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

Joint Workshop of the CEPC
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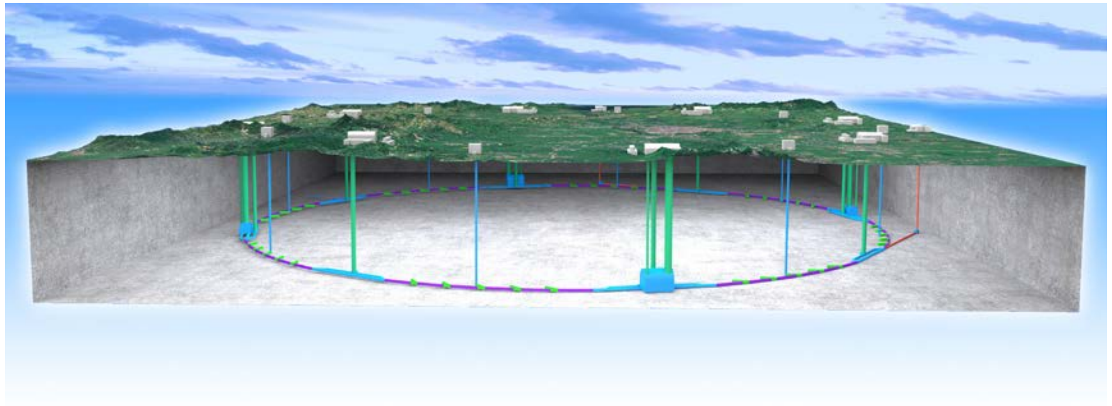
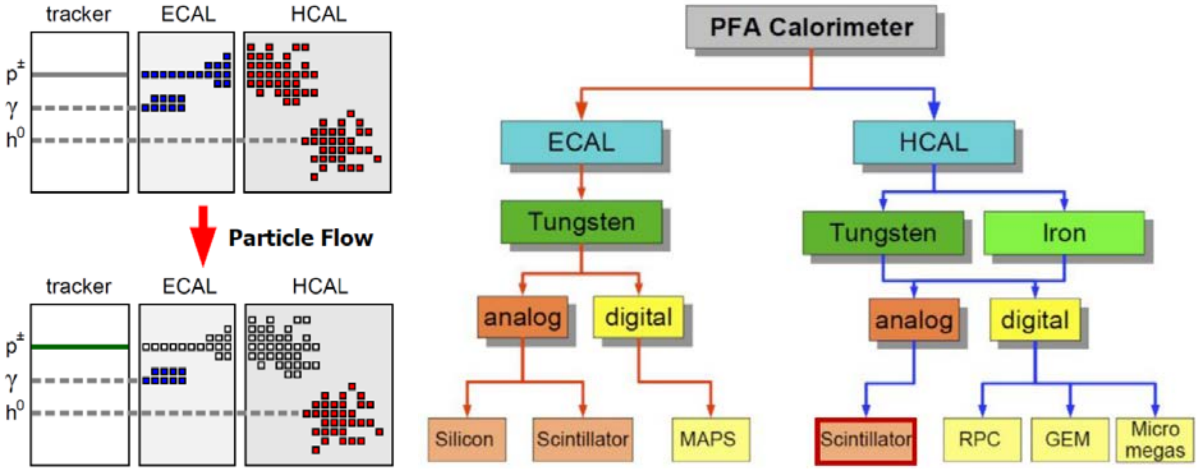
Motivations

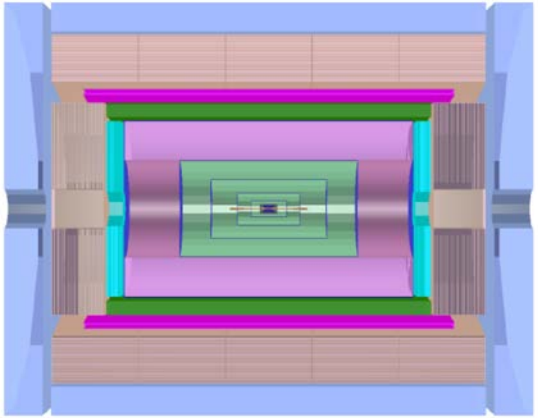
- Future electron-position colliders (e.g. CEPC)
  - Main physical goal: precision measurements of the Higgs and Z/W bosons
  - Challenge: unprecedented jet energy resolution $\sim 30\%\sqrt{E(GeV)}$
- Particle Flow Algorithm (PFA)
  - Choose sub-detector best suited for each particle type (charged, 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

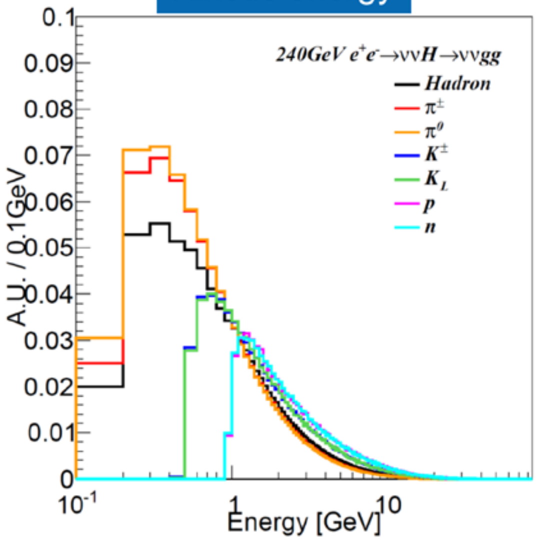
- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- <u>CEPC 4^{th} concept detector</u>: crystal ECAL + scintillating glass HCAL
  - A leap in terms of sampling fractions
  - Aim to improve the energy resolution: esp. the hadronic resolution
  - Physics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



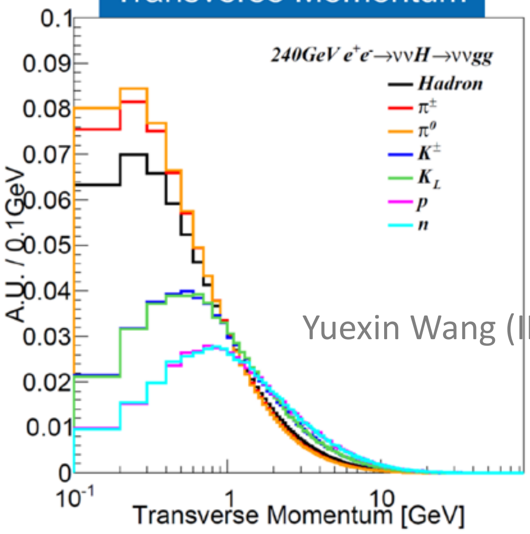
Calorimeters: crystal ECAL and Scintillating Glass HCAL

Report on crystal ECAL: High-granularity crystal calorimeter: R&D status

Kinetic energy

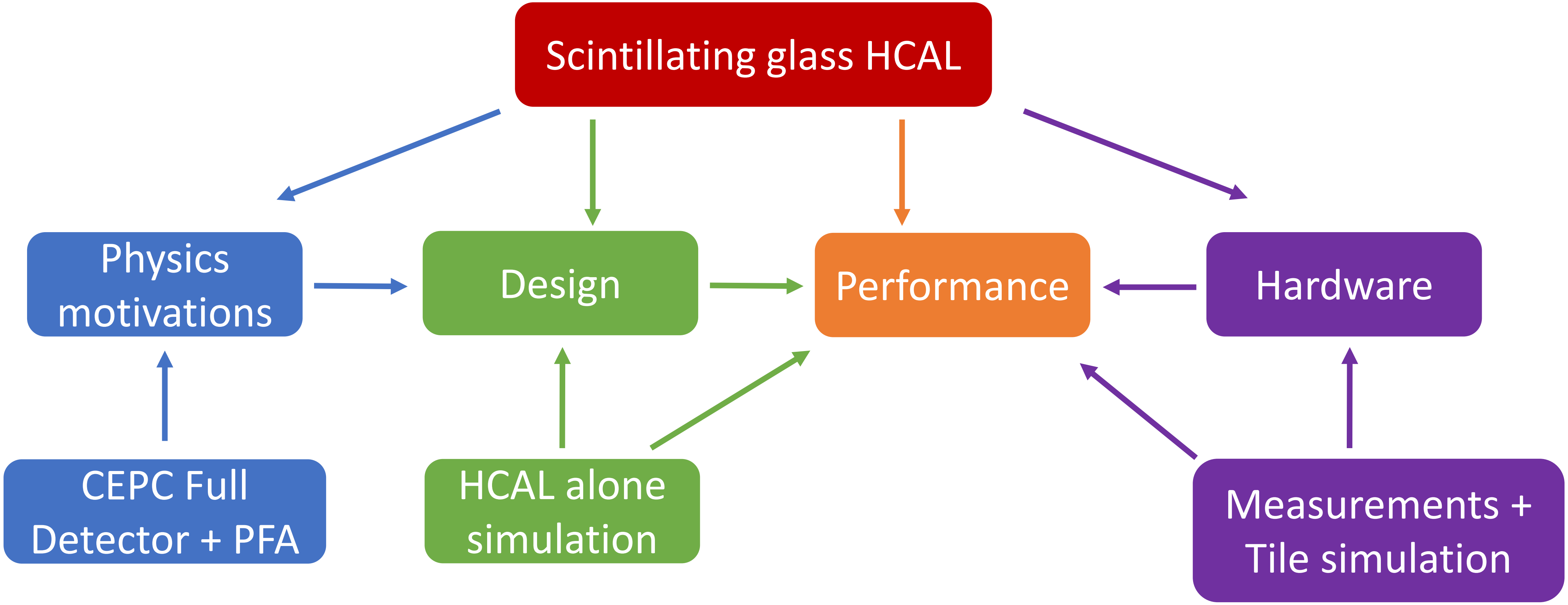


Transverse Momentum



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
  - Experiment and optical simulation
  - Requirements for basic detected unit
- Summary and prospects

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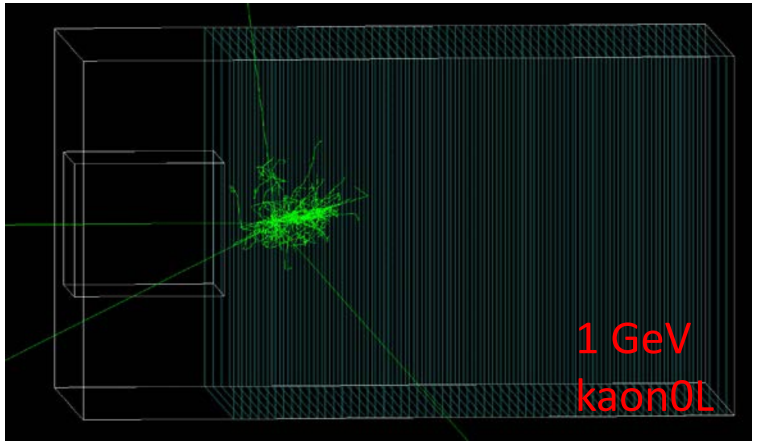
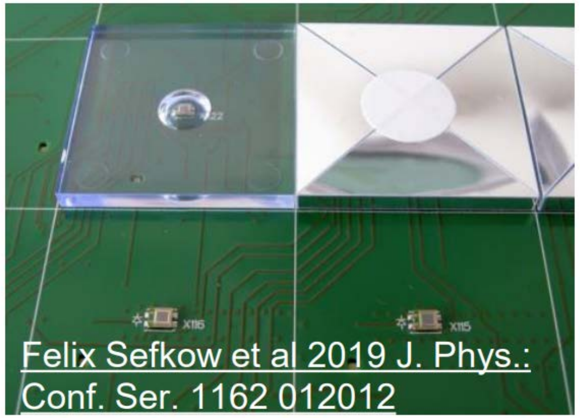
HCAL setup in Geant4 simulation

- 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)

