Studies on timing performance of BGO crystal scintillator

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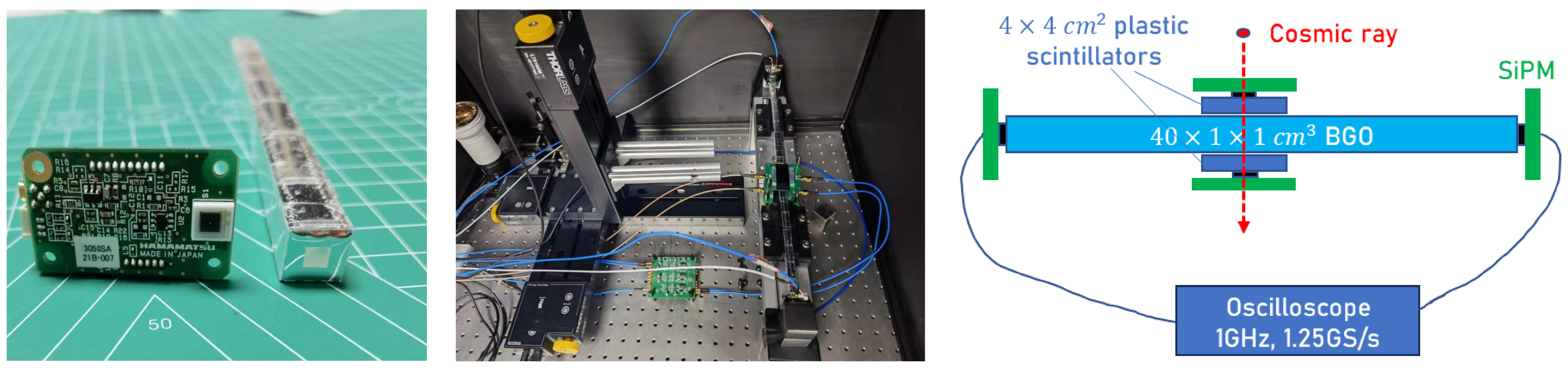
Introduction

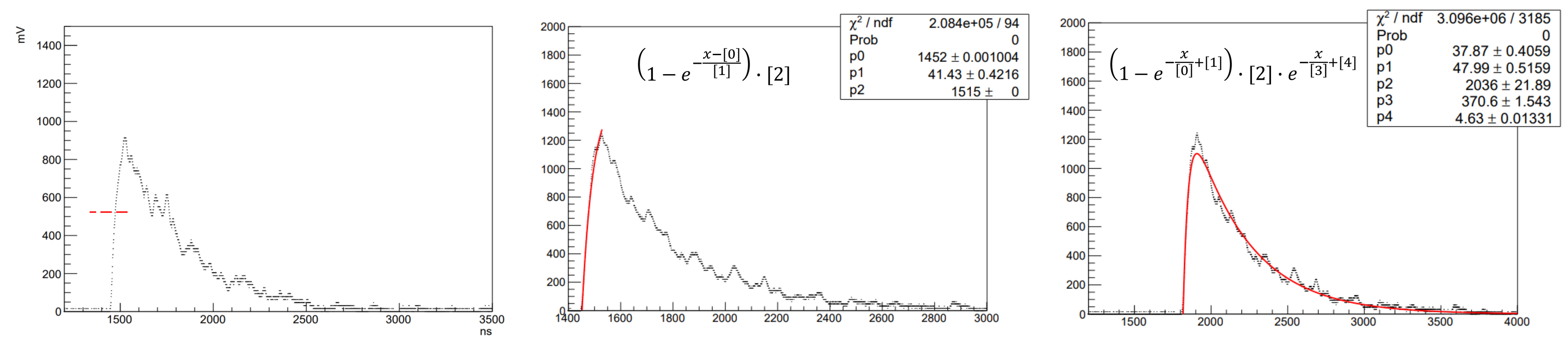
The future Circular Electron-Positron Collider (CEPC) is envisioned as a large-scale Higgs factory. For its detector system, a highly granular crystal electromagnetic calorimeter has been proposed to deliver 5D information, encompassing the x, y, z coordinates, energy (E), and time (t). This calorimeter features a homogeneous structure with long crystal scintillator bars as the active material, with BGO crystals and SiPMs identified as the preferred components. The role of time information in calorimeters is increasingly critical; it not only helps distinguish pile-up effects but also aids in particle identification, shower reconstruction, and enhances the calorimeter's energy resolution. Therefore, optimizing and understanding the timing performance of this detector design is of paramount importance. The timing resolution of the detector unit, consisting of a BGO crystal and two SiPMs, was thoroughly studied through beam tests and simulations under various conditions.

