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

Crystal Calorimeter R&D Updates

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CEPC Calorimeter Weekly Meeting on R&D Activities

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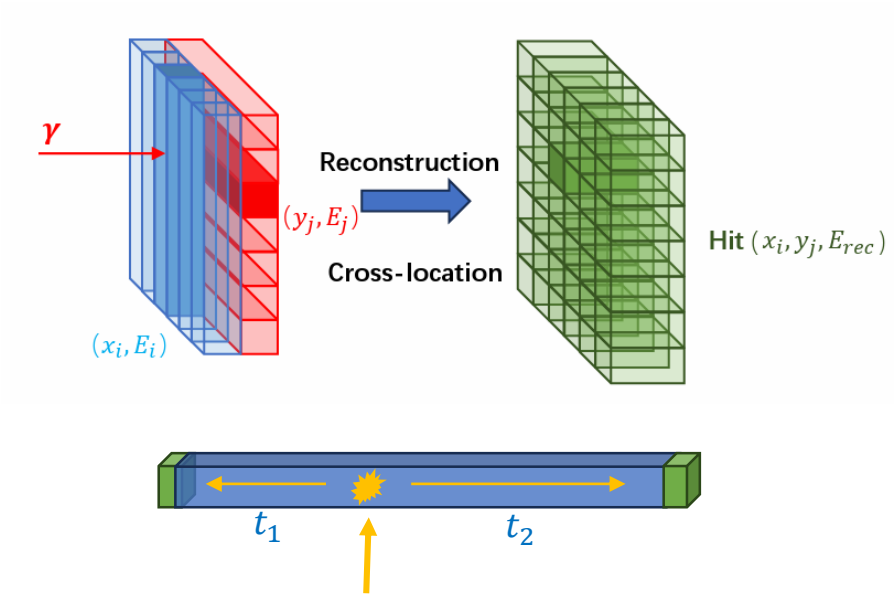
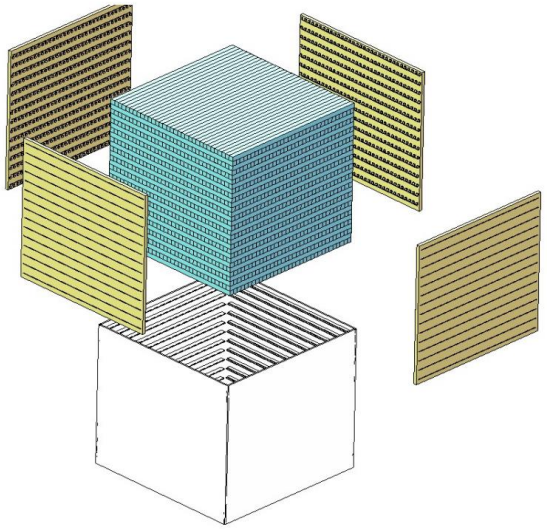
Crystal ECAL for CEPC: R&D activities

- Design of the crystal ECAL
  - 1×1×40 cm^3 crystal units, double-side readout with SiPM
  - Long crystal bars instead of small crystal cubes
    - Save #channels and minimize dead materials
    - Achieve high granularity with information from adjacent layers
  - Double-sided readout
    - Positioning potentials with timing at two sides



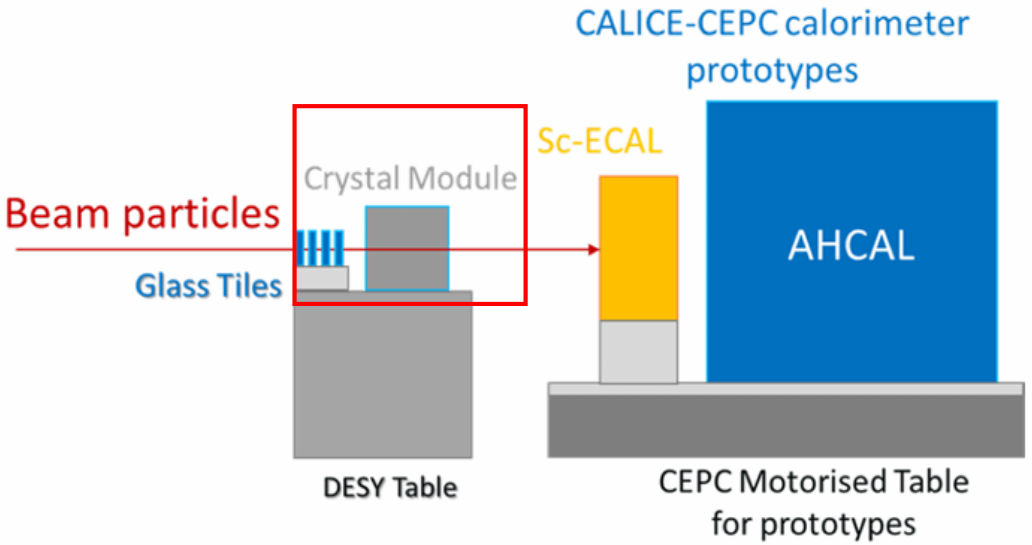


➢ A tower made up of 1×1×40 cm^3 crystals

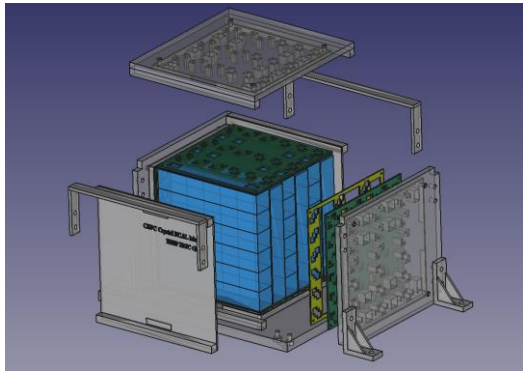
- Key issues need to be validated
  - Estimator for system-level performance
    - Beamtest with small crystal module
  - Requirements on timing performance
    - Experiments/simulations with long crystal bars

