Development of highly granular hadronic calorimetry with glass scintillator tiles

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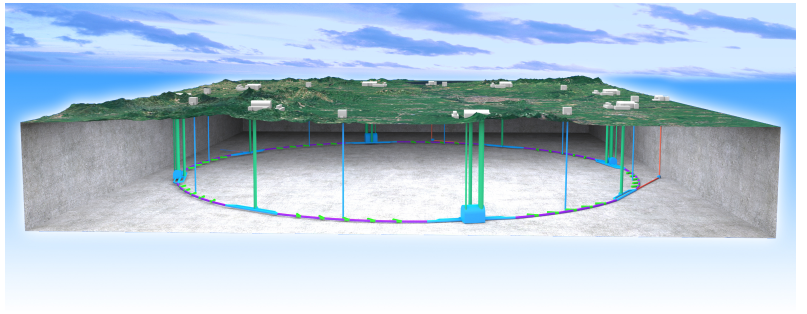
闪烁玻璃合作组
Glass Scintillator Collaboration

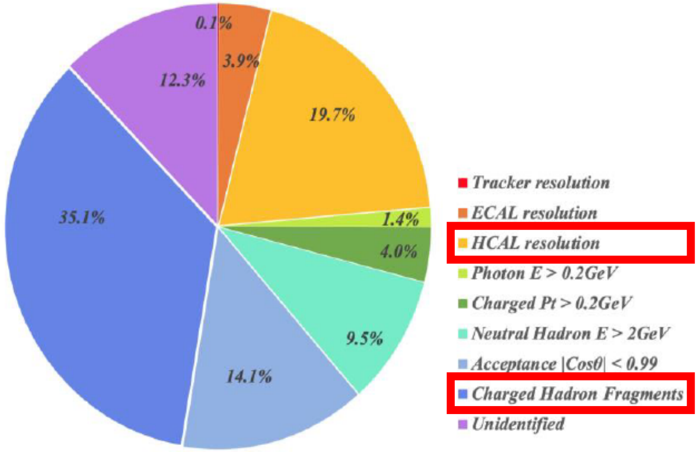
Motivations

- Future electron-position colliders: e.g. CEPC
  - Main physical goals: precision measurements of Higgs/Z/W bosons
  - Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$



- CEPC detector with highly granular calorimeters (PFA-oriented)
  - Boson Mass Resolution (BMR): ~4% in the baseline design
  - Next stage goal: BMR 4%→3%
  - Dominant factors in BMR: charged hadron fragments & HCAL resolution

BMR factorization based on PFA



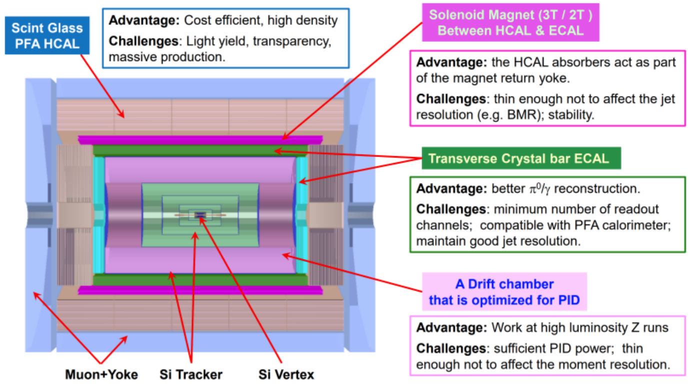
- New concept: glass scintillator HCAL
  - Sampling scintillator-steel HCAL (a la CALICE-AHCAL): to use glass scintillator tiles instead of plastic
  - Higher energy sampling fraction → requires high density and light yield
  - Expect better hadronic energy resolution

Yuexin Wang (IHEP)

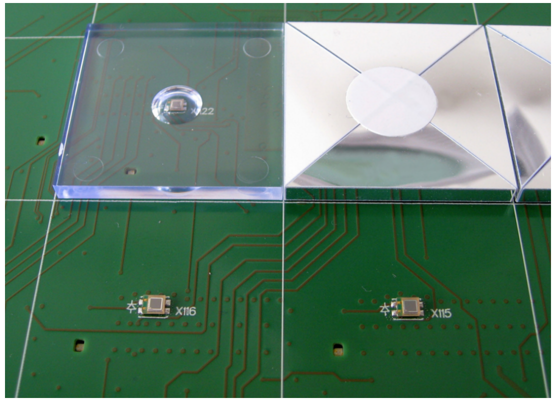
Hadronic calorimeter with glass scintillator tiles

- CEPC 4th concept detector: PFA-oriented
  - Hadronic calorimeter (HCAL) with glass scintillator tiles
  - Requires glass scintillator with high density and light yield
  - Expect better hadronic energy resolution
- R&D activities for glass scintillator HCAL
  - HCAL design and simulation studies
  - PFA optimisation and physics performance studies
    - Key Parameter: Boson Mass Resolution (BMR)
  - Hardware developments: testing Glass scintillator tiles
    - Key parameters: MIP response, scintillation times

CEPC 4th concept detector



“SiPM-on-Tile” design for CALICE-AHCAL



Outline

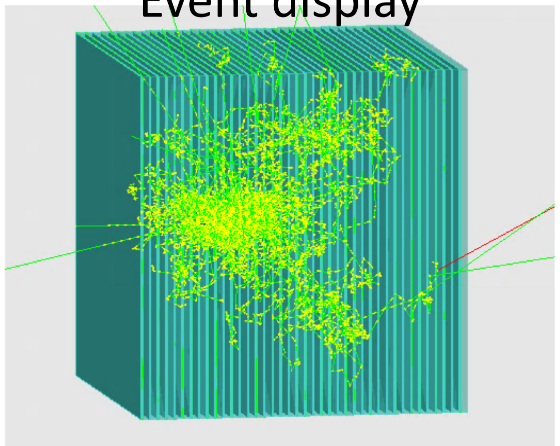
- Motivations
- Standalone simulation of GS-HCAL
  - Design optimisation
  - Software compensation
- Glass scintillator material R&D
  - Key parameters: density, light yield, decay time
- Beamtest of glass scintillator tiles
  - Key parameter: MIP response
- Summary

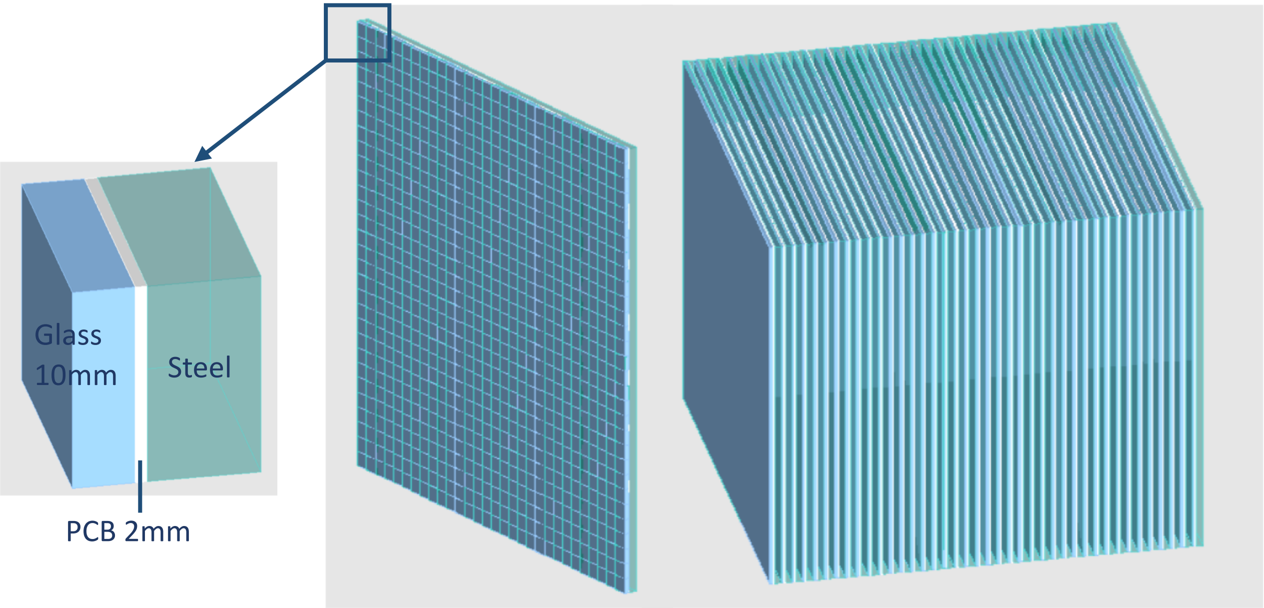
GS-HCAL simulation setup

- GS-HCAL geometry
  - Refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Replace plastic scintillator with glass scintillator
- Glass scintillator material
  - Composition: Gd-B-Si-Ge-F-Ce^{3+}
  - Nuclear interaction length: 23.83 cm
  - MIP response: 7 MeV/cm
- GS-HCAL nominal parameters

Total number of layers	**40**
Total nuclear interaction length	**5 λ**
Glass tile size	**40×40×10 mm³**
Glass density	**6 g/cm³**
Readout threshold	**0.1 MIP**

