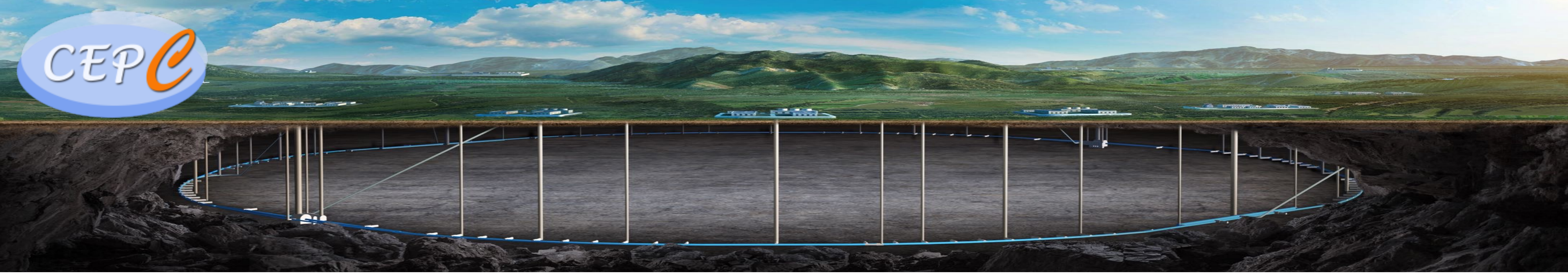

CEPC Electromagnetic Calorimeter

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Chinese Academy of Sciences

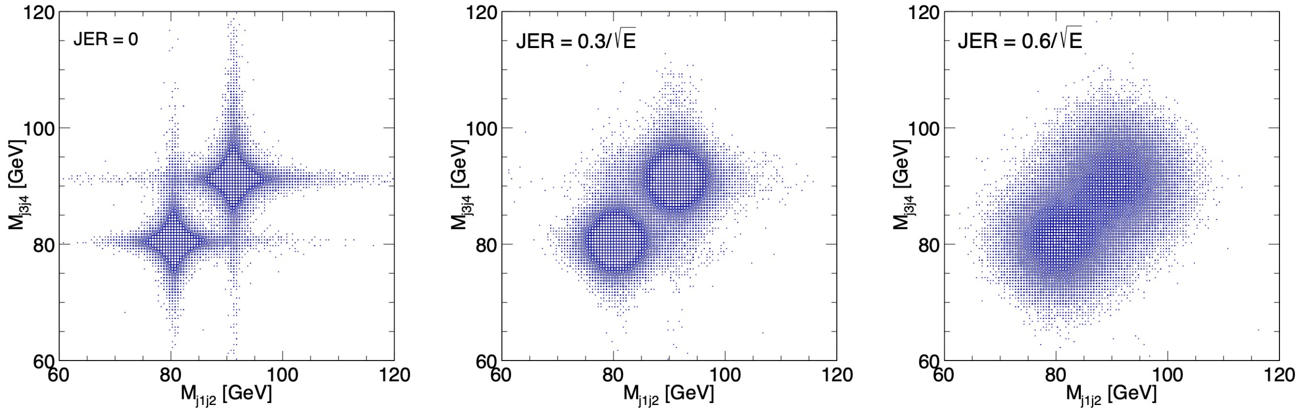
Content

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)

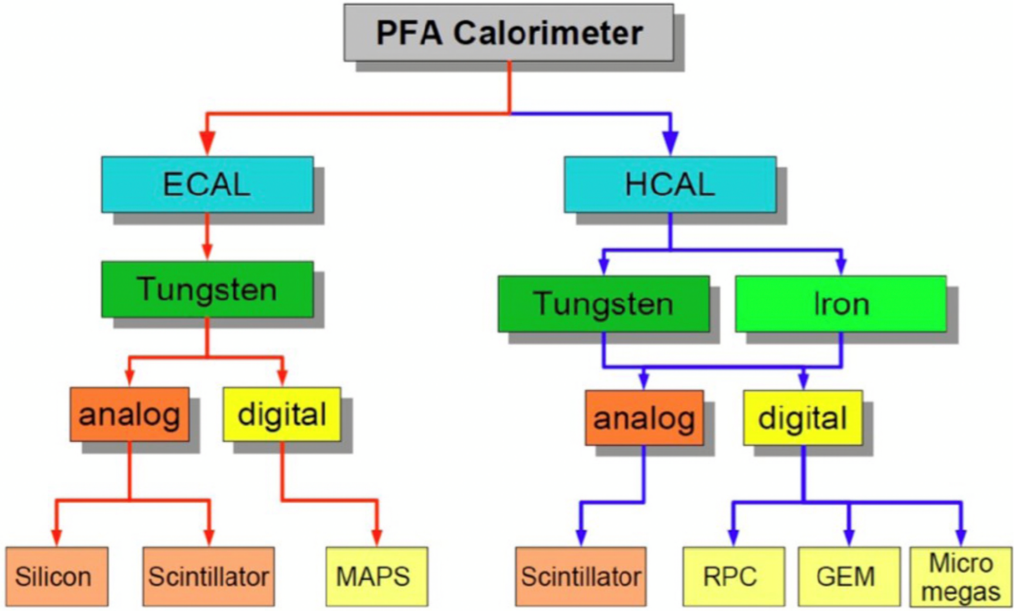
- General remarks: the CEPC calorimetry system (in the reference detector) will based on the particle-flow paradigm → high granularity in 3D
  - Aim to achieve an unprecedented Boson Mass Resolution (BMR) of 3 – 4%

ECAL requirements

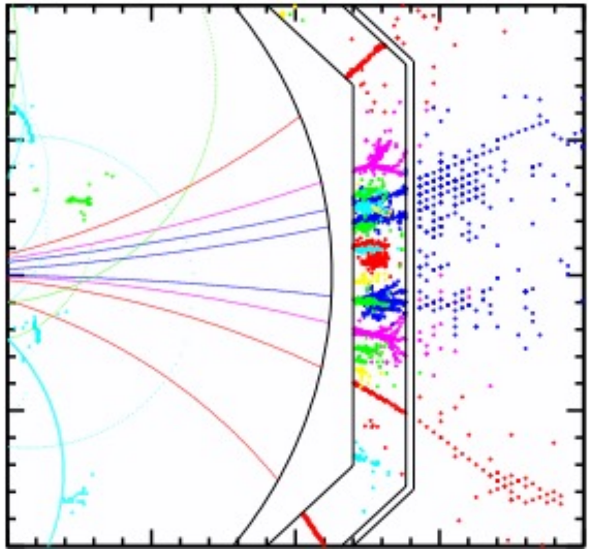
Parameter	Conservative	Ambitious	Remarks
EM energy resolution	$\frac{\sigma_E}{E} = 15\%/\sqrt{E(GeV)} \oplus 1\%$	$\sigma_E/E = 3\%/\sqrt{E(GeV)} \oplus 1\%$	Jet performance; flavor physics
Longitudinal Depth	$24X_0$ (with longitudinal segmentations)		Full containment of EM showers
Transverse Granularity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

Technical option survey

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

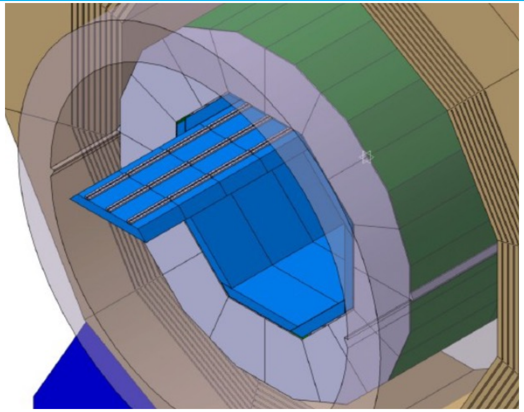


Highly granular (imaging) calorimetry
+ particle flow algorithm (PFA)

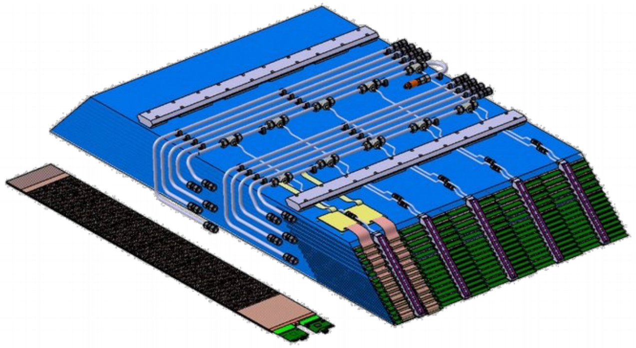


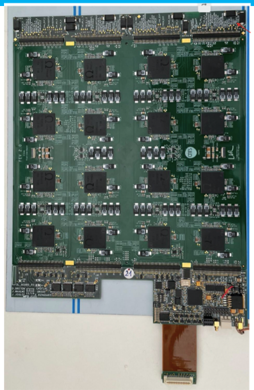
PFA calorimetry: various tech. options explored in the **CALICE collaboration** in past 20 years

SiW-ECAL option

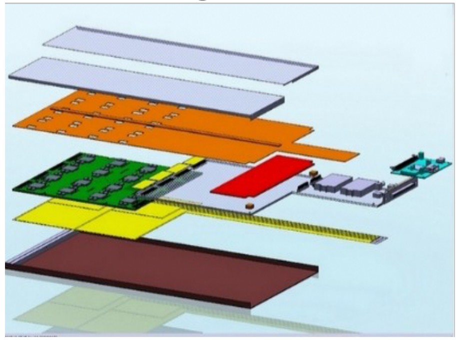


Silicon sensors+ CuW

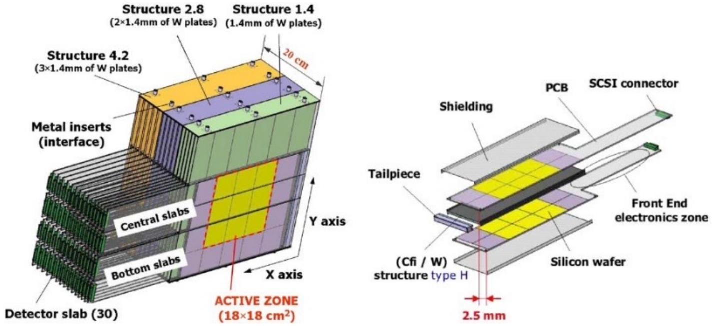


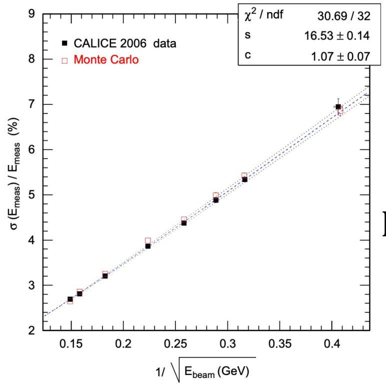


Stacking structure



CALICE SiW-ECAL Physics Prototype

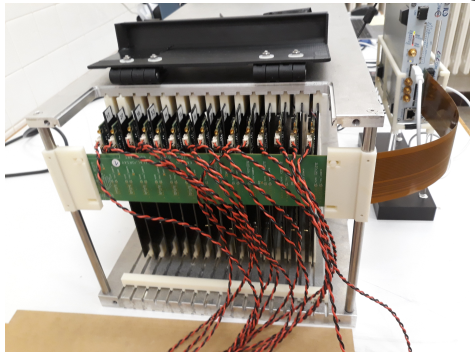




EM resolution in beamtest:

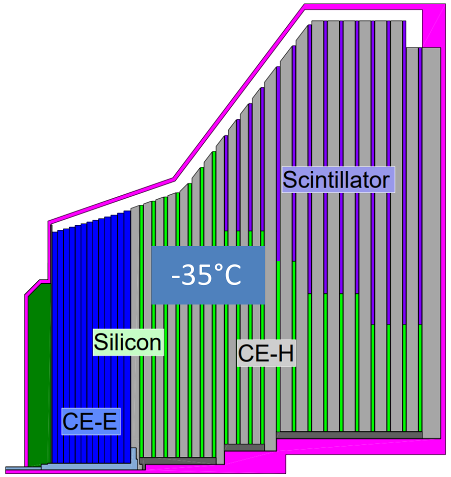
$16.5\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

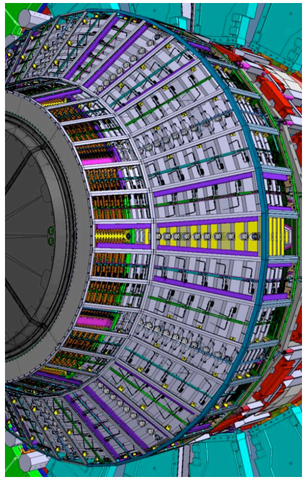
CALICE SiW-ECAL Technological Prototypes

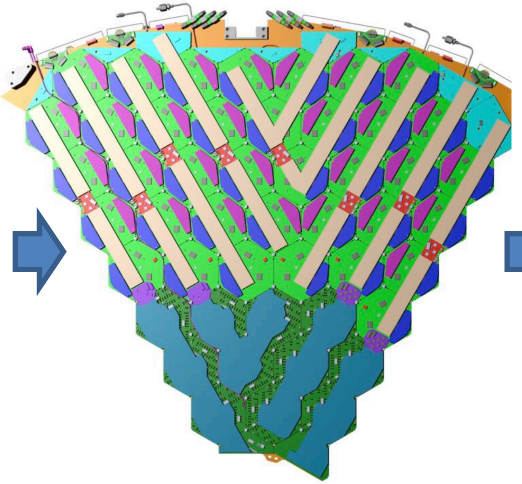


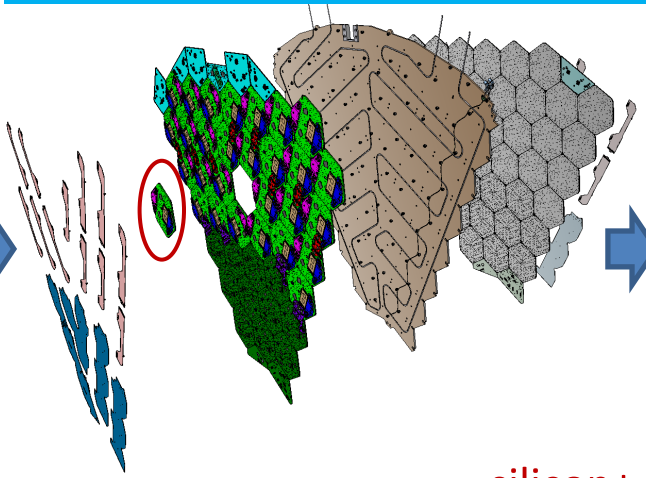
- Large area silicon sensors (pixelated) interleaved with CuW plate (compact showers)
- Baseline ECAL option in CEPC CDR: extensive Higgs physics studies
- Hardware activities in CALICE collaboration, no involvements of CEPC-calo groups
  - Application in CMS-HGCAL project (silicon sector): many synergies

SiW-ECAL option: synergies with CMS-HGCAL

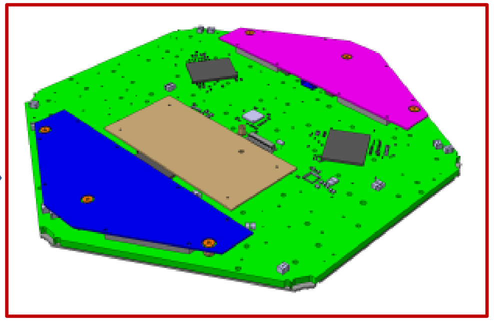




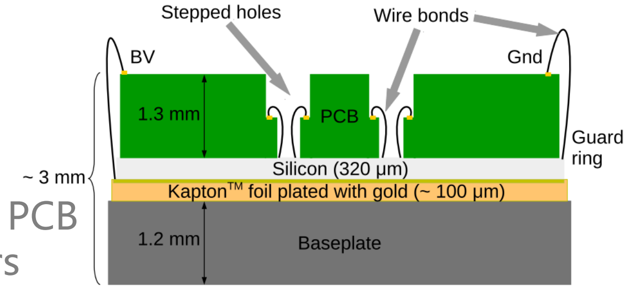




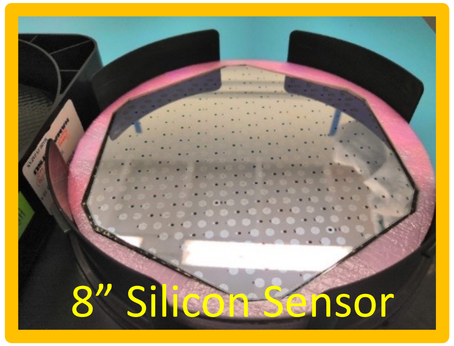
8-inch silicon module

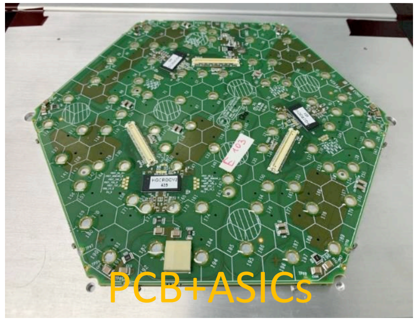


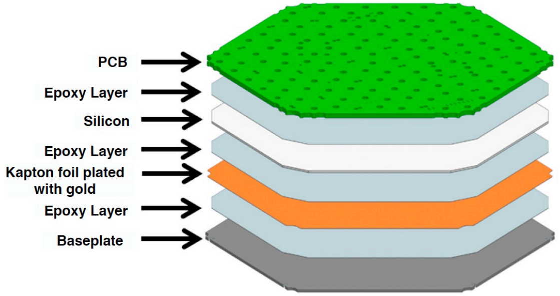
silicon+ PCB + ASICs (HGCROC)



Wire-bonding for PCB and silicon sensors

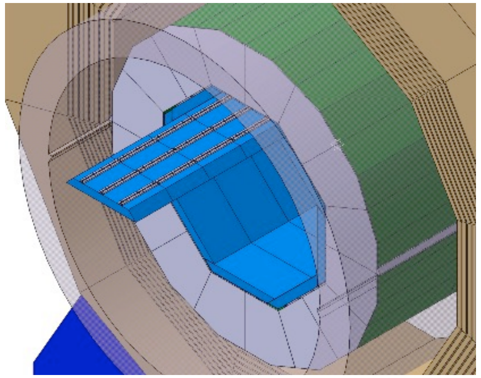


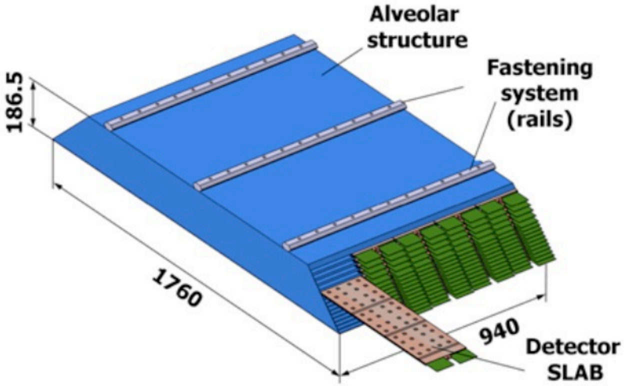


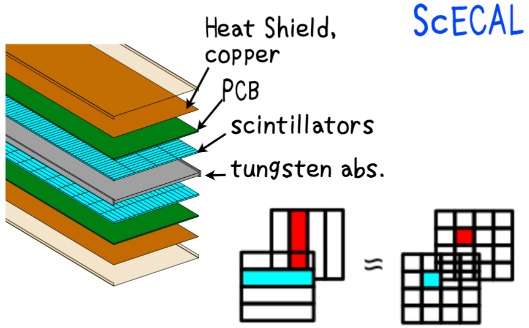


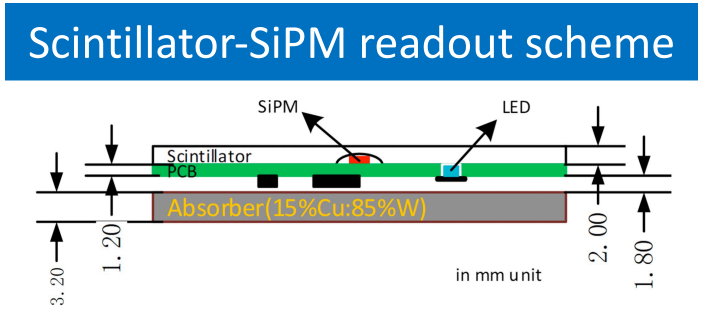
- CMS-HGCAL taskforce successfully established two centers at IHEP
  - MAC (Module Assembly Center) Beijing Site, with 6 MACs around the world
  - SQC (Sensor Quality Control) Beijing Site, with 5 SQCs around the world

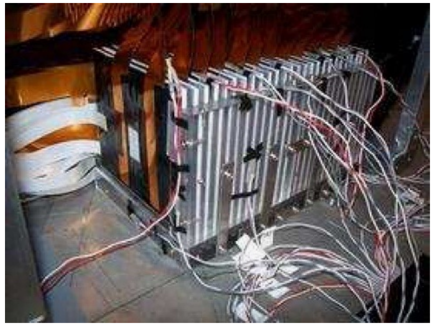
ScW-ECAL option

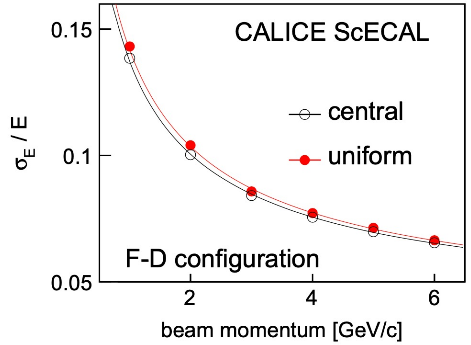


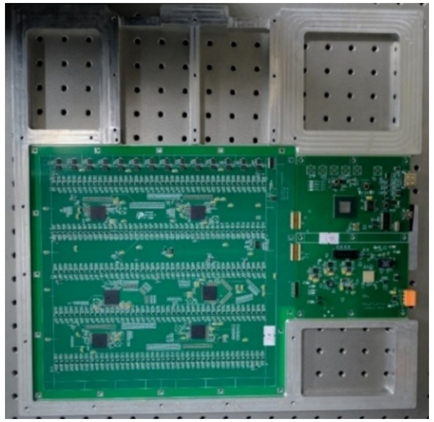










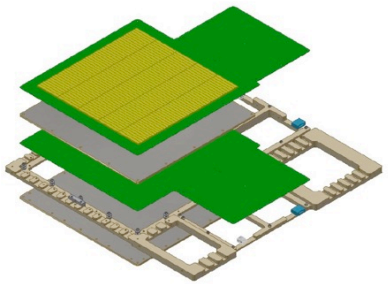


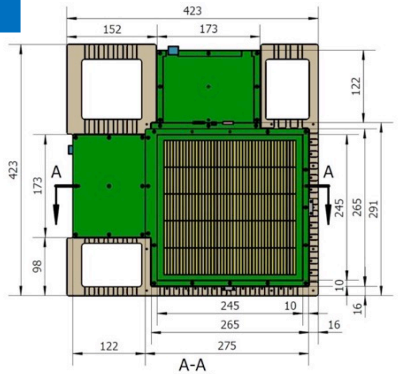
- Scintillator strips + SiPMs, interleaved with CuW plate (compact showers)
- An alternative ECAL option in CEPC CDR
- Strong involvements of Chinese and Japanese groups in the CALICE collaboration
  - Developed a technological prototype, followed by successful beamtests at CERN PS/SPS

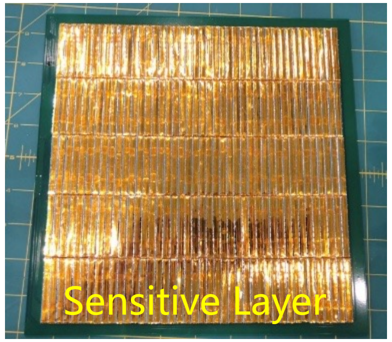
ScW-ECAL option

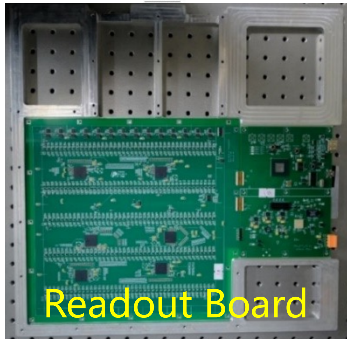
ScW-ECAL tech. prototype

"Super-layer" design



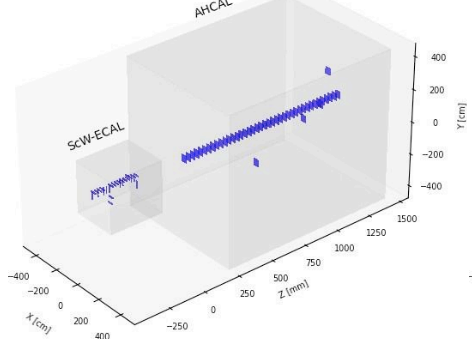




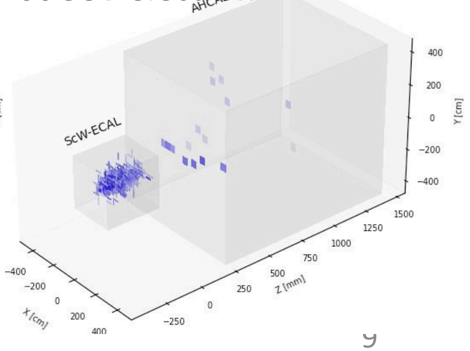


- ScW-ECAL tech. prototype developed in 2016-2020
  - (Effective) Transverse granularity of $5 \times 5\ \mathrm{mm}^2$
  - 6,720 channels, 32 longitudinal sampling layers (22X0)
  - Successful beamtest campaigns at CERN in 2022-2023
    - Collected data sets with various beam particles