Energy response of crystal modules: 2023 CERN and DESY beam-tests

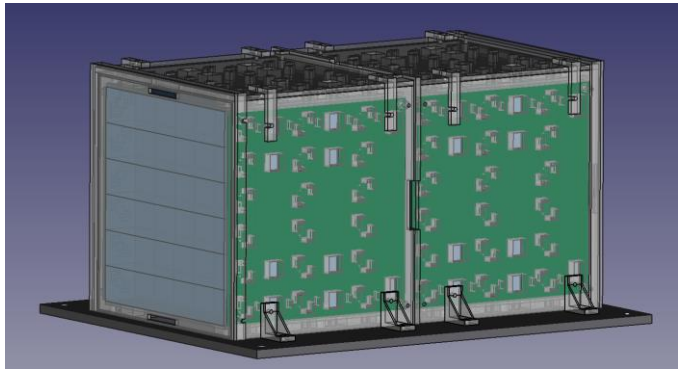
- Motivations
  - Identify critical questions/issues on the system level
    - Mechanical design, PCB and electronics…
  - Evaluate EM performance with TB data
  - Validation of simulation and digitization
- Beam-test at CERN T9 beamline
  - One module for commissioning and first parasitic tests
  - Muon, electron and pion beam
- Beam-test at DESY TB 22beamline
  - Two modules for EM energy response study
  - Electron beam



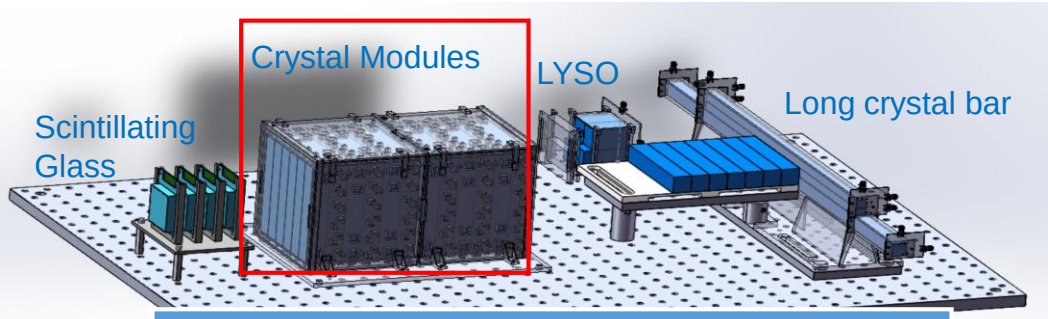
Overview of the 2023 CERN beamtest tasks



72 channels , $10.7X_0$



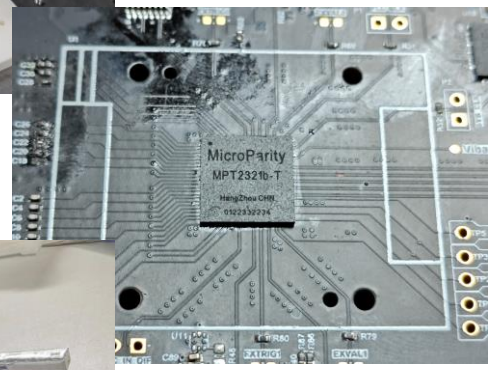
144 channels, $21.4X_0$



Overview of the 2023 DESY beamtest tasks

Overview of 2024 CERN beamtest

- Crystal ECAL beamtest from June 26 to July 10: general missions
  - Crystal module with CAEN FERS-5200 readout system
    - Energy response with muon and electron
    - Potential timing measurements (0.5 ns LSB)
    - Validations for previous beamtests
  - Crystal module with high dynamic range MPT-2321 chip
    - First application for HEP: energy measurements with 32 channels
    - Timing performance with 100 ps LSB
  - Long crystal bar: time resolution
    - MIP response and time resolution with crystal bars
    - Performance comparison with BGO/PWO/BSO crystals
    - Validation of the simulation-digitization model
  - Additional tasks (optional)
    - Scintillation glass / plastic scintillator / …



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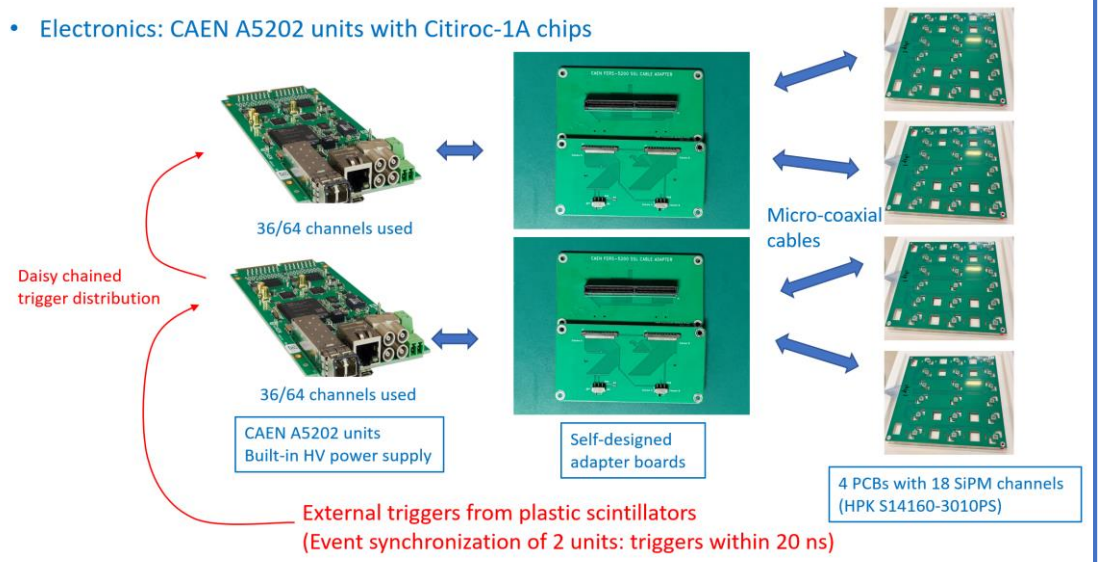
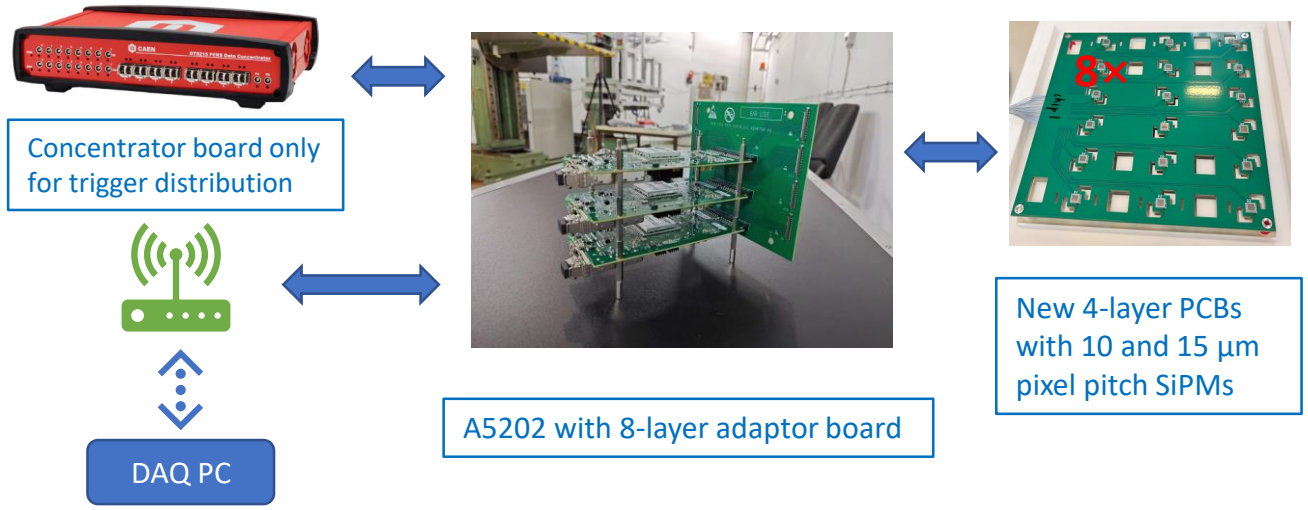
- Preparation for all test missions and the complete system
- Materials have been sent to CERN

