CEPC Electromagnetic Calorimetry: R&D activities and highlights

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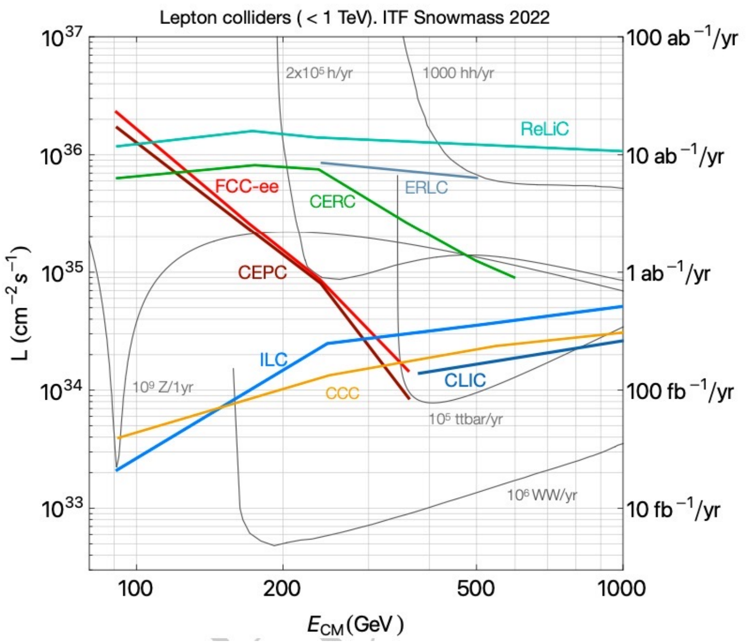
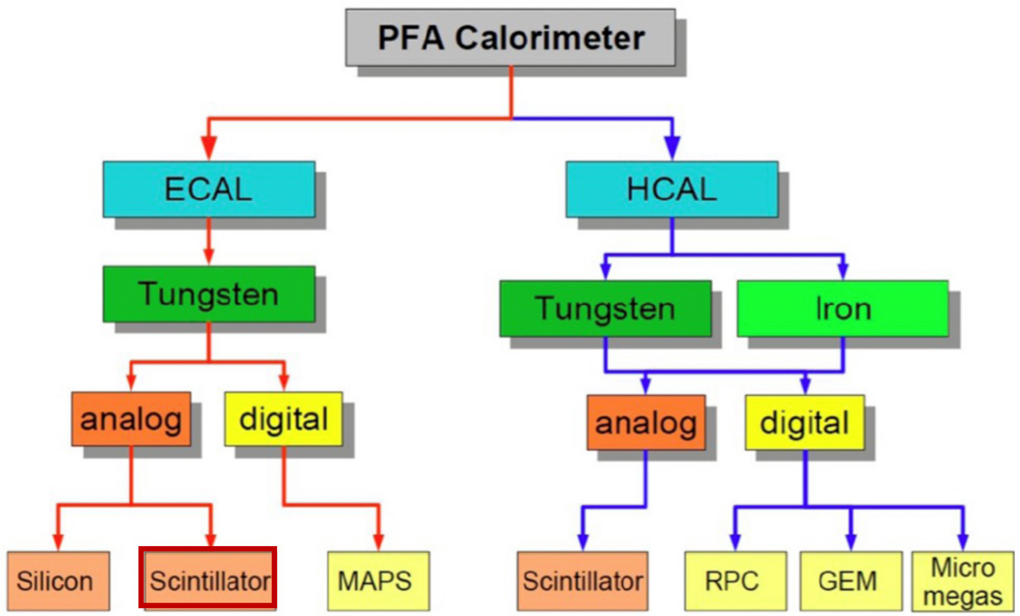
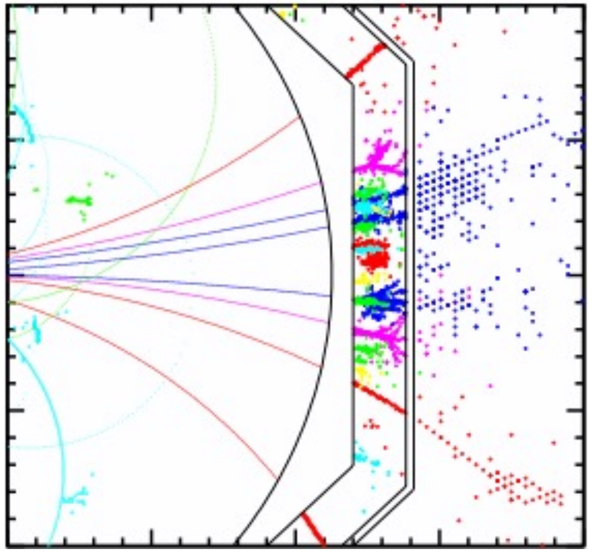
July 2, 2026

High granularity calorimetry







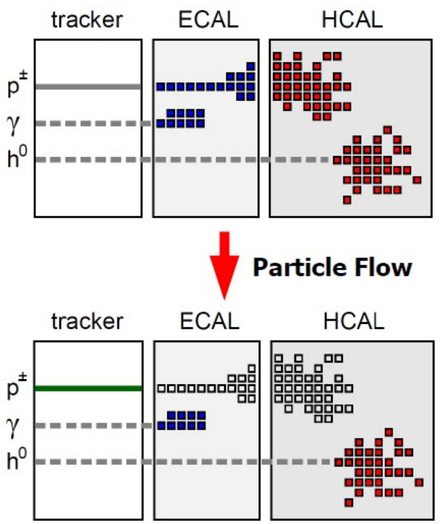
- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry solution: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: options explored in CALICE/DRD-Calo collaborations
- Scintillator-Tungsten ECAL and high-granularity crystal calorimeter (major focus)

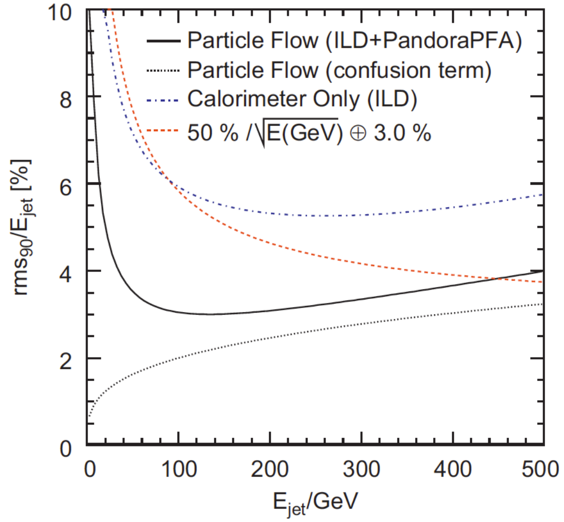
Particle-flow paradigm

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
  - To achieve unprecedented jet energy resolution of $\sim 30\%/\sqrt{\mathrm{E_{jet}}}$
  - **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
  - **Matching** of charged tracks and clusters; **merging** neutral clusters
- PFA-oriented calorimeters: **high granularity** (1-10 million channels)

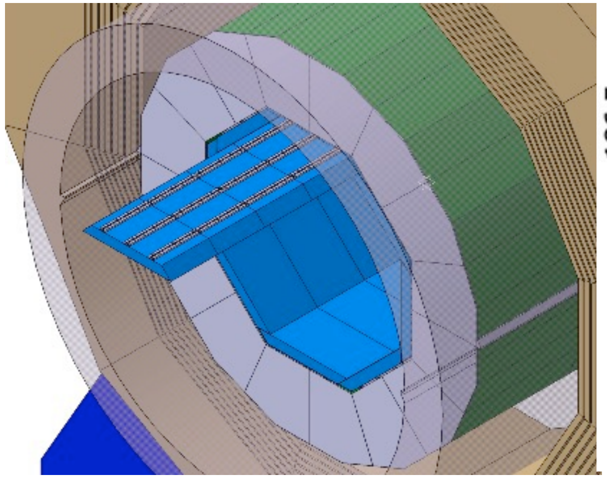
Multiple particles in a jet

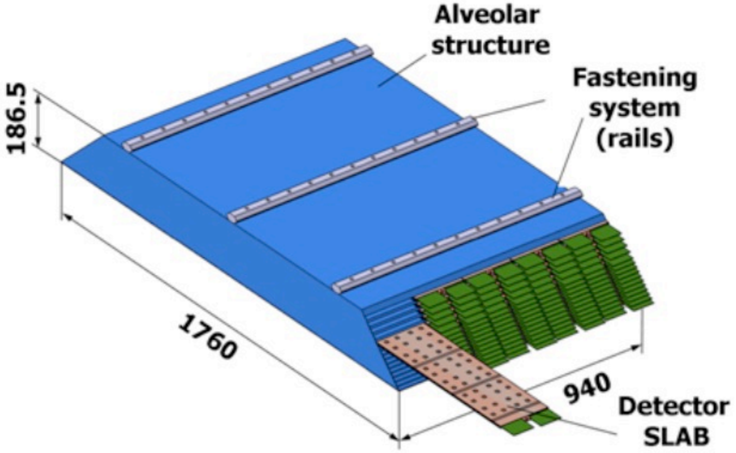


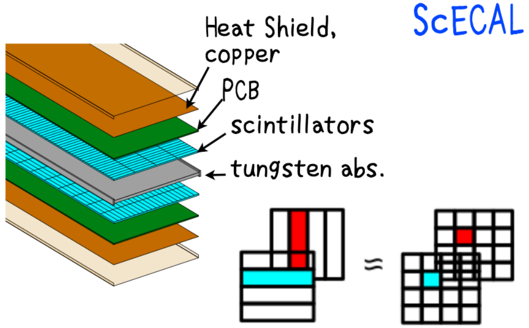


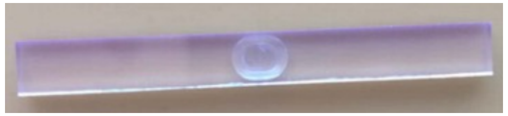
https://doi.org/10.1016/j.nima.2009.09.009

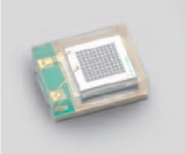
Scintillator-tungsten ECAL

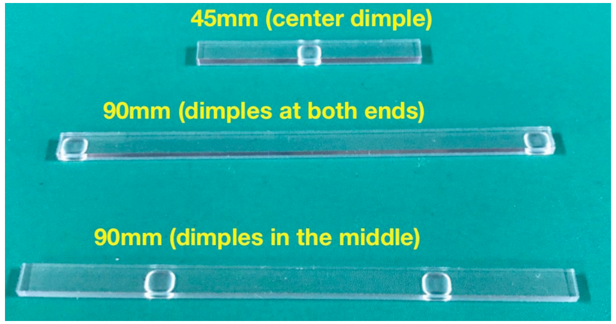










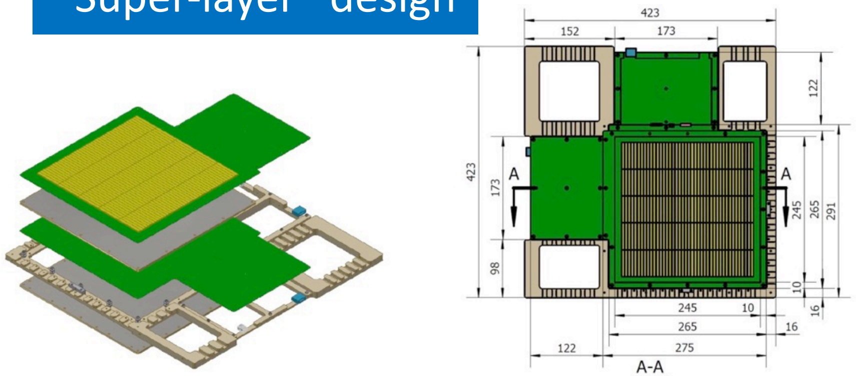


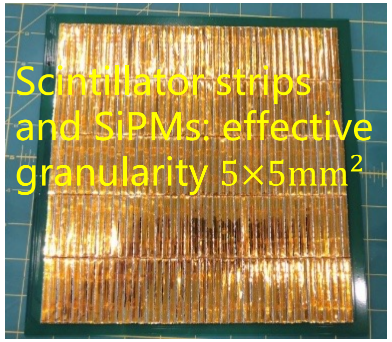
- ScW-ECAL: scintillator strips with SiPM readout + CuW absorber
  - A cost-effective option with plastic scintillator and less readout channels than SiW-ECAL
  - Effective transverse granularity of $5\times5\mathrm{mm}^2$
  - Pattern recognition issue (“ghost hits”): to be addressed by the “Strip-Splitting” algorithm