100GeV muon

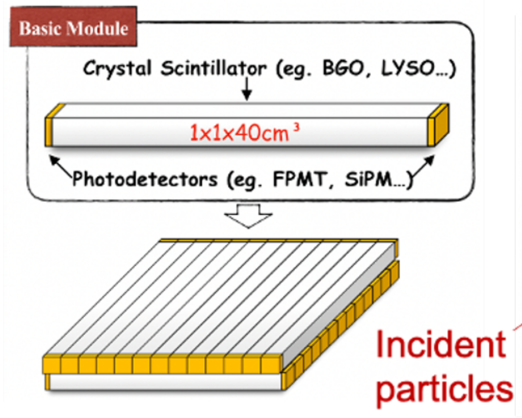


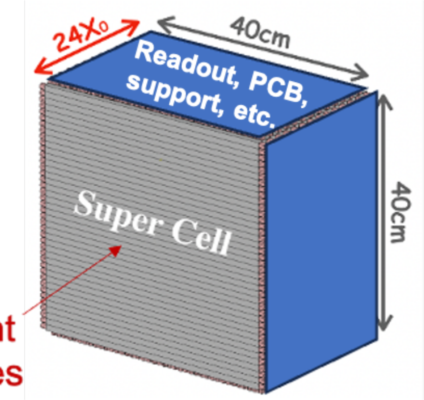
60GeV electron



4D Crystal ECAL option

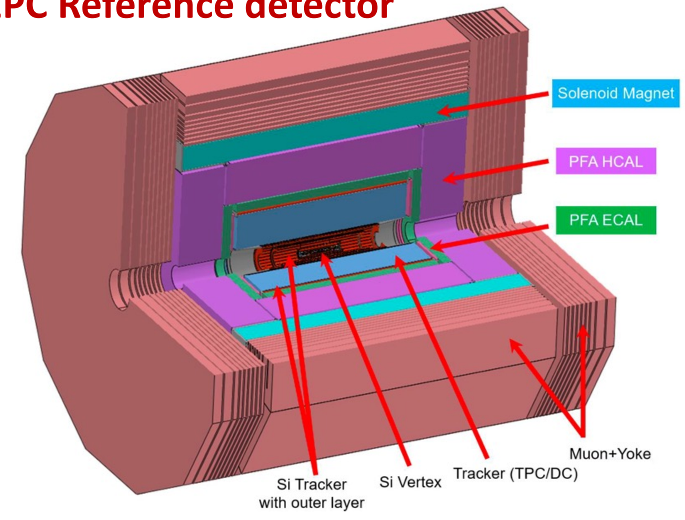
- A new option: development started since ~2020
- Compatible for PFA: Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E = 3\%/\sqrt{E}$
- Minimal longitudinal dead material: orthogonal arranged bars
  - 3D positioning with two-sided readout for timing

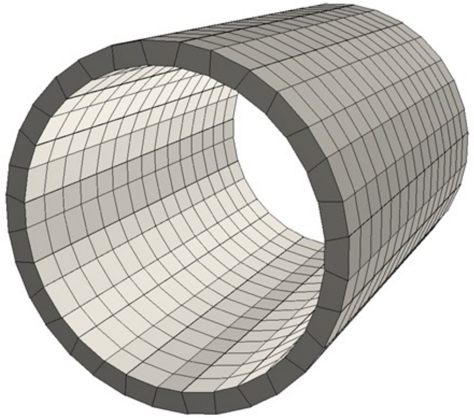




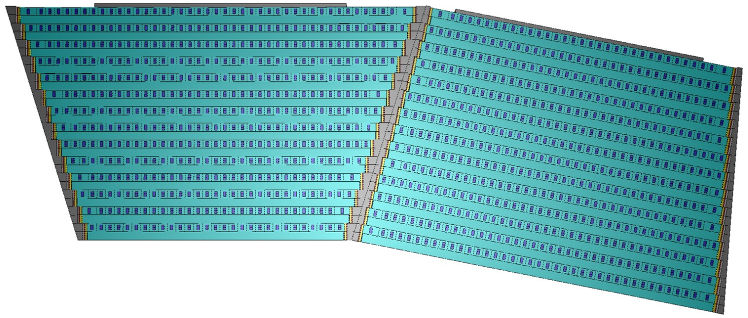
- **BGO bars in $1\times1\times\sim40\ cm^3$**
- **Effective granularity $1\times1\times2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**

CEPC Reference detector



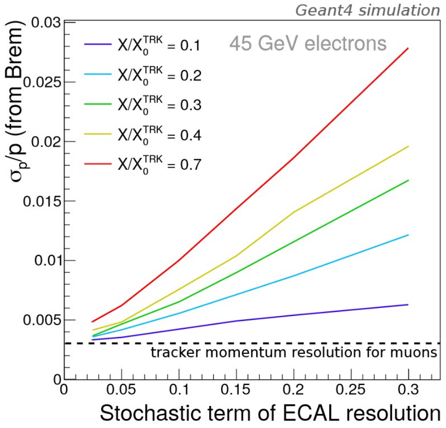


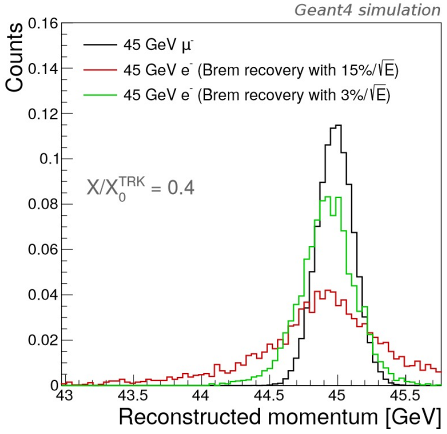
32-side polygon, depth 24 X_0
28 longitudinal layers

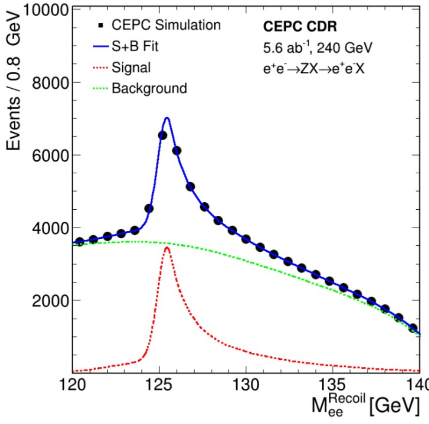


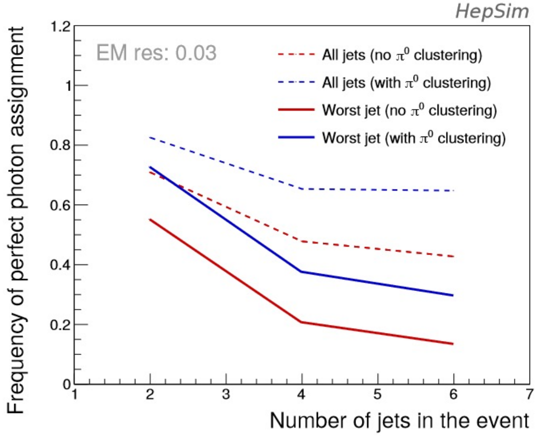
Crystal ECAL: physics motivations

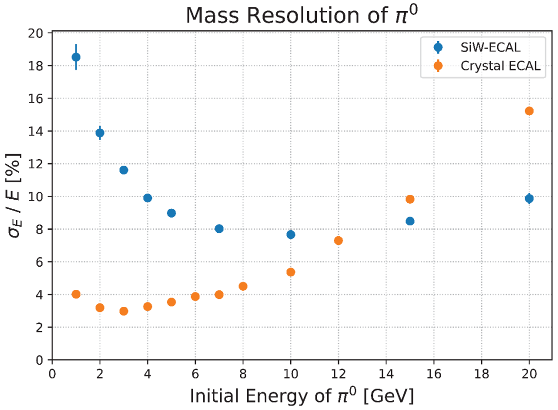
- Crystal provides an energy resolution to photons and electrons at the level of $3\%/\sqrt{E}$
  - Significantly enhance EM performance with similar budget of SiW-ECAL
- Higgs and EW physics programs
  - Precision measurements of Higgs recoil mass: e.g. *Bremsstrahlung energy corrections* of **electrons** 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)











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 of PFA calorimetry, provides optimal EM resolution

Main Technical Challenges

- 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

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

→

Hardware activities: addressing crucial issues

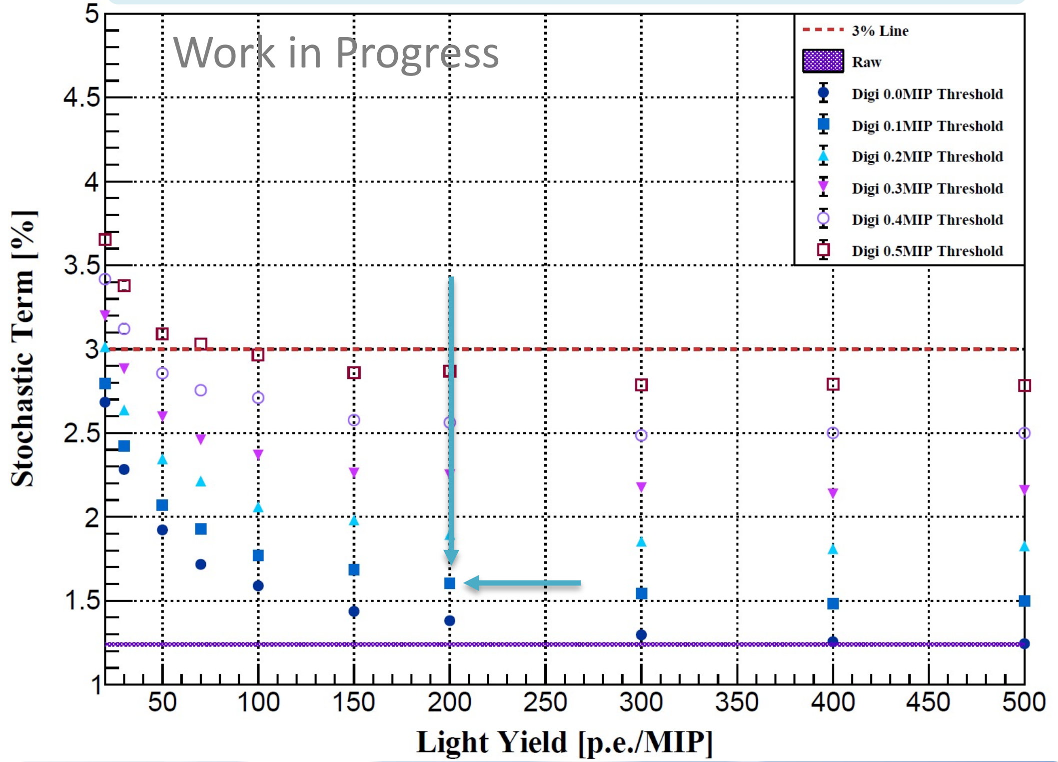
- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal dimensions
- Dynamic range of electronics
- Energy response of crystal module

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

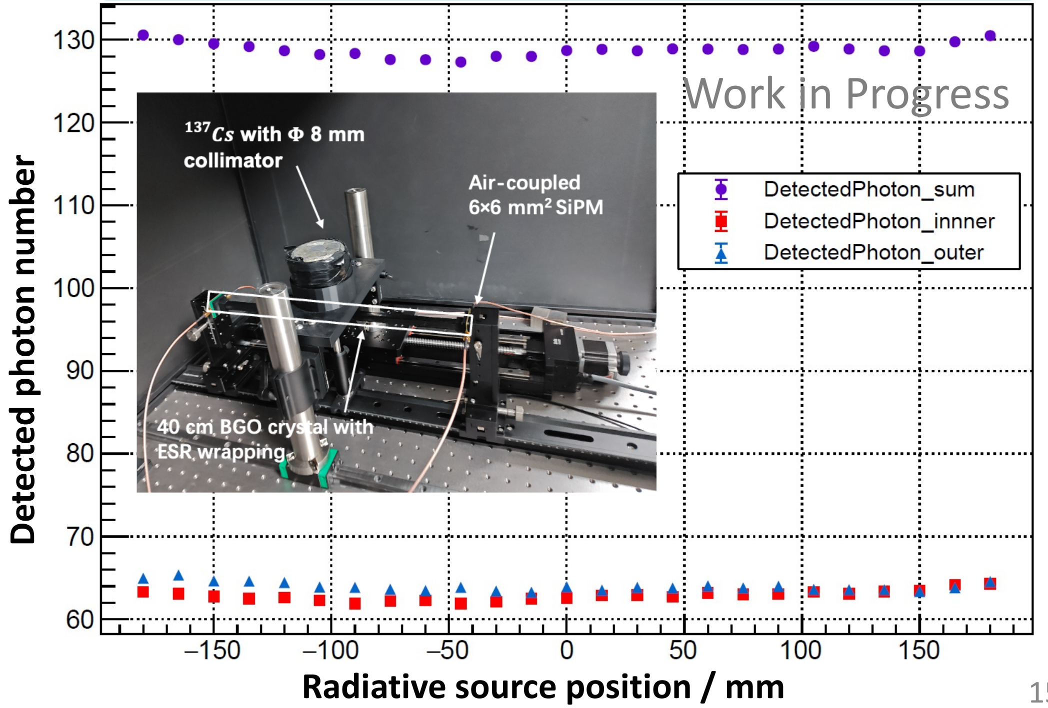
- **MIP response: >200 p.e./MIP → $\sigma_E/E = 3\%/\sqrt{E}$**
- **Energy threshold: 0.1 MIP**

Light yield v.s. energy resolution



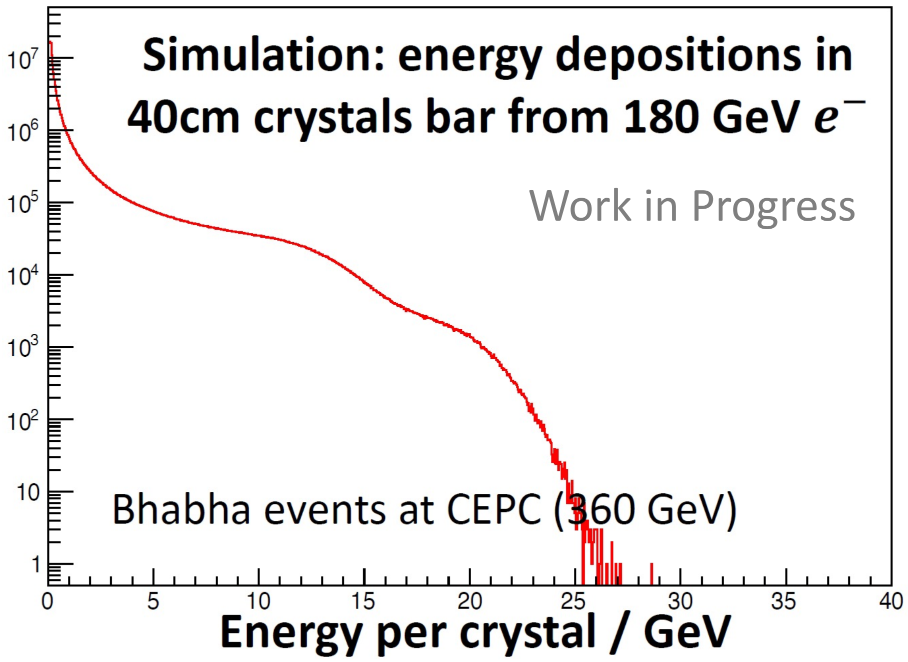
- **Uniformity along one 40 cm crystal bar: ~2.5%**
  - **Can be further improved after calibration**

Response uniformity along bar



R&D efforts and results: dynamic range

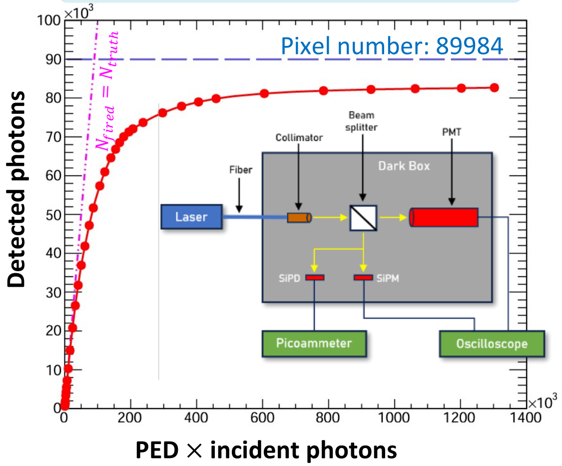
- Simulation of high energy electrons: maximum energy per crystal
- Test-stand with pico-second laser: SiPM non-linearity effects (target for ***6μm pixel pitch***)
- Beamtest of crystal-SiPM units with a state-of-art chip: dynamic range of SiPM and ASIC



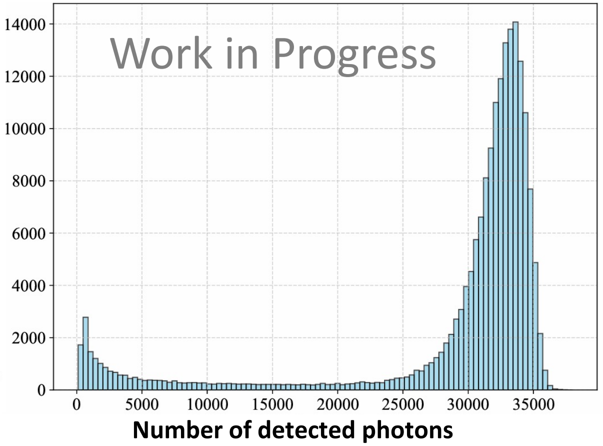
~30 GeV as max. energy deposition per crystal bar

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

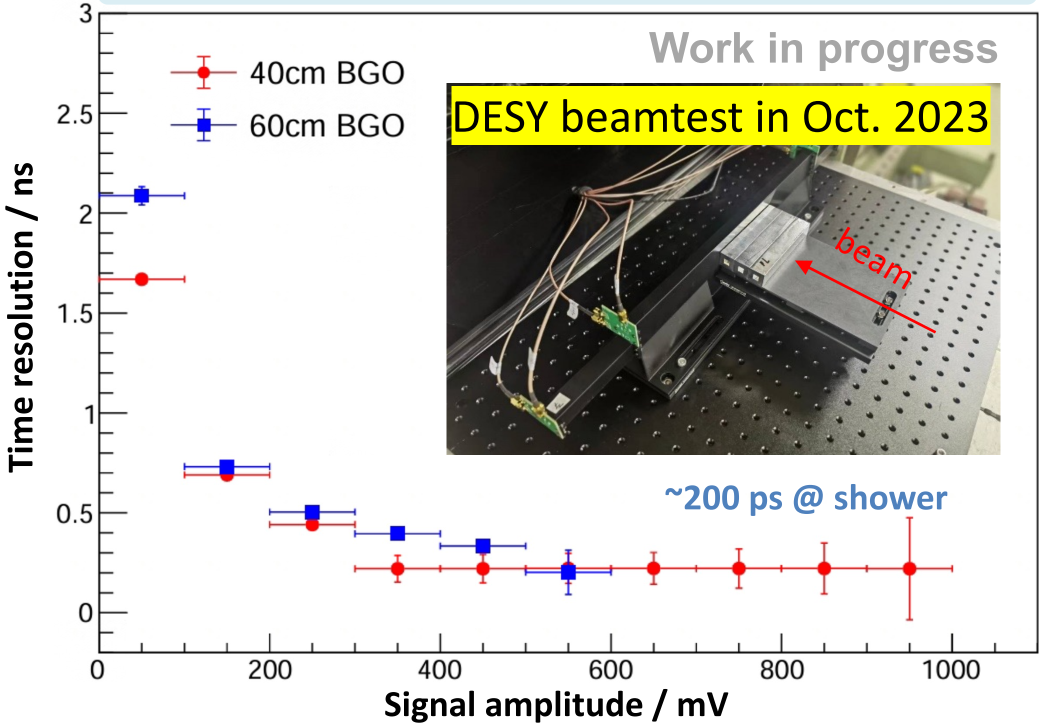
R&D efforts and results: timing studies

Dedicated beamtests for timing studies with MIP and EM showers

Timing performance within EM showers

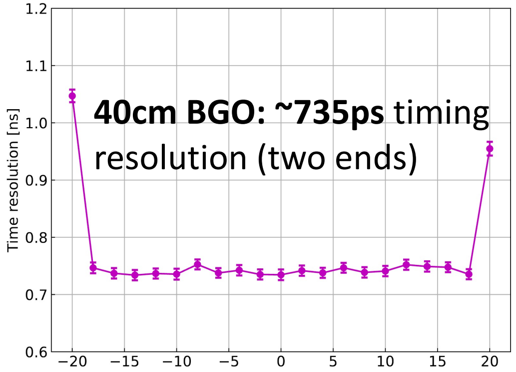
- Tested 40cm/60cm BGO bars with 5GeV electron beam
- ~200 ps within EM showers (>12 MIPs)

Time resolution vs signal amplitude

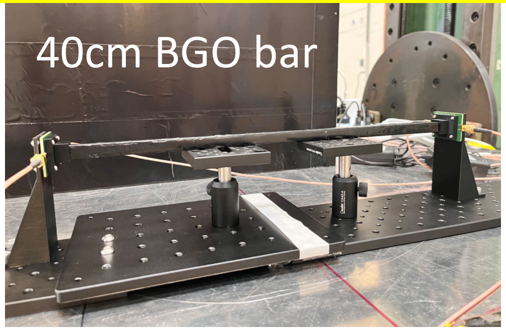


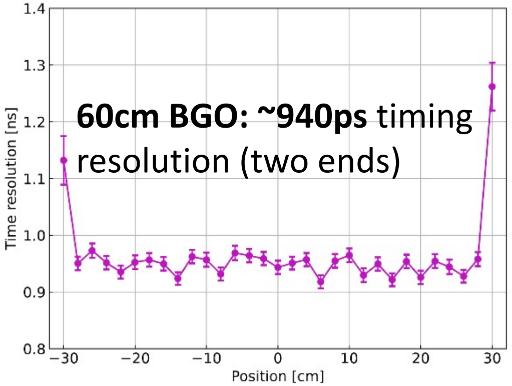
Timing performance with MIP-like particles

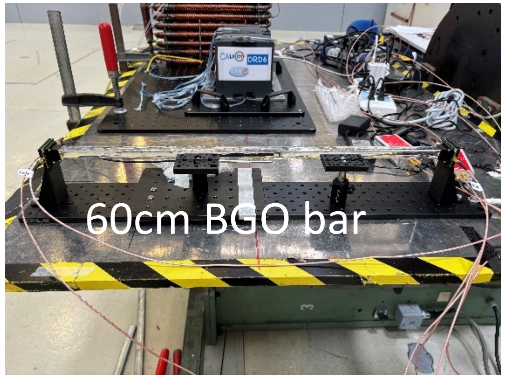
- 10 GeV π^- beam to scan 40cm and 60cm BGO bars
- 40cm BGO: MIP timing resolution of 520 ps at a single end
- 60cm BGO: MIP timing resolution of 665 ps at a single end



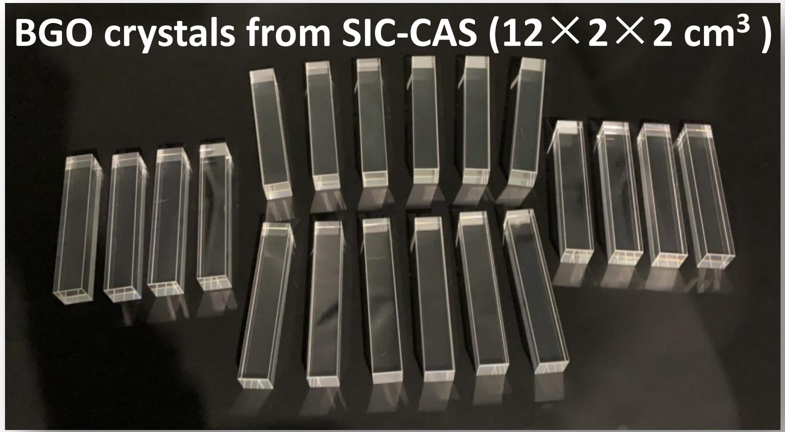
CERN beamtest in Jul. 2024

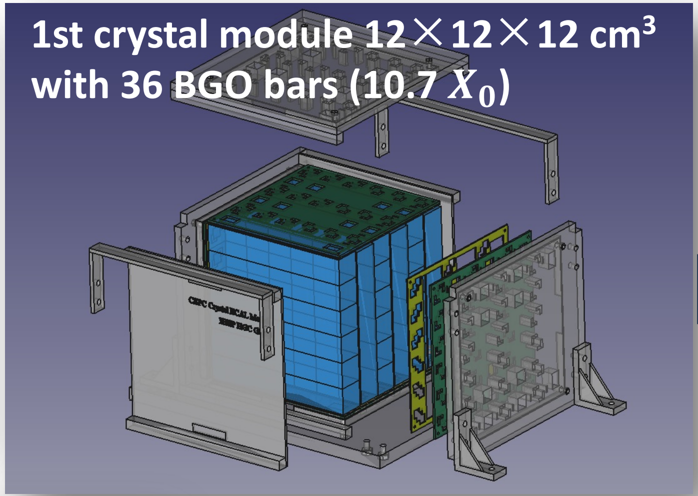


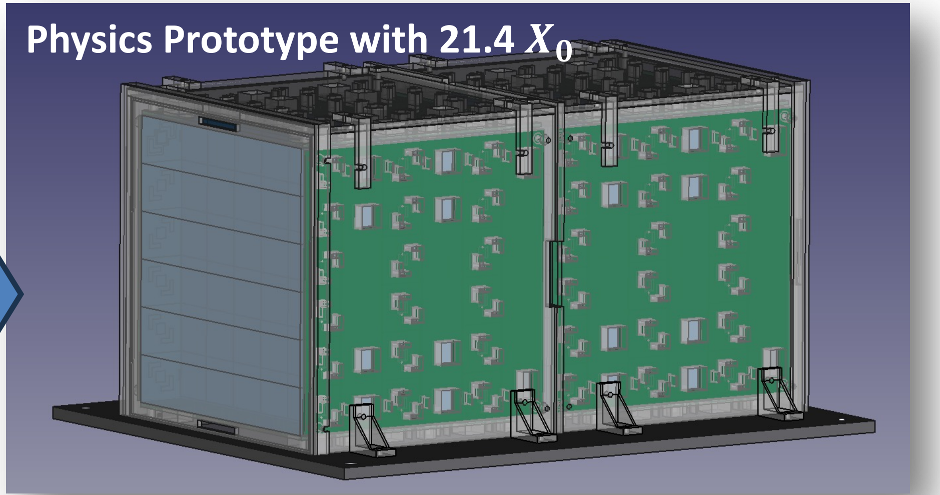


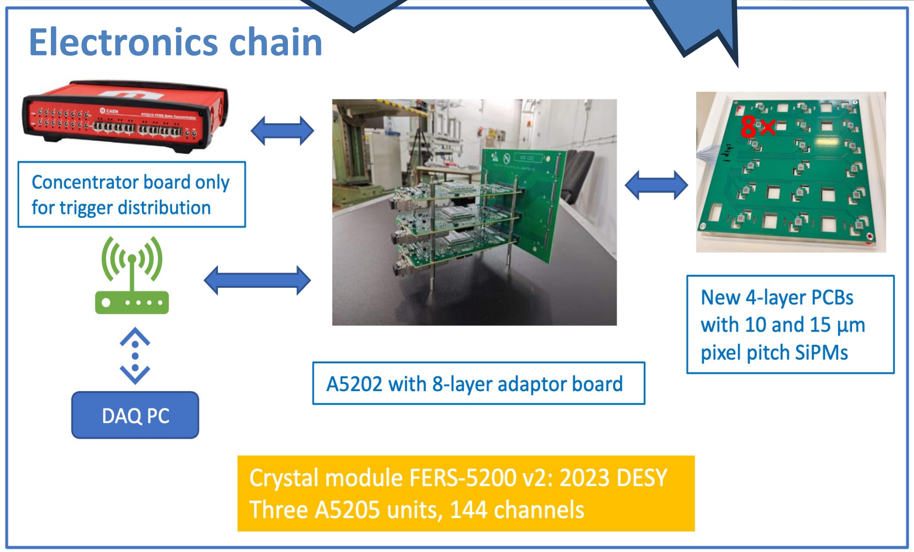


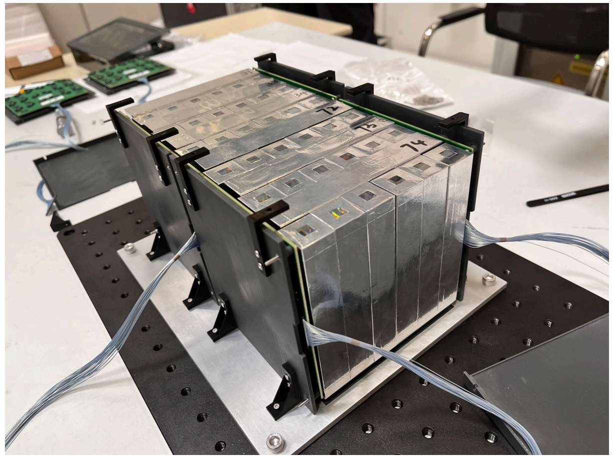
4D Crystal Calorimeter: First Physics Prototype


