CEPC Electromagnetic Calorimeter R&D: status and highlights

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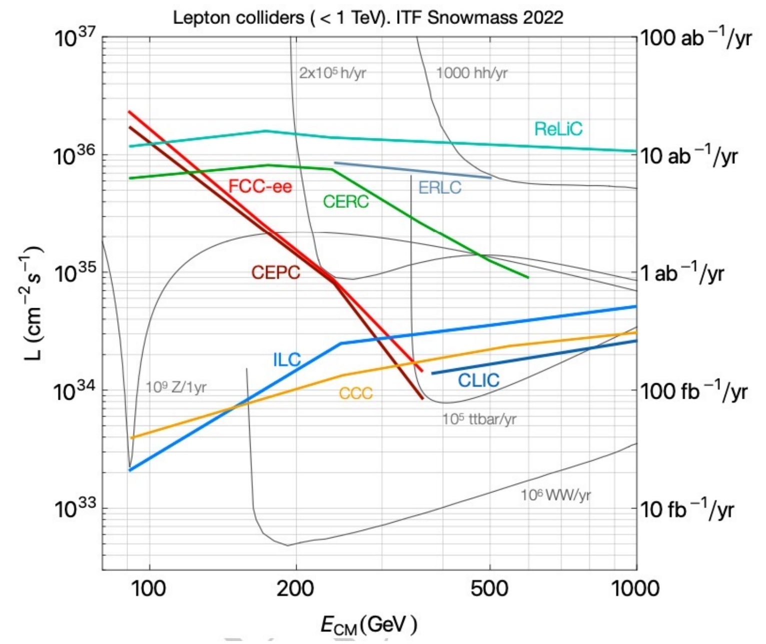
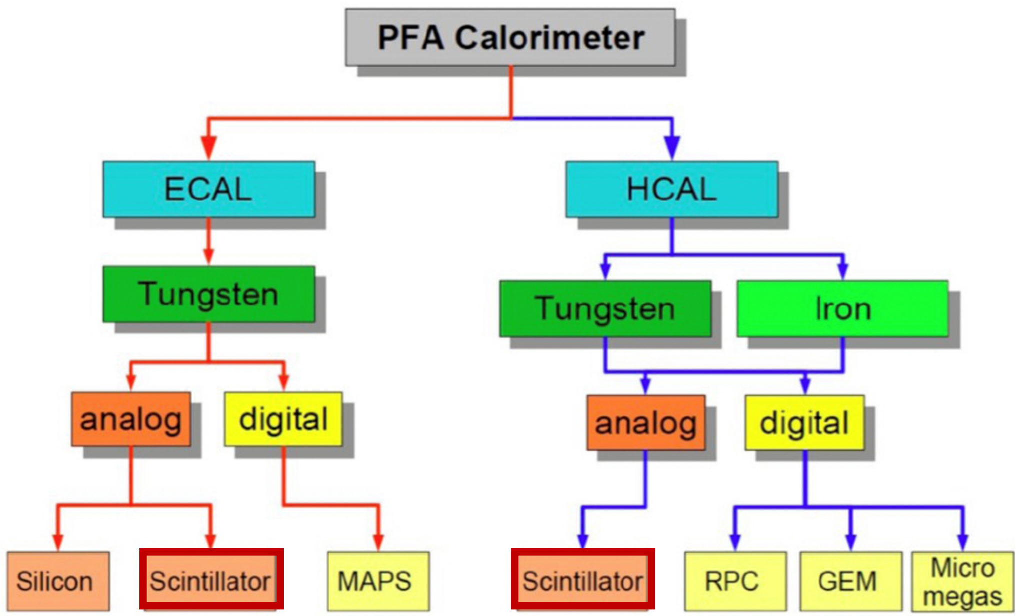
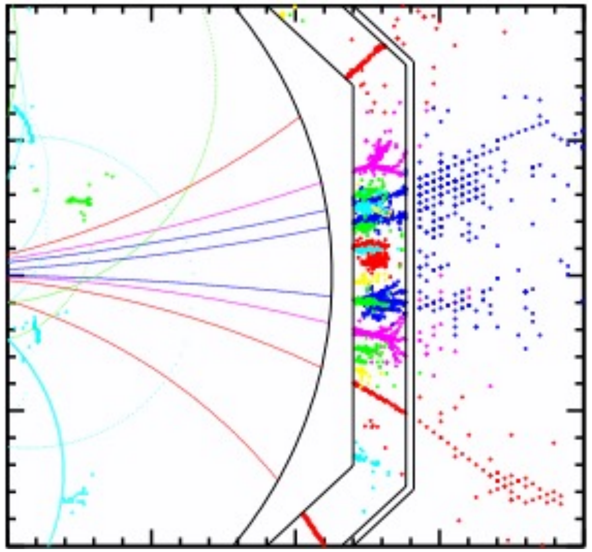
for CALICE/DRD6 and CEPC calorimeter teams

CLHCP2024 in Qingdao, Nov. 14, 2024

High granularity calorimetry



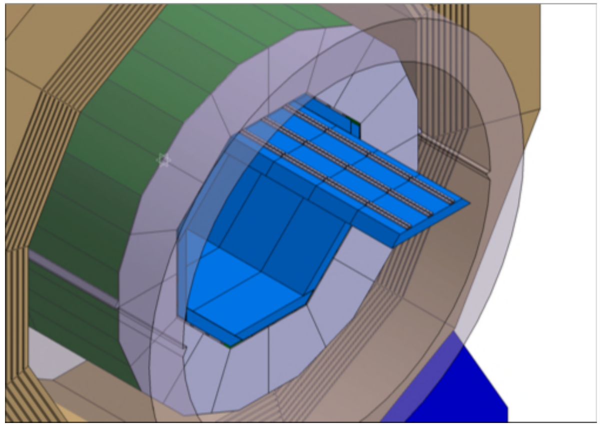


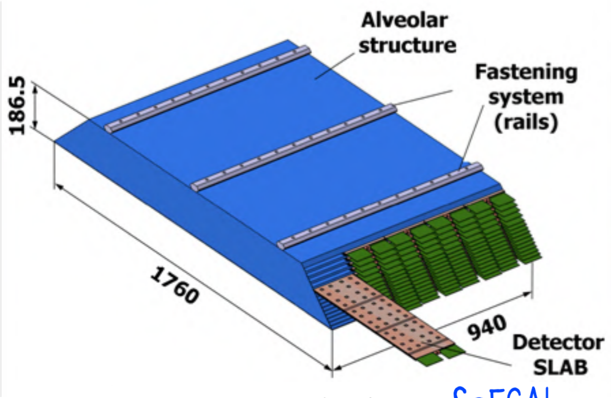


- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
- Focus in this talk: **scintillator-SiPM** ECAL prototype and **new crystal ECAL**

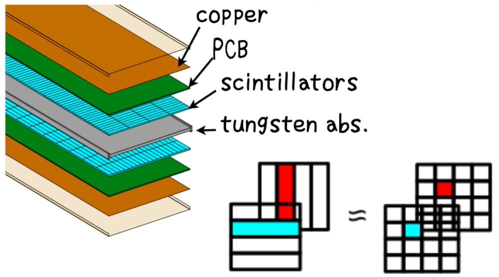
Scintillator-tungsten ECAL in a nutshell

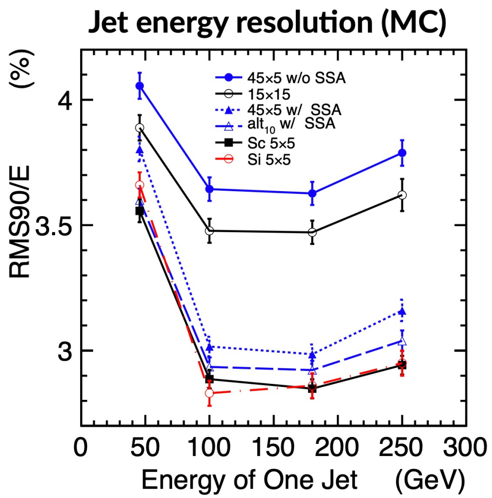
- Scintillator-strip Tungsten ECAL (ScW-ECAL)
  - Technical option for CALICE PFA-oriented high-granularity calorimeter
  - Scintillator strip (45mm×5mm×2mm) read out by SiPM
  - Effective segmentation of 5×5mm² by strips aligned alternately in horizontal and vertical orientations
- Significant reduction of readout channels($10^8 \rightarrow 10^7$) retaining performance
  - Cost reduction
  - Power consumption reduction→ advantageous especially for CEPC



