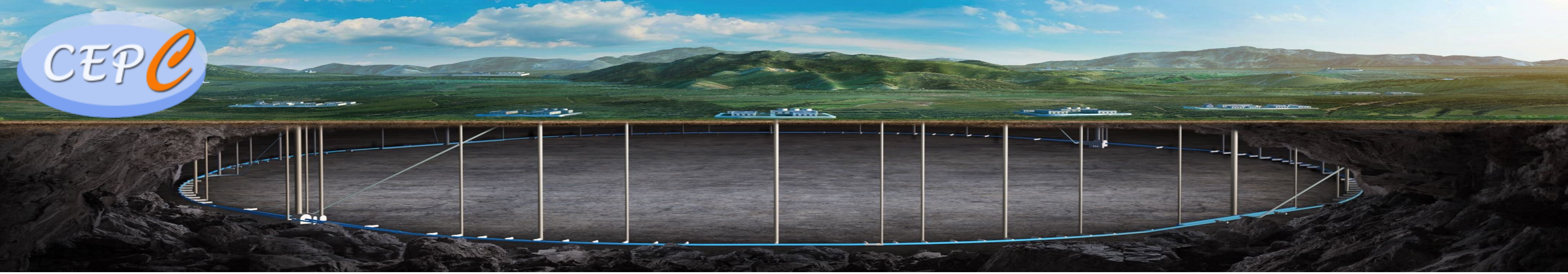

CEPC Electromagnetic Calorimeter (Rehearsal Draft)

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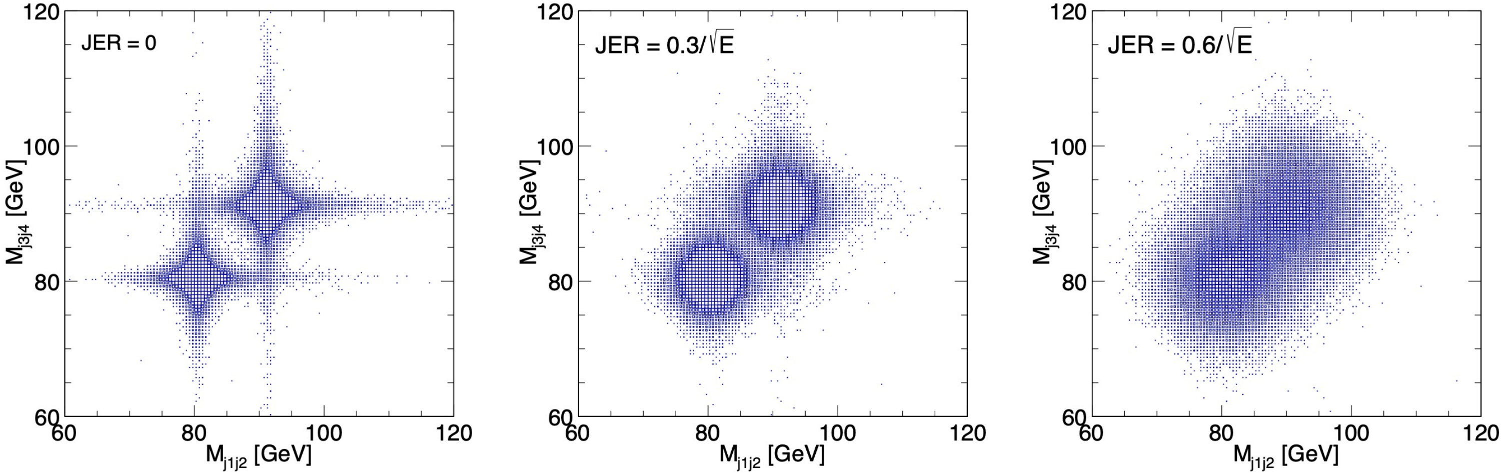
Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design including electronics, cooling and mechanics
- Readout electronics
- Performance from simulation
- Research team and working plan
- Summary

Introduction

- This talk is about the design and developments of the electromagnetic calorimetry system (related to the RefDet TDR Ch06)
- General remarks: the calorimetry system (in the CEPC reference detector) will based on the particle-flow paradigm → high granularity in 3D space
  - Aim to achieve an unprecedented jet energy resolution (JER) of $\sim 30\%/\sqrt{E_j(GeV)}$



(a) (b) (c)

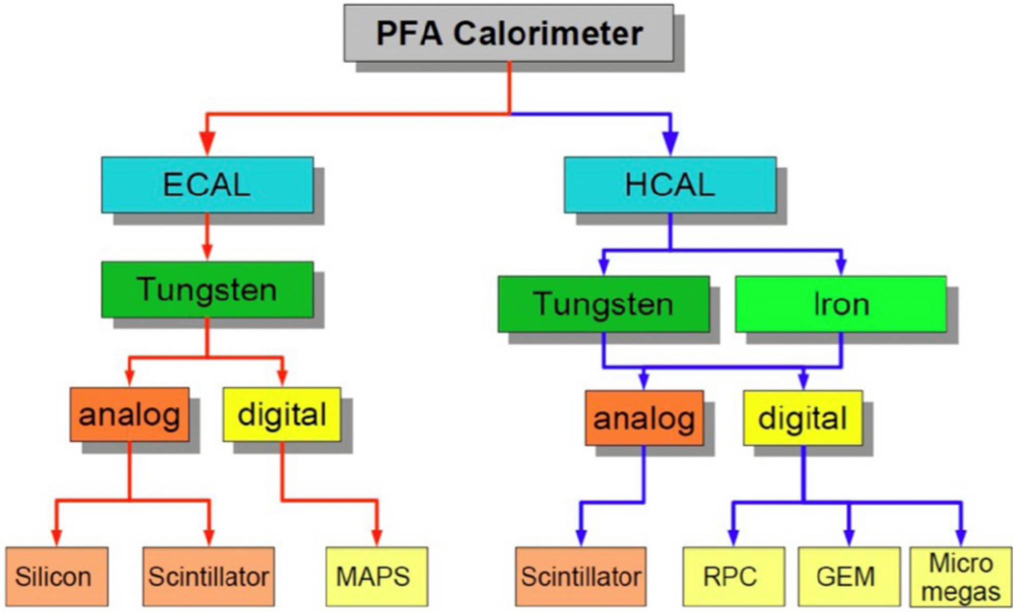
ECAL requirements

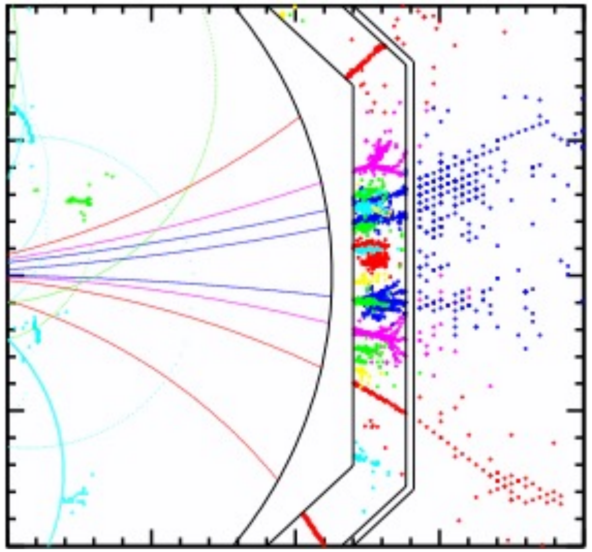
Parameter	Conservative	Ambitious	Remarks
EM energy resolution	$\sigma_E/E = 15\%/\sqrt{E(GeV)}$	$\sigma_E/E = 3\%/\sqrt{E(GeV)}$	Jet performance; flavor physics
Longitudinal Granularity and Depth	26 – 30 layers, total depth of $24X_0$		Full containment of EM showers
Transverse Granularity	$10\times10\ mm^2$		$H \rightarrow gg$ (gluon jets); $Z \rightarrow \tau\tau$
Signal Dynamic Range	0.1 MIP - 3000 MIPs		0.1 MIP as trigger threshold; Bhabha electrons at 360 GeV
Time Resolution (1-MIP signal)	1 ns	0.5 ns	Bunch crossing ID; timing to improve clustering and hadron performance
Power Consumption (per channel)	15 mW/ch		o(1M) channels in final detector

Technical option survey

- Three major options for CEPC electromagnetic calorimeter
  - Silicon-tungsten (SiW): sampling calorimeter
  - Scintillator-tungsten (ScW): sampling calorimeter
  - Crystal: homogeneous calorimeter (new!)

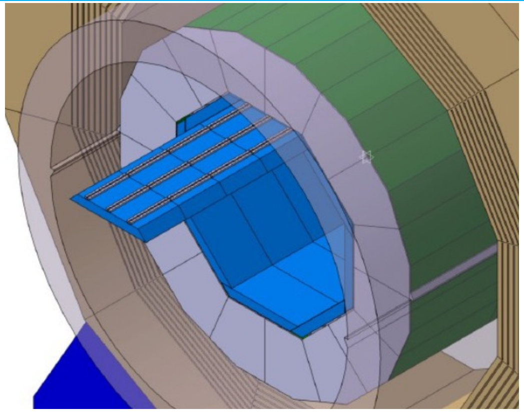
Highly granular (imaging) calorimetry
+ particle flow algorithm (PFA)



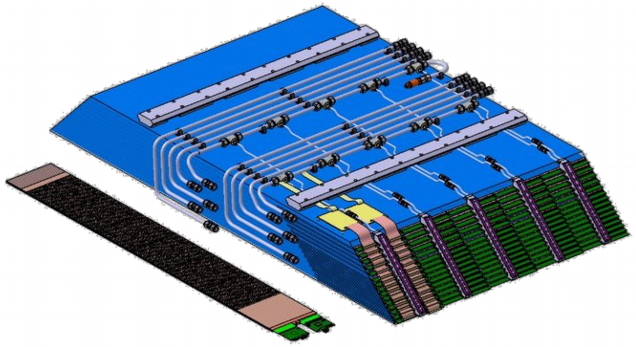


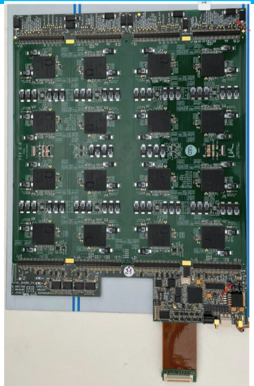
PFA calorimetry: various options explored in the CALICE collaboration in past 20 years

SiW-ECAL option

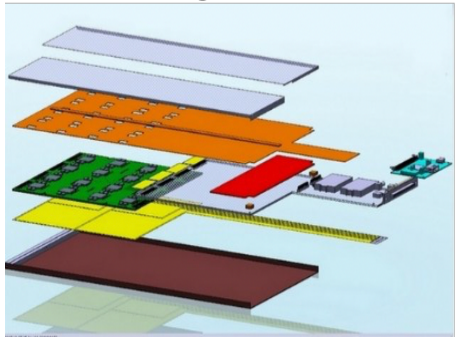


Silicon sensors+ CuW



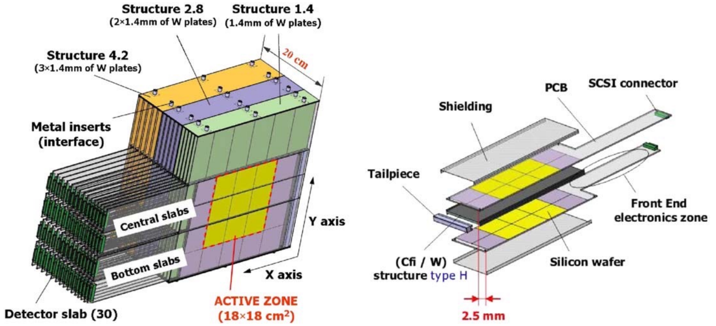


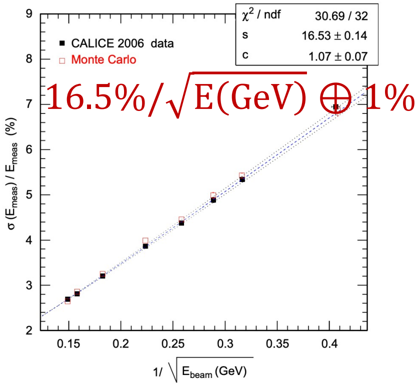
Stacking structure

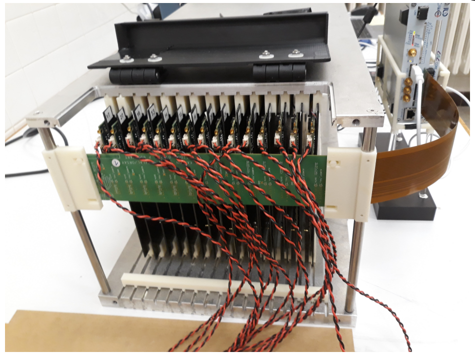


CALICE SiW-ECAL Technological Prototypes

CALICE SiW-ECAL Physics Prototype

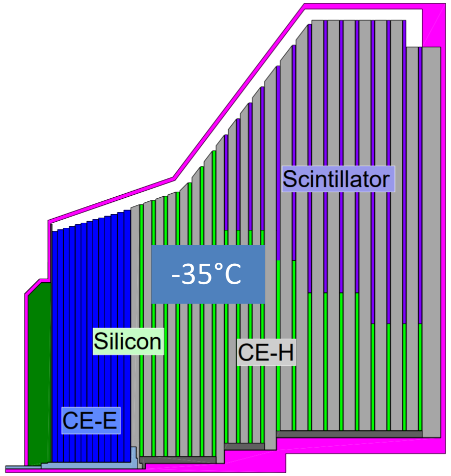


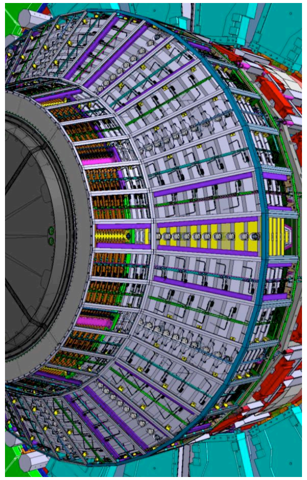


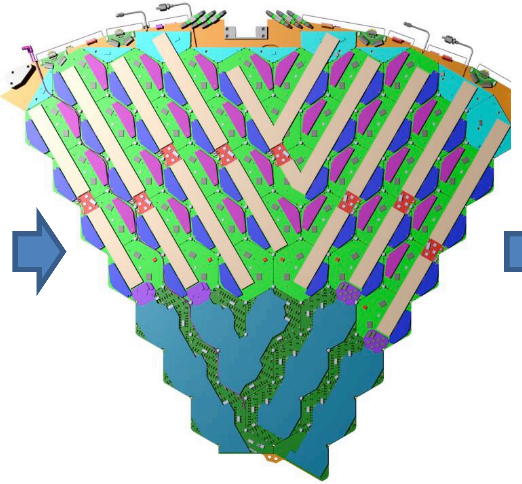


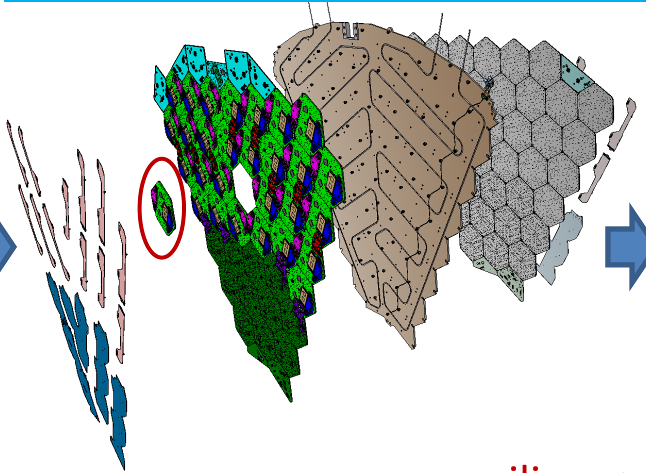
- Large area silicon sensors (pixelated) interleaved with CuW plate (compact showers)
- Baseline option in CEPC CDR: extensive Higgs physics studies
- Hardware activities in CALICE collaboration, no involvements of Chinese groups
  - Application in CMS-HGCAL project (silicon sector): many synergies

SiW-ECAL option: synergies with HGCAL

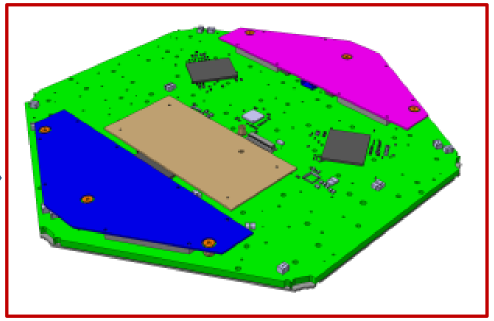




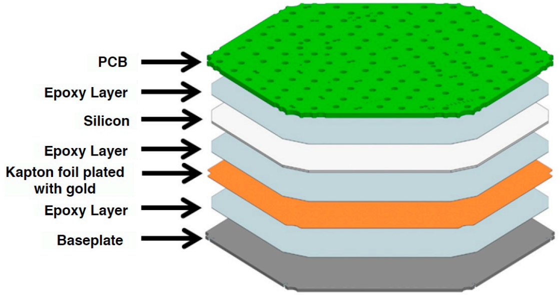


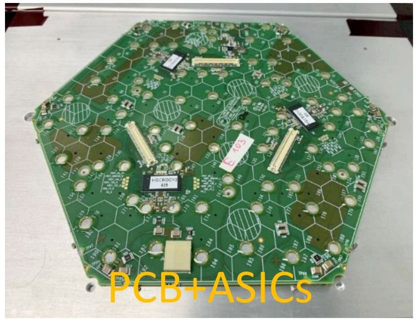


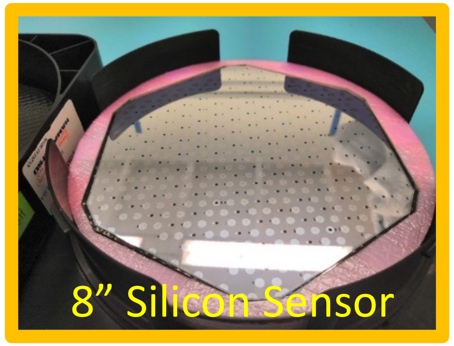
8-inch silicon module

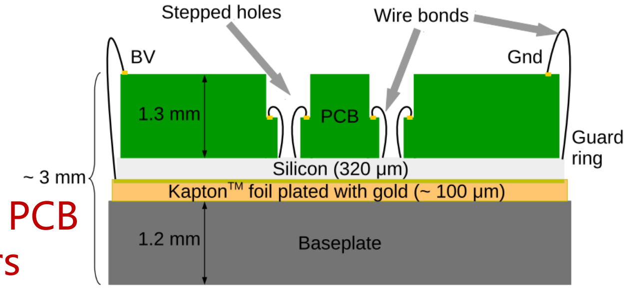


silicon+ PCB + ASICs (HGCROC)





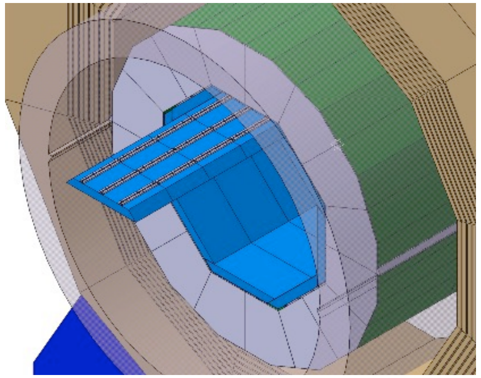


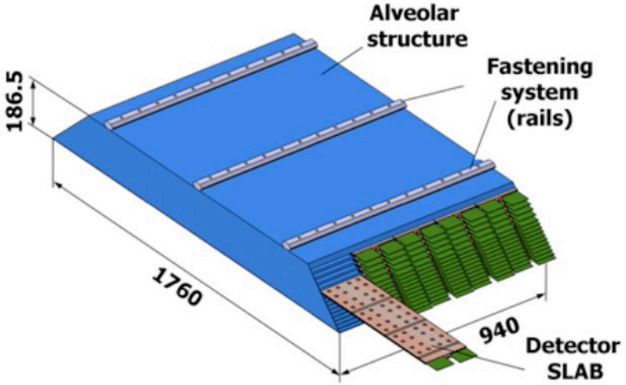


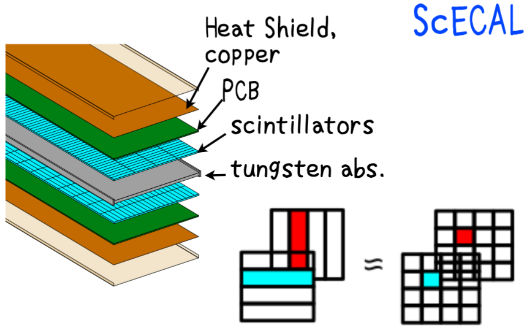
Wire-bonding for PCB and silicon sensors

- Established two centers at IHEP for CMS-HGCAL
  - MAC (Module Assembly Center) Beijing, with 6 MACs around the world
  - SQC (Sensor Quality Center) Beijing Site, with 5 SQCs around the world

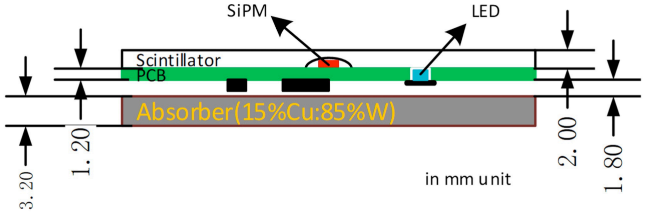
ScW-ECAL option

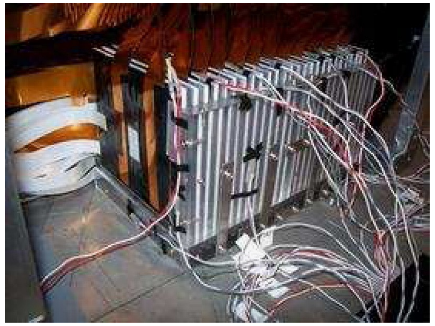


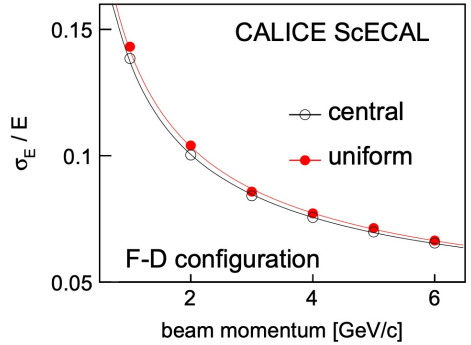


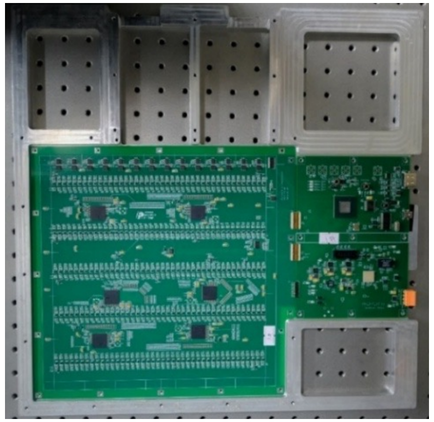


Scintillator-SiPM readout scheme







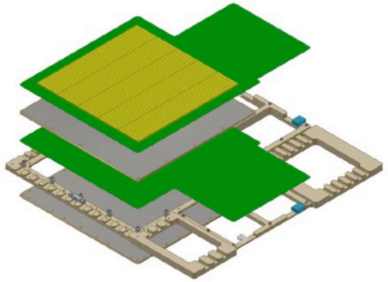


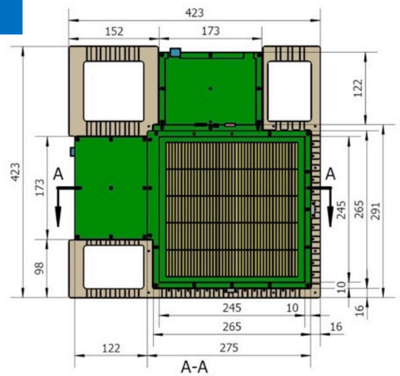
- Scintillator strips + SiPMs, interleaved with CuW plate (compact showers)
- Alternative option in CEPC CDR
- Strong involvements of Chinese groups in CALICE collaboration
  - Development of technological prototype, followed by successful beamtests at CERN