BGO crystals from SIC-CAS (12×2×2 cm^3)


1st crystal module 12×12×12 cm^3 with 36 BGO bars (10.7 X_0)


Physics Prototype with 21.4 X_0





First crystal calorimeter prototype
- Successfully developed in 2021-23
- With commercial ASICs

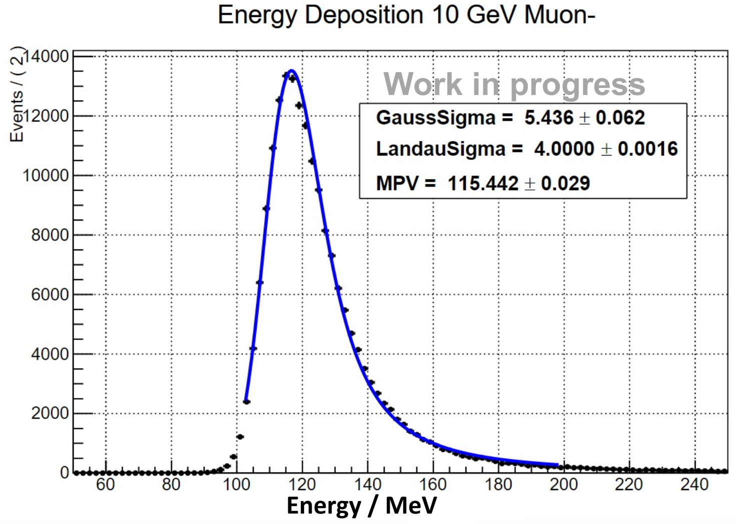
Major motivations
- Critical issues at system integration
- EM performance in system level
- Validation of simulation and digitization with beamtest data

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

Beam tests: 4D Crystal Calorimeter Prototype

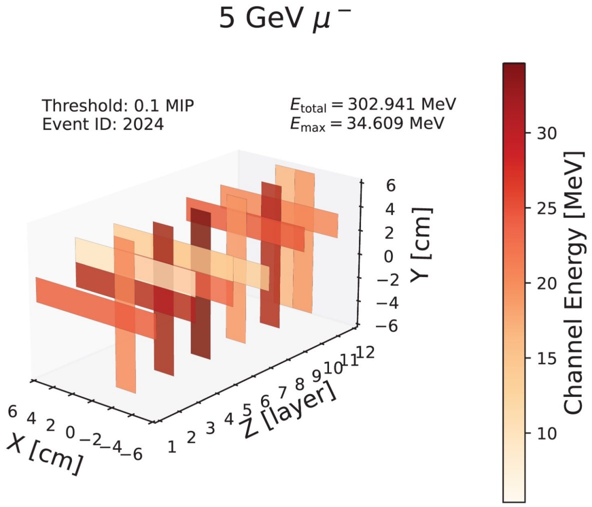
2023 CERN beam test at PS-T9

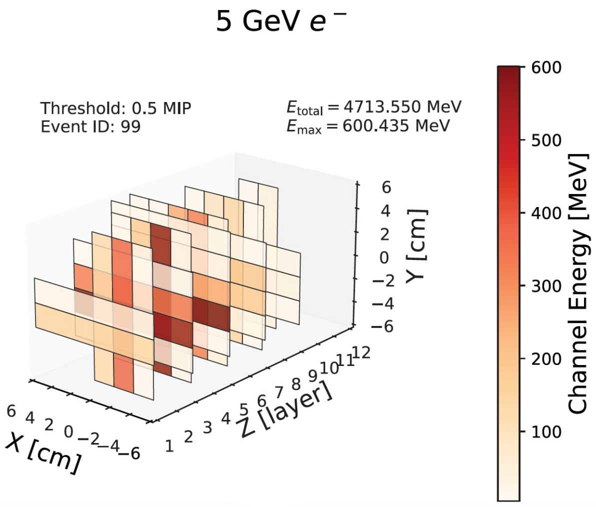
- Successful system commissioning
- Clear MIP signals for all channels

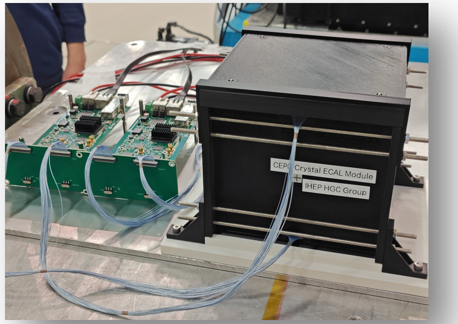


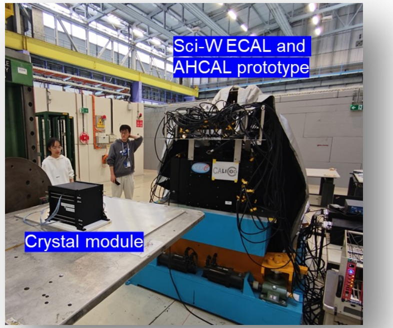
2024 CERN beam test at PS-T9 (June 24 – July 10)

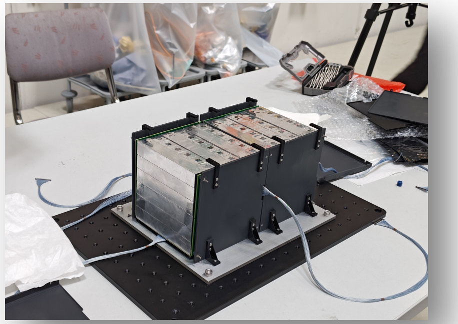
- Promising EM resolution with 1-10 GeV/c e^- beam
- Data analysis: detailed calibrations, shower profiles



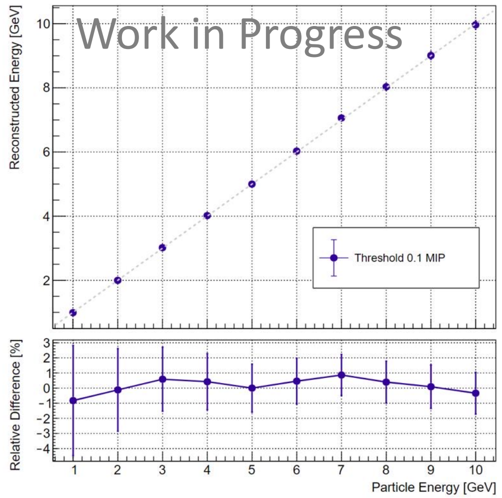


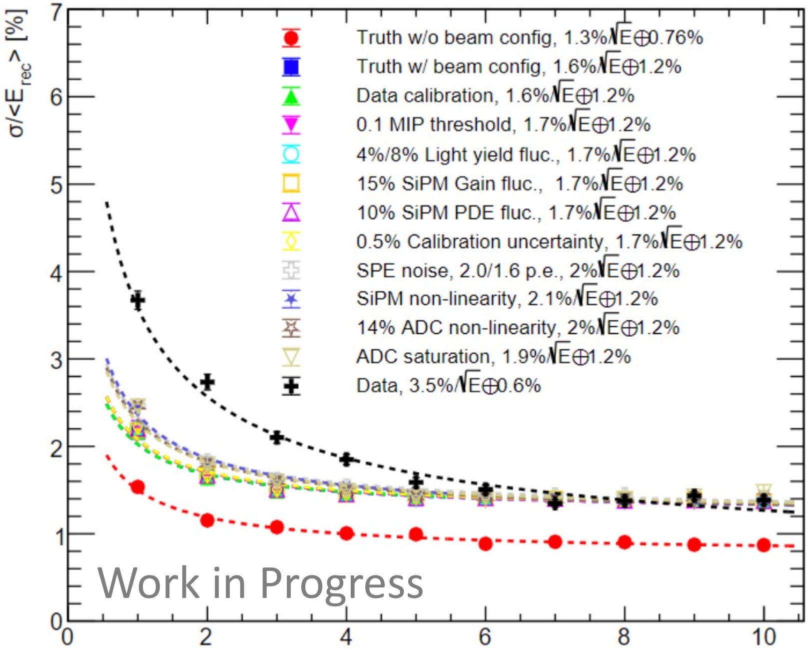






Crystal Calorimeter Prototype: 2024 CERN beamtest

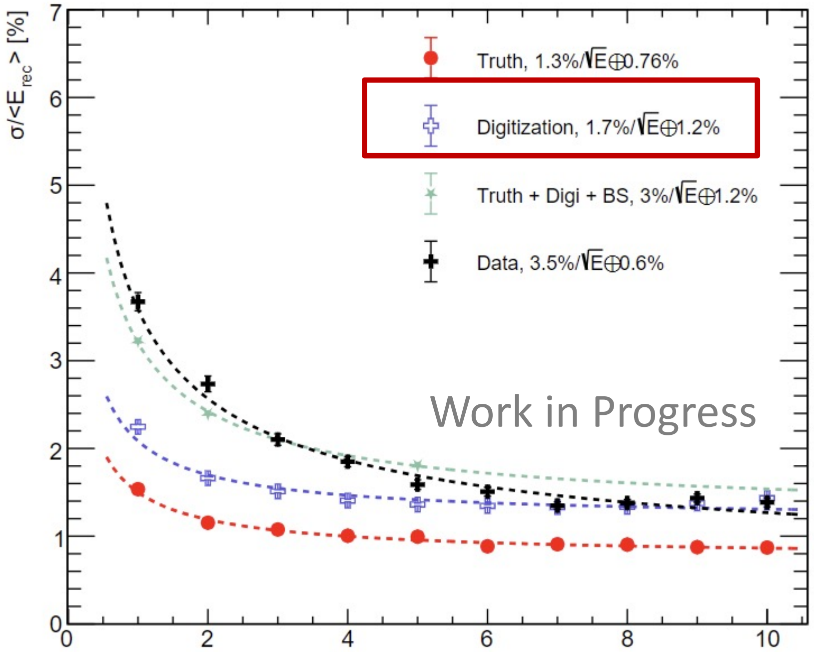




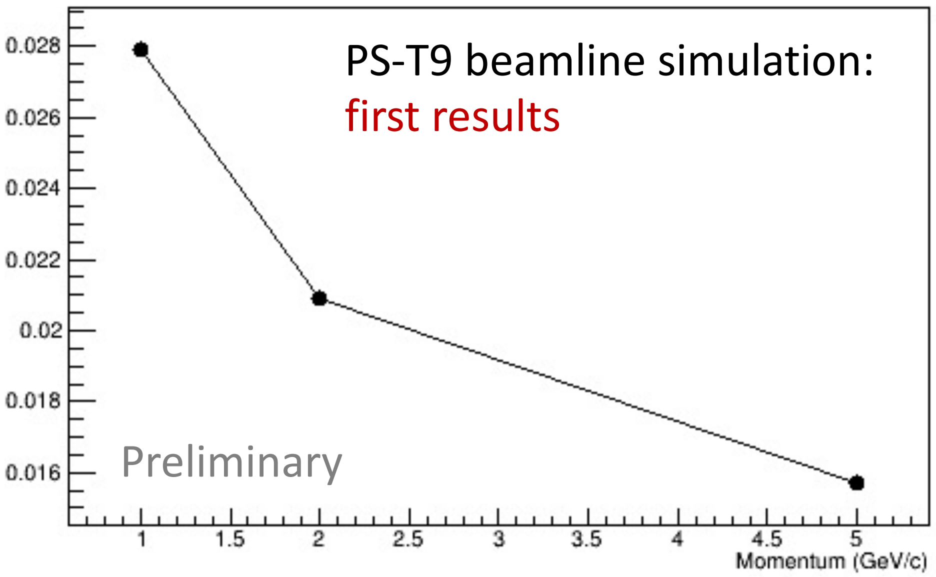
- Studies based on electron beam data in 1 – 10 GeV
  - Data taken with ALL beam instrumentation in upstream: Cherenkov detectors (XCET), SciFi trackers for beam profiles
- EM response linearity within $\pm 1\%$
  - Better understanding of calibration precision (~0.5%) and corrections of crosstalk in ASIC neighbouring channels
- EM energy resolution
  - MC/data generally good consistency in higher energy region
  - In lower energy region (< 4GeV), noticeable discrepancy
  - CERN expert confirmed our observation: larger beam momentum spread in data than expected from beamline lattice (~1%)
- Extensive studies on PS-T9 beamline
  - Kind help of CERN beamline physicist: beamline simulation to quantify impacts to momentum due to beam instrumentation

Crystal Calorimeter Prototype: 2024 CERN beamtest

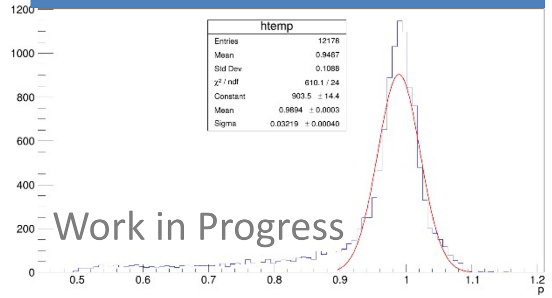
EM resolution: data/MC



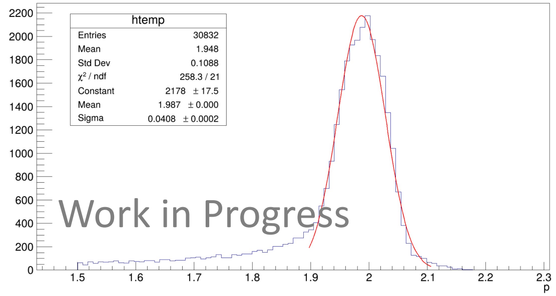
Beam momentum spread in simulation



Beam momentum at 1 GeV



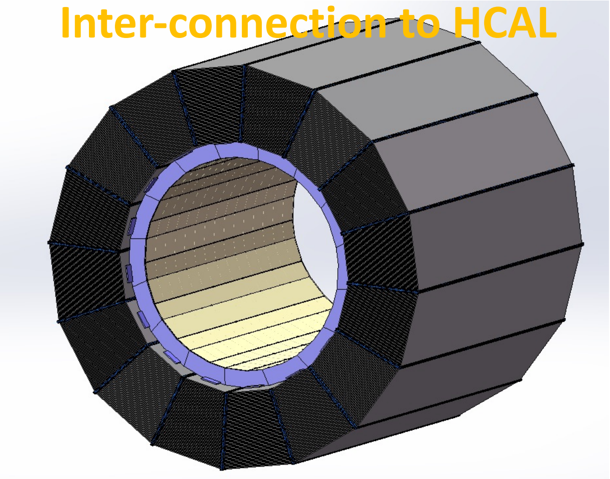
Beam momentum at 2 GeV

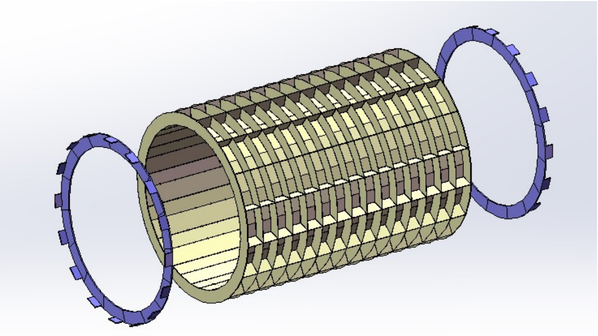


- MC + digitisation can be generally consistent with data by including beam properties
  - Implementing momentum spread from PS-T9 beamline simulation (1, 2 and 5 GeV electrons), kindly shared by CERN beamline expert → ongoing crosschecks
  - EM performance majorly dominated by beam spread in lower energy (e.g. ~3% at 1GeV)
  - Crystal prototype expected EM performance (preliminary): $1.7\%/\sqrt{E} \oplus 1.2\%$

ECAL mechanics design

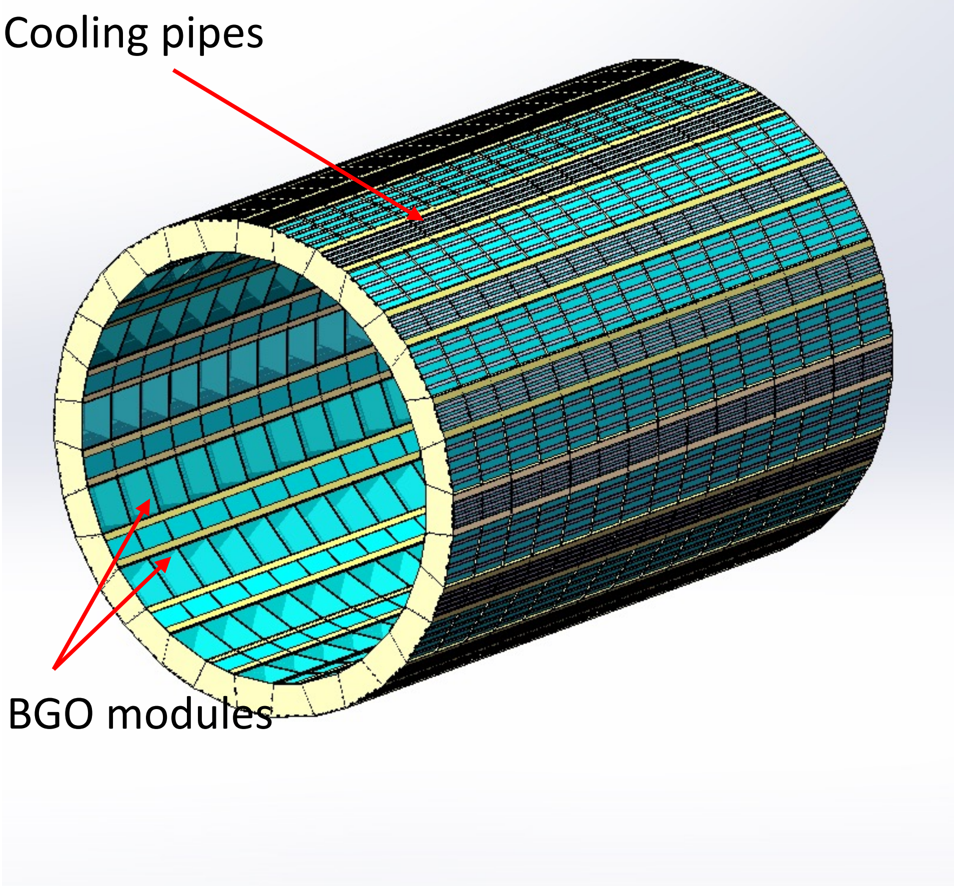
- Crystal ECAL mechanics integrated with active cooling



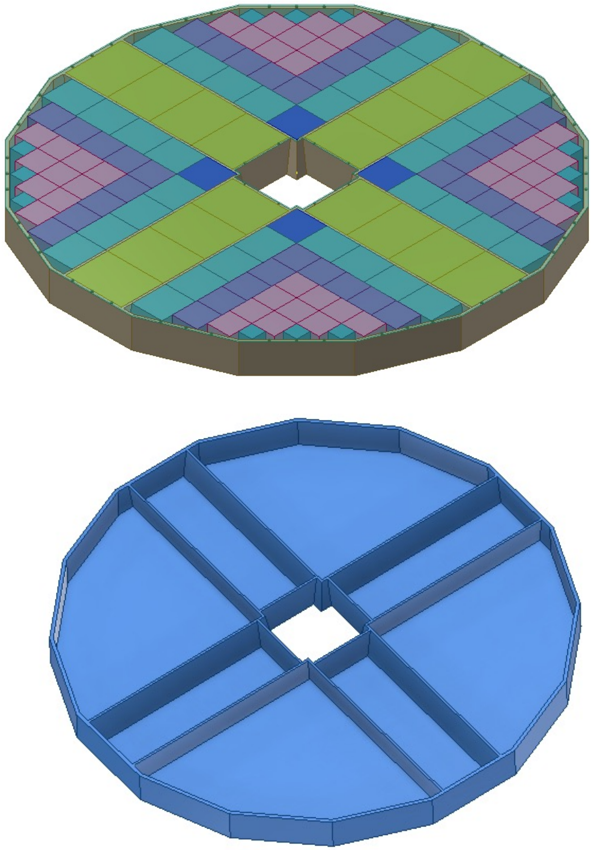


Flanges to fix ECAL to HCAL

Barrel ECAL design

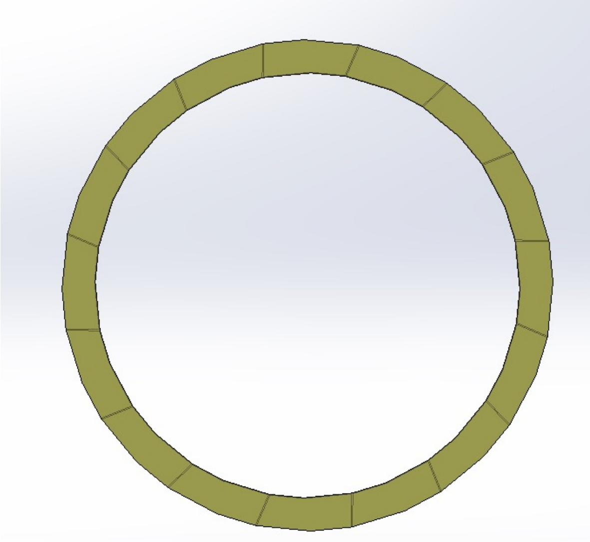


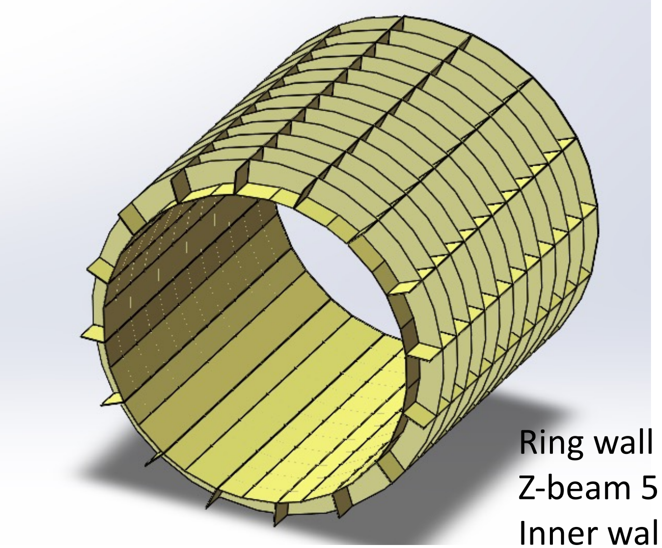
Endcap ECAL design

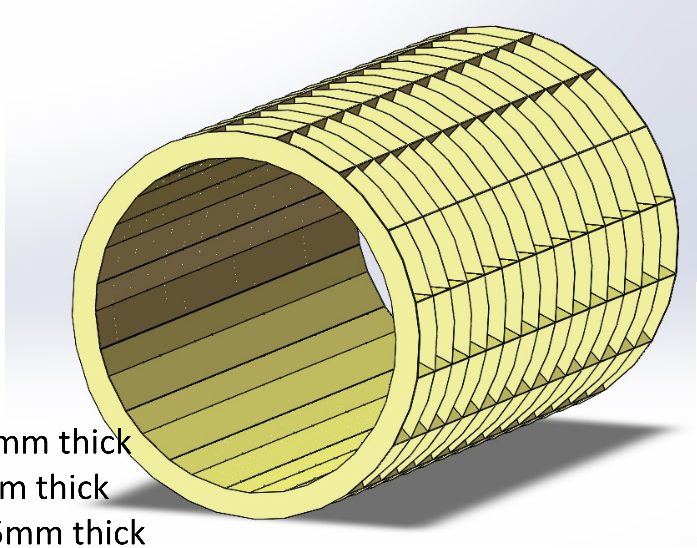


- Support structure is based on Carbon-Fibers for BGO modules (in cyan)

