Development of a Highly Granular Crystal ECAL for CEPC

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On Behalf of CEPC Calorimeter Working Group

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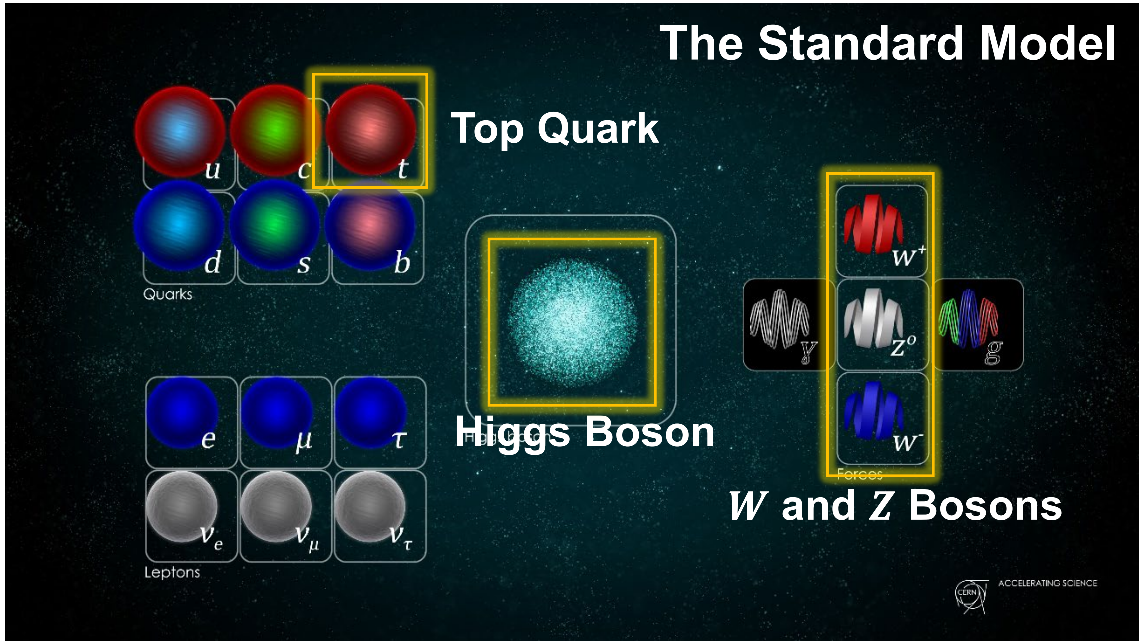
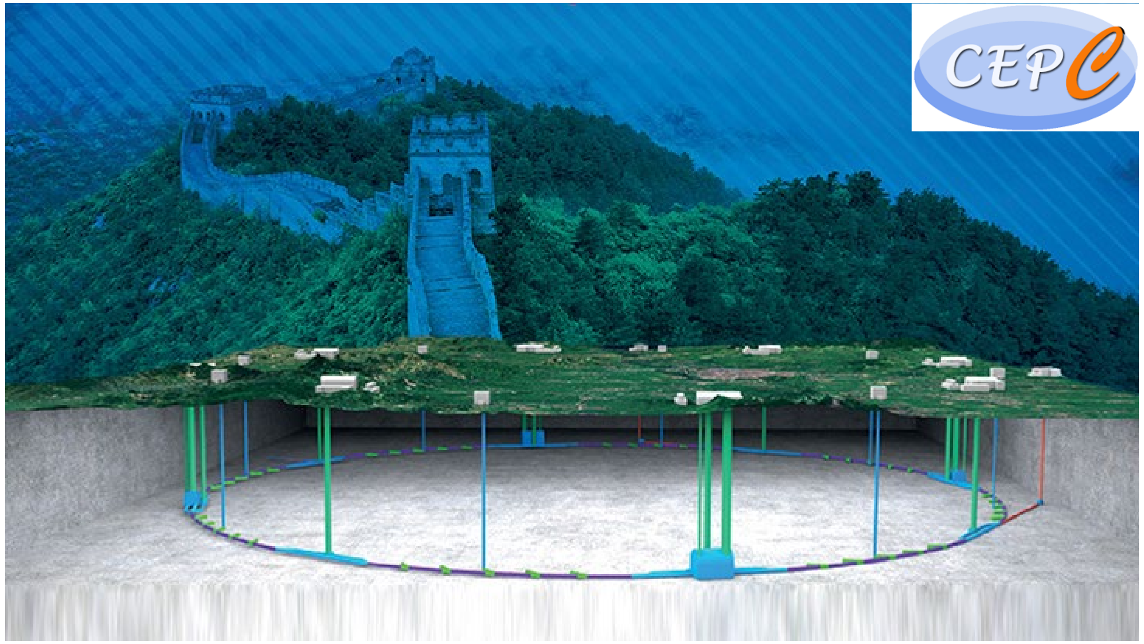
CEPC as a Higgs Factory

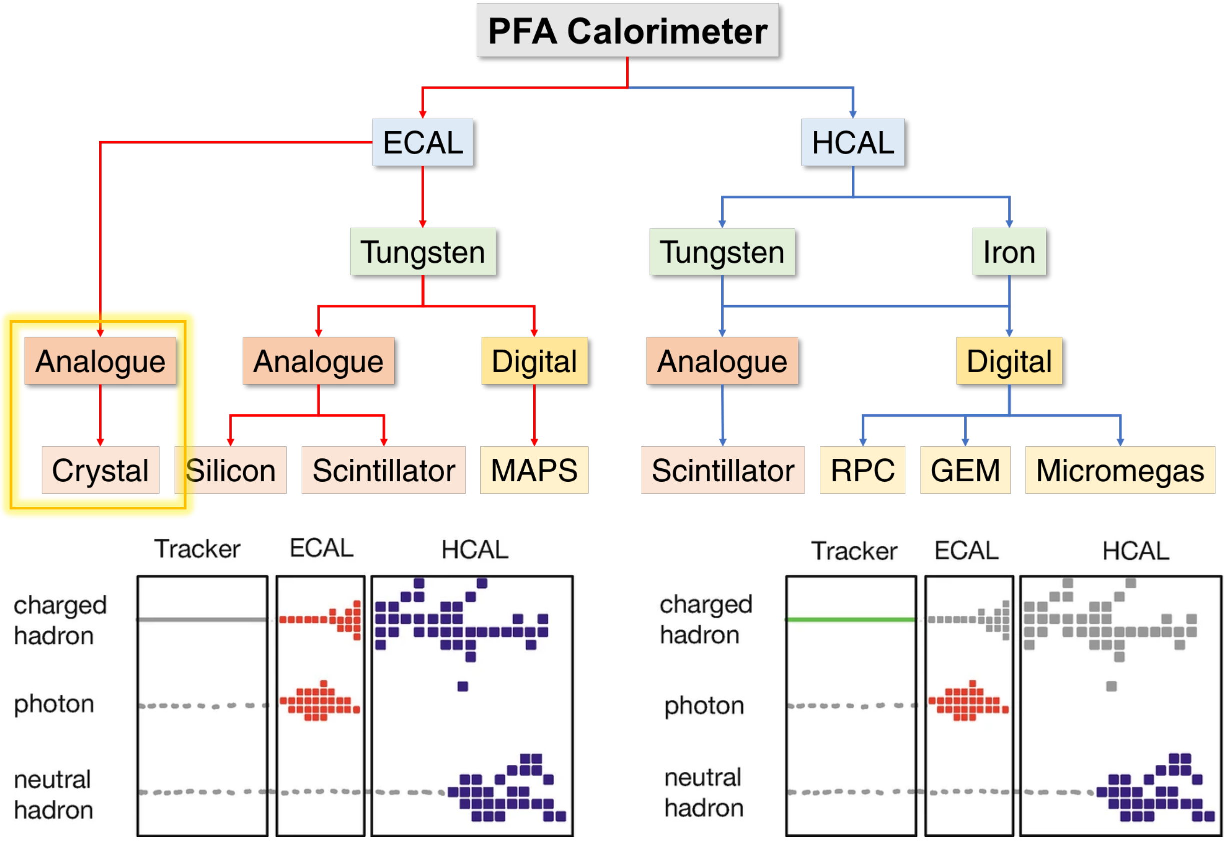
- CEPC studies **the Higgs boson**, and uses it to explore new physics BSM.
- CEPC will also act as ***W*/*Z* and top factories**.