Timing Methods

- Setup of a cosmic ray experiment

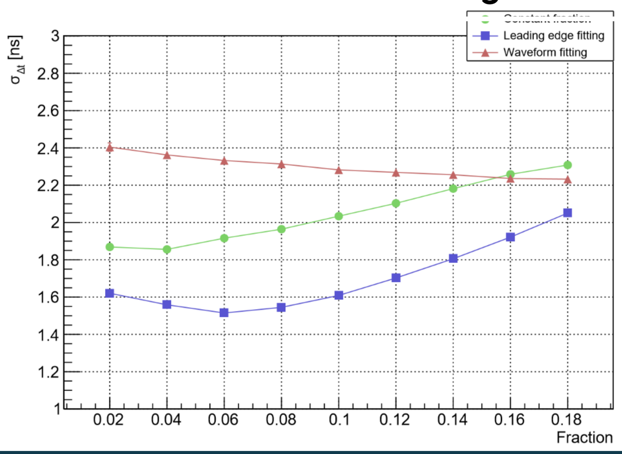


- Comparison of three timing methods



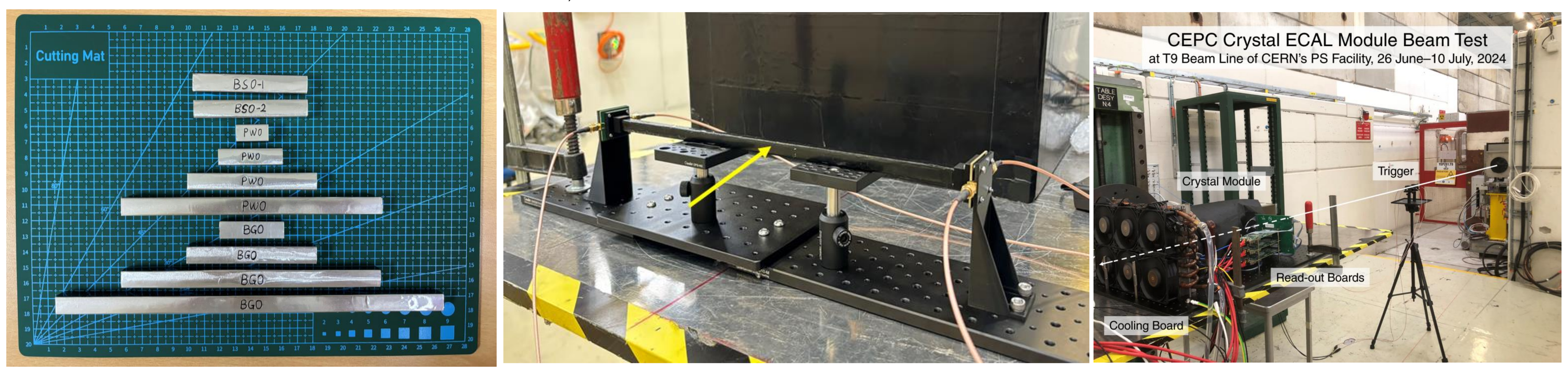
a. Constant fraction b. Leading edge fitting c. Waveform fitting