Crystal module with CAEN FERS-5200 readout system

- Iterations of the readout system



Crystal module FERS-5200 v1: 2023 CERN
Two A5205 units, 72 channels



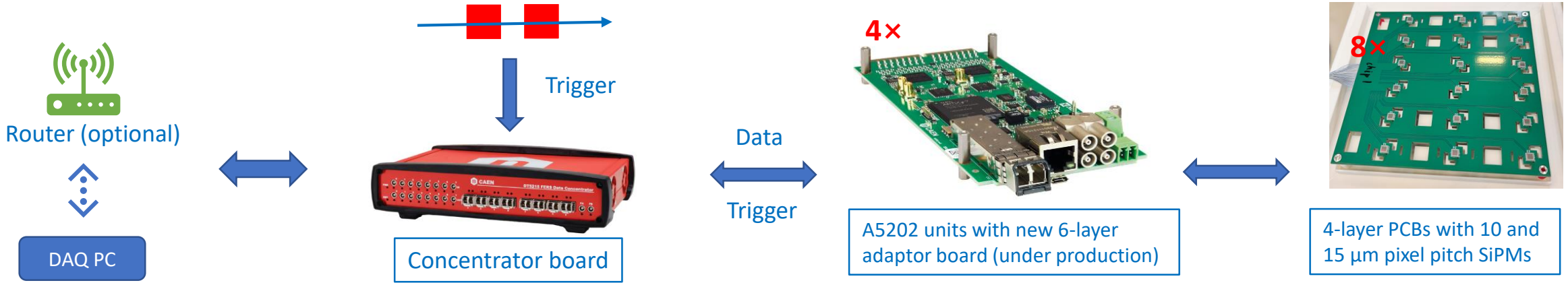
Crystal module FERS-5200 v2: 2023 DESY
Three A5205 units, 144 channels

- Further improvements
  - Low noise and low channel-wise crosstalk
  - Easy synchronization: start time and trigger
  - Data readout via TDlink (optical fiber)

- New adapter boards
- Lab tests with concentrator board
- New official software with zero suppression
- Tests with high-intensity laser: crosstalk

Crystal module with CAEN FERS-5200 readout system

- New readout scheme



Finished items

- New design of low crosstalk adaptor board
- Lab tests with concentrator board: successful DAQ via TDlink
- Test with on-board temperature sensor: output and compensation
- Test of zero suppression
  - Only available under charge measurement mode
- Test with high-intensity laser
  - Low gain overflow events could introduce crosstalk into adjacent channels (e.g. channel 12 → 11, 13)

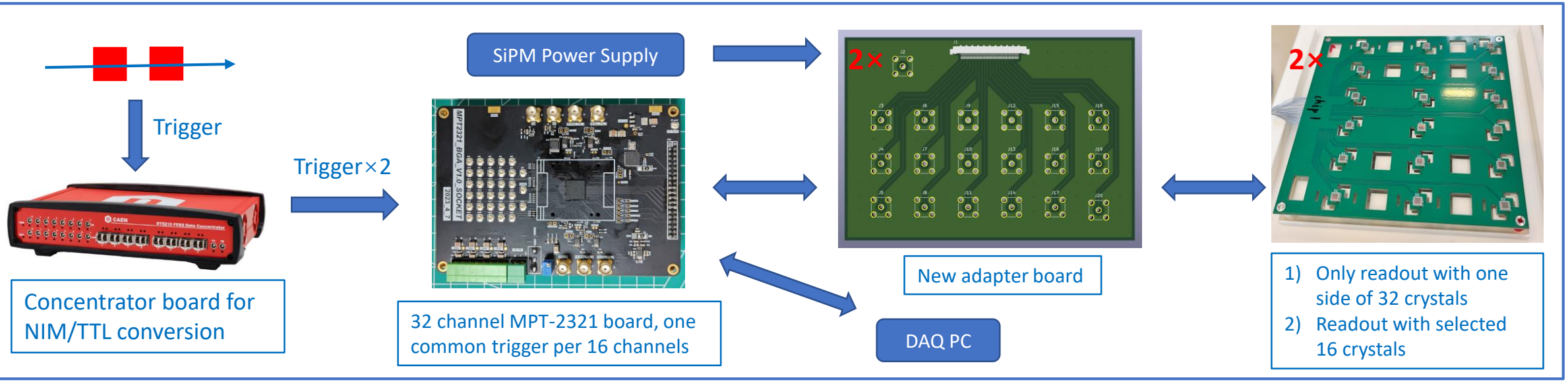
Ongoing items

- 3D print support backup: to be submitted for production
- Further lab tests with laser (optional)
- Repeated measurements of crystals (after beamtest)

