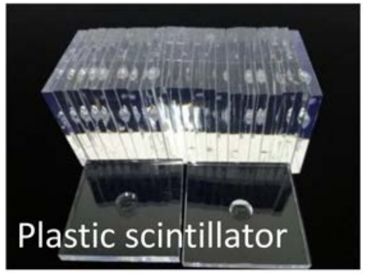
Detected photons vs. tile size



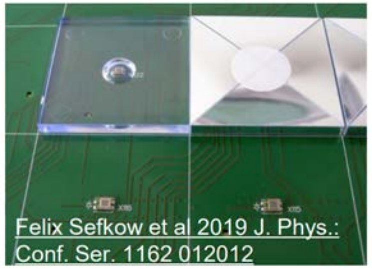
Detected photons vs. tile size



Tiles for AHCAL (30x30x3mm)



"SiPM-on-Tile" design for HCAL



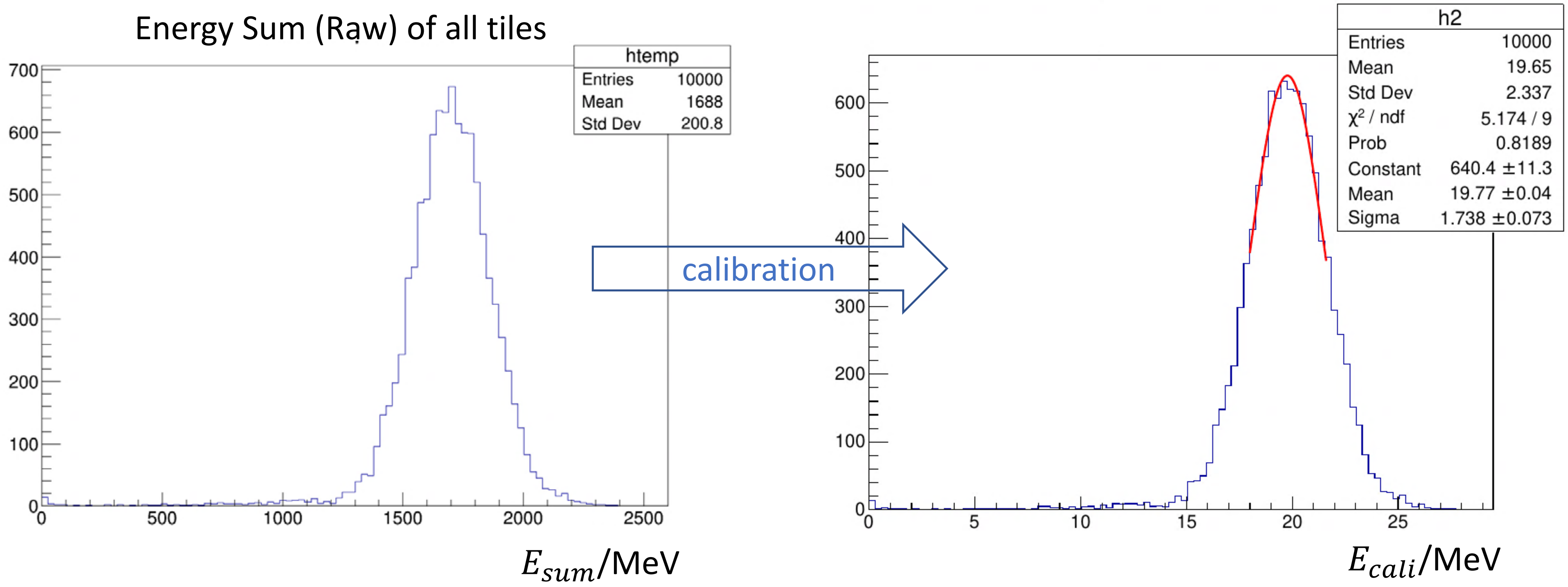
- Realistic parameters: ~65 p.e./MIP, using large size $6\times6\ mm^2$ SiPM
- Ideal parameters: ~160 p.e./MIP ⟶ possible to use smaller SiPM
- Next plans:
  - Improve uniformity through tile-designs: "SiPM-on-Tile" is a feasible option
  - Scintillating glass R&D: improve both density and light yield