Event display

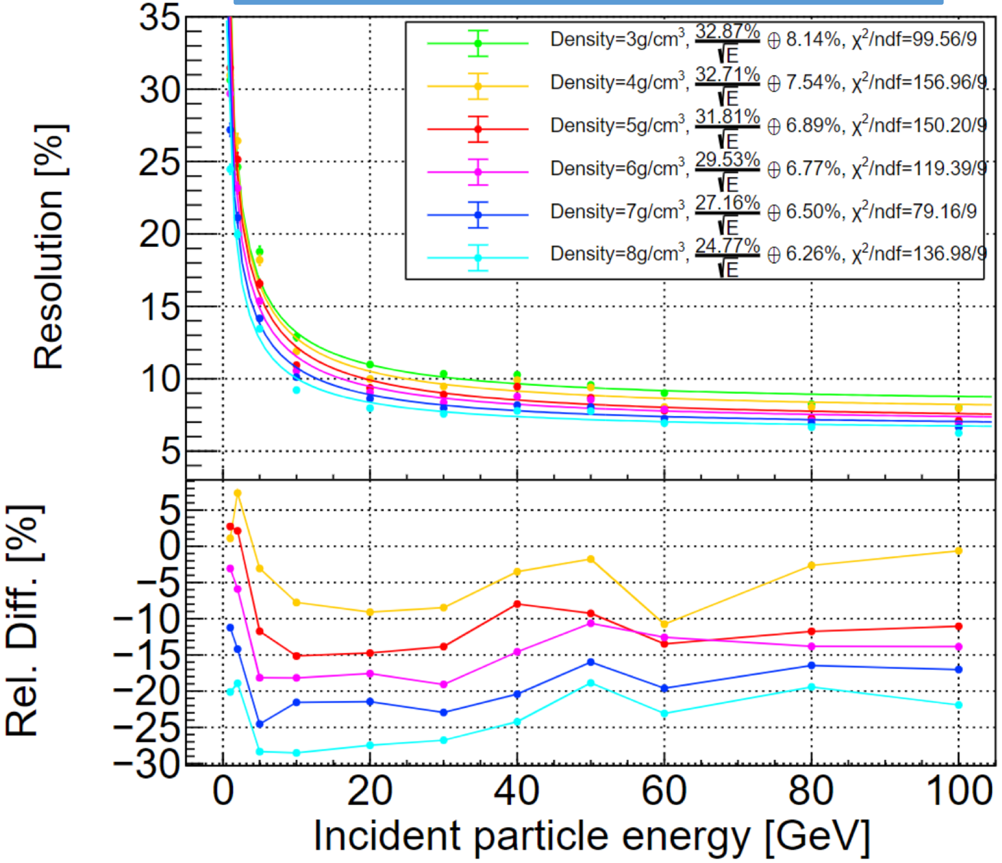




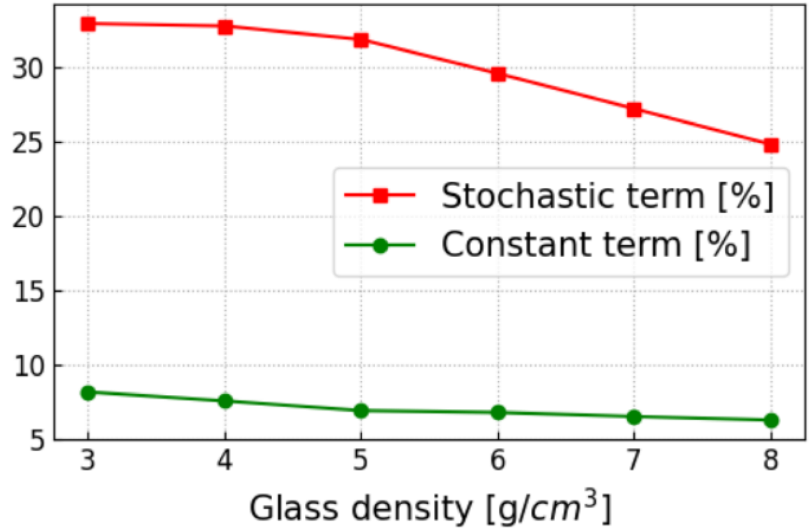
Impact of glass density to energy resolution

MC sample: pi-

Energy resolution vs. glass density



- Varying glass scintillator density: 3 to 8 g/cm^3
  - Shower starting layer < 5 (to reduce leakage effects)
- Extraction of stochastic and constant terms in energy resolution



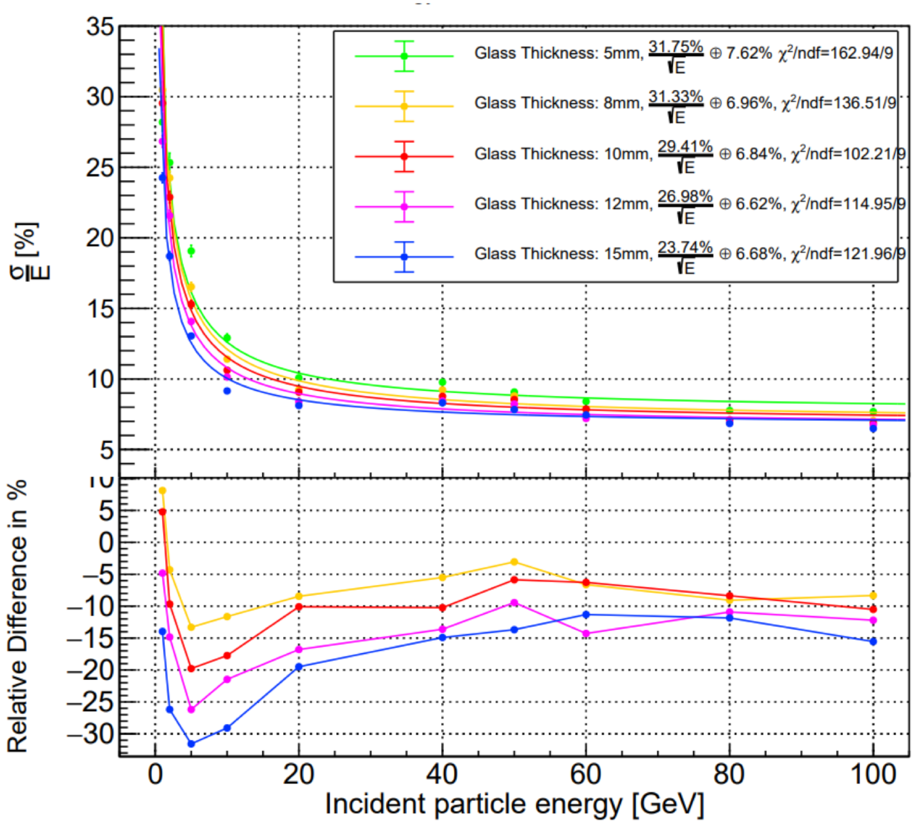
➢ Increasing density can improve hadronic energy resolution

➢ Considering constraints of light yield in glass R&D, target density set as ~6 g/cm^3

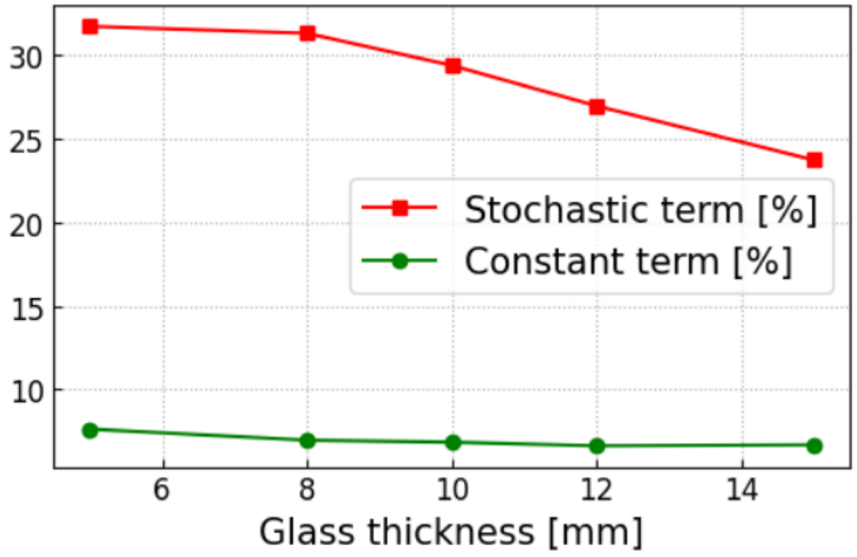
Impact of glass thickness to energy resolution

MC sample: pi-

Energy resolution vs. glass thickness



- Varying glass scintillator thickness: 5 to 15 mm
  - Shower starting layer < 5 (to reduce leakage effects)
- Extraction of stochastic and constant terms in energy resolution



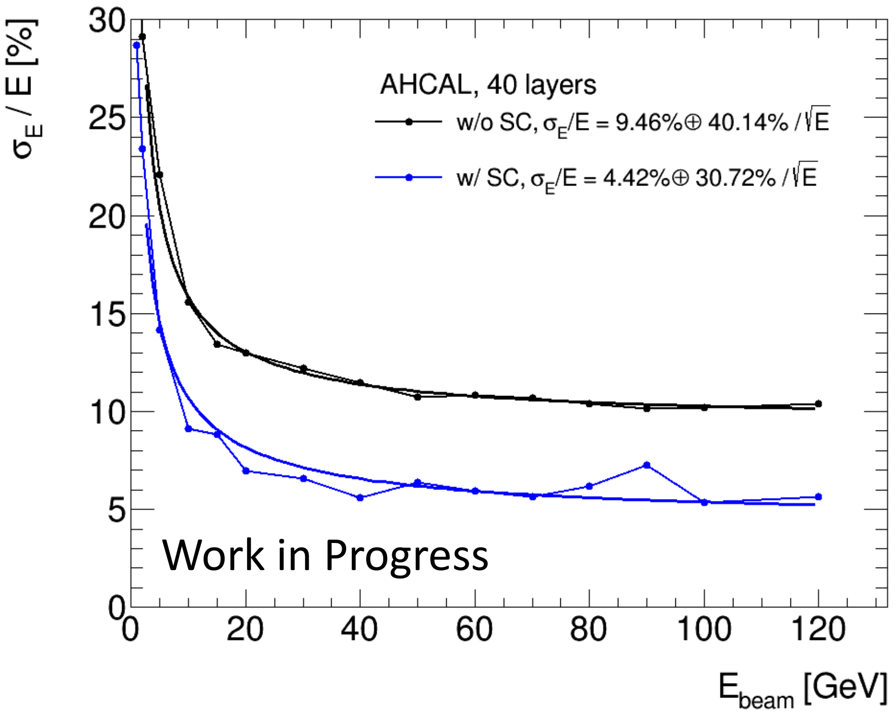
➢ The hadronic energy resolution can be improved with thicker glass tiles, especially the stochastic term

➢ Glass thickness of 10 mm will be chosen for current design

Yong Liu (liuyong@ihep.ac.cn)

Software compensation for ScintGlass HCAL

- Further improvements to hadronic energy resolution
  - Hadronic showers: EM core (compact) + purely hadronic component (sparse)
  - Software compensation: determine weights based on energy density for EM/hadronic parts



- ScintGlass HCAL option
  - Unequal response to EM/had. (e/h>1)
- Preliminary simulation studies
  - Software compensation shows a significant improvement in energy resolution

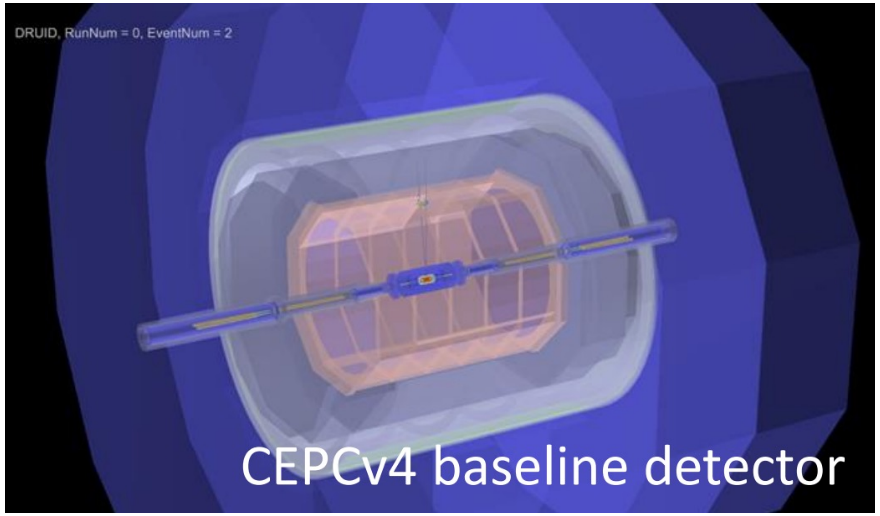
SC techniques applied in H1, ATLAS, CALICE-AHCAL, CMS-HGCAL; PandoraPFA

