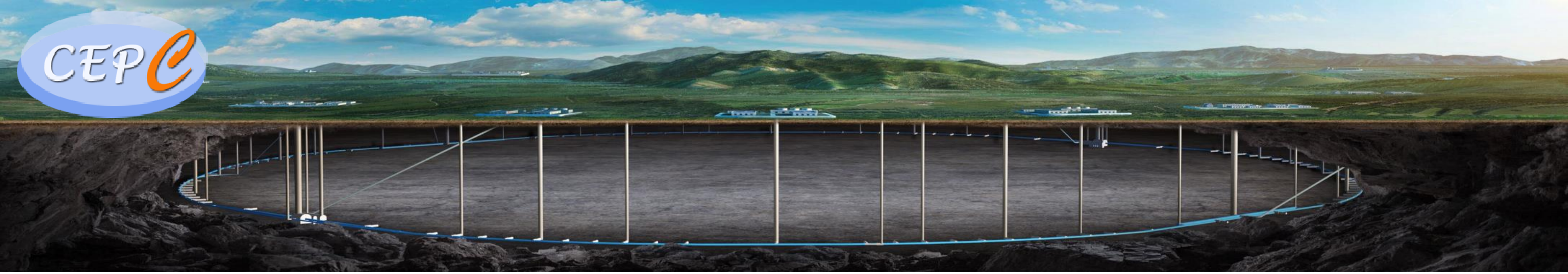


CEPC Electromagnetic Calorimeter

Yong Liu (IHEP),
for the CEPC Ref-TDR ECAL team

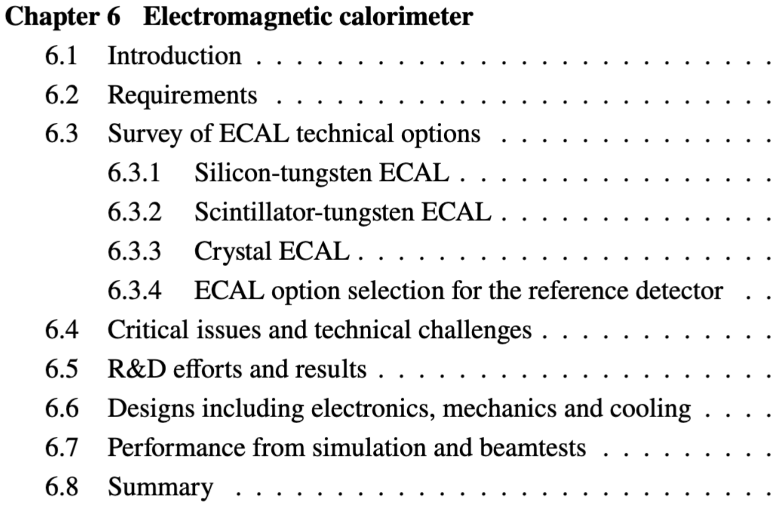
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Content

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

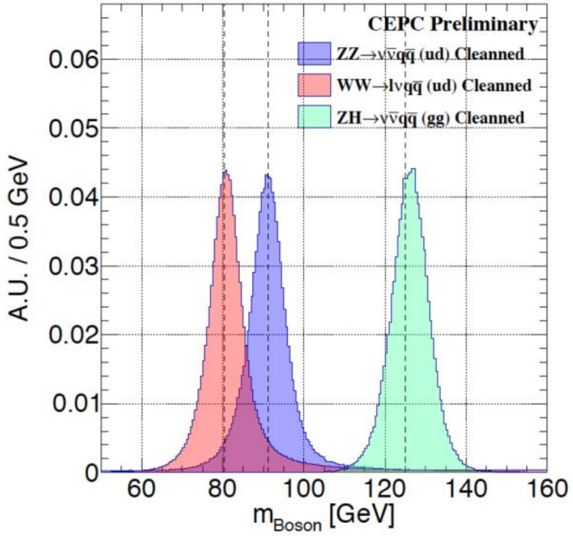
Introduction

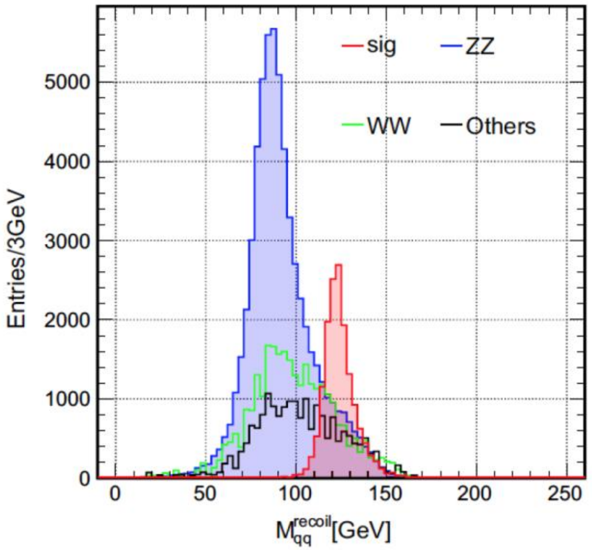
RefDet TDR Outline



Chapter 6 Electromagnetic calorimeter

Why do we need to pursue BMR<4% ?

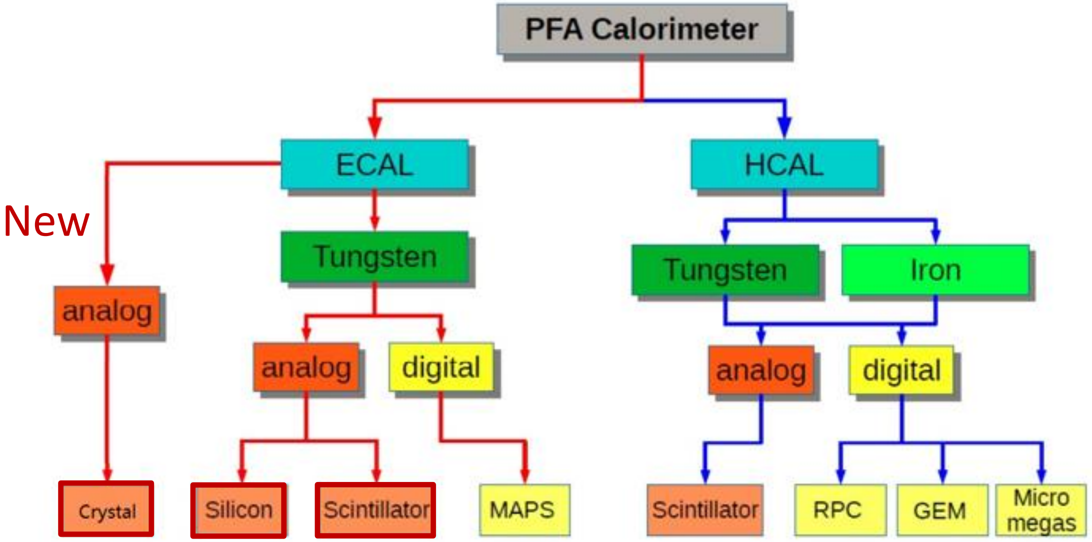




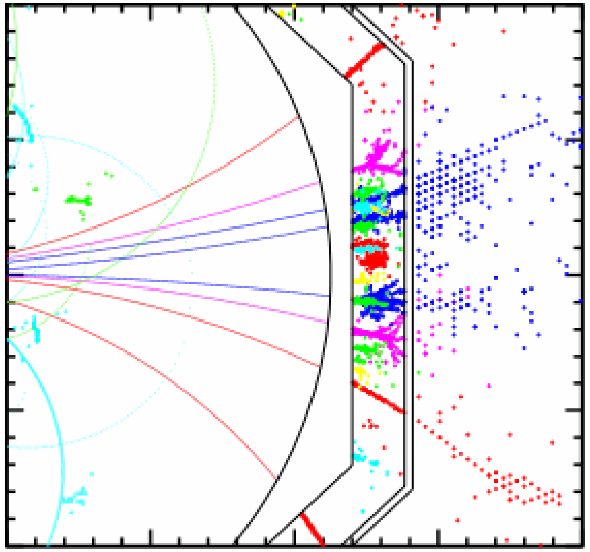
- This talk is about the design and developments of the electromagnetic calorimetry system (related to the RefDet TDR Chapter 06)
- Requirements: CEPC calorimetry system in the reference detector will based on the particle-flow paradigm → high granularity in 3D
  - Aim to achieve an unprecedented Boson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

Technical option survey

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



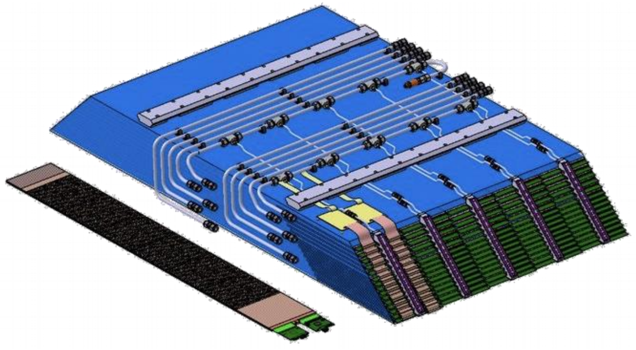
Highly granular (imaging) calorimetry
+ particle flow algorithm (PFA)



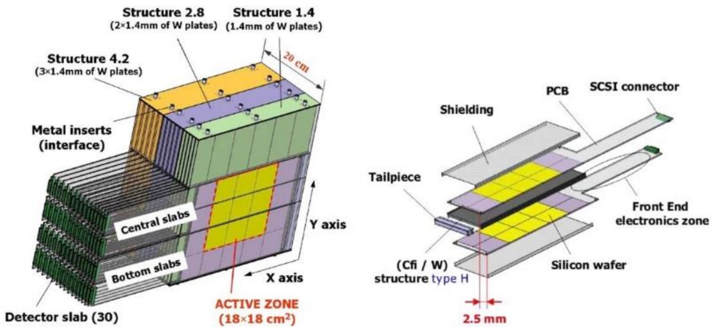
PFA calorimetry: various tech. options explored in the **CALICE collaboration** in past 20 years

SiW-ECAL option

Silicon sensors+ CuW

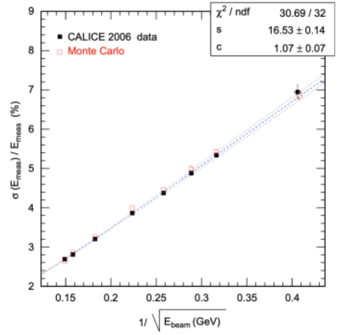


CALICE SiW-ECAL Physics Prototype

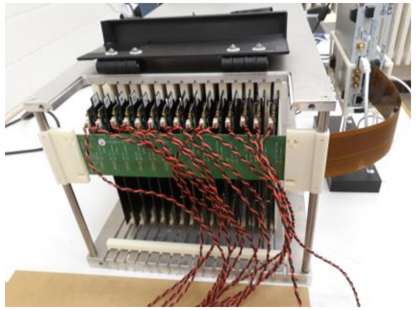


EM resolution in beamtest:

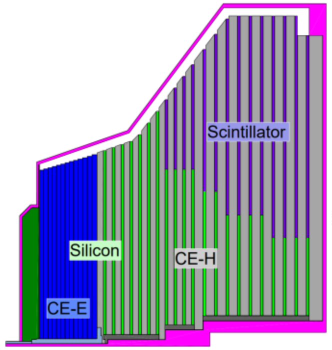
$16.5\%/\sqrt{\mathrm{E(GeV)}} \oplus 1\%$

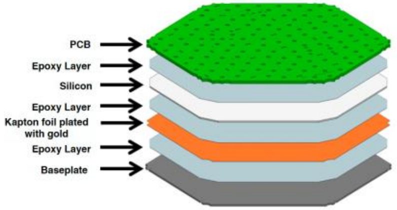


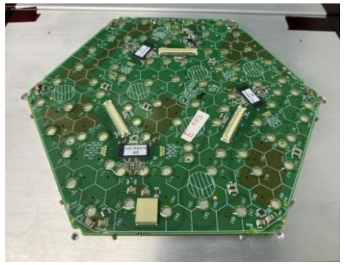
SiW-ECAL Tech. Prototype



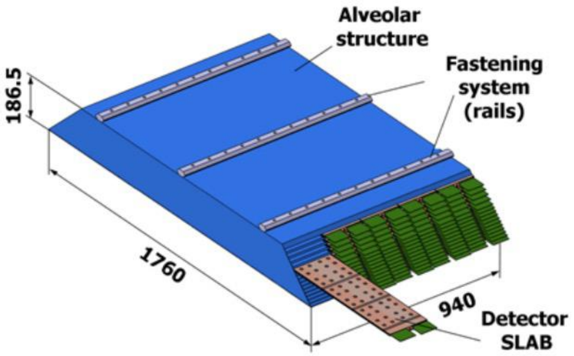
- Silicon-Tungsten option
  - Silicon sensors (pixelated) interleaved with CuW plates (compact showers)
  - Baseline ECAL option in CEPC CDR: extensive Higgs physics studies
  - Active hardware activities in CALICE collaboration: prototypes/beamtests
- Strong synergies with CMS-HGCAL: application in silicon sector
  - HGCAL taskforce successfully established two sites at IHEP
    - MAC (Module Assembly Center) Beijing Site (1/6 MACs)
    - SQC (Sensor Quality Control) Beijing Site (1/5 SQCs)

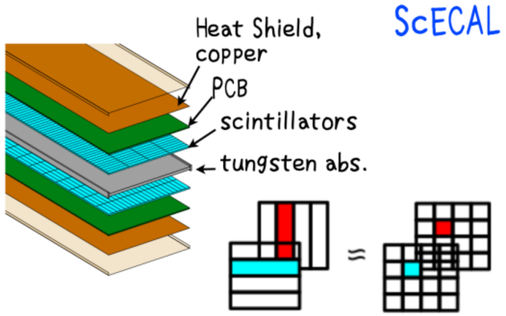




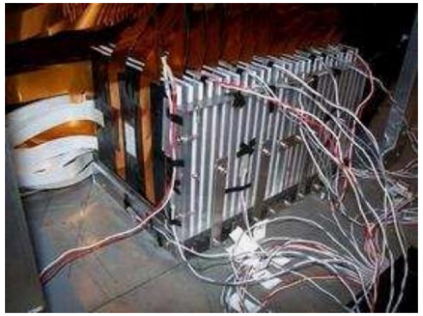


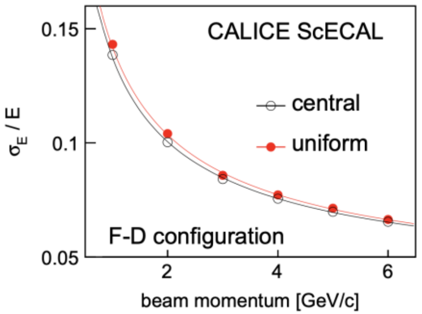
ScW-ECAL option





CALICE SiW-ECAL Physics Prototype





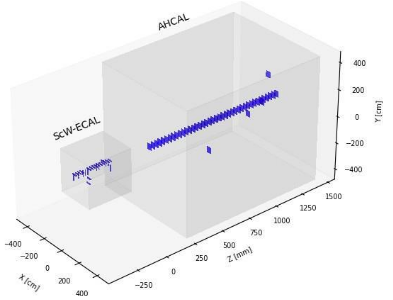
EM resolution in beamtest:

$13.3\%/\sqrt{\mathrm{E(GeV)}} \oplus 3.6\%$

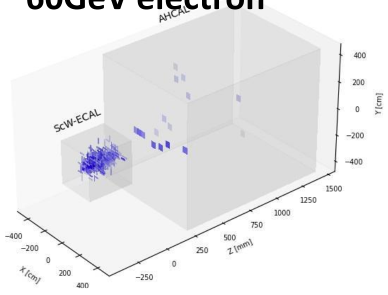
CALICE ScW-ECAL Tech. Prototype

- Scintillator-Tungsten option
  - Scintillator strips + SiPMs as sensitive layers
  - Cost effective option for fine transverse granularity ($5 \times 5\ \mathrm{mm}^2$)
- ScW-ECAL tech. prototype in 2016-2021
  - Developed by Chinese and Japanese groups in CALICE collaboration
  - Successful beamtests at CERN PS/SPS in 2022-2023
  - Collected data sets with various beam particles

100GeV muon

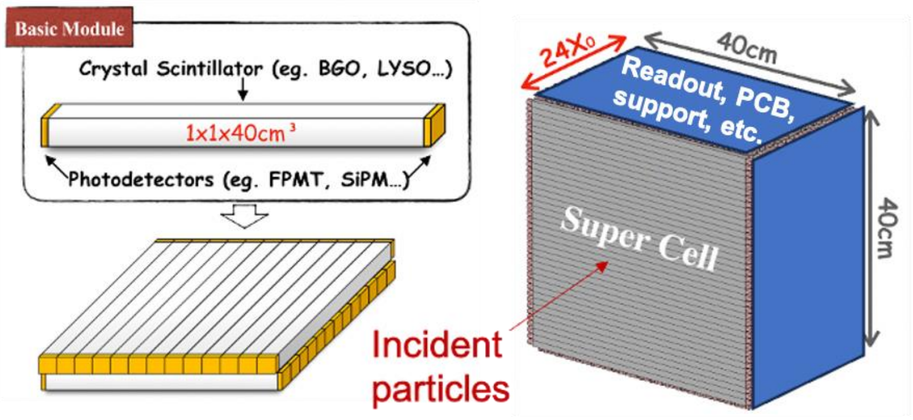


60GeV electron



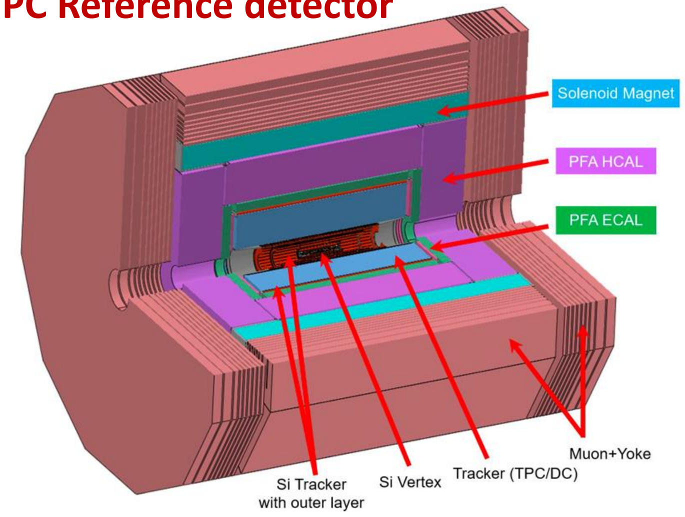
4D Crystal ECAL option

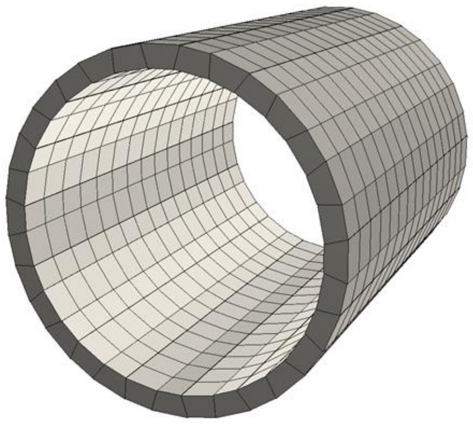
- A new option: development started since ~2020
- Compatible for PFA: Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E = 3\%/\sqrt{E}$
- Minimal longitudinal dead material: orthogonal arranged bars
  - 3D positioning with two-sided readout for timing



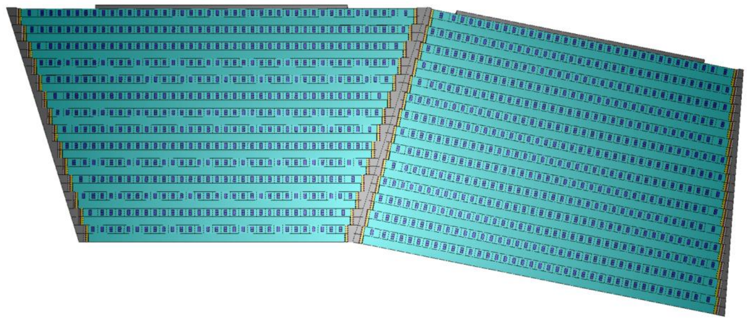
- **BGO bars in $1 \times 1 \times {\sim}40\ cm^3$**
- **Effective granularity $1 \times 1 \times 2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**

CEPC Reference detector



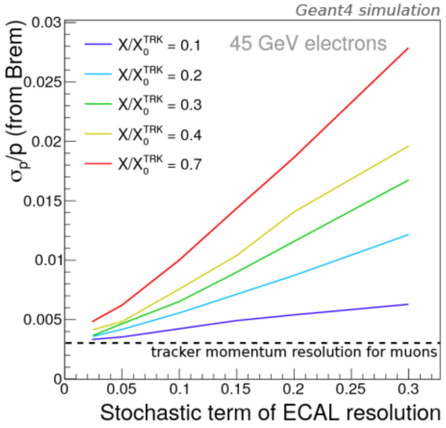


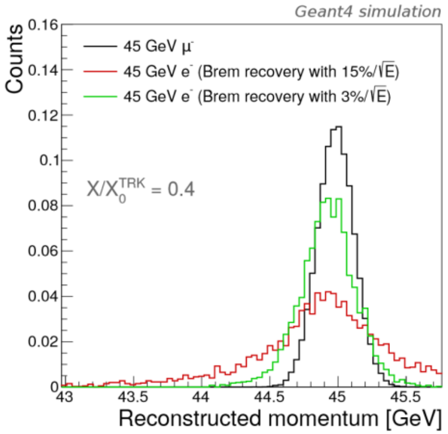
32-side polygon, depth 24 X_0
28 longitudinal layers



Crystal ECAL: physics motivations

- Crystal provides an energy resolution to photons and electrons at the level of $3\%/\sqrt{E}$
  - Significantly enhance EM performance with similar budget of SiW-ECAL
- Higgs and EW physics programs
  - Precision measurements of Higgs recoil mass: e.g. *Bremsstrahlung energy corrections* of **electrons** in $\mathrm{ZH} \rightarrow \mathrm{eeX}$
  - To further enhance jet performance by fine reconstruction of neutral pions ($\pi^0 \rightarrow \gamma\gamma$), esp. in 4-/6-jet scenarios
- Flavour physics programs: benefit from excellent performance for photons and neutral pions
- Searches for new physics beyond Standard Model
  - Using photons as a portal to search for new particles (e.g. Axion-Like Particles)





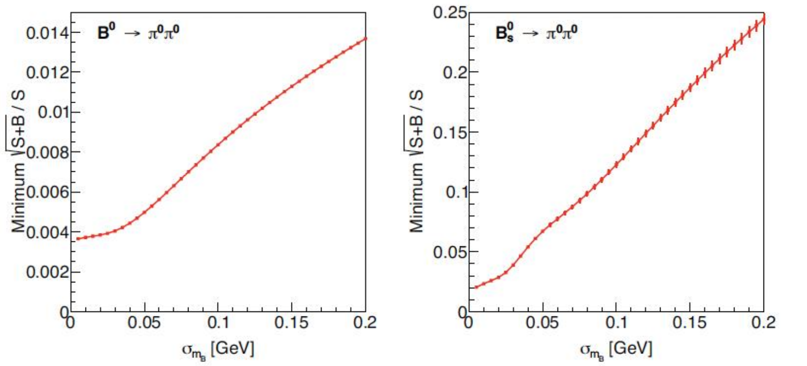
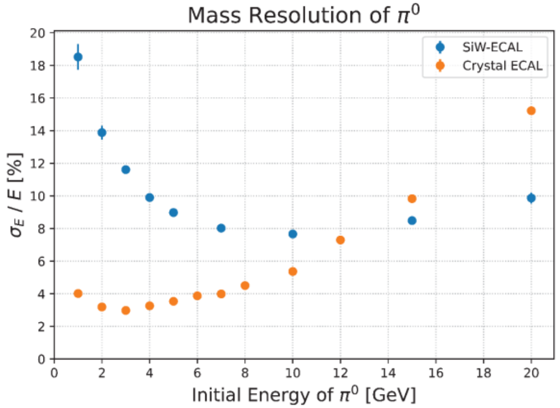


Figure 24. Measurement precision of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) versus B-meson mass resolution σ_{m_B}.



