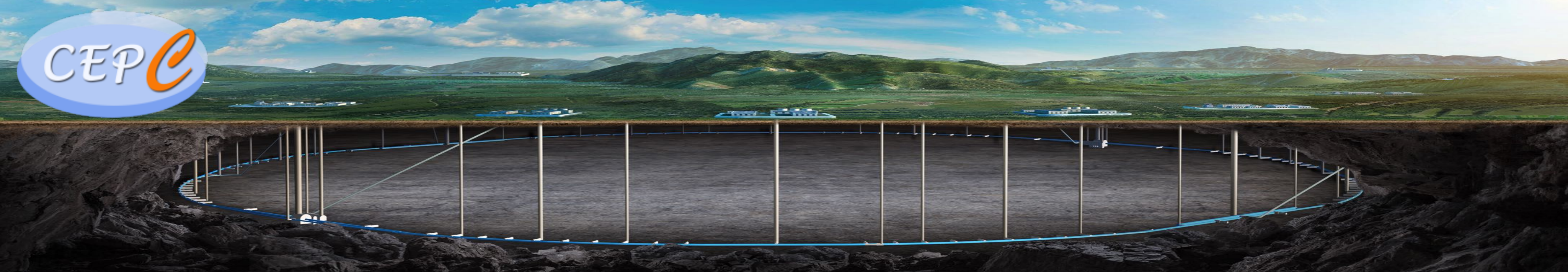

CEPC Electromagnetic Calorimeter

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Chinese Academy of Sciences

Aug. 7th, 2024, CEPC Detector Ref-TDR Review

Content

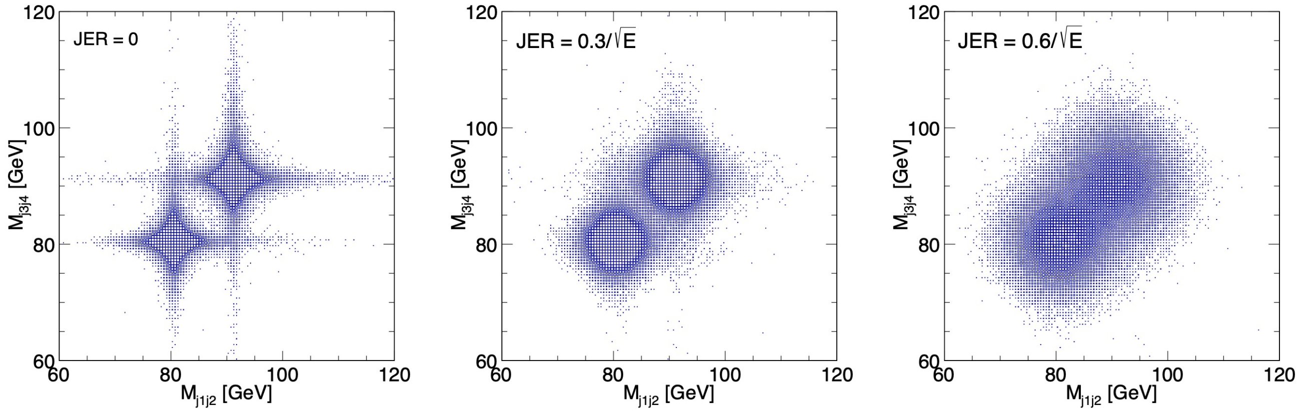
- Introduction
- Requirements
- Technology survey and option selection
- Technical challenges
- R&D efforts and results
- Detailed design including electronics, cooling and mechanics
- Readout electronics
- Performance from simulation
- Research team and working plan
- Summary

Introduction

RefDet TDR Outline

Chapter 6 Electromagnetic calorimeter

Separation of Higgs hadronic decays in jets



(a) (b) (c)

- This talk is about the design and developments of the electromagnetic calorimetry system (related to the RefDet TDR Chapter 06)
- General remarks: the calorimetry system (in the CEPC reference detector) will based on the particle-flow paradigm → high granularity in 3D
  - Aim to achieve an unprecedented Boson Mass Resolution (BMR) of 3 – 4%

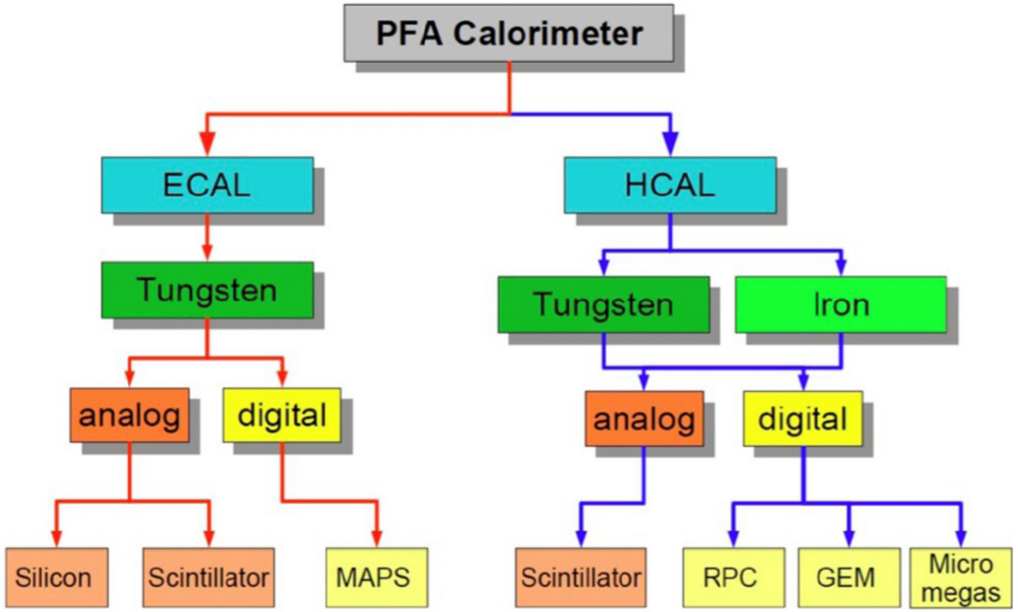
ECAL requirements

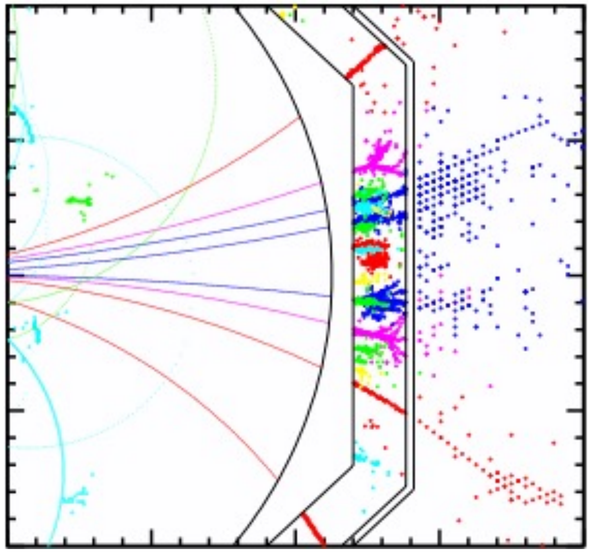
Parameter	Conservative	Ambitious	Remarks
EM energy resolution	$\frac{\sigma_E}{E} = 15\%/\sqrt{E(GeV)} \oplus 1\%$	$\sigma_E/E = 3\%/\sqrt{E(GeV)} \oplus 1\%$	Jet performance; flavor physics
Longitudinal Granularity and Depth	26 – 30 layers, total depth of $24X_0$		Full containment of EM showers
Transverse Granularity	$10\times10\ mm^2$		$H \to gg$ (gluon jets); $Z \to \tau\tau$
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!)

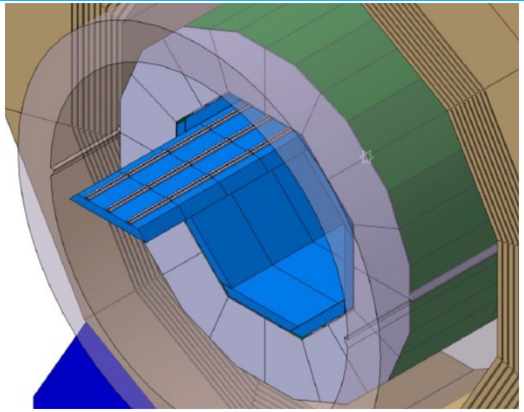
Highly granular (imaging) calorimetry
+ particle flow algorithm (PFA)



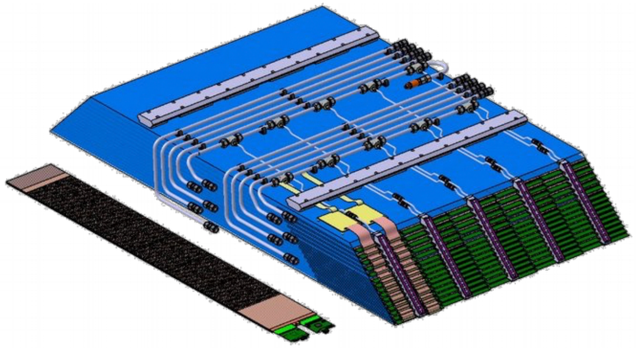


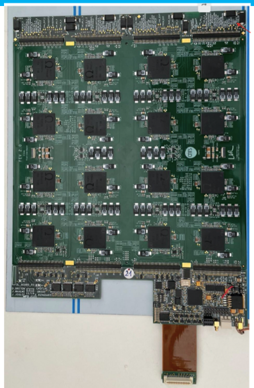
PFA calorimetry: various options explored in the CALICE collaboration in past 20 years

SiW-ECAL option

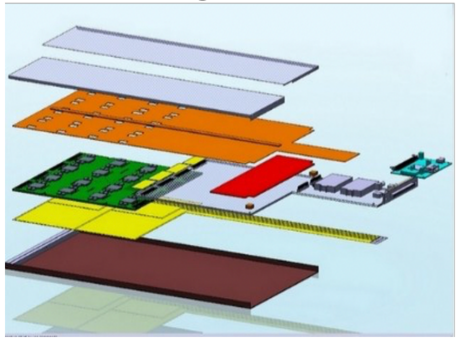


Silicon sensors+ CuW

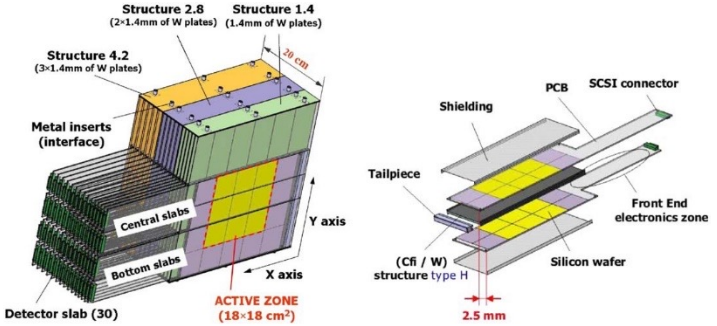


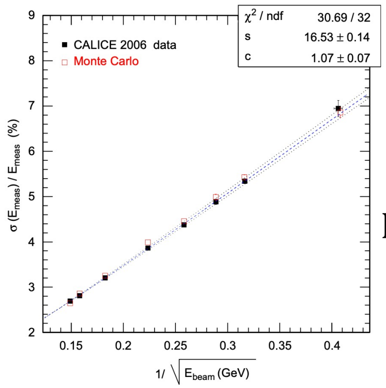


Stacking structure



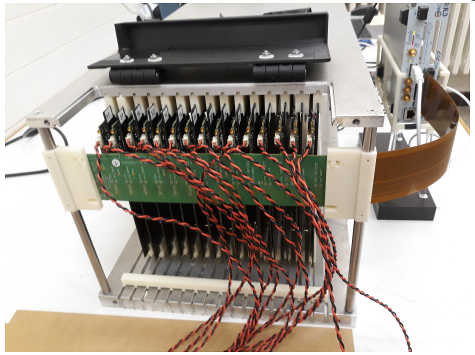
CALICE SiW-ECAL Physics Prototype





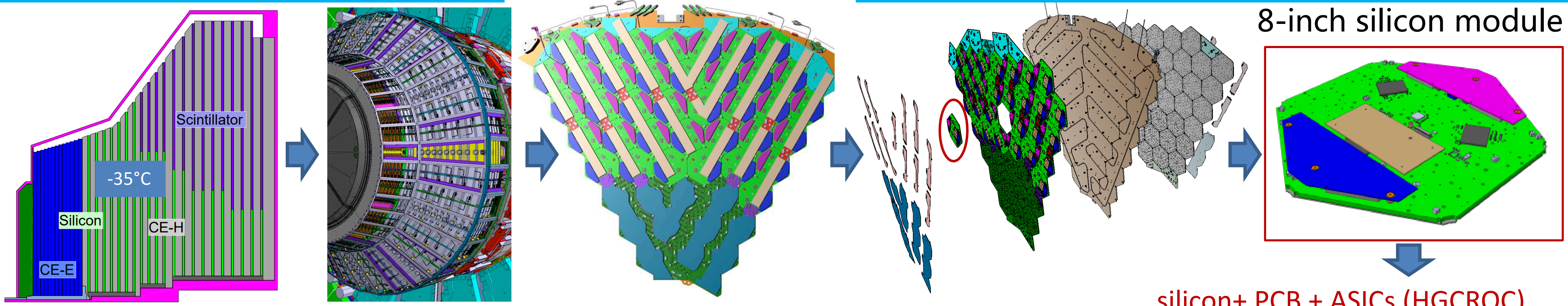
EM resolution in beamtest:
$16.5\%/\sqrt{E(GeV)} \oplus 1\%$

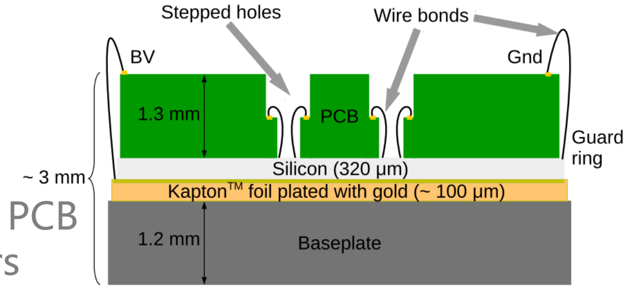
CALICE SiW-ECAL Technological Prototypes



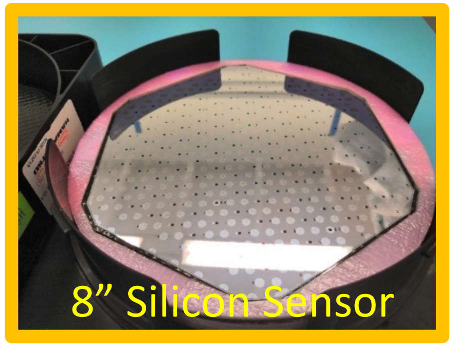
- Large area silicon sensors (pixelated) interleaved with CuW plate (compact showers)
- Baseline option in CEPC CDR: extensive Higgs physics studies
- Hardware activities in CALICE collaboration, no involvements of CEPC-calo groups
  - Application in CMS-HGCAL project (silicon sector): many synergies

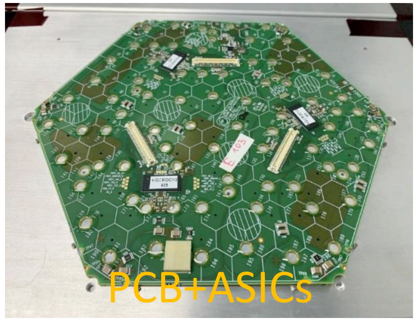
SiW-ECAL option: synergies with HGCAL





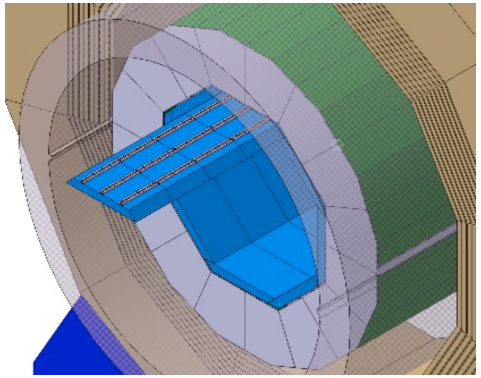
Wire-bonding for PCB and silicon sensors

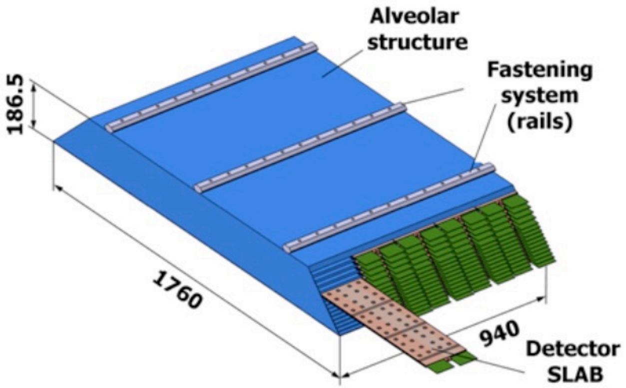


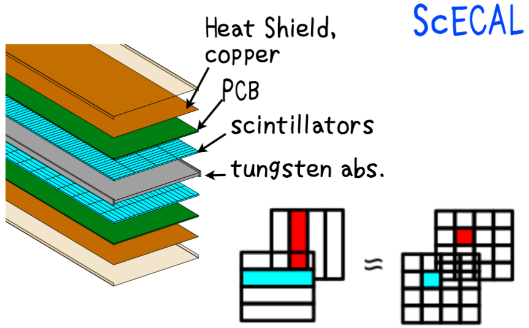


- Established two centers at IHEP for CMS-HGCAL project
  - MAC (Module Assembly Center) Beijing Site, with 6 MACs around the world
  - SQC (Sensor Quality Center) Beijing Site, with 5 SQCs around the world

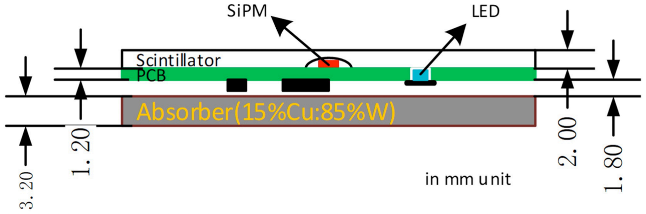
ScW-ECAL option

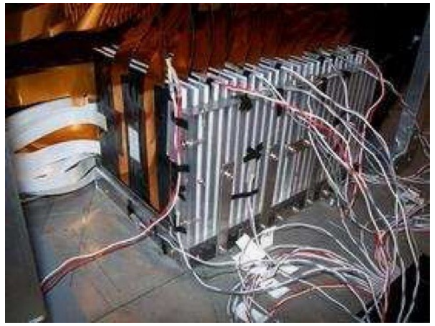


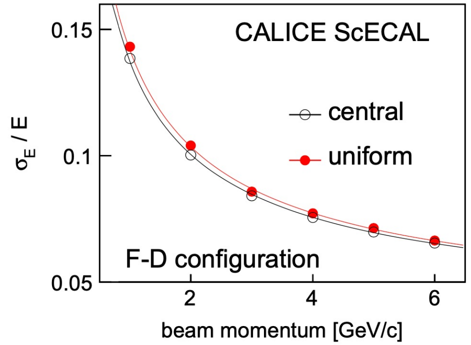


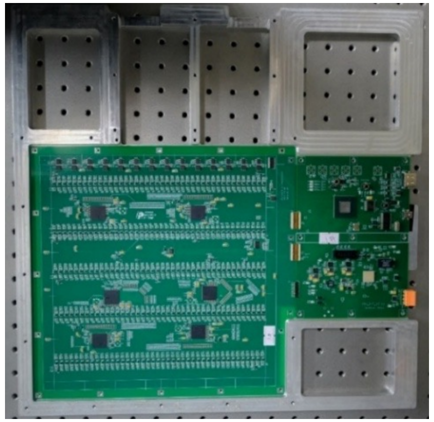


Scintillator-SiPM readout scheme







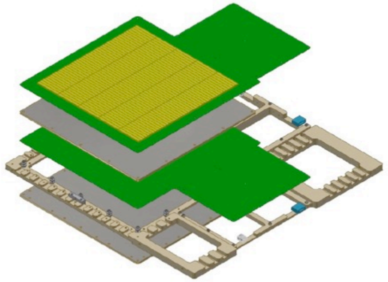


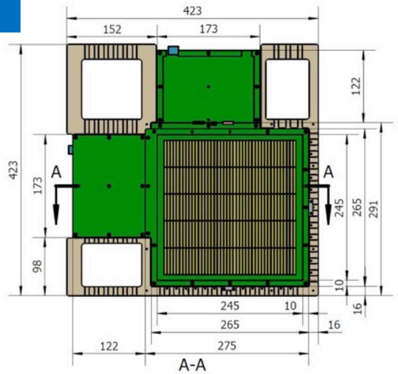
- Scintillator strips + SiPMs, interleaved with CuW plate (compact showers)
- Alternative option in CEPC CDR
- Strong involvements of Chinese and Japanese groups in CALICE collaboration
  - Development of a technological prototype, followed by successful beamtests at CERN