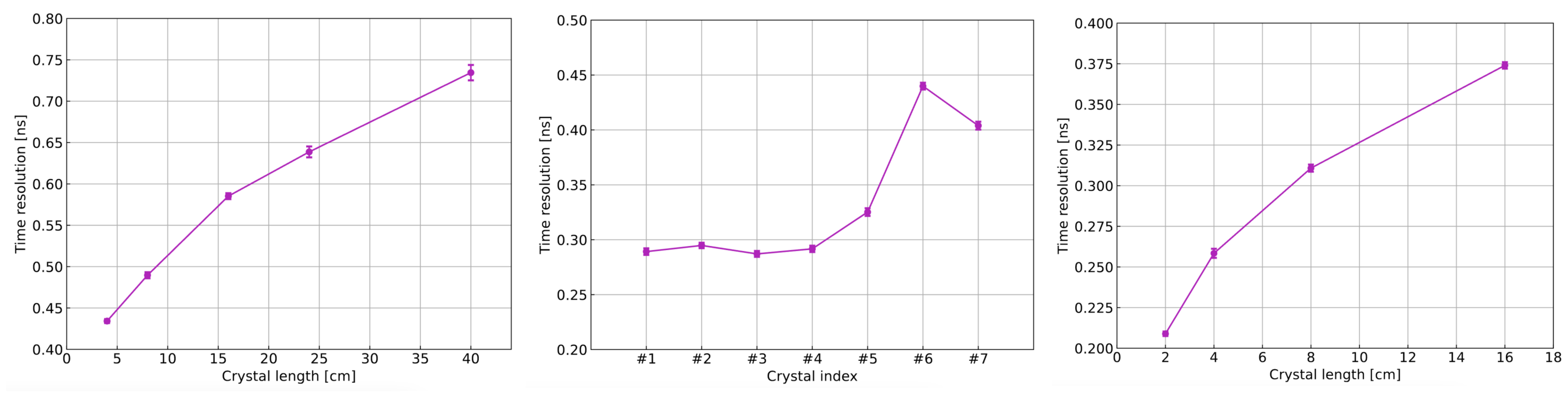
- The method of leading edge fitting gives the best time resolution result.
- Time resolution depends on the fraction. Stochastic fluctuation of photon's arrival time increase as the fraction, while the noise decreases with increasing threshold.



Time resolution - MIP

- CERN PS T9, 10GeV pion beam, 26 Jun. ~ 10 Jul. 2024
- The time resolution of BGO with lengths ranging from 4 to 40 cm is from 0.45 to 0.75 ns, and it worsens with increasing doping concentration. For PWO crystals, with lengths ranging from 2 to 16 cm, the time resolution is between 0.2 and 0.375 ns, which is better than that of BGO.