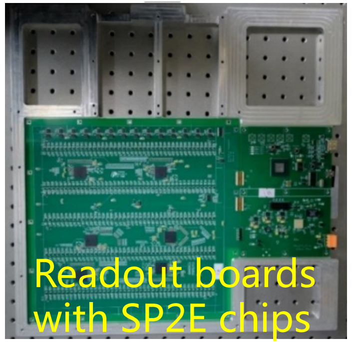
Scintillator-tungsten ECAL prototype

ScW-ECAL tech. prototype

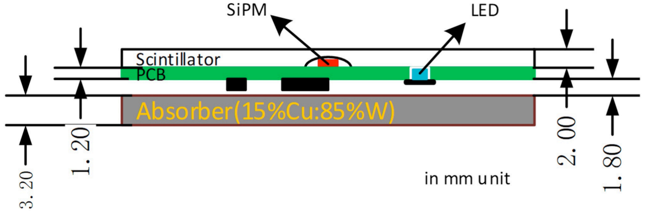
“Super-layer” design



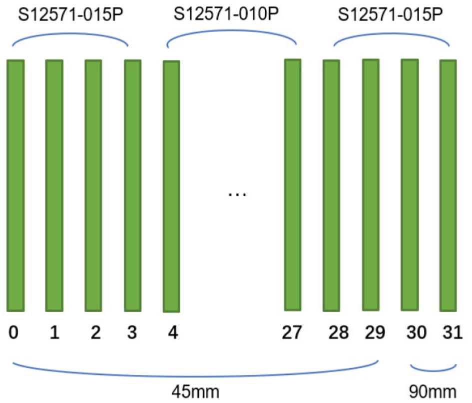




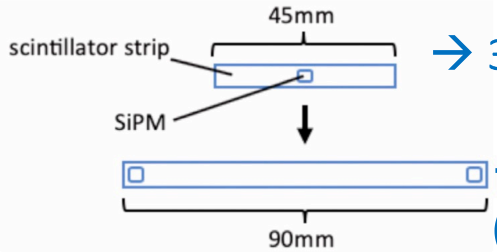
Scintillator-SiPM readout scheme



Sensitive layer arrangements



- ScW-ECAL prototype: developed in 2016-2020
  - Transverse area 22×22 cm^2, 32 longitudinal layers
  - 6,720 channels based on SPIROC2E (192 chips)
  - Total weight ~350 kg

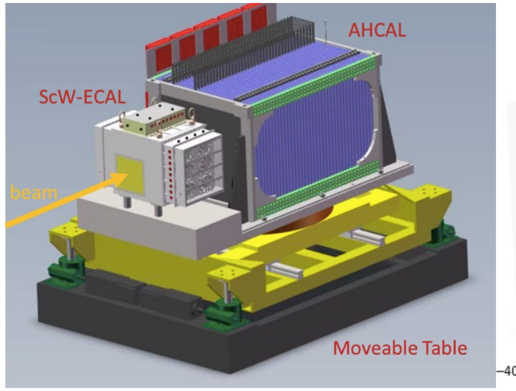


→ 30 sampling layers

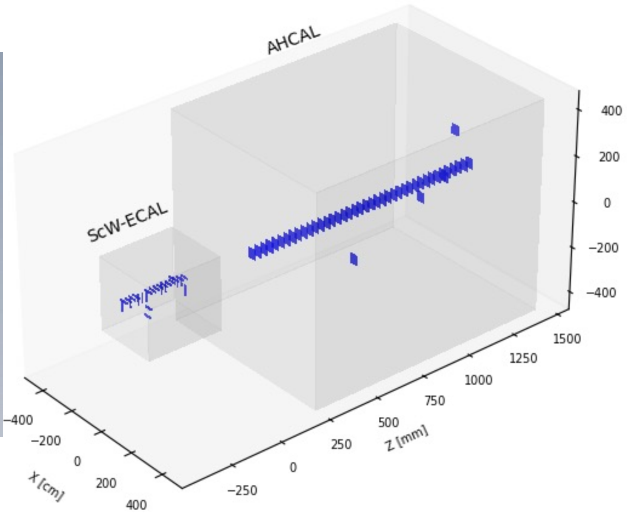
→ 2 sampling layers (in the rear part)

CERN beam test campaigns in 2022-2023

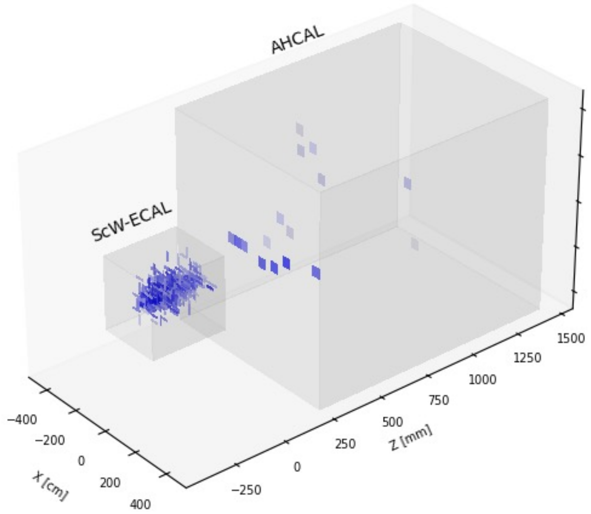
- Testbeam data samples
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS (also up to 250 GeV)
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS



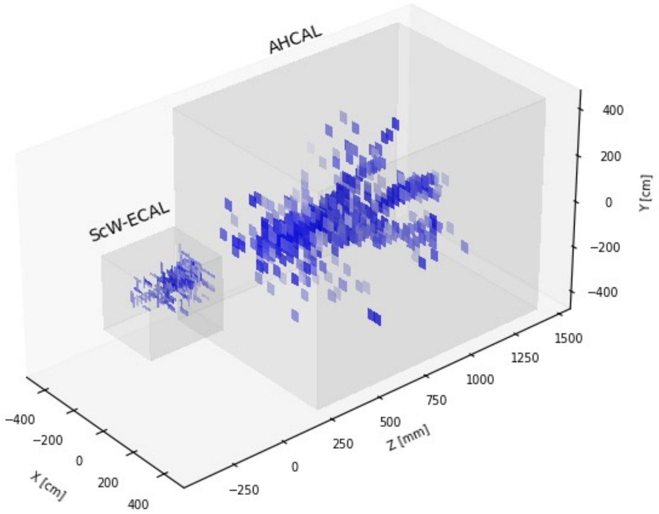
100 GeV μ^-



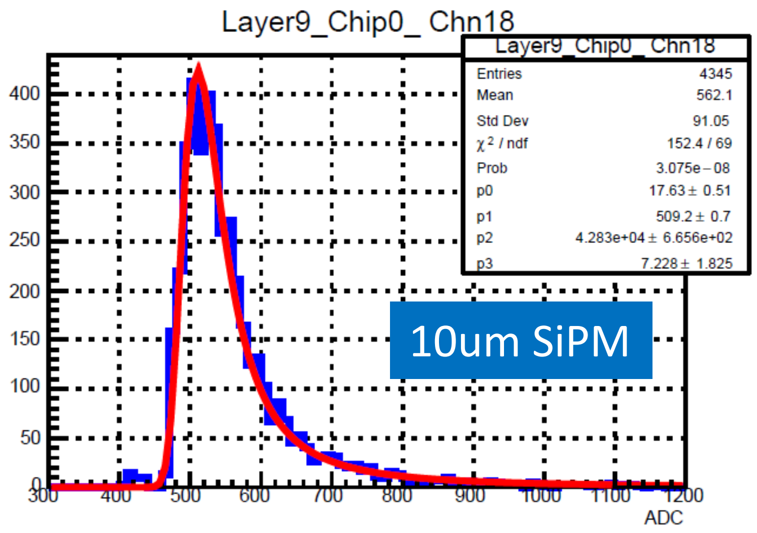
60GeV e^-

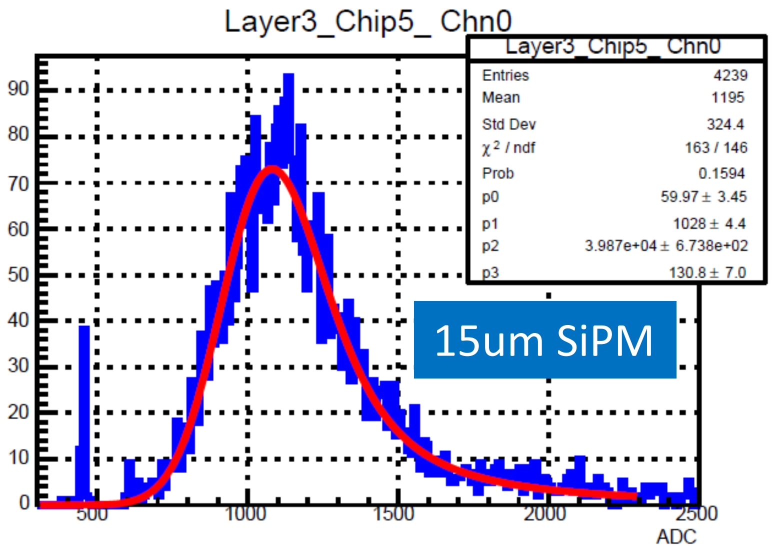


60 GeV π^-

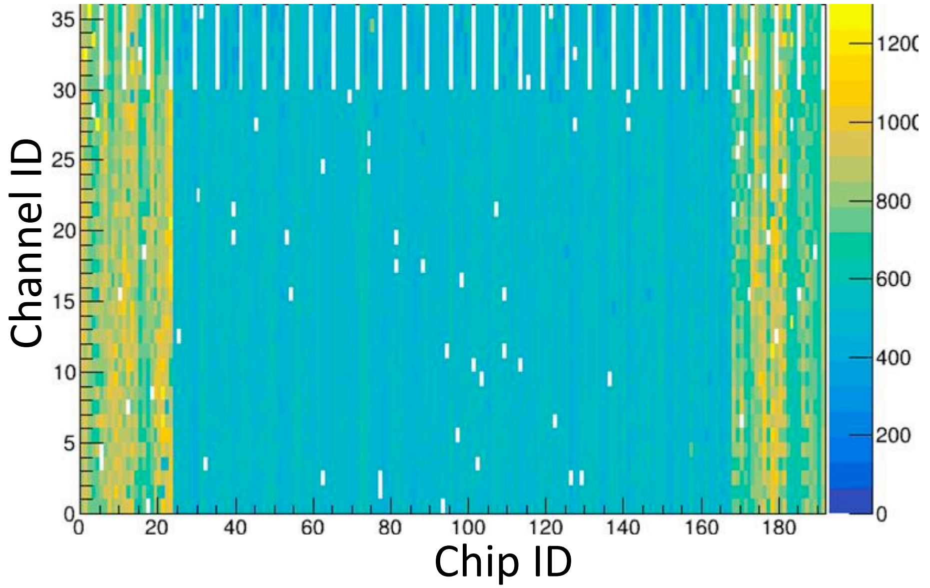


CERN beam test campaigns in 2022-2023

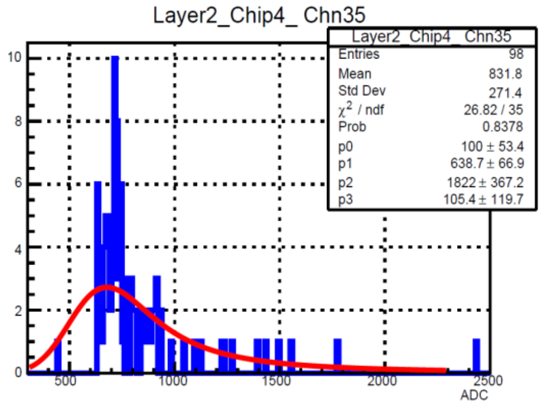




Intercalibration Ratio: ChipID vs ChnID



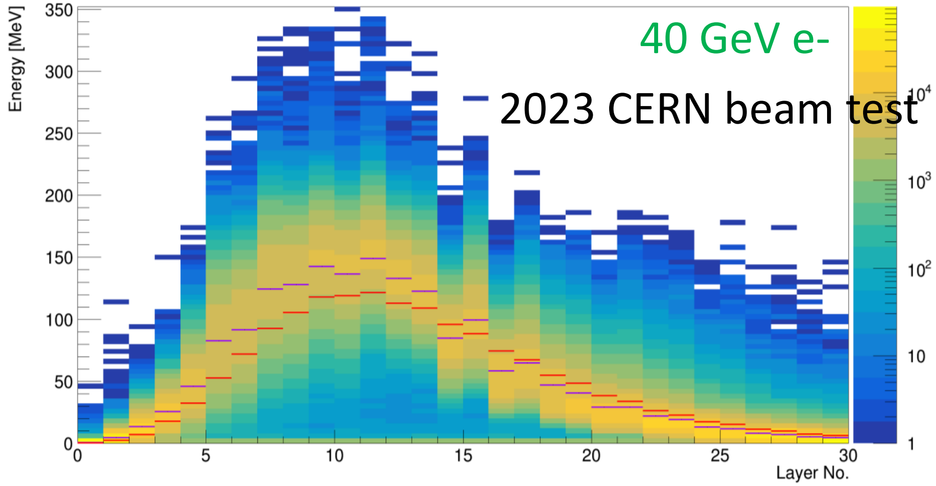
- MIP calibration with 100 GeV muon
  - Extracted MPV value from Landau distribution convoluted with Gaussian
  - Muon tracking algorithm applied to improve fitting quality
- Remaining issue: channels with 10 μm SiPMs
  - The MIP signal-to-noise ratio (SNR) is low and the trigger threshold was relatively high in MIP spectra