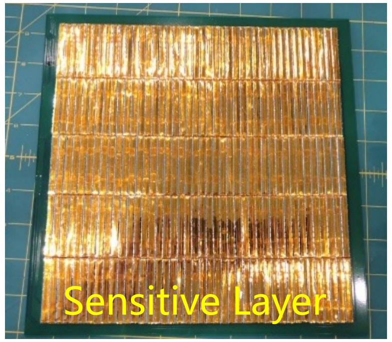
ScW-ECAL option

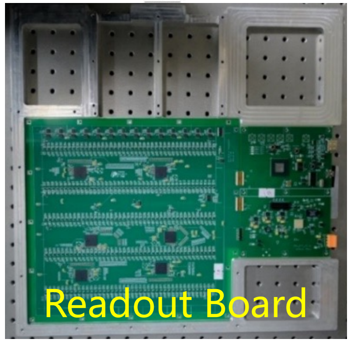
ScW-ECAL tech. prototype

"Super-layer" design



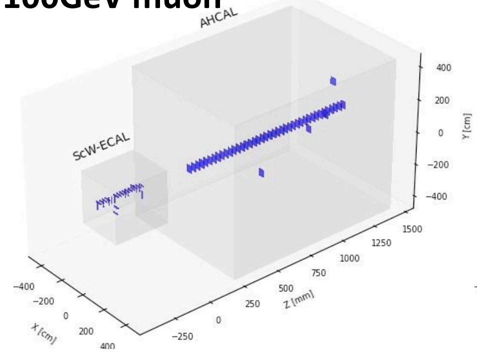




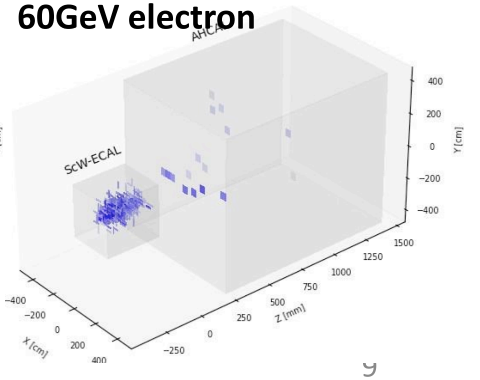


- ScW-ECAL tech. prototype developed in 2016-2020
  - (Effective) Transverse granularity of $5{\times}5\ \mathrm{mm}^2$
  - 6,720 channels, 32 longitudinal sampling layers (22X0)
  - Successful beamtest campaigns at CERN in 2022-2023
    - Collected data sets with various beam particles

100GeV muon

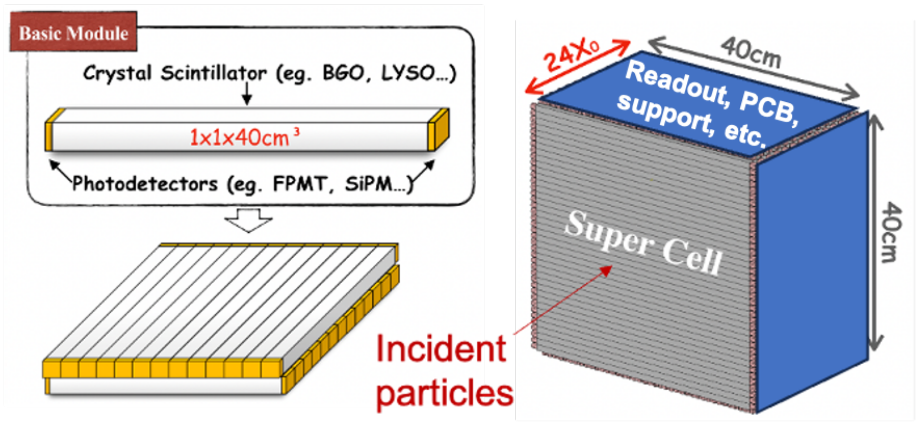


60GeV electron



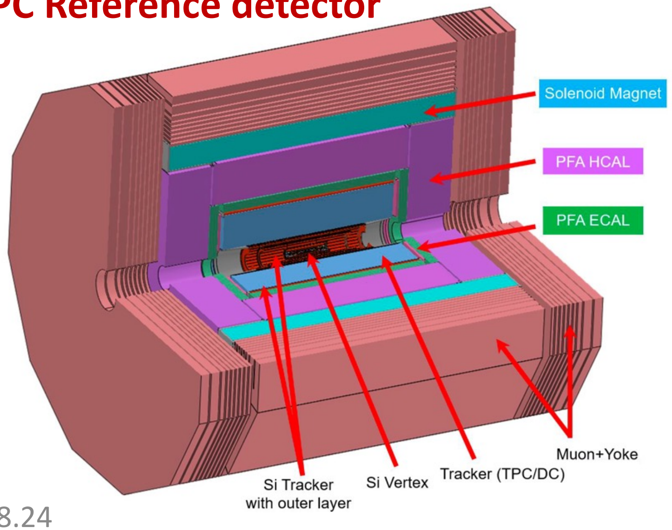
4D Crystal ECAL option

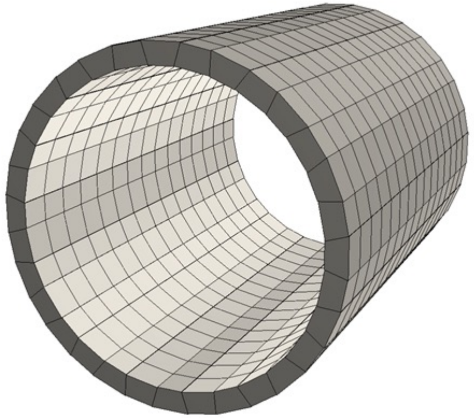
- A new option: development started since ~2020
- Compatible for PFA, Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E = 3\%/\sqrt{E}$
- Minimal longitudinal dead material: orthogonal arranged bars
  - 3D positioning with two-sided readout for timing



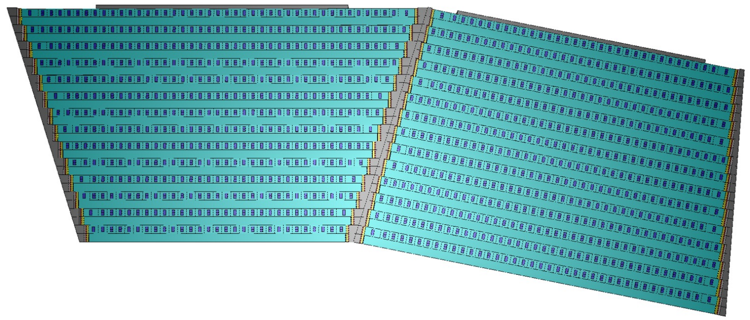
- **BGO bars in $1{\times}1{\times}{\sim}40\ cm^3$**
- **Effective granularity $1{\times}1{\times}2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**

CEPC Reference detector





32-side polygon, depth 24 X_0
28 longitudinal layers



Technical options: comparison and option selection

Technical Option	Silicon-Tungsten ECAL	Scintillator-Tungsten ECAL	Crystal ECAL
EM energy resolution	$\sigma_E/E = 17\%/\sqrt{E(GeV)}$	$\sigma_E/E = 13\%/\sqrt{E(GeV)}$	$\sigma_E/E = 3\%/\sqrt{E(GeV)}$
Particle-Flow Algorithm(s)	Arbor; Pandora	Arbor; Pandora	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

Selected as a baseline option for the CEPC reference detector

Option selection

- *Crystal ECAL*, as a novel option, shows significantly better EM performance

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)
  - SiPMs, crystals due to irradiation (instantaneous, long-term) and 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	Balance between S/N and dynamic range
Crystal non-uniformity	< 1%	Along the crystal length and between crystals
Dynamic range	0.1~3000 MIPs / channel	Maximum energy deposition with 360 GeV Bhabha
Timing resolution	~500 ps @ 1 MIP	Bunch crossing ID; clustering and hadron performance
Temperature stability	Stable at 0.05℃	Reference from CMS ECAL; validation with beamtest

Detector requirements

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

→

Hardware activities: addressing crucial issues

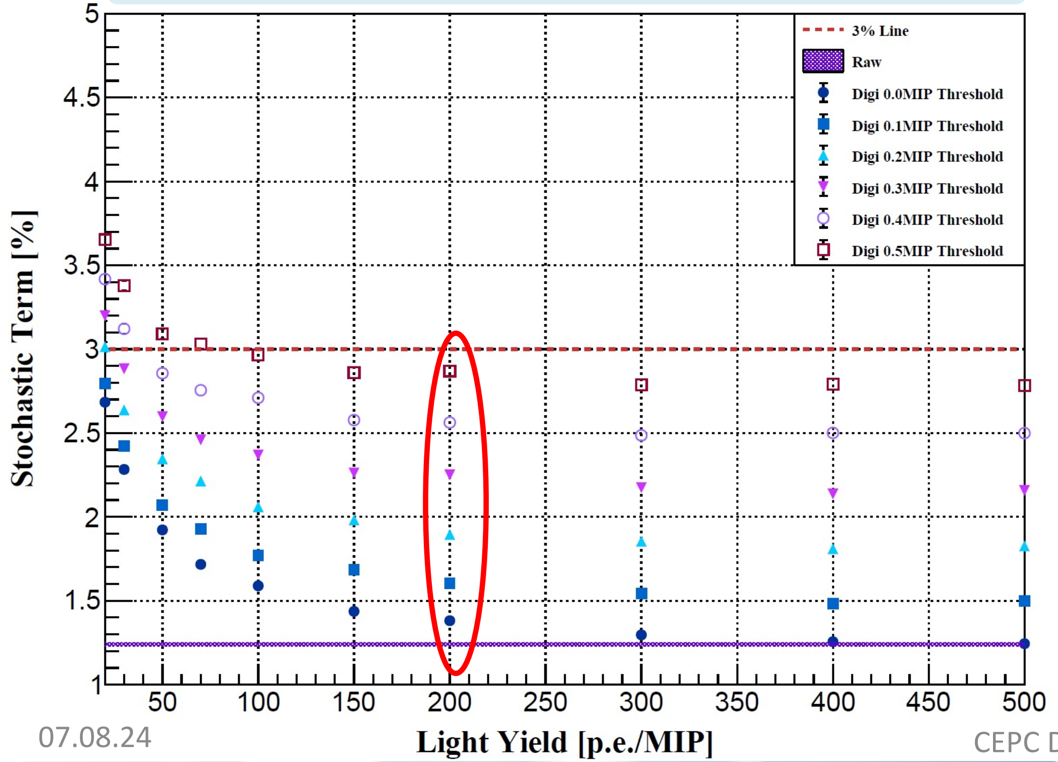
- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal dimensions
- Dynamic range of electronics
- Energy response of crystal module

R&D efforts and results: MIP response, uniformity

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

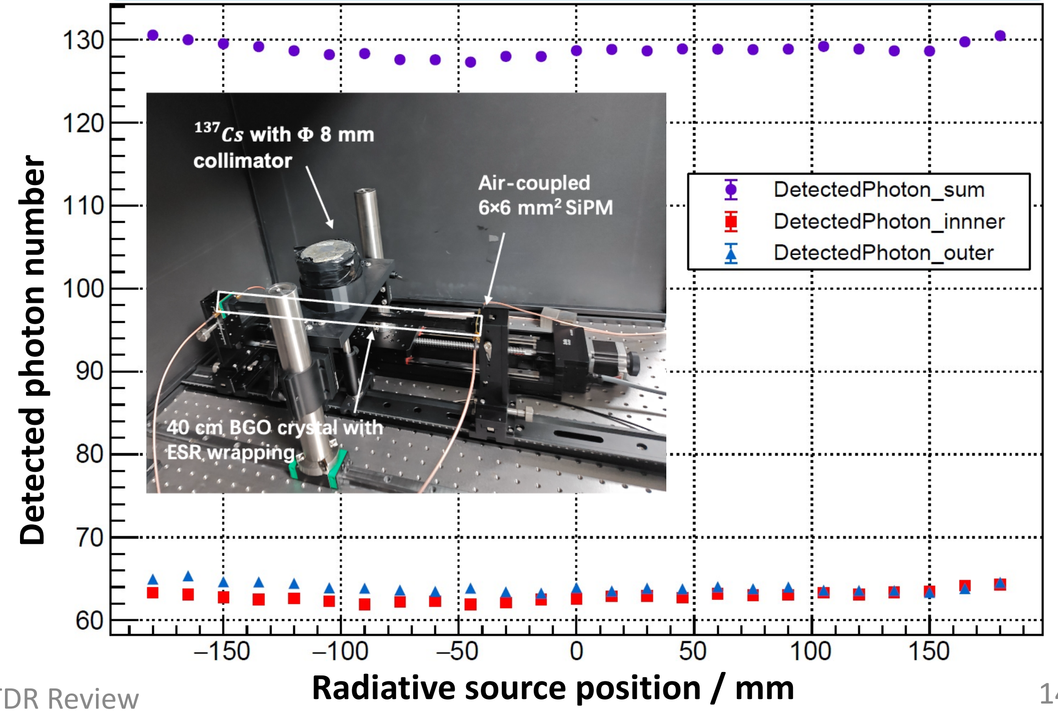
MIP response: >200 p.e./MIP → $\sigma_E/E = 3\%/\sqrt{E}$
Energy threshold: 0.1 MIP

Light yield v.s. energy resolution



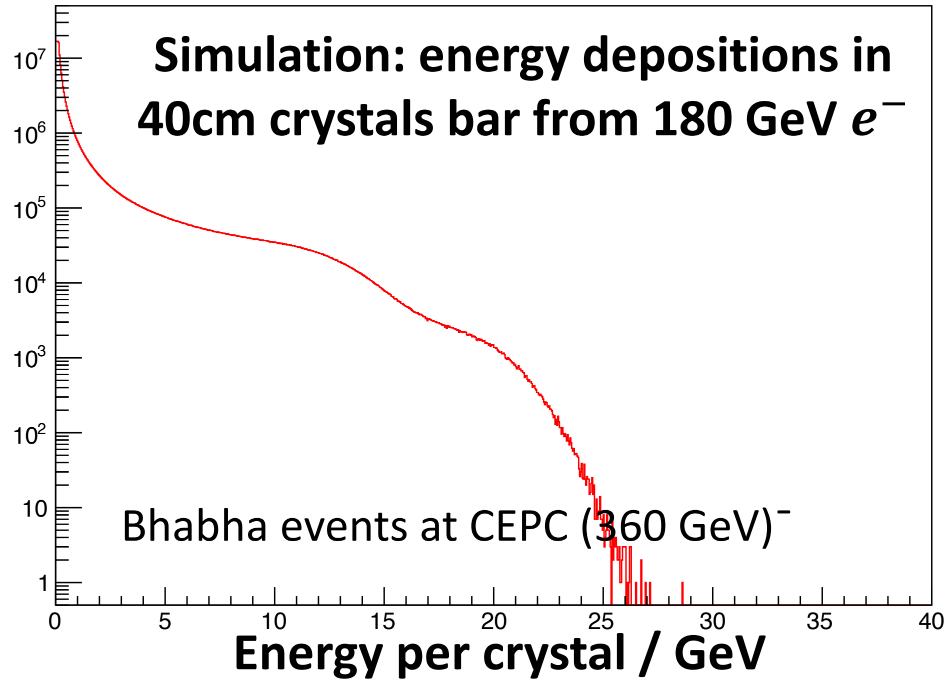
Uniformity along one 40 cm crystal bar: ~2.5%
- Can be further improved after calibration

Response uniformity along bar



R&D efforts and results: dynamic range

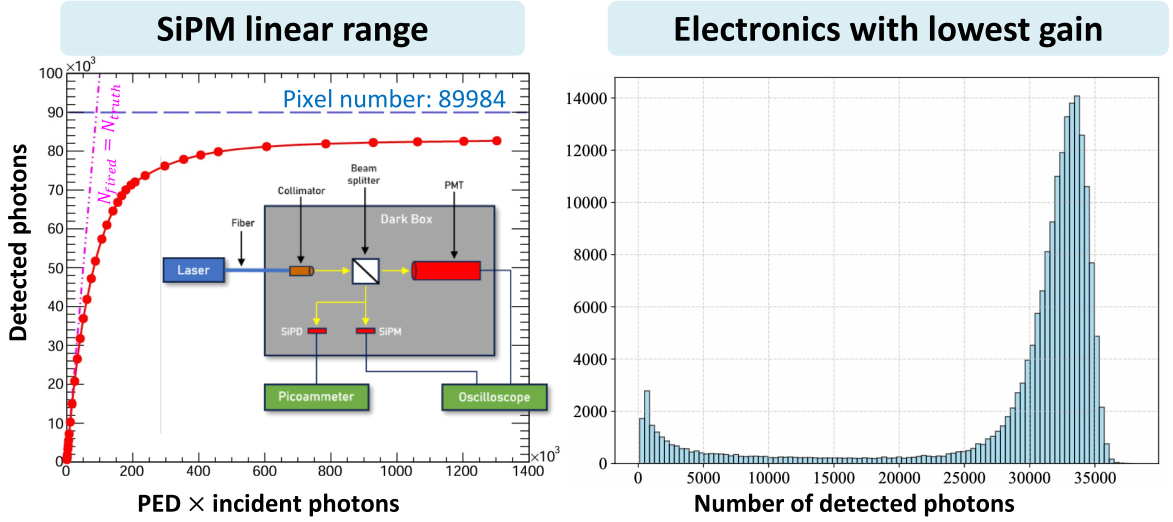
- Simulation of high energy electrons: maximum energy per crystal
- Test-stand with pico-second laser: SiPM non-linearity effects (with various pixel pitches)
- Beamtest of crystal-SiPM units with a state-of-art chip: dynamic range of both SiPM and ASIC