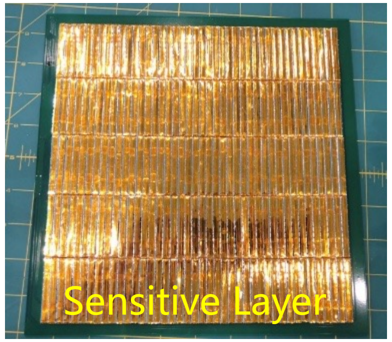
ScW-ECAL option

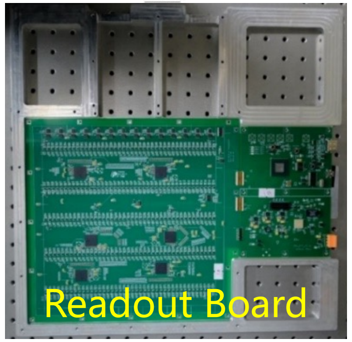
ScW-ECAL tech. prototype

“Super-layer” design

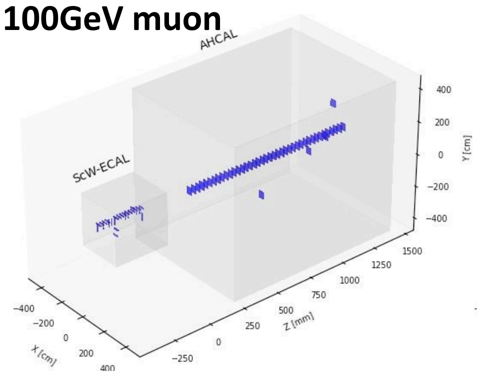


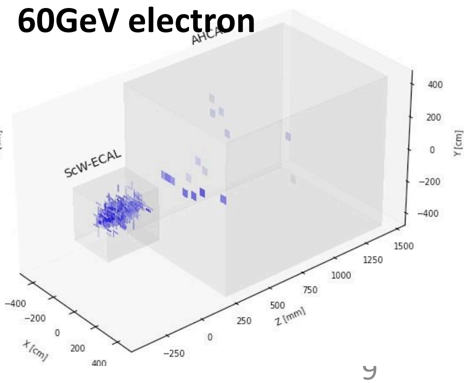






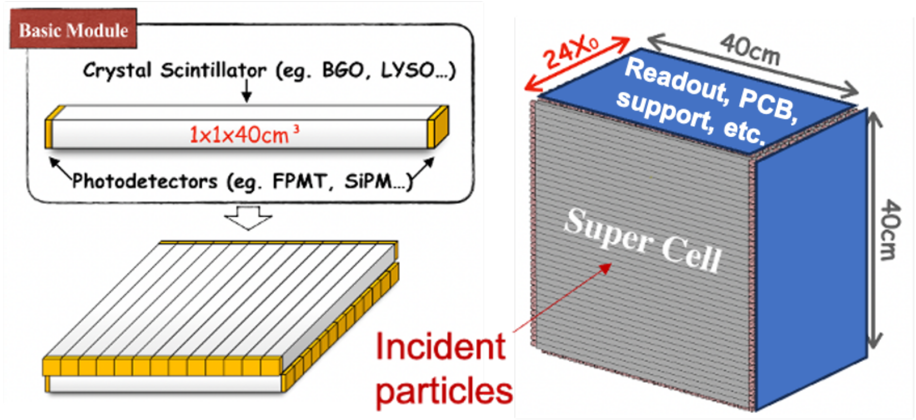
- ScW-ECAL tech. prototype developed in 2016-2020
  - (Effective) Transverse granularity of $5{\times}5\ \mathrm{mm}^2$
  - 6,720 channels, 32 longitudinal sampling layers (22X0)
  - Successful beamtest campaigns at CERN in 2022-2023
    - Collected data sets with various beam particles





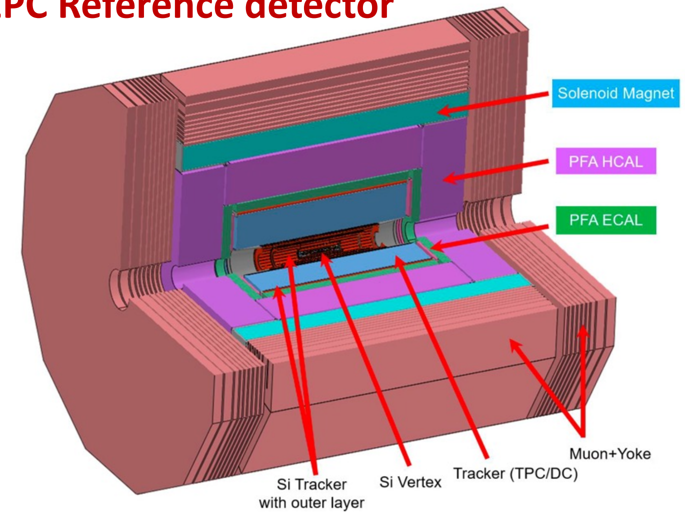
4D Crystal ECAL option

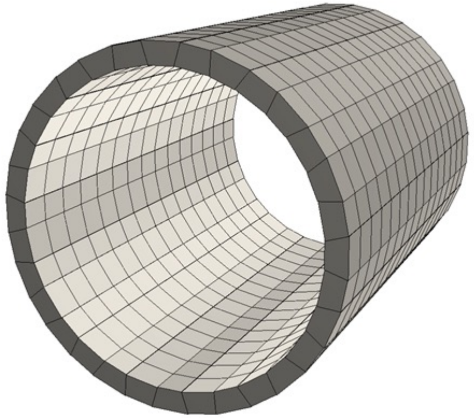
- A new option: development started since ~2020
- Compatible for PFA, Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E = 3\%/\sqrt{E}$
- Minimal longitudinal dead material: orthogonal arranged bars
  - 3D positioning with two-sided readout for timing



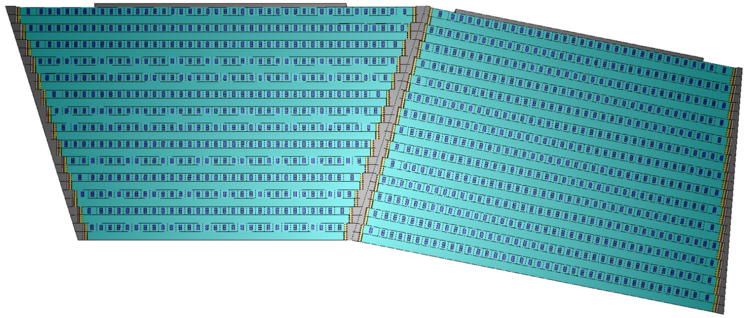
- **BGO bars in $1\times1\times{\sim}40\ cm^3$**
- **Effective granularity $1\times1\times2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**

CEPC Reference detector





32-side polygon, depth 24 X_0
28 layers in longitudinal



Technical options: comparison and selection

Technical Option	Silicon-Tungsten ECAL	Scintillator-Tungsten ECAL	Crystal ECAL
EM energy resolution	$\sigma_E/E = 17\%/\sqrt{E(GeV)}$	$\sigma_E/E = 13\%/\sqrt{E(GeV)}$	$\sigma_E/E = 3\%/\sqrt{E(GeV)}$
PFA compatibility	Pandora, Arbor	Pandora, Arbor	New dedicated PFA (ongoing developments)
Jet Performance (with a full detector)	Boson Mass Resolution (BMR) <4%		
Technical Readiness Level (prototypes, beamtests)	Physics Prototype (2006-2010) Technological Prototype (2011-now)	Physics Prototype (2007) Technological Prototype (2016 - 2021)	First Physics Prototype (2022-2024)
Novelty Level	ILD (proposed in ILC TDR 2013), followed by several detector concepts: CLICdp CDR (2012), CEPC CDR (2018), FCC CDR (2019)		A completely new concept proposed by the CEPC team

Summary

- The crystal ECAL, as a novel option, shows significantly better EM performance

Selected as a baseline option for the CEPC reference detector

Main Technical Challenges

- High granularity: ~1M channels
  - Multi-channel ASIC embedded in readout boards
  - Hermetic design: minimum space for mechanics and services (cooling, cabling)
  - Low power consumption, given material budget and hermicity
  - Mass production capability and scalability to a final detector
- Beam-induced backgrounds
  - Data throughput, pile-ups (events + backgrounds)
- Irradiation damages
  - SiPM, crystal: monitoring, calibration, annealing
  - ASIC, FPGA: radiation tolerant
- In-situ calibration system (on-detector)
  - SiPM, crystal due to irradiation (instantaneous, long-term), temperature

Crystal ECAL: specifications

Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	Ensure EM resolution $\sim 3\%/\sqrt{E}$
Energy threshold	0.1 MIP	Lowest possible; depends on S/N and light yield
Crystal non-uniformity	< 1%	Along the crystal length and between crystals
Dynamic range	0.1~3000 MIPs / channel	Maximum deposited energy in 360 GeV Bhabha events
Timing resolution	~500 ps @ 1 MIP	For position reconstruction
Temperature stability	Stable at $0.05℃$	Reference from CMS ECAL

Detector requirements

- Moderate MIP light yield
- Good uniformity
- Optimal time resolution
- Large dynamic range
- High S/N

→

Hardware activities: addressing crucial issues

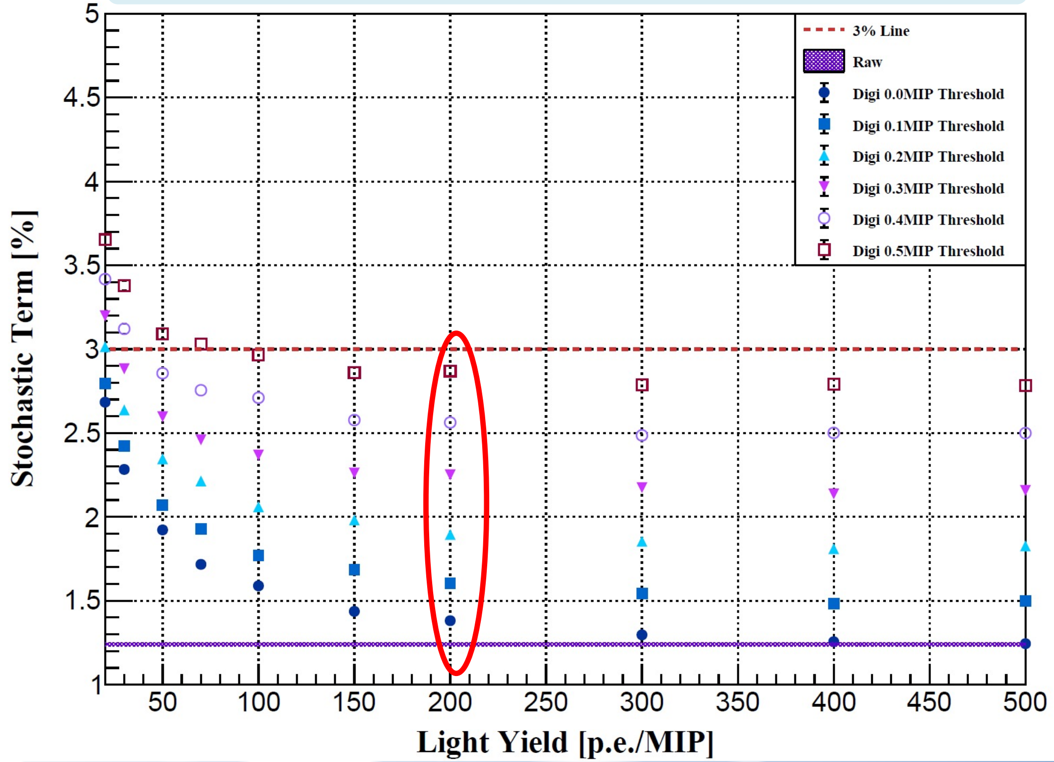
- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal sizes/Edep
- Dynamic range of electronics
- Energy response of crystal module

R&D efforts and results: MIP response, uniformity

- Geant4 full simulation with digitization: shower studies, requirements
- Dedicated setup for energy resolution, uniformity with radioactive sources

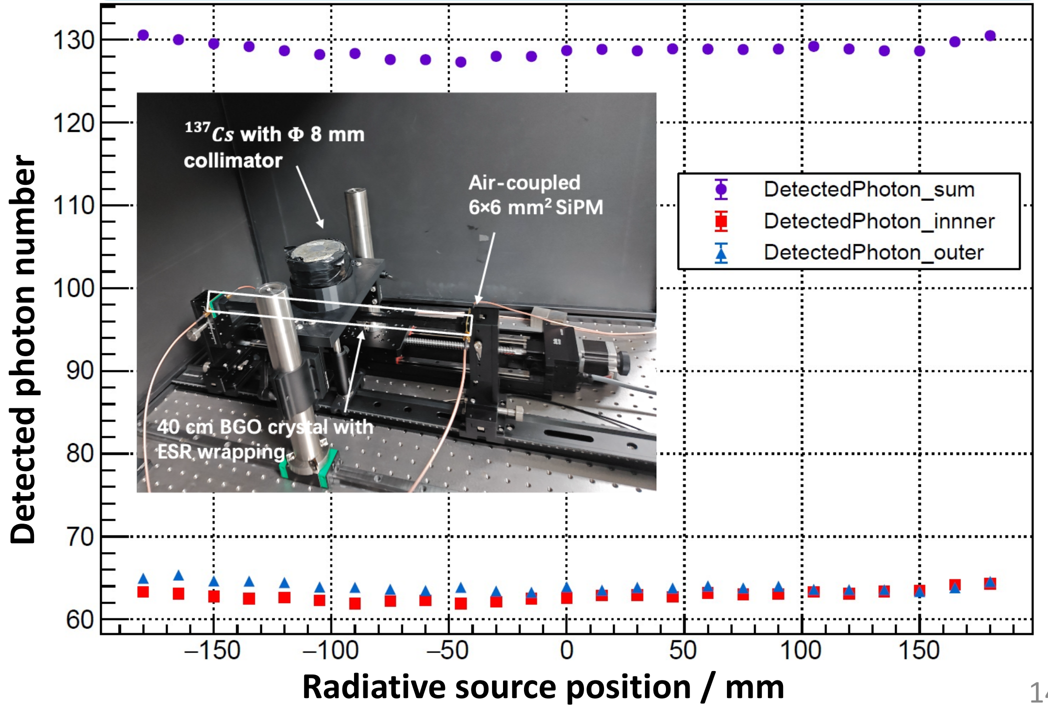
MIP response: >200 p.e./MIP → $\sigma_E/E = 3\%/\sqrt{E}$
Energy threshold: 0.1 MIP

Light yield v.s. energy resolution



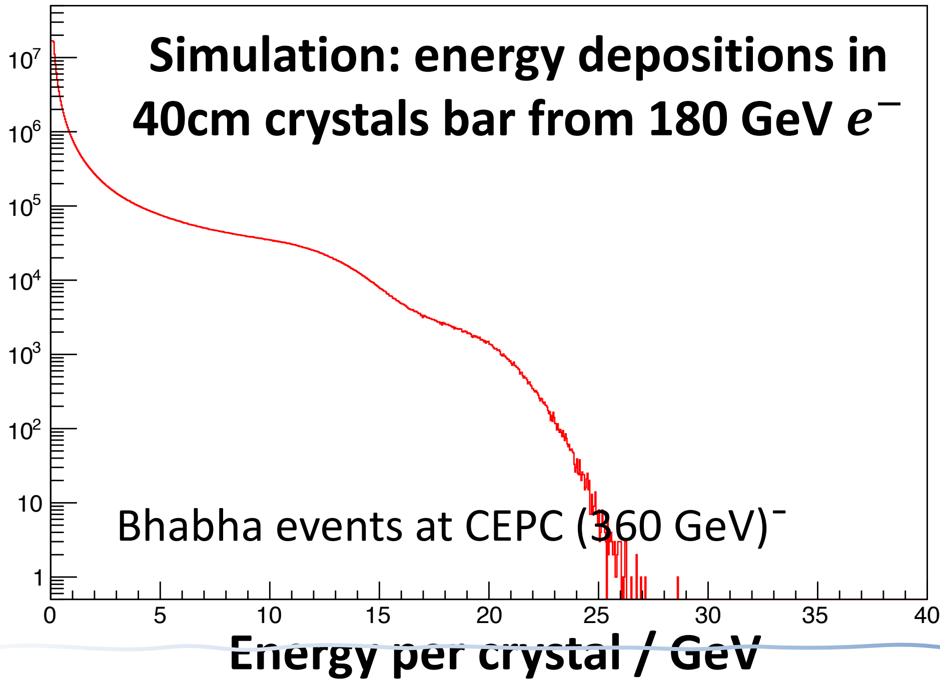
Uniformity along one 40 cm crystal bar: ~2.5%
- Can be further improved by calibration system

Response uniformity along bar



R&D efforts and results: dynamic range

- Simulation of high energy electrons: maximum energy per crystal
- Test-stand with pico-second laser: SiPM non-linearity effects (with various pixel pitches)
- Beamtest of crystal-SiPM units with a state-of-art chip: dynamic range of both SiPM and ASIC

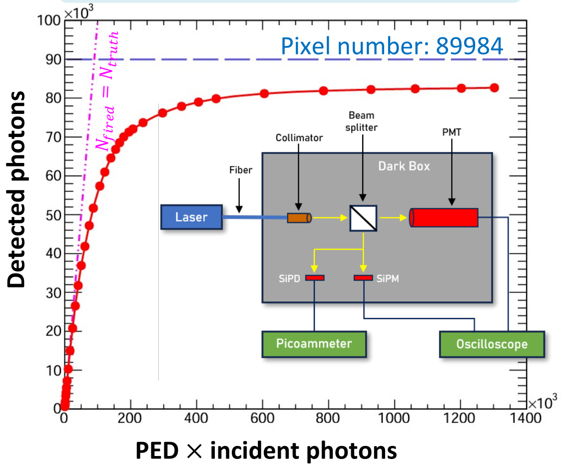


~30 GeV as max. energy deposition per crystal bar

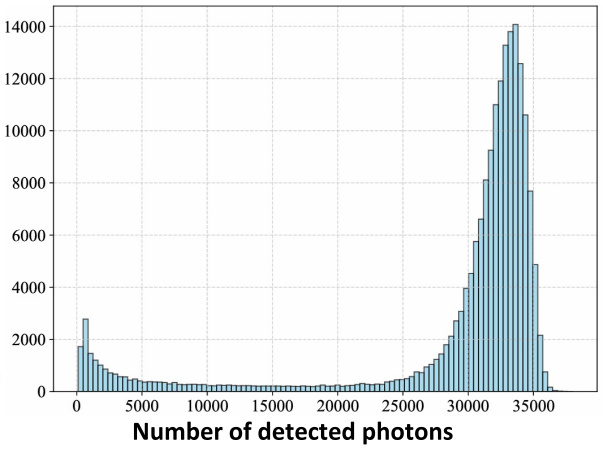
Laser system for SiPM non-linearity studies

Electronic chip dynamic range: ~33000 p.e. for 25um SiPM

SiPM linear range



Electronics with lowest gain



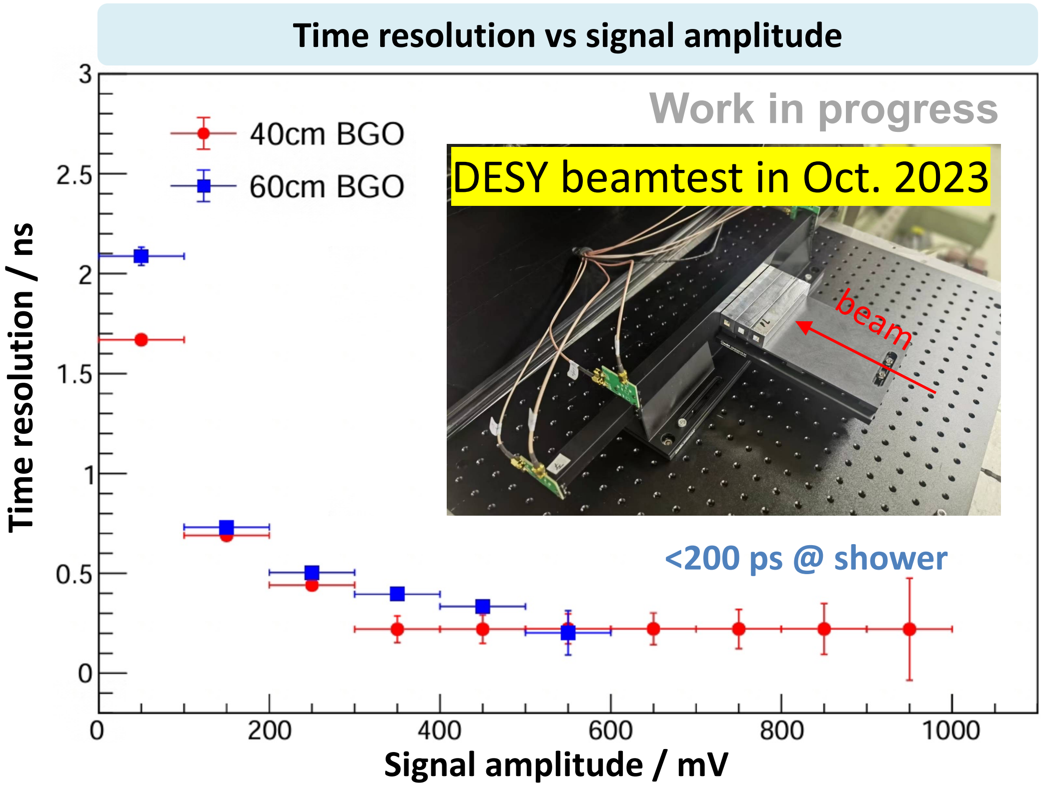
2023 DESY beamtest: crystal-SiPM units and a state-of-art front-end chip with EM showers induced by 5 GeV electrons

R&D efforts and results: timing studies

- Dedicated beamtests for timing studies with MIP and EM showers

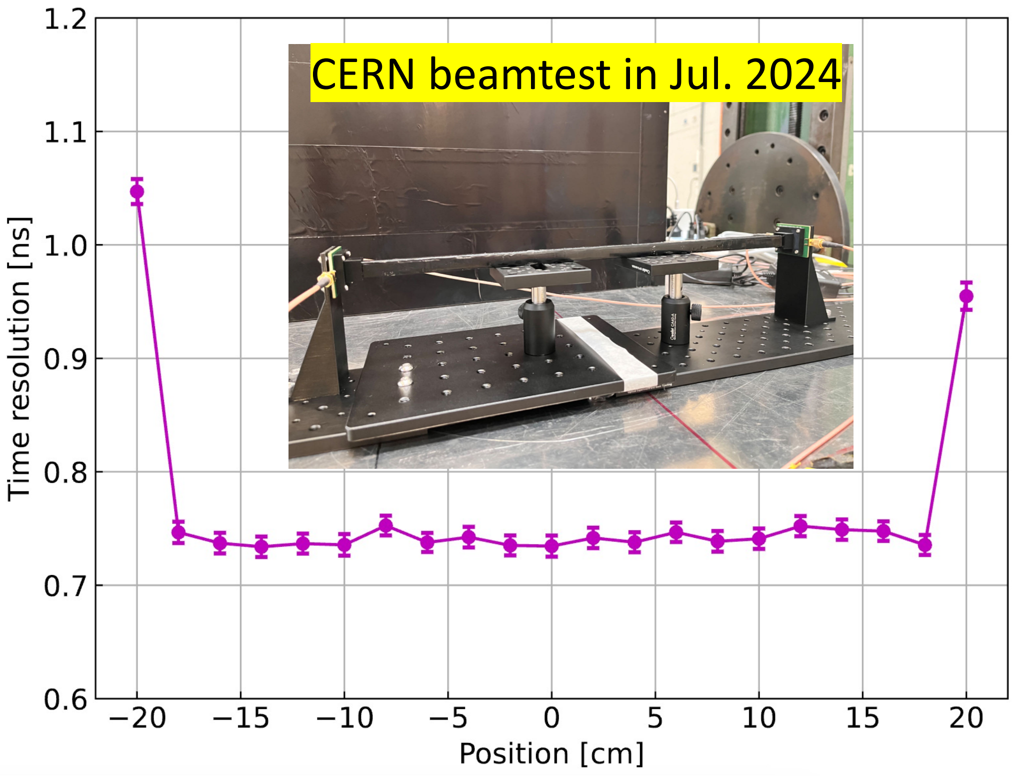
Timing performance within EM showers

- 5GeV e^- beam to test 40cm BGO bar with 25 μm SiPM
- <200 ps within EM showers (>12 MIPs)

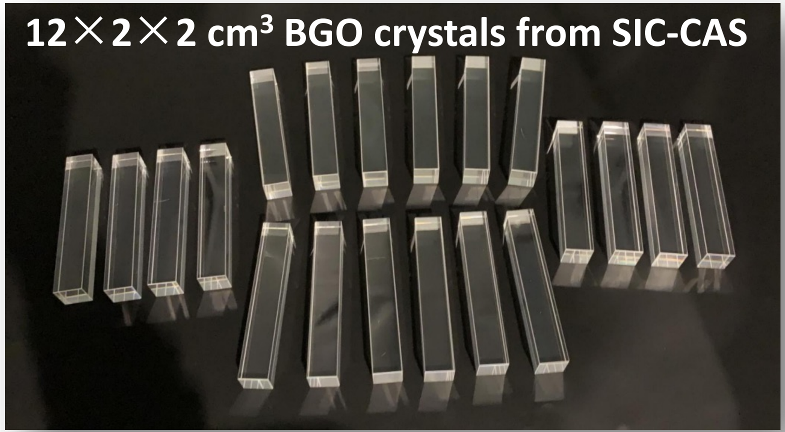


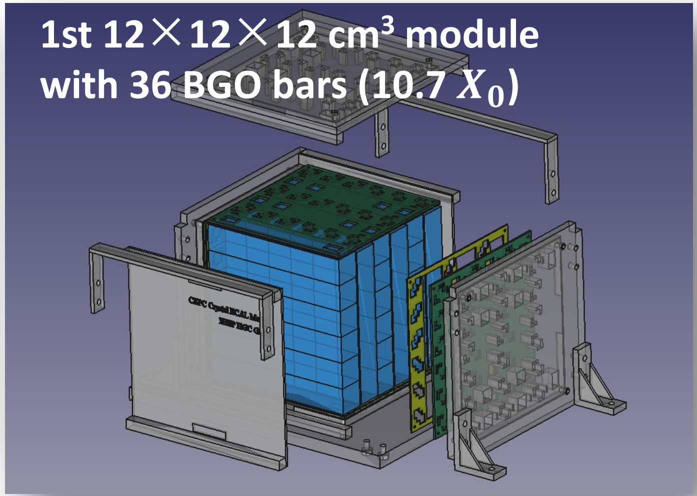
Timing performance with MIP-like particles

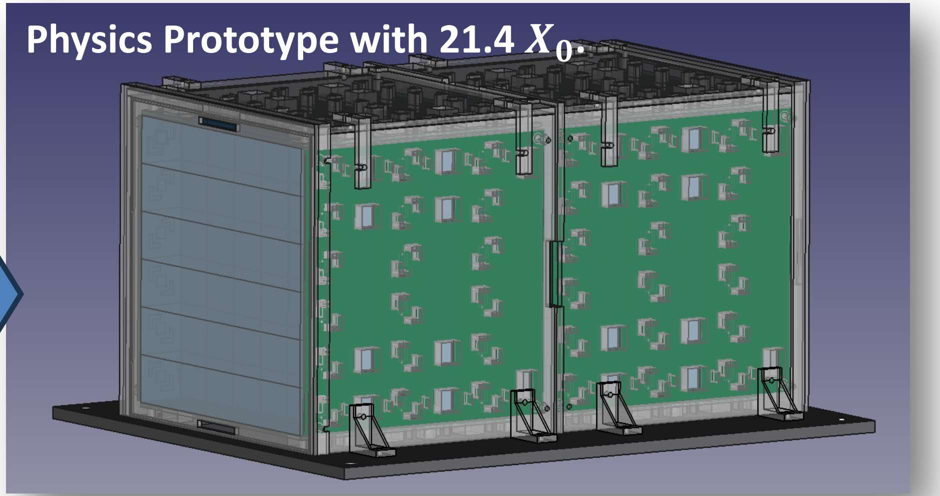
- 10 GeV π^- beam to scan one 40cm BGO bar along its length
- 1-MIP timing resolution: 735 ps for 2 ends → 520 ps single end