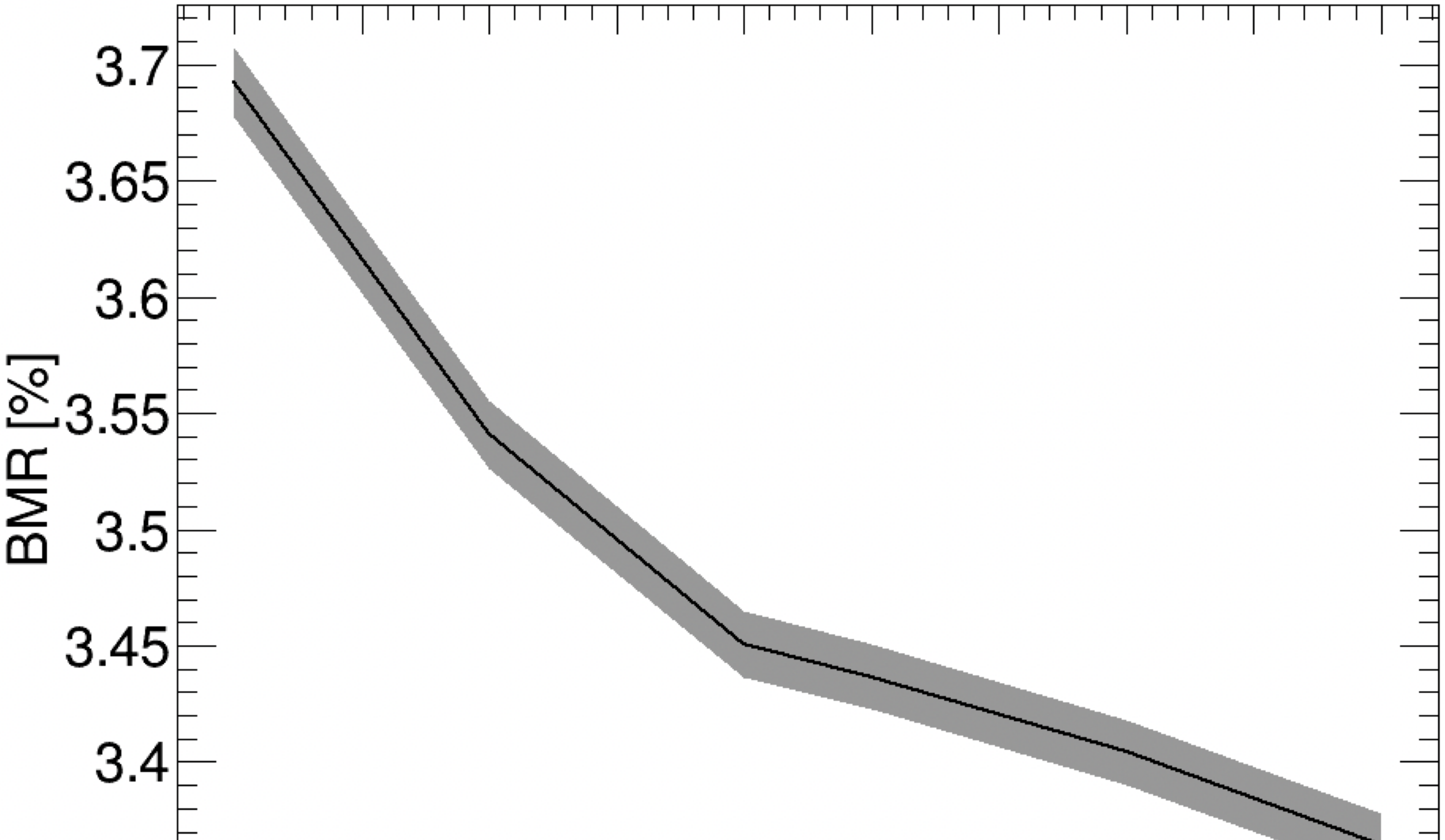
Optimisation based on PFA studies

Peng Hu (IHEP)

- Adapted from CEPC baseline detector
  - ScintGlass-Steel HCAL + Si-W ECAL
- Higgs benchmark with two gluon jets (at 240 GeV)
- Physics performance evaluation
  - Boson Mass Resolution (BMR): resolution of the Higgs invariant mass
  - Full simulation + PFA reconstruction by Arbor

Total number of layers	**40**
Total nuclear interaction length	**6 λ**
Glass density	**6 g/cm^3**
Energy threshold	**0.1 MIP**

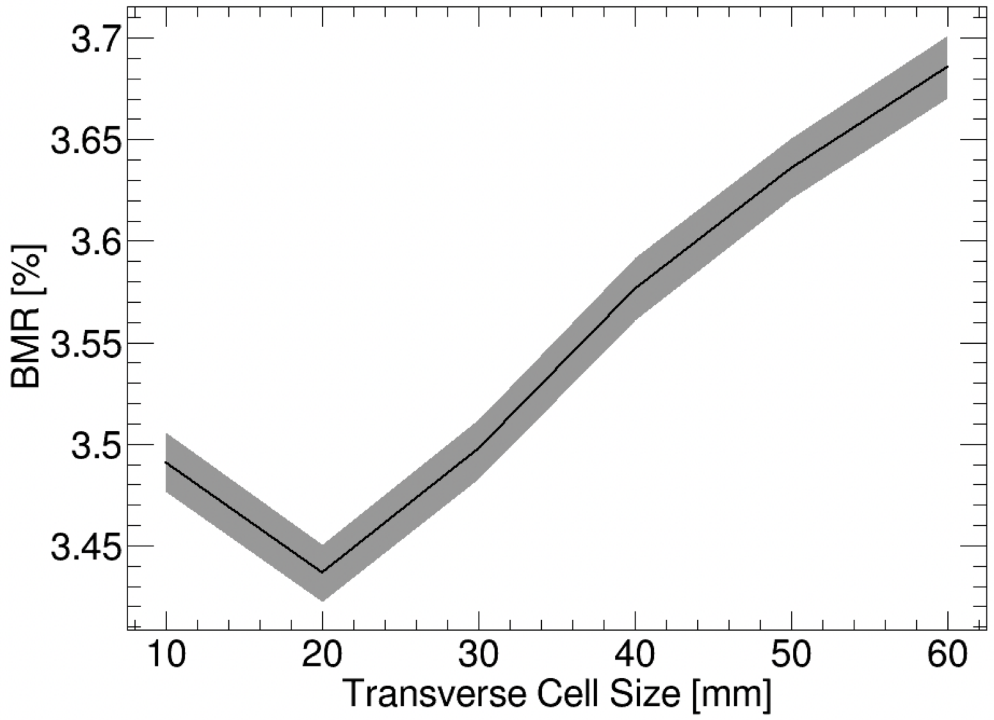


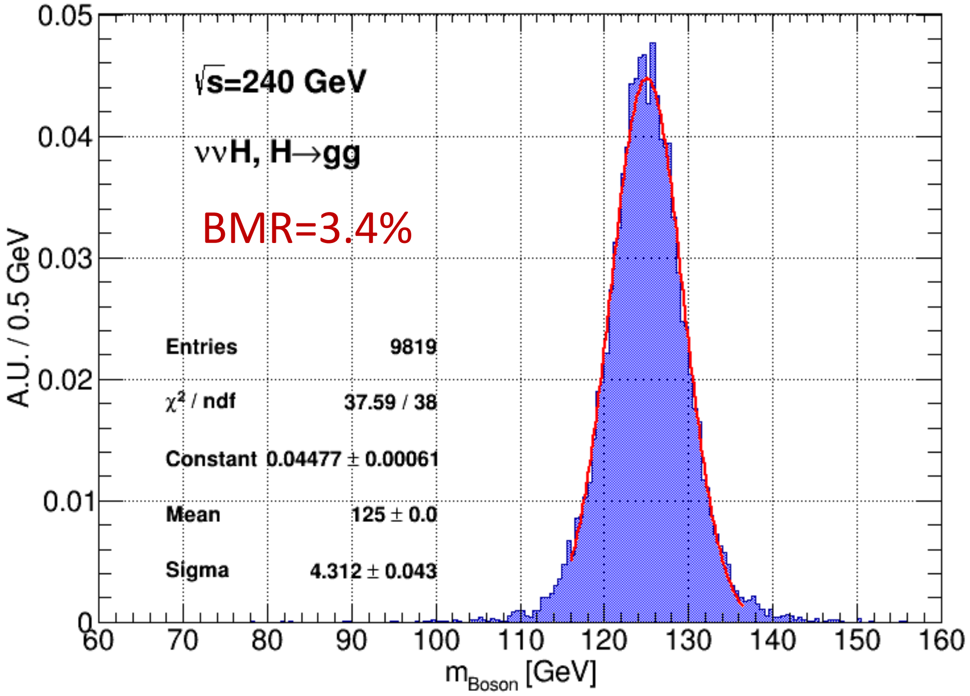


BMR [%]
3.7
3.65
3.6
3.55
3.5
3.45
3.4

BMR vs. transverse granularity

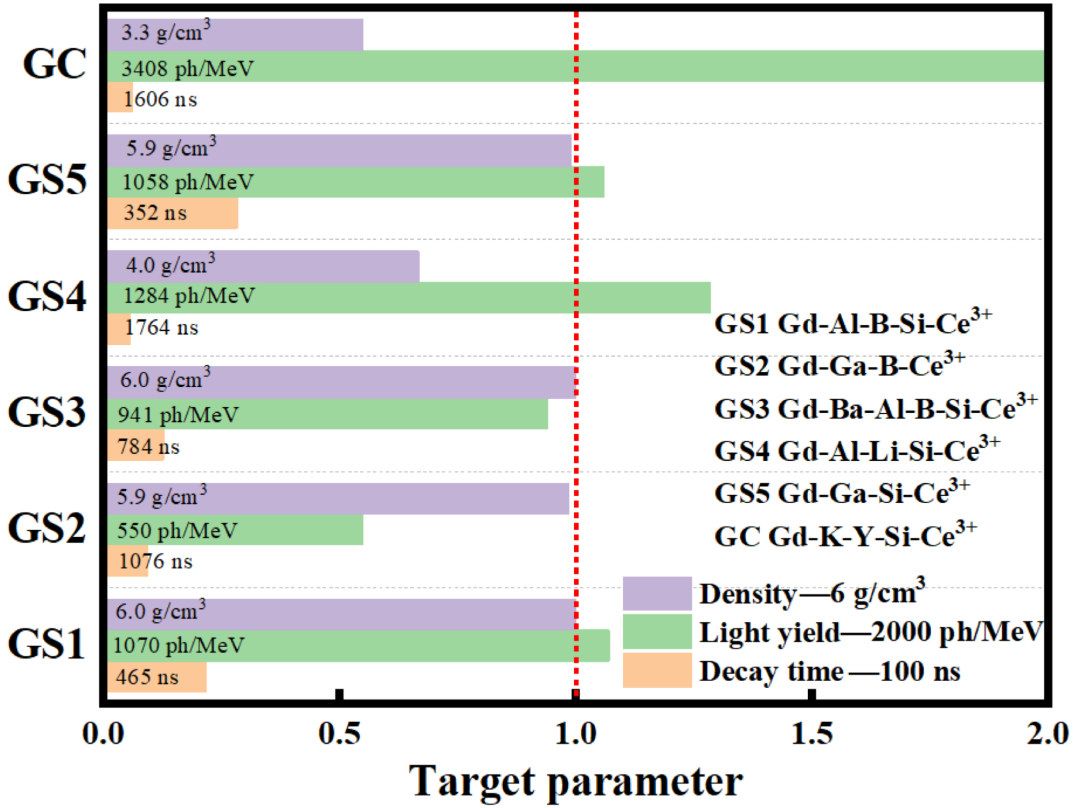
Peng Hu (IHEP)