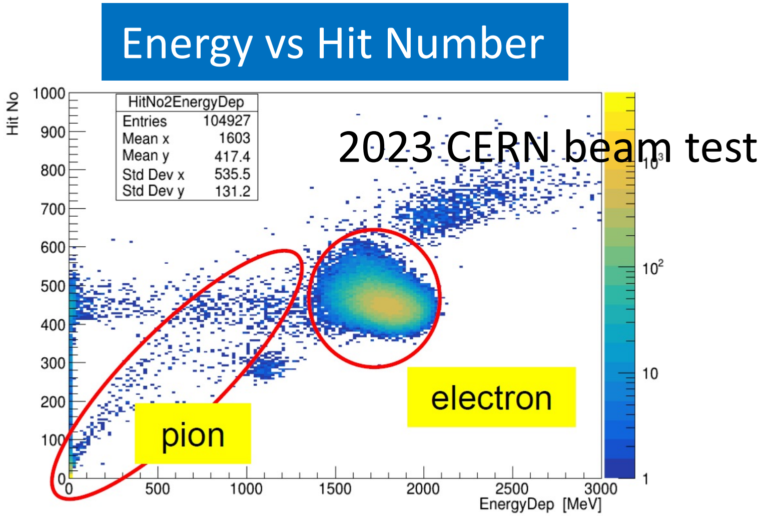


2025 KEK beam test: motivations

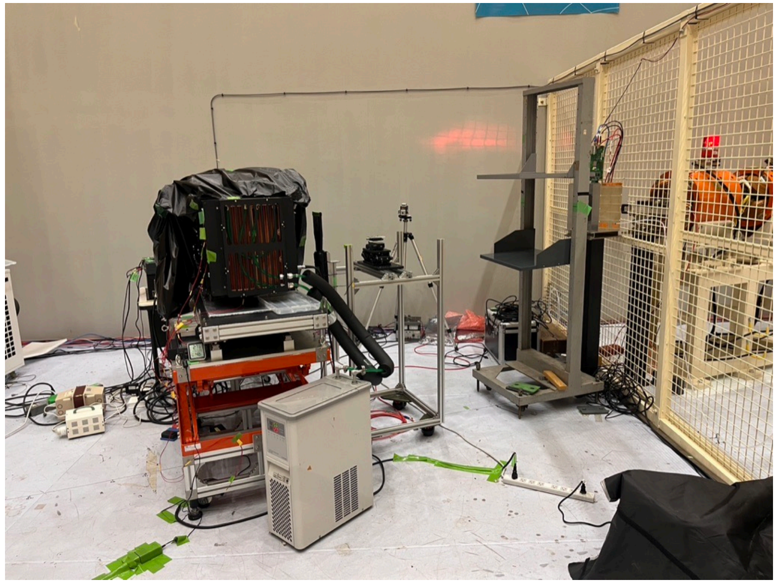
- Goals for new MIP calibration runs
  - To re-do especially for channels with 10 um SiPMs (low signal-to-noise ratio)
  - Better temperature control than at CERN: lower temperature and better uniformity
  - To optimise trigger threshold in order not to cut into MIP spectrum
- EM performance studies with low-energy electrons (< 6 GeV)
  - Better electron beam purity than at CERN

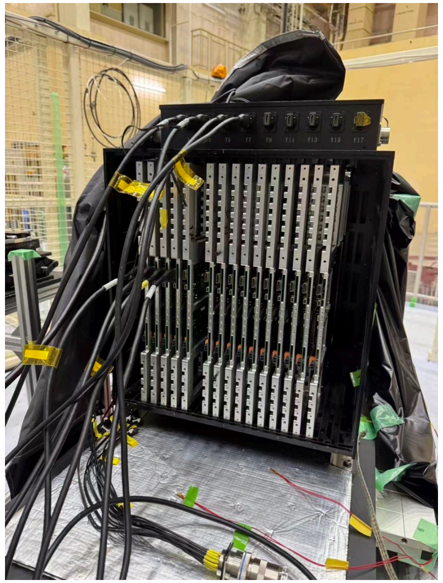
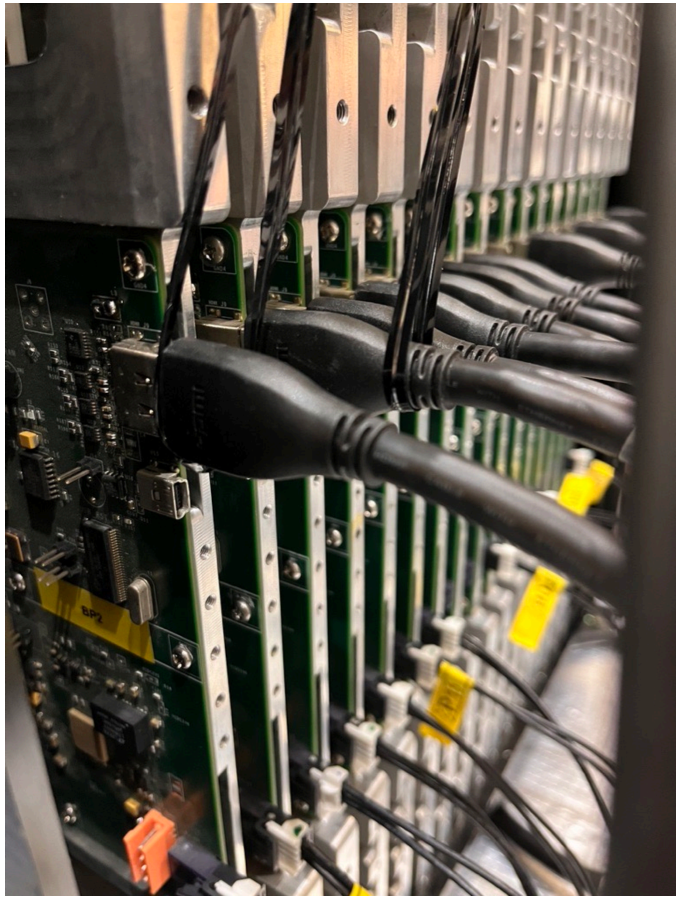
Longitudinal Shower Profile: MC vs Data





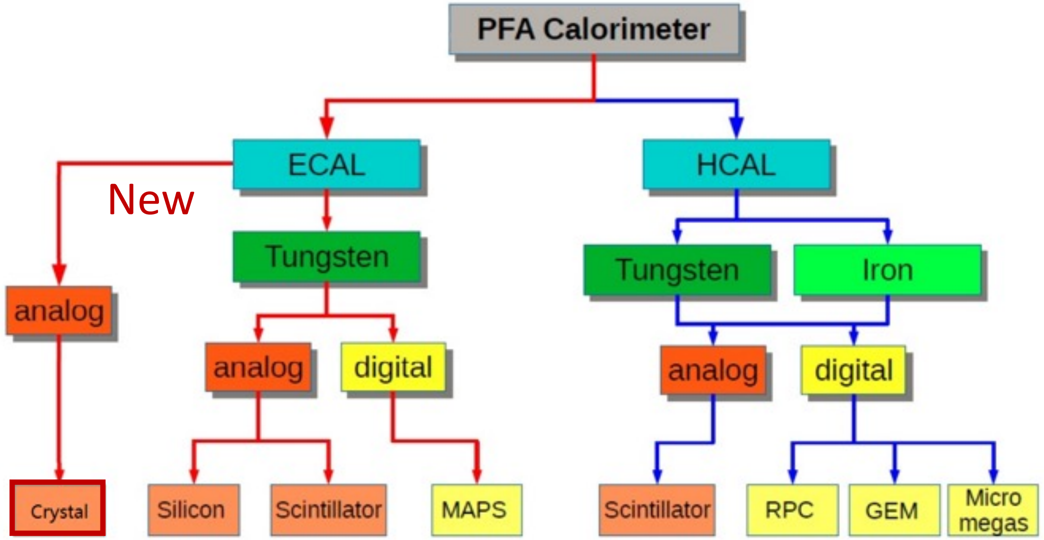
2025 KEK beam test: overview

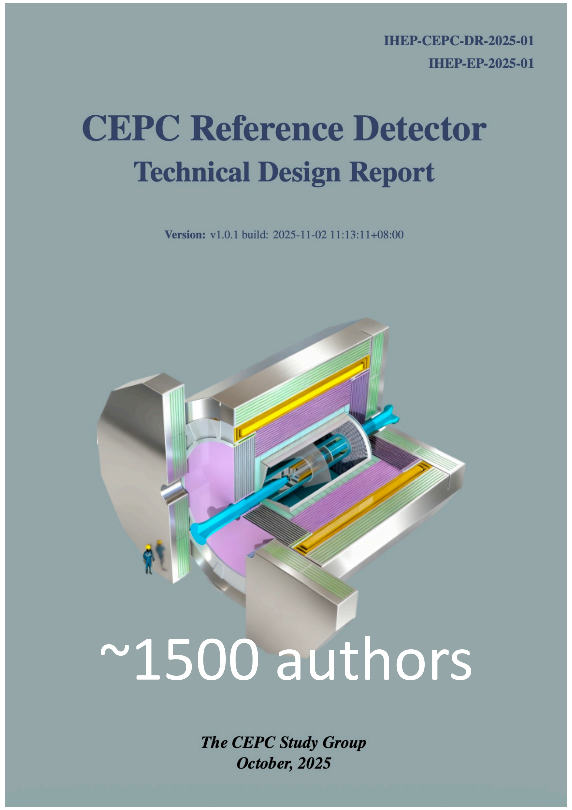


- Beam test period: May 26 – June 10, 2025
- MIP calibration runs: 5 GeV electrons (excluding CuW plates)
- Energy scans: 0.5 – 5.8 GeV electrons
    - 0.5 – 5.5 GeV with a step of 0.5 GeV
    - Maximum energy of 5.8 GeV
    - Different layer configurations

High-granularity crystal calorimeter




IHEP-CEPC-DR-2025-01
IHEP-EP-2025-01

CEPC Reference Detector
Technical Design Report

Version: v1.0.1 build: 2025-11-02 11:13:11+08:00

~1500 authors

The CEPC Study Group
October, 2025

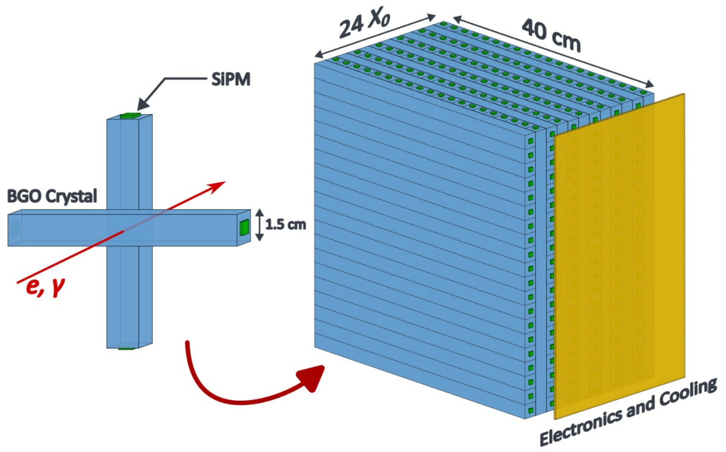
- The **first** electromagnetic calorimeter of this type
  - Homogeneous: excellent EM energy resolution
  - Imaging capability: compatible with PFA for jets
- Selected as the baseline ECAL option in CEPC Ref-TDR
  - Detector name: AGORA (an English word that means "gathering place" or "assembly"

