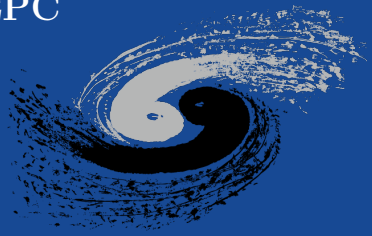
中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

A Highly Granular Crystal ECAL for CEPC



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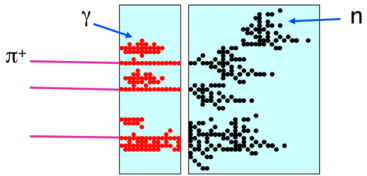
on behalf of the CEPC Calorimeter Working Group

June 17, 2025

Motivation

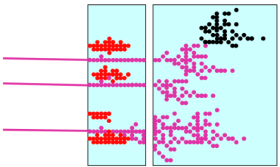
- Future precision lepton collider experiments require **exceptional jet energy resolution**;
- **Reason:**
  → hadronic final states common in processes of interest;
  → **e.g** $e^+e^- \to ZH \to \nu\bar{\nu}gg$;
  → BMR required to be 3–4 %
- ***Particle Flow***:
  - **tracker**
    → momentum of charged particles;
  - **highly-granular calorimeters**
    → measure energy deposits by particles;
  - **sophisticated clustering algorithms**
    → split deposits;
    → neutral particles → calorimeter;
    → charged particles → associated to track

Traditional Calorimetry



$E_{JET} = E_{ECAL} + E_{HCAL}$

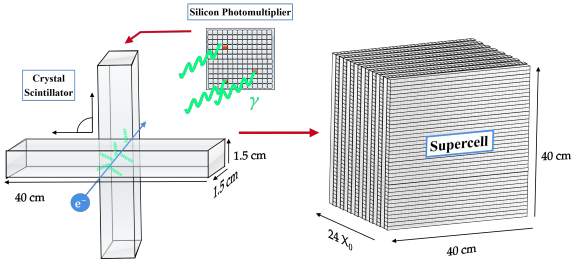
Particle Flow



$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

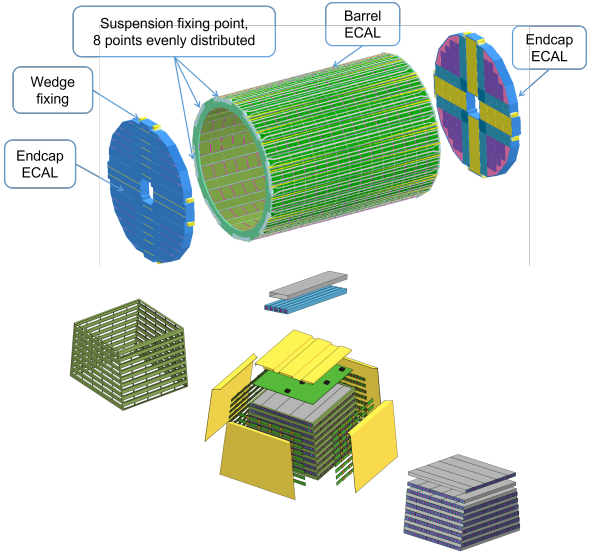
A Highly Granular Crystal ECAL

- **Highly Granular Crystal ECAL**:
  - **scintillating crystal active material**
    → 2–3 %/$\sqrt{\text{GeV}}$ energy resolution expected;
  - **'cross-hatched' crystal bar design**
  - **4D readout:**
    → spatial position, energy;
  - **the best of both worlds**
    → granularity & energy resolution



A Highly Granular Crystal ECAL

- Scalable, modular design for CEPC ECAL
- **Design features:**
  - **Crystal Bars:** 15 mm × 15 mm × 400 mm
  - **Transverse Granularity:** 15 mm × 15 mm
  - **Depth:** 18 layers, 24 X_0
  - **ECAL barrel:** 480 modules
  - **ECAL endcap:** 224 modules
  - **Structure:** Carbon-Fiber
- FEA studies on:
  → stress
  → deformation
  → temperature gradient
- **No 'show-stopper' seen**



CEPC Requirements

Evaluation	Requirement	R&D
BMR	< 3–4%	Dedicated crystal PFA
EM Res.	$\leq 3\%/\sqrt{E}$	Crystal light yield, SiPM linearity
Threshold	< 0.1 MIP	Effect of noise (SiPM)
Uniformity	$< 1\%$	Uniformity of long bar
Dynamic Range	1-3000 MIP	SiPM dynamic range