~30 GeV as max. energy deposition per crystal bar

Laser system for SiPM non-linearity studies

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

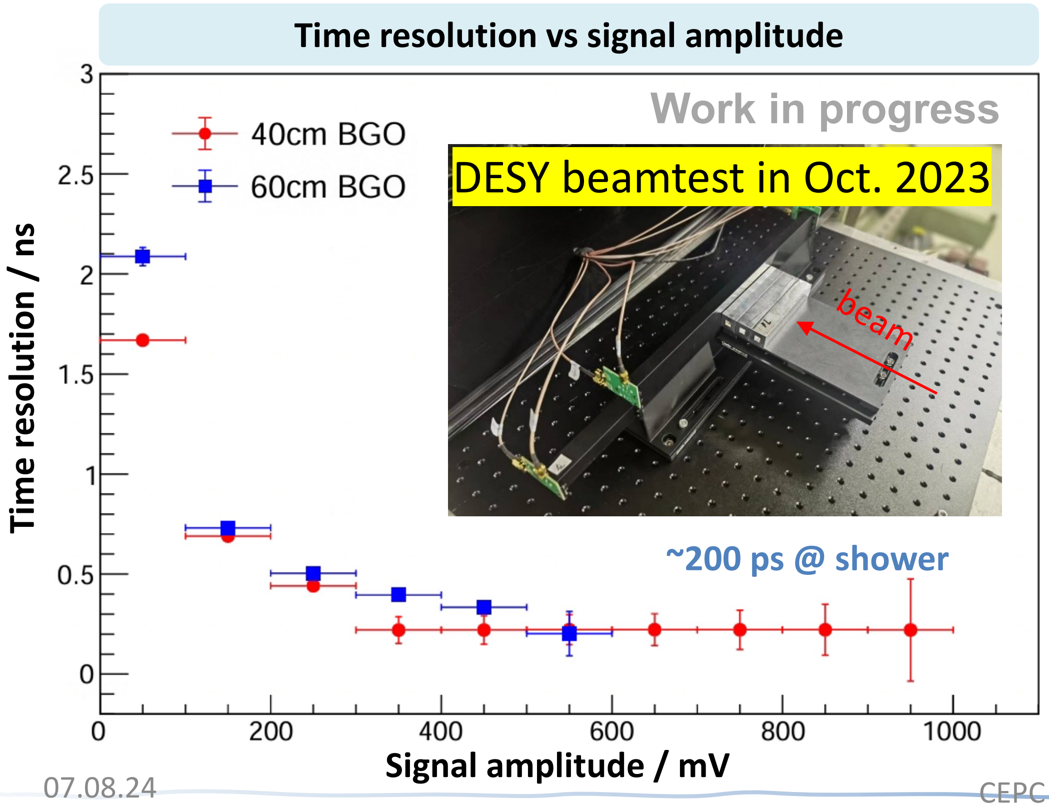


2023 DESY beamtest: crystal-SiPM units and a state-of-art front-end chip with EM showers induced by 5 GeV electrons

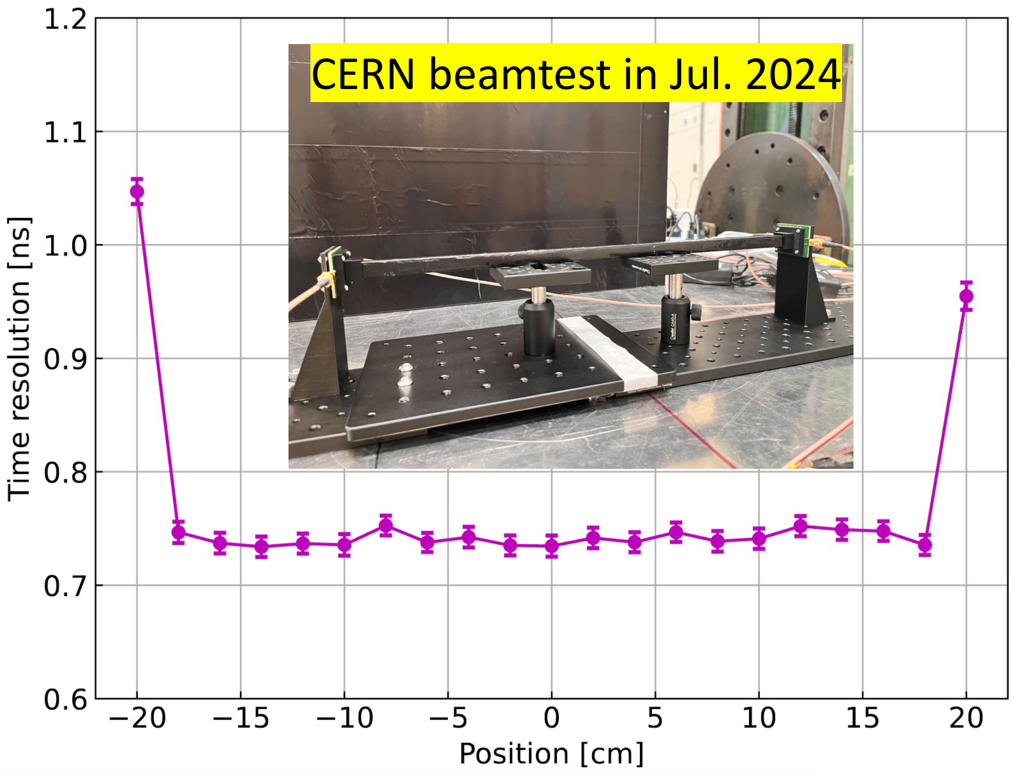
R&D efforts and results: timing studies

- Dedicated beamtests for timing studies with MIP and EM showers

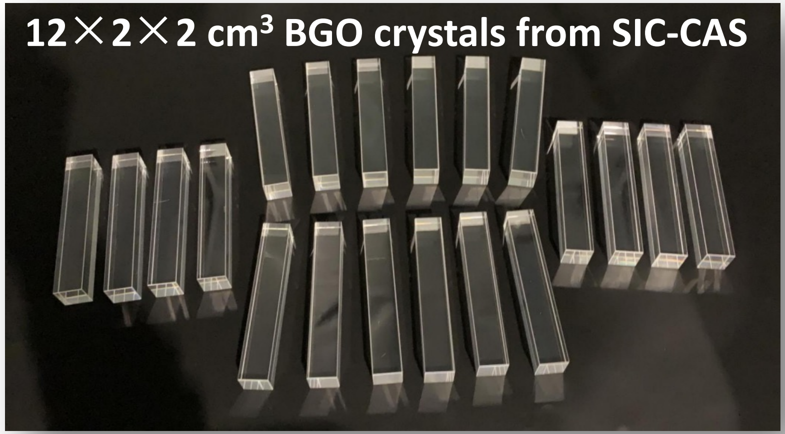
Timing performance within EM showers
- 5GeV e^- beam to test 40cm BGO bar with 25 μm SiPM
- ~200 ps within EM showers (>12 MIPs)

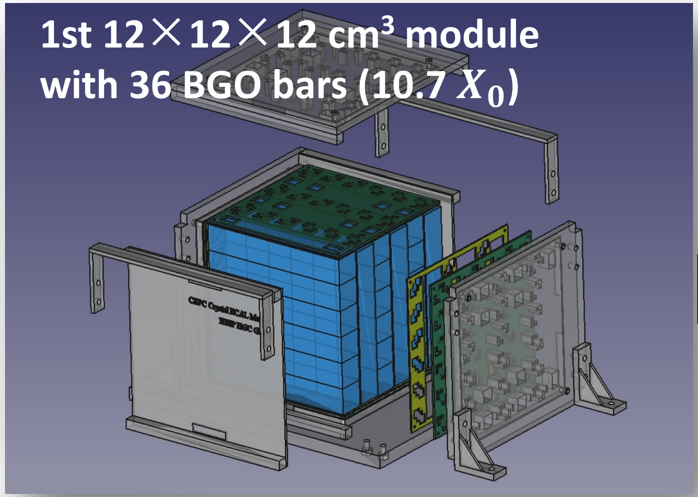


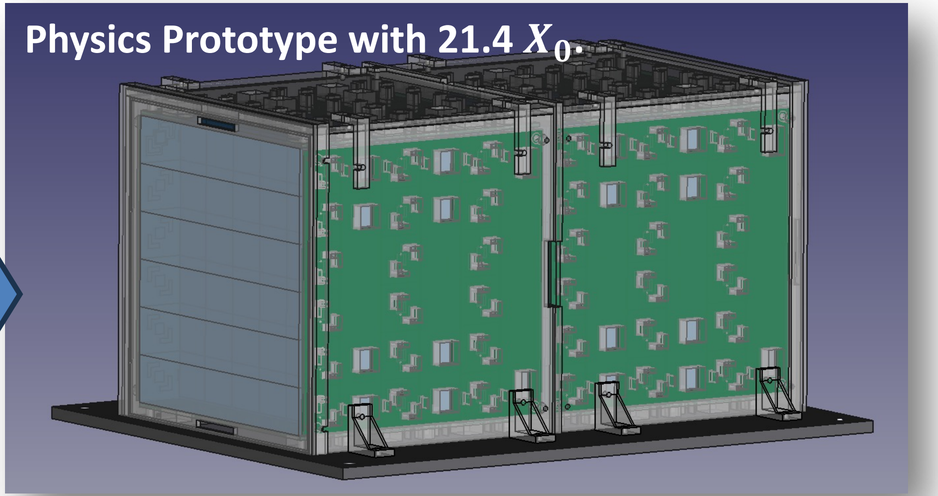
Timing performance with MIP-like particles
- 10 GeV π^- beam to scan one 40cm BGO bar along its length
- 1-MIP timing resolution: 735 ps for 2 ends → 520 ps single end

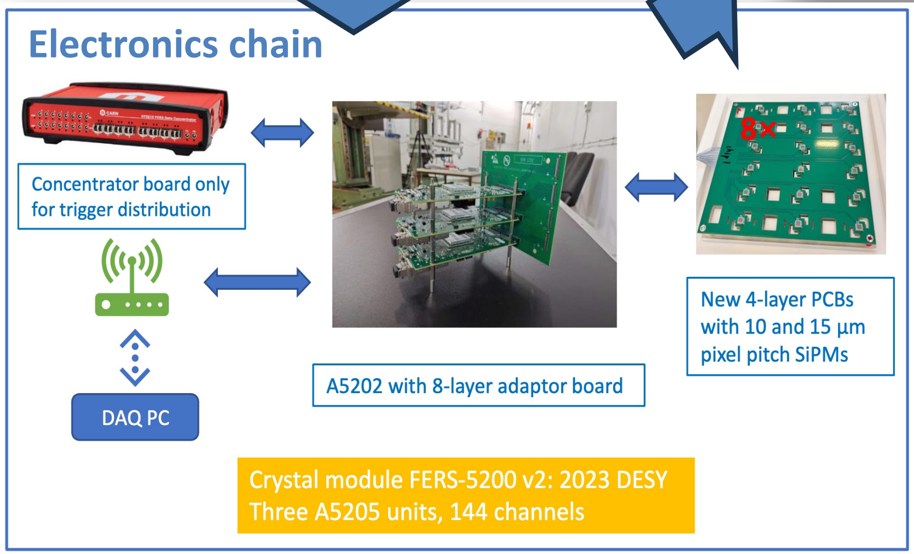


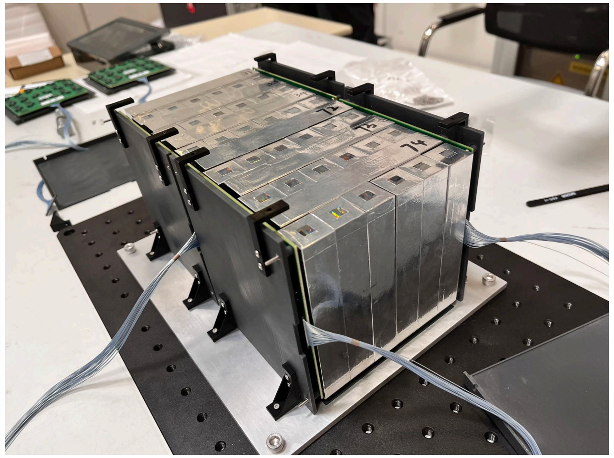
4D Crystal Calorimeter: First Physics Prototype











First crystal calorimeter prototype

- Successfully developed in 2021-23
- With commercial ASICs

Major motivations

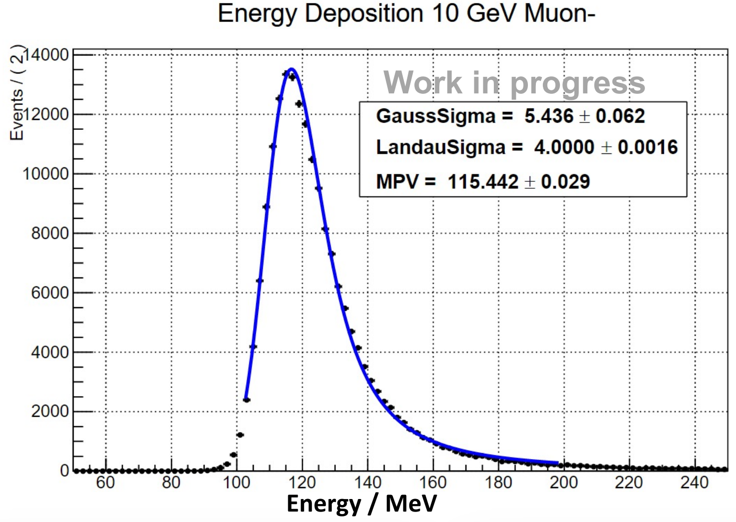
- Critical issues at system integration
- EM performance in system level
- Validation of simulation and digitization with beamtest data

Custom-made readout boards (144-ch), equipped with 6 ASICs (CITIROC-1A) → Custom-made ASIC in planning

Beam tests: 4D Crystal Calorimeter Prototype

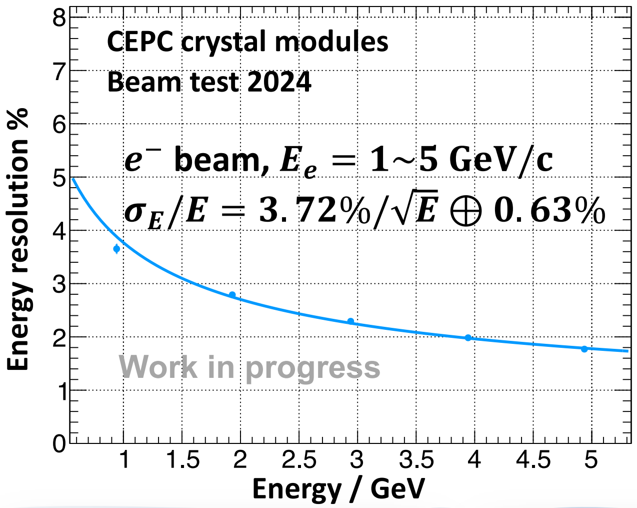
2023 CERN beam test at PS-T9

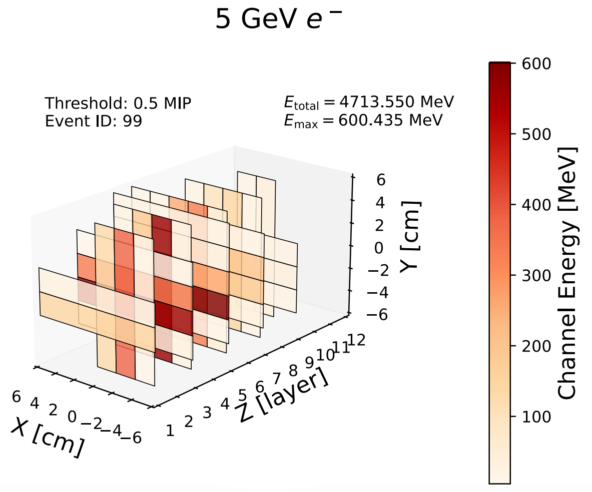
- Successful system commissioning
- Clear MIP signals for all channels

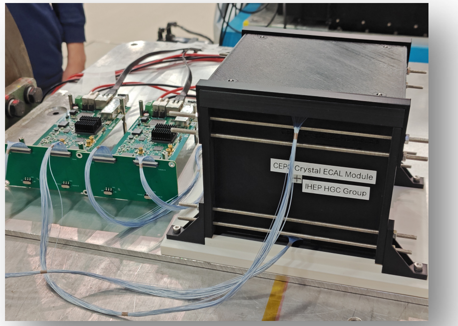


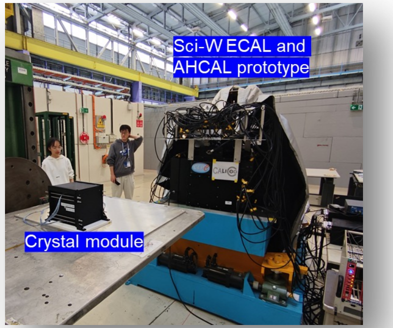
2024 CERN beam test at PS-T9: finished in July 10th

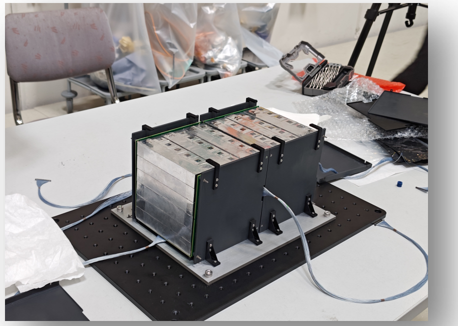
- Promising EM resolution with 1-5 GeV/c e^- beam
- Data analysis is still ongoing: detailed calibrations, shower profiles











Beam tests: 4D Crystal Calorimeter Prototype

2023 CERN beam test at PS-T9

- Successful system commissioning
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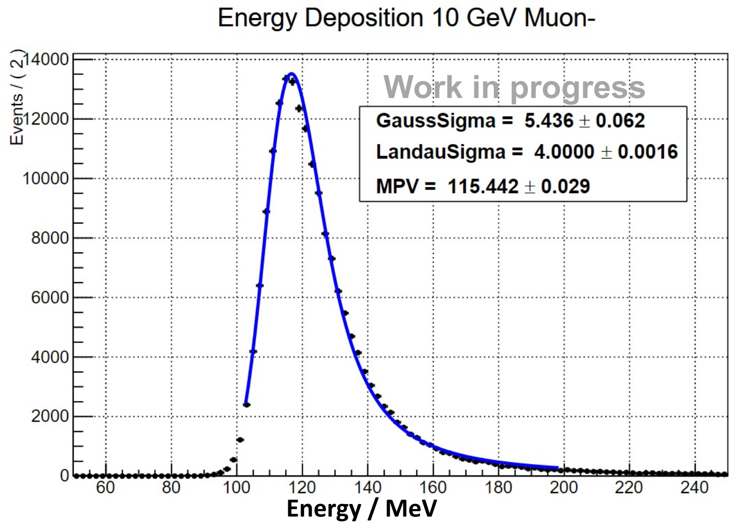

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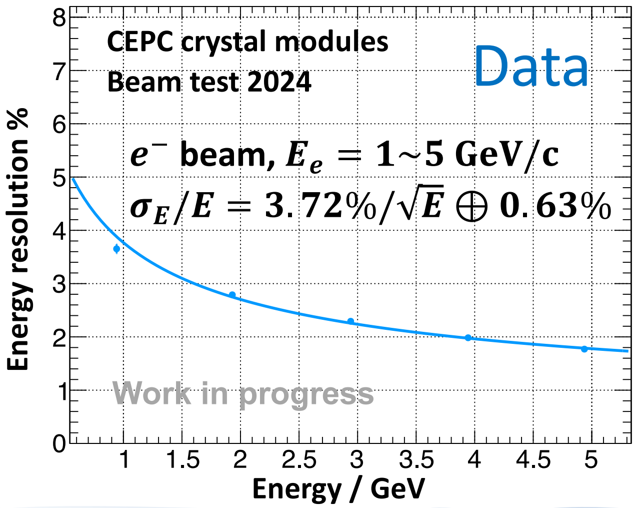
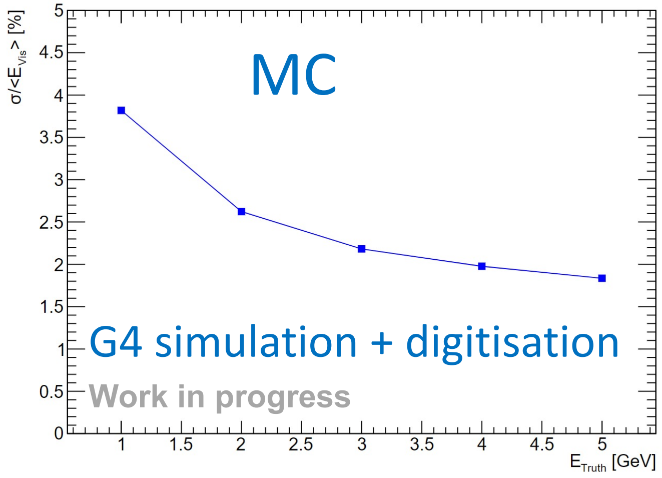
- Data analysis is still ongoing: detailed calibrations, shower profiles