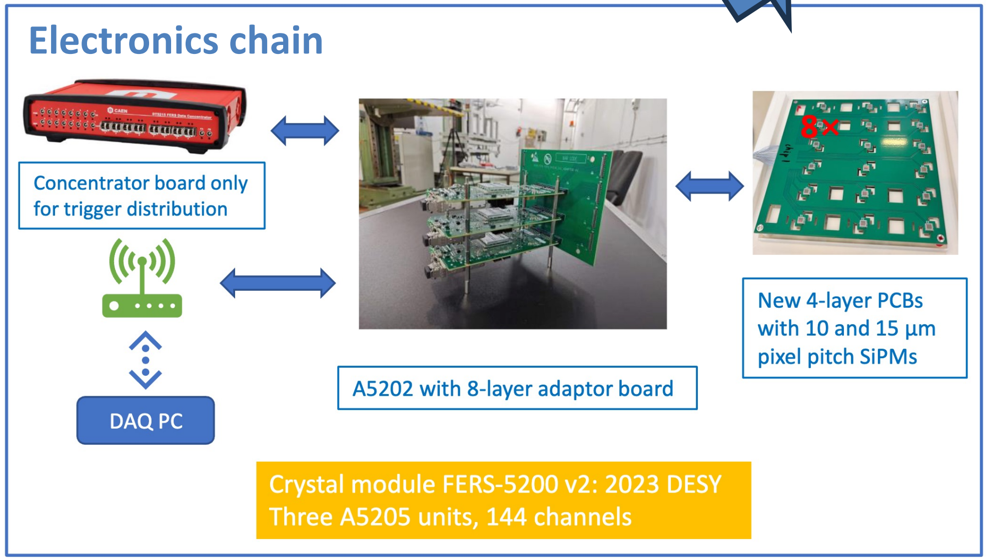


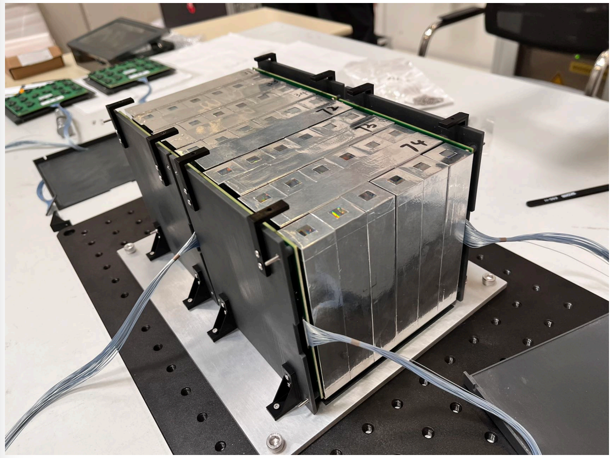
4D Crystal Calorimeter: First Physics Prototype











First crystal calorimeter prototype

- Successfully developed in 2021-23

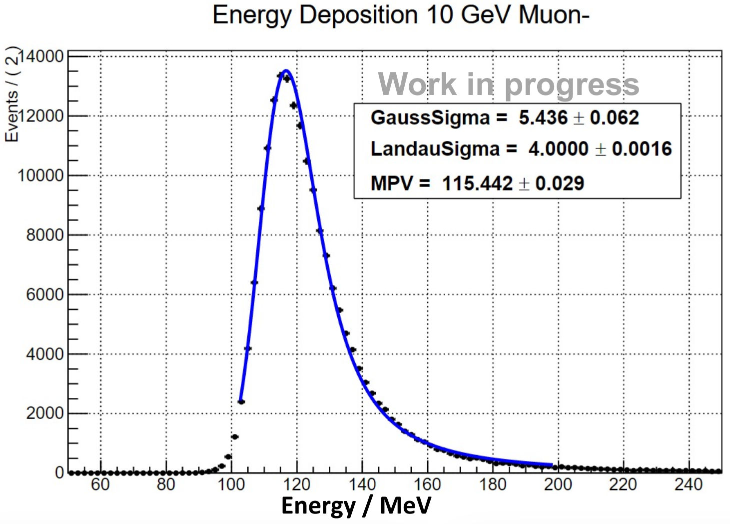
Major motivations

- Critical issues at system integration
- EM performance in system level
- Validation of simulation and digitization with beamtest data

Beam tests: 4D Crystal Calorimeter Prototype

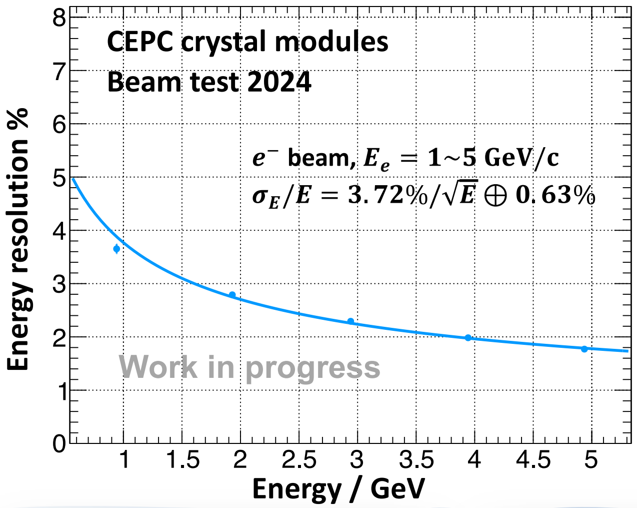
2023 CERN beam test at PS-T9

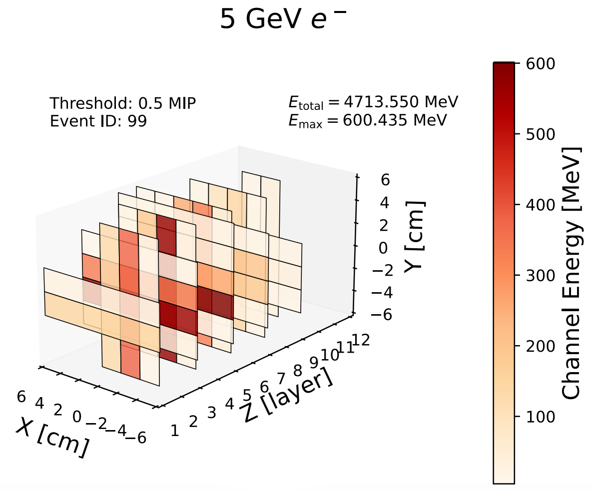
- Successful system commissioning
- Clear MIP signals for all channels

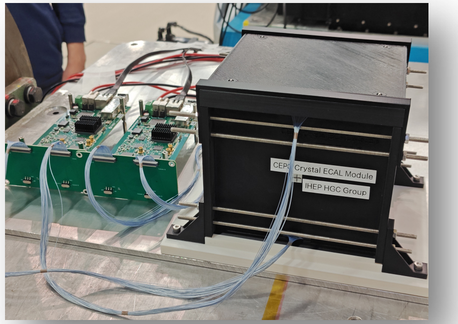


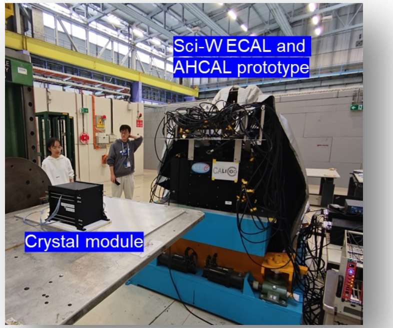
2024 CERN beam test at PS-T9: finished in July 10th

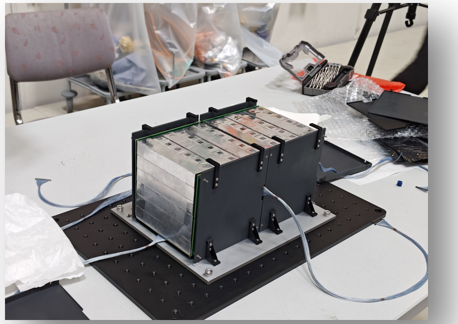
- Promising EM resolution with 1-5 GeV/c e^{-} beam
- Data analysis is still ongoing: detailed calibrations, shower profiles



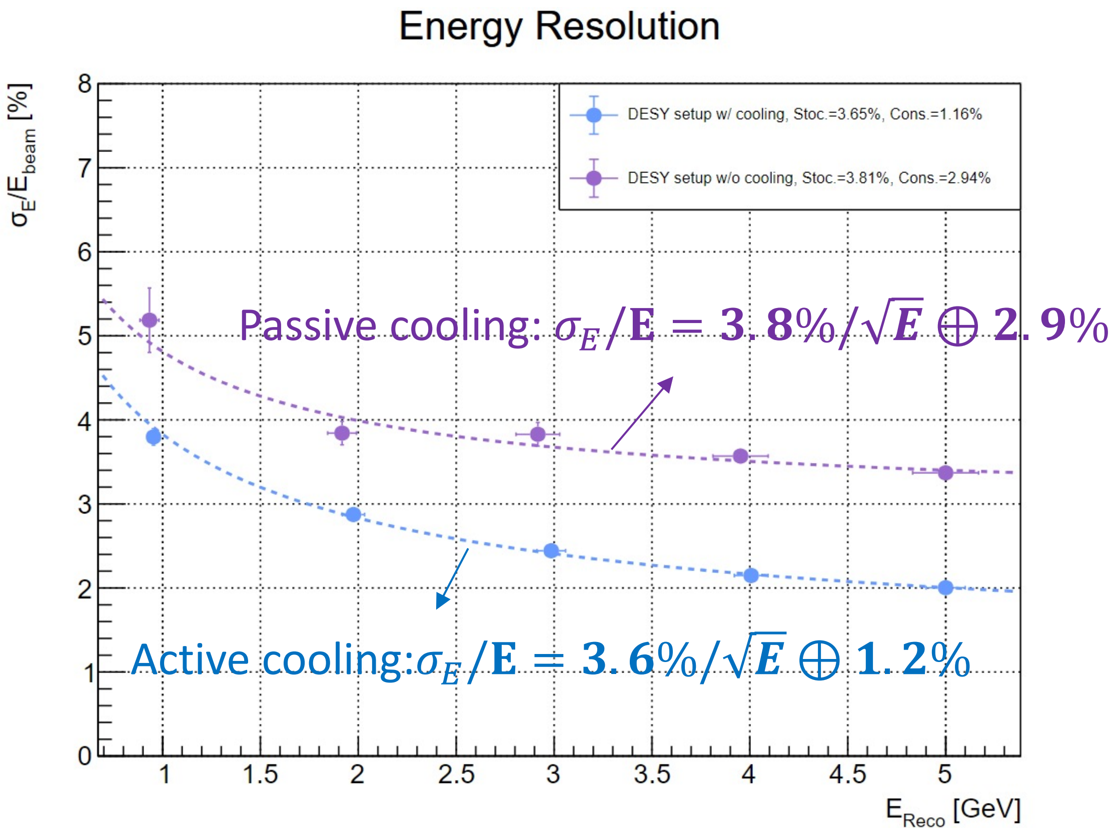


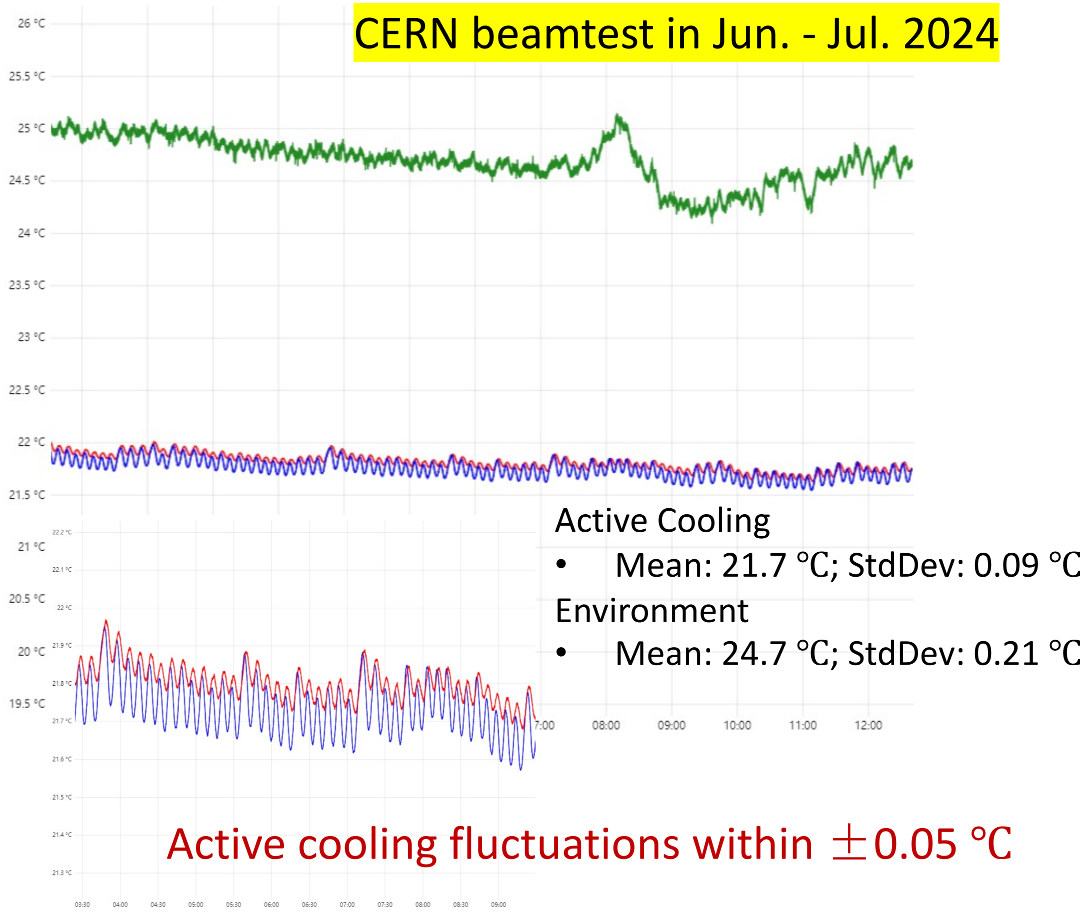






Crystal ECAL: impacts of temperature stability

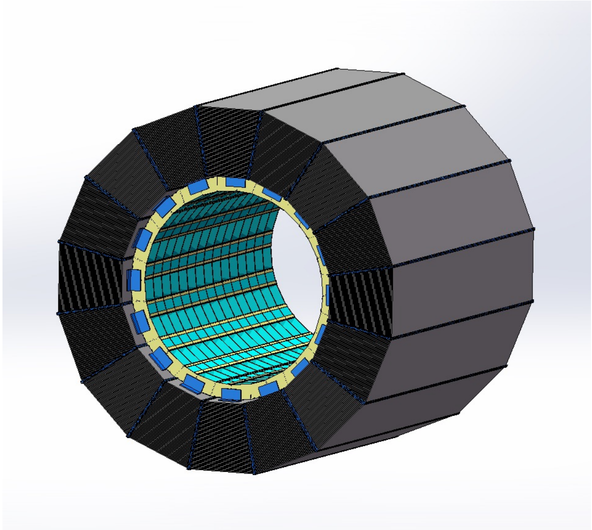


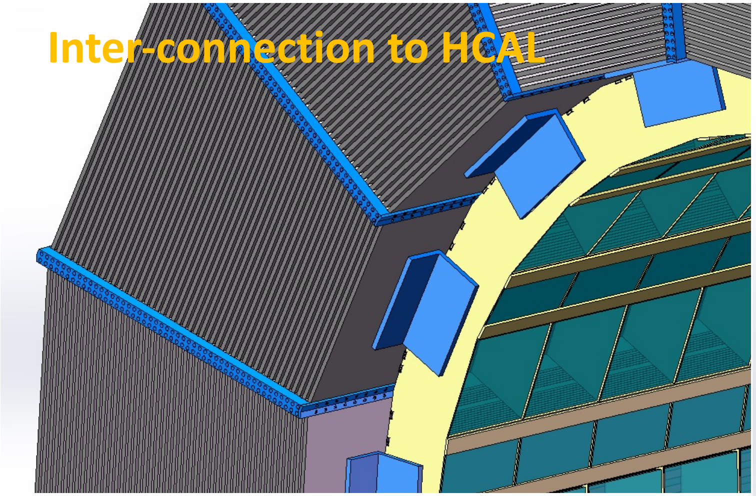


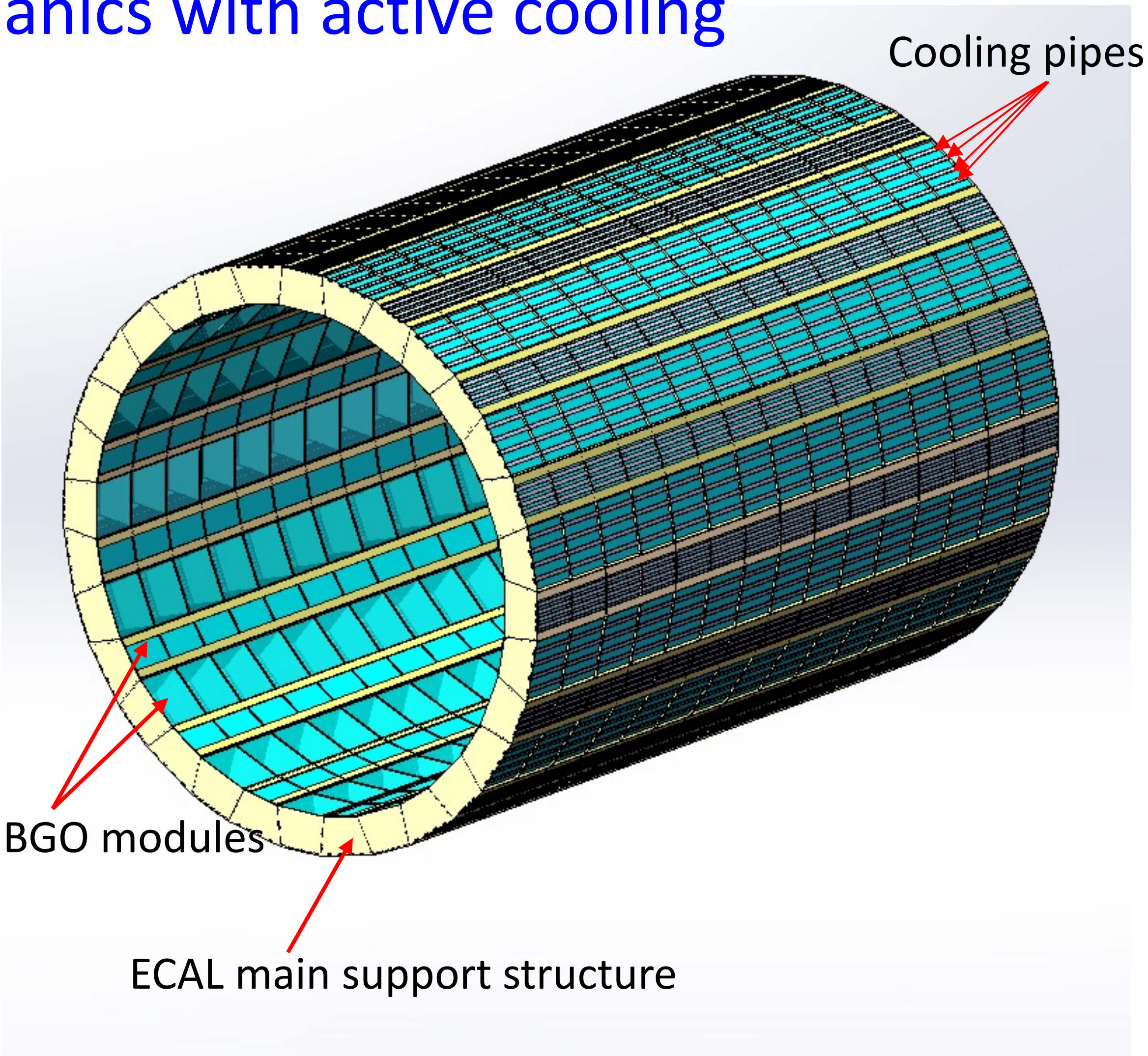
- Temperature stability is crucial to crystal ECAL
  - Significant impact to constant term of EM resolution
  - Specification on stability of ±0.05 ℃ is validated with beamtest data

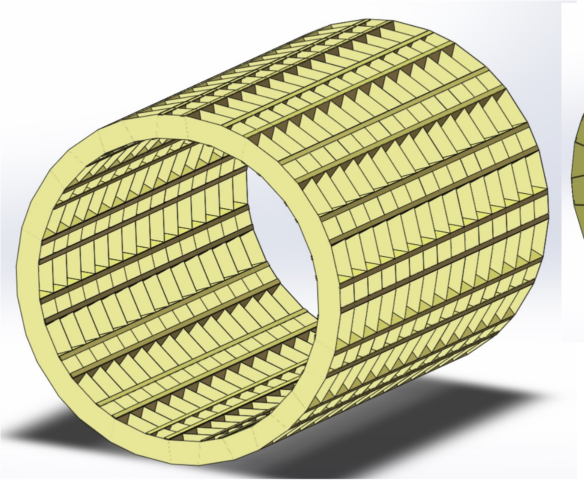
ECAL mechanics design: barrel

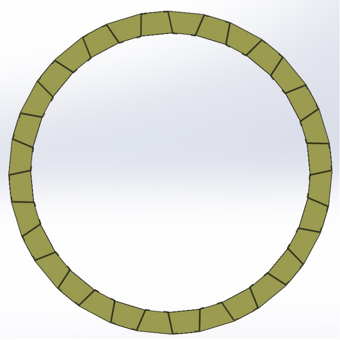
- A first complete design of ECAL mechanics with active cooling