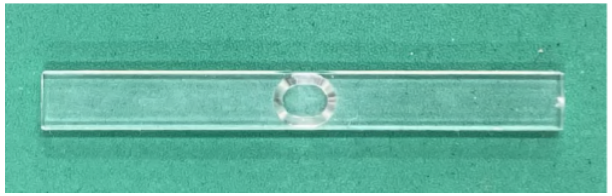


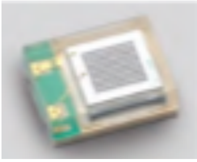
ScECAL





Scintillator strip (45mm×5mm×2mm)



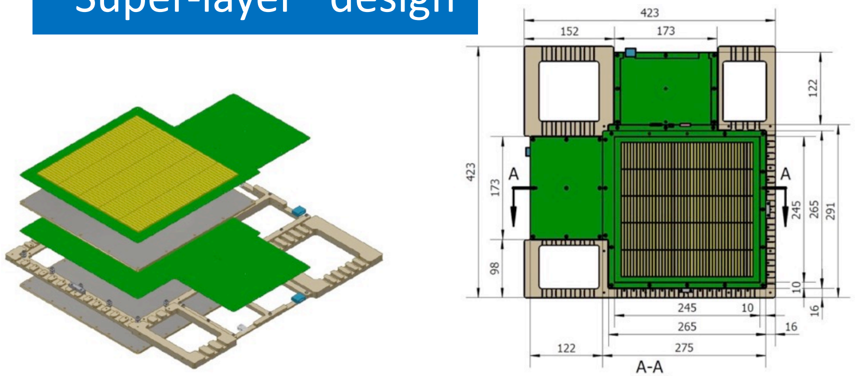


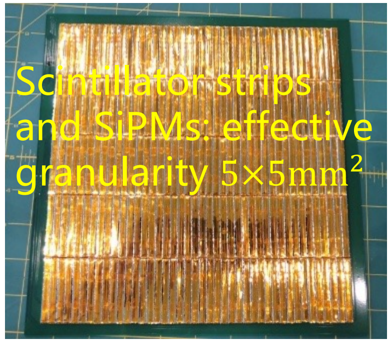
SMD-SiPM in cavity

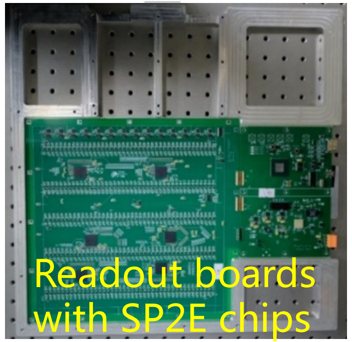
Scintillator-tungsten ECAL prototype

ScW-ECAL tech. prototype

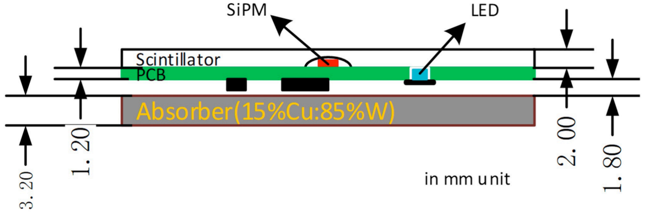
"Super-layer" design



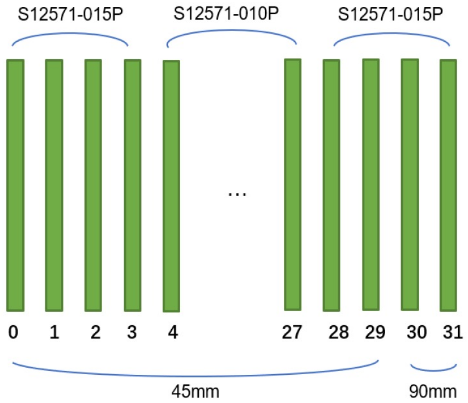




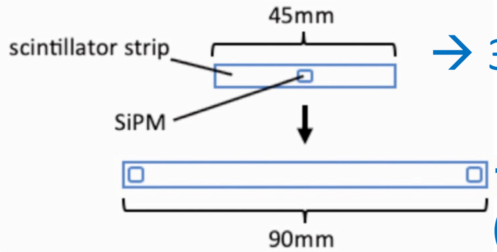
Scintillator-SiPM readout scheme



Sensitive layer arrangements



- ScW-ECAL prototype: developed in 2016-2020
  - Transverse area of ~22x22 cm, 32 longitudinal sampling layers
  - 6,720 channels, ~350 kg, SPIROC2E (192 chips)
- Beamtest campaigns at CERN in 2022-2023
  - Along with CEPC-AHCAL prototype



→ 30 sampling layers

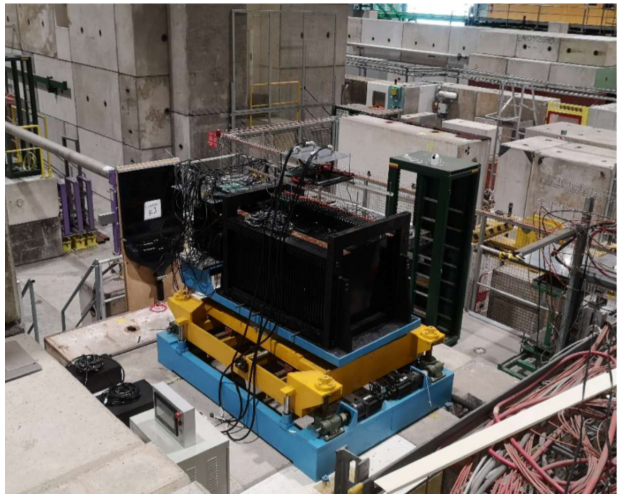
→ 2 sampling layers (in the rear part)

CERN beamtests in 2022-2023

Oct 19 – Nov 2, 2022 — SPS H8 beamline

Apr 26 – May 10, 2023 — SPS H2 beamline

May 17 – 31, 2023 — PS T9 beamline

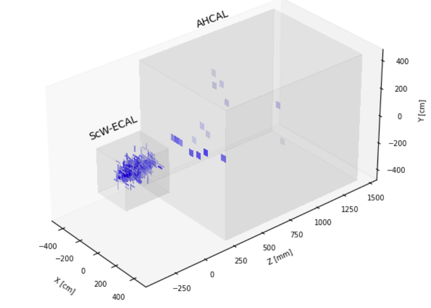


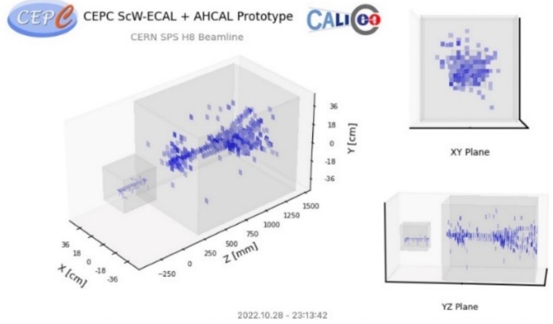
- Successful beamtest campaigns
  - Two prototypes (ScW-ECAL and AHCAL)
  - Both mounted on a motorised stage (XYZ+U)
  - Impressions: a few cubic meters and ~10 tons

CERN beamtests in 2022-2023

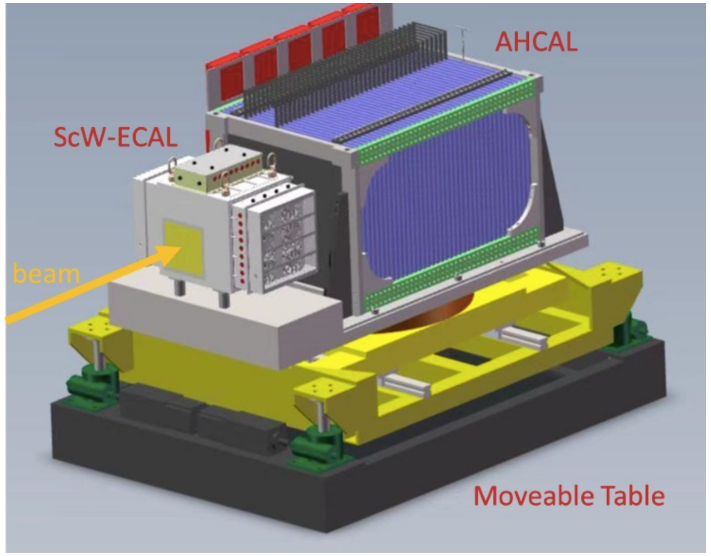
Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline