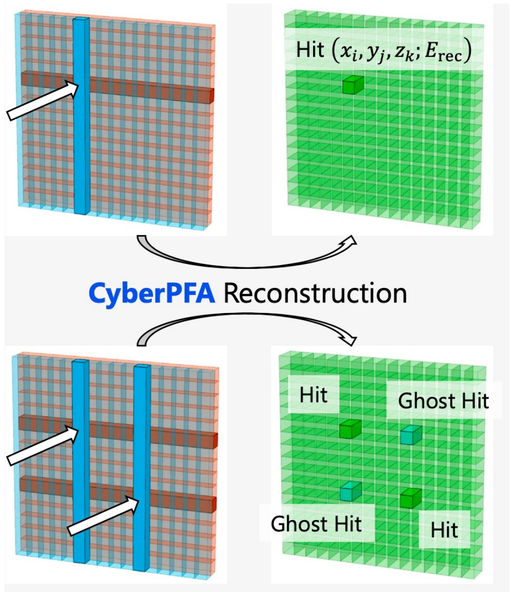
AGORA
ADVANCED GLASS OPTIMIZED RESEARCH APPARATUS

High-Granularity Crystal Calorimeter in DRD-Calo

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

- **HGCCAL** for future Higgs e^+e^- factories
  - Optimal EM resolution: $\leq 3\%/\sqrt{E(GeV)}$
  - Fine segmentations for particle-flow algorithm
- Design features
  - Long crystals: orthogonal arrangement for **positioning**
  - Reduced number of **readout** channels
  - Minimum dead materials between layers
- Challenges
  - Integration: light-weighted *mechanics, cooling, readout*
  - Pattern recognition: to resolve ambiguities
  - Readout
    - A large dynamic range for SiPM + ASIC
    - Front-end ASIC: low-power (millions of channels), continuous readout (high rate at circular colliders)

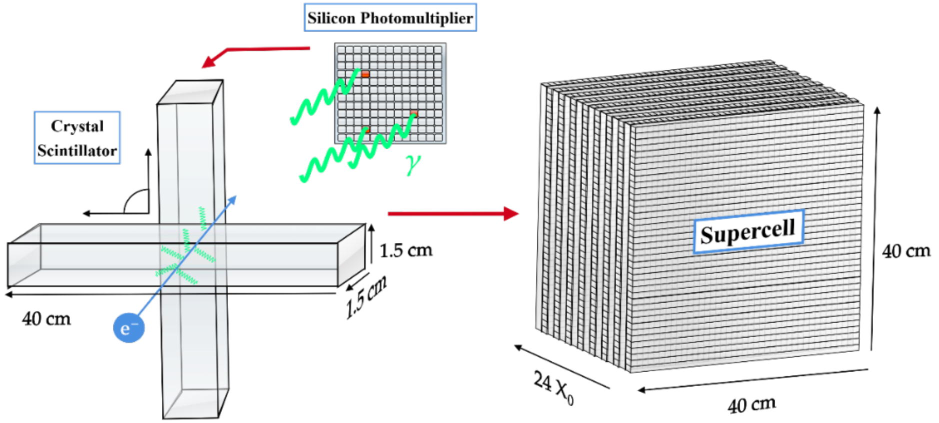




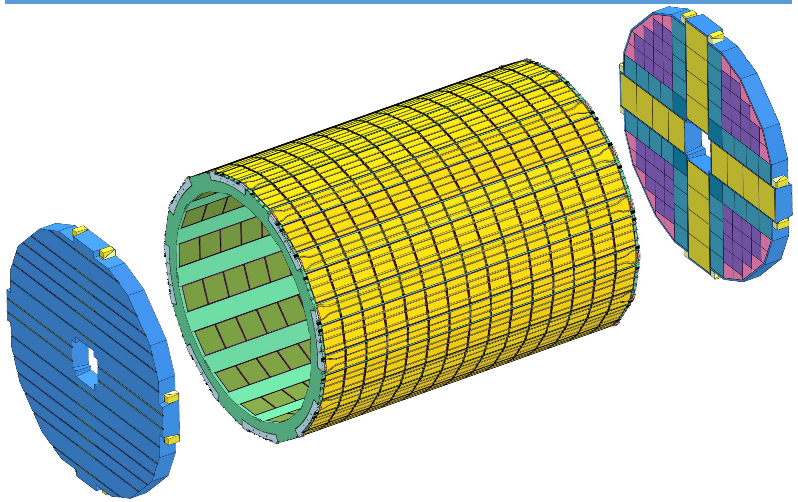
High-granularity crystal calorimeter: overview

- Compatible for PFA: Boson mass resolution (BMR) < 4%
- Optimal EM performance: $\sigma_E/E < 3\%/\sqrt{E(GeV)} \oplus 1\%$
- Long crystal bars in orthogonal arrangement
  - Minimum longitudinal dead material
  - Significant reduction of readout channels
  - 3D positioning with two-sided SiPM readout

Module schematics



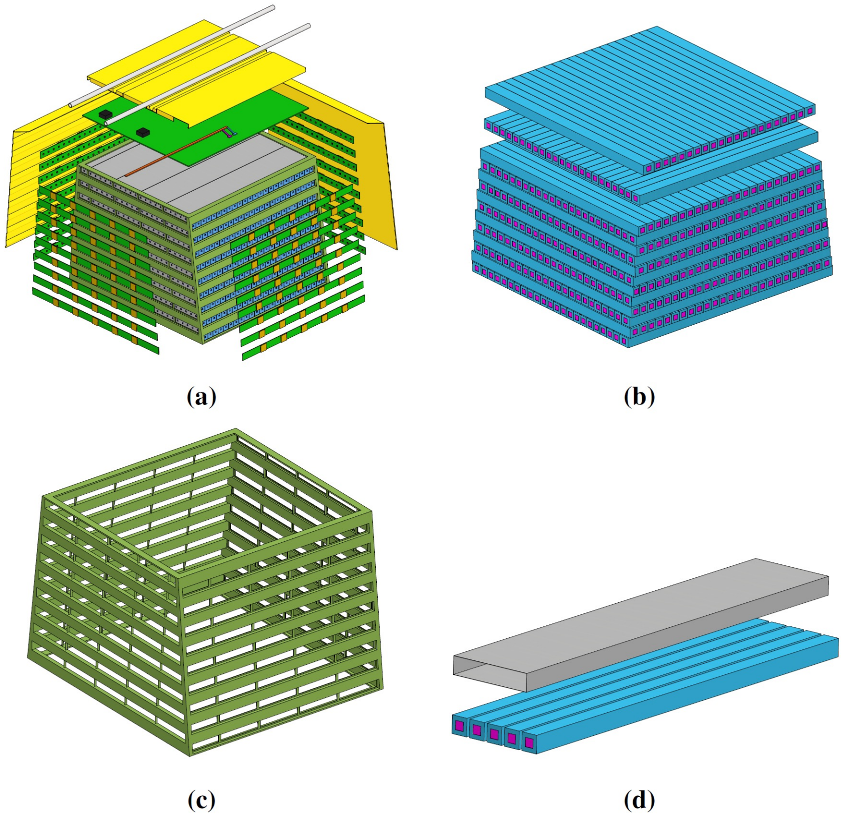
Mechanics design: barrel + endcaps



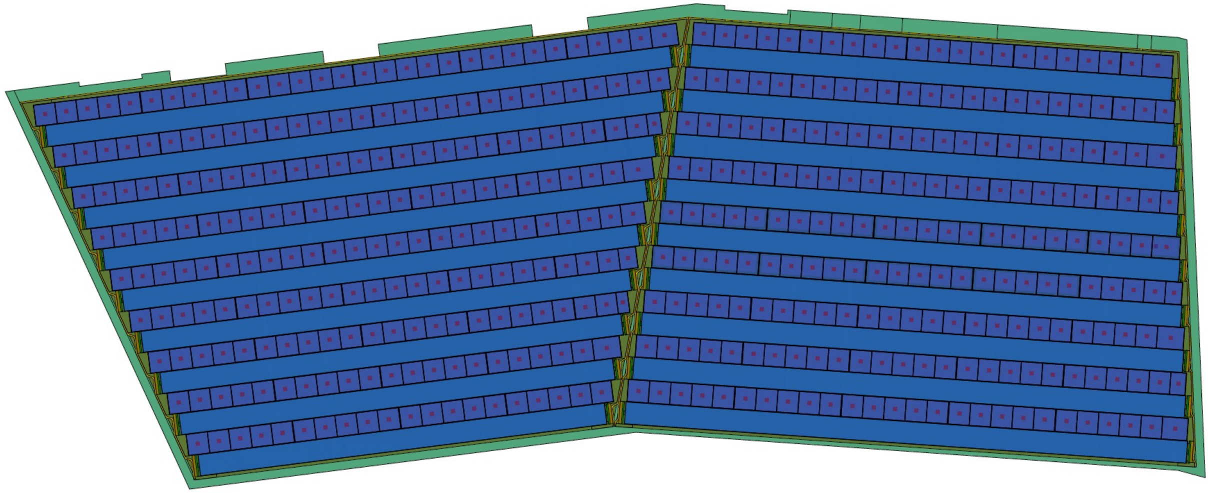
- ECAL design features: high granularity, modularity and hermeticity
  - Crystal bar dimensions: 15×15×~400 mm^3
  - Transverse (effective) granularity: 15×15 mm^2
  - Total depth of 24 X_0 with 18 longitudinal layers
- Barrel: 480 modules (411k channels, ~17.9 m^3 crystals)
- Endcaps: 224 modules (160k channels, ~6.3 m^3 crystals)

Calorimeter module design

- Module boundary optimised: to avoid projectile gaps (i.e. not pointing to Interaction Point)
- Aim for feasibility of **mass production** and **<u>system integration</u>** (withinin limited space)
- **Integration** of crystals, readout boards, cabling, cooling plates/pipes and mechanics



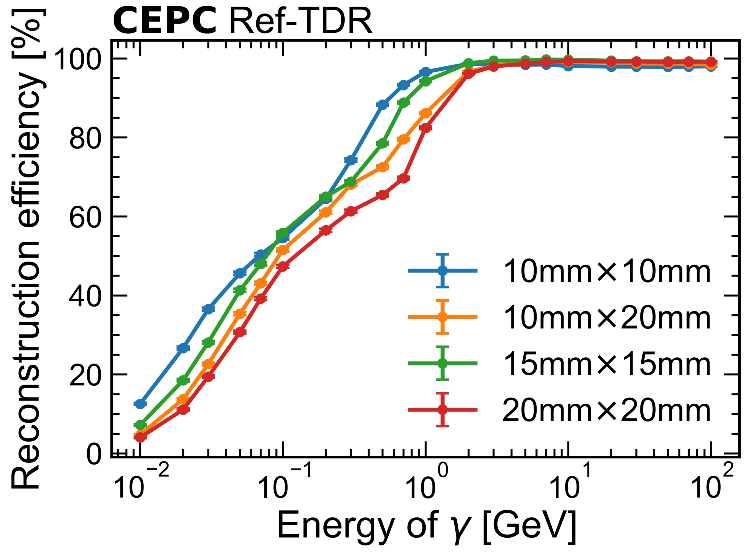
- Mechanics structure based on carbon-fibres
  - Mechanical strength and stability for dense crystals
  - Light-weight: minimum material budget



