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HCAL with Scintillating Glass: Geant4 simulation and measurements

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December 15, 2021

Outline

- Motivations
- Simulation of scintillating glass for HCAL
  - Scintillator HCAL: setup in Geant4 simulation
  - Preliminary performance comparison
    - plastic scintillator
    - scintillating glass
  - Hadronic energy resolution of HCAL with Scintillating Glass
    - density, Gadolinium concentration, energy threshold, timing cut, light yield
- Optical simulation: a single scintillating glass tile
- Cosmic ray measurements of a scintillating glass tile
- Summary

Motivations

- A novel concept of PFA HCAL with heavy scintillating glass tiles
- Major motivations
  - Higher density provides higher energy sampling fraction
  - Certain doping to enhance neutron capture: improve hadronic response
  - More compact HCAL layout (given 4~5 nuclear interaction lengths in depth)
- Geant4 full simulation established to address key issues
  - One model for a full hadronic calorimeter
    - To study hadronic energy resolution of single particles
  - Another model of optical simulation for a single glass tile
    - Essential to guide R&D activities of heavy scintillating glass
    - Key properties: density, components (doping), intrinsic light yield, transmission, emission, decay time, etc.

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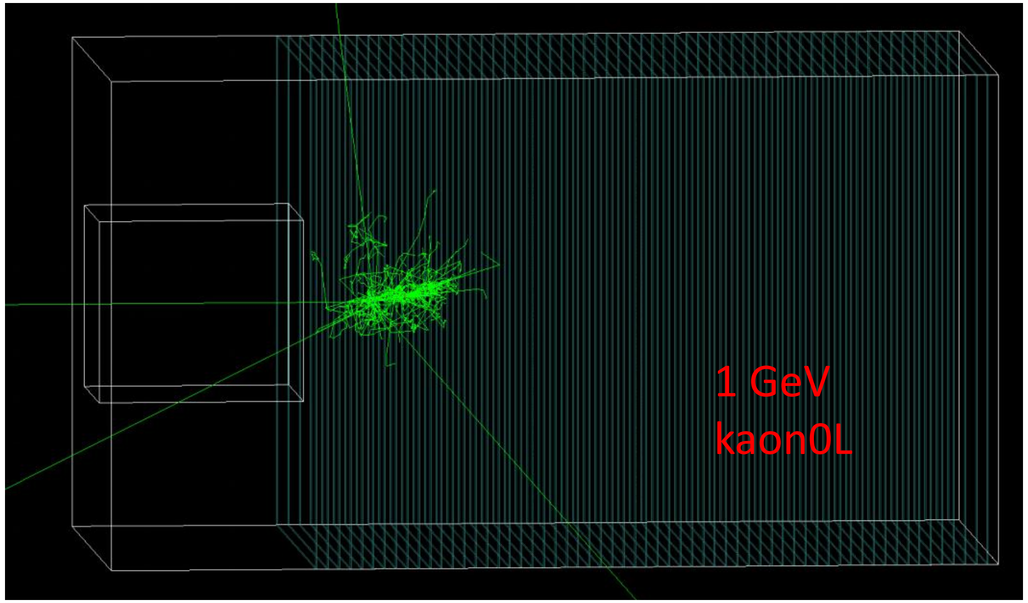
HCAL: setup in Geant4 simulation

HCAL geometry

- Transverse plane: $108 \times 108 cm^2$
- 60 longitudinal layers, each with
  - Scintillator: 3mm
  - PCB: 2.1mm
  - Absorber (steel): 20mm



Scintillator materials

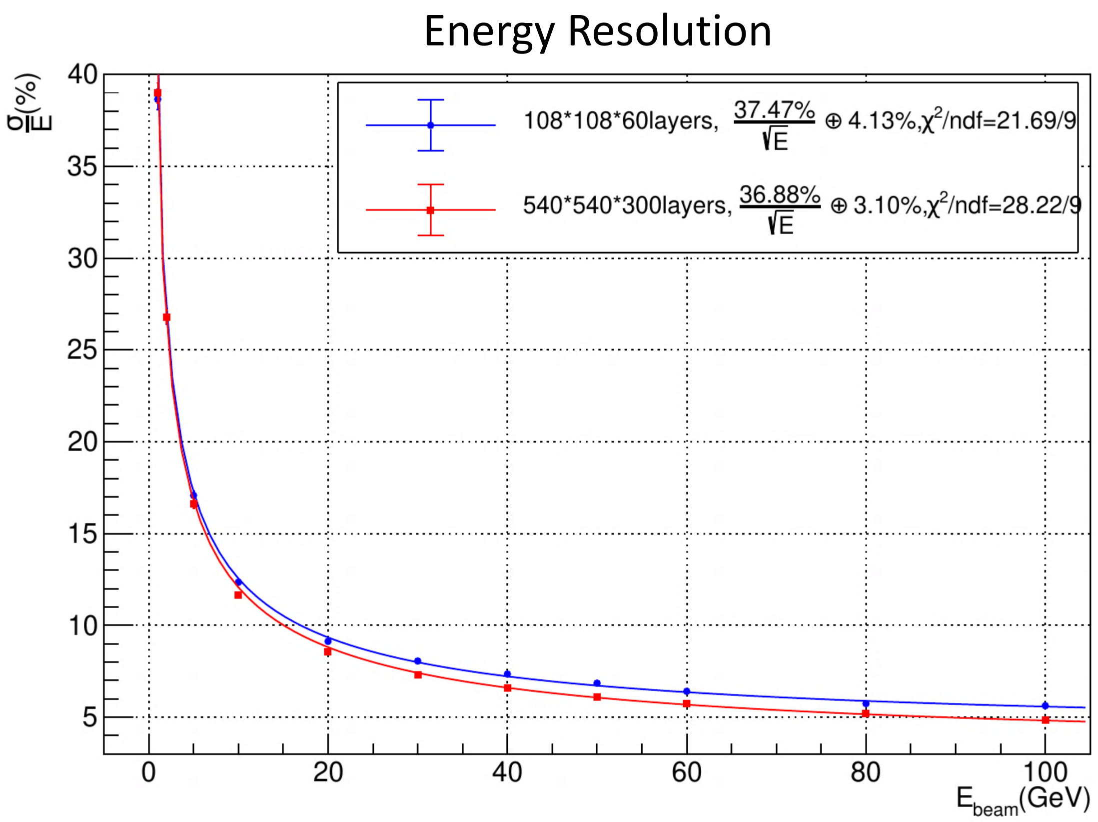
- Plastic scintillator (polystyrene) as baseline reference
- Scintillating glass: $25SiO_2 - 30B_2O_3 - 10Al_2O_3 - 34Gd_2O_3{:}1Ce^+$

  density = 4.94 g/cm^3

By Sen Qian

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

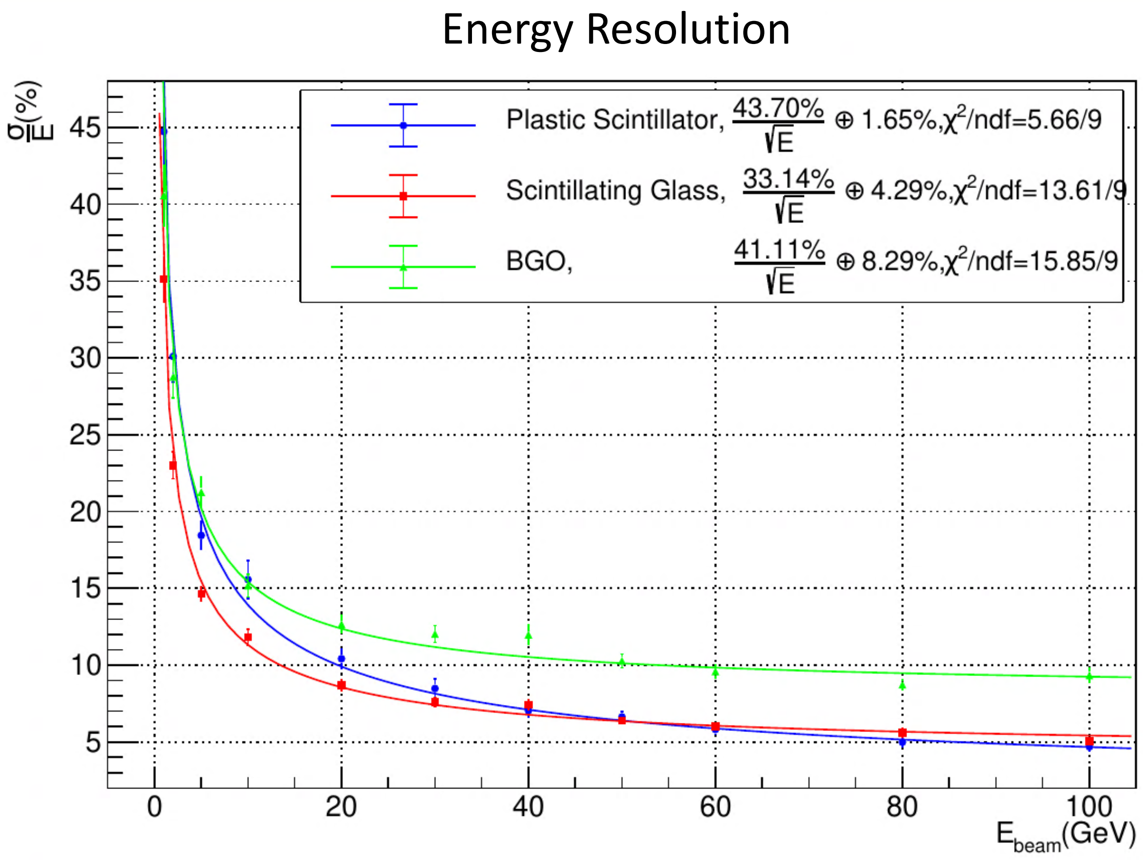
HCAL: evaluate leakage effects



- 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)