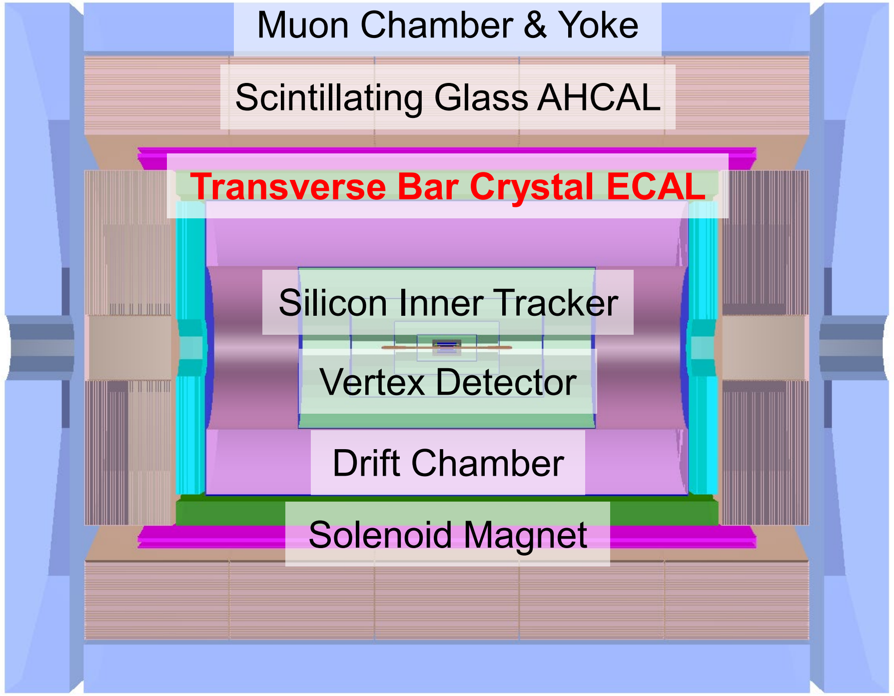




Overview of the CEPC Detector

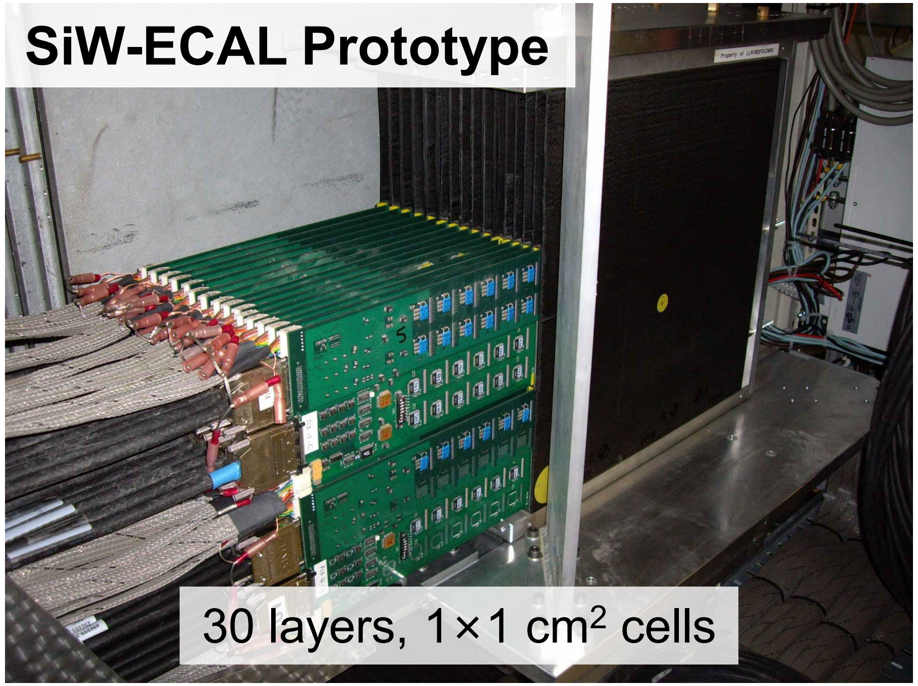
- CEPC requires a boson mass resolution (**BMR**) of $\mathbf{(3\text{–}4)\%}$ and jet energy resolution (**JER**) of $\mathbf{\sim 30\%/\sqrt{\mathit{E}\ [GeV]}}$.
- **The 4th detector concept**, based on particle flow algorithm (**PFA**).

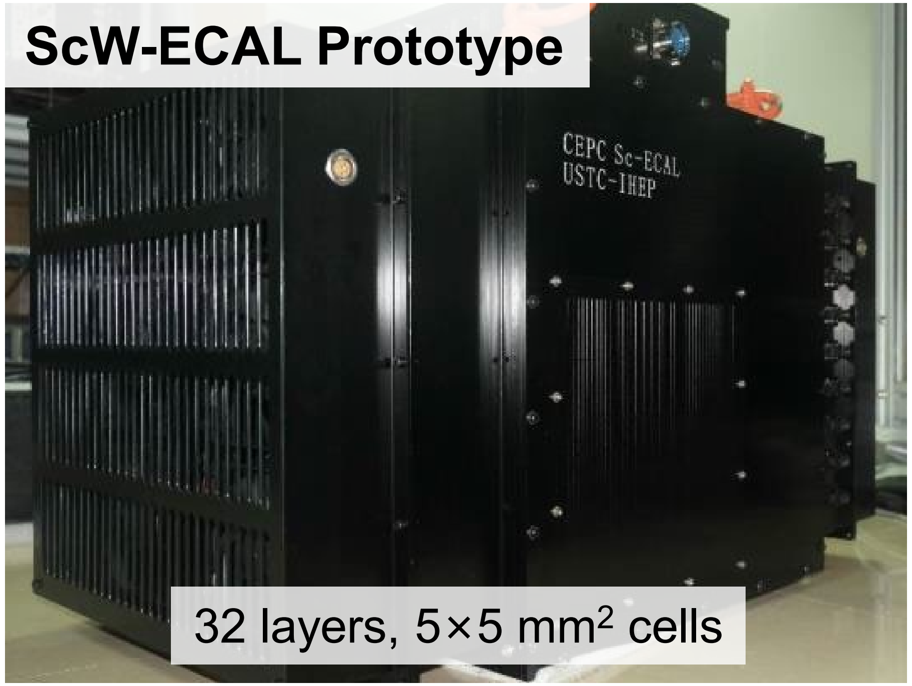




Sampling ECAL Designs

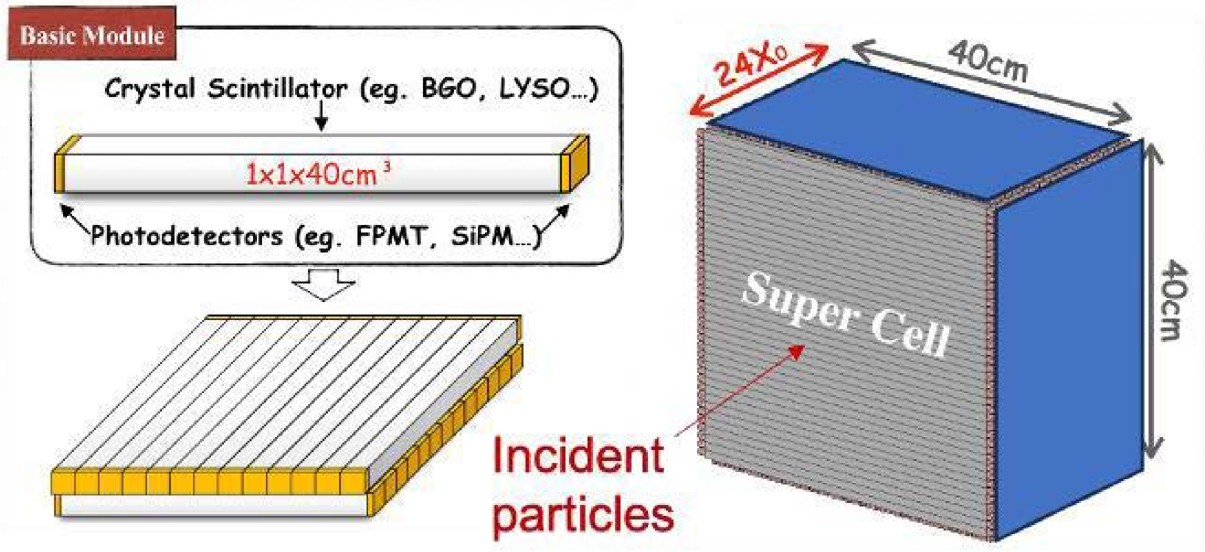
- **Two designs:** **SiW-ECAL** & **ScW-ECAL**.
- **Energy resolution:** $\mathbf{(15\text{–}20)\%/\sqrt{\boldsymbol{E}\ [GeV]}}$ (from beam tests).
- **Restriction:** not sensitive enough to photons.