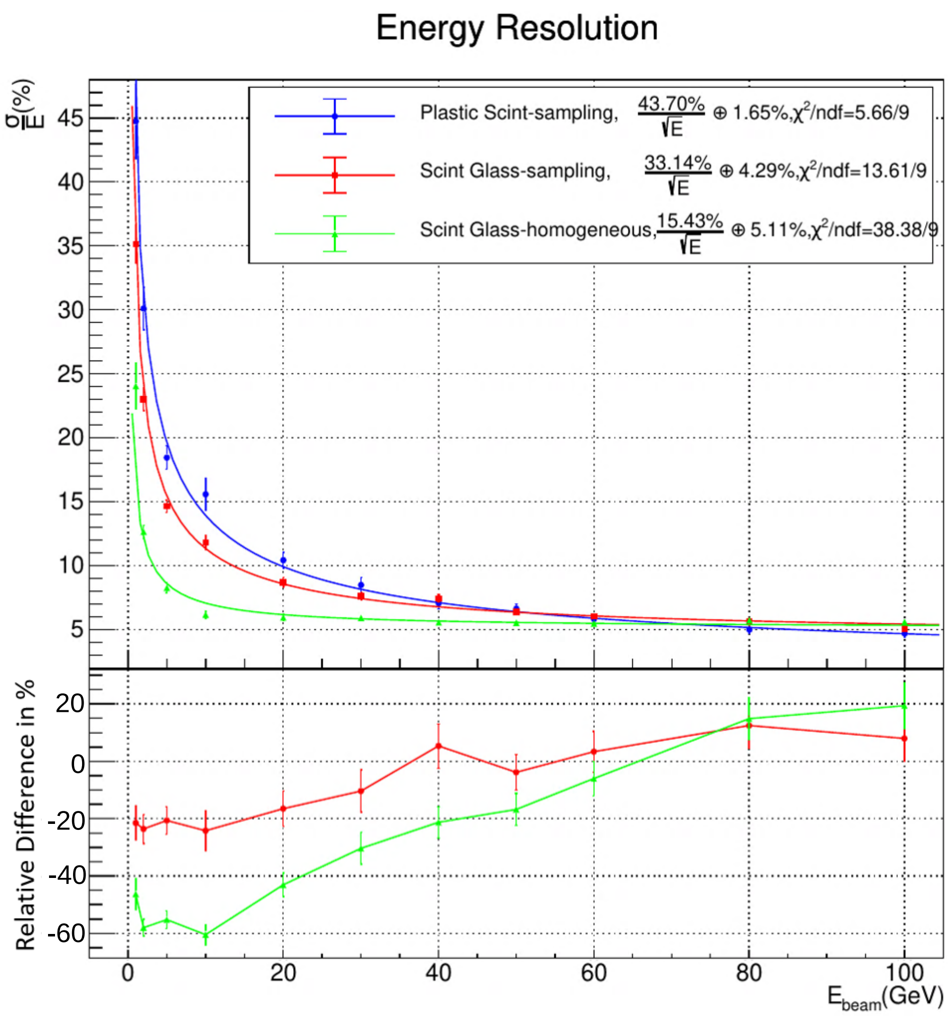


“SiPM-on-Tile” design for HCAL



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

HCAL: plastic scintillator vs scintillating glass

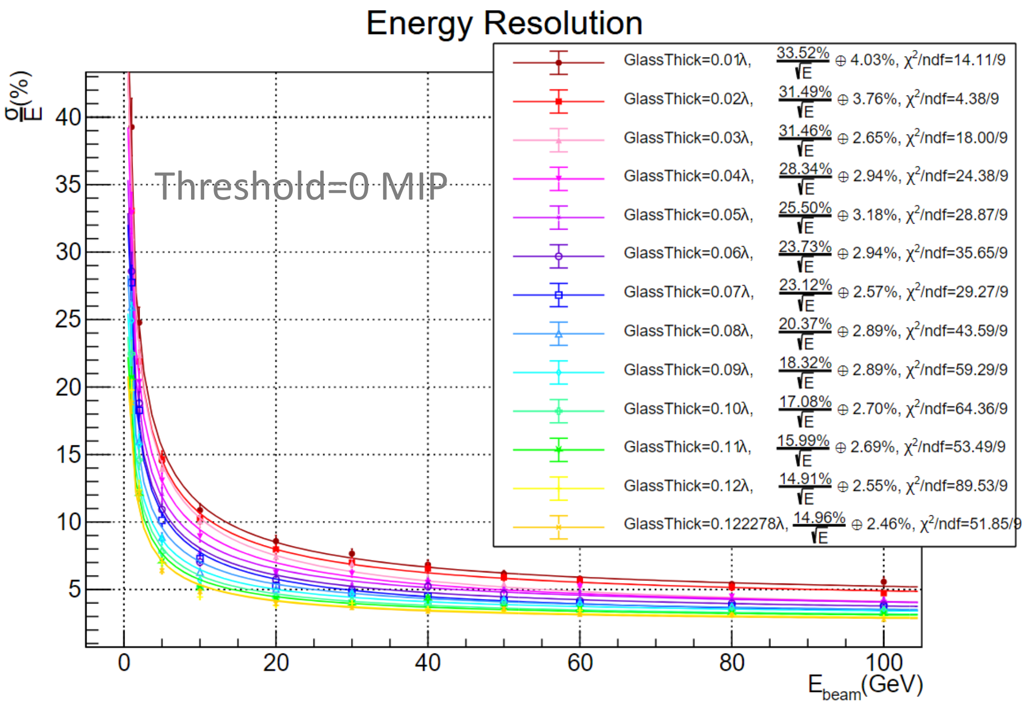


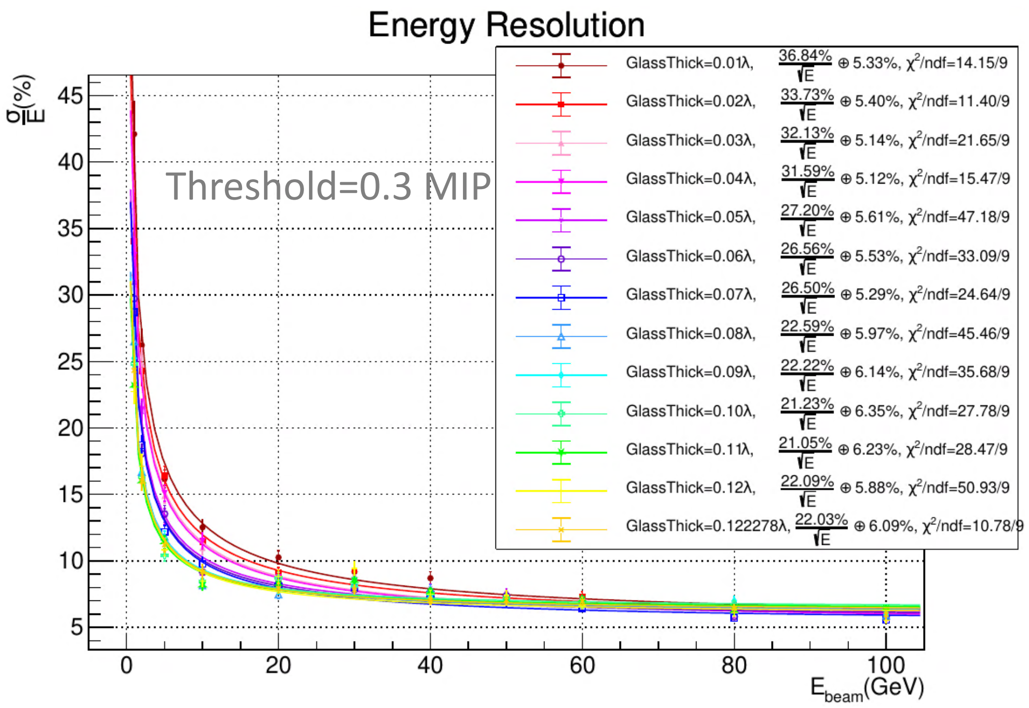
- Incident particle: K_L^0
- Preliminary performance comparison
  - Same thickness of sensitive materials: 3mm
  - No energy threshold applied
- Scintillating glass: better hadronic energy resolution in low energy region (<30GeV)
  - Note that majority of hadrons in jets at CEPC are with low energy
- 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 ~$0.12\lambda_I$: the same as AHCAL (3mm plastic tile, 20mm steel)
  - $\lambda_I = 22.4cm$

Incident particle: K_L^0





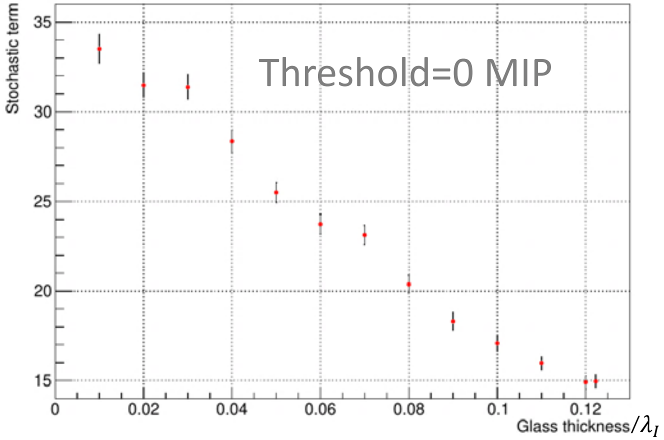
- Energy threshold significantly impacts hadronic energy resolution
- The empirical formula ($A/\sqrt{E(GeV)} \oplus C$) can not well describe curves
  - (Note the χ^2/ndf values) Not fully follow the Poisson distribution

Orange curve corresponds to the homogeneous HCAL

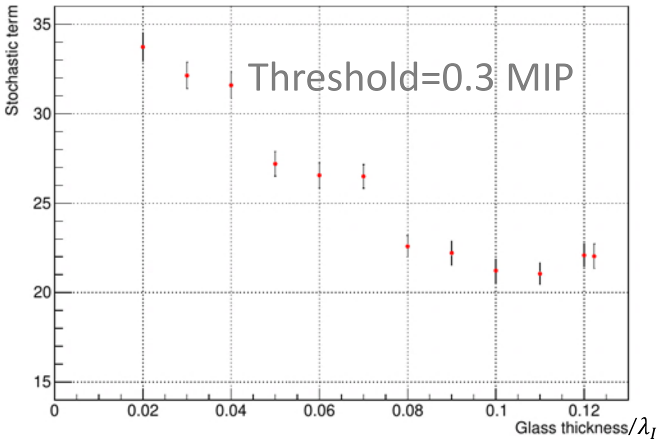
Impact of thickness to hadronic energy resolution

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

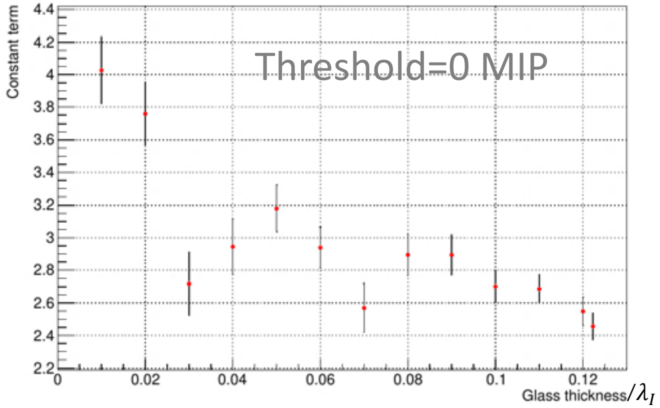
Stochastic term vs. glass thickness



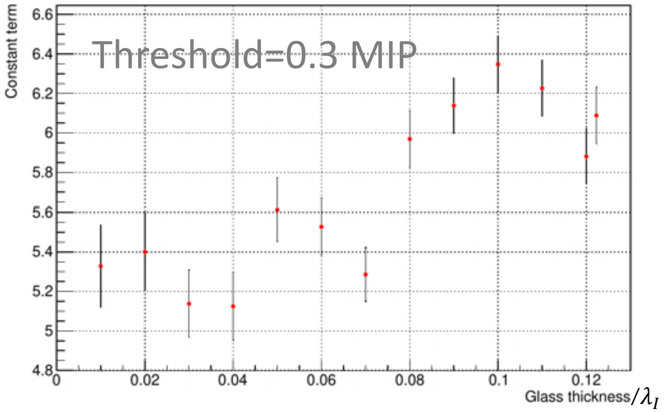
Stochastic term vs. glass thickness



Constant term vs. glass thickness



Constant term vs. glass thickness



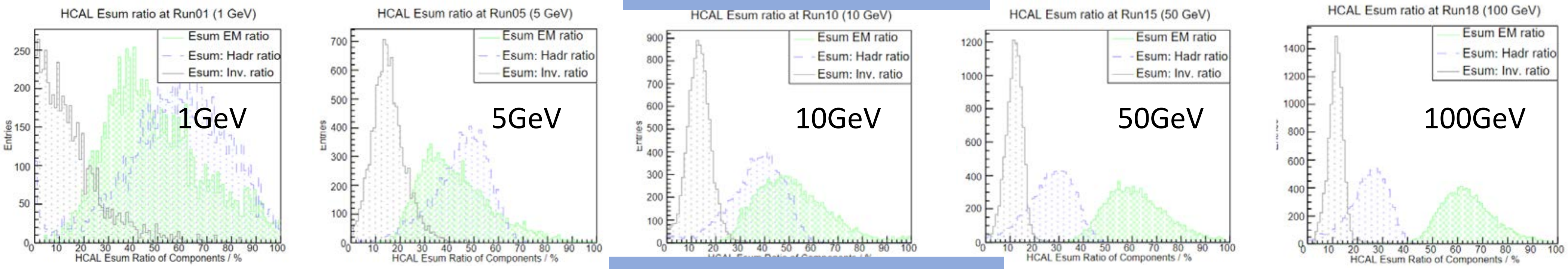
- Energy threshold has a significant impact on the energy resolution
- With the 0.3 MIP threshold, resolution will not be improved when glass thicker than ~0.08 λ_I (18mm)
- Higher threshold significantly degrades the constant term
- Lower threshold would always be desirable for better resolution

Categorize energy depositions

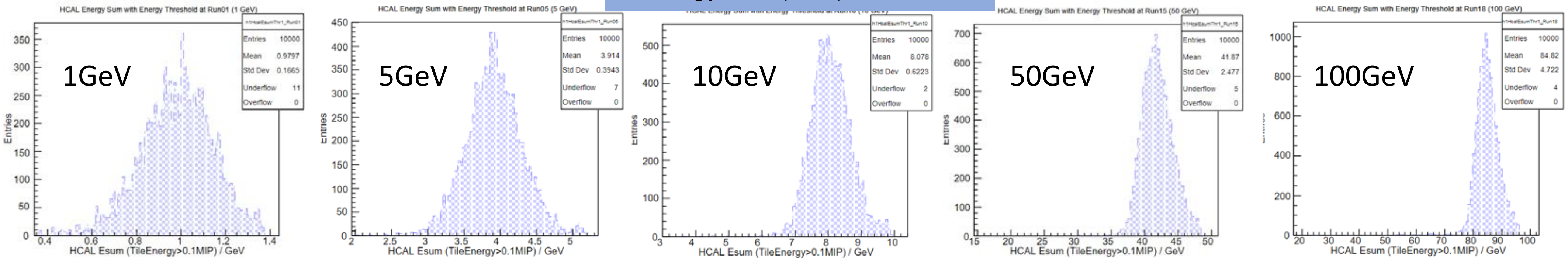
- Categorize energy depositions of hadronic showers: EM, hadronic, invisible