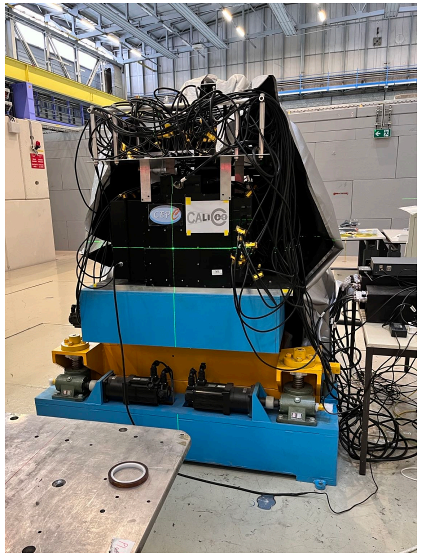
- Collected decent statistics of testbeam data samples
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS (also up to 250 GeV)
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS





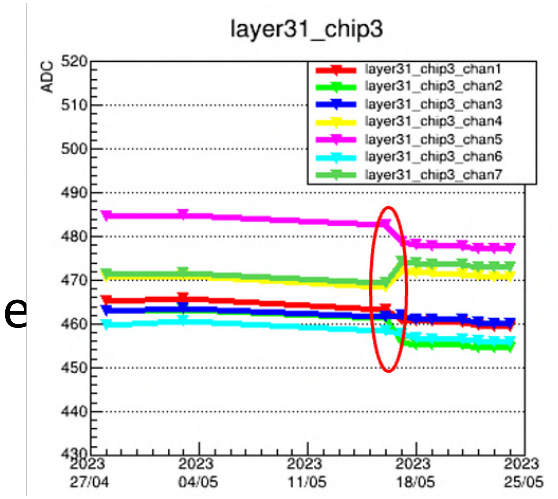
Overlapped energy points (10-15 GeV) at PS and SPS

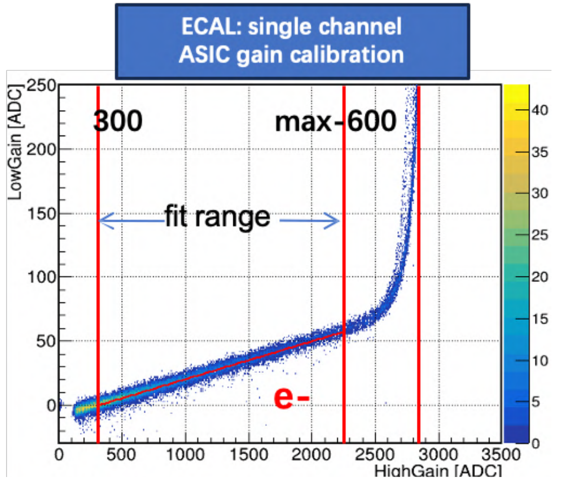


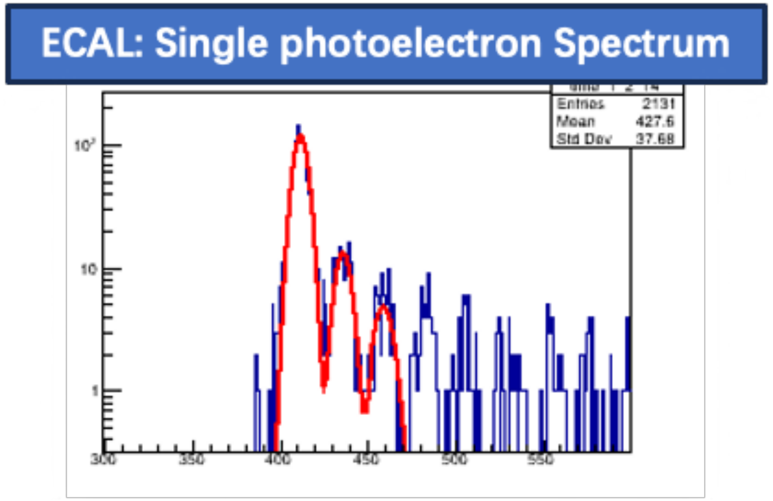


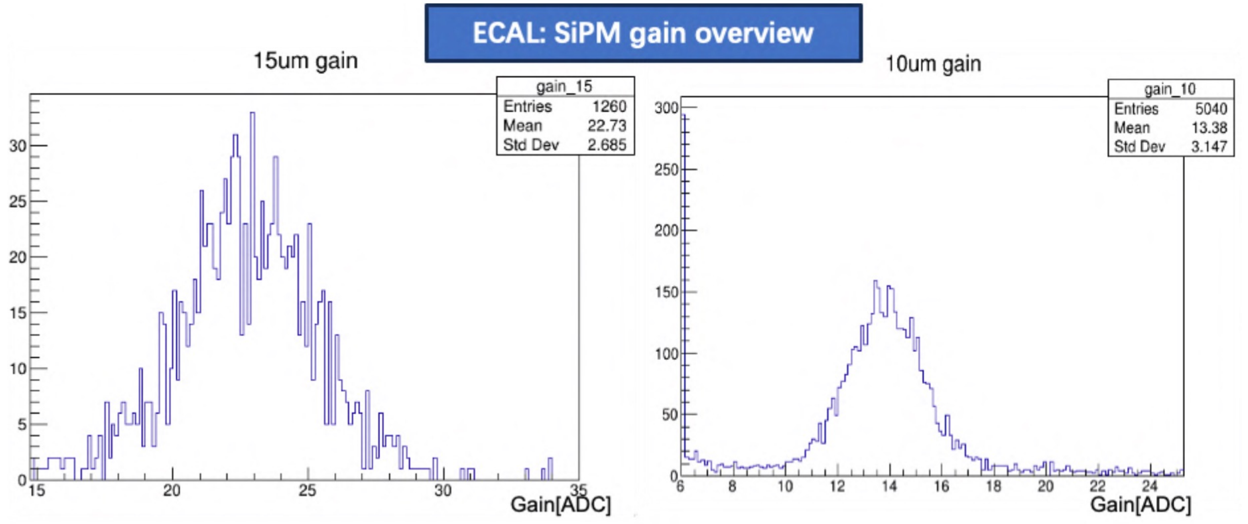
ScW-ECAL: calibration in beamtests

- Pedestal calibration
  - Stable pedestal during beam tests.
- ASIC gain calibration (SPIROC2E)
  - Large dynamic range with high-gain/low-gain mode
  - Inter-calibration btw high-gain/low-gain
- SiPM gain calibration
  - SiPM gain calibration with LED data





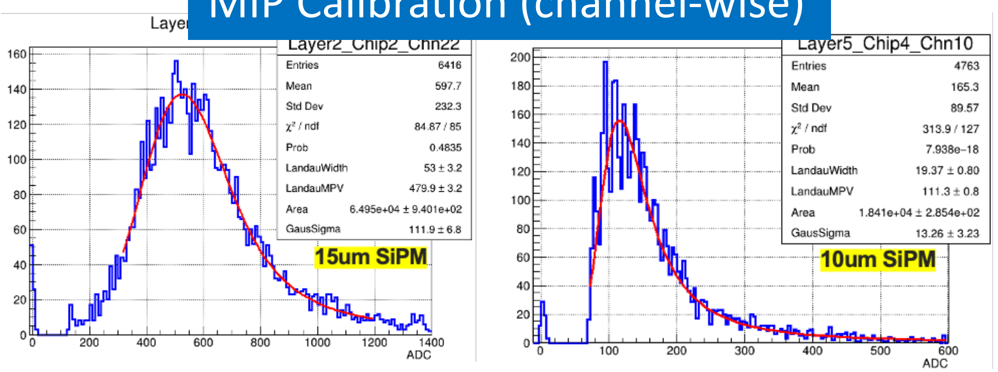




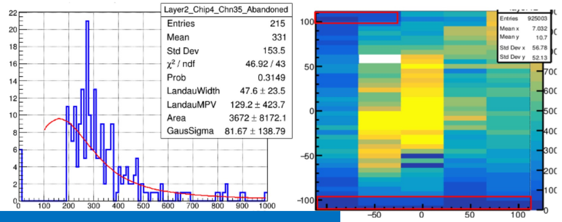
ScW-ECAL: beamtest data analysis

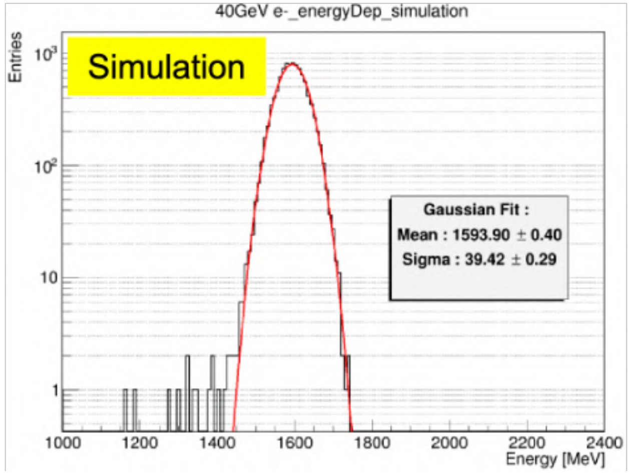
- MIP calibration
  - Position scans with 106GeV muon for all channels
  - Excluding noise hits especially for 10um SiPM with muon track fit
  - Not well calibrated for 30% of channels (10um)
- Comparison between data and simulation
  - Need to understand discrepancy in data/MC