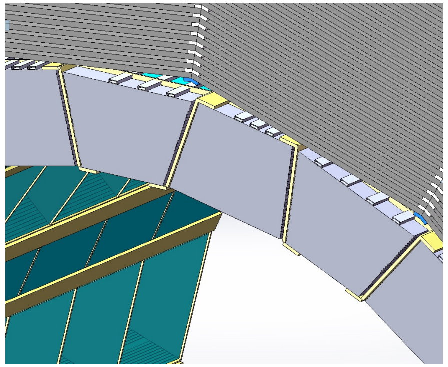






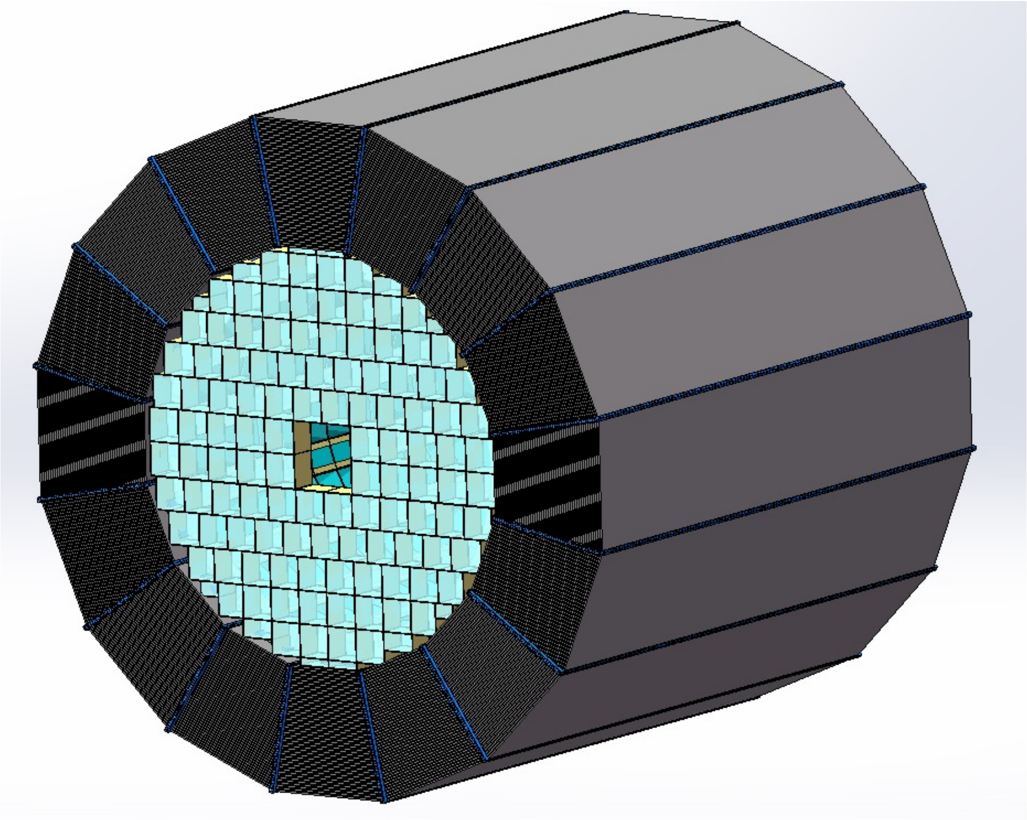


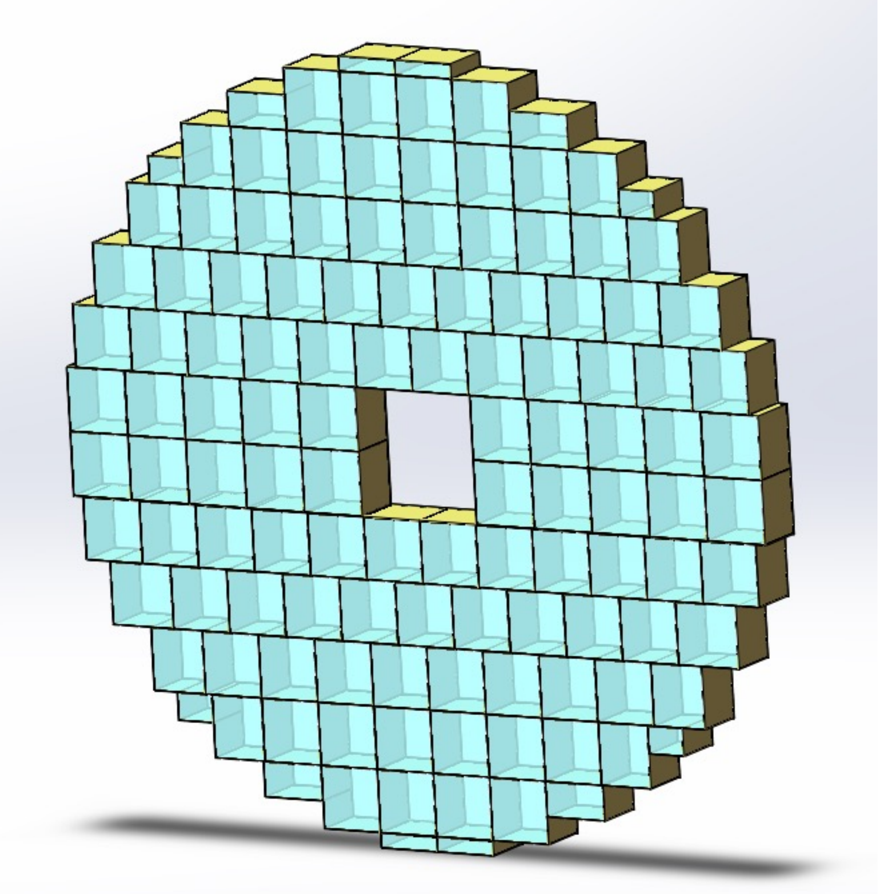




ECAL mechanics design: endcaps

- A preliminary design proposed for ECAL endcaps

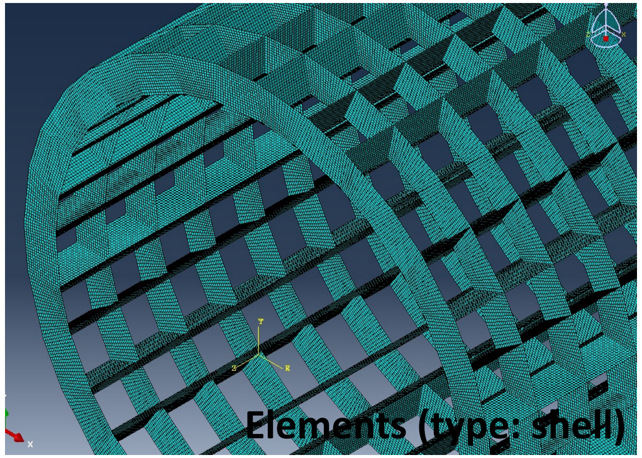


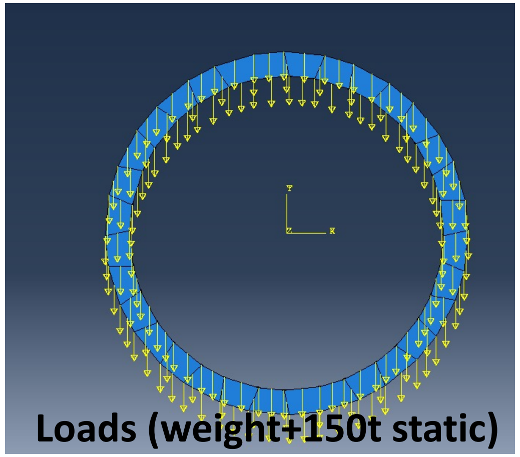


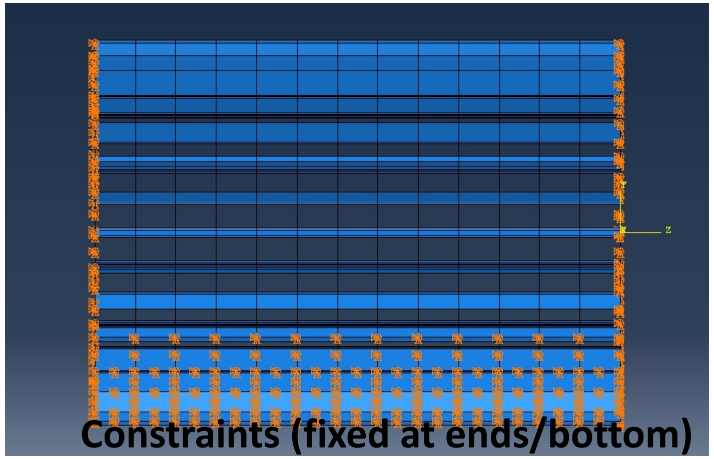
- ECAL endcap structure is based on 3mm CFRP, with BGO modules (in cyan)

ECAL mechanics design: FEA simulation

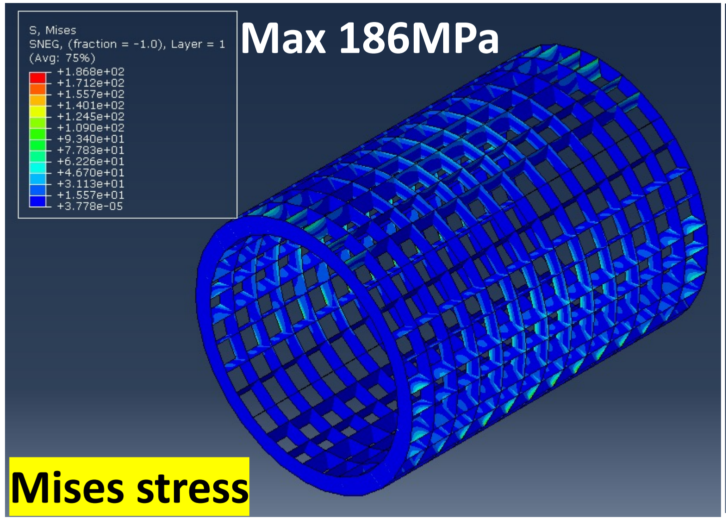
- FEA simulation studies on ECAL mechanics (ongoing): further iterations + validation

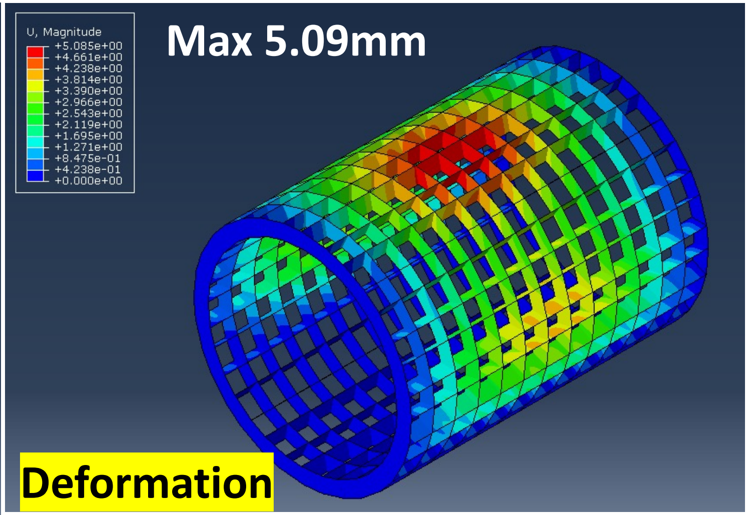


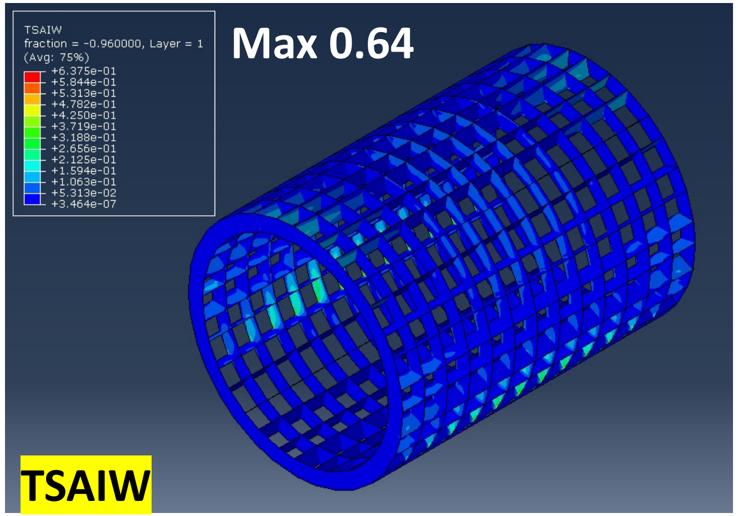




- **Material** :T700 reinforced epoxy resin.
- **TSAIW=0.64 (**When **TSAIW=1**, material begins to fail**)**
- **Safety factor** of the structure is 1/0.64=**1.56**

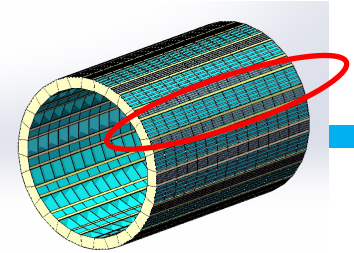






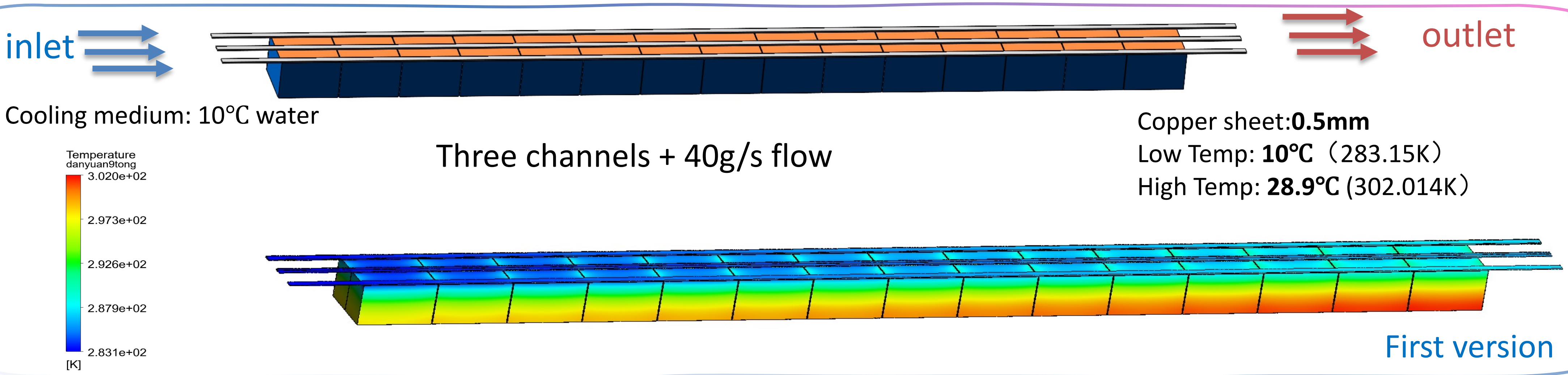
(Failure parameters of composite materials)

ECAL cooling system



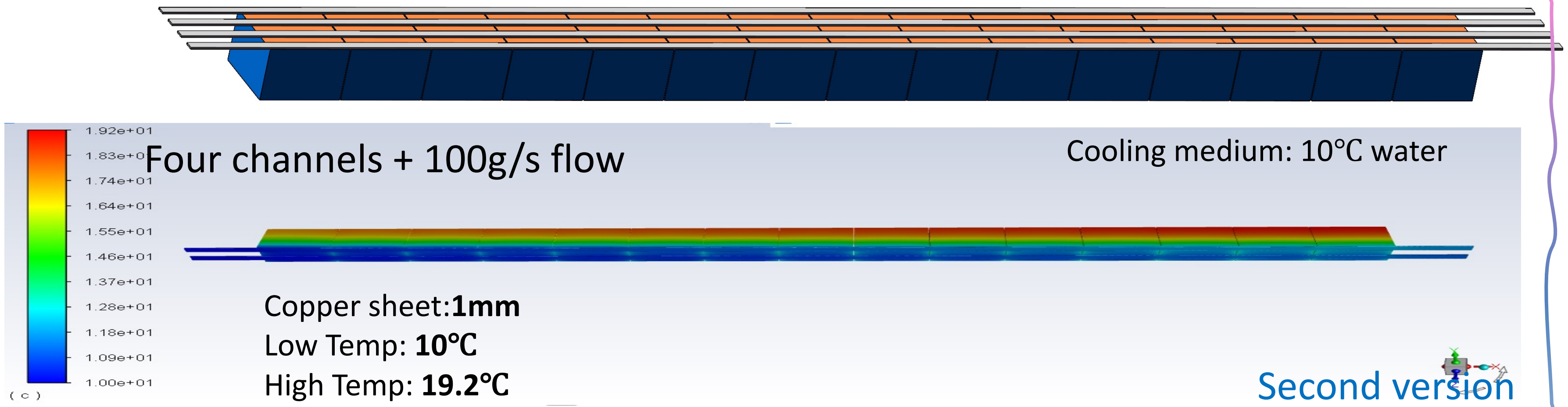
- FEA simulation studies on ECAL cooling

Cooling for 1/32 barrel module
42W for each module **(15mW/ch)**



Copper sheet:**0.5mm**
Low Temp: **10℃**（283.15K）
High Temp: **28.9℃** (302.014K）

First version



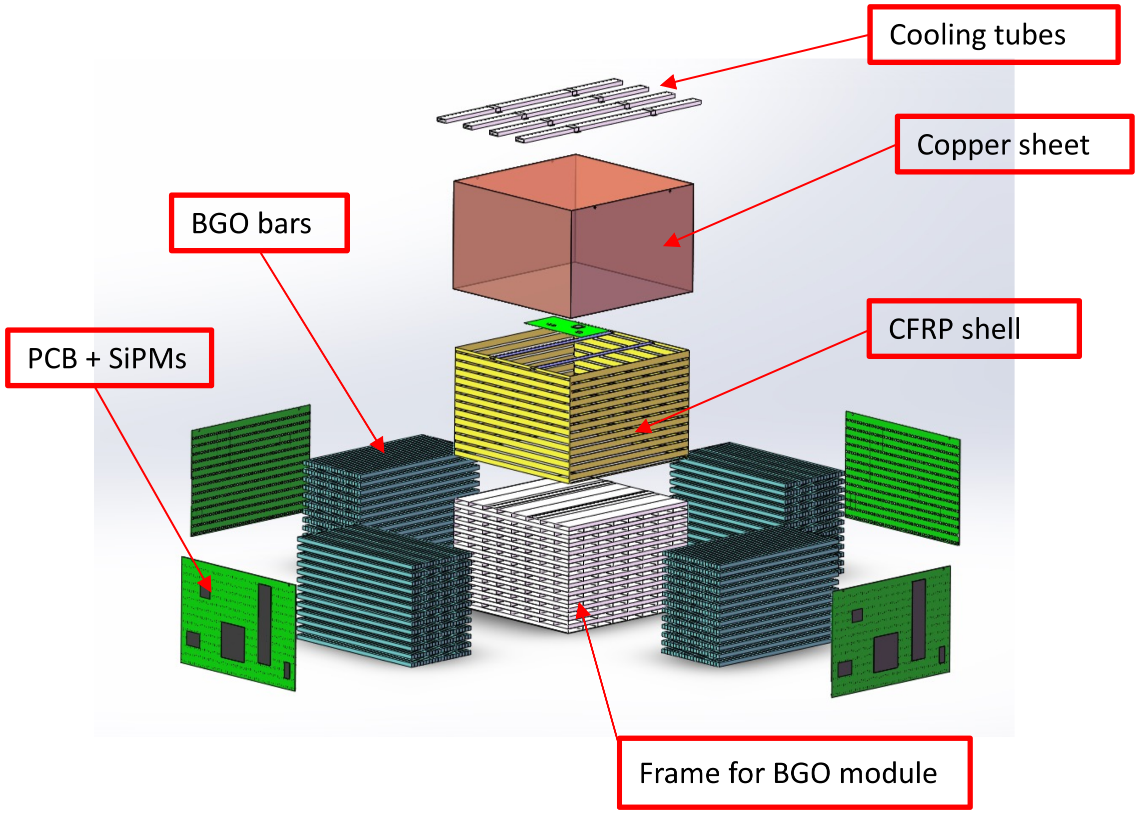
Copper sheet:**1mm**
Low Temp: **10℃**
High Temp: **19.2℃**

Second version

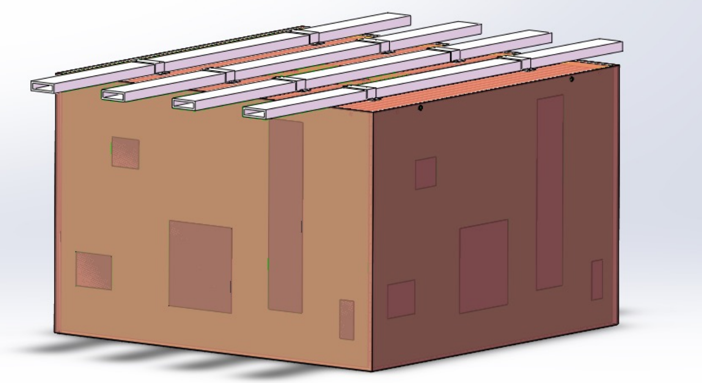
Temperature requirements:
Gradient within ± 1.5℃
Stability within ± 0.05℃

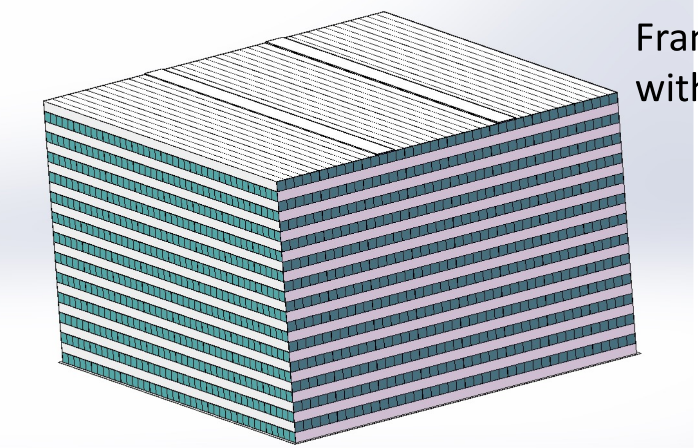
ECAL module integration

- FEA simulation studies on ECAL mechanics (ongoing): further iterations + validation



Cooling system

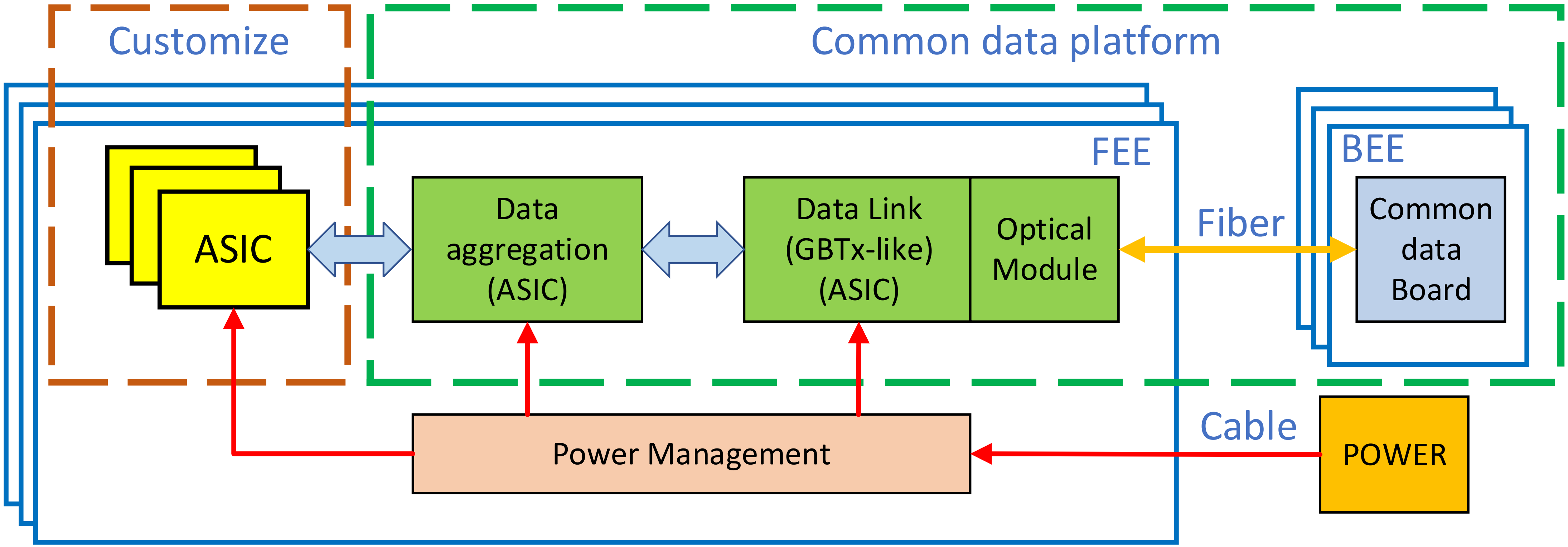




Frame is made of CFRP with 5 BGO bars in 1 cell.

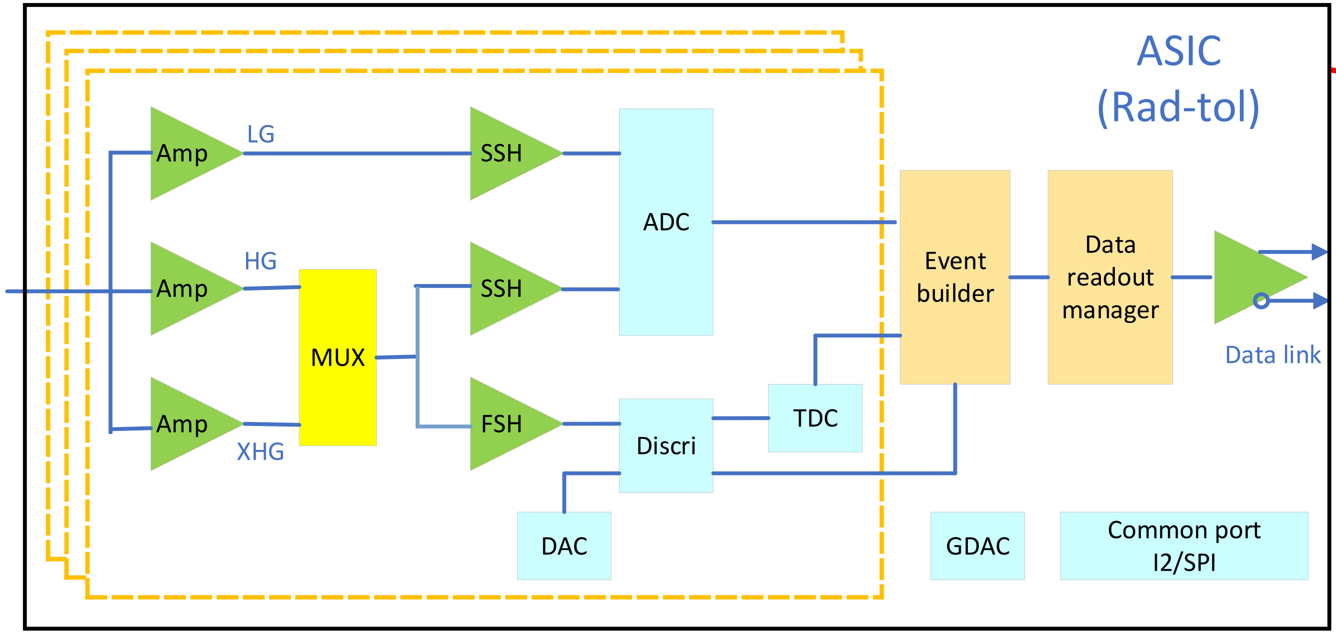
Frame + BGO bars

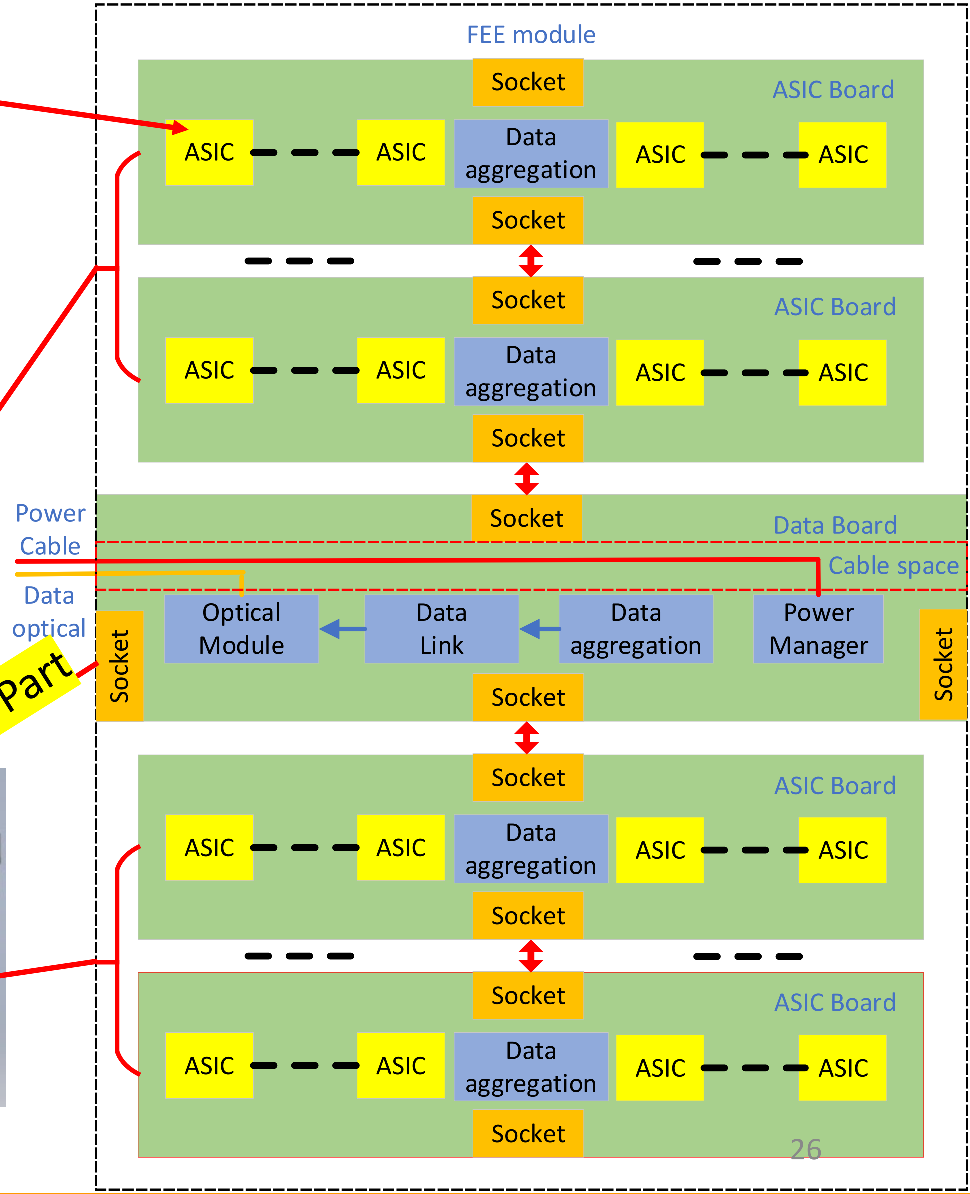
Electronics diagram for ECAL & HCAL



- **Energy and time measurements:** ASIC for ECAL & HCAL
- **Data transmission:** common data platform (refer to the "Electronics TDR Report")
- **Trigger mode:** trigger-less readout in Front-End Electronics (FEE)