- Already have extensive test experiences
- Generally well-prepared for beamtest

Crystal module with high dynamic range MPT-2321 chip

- Newly designed readout system



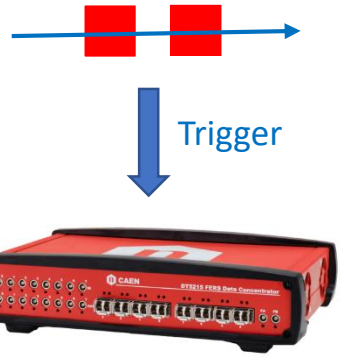
- Goals of the beamtest with MPT-chip
  - First system-level test with high dynamic range electronics
  - Energy response tests
  - Evaluate timing performance
- Ongoing items
  - Adapter boards just arrived, waiting for soldering
  - Lab test with laser
  - Batch test of 32 channels to adjust parameters

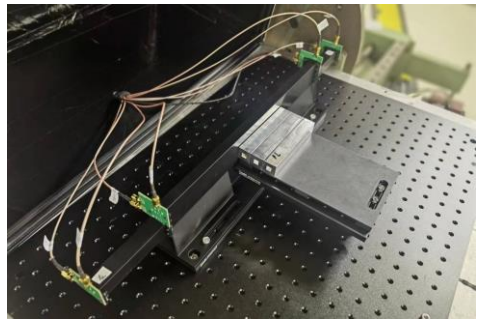
- First multi-channel application
- Still preparation works to be done
  - Event synchronization: to be refined
  - Key issues: threshold and hold-delay time

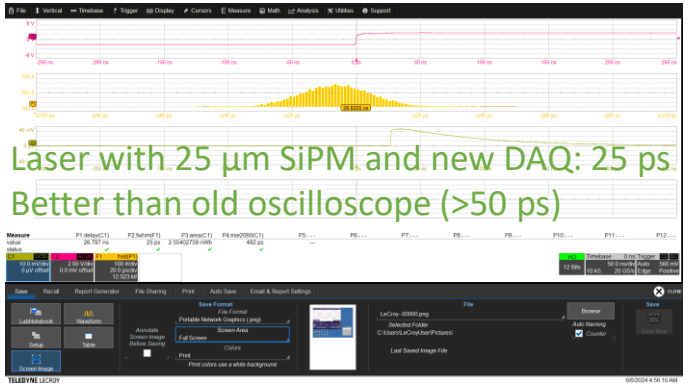
Long crystal bar: time resolution

- Time resolution: determine requirements for CEPC
- Long crystal bar beamtest setup: similar to the previous test
  - Data taking with oscilloscopes (2.5 GS/s)
  - BGO/PWO/BSO crystals
  - SiPM: NDL 6 μm, HPK 10/15/25 μm
  - NDL/CAEN/SJTU preamplifier

Ongoing items
- Small PCB production for short crystal test
  - Improved design for anti-interference
- Lab tests with new high bandwidth and sampling rate oscilloscope
  - Laser or small BGO crystal with Cs-137





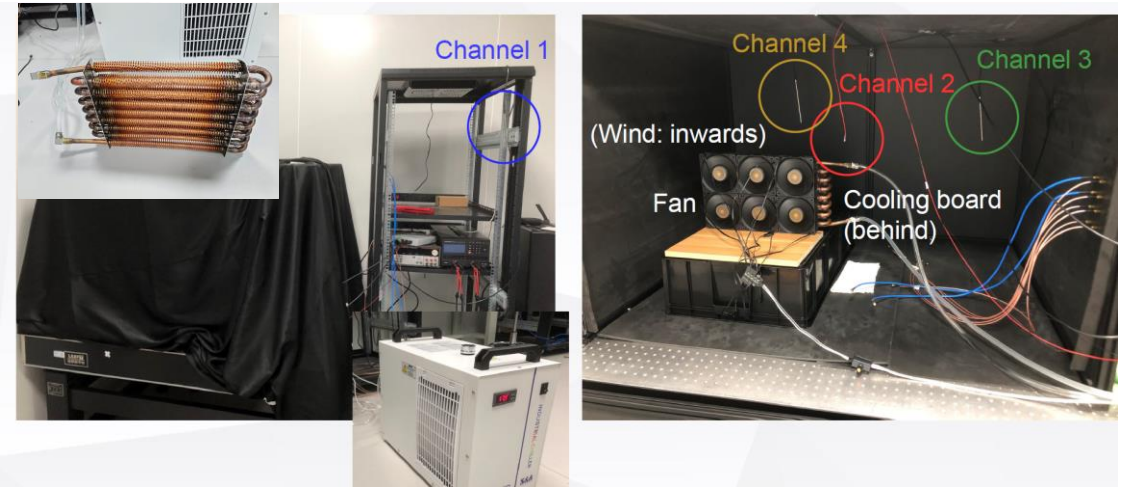


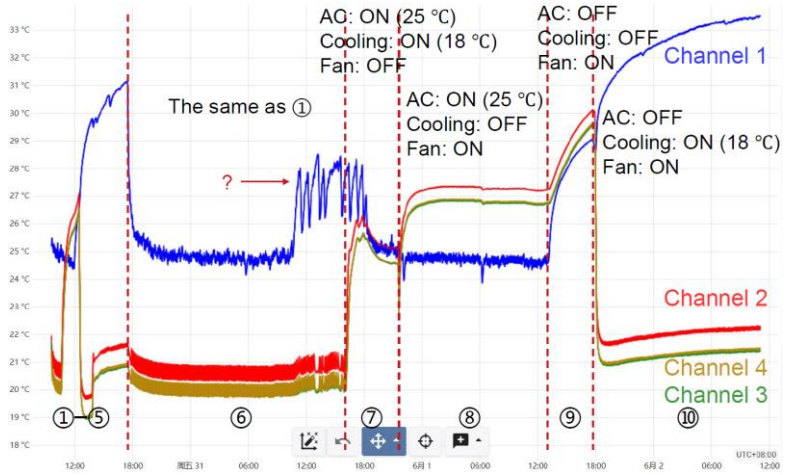
- Generally well-prepared for beamtest
- Figure out whether previous results are limited by the DAQ system
  - For crystal ECAL timing: urgent task to understand the feasibility