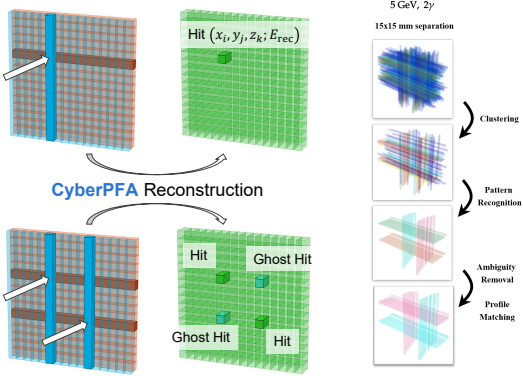
Take Home Message:

A wide variety of R & D is required to bring this design to life.

CyberPFA

- **Unique crystal bar design**
  → hit ambiguity
  → overlap: crystal ρ_M larger than for W
  → requires dedicated PFA;

- **Key summary of CyberPFA**
  → **Clustering:** Global/local maxima identification.
  → **Pattern Recognition:** Track-ECAL-HCAL association, topological merging.
  → **Energy Splitting:** EM profile-based correction.
  → **Ambiguity Removal:** Track + neighbour module + energy + timing info.



CyberPFA Performance

- CyberPFA performance studied:

  → full DD4HEP CEPC ECAL simulation
  (+ glass scint. HCAL);

  → $1\gamma/2\gamma$ reconstruction;

- Efficiency:

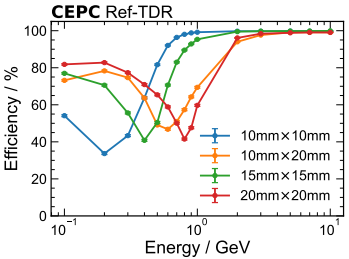
  → $\frac{|E_{\mathrm{PFO}}-E_\gamma|}{E_\gamma} < 30\,\%$

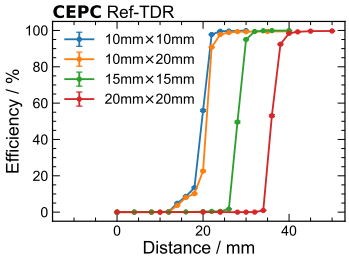
  → Photon angle
  $\theta \in [-0.98, 0.98]$, $\phi \in [0, 2\pi]$

  → 1 neutral PFO reconstructed;

  → **Caveat:**
  correct # PFOs and confusion → different metrics

- 15 mm × 15 mm **bar chosen**





Take Home Message: $1\,\gamma$

- Longitudinal granularity → critical for γ reco;
- Local minimum → overlap region, sub-GeV & GeV γ algorithms;

Take Home Message: $2\,\gamma$

- 2γ separation depends on transverse granularity;

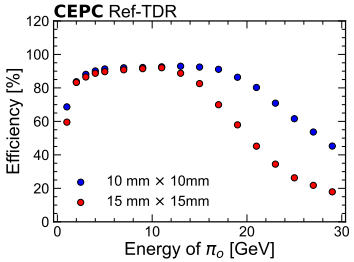
CyberPFA Performance

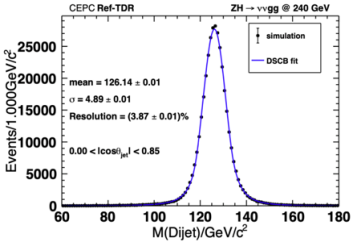
- CyberPFA performance studied:

  → full DD4HEP CEPC ECAL simulation (+ glass scint. HCAL);

  → π^0 energy reconstruction;

  → Higgs dijet mass from $e^+e^- \to HZ \to \nu\bar{\nu}gg$ at $\sqrt{s} = 240\,\text{GeV}$





Take Home Message: π^0

- CyberPFA/shower profile → π^0 discrimination;
- π^0s from τ decay/jet typically 1–10 GeV;

Take Home Message: BMR

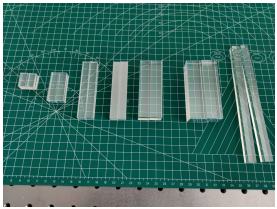
- BMR:

  → $\sigma(m_{jj}) = 4.89 \pm 0.01\,\text{GeV}$

  → $3.87 \pm 0.01\,\%$
- **CyberPFA achieves required CEPC resolution**

Key Ingredients

Scintillating Crystal



Requirements

- Fast response;
- Radiation hardness;
- Feasible to manufacture ($1.5\,\text{cm} \times 1.5\,\text{cm} \times 40\,\text{cm}$);