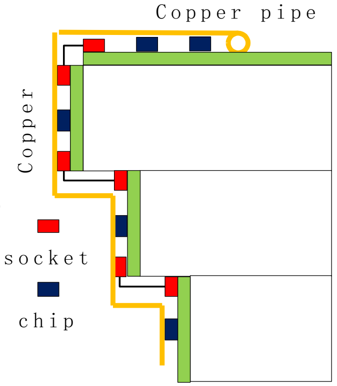
Readout electronics for ECAL

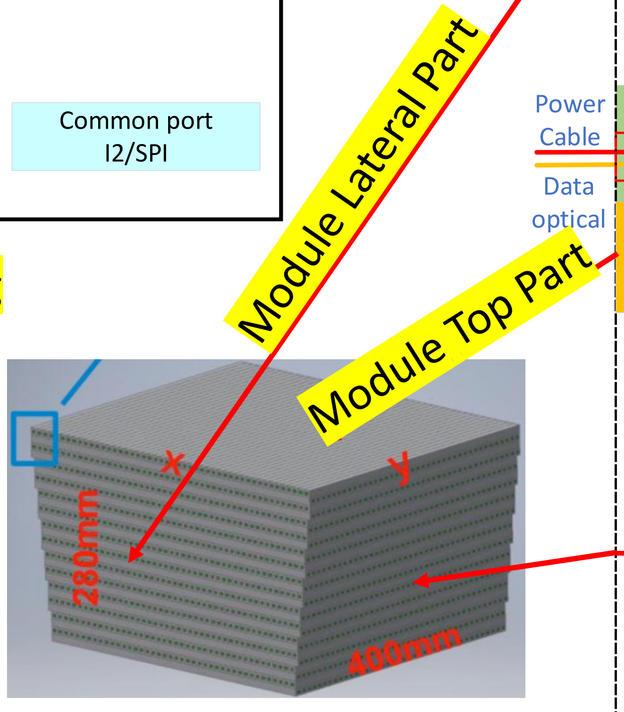




- For different options, FEE module can be one PCB or multiple PCBs
- PCB dimensions: flexible to different options
- 15mW/ch (estimate)

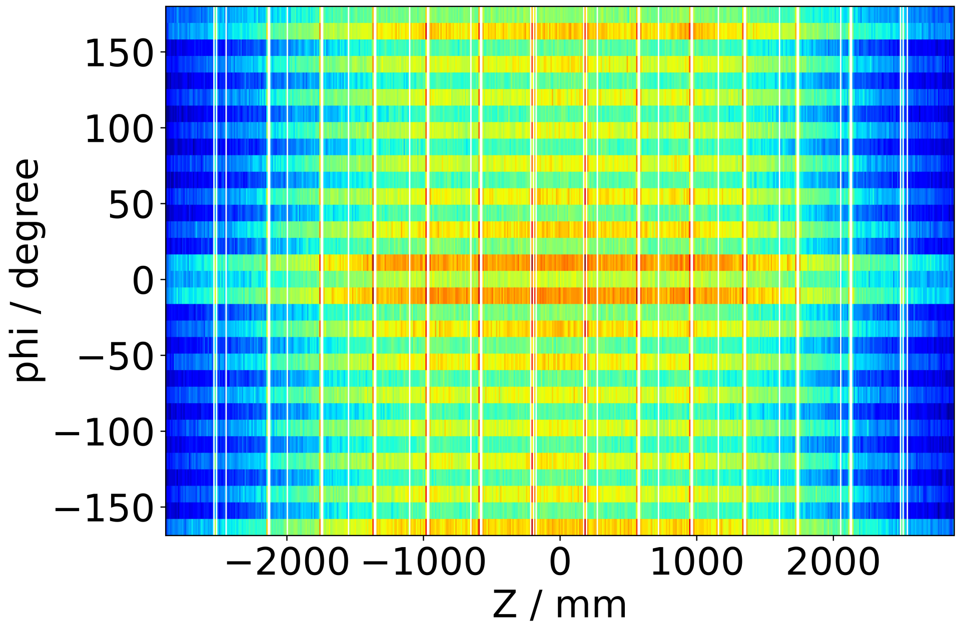
Passive Cooling

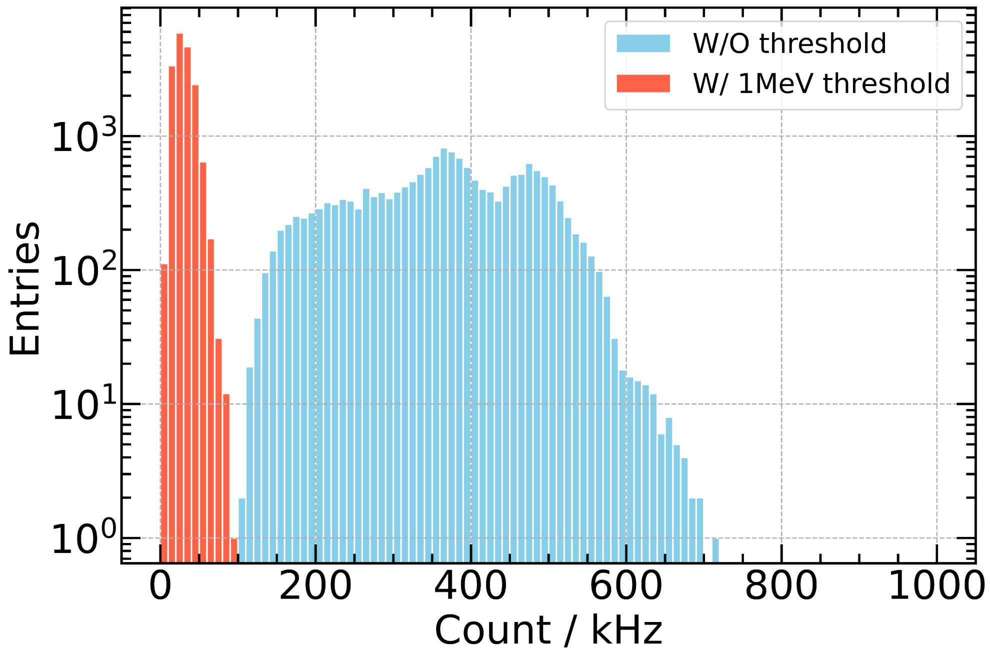




Beam-induced backgrounds: simulation studies

Hit map of 1st layer in crystal barrel ECAL

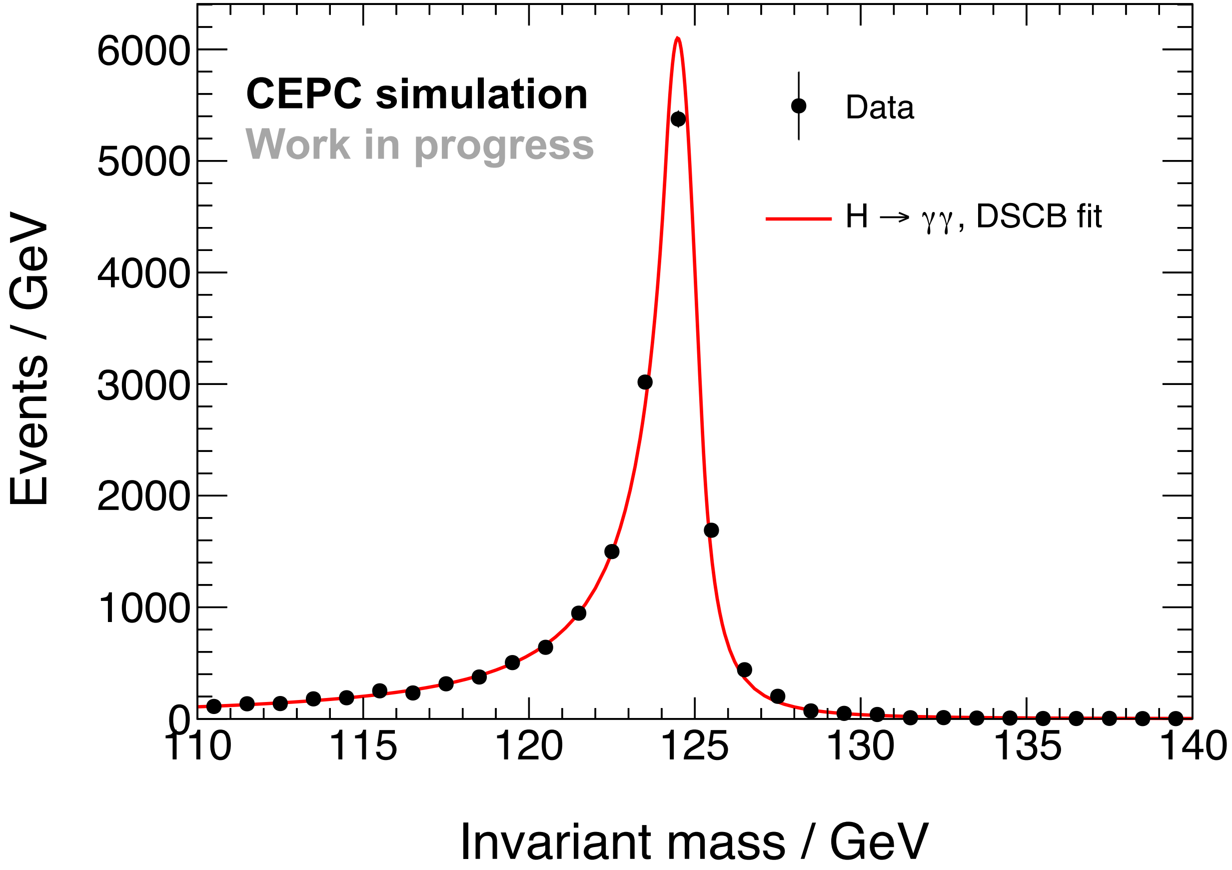




- Simulation studies on beam background in Higgs mode: crystal ECAL barrel
  - Including physics events + backgrounds (major contributions from pair production)
  - With threshold, rate can be significantly reduced: 100kHz (0.1 MIP threshold) from 700kHz (0 threshold)
  - Need to further investigate impacts of pile-ups, and endcap regions

Physics performance in simulation: $H \to \gamma\gamma$

- Physics process: $ee \to ZH \to \nu\nu\gamma\gamma$ in $\sqrt{s} = 240$ GeV
  - Full simulation and digitization, with energy correction in crack regions



Double-side CB fit, $\sigma(m_{\gamma\gamma})$ = 0.57 GeV

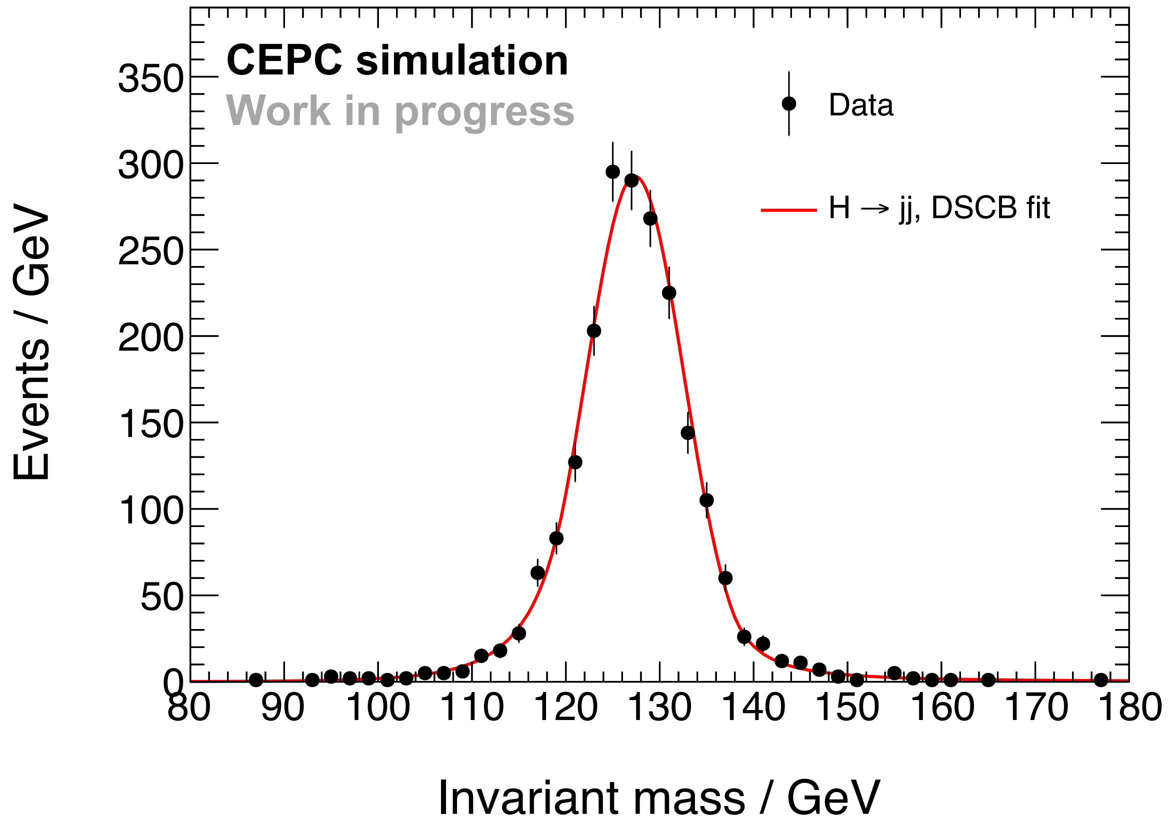
Long tail from

- Lossy processes of crystal calorimeter
- Imperfect correction in crack region.

Can be fixed with better photon energy correction in the future.

Physics performance in simulation: $H \to gg$

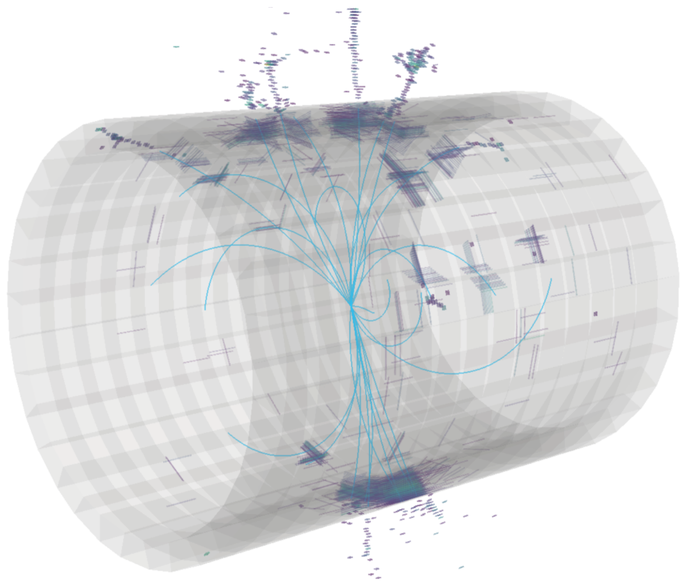
- Physics process: $ee \to ZH \to \nu\nu gg$ in $\sqrt{s} = 240$ GeV
  - Full reconstruction of two gluon jets in CEPC detector
    - Vertex, Silicon + TPC tracker, crystal ECAL, ScintGlass HCAL



$m_{jj} = 127.3$ GeV, $\sigma(m_{jj}) = 5.23$ GeV

Boson mass resolution (BMR) 4.11%.

With truth track: BMR 3.73%.

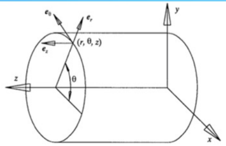


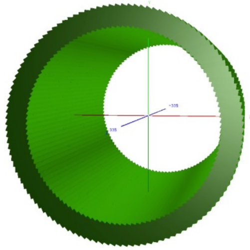
Alternative ECAL design: stereo crystals

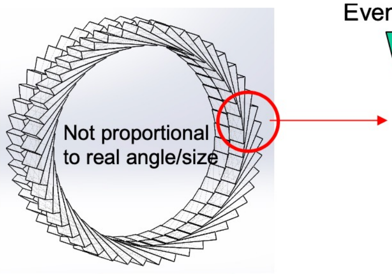
- Stereo design with long crystal bars inclined
  - Simulation studies on reconstruction and separation capability of two particle
  - Ongoing designs on mechanics, cooling and integration

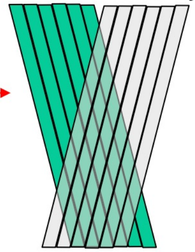
Stereo Crystal Electromagnetic Calorimeter: Design

- To improve the 3D position resolution
  - Pointing angle of even layers alone Z: α
  - Pointing angle of odd layers alone Z: $\alpha' = -\alpha$

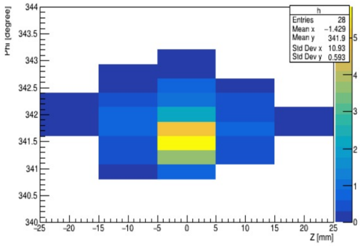




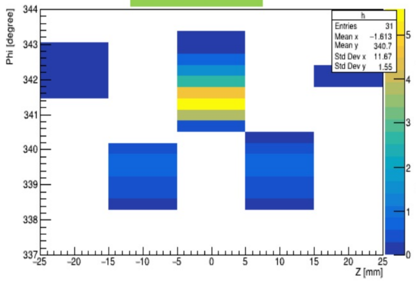




Traditional Crystal Ecal

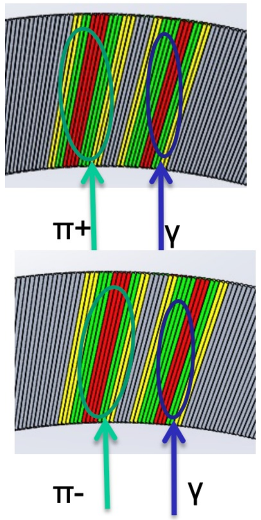


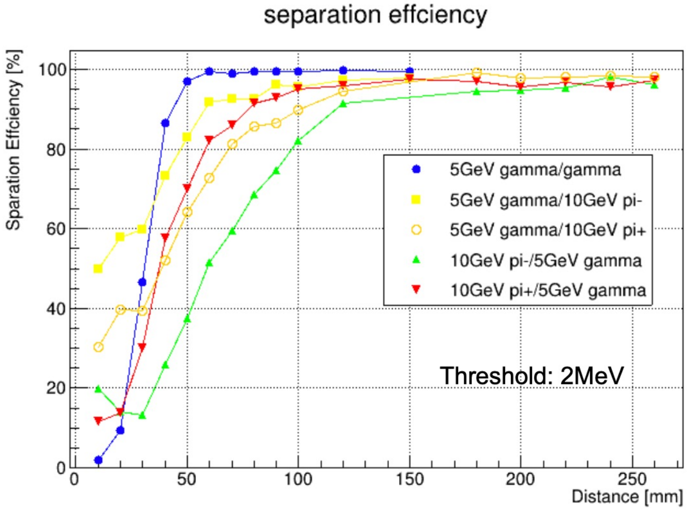
SCEcal

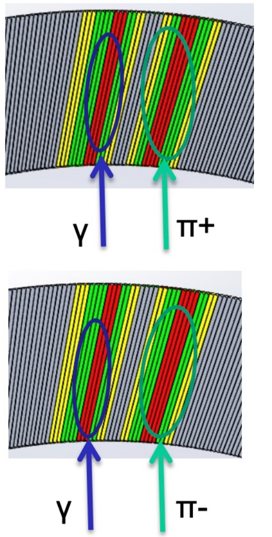


Separation between γ/π

- 5 GeV γ/10GeV π, vary distance along phi between them
- Success reconstruction: 3.3GeV<E_γ<6.6GeV
- Different π/γ separation power: pointing angle / magnetic field







Taskforce on CEPC ECAL

- Detector: Jiyuan Chen, Junfeng Chen, Dejing Du, Fangyi Guo, Hengne Li, Jianbei Liu, Yong Liu, Baohua Qi, Jiaxuan Wang, Haijun Yang, Huaqiao Zhang, Yang Zhang, Yunlong Zhang, Zhiyu Zhao
- Electronics: Jinfan Chang, Wei Wei, Xiongbo Yan
- Mechanics: Shaojing Hou
- Software: Fangyi Guo, Weizheng Song, Shengsen Sun, Yang Zhang

Institutions as working groups in CALICE and DRD6 collaborations

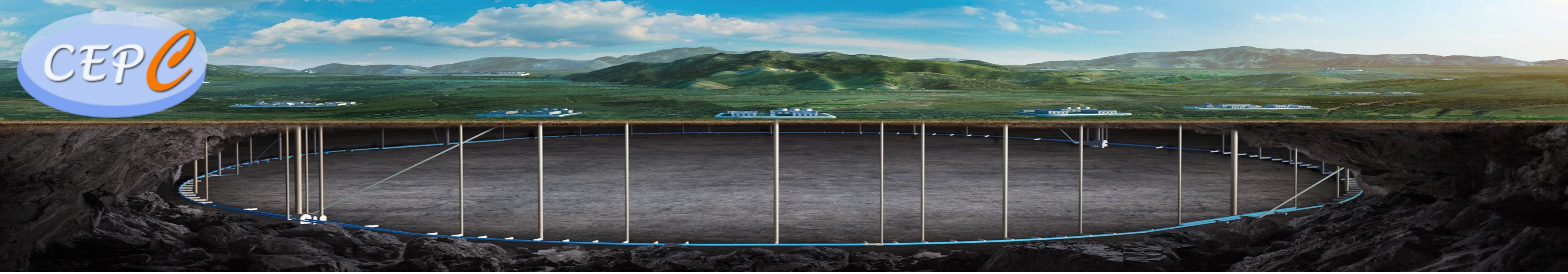
- IHEP, SIC-CAS, SJTU/TDLI, USTC, SCNU
- Shinshu U. and U. Tokyo (on ScW-ECAL option)

Working plan

- Near future activities within 2024 for reference TDR
  - Beam-induced backgrounds: simulation in both barrel and endcap regions, studies impacts to performance, estimate of data throughput
  - Mechanics and cooling: refine FEA simulations, validation by dedicated tests
  - Detector: fully exploit beamtest data on EM performance and validation studies
  - Software: geometry updates (interplay with mechanics/cooling), digititstaion (inputs from beamtest and electronics)
  - Calibration schemes: sensitive units (SiPM, crystal, ASIC) versus environment (temperature, irradiation doses)
  - Particle flow performance: further optimization studies

Summary

- Overview of CEPC ECAL options and dedicated R&D in past 8 years
- Crystal selected as a baseline option for the CEPC reference detector
  - Extensive studies on simulation performance and specifications
  - Steady progress with prototyping/beamtests, and dedicated PFA developments
  - First designs of general design, mechanics, cooling and readout electronics
- More efforts in planning to address critical issues for reference detector TDR
  - Beam-induced backgrounds and data throughput
  - System integration issues with mechanics, cooling and readout electronics
  - Calibration schemes (on-board designs for in-situ): SiPM, crystal, ASIC



Thank you for your attention!