Summary and prospects

- A novel HCAL concept with high-density scintillating glass
  - Aim to improve energy resolution, especially hadronic energy resolution
- Performance of scintillating glass HCAL
  - Better hadronic energy resolution in low energy region (<30GeV)
  - Homogeneous glass HCAL improves the BMR by at least 10%
- Measurements of scintillating glass samples
  - Transmission/emission spectra, light yield, energy resolution and decay time
- Studies on the performance of basic detected unit
  - MIP response: cosmic-ray test and simulation
  - Impact of uniformity and tile size
- 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 both light yield and density, develop large-sized samples

Backups

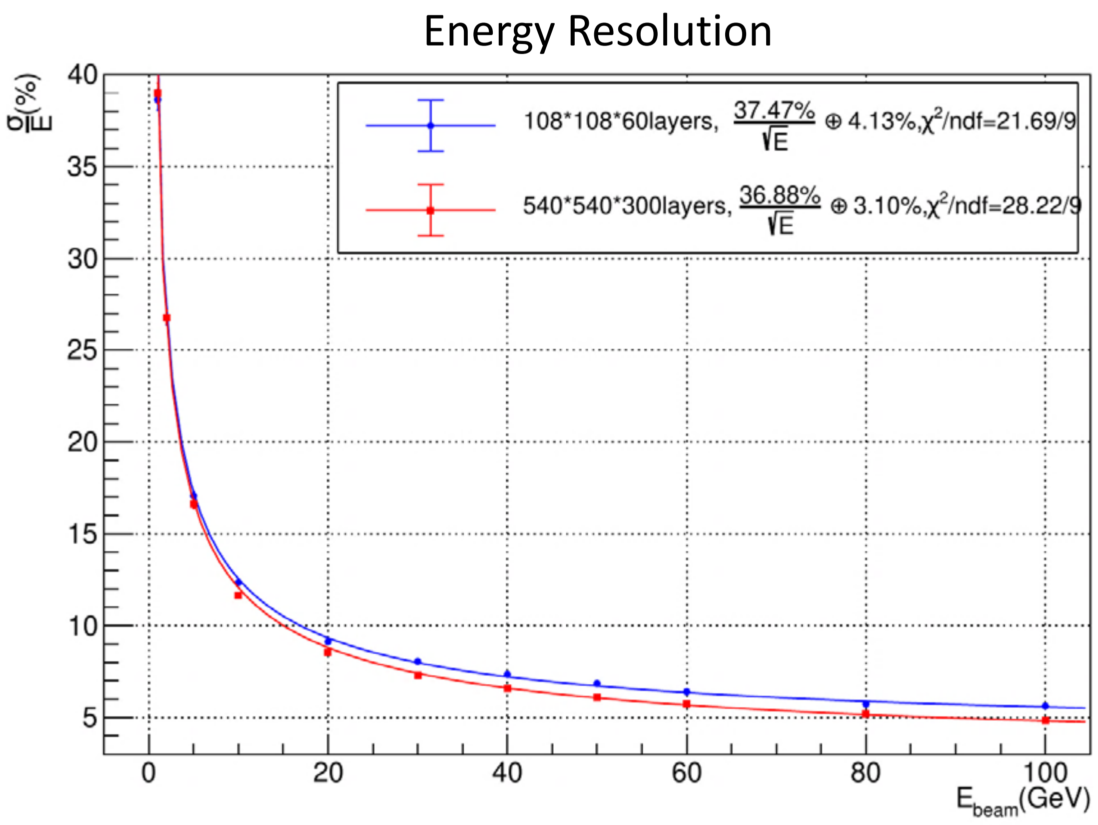
Definition of energy resolution



Incident particle: 20GeV K_L^0

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

HCAL: evaluate leakage effects

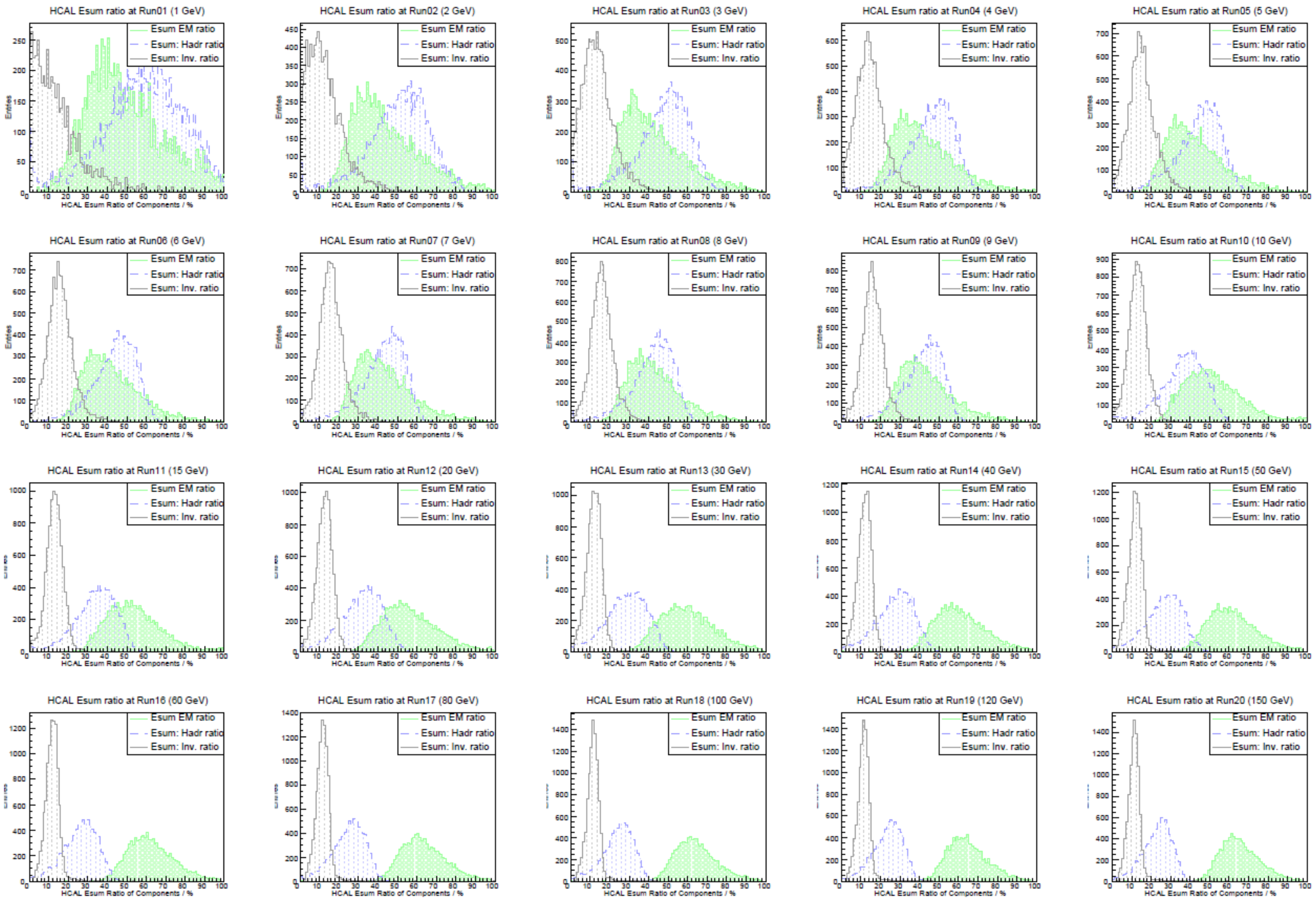


- Geometry size
  - Baseline: 108cm×108cm×60layers(~1.5m)
  - Ideal: 540cm×540cm×300layers(~7.5m)
- Incident particle: kaon0L (1-100 GeV)

- The impact of shower leakage to energy resolution in the 60 layer is estimated (~1% level)