Options

- **BGO** (current choice)
- **BSO**

SiPM

Requirements

- High dynamic range;
- Low dark noise rate;
- Radiation hardness;

Options

- **NDL** (tentative choice)
- **Hamamatsu**

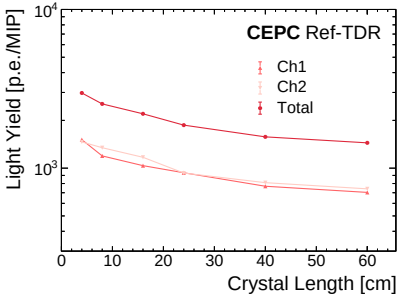
Crystal Light Yield

- π^- beam from CERN PS-T9 beamline used to assess:

  $\rightarrow$ light yield
  (MPV of SiPM MIP response)

- Different BGO bar lengths studied;

- **Paper: 2503.16880**



Take Home Message: Light Yield

- BGO light yield achieves CEPC requirements:
  - 400 p.e./MIP minimum required;
  - 800 p.e./MIP obtained for $1 \times 1 \times 40\,\mathrm{cm}^3$
- longer bar $\rightarrow$ reduced yield (self-absorption)

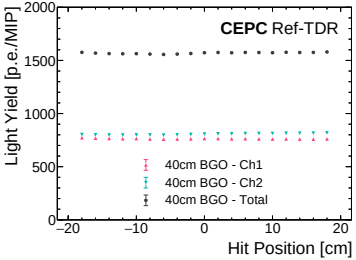
Crystal Uniformity

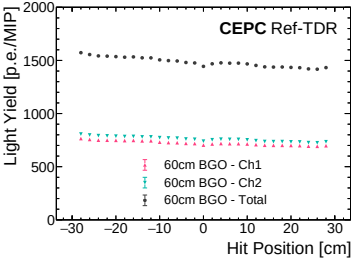
- π^- beam from CERN PS-T9 beamline used to assess:

  $\rightarrow$ light yield as a function of position along crystal bar;

- uniformity affects 'constant term' of resolution;

- 2 different lengths of BGO studied;



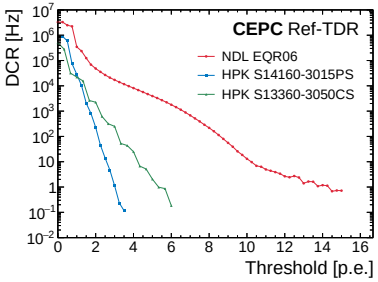


Take Home Message: Uniformity

- 40 cm: $\frac{\text{Max}-\text{Min}}{\text{Mean}} = 1.5\,\%$, $\frac{\text{Std.Dev}}{\text{Mean}} = 0.4\,\%$
- 60 cm: $\frac{\text{Max}-\text{Min}}{\text{Mean}} = 10.5\,\%$, $\frac{\text{Std.Dev}}{\text{Mean}} = 3\,\%$
- In both cases, resolution degrades at sub-percent level;

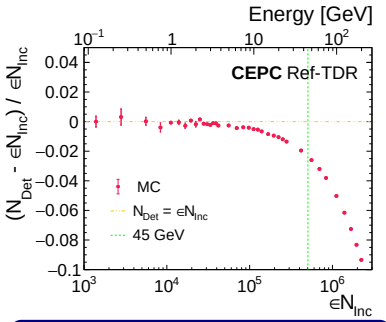
SiPM Properties

- SiPM choice critical:
  - → dark noise rates;
  - → rise time of pulse;
  - → saturation effects;
- NDL EQR06:
  - → 6 μm pixel
  - → 240,000 pixels
- HPK S14160-3010PS:
  - → 10 μm pixel
  - → 90,000 pixels



Take Home Message:
Dark Count Rate vs Energy Threshold

- DCR of NDL SiPM considerably higher than Hamamatsu;
- DCR 1 Hz @ 0.1 MIP cut - **negligible**



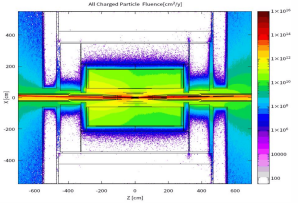
Take Home Message:
Saturation Simulation