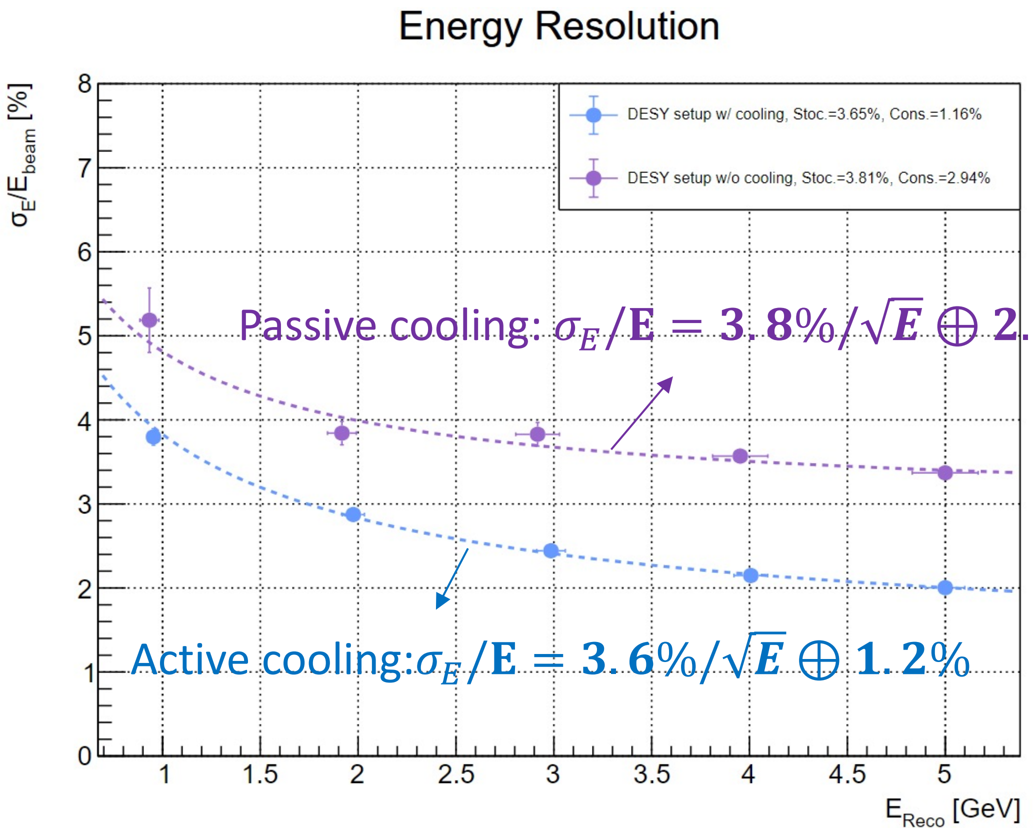


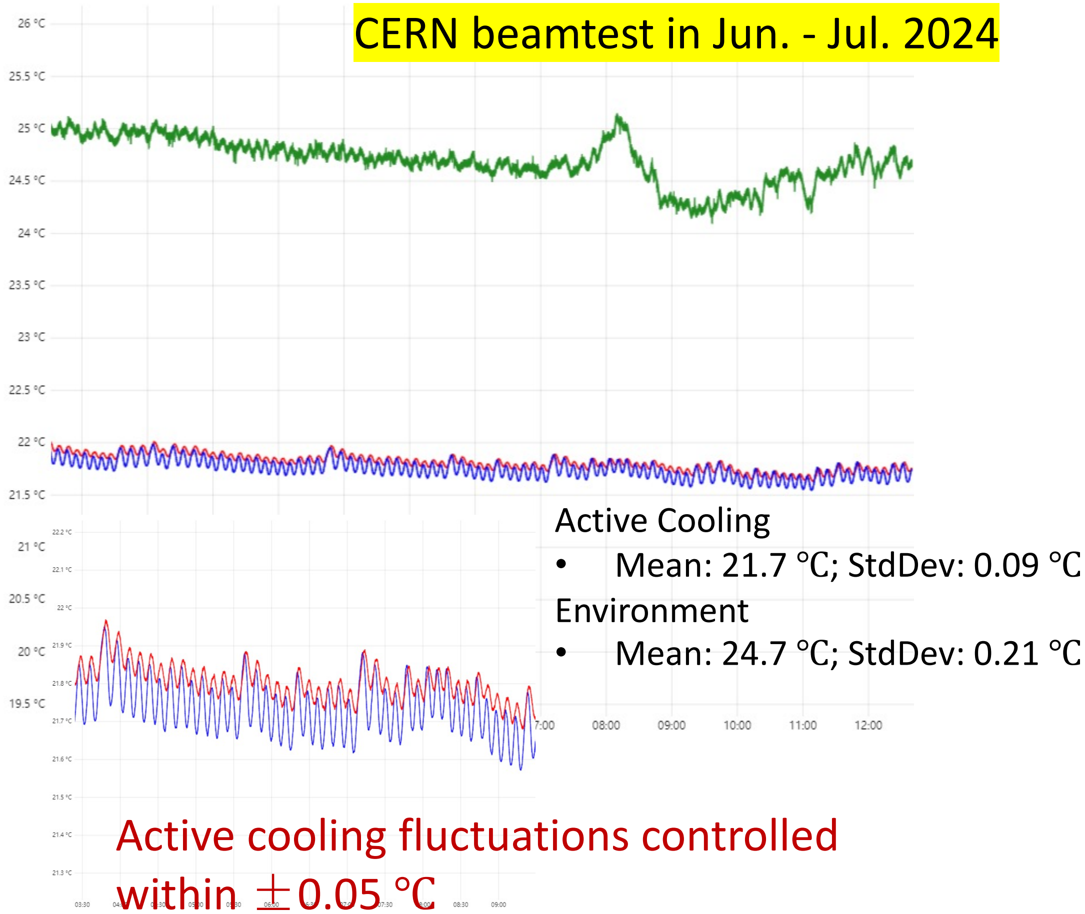


Ongoing studies on fresh/preliminary results on EM performance

- Limitations of commercial ASIC: pedestal shifts (stability), High Gain and Low Gain switch
  - Implemented into digitisation model: generally can reproduce beamtest data
- *Gaussian* fitting to reconstructed energy (asymmetric distribution) → *Crystal Ball* function

Crystal ECAL: impacts of temperature stability

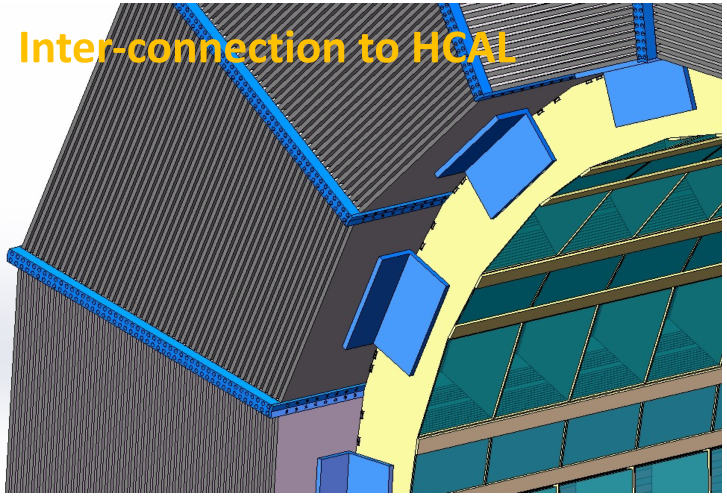




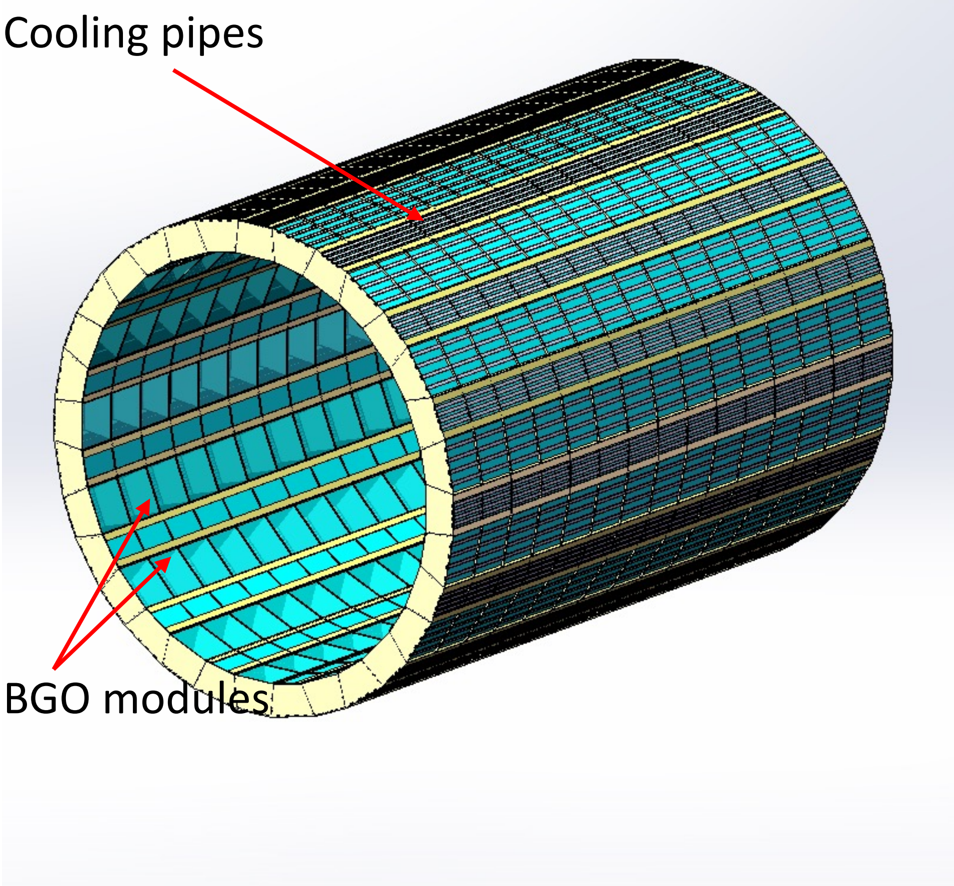
- Temperature stability is crucial to crystal ECAL
  - Significant impact to constant term of EM resolution
  - Specification on stability of ±0.05 ℃ is validated with beamtest data

ECAL mechanics design

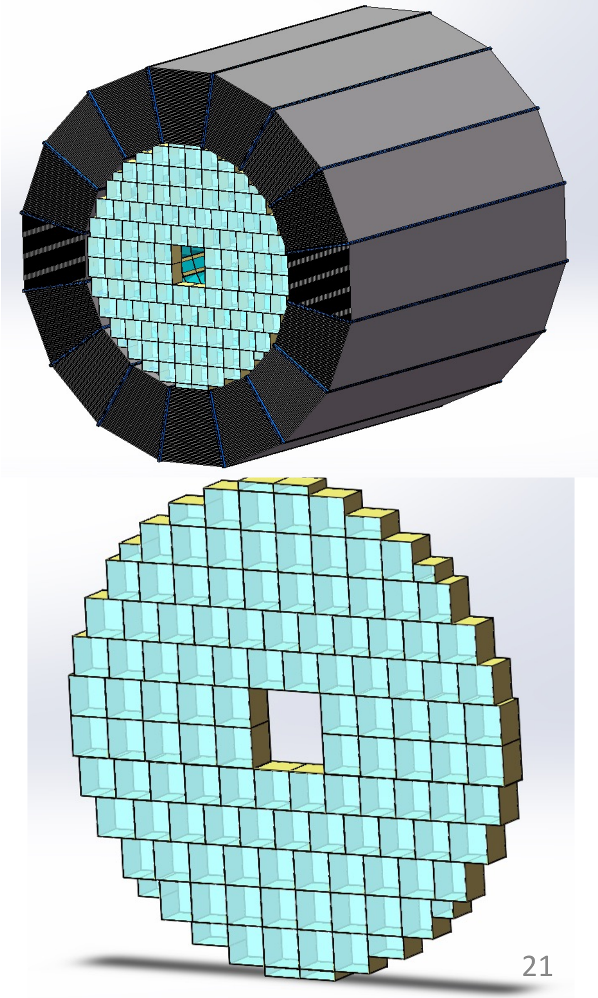
A first design of ECAL mechanics with active cooling



Barrel ECAL design



Endcap ECAL design



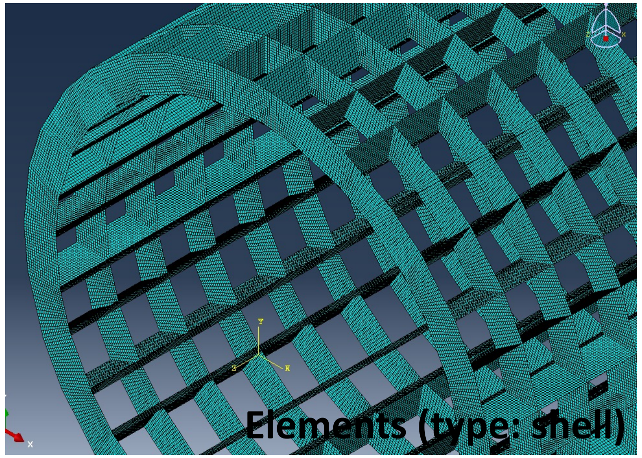
Barrel ECAL parameters

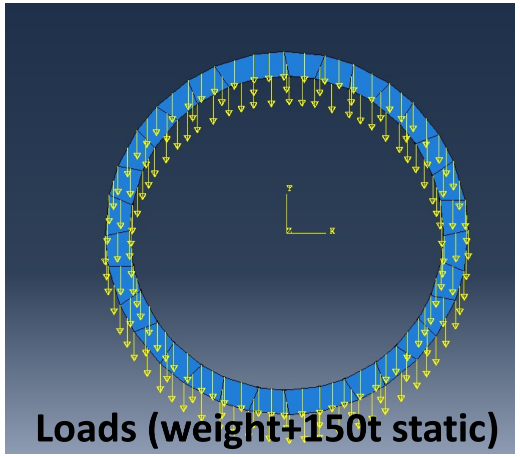
Parameter	Value / mm
Inner radius	1900
Outer radius	2200
Length	5900
Crystal length	~ 400
# Modules in $r-\phi$	32
# Modules in Z	15
ϕ Projectivity tilt	12°
# Layers	28

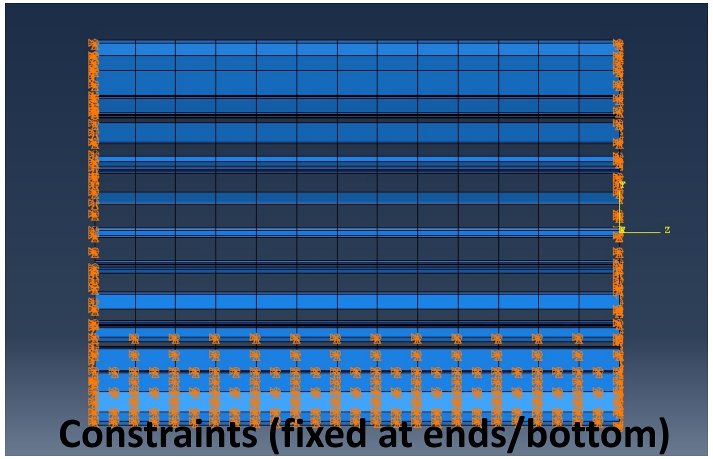
- Support structure is based on Carbon-Finbers for BGO modules (in cyan)

ECAL mechanics design: FEA simulation

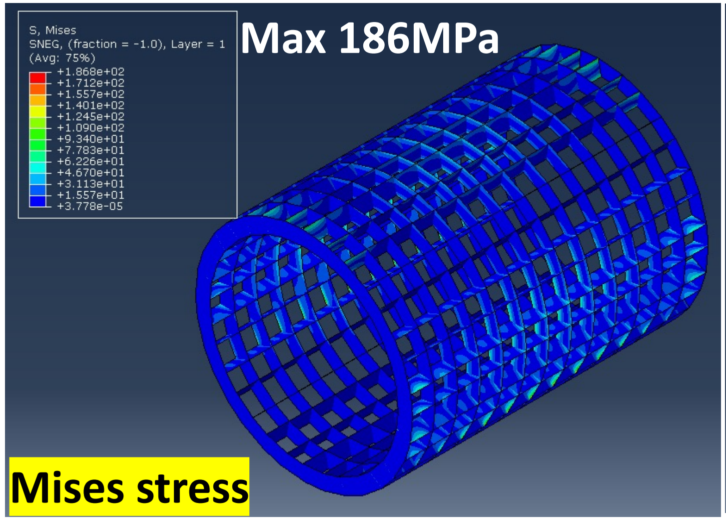
- FEA simulation studies on ECAL mechanics (ongoing): further iterations + validation

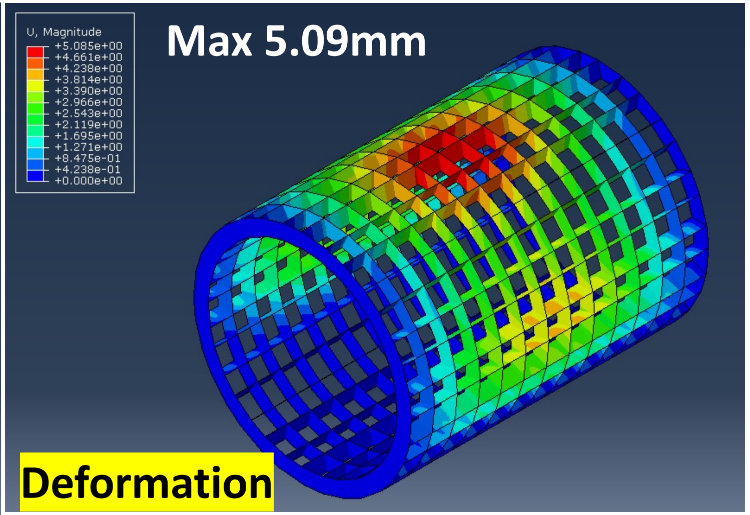


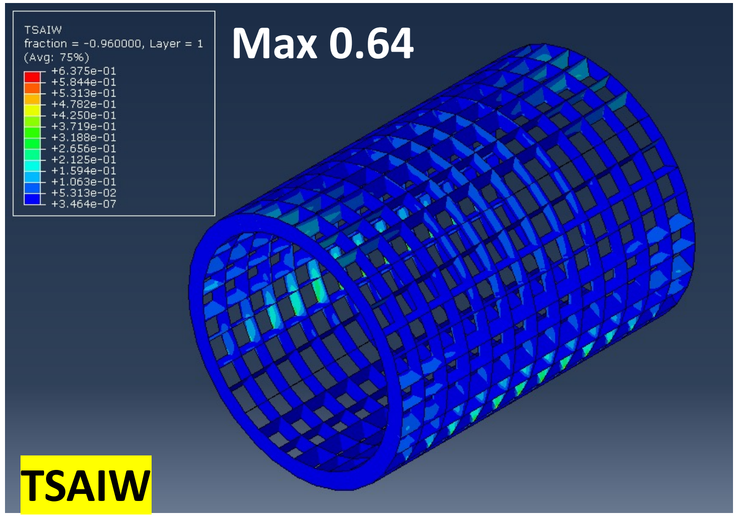




- **Material** :T700 reinforced epoxy resin.
- **TSAIW=0.64 (**When **TSAIW=1**, material begins to fail**)**
- **Safety factor** of the structure is 1/0.64=**1.56**

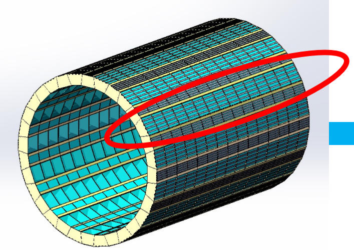






(Failure parameters of composite materials)

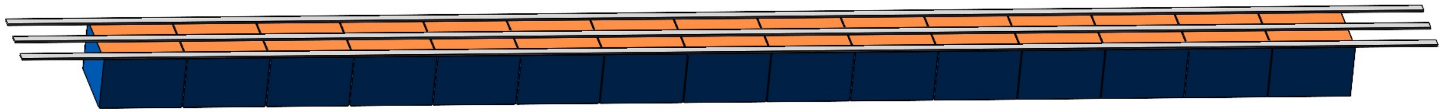
ECAL cooling system



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

FEA simulation studies on ECAL cooling

inlet

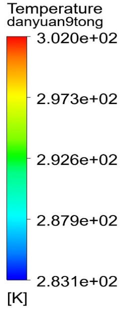


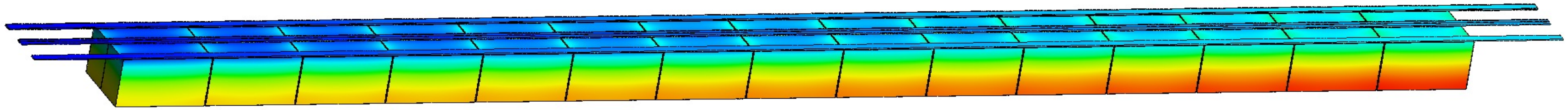
outlet

Cooling medium: 10℃ water

Three channels + 40g/s flow

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

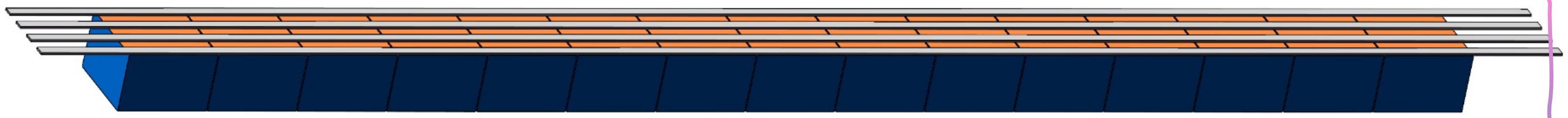


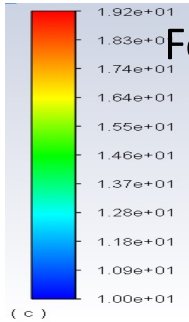


First version

Temperature requirements:
Gradient within $\pm\mathbf{1.5}$℃
Stability within $\pm\mathbf{0.05}$℃

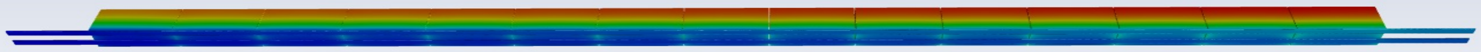
Plan to investigate cooling with future low-power ASIC (expected < 10mW/ch)