Incident particle: K_L^0
homogeneous HCAL

Component Energy Ratio



Energy Sum (Raw) of all tiles



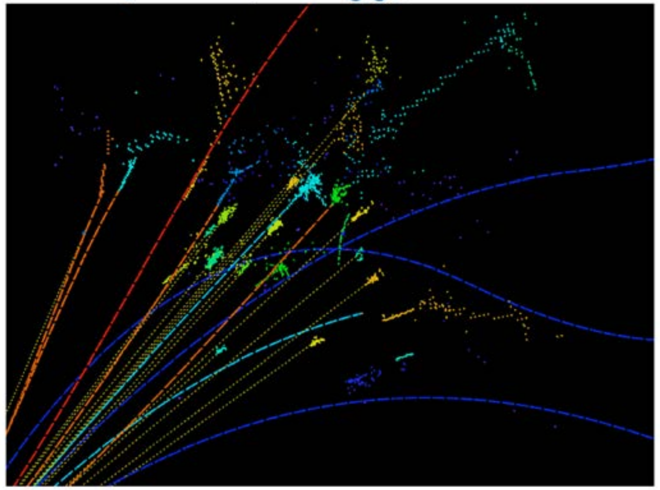
- EM energy deposition usually detected with higher efficiency
- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Yong Liu (IHEP)

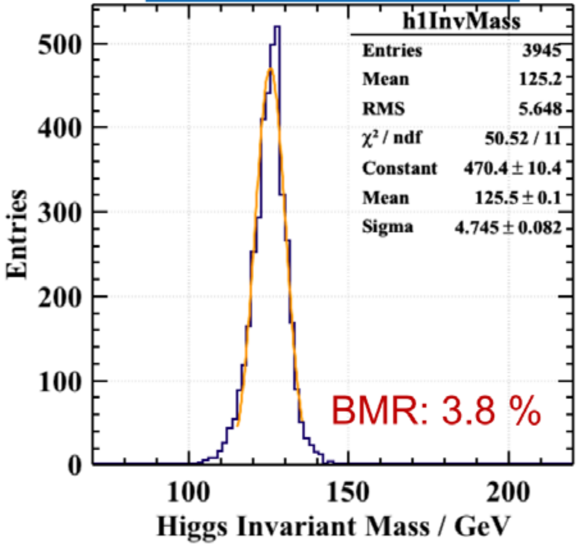
Physical performance: BMR

Dan Yu (IHEP)

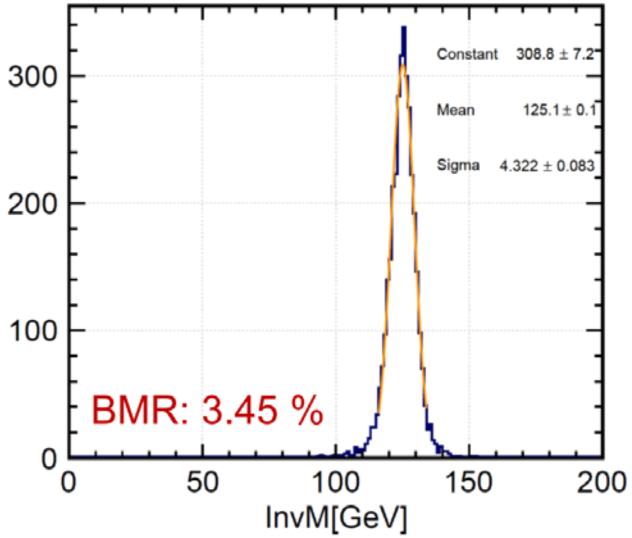
$ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV



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

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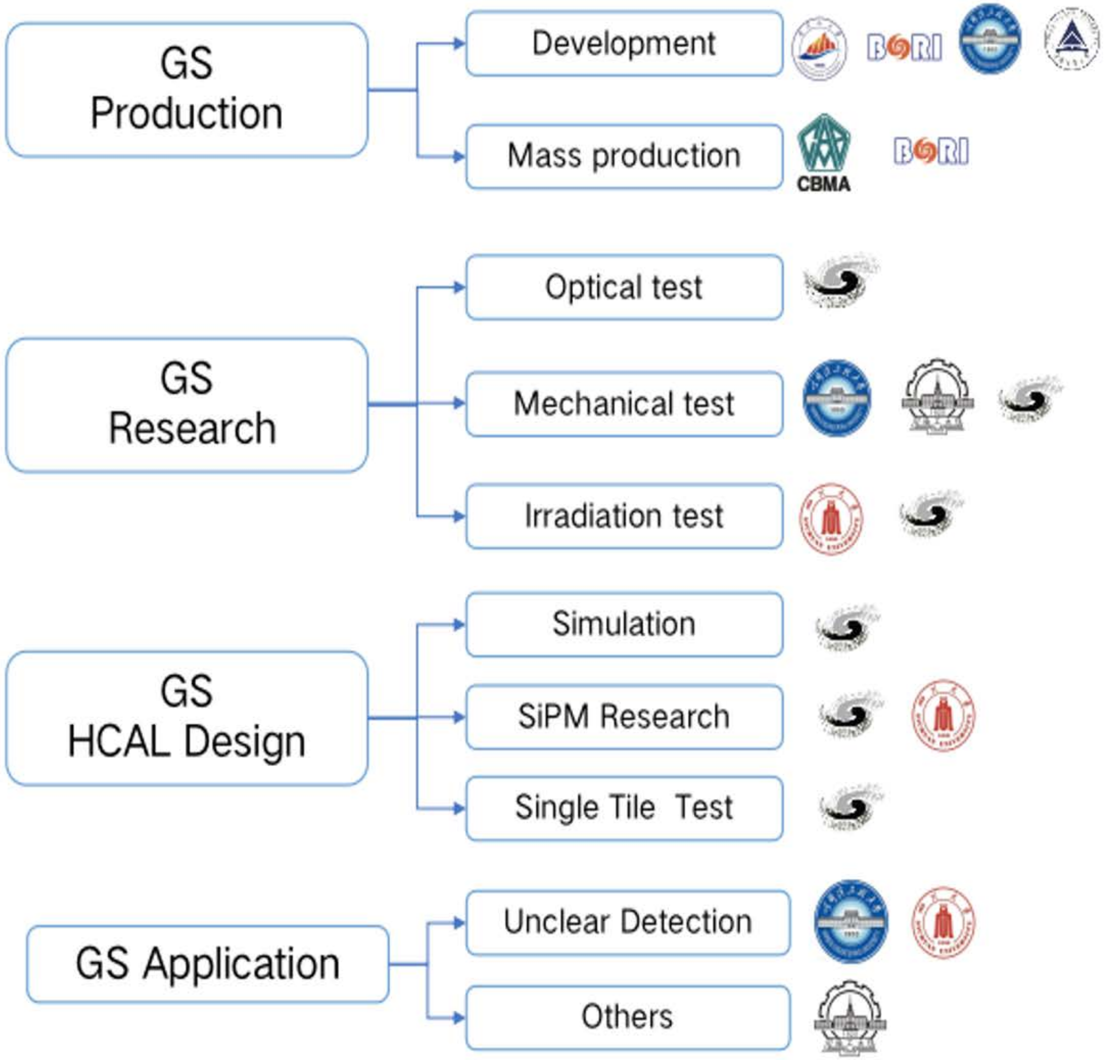
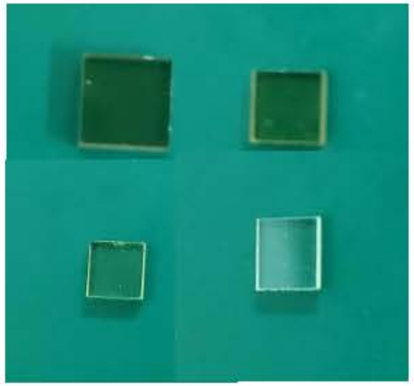
Glass Scintillators R&D Group



- 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



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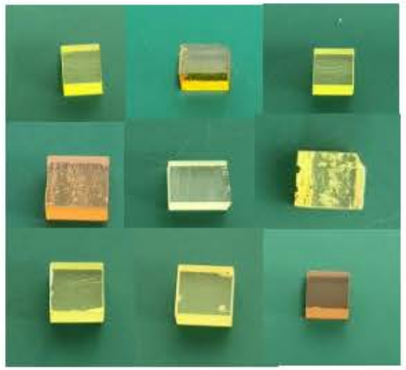

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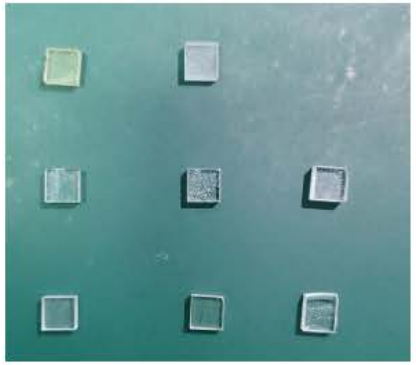

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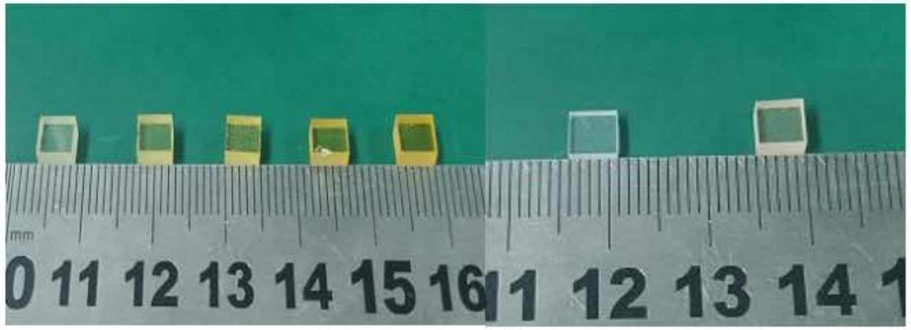

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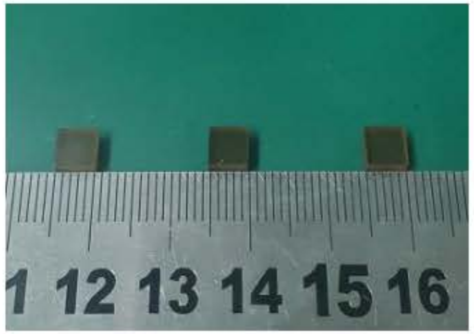
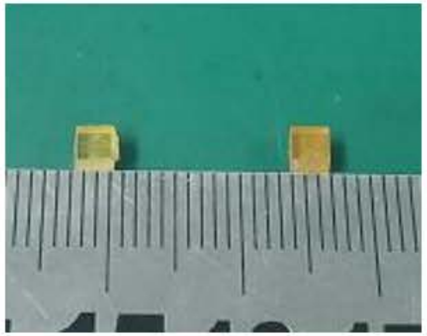


2021.11.22



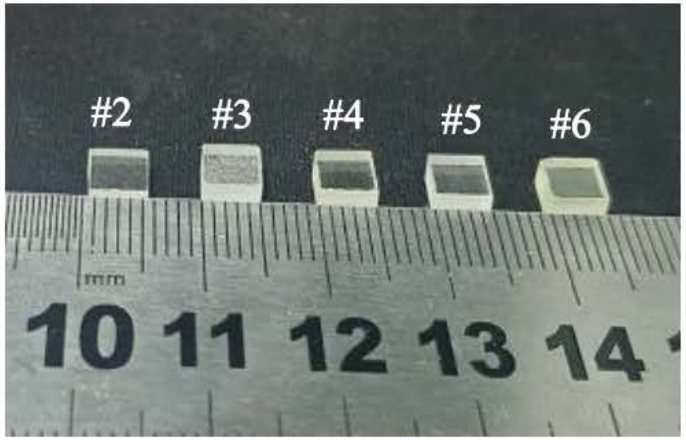
2021.11.23

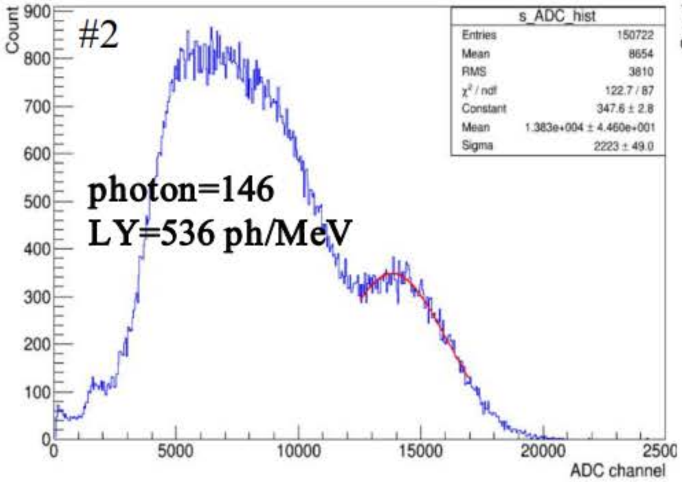
- Comprehensive measurements of key properties
  - Transmission/emission spectra, light yield and decay time
- Over 30 pieces of scintillating glass have been tested, most of which have poor performance
- The best performance glass with the composition: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$

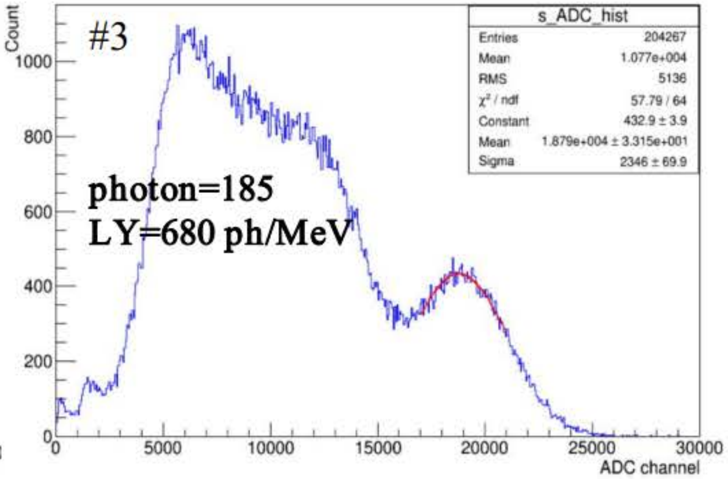
Zhehao Hua (IHEP)