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

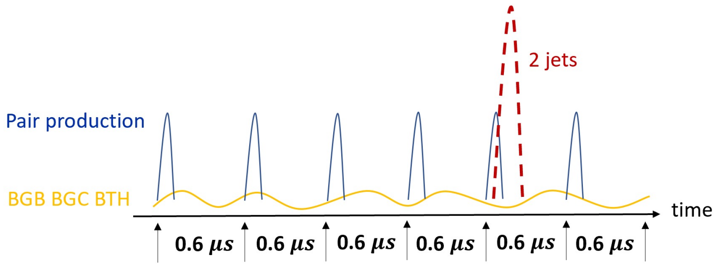
References

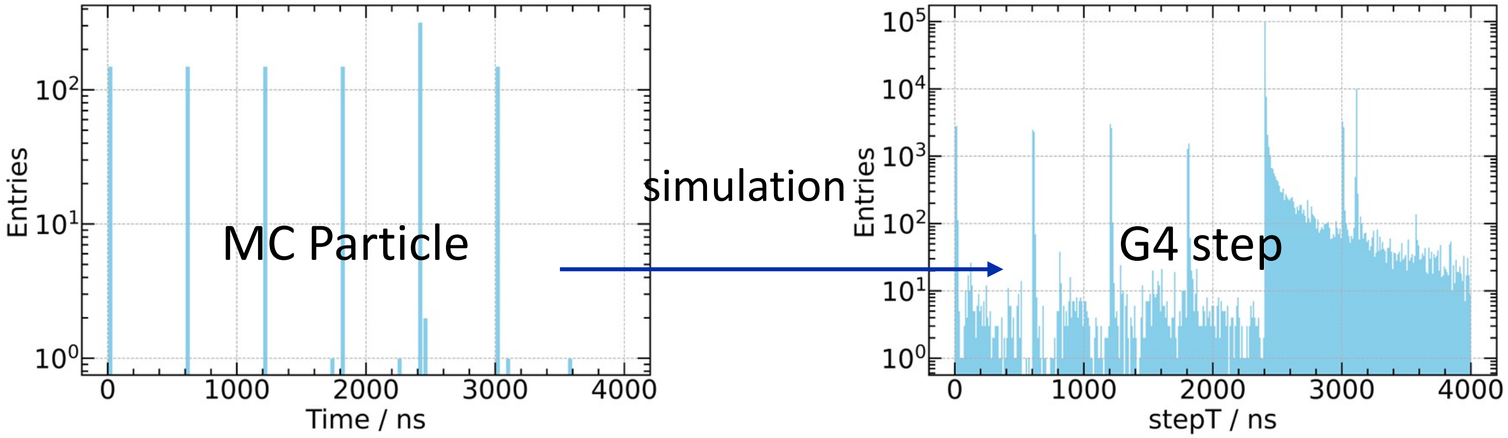
- C. Adloff et al., Response of the CALICE Si-W electromagnetic calorimeter physics prototype to electrons, Nuclear Instruments and Methods in Physics Research A 608 (2009) 372–383
- K. Francis et al., Performance of the first prototype of the CALICE scintillator strip electromagnetic calorimeter, Nuclear Instruments and Methods in Physics Research A 763 (2014) 278–289
- CEPC Conceptual Design Report Volume II - Physics & Detector, IHEP-CEPC-DR-2018-02

Beam-induced backgrounds: simulation studies

Background	Rate/Hz	$N_{MCParticle}$ / 3.6 μs time window
Pair production	---	~ 7800
Beam-Gas Bremsstrahlung (BGB)	**83,280.65**	~ 0.30
Beam-Gas Coulomb (BGC)	**884,002.12**	~ 3.18
Beam Thermal Photon Scattering (BTH)	**623,520.09**	~ 2.24
Synchrotron Radiation	---	---
Radiative Bhabha	---	---
Touschek	---	---

- **Higgs mode**:
  - pair production: double beams, e+-
  - BG: single beam
- Using **4 types** of beam backgrounds.
- **Simulation Time Window**: 3.6 us (6 collisions and 6 bunch spacing)
  - Considering physics events and beam background events.
  - Taking into account the scintillation decay time of the crystal and the shaping time of the electronics.

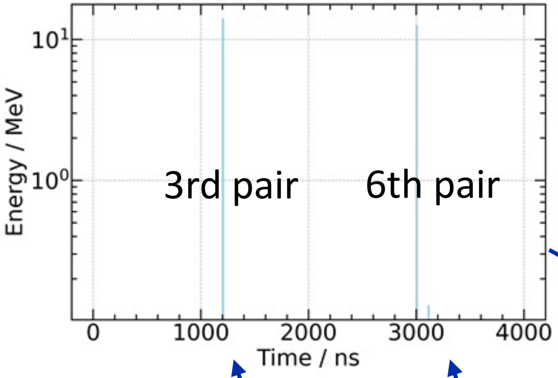


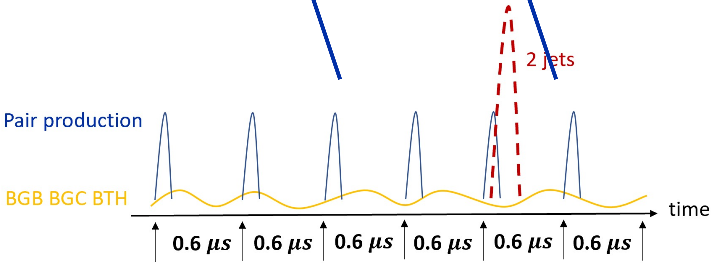


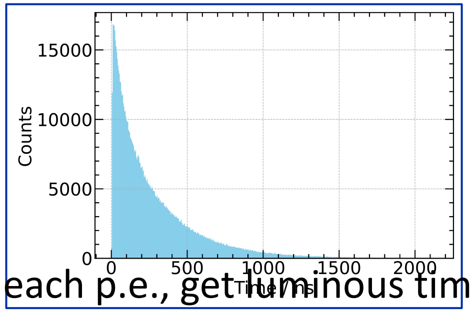
Beam-induced backgrounds: time structures

single crystal bar

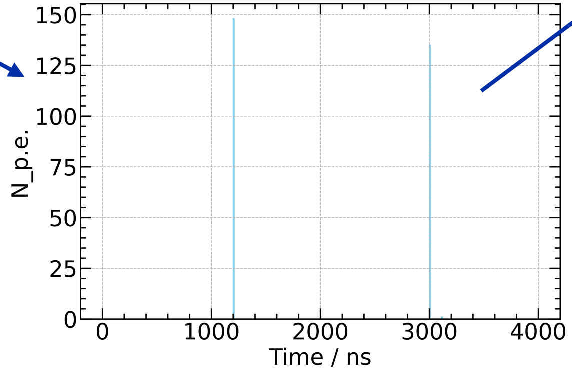
step (E, T)



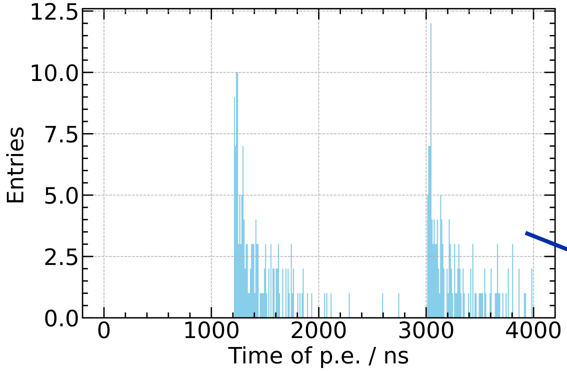


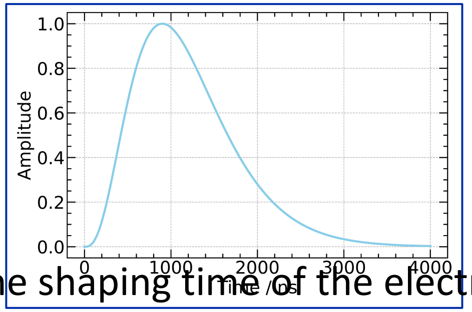


For each p.e., get luminous time and transmission time



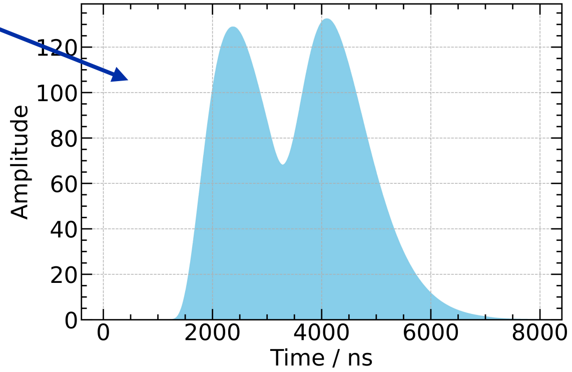
Detected Np.e in SiPM: 100 p.e./Mip



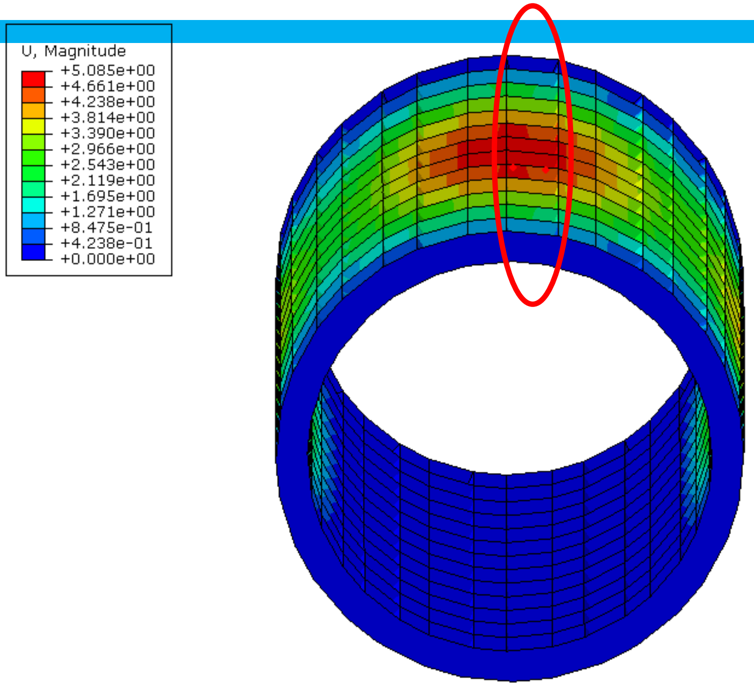


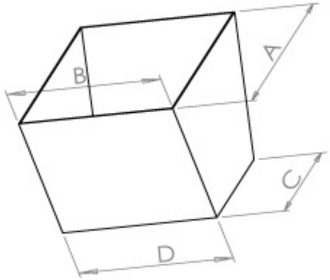
the shaping time of the electronics: CR-(RC)3

time structure of single crystal with 2 pair production

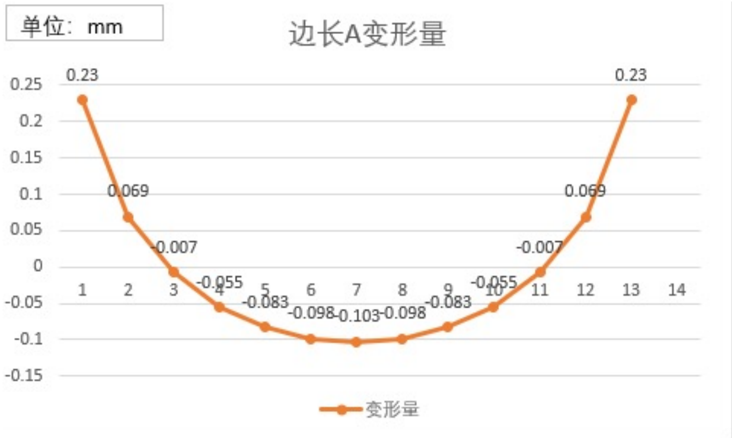


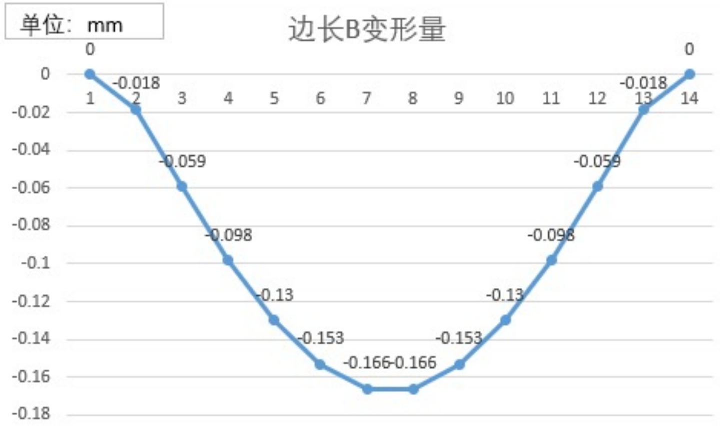
Mechanics: FEA studies on deformation

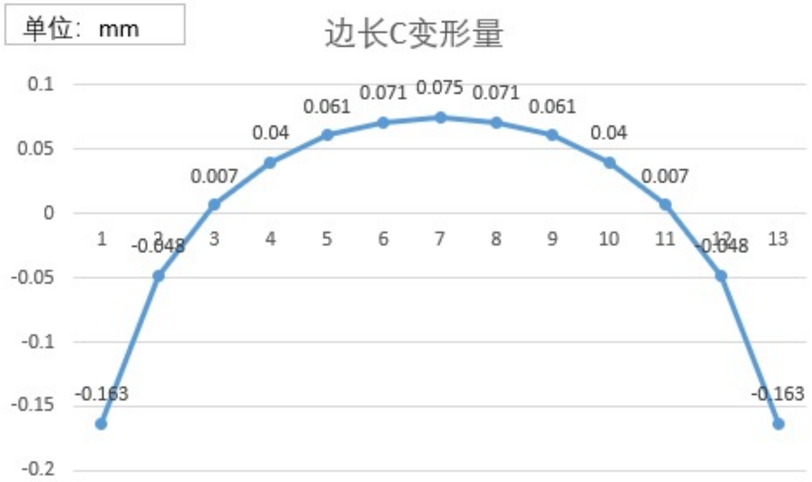


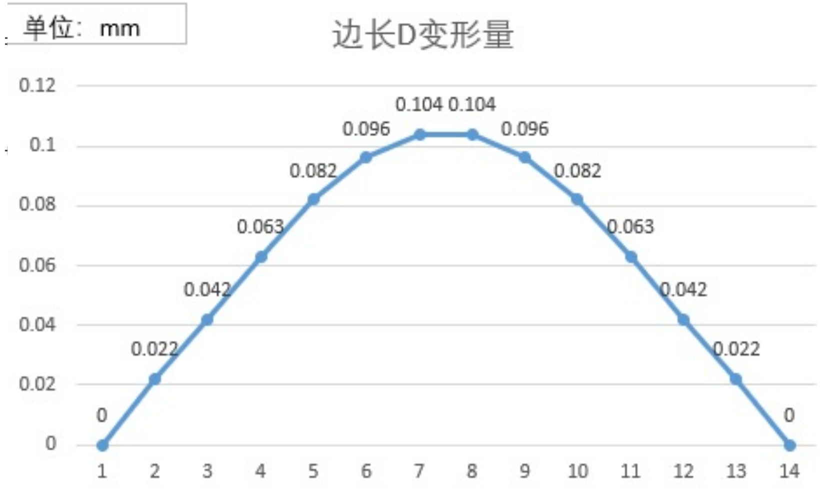


A/B/C/D are the sides of the cell



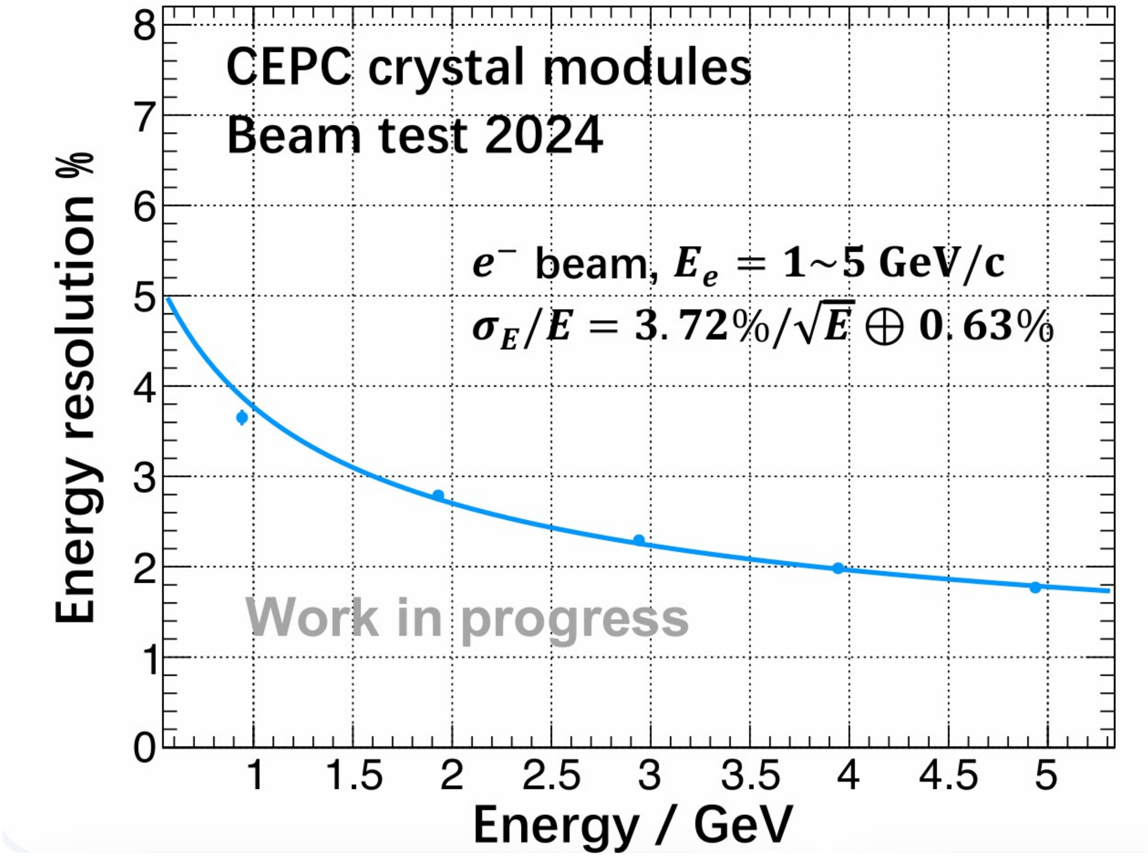


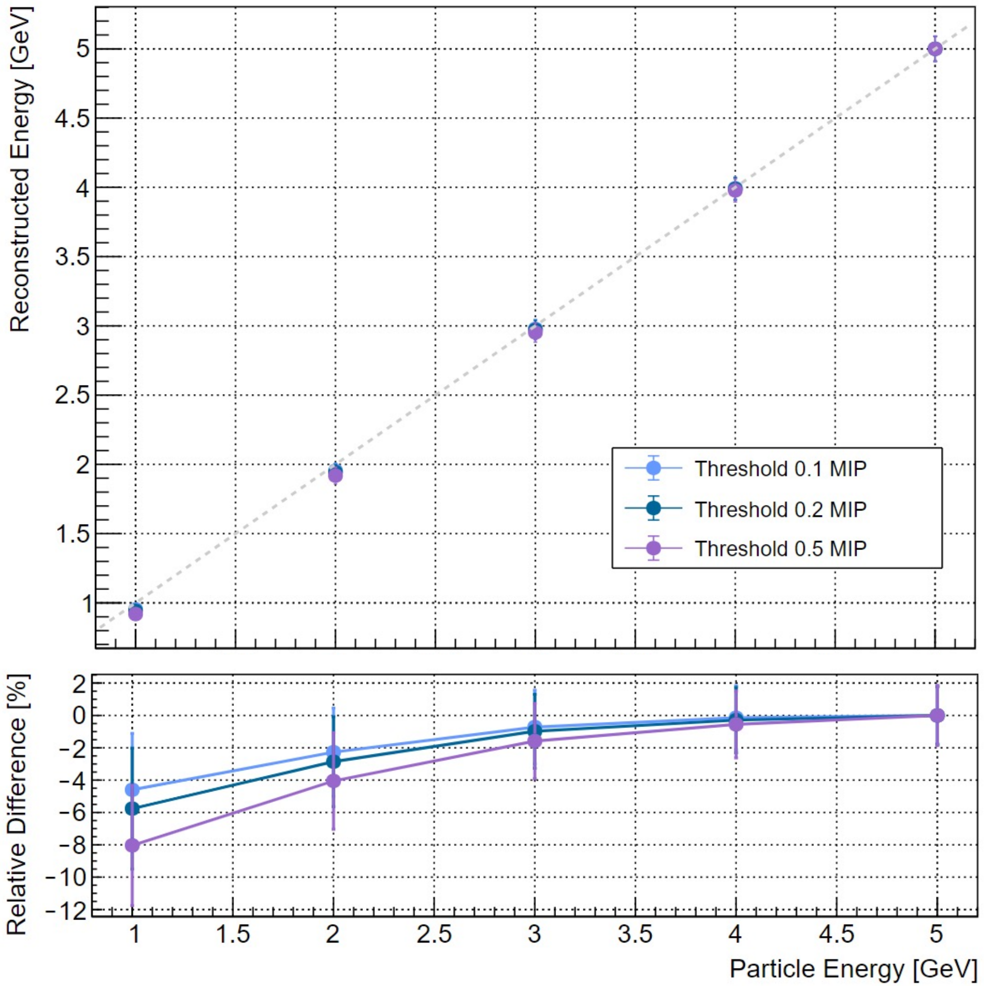




The BGO is brittle, so we have to know the deformation of each cell . According to the FEA, the maximum deformation of the cells is 0.23mm.

CERN setup: energy resolution





Planning

- R&D planning to address critical issues: beyond 2024
  - Radiation damages in SiPM and crystal: mitigation solutions

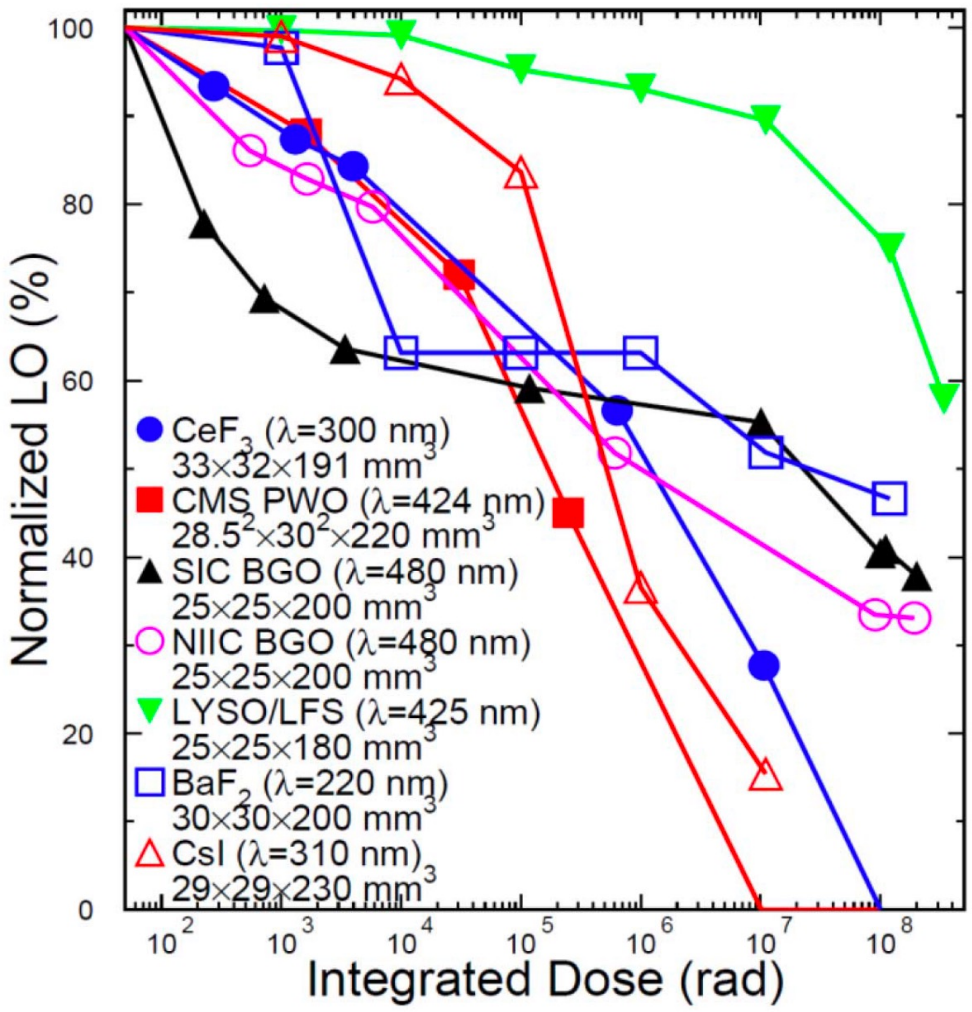


Fig. 21. Normalized LO as a function of integrated dose for various crystals.