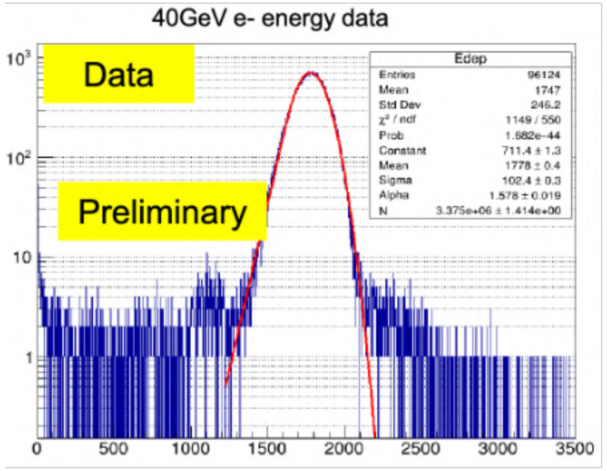
MIP Calibration (channel-wise)



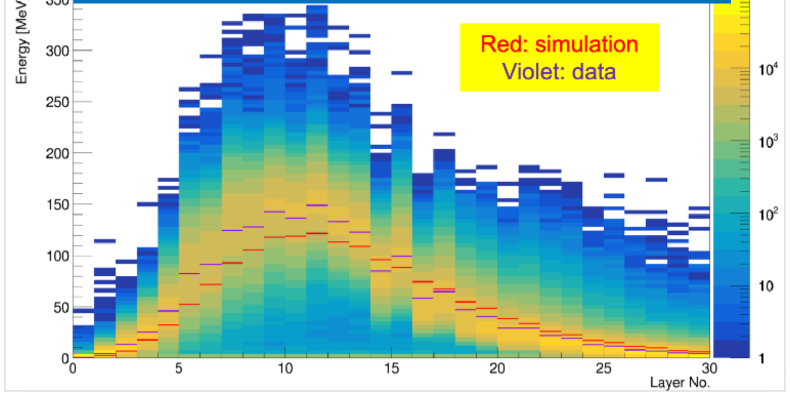
Inadequate statistics on edge channels



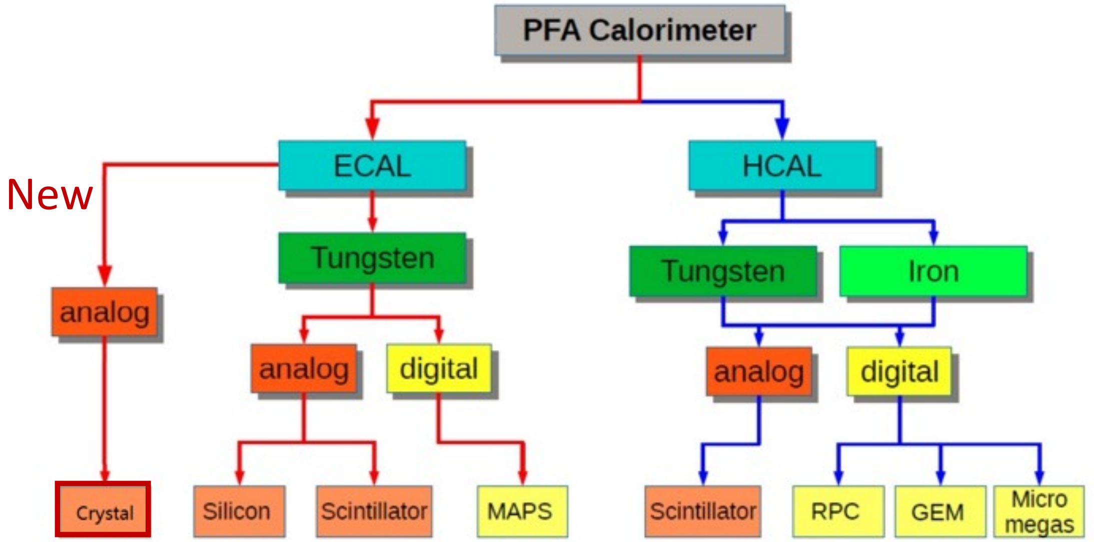




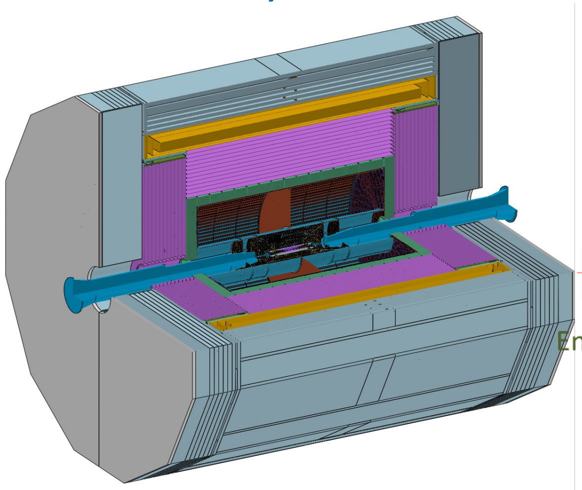
EM Shower Longitudinal Profile



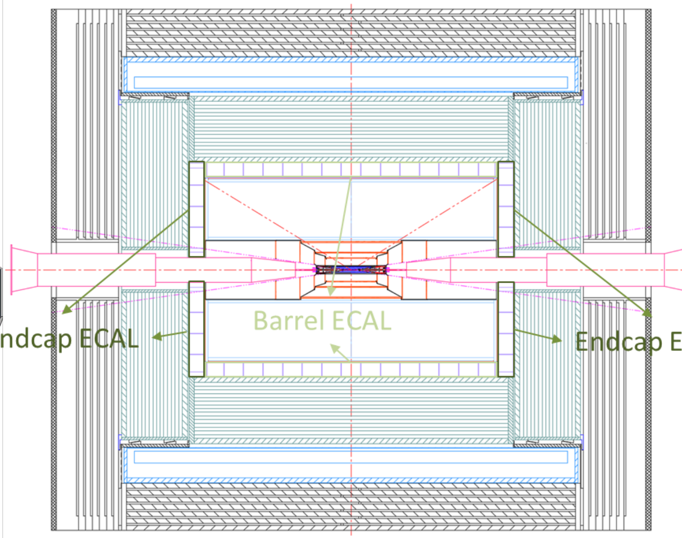
Crystal ECAL: compatible with PFA

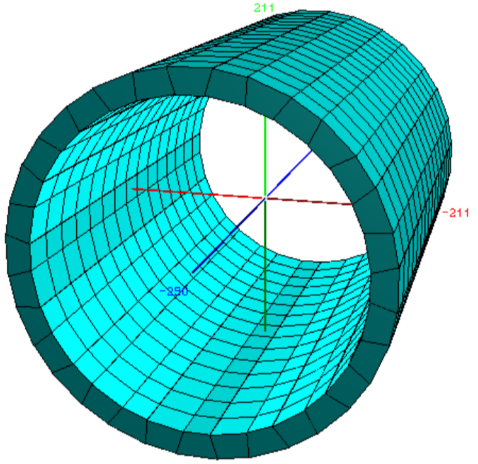


Calorimetry system in CEPC Reference Detector: crystal ECAL and ScintGlass HCAL

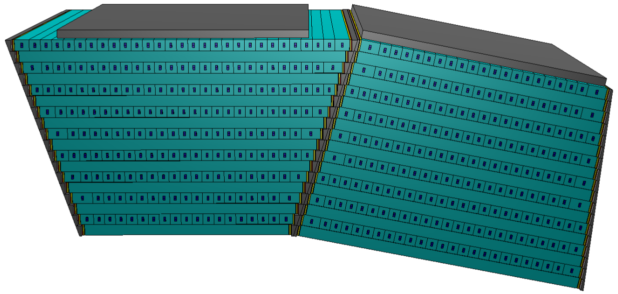


Barrel Crystal ECAL





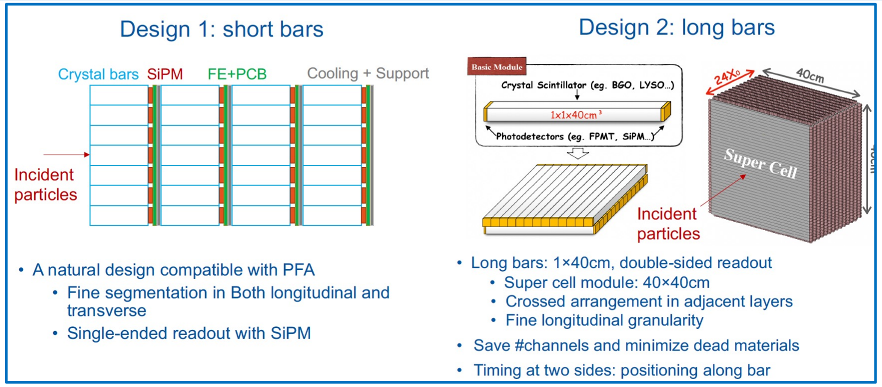
Crystal ECAL: Barrel Modules



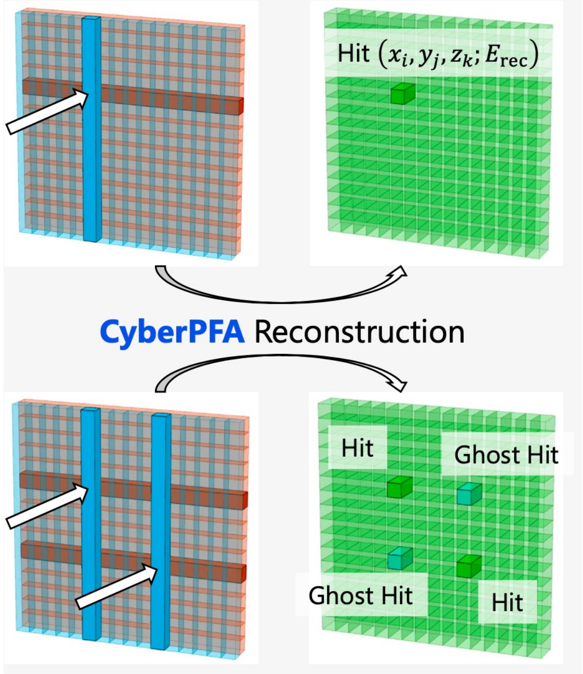
- CEPC reference detector design
- New electromagnetic calorimeter
  - Crystal ECAL with high-granularity for PFA
  - To achieve optimal EM energy resolution

High-Granularity Crystal Calorimeter (HGCCAL)