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

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): 3-4%**		
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

Baseline ECAL option for the CEPC reference detector

- ***Crystal ECAL***, as a novel option of PFA calorimetry, provides optimal EM resolution

Crystal ECAL: Main Technical Challenges

- Particle-flow algorithm: pattern recognition and ambiguity issue for long bars
- High granularity: at the level of 1 million 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

Detector requirements

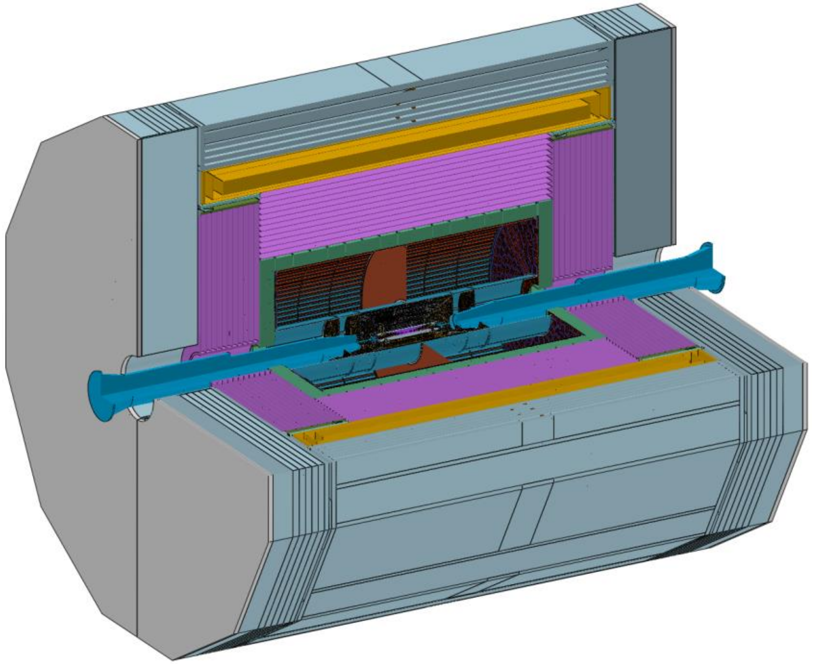
- PFA compatibility and BMR<4%
- Moderate MIP light yield
- Good uniformity
- Optimal time resolution
- Large dynamic range
- Moderate S/N ratio

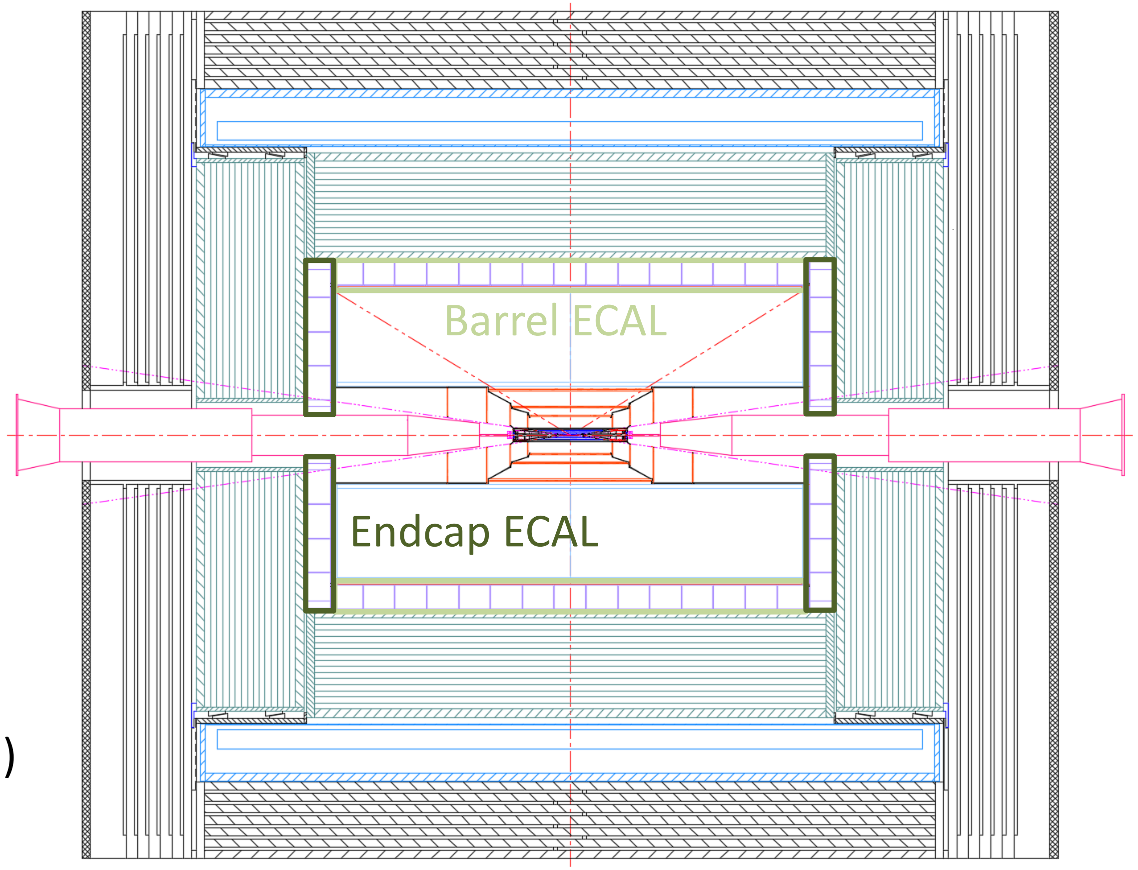
R&D activities: addressing crucial issues

- New PFA to address pattern recognition issues
- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal dimensions
- Dynamic range of electronics
- Energy response of crystal module

Crystal ECAL: mechanics and software

- Physics performance studies in CEPC software (CEPCSW)
  - Implemented with geometry of **mechanics design** and digitistation (**prototyping and beamtests**)



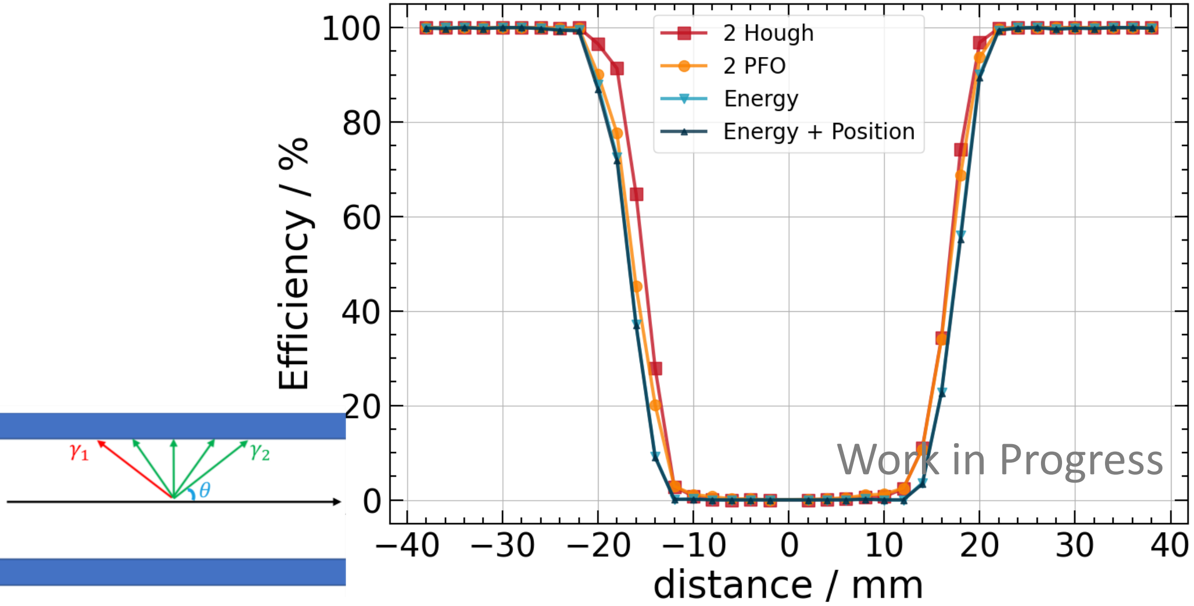


Depth: 24X0 with scintillating crystals (BGO or BSO)
Barrel ECAL: 5800 mm in length
Endcap ECAL: 4260 mm in outer diameter

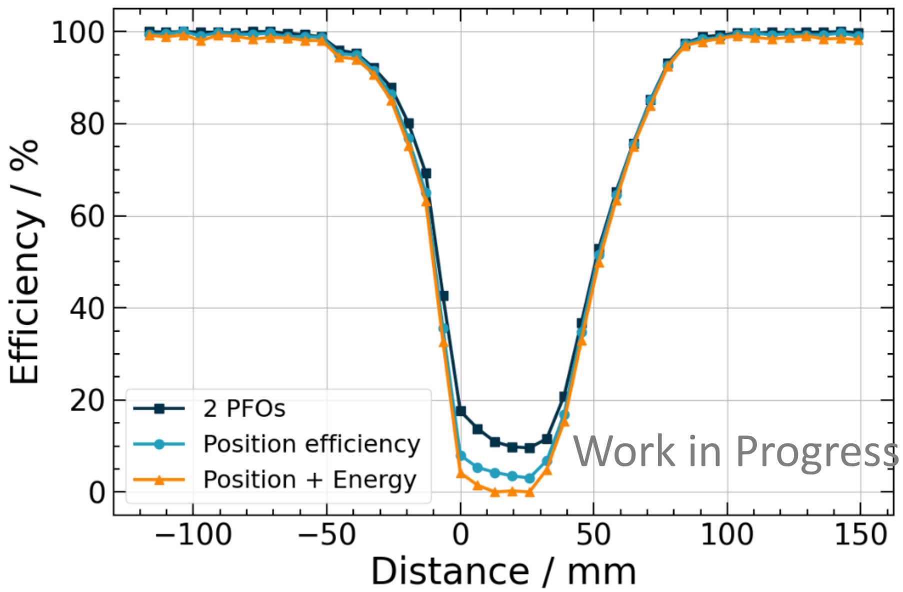
Performance in simulation: separation power

- **New PFA reconstruction software** developed for the design of long crystal bars
- Separation power of close-by particles: key performance in particle flow
  - $\gamma-\gamma$ separation: 100% efficiency for distance > 20mm
  - $\gamma-\pi$ separation : 100% efficiency for distance > 50~100mm

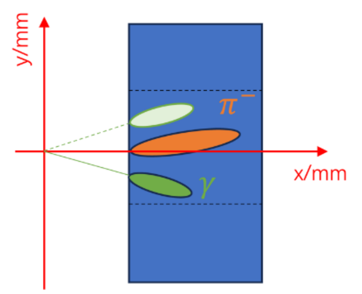
Details in the “Software and Computing” talk



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



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

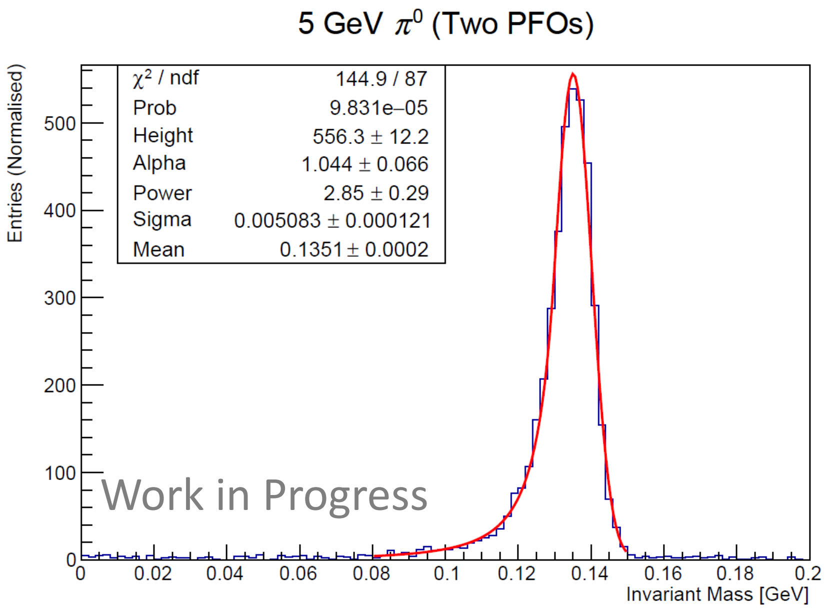


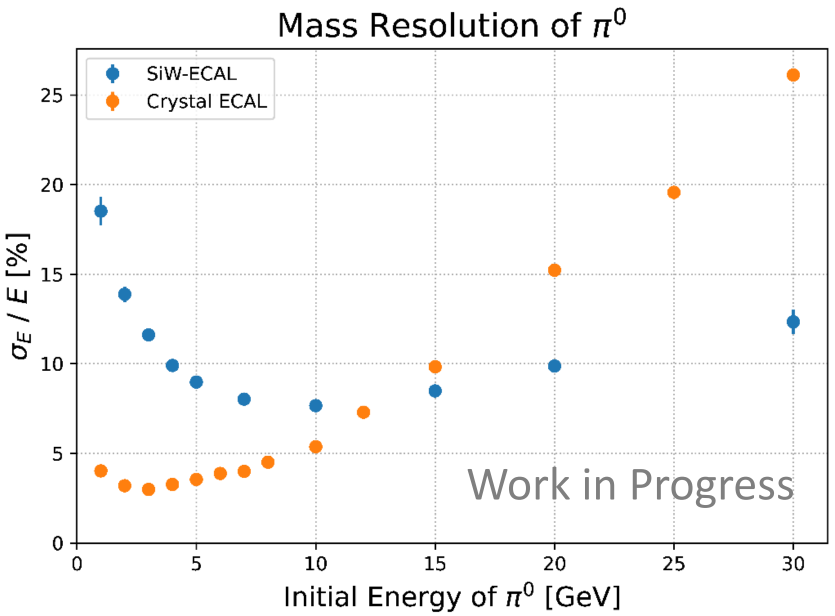
*Asymmetry pattern is due to the magnetic field

Performance in simulation: neutral pions

Using CyberPFA for long crystal bars

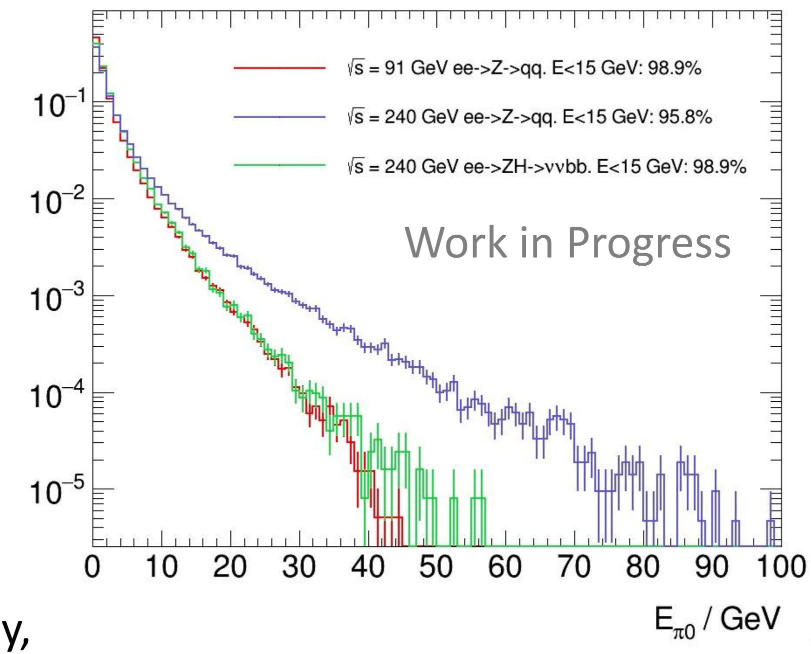
- Crystal ECAL shows excellent performance for single π^0 in 1-10 GeV
  - More than 95% of π^0 with energy <15 GeV in jets from Higgs and Z
  - Ongoing crosschecks to further improve π^0 performance in higher energy





EM resolution dominates in lower energy,
angular resolution prevails in higher energy

Energy of π^0 in jets from H/Z bosons

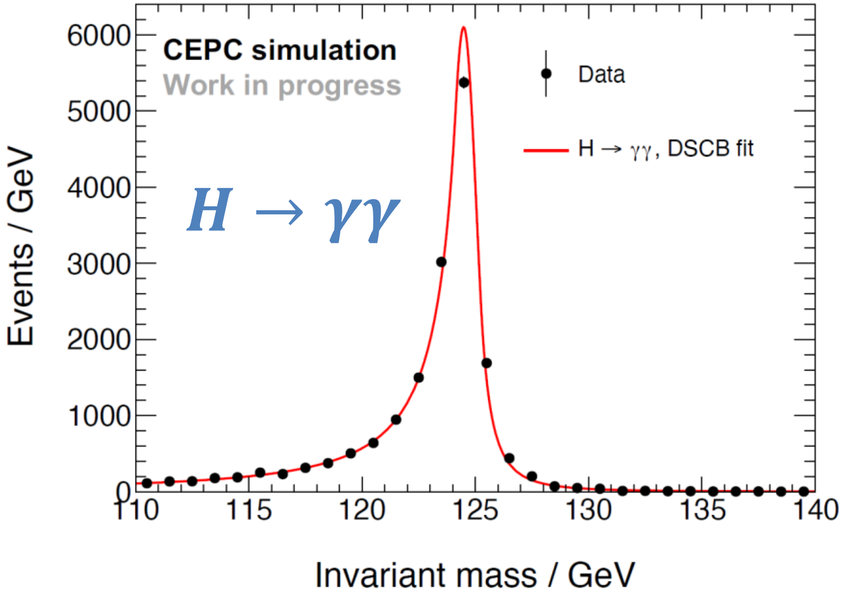


Physics performance in simulation: Higgs boson

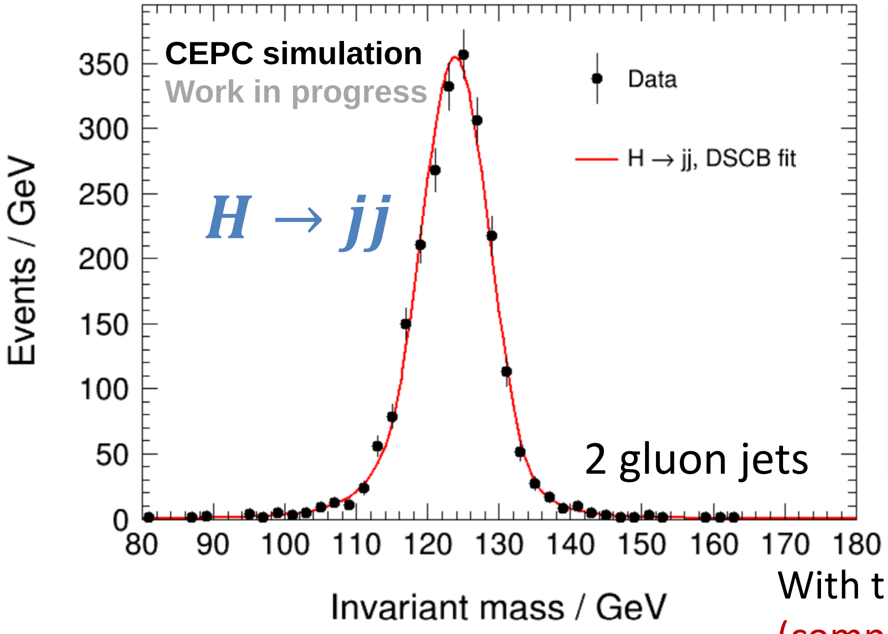
Using CyberPFA for long crystal bars

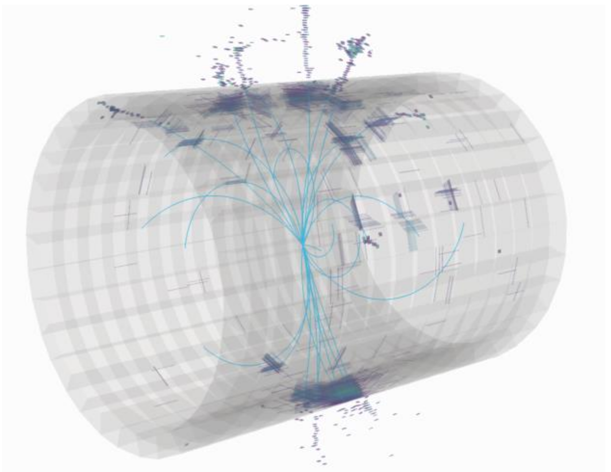
- Higgs benchmark studies at CEPC 240 GeV
  - Higgs decays to 2 photons (EM performance) and 2 gluon jets (PFA performance)

$ZH \rightarrow \nu\nu\gamma\gamma\ (H \rightarrow \gamma\gamma)$: $\sigma(m_{\gamma\gamma})$ = 0.57 GeV



$ZH \rightarrow \nu\nu gg\ (H \rightarrow gg)$ at **240GeV** : BMR = 3.95%





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

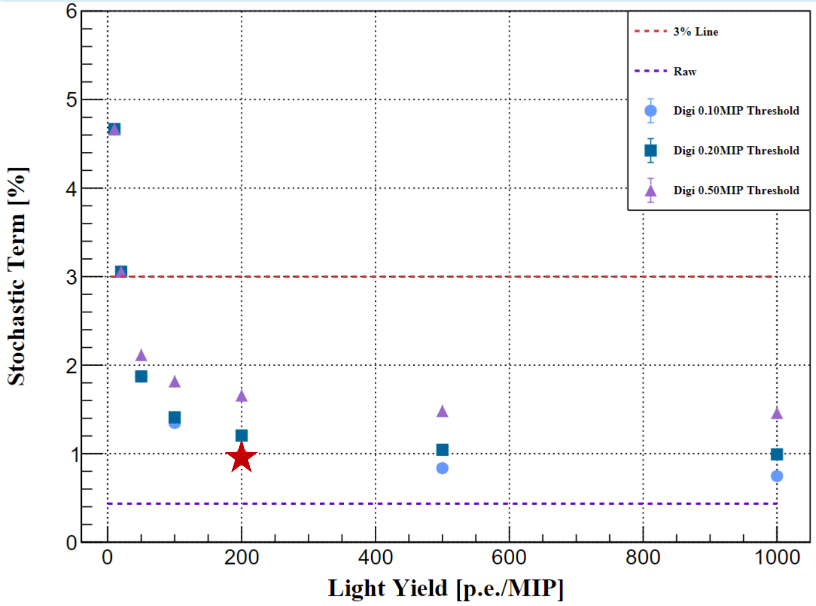
- Tracker + crystal bar ECAL + GS-HCAL, barrel only
- Improvements are expected with further optimizations (tracking, clustering...)