HCAL: plastic scintillator vs scintillating glass vs BGO

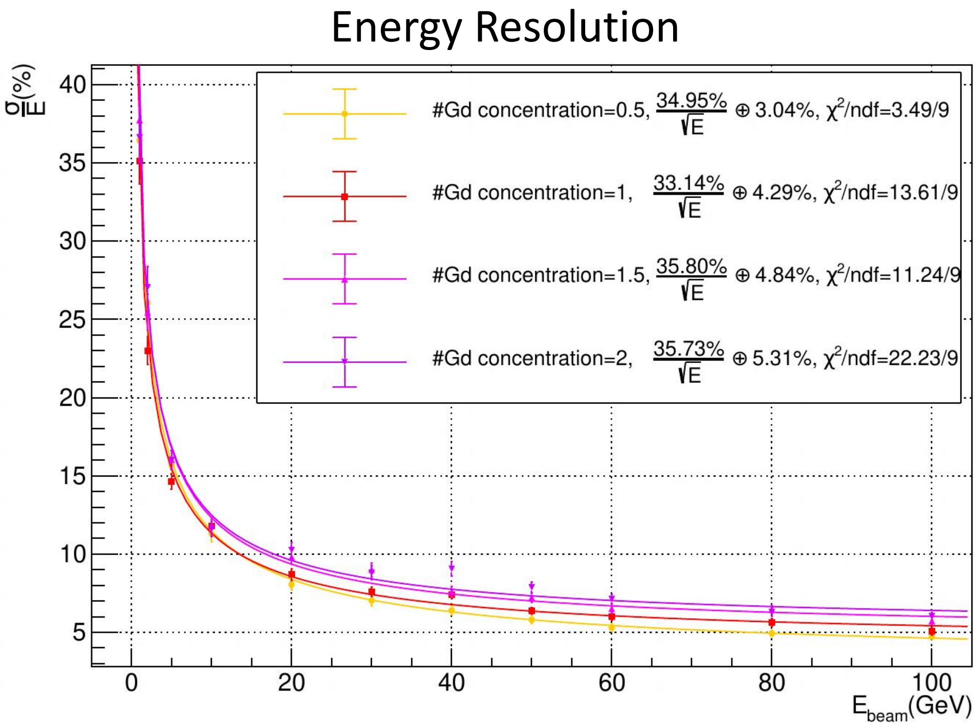


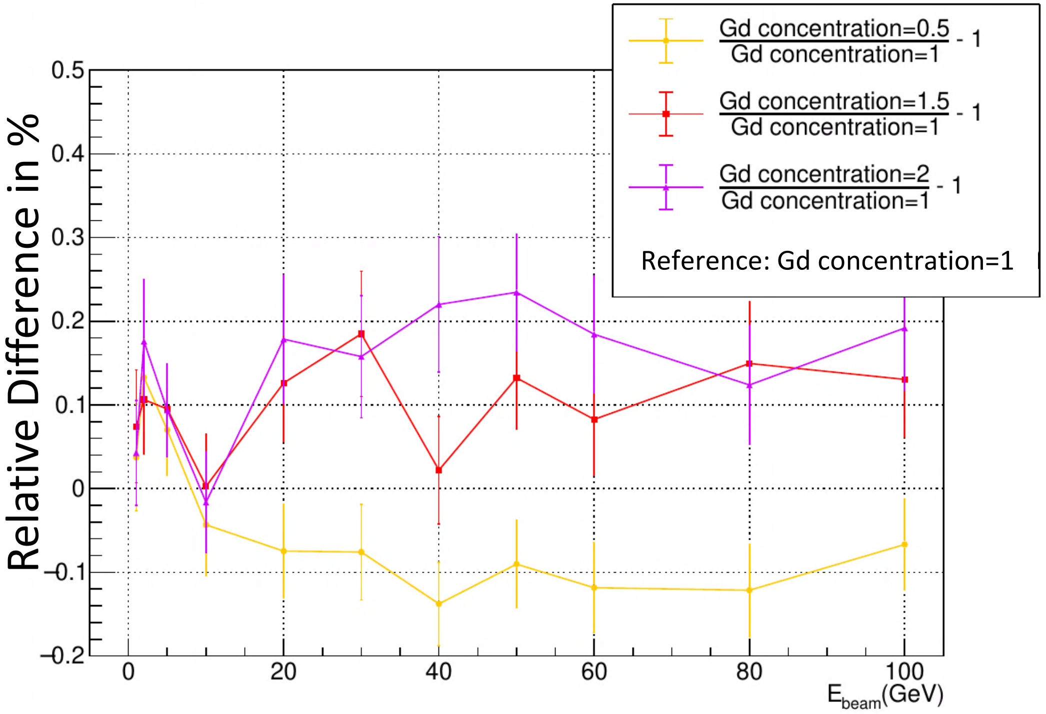
- Preliminary performance comparison
  - Same thickness of sensitive materials: 3mm
  - No energy threshold applied
- Scintillating glass: better hadronic energy resolution in low energy region (<30GeV)
  - Note that majority of hadrons in jets at CEPC are with low energy
- Further issue: constant term
  - To be further understood

Impact of Gd concentration to hadronic energy resolution

- Varying Gadolinium concentration, fixed density
- Incident particle: kaon0L (1-100 GeV)
- Energy threshold and timing cut not included

Baseline reference (Gd concentration = 1) :
$25SiO_2 - 30B_2O_3 - 10Al_2O_3 - 34Gd_2O_3 : 1Ce^+$

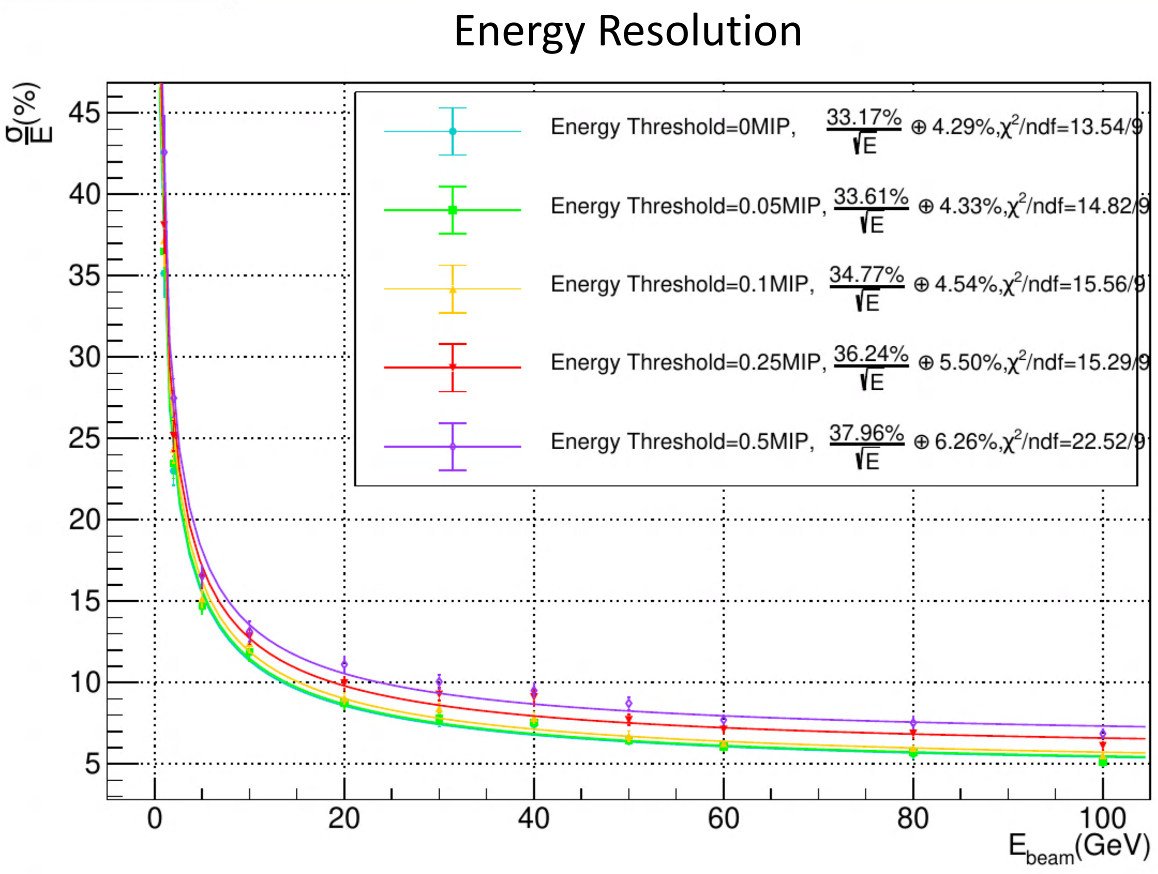




- Increasing Gd concentration can improve the constant term, but the Stochastic term remains to be further understood.
- In general, the hadronic energy resolution is insensitive to the Gd concentration.