Crystal	Dimension (cm)
BGO	1.5×1.5×60
	1×1×40/8/4
PWO	1×1×16/4/8/2
BSO	1×1×6.95

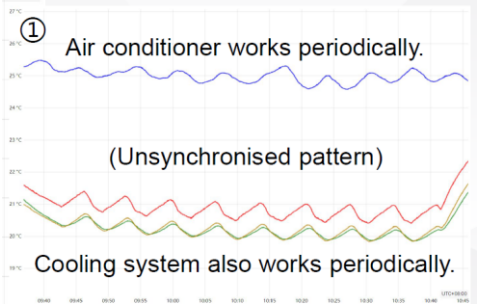
Additional preparation works

- Trigger system
  - $1\times1\times1$ cm^3 plastic scintillator, 3 or 4 cm triggers are also available
  - Support and collimation need to be checked
- Cooling system
  - A water cooling system has been preliminary tested, planned to be used at CERN
  - When the temperature difference is ~10 ℃, the fluctuation inside the box is ~0.2 ℃





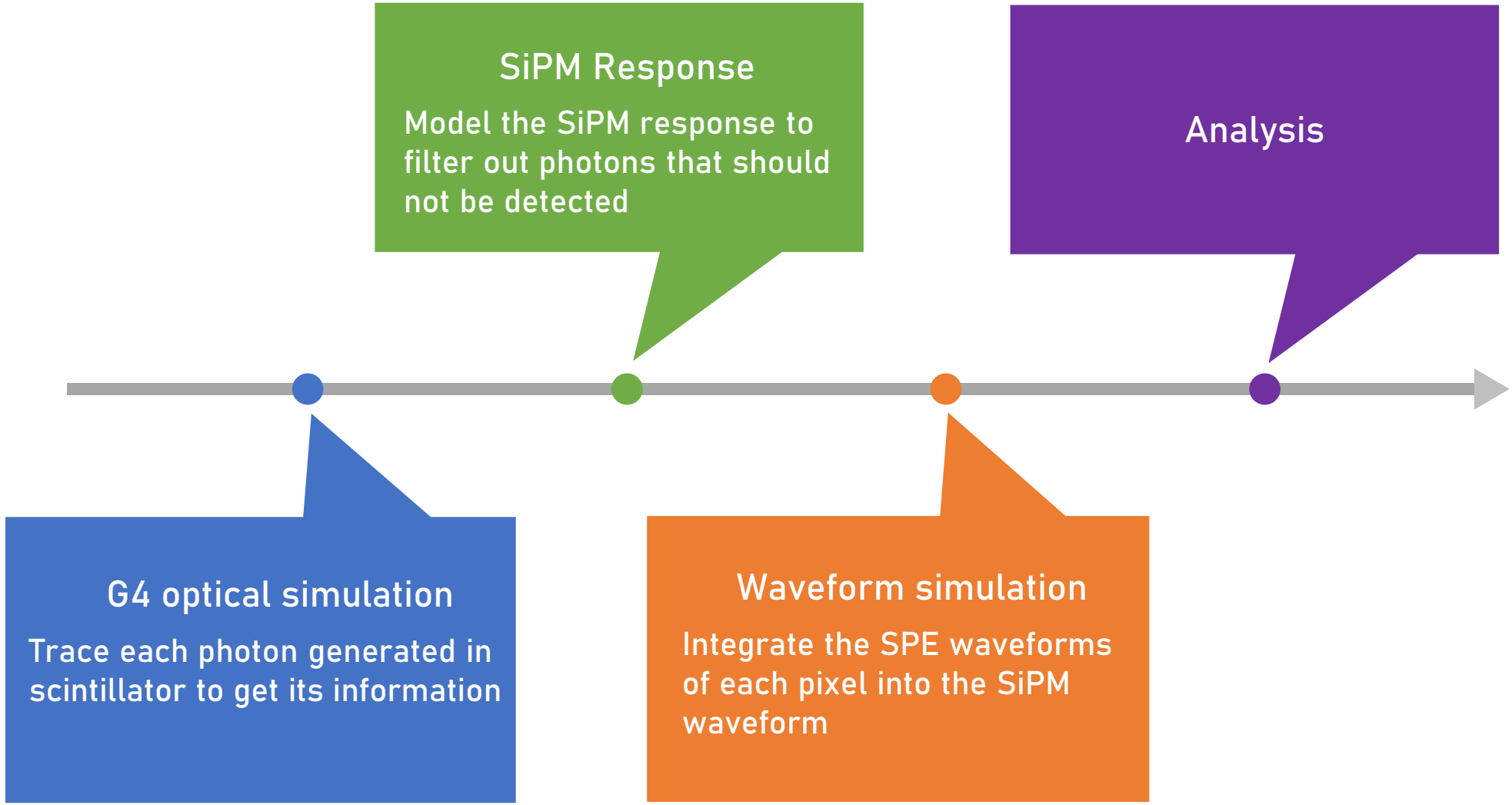
Channel	Temperature in/at
1	Room
2	Front of the dark box
3	Inner corner, near the board
4	Inner corner, far from the board