Four channels + 100g/s flow

Cooling medium: 10℃ water

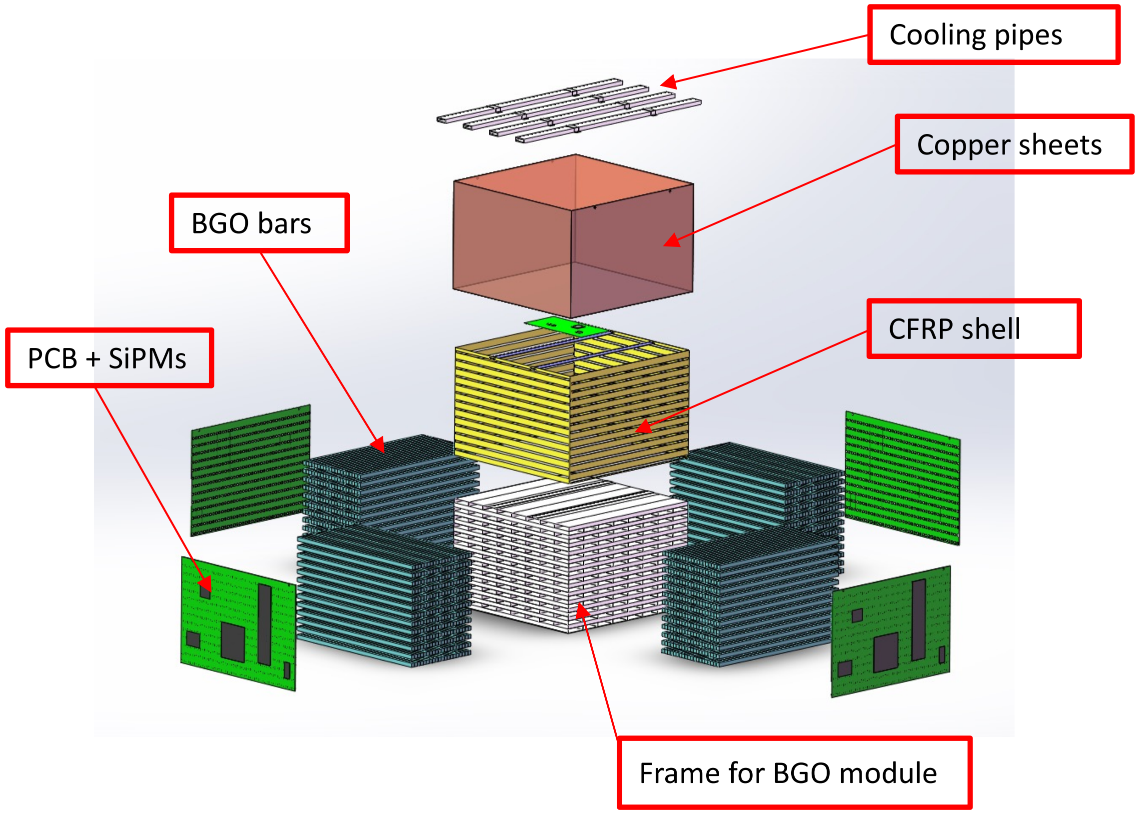


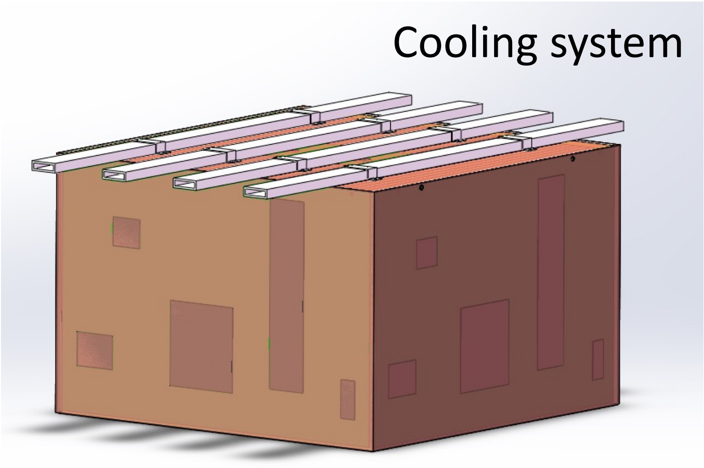
Copper sheet:**1mm**
Low Temp: **10℃**
High Temp: **19.2℃**

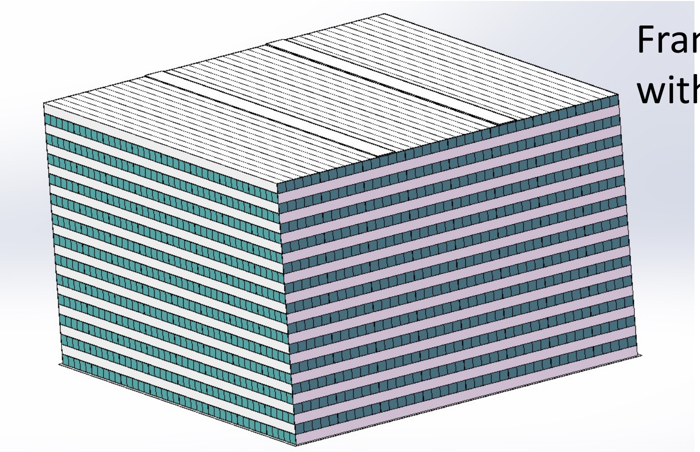
Second version

ECAL module integration

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



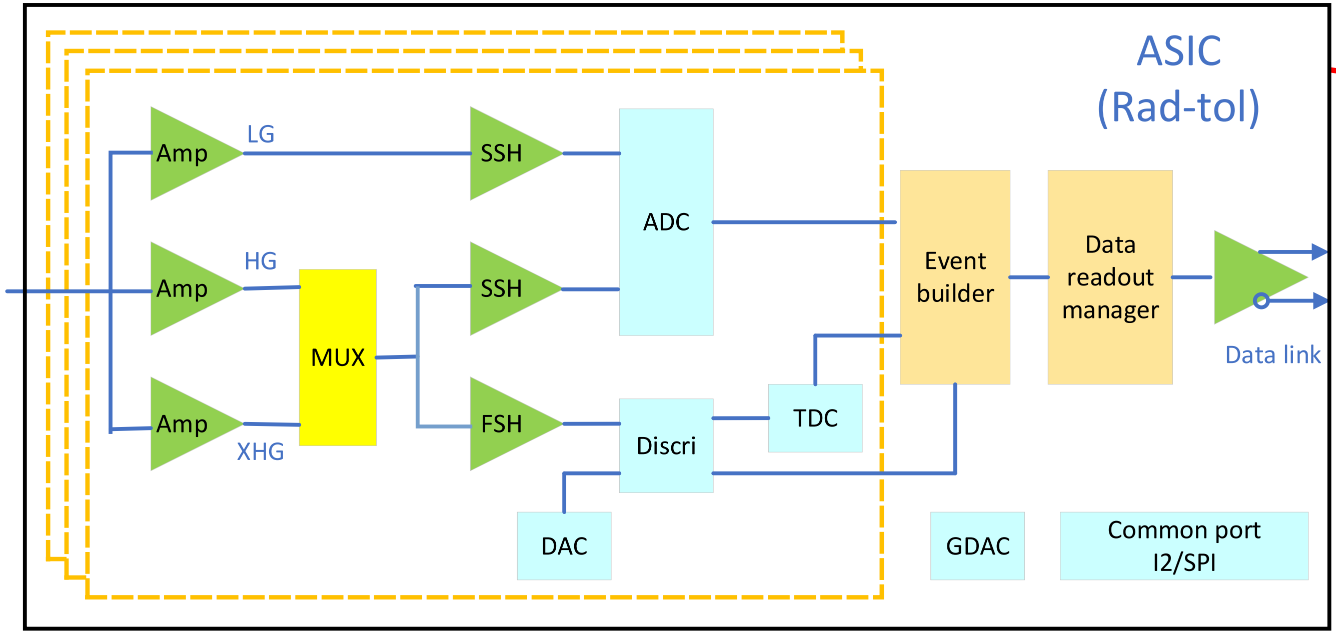




Frame is made of CFRP with 5 BGO bars in 1 cell.

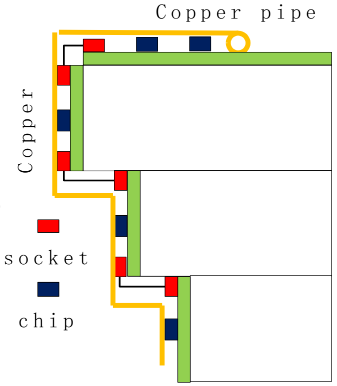
Frame + BGO bars

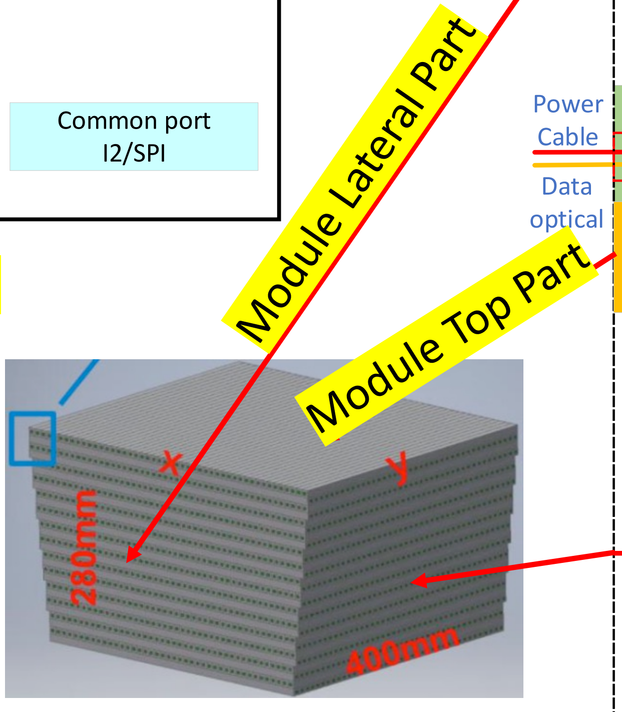
Readout electronics for ECAL

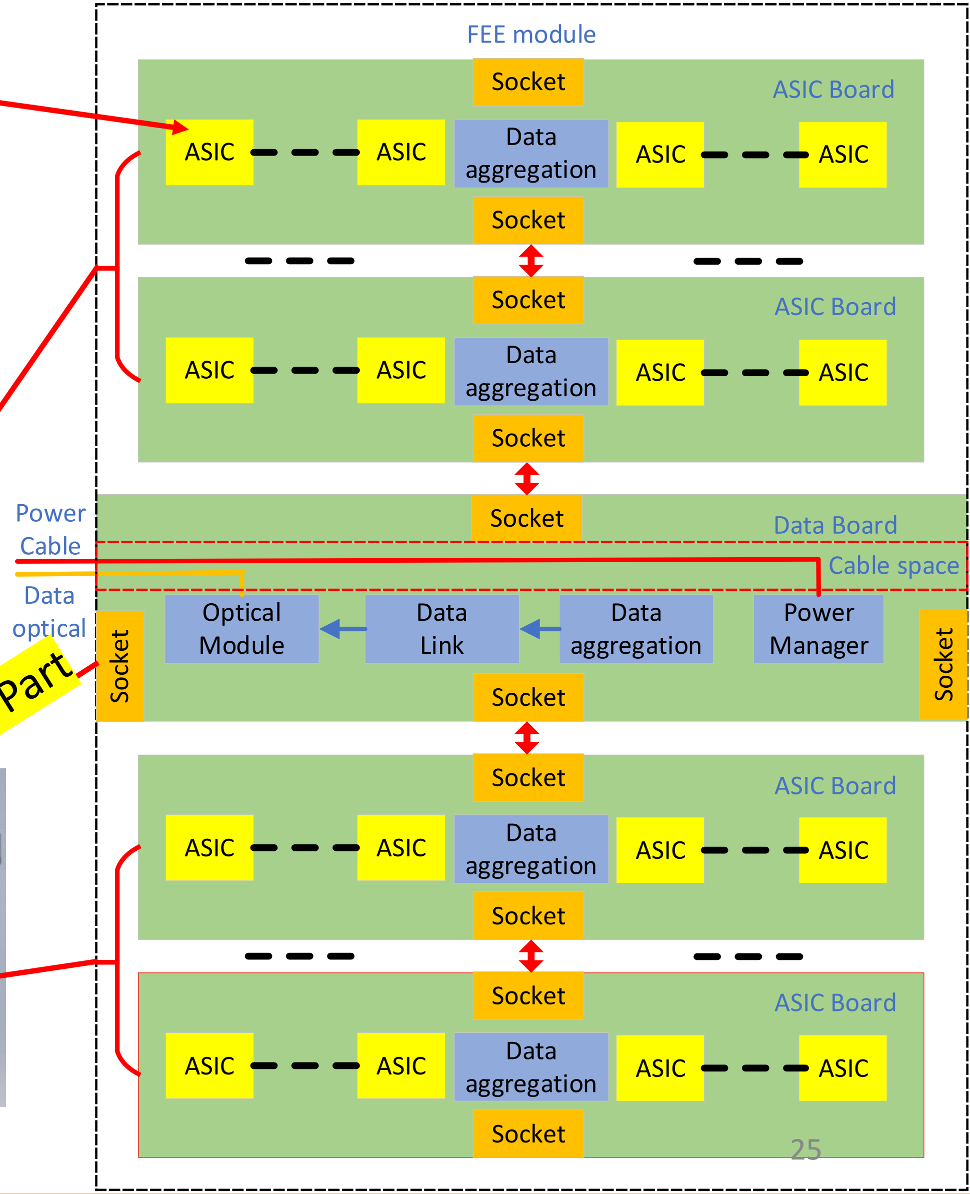


- For different options, FEE module can be one PCB or multiple PCBs
- PCB dimensions: flexible to different options
- 15mW/ch (estimate)

Passive Cooling

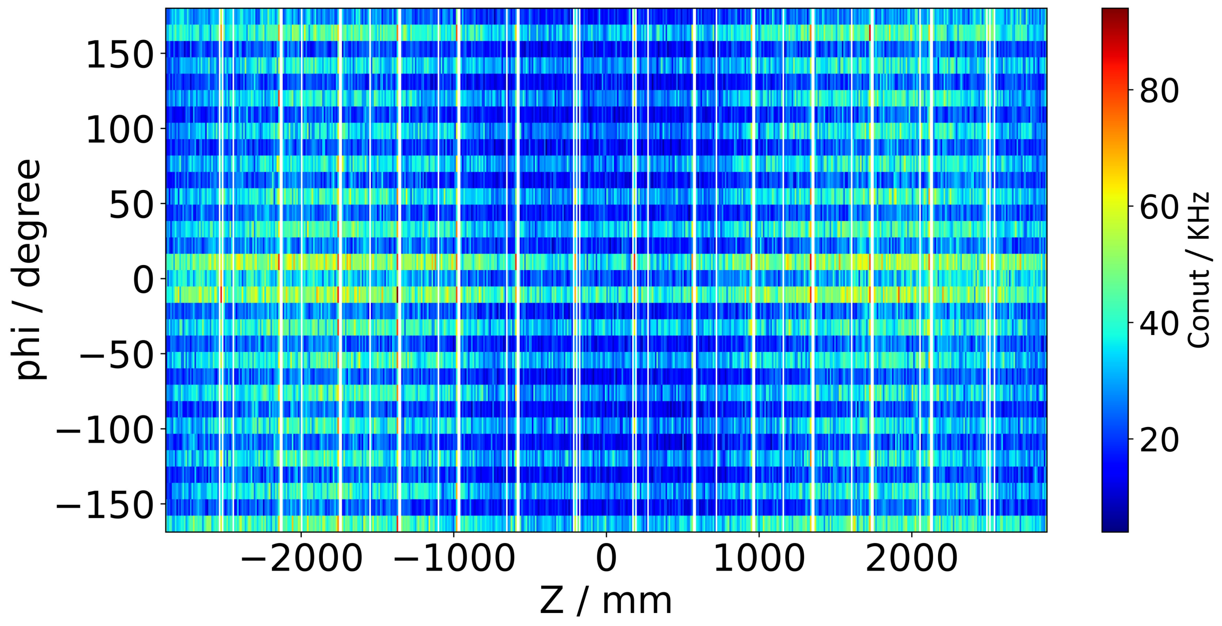




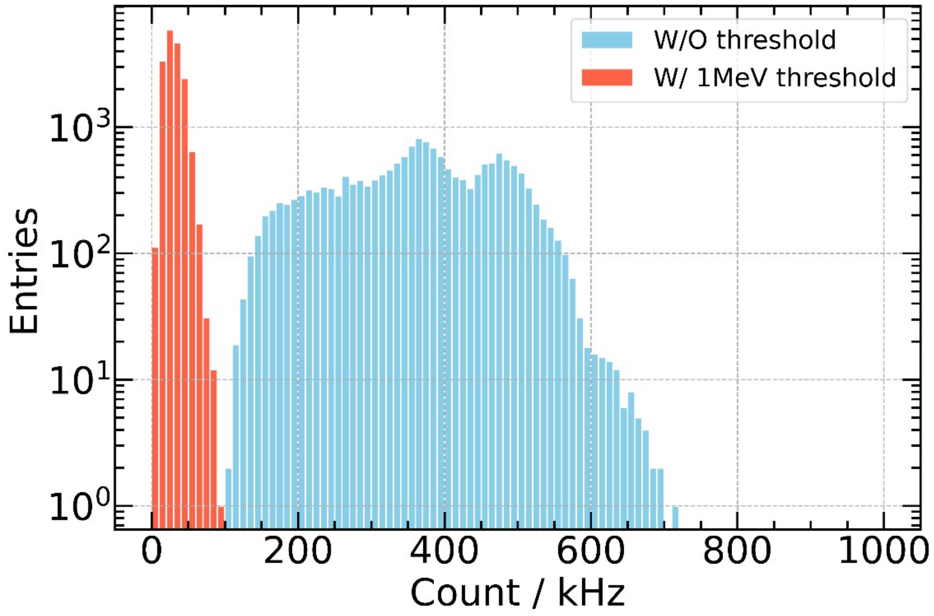


Beam-induced backgrounds: simulation studies

Hit rate map of 1st layer in barrel ECAL (0.1MIP threshold)



Hit rate suppression with 0.1 MIP threshold

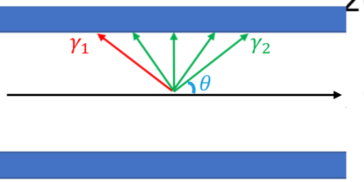


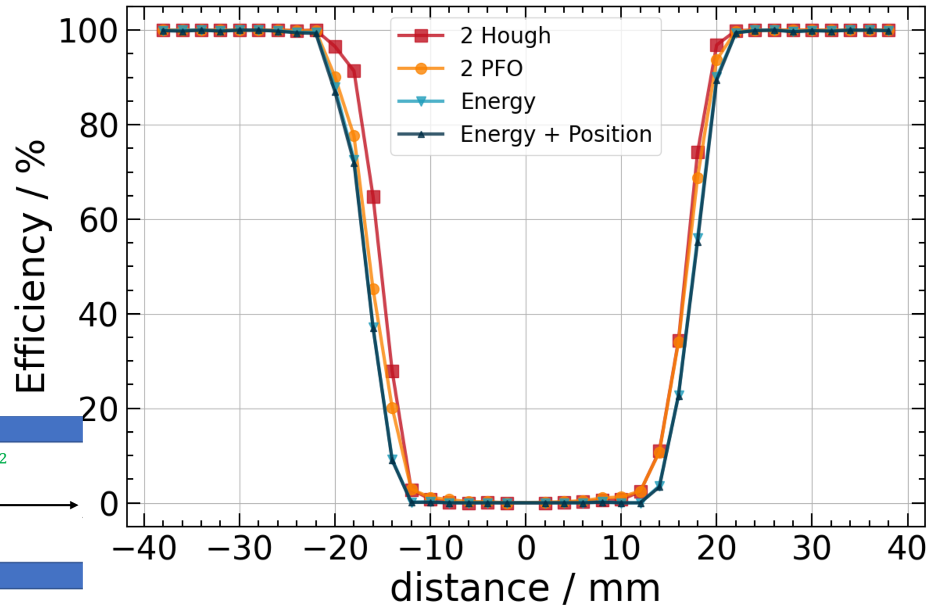
- Simulation studies on beam background in Higgs mode: crystal ECAL barrel
  - Including physics events + backgrounds (major contributions from pair production)
  - With threshold, rate can be significantly reduced: 100kHz (0.1 MIP threshold) from 700kHz (0 threshold)
  - Need to further investigate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

Performance in simulation: separation power

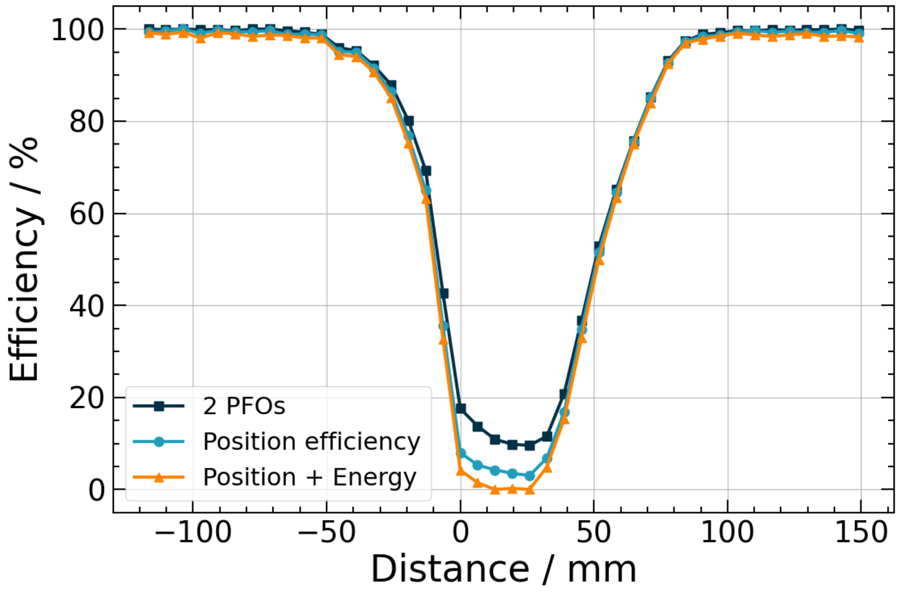
- Separation power of close-by particles: key performance in PFA
  - $\gamma-\gamma$ separation: 100% efficiency for distance > 20mm
  - $\gamma-\pi$ separation : 100% efficiency for distance > 50~100mm