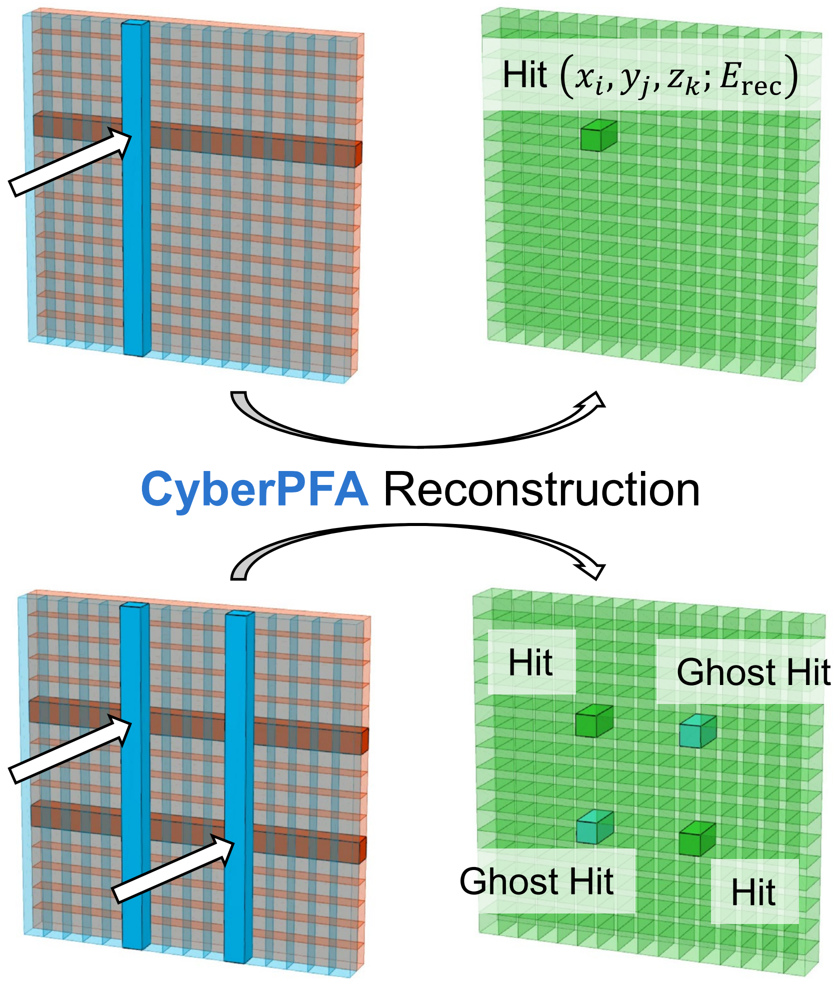




Crystals for ECAL — a New Concept

- **Intrinsic EM energy resolution:** $\sim 3\%/\sqrt{E\ [\mathrm{GeV}]} \oplus 1\%$.
- **Structure:** **crossed-bar** BGO crystals, **dual read-out** with SiPM.