- BMR improved with finer transverse granularity
  - Granularity of ~10x10mm: pattern recognition issue with dramatically more #hits
- Optimal BMR has reached 3.4%
  - Can be further improved by optimization of PFA parameters (goal: BMR ~3%)

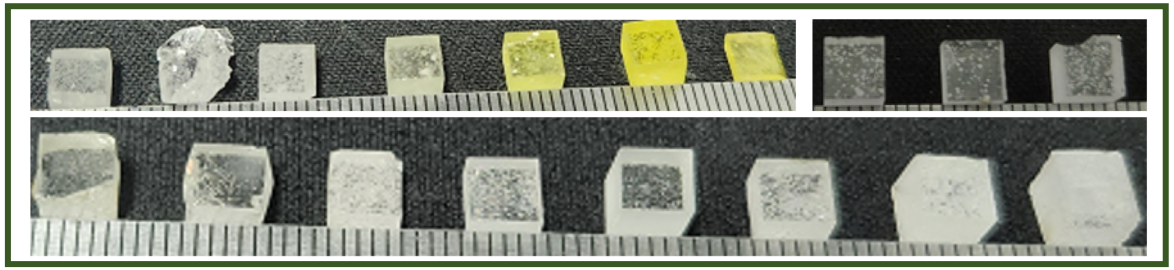
Summary: Glass Scintillator R&D

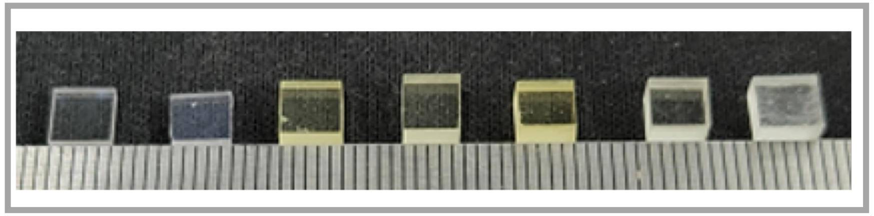


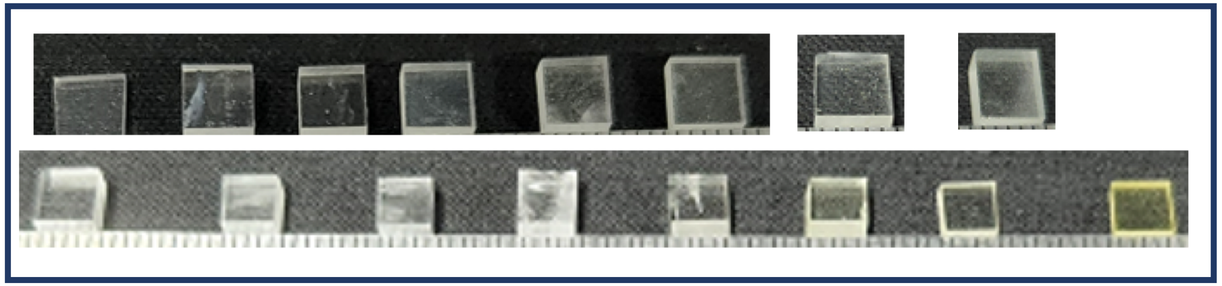
- Targets
  - 6 g/cm³, 2000 ph/MeV, 100 ns
- Best glass sample in mm scale
  - 5.9 g/cm³, 1058 ph/MeV, 352 ns
- Challenges
  - Increase density while keeping high light yield and transparency
  - Synthesizing large cm-scale glass tiles with good scintillation and optical properties

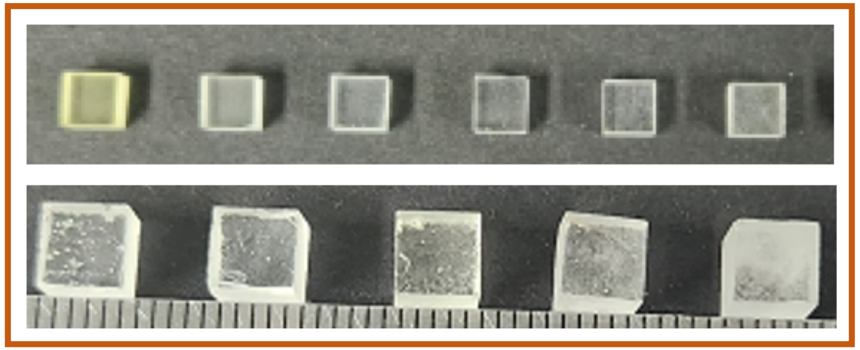
Glass Scintillator R&D

- Over 400 samples of glass scintillator produced in the past year
- Different colored boxes correspond to samples from different institutes in collaboration

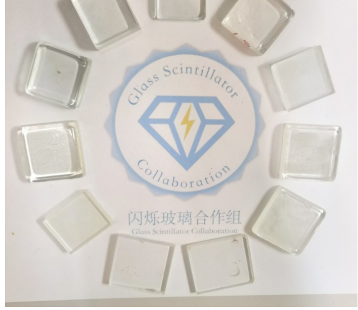


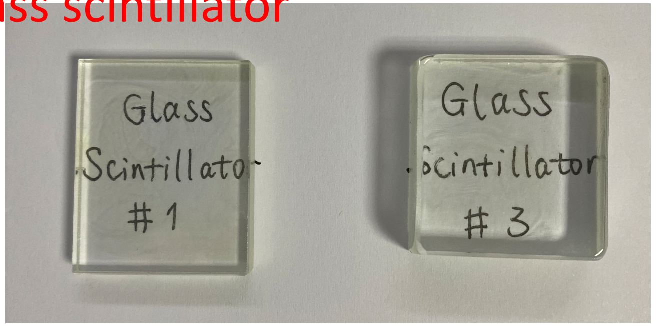




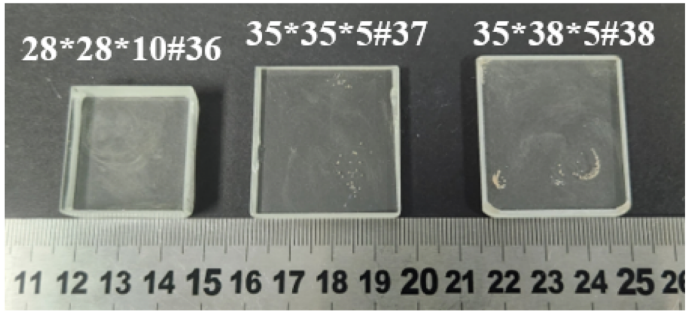


R&D of large size glass scintillator





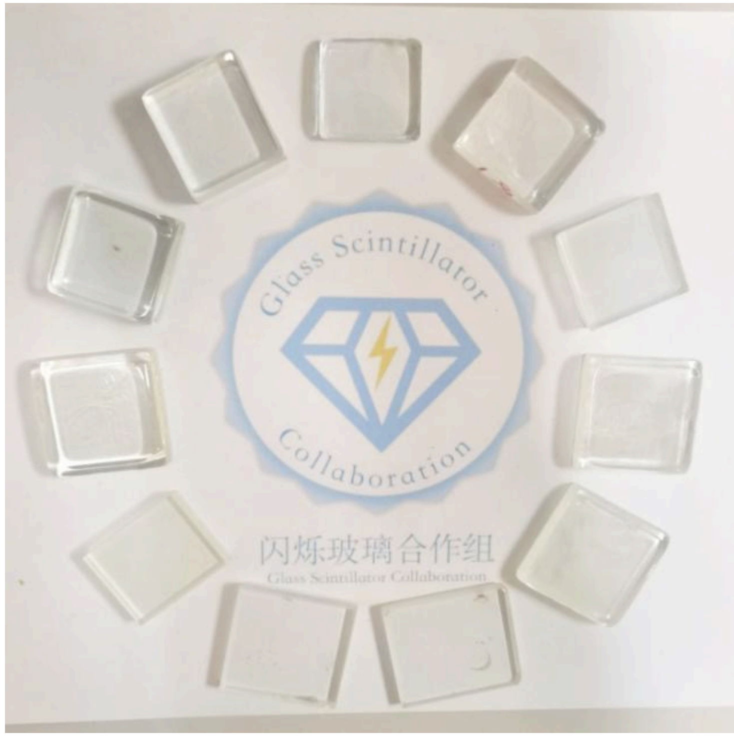
Gd-Al-B-Si-Ce^{3+} glass
42mm*51mm*10mm



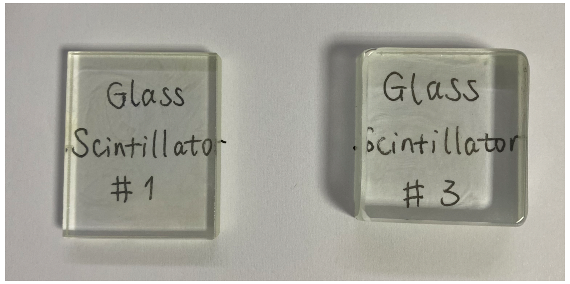
Introduction: CERN beam test

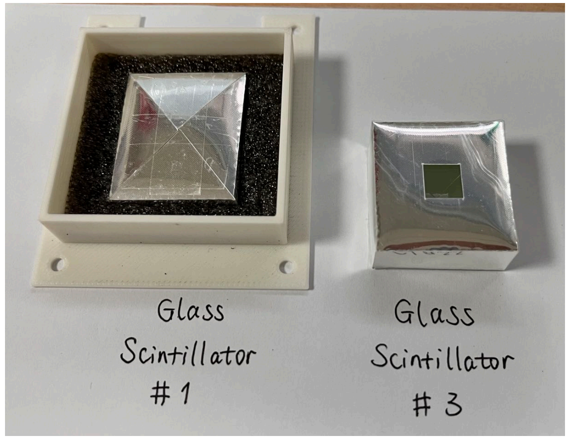
- 11 scintillator glass tiles successfully delivered from IHEP to CERN in May 2023
  - Parasitic runs with CALICE-CEPC calorimeter prototypes
- **Motivation**: use muon beam to measure MIP response of each glass tile