ECAL mechanics: main structure for barrel modules

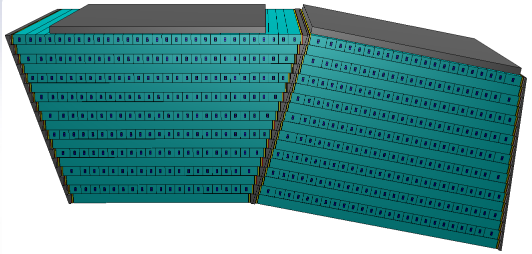






Ring wall 3mm thick
Z-beam 5mm thick
Inner wall 5mm thick

Two crystal modules in one phi/z segment



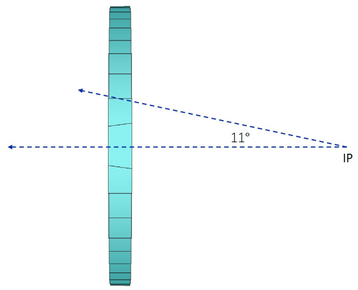
Barrel ECAL parameters

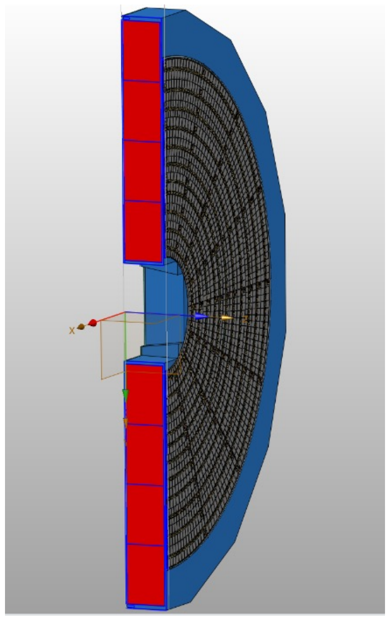
Parameters	Value
Inner Radius	1830 mm
Outer Radius	2130 mm
Length in Z	5800 mm
(Typical) Crystal Length	400 mm
#Modules in R-Phi	32
#Modules in Z	15
Tilted Angle in Phi	12 degrees
Longitudinal Layers	28

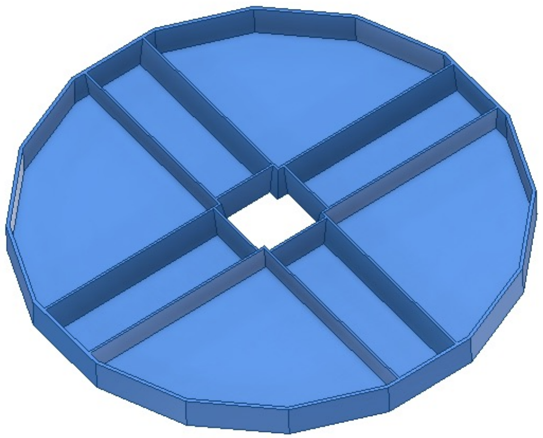
- Main structure of ECAL is based on carbon fibers
- Barrel ECAL modularity
  - 16 segments in phi, 15 segments along Z-axis
  - In each segment: two crystal modules in trapezoid-shape, one in upwards and the other in downwards

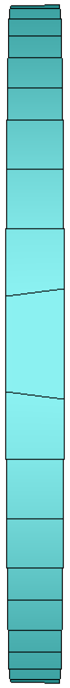
Endcap crystal ECAL: first designs

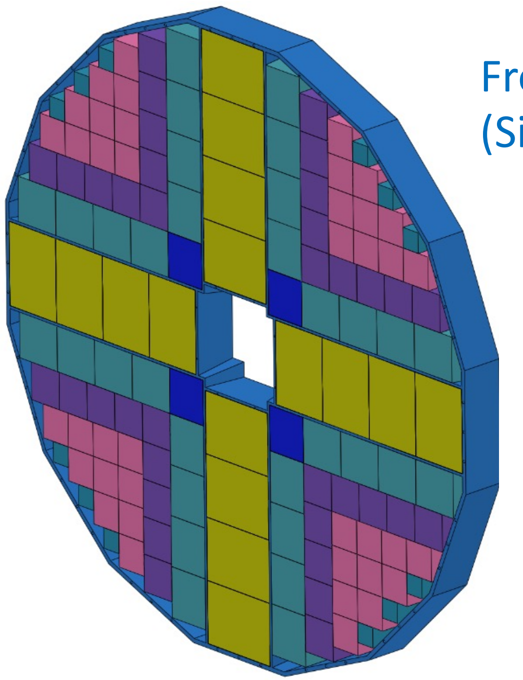
- Endcap crystal modules: 6 different types
  - Trapezoid modules (in blue and yellow) to avoid projectile cracks
- Supporting frame to hold both endcap ECAL and OTK
- Planning: FEA simulation for stability, deformation and cooling

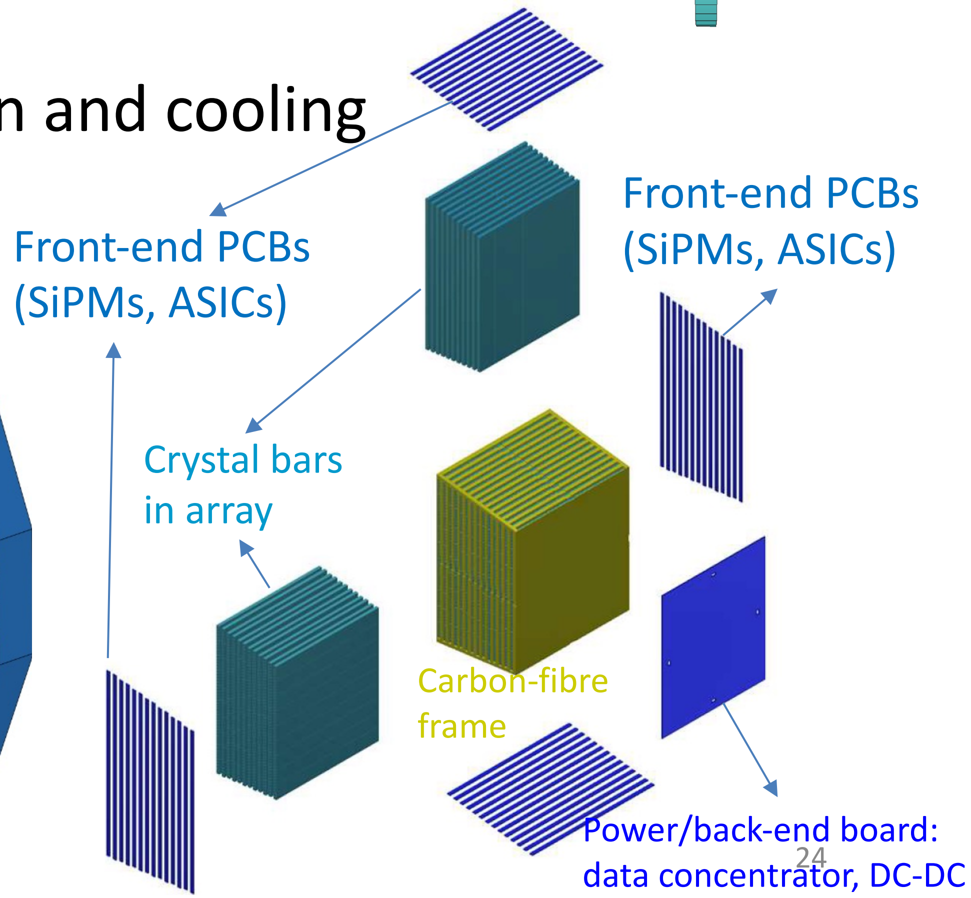




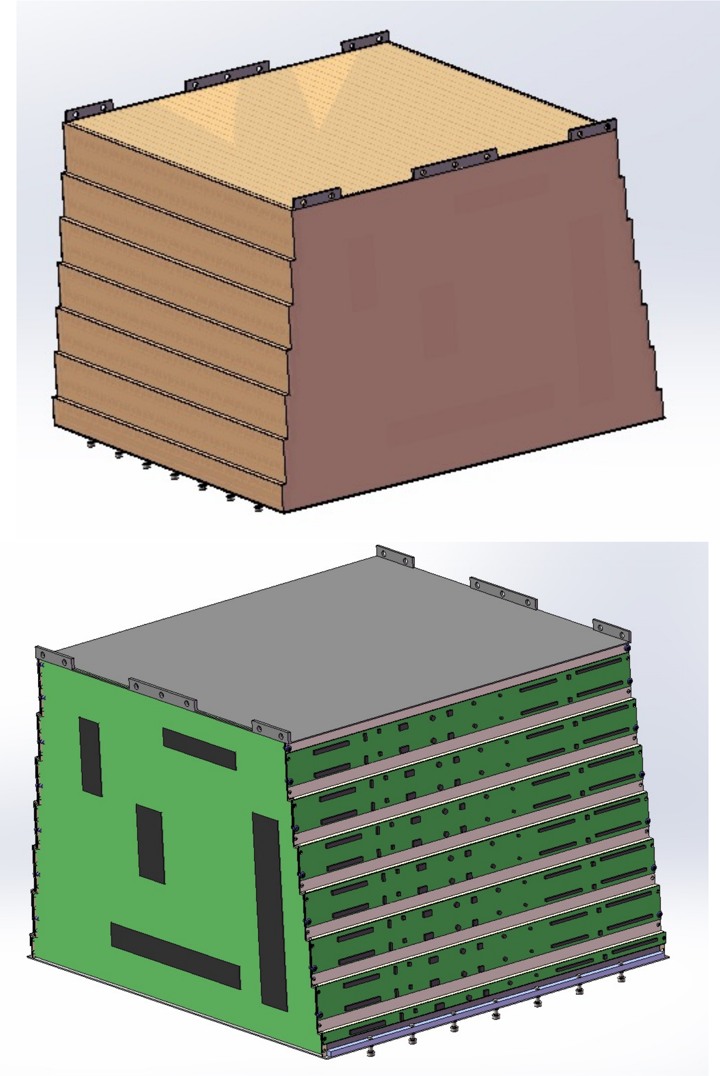


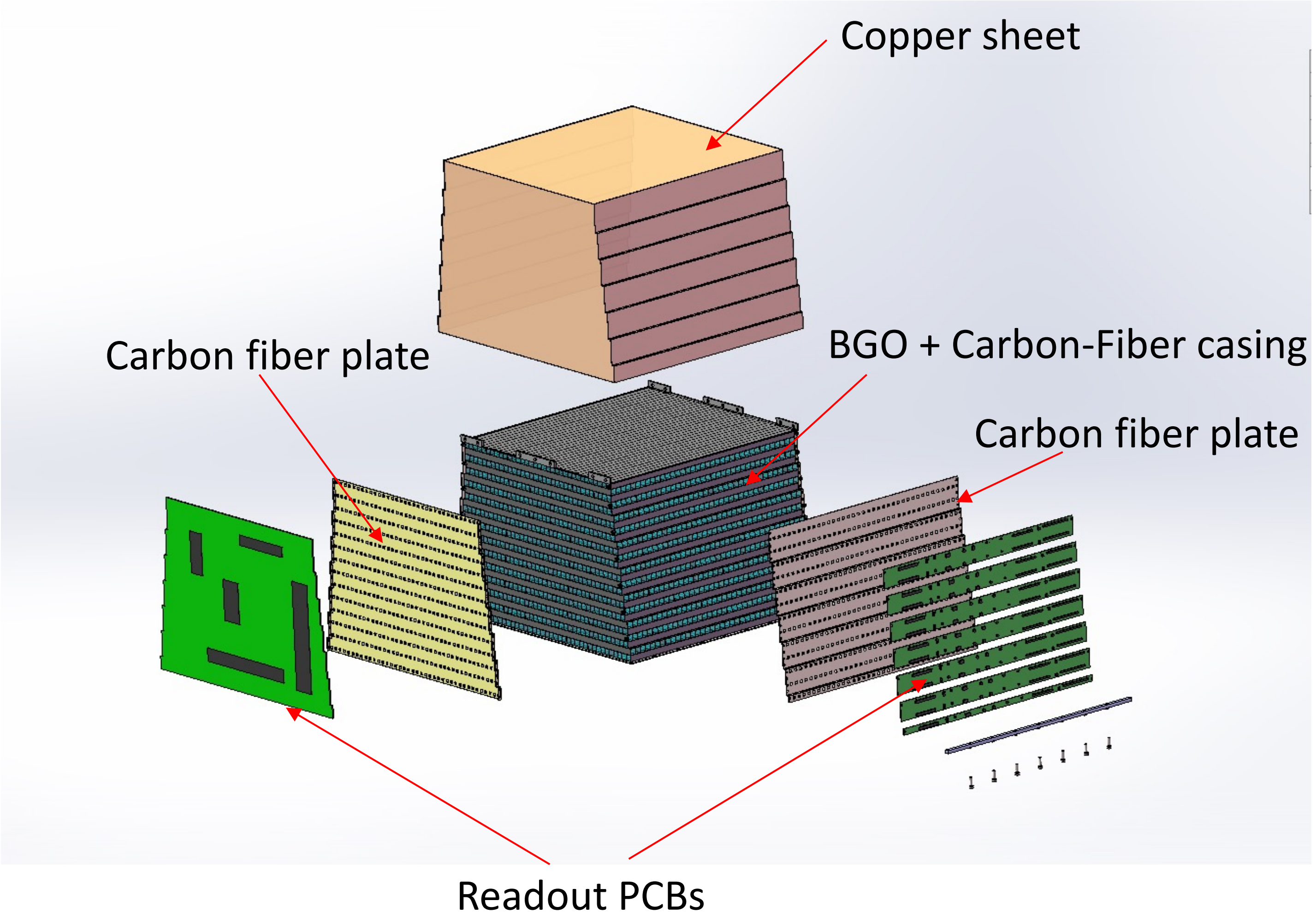






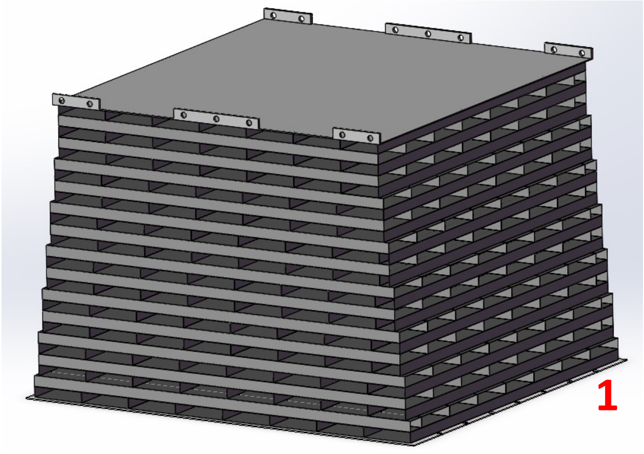
Barrel ECAL: module integration



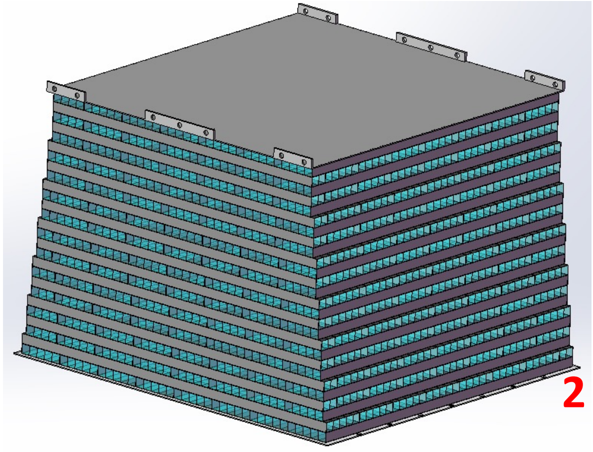


Barrel ECAL: module integration

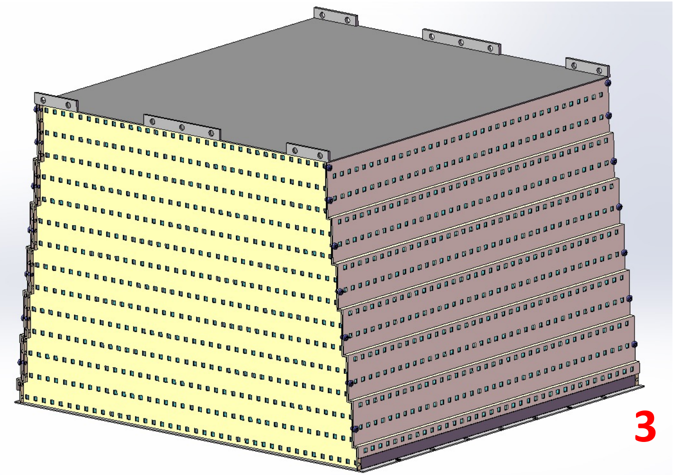
CF structure to protect BGO bars



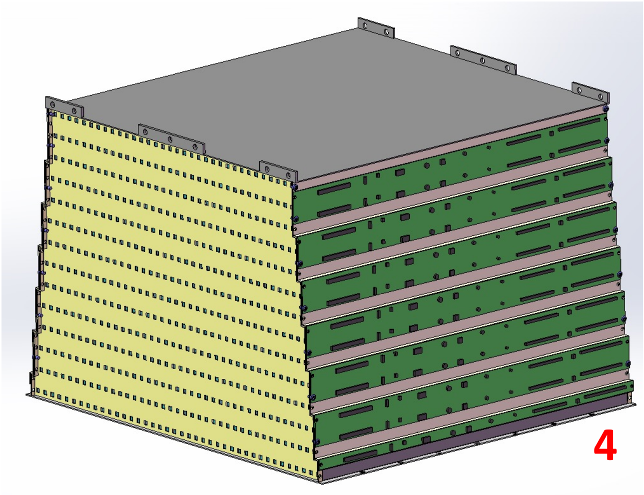
Install BGO crystal bars
(grouping 5 BGO bars per casing)



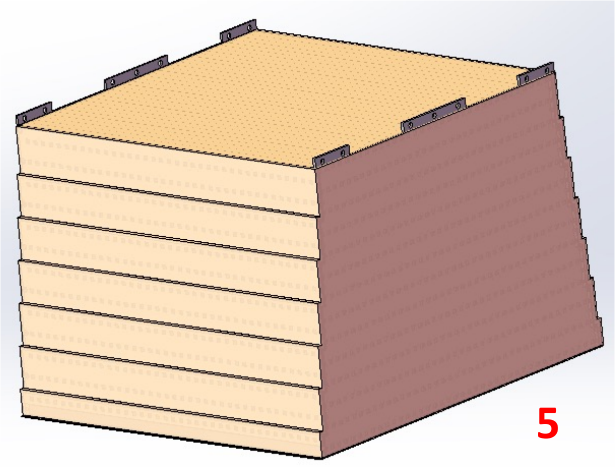
Install plates to “seal” and fix BGO bars, with holes for couplings with SiPM



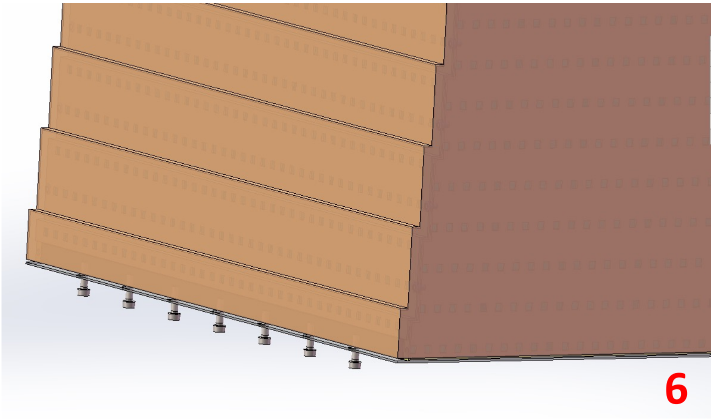
Install front-end readout PCBs



Install copper sheets for passive heat dissipation

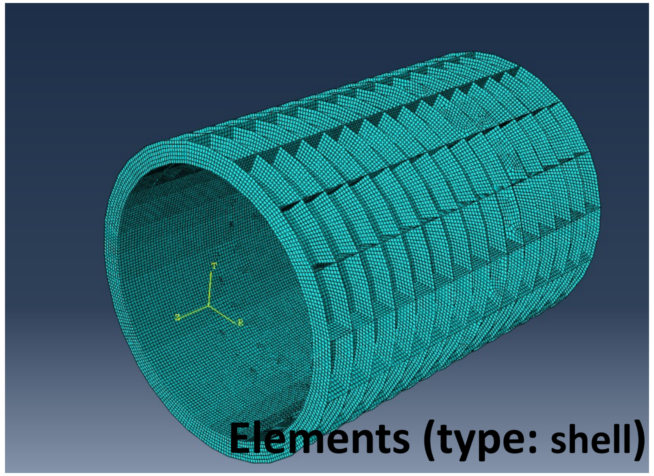


Assemble the module into the main support structure

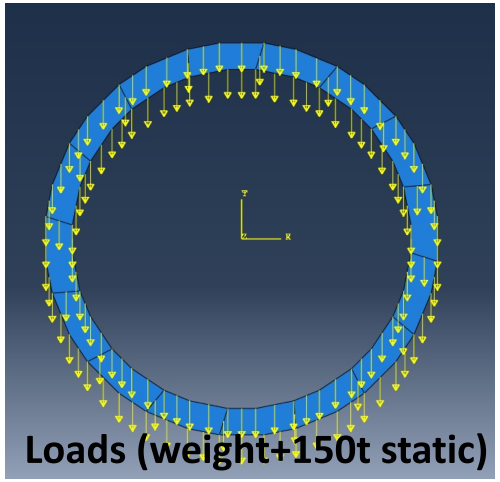


Barrel ECAL mechanics: FEA simulation

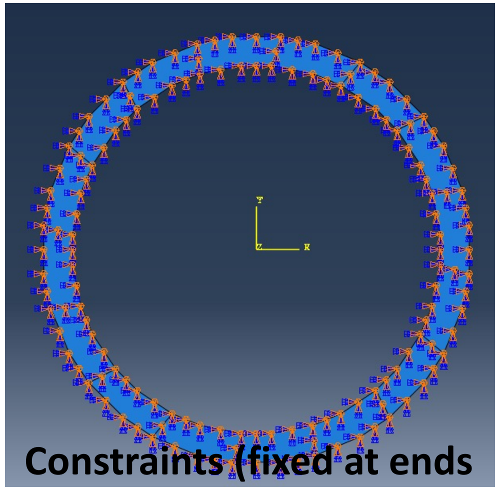
- FEA simulation studies on ECAL mechanics (ongoing): optimization + validation



Elements (type: shell)



Loads (weight+150t static)



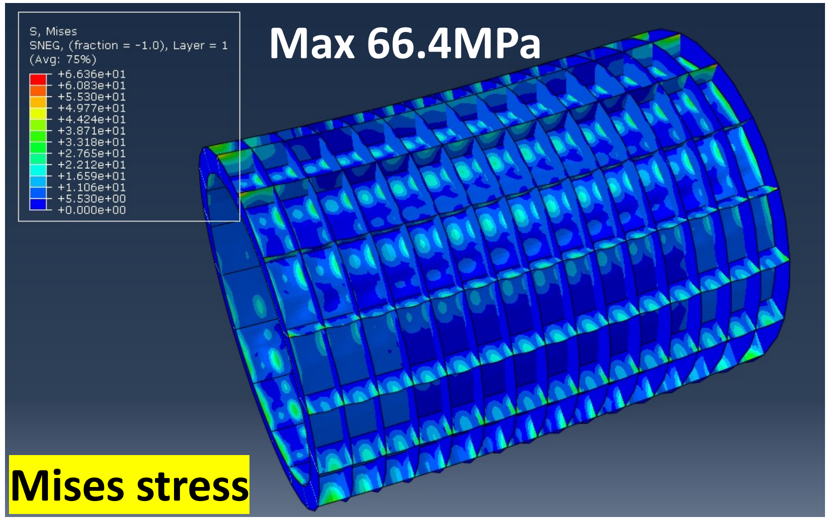
Constraints (fixed at ends

- **Material** :T700 reinforced epoxy resin
- **TSAIW= 0.117**

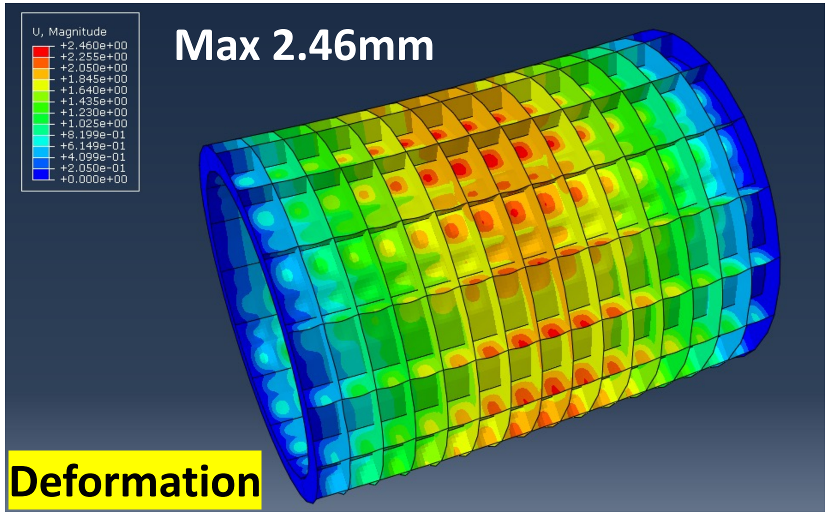
(When **TSAIW=1**, material begins to fail)

- **Safety factor** of this structure is 1/0.117=8.5

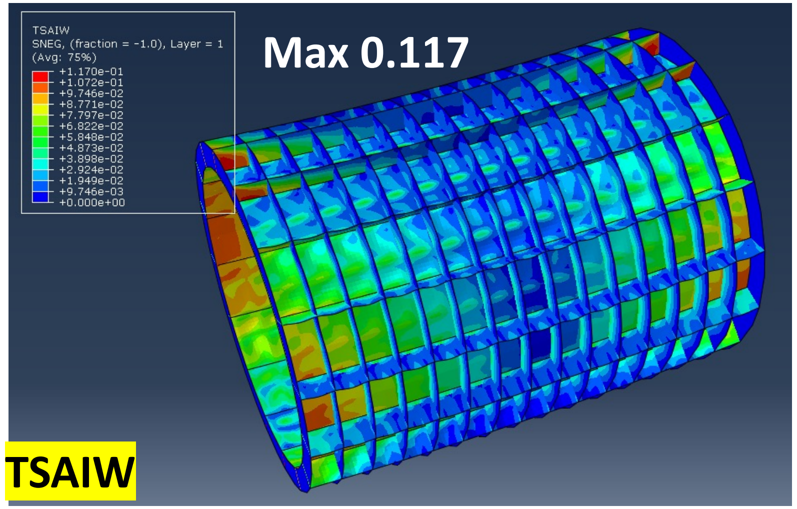
→ Still plenty of room to optimise



Mises stress



Deformation



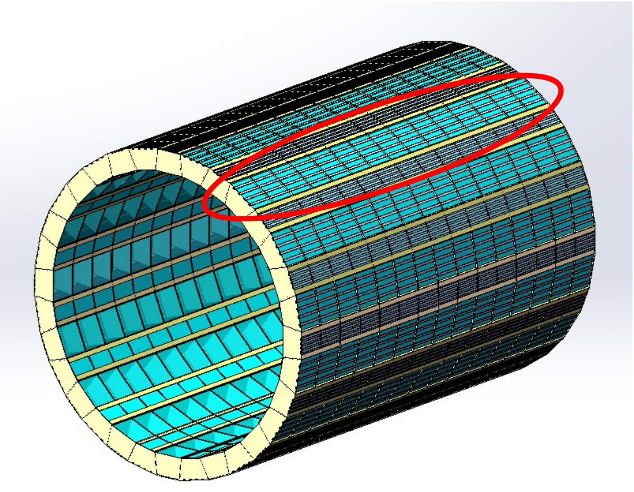
TSAIW

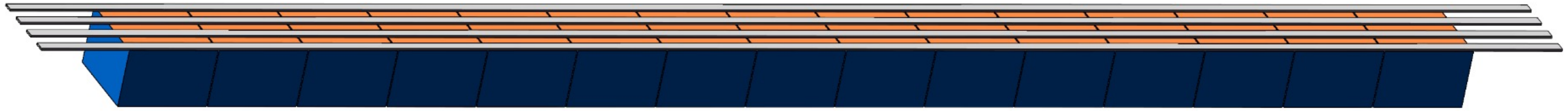
(Failure parameters of composite materials)

