CEPC Calorimetry System

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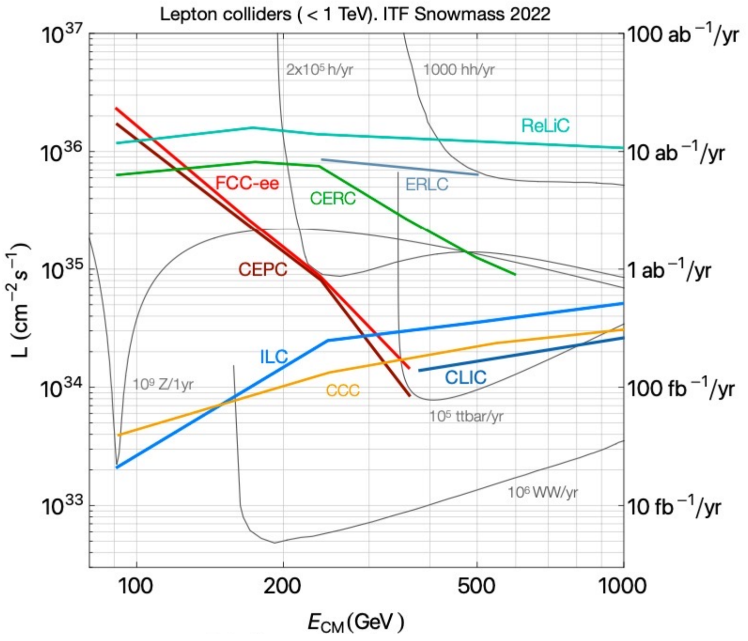
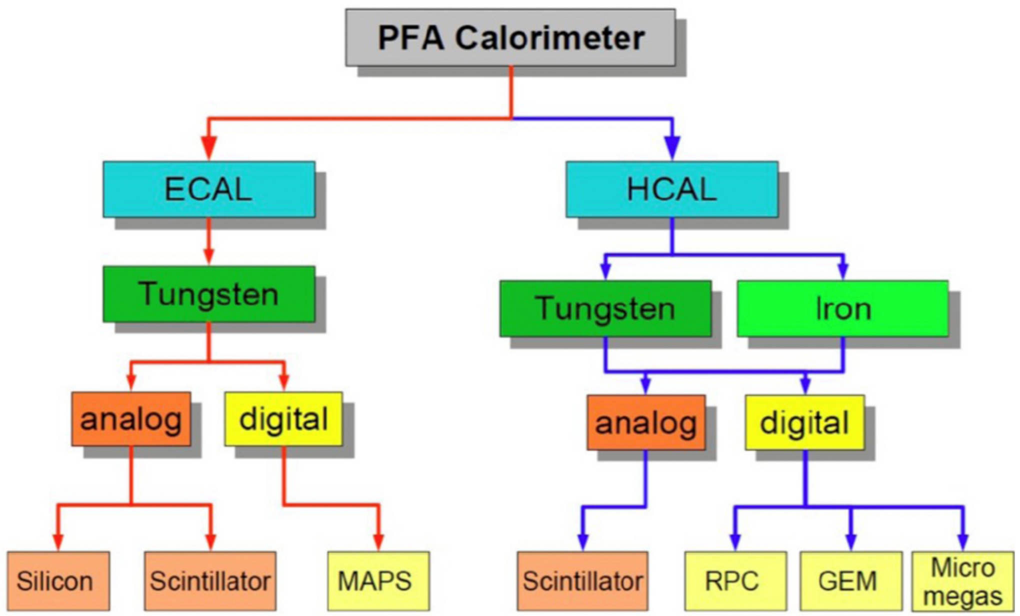
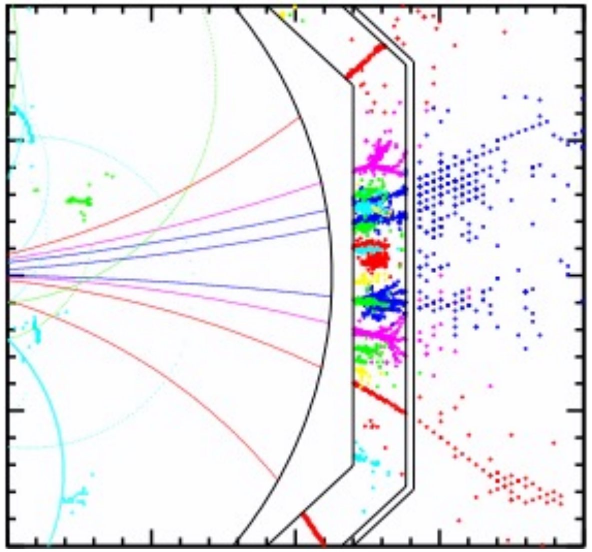
2024 CEPC Mechanics Workshop, Luoyang, Henan

August 23, 2024

High granularity calorimetry





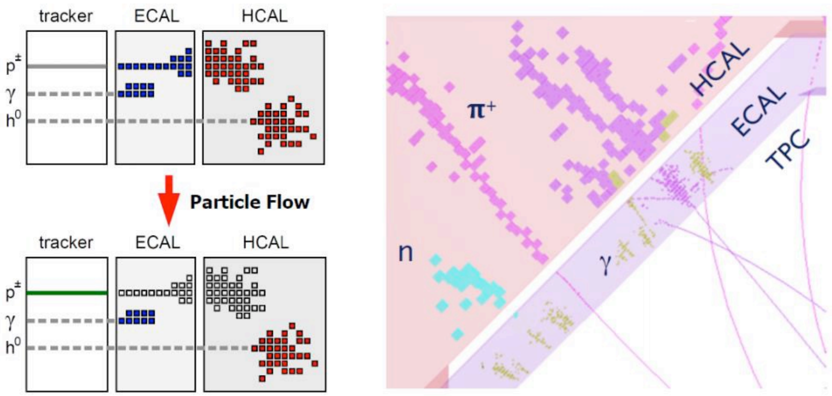


- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration in past 20 years
- New technical options with crystal/glass: being explored by CEPC calorimetry teams

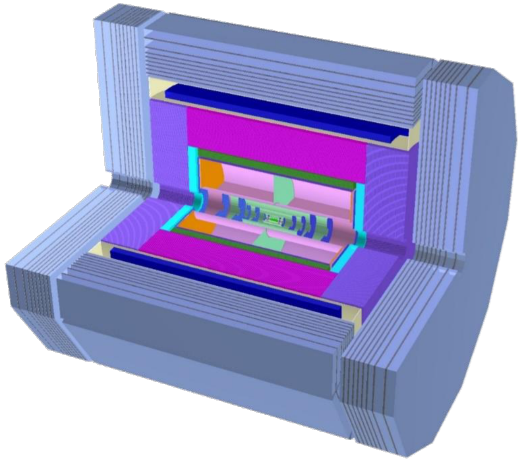
Calorimetry options in CEPC Reference TDR

- High-granularity calorimetry with particle flow
  - Boson Mass Resolution: 3 – 4 %
  - Pursuit of optimal EM/had. energy resolution
- Electromagnetic calorimeter
  - Crystal option: 3D-positioning and timing
  - To improve EM energy resolution from $\sim 16\%/\sqrt{E}$ (CEPC-CDR) to $\sim 3\%/\sqrt{E}$
- Hadron calorimeter
  - Scintillating glass (dense and bright): in shape of tiles to achieve high granularity (PFA-compatible)
  - To improve hadron energy resolution from $\sim 60\%/\sqrt{E}$ (CEPC-CDR) to $30\% \sim 40\%/\sqrt{E}$

PFA-oriented Calorimetry



CEPC Reference Detector



Calorimeters: crystal ECAL and ScintGlass HCAL

CEPC ECAL option selection

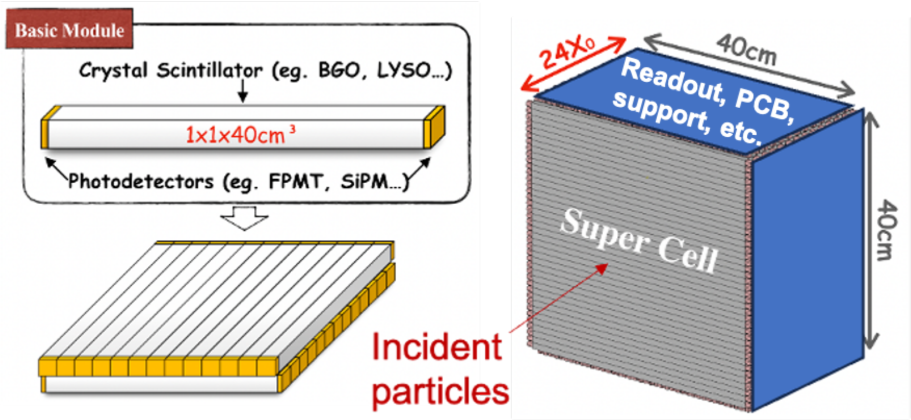
Technical Option	Silicon-Tungsten ECAL	Scintillator-Tungsten ECAL	Crystal ECAL
EM energy resolution	$\sigma_E/E = 17\%/\sqrt{E(GeV)}$	$\sigma_E/E = 13\%/\sqrt{E(GeV)}$	$\sigma_E/E = 3\%/\sqrt{E(GeV)}$
Particle-Flow Algorithm(s)	Arbor; Pandora	Arbor; Pandora	New dedicated PFA (ongoing developments)
Jet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

- *Crystal ECAL*, as a novel option, can significantly improve CEPC discovery potentials with photons as a portal for new physics beyond Standard Model

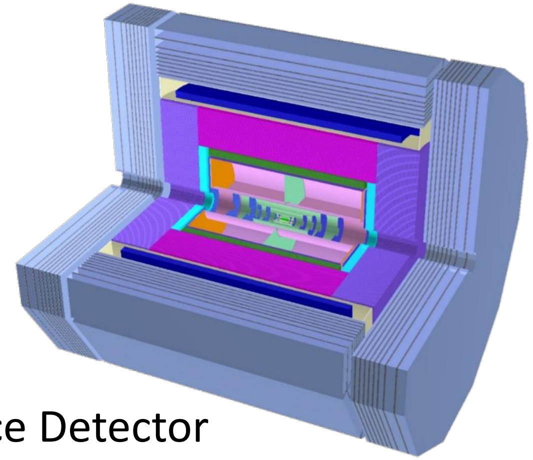
Selected as a baseline option for the CEPC reference detector

CEPC Crystal ECAL

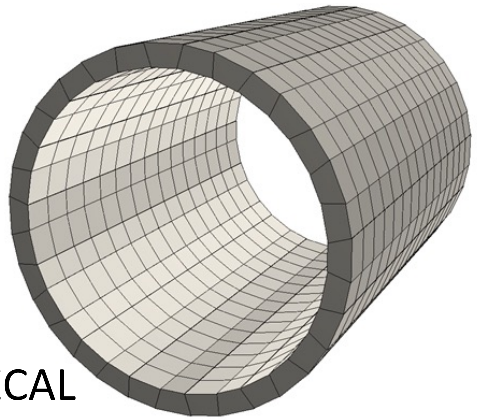
- Homogenous calorimeter based on crystals
  - High granularity in longitudinal and transverse directions
  - Optimal EM performance: $\sigma_E/E = 3\%/\sqrt{E}$
  - Compatible for PFA: Boson Mass Resolution (BMR) 3 – 4 %
- Long crystal bars in orthogonal arrangement
  - Minimal dead materials in longitudinal layers
- Dedicated R&D activities
  - Crystal calorimeter prototypes and beamtests: EM performance
  - A new algorithm particle-flow reconstruction: jet performance



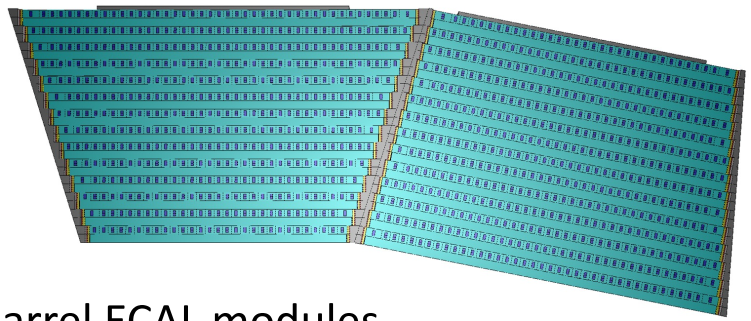
- **BGO bars in $1\times1\times\sim40\ cm^3$**
- **Effective granularity $1\times1\times2\ cm^3$**
- **Modules with cracks not pointing to IP (with an inclined angle of 12 degrees)**