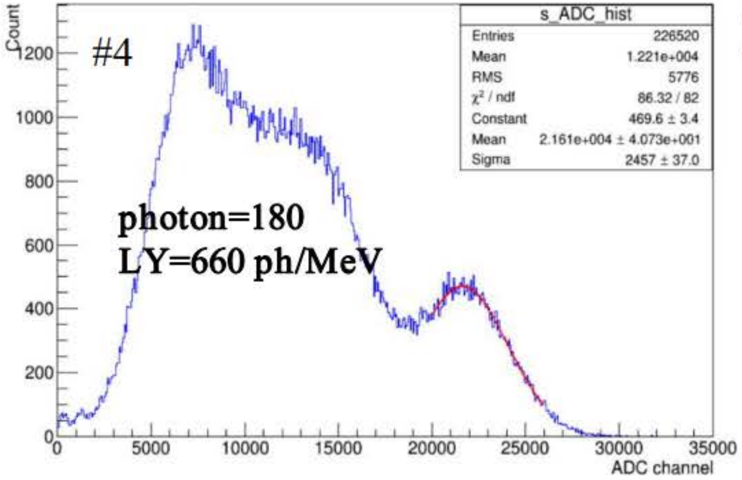
Measurements of light yield

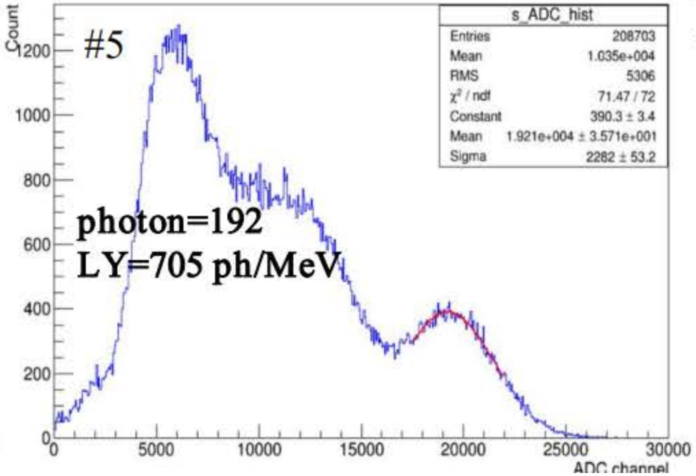
$$LY_s = \frac{Mean_{energy} * 1000keV}{Mean_s * PDE_w * PCE * Energy}$$

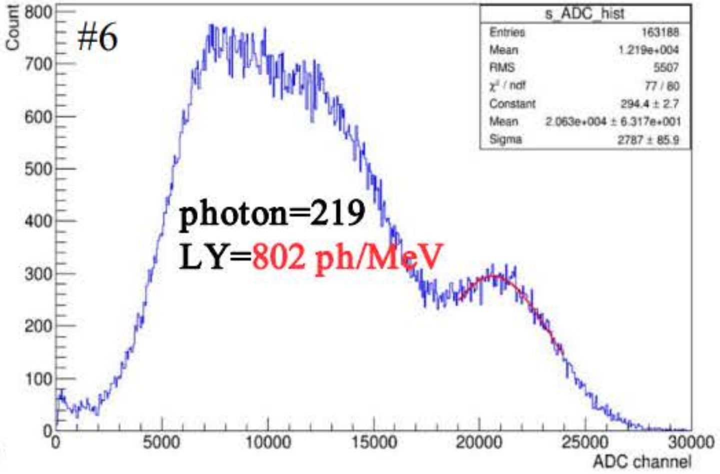












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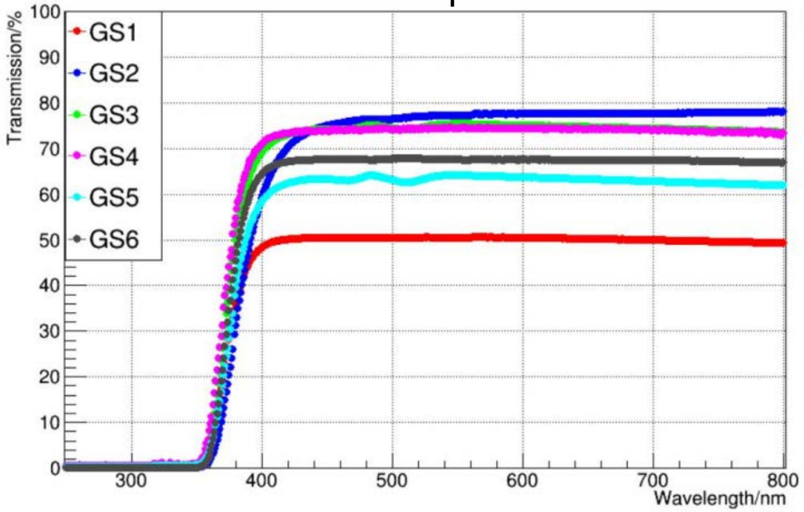
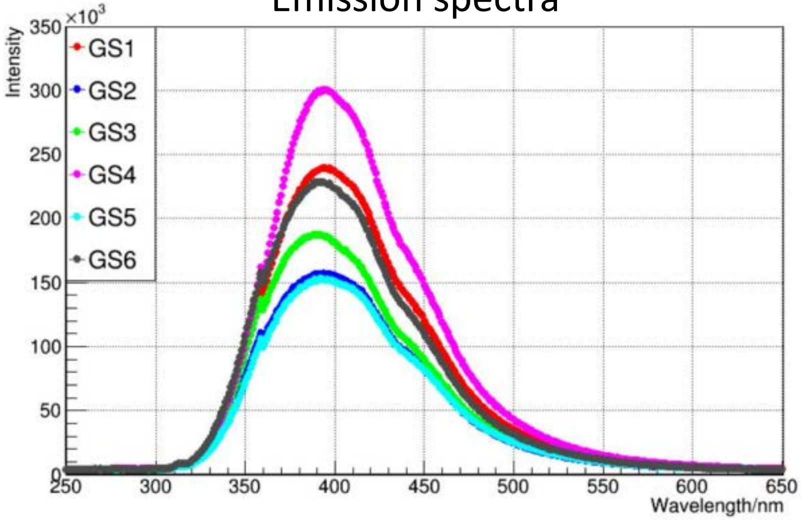
Transmission spectrum, emission spectra and decay time

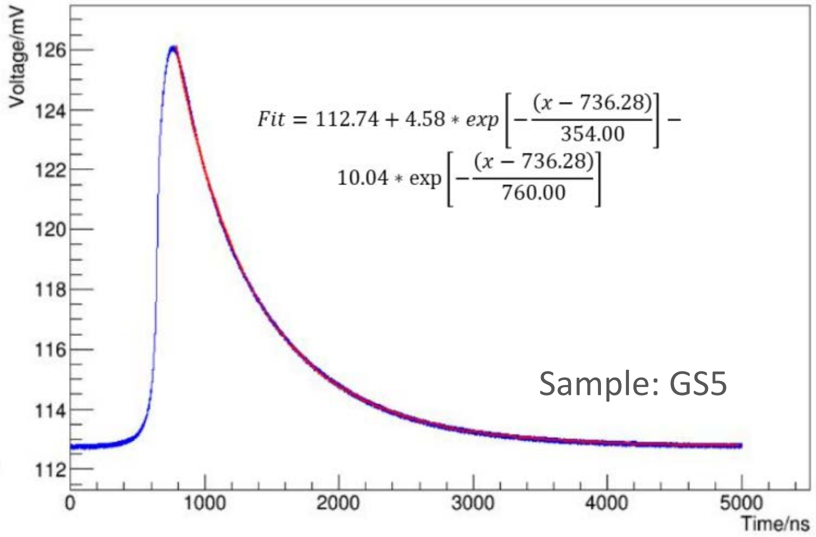
Transmission spectrum



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

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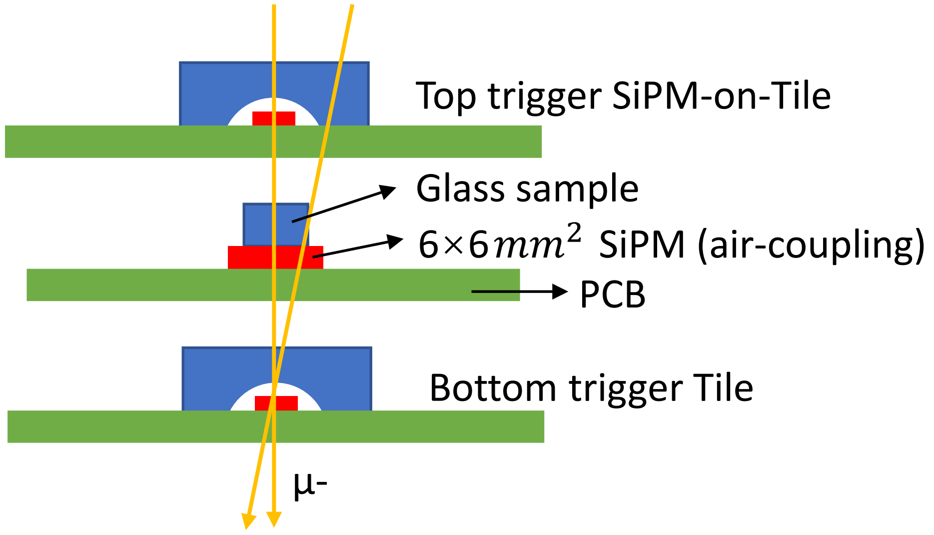
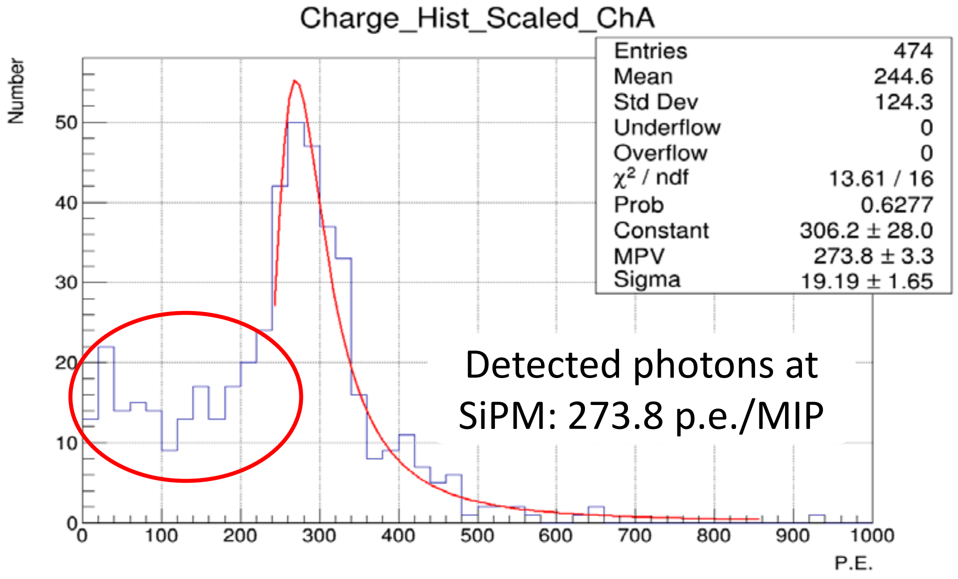
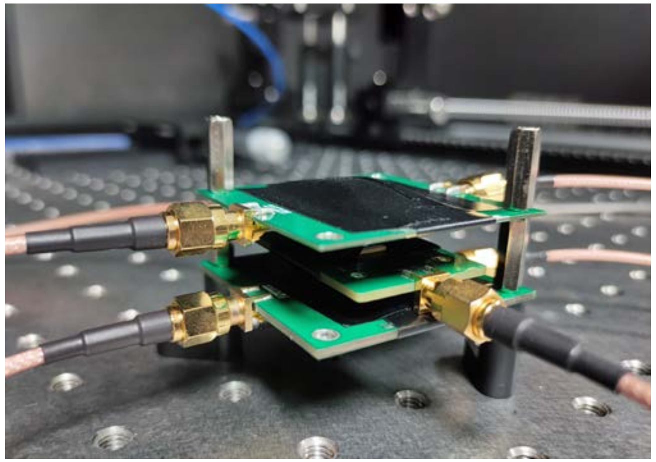
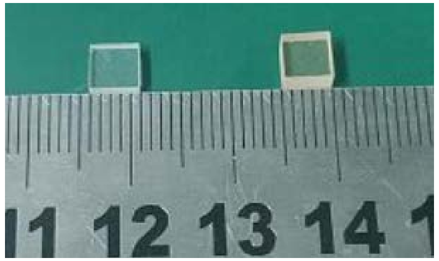
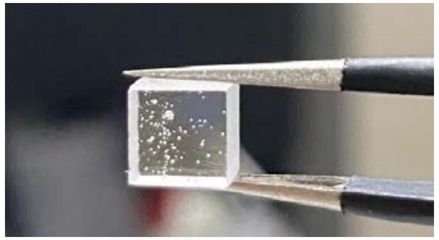
MIP response: cosmic-ray test