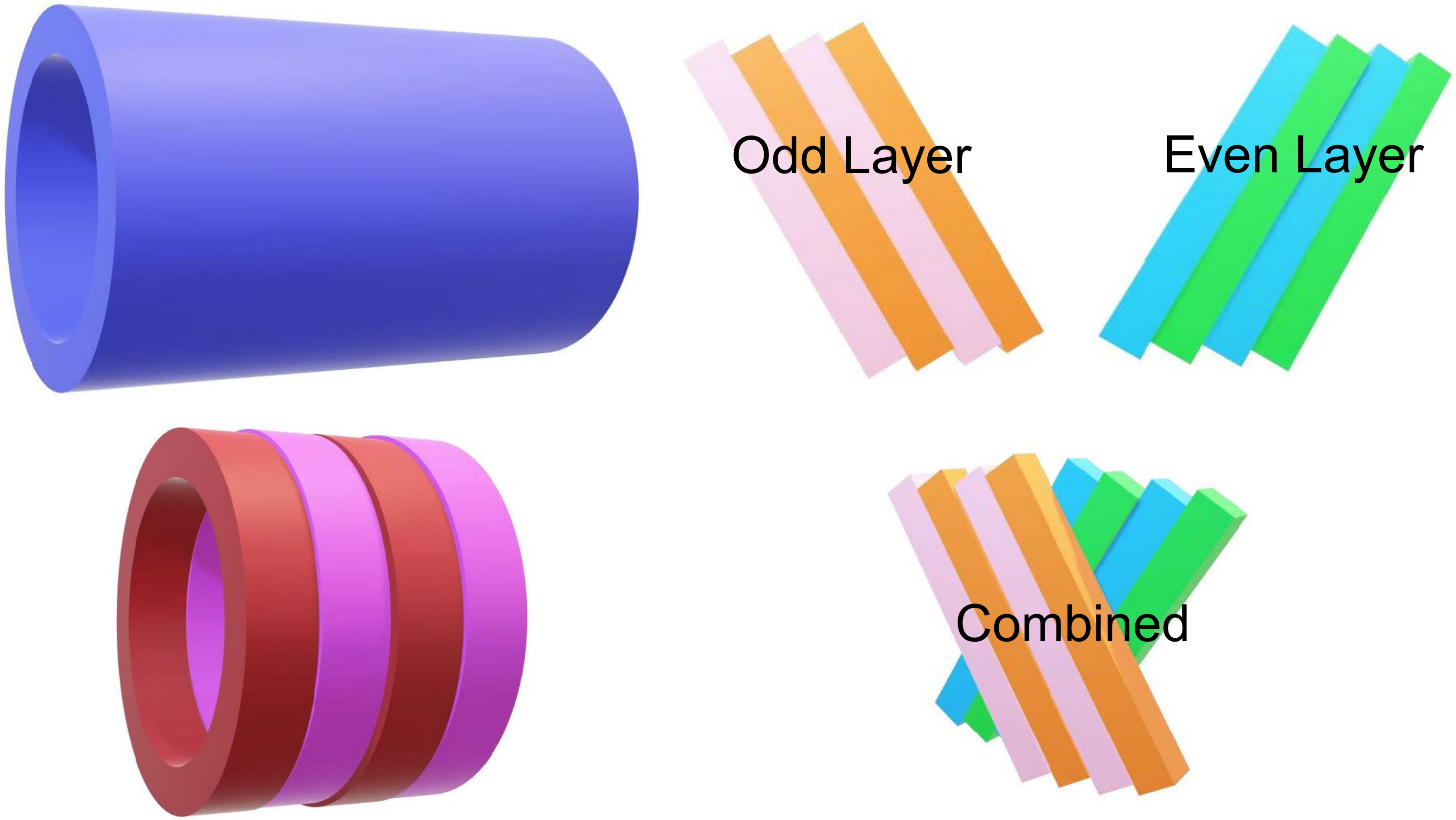


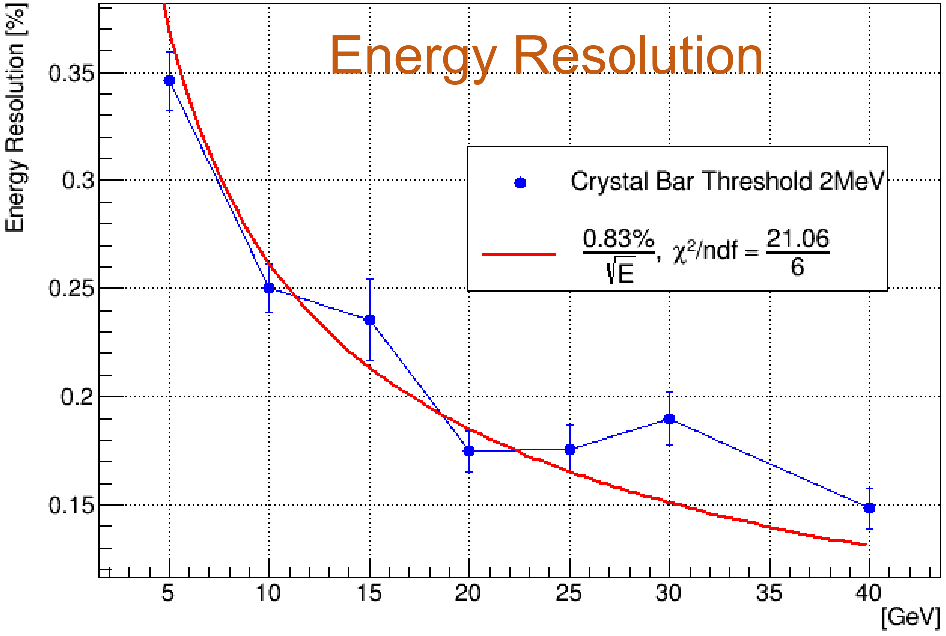


CyberPFA: https://indico.ihep.ac.cn/event/22089/contributions/168749/

Stereo ECAL — Another Proposal

- **Target:** improve 3D position resolution.
- **Preliminary results:** an energy resolution of **~0.35%** for 5 GeV photons.





Reconstruction of muon momentum: https://indico.ihep.ac.cn/event/22089/contributions/169308/

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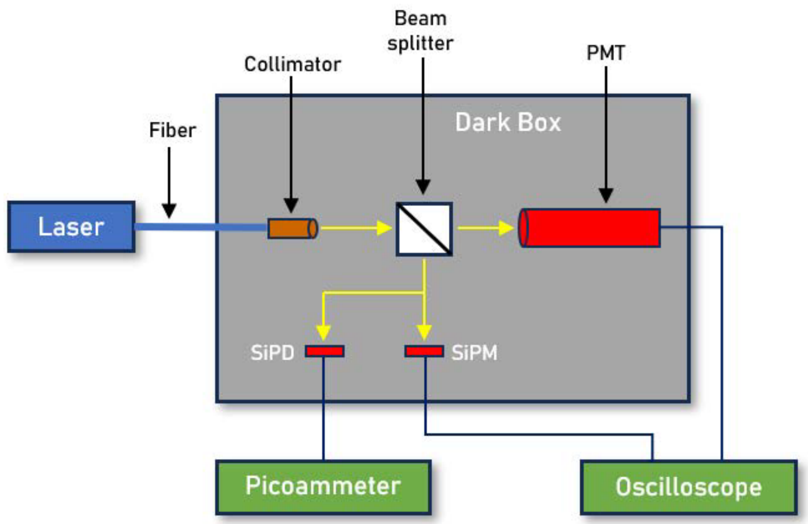
PART ONE

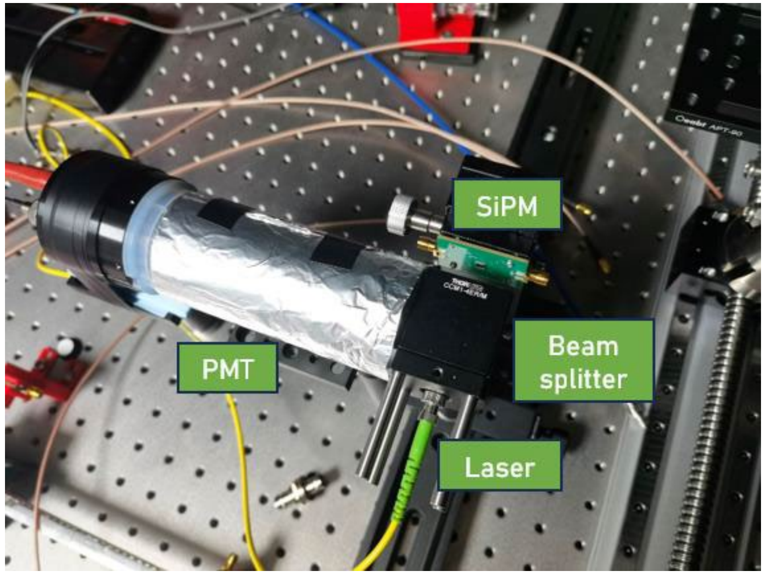
Performance Study of SiPMs & Crystals

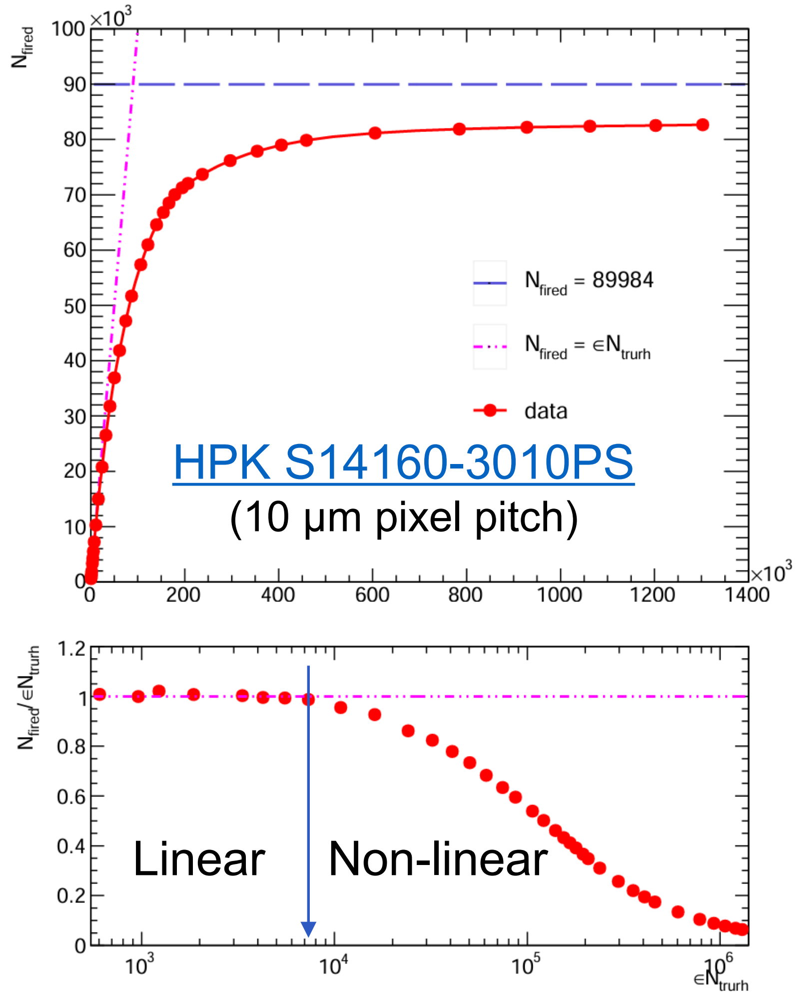
SJTU

Dynamic Range and Linearity of SiPM

- **Set-up:** pico-second laser, PMT, Si-PD, SiPM.
- **Conclusions:**
  - Saturation value is **~90%** of the pixel number.
  - Linearity ends at **~7.5×10^3 pe**.