CEPC Reference Detector



Barrel ECAL



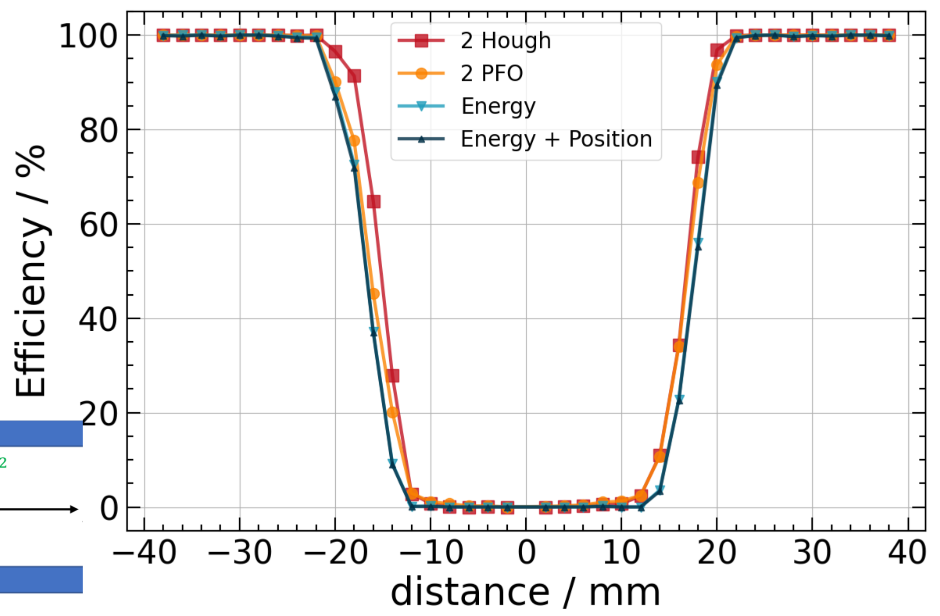
Barrel ECAL modules

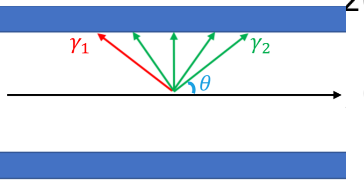
Performance in simulation: separation power

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

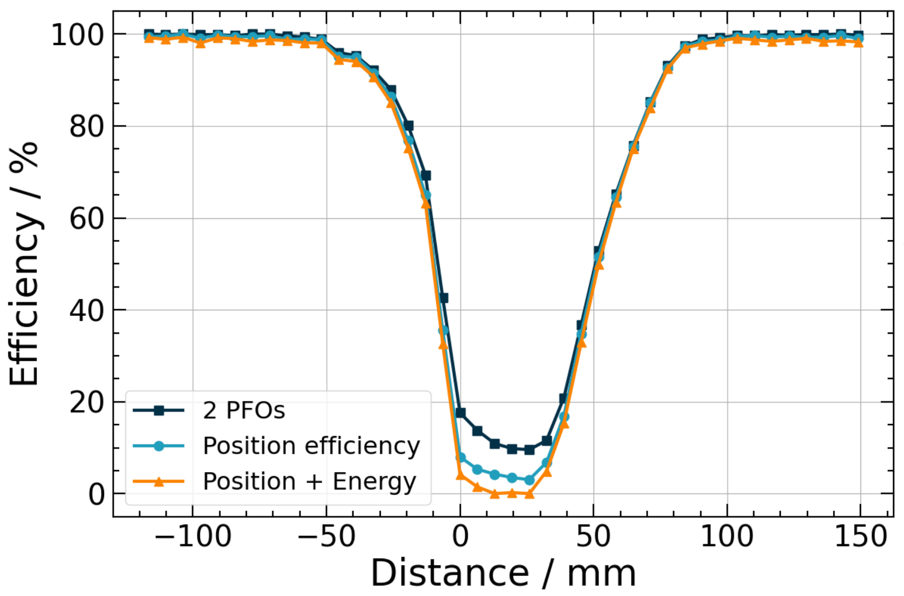
Based on a new and dedicated PFA for crystal ECAL (CyberPFA)

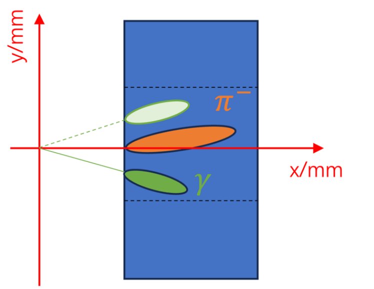
$\gamma - \gamma$ separation for 5 GeV photons





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

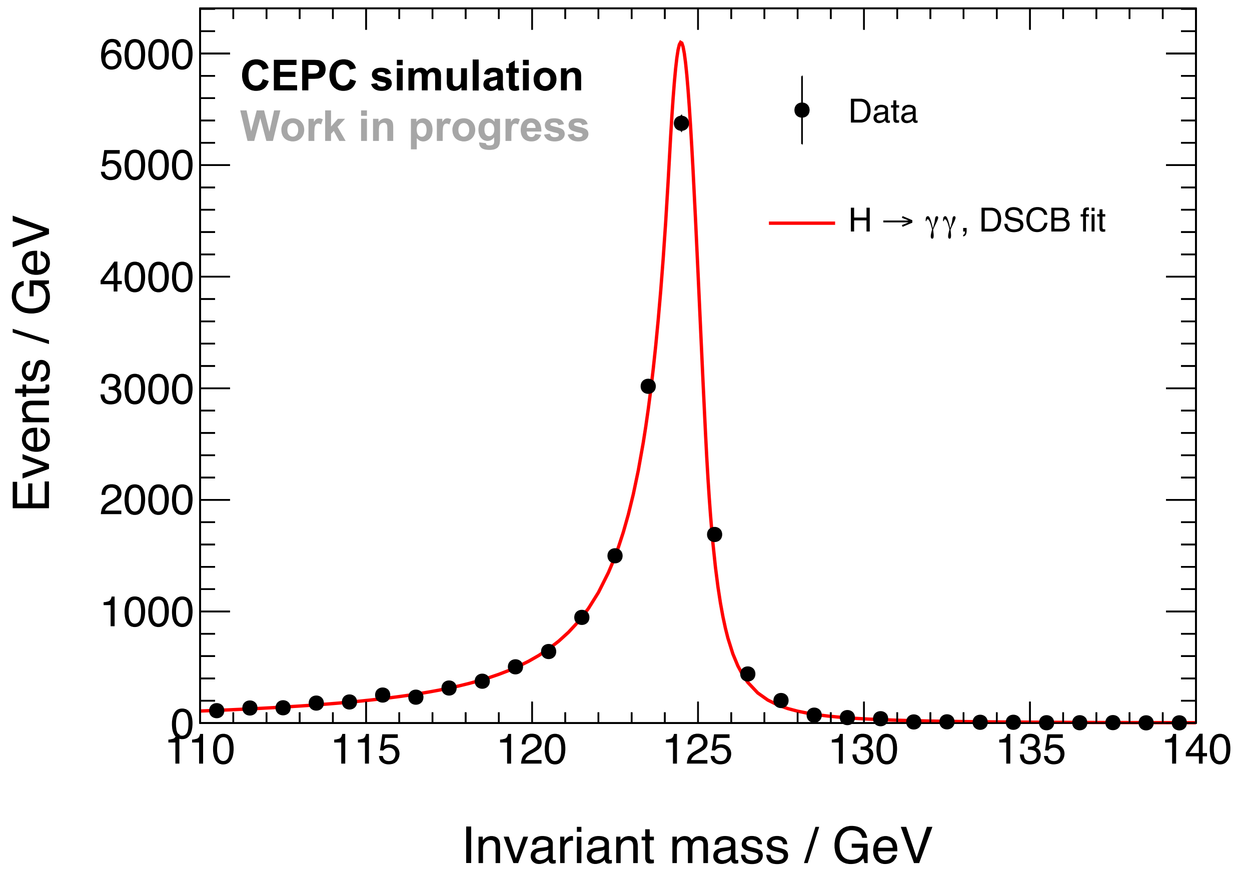




*Asymmetry pattern is due to the magnetic field

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

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



Based on a new and dedicated PFA for crystal ECAL (CyberPFA)

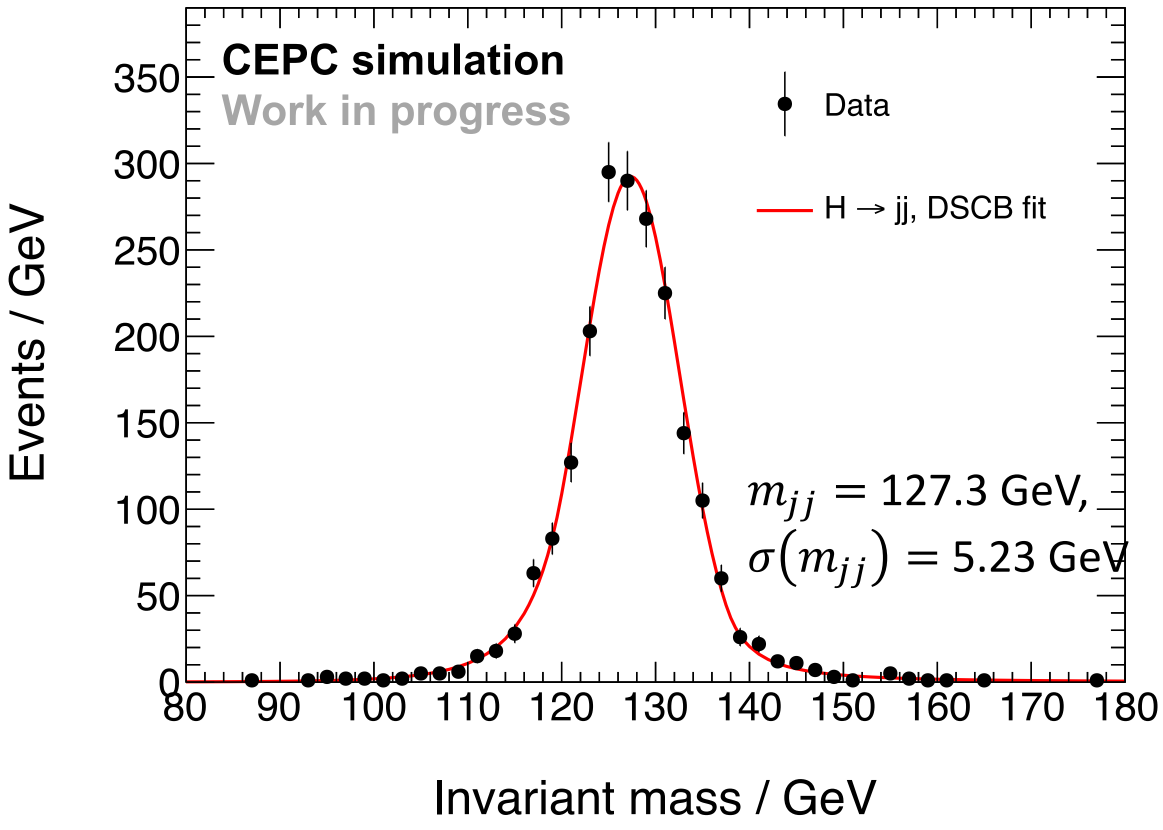
Double-side CB fit, $\sigma(m_{\gamma\gamma})$ = 0.57 GeV

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

Can be fixed with better photon energy correction

Physics performance in simulation: $\boldsymbol{H \to gg}$

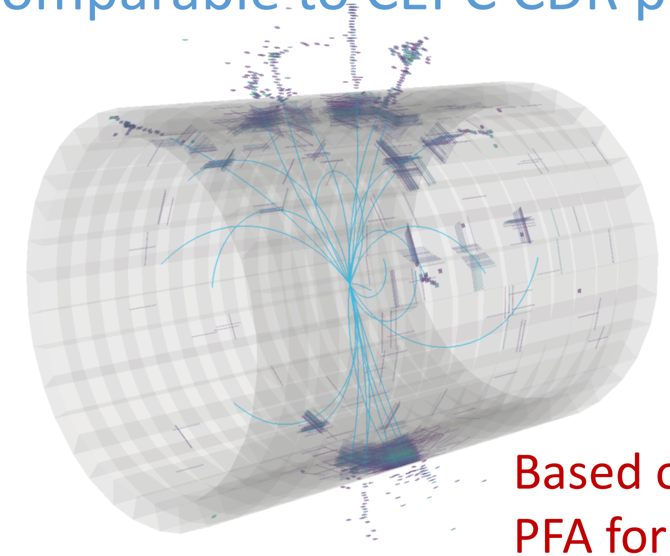
- Physics process: $\boldsymbol{ee \to ZH \to \nu\nu gg}$ in $\sqrt{s} = \mathbf{240}$ GeV
  - Full reconstruction of two gluon jets in the full CEPC detector
  - Dedicated developments of PFA for long crystal bars



Boson mass resolution (BMR): 4.11%

With truth tracking: BMR 3.73%

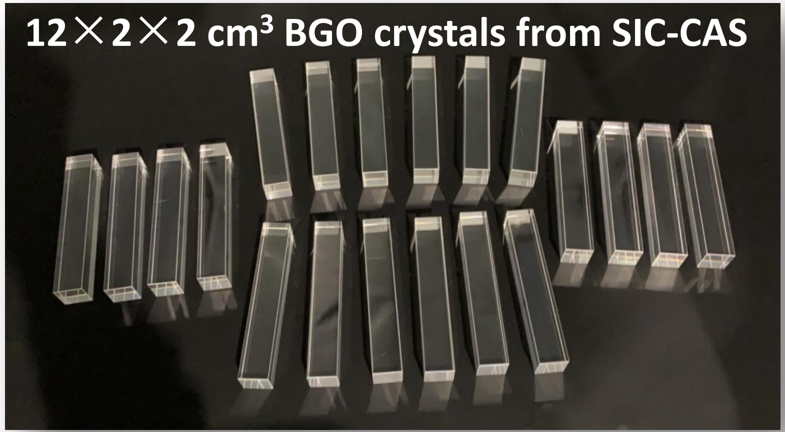
(comparable to CEPC CDR performance)