Impact of energy threshold to hadronic energy resolution

$25SiO_2 - 30B_2O_3 - 10Al_2O_3 - 34Gd_2O_3: 1Ce^+$

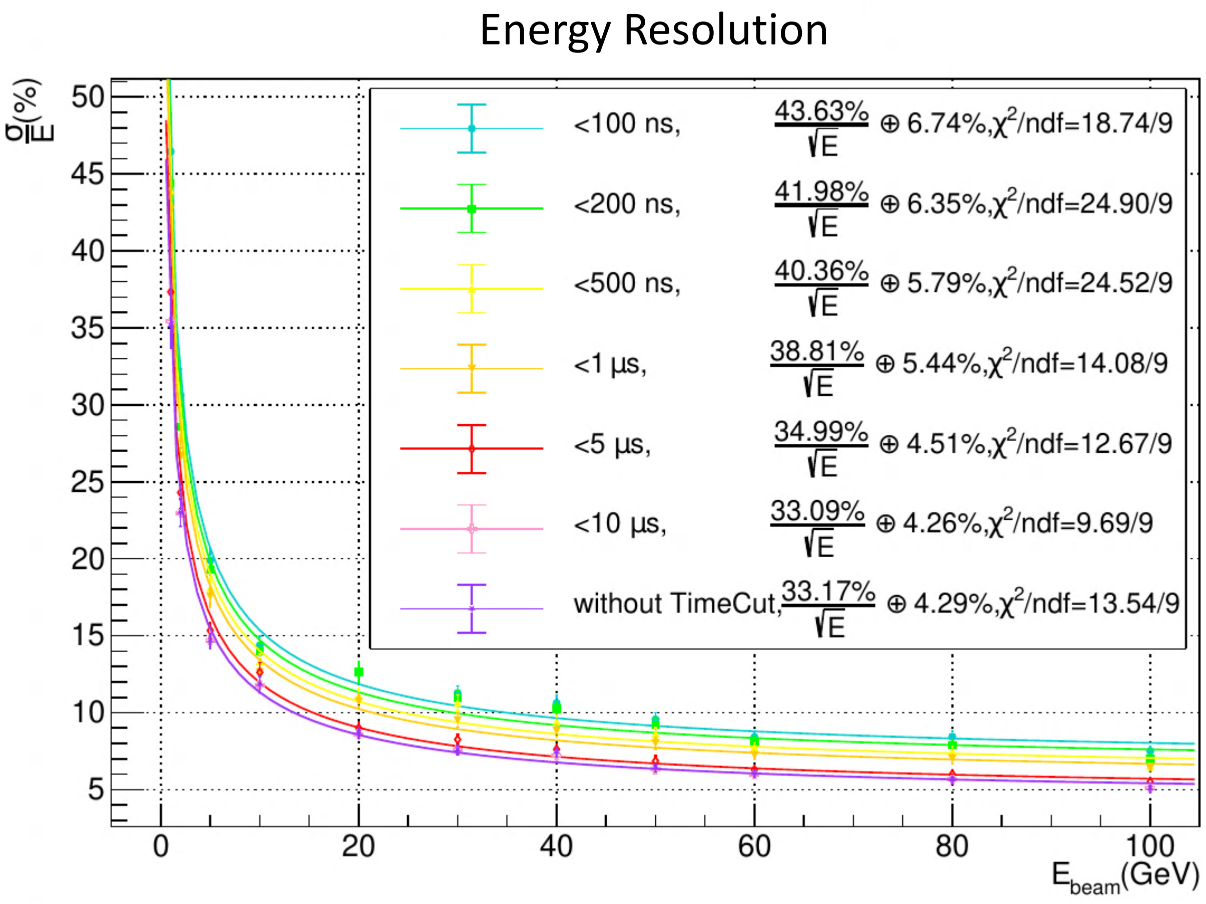


- Varying energy thresholds
- Incident particle: kaon0L (1-100 GeV)
- Timing cut not included

- Higher energy threshold leads to worse hadronic energy resolution.

Impact of timing cut to hadronic energy resolution

$25SiO_2 - 30B_2O_3 - 10Al_2O_3 - 34Gd_2O_3 : 1Ce^+$



- Varying timing cut
- Incident particle: kaon0L (1-100 GeV)
- Energy threshold not included

- Smaller timing cut leads to worse hadronic energy resolution.

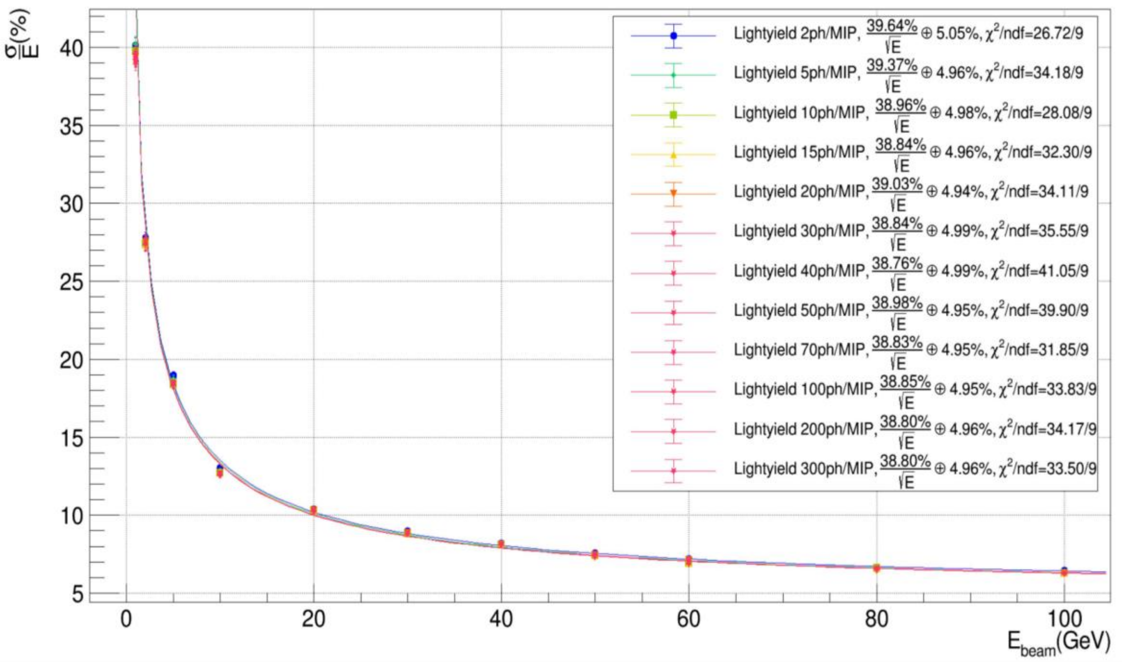
Impact of light yield to hadronic energy resolution

- Incident particle: kaon0L (1-100 GeV)
- Energy threshold and timing cut not included