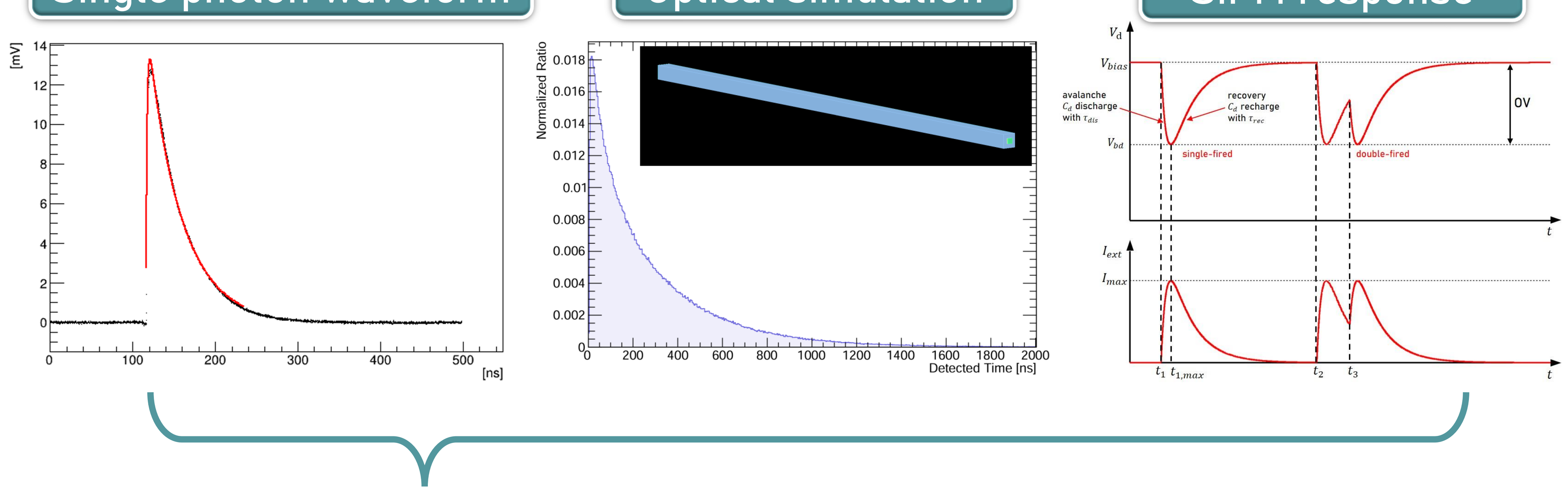


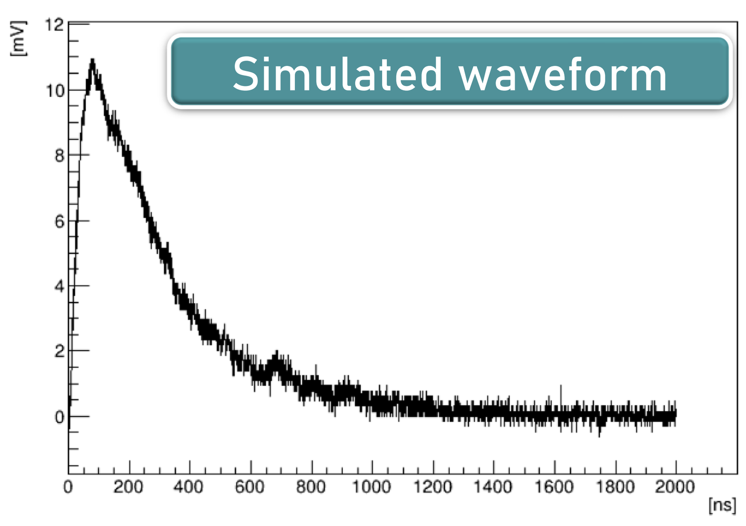
a. Results of 4~40cm BGO bars. The time resolution improves as the crystal length decreases.

b. 2cm BGO with different doping concentrations (100ppm, 200ppm, 500ppm, 1000ppm, 2000ppm, 5000ppm, 5000ppm)

c. Results of 2~16cm PWO. The time resolution of PWO is better than that of BGO with the same length, dominated by decay time.