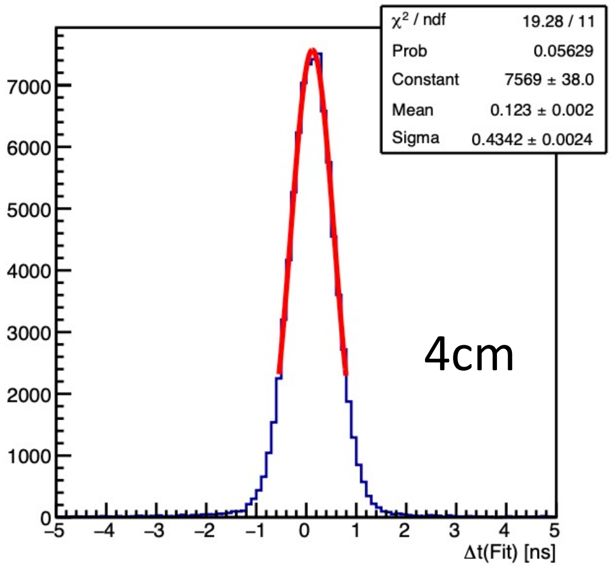
Further R&D prospects: mid/long-term

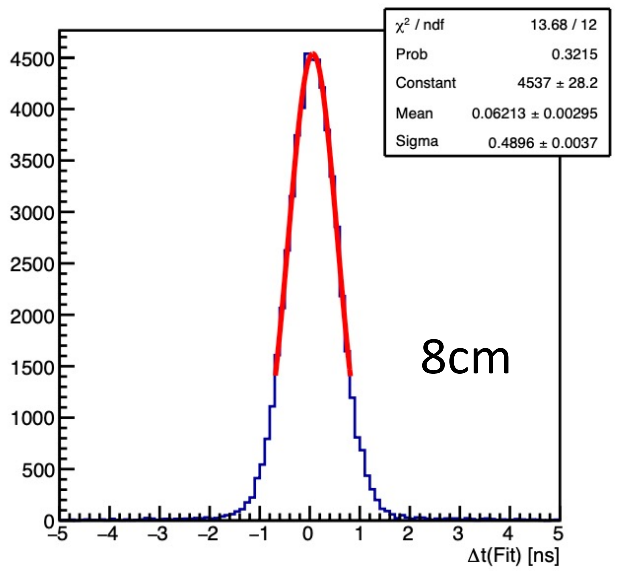
- Homogeneous ECAL with scintillating glass
  - Scintillating glass: similar properties (density and scintillation time) to crystals, but great potentials in cost effectiveness
  - Scintillating glass in the form factor of cubes or short bars
    - Highly granular in transverse/longitudinal: naturally compatible with particle flow
    - Best suit for light collection efficiency -> less stringent requirement on intrinsic light yield
  - Critical issues on scintillating glass
    - Radiation length: ~40% longer than BGO, ECAL depth expected significantly larger
    - Irradiation damage: transparency along with TID and NIEL doses
    - Undesired effects in strong magnetic fields: e.g. after-glow

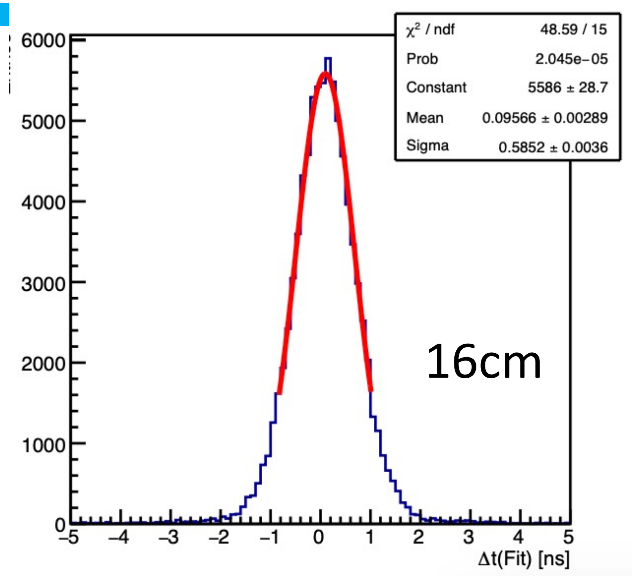
Time Performance of Crystal Bar

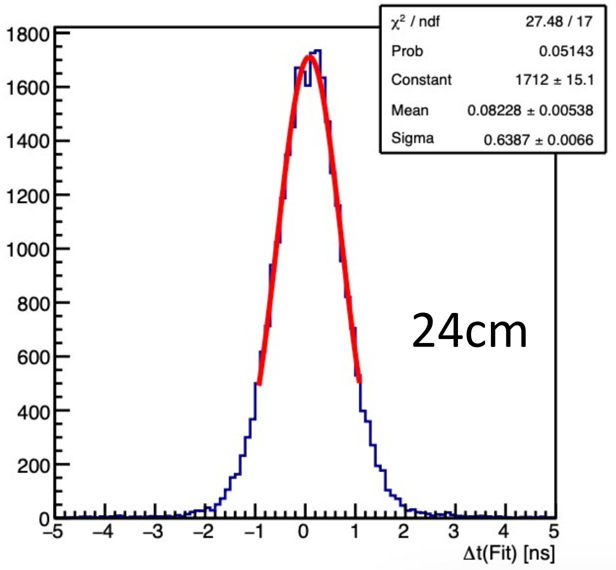
Time performance of BGO with different lengths

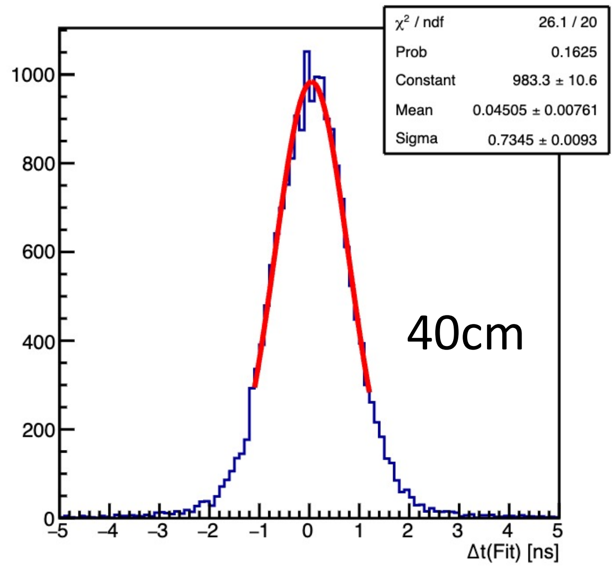
- SiPM: S13360-6025PE
- NDL preamp 20dB
- 10 GeV pion- beam

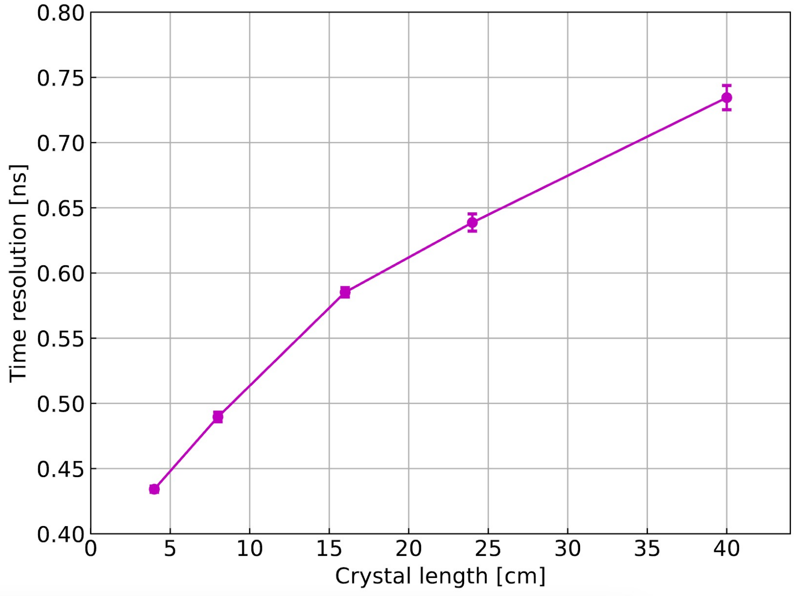






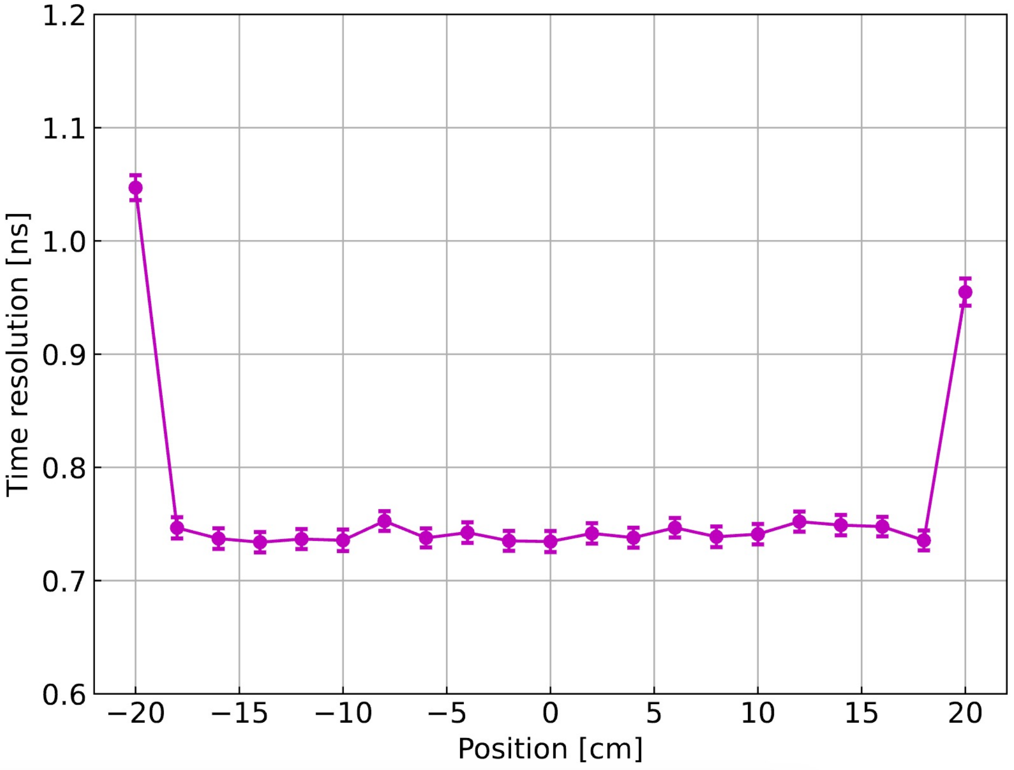






Time performance of 40cm BGO with different positions

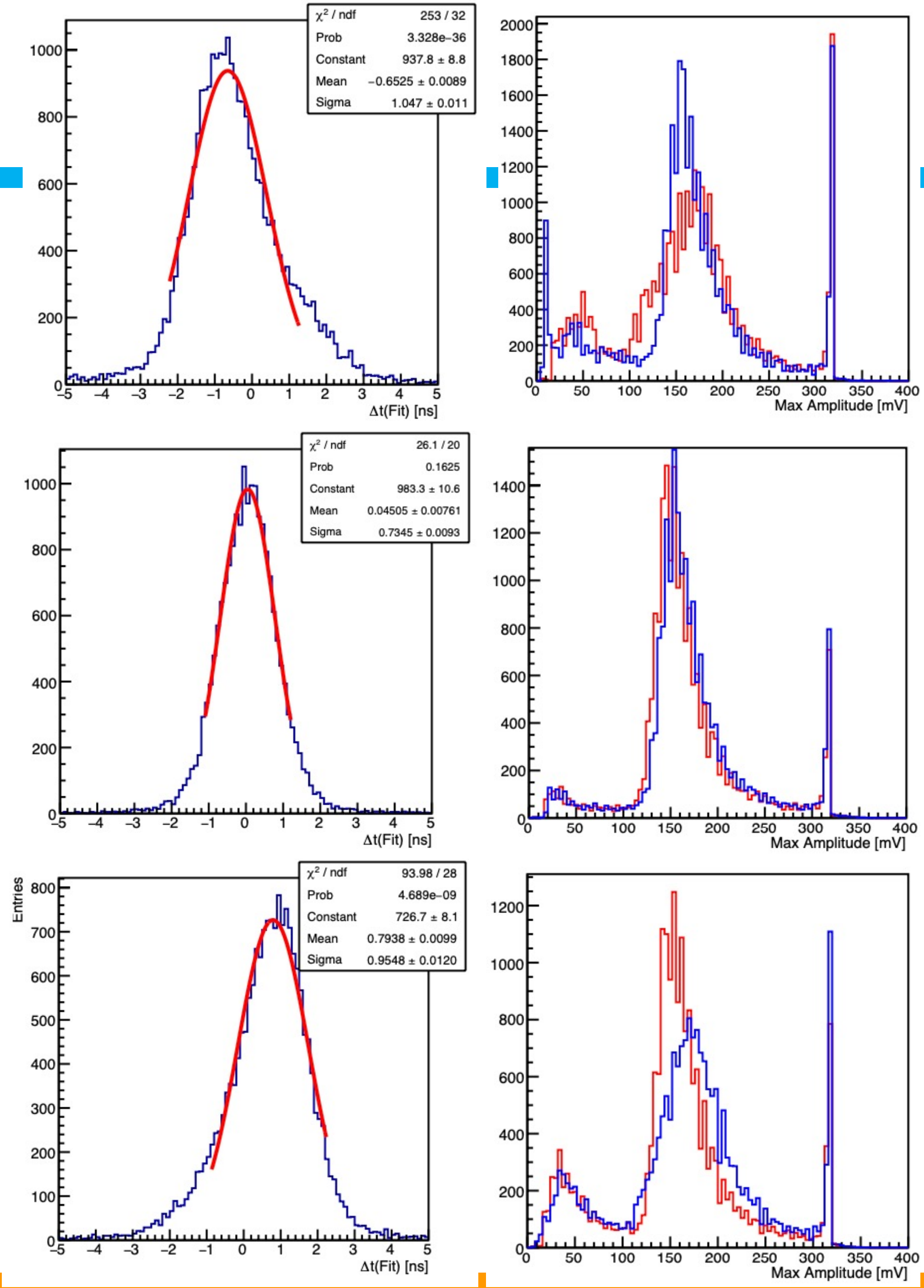
- SiPM: S13360-6025PE
- NDL preamp 20dB
- 10 GeV pion- beam



-20cm

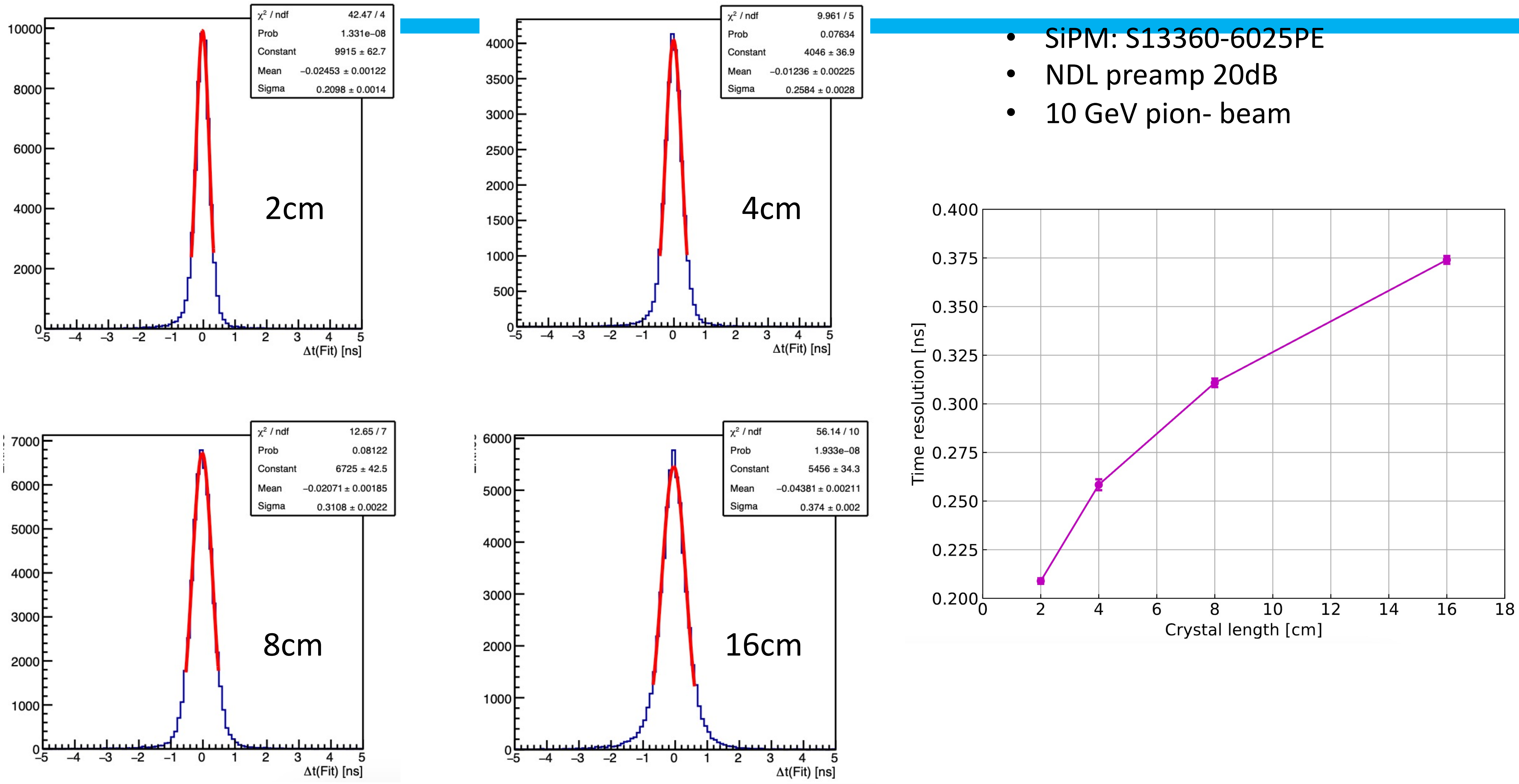
0cm

20cm



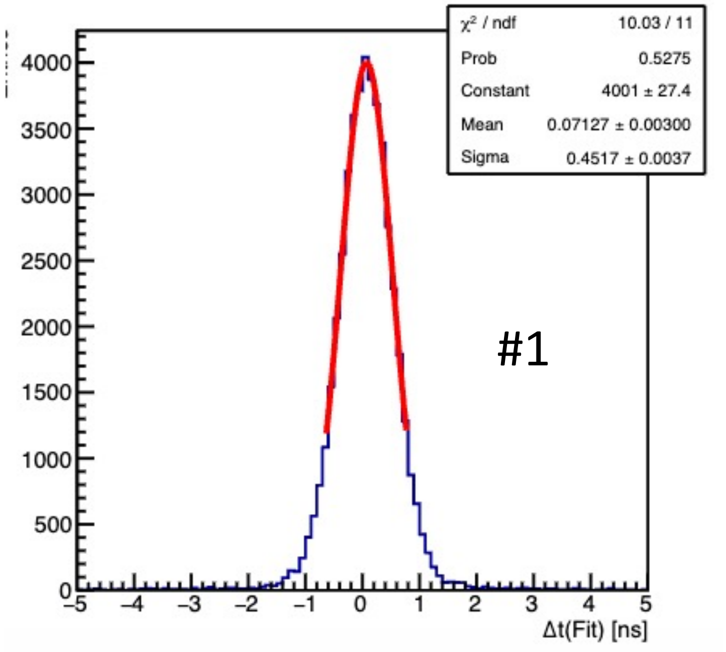
Time performance of PWO with different lengths

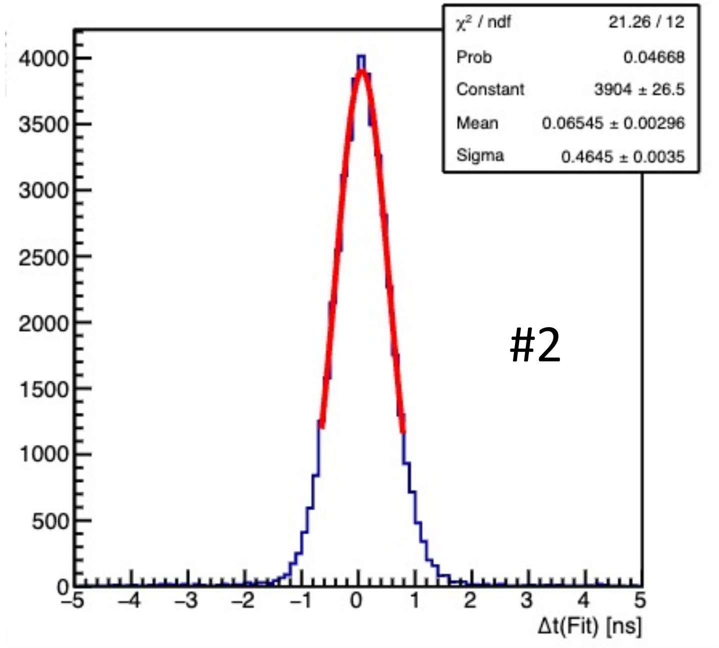
- SiPM: S13360-6025PE
- NDL preamp 20dB
- 10 GeV pion- beam

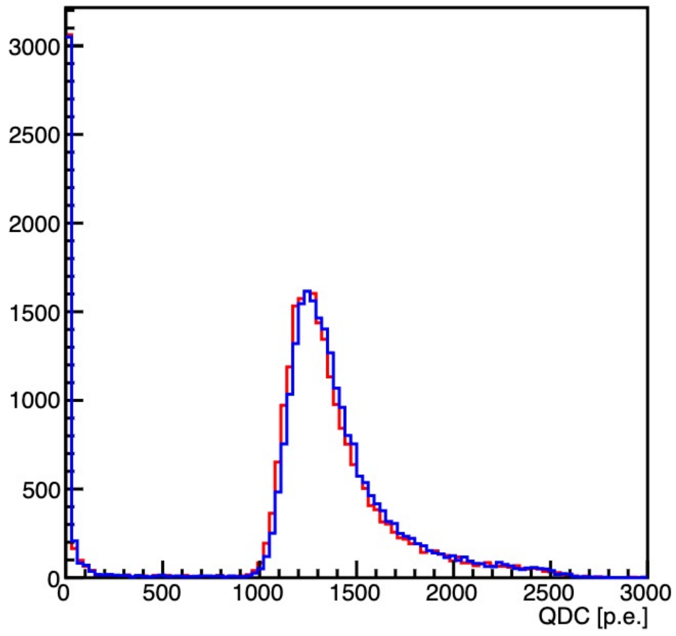


BSO crystal: beamtest

7cm BSO

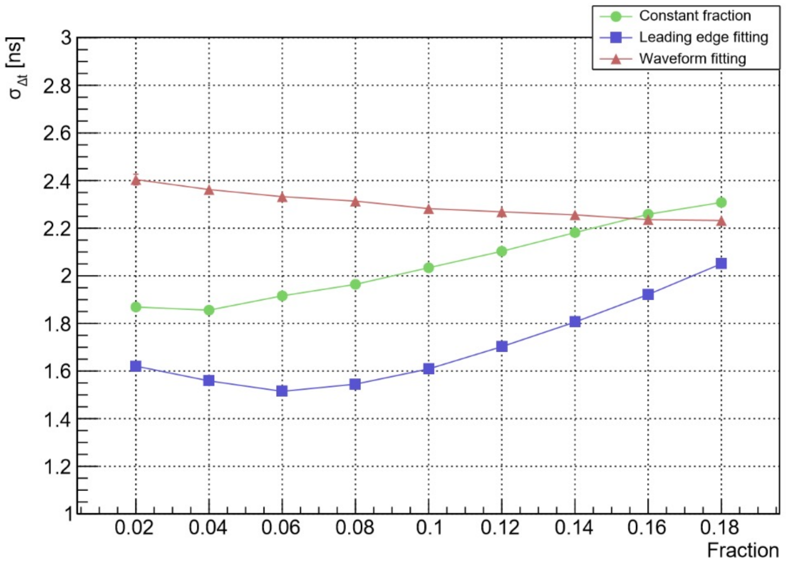




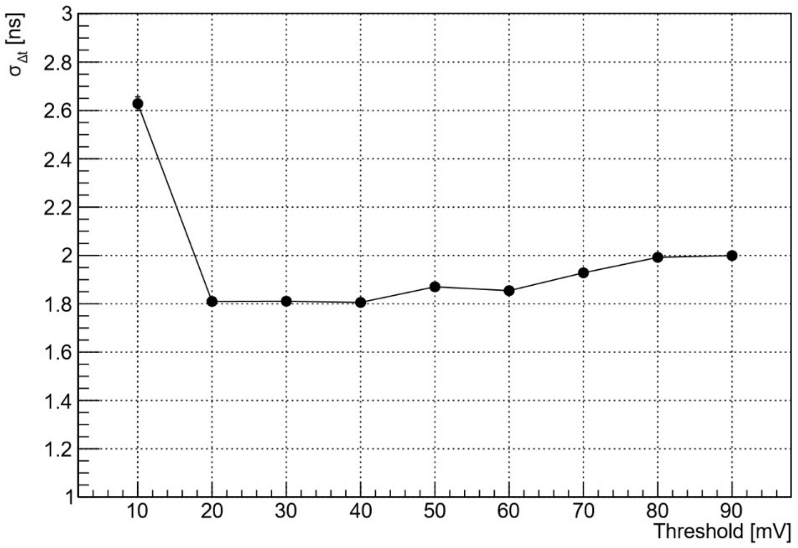


Timing schemes

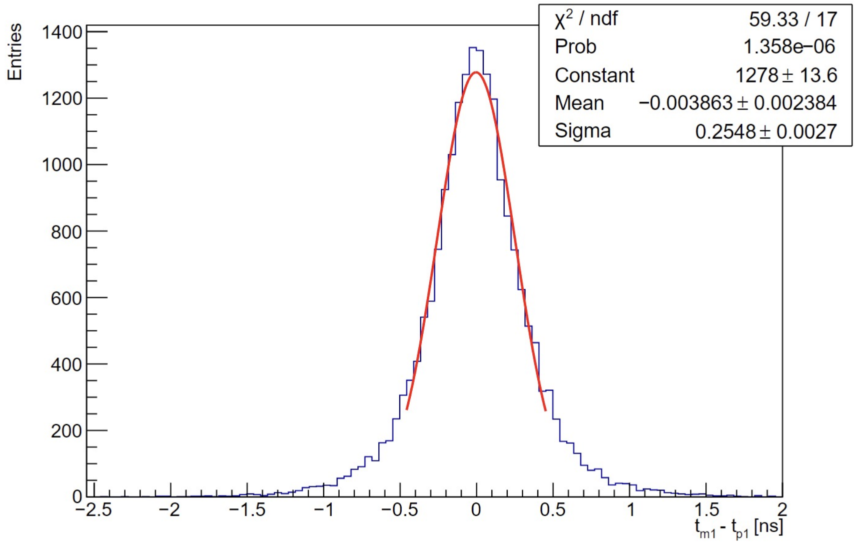
- Constant fraction timing
- Leading edge fitting (best)
- Waveform fitting