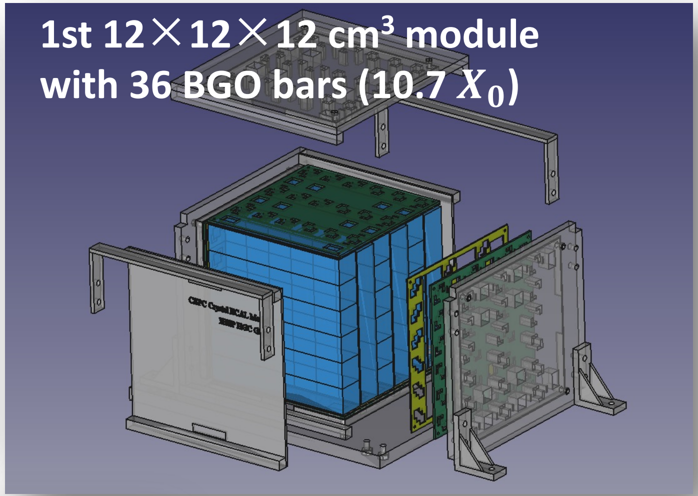


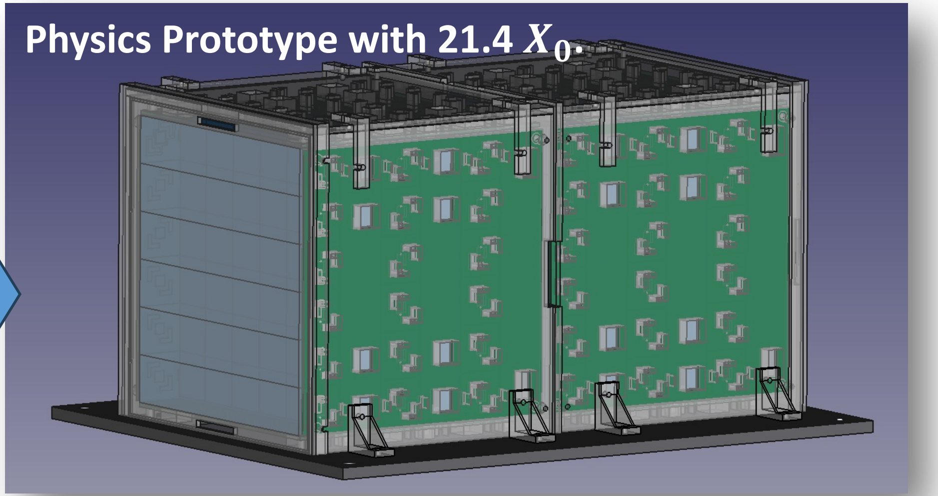
Based on a new and dedicated PFA for crystal ECAL (CyberPFA)

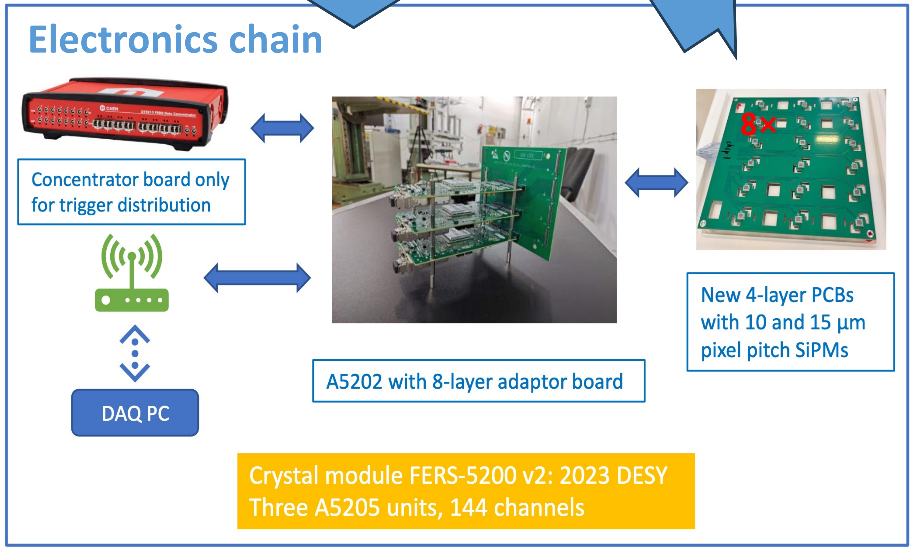
Vertex, Silicon + TPC tracker, crystal ECAL, ScintGlass HCAL

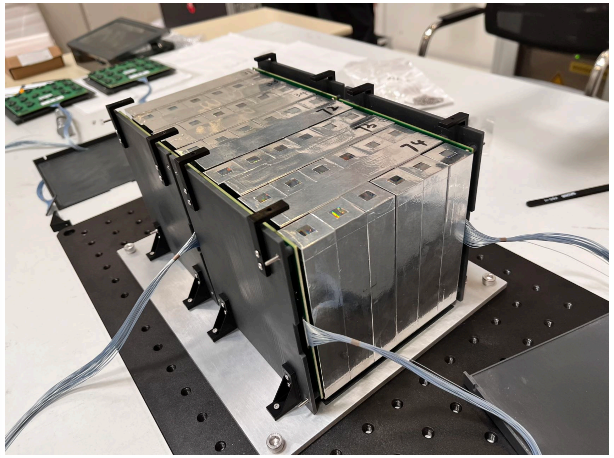
Crystal Calorimeter: First Physics Prototype











First crystal calorimeter prototype

- Successfully developed in 2021-23
- With commercial ASICs

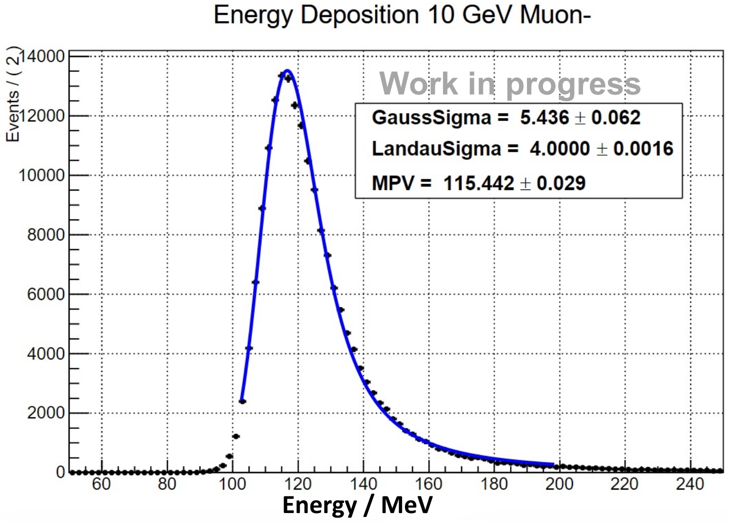
Major motivations

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

Beam tests: Crystal Calorimeter Prototype

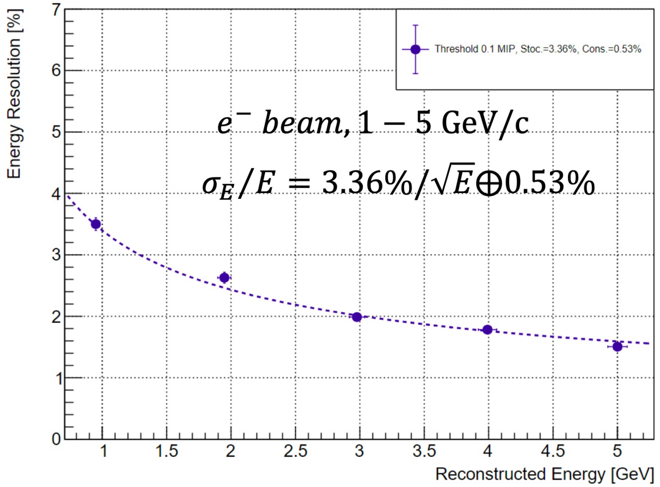
2023 CERN beam test at PS-T9

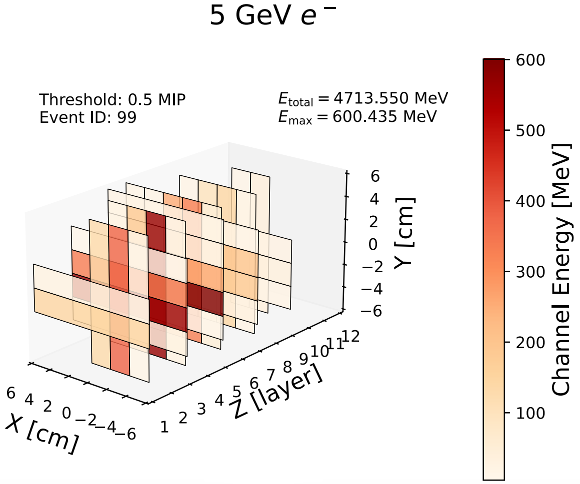
- Successful system commissioning
- Clear MIP signals for all channels

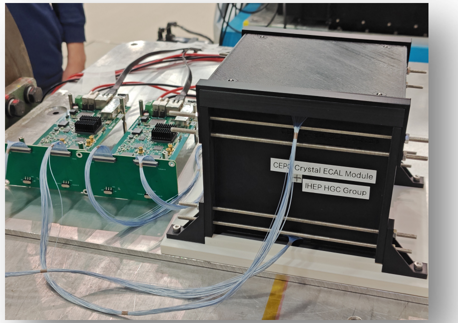


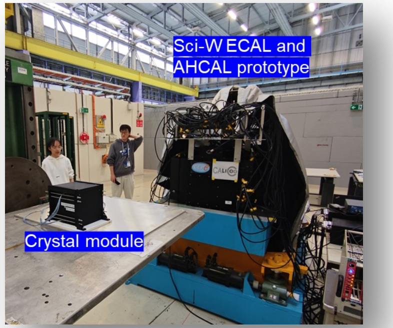
2024 CERN beam test at PS-T9: finished in July 10th

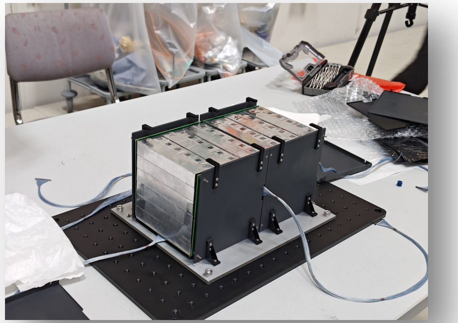
- Promising EM resolution with 1-5 GeV/c e^- beam
- Data analysis is still ongoing: detailed calibrations, shower profiles