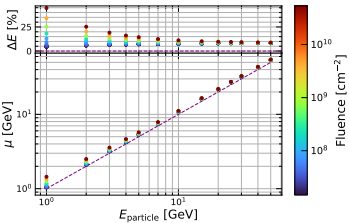
Where N_{inc} corresponds to 45 GeV

- NDL EQR06
  - → 2.4 % deviation
- HPK S14160-3010PS at 45 GeV
  - → 31 % deviation

SiPM Radiation Damage Studies

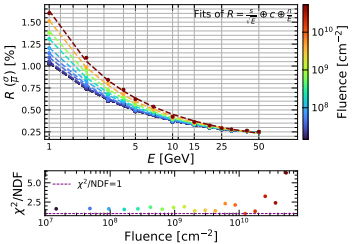
- Electron shower simulation combined with SiPM dark count simulation;
- Key figures-of-merit for energy response studied as a function of DCR (fluence);
- Studied up to $\Phi \sim 5 \times 10^{10}\,\mathrm{cm}^{-2}$
- **Paper: 2502.15353**





Take Home Message: Linearity

- Severe degradation in linearity of response at $< 10\,\mathrm{GeV}$;
- Maximum: 45 % deviation of 1 GeV showers at max. fluence;

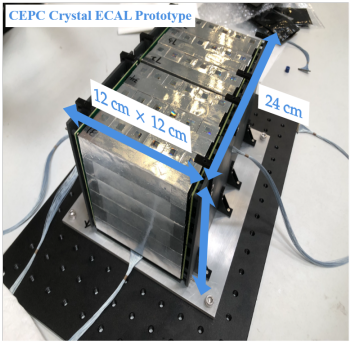


Take Home Message: Resolution

- Degradation in stochastic resolution term of around $0.5\,\%/\sqrt{\mathrm{GeV}}$

Prototype Design

- **A small ECAL prototype was designed**
- **Prototype utilises:**
  → BGO crystal;
  → support structure;
  → heat disappation system;
  → trigger system;
- **Dimensions:**
  12 cm × 12 cm × 24 cm
  → 95 % containment of 10 GeV e-showers;
- **Resolution**:
  Geant 4 simulation
  Prototype: $1.55\,\%/\sqrt{\mathrm{GeV}} \oplus 0.36\,\%$
  Full Module: $1.19\,\%/\sqrt{\mathrm{GeV}} \oplus 0.20\,\%$

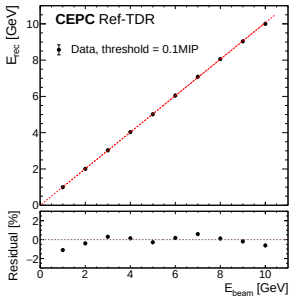


Take Home Message

The ECAL design is sufficient for further R&D efforts to evaluate the performance;

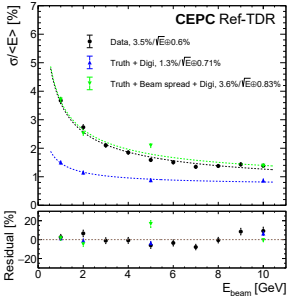
Prototype At Testbeam

- 1-10 GeV e^- at CERN PS-T9 in 2024;
- Linearity & resolution measured;
- **Caveat: Upstream instrumentation**
  → Cherenkov detectors (XCET), SciFi trackers (beam profiles)
  → beam spread, resolution degraded
  → beamline simulation required
  → influence estimated/'removed'



Take Home Message: Linearity

- Linear response within 1 %
- Large error bars → 'bug'



Take Home Message: Resolution

- Resolution, inc. digitisation → $1.31\,\%\sqrt{\mathrm{GeV}} \oplus 0.71\,\%$
- Data and MC are close when BIB is included;

Conclusion

- **Hardware:**
  - Effective design and testing ECAL prototype.
  - Studied and simulated performance of crystal and SiPMs;
- **Software:**
  - CyberPFA achieves a BMR of 3.87% $\rightarrow$ achieves the requirements of CEPC
- **Future Endeavours:**
  - Develop full-scale prototype; confirm with precise beam tests.
  - Perform radiation studies of SiPMs/crystal.
  - Develop and refine CyberPFA to further improve event reconstruction;

Cost Breakdown

System	Cost (kCHF)
Electromagnetic Calorimeter	114,968
Scintillating Crystal	105,915
SiPM	714
Electronics (FEE)	1,099
Mechanics	3,796
Cooling	96
Installation (3%)	3,349
Extra cost for back-end electronics	2,780