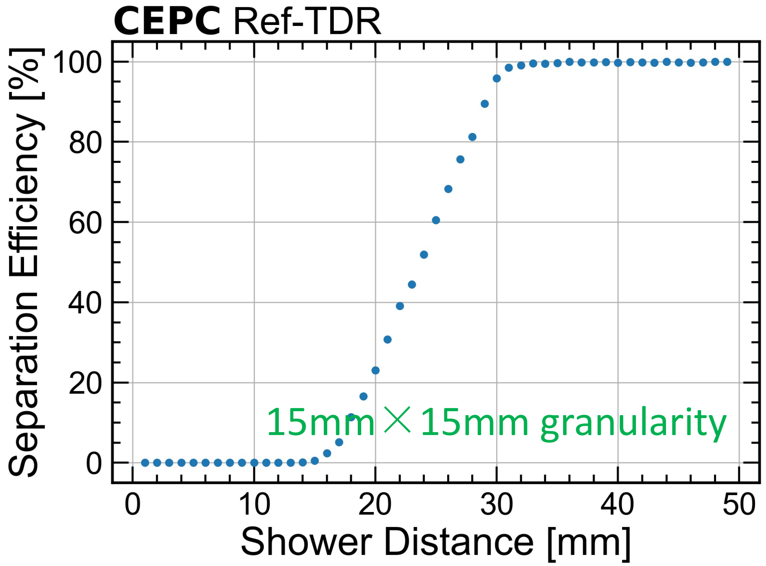
Performance: photons and neutral pions

- Single photon reconstruction efficiency
  - Optimisation for low-energy photons: good efficiency in sub-GeV region
- Two-photon separation efficiency: focus on resolving close-by showers
- Neutral pion reconstruction efficiency and mis-identification rate
  - Promising performance in the wide energy range of 2 – 40 GeV

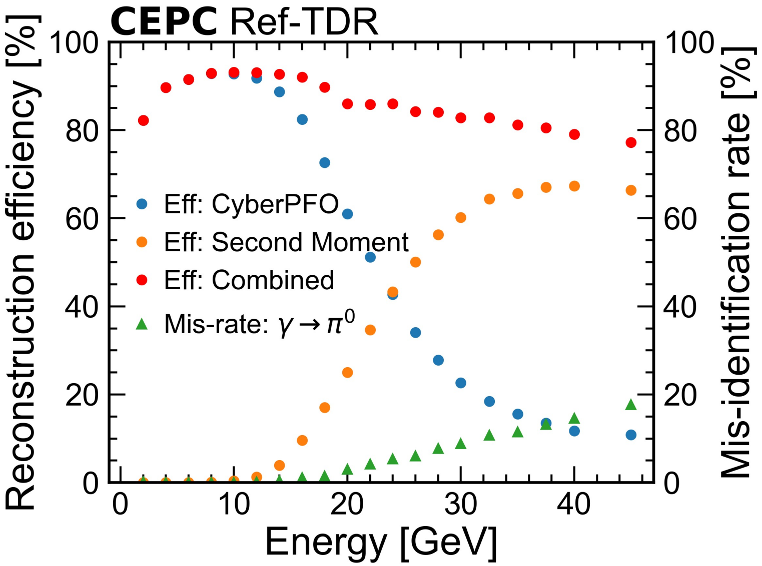
Rec. Efficiency vs. Granularity



Two-Photon Separation Efficiency



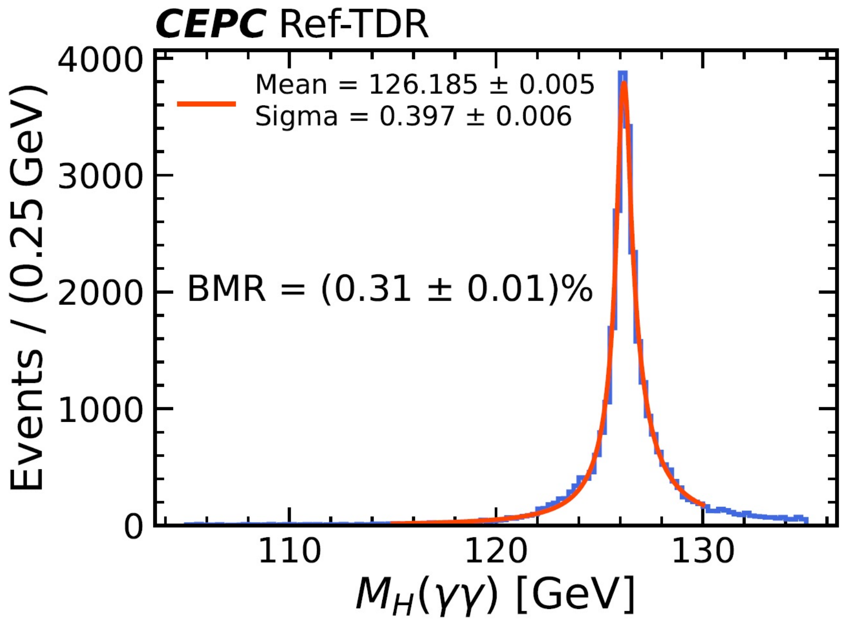
π^0 Rec. Efficiency and Purity



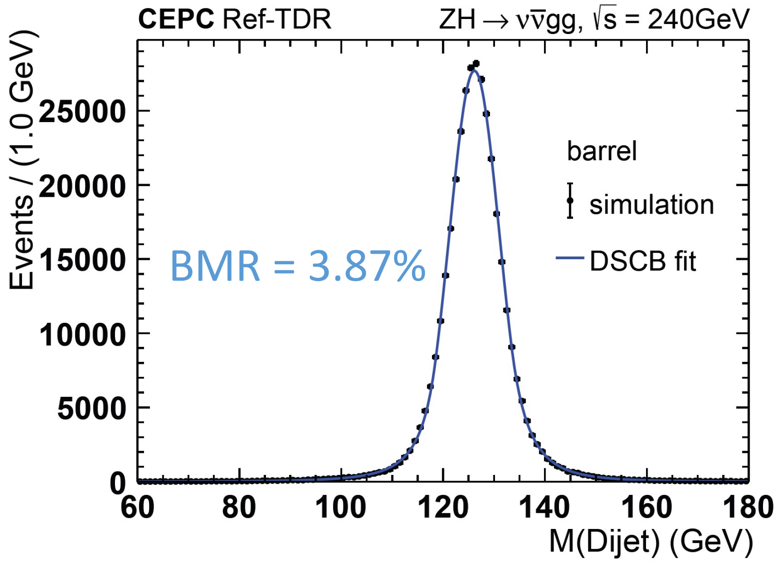
Performance: Higgs boson

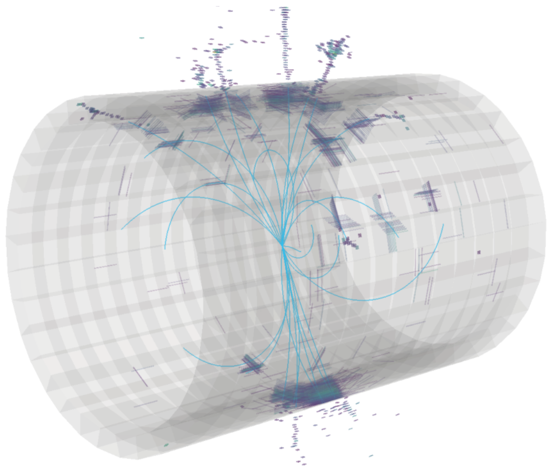
- Higgs benchmark studies at 240 GeV
  - Higgs decays to 2 photons (EM performance) and 2 gluon jets (PFA performance)
  - PFA performance with a crystal ECAL: meet the requirement of BMR<4%

$ZH \rightarrow \nu\nu\gamma\gamma\ (H \rightarrow \gamma\gamma)$



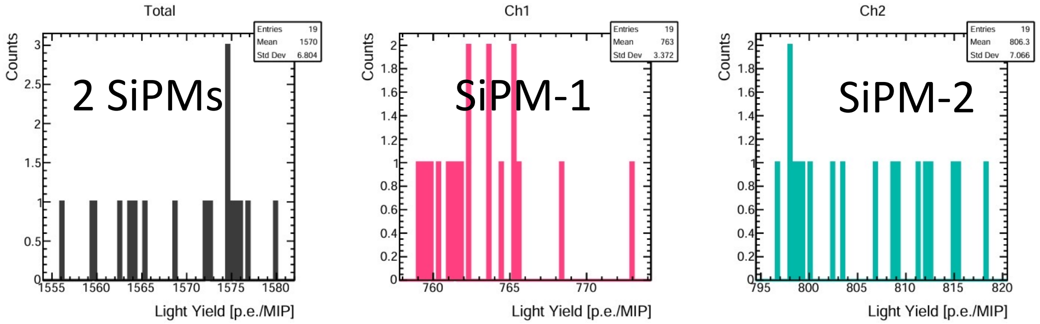
$ZH \rightarrow \nu\nu gg\ (H \rightarrow gg)$ at **240GeV**

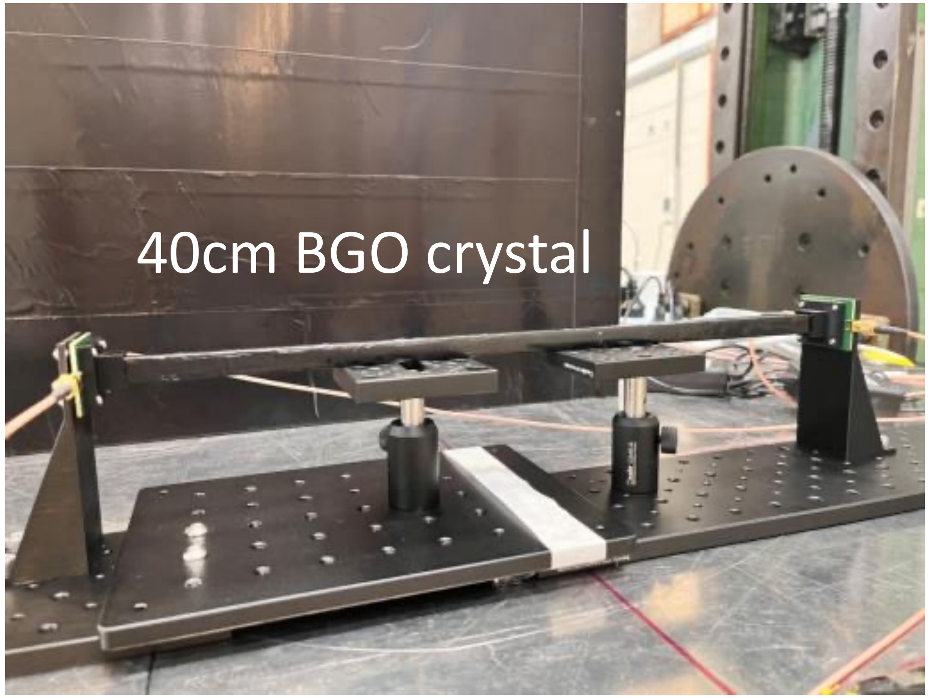


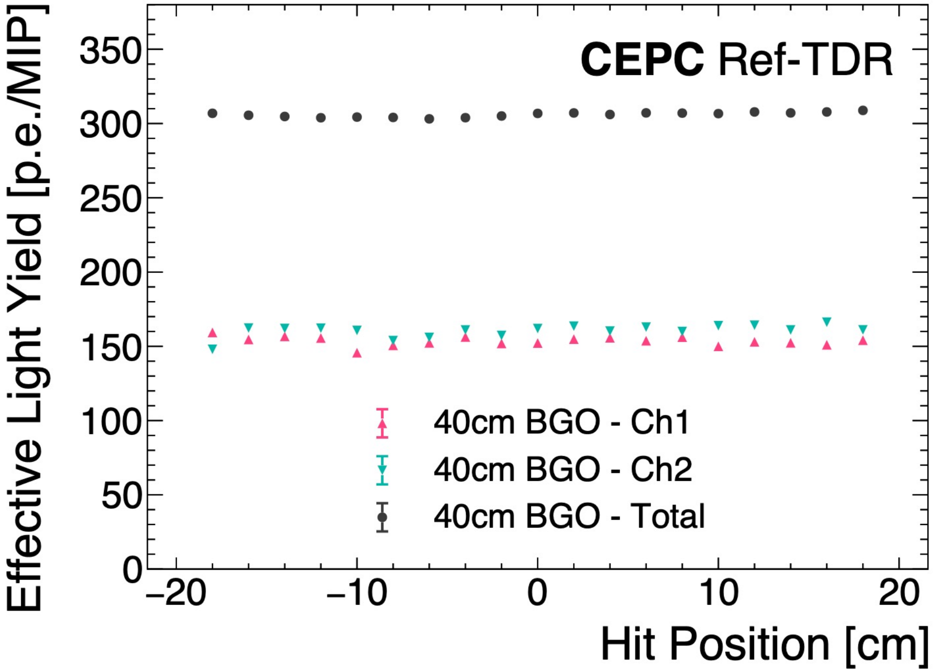


BGO response uniformity

- 40cm BGO crystal bar tested at CERN
  - Using 10 GeV pion beams
  - MIP response uniformity and timing resolution
- Response uniformity: 0.4% (standard deviation)