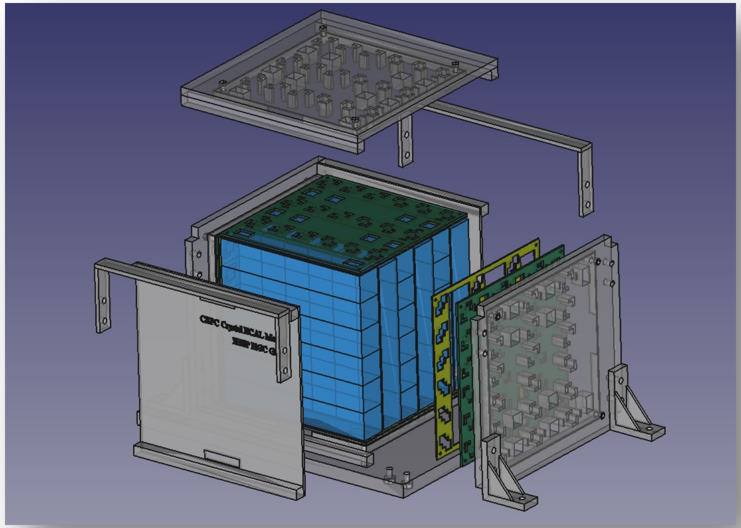


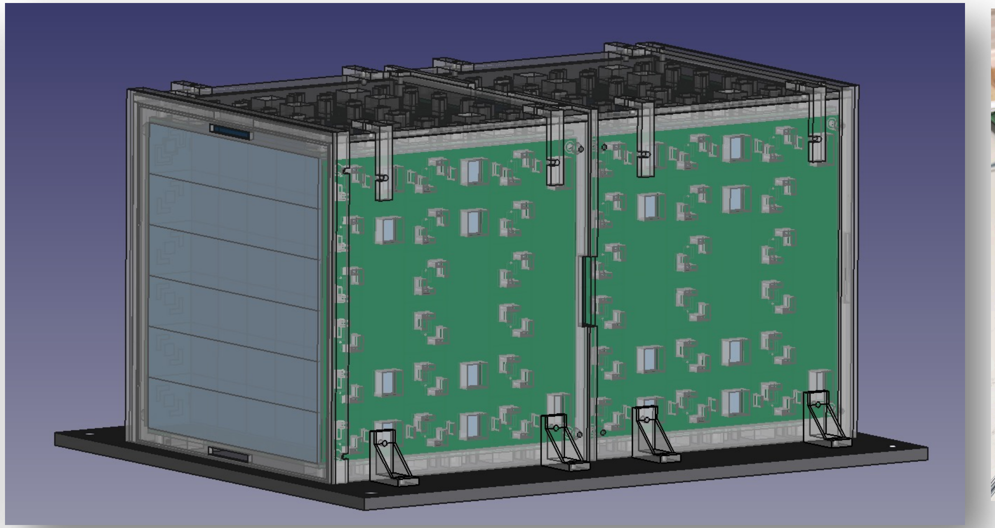


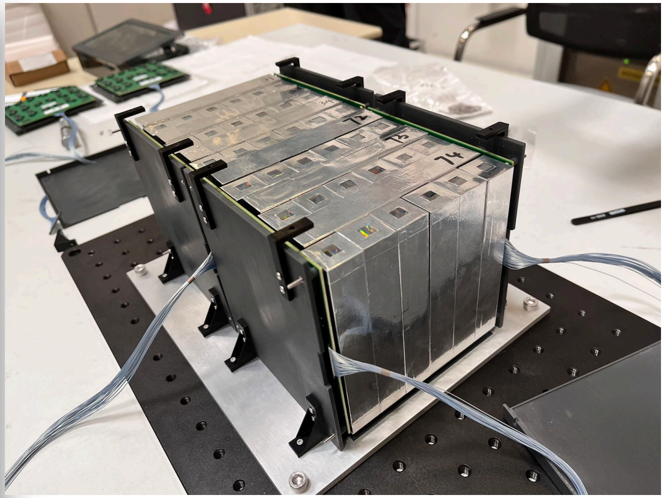




Crystal Calorimeter Prototype: mechanics







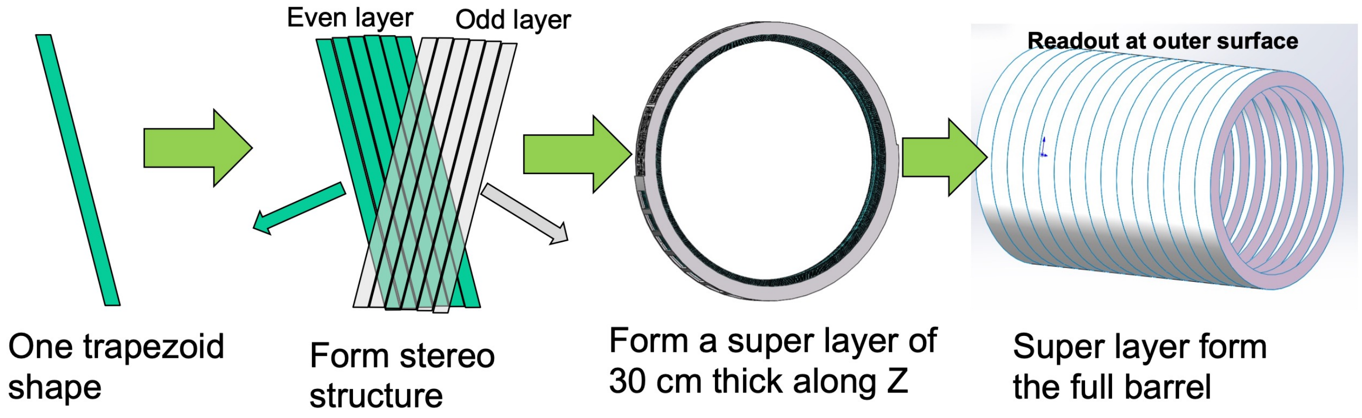
- Special considerations of mechanics for crystals
  - Weight of crystals (density=$\sim 7\mathrm{g/cm^3}$) needs to be decoupled with readout boards
  - Many holes in readout boards: reserved for support structure
  - *3D-printed plastics* for light-weighted and custom-designed support structure
  - Tolerances of crystal dimensions (production + polishing) and reflector wrapping
- Still a long way ahead towards full crystal modules
  - Full integration of readout electronics and cooling

Observed significant deformation in 3D-printed structures in the long run

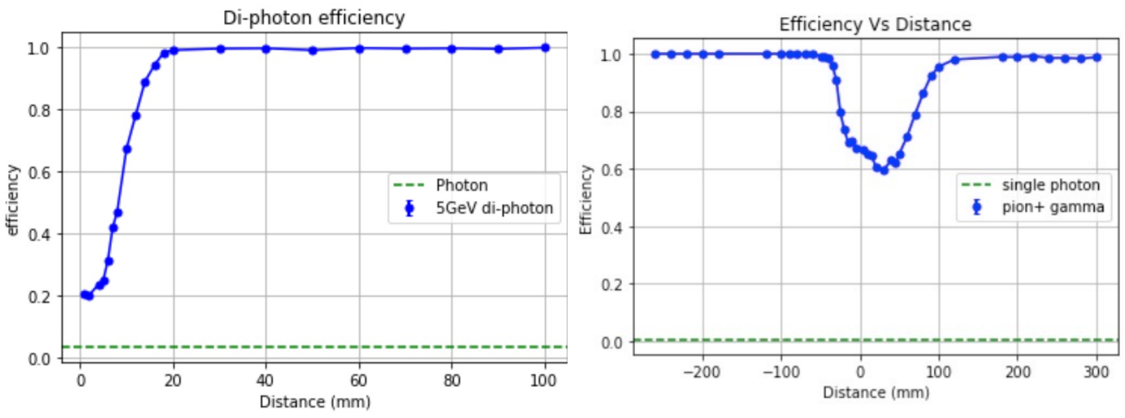
Alternative ECAL design: stereo crystals

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

Only one freedom left, α or longitudinal sampling N_R



Separation power of two particles



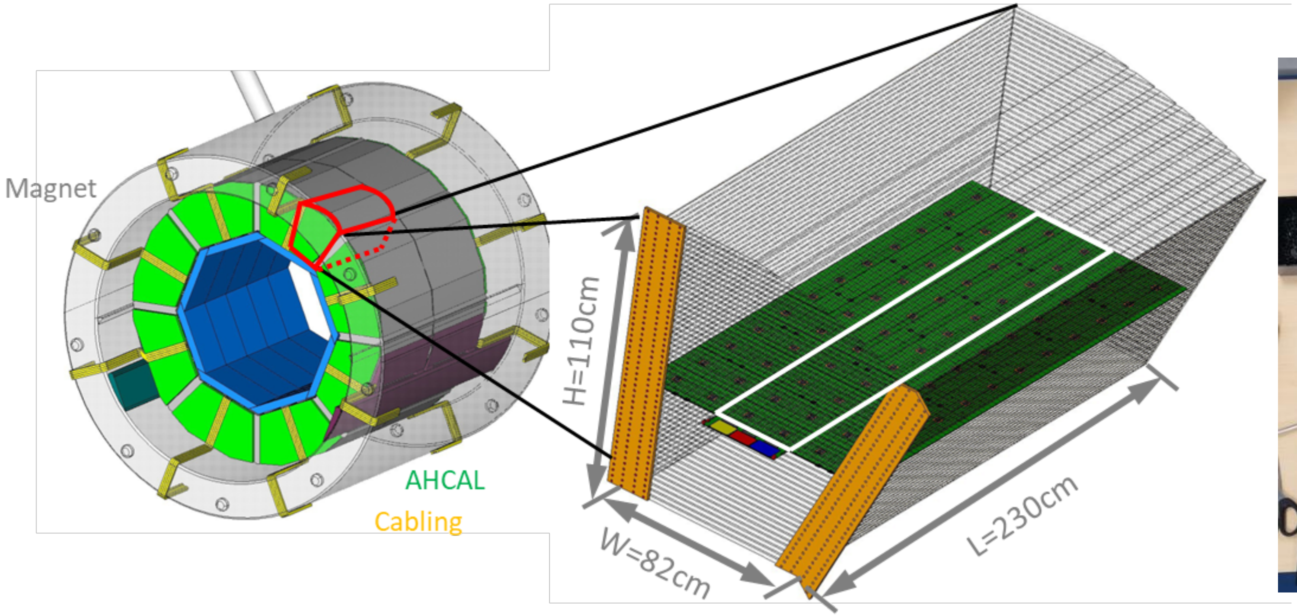
- Simulation studies on reconstruction: promising separation power of two particles
- Ongoing designs on mechanics, cooling and integration

Technical challenges: crystal ECAL mechanics

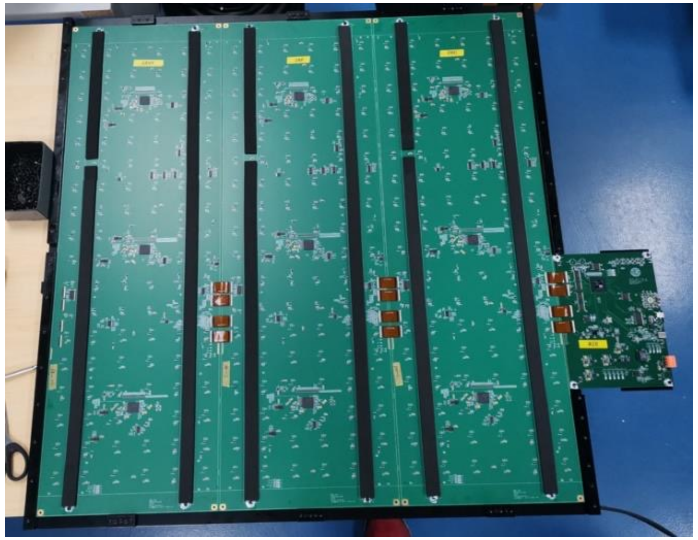
- *Mechanics* hereby has a more general meaning
  - ***Support structure*** for crystal modules integrated with a ***cooling*** system

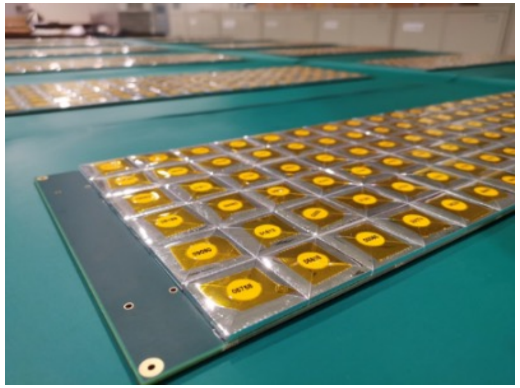
- High granularity with a compact design
  - Minimum space for system integration (support, cabling, cooling)
- Scintillating crystals
  - Fragile: requires dedicated mechanical protection for long-term stability
- Crystal ECAL performance: optimal energy resolution
  - Light-weighted support structure: ensures low material budget and high strength
  - Stable temperature control: crystals and photosensors are temperature dependent

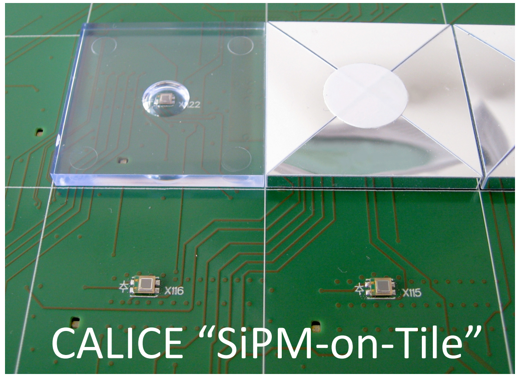
CEPC hadron calorimeter: scintillator options



CEPC-AHCAL prototype:
one sensitive layer

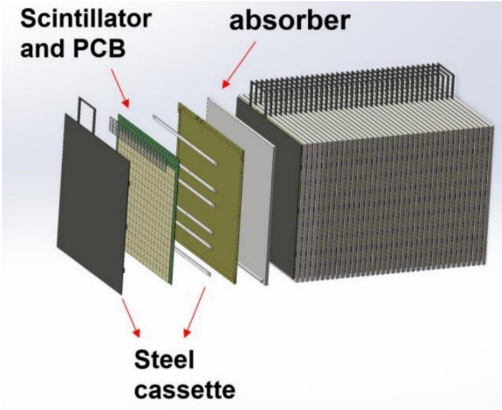




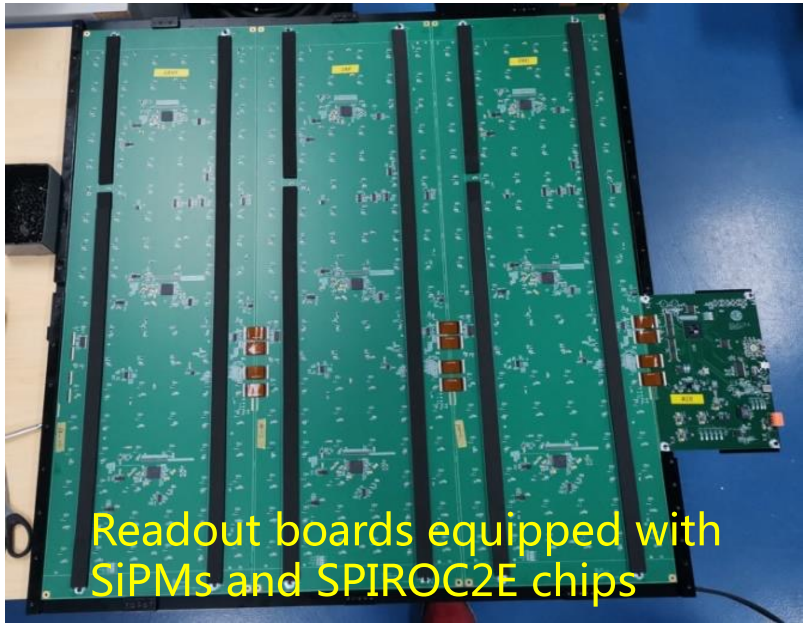


- Sampling HCAL: scintillator (sensitive) + steel (absorber)
- Two major HCAL options based on scintillator
  - *Plastic Scintillator*: mature technology, CEPC-AHCAL full-scale prototype developed
  - *Glass Scintillator*: new technology, no full-scale prototype yet

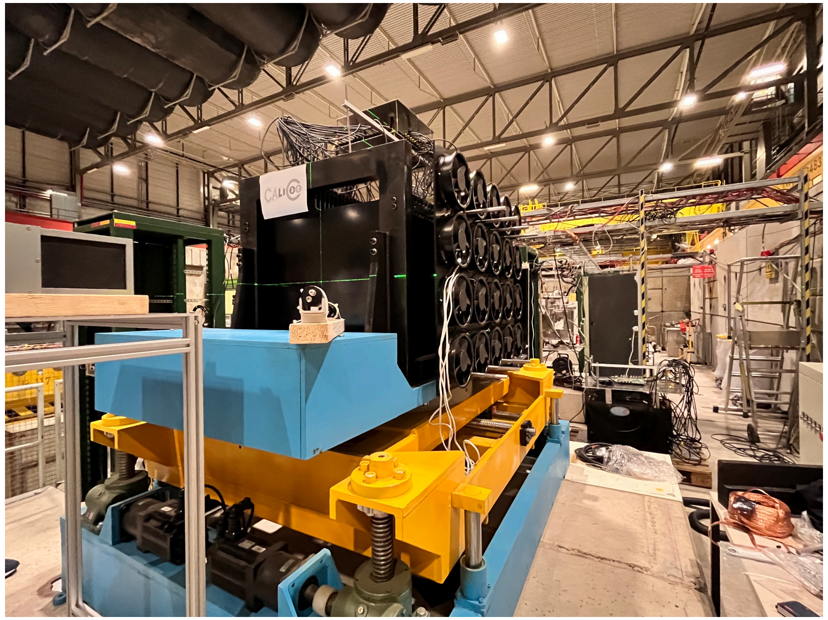
CEPC HCAL prototype: developments and beamtests