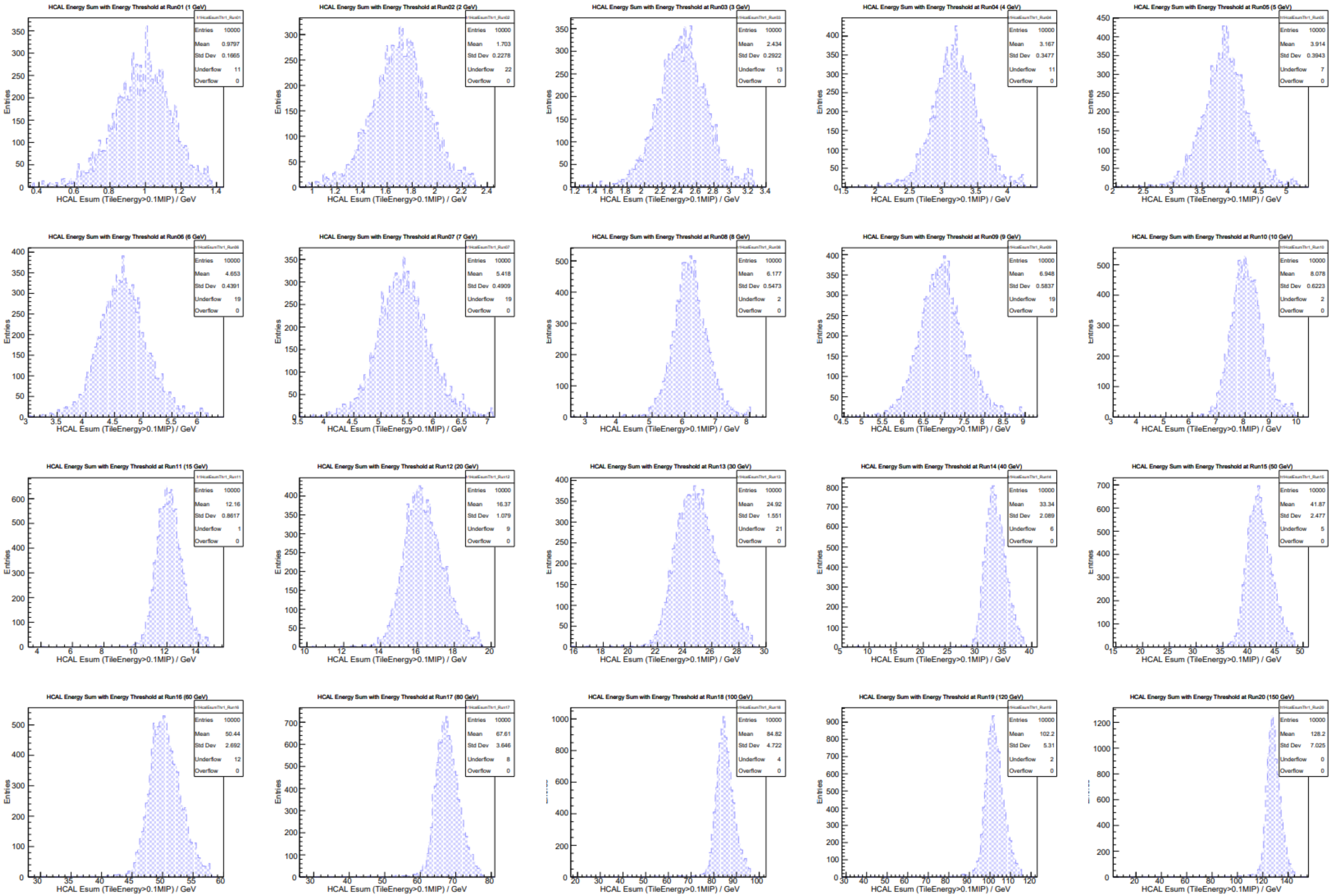
Homogeneous HCAL: energy deposition with K_L^0