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

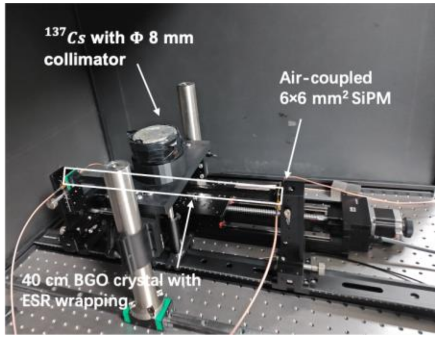
- **MIP response:** >200 p.e./MIP → $\sigma_E/\mathbf{E} < 3\%/\sqrt{E}$
- **Energy threshold:** 0.1 MIP

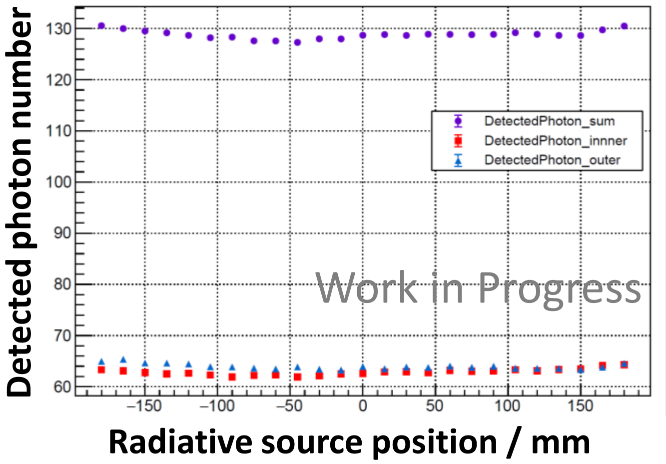
Light yield vs. energy resolution



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

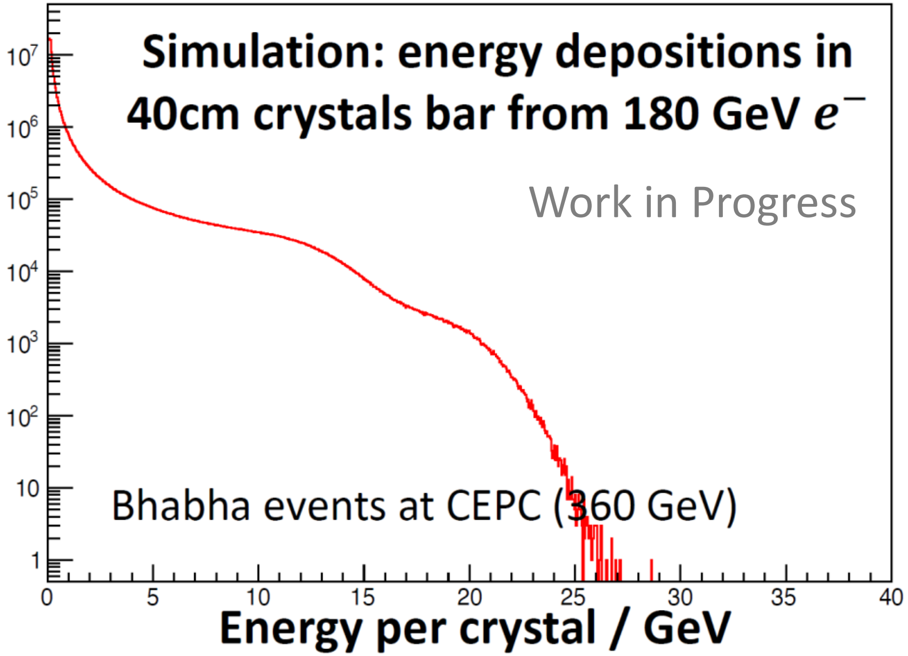
Response uniformity along bar





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 (target for ***6μm pixel pitch***)
- Beamtest of crystal-SiPM units with a state-of-art chip: dynamic range of SiPM and ASIC

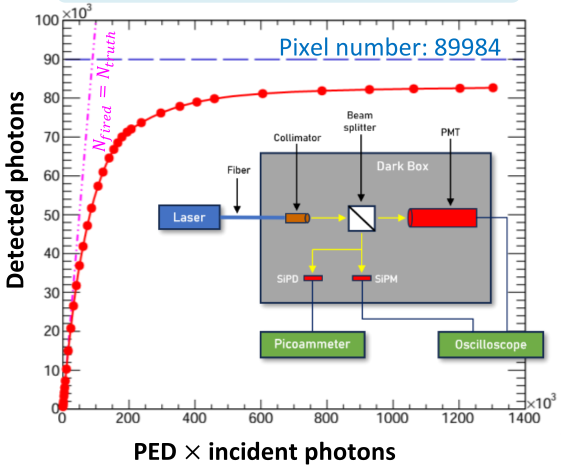


~30 GeV as max. energy deposition per crystal bar

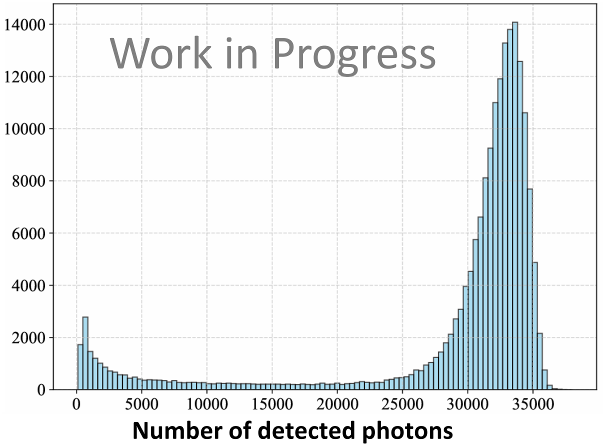
Pico-laser system for SiPM non-linearity studies in lab

State-of-art ASIC dynamic range: ~1.2nC tested in showers

SiPM linear range



ASIC 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

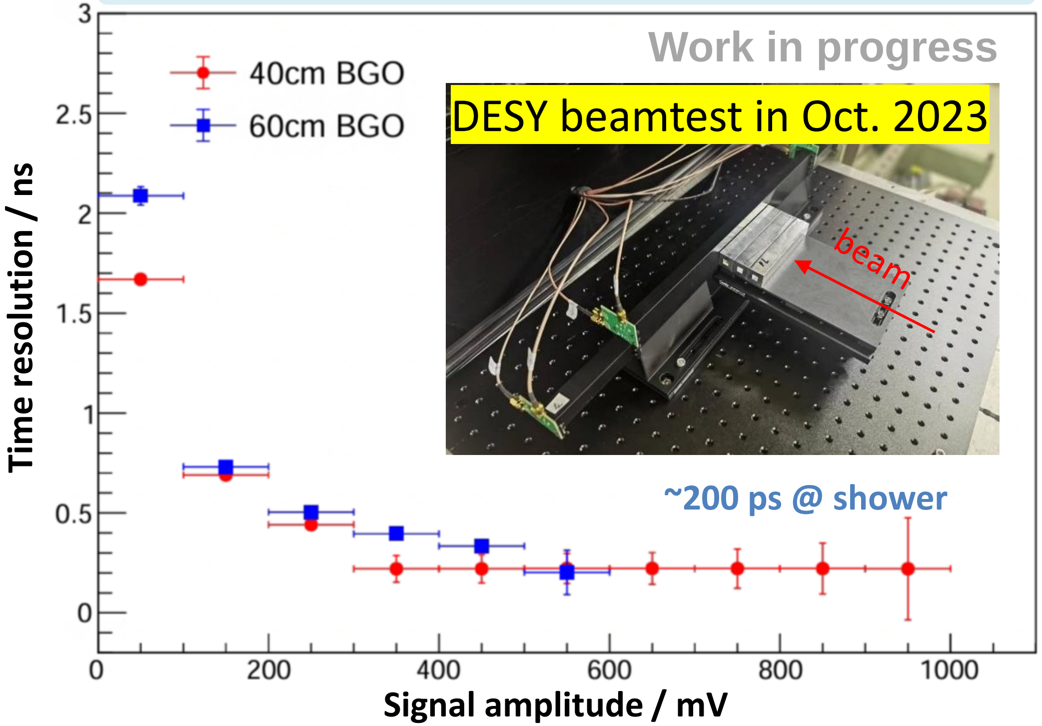
R&D efforts and results: timing studies

Dedicated beamtests for timing studies with MIP and EM showers

Timing performance within EM showers

- Tested 40cm/60cm BGO bars with 5GeV electron beam
- ~200 ps around EM shower maximum (>12 MIPs)

Time resolution vs signal amplitude

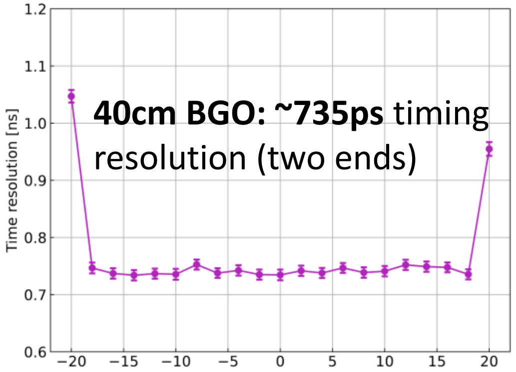


DESY beamtest in Oct. 2023

~200 ps @ shower

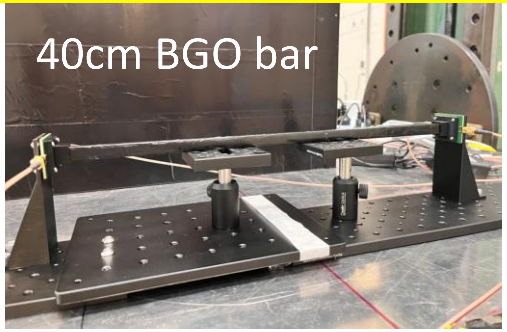
Timing performance with MIP-like particles

- 10 GeV π^- beam to scan 40cm and 60cm BGO bars
- 40cm BGO: MIP timing resolution of 520 ps at a single end
- 60cm BGO: MIP timing resolution of 665 ps at a single end

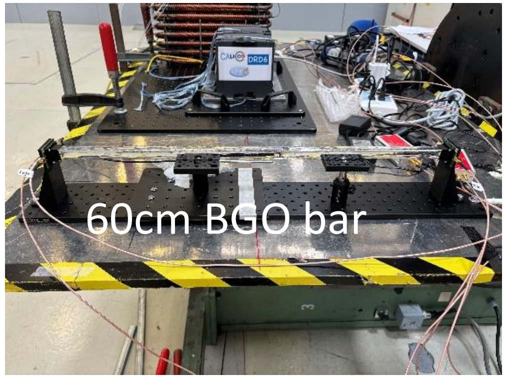


40cm BGO: ~735ps timing resolution (two ends)

CERN beamtest in Jul. 2024

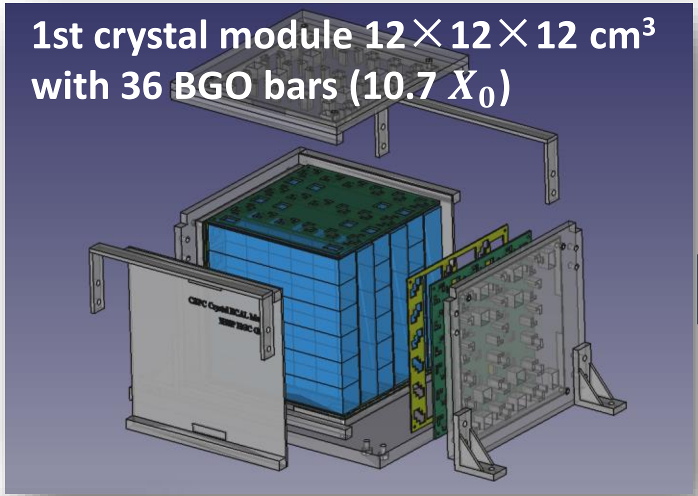


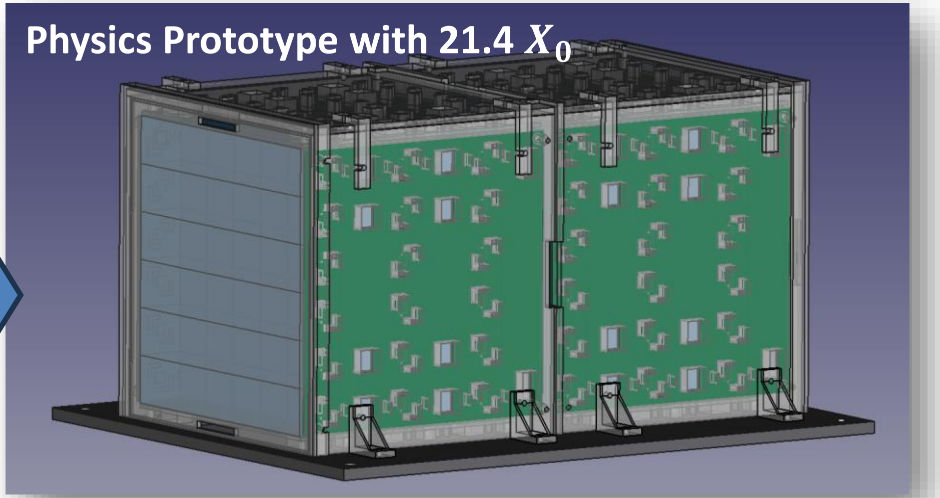
60cm BGO: ~940ps timing resolution (two ends)

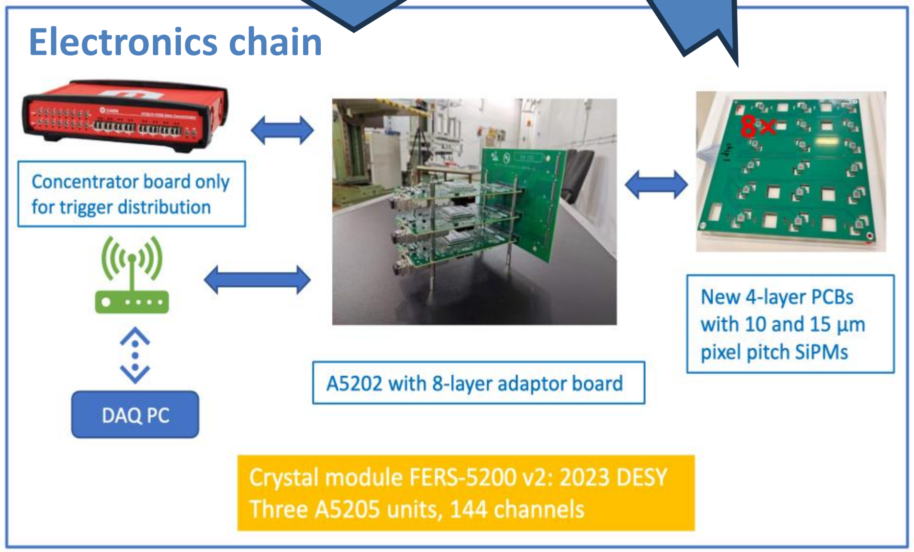


4D Crystal Calorimeter: First Physics Prototype


BGO crystals from SIC-CAS (12×2×2 cm³)


1st crystal module 12×12×12 cm³ with 36 BGO bars (10.7 X_0)


Physics Prototype with 21.4 X_0


Electronics chain

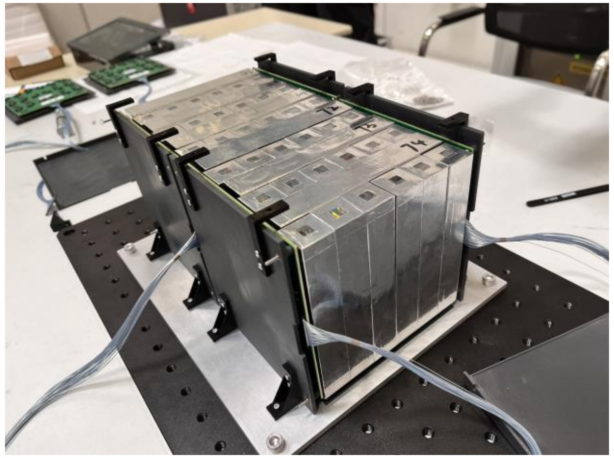
Concentrator board only for trigger distribution

DAQ PC

A5202 with 8-layer adaptor board

New 4-layer PCBs with 10 and 15 µm pixel pitch SiPMs

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



First crystal calorimeter prototype

- Successfully developed in 2021-23
- With commercial ASICs

Major motivations

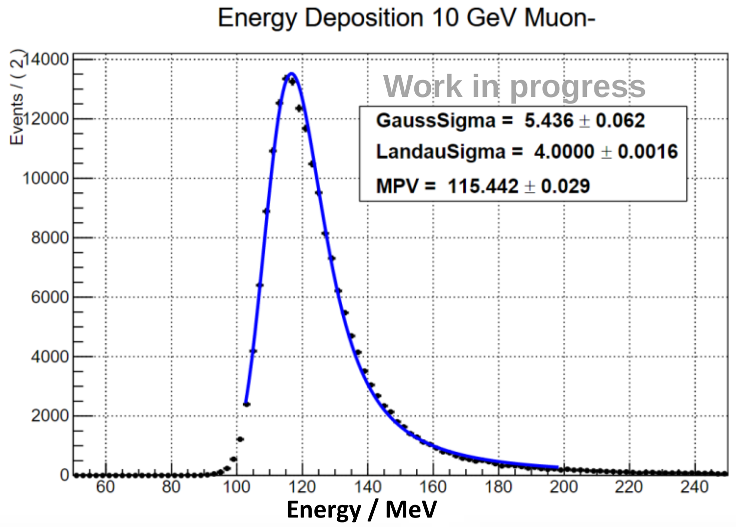
- Critical issues at system integration
- EM performance in system level
- Validation of simulation and digitization with beamtest data

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

Beam tests: 4D Crystal Calorimeter Prototype

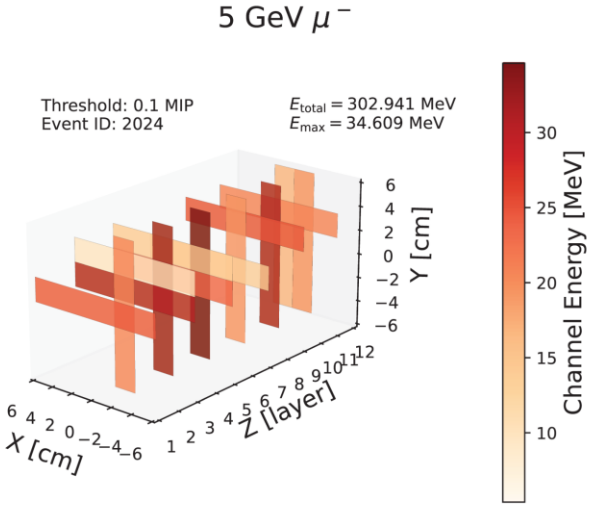
2023 CERN beam test at PS-T9

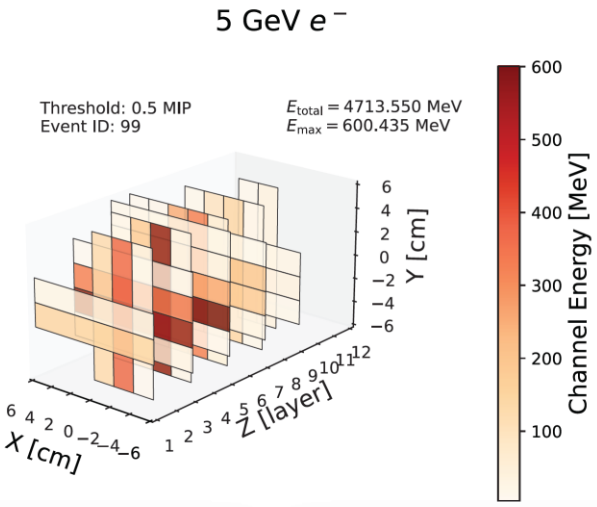
- Successful system commissioning
- Clear MIP signals for all channels

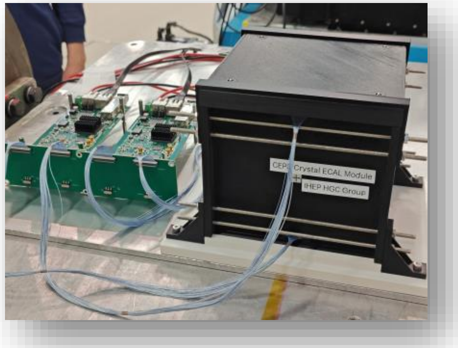


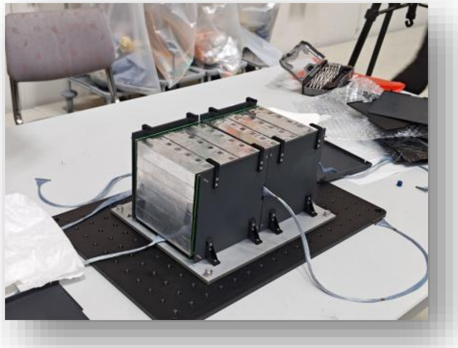
2024 CERN beam test at PS-T9 (June 24 – July 10)

- Promising EM resolution with 1-10 GeV/c e^- beam
- Data analysis: detailed calibrations, shower profiles

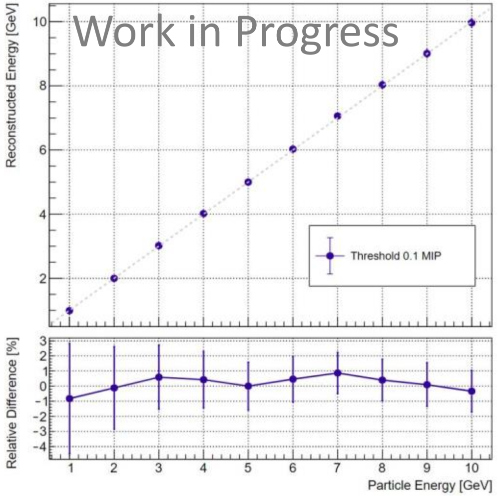


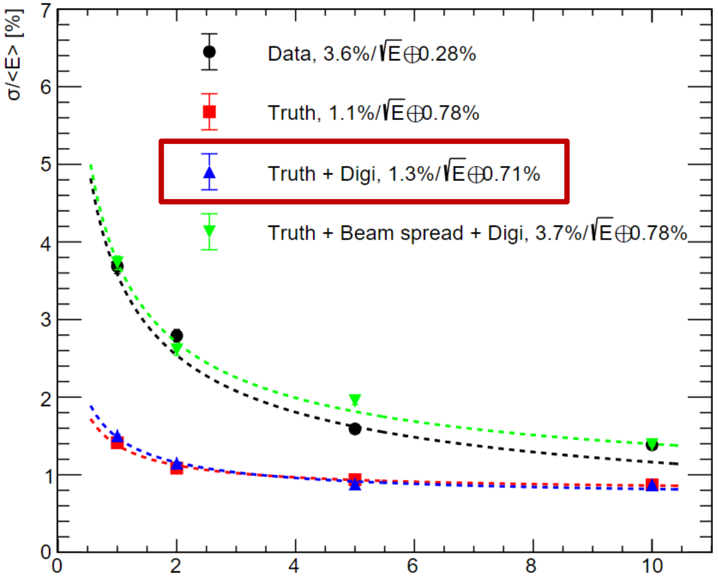






Crystal Calorimeter Prototype: 2024 CERN beamtest





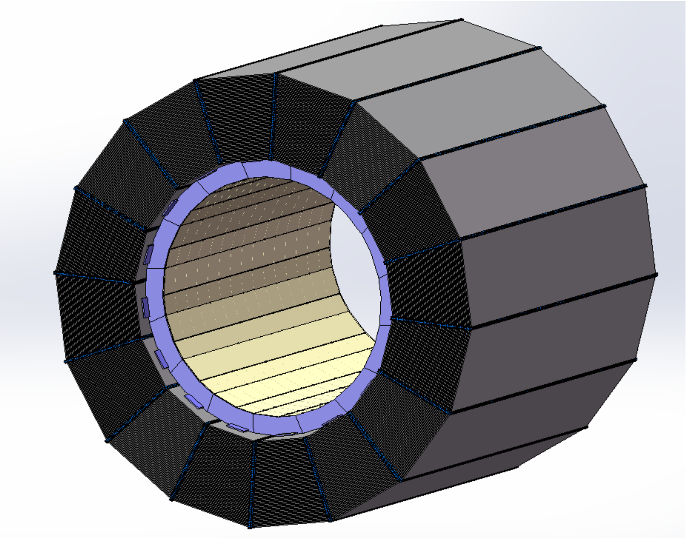
- Studies based on electron beam data in 1 – 10 GeV
  - Data taken with ALL beam instrumentation in upstream: Cherenkov detectors (XCET), SciFi trackers for beam profiles
- EM response linearity within $\pm 1\%$
  - Better understanding of calibration precision (~0.5%) and corrections of crosstalk in ASIC neighbouring channels
- EM energy resolution
  - CERN expert confirmed our observation: larger beam momentum spread in data than expected from beamline lattice (~1%)
  - Calorimeter EM performance majorly dominated by beam spread in lower energy (typically ~3% at 1GeV)
  - **Extensive studies on PS-T9 beamline** (with kind help of CERN expert) to quantify momentum spread due to beam instrumentation
  - Crystal prototype EM performance (preliminary): $1.3\%/\sqrt{E} \oplus 0.7\%$

ECAL mechanics design

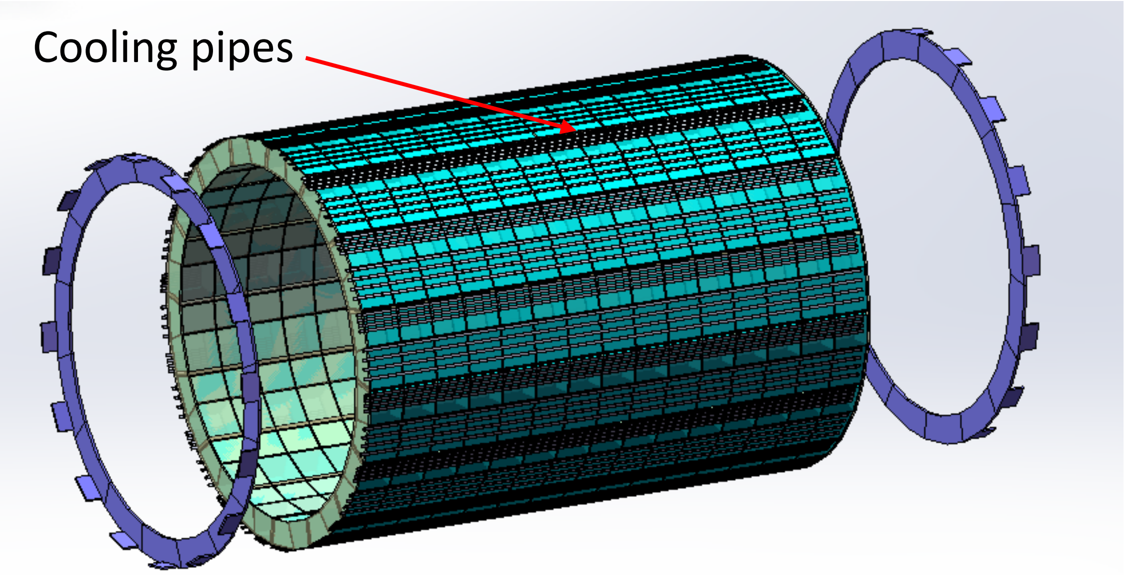
- Crystal ECAL mechanics integrated with active cooling