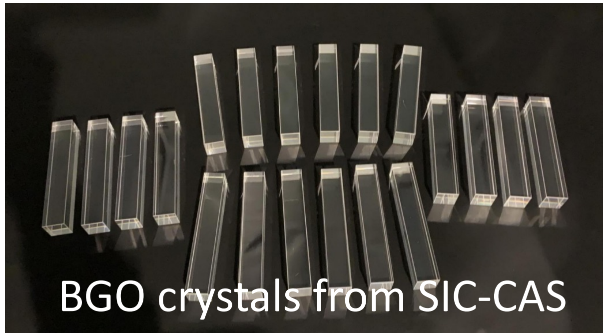
- HGCCAL proposed for future Higgs e^+e^- factories
  - Optimal EM resolution: $2\sim3\%/\sqrt{E}$
  - Fine segmentations for particle-flow algorithm
- Two designs and features
  - Short crystals: naturally compatible with PFA
  - Long crystals (major focus): minimize dead materials between longitudinal layers and readout channels
- Challenges
  - Integration: light-weighted materials of *mechanics*, *cooling* and *readout boards*
  - Pattern recognition: how to resolve ambiguities
  - Readout scheme
    - Large dynamic range for SiPM + ASIC
    - Front-end ASIC: low-power (millions of channels), continuous readout (high rate at circular colliders)

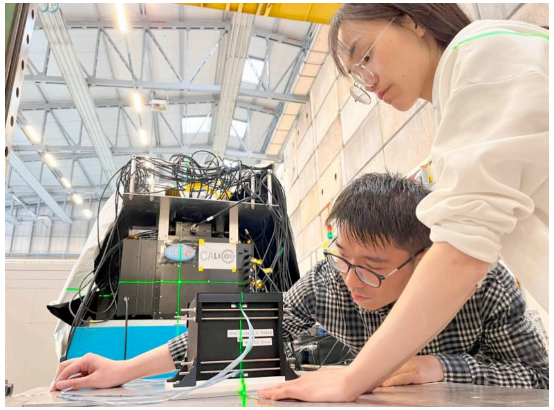


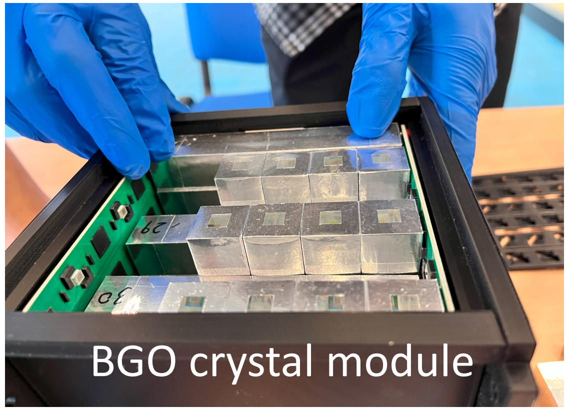
DRD6: Calorimetry (CERN-DRDC-2024-004)