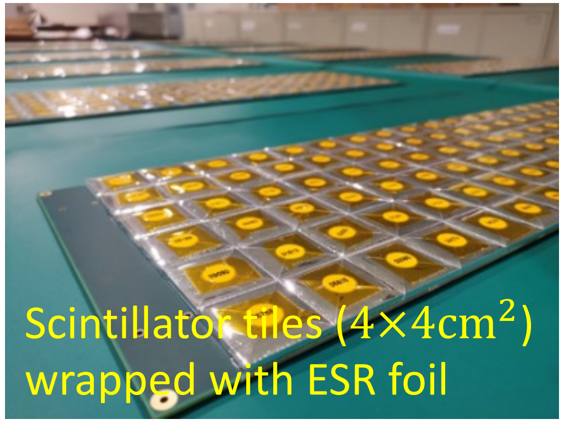


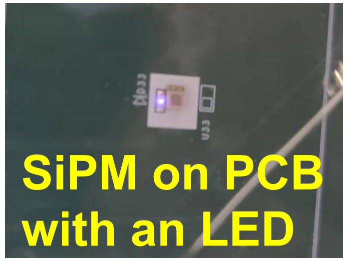
1 full layer: 3 HBUs + cassette



Beamtest Setup



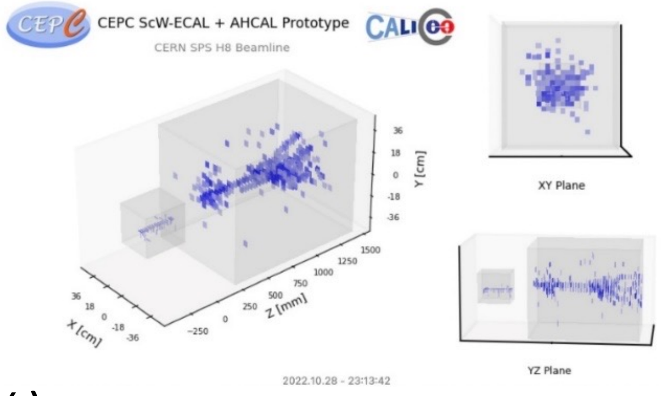




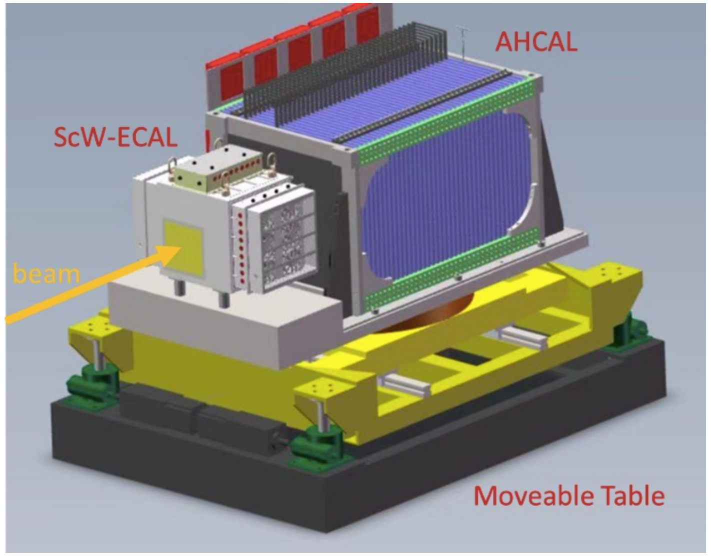
- CEPC HCAL prototype with *plastic scintillator* tiles
  - Transverse size $72{\times}72\ \mathrm{cm}^2$, 40 longitudinal layers ($\sim 4.6\lambda_I$)
  - 12960 readout channels, SPIROC2E (360 chips), ~5 ton in weight
  - Developed during 2018 – 2022 (IHEP, SJTU, USTC; Shinshu, Tokyo)

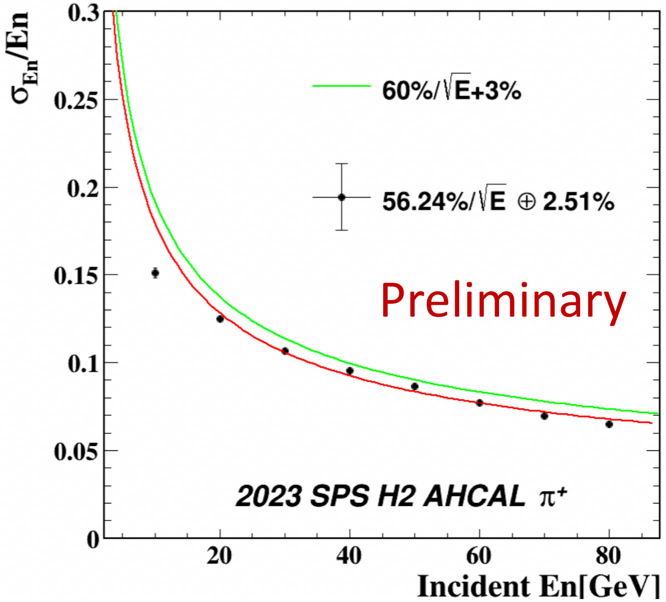
CEPC HCAL prototype: developments and beamtests

Oct 19 – Nov 2, 2022 — SPS H8 beamline
Apr 26 – May 10, 2023 — SPS H2 beamline
May 17 – 31, 2023 — PS T9 beamline

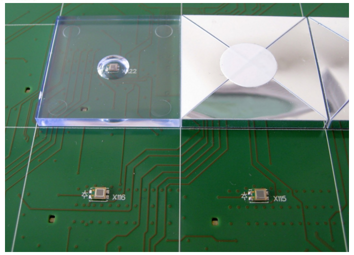


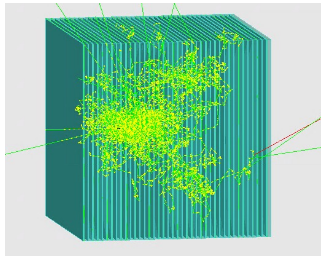
- Collected decent statistics of testbeam data samples
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS (also up to 250 GeV)
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS
- Hadron energy resolution: $56.2\%/\sqrt{E} \oplus 2.5\%$ (expected $60\%/\sqrt{E} \oplus 3\%$)

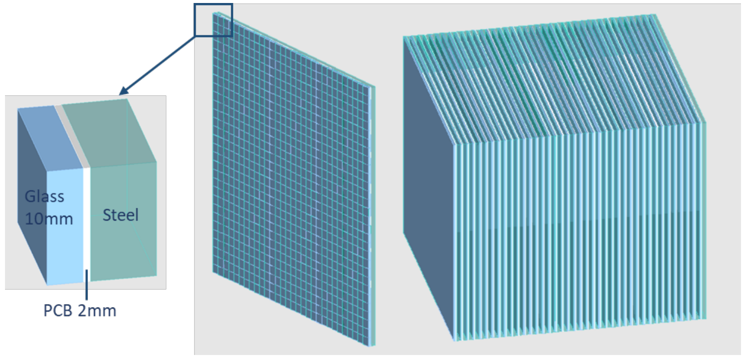


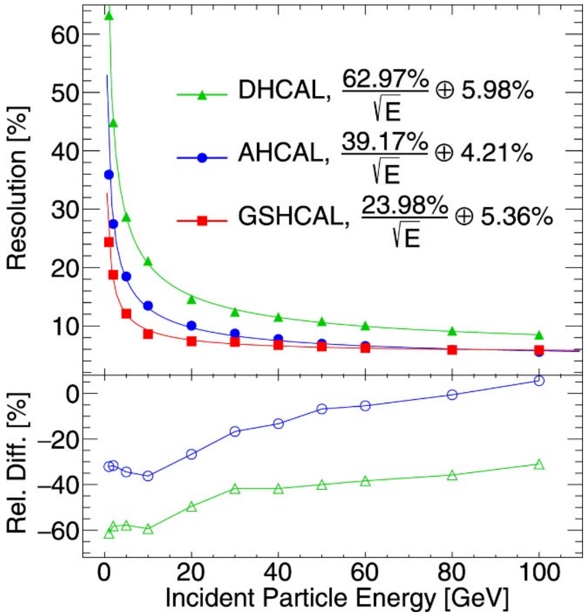


Glass Scintillator HCAL

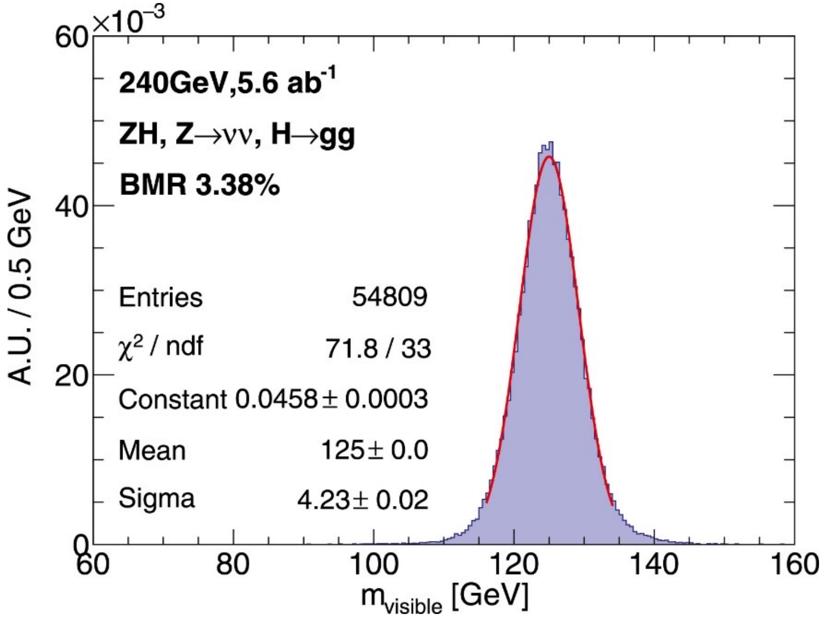






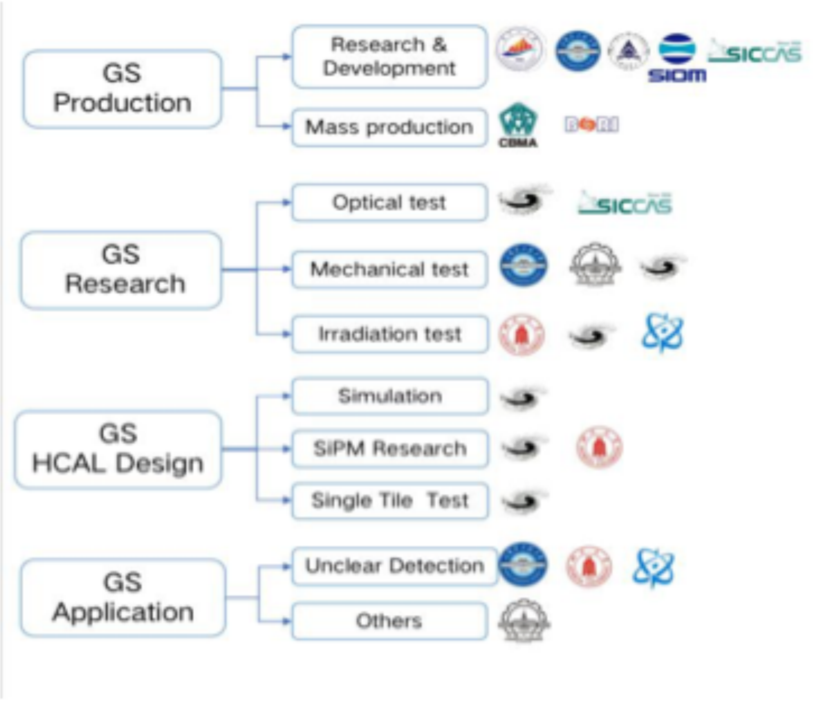


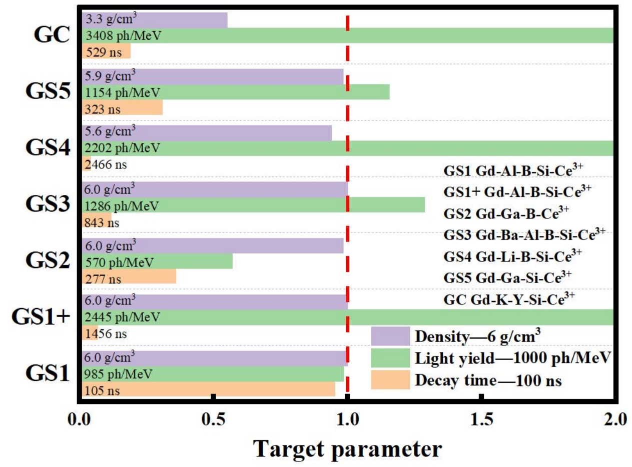
Peng Hu et al, GSHCAL for future Higgs factories