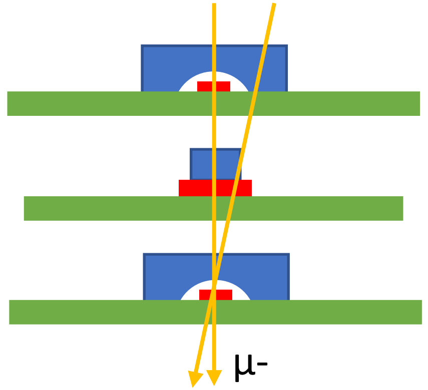


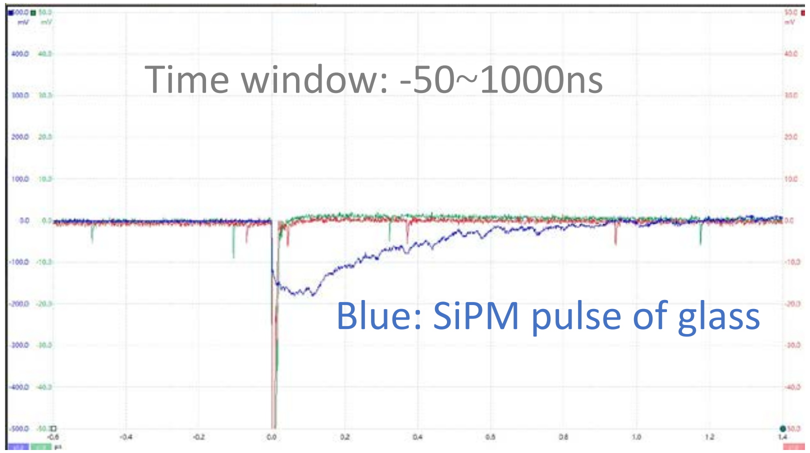




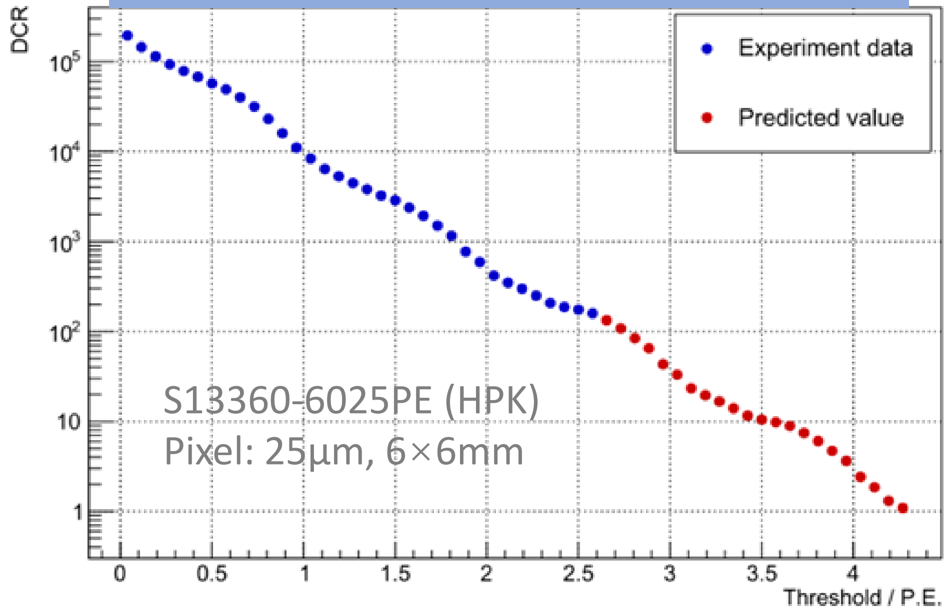
- Glass sample size: $4.5\times4.5\times3.5mm^3$
- MIP response: 274 p.e./MIP
- Plastic scintillator triggers cover larger area than sample does, some comic rays cross part of the sample

Hardware performance

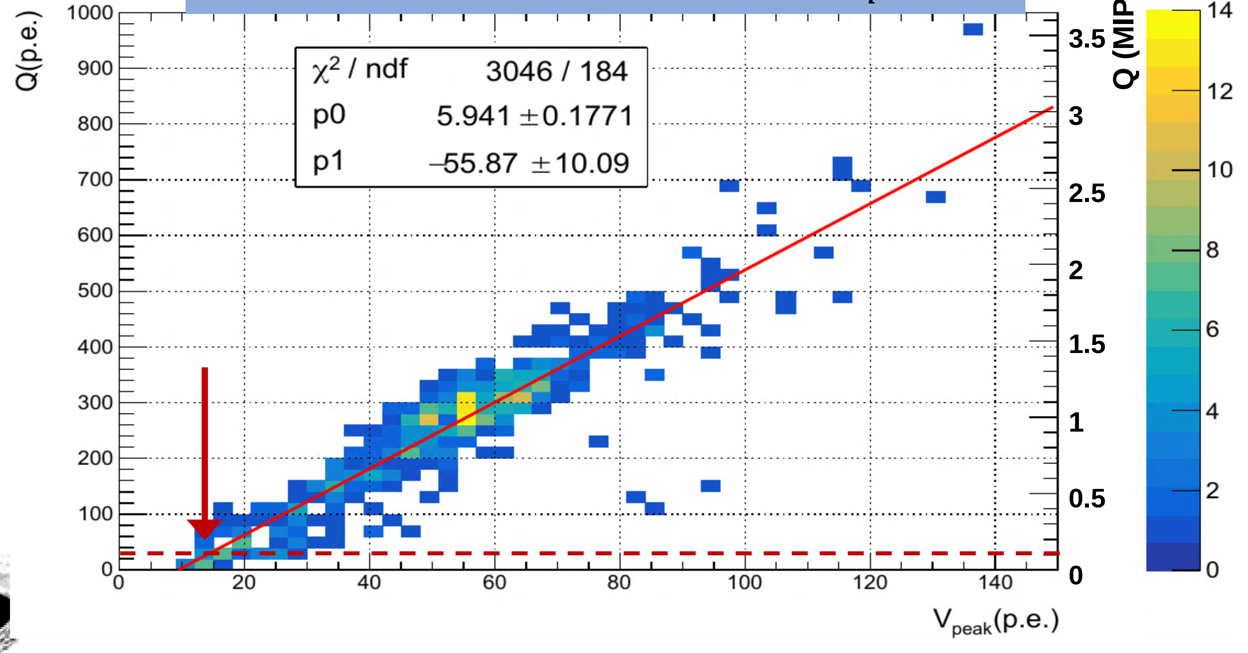




Dark count rate vs. voltage threshold



Cosmic muon data: Charge vs. V_{peak}

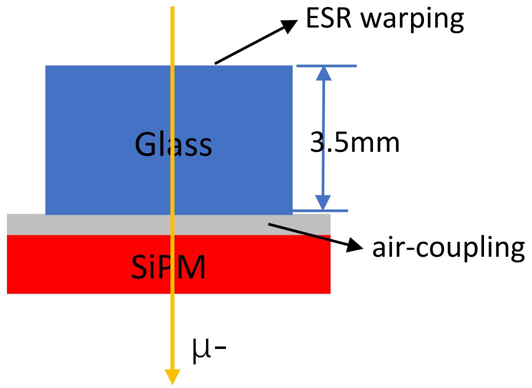


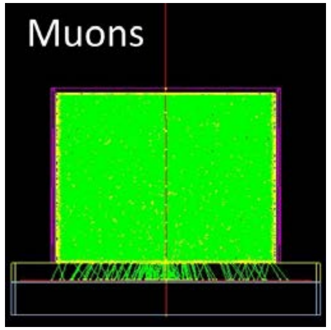
- When threshold > 4.5 p.e., the impact of SiPM dark noise (< 1 Hz) can be ignored

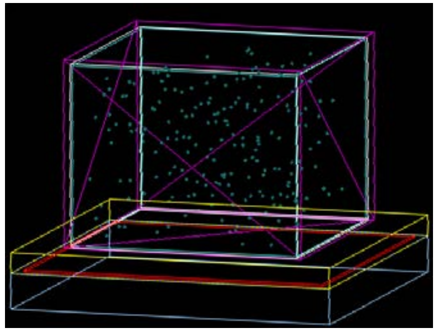
- 0.1 MIP → 14 p.e (V_{peak})
- Energy threshold of 0.1 MIP is feasible

MIP response: optical simulation

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

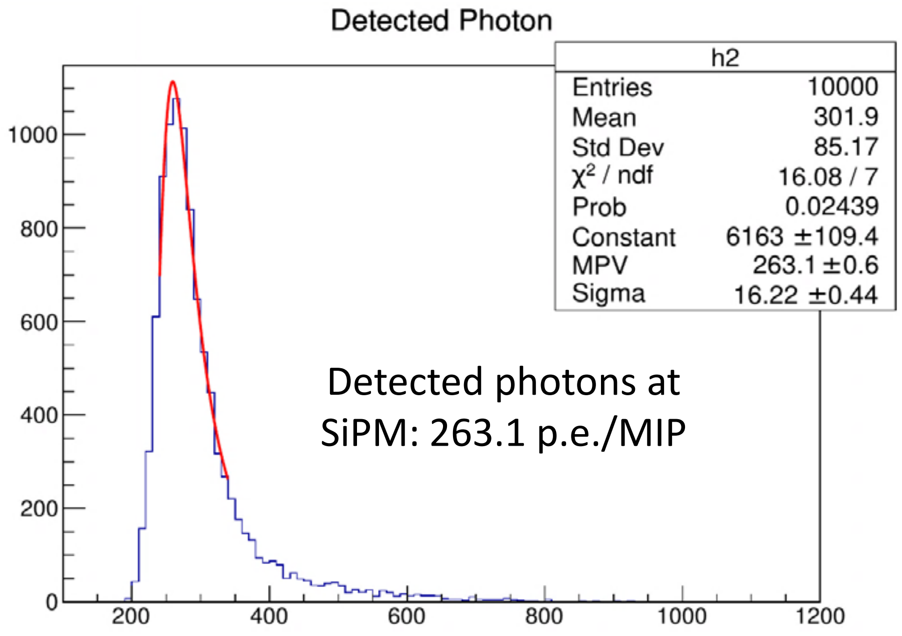






Properties of scintillating glass
- Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
- Density: 4.94 g/cm^3
- Refractive index: 1.67
- Transmittance: 64%
- Emission peak: 394 nm
- Light yield: 881 ph/MeV

(All data based on measurements)

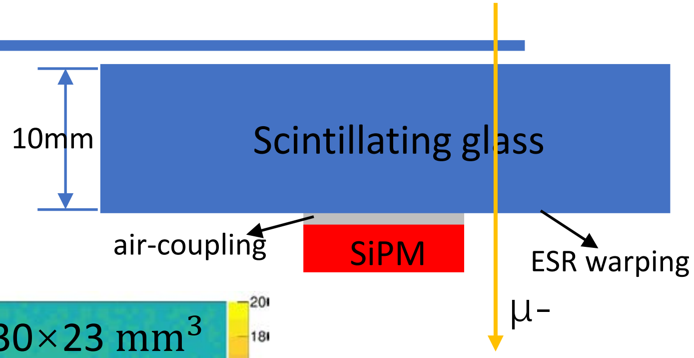


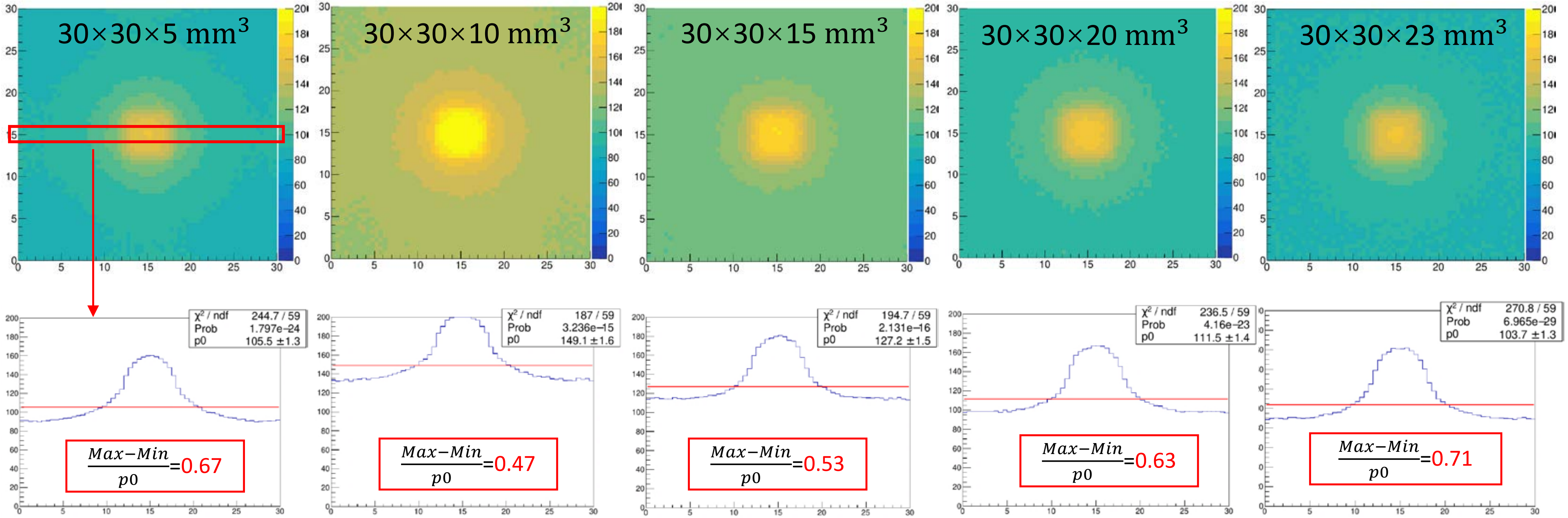
Detected photons at SiPM: 263.1 p.e./MIP

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

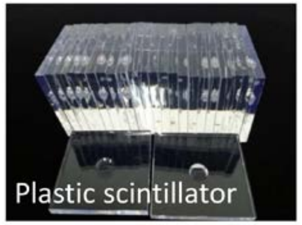
Uniformity scan: impact of tile thickness