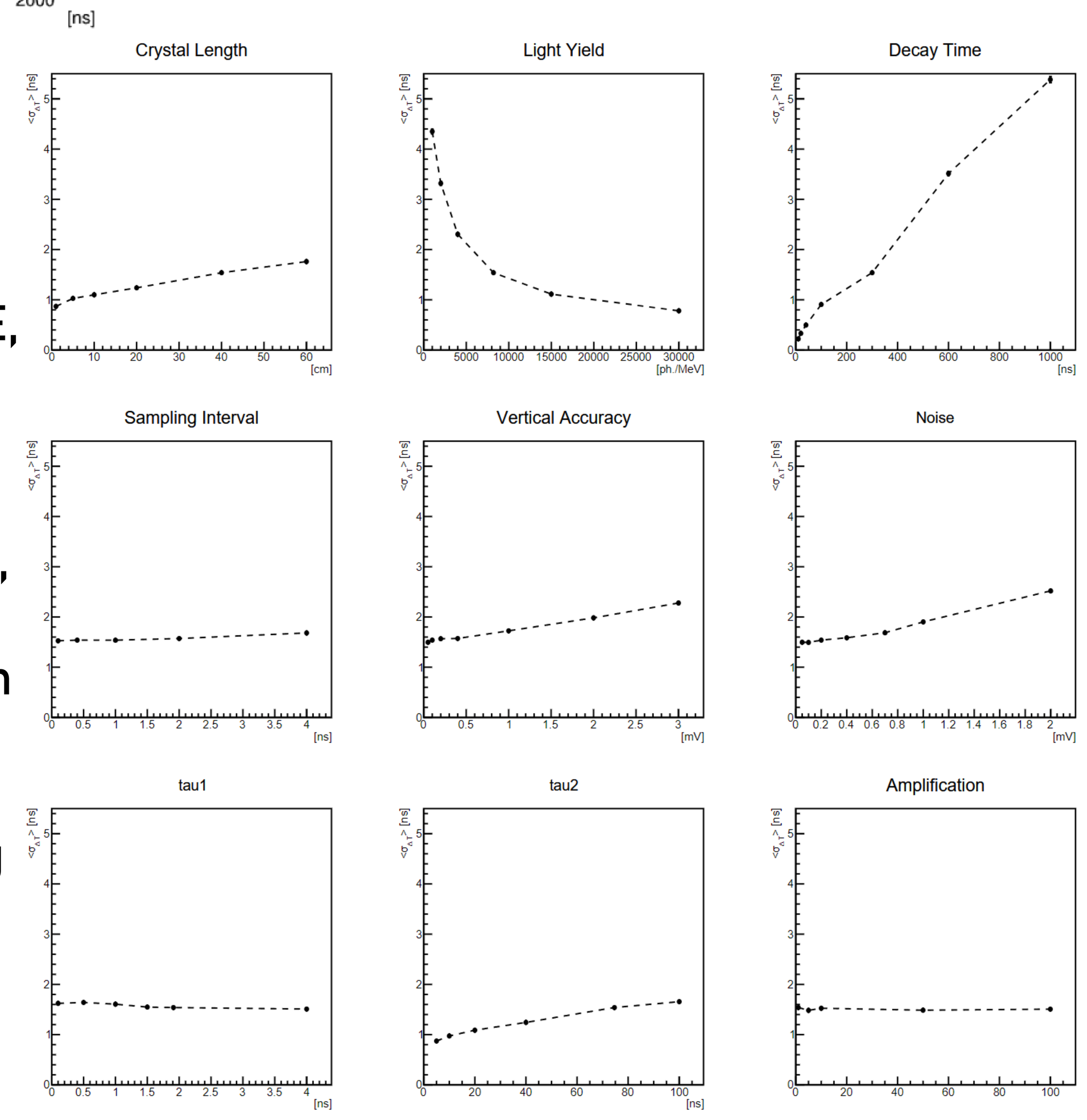
Simulation





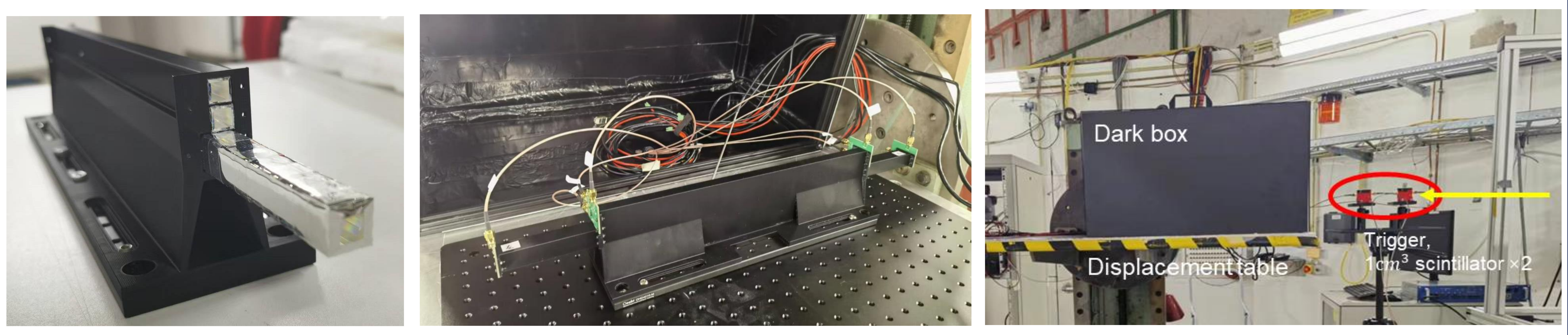
- Track the time, wavelength and other information of each detected photon in Geant4. Then, combine the measured single-photon waveform and SiPM response principle to superimpose and obtain the final waveform.

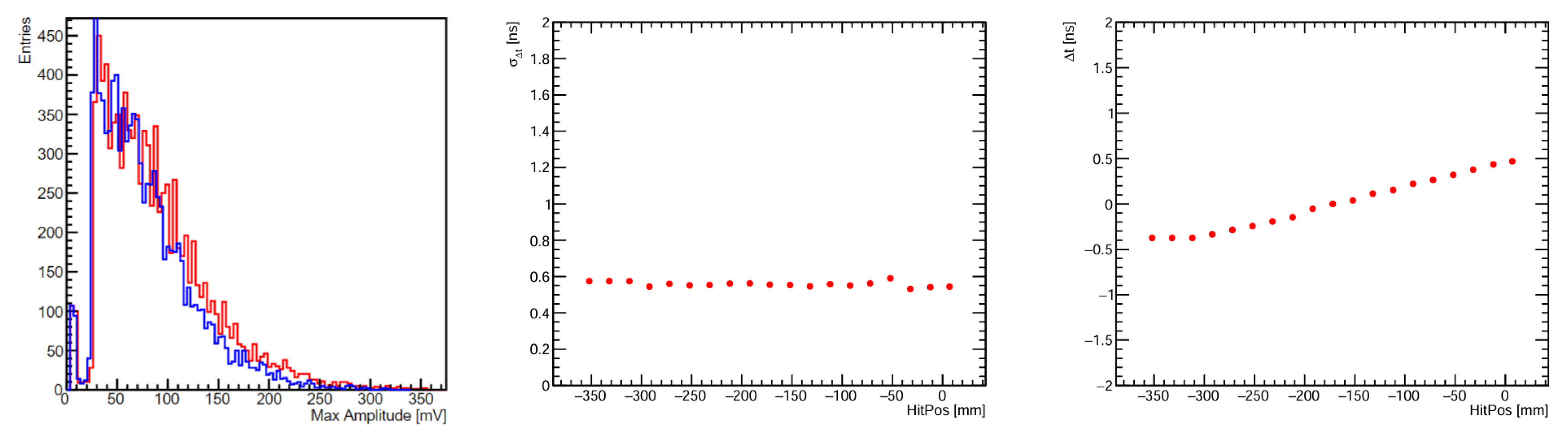
- Adjustable parameters:
  - Crystal: type, geometry, optical properties
  - SiPM: pixel density, PDE, recovery time, waveform
  - DAQ: sampling rate, vertical accuracy, noise, amplification
- Light yield and scintillation decay time have the greatest impact on time resolution, while sampling rate and amplification factor have minimal effect on time resolution.