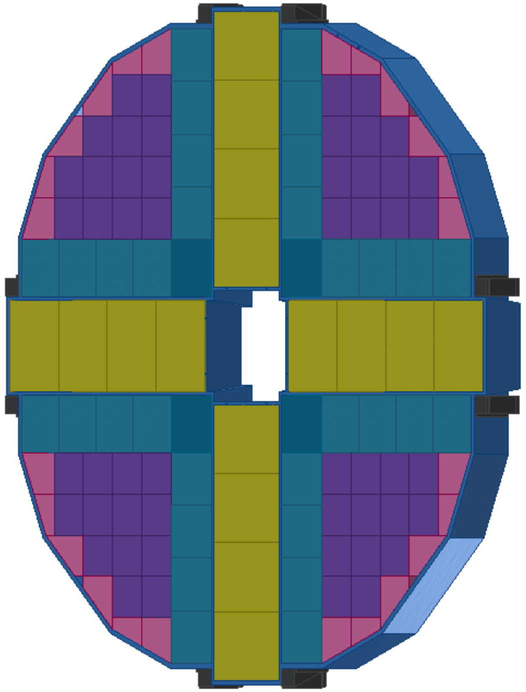
Endcap ECAL design

Barrel ECAL design



Inter-connection to HCAL

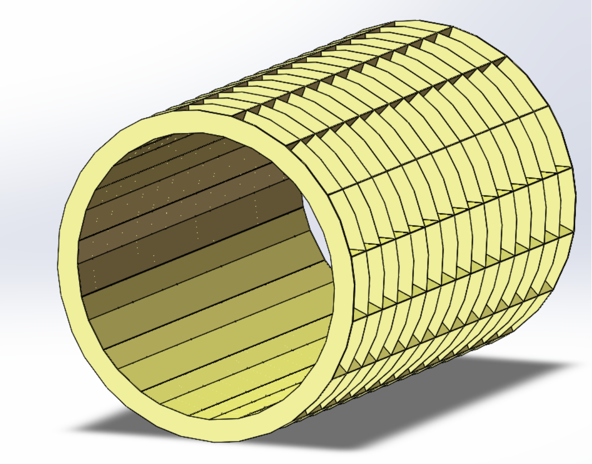




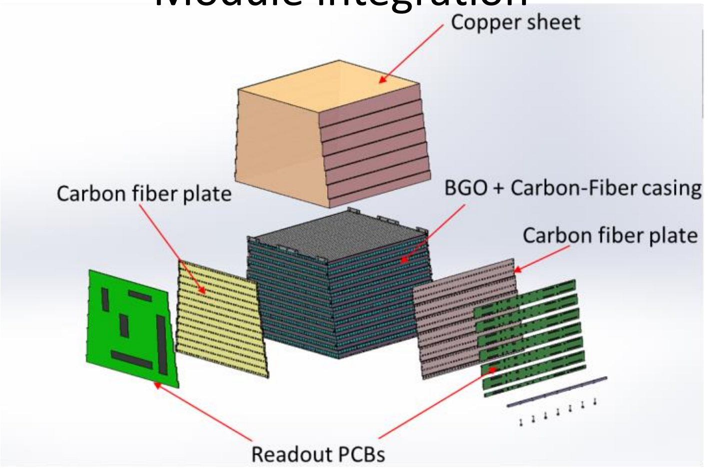
- Carbon-Fiber structure for crystal modules

ECAL mechanics: main structure and barrel modules

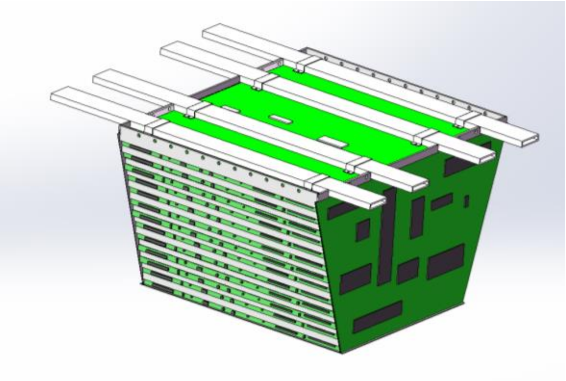
Main structure



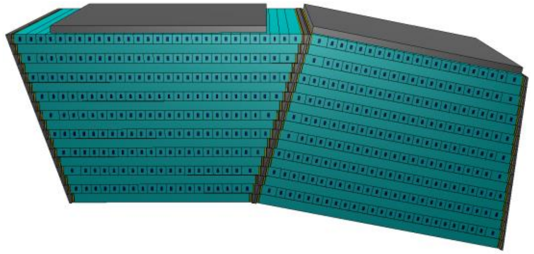
Module integration



Cooling pipes for a module



Two crystal modules in one phi/z segment



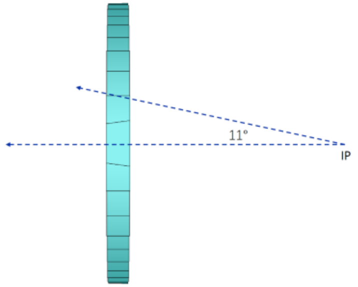
Barrel ECAL parameters

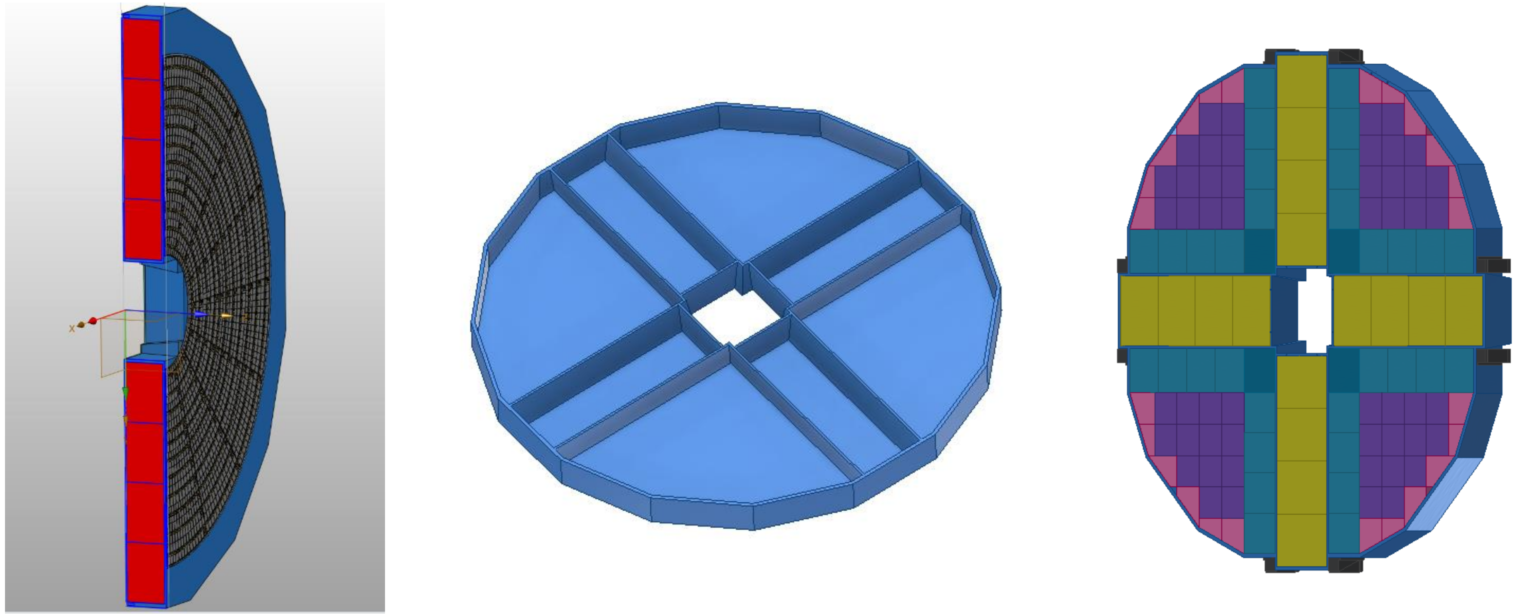
Parameters	Value
Inner Radius	1830 mm
Outer Radius	2130 mm
Length in Z	5800 mm
(Typical) Crystal Length	400 mm
#Modules in R-Phi	32
#Modules in Z	15
Tilted Angle in Phi	12 degrees
Longitudinal Layers	28

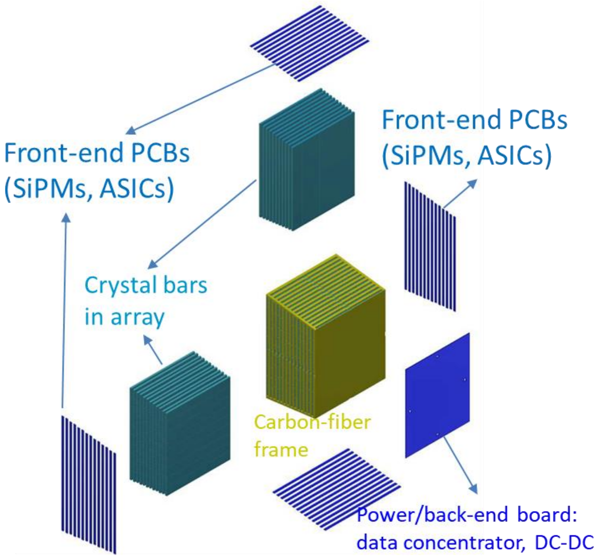
- Main structure is based on carbon fibers
  - Ensure mechanical strength/stability and lowest possible materials
- Barrel ECAL modularity
  - 16 segments in phi, 15 segments along Z-axis
  - In each segment: two crystal modules in trapezoid-shape
  - Optimised module boundaries (in R-phi): not projectile to IP

ECAL mechanics: endcap structure and modules

- Endcap crystal modules
  - Optimised module boundaries to avoid projectile cracks to IP
  - 6 different types, trapezoid modules in blue and yellow
- Supporting frame to hold both endcap ECAL and OTK
- Planning: FEA simulation for stability, deformation and cooling







Front-end PCBs (SiPMs, ASICs)

Front-end PCBs (SiPMs, ASICs)

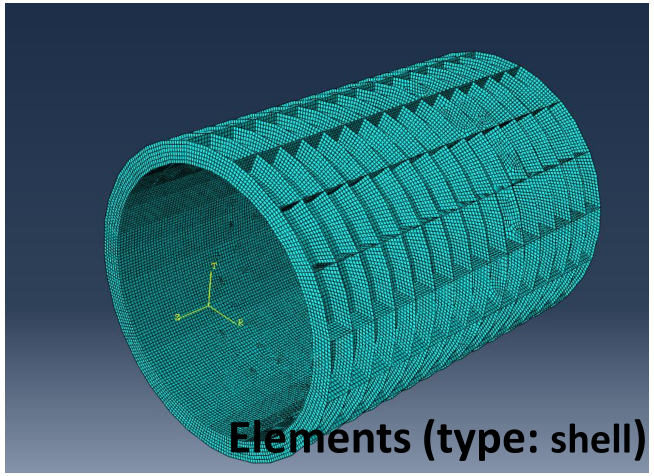
Crystal bars in array

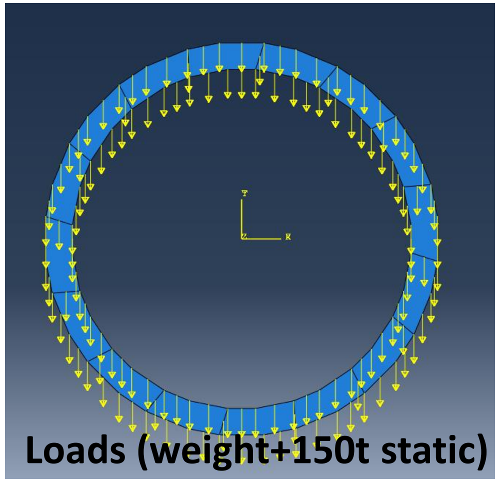
Carbon-fiber frame

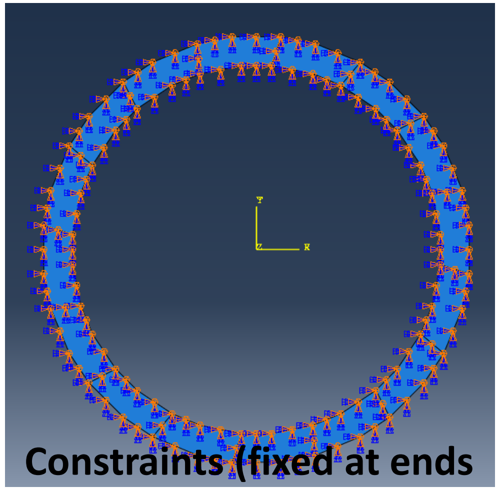
Power/back-end board: data concentrator, DC-DC

Barrel ECAL mechanics: FEA simulation

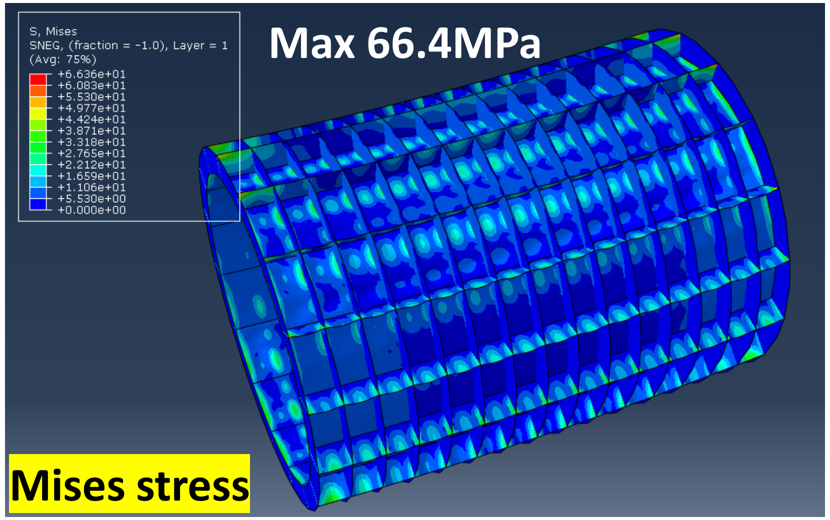
- FEA simulation studies on ECAL mechanics (ongoing): optimization + validation


Elements (type: shell)

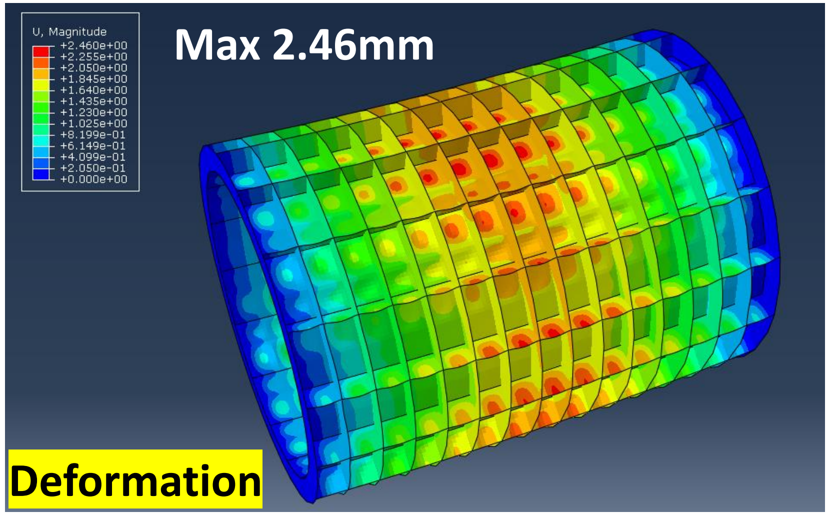

Loads (weight+150t static)


Constraints (fixed at ends

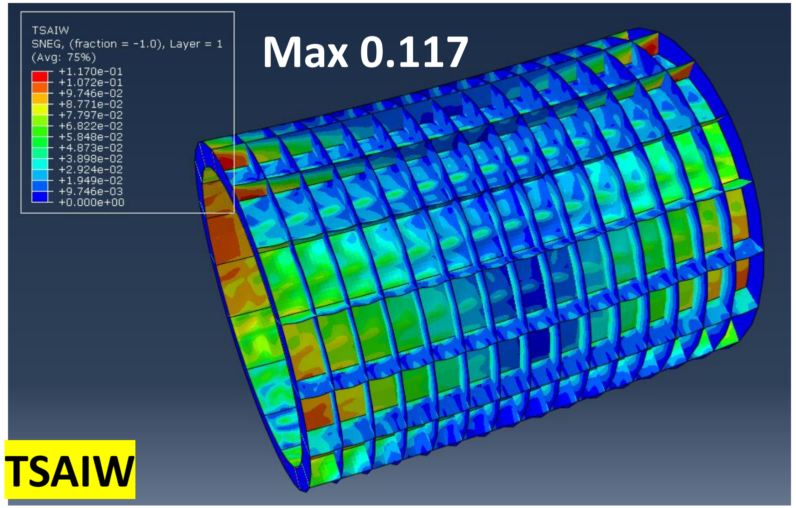
- **Material** :T700 reinforced epoxy resin



Mises stress



Deformation



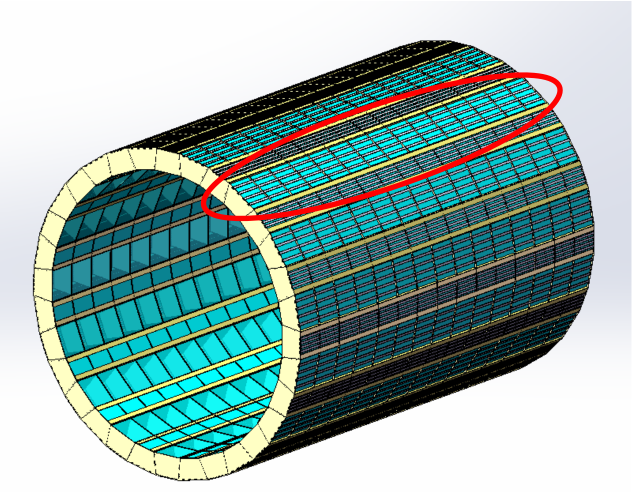
TSAIW

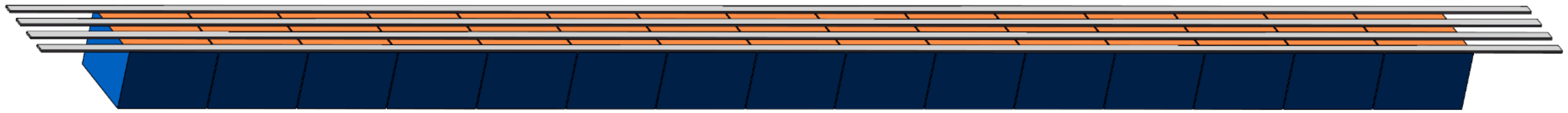
(Failure parameters of composite materials)

Barrel ECAL cooling system

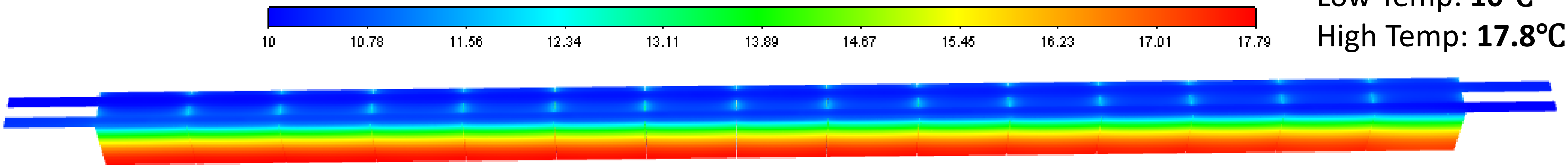
- FEA simulation studies on ECAL cooling
  - Preliminary result: temperature gradient of ~8 degrees
  - Ongoing studies in calorimeter simulation to quantify its possible impacts to EM performance

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





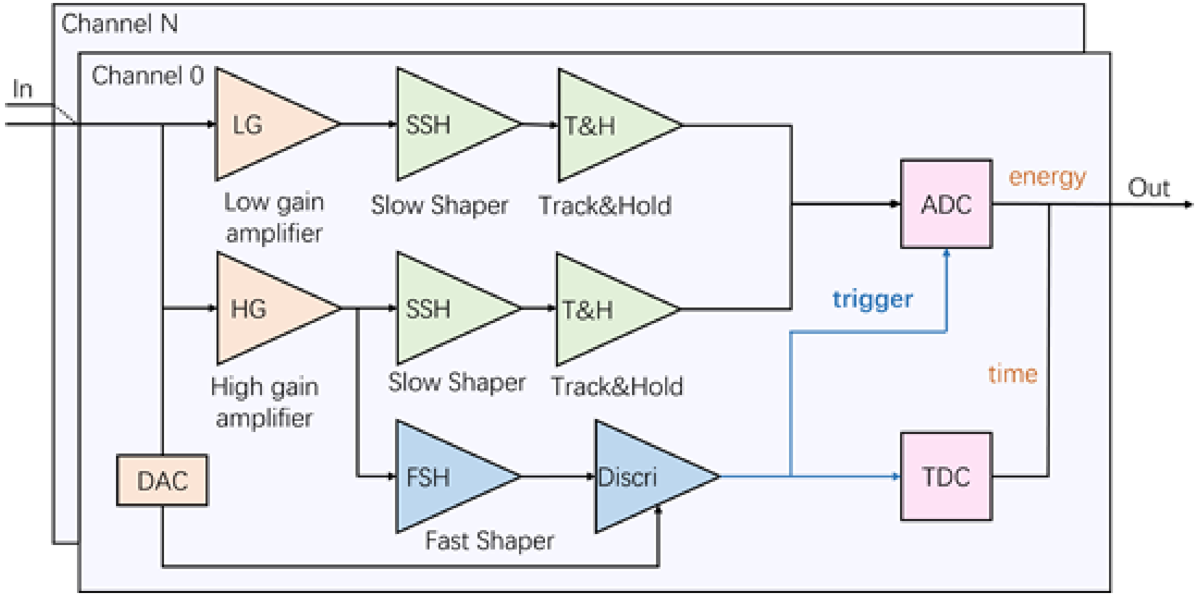
Copper sheet:**1mm**
Low Temp: **10℃**
High Temp: **17.8℃**