- Glass Scintillator HCAL (GSHCAL)
  - Expect significantly better hadronic energy resolution than the Plastic Scintillator option
  - Glass scintillator tiles as sensitive components: fine segmentation for PFA compatibility
- Dedicated R&D activities
  - Glass scintillator R&D: high density (~6 g/cc), bright (>1000 ph/MeV), fast scintillation, cost effective
  - HCAL performance studies in simulation and tests of glass tiles

Glass Scintillator Collaboration



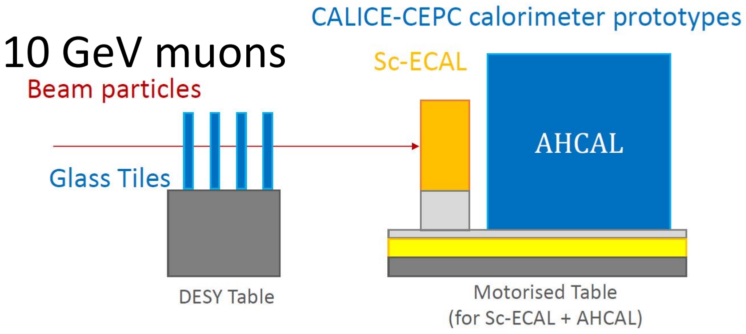


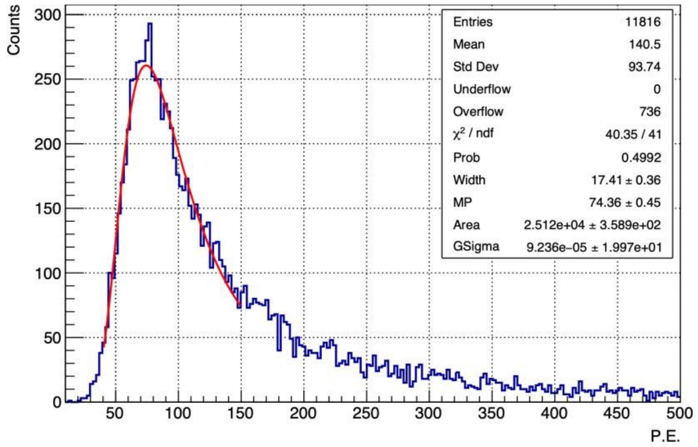
GS Collab. Spokesperson: Sen Qian (IHEP)

- Glass Scintillator Collaboration established in Oct. 2021
- GS R&D activities with 3 CAS institutes, 5 universities, 3 industrial partners

Glass scintillator in beam/cosmic tests (2023-2024)

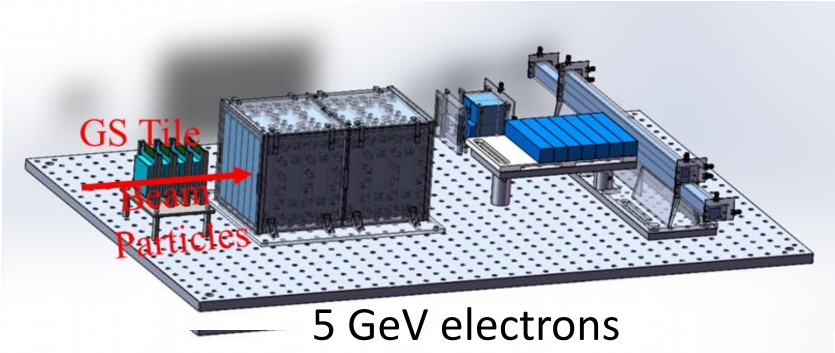
11 glass tiles tested at CERN (May 2023)

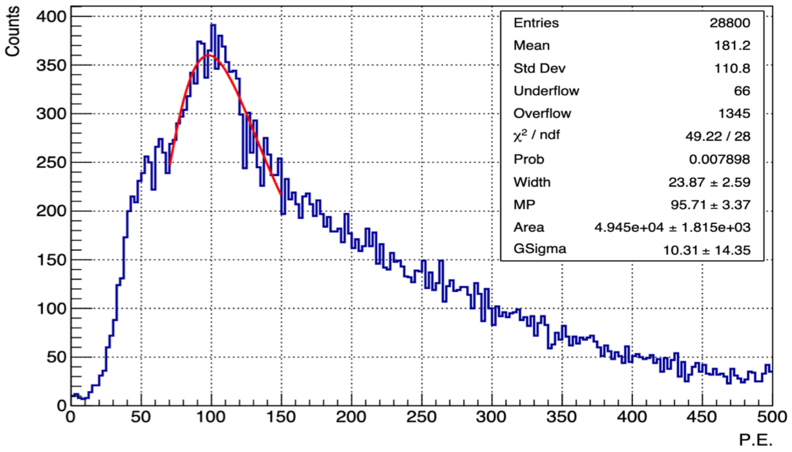




MIP response: 60 – 70 p.e.

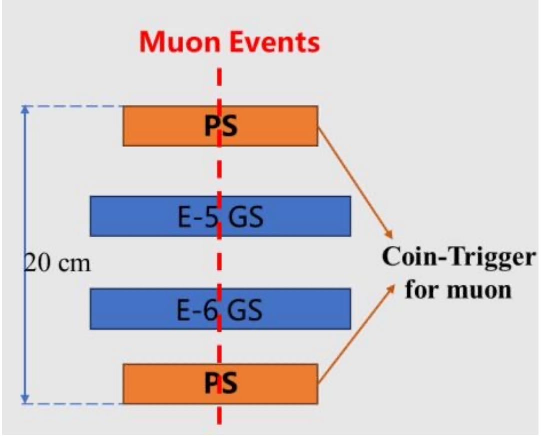
9 glass tiles tested at DESY (Oct. 2023)

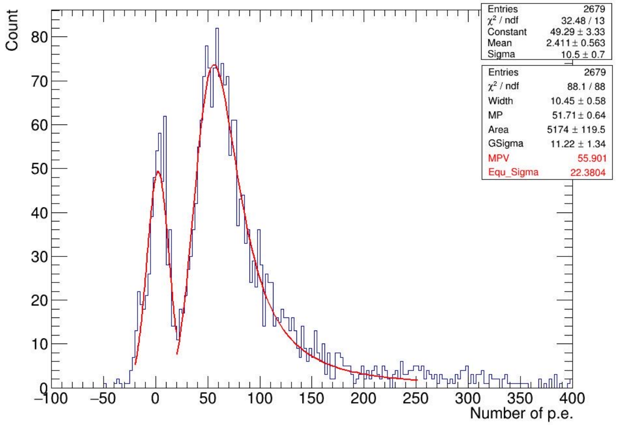




MIP response: 80 – 90 p.e.

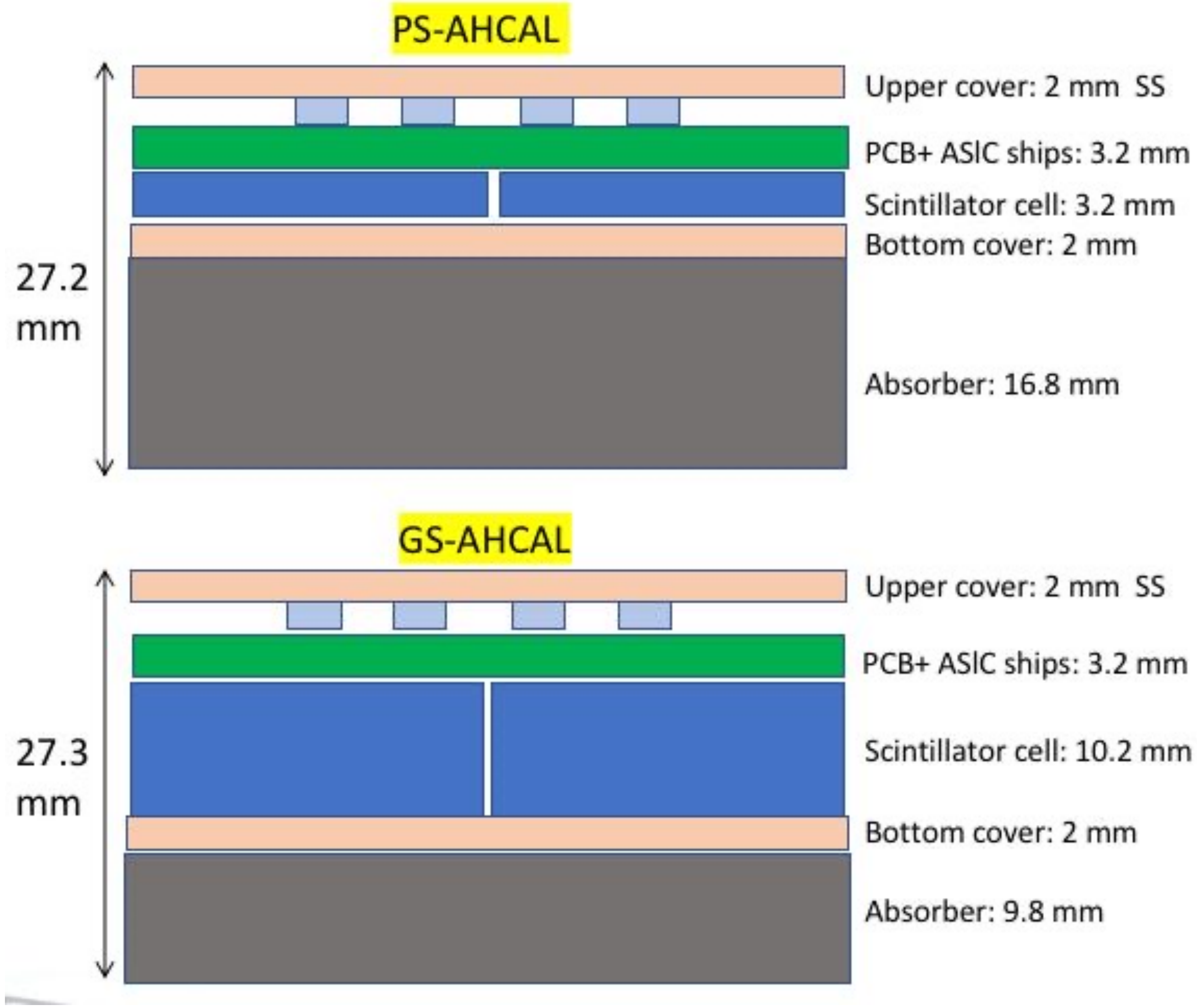
4 glass tiles tested at IHEP (Apr. 2024)

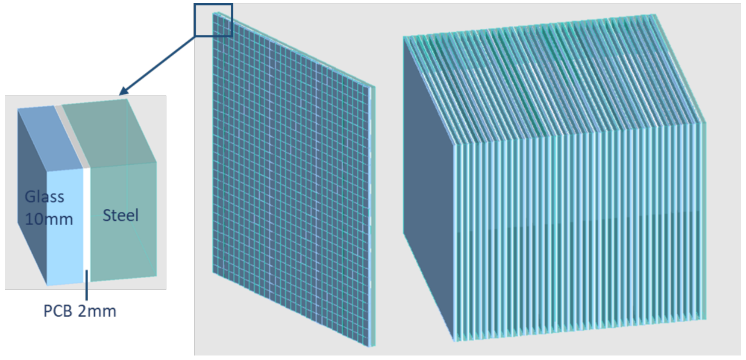


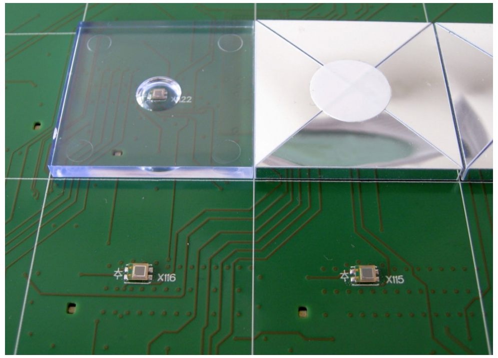


MIP response: 50 – 60 p.e.