Barrel ECAL cooling system

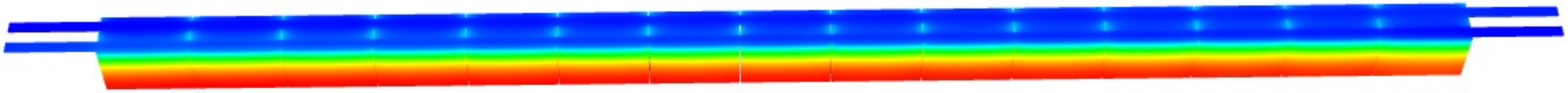
- FEA simulation studies on ECAL cooling
  - Preliminary result: temperature gradient of ~8 degrees
  - Ongoing studies in calorimeter simulation to quantify its possible impacts to EM performance

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



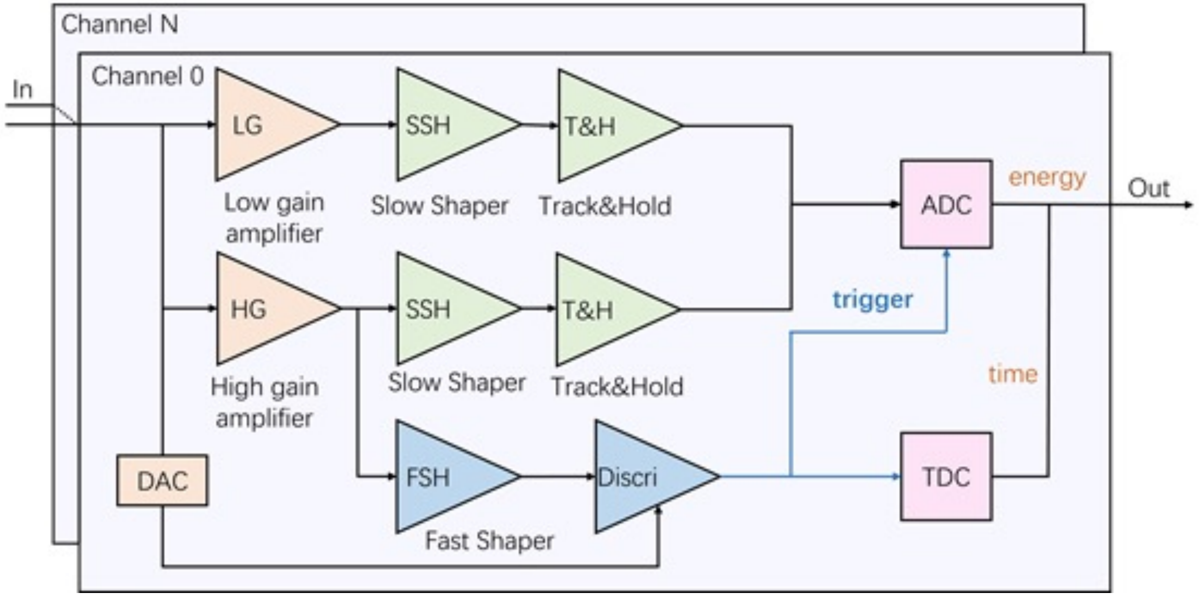


Copper sheet:**1mm**
Low Temp: **10℃**
High Temp: **17.8℃**



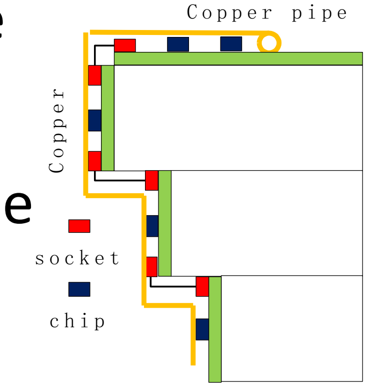
Plan to investigate cooling with future low-power ASIC (expected < 10mW/ch)

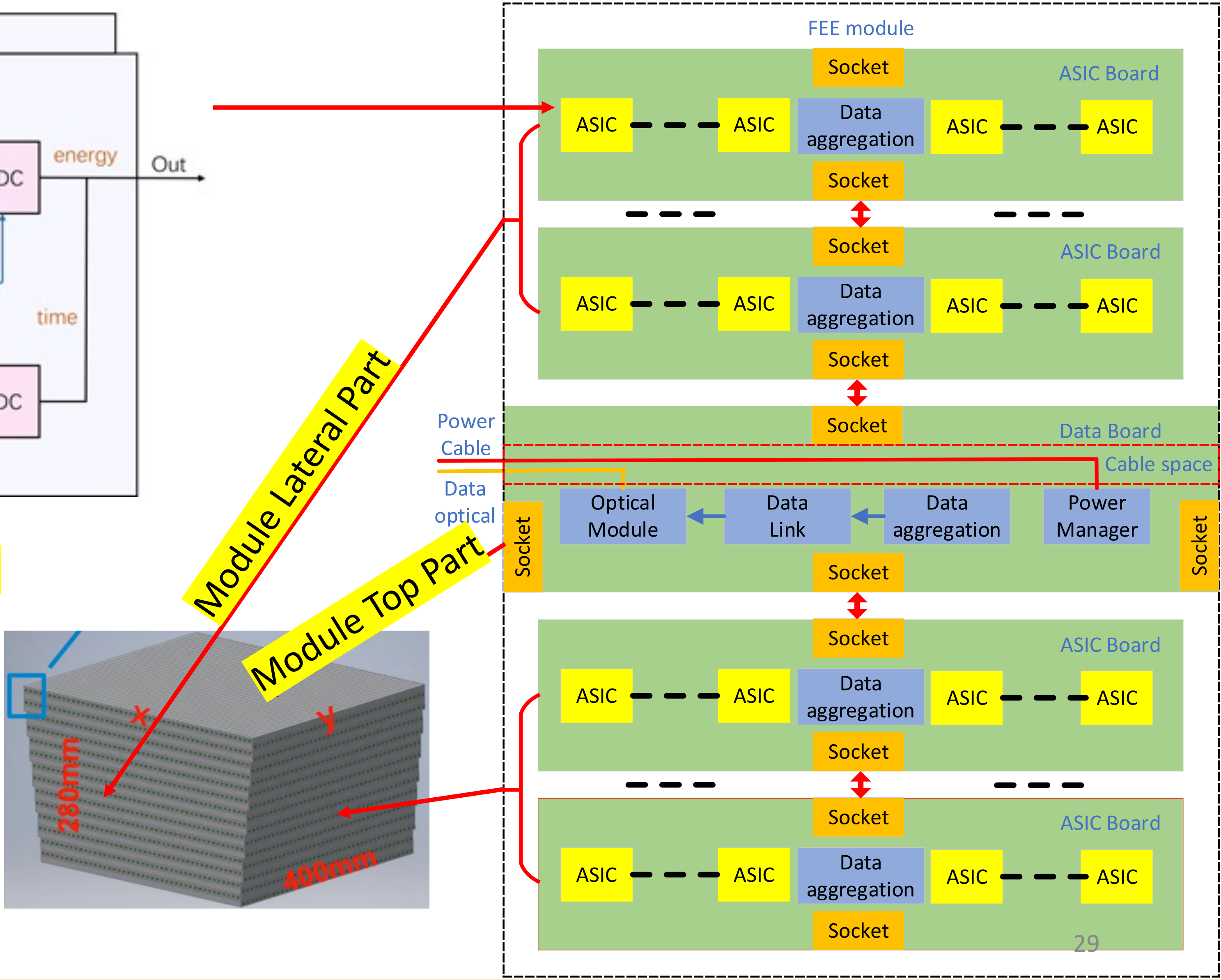
Readout electronics for ECAL



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

Passive Cooling



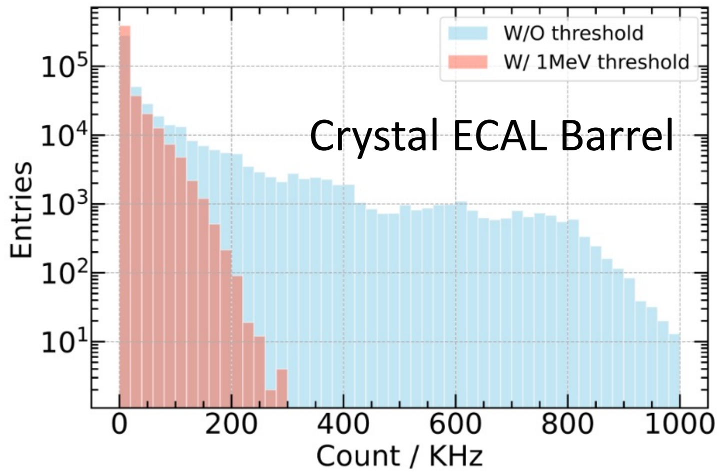


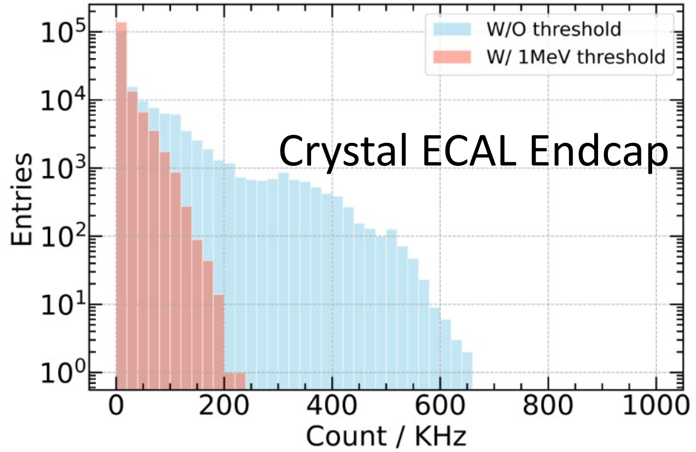
Beam-induced backgrounds: simulation studies

- **50MW** Higgs runs (355ns bunch spacing): updates from 30MW
  - Count rate: 650kHz – 1MHz in all energy hits
  - Rate reduced to 200-300 kHz with 0.1 MIP threshold

Beam Backgrounds		50MW Higgs (355 ns)	50MW Z-pole (23 ns)
Luminosity dependent	Pair Production	1300/BX	TBD
Single Beam	Beam-Thermal Photon	359kHz *2	265MHz *2
	Beam-Gas Bremsstrahlung	41kHz *2	19MHz *2
	Beam-Gas Coulomb	238kHz *2	2.4GHz *2
	Touschek Scattering	/	6.2GHz *2

Table remade from the talk of Weizheng



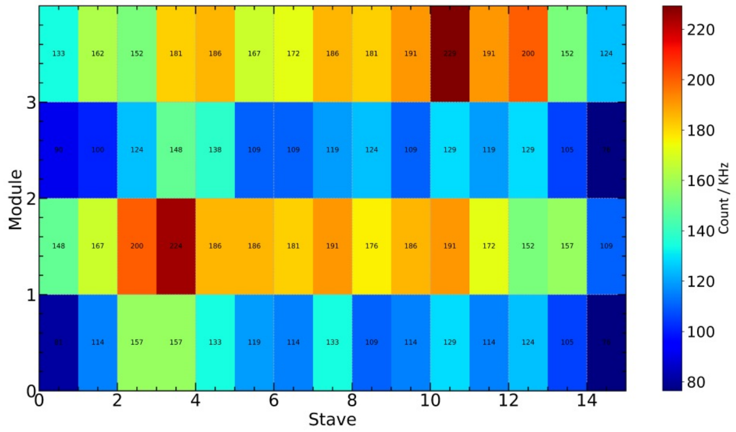


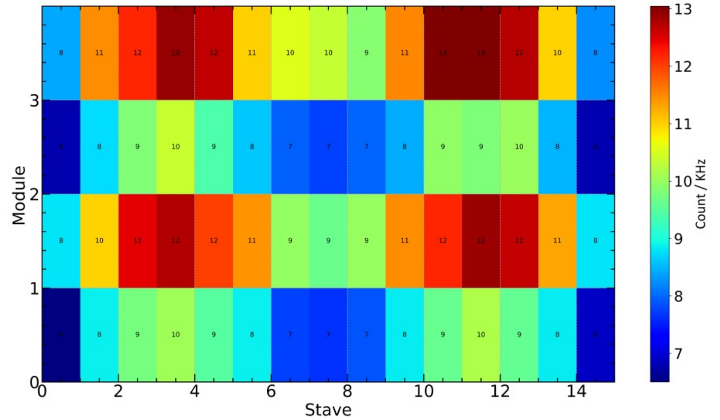
Beam-induced backgrounds: simulation studies

- **50MW** Higgs runs (355ns bunch spacing): updates from 30MW
  - Barrel module: maximum rate[1] (~100 kHz) vs. mean rate[2] (a few kHz)
  - Patterns in even/odd staves: different crystal lengths in the first layer (300mm/400mm)

Beam Backgrounds		50MW Higgs (355 ns)	50MW Z-pole (23 ns)
Luminosity dependent	Pair Production	1300/BX	TBD
Single Beam	Beam-Thermal Photon	359kHz *2	265MHz *2
	Beam-Gas Bremsstrahlung	41kHz *2	19MHz *2
	Beam-Gas Coulomb	238kHz *2	2.4GHz *2
	Touschek Scattering	/	6.2GHz *2

Maximum rate[1] : max. rate in a crystal bar per module
Mean rate[2] : average over all crystal bars over threshold per module

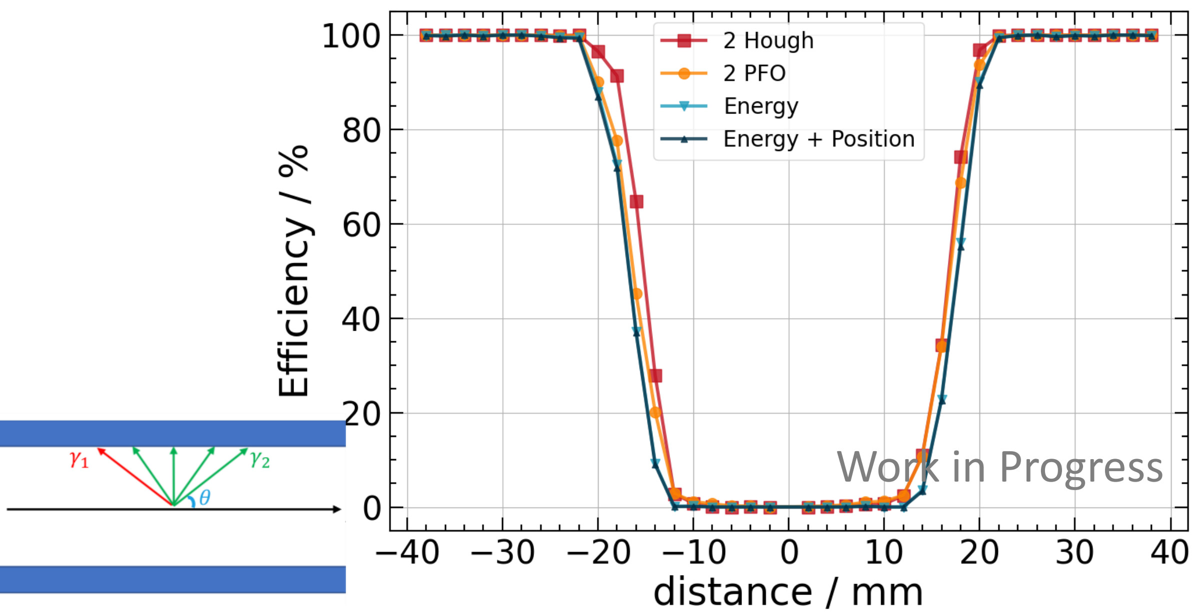




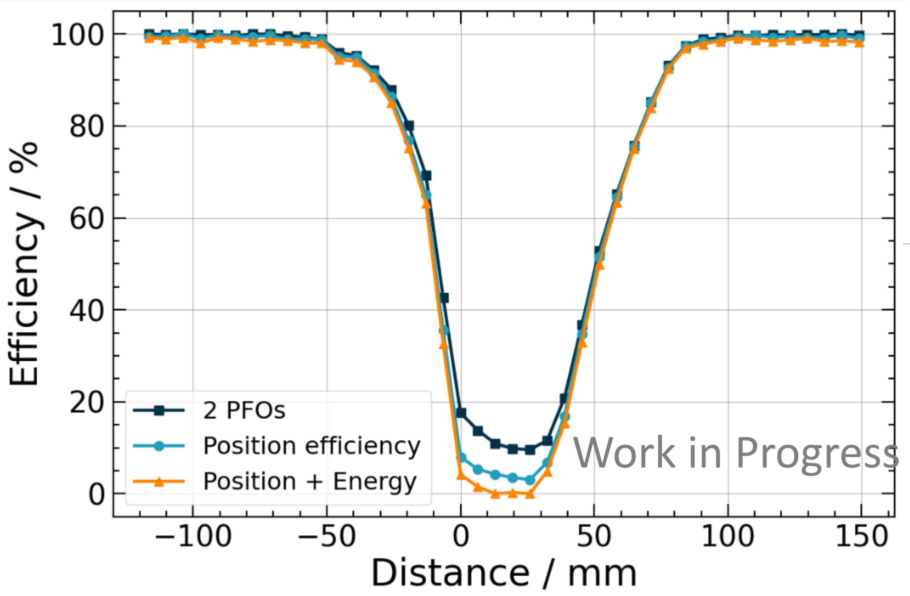
Performance in simulation: separation power

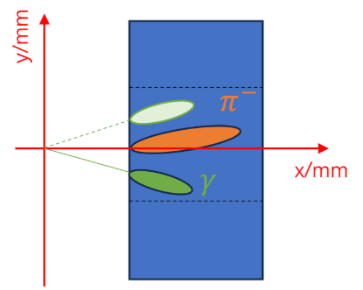
- New PFA reconstruction software developed for the design of long crystal bars
- Separation power of close-by particles: key performance in particle flow
  - $\gamma - \gamma$ separation: 100% efficiency for distance > 20mm
  - $\gamma - \pi$ separation : 100% efficiency for distance > 50~100mm

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



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



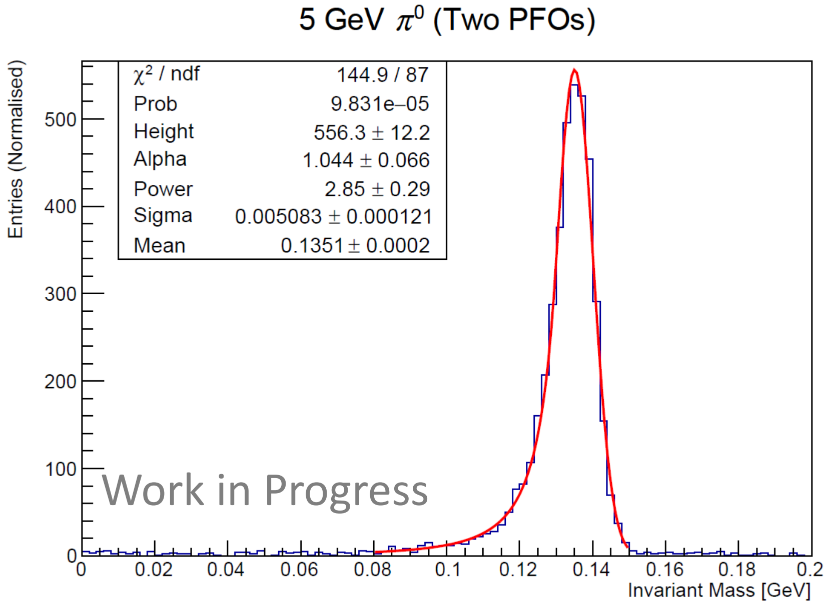


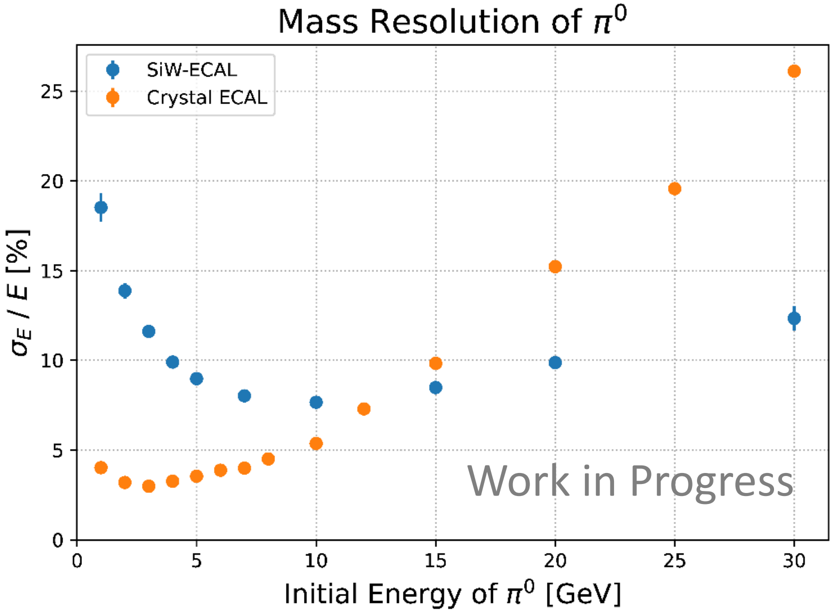
*Asymmetry pattern is due to the magnetic field

Performance in simulation: neutral pions

Using CyberPFA for long crystal bars

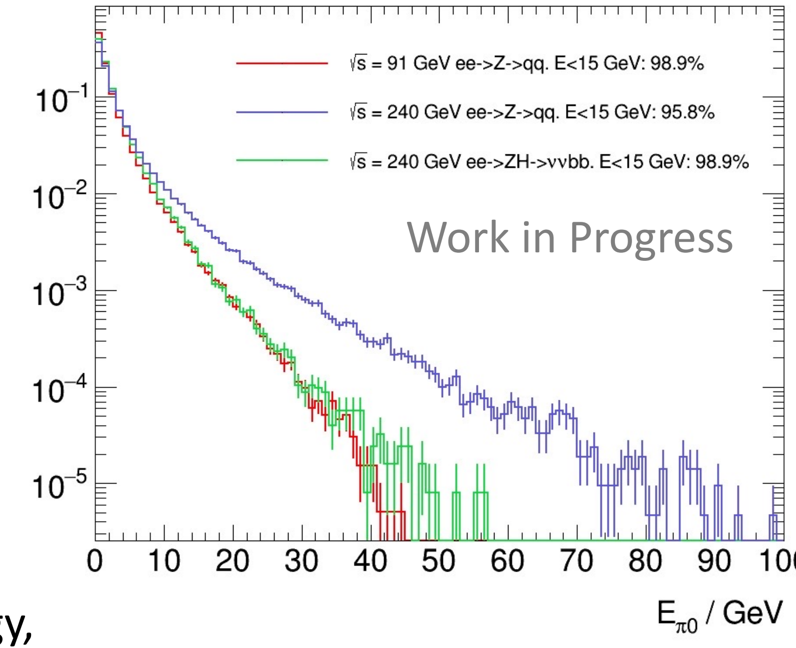
- Crystal ECAL shows excellent performance for single π^0 in 1-10 GeV
  - More than 95% of π^0 with energy <15 GeV in jets from Higgs and Z
  - Ongoing crosschecks to further improve π^0 performance in higher energy





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

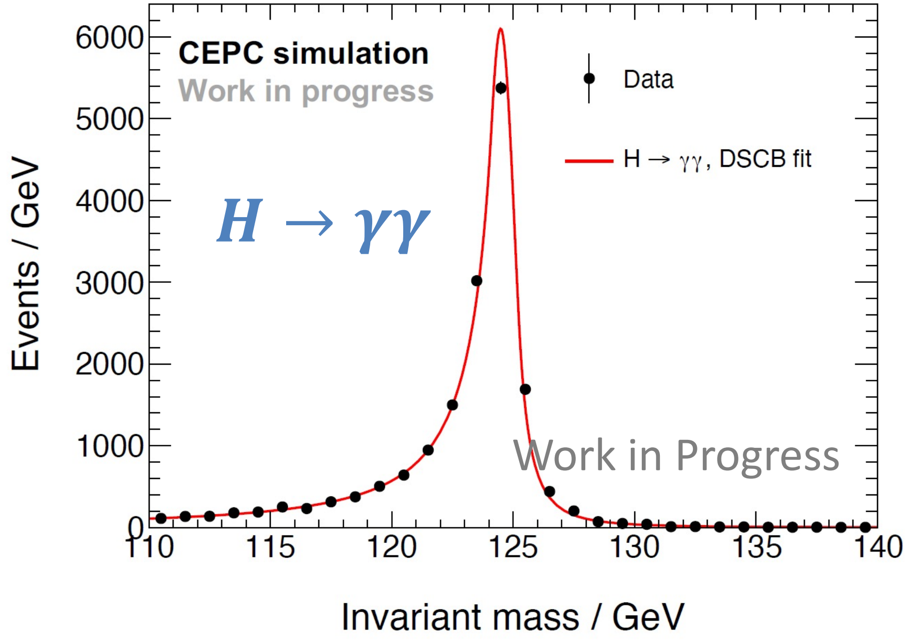
Energy of π^0 in jets from H/Z bosons



Physics performance in simulation: Higgs boson

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

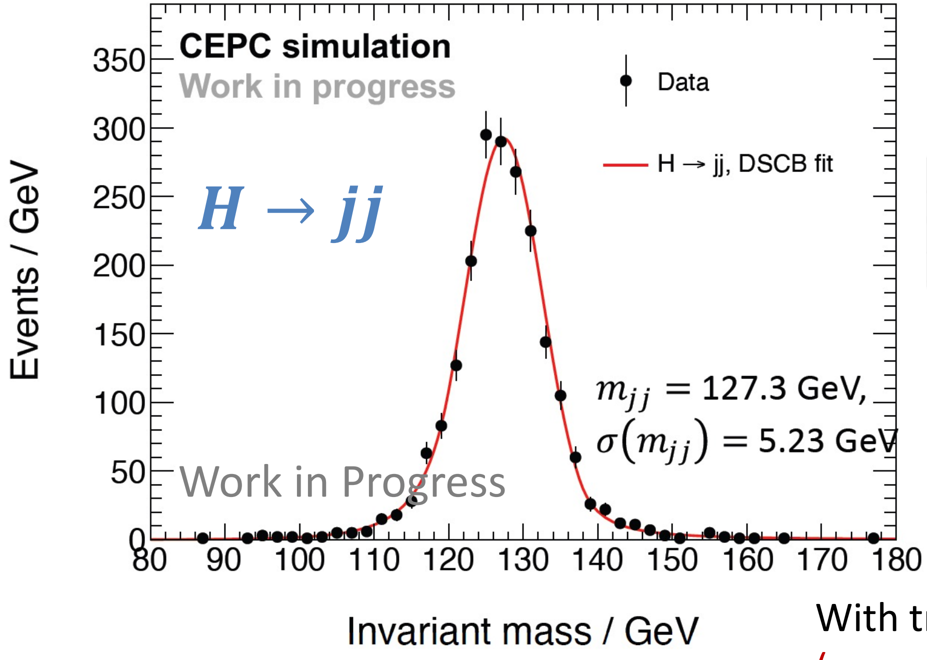
$ZH \to \nu\nu\gamma\gamma\ (H \to \gamma\gamma)$: $\sigma(m_{\gamma\gamma})$ = 0.57 GeV