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

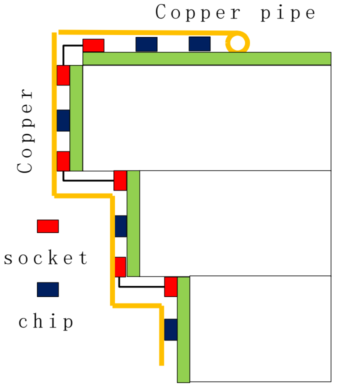
Readout electronics for ECAL

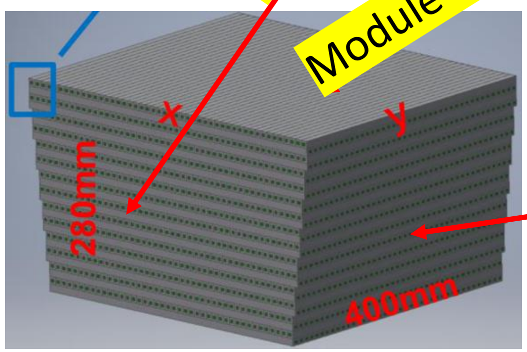
Details in the “Electronics” talk



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

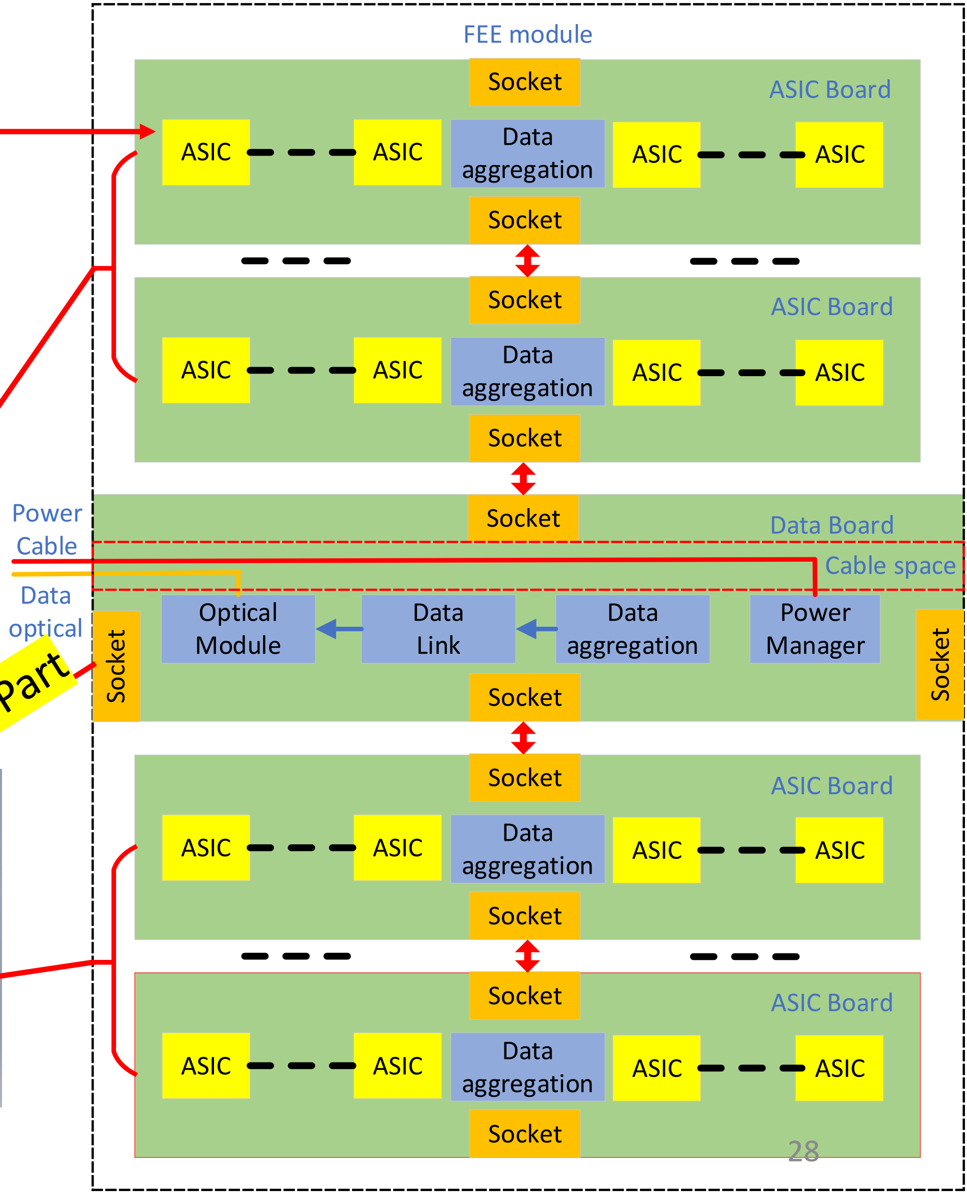
Passive Cooling





Module Lateral Part

Module Top Part



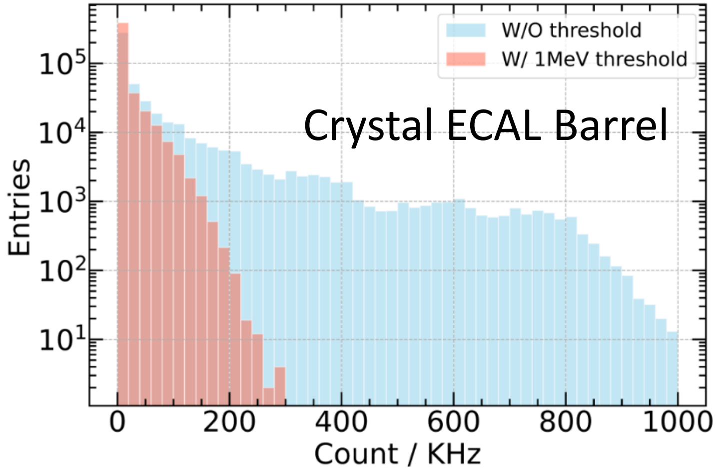
Beam-induced backgrounds: simulation studies

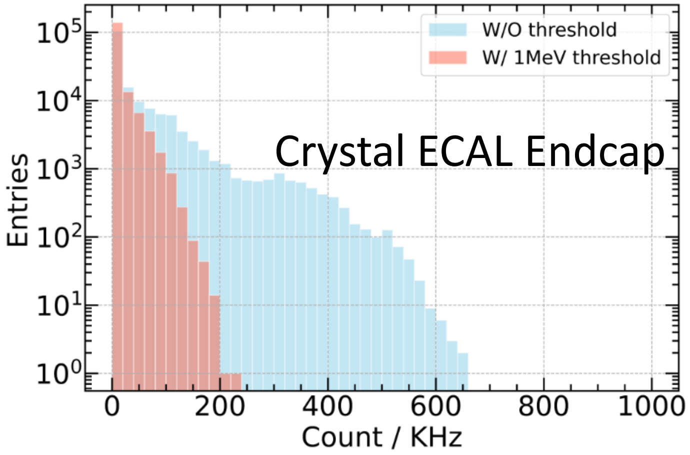
- **50MW** Higgs runs: 355ns bunch spacing
  - Hit rate 200-300 kHz with 0.1 MIP threshold
  - Barrel : maximum rate[1] (230 kHz) vs. mean rate[2] (13 kHz)

Beam Backgrounds		50MW Higgs (355 ns)
Luminosity dependent	Pair Production	1300/BX
Single Beam	Beam-Thermal Photon	359kHz *2
	Beam-Gas Bremsstrahlung	41kHz *2
	Beam-Gas Coulomb	238kHz *2
	Touschek Scattering	/

Maximum rate[1] : max. rate in a crystal bar per module

Mean rate[2] : average over all crystal bars over threshold per module

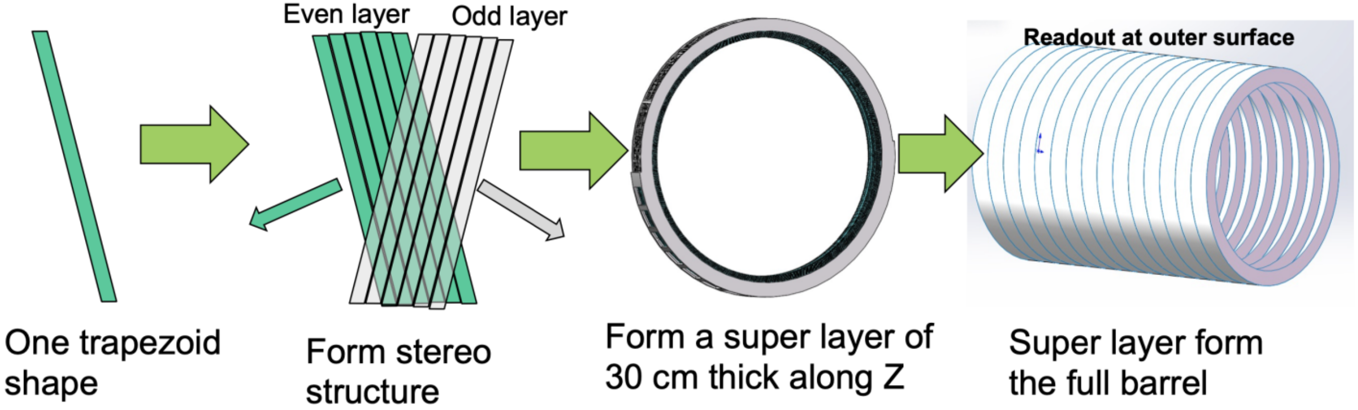




Alternative ECAL design: stereo crystals

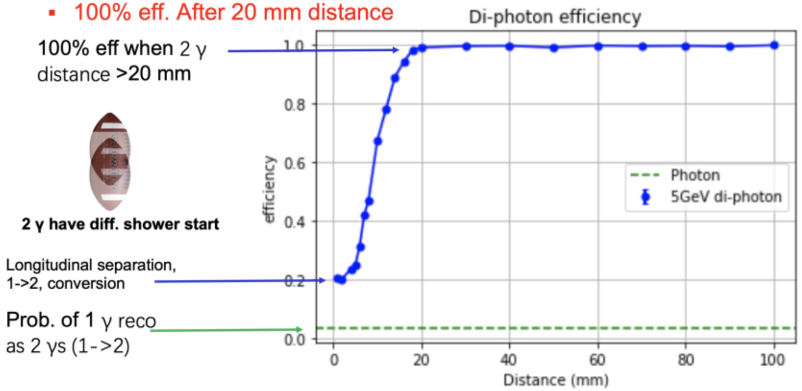
- Stereo design with long crystal bars inclined
  - Longitudinal segmentation by tilting crystal bars
  - Single-end readout: 50% less readout channels than crossed bars (two-sided readout)

Only one freedom left, α or longitudinal sampling N_R

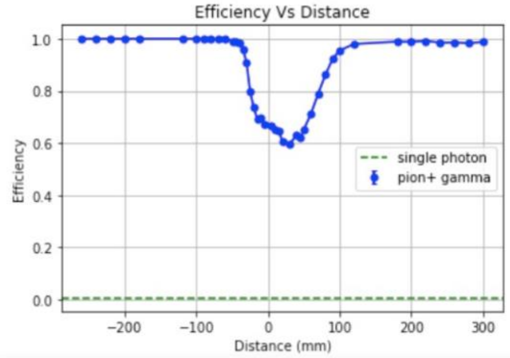


Separation power of two particles

- 100% eff. After 20 mm distance



- Applied to separate 5 GeV photon and 10 GeV π +
  - ~100% efficiency when > 100 mm distance



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

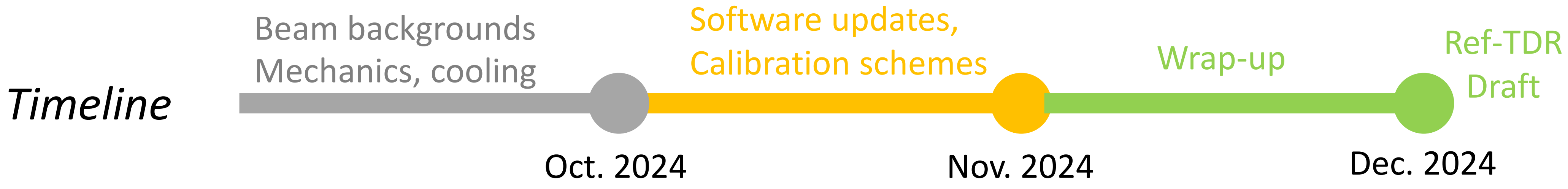
Taskforce and collaborations

- Taskforce working on CEPC ECAL
  - Detector (hardware/software): physicists (9), postdocs (3), students (8)
  - Engineers in electronics (3) and mechanics (2)
- 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
  - China: IHEP, SIC-CAS, SJTU/TDLI, USTC, SCNU
  - Japan: Shinshu U. and U. Tokyo (on ScW-ECAL option)

CEPC calorimeter team in beamtests

Working plan

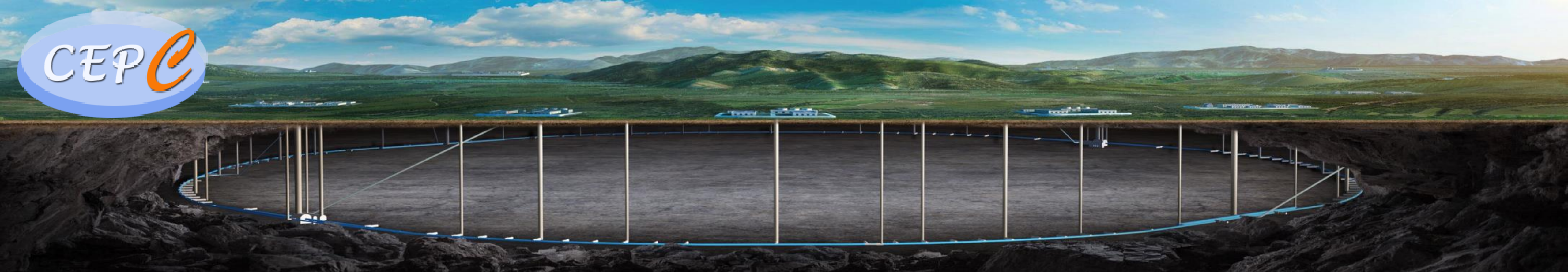
- Near future planning: towards reference detector TDR
  - Beam-induced backgrounds: impacts to physics performance, data throughput
  - Mechanics and cooling: FEA simulations, validation by dedicated tests
  - Detector: fully exploit beamtest data on EM performance and validation studies
  - Software: geometry updates (interplay with mechanics/cooling), digitisation
  - Calibration: sensitive units (SiPM, crystal, ASIC) versus temperature, irradiation
  - Particle flow performance: further optimizations



- Long-term planning beyond TDR (in next 3-4 years)
  - R&D on crystal detector units: joint efforts on **BSO crystal**, new **SiPM** and readout **chip**
  - Full-scale calorimeter prototype integrated with mechanics and cooling
  - Radiation damages in crystal and SiPM and possible solutions

Summary

- Overview of CEPC ECAL options and dedicated R&D activities 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 for SiPM-crystal units and 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

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- The CALICE Collaboration, 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
- New perspectives on segmented crystal calorimeters for future colliders: M.T. Lucchini et al 2020 JINST 15 P11005
- Prospects for $B^0_{(s)} \rightarrow \pi^0\pi^0$ and $B^0_{(s)} \rightarrow \eta\eta$ modes and corresponding *CP* asymmetries at Tera-*Z*, JHEP12(2022)135
- 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

ECAL requirements

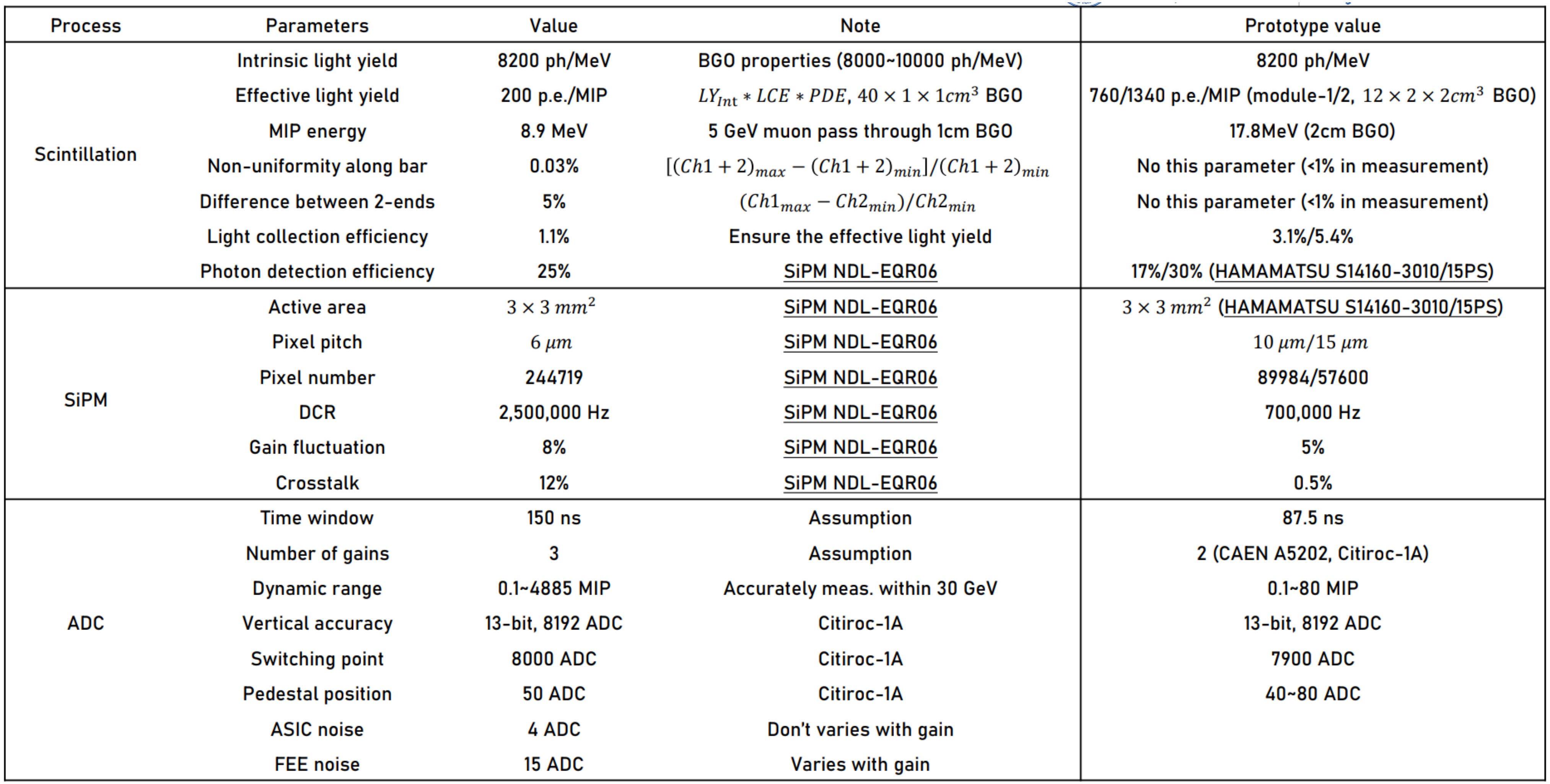
Parameter	Conservative	Ambitious	Remarks
EM energy resolution	$\frac{\sigma_E}{E} = 15\%/\sqrt{E(GeV)} \oplus 1\%$	$\sigma_E/E = 3\%/\sqrt{E(GeV)} \oplus 1\%$	Jet performance; flavor physics
Longitudinal Depth	$24X_0$ (with longitudinal segmentations)		Full containment of EM showers
Transverse Granularity	$10 \times 10\ mm^2$		$H \rightarrow gg$ (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

Summary: crystal ECAL with long bars

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1830 mm	350 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$	NA
Longitudinal Depth	$24X_0$ (268.3 mm BGO)		NA
Modularity	28 modules in phi, 15 rings along Z	6 types of modules	NA
Material Volume (m³)	17.8	6.5	24.3
Readout channels	0.96 M	0.39 M	1.35 M
Power dissipation	14.4 kW	5.9 kW	20.3 kW

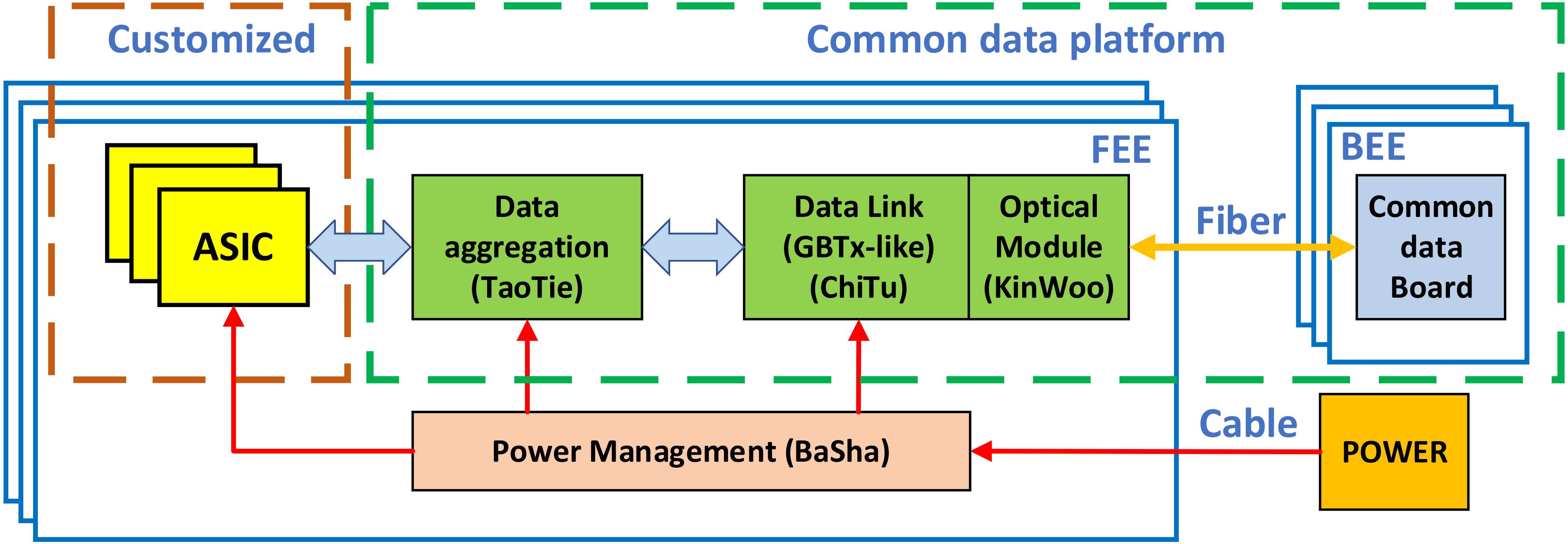
Crystal ECAL digitistation

- A summary table on digitisation: ongoing validation studies



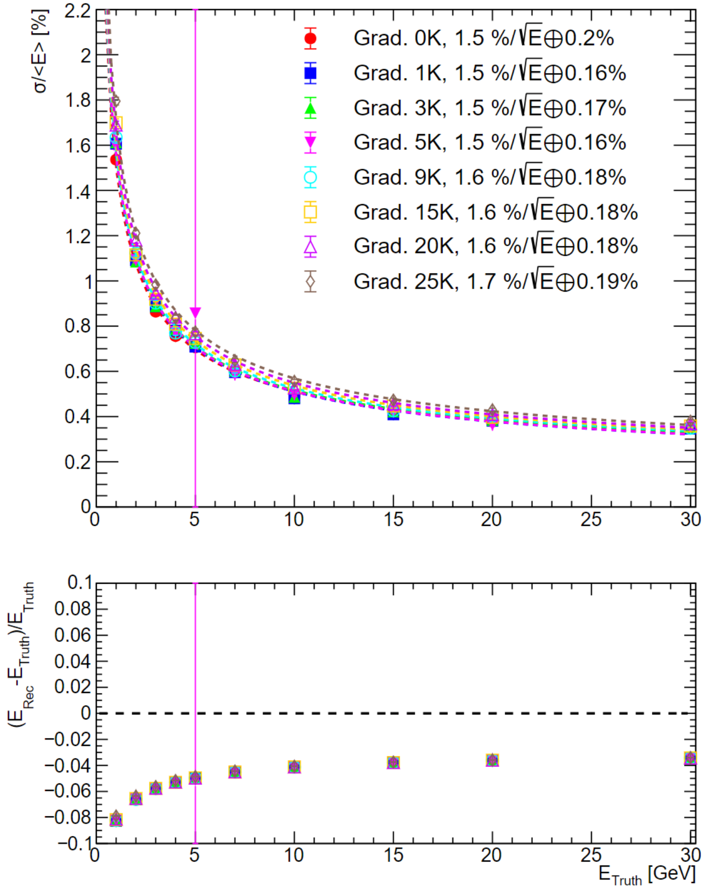
Process	Parameters	Value	Note	Prototype value
Scintillation	Intrinsic light yield	8200 ph/MeV	BGO properties (8000~10000 ph/MeV)	8200 ph/MeV
	Effective light yield	200 p.e./MIP	$LY_{Int} * LCE * PDE$, $40 \times 1 \times 1cm^3$ BGO	760/1340 p.e./MIP (module-1/2, $12 \times 2 \times 2cm^3$ BGO)
	MIP energy	8.9 MeV	5 GeV muon pass through 1cm BGO	17.8MeV (2cm BGO)
	Non-uniformity along bar	0.03%	$[(Ch1+2)_{max} - (Ch1+2)_{min}]/(Ch1+2)_{min}$	No this parameter (<1% in measurement)
	Difference between 2-ends	5%	$(Ch1_{max} - Ch2_{min})/Ch2_{min}$	No this parameter (<1% in measurement)
	Light collection efficiency	1.1%	Ensure the effective light yield	3.1%/5.4%
	Photon detection efficiency	25%	SiPM NDL-EQR06	17%/30% (HAMAMATSU S14160-3010/15PS)
SiPM	Active area	$3 \times 3\ mm^2$	SiPM NDL-EQR06	$3 \times 3\ mm^2$ (HAMAMATSU S14160-3010/15PS)
	Pixel pitch	$6\ \mu m$	SiPM NDL-EQR06	$10\ \mu m/15\ \mu m$
	Pixel number	244719	SiPM NDL-EQR06	89984/57600
	DCR	2,500,000 Hz	SiPM NDL-EQR06	700,000 Hz
	Gain fluctuation	8%	SiPM NDL-EQR06	5%
	Crosstalk	12%	SiPM NDL-EQR06	0.5%
ADC	Time window	150 ns	Assumption	87.5 ns
	Number of gains	3	Assumption	2 (CAEN A5202, Citiroc-1A)
	Dynamic range	0.1~4885 MIP	Accurately meas. within 30 GeV	0.1~80 MIP
	Vertical accuracy	13-bit, 8192 ADC	Citiroc-1A	13-bit, 8192 ADC
	Switching point	8000 ADC	Citiroc-1A	7900 ADC
	Pedestal position	50 ADC	Citiroc-1A	40~80 ADC
	ASIC noise	4 ADC	Don't varies with gain	
	FEE noise	15 ADC	Varies with gain	