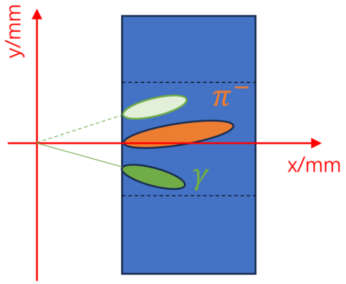
$\gamma-\gamma$ separation for 5 GeV photons





$\gamma-\pi$ separation for 5 GeV γ and π^-

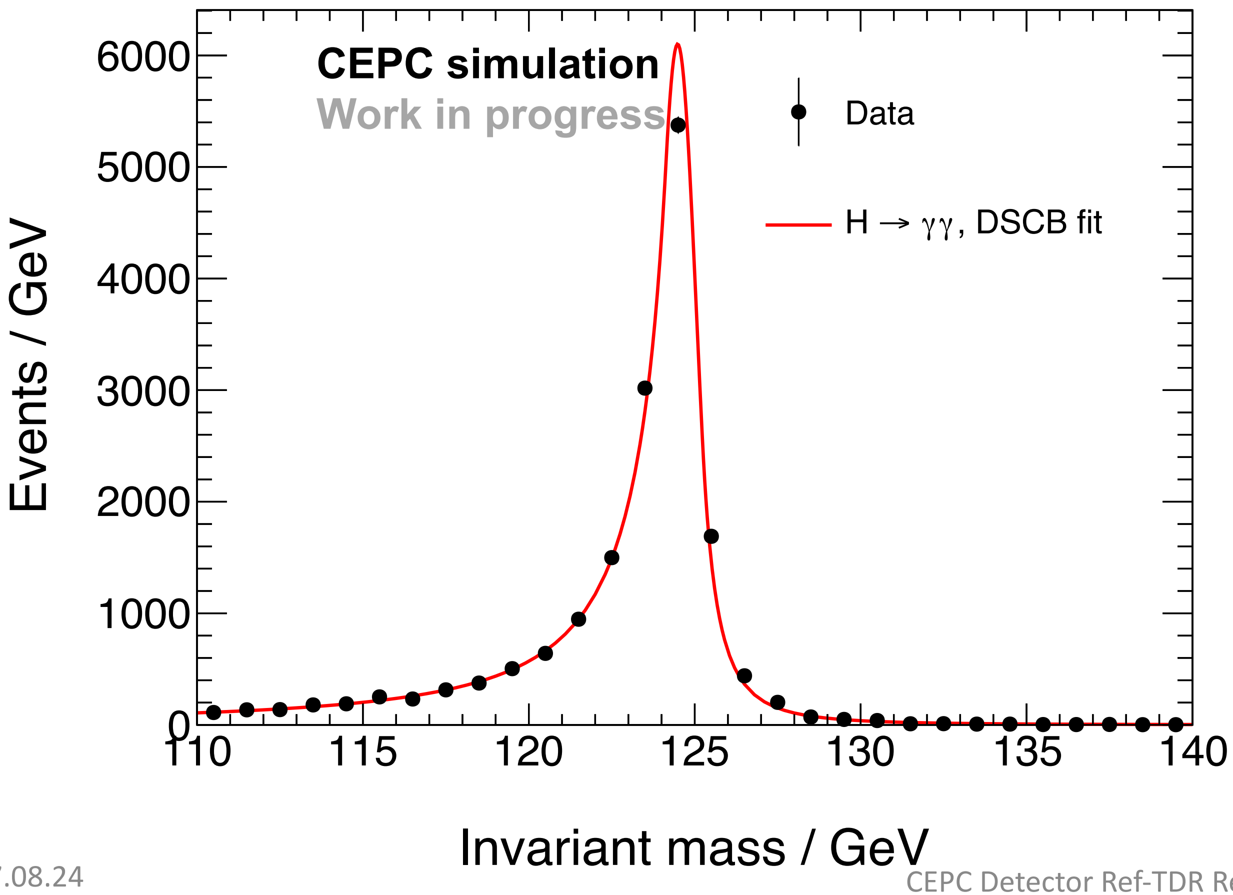




*Asymmetry pattern is due to the magnetic field

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

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



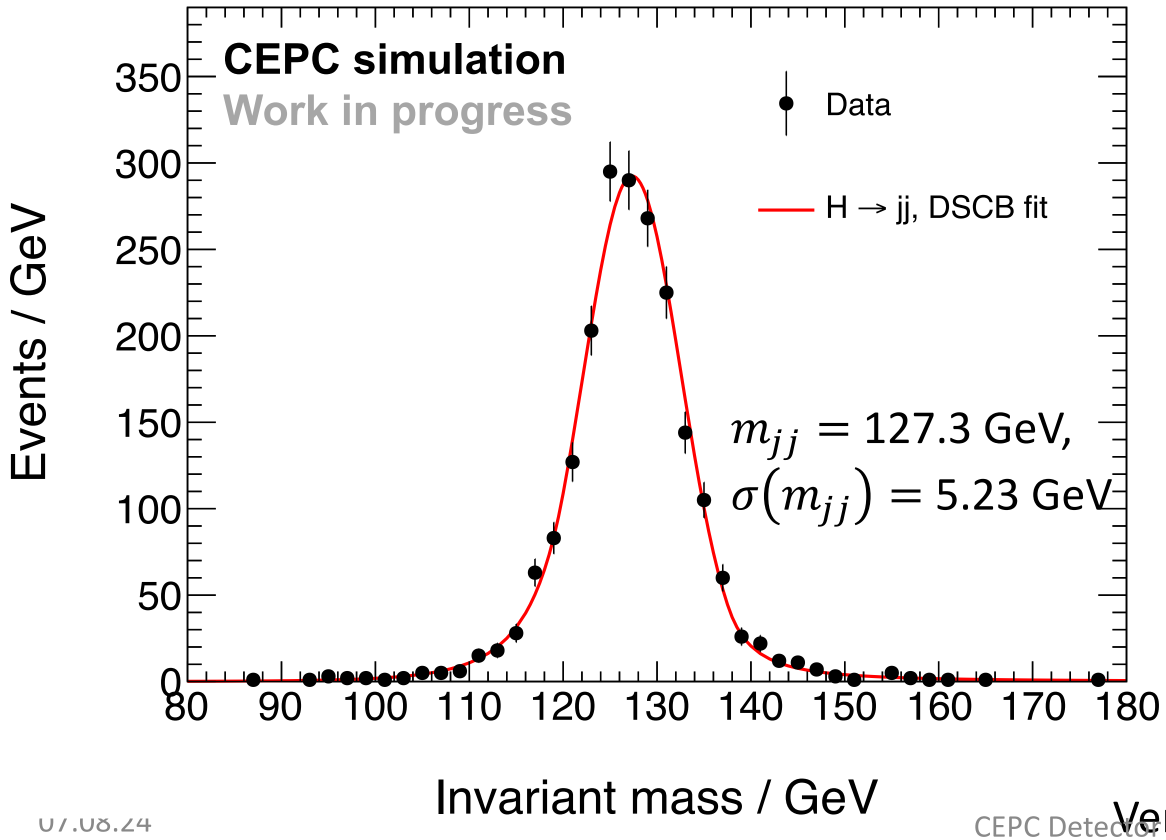
Double-side CB fit, $\sigma(m_{\gamma\gamma})$ = 0.57 GeV

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

Can be fixed with better photon energy correction

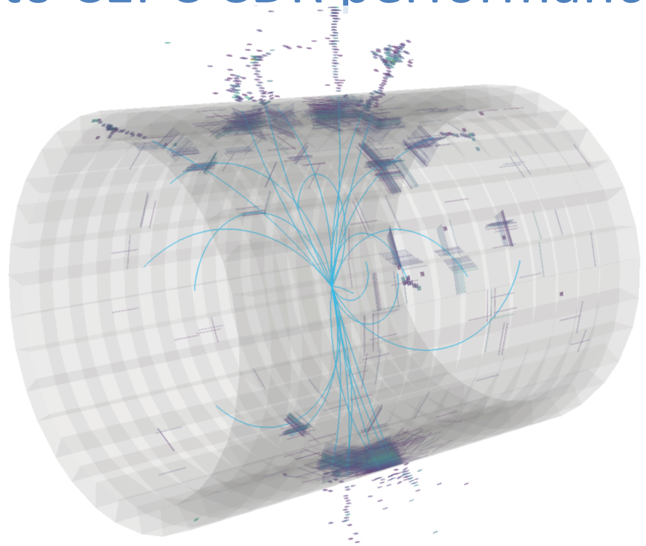
Physics performance in simulation: $H \rightarrow gg$

- Physics process: $ee \rightarrow ZH \rightarrow \nu\nu gg$ in $\sqrt{s} = 240$ GeV
  - Full reconstruction of two gluon jets in the full CEPC detector
  - Dedicated developments of PFA for long crystal bars



Boson mass resolution (BMR): 4.11%

With truth tracking: BMR 3.73%
(comparable to CEPC CDR performance)

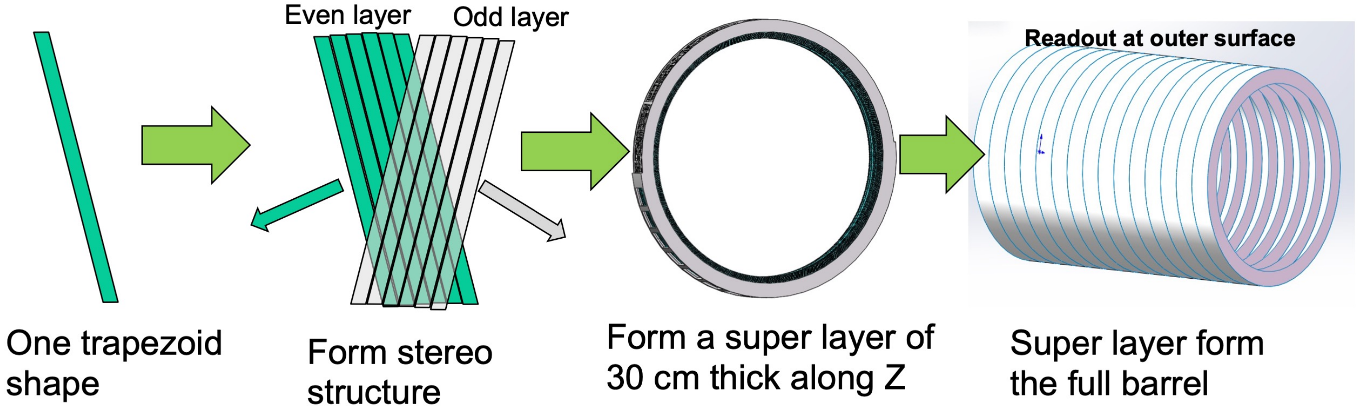


Vertex, Silicon + TPC tracker, crystal ECAL, ScintGlass HCAL

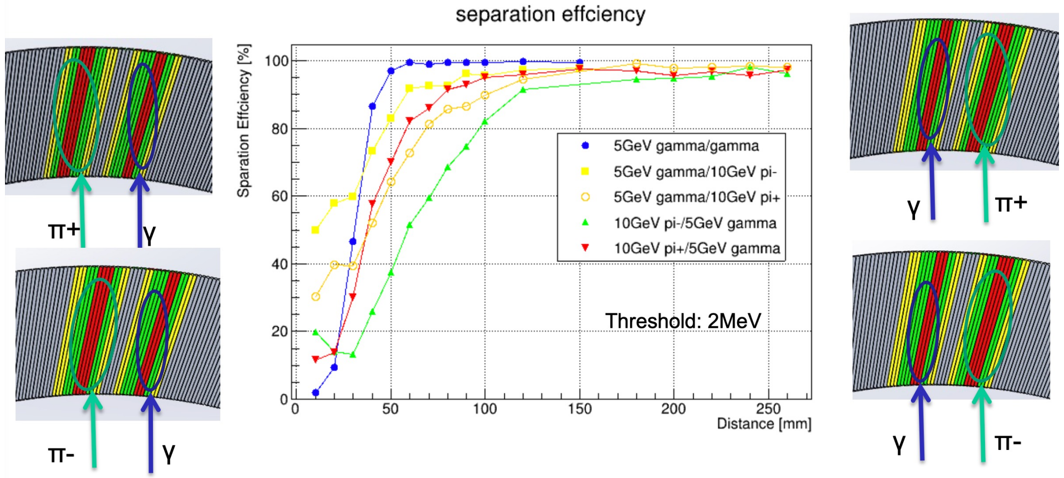
Alternative ECAL design: stereo crystals

- Stereo design with long crystal bars inclined
  - Longitudinal segmentation by tilting crystal bars
  - Single-end readout: 50% less readout channels than crossed bars (two-sided readout)

Only one freedom left, α or longitudinal sampling N_R



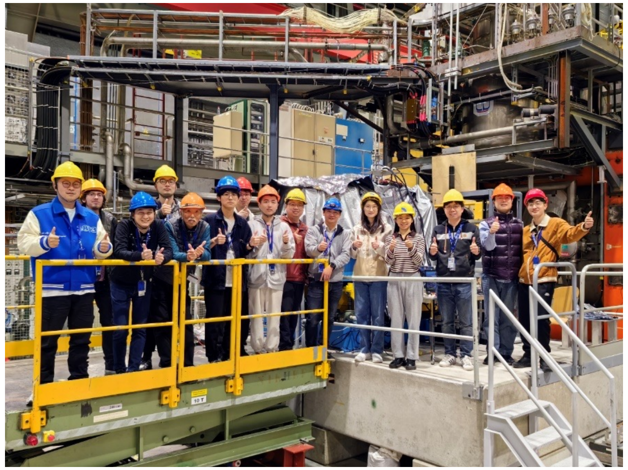
Separation power of two particles



- Simulation studies on reconstruction: promising separation power of two particles
- Ongoing designs on mechanics, cooling and integration

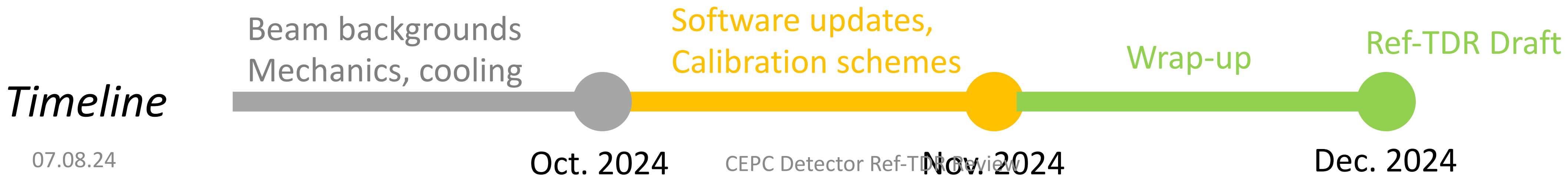
Taskforce and collaborations

- Taskforce working on CEPC ECAL
  - Detector (hardware/software): physicists (8), postdocs (3), students (8)
  - Engineers in electronics (3) and mechanics (1)
- Many members deeply involved in large-scale experiments/projects
  - BES-III Experiment: Electromagnetic Calorimeter with 6,240 CsI(Tl) crystals
  - JUNO Experiment: 20,000 ton ultra-pure liquid scintillator
  - CMS HGCAL project for HL-LHC: ~5,000 silicon modules (8-inch) at MAC-Beijing
- 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)



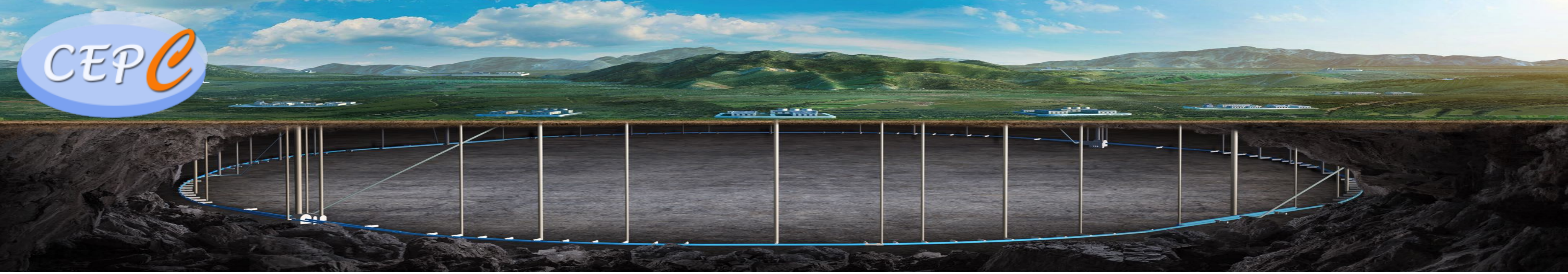
Working plan

- Near future activities (in 2024): towards reference detector TDR
  - Beam-induced backgrounds: simulation in barrel and endcap regions, impacts to physics 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), digitistaion (inputs from beamtest and electronics)
  - Calibration: sensitive units (SiPM, crystal, ASIC) versus temperature, irradiation
  - Particle flow performance: further optimizations



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



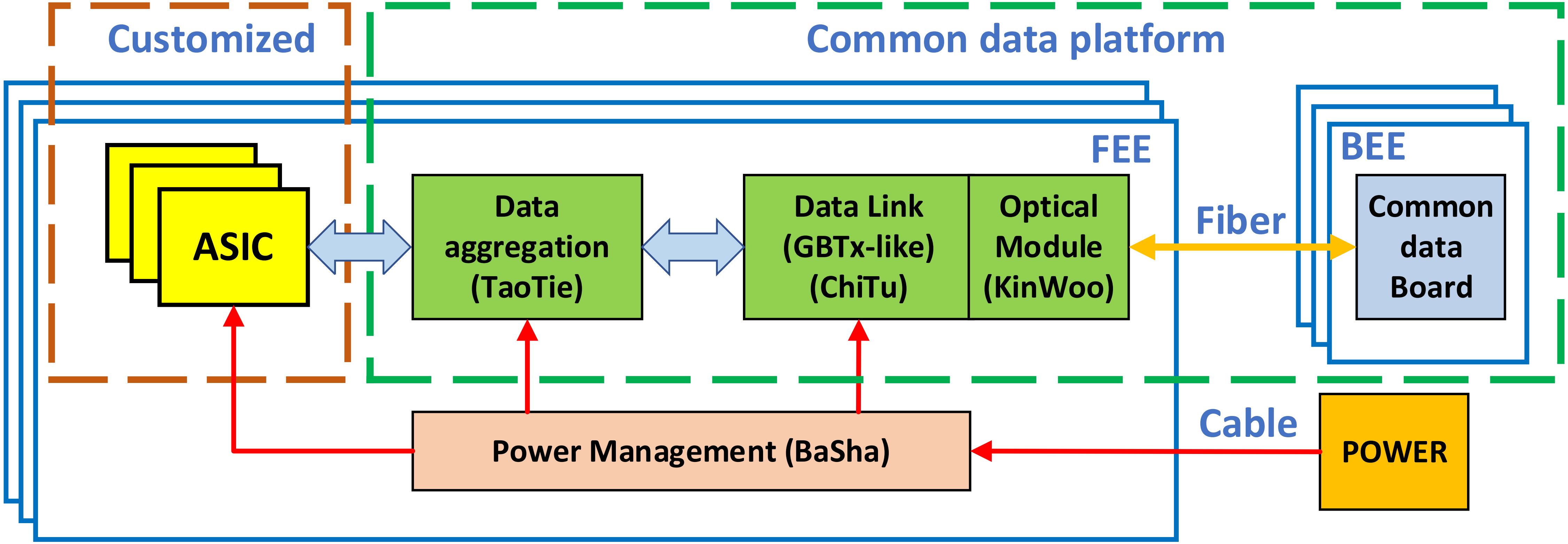
Thank you for your attention!