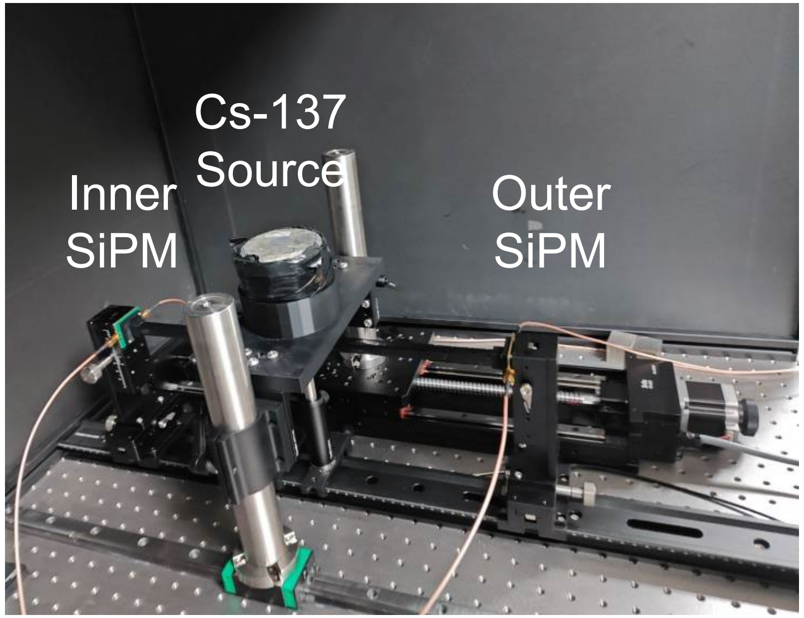


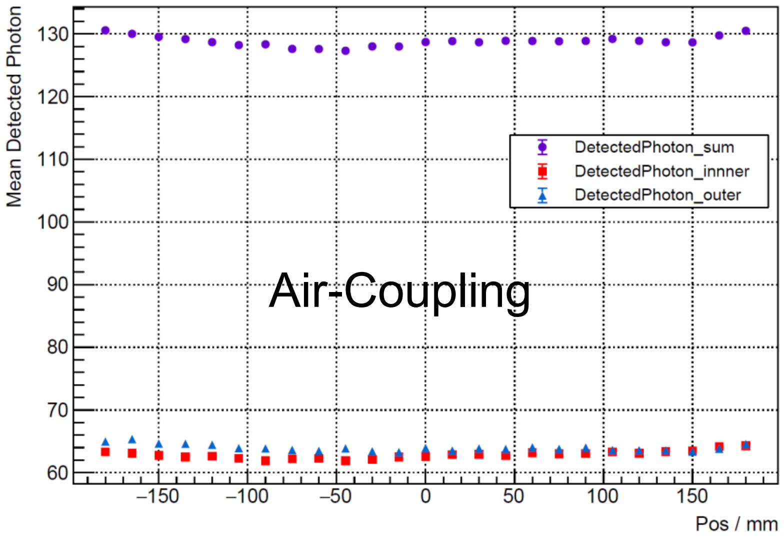


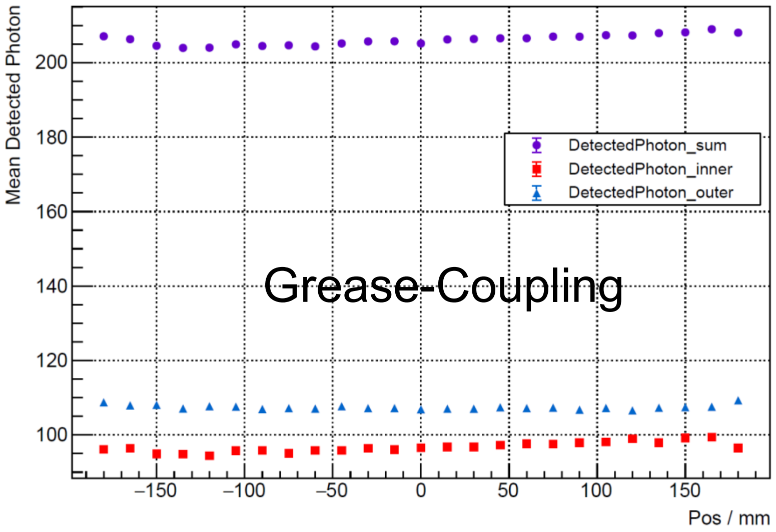
More results of dynamic range studies: https://indico.ihep.ac.cn/event/22089/contributions/169160/

Uniformity of BGO Crystal Bars

- **Set-up:** $1\times1\times40$ cm^3 BGO crystal bar, **air/grease-coupled** to SiPM, scanning with Cs-137 source (~8 mm collimator).
- **Conclusions:**
  - Good uniformity at **~2.5% level** along a single crystal bar.
  - Optical grease increases the number of detected photons by **~59%**.

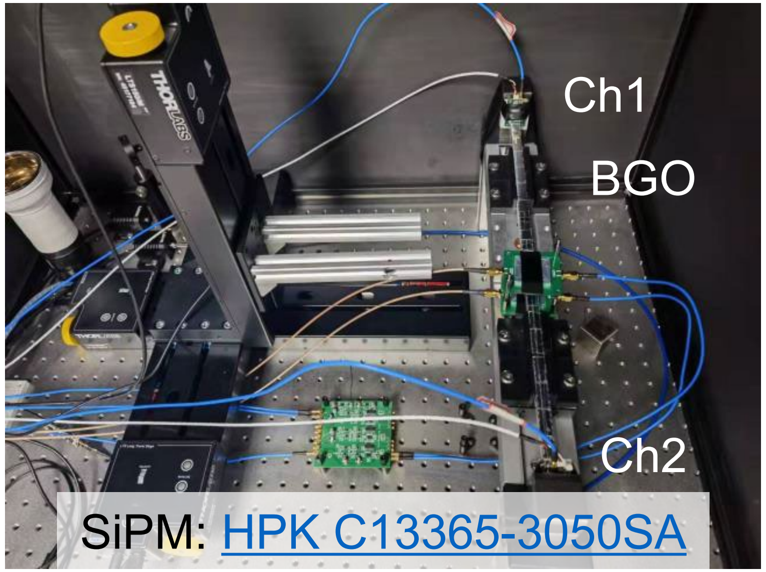


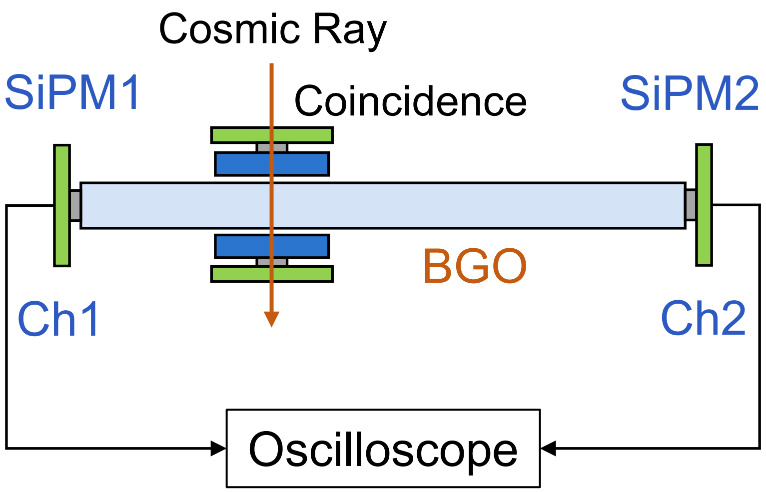


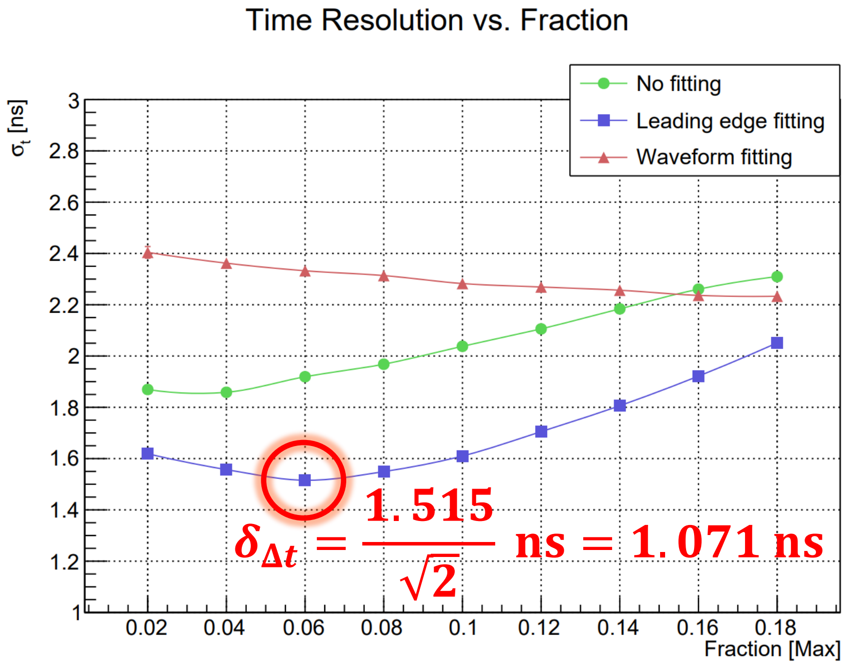


Time Resolution of BGO Crystal Bars

- **Set-up:** 1×1×40 cm^3 BGO crystal bar, dual read-out with SiPM.
- **Methods:** leading-edge fitting & constant fraction timing.
- **Conclusions:**
  - **Leading-edge fitting** yields the best time resolution.
  - Time resolution of **~1 ns** at **1 MIP signal level**.