- DAQ with oscilloscope: streaming mode development
- Elog for experiment record

Updates on timing studies: workflow

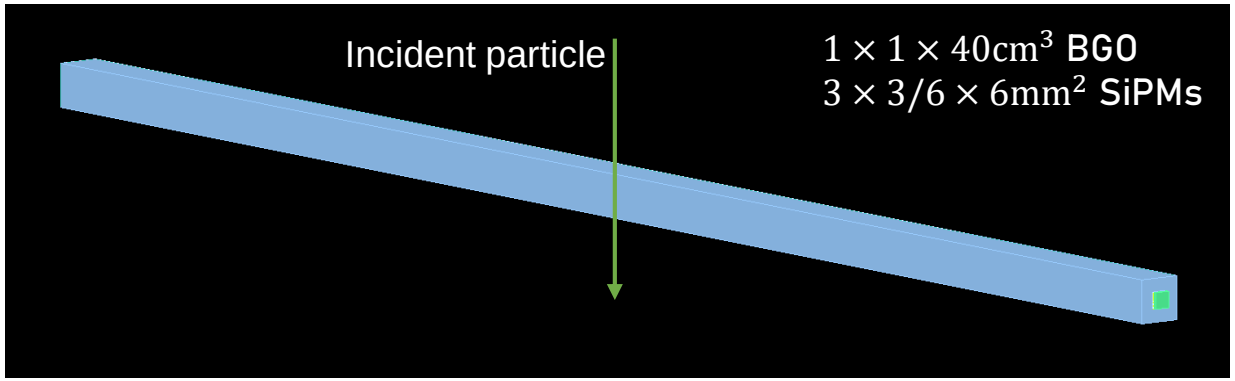
Zhiyu Zhao



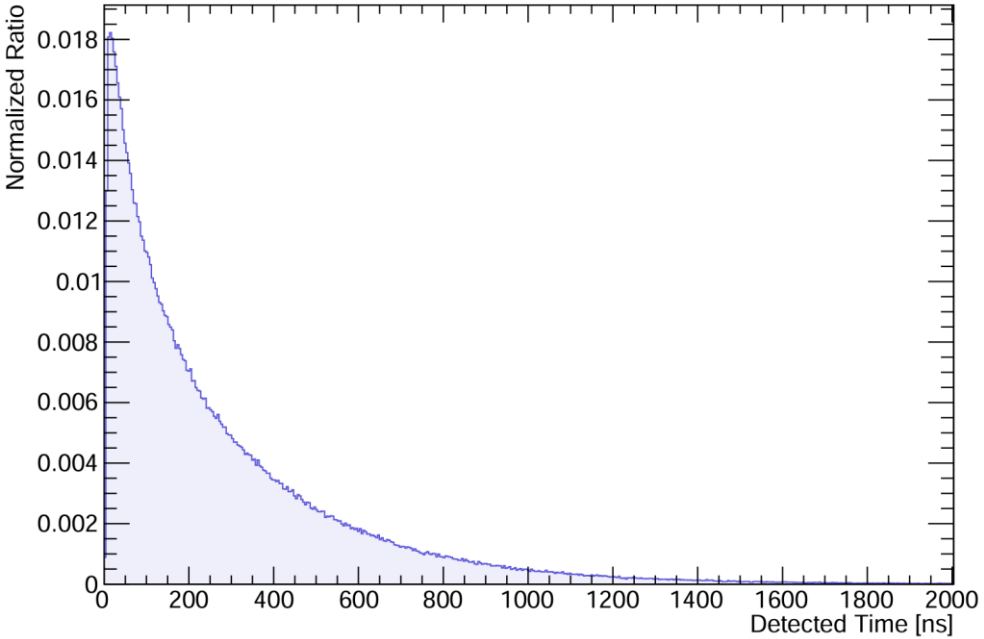
Geant4 optical simulation: detection time of every optical photon

Zhiyu Zhao

- Photon detection time is critical for SiPM response
- Time duration is ~2 μs, because of the slow component (300 ns) in BGO and long transportation length
  - Pixels of SiPMs can be fired multiple times, considering recovery



Light yield	Decay time	Refl. film
8200 ph/MeV	60ns(9%), 300ns(91%)	ESR

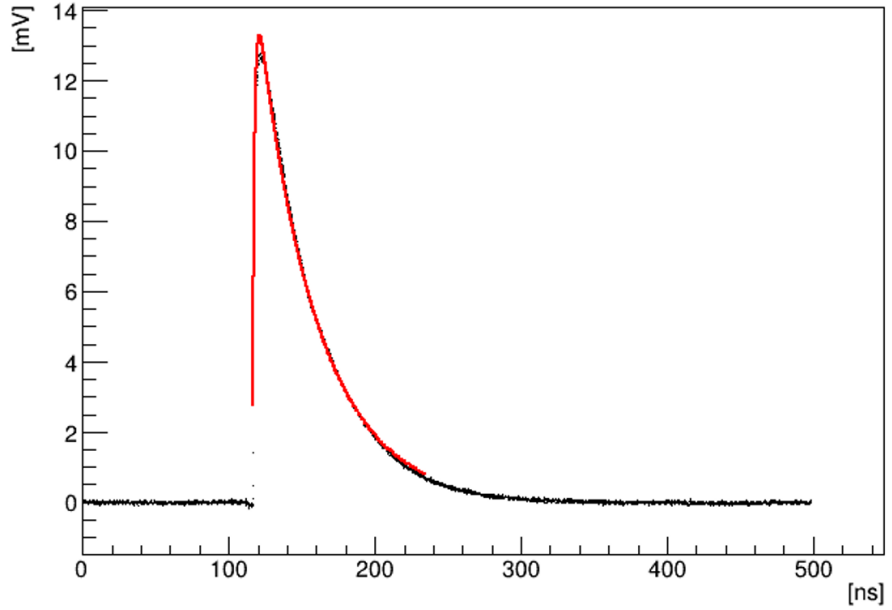


➢ Can also get the type(Cherenkov or scintillation), travel length, wavelength, etc. of photons

Single photoelectron waveform

Zhiyu Zhao

- Single photoelectron (SPE) waveform can not be displayed without an amplifier, while its bandwidth affects the output SPE waveform
- Obtain the approximate SPE waveform with a pico-second laser (<40 ps pulse width) set to a moderate intensity, without amplifiers



Fitting function: $f(t) = A \cdot \left(1 - e^{-\frac{t-t_0}{\tau_1}}\right) \cdot e^{-\frac{t-t_0}{\tau_2}}$

SiPM	HPK S13360-6025PE	HPK S14160-3015PS
Active area	$6 \times 6\ \mathrm{mm}^2$	$3 \times 3\ \mathrm{mm}^2$
Pixel pitch	25 μm	15 μm
τ_1	1.91 ns	1.5 ns
τ_2	74.64 ns	40 ns
Gain	6.42 ns·mV/p.e.	2.94 ns·mV/p.e.