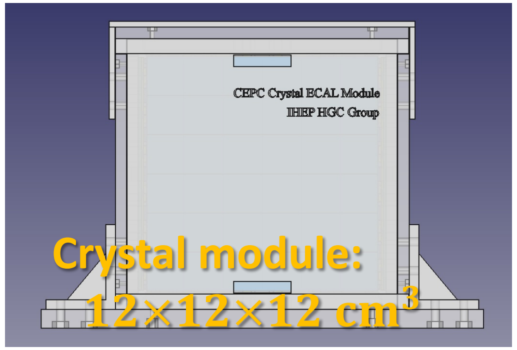


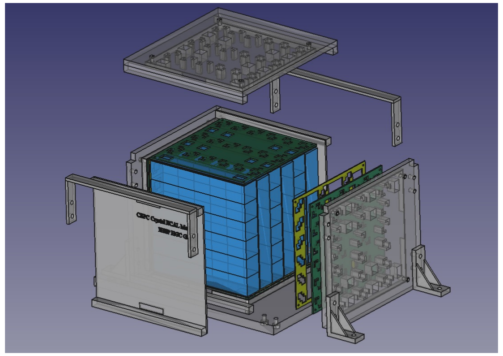
Crystal module in 2023 CERN beamtest

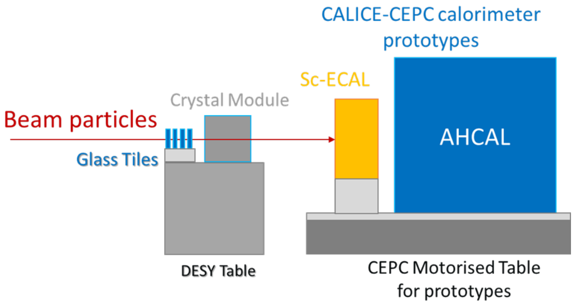


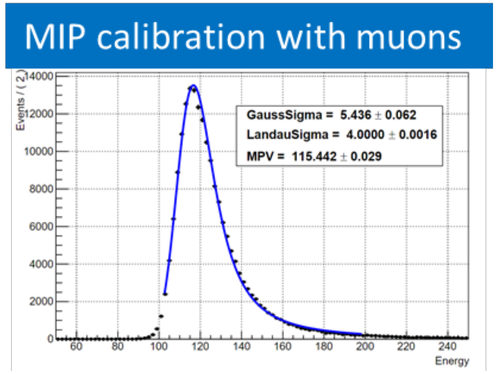








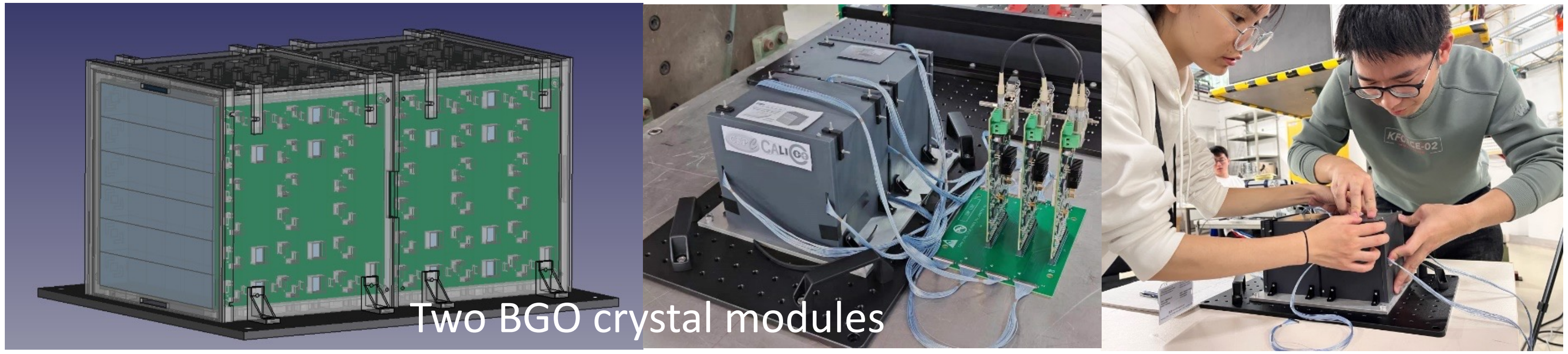




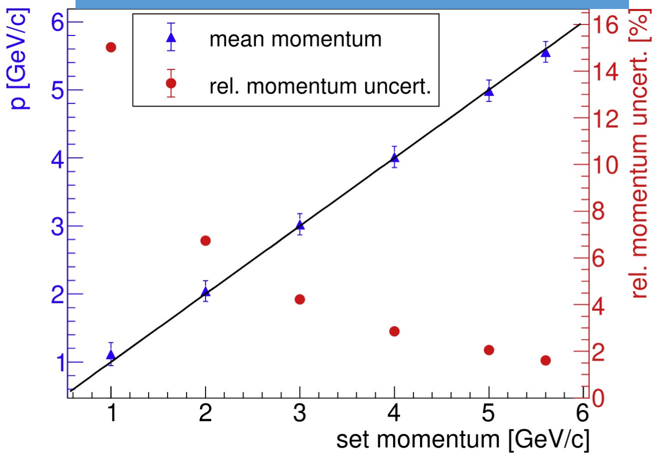
- Successfully developed the first HGCCAL *module*
  - Tested in parasitic runs with CALICE scintillator calorimeter prototypes at CERN PS-T09
- Data taking with muons and electrons
  - Successful commissioning for all 72 channels, scans of ASIC parameters (shaping time, threshold, …)

Crystal modules: 2023 DESY beamtest

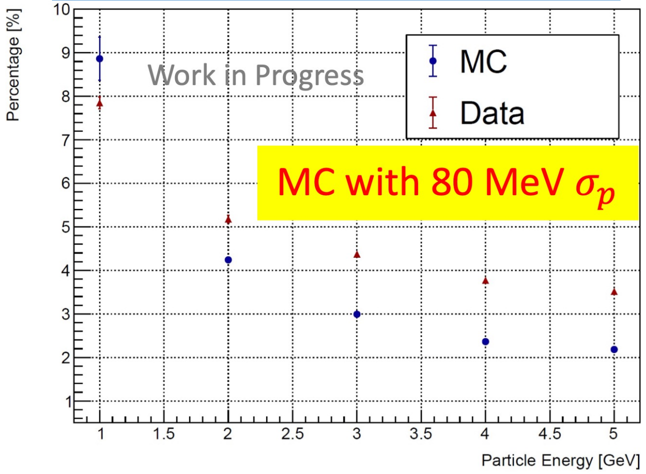
The DESY II test beam facility



Beam momentum spread: measurement at TB21



EM resolution: data vs. MC

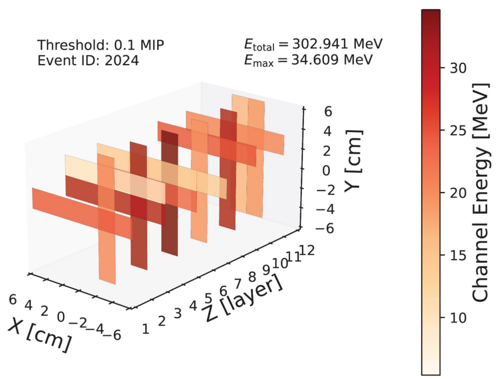


- Crystal calorimeter modules ($21X_0$)
- DESY beamtest: electron beam (1-6 GeV) at TB22 beamline
  - Motivations: system integration, EM shower performance
  - EM Performance: dominated by TB22 beam momentum spread
  - DESY beamline momentum spreads
    - TB21: measured with dipole magnet and beam telescope **~16% (at 1GeV)**
    - **TB22: no direct measurements**, expected at ~8% at 1 GeV from our testbeam data; but spread seems not to follow 1/p function as in TB21

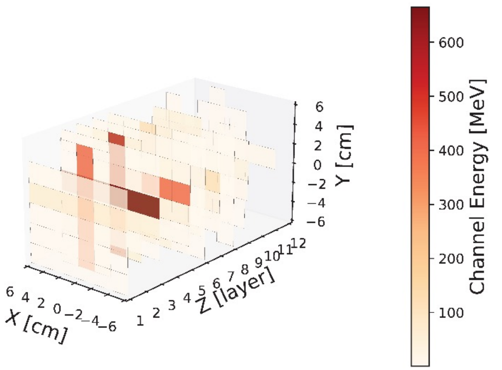
Crystal modules: 2024 CERN beamtest

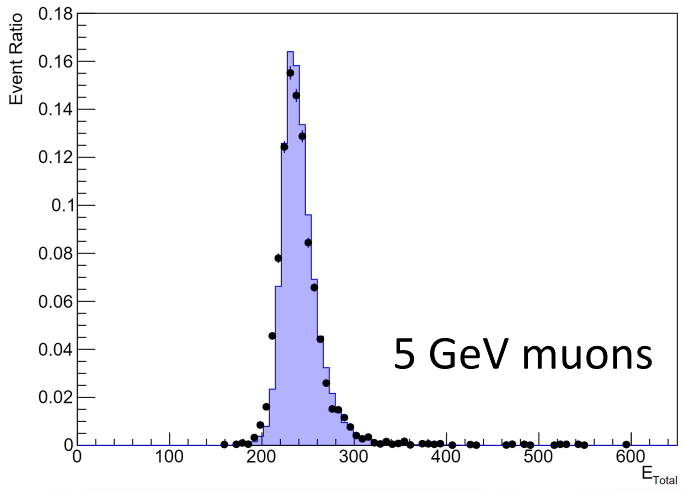
- 2 weeks at PS-T9: data taking with muon and electron beams
  - MIP calibration (5 GeV muons), EM performance (1– 10 GeV electrons)
  - Extensive studies on detector calibration, simulation digitisation, beam momentum