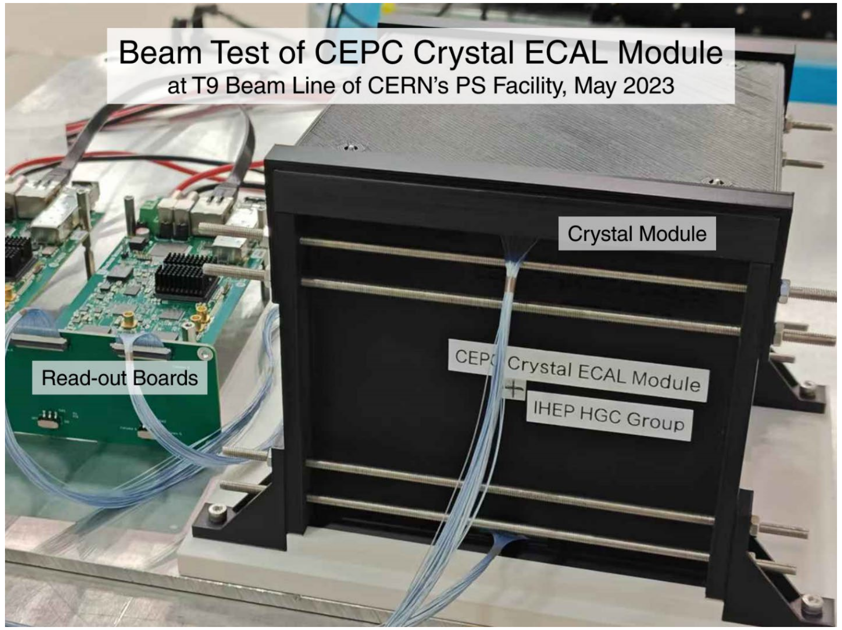


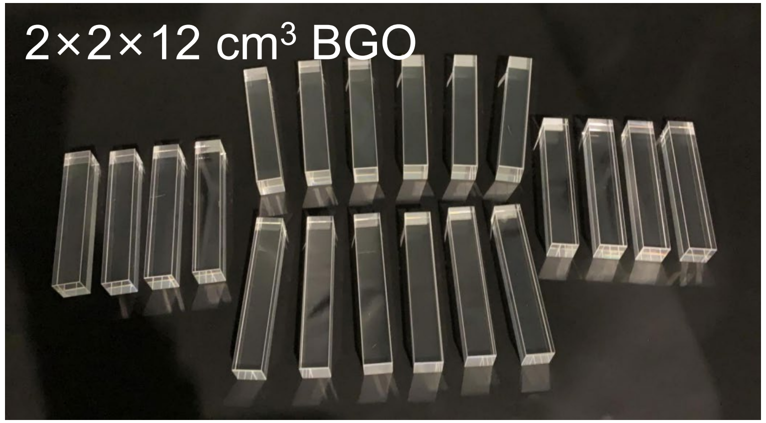
$$\delta_{\Delta t} = \frac{1.515}{\sqrt{2}} \text{ ns} = 1.071 \text{ ns}$$

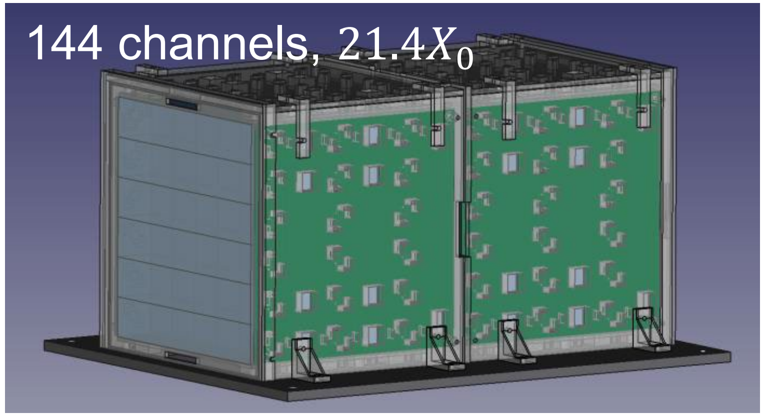
More results of timing studies: https://indico.ihep.ac.cn/event/22089/contributions/169159/

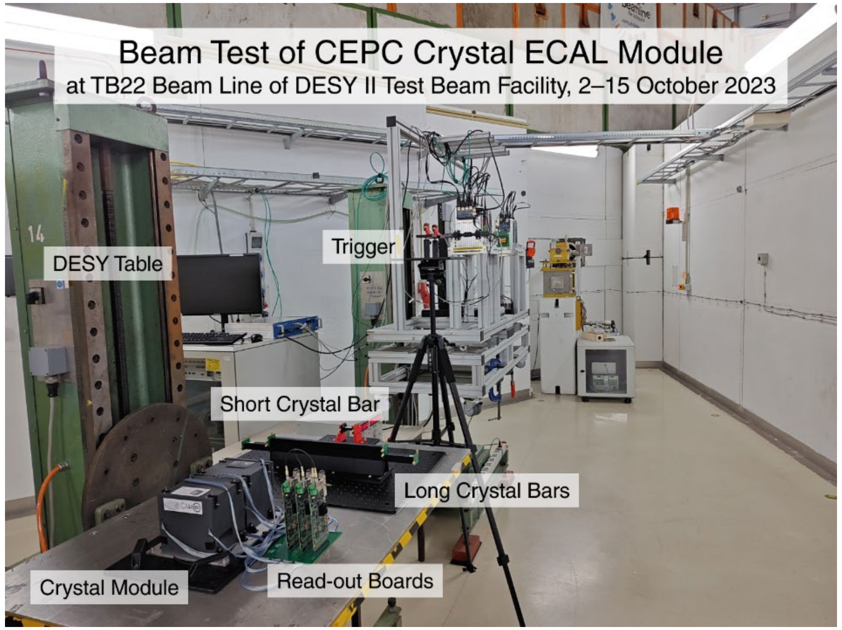
Overview of the 2023 Beam Tests

- **At CERN in May:** small-scale crystal module ($10.7X_0$).
- **At DESY in October:** module with **twice thickness** ($21.4X_0$), crystal bars of different sizes.