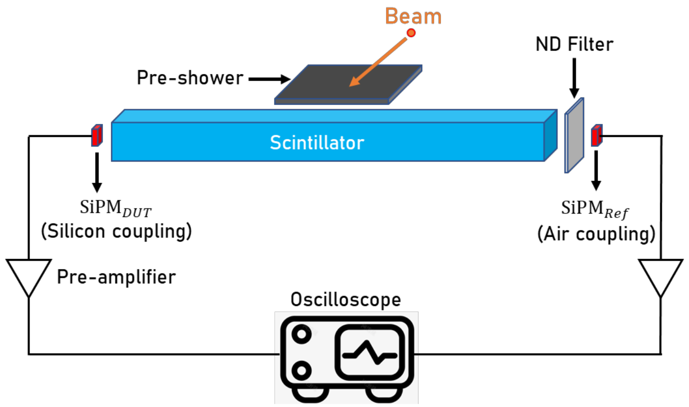




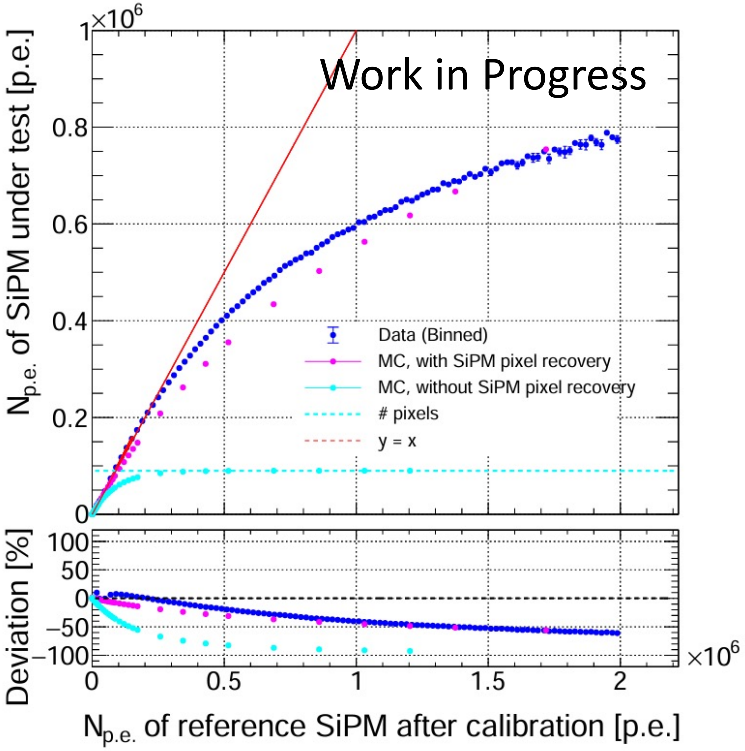


BGO-SiPM response tested with beams

- 40cm BGO tested with SiPMs to study response in a wide dynamic range
  - Tested with electrons up to 300 GeV (SPS-H2)
  - Used tungsten plate to induce showers and large energy depositions
  - First quantitative studies on impact of SiPM pixel recovery during BGO scintillation time



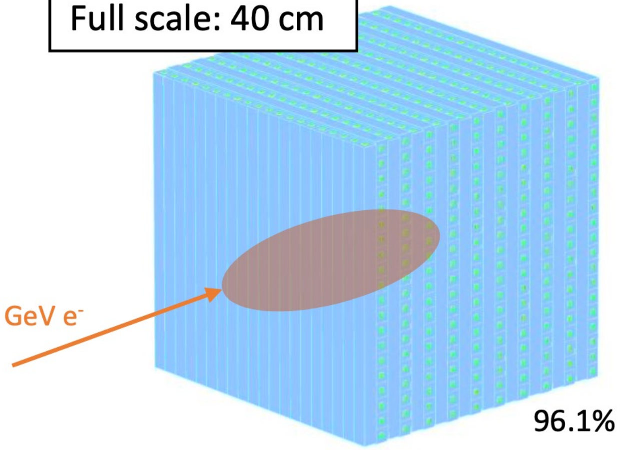
BGO-SiPM response simulation includes SiPM pixel recovery, PDE, crosstalk, BGO scintillation and photon propagation, etc.



Prototype dimensions: simulation studies

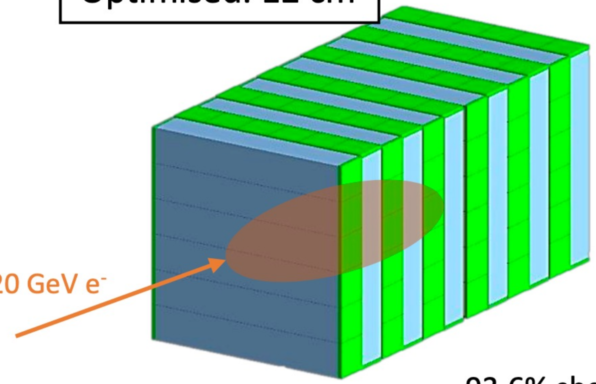
- Major focus of the first prototype
  - **Key performance** validation: linearity, energy resolution
  - System integration: crystals, readout and mechanics
- Prototype dimensions: Geant4 simulation studies
  - Benefit from compact EM shower profiles in nature
  - $12 \times 12 \times 24\ \text{cm}^3$ can reasonably contain EM showers

Full scale: 40 cm



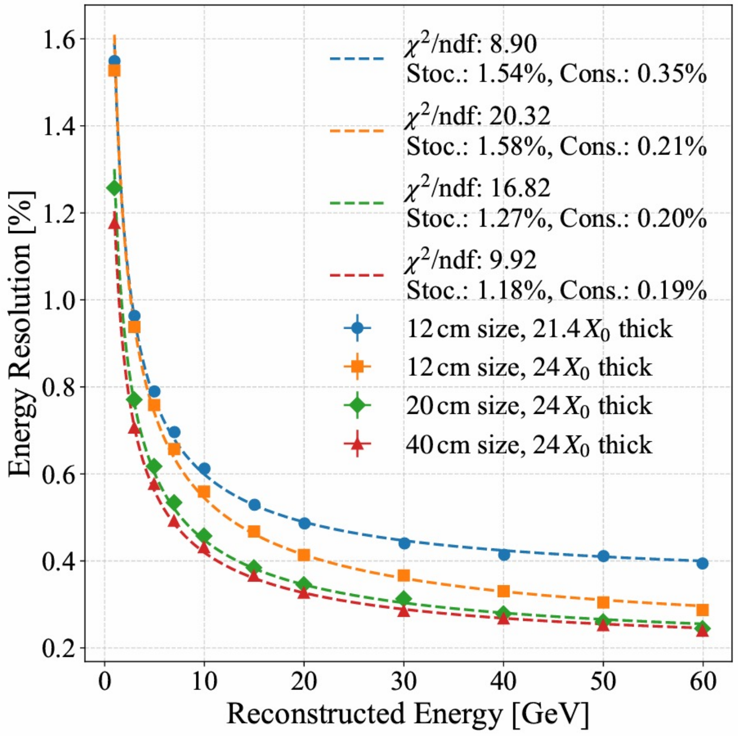
96.1% shower energy contained

Optimised: 12 cm



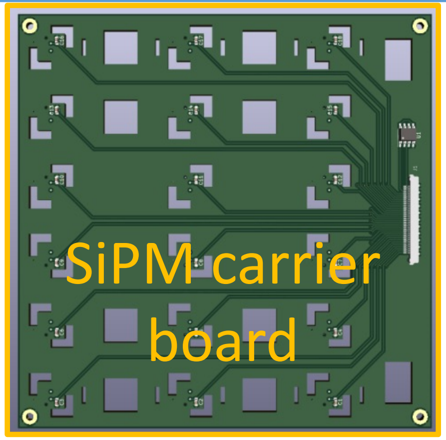
93.6% shower energy contained

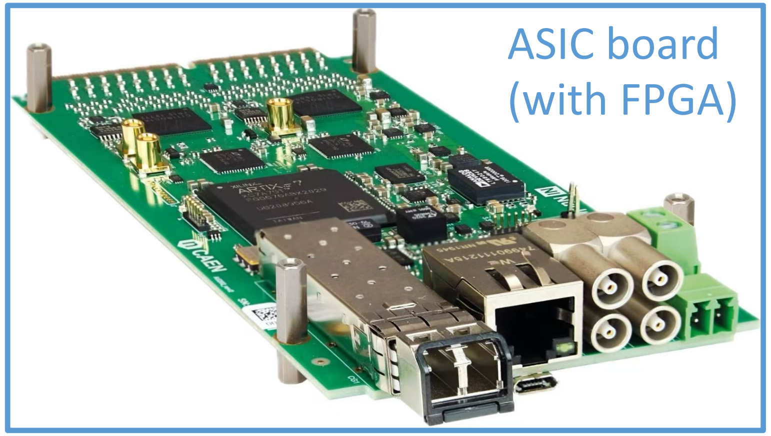
EM energy resolution with different prototype dimensions

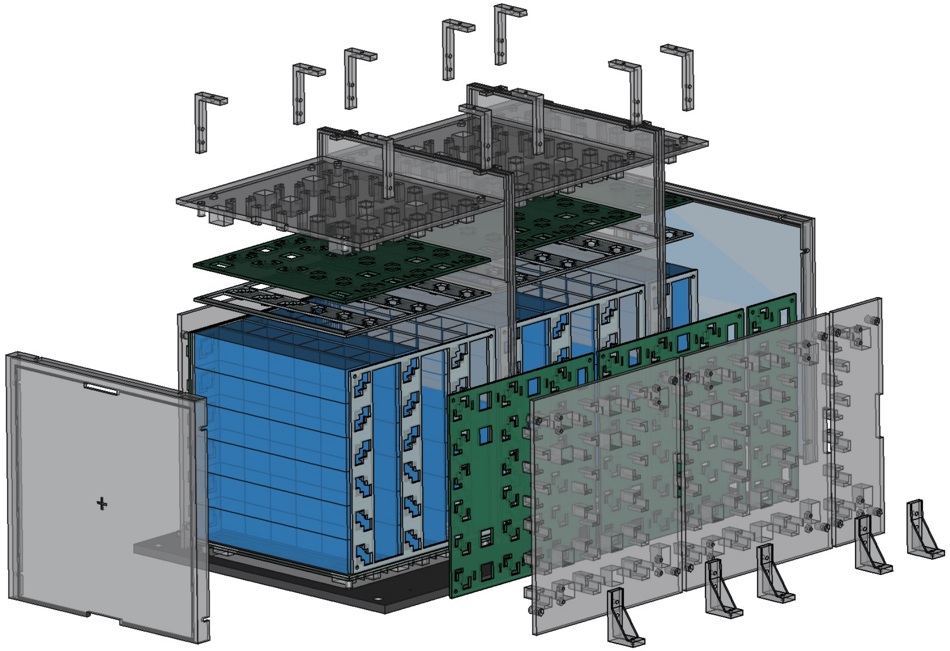


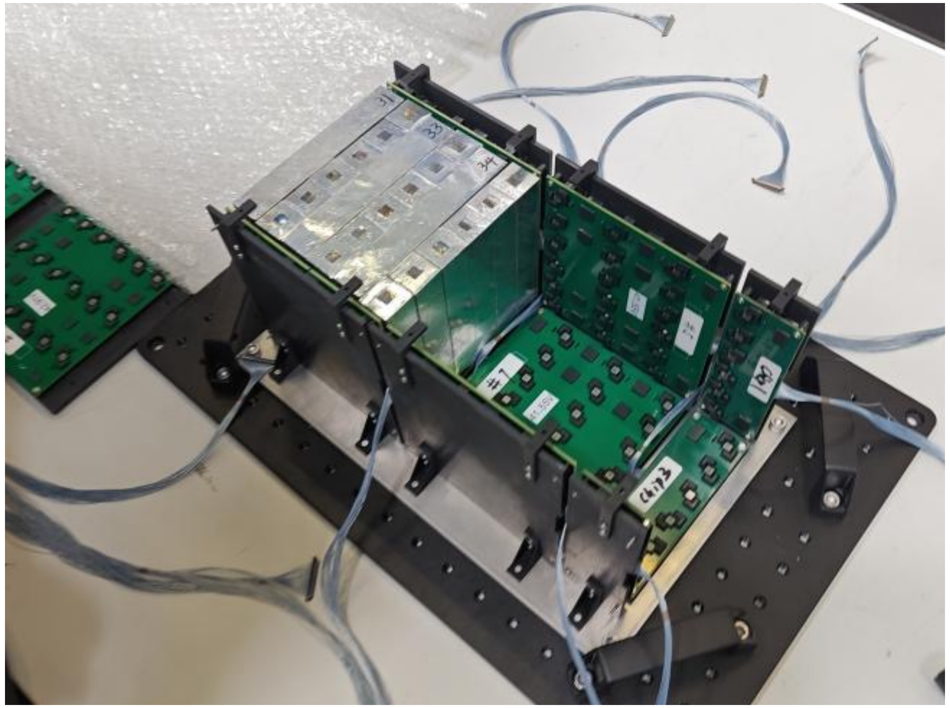
Prototype: system integration

- SiPM-carrier board: custom-designed
  - Bias voltage, SiPM signals, temperature
- Light-weight mechanics for crystals
  - To minimise material budget
- Micro-coaxial cables: high pin-count
  - Reliable connection of SiPMs and ASICs