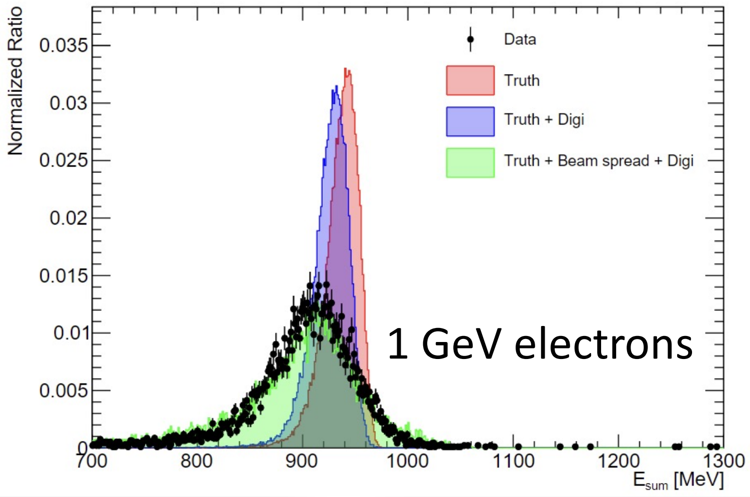
5 GeV μ^-

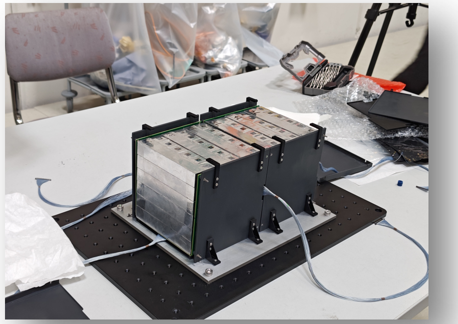


3 GeV e^- (0.1 MIP Threshold)

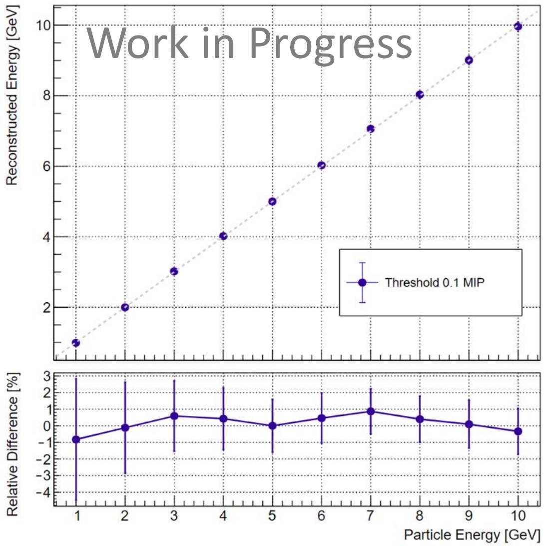


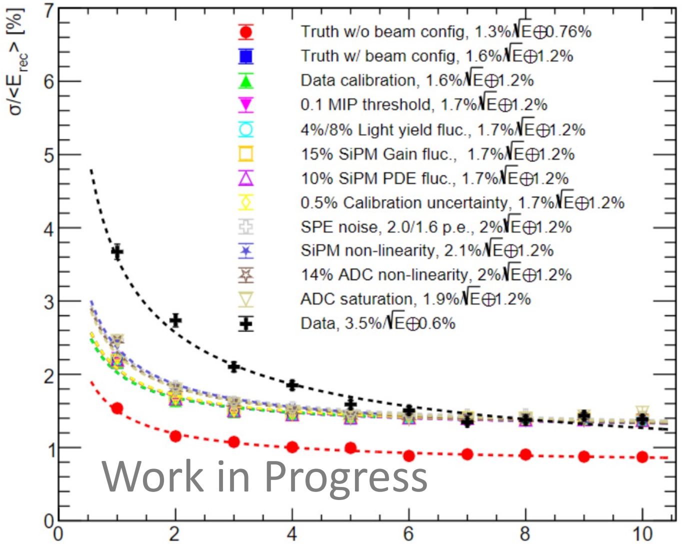






Crystal Calorimeter Prototype: EM performance

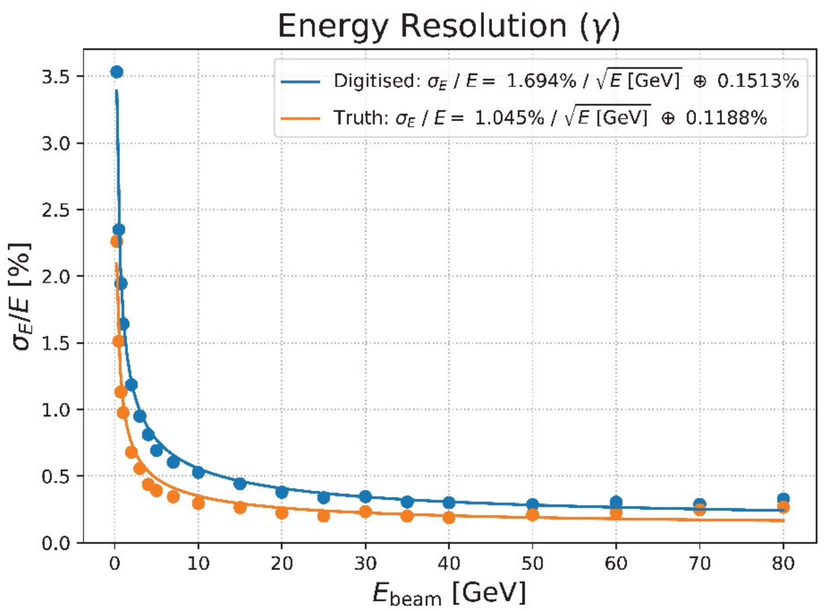


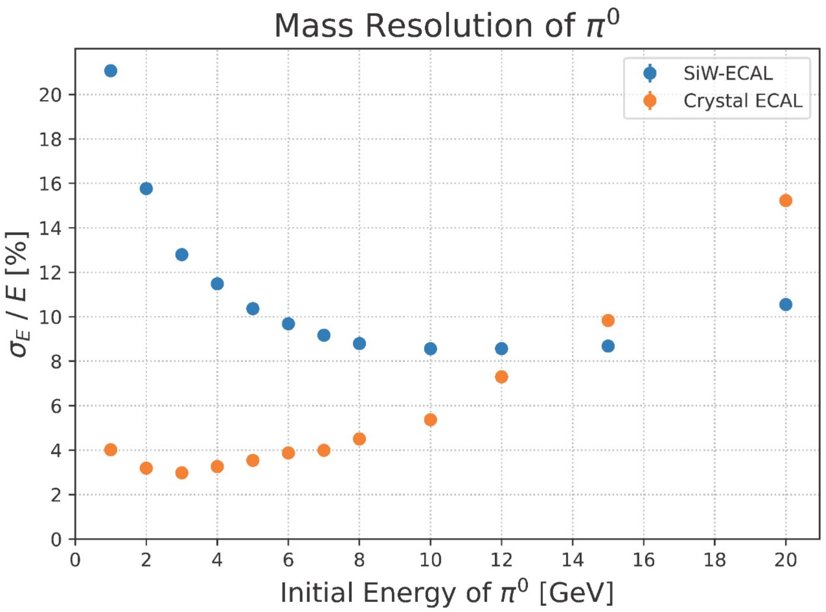


- Studies based on electron data in 1 – 10 GeV
  - Data taken with *ALL beam instrumentation* in upstream: Cherenkov detectors (XCET), SciFi trackers (beam profilers)
- EM response linearity within $\pm 1\%$
  - Better understanding of calibration precision (~0.5%) and corrections of crosstalk in ASIC 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
  - Preliminary EM performance after excluding beam momentum spread: $< 2\%/\sqrt{E} \oplus 1\%$

Crystal ECAL: EM performance in simulation

- Singe photon: EM resolution
  - <2% EM resolution with Geant4 simulation + digitisation
  - Ongoing studies to further improve digitisation, by including more realistic factors
- Neutral pions: mass resolution
  - Crystal ECAL shows better performance at lower energies (<15 GeV)