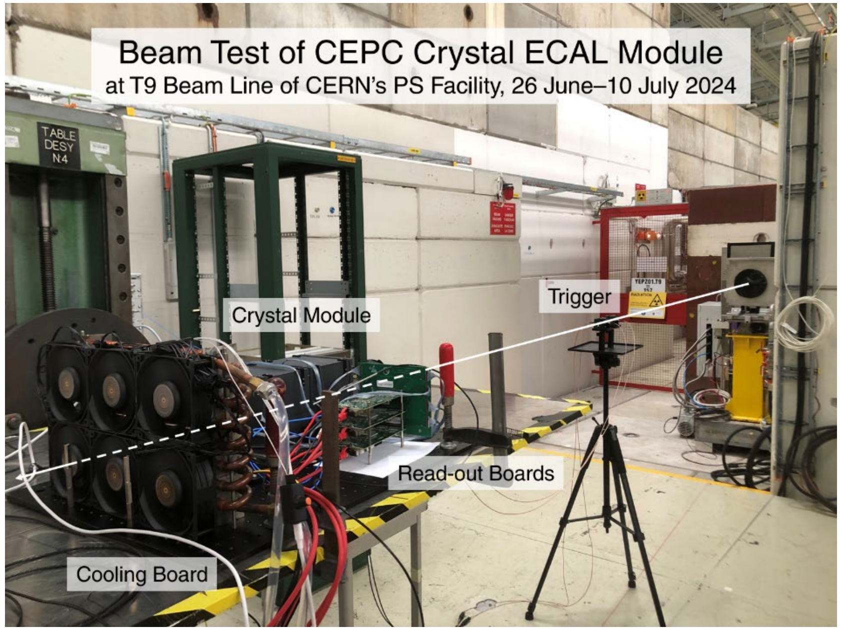


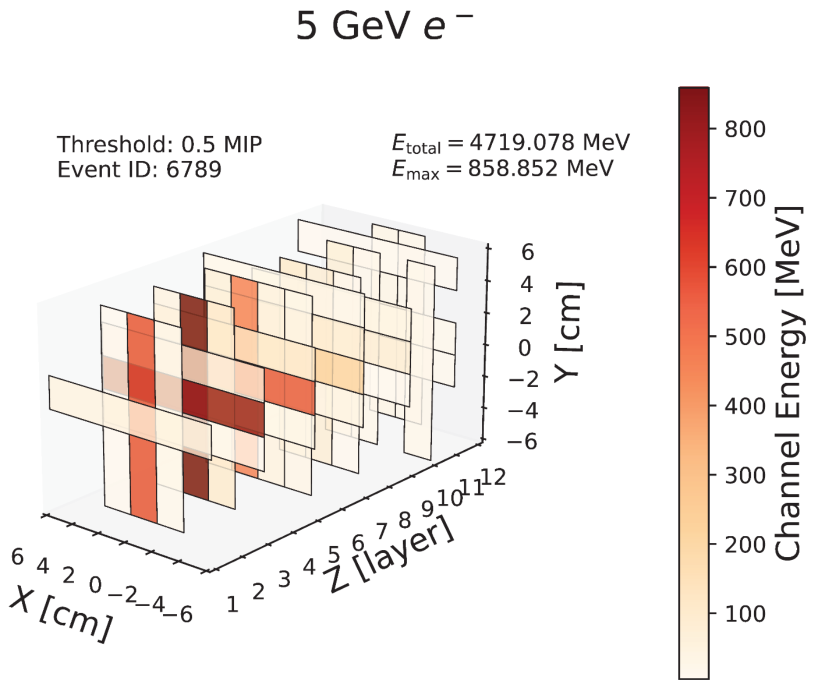


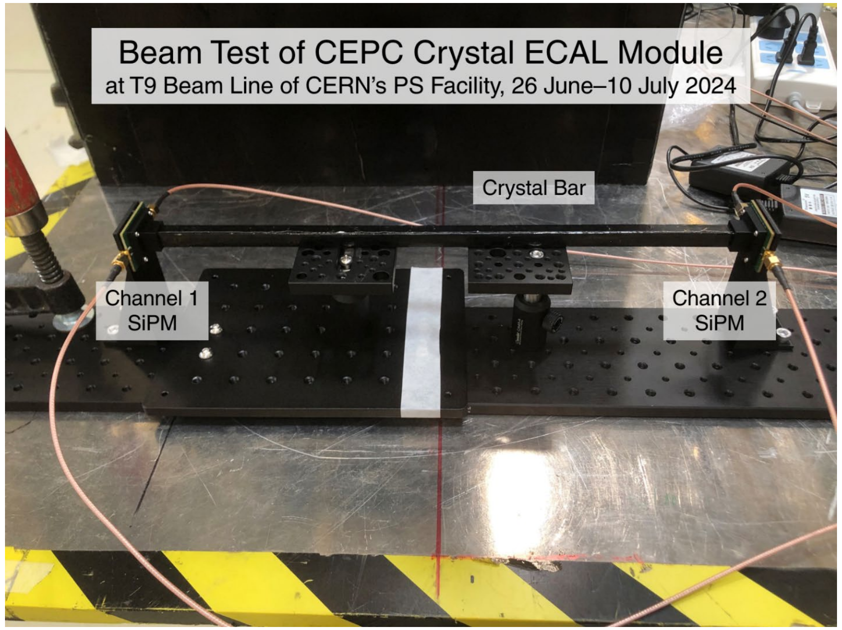


Overview of the 2024 CERN Beam Test

- **Set-up:** crystal module, crystal bars, external trigger, water-cooling board.
- **Targets:**
  - Study the **EM energy resolution** of the crystal module.
  - Study the **time resolution** of single crystal bars of different sizes.







Results of beam tests: https://indico.ihep.ac.cn/event/22089/contributions/169161/

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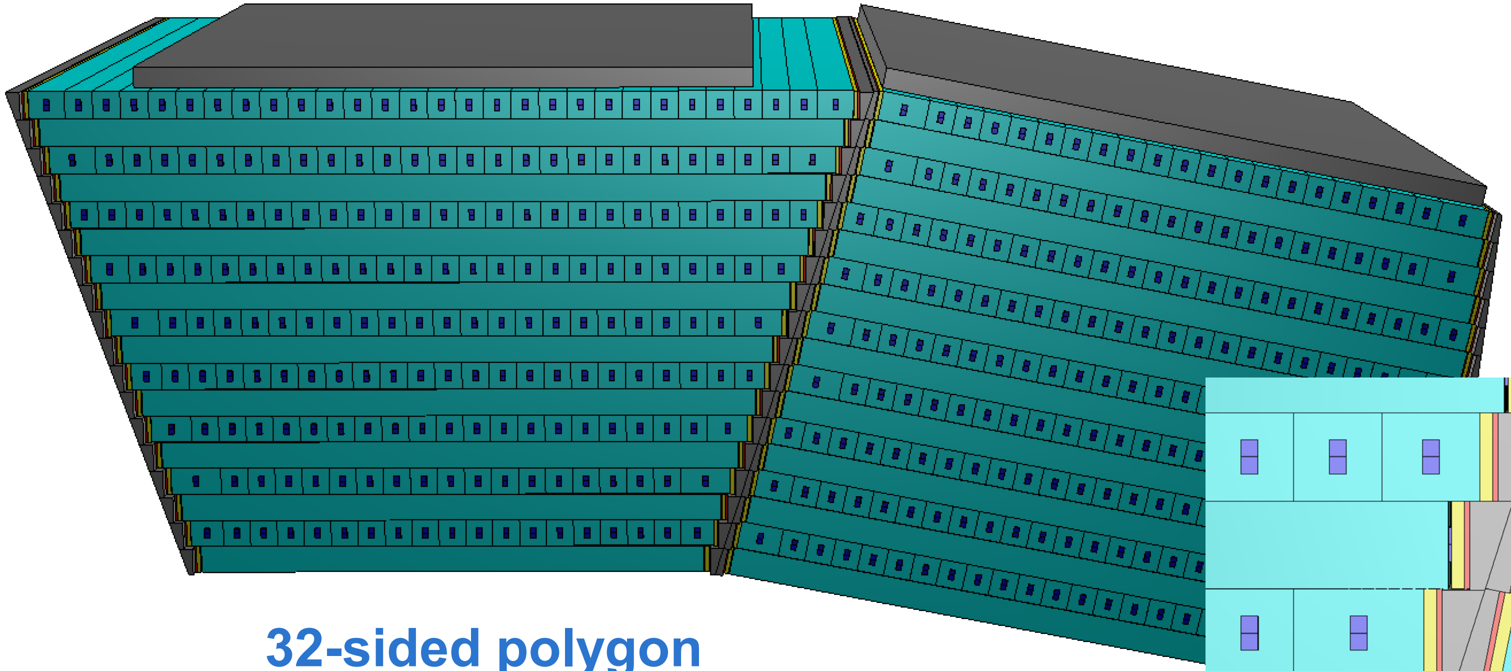
PART TWO