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

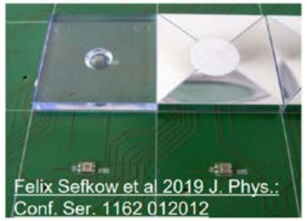




Tiles for AHCAL (30x30x3mm)



"SiPM-on-Tile" design for HCAL



- 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

Requirements for basic detected unit

Key parameters	Value	Notes
Tile size	$30\times30\ \mathrm{mm}^2$	Reference CALICE-AHCAL
Tile thickness	10 mm	Considering: energy resolution, uniformity and MIP response
Density	6-7 $\mathrm{g/cm^3}$	
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

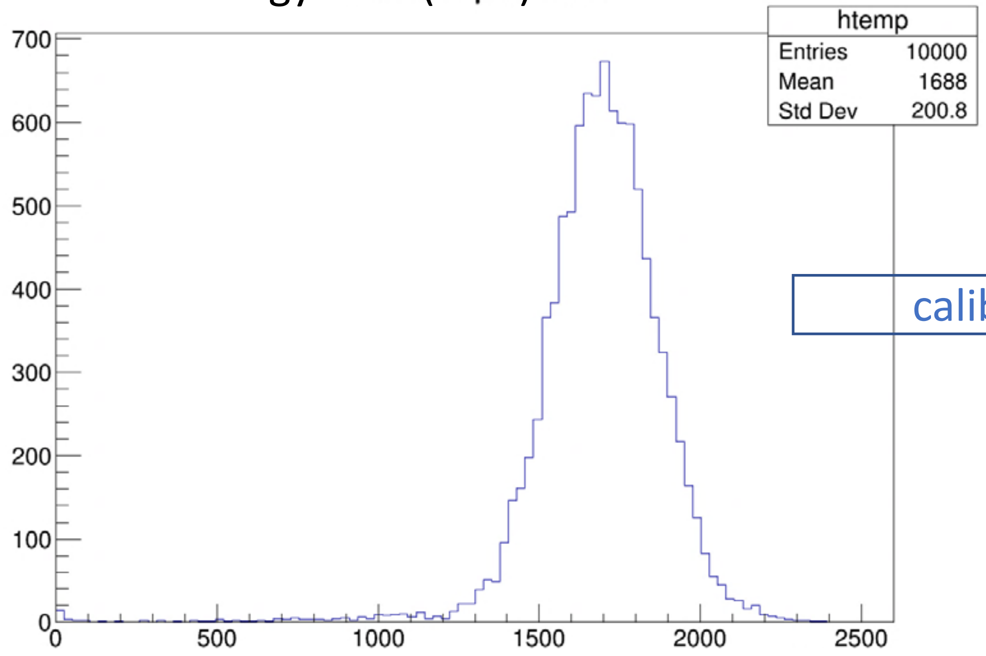
Summary and prospects

- 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
  - Experiment: cosmic-ray test and hardware performance
  - Simulation: MIP response and impact of uniformity
  - Requirements for basic detected unit
- Prospects
  - To further improve the energy resolution: e.g. “Software compensation” technique
  - Improve MIP light yield of a scintillating glass tile through tile-designs
  - Scintillating glass R&D: improve density, light yield and transmittance, develop large-sized samples

Backups

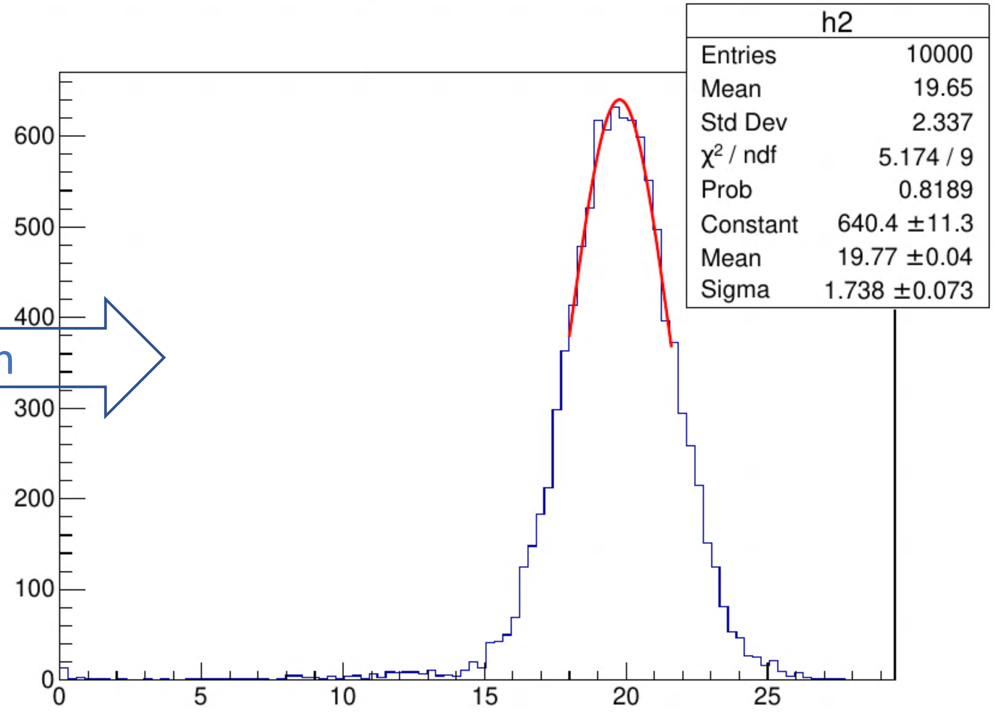
Definition of energy resolution

Energy Sum (Raw) of all tiles



E_{sum}/MeV

calibration

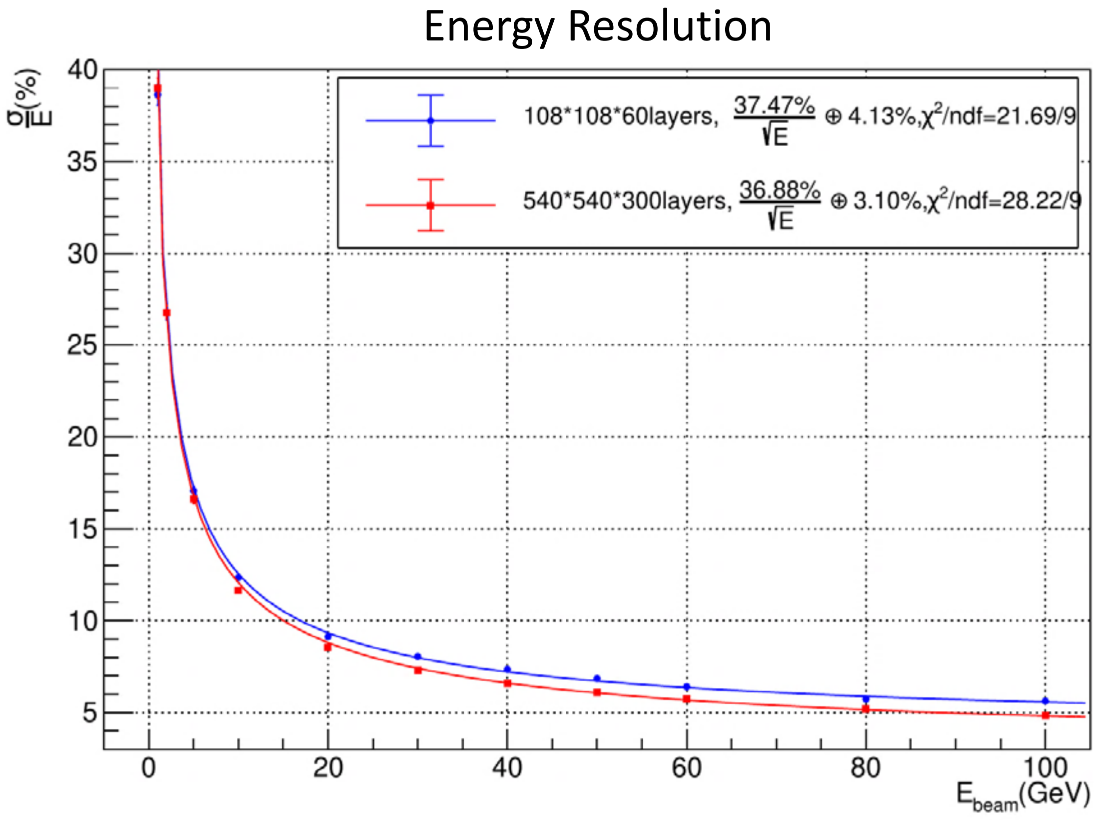


E_{cali}/MeV

Incident particle: 20GeV K_L^0

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

HCAL: evaluate leakage effects

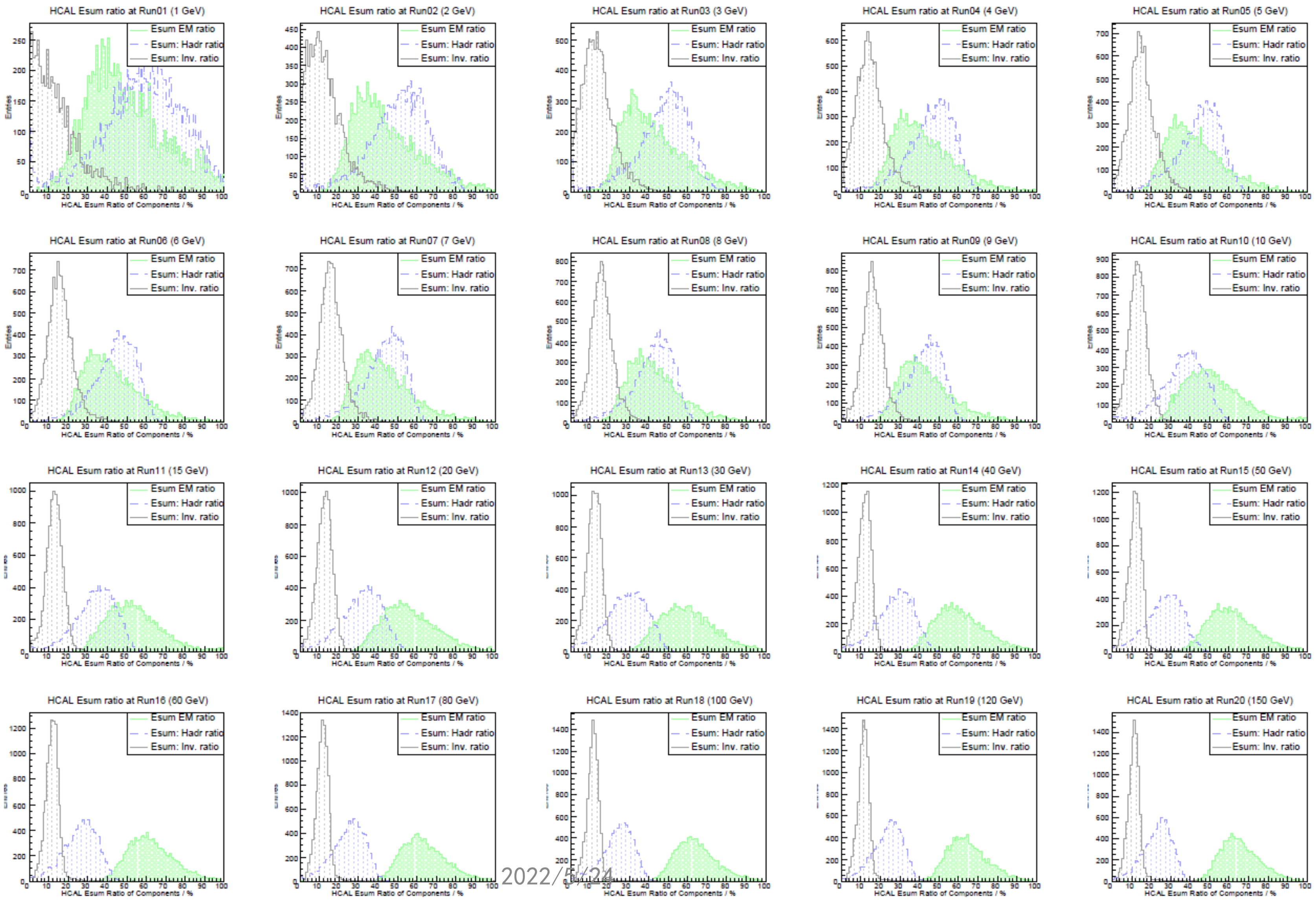


- Geometry size
  - Baseline: 108cm×108cm×60layers(~1.5m)
  - Ideal: 540cm×540cm×300layers(~7.5m)
- Incident particle: kaon0L (1-100 GeV)