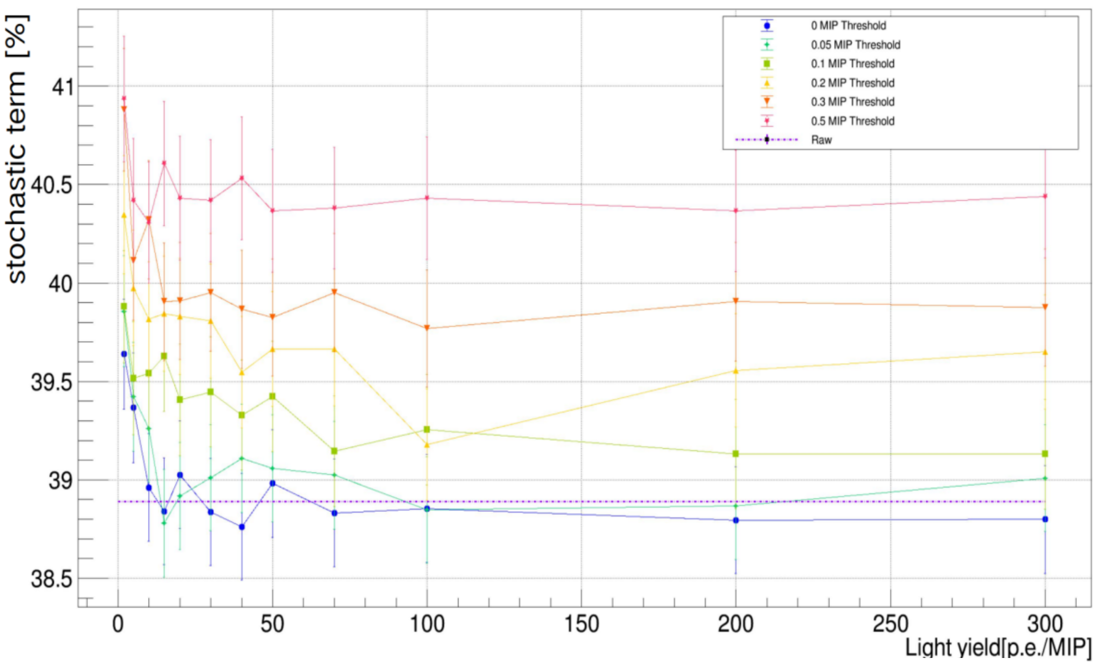
$42SiO_2$-$5Al_2O_3$-$22BaF_2$-$9NaF$-$3CaF_2$-$3Gd_2O_3$-$9GdF_3$-$7TbF_3$

References: https://doi.org/10.1016/j.jeurceramsoc.2021.05.064

Energy Resolution



Light yeild vs Stochastic Term



- Increasing light yield can not significantly improve hadronic energy resolution.
- Factors affecting hadronic energy resolution
  - Intrinsic hadronic energy fluctuation and sampling fluctuation (dominant)
  - Photon statistics fluctuation(non-dominant)
- Prospect: higher light yield would help achieve lower the energy threshold

By Lishuang Ma

Light yield vs Density

- Incident particle: kaon0L (1-100 GeV)
- Energy threshold and timing cut not included

$42SiO_2$-$5Al_2O_3$-$22BaF_2$-$9NaF$-$3CaF_2$-$3Gd_2O_3$-$9GdF_3$-$7TbF_3$

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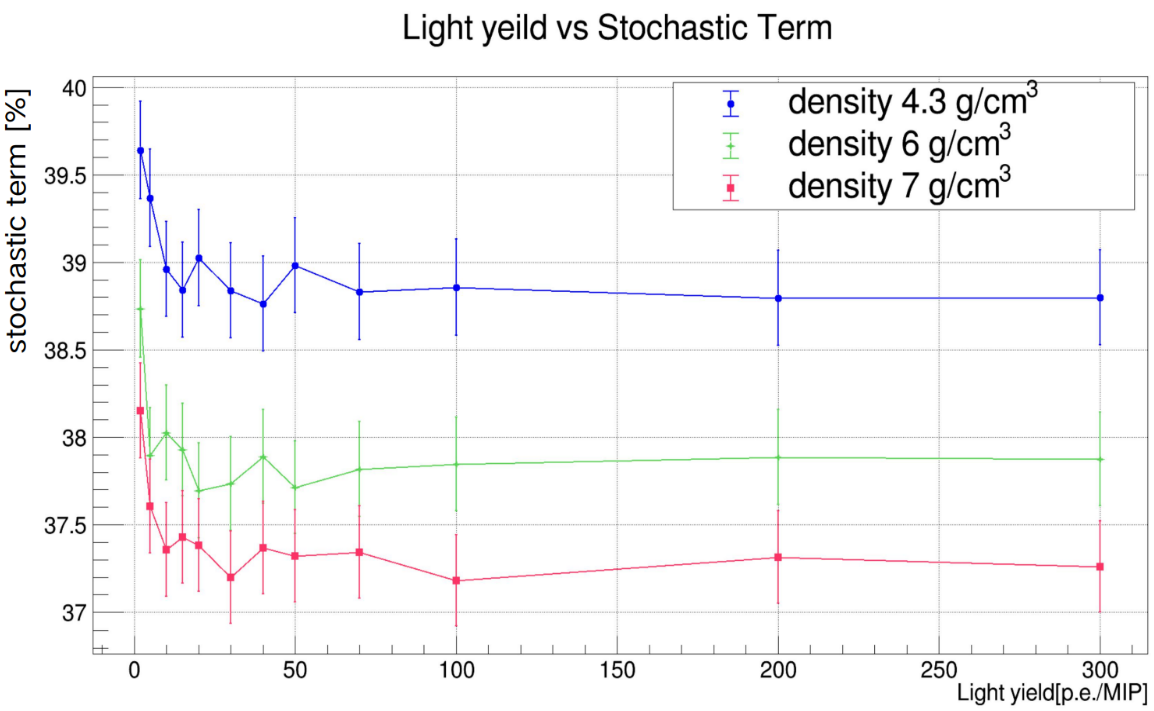

- When density increases to 7 g/cm^3 from 6 g/cm^3, the stochastic term only improves <1.5%.
- Considering the constraints of light yield in glass R&D, we initially set the target density as 6 g/cm^3.

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    - scintillating glass
  - Hadronic energy resolution of HCAL with Scintillating Glass
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- **Optical simulation: a single scintillating glass tile**
- Cosmic ray measurements of a scintillating glass tile
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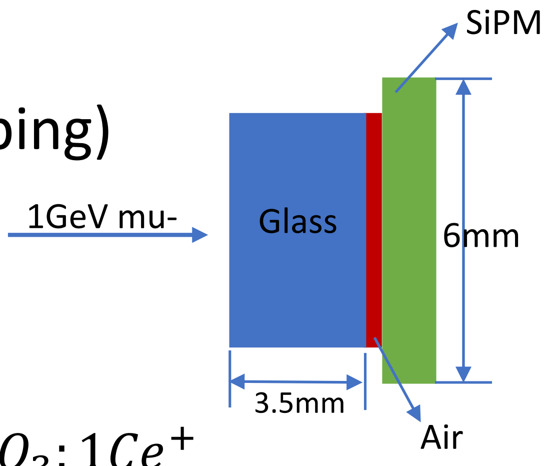
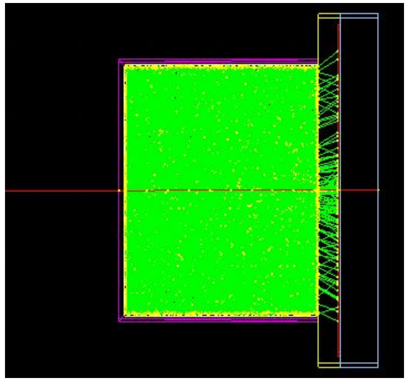
Optical simulation: setup in Geant4

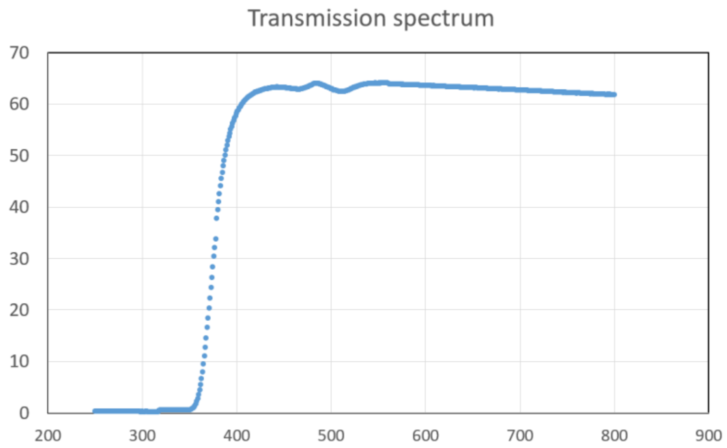
- Geometry setup
  - Scintillating glass($4.5\times4.5\times3.5mm^3$, ESR wrapping)
  - Coupling agent: Air
  - SiPM($6\times6\ mm^2$)
- Properties of scintillating glass
  - Component: $25SiO_2-30B_2O_3-10Al_2O_3-34Gd_2O_3{:}1Ce^+$
  - Density: 4.94 g/cm^3
  - Refractive index: 1.67
  - Transmission: 63%
  - Emission peak: 394 nm
  - Light yield: 881 ph/MeV