Glass tiles (cm-scale) before wrapping



Glass tiles wrapped with Teflon and black tapes

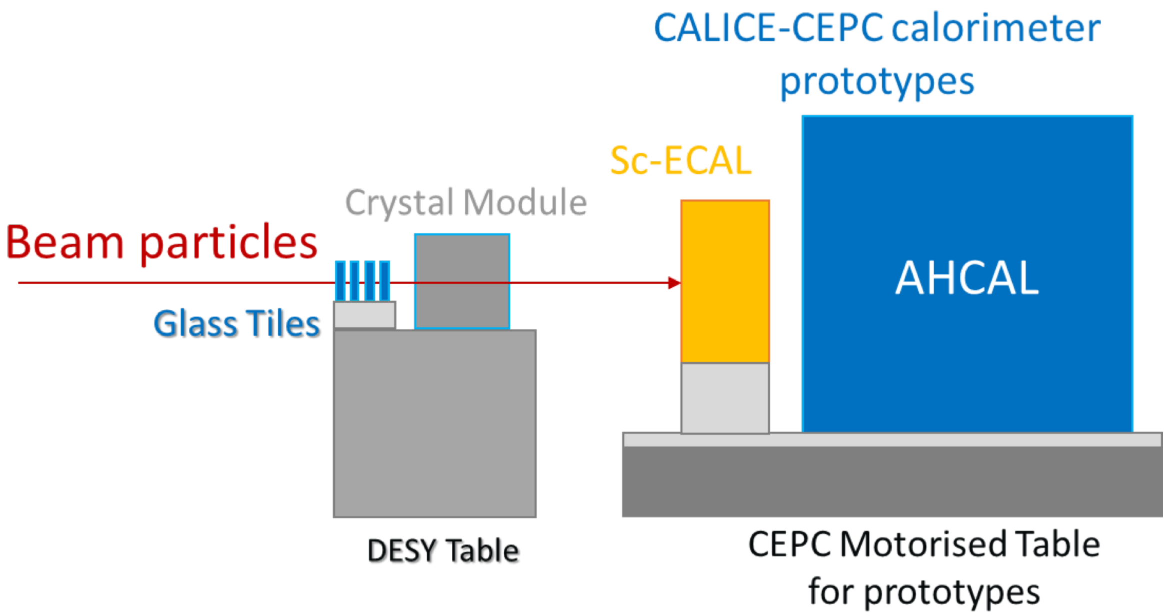


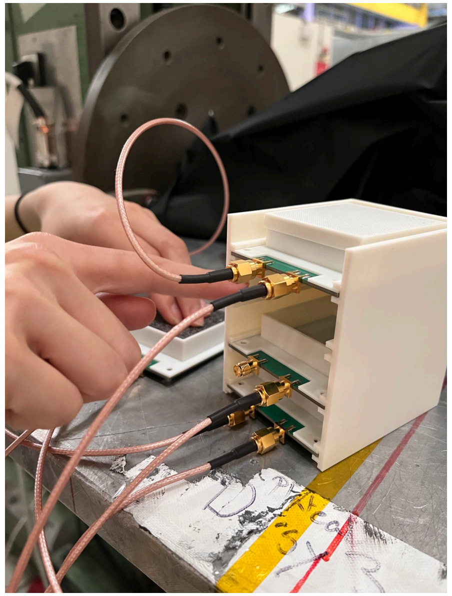


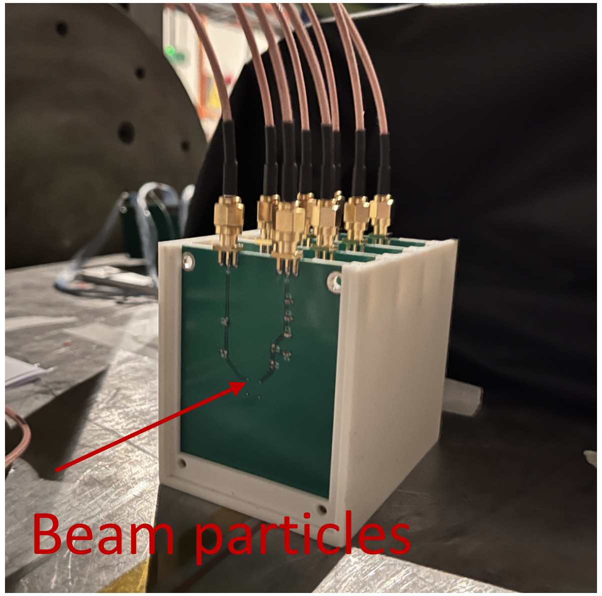
Two glass tiles re-wrapped with ESR

Beamtest setup at CERN PS-T9 beamline

- Beam test setup
  - 4 tiles with individual SiPM readout
  - 3 glass tiles and 1 plastic tile (reference)
  - Data acquisition using a 4-ch fast oscilloscope (5GS/s)
- Data sets with 10 GeV muons







DESY Table: remote control for vertical/horizontal movements of crystal module and glass tiles

Move IN/OUT of beamline: coordination with testing of CEPC calorimeter prototypes

Glass tiles with muon beam

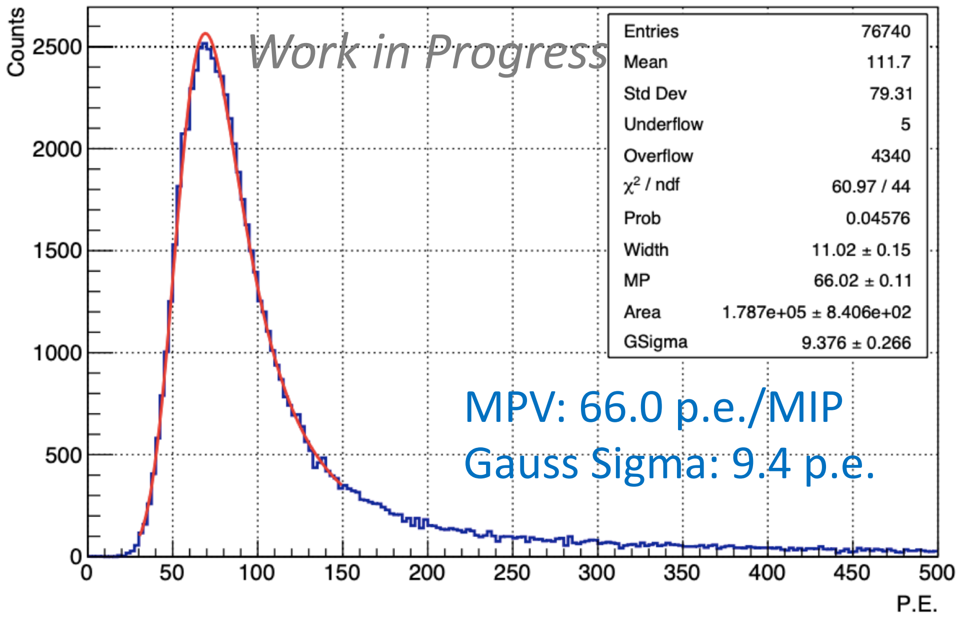
- Use 10 GeV muons to test 11 glass tiles and a plastic scintillator tile (reference)
- Glass scintillator: performance target (reminder)
  - ~150 p.e./MIP for large-scale glass tiles (3-4cm in length, 1cm in thickness)

Typical waveforms with muon beam:

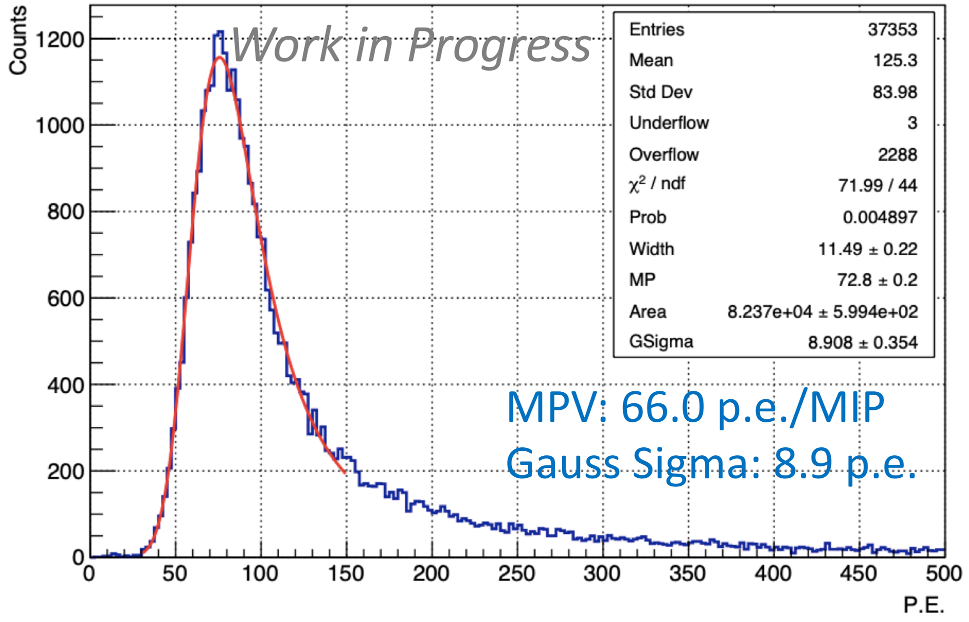
- 1 plastic tile (blue)
- 3 glass tiles (green, yellow, red)

Preliminary beamtest results

- Observed clear MIP signals in all 11 glass samples
  - Various glass tile dimensions: 25-40 mm in length, 5-10mm in thickness
- Preliminary results quite promising
  - Typical MIP response: 15 – 74 p.e./MIP