Electronics diagram for ECAL & HCAL

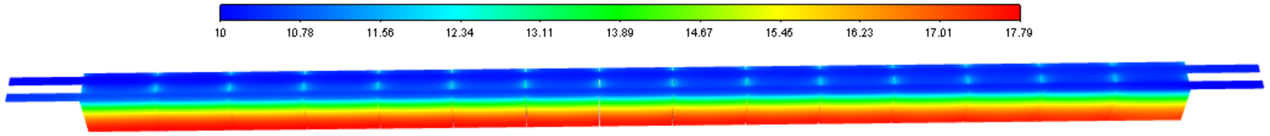


- Energy and time measurements: ASIC for ECAL & HCAL
- Data transmission: common data platform (refer to the “Electronics TDR Report”)
- Trigger mode: trigger-less readout in Front-End Electronics (FEE)

Temperature impacts to crystal-SiPM



- Linear modeling of temperature gradient
  - The same temperature change for a given distance
- Assuming temperature difference can not be corrected, which is especially true for crystals
- Check EM performance by varying temperature gradient (Tmax - Tmin)
- Preliminary result: **temperature gradient of 5 degrees** seems to introduce no significant impact

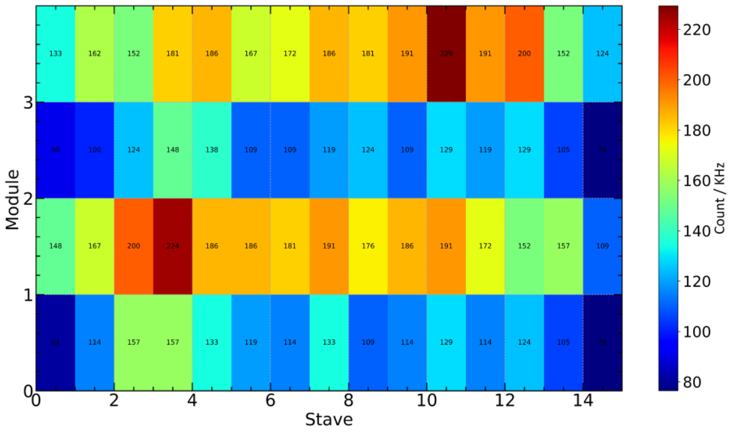


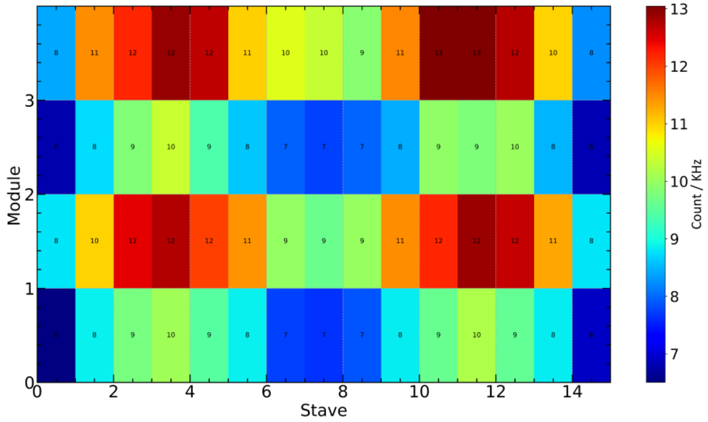
- 100p.e./MIP, 0.1MIP threshold per channel, 12-bit ADC
- 150ns time window, 2,500,000 Hz DCR
- Temperature dependence of BGO light yield: -1.38%/K, doi:10.1007/s11433-014-5548-4
- Temperature dependence of SiPM(HAMAMATSU S13360-3050CS) gain: -3%/K, doi:10.1016/j.nima.2016.09.053
- Temperature dependence of SiPM(HAMAMATSU S13360-3050CS) DCR vs temperature, doi:10.1016/j.nima.2016.09.053

Beam-induced backgrounds: simulation studies

- **50MW** Higgs runs (355ns bunch spacing): updates from 30MW
  - Barrel module: maximum rate^1 (230 kHz) vs. mean rate^2 (13 kHz)
  - Patterns in even/odd staves: different crystal lengths in the first layer (300mm/400mm)

Beam Backgrounds		50MW Higgs (355 ns)
Luminosity dependent	Pair Production	1300/BX
Single Beam	Beam-Thermal Photon	359kHz *2
	Beam-Gas Bremsstrahlung	41kHz *2
	Beam-Gas Coulomb	238kHz *2
	Touschek Scattering	/





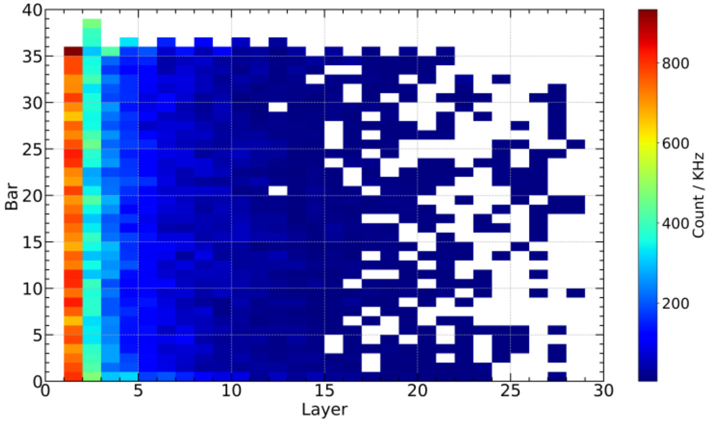
Maximum rate^1 : max. rate in a crystal bar per module

Mean rate^2 : average over all crystal bars over threshold per module

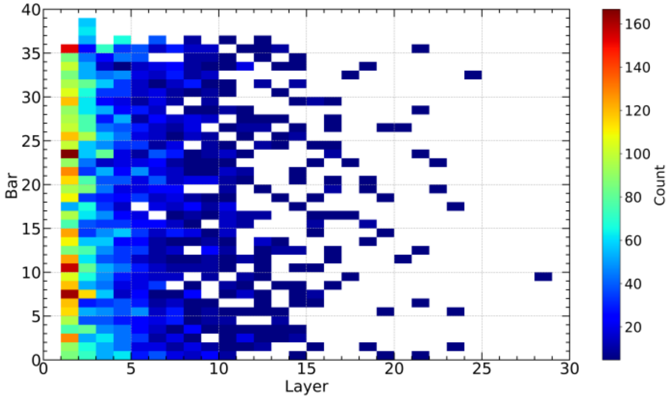
Beam-induced backgrounds at CEPC: TID

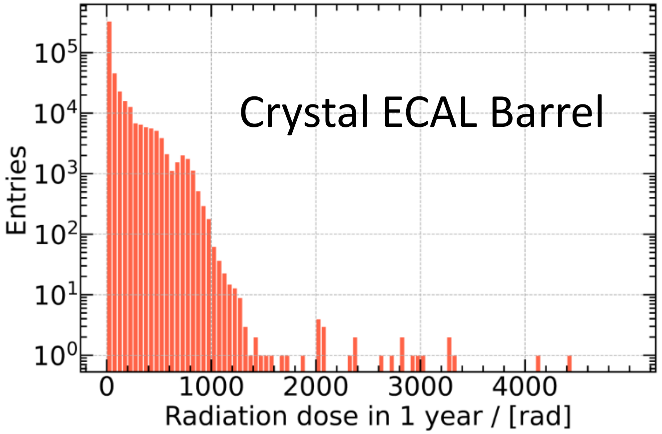
- **50MW** Higgs runs (355ns bunch spacing): updates from 30MW
  - TID per year: ~4k rad for barrel crystals; 50k rad for endcap crystals

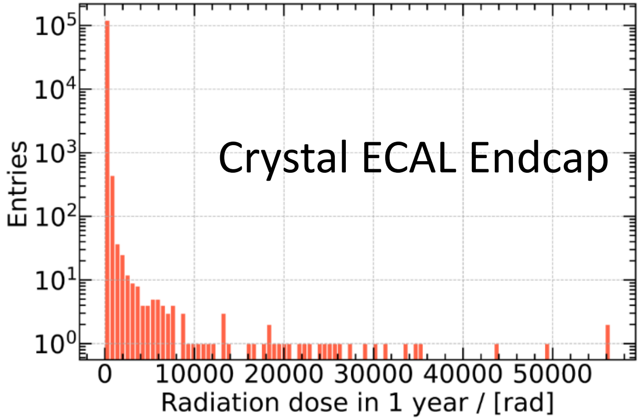
Barrel Module: BarID vs LayerID (raw hits)



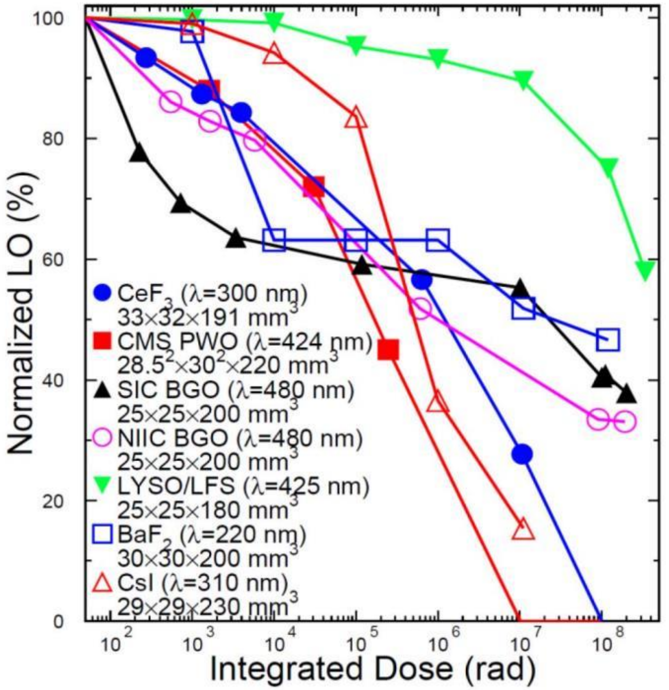
Barrel Module: BarID vs LayerID (hits>1MeV)







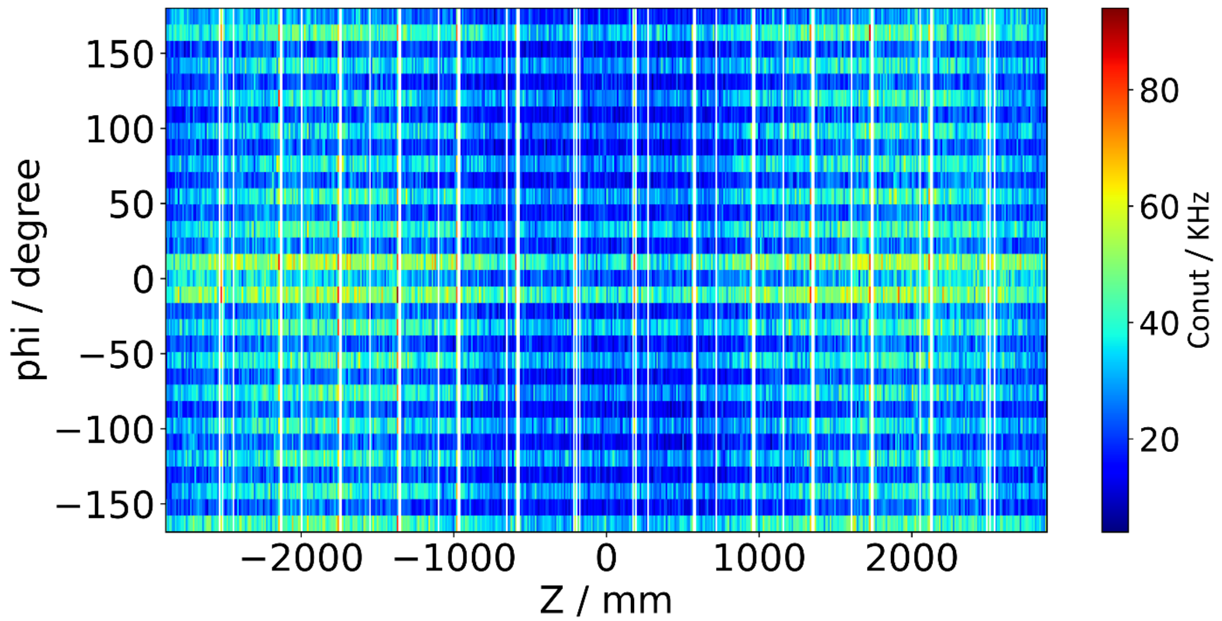
Radiation Damages to Crystals



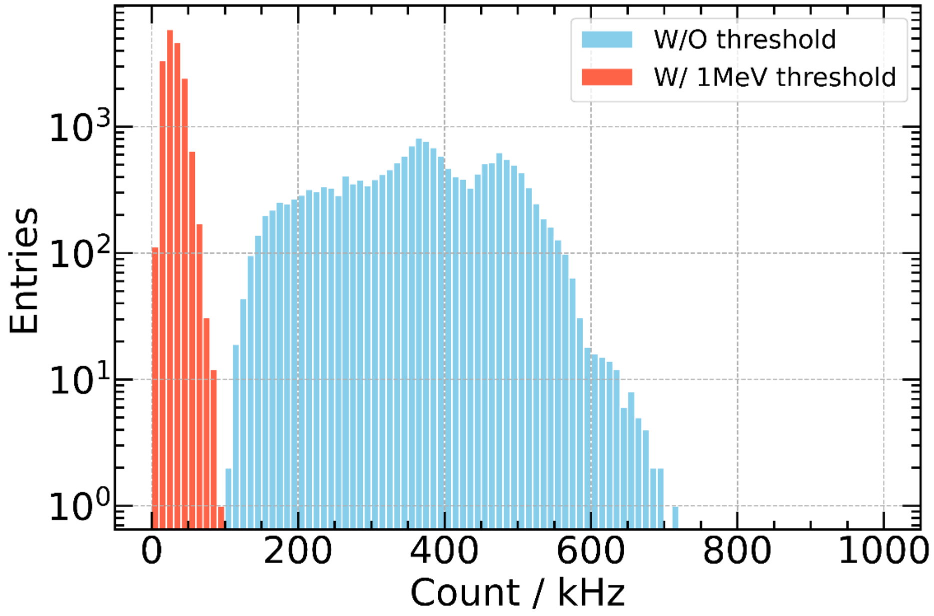
BGO: dramatic Light Output (LO) drop at TID<1kRad and TID>10Mrad

Beam-induced backgrounds: simulation studies

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



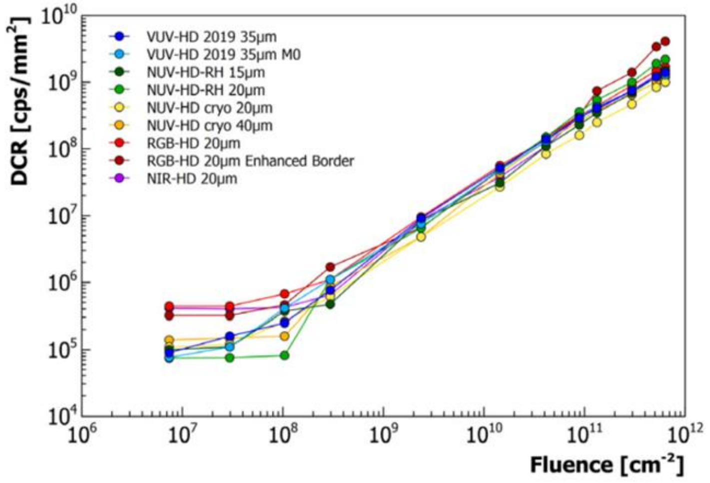
Hit rate suppression with 0.1 MIP threshold

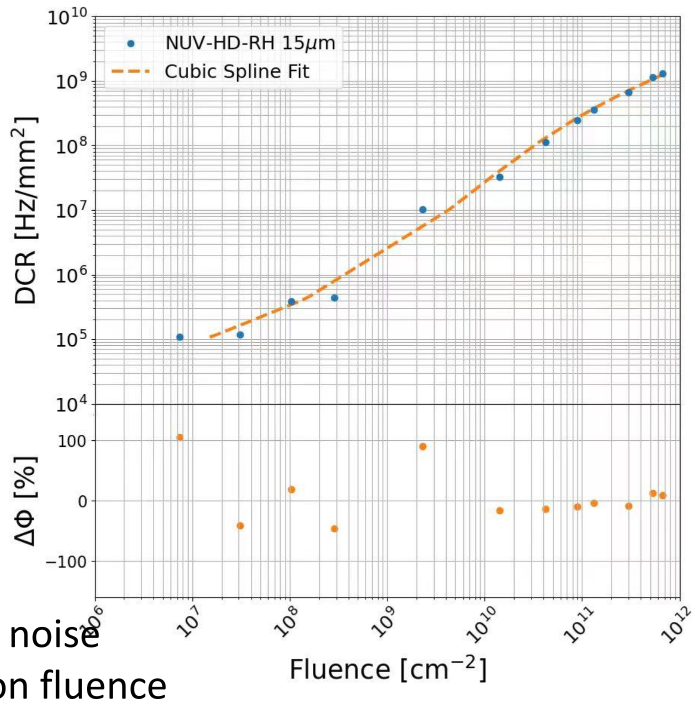


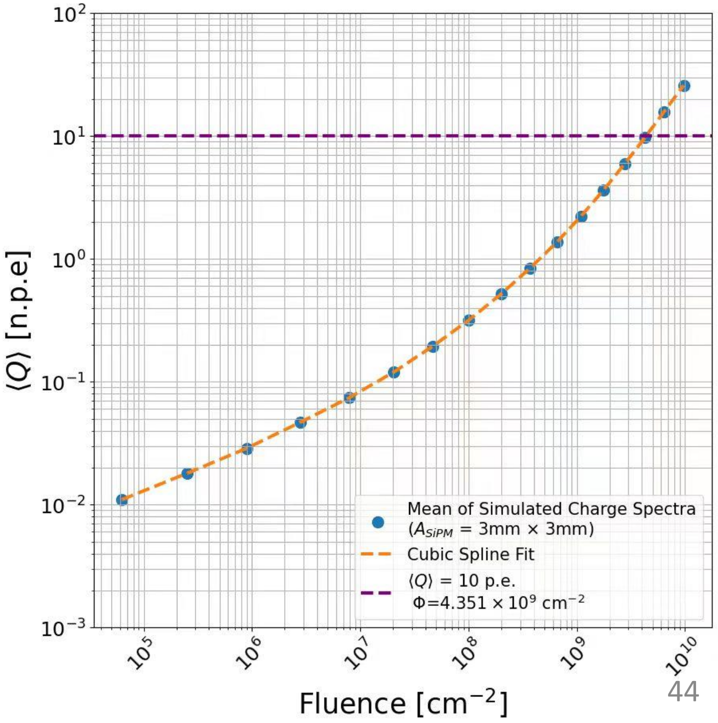
- Simulation studies on beam background in Higgs mode: crystal ECAL barrel
  - Including physics events + backgrounds (major contributions from pair production)
  - With threshold, rate can be significantly reduced: 100kHz (0.1 MIP threshold) from 700kHz (0 threshold)
  - Ongoing simulation studies to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

SiPM irradiation damage: neutron fluence

- Simulation based on measurements: SiPM DCR vs. neutron fluence
- Estimate noise-only events above 0.1MIP trigger threshold (10 p.e.) for ECAL
- Preliminary conclusion: $\mathbf{4.3 \times 10^9 n_{eq}(1MeV)/cm^2}$ is likely the limit for SiPM operated at room temperature; beyond this limit, SiPM needs specific cooling



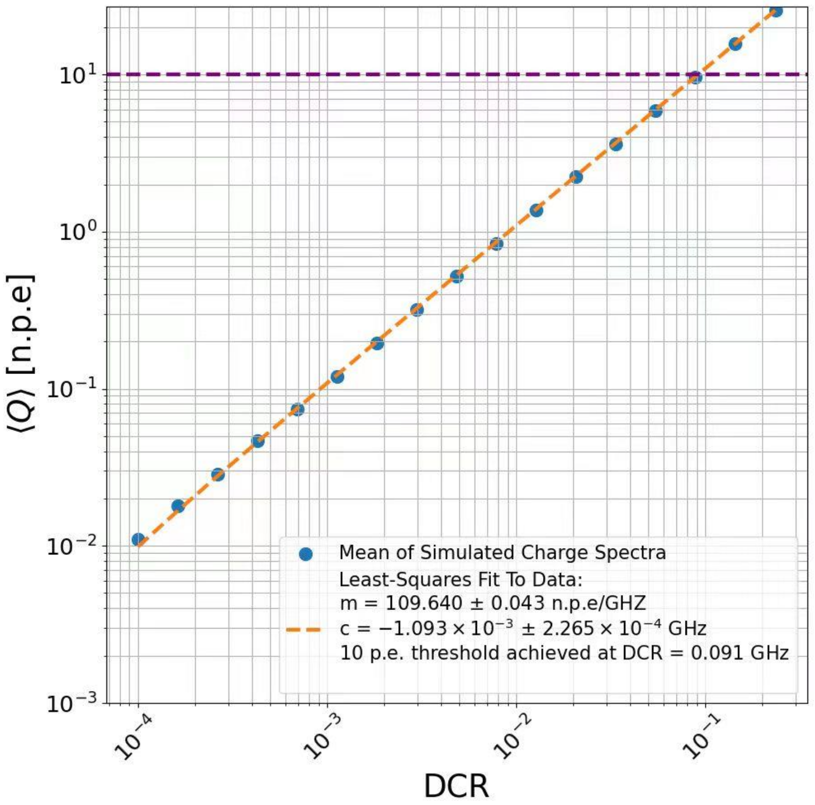


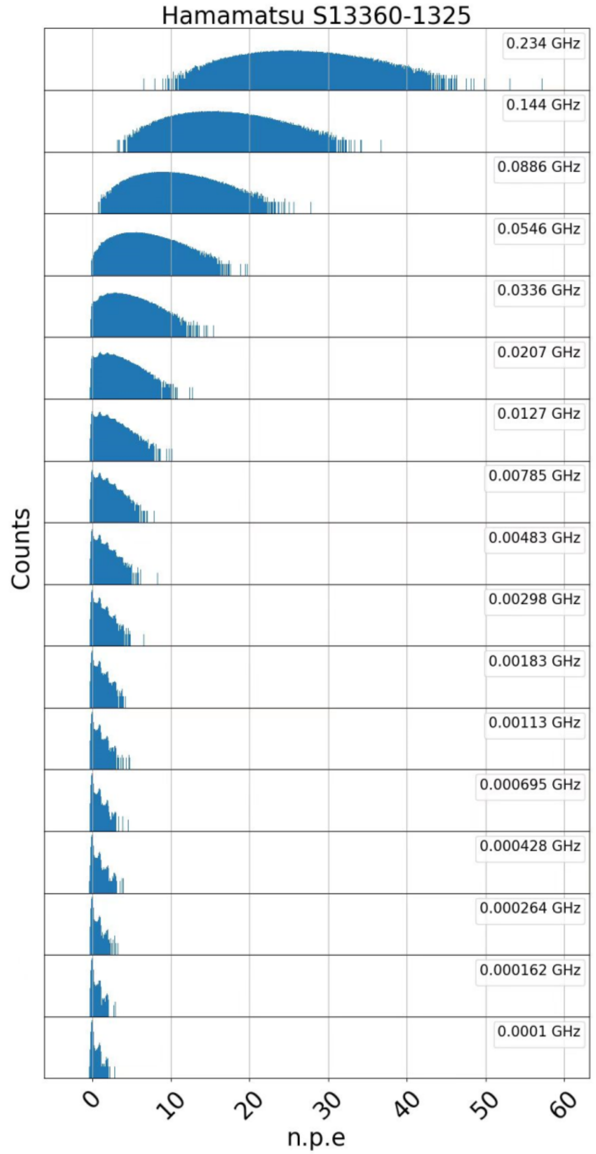


When SiPM DCR=91MHz, it can produce average 10 p.e. noise
SiPM NDL- EQR06，pct=12%, DCR increases with neutron fluence