- The waveforms consist of hundreds of p.e., but similar to SPE waveform
- The typical amplitude of SPE is smaller than 0.1 mV without any amplifier

Waveform simulation

Zhiyu Zhao

- Photon tracing in Geant4 → SiPM response → SPE waveform integrating → Waveform digitization
  - SiPM response including: pixel density, PDE, pixel recovery, crosstalk
  - Parameters in waveform digitization come from the setup in beamtest

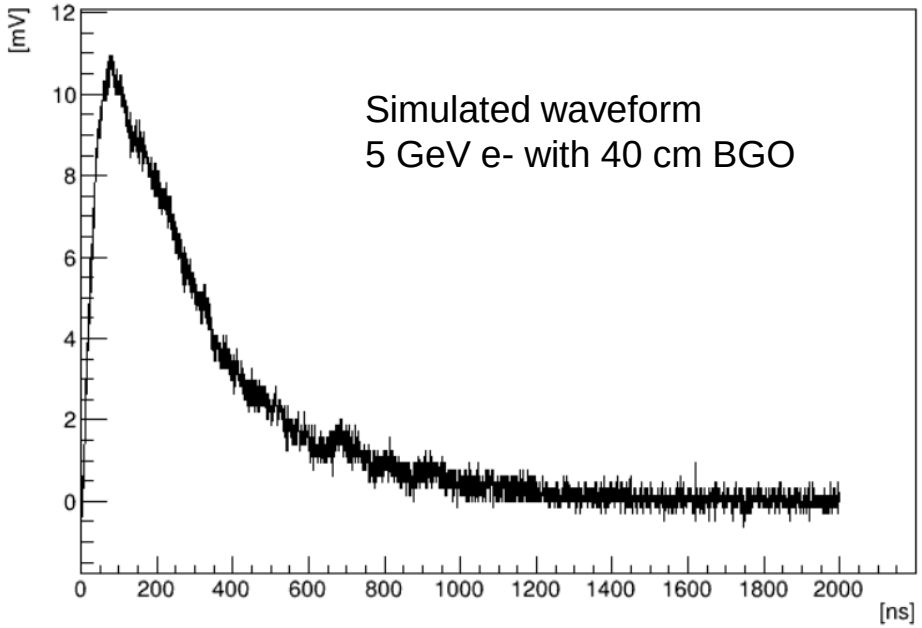


Table 1. Simulation parameters with S13360-6025PE

Sampling rate	Vertical accuracy	Noise	τ_1	τ_2	Gain (QDC/p.e.)	Amp	SPE fluc.
2.5 GS/s	8bit, 10-200mV	0.2 mV	1.91 ns	74.64 ns	6.42	x1	10%

Table 2. Simulation parameters with S14160-3015PS

Sampling rate	Vertical accuracy	Noise	τ_1	τ_2	Gain (QDC/p.e.)	Amp	SPE fluc.
2.5 GS/s	8bit, 10-200mV	0.2 mV	1.5 ns	40 ns	2.94	x1	10%

Impact of crystal size, decay time and light yield

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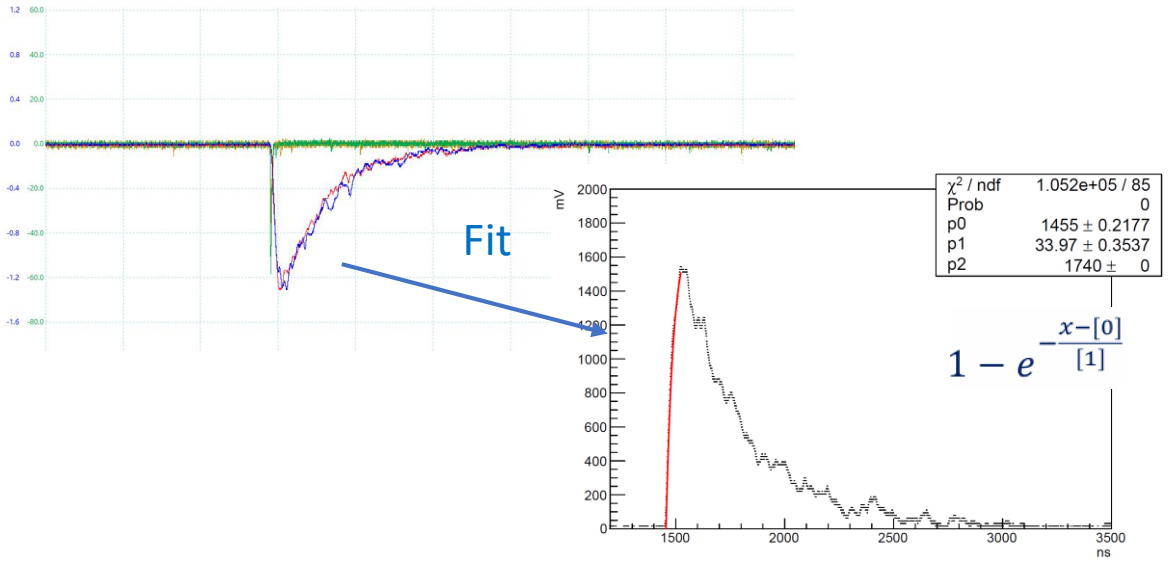
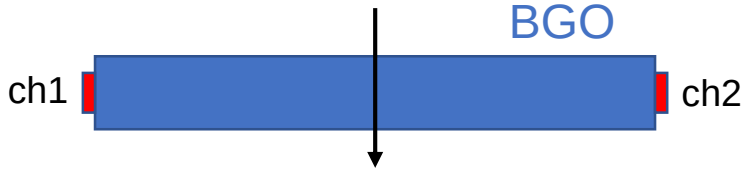


5GeV e-, $3 \times 3mm^2$ SiPM(HPK S14160-3015PS)