Prototype development and beam tests

- Prototype with 2×2×12 cm^3 BGO crystal bars: to evaluate EM performance

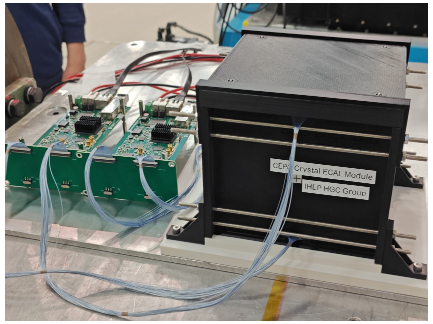
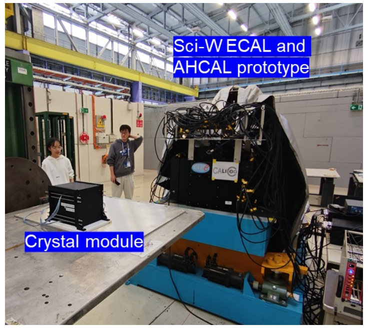
Module test
- **Successful** commissioning
- **MIP signals** in all channels

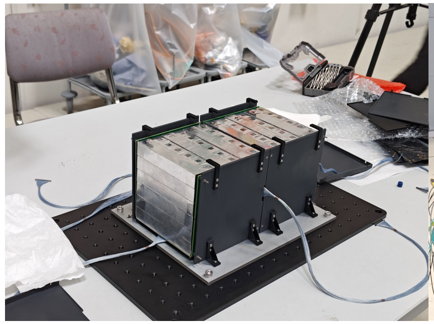
First prototype beam test
- **Validated** digitisation
- **Consistency** for data/MC
- Beam momentum spread

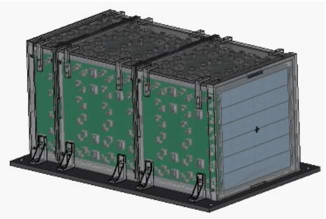
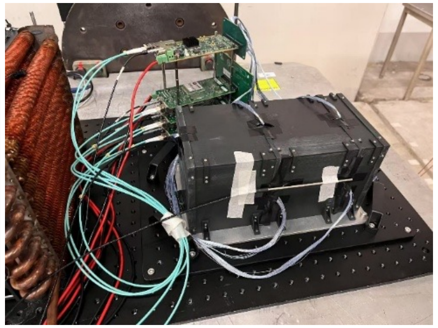
(due to *Beam Instrumentation*)

Improved beam test in 2025
- **Minimum upstream materials**

in the beamline: removed all *BI*
- **Prototype depth >24X$_0$**: to study shower leakage effects



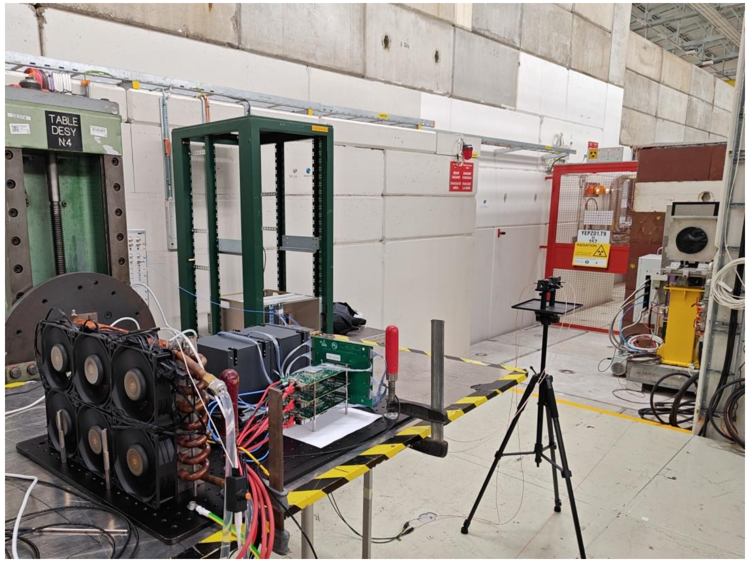



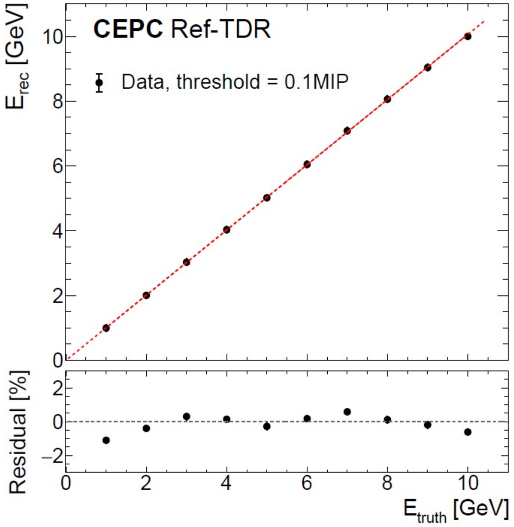
HGCCAL module
- Dimensions: 12×12×12 cm^3
- 36 BGO bars (10.7 X_0)
- 72 readout channels

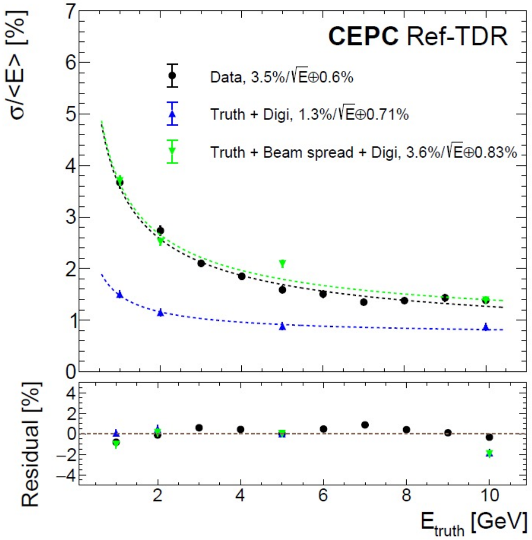
First HGCCAL Prototype
- Dimensions: 12×12×24 cm^3
- 72 BGO bars (21.4 X_0)
- 144 readout channels
- Active cooling

HGCCAL Prototype in 2025
- Dimensions: 12×12×28 cm^3
- 72 BGO + 12 BSO bars (24.9 X_0)
- 168 readout channels
- Active cooling

HGCCAL prototype: first beam test



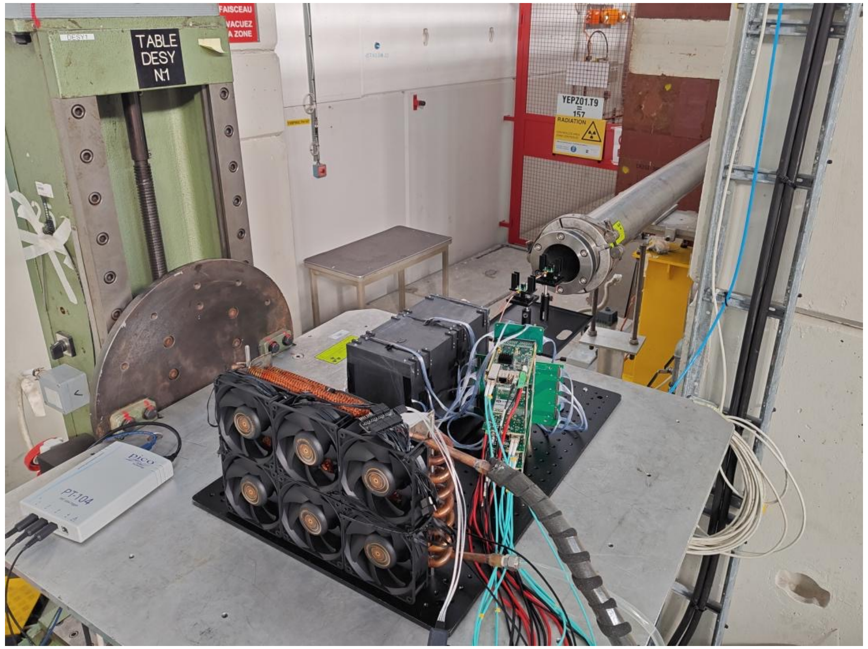




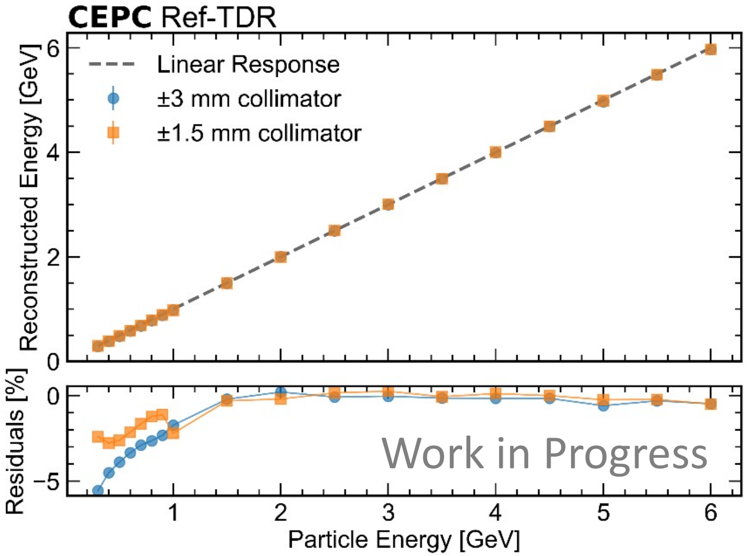
- Studies based on electron beam data in 1 – 10 GeV
  - Beam data taken with *Beam Instrumentation* in upstream
  - Beamline simulation: to quantify momentum spread
- EM response linearity within $\pm 1\%$
- EM energy resolution
  - Including beam momentum spread
    - $\sigma_E/E = 3.6\%/\sqrt{E(GeV)} \oplus 0.3\%$
  - Excluding momentum spread
    - Using beamline simulation as input
    - $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$