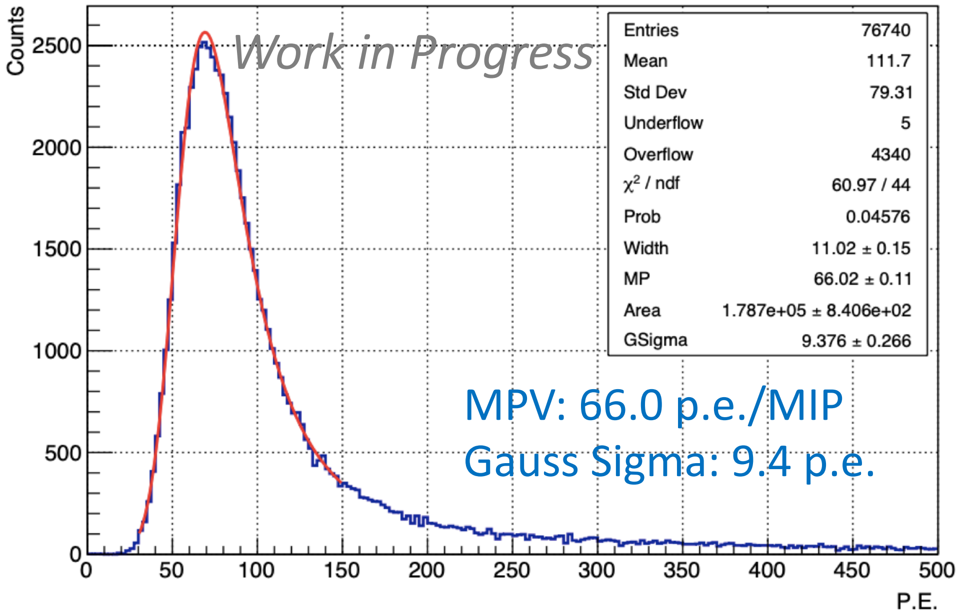


Glass scintillator tile #3: $29.8 \times 28.1 \times 10.2\ \mathrm{mm}^3$

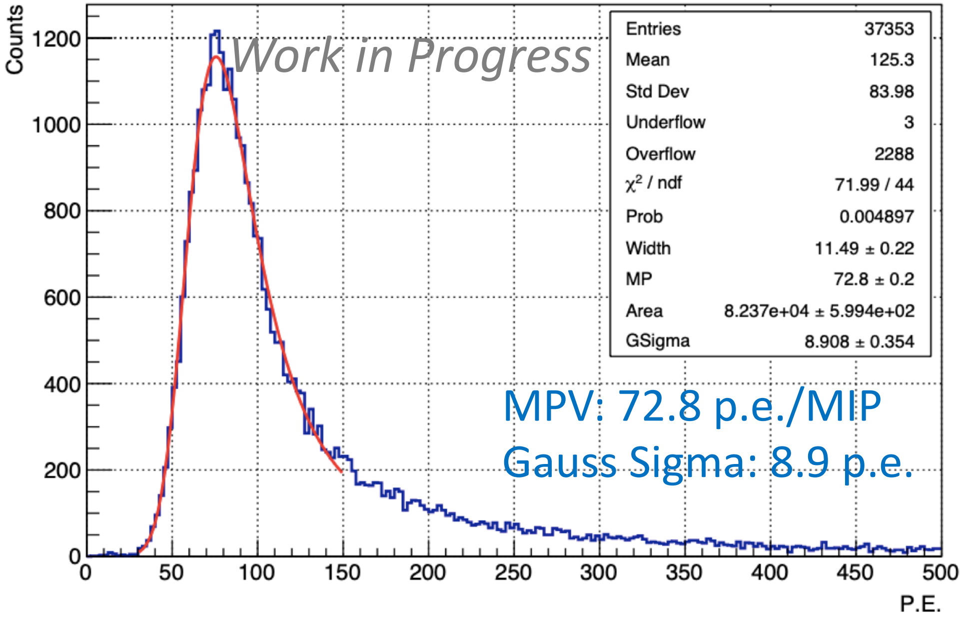


Glass scintillator tile #11: $30.5 \times 30.0 \times 8.7\ \mathrm{mm}^3$

- Muon energy spectrum: MIP response
  - Fitting by Landau (energy deposition) convoluted with Gaussian (resolution)
- Energy deposition MPVs: 66 p.e./MIP (#3); 73 p.e/MIP (#11)
- Energy resolutions: 14.2% @7.7 MeV (#3); 12.2% @6.7 MeV (#11)



Glass scintillator tile #3: $29.8\times28.1\times10.2\ \mathrm{mm}^3$

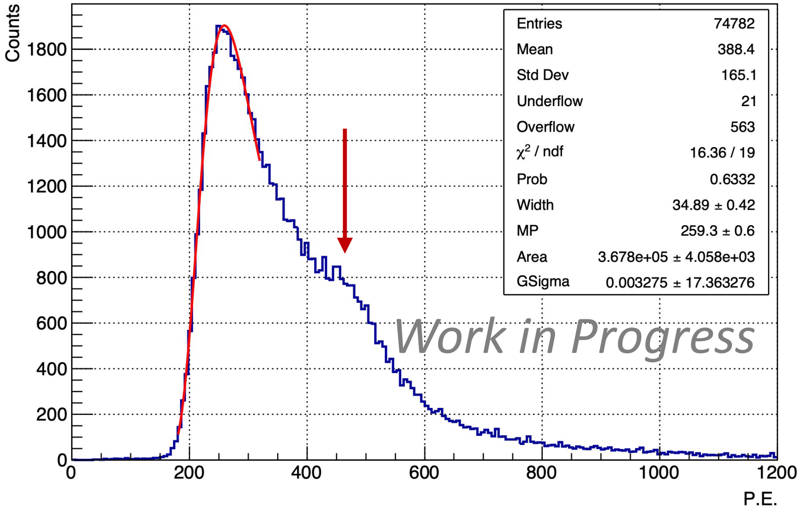


Glass scintillator tile #11: $30.5\times30.0\times8.7\ \mathrm{mm}^3$

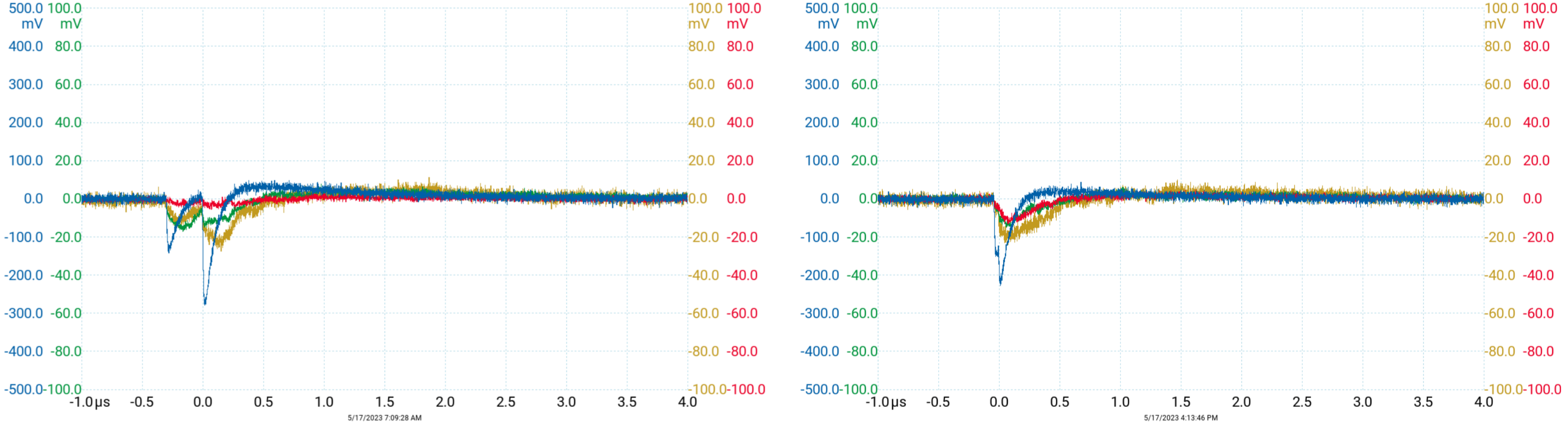
Energy deposition MPV of 7.58MeV for 10mm thick tile (based on G4 simulation with 10 GeV muons)

Preliminary beamtest results with muons

- Observed clear MIP signals in all 11 glass samples
- Muon beam results look promising
- Observed (unexpected) structures in energy spectrum
    - (Partially) due to incidence of two muons



Plastic scintillator: 259 p.e./MIP
($40 \times 40 \times 10\ \mathrm{mm}^3$)



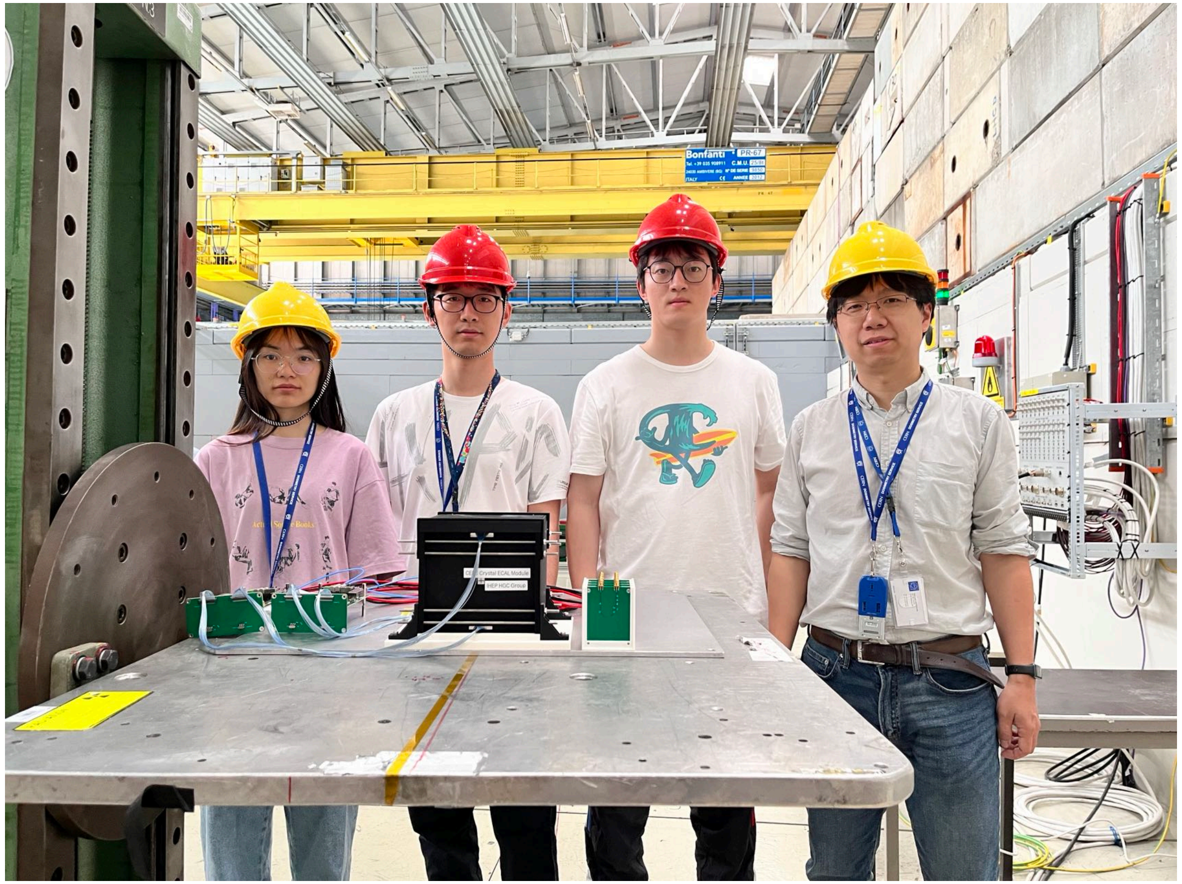
SiPM-Tile waveforms: two muons in a short time window

Summary: beamtest results of 11 glass tiles

Index	Dimensions (mm)	Muon response (p.e./MIP)	Scale to 10mm thickness (p.e/MIP)
#1	33.5×27.6×5.1	15	29
#1 ESR		42	82
#2	30.2×29.5×6.6	35	53
#3	29.9×28.1×10.2	66	65
#3 ESR		69	68
#4	37.2×35.1×5.3	31	59
#5	40.0×35.1×4.2	38	91
#6	30.3×29.8×9.4	67	71
#7	34.8×34.8×7.5	60	80
#8	27.8×25.6×5.0	41	82
#9	34.6×34.7×7.5	69	92
#10	34.7×35.2×7.4	74	100
#11	30.5×30.0×8.7	73	84

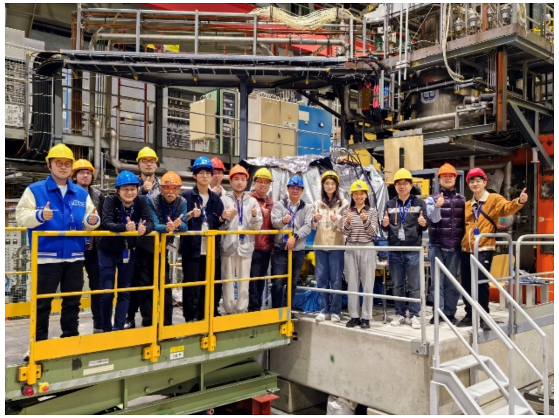
Acknowledgements

- Strong teamwork and team's hardworking spirit in day and night
- Enormous and substantial support from CERN and CALICE