CEPC HCAL: plastic vs glass scintillator







- Share many similarities and synergies
  - Sampling structure
  - Similar SiPM and electronics
  - Almost the same thickness

→ replace plastic with glass tiles

- Challenges to mechanics
  - More weight with glass tiles
  - Thinner steel absorber plates

Technical challenges: glass scintillator HCAL mechanics

- *<u>Mechanics</u>* hereby has a more general meaning
  - ***Support structure*** for HCAL modules integrated with a ***cooling*** system
- High granularity with a compact design
  - Minimum space for system integration (support, cabling, cooling)
- Sampling structure with glass scintillator
  - Control of deformation due to higher density glass and thinner steel absorber
- Steel absorber plates
  - Low magnetic permeability: within 2 – 3 T magnetic field
  - Production quality/cost: thickness tolerance control over square-meter steel plates
- HCAL performance: optimal energy resolution
  - Stable temperature control: glass and photosensors are temperature dependent

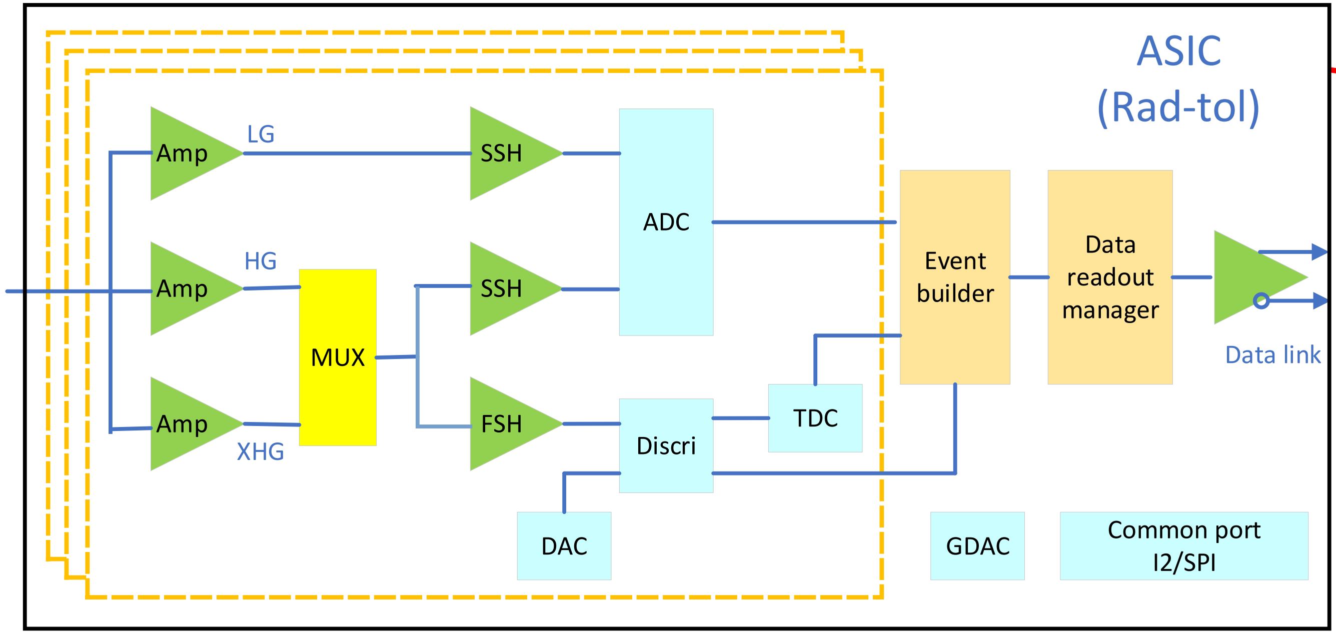
Summary and planning

- Overview of CEPC calorimeter options and dedicated R&D activities
- Calorimeter option selection for the CEPC reference detector
  - ECAL option: crystal
  - HCAL option: glass scintillator and steel
- More efforts to address critical issues for CEPC Ref-TDR
  - System integration with mechanics (+cooling) and readout electronics
  - Beam-induced backgrounds and data throughput
  - Calibration schemes (on-board designs for in-situ): SiPM, crystal, ASIC

Thank you!

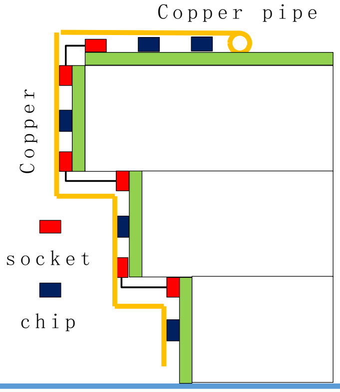
Backup

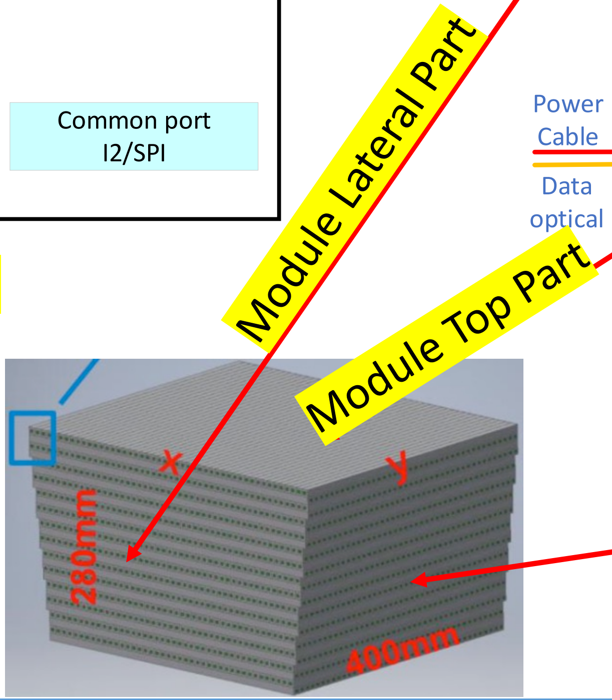
Readout electronics for CEPC ECAL

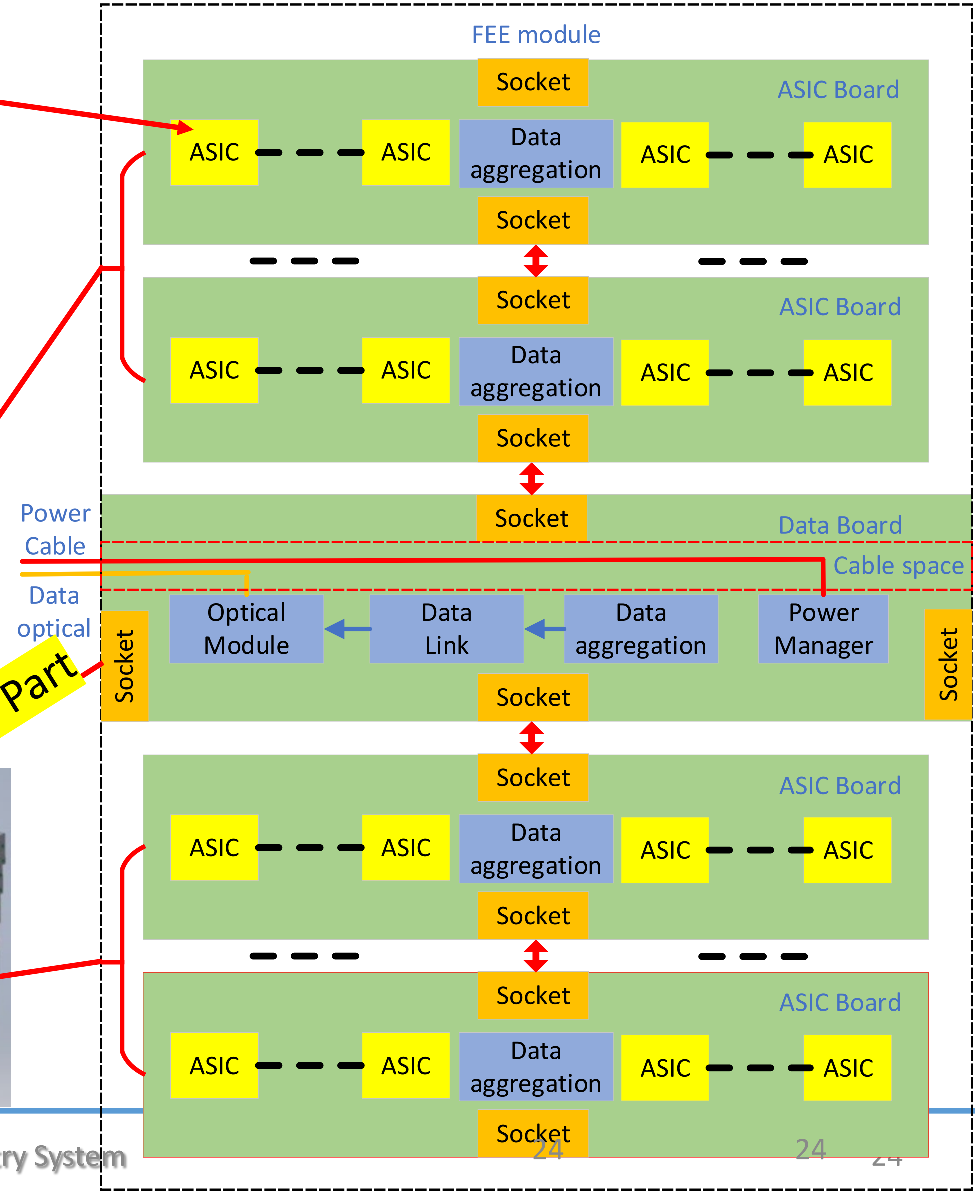


- For different options, FEE module can be one PCB or multiple PCBs
- PCB dimensions: flexible to different options
- 15mW/ch (estimate)