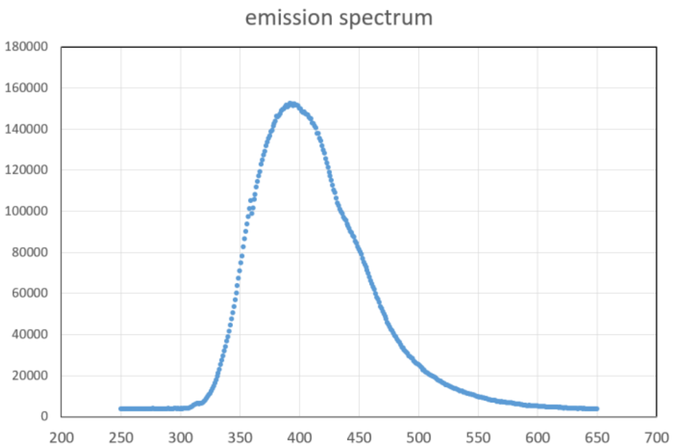
  (Based on the data of the measurements by Zhehao Hua)





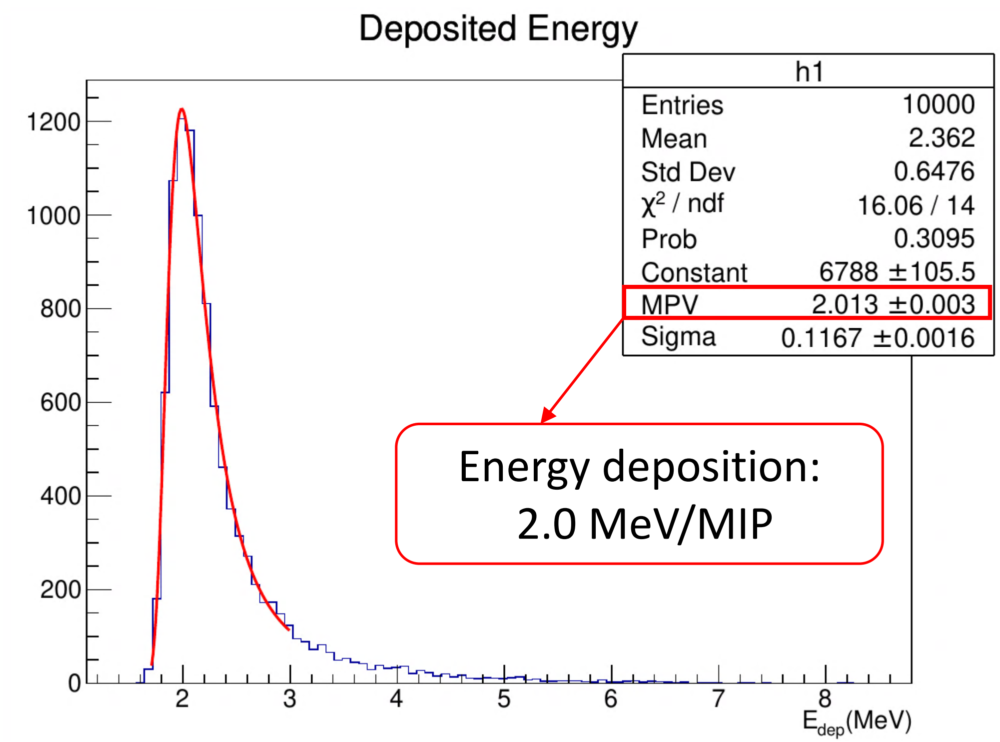
1 GeV mu-

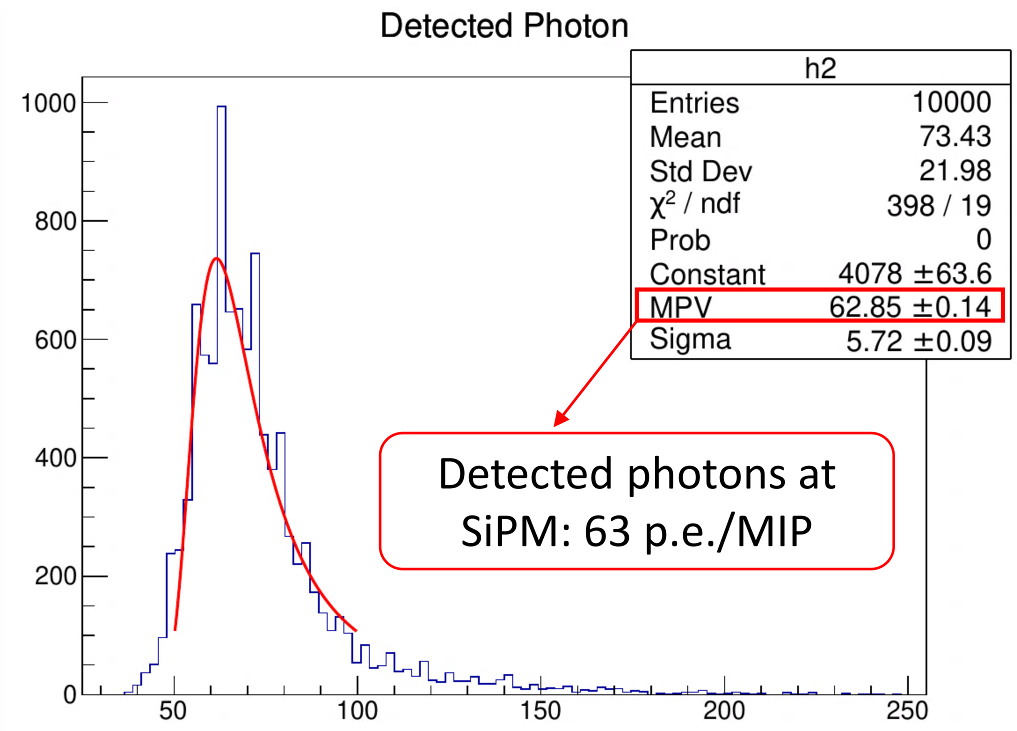




Optical simulation: MIP response

- Incident particle: 1 GeV mu- (regard as MIP particle)





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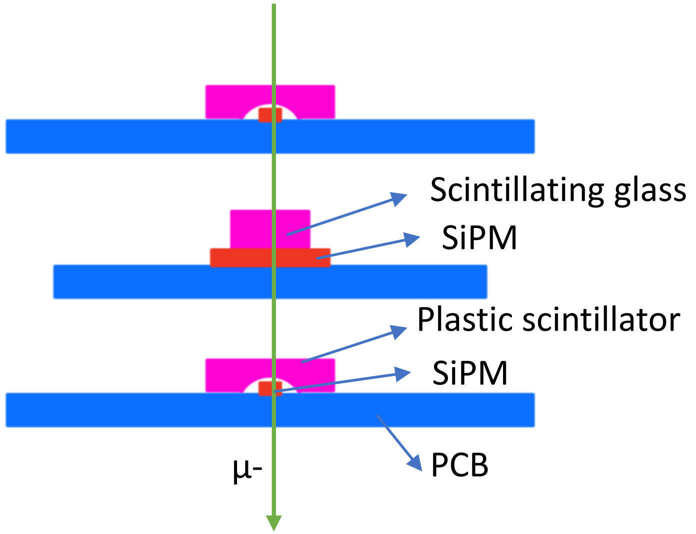
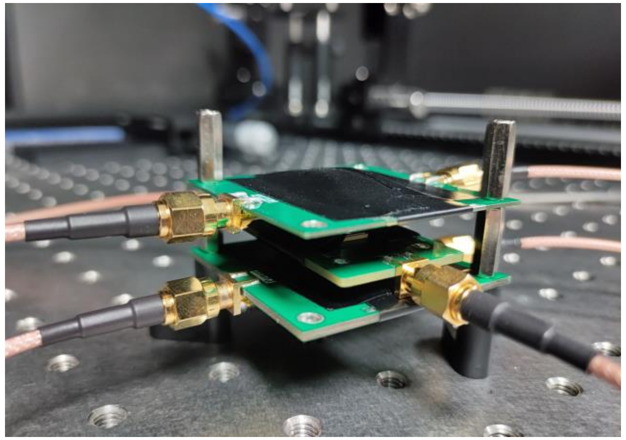
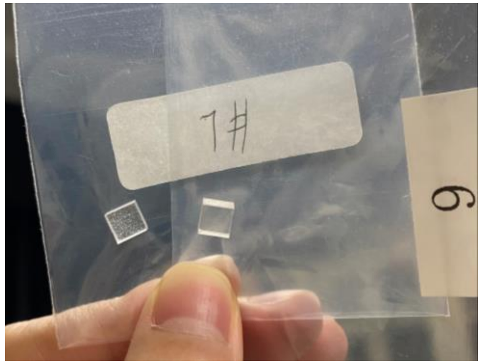
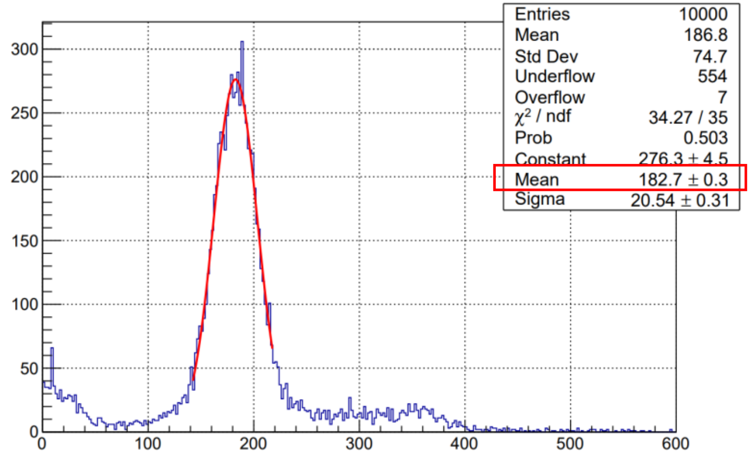
Cosmic ray measurements : setup