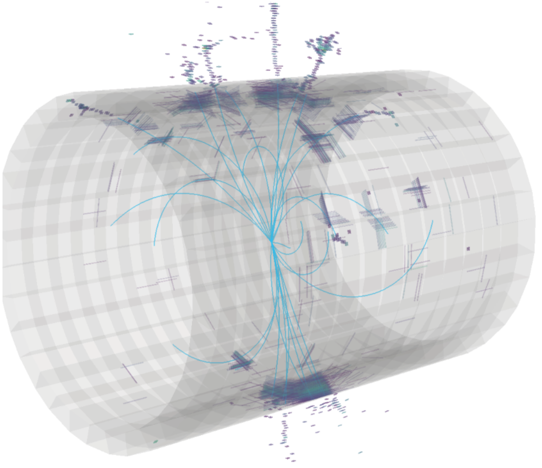


Double-side Crystal Ball fit

Long tail from lossy processes of crystal calorimeter and imperfect correction in crack region -> can be improved

$ZH \to \nu\nu gg\ (H \to gg)$ at **240GeV** : BMR = 4.1%





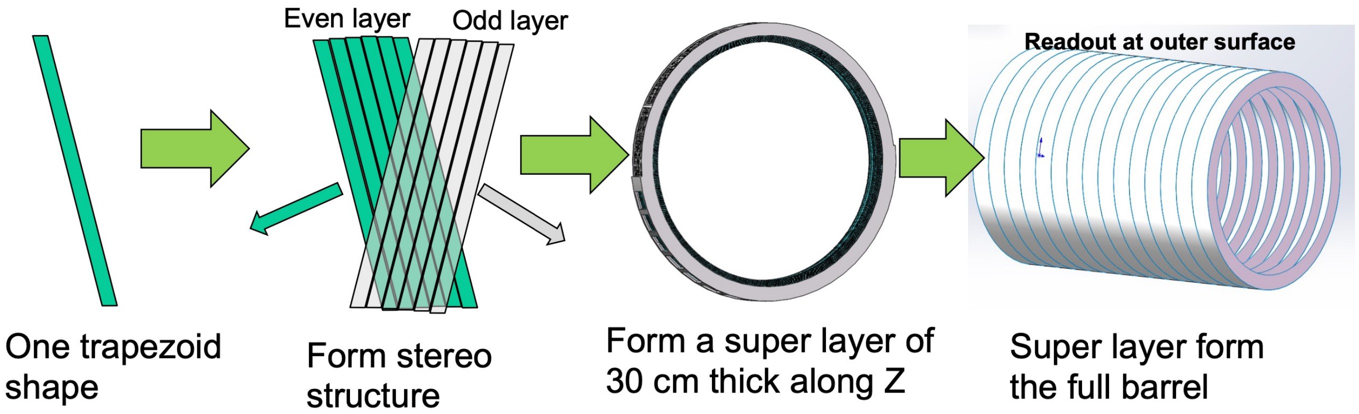
With truth tracking: **BMR 3.73%**
(comparable to CEPC CDR performance)

Reconstruction of two gluon jets in the full CEPC detector (Vertex, Silicon + TPC tracker, crystal ECAL, ScintGlass HCAL)

Alternative ECAL design: stereo crystals

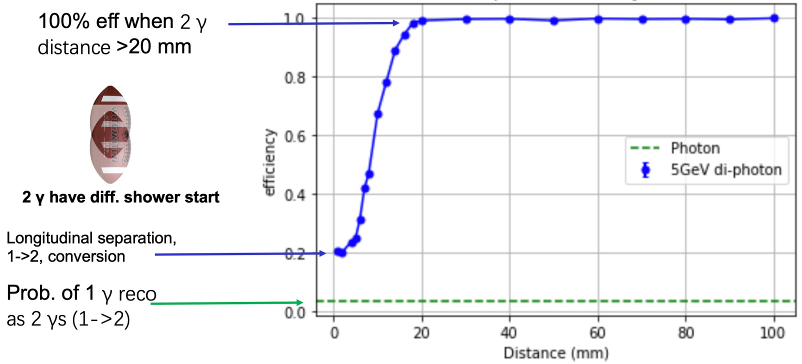
- Stereo design with long crystal bars inclined
  - Longitudinal segmentation by tilting crystal bars
  - Single-end readout: 50% less readout channels than crossed bars (two-sided readout)

Only one freedom left, α or longitudinal sampling N_R

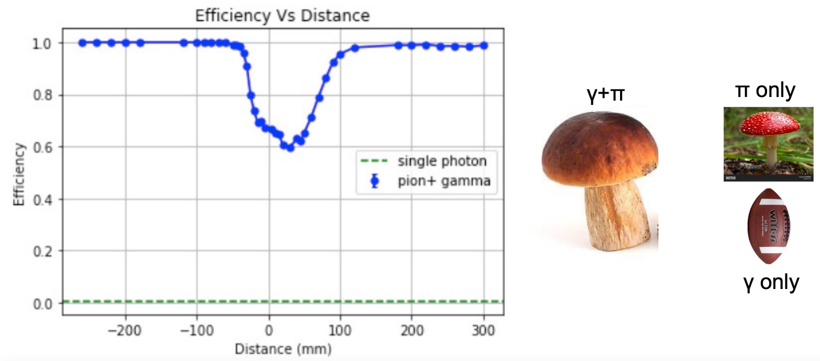


Separation power of two particles

- 100% eff. After 20 mm distance



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

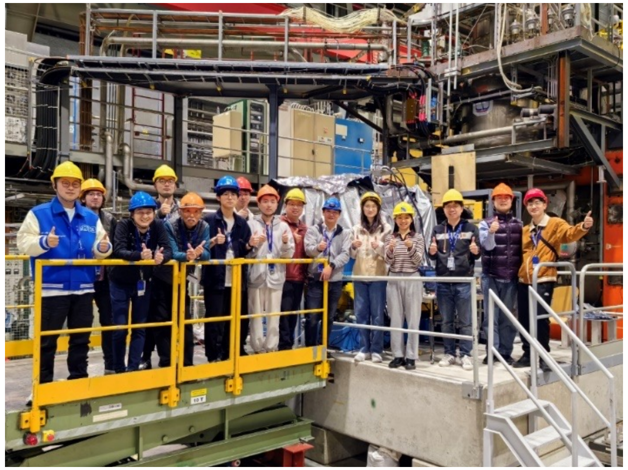


- Simulation studies on reconstruction: promising separation power of two particles
- Ongoing designs on mechanics, cooling and integration

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)

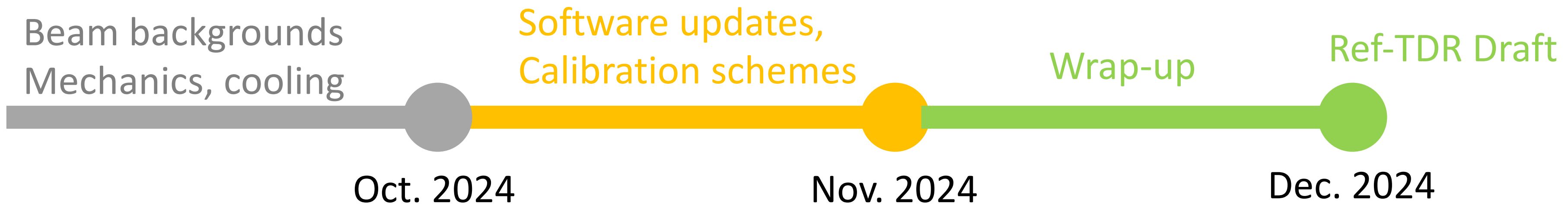
CEPC calorimeter team in beamtests



Working plan

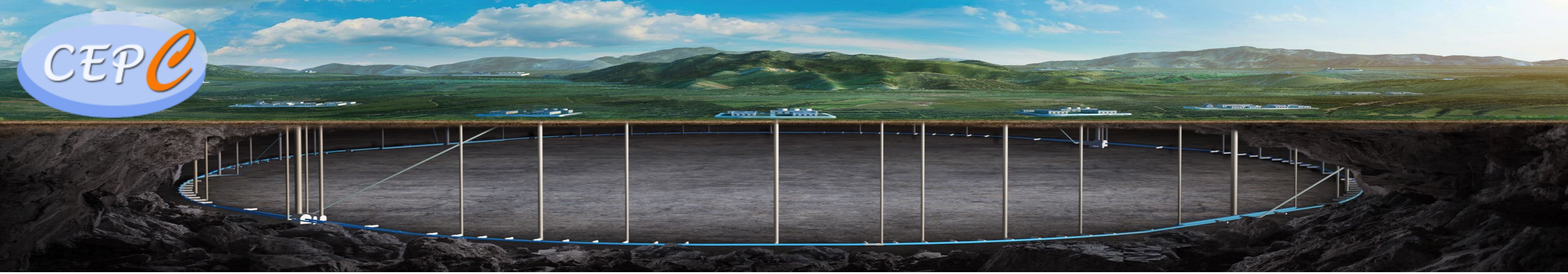
- Near future activities (in 2024): towards reference detector TDR
  - Beam-induced backgrounds: simulation in barrel and endcap regions, impacts to physics performance, estimate of data throughput
  - Mechanics and cooling: refine FEA simulations, validation by dedicated tests
  - Detector: fully exploit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

Timeline



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

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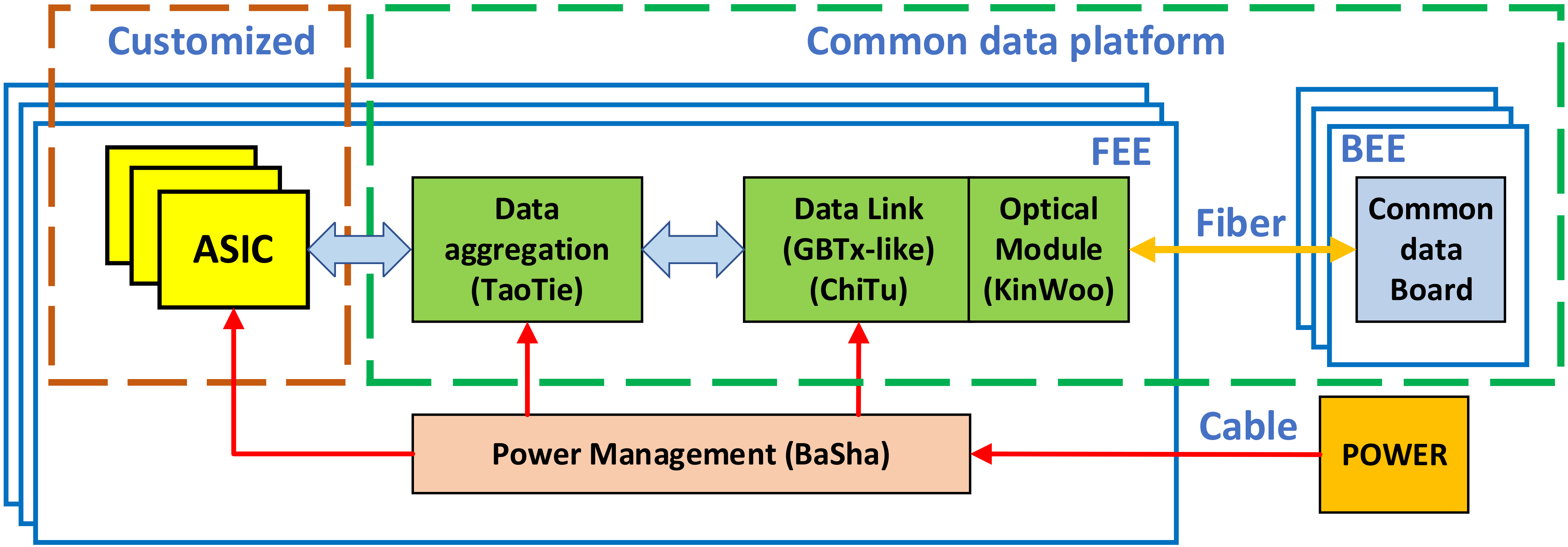
- The CALICE Collaboration, Response of the CALICE Si-W electromagnetic calorimeter physics prototype to electrons, Nuclear Instruments and Methods in Physics Research A 608 (2009) 372–383
- The CALICE Collaboration, Performance of the first prototype of the CALICE scintillator strip electromagnetic 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
- 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

Summary: crystal ECAL with long bars

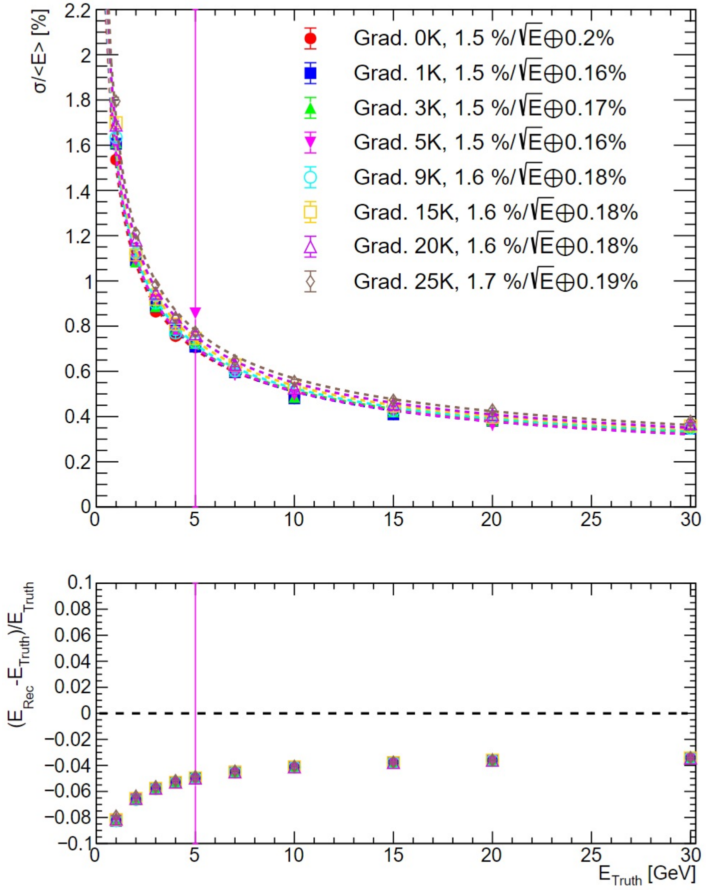
Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for ECAL	1900 mm	350 mm	NA
Length for barrel; Outer radius for endcap	5900 mm	1900 mm + $24X_0$ (*2168.3mm for BGO*)	NA
Longitudinal Depth	$24X_0$ (268.3 mm BGO)		NA
Modularity	28 modules in phi, 15 rings along Z	6 types of modules	NA
Material Volume (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

Electronics diagram for ECAL & HCAL

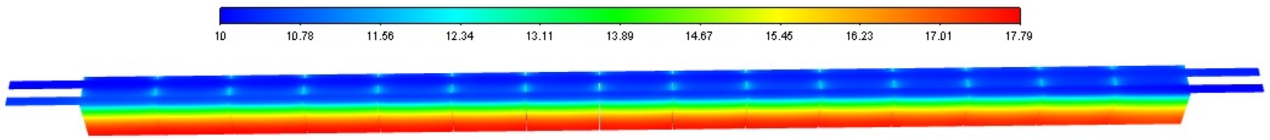


- Energy and time measurements: ASIC for ECAL & HCAL
- Data transmission: common data platform (refer to the “Electronics TDR Report”)
- Trigger mode: trigger-less readout in Front-End Electronics (FEE)

Temperature impacts to crystal-SiPM



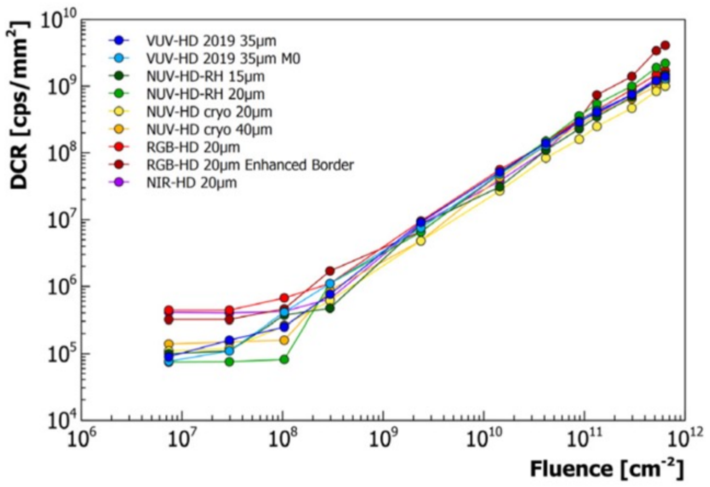
- Linear modeling of temperature gradient
  - The same temperature change for a given distance
- Assuming temperature difference can not be corrected, which is especially true for crystals
- Check EM performance by varying temperature gradient (Tmax - Tmin)
- Preliminary result: **temperature gradient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

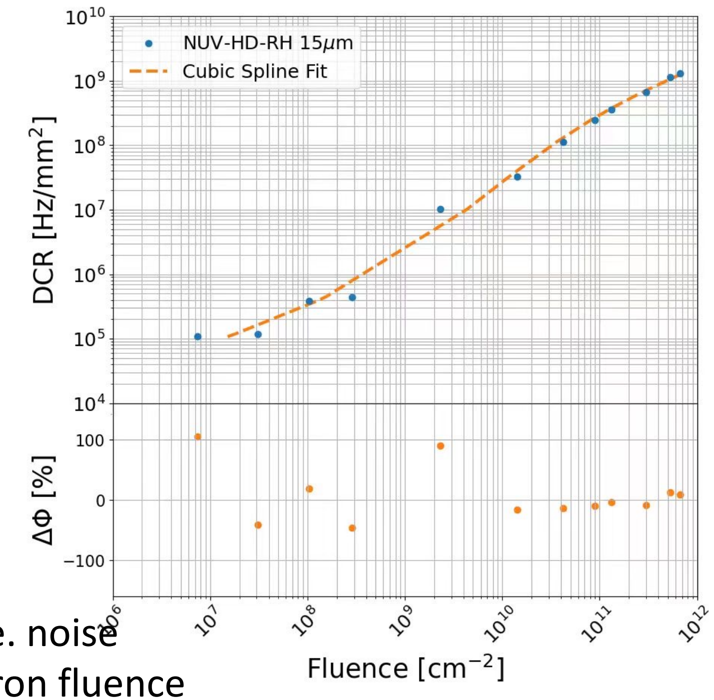


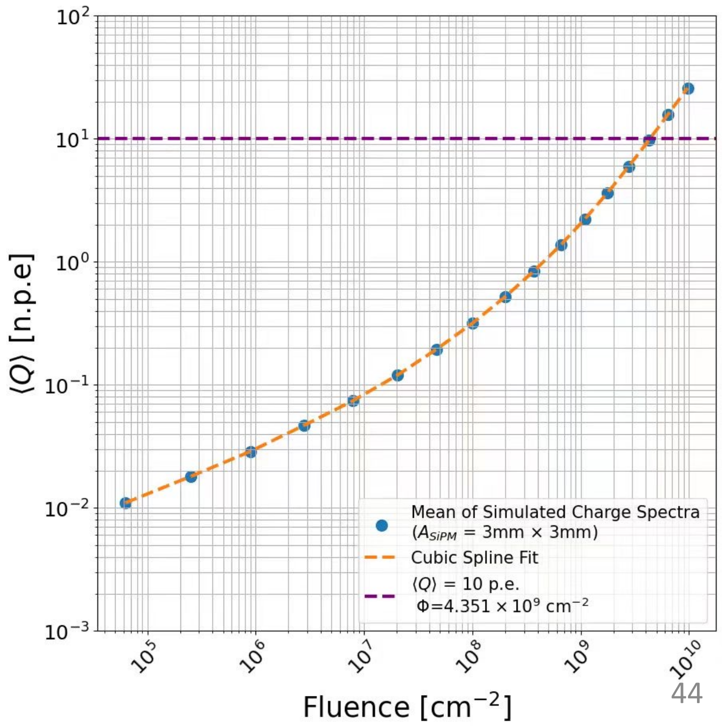
- 100p.e./MIP, 0.1MIP threshold per channel, 12-bit ADC
- 150ns time window, 2,500,000 Hz DCR
- Temperature dependence of BGO light yield: -1.38%/K, doi:10.1007/s11433-014-5548-4
- Temperature dependence of SiPM(HAMAMATSU S13360-3050CS) gain: -3%/K, doi:10.1016/j.nima.2016.09.053
- Temperature dependence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

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: $\boldsymbol{4.3\times10^{9} n_{eq}(1MeV)/cm^{2}}$ is likely the limit for SiPM operated at room temperature; beyond this limit, SiPM needs specific cooling



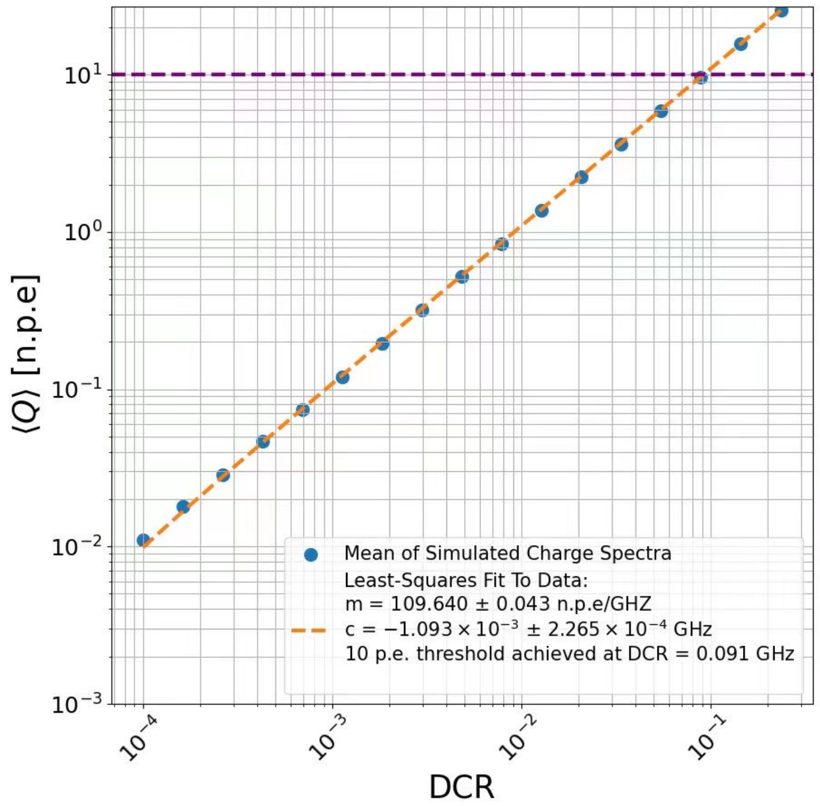


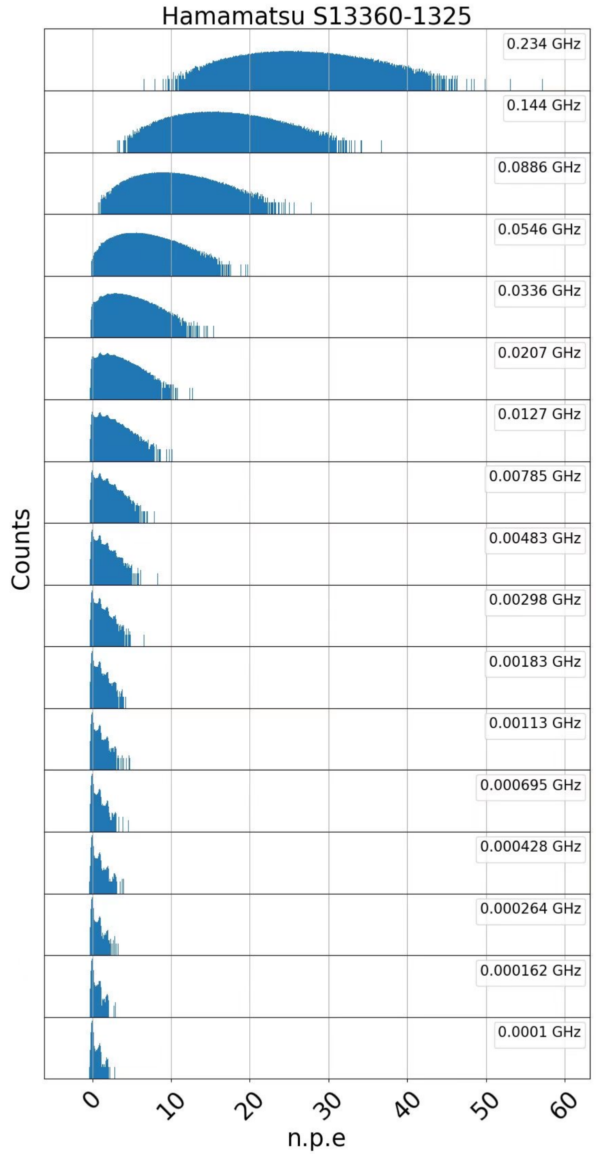


When SiPM DCR=91MHz, it can produce average 10 p.e. noise
SiPM NDL- EQR06, pct=12%, DCR increases with neutron fluence