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
- Crystal calorimeter R&D: contributions at CALOR 2024
  - Development of high-granularity crystal calorimeter
  - SiPM dynamic range studies
  - Particle-flow software and performance of crystal ECAL
  - Stereo Crystal ECAL
- High-granularity crystal calorimeter talk at ICHEP2024

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)

R&D efforts and results: dynamic range

SiPM with 10um/15um pixel pitch

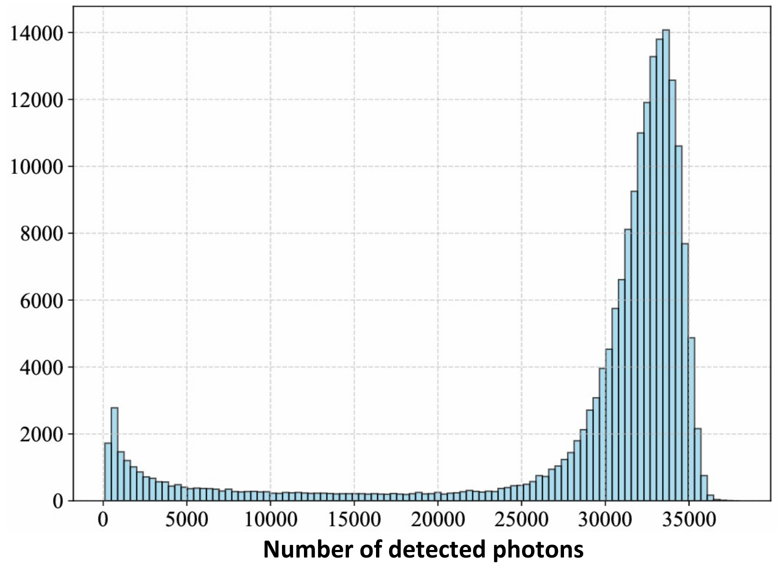
Type no.	Dark count rate*5 DCR typ. (kcps)	Dark count rate*5 DCR max. (kcps)	Direct crosstalk probability Pct (%)	Terminal capacitance at Vop*6 Ct (pF)	Gain M	Temperature coefficient of Vop ΔTVop (mV/°C)
S14160-1310PS	120	360		100		
S14160-3010PS	700	2100		530	1.8×10^5	
S14160-6010PS NEW	3000	10000	<1	2200		34
S14160-1315PS	120	360		100		
S14160-3015PS	700	2100		530	3.6×10^5	
S14160-6015PS NEW	3000	10000		2200		

SiPM with 25um pixel pitch

Type no.	Measurement conditions	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection efficiency PDE*4 λ=λp (%)	Dark count*5 Typ. (kcps)	Dark count*5 Max. (kcps)	Terminal capacitance Ct (pF)	Gain M	Breakdown voltage VBR (V)	Crosstalk probability (%)	Recommended operating voltage Vop (V)	Temperature coefficient at recommended operating voltage ΔTVop (mV/°C)
S13360-1325PE		320 to 900			70	210	60					
S13360-3025CS		270 to 900			400	1200	320					
S13360-3025PE	Vover =5 V	320 to 900		25				7.0×10^5		1	VBR + 5	54
S13360-6025CS		270 to 900			1600	5000	1280					
S13360-6025PE		320 to 900										

Dynamic range of a state-of-art chip:
~33000 p.e. for 25um SiPM

Electronics with lowest gain



- State-of-art ASIC dynamic range
  - Expected to reach ~128k p.e. for SiPM with 10um pixel pitch

Summary: crystal ECAL with long bars

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	350 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$ (*2168.3mm for BGO*)	NA
Longitudinal Depth	$24X_0$ (268.3 mm BGO)		NA
Modularity	28 modules in phi, 15 rings along Z	No concrete design (ideal cylinder for now)	NA
Material Volume (m^3)	20.2	7.8	28.0
Readout channels	0.92 M	0.36 M	1.3 M
Power dissipation	18.4 kW	7.2 kW	25.6 kW

Data throughput estimate: first simulation results

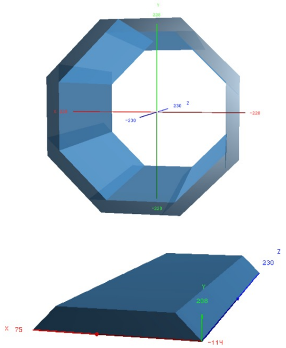
Crystal bar ECAL data size estimation

- **Luminosity (CEPC accelerator TDR, 2023)**
  - $\mathcal{L} = 115\times10^{34}\ cm^{-2}s^{-1}$ / IP @ 30 MW
  - $\mathcal{L} = 192\times10^{34}\ cm^{-2}s^{-1}$ / IP @ 50 MW

Physics Process @ Z mode	σ (nb) @ $\sqrt{s} = 91.2GeV$	Rate (kHz) @ 30 MW	Rate (kHz) @ 50 MW
$e^+e^- \to q\bar{q}$	30.20	34.7	58.0
$e^+e^- \to \mu^+\mu^-$	1.51	1.73	2.90

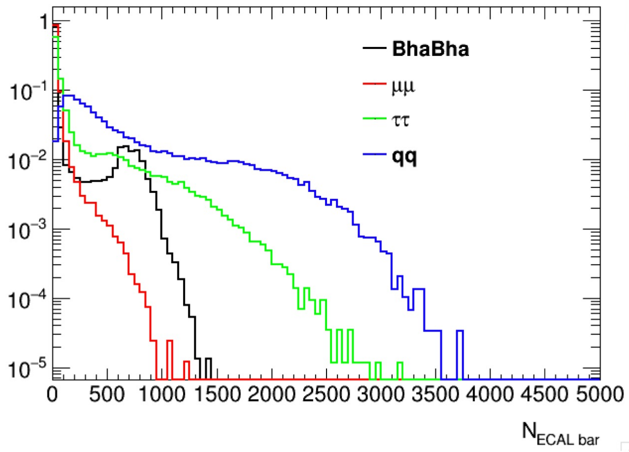
*No $ee \to \tau\tau$ cross section, but should at the same level as $ee \to \mu\mu$.

- **Simulation geometry: Octagonal ECAL**
  - Inner R = 1860 mm, depth 280 mm, Z = 6700 mm.
  - In each module: 4*11 blocks, bar length 400~600 mm, bar size ~60k.
  - Physical process: $\sqrt{s} = 91$ GeV, Bhabha, $ee \to Z/\gamma^* \to \mu\mu/\tau\tau/qq$.
- **Digitization:**
  - Bar energy threshold 0.1 MeV.



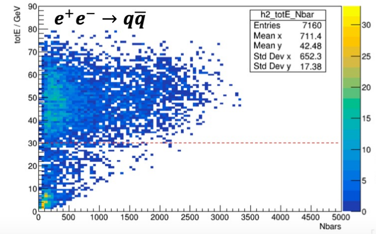
Crystal bar ECAL data size estimation

- **Fired bar size in each module**



Process	Barrel acceptance*	Rate @ 30 MW [kHz]	Rate @ 50 MW [kHz]
Bhabha	48.7%		
$e^+e^- \to \mu\mu$	-		
$e^+e^- \to \tau\tau$ **	82%	1.42	2.38
$e^+e^- \to q\bar{q}$	99.4%	34.5	57.7
$e^+e^- \to q\bar{q}$ $(E_{tot} > 30\ GeV)$	79.9%	27.7	46.3

*Definition: deposit >1GeV energy in ECAL.
*Use $\sigma(ee \to \mu\mu)$ and it's rate.



Can set a safe case:
5k bars @ E>30 GeV

Crystal bar ECAL data size estimation

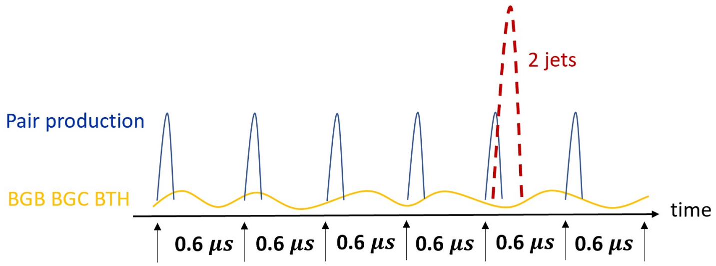
- **Readout:**
  - Double-side readout, so 2 channels / bar.
  - data size = 32bit / channel.
  - Data size for the hottest module (only count $e^+e^- \to q\bar{q}$ process):
    - 30 MW: 27.7 [kHz] * 5k [bars] * 2 * 32 [bit] = 8.86 Gbits/s = 1.1 GB/s
    - 50 MW: 46.3 [kHz] * 5k [bars] * 2 * 32 [bit] = 14.8 Gbits/s = 1.9 GB/s

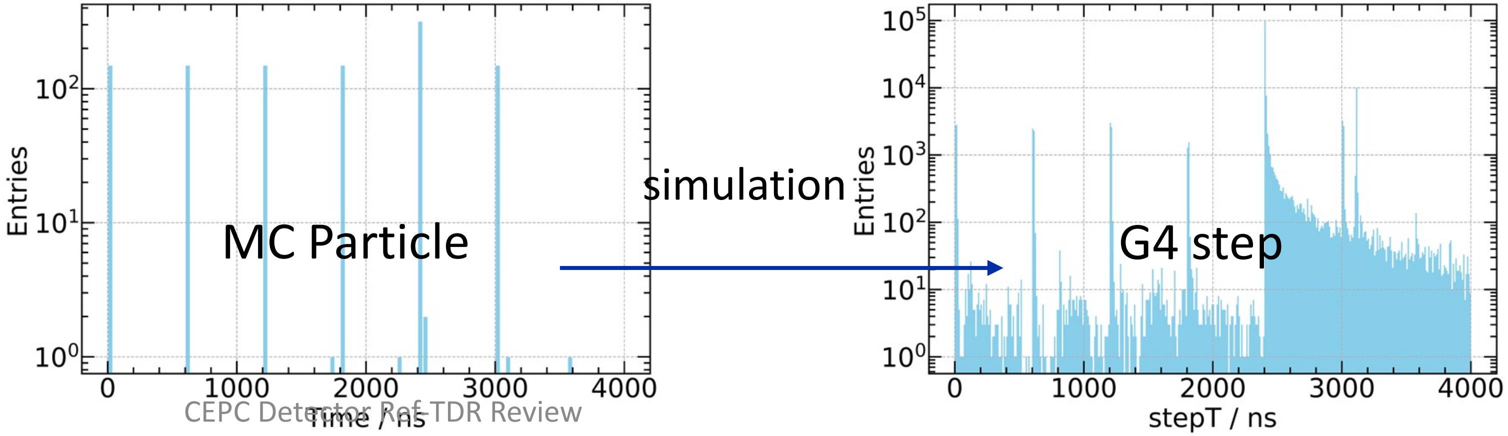
- Plan to update estimates with the latest ECAL geometry implemented

Beam-induced backgrounds: simulation studies

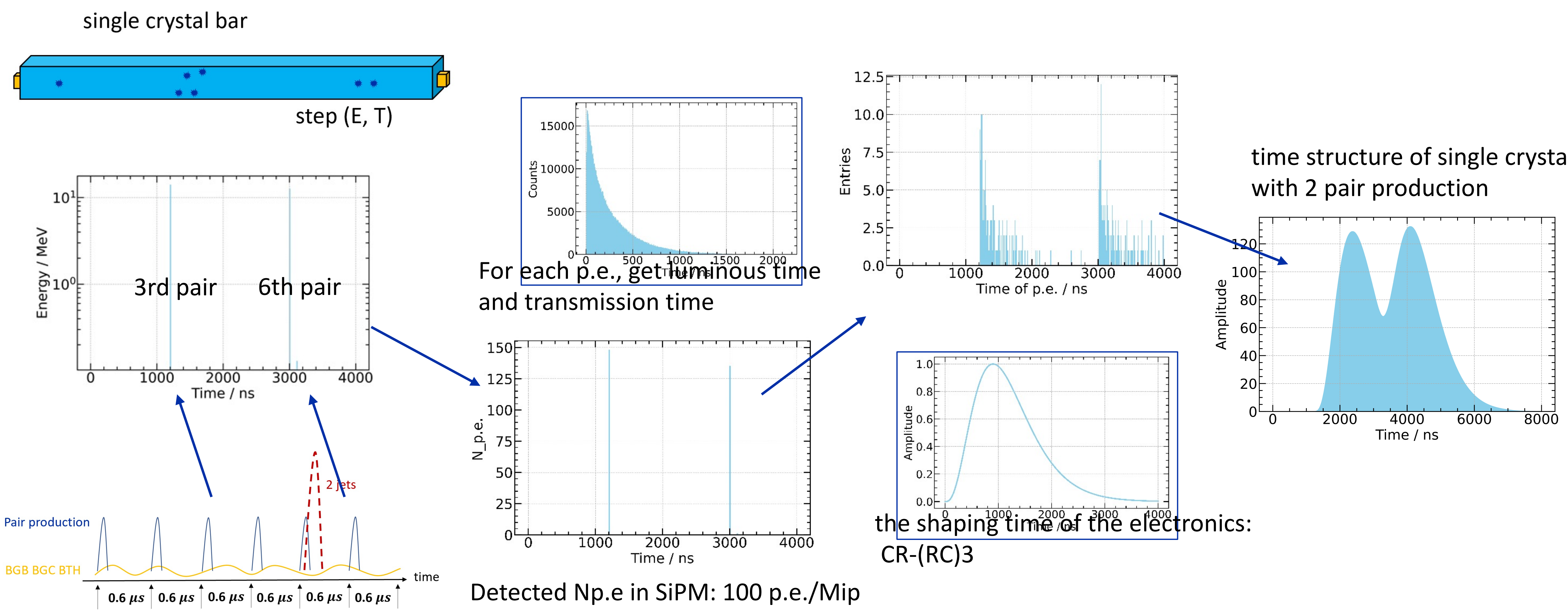
Background	**Rate/Hz**	**$N_{MCParticle}$ / 3.6 μs time window**
Pair production	---	~ 7800
Beam-Gas Bremsstrahlung (BGB)	**83,280.65**	~ 0.30
Beam-Gas Coulomb (BGC)	**884,002.12**	~ 3.18
Beam Thermal Photon Scattering (BTH)	**623,520.09**	~ 2.24
Synchrotron Radiation	---	---
Radiative Bhabha	---	---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