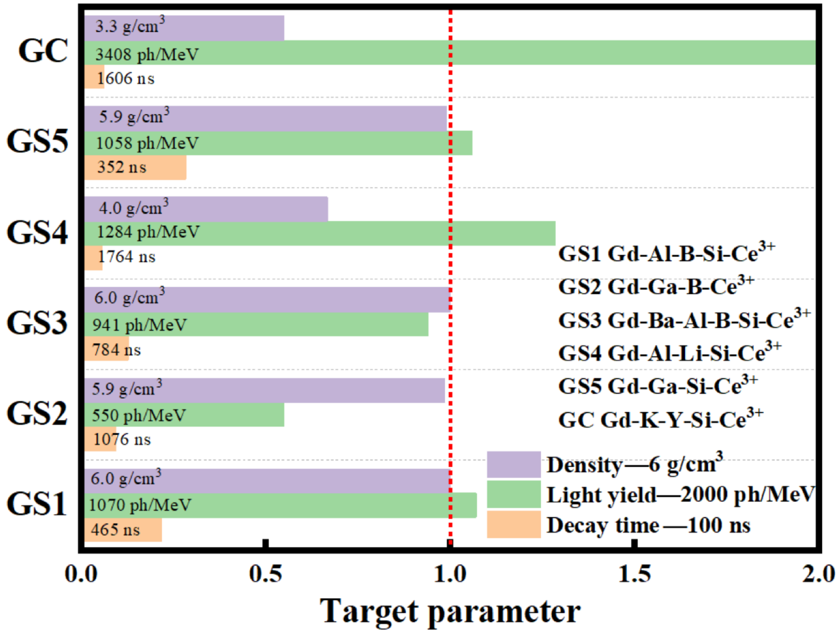
Very successful beam test campaigns:

A big Thank You to CALICE and CEPC calorimeter teams



Summary and prospects

- Simulation studies
  - Guidance for glass R&D and HCAL design
  - Single hadrons: hadronic energy resolution
  - Higgs benchmark with jets: BMR optimization
- CERN beamtest in May 2023
  - Full muon data sets for all 11 scintillator glass tiles
  - Evaluation of key parameters
    - MIP response, energy resolution
  - Preliminary results promising
- Prospects
  - Design optimization for optimal performance
  - R&D of new batches of large-scale glass tiles



Thank you!

Backup

Digitization in simulation

Digitization:

- Energy deposition
- Incident photons
- SiPM response
- Charge output
- Digitized energy

Edep

↓ Photon statistics (Poisson distribution)

Scintillation photons

↓ $$Nfired = Npixel \times e^{-\frac{Nphoton}{Npixel}}$$

Detected photons

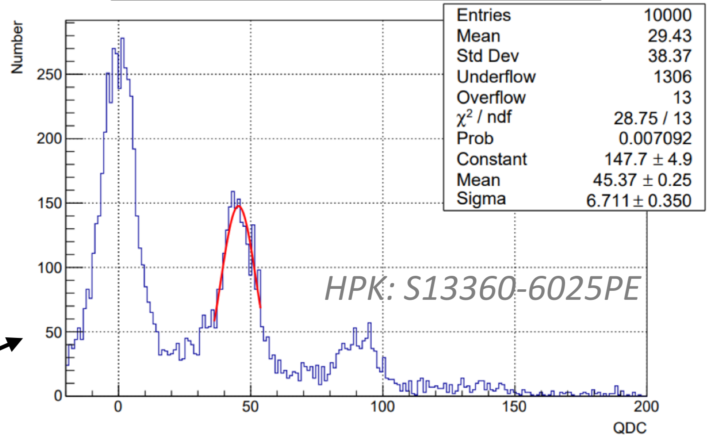
↓ SiPM gain and its error

Charge

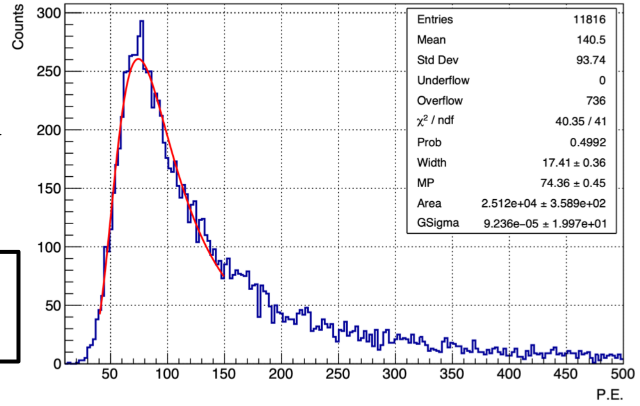
↓ MIP cut

Edigi

Single photon calibration



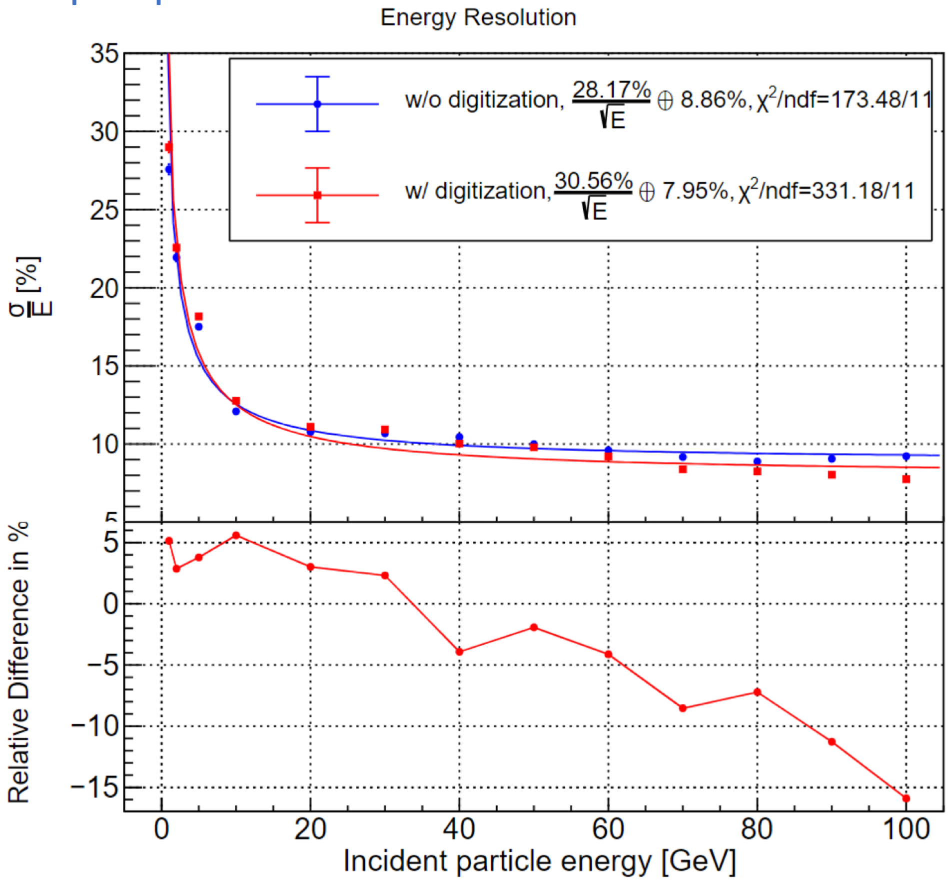
MIP response of glass tile



74p.e./MIP @ 7.4mm thick
100p.e./MIP @ 10mm thick

Preliminary result of digitization

MC sample: pi-



- Influence of digitization on energy response
    - Energy threshold = 0.1 MIP
    - Shower starting layer < 5 (to reduce energy leakage effects)
- Digitalization has little effect on energy resolution
- To further complete digitization method
    - Single photon and MIP calibration should be measured with the chip
    - Differences between channels

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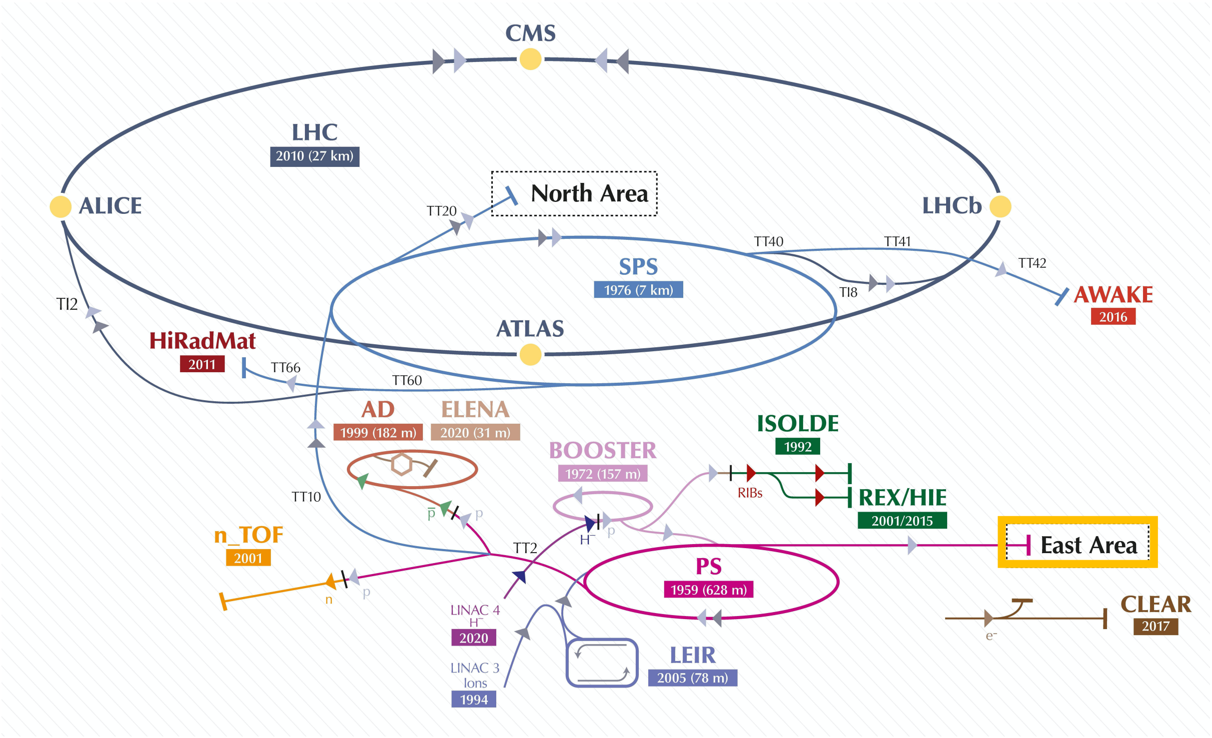
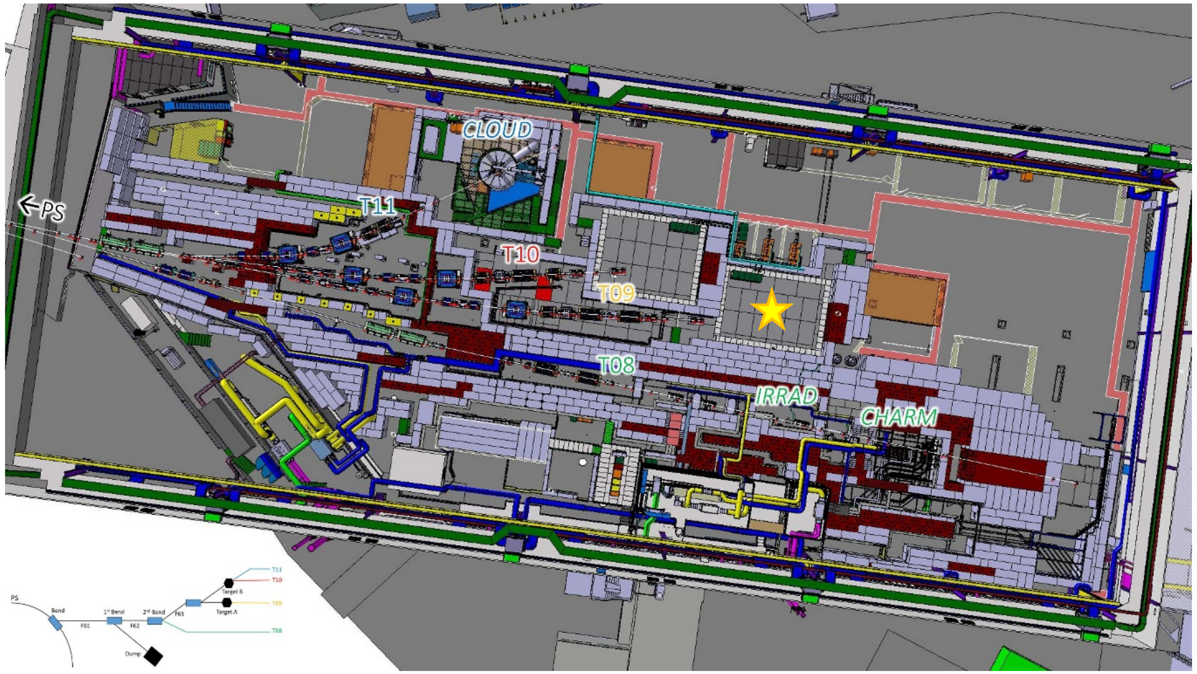
CERN PS and T9 beamline