- Scintillating glass: #7
  - $4.5\times4.5\times3.5mm^3$, ESR wrapping
- SiPM: S13360-6025PE(HPK)
  - $6\times6\ mm^2$, 25μm pixel pitch
  - Bias voltage: 57.57V
- Coincidence with two plastic scintillator($1\times1\ cm^2$)



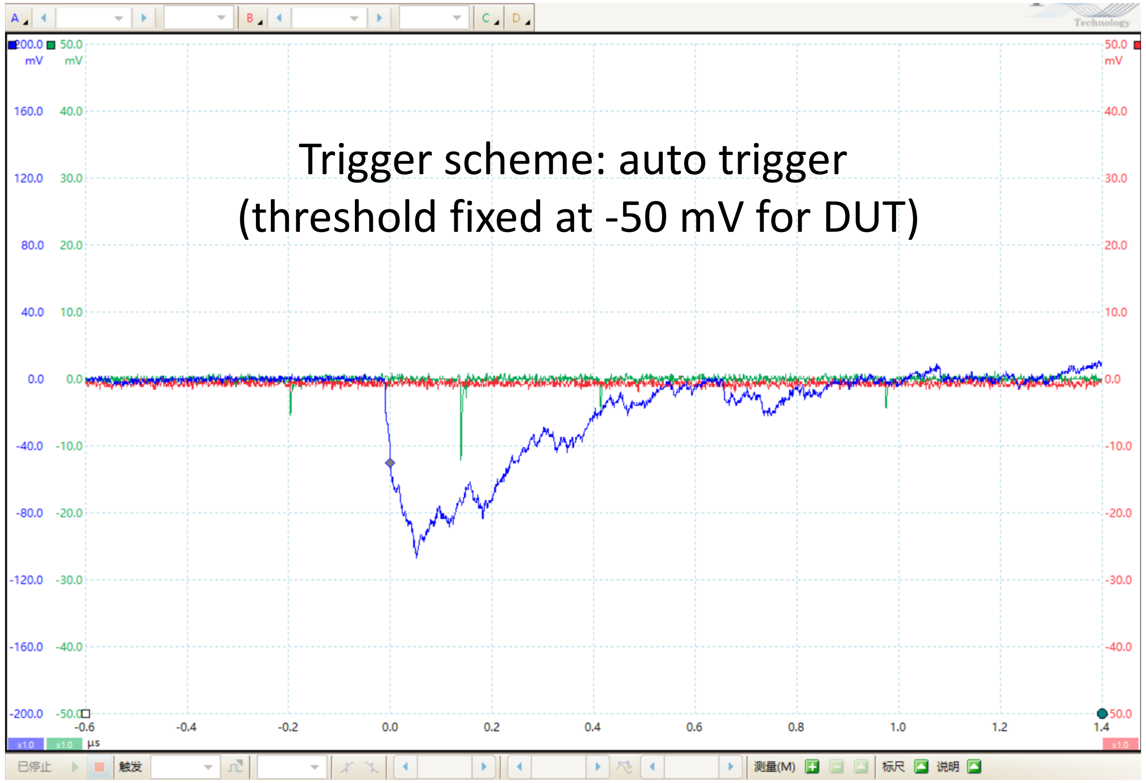


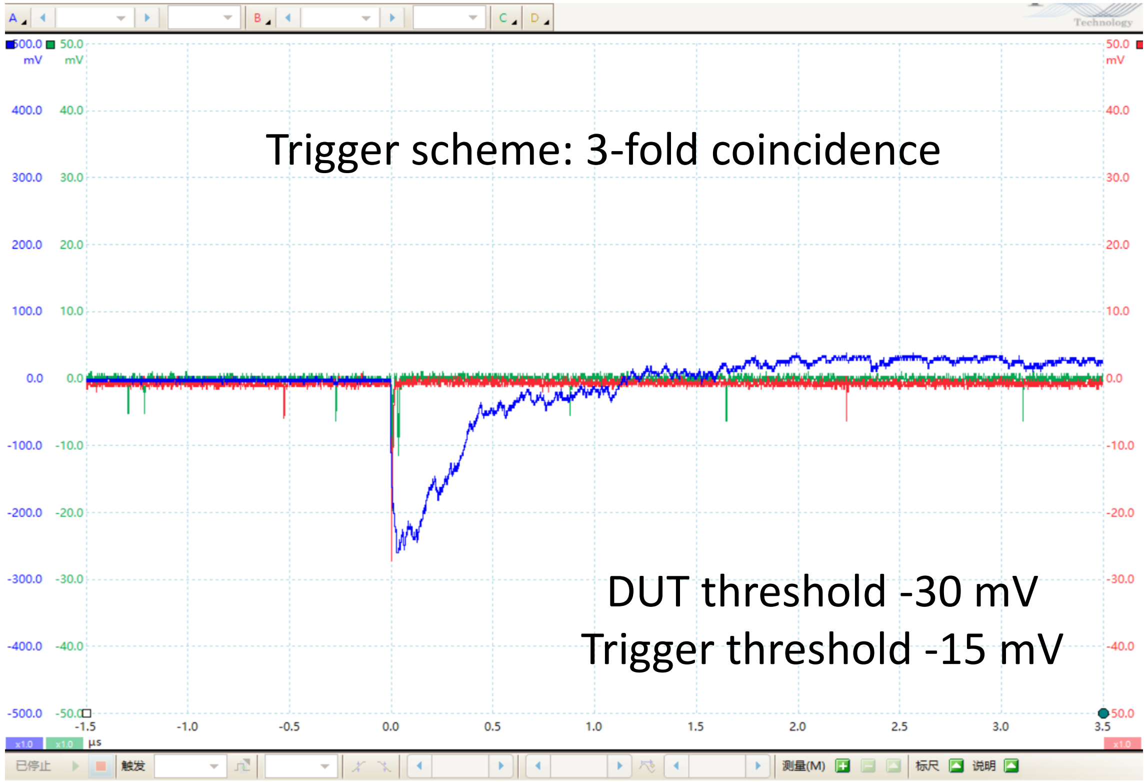


Single photon calibration
(dark noise)

Cosmic ray measurements : typical events

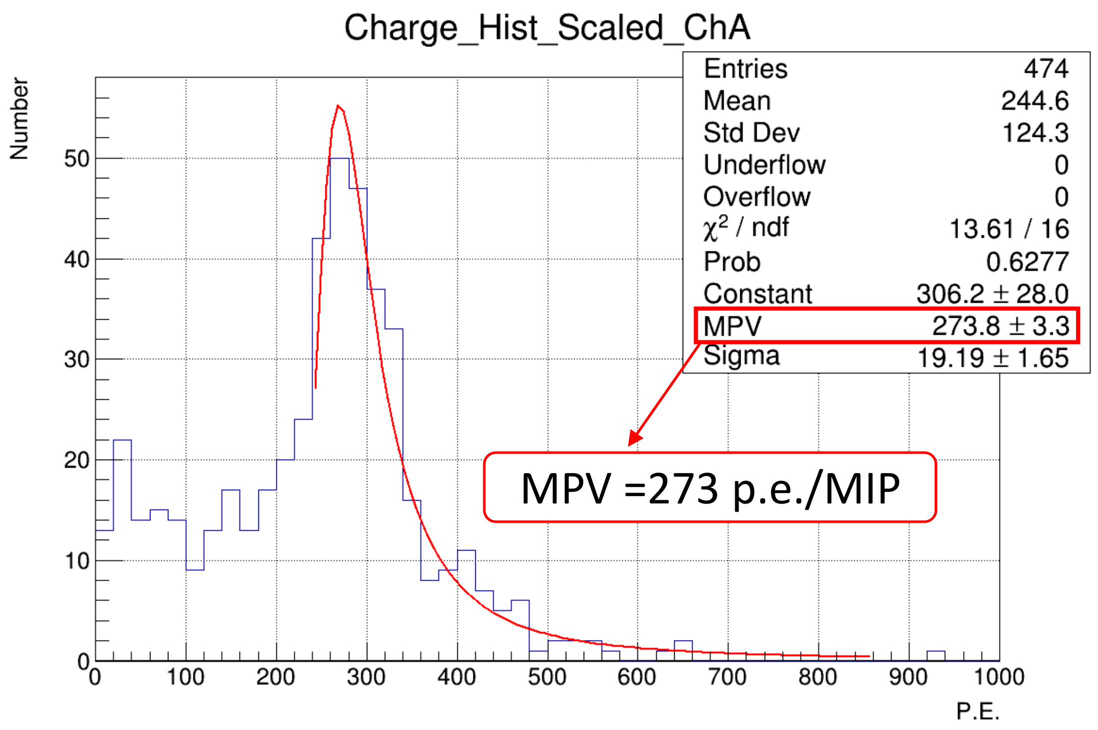
- DUT: scintillating glass cube + SiPM (blue pulses)
- Trigger: 2 sets of plastic scintillator tile + SiPM (red pulses, green pulses)