Size	Decay time	Light yield	Time resolution
$1 \times 1 \times 40\ \mathrm{cm}^3$	60/300 ns	8200 ph/MeV	1.558 ns
$1 \times 1 \times 6.95\ \mathrm{cm}^3$	60/300 ns	8200 ph/MeV	0.7755 ns
$1 \times 1 \times 40\ \mathrm{cm}^3$	25/100 ns	8200 ph/MeV	0.7521 ns
$1 \times 1 \times 40\ \mathrm{cm}^3$	60/300 ns	2000 ph/MeV	3.671 ns
$1 \times 1 \times 6.95\ \mathrm{cm}^3$	25/100 ns	2000 ph/MeV	0.7348 ns

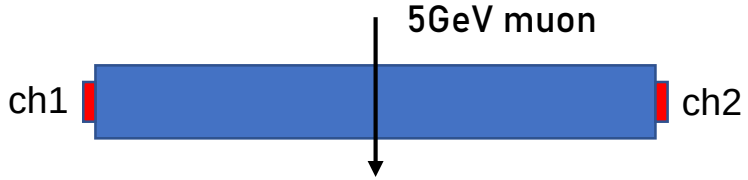
- "Fitting": leading edge fitting timing
  - Obtain a smoother rising edge of the signal
  - Selection of time stamps is consistent with CDF

- Reducing the crystal length and decay time improves the time resolution
- Decreasing the light yield worsens the time resolution

Impact of SiPM type and a glance of BSO

Zhiyu Zhao

- Time performances of the two SiPMs are different
  - Time constant, gain, and number of p.e. could affect it, to be checked



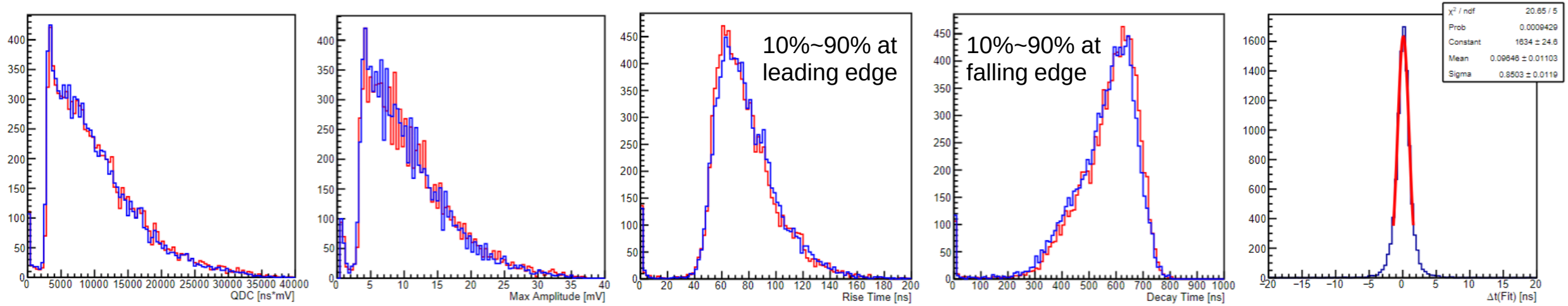
	Size	Decay time	Light yield	MIP response (ch1+ch2)	Time resolution	
HPK S13360-6025PE	$1 \times 1 \times 40\ \mathrm{cm}^3$	60/300 ns	8200 ph/MeV	1200 pe/MIP	1.876 ns	← BGO
	$1 \times 1 \times 40\ \mathrm{cm}^3$	25/100 ns	2000 ph/MeV	260 pe/MIP	1.759 ns	← BGO with BSO scintillating par.

	Size	Decay time	Light yield	MIP response (ch1+ch2)	Time resolution	
HPK S14160-3015PS	$1 \times 1 \times 40\ \mathrm{cm}^3$	60/300 ns	8200 ph/MeV	600 p.e./MIP	2.513 ns	← BGO
	$1 \times 1 \times 40\ \mathrm{cm}^3$	25/100 ns	2000 ph/MeV	150 pe/MIP	2.834 ns	← BGO with BSO scintillating par.

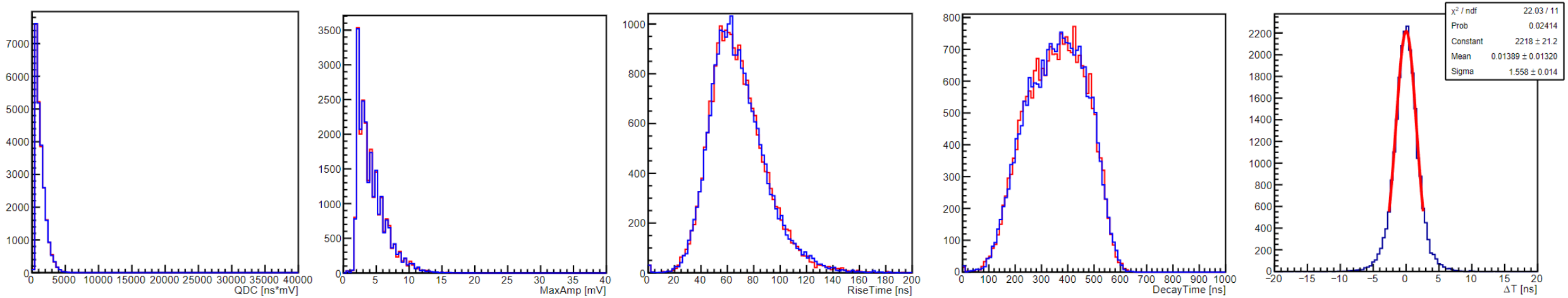
Waveform comparison: data vs. MC

Zhiyu Zhao

Data: 5GeV e-, 40cmBGO, $3 \times 3mm^2$ SiPM



Simulation: 5GeV e-, 40cmBGO, $3 \times 3mm^2$ SiPM



Summary

- Preparation of crystal ECAL beamtest
  - Crystal module with CAEN FERS-5200 readout system
  - Crystal module with high dynamic range MPT-2321 chip
  - Long crystal bar: time resolution
- Updates on timing studies
  - Geant4 optical simulation
  - Waveform simulations for time resolution
  - Comparison to data: simulations still need to be improved