SiPM irradiation damage: neutron fluence

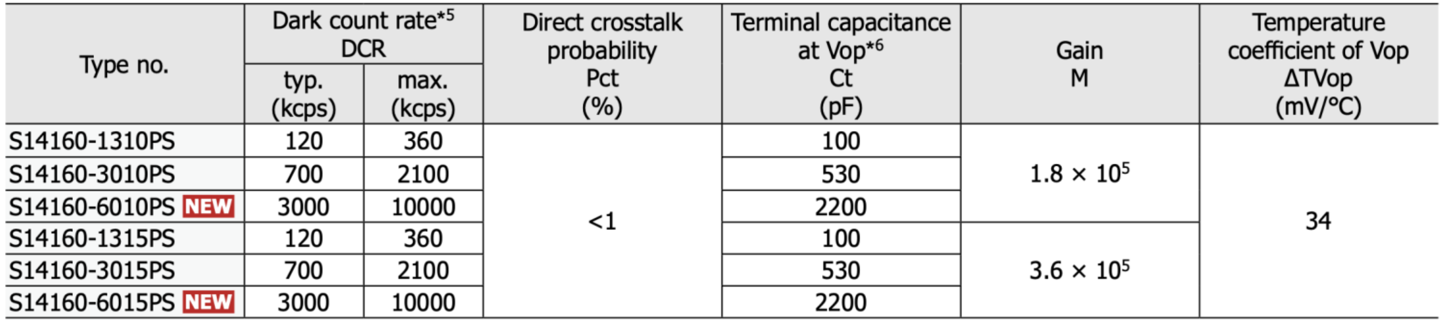
- Estimate noise-only events above 0.1MIP trigger threshold (10 p.e.) for ECAL
  - Based on the Hamburg SiPM simulation model





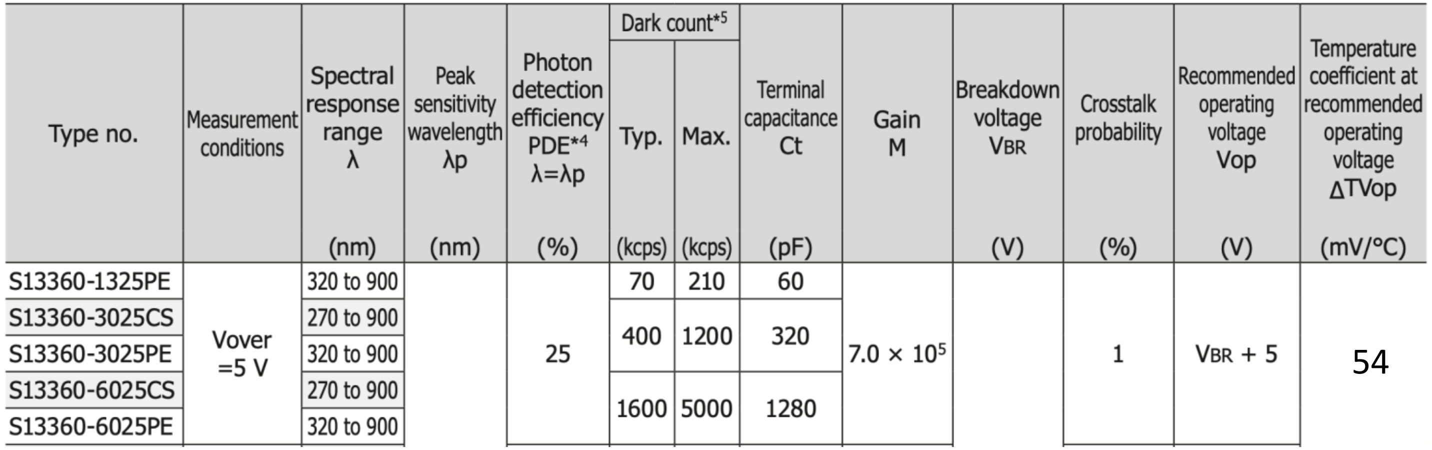
R&D efforts and results: dynamic range

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	<1	100	1.8×10^5	34
S14160-3010PS	700	2100		530		
S14160-6010PS NEW	3000	10000		2200		
S14160-1315PS	120	360		100	3.6×10^5	
S14160-3015PS	700	2100		530		
S14160-6015PS NEW	3000	10000		2200		

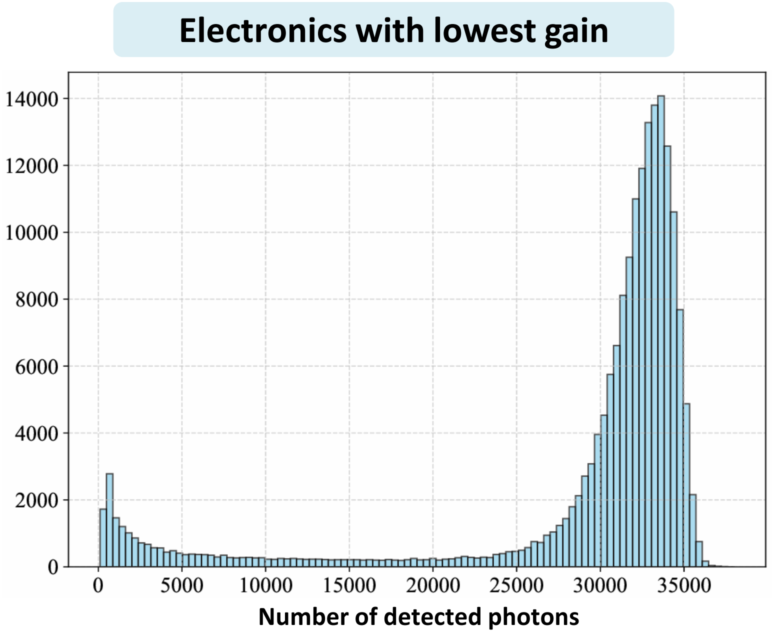
SiPM with 25um pixel pitch



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	Vover =5 V	320 to 900		25	70	210	60	7.0×10^5		1	VBR + 5	54
S13360-3025CS		270 to 900			400	1200	320					
S13360-3025PE		320 to 900										
S13360-6025CS		270 to 900			1600	5000	1280					
S13360-6025PE		320 to 900										

Dynamic range of a state-of-art chip:

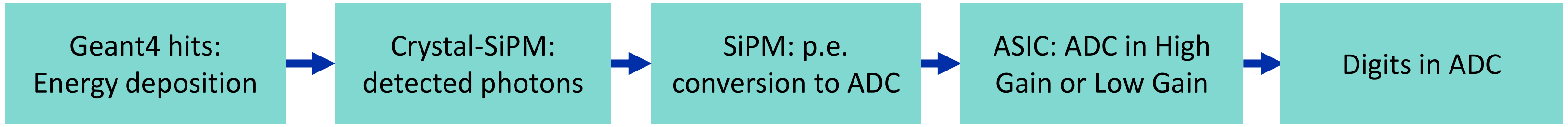
~33000 p.e. for 25um SiPM



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

Digitization and single photons energy resolution

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

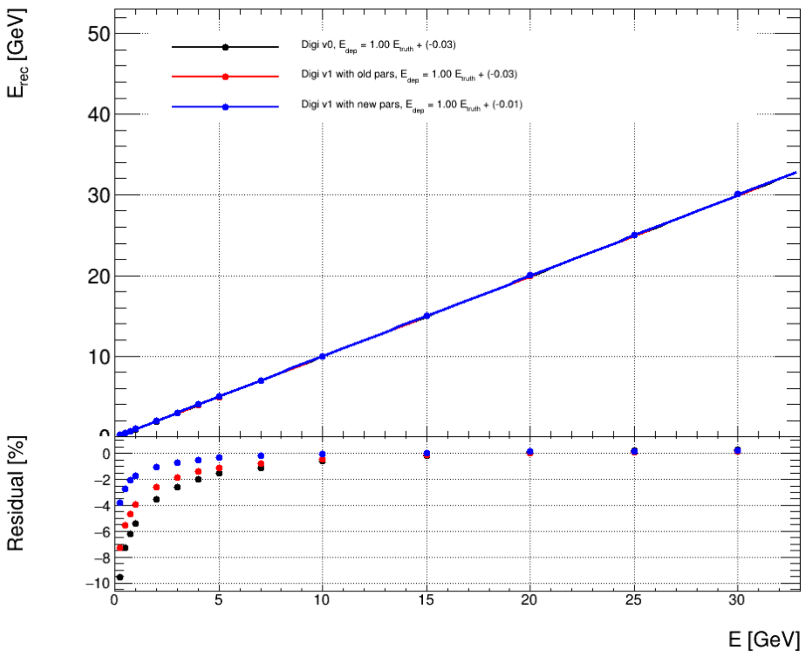


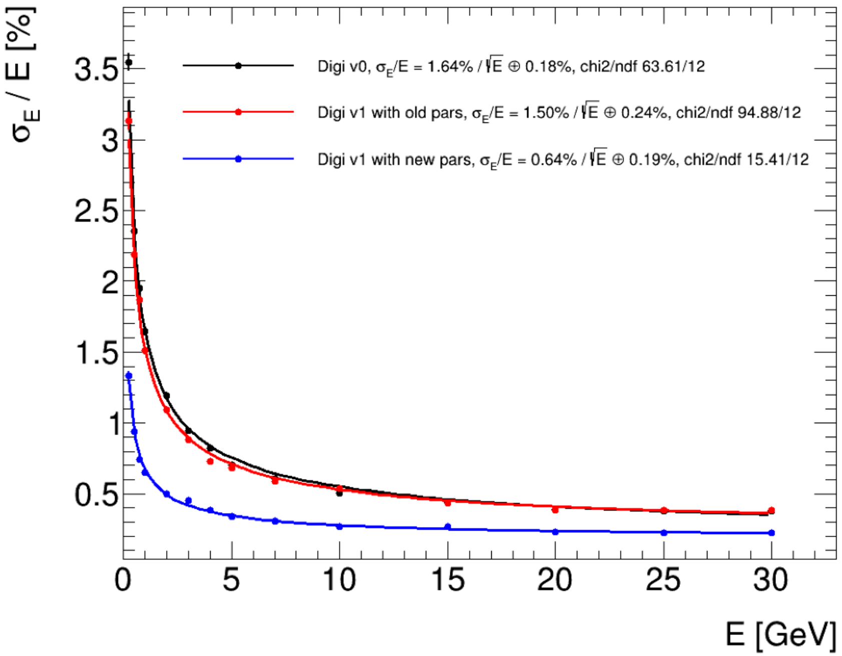
Geant4 hits: Energy deposition → Crystal-SiPM: detected photons → SiPM: p.e. conversion to ADC → ASIC: ADC in High Gain or Low Gain → Digits in ADC

Poisson Distribution based on muon data of long crystal bar

SiPM gain calibration from LED data

HG-LG conversion

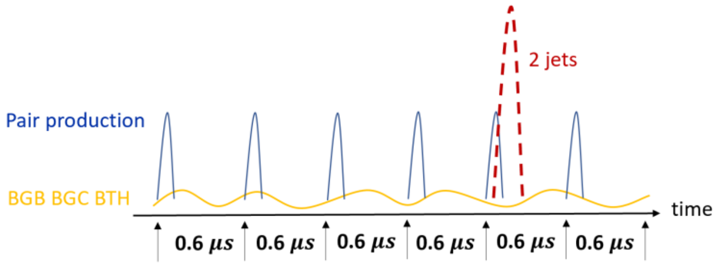


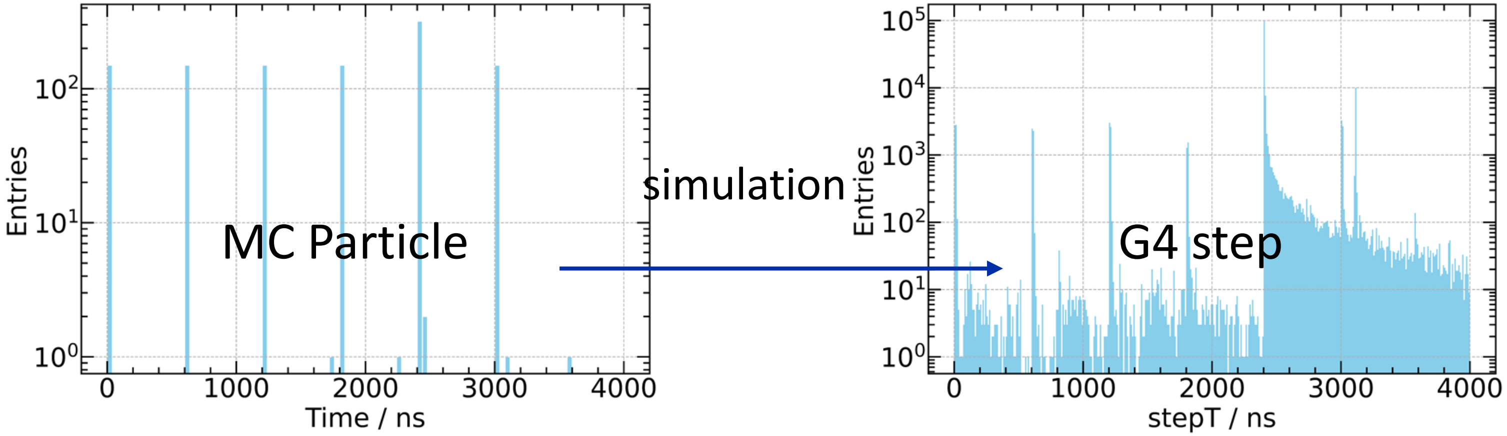


Beam-induced backgrounds: simulation studies

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	---	---

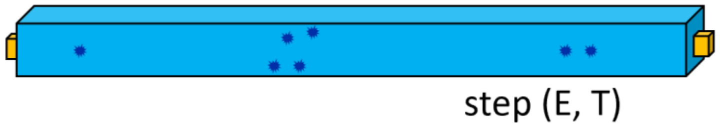
- **Higgs mode**:
  - pair production: double beams, e+-
  - BG: single beam
- Using **4 types** of beam backgrounds.
- **Simulation Time Window**: 3.6 us (6 collisions and 6 bunch spacing)
  - Considering physics events and beam background events.
  - Taking into account the scintillation decay time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

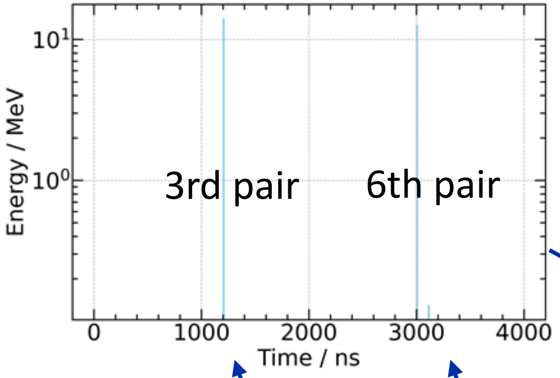


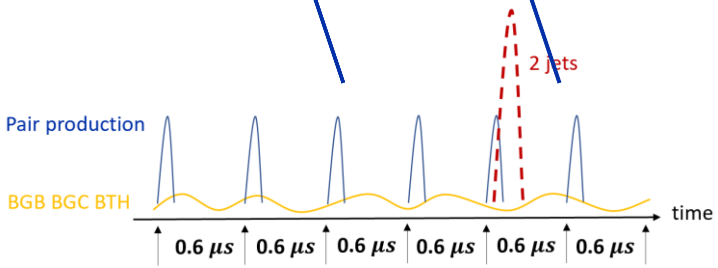


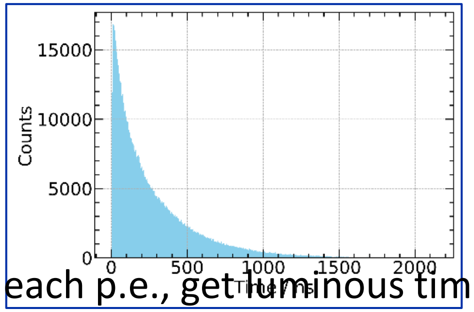
Beam-induced backgrounds: time structures

single crystal bar

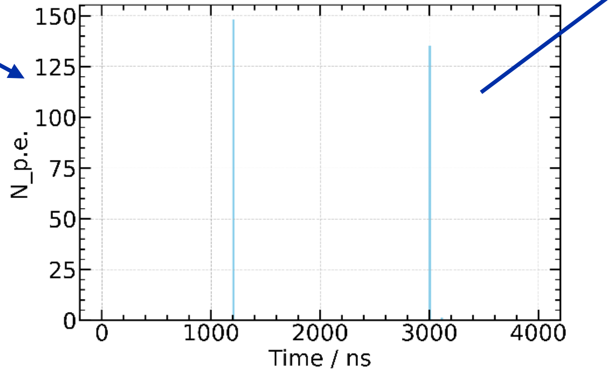




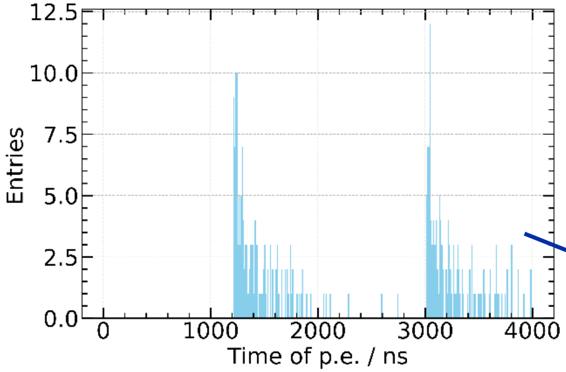


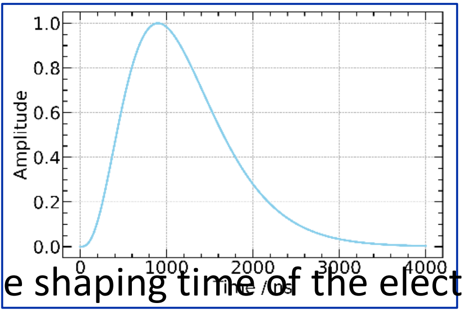


For each p.e., get luminous time and transmission time



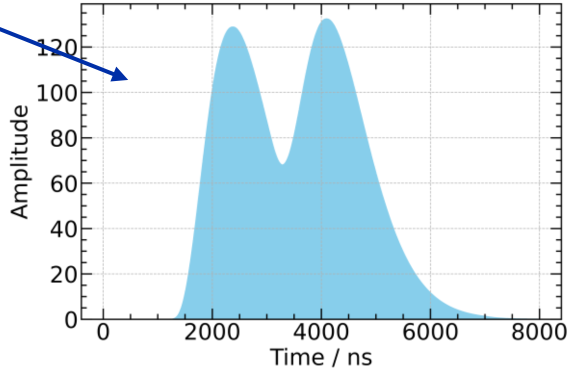
Detected Np.e in SiPM: 100 p.e./Mip



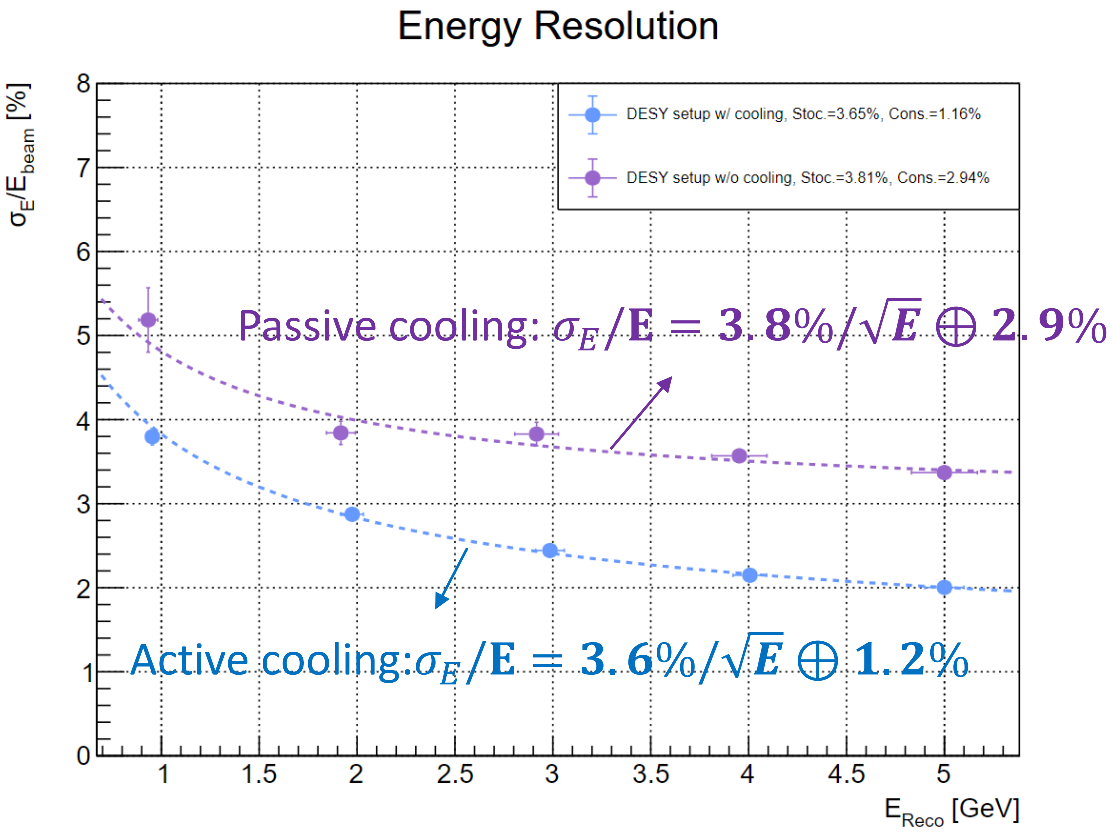


the shaping time of the electronics: CR-(RC)3

time structure of single crysta
with 2 pair production

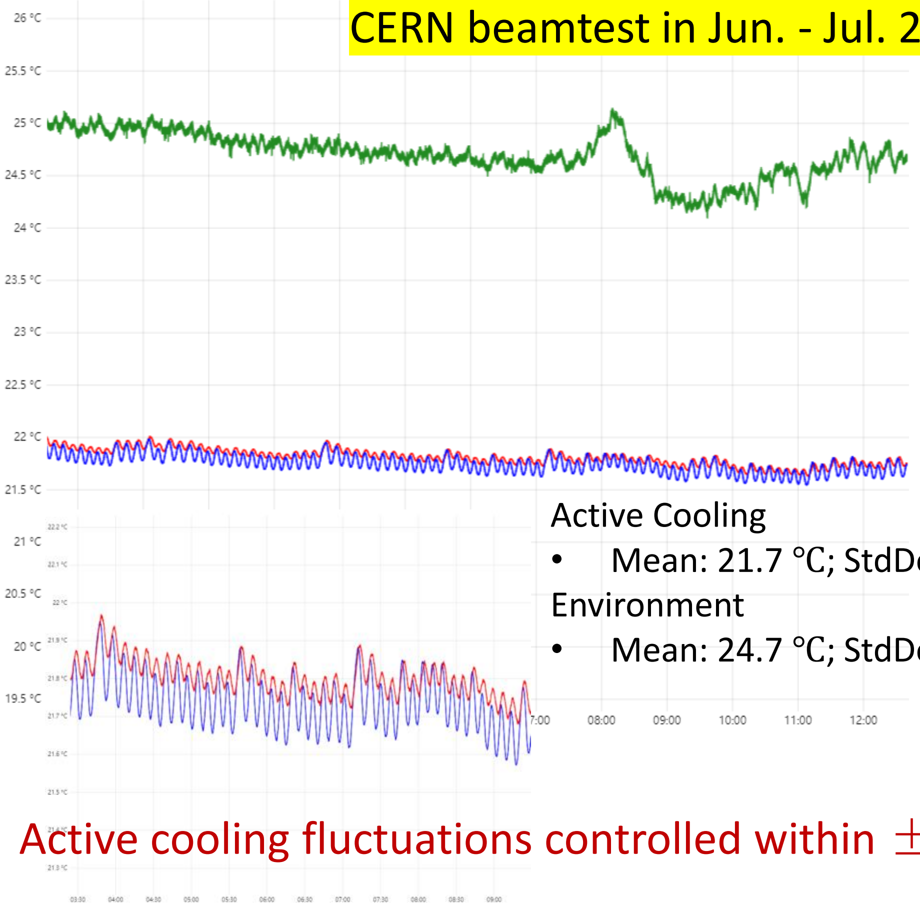


Crystal ECAL: impacts of temperature stability



Passive cooling: $\sigma_E/\mathbf{E} = \mathbf{3.8\%}/\sqrt{\boldsymbol{E}} \oplus \mathbf{2.9\%}$

Active cooling: $\sigma_E/\mathbf{E} = \mathbf{3.6\%}/\sqrt{\boldsymbol{E}} \oplus \mathbf{1.2\%}$