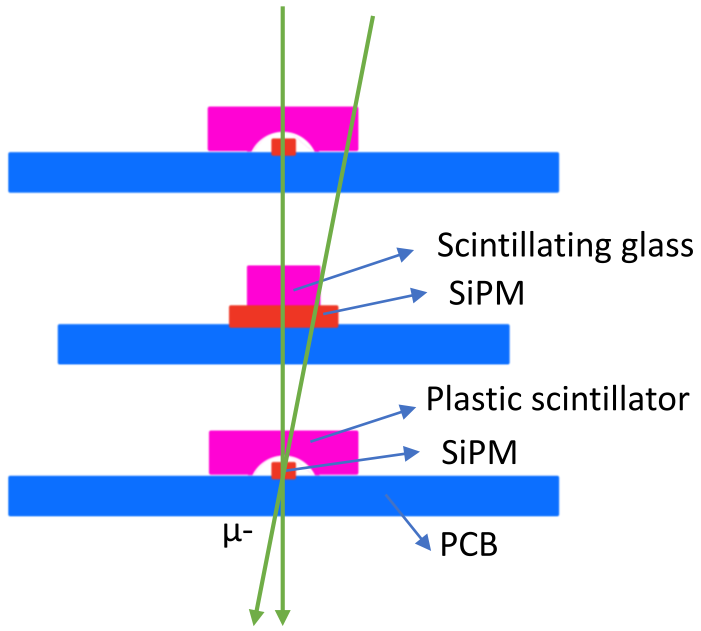




The results of cosmic ray measurements

- Trigger scheme: 3-fold coincidence



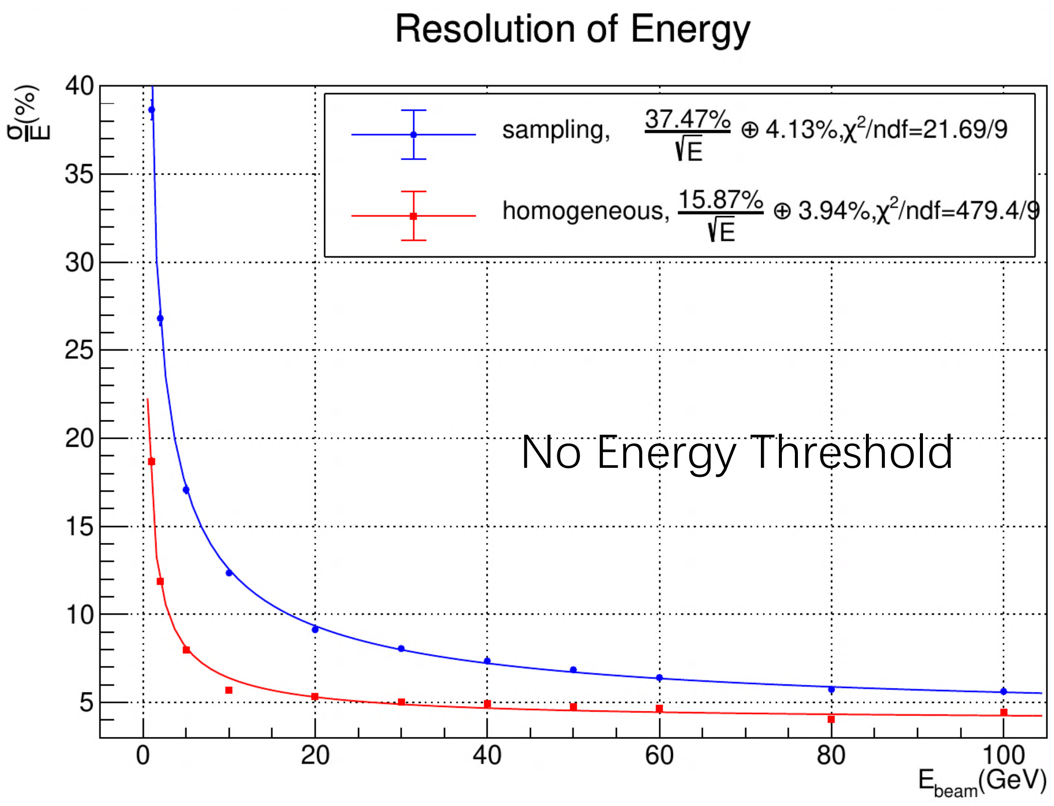


Summary

- A novel HCAL concept with high-density scintillating glass
  - To improve hadronic energy resolution, especially in low energy region
- HCAL performance in simulation
  - Increasing density of scintillating glass does not significantly improve energy resolution
  - Hadronic energy resolution also depends on energy threshold and time window
  - Increasing light yield cannot significantly improve hadronic energy resolution
- Studies with a single scintillating glass cube (size in mm)
  - Performed Geant4 optical simulation and cosmic-ray tests
- Plans and prospects
  - Considering the complexity of glass development, we initially target the density of 6 g/cm^3
  - Light yield with a single HCAL tile (size in cm): simulation and measurements
  - Higher light yield would help achieve lower the energy threshold

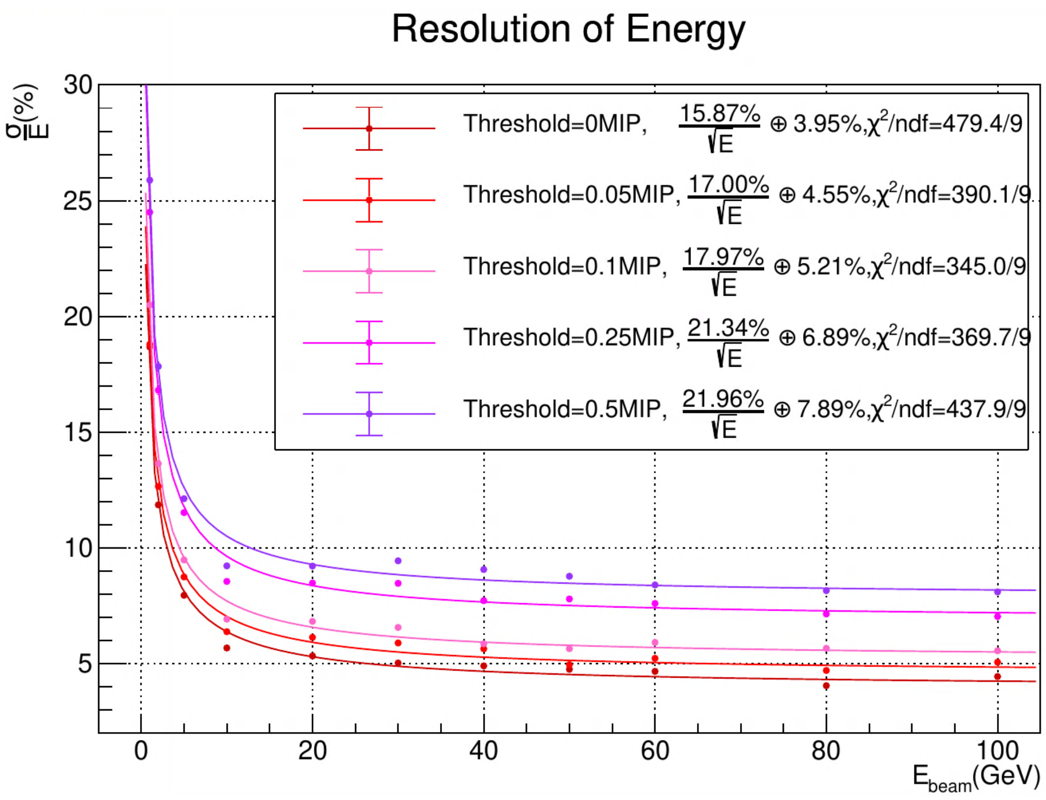
Backups

HCAL: sampling vs homogeneous



Sampling ⟶ Homogeneous

Steel ⟶ Glass



Homogeneous HCAL is sensitive to energy thresholds.