Categorize energy depositions: EM, hadronic, invisible



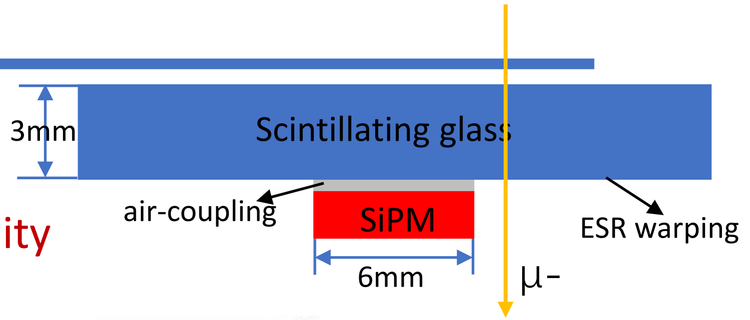
Homogeneous HCAL: energy deposition with K_L^0

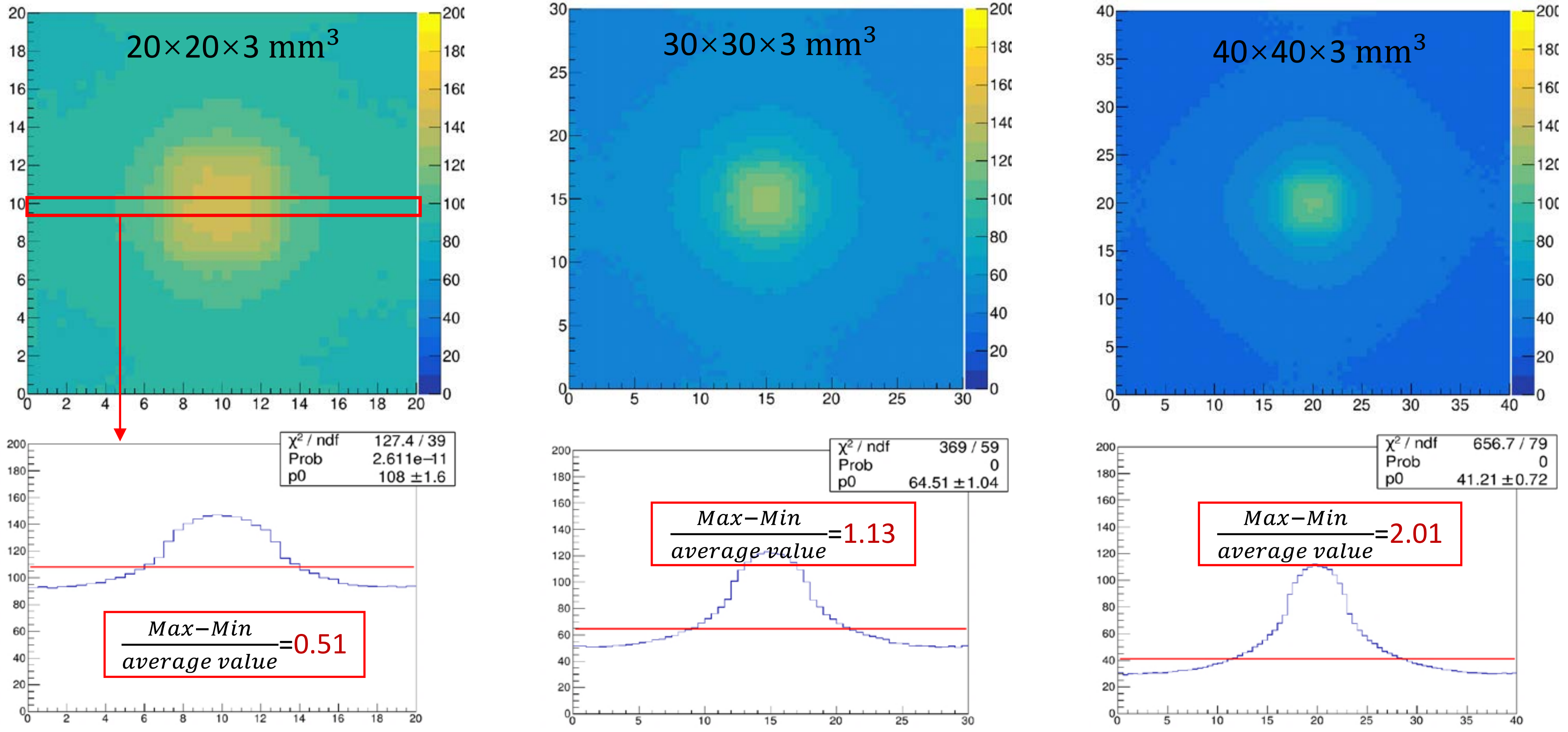
Energy sum



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





$\frac{Max-Min}{average\ value}$=0.51

$\frac{Max-Min}{average\ value}$=1.13

$\frac{Max-Min}{average\ value}$=2.01

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

Calculation of light yield