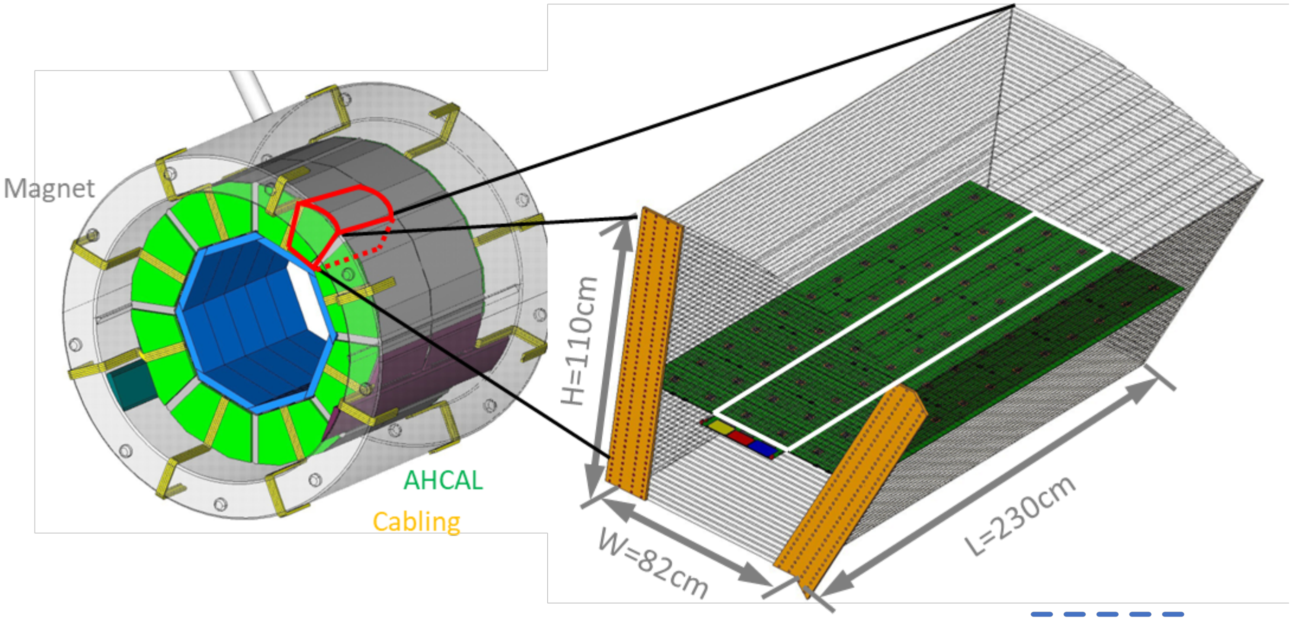
Passive Cooling

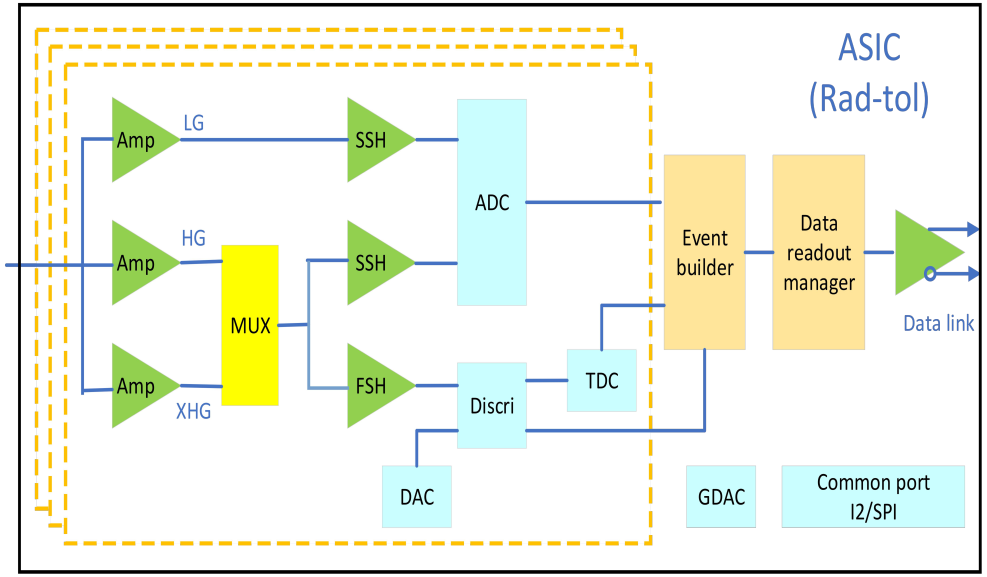


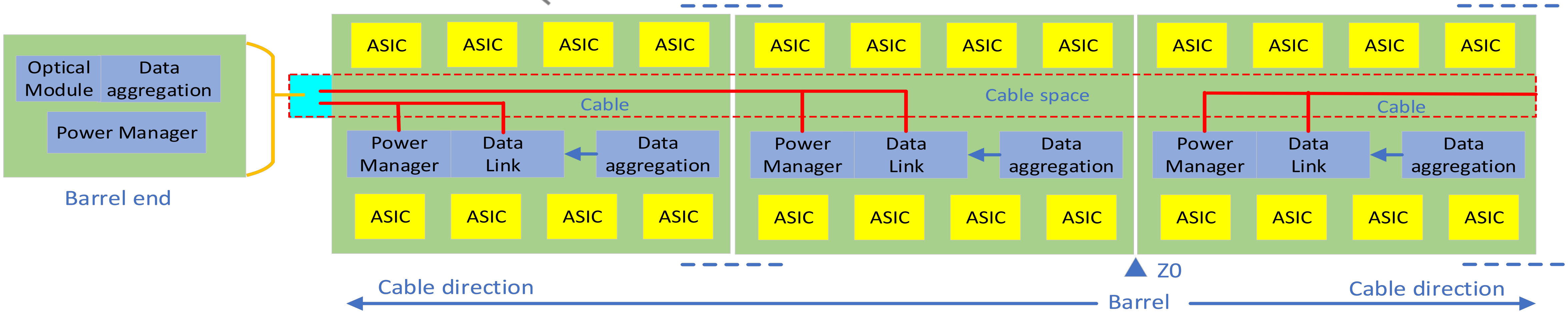


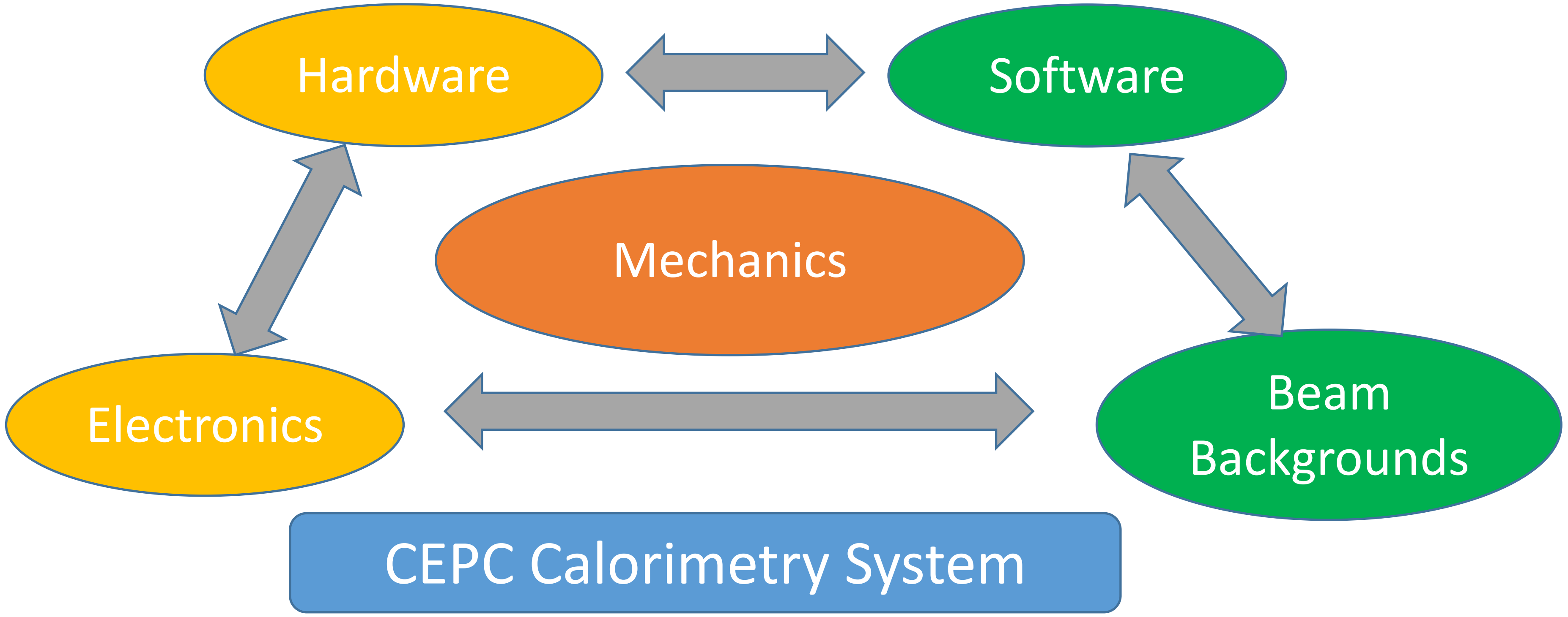


Readout electronics for CEPC HCAL





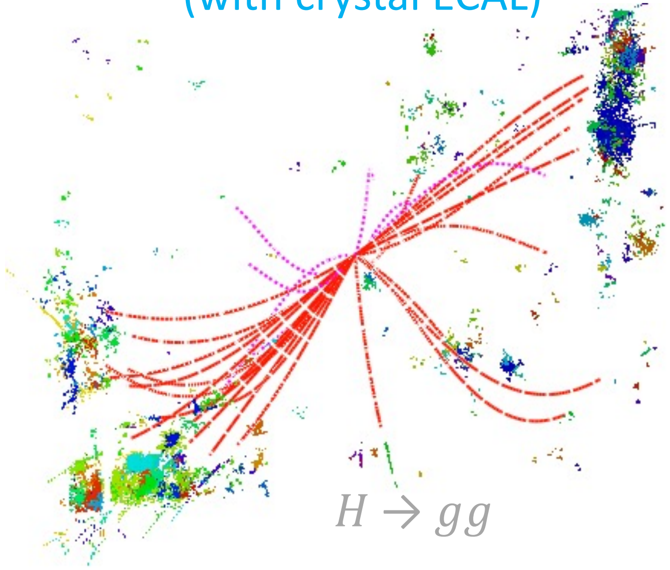



Hardware
Software
Mechanics
Electronics
Beam Backgrounds
CEPC Calorimetry System

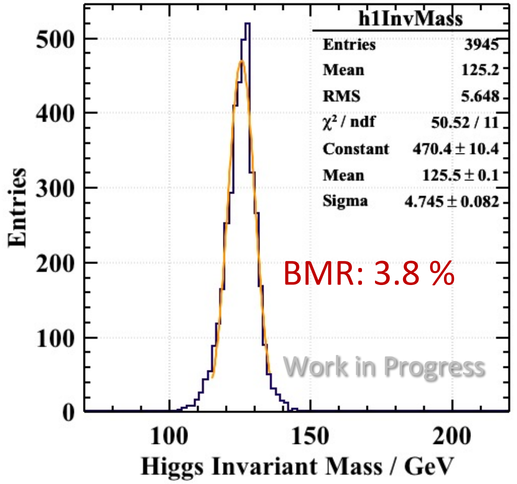
Higgs physics benchmarks

- Physics potentials with crystals
  - Photons and jets
- Boson Mass Resolution (BMR)
  - Jets ($H \rightarrow gg$): 3.8 % → 3.6%
  - Photons ($H \rightarrow \gamma\gamma$): 2.1% → 1.2%

Higgs to 2 gluon jets
(with crystal ECAL)

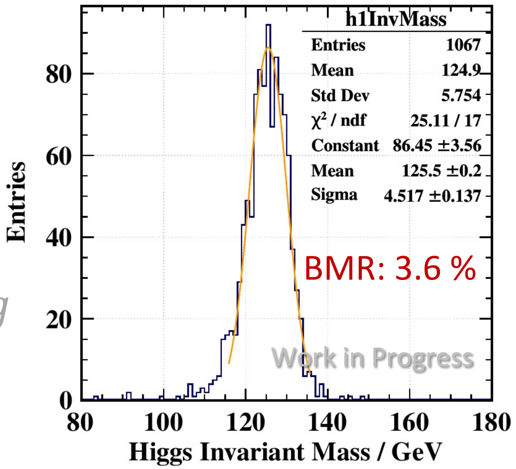


Detector with SiW-ECAL option

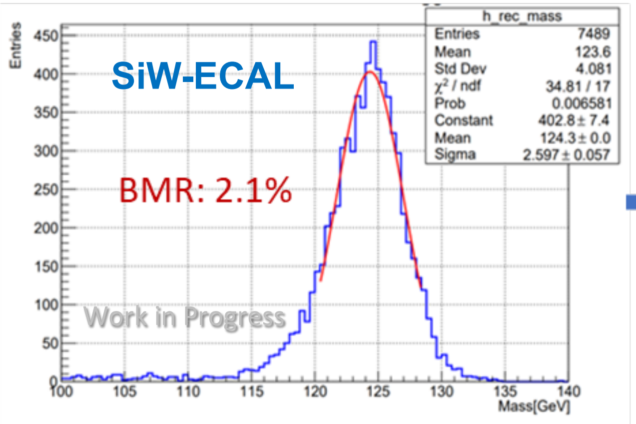


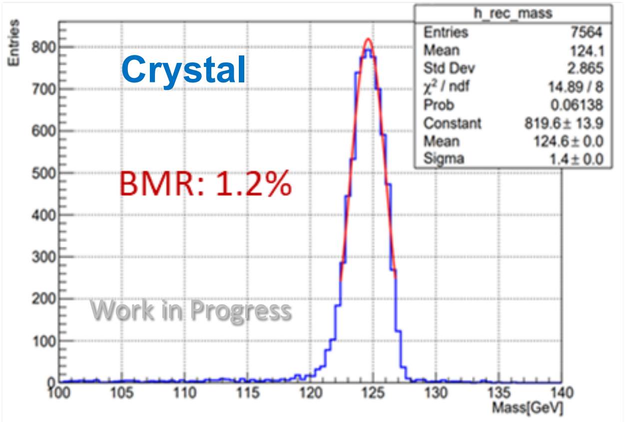
$H \rightarrow gg$

Detector with crystal ECAL option



BMR ($H \rightarrow \gamma\gamma$)



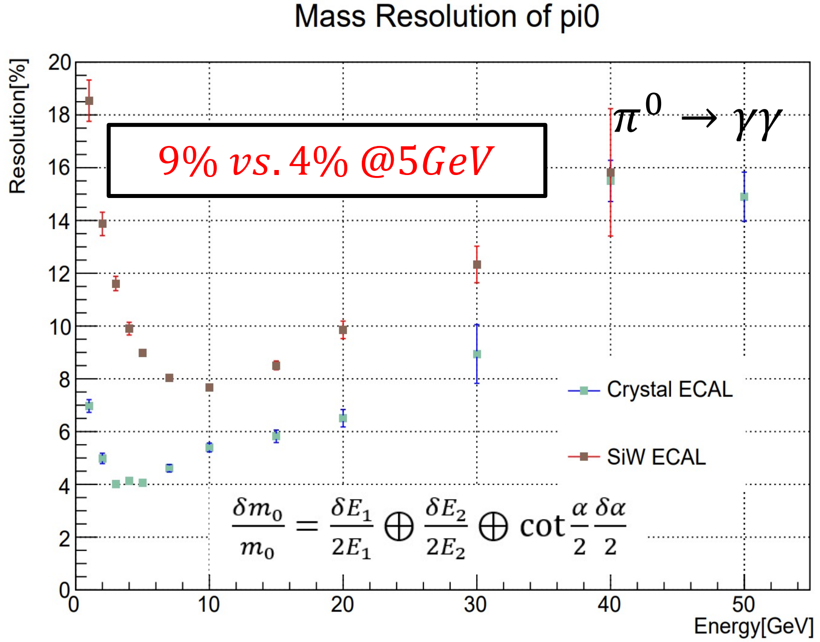


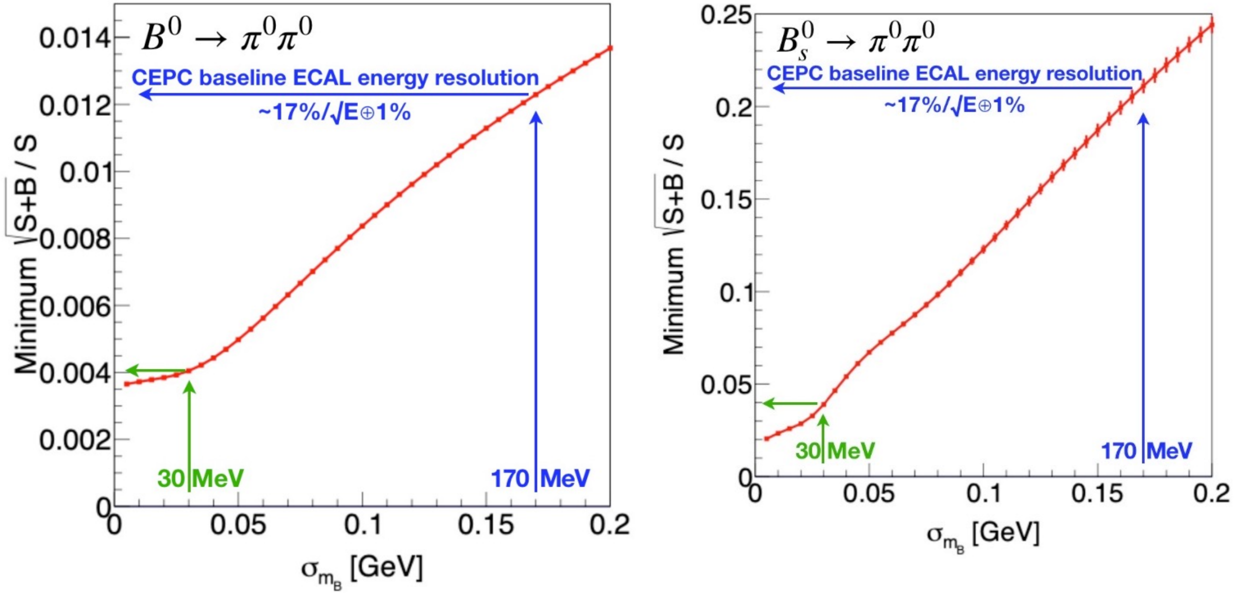
Flavor physics potentials

- Crystal ECAL
  - Higher sensitivity to photons and much better EM resolution
- Potentials for π^0/γ in flavor physics

B0 to pipi @CEPC(CEPC Flavor Physics/New Physics/Detector Technology Workshop, Fudan, 2023), Yuexin Wang

ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
$17\%/\sqrt{E}\oplus 1\%$	170	~ 1.2%	~ 21%
$3\%/\sqrt{E}\oplus 0.3\%$	30	~ 0.4%	~ 4%





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