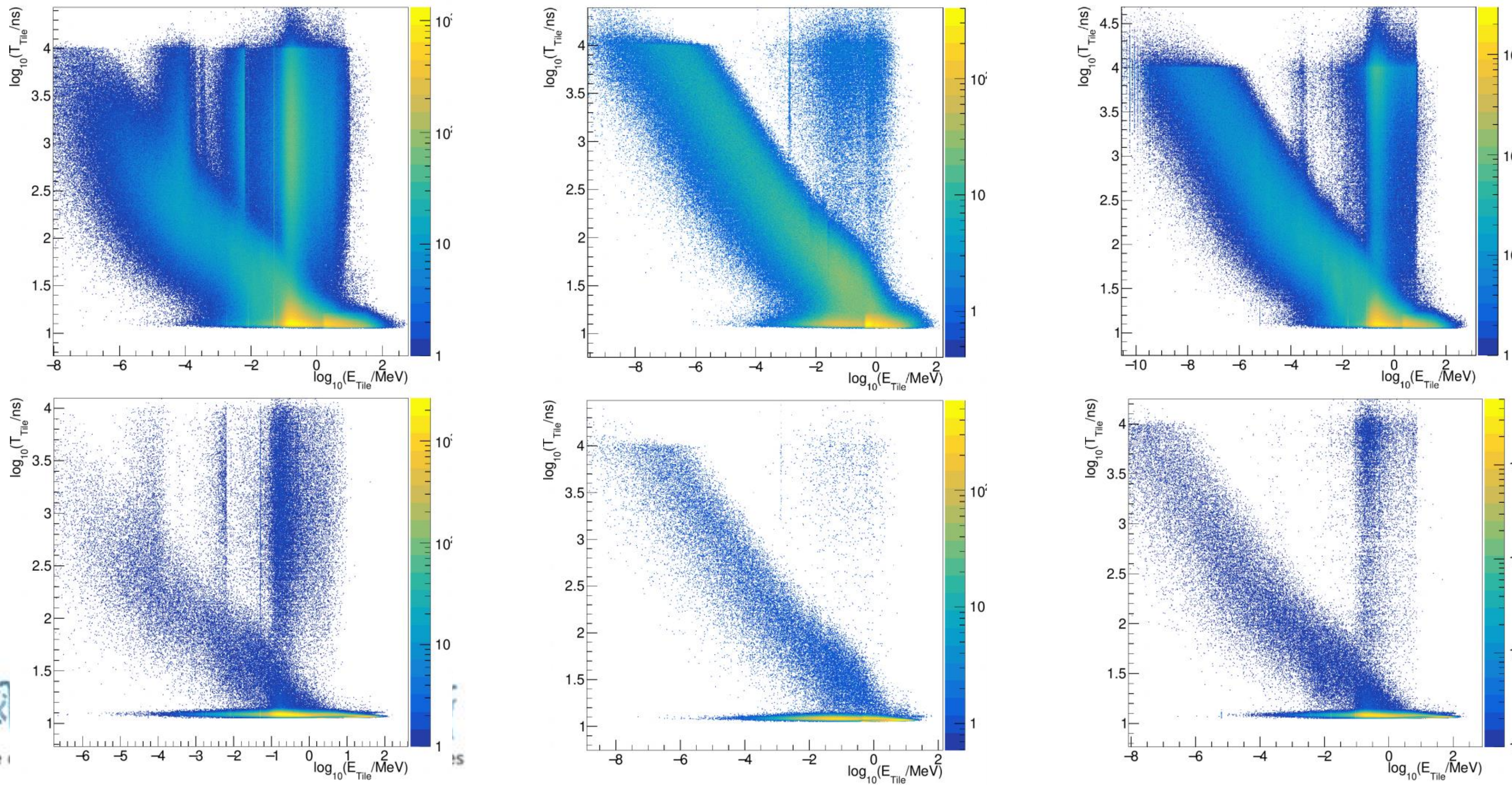
HCAL: Tiles time & energy distribution

- Birks' constant, energy threshold and timing cut not included
- Incident particle: kaon0L and e- (10GeV)

Scintillating Glass | Plastic Scintillator | BGO

kaon0L

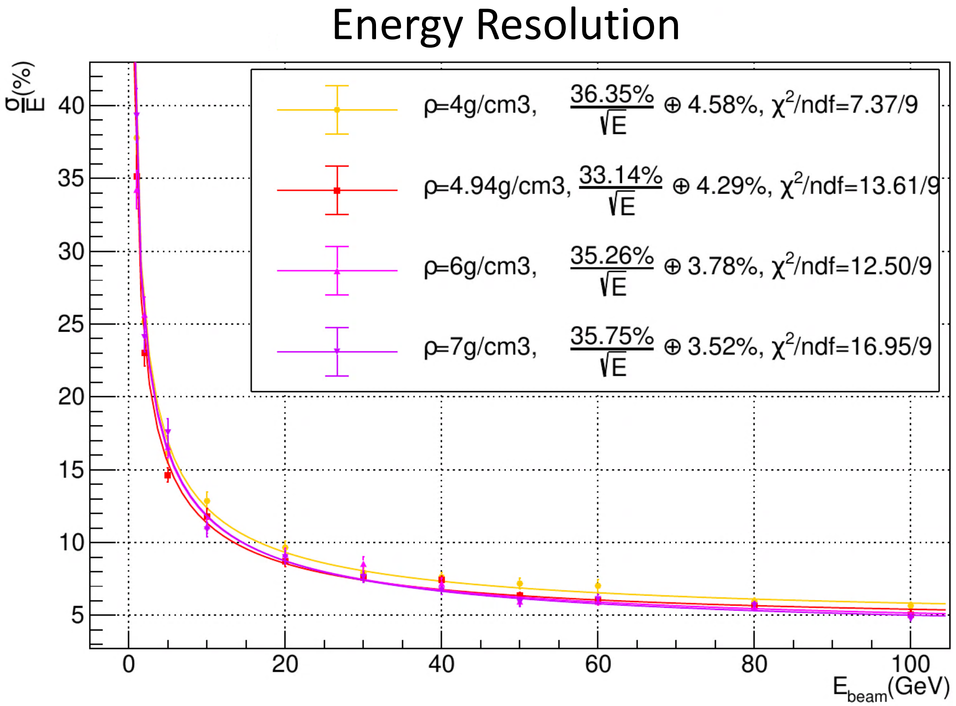
e-

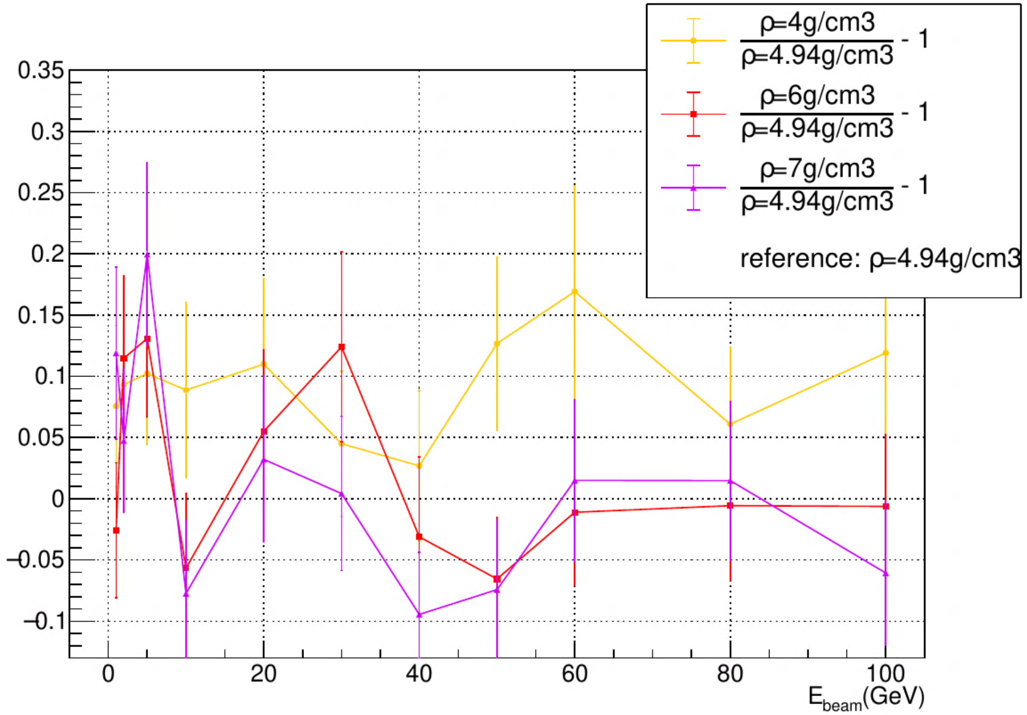


Impact of density to hadronic energy resolution

- Varying scintillating glass density, fixed component
- Incident particle: kaon0L (1-100 GeV)
- Energy threshold and timing cut not included

$$25SiO_2 - 30B_2O_3 - 10Al_2O_3 - 34Gd_2O_3{:}1Ce^+$$





- Increasing density can improve the constant term, but the Stochastic term remains to be further understood.
- In general, the hadronic energy resolution is insensitive to the density.