CERN beamtest in Jun. - Jul. 2024

Active Cooling
- Mean: 21.7 ℃; StdDev: 0.09 ℃

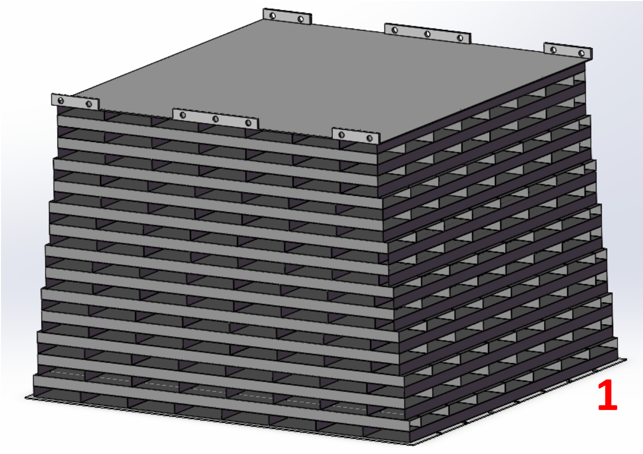
Environment
- Mean: 24.7 ℃; StdDev: 0.21 ℃

Active cooling fluctuations controlled within ±0.05 ℃

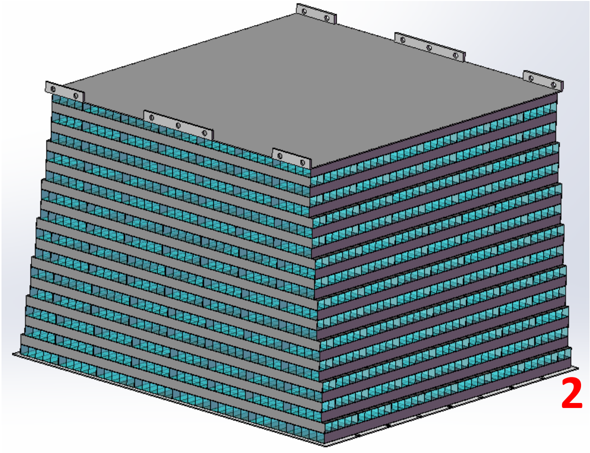
- Temperature stability is crucial to crystal ECAL
  - Significant impact to constant term of EM resolution
  - Stability of ±0.05 ℃ in beamtest data

Barrel ECAL: module integration

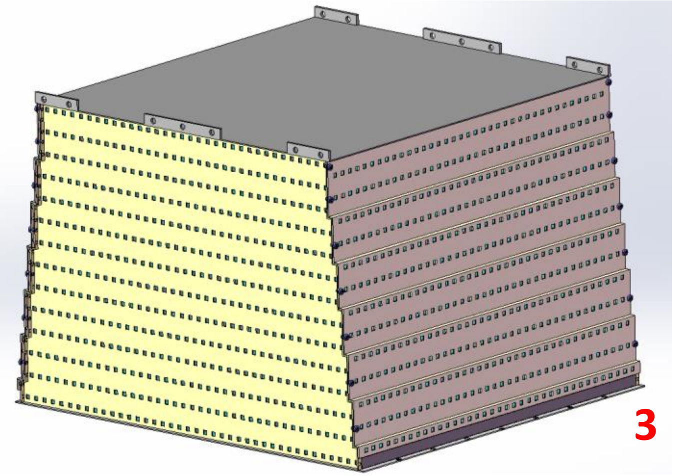
CF structure to protect BGO bars



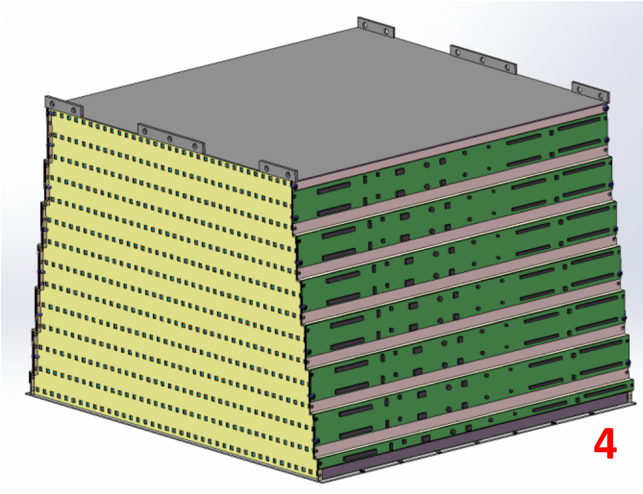
Install BGO crystal bars
(grouping 5 BGO bars per casing)



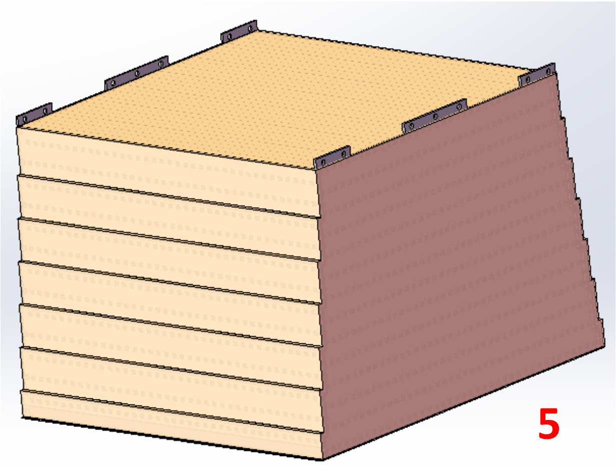
Install plates to “seal” and fix BGO bars, with holes for couplings with SiPM



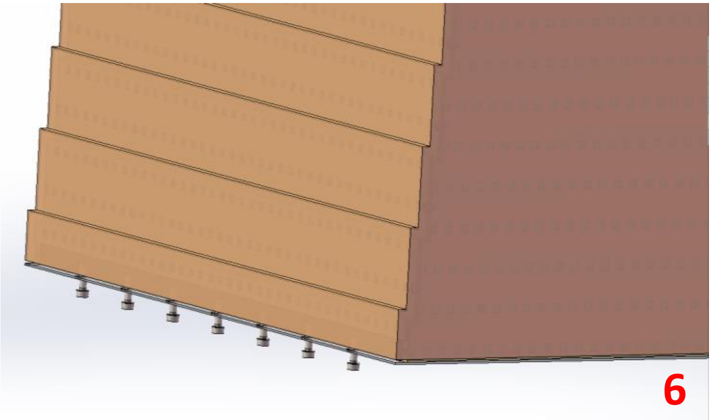
Install front-end readout PCBs



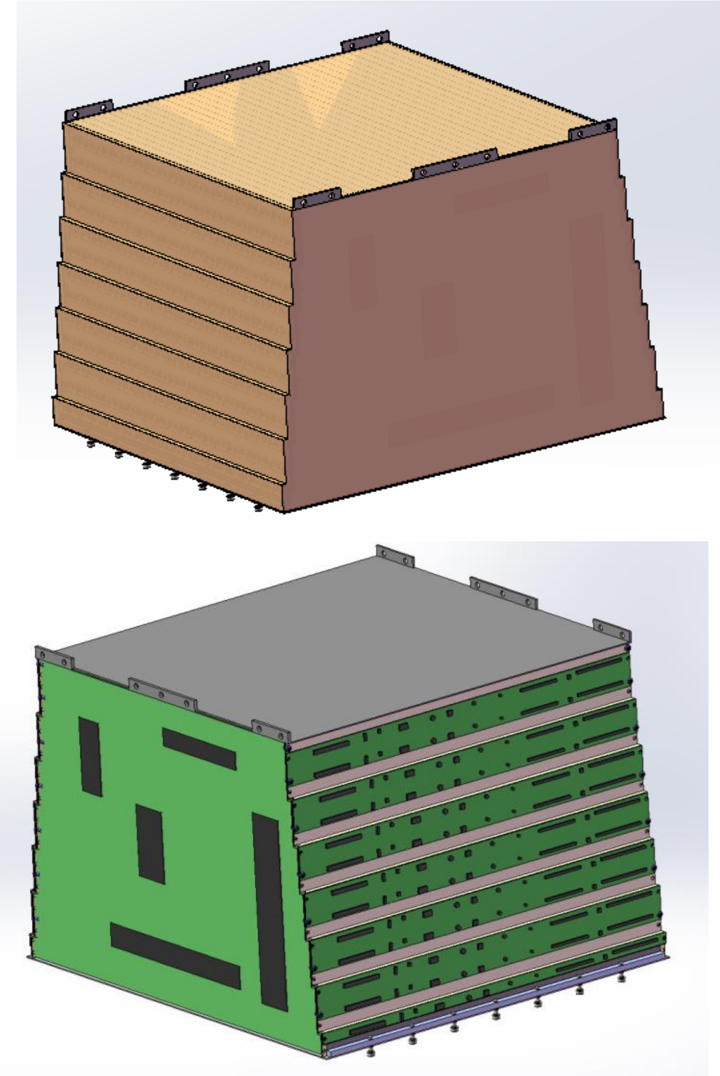
Install copper sheets for passive heat dissipation

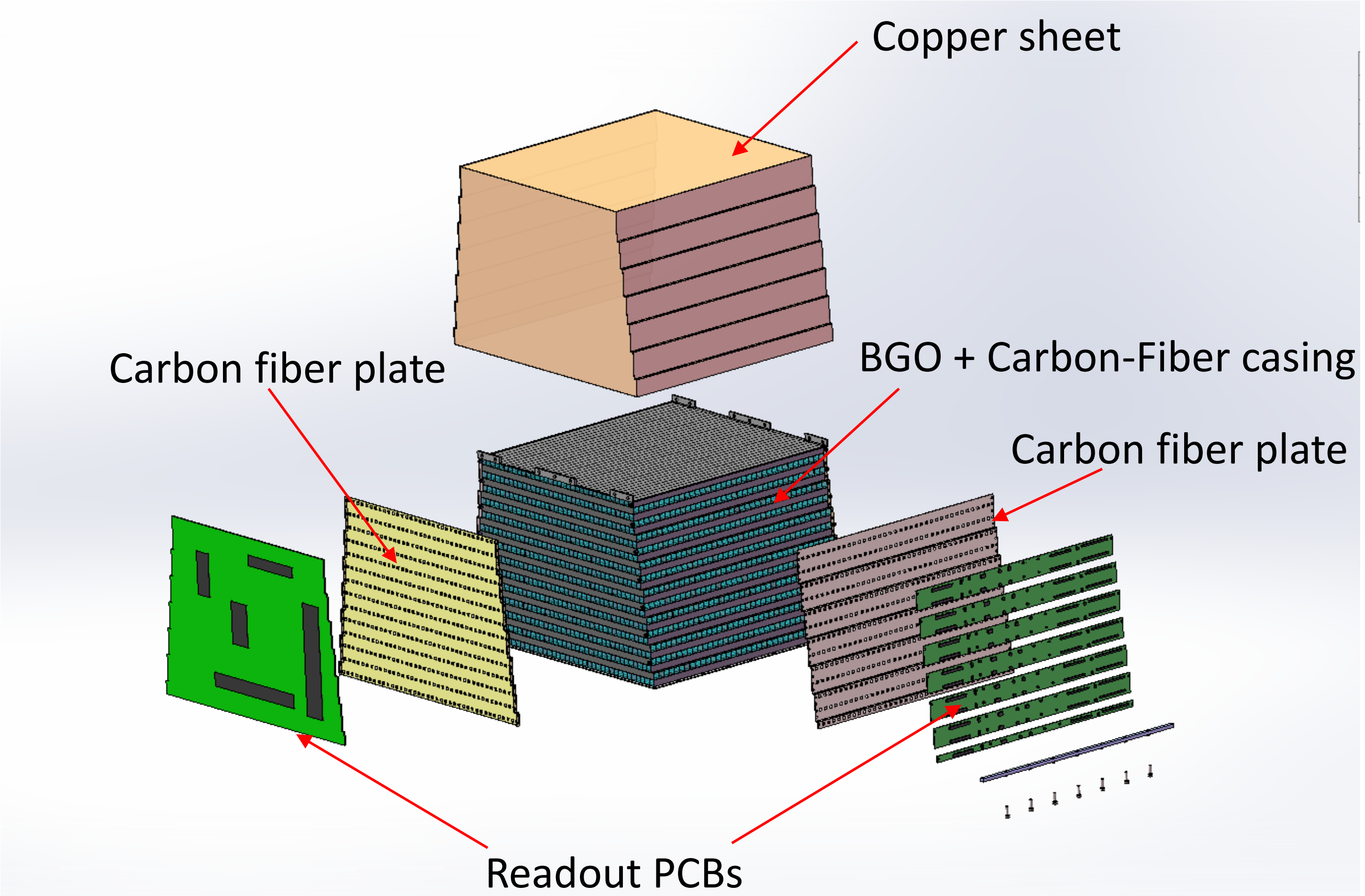


Assemble the module into the main support structure



Barrel ECAL: module integration





Copper sheet

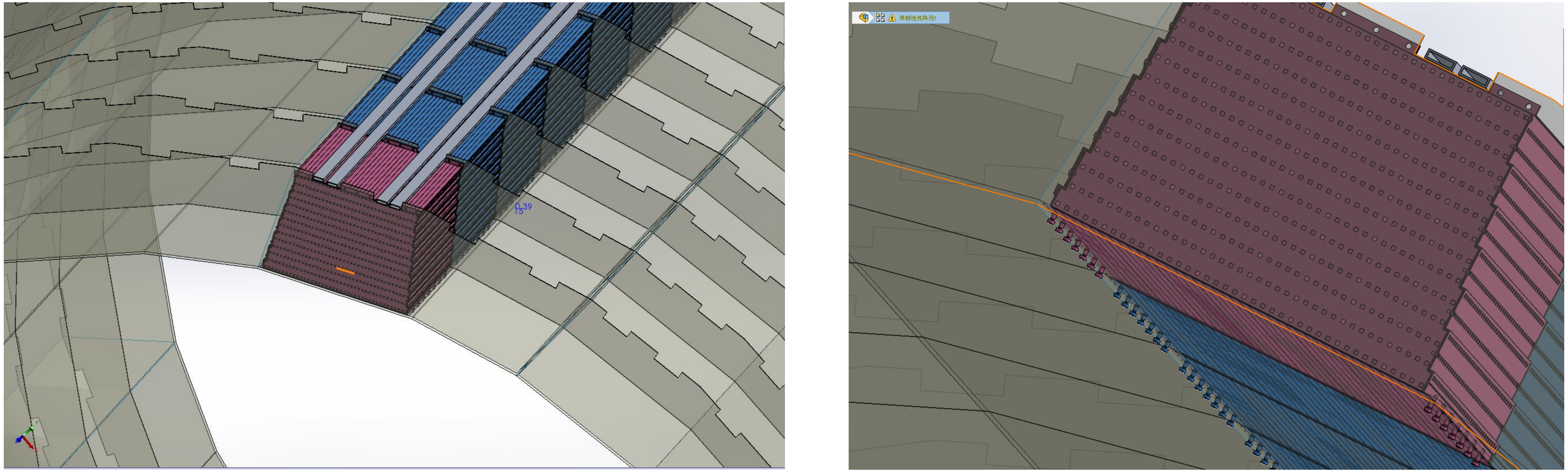
Carbon fiber plate

BGO + Carbon-Fiber casing

Carbon fiber plate

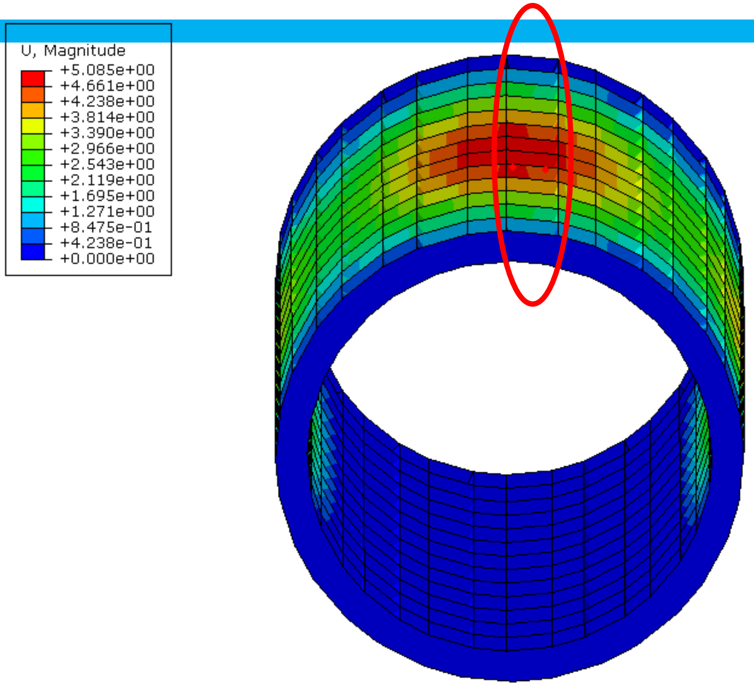
Readout PCBs

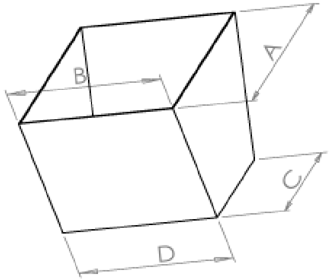
Barrel ECAL: integrate modules in main structure



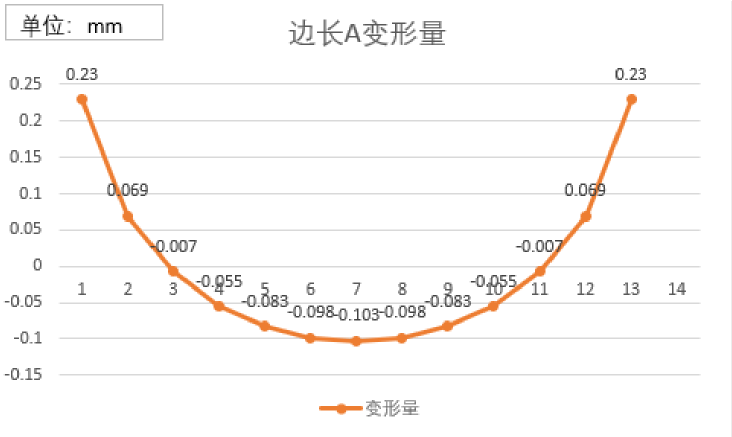
- Each module is fixed in the main support structure by bottom bolts
- Four active cooling pipes are installed at the top of each row of modules

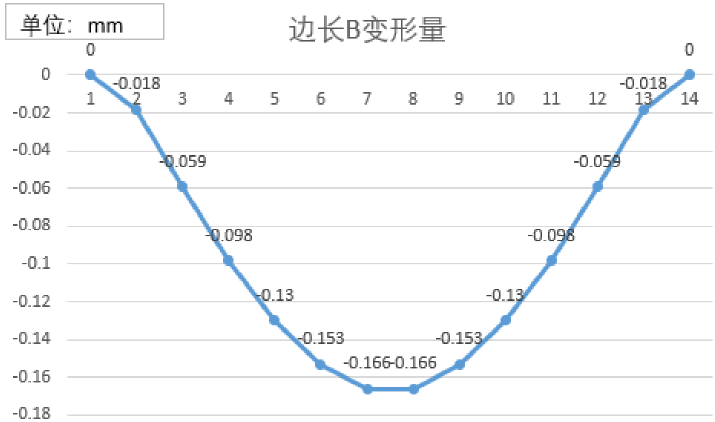
Mechanics: FEA studies on deformation

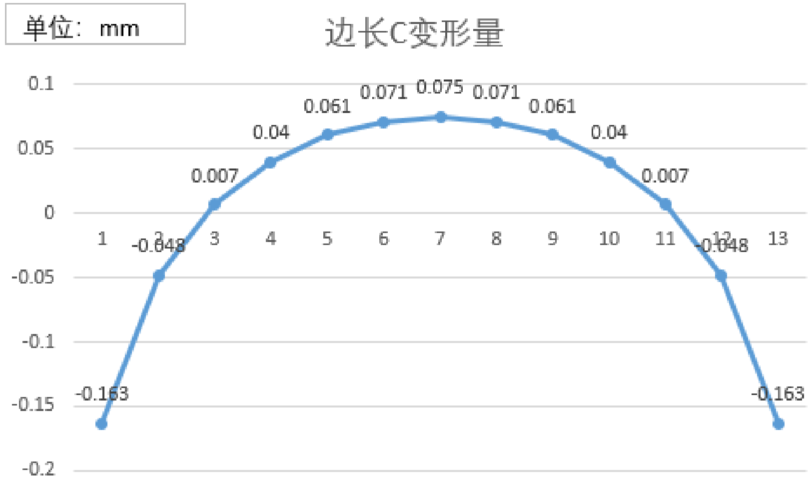


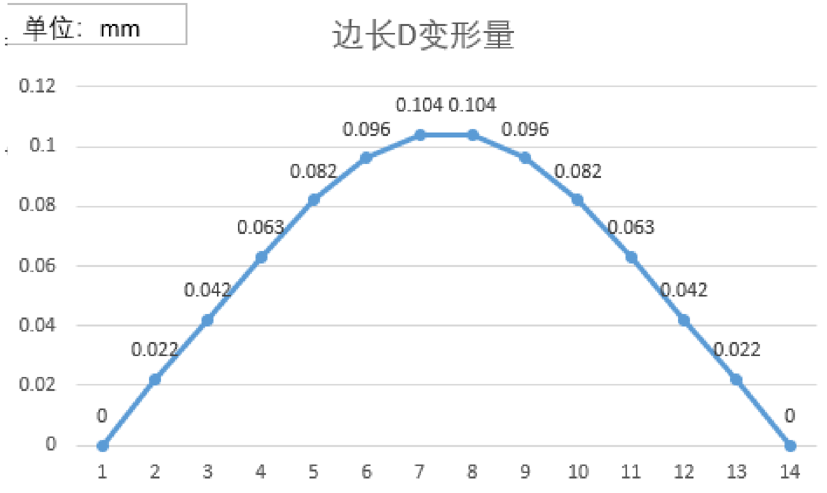


A/B/C/D are the sides of the cell





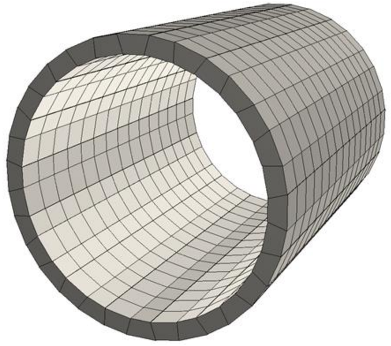


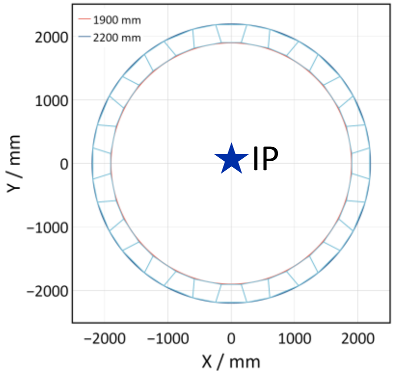


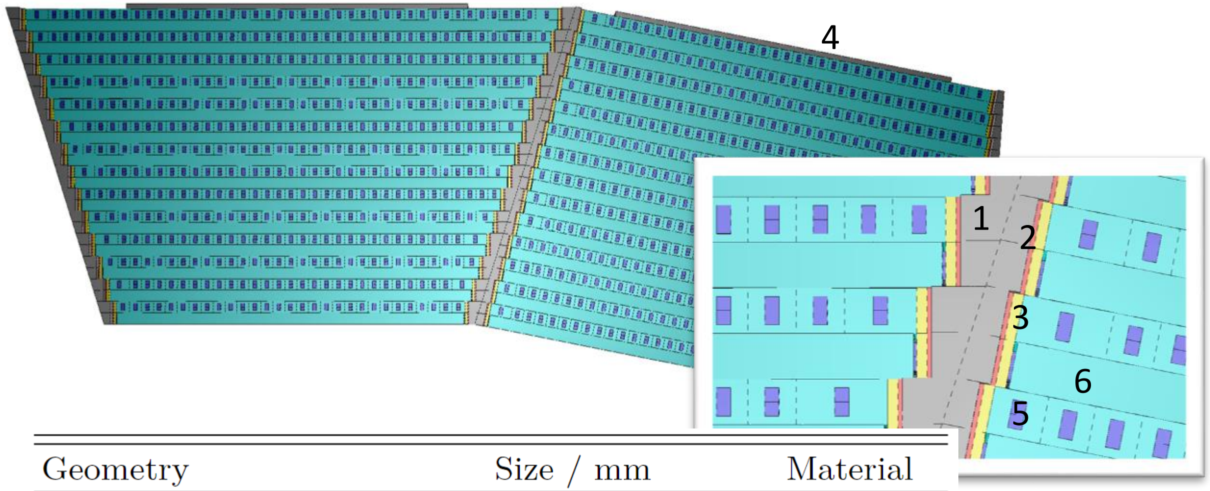
The BGO is brittle, so we have to know the deformation of each cell . According to the FEA, the maximum deformation of the cells is 0.23mm.

ECAL barrel: geometry and materials

- 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	∼ 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

Barrel ECAL geometry: detailed design