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

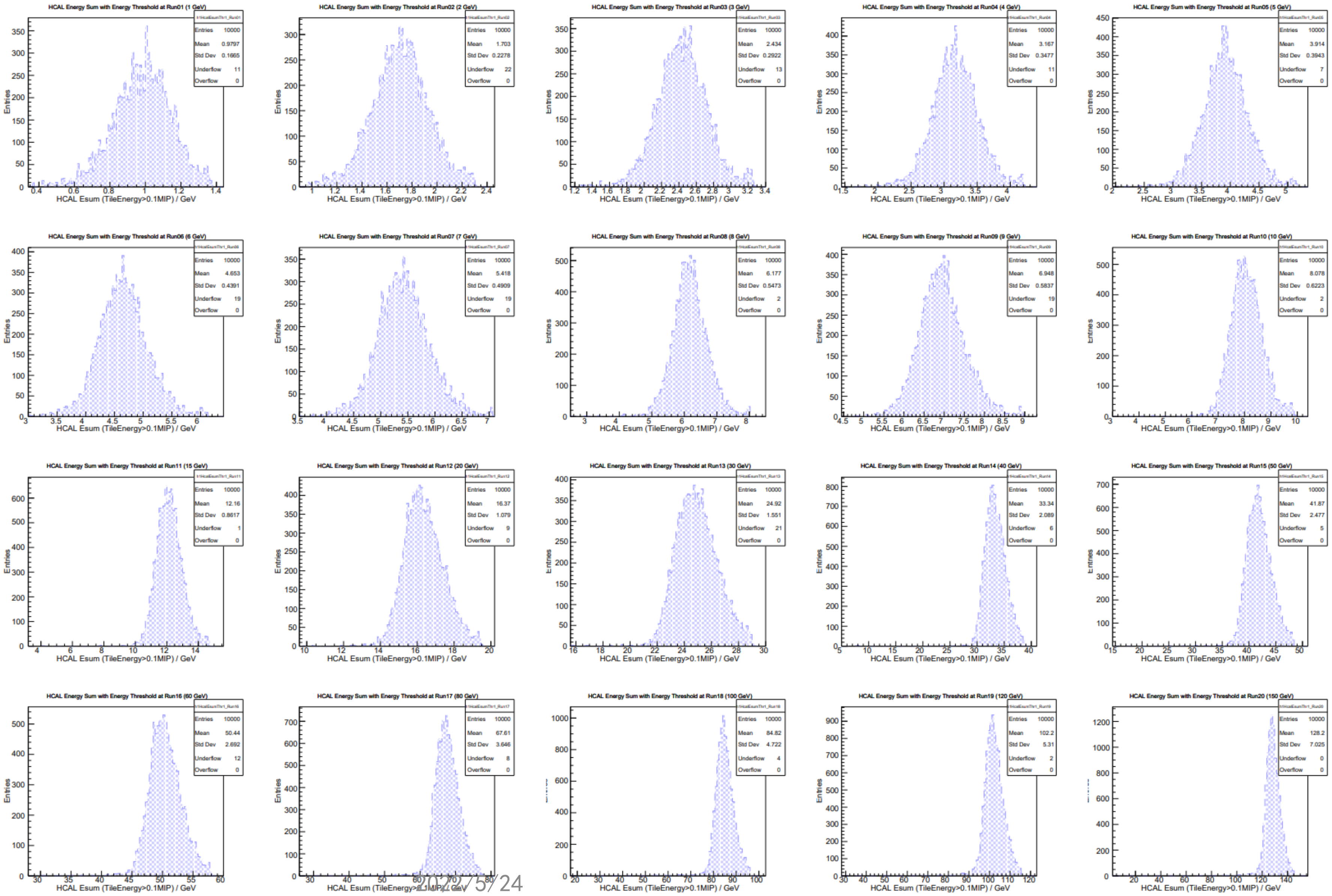
Homogeneous HCAL: energy deposition with K_L^0

Categorize energy depositions: EM, hadronic, invisible



Homogeneous HCAL: energy deposition with K_L^0

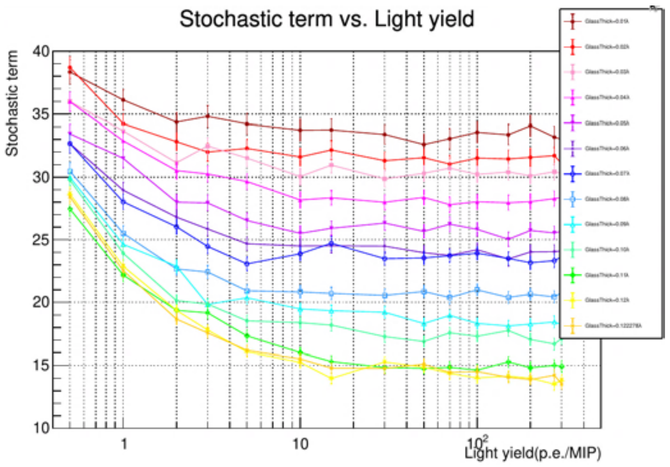
Energy sum

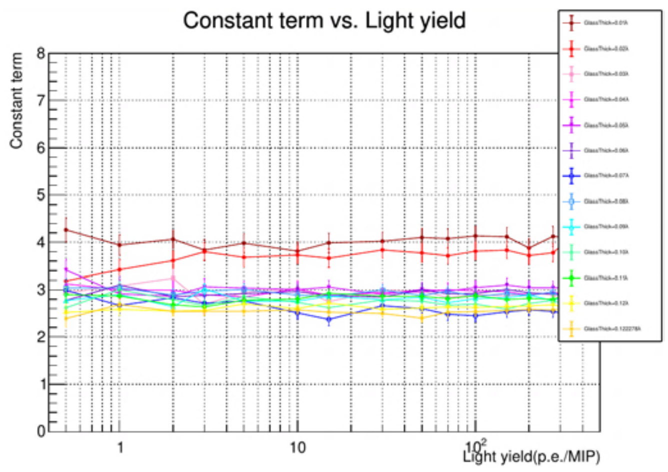


Impact of light yield for energy resolution

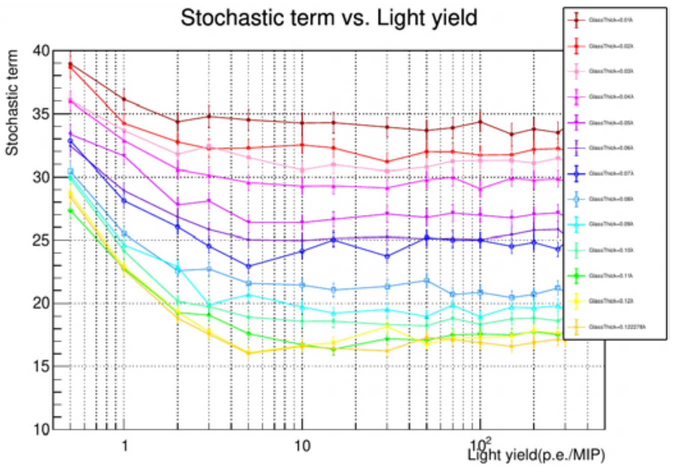
Incident particle: kaon0L (1-100GeV)

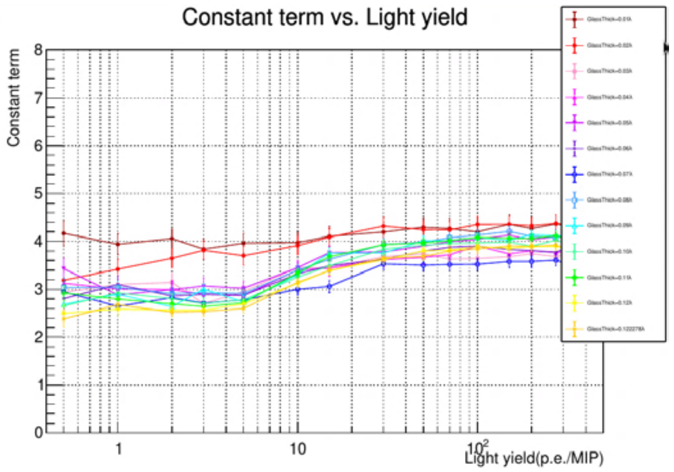
Threshold= 0 MIP



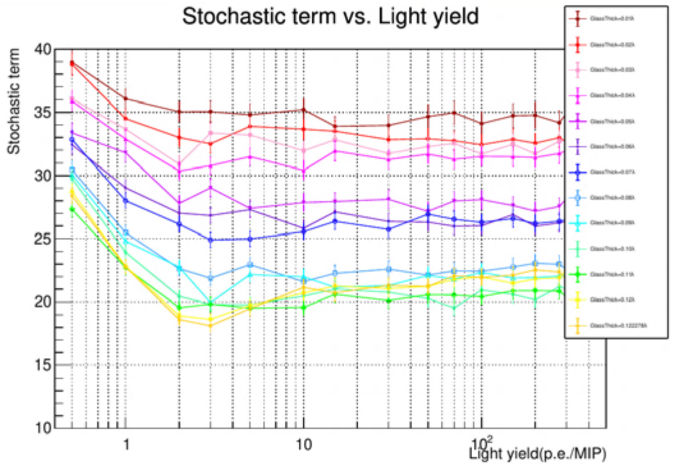


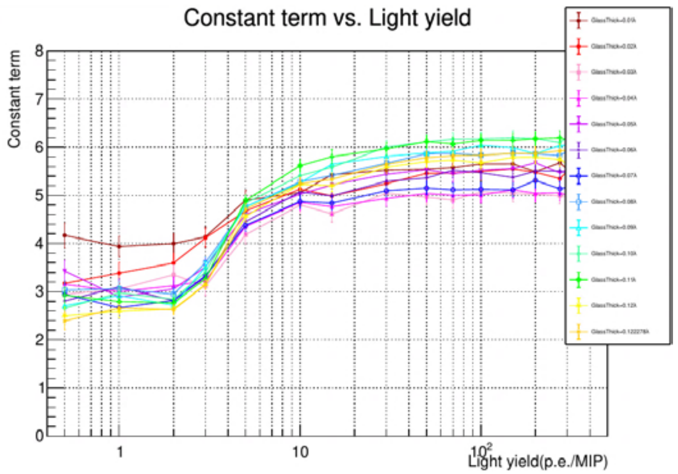
Threshold= 0.1 MIP





Threshold= 0.3 MIP





Calculation of light yield

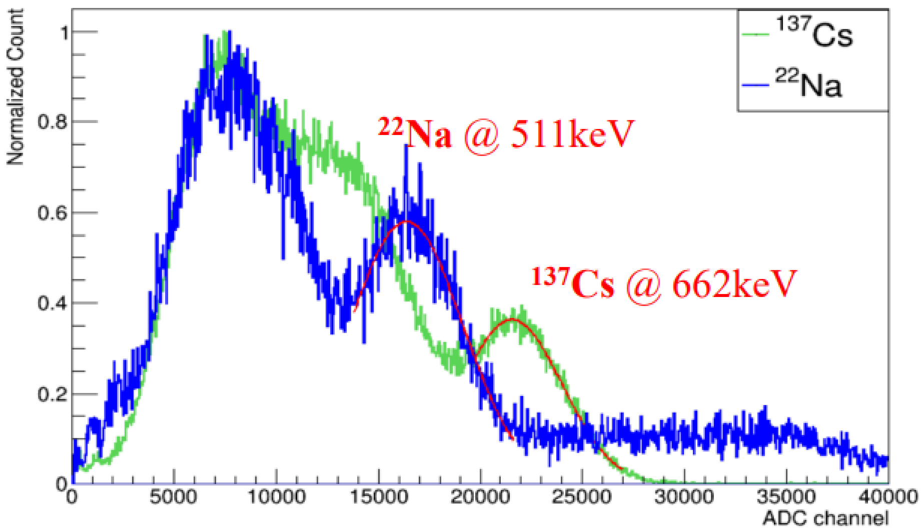
--Absolute light yield: The formula of the light yield： $LY_s = \frac{Mean_{energy} * 1000\text{keV}}{Mean_s * PDE_w * PCE * Energy}$

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

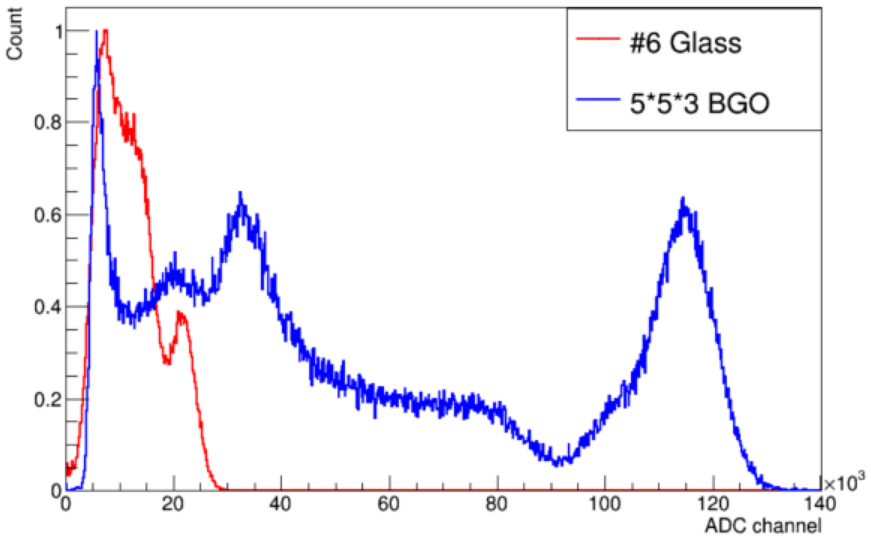
--Relative light yield: Calculate the relative light yield of glass through BGO standard crystal,