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

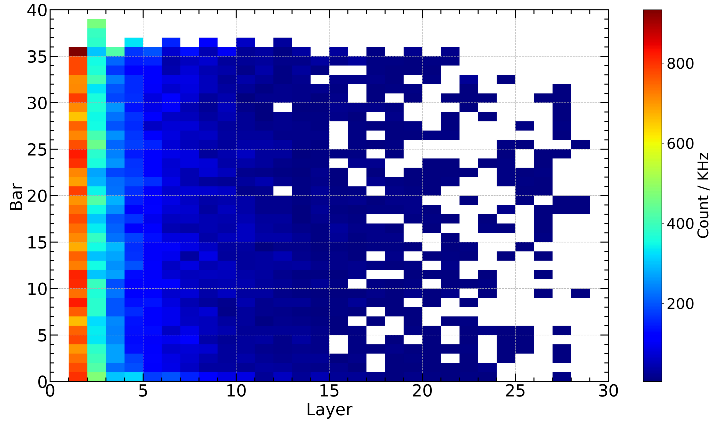




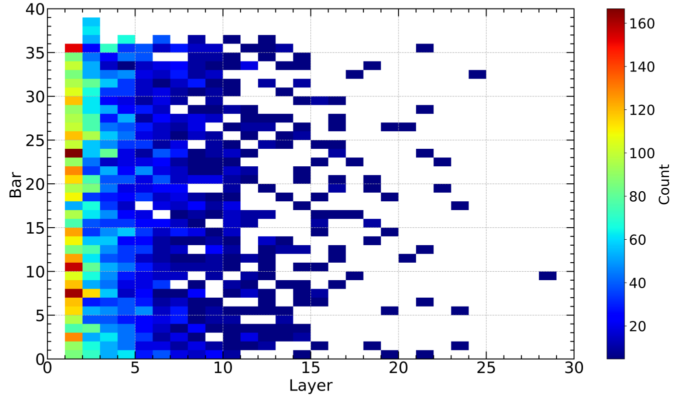
Beam-induced backgrounds at CEPC: TID

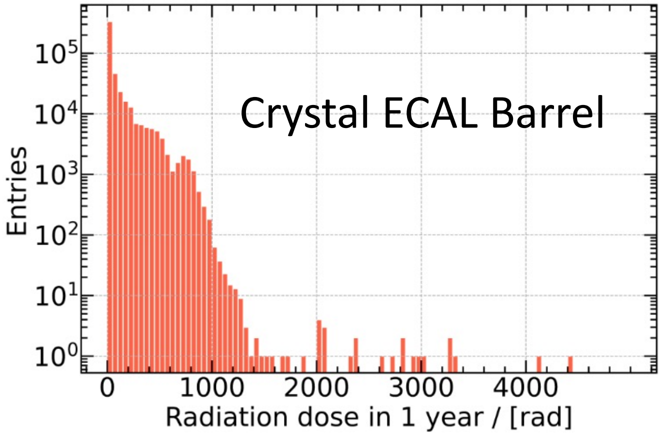
- **50MW** Higgs runs (355ns bunch spacing): updates from 30MW
  - TID per year: ~4k rad for barrel crystals; 50k rad for endcap crystals

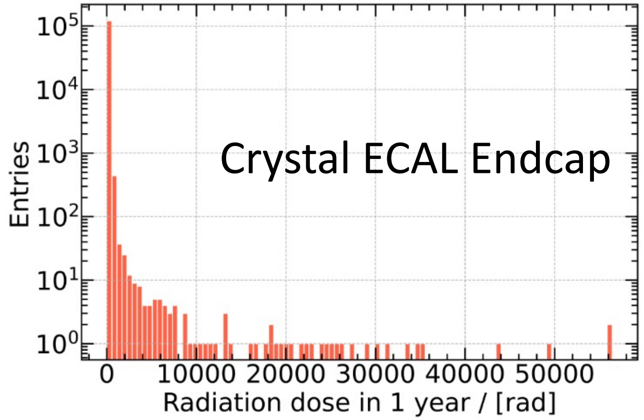
Barrel Module: BarID vs LayerID (raw hits)



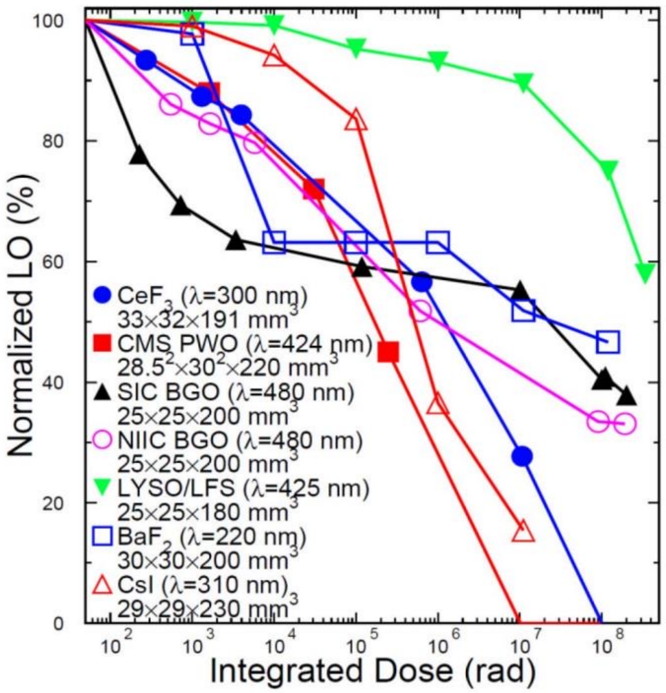
Barrel Module: BarID vs LayerID (hits>1MeV)







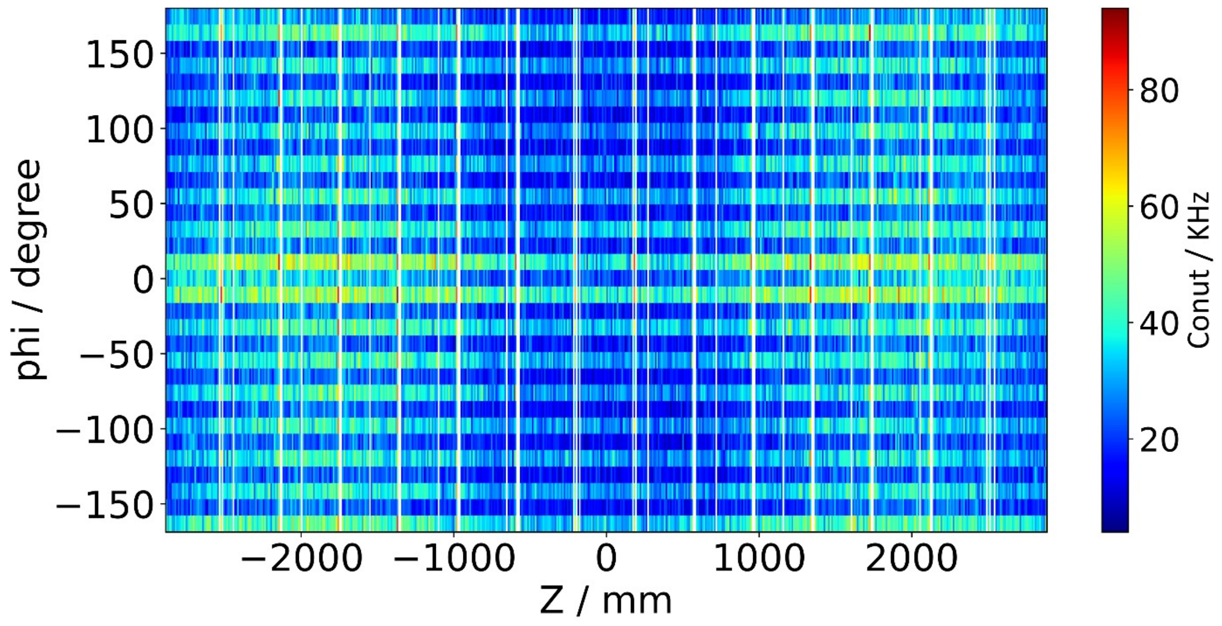
Radiation Damages to Crystals



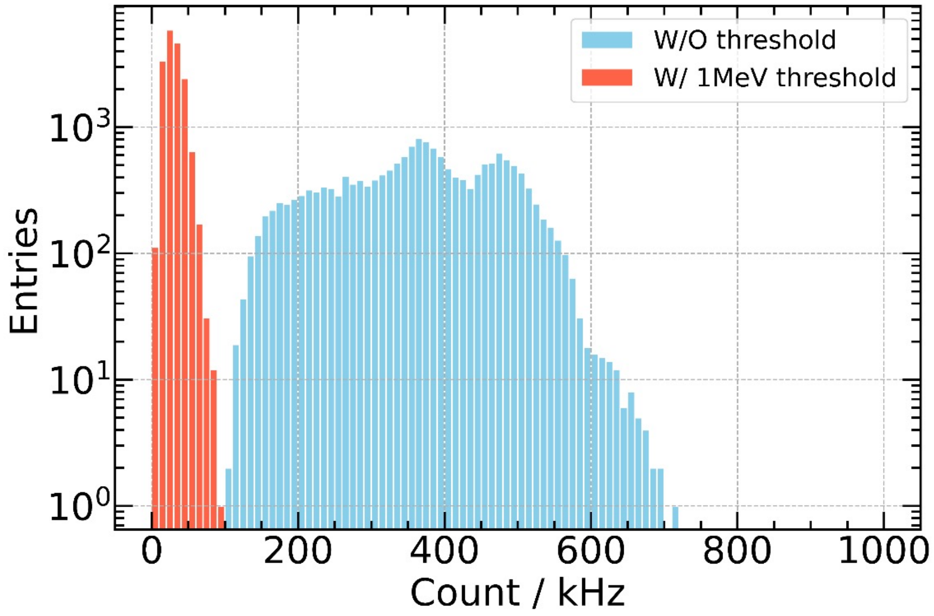
BGO: dramatic Light Output (LO) drop at TID<1kRad and TID>10Mrad

Beam-induced backgrounds: simulation studies

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

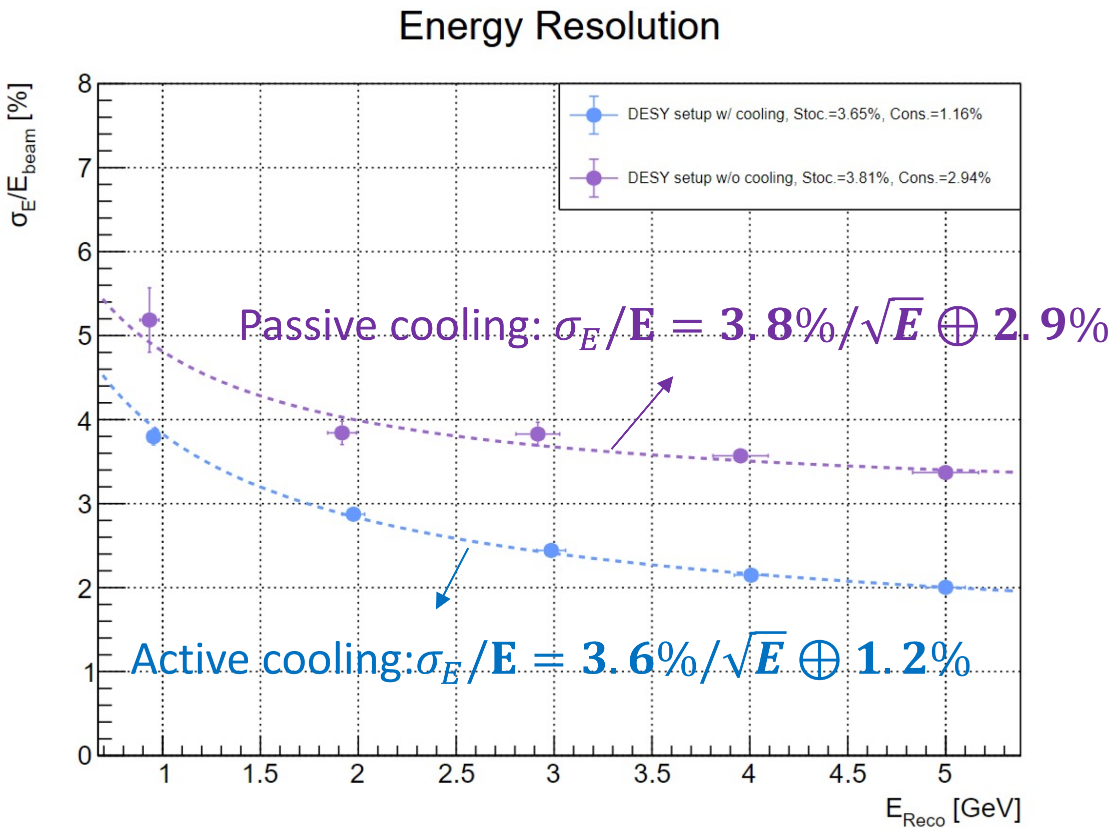


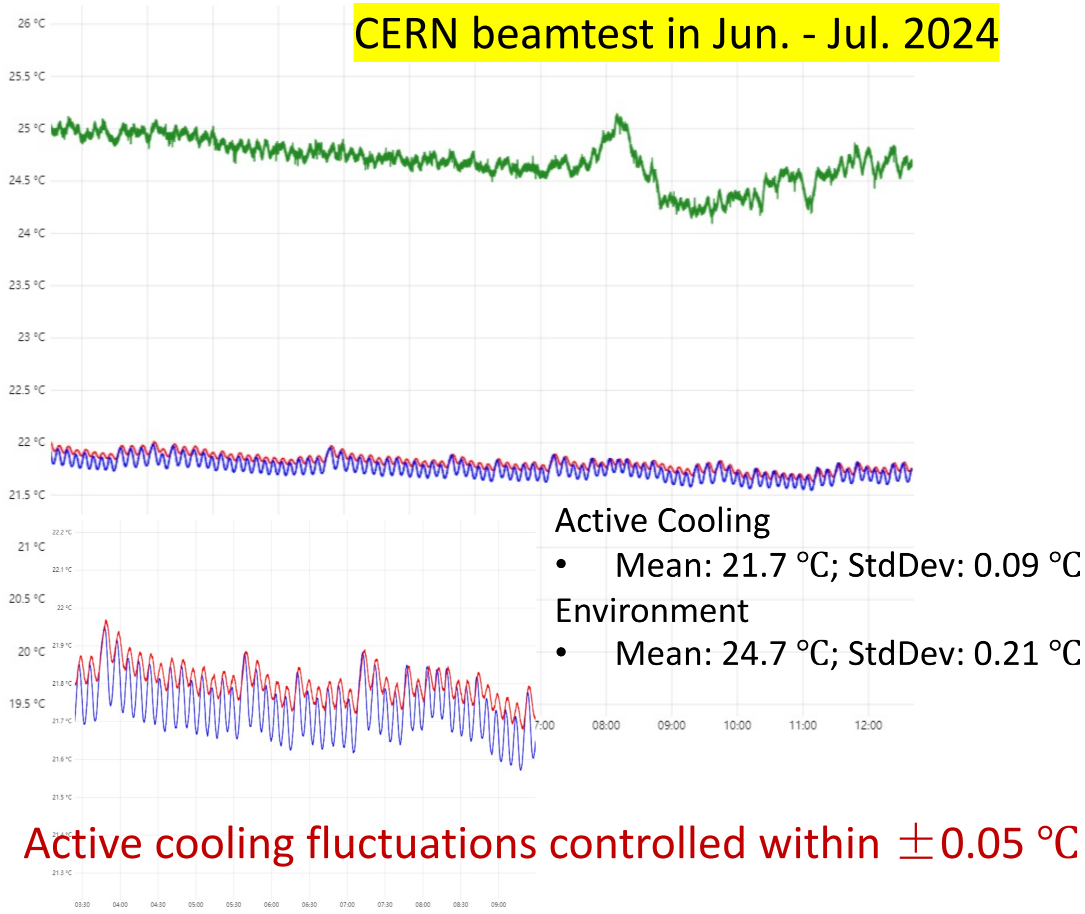
Hit rate suppression with 0.1 MIP threshold



- 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

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

R&D efforts and results: dynamic range

SiPM with 10um/15um pixel pitch

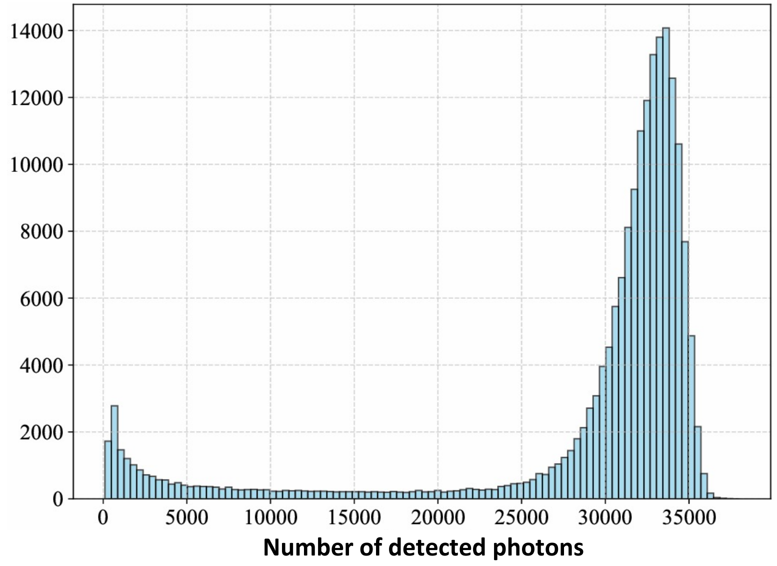
Type no.	Dark count rate*5 DCR typ. (kcps)	Dark count rate*5 DCR max. (kcps)	Direct crosstalk probability Pct (%)	Terminal capacitance at Vop*6 Ct (pF)	Gain M	Temperature coefficient of Vop ΔTVop (mV/°C)
S14160-1310PS	120	360	<1	100	1.8×10^5	34
S14160-3010PS	700	2100		530		
S14160-6010PS NEW	3000	10000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

Electronics with lowest gain

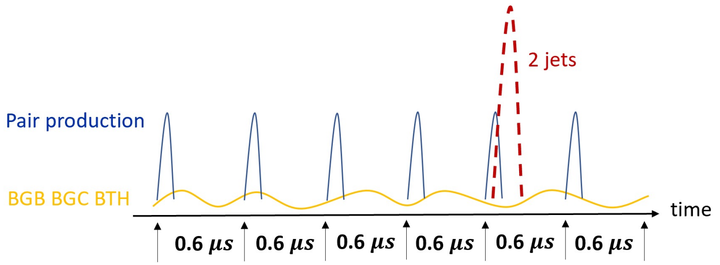


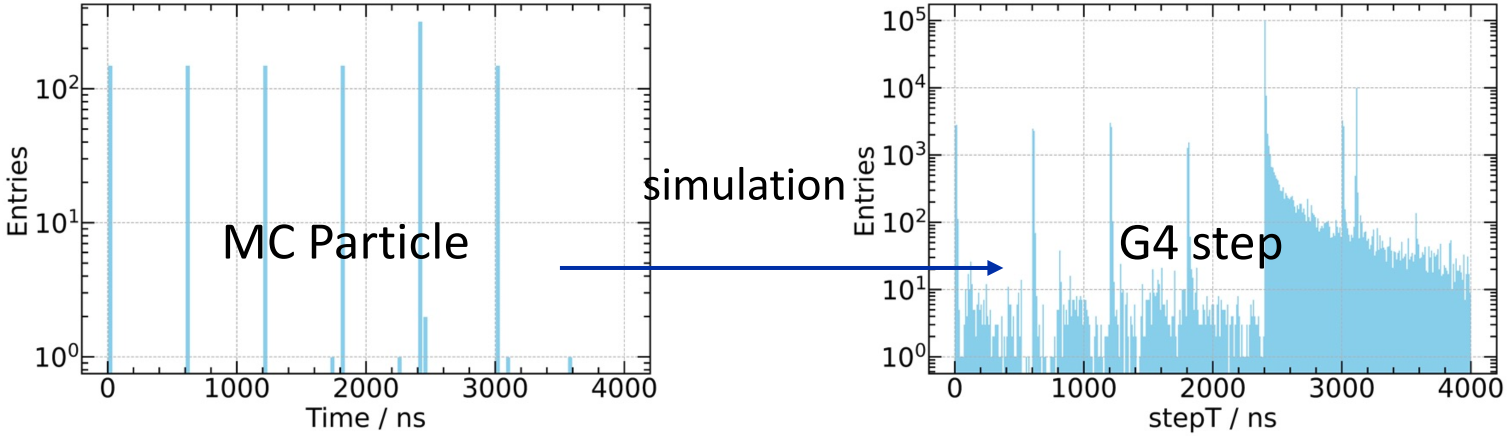
- State-of-art ASIC dynamic range
  - Expected to reach ~128k p.e. for SiPM with 10um pixel pitch

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	---	---

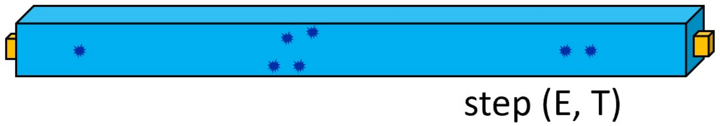
- **Higgs mode**:
  - pair production: double beams, e+-
  - BG: single beam
- Using **4 types** of beam backgrounds.
- **Simulation Time Window**: 3.6 us (6 collisions and 6 bunch spacing)
  - Considering physics events and beam background events.
  - Taking into account the scintillation decay time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

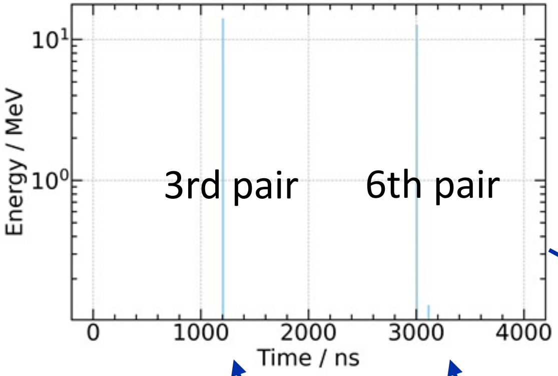


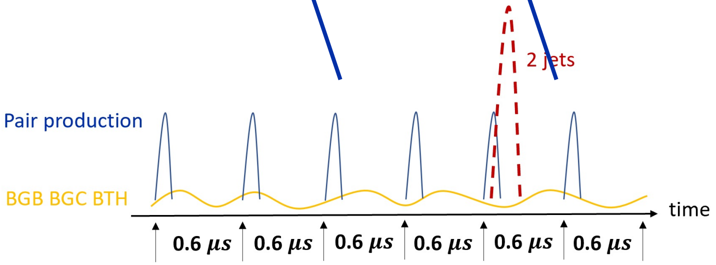


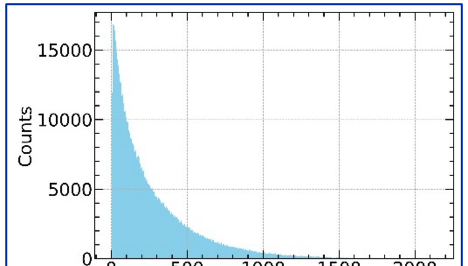
Beam-induced backgrounds: time structures