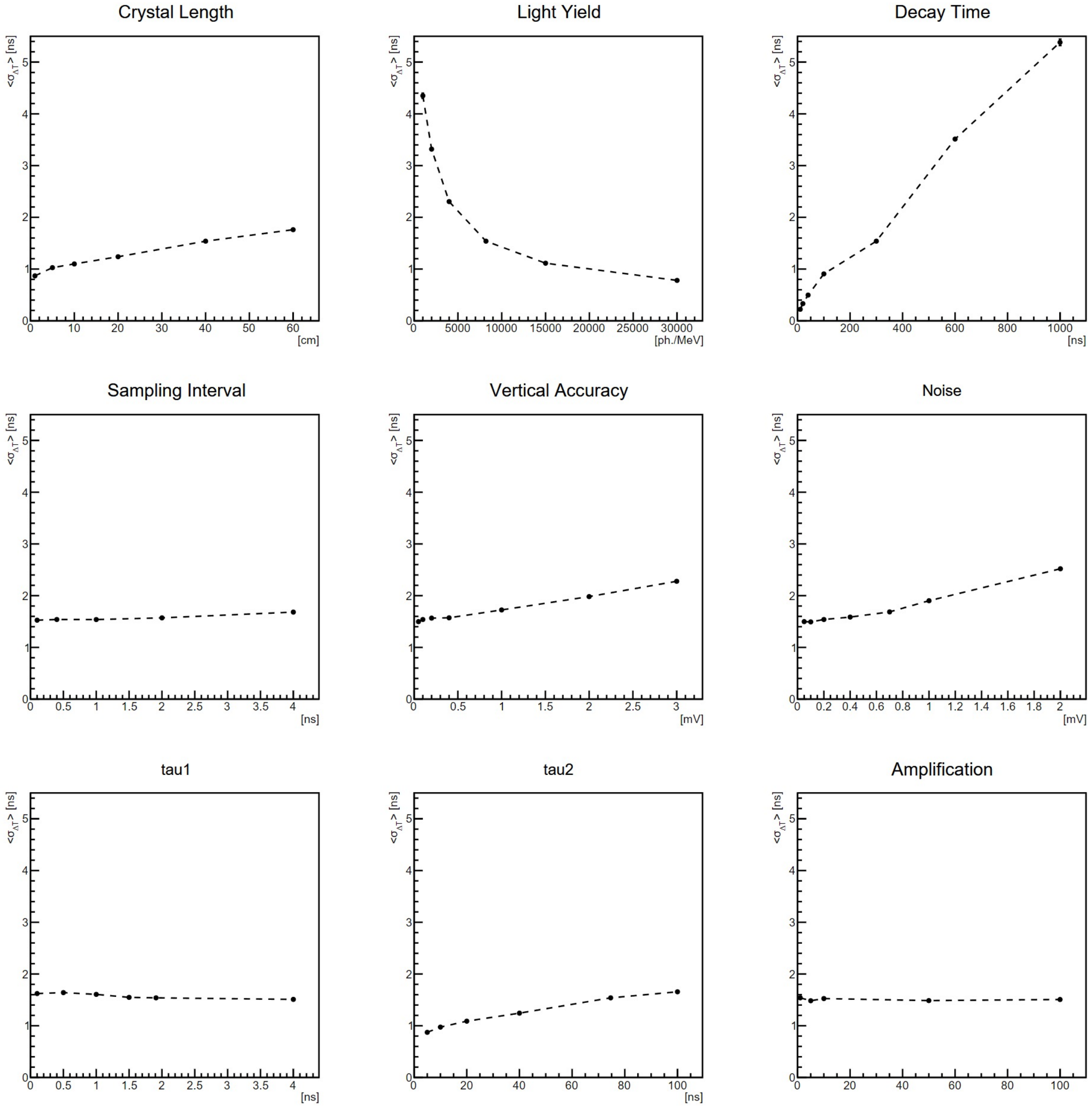
- Fixed threshold timing



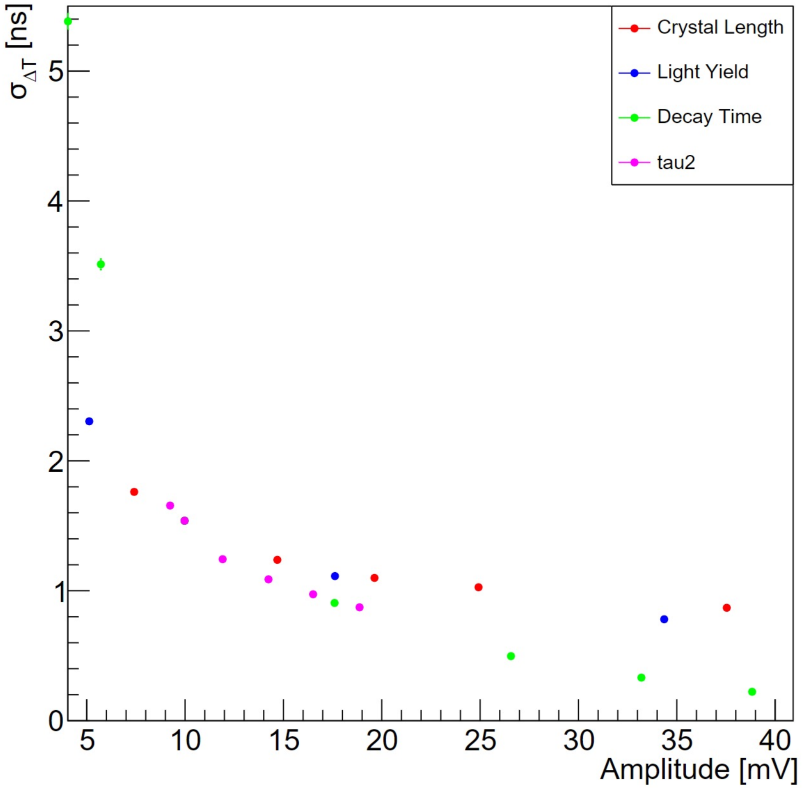
- Timing with the first detected photons at both ends in G4 optical simulation



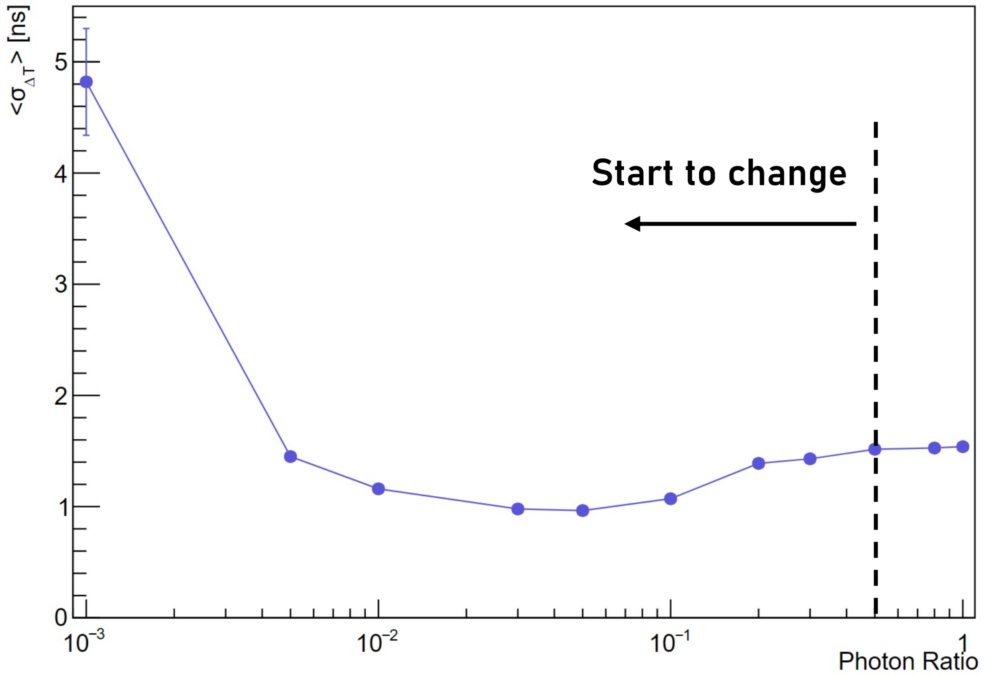
Factors Affecting Time Resolution

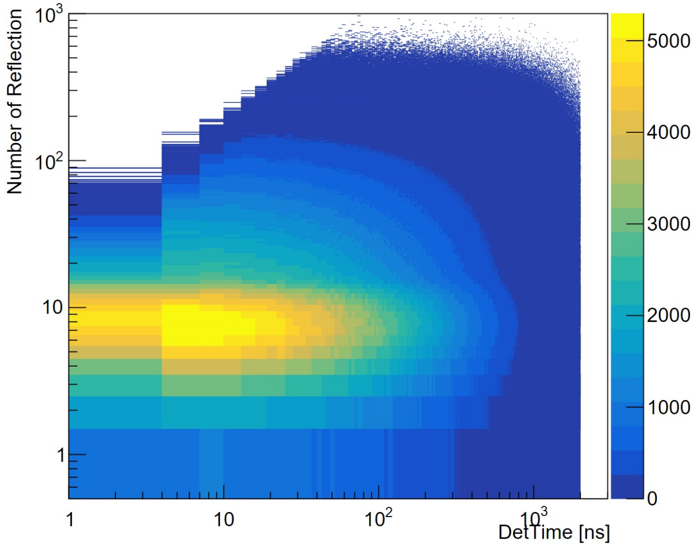


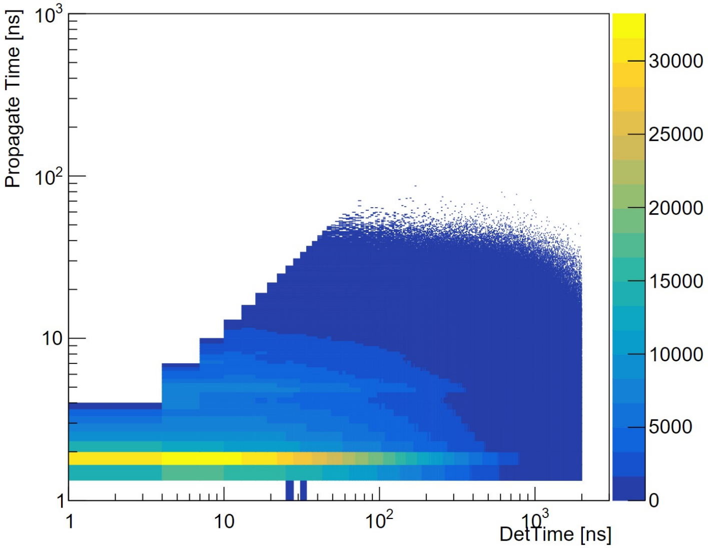
- Basic setup:
  - 40cmBGO, 60/300ns decay time, 8200 ph./MeV
  - 1.25 GS/s, 0.1mV vertical accuracy, 0.2mV noise
  - τ_1: 1.91ns, τ_2: 74.64ns, amplification: x1
  - 5GeV mu-

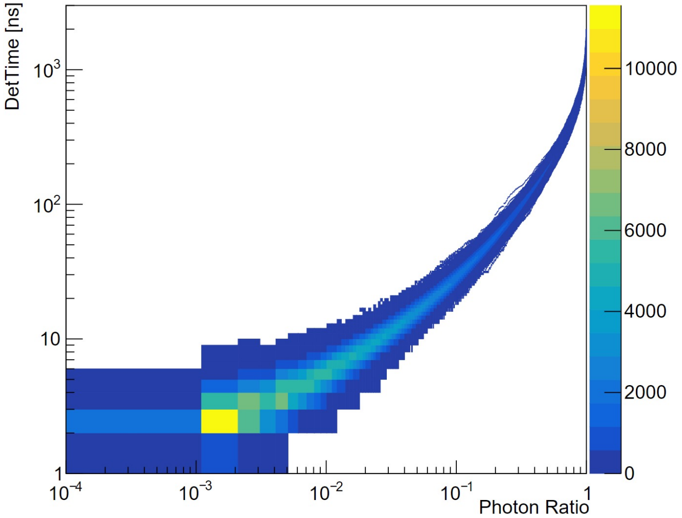


Photon fraction





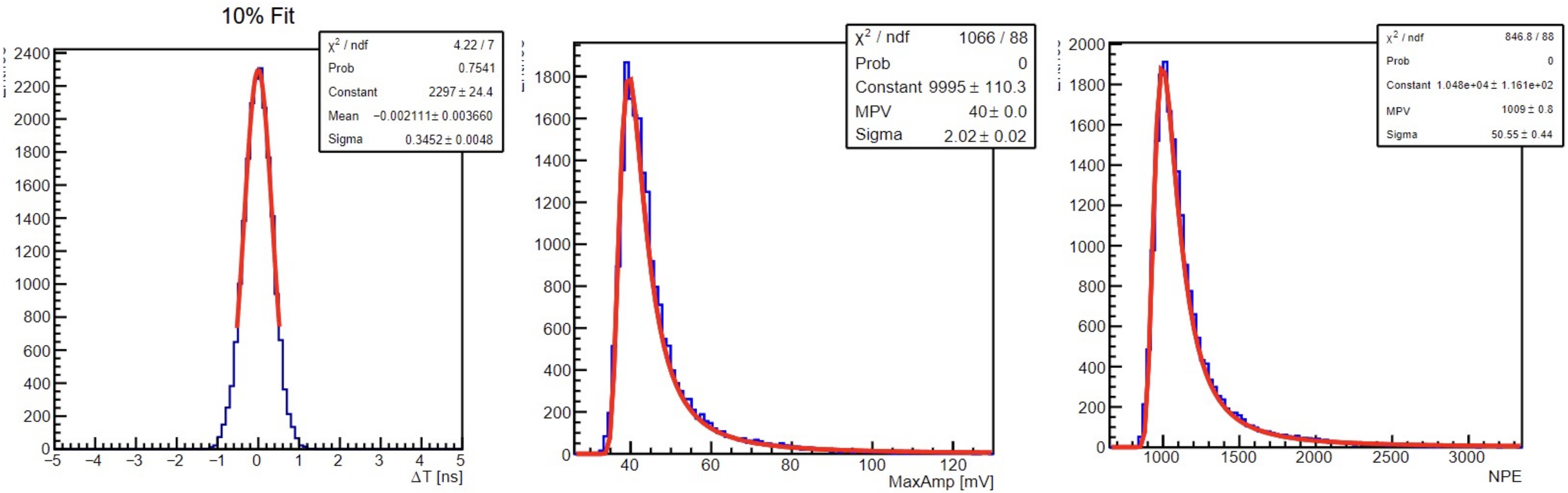




- Photon ratio: proportion of photons detected first, which were used to generate waveform
- Only the first 50% of photons contribute to the time resolution
  - <200ns, which falls within the waveform rise time
  - 8~9 reflections

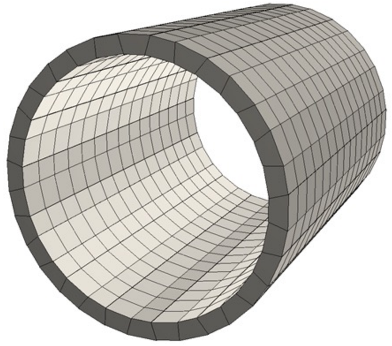
LYSO long bar: timing resolution

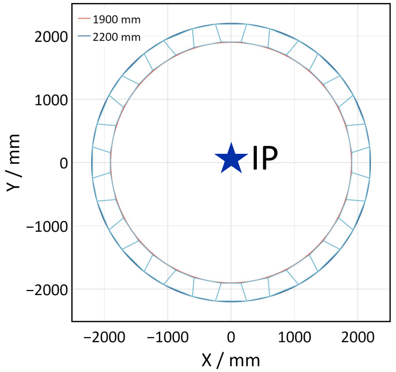
- Setup:
  - 40cmLYSO, 40ns decay time, 30000 ph./MeV
  - 1.25 GS/s, 0.1mV vertical accuracy, 0.2mV noise
  - τ_1: 1.91ns, τ_2: 74.64ns, amplification: x1
  - 5GeV mu-



1.Geometry design of ECAL barrel
2.Geometry and material description of ECAL barrel

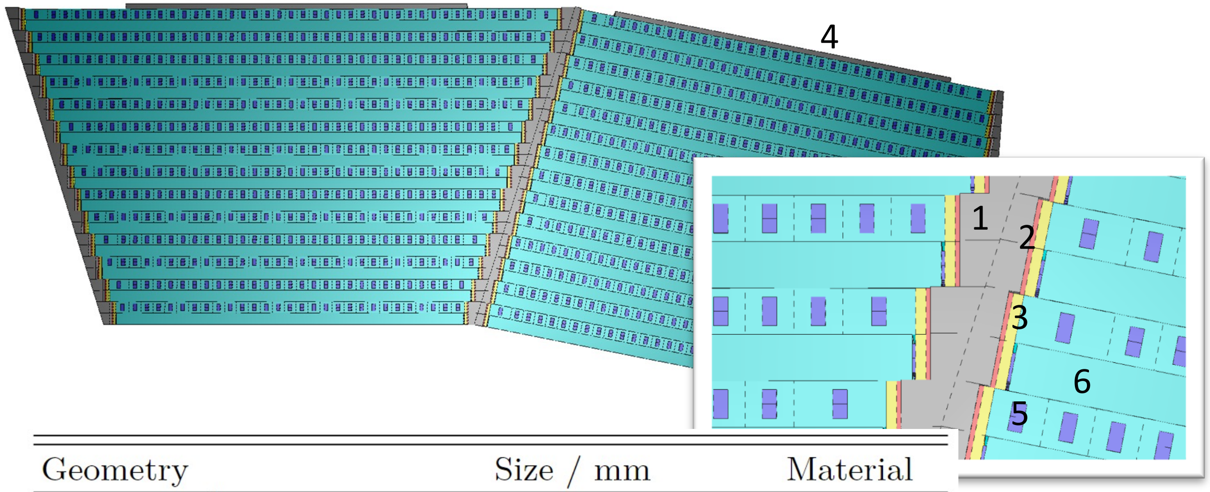
- Design of 32-side crystal ECAL geometry.
  - Invert trapezoid module with minimized crack angle: reduce energy leakage.
  - Correspondence of layers between adjacent modules: clear shower structure.
- A realistic crystal ECAL geometry has been implemented with DD4HEP and released at CEPCSW MR !9.
- Summary of all crystal ECAL parameters.
- Fine geometry and material description.





Parameter	Value / mm
Inner radius	1900
Outer radius	2200
Length	5900
Crystal length	$\sim$ 400
# Modules in $r-\phi$	32
# Modules in Z	15
ϕ Projectivity tilt	12°
# Layers	28

Parameter / mm	Anti-Trapezoidal	Trapezoidal
Bottom length	314.598	435.106
Top length	492.657	369.809
Module height	280.232	292.216
Layer height	9.651	10.079
Crystal height	9.451	9.879
Radiation length	23.628 X_0	24.698 X_0



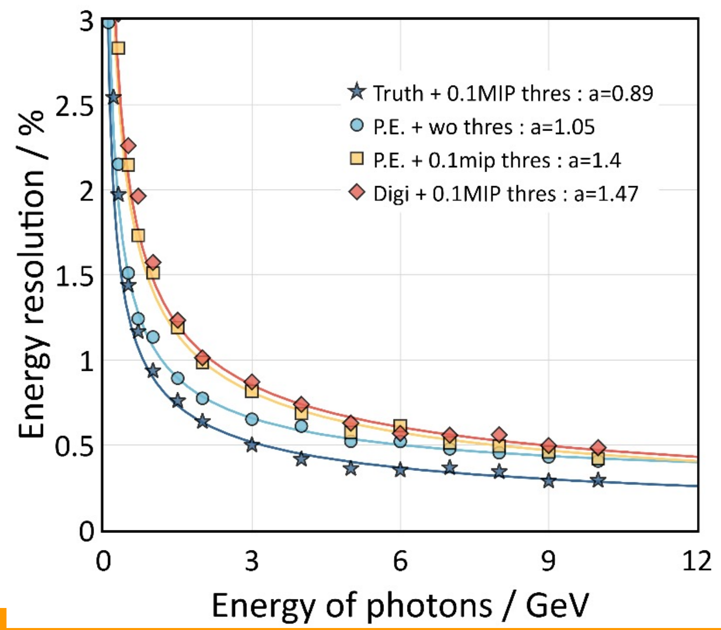
Geometry	Size / mm	Material
Supporting[1]	5	carbon fiber
Cooling[2]	1	copper
Electronics front end[3]	1.2+1	PCB+ASIC
Electronic back board[4]	10	PCB
Electro-optical device[5]	3*3*0.8	SiPM
Wrapping[6]	0.1	ESR
Crystal[6]	~10*10*400	BGO

Digitization and single photons energy resolution

- Digitization: energy deposition → digits in ADC, considering crystal scintillation and electronic design.

Geant4 hits: Energy deposition → Crystal-SiPM: detected photons → SiPM: p.e. conversion to ADC → ASIC: ADC in High Gain or Low Gain → Digits in ADC

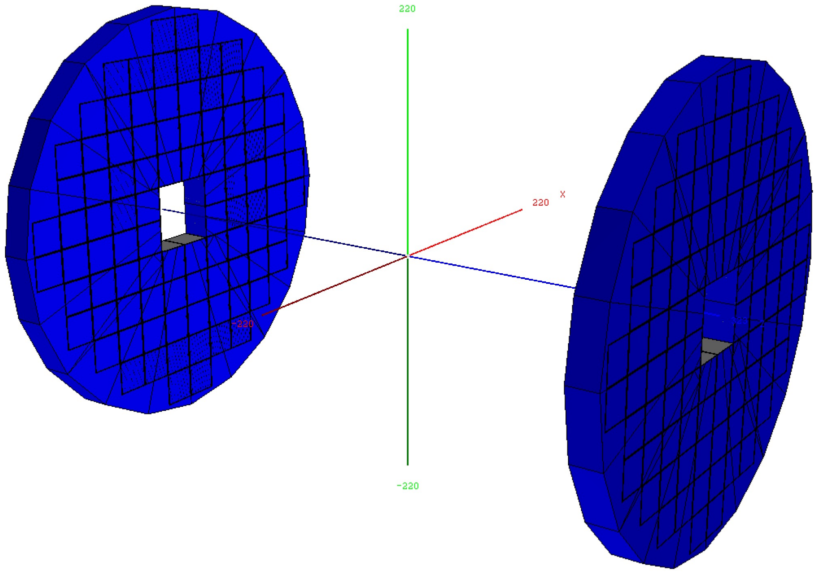
Crystal-SiPM: detected photons	SiPM: p.e. conversion to ADC	ASIC: ADC in High Gain or Low Gain
Poisson Distribution based on muon data of long crystal bar	SiPM gain calibration from LED data	HG-LG conversion

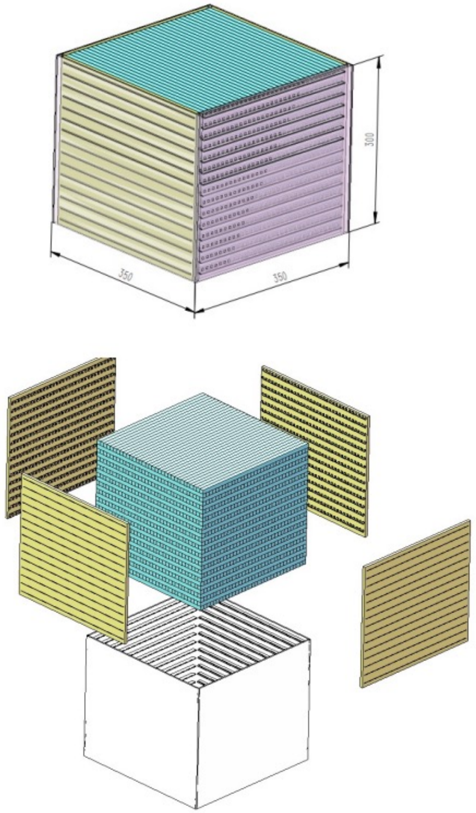


Geometry of ECAL endcap

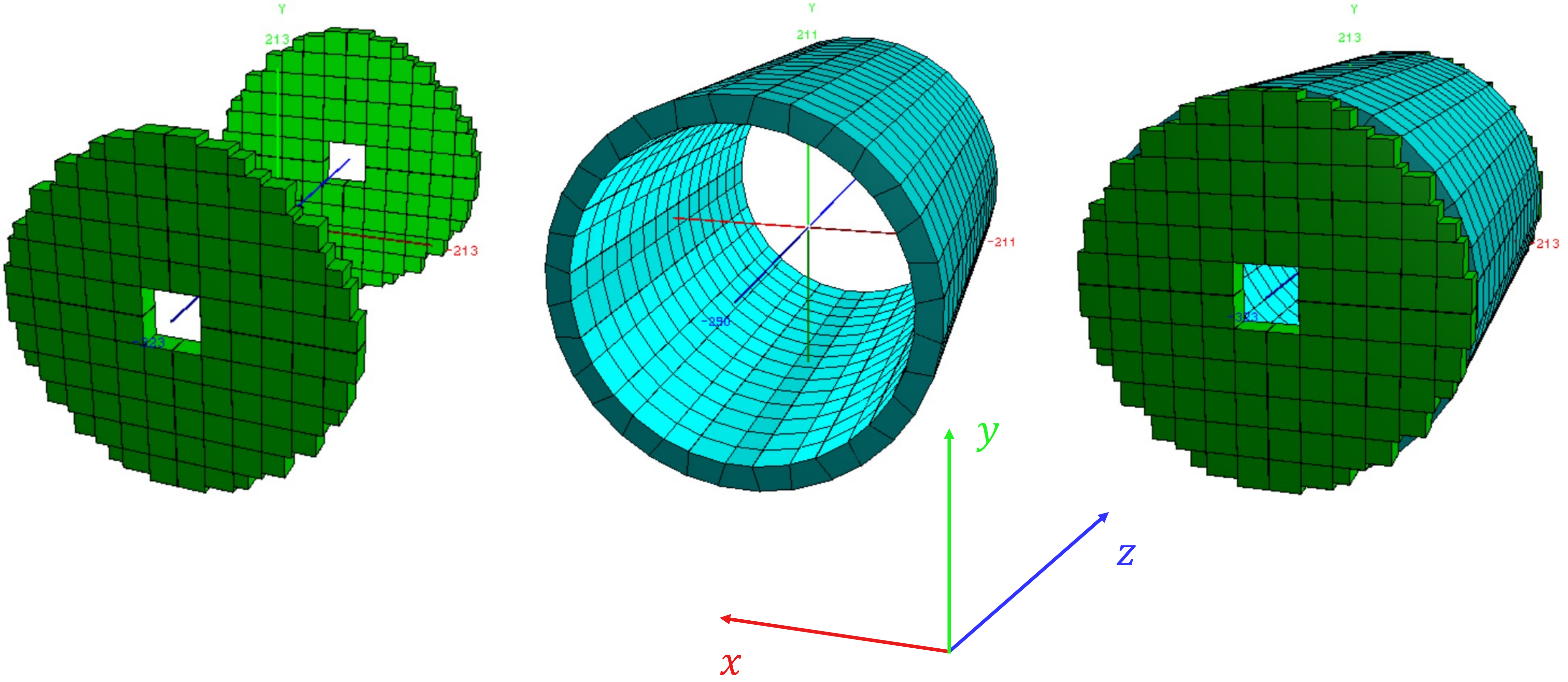
- 1^{st} version (very preliminary).
- Consist of several same modules, right plot shows single module.
- Dead material (carbon fiber, electronics and so on) is similar w
barrel

Parameter	Value
Inner radius	350 mm
Outer radius	2200 mm
Z start	2930 mm
Z depth	300mm (24 X_0 268.8 mm)





Overall Structure



Detailed Design (Barrel)