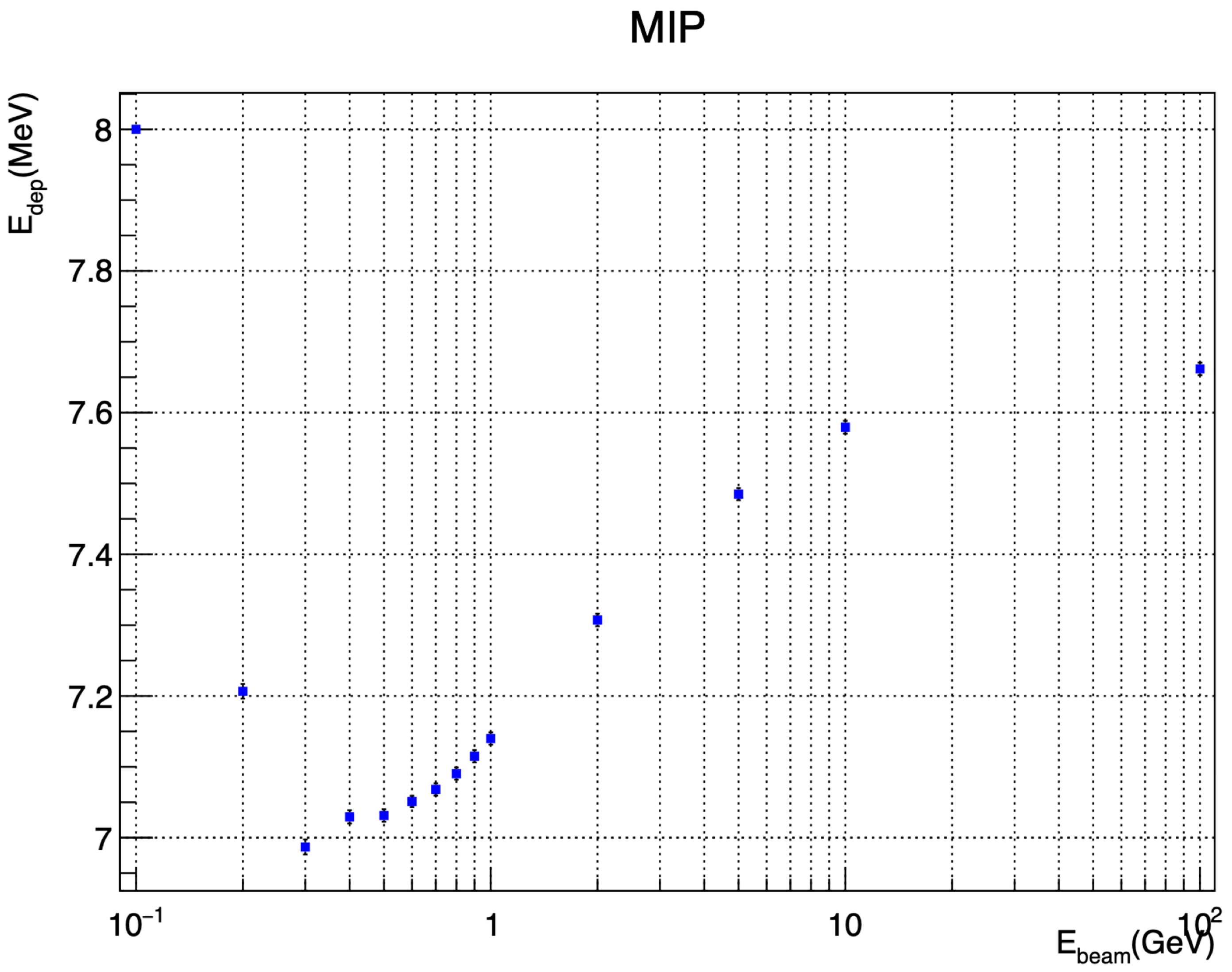
- CERN Proton Synchrotron (PS): primary 24GeV protons
- Secondary beam particles at PS-T09
  - Muons and charged hadrons: up to 15 GeV/c
  - Electrons: up to 5 GeV/c



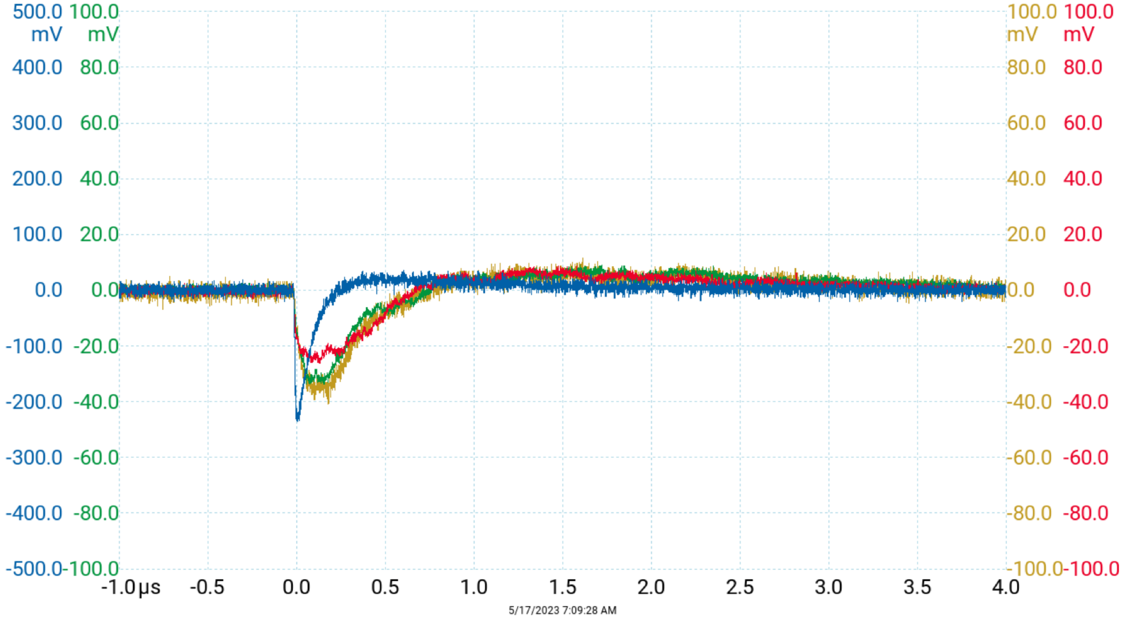
★ East Area (B.157) PS-T9

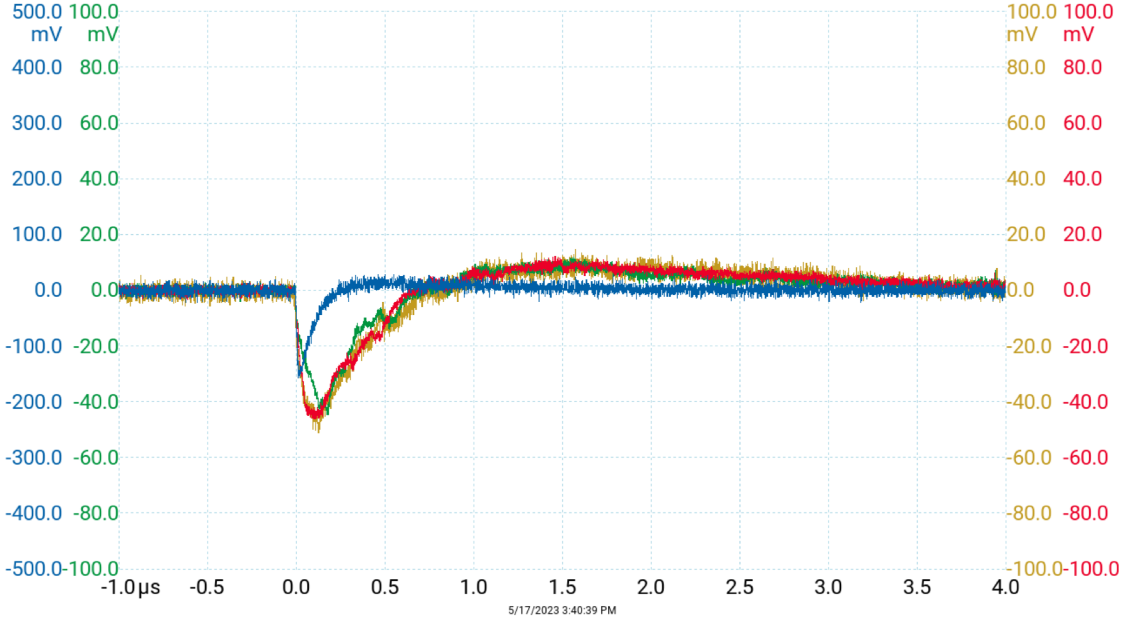


MIP energy deposition vs muon energy: Geant4 simulation



Typical waveforms with muons





Fitting with two Landau+Gauss functions