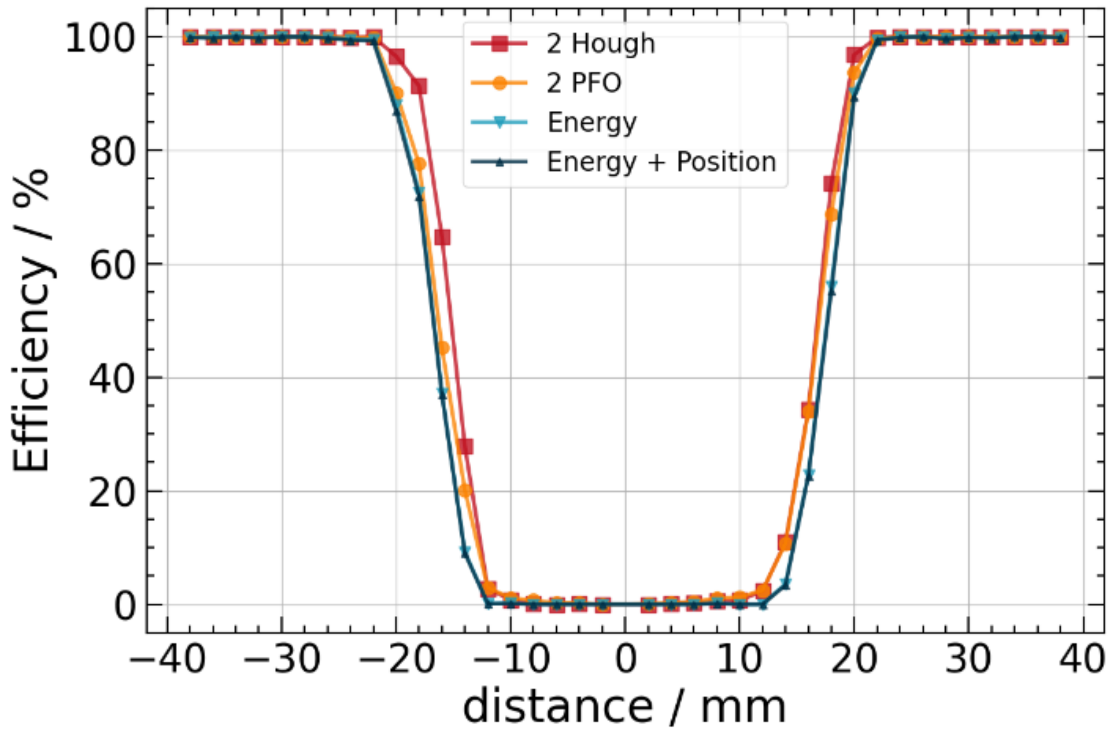




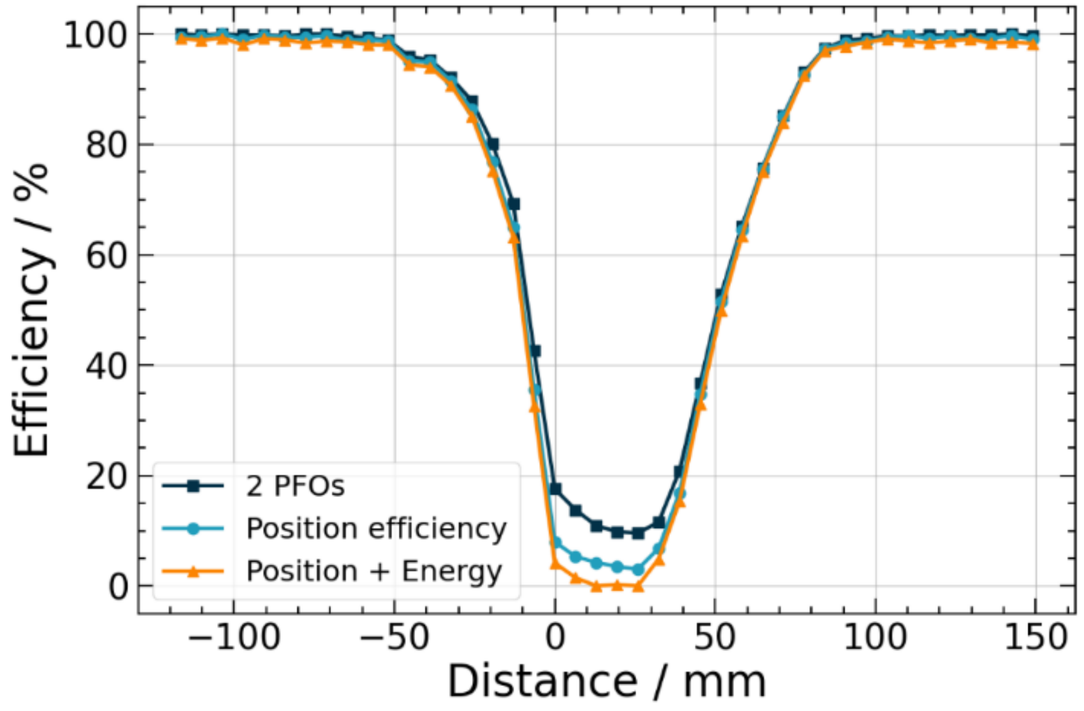
Crystal ECAL: two-particle separation power

- New PFA reconstruction software for the long-bar design
  - Integrated in CEPCSW to evaluate separation power, which is crucial to PFA performance
  - Preliminary results look quite promising

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



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



Summary and prospects

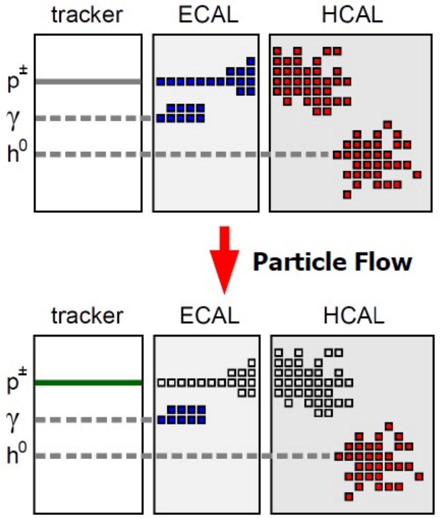
- Scintillator-Tungsten Calorimeter
  - Technological prototype successfully developed during 2016 - 2021
  - Smooth beam test campaigns at CERN PS/SPS during 2022-2023
  - Collected sufficient statistics of data samples in a wide energy range
    - Detector performance evaluation and shower studies
- High-Granularity Crystal Calorimeter
  - A novel calorimeter design, as the baseline option for CEPC reference detector
  - Aim for compatibility with PFA and optimal EM performance
  - Steady progress in several aspects: simulation, reconstruction and prototyping
- Preliminary results look promising and encouraging
  - More detailed studies are also ongoing
- International collaborations: previously CALICE and now DRD6

Thank you!

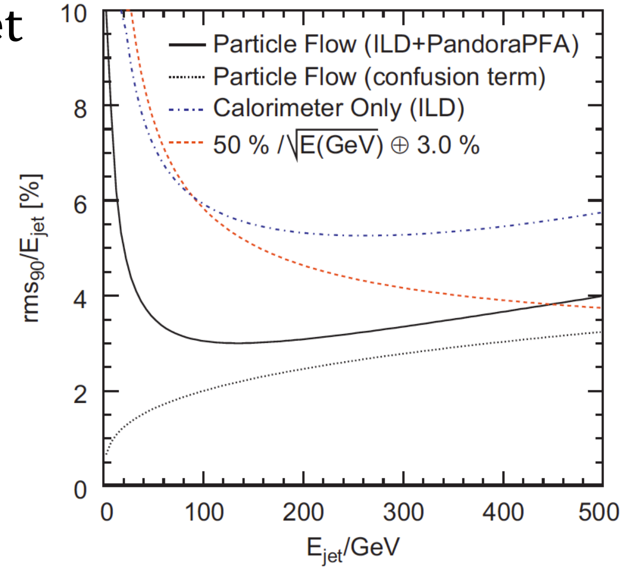
Backup

Particle-flow algorithm

Components in jets	Sub-Detectors	Energy fraction (average) within a jet	Detector Resolution
charged particles ($X^{\pm}$)	Tracker	$60\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$30\%\ E_j$	$0.15\ \sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$10\%\ E_j$	$0.55\ \sqrt{E_h}$

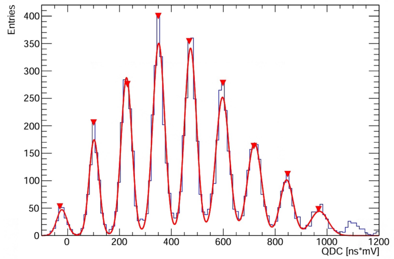


- Particle Flow Algorithm (PFA)
  - To achieve unprecedented jet energy resolution of $\sim 30\%/\sqrt{\mathrm{E_{jet}}}$
  - (Reminder: multiple particles within a jet)
  - **Choose a sub-detector best suited for each particle type**
  - Charged particles measured in tracker
  - Photons in ECAL and neutral hadrons in HCAL
- Separation of close-by particles in the calorimeters
- PFA-oriented calorimeters: high granularity (1~10 million channels)



Simulation and digitisation

- Geant4 simulation including detailed geometry of ScW-ECAL and AHCAL prototypes
- Digitisation: energy depositions (Geant4) → digits in ADC
  - Same technology: scintillator-SiPM and ASIC in two prototypes
  - Procedure implemented for each readout channel



Geant4 hits: Energy deposition → Scintillator-SiPM: detected photons → SiPM non-linearity → SiPM: p.e. conversion to ADC

MC truth

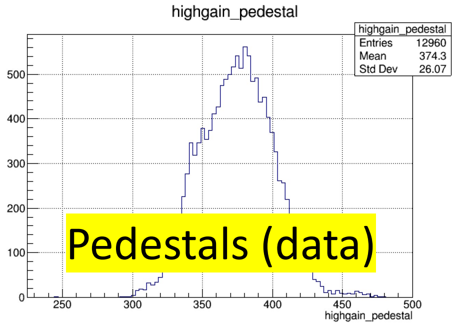
Poisson Distribution based on muon data

SiPM saturation curve from measurements

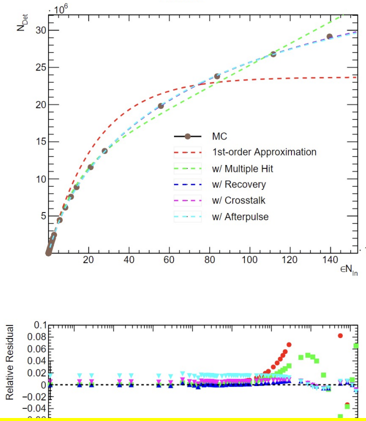
SiPM gain calibration from LED data

Pedestals (Electronics)

Extracted from data

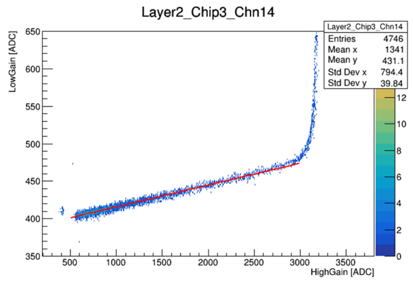


Pedestals (data)



SiPM saturation (data)

ASIC HG-LG ADC (data)



ASIC: ADC in High Gain or Low Gain

SPIROC2E HG-LG slope extracted from beam data

Key: digitisation is fully based on calibration data