HGCCAL prototype: beam test in 2025

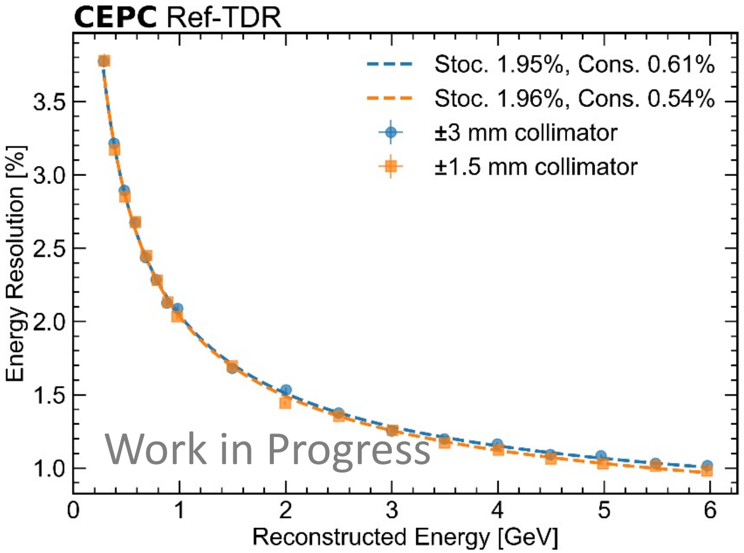
- **Preliminary results**: using electron data at CERN PS-T9
  - **Removed** all Beam Instrumentation components → **confirmed less momentum spread**
  - EM response linearity within $\pm 1\%$
  - EM energy resolution: $\sigma_E/E = 1.95\%/\sqrt{E(GeV)} \oplus 0.6\%$ **(including beam momentum spread)**
- Evaluated key performance: EM resolution achieved $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$
  - Even in the presence of beam momentum spread



EM response linearity (data)



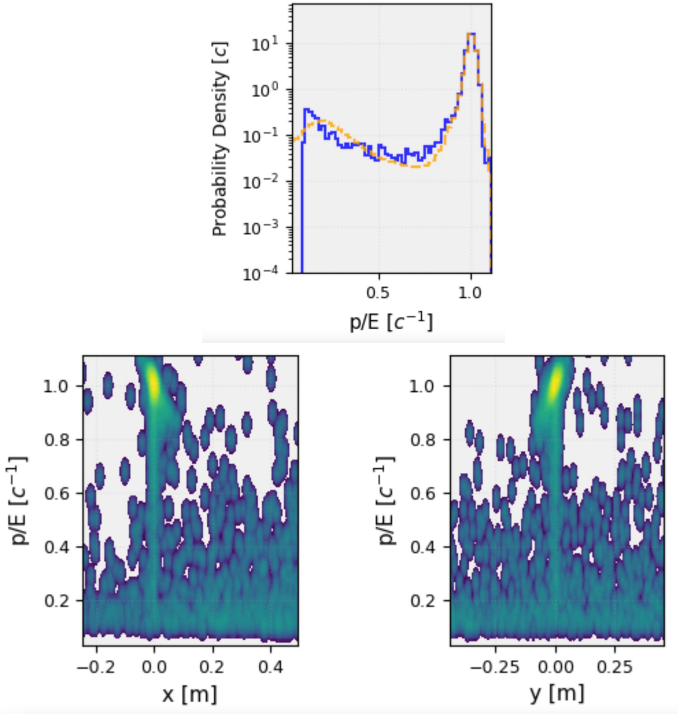
EM energy resolution (data)



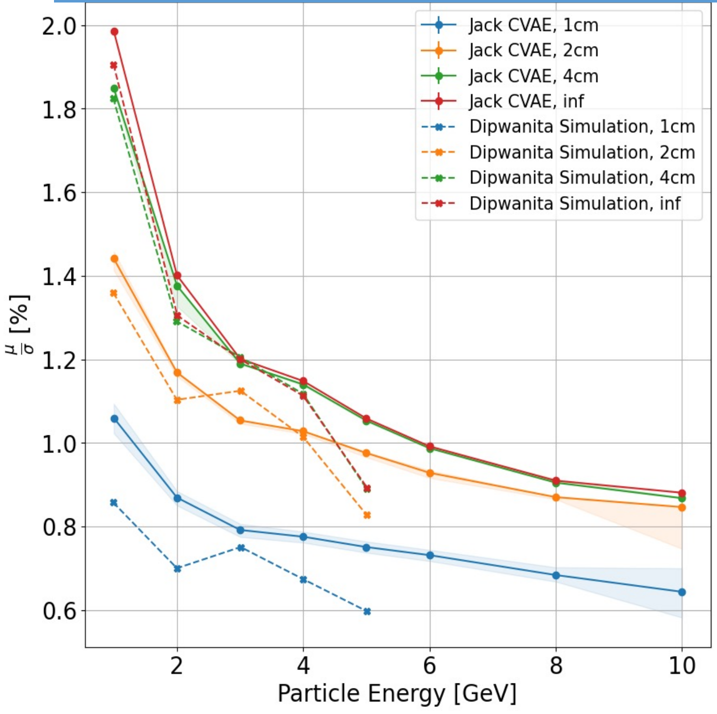
Ongoing studies and planning

- Beamline simulation: collaboration with CERN colleagues to quantify momentum spread
- HGCCAL testbeam data processing in Key4Hep: the first user case (details in talk at Ancona)
- EM shower profiles (longitudinal and lateral): studies with electron data
- PID studies with HGCCAL alone: with data of electron, pion, muon beams

1 GeV positrons in beamline MC



Beam momentum spread (MC)



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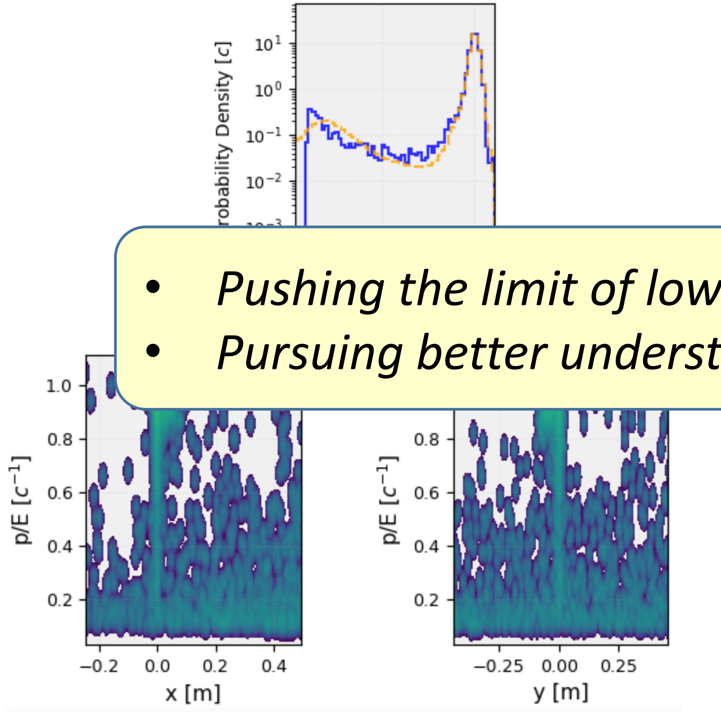
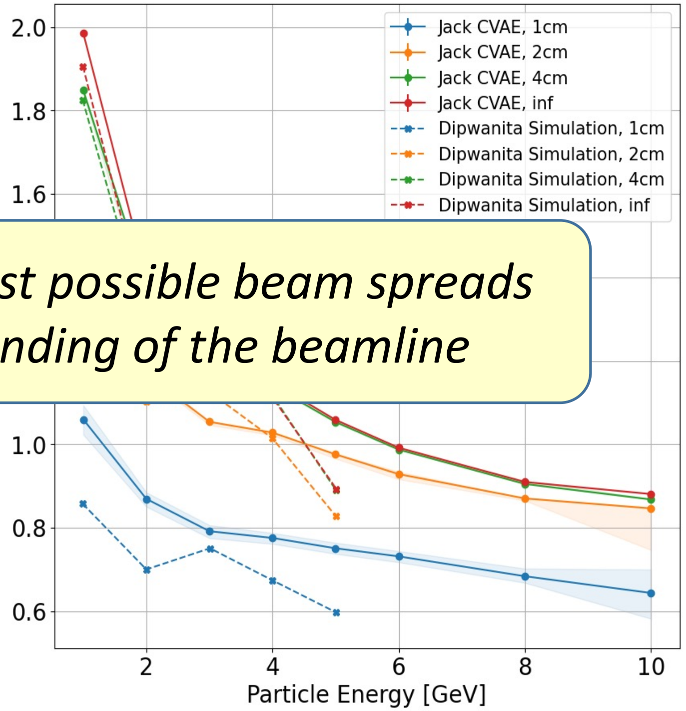
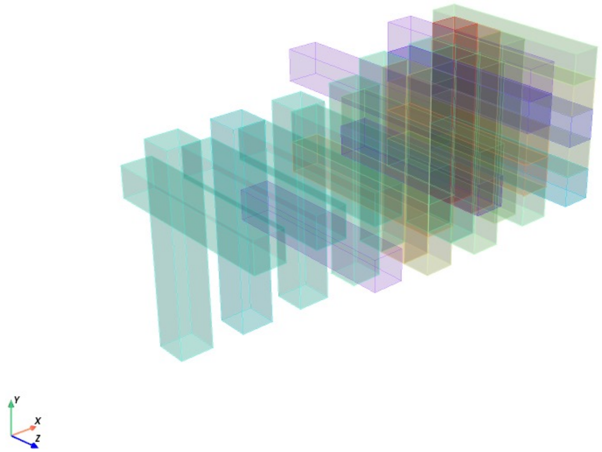


Beam momentum spread (MC)



- *Pushing the limit of lowest possible beam spreads*
- *Pursuing better understanding of the beamline*

- Planning
  - First hadronic interactions in longitudinal layers with pions

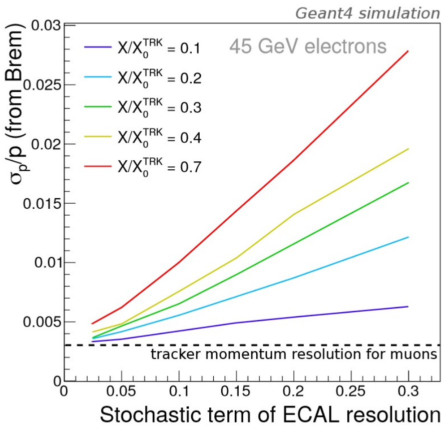


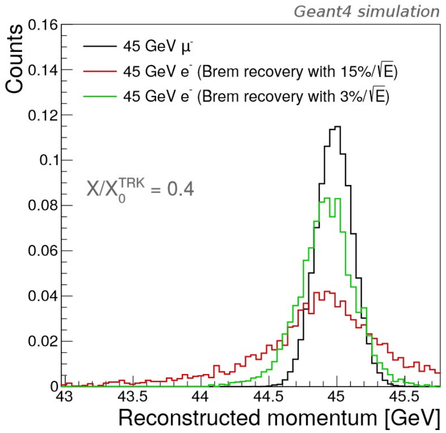
Summary and prospects

- Scintillator-Tungsten ECAL: technological prototype developed and tested with beams
- A new PFA-oriented ECAL option for a future Higgs factory
  - **Homogeneous imaging** calorimetry: the first of this type
  - Design featuring **high granularity**, **modularity** and **hermeticity**
    - Crystals and SiPMs fully integrated in mechanics, cooling and readout electronics
- Extensive studies on simulation and prototyping
  - A new PFA for crystal ECAL design (CyberPFA): demonstration of BMR<4% for jets
  - Prototype successfully developed and tested in high-energy beams
  - Evaluated key performance: EM resolution achieved $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$
- Team actively involved in international collaborations
  - Members of CALICE and DRD-Calo collaborations

Backup

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





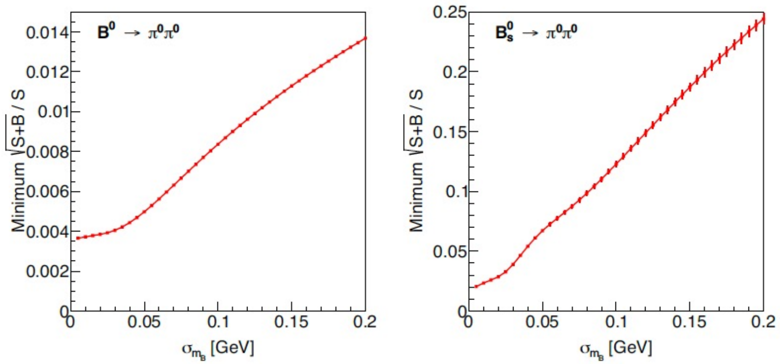


Figure 24. Measurement precision of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) versus B-meson mass resolution σ_{m_B}.