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

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



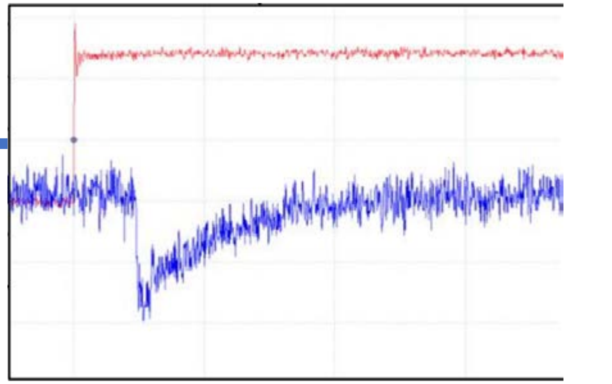
LY of the GS =802ph/MeV



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

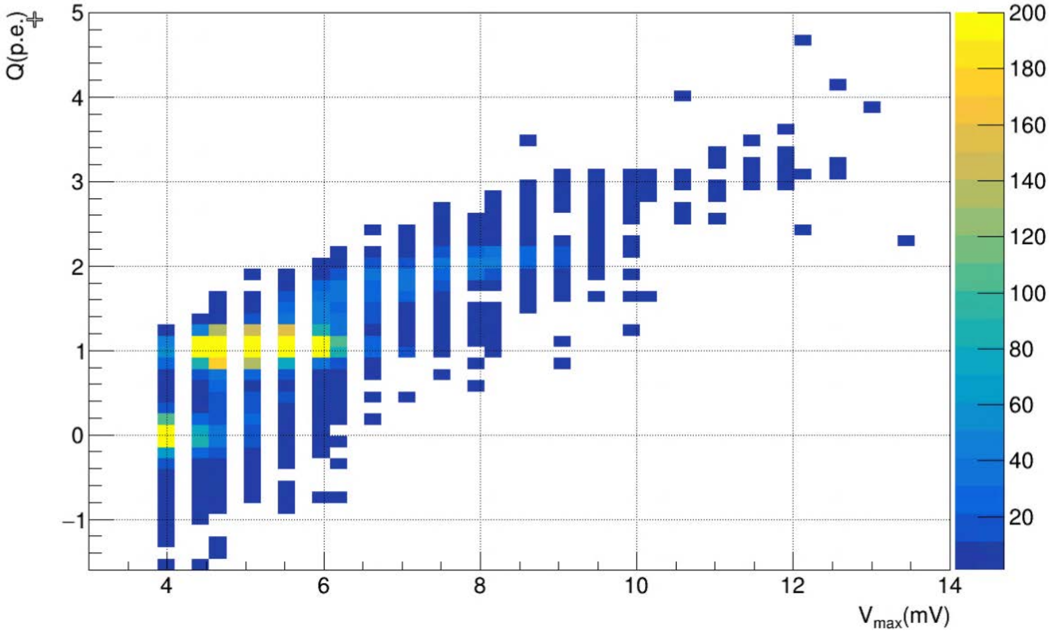
By Zhehao Hua

Voltage amplitude of single photon



SiPM (HPK, S13360-6025PE): voltage amplitude of single photon

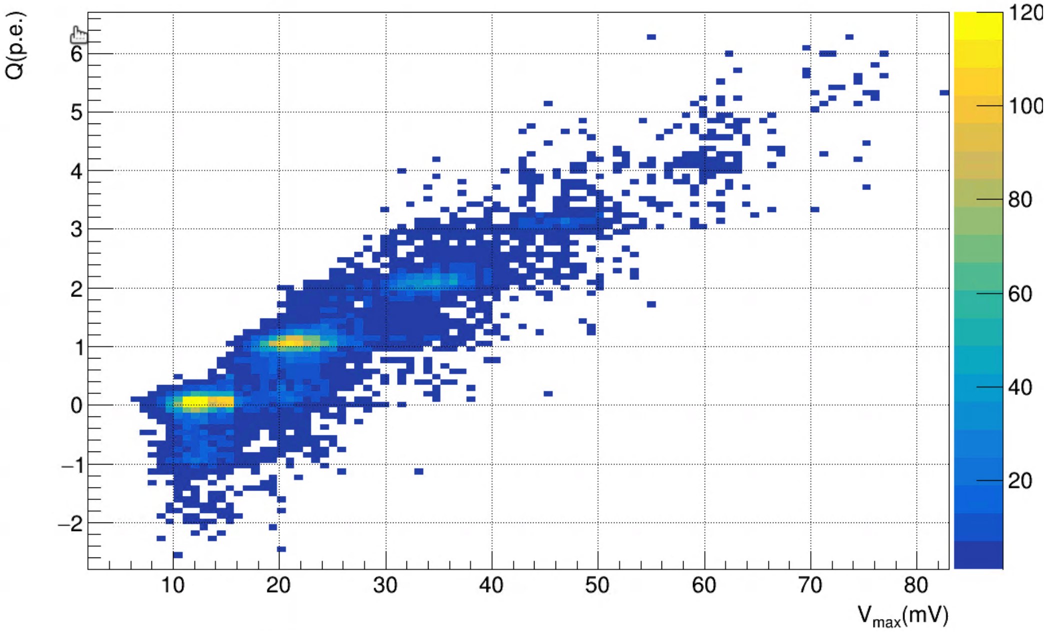
Charge vs. Vpeak



20dB

1p.e. → 3mV

Charge vs. Vpeak

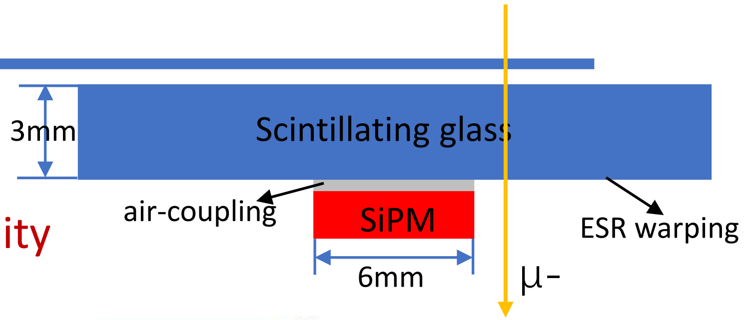


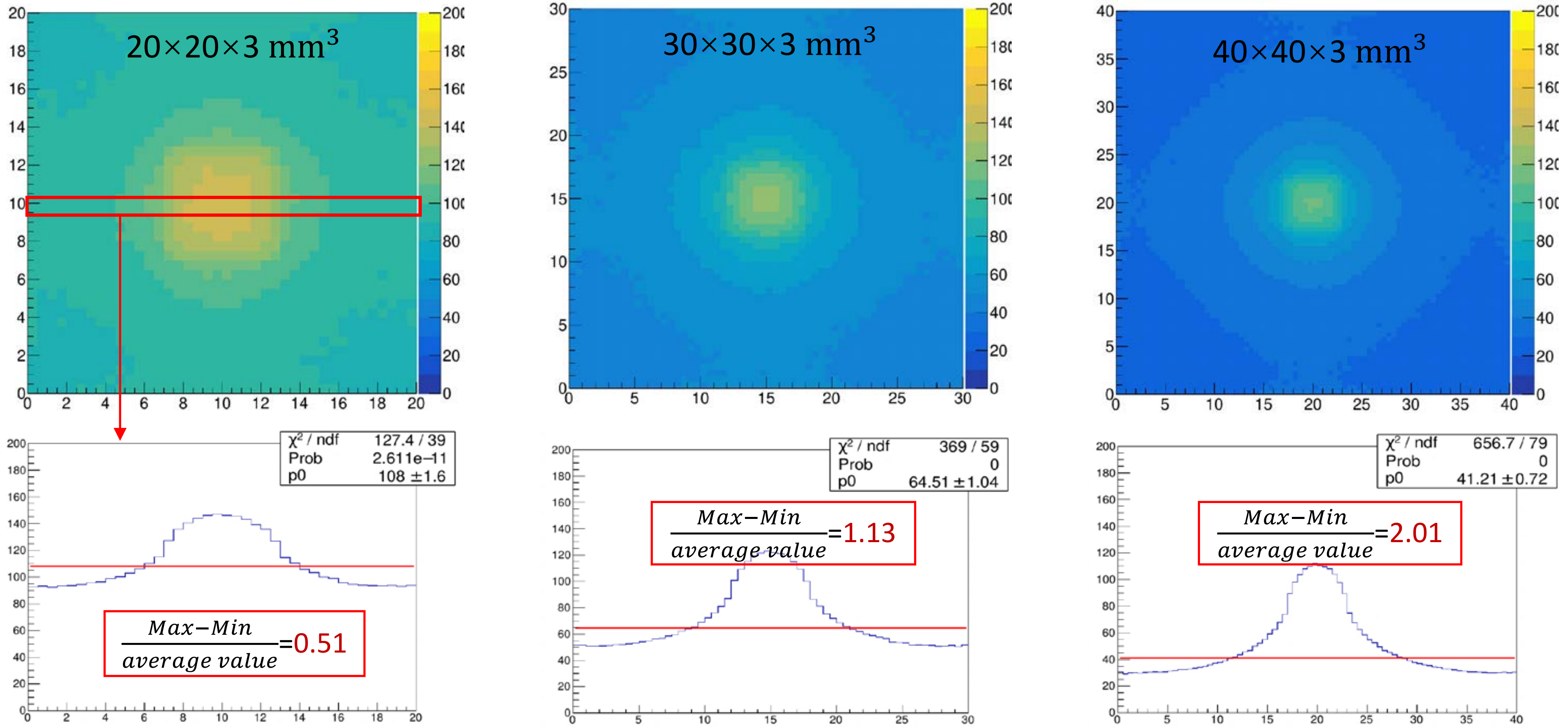
42dB

1p.e. → 12mV

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

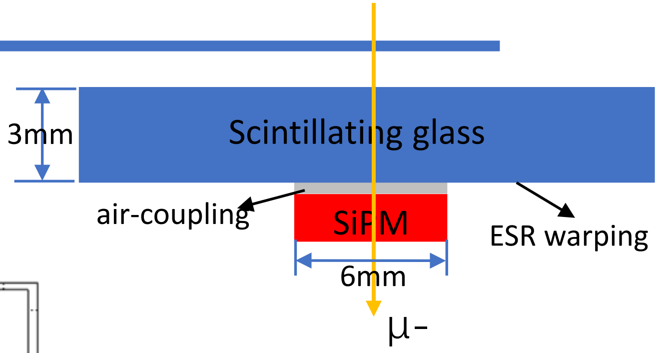




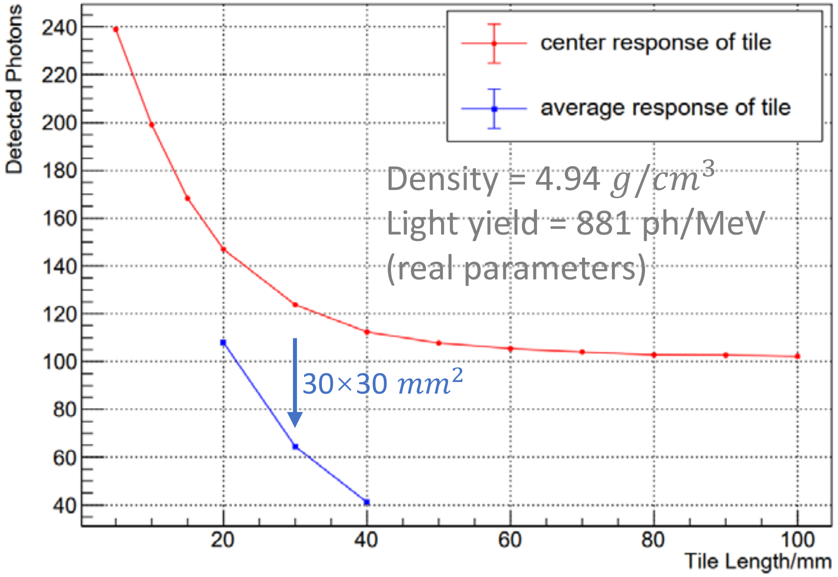
Incident particle: mu-
change hit position
(0.5mm step)

Impact of scintillating glass tile size

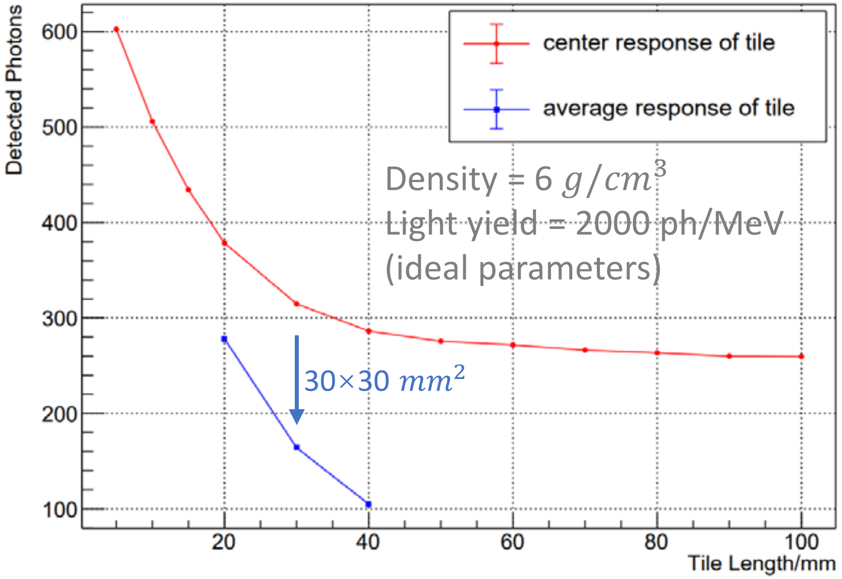
- Assumption: larger tile properties remain the same as small glass samples
- Vary transverse size, fixed tile thickness at 3 mm (AHCAL baseline design)



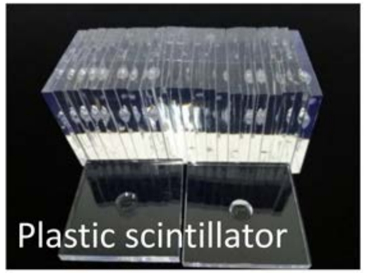
Detected photons vs. tile size



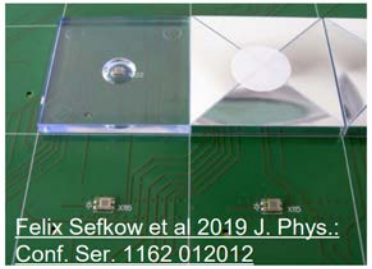
Detected photons vs. tile size



Tiles for AHCAL (30x30x3mm)



'SiPM-on-Tile" design for HCAL



- Realistic parameters: ~65 p.e./MIP, using large size 6×6 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