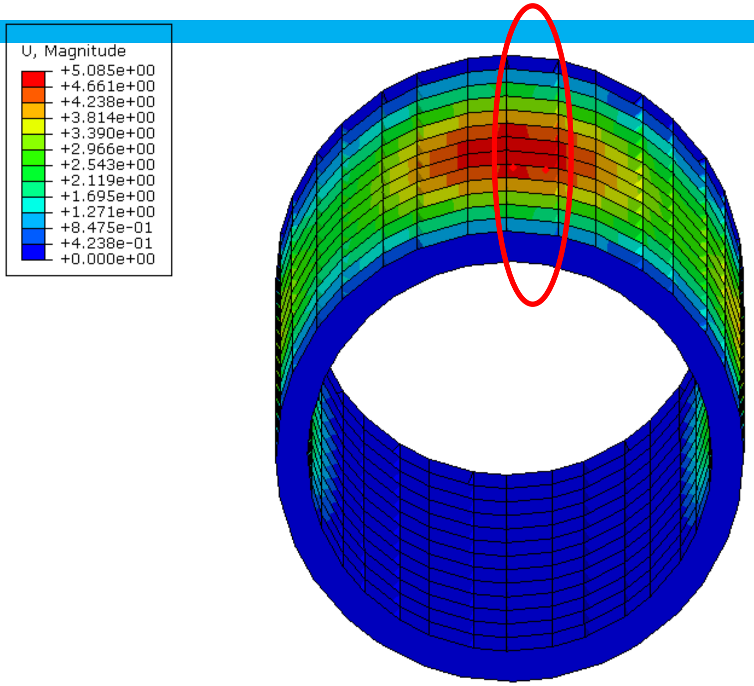


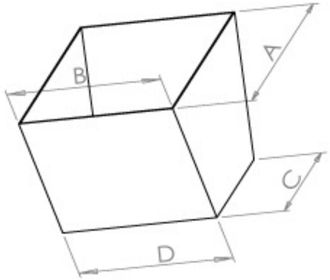


Beam-induced backgrounds: time structures

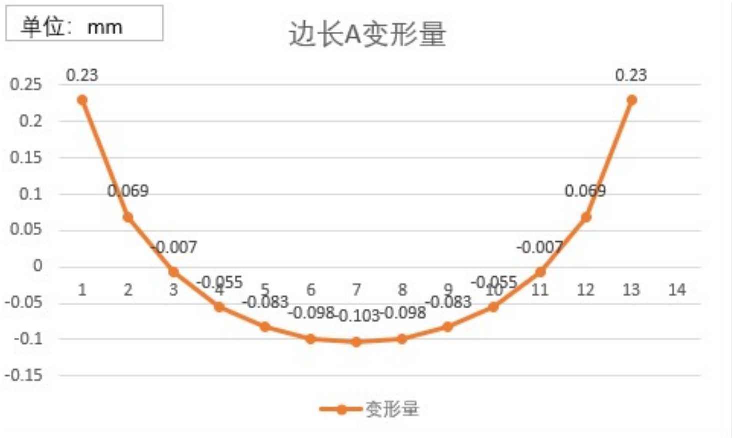


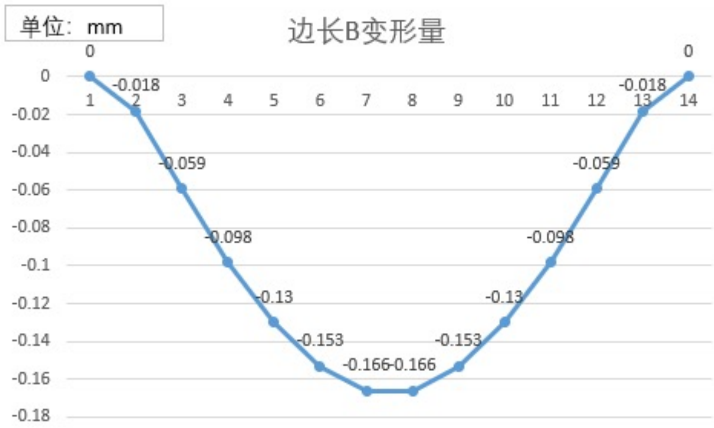
Mechanics: FEA studies on deformation

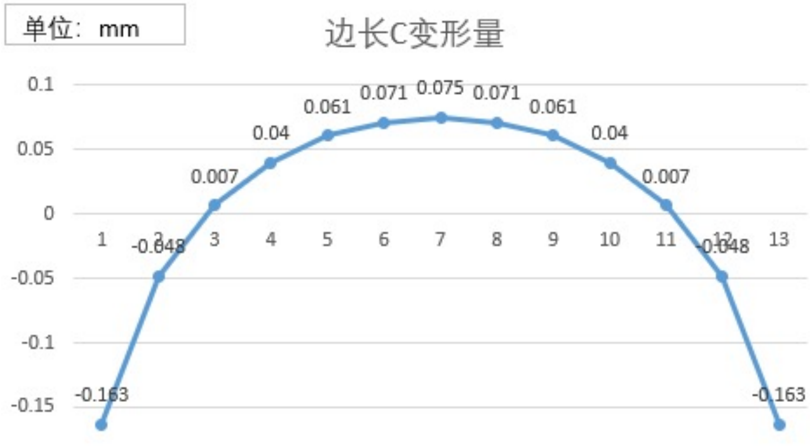


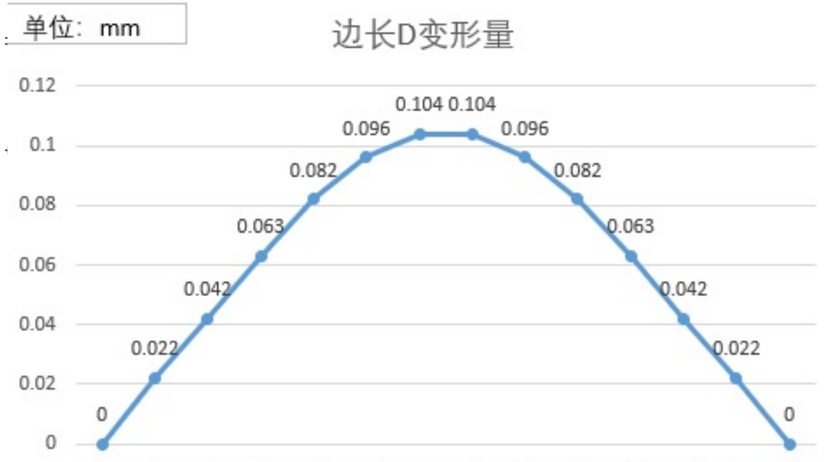


A/B/C/D are the sides of the cell



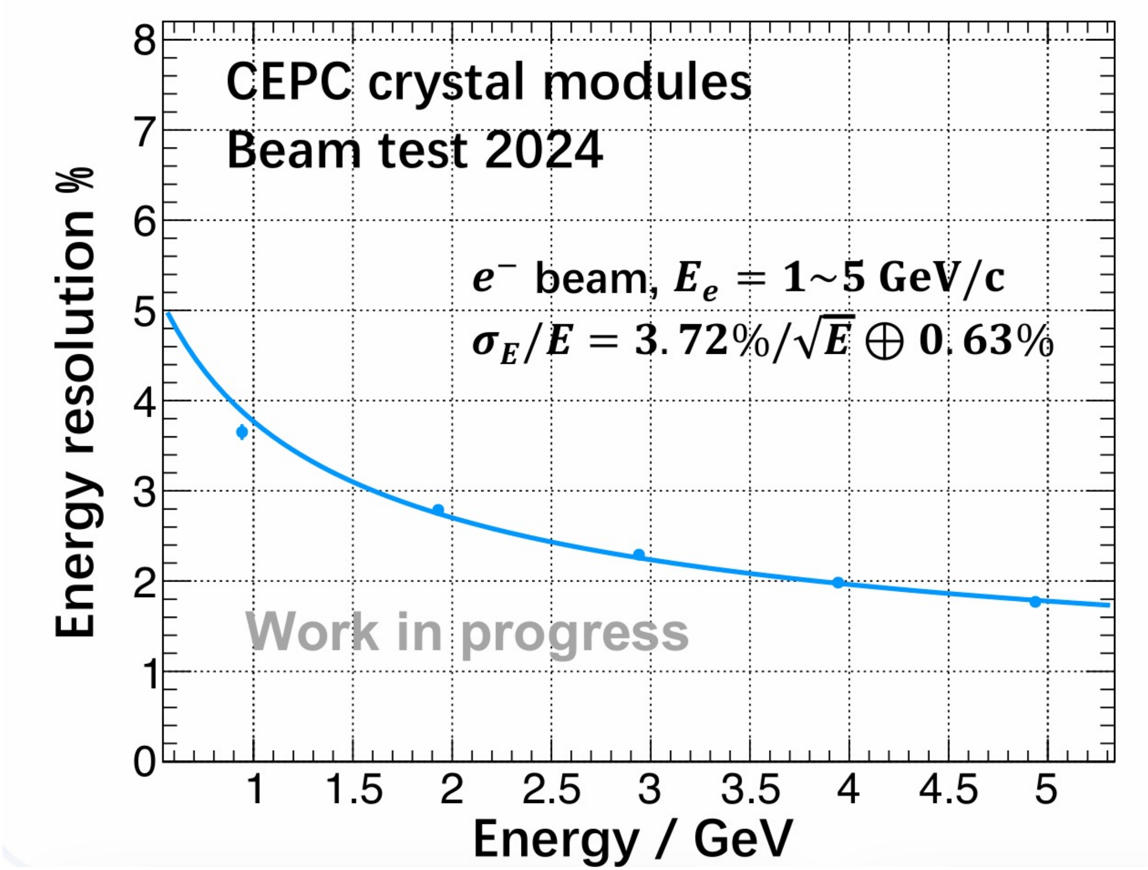


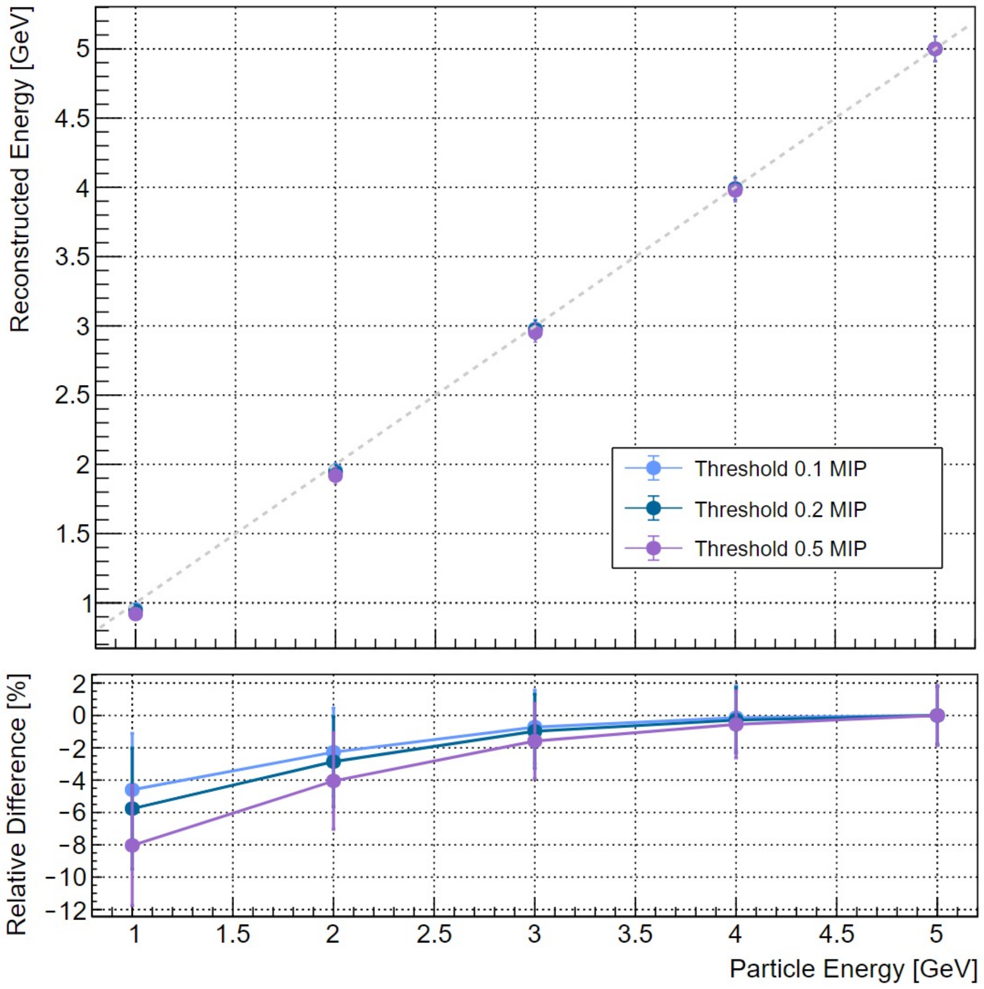




The BGO is brittle, so we have to know the deformation of each cell . According to the FEA, the maximum deformation of the cells is 0.23mm.

CERN setup: energy resolution





Planning

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

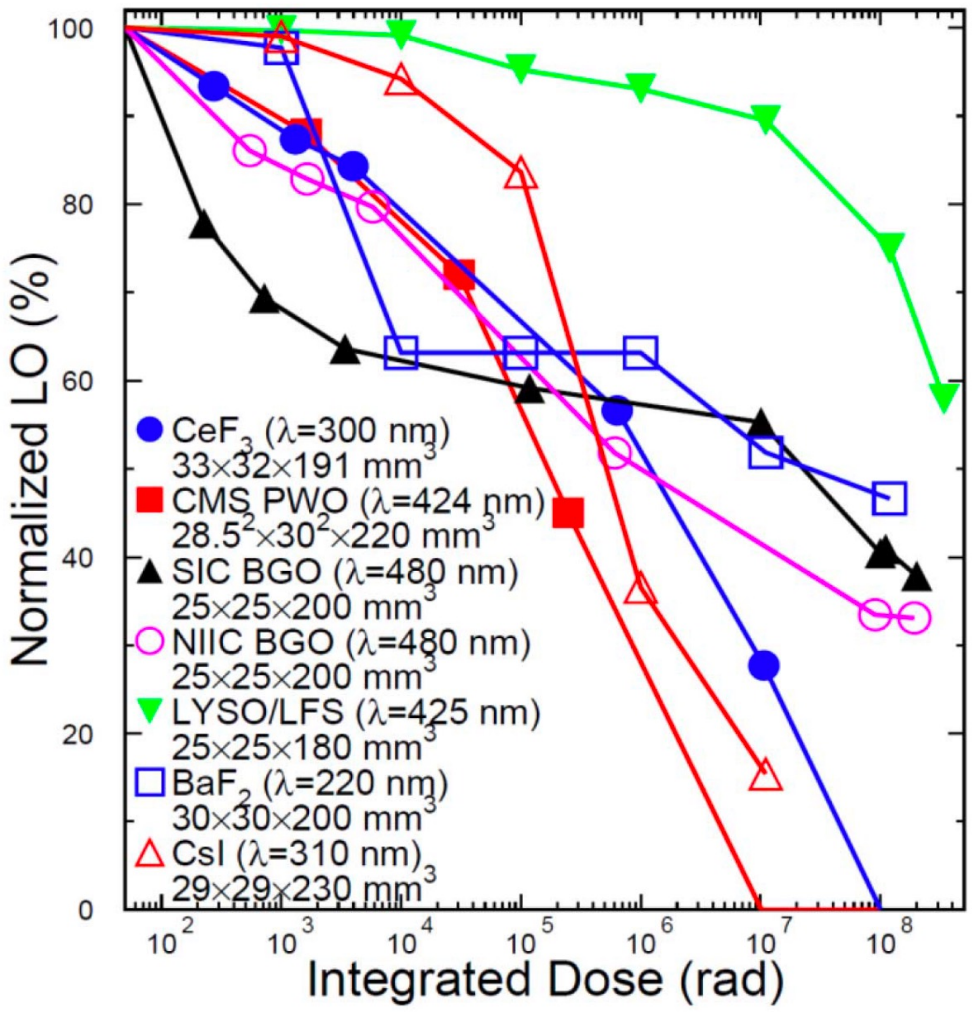
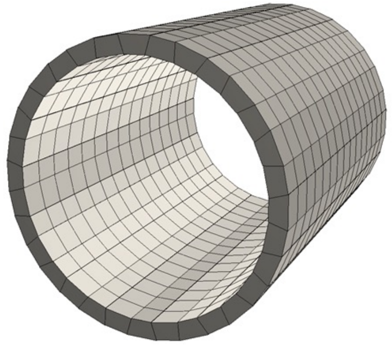
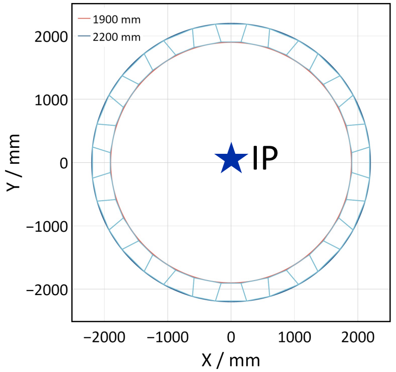


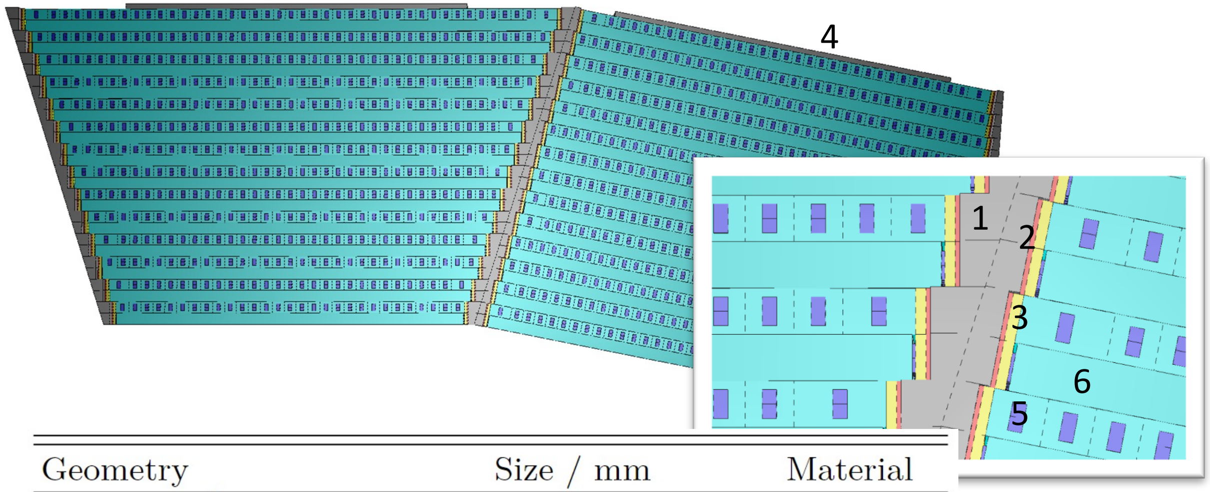
Fig. 21. Normalized LO as a function of integrated dose for various crystals.

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

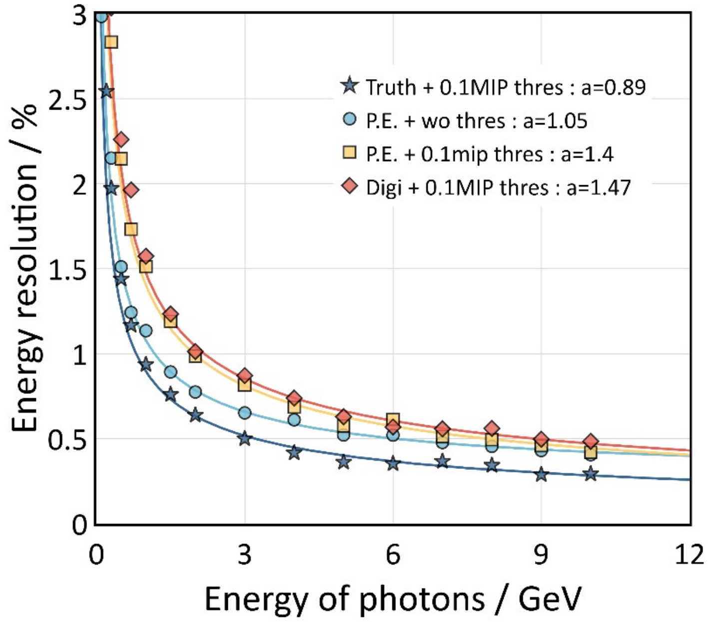
Geometry	Size / mm	Material
Supporting[1]	5	carbon fiber
Cooling[2]	1	copper
Electronics front end[3]	1.2+1	PCB+ASIC
Electronic back board[4]	10	PCB
Electro-optical device[5]	3*3*0.8	SiPM
Wrapping[6]	0.1	ESR
Crystal[6]	~10*10*400	BGO

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

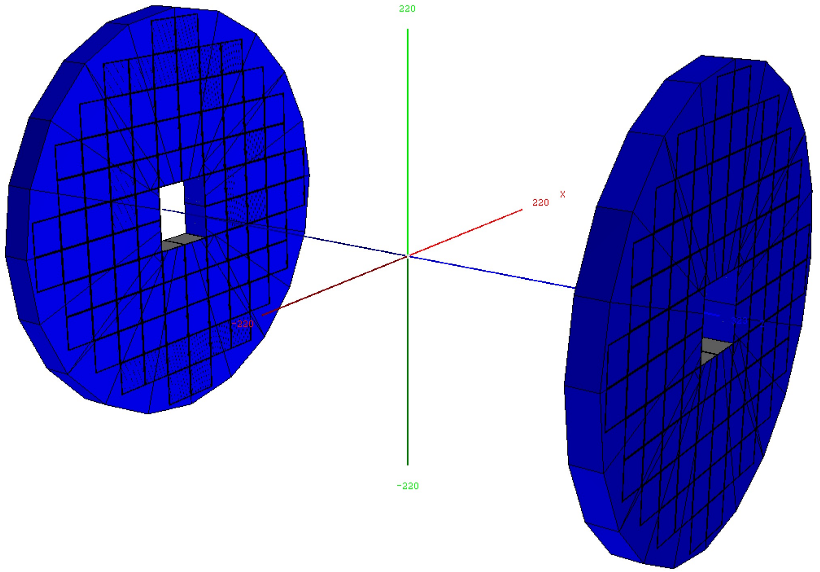
- Crystal-SiPM: detected photons — Poisson Distribution based on muon data of long crystal bar
- SiPM: p.e. conversion to ADC — SiPM gain calibration from LED data
- ASIC: ADC in High Gain or Low Gain — HG-LG conversion

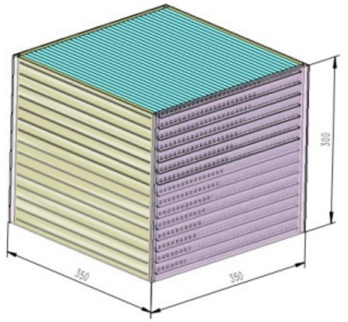


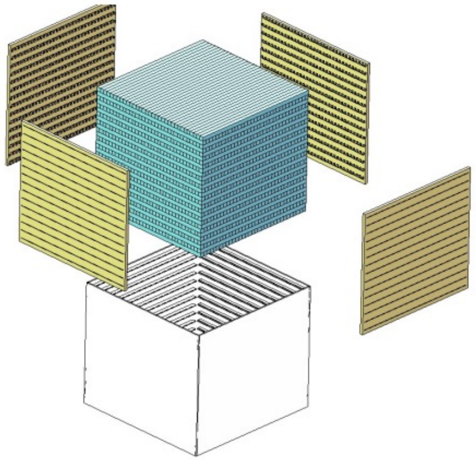
Geometry of Crystal ECAL endcap

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

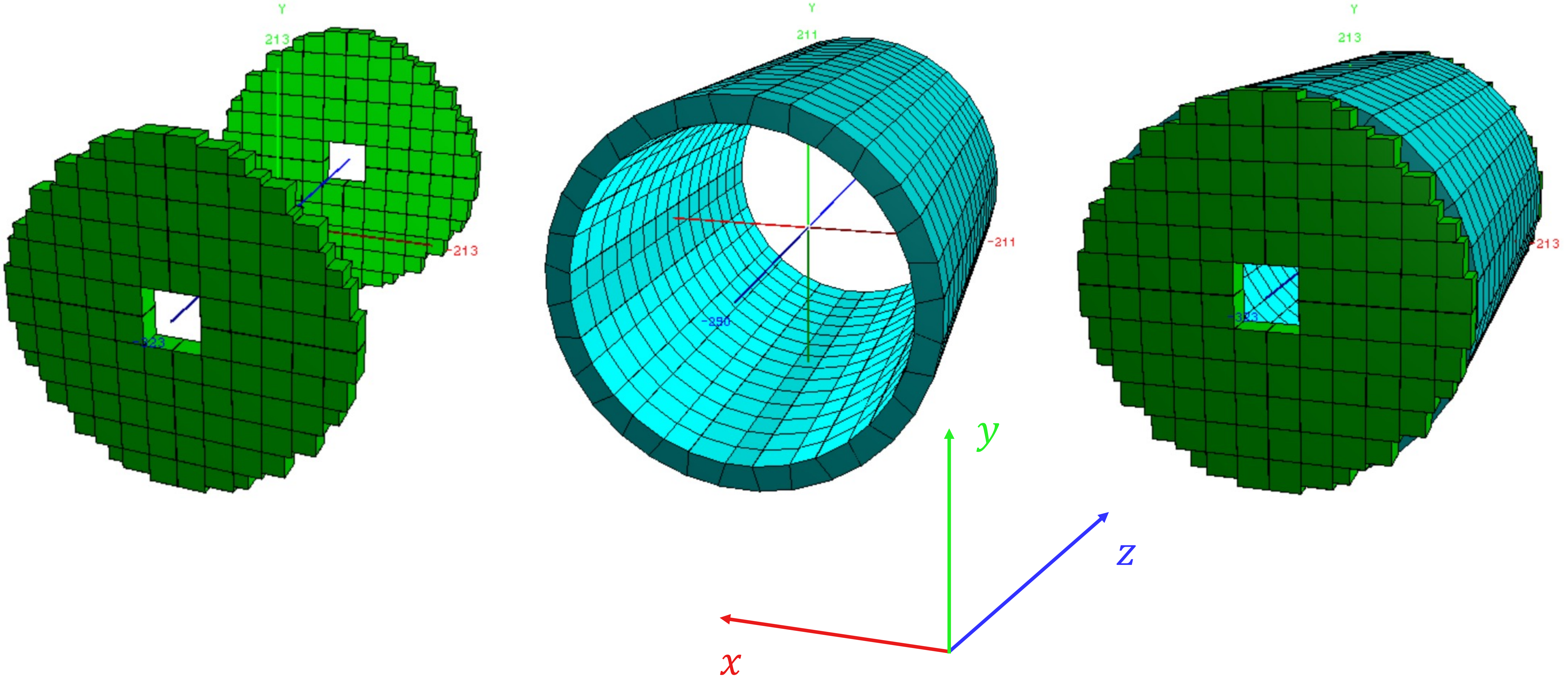
Parameter	Value
Inner radius	350 mm
Outer radius	2200 mm
Z start	2930 mm
Z depth	300mm (24 X_0 268.8 mm)







Overall Structure



Detailed Design (Barrel)