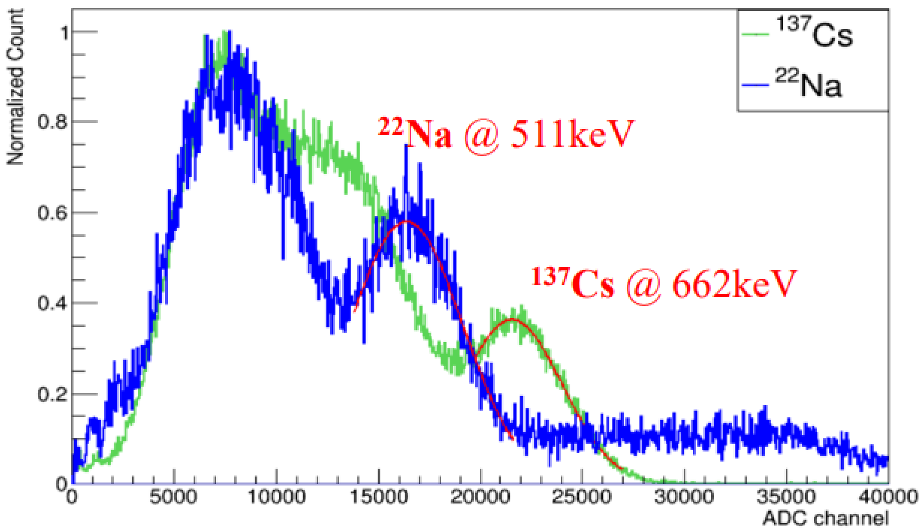
--Absolute light yield: The formula of the light yield: $LY_s = \frac{Mean_{energy} * 1000keV}{Mean_s * PDE_w * PCE * Energy}$

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

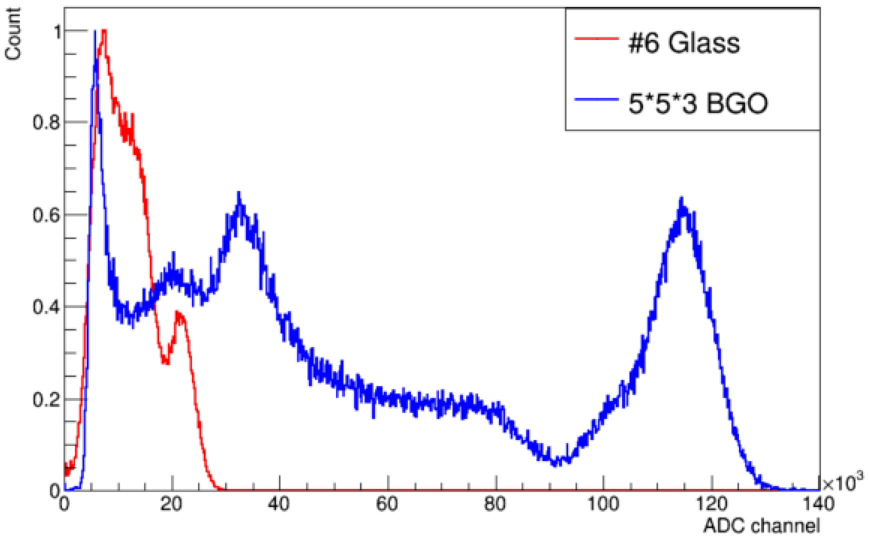
--Relative light yield: Calculate the relative light yield of glass through BGO standard crystal,

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

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