single crystal bar

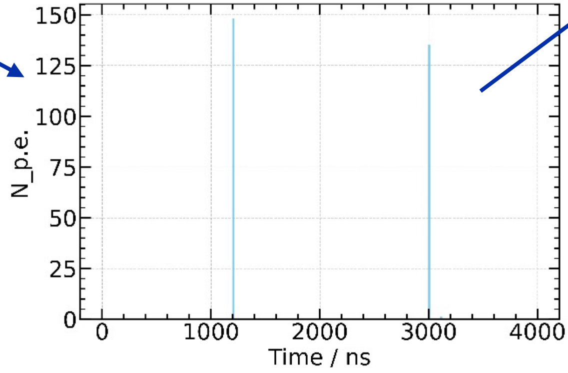




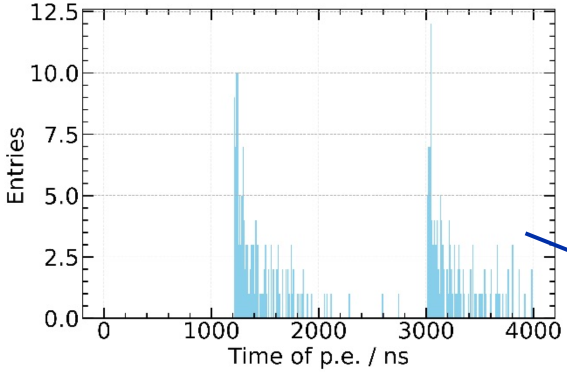


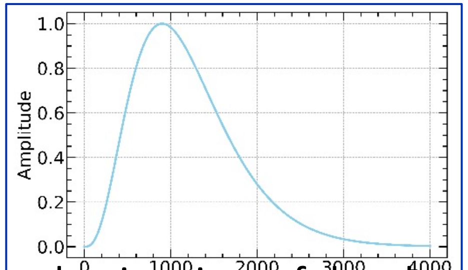


For each p.e., get luminous time and transmission time



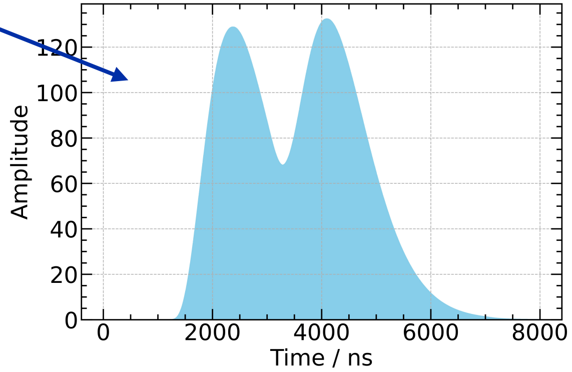
Detected Np.e in SiPM: 100 p.e./Mip



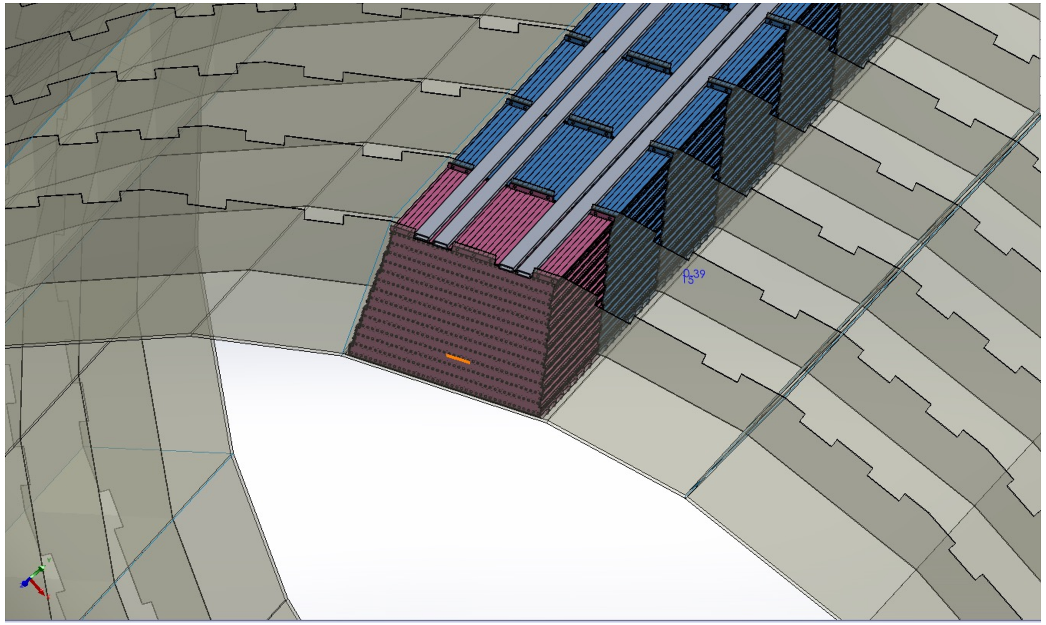


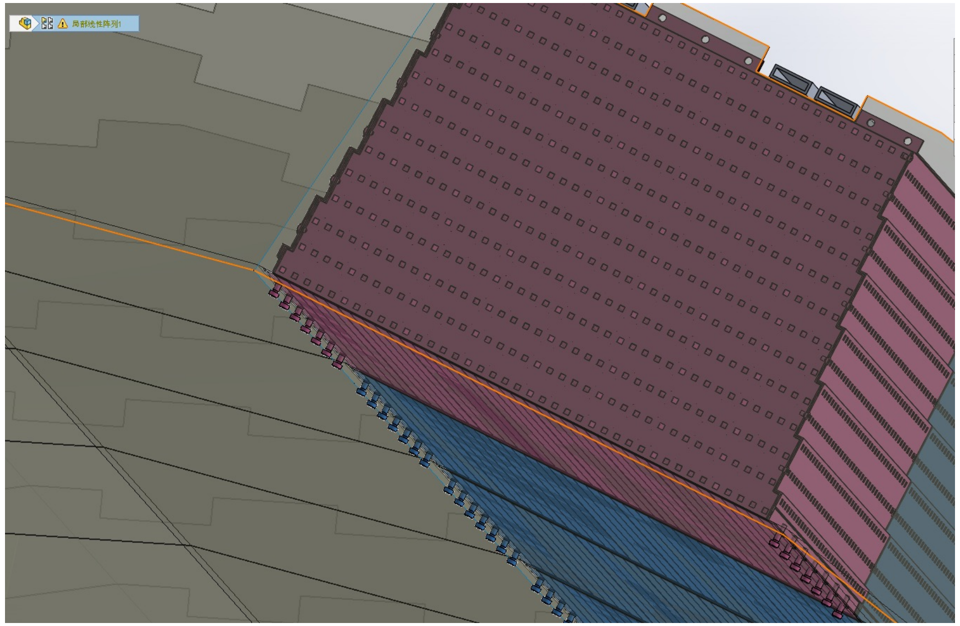
the shaping time of the electronics: CR-(RC)3

time structure of single crystal with 2 pair production



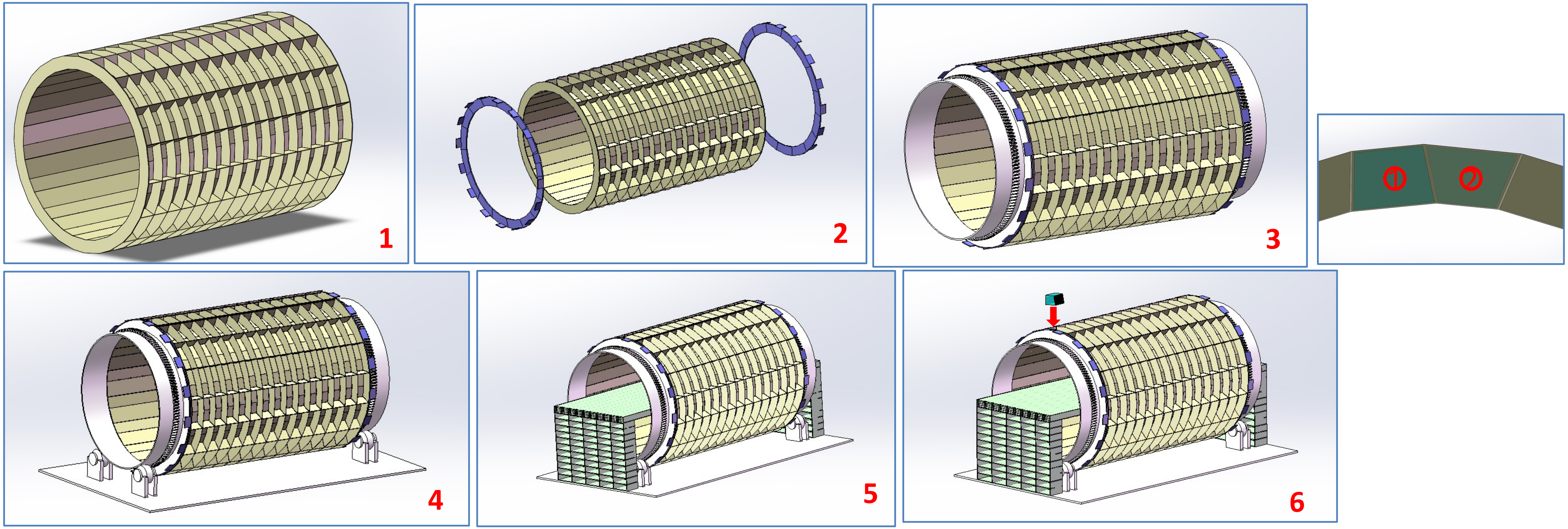
Barrel ECAL: integrate modules in main structure





- 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

Barrel ECAL: Installation procedures

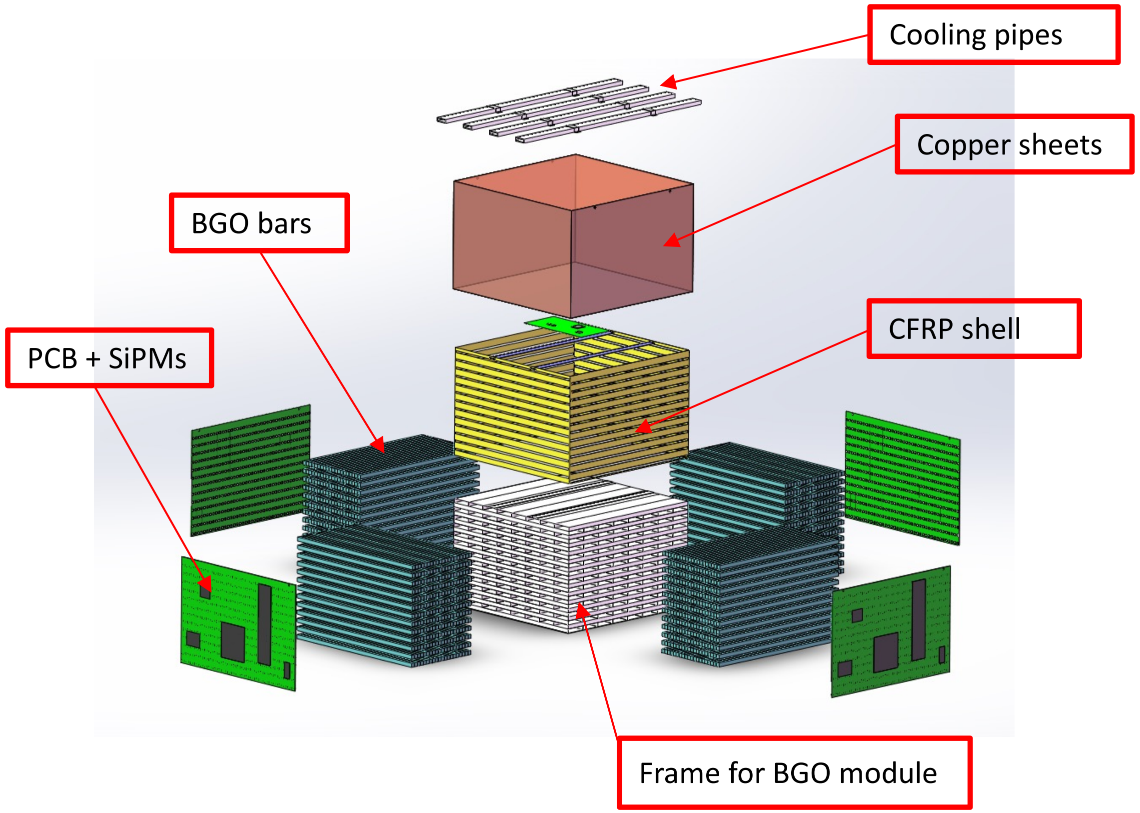


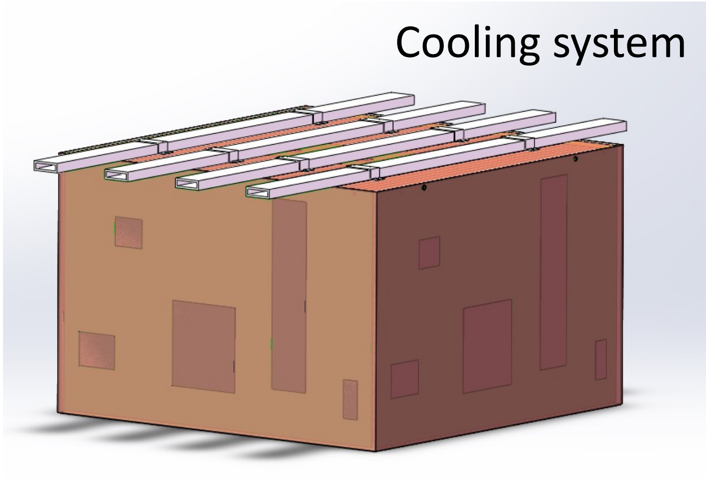
Installation procedure

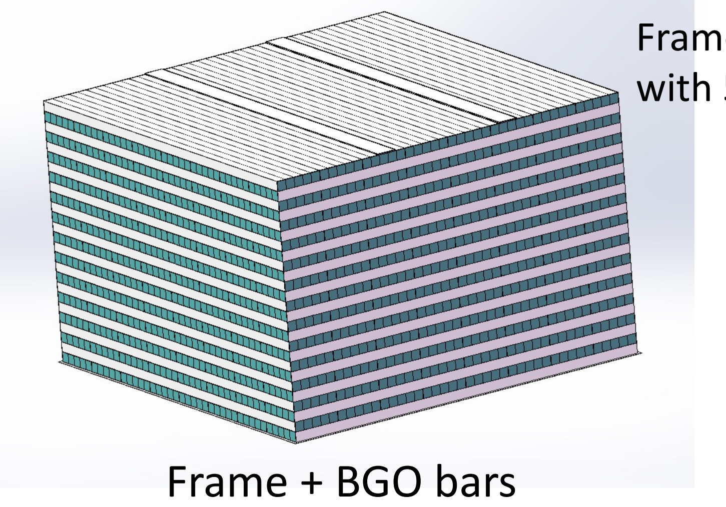
1. The overall processing of carbon fiber structure is completed;
2. Install stainless steel flanges on both sides (thickness 20mm);
3. Install steel rotating cylinder on both sides;
4, install the lateral rotary tooling (mining machinery screen commonly used transmission system);
5, the installation platform is built in the cylinder (2m high, 3.5m wide);
6. Install trapezoidal module from top to bottom, and use crane to lift to corresponding position, workers tighten the bolts on the installation platform. Install the module 1 first, and then the module 2.
7. After the assembly of the cylinder, the rotating cylinder on both sides can be used as the subsequent overall installation tool, and it can be removed after the completion of ECAL and HCAL installation.

ECAL module integration

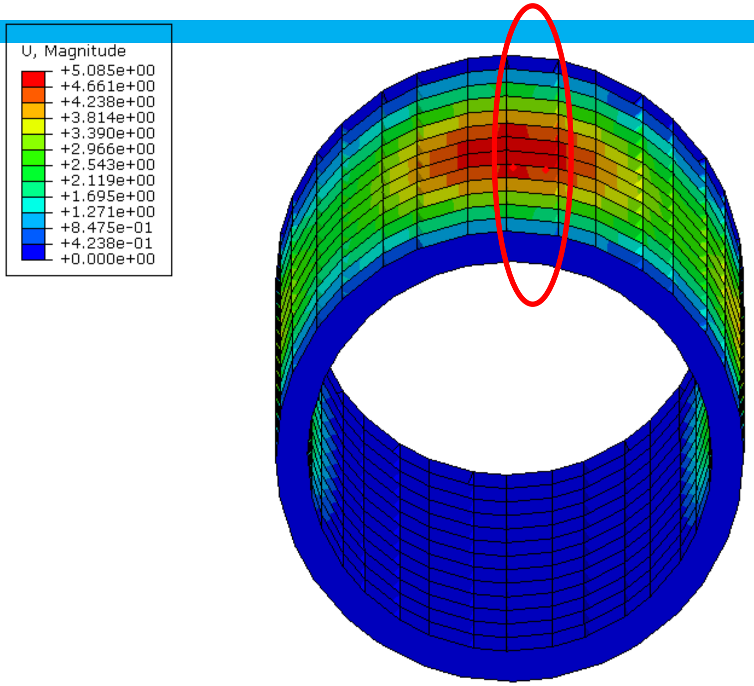
- FEA simulation studies on ECAL mechanics (ongoing): further iterations + validation

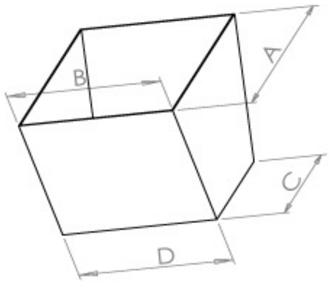




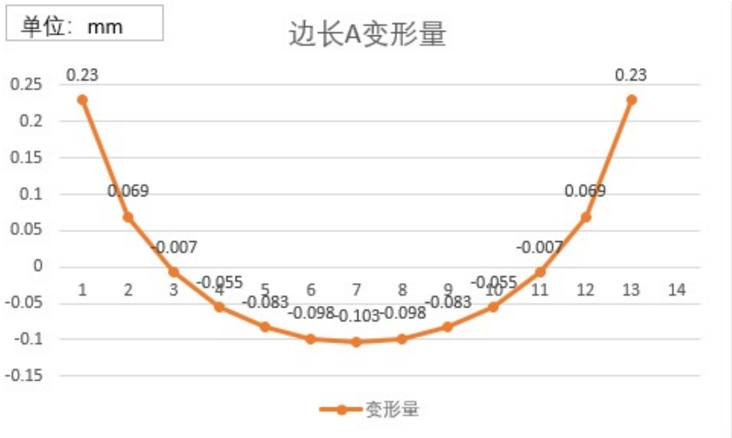


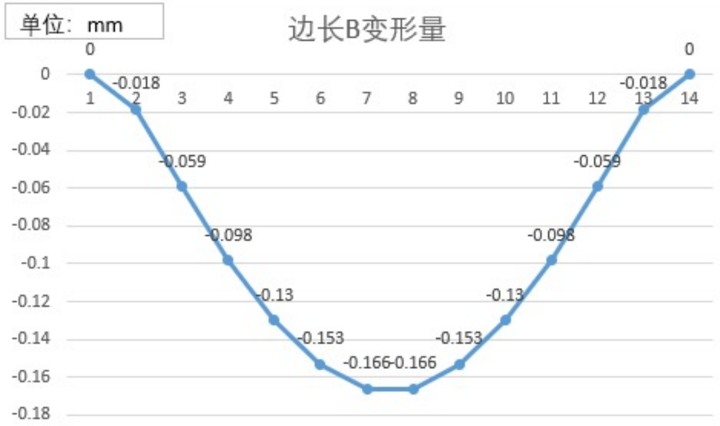
Mechanics: FEA studies on deformation

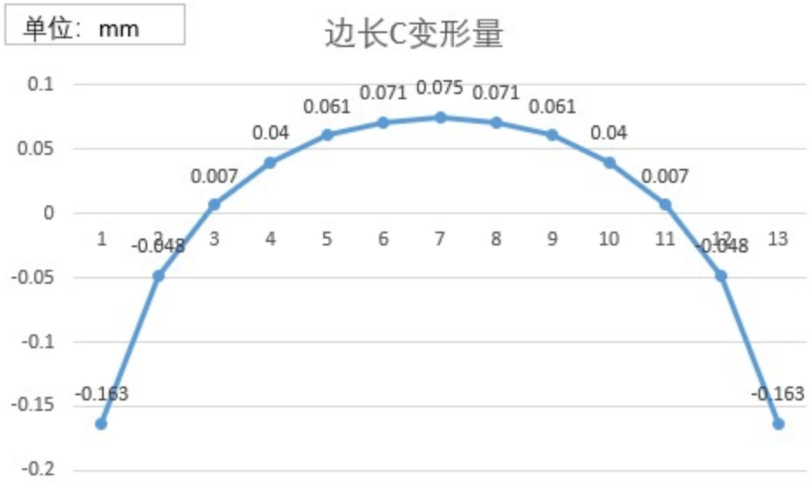


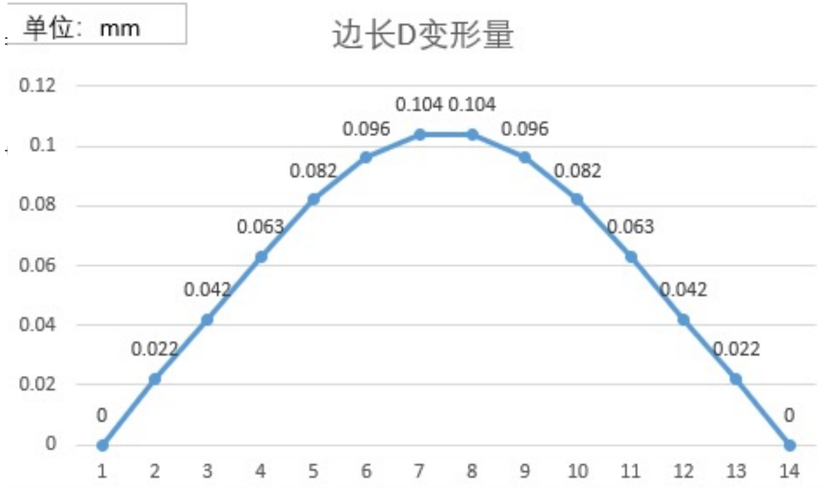


A/B/C/D are the sides of the cell





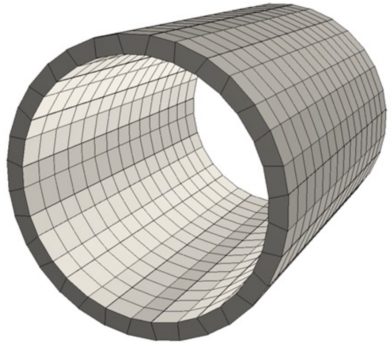


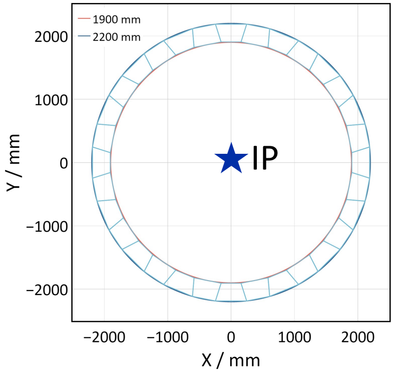


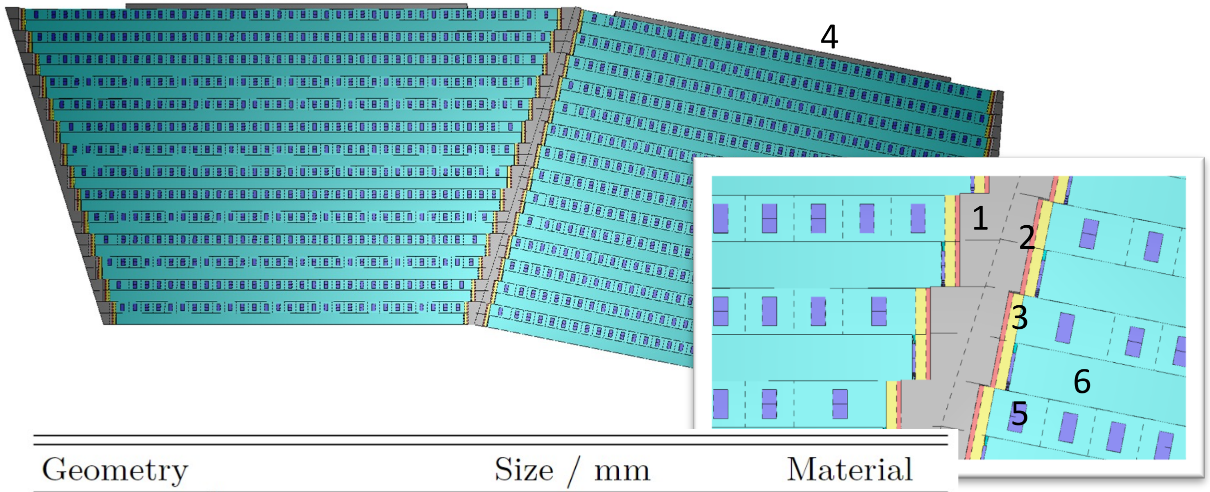
The BGO is brittle, so we have to know the deformation of each cell . According to the FEA, the maximum deformation of the cells is 0.23mm.

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.





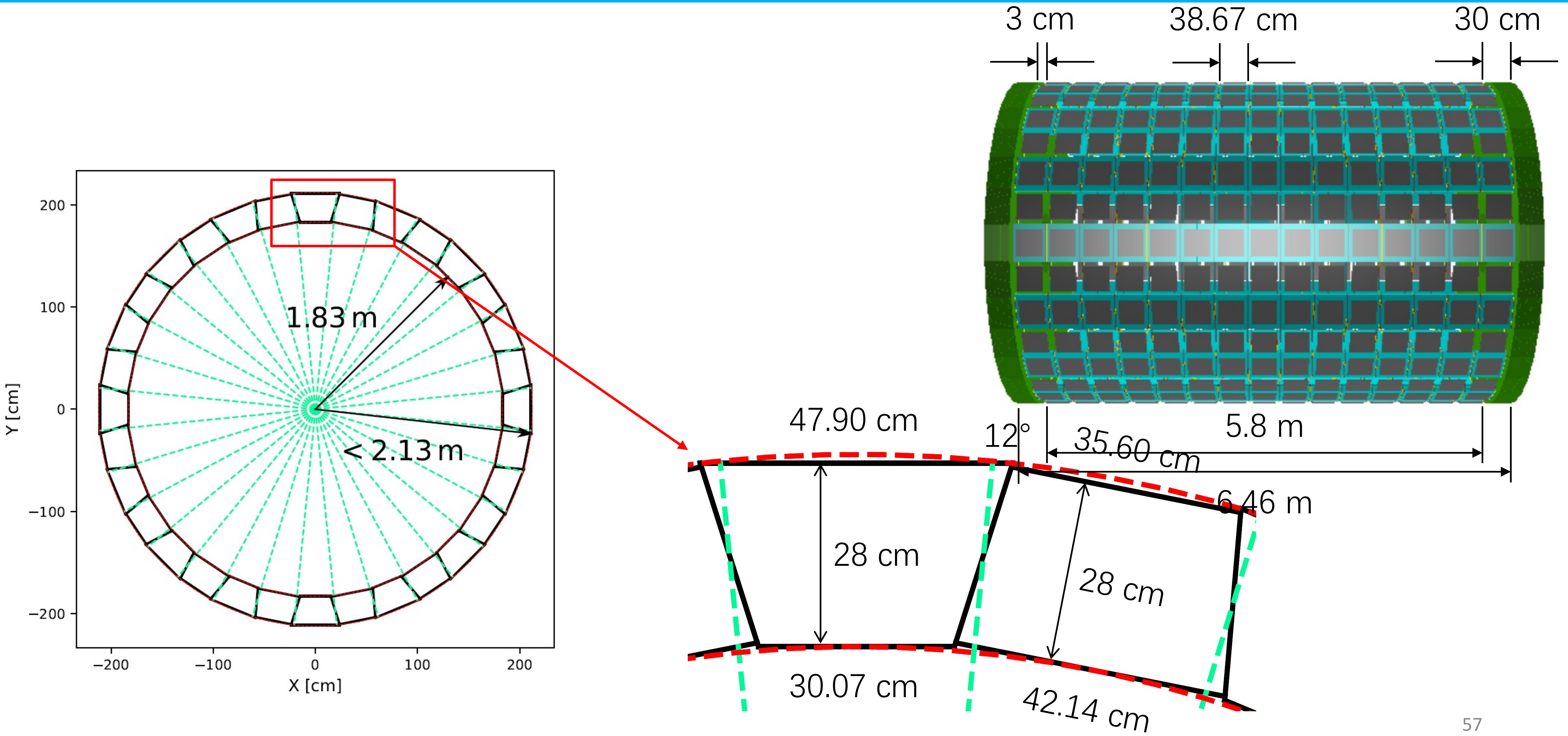


Parameter	Value / mm
Inner radius	1900
Outer radius	2200
Length	5900
Crystal length	$\sim$ 400
# Modules in $r-\phi$	32
# Modules in Z	15
ϕ Projectivity tilt	12°
# Layers	28

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

Barrel ECAL geometry: detailed design



Digitization and single photons energy resolution

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

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

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