Time resolution - Electron

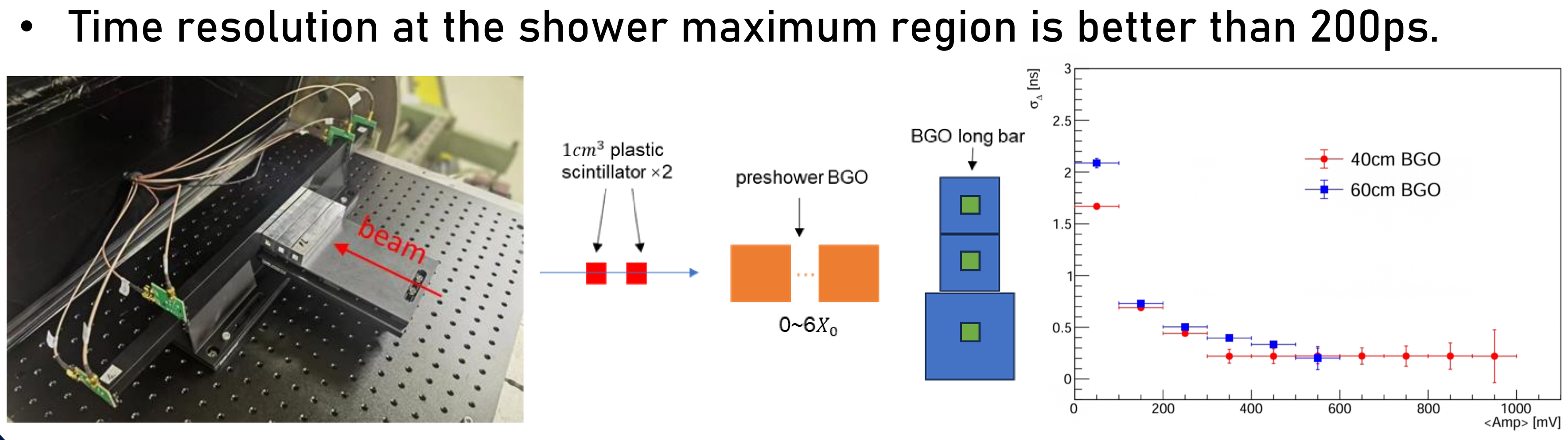
- DESY TB22, 1~5GeV electron beam, Oct. 2023





a. Signal Amplitude b. Time resolution scanning for 40cm BGO c. Time difference at various incident positions

- Additional crystals are placed in front of the tested crystal as a pre-shower to study the time resolution of EM showers at different depths.
- Time resolution at the shower maximum region is better than 200ps.



Summary

This study investigate the time resolution of the BGO-SiPM module, the basic unit of the highly granular crystal ECAL. Through comparative analysis, the leading-edge fitting method was identified as the optimal timing technique. Beam tests were conducted under various conditions, measuring the time resolution of BGO crystals (4 to 40cm) at 1-MIP using a pion beam, with results ranging from 0.45 to 0.75ns. An electron beam was also used to assess a 40/60cm BGO crystal at different shower depths, achieving an optimal resolution of 0.2 ns. Simulations were performed to identify key factors influencing time resolution, such as light yield and decay time.