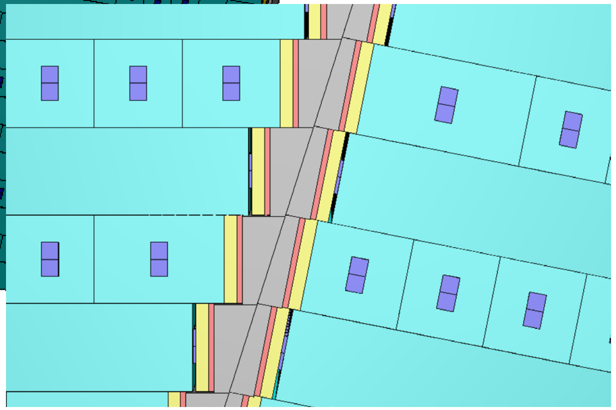
Simulation & Reconstruction with CEPCSW

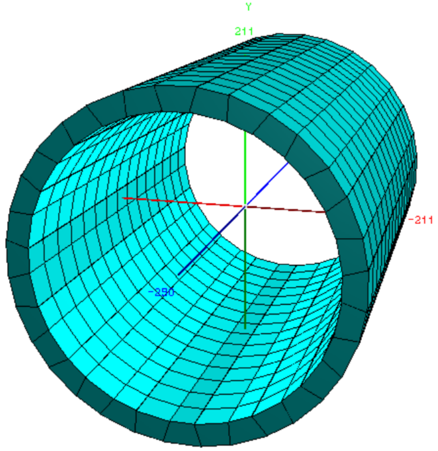
Realisation of Crystal ECAL in CEPCSW

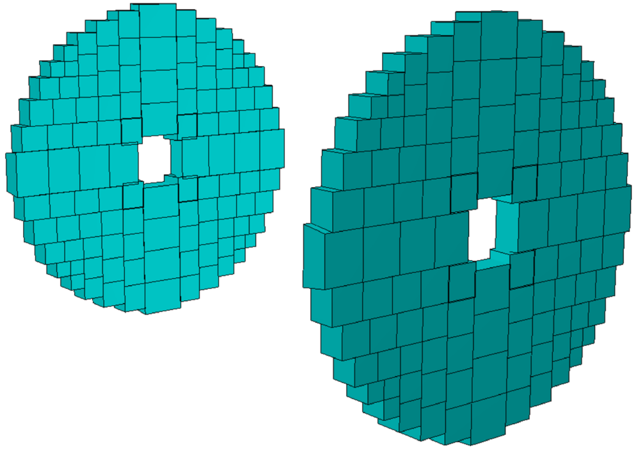
- **Targets:** maximise E_{dep} in crystals; avoid cracks pointing to IP.
- **Dead materials:** ESR, PCB, SiPM, carbon fibre, cooling plate.



32-sided polygon







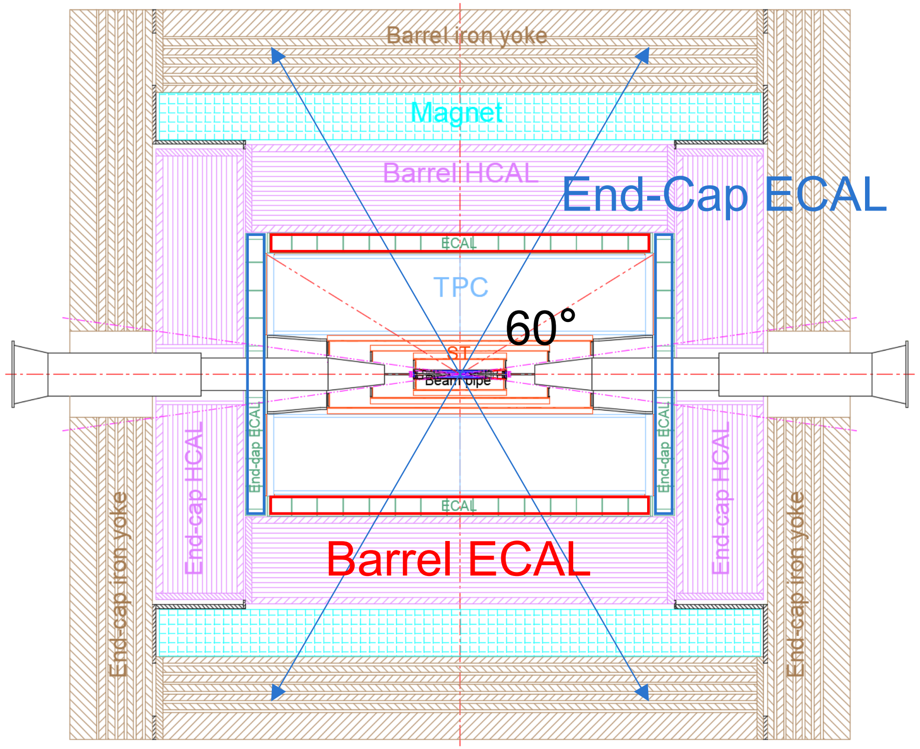
Specifications of Crystal ECAL

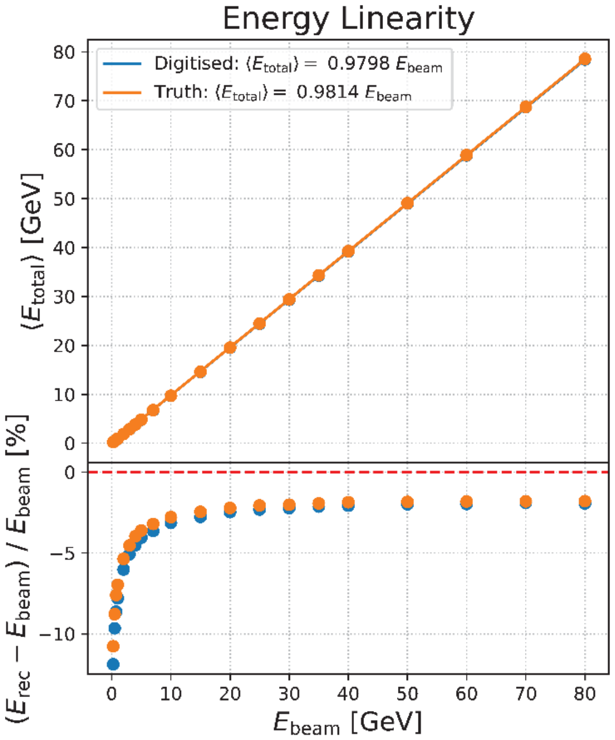
- **Additional issues:** linearity of SiPM, radiation damage, attenuation in crystal bars, photon detection efficiency, etc.

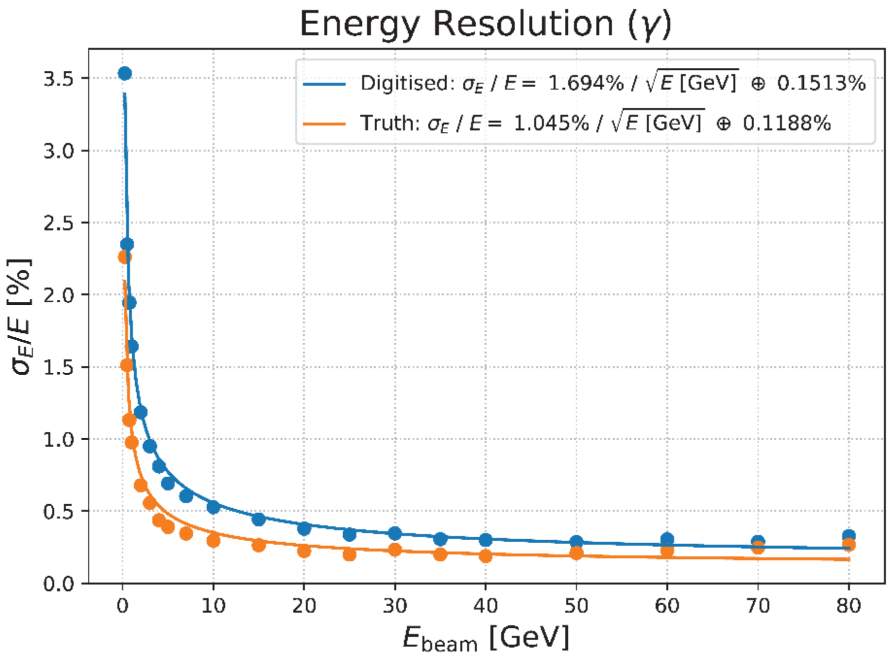
Key Parameters	Value	Remarks
MIP Light Yield	~200 pe/MeV	8.9 MeV/MIP in 1 cm BGO
Energy Threshold	0.1 MIP	Depends on S/N and light yield
Crystal Non-Uniformity	< 1%	Along the crystal and among the crystals
Dynamic Range	(0.1–3000) MIP/channel	Up to 30 GeV per crystal bar
Time Resolution	~500 ps @ 1 MIP	Ideal performance from Geant4 simulation

Linearity and Energy Resolution

- **Set-up:** ECAL-only; **(0.25–80) GeV photon** (discrete energies), barrel region.
- **Conclusion:** good linearity (**> 10 GeV**), high energy resolution ($\mathbf{1.694\%/\sqrt{\mathit{E}\ [GeV]} \oplus 0.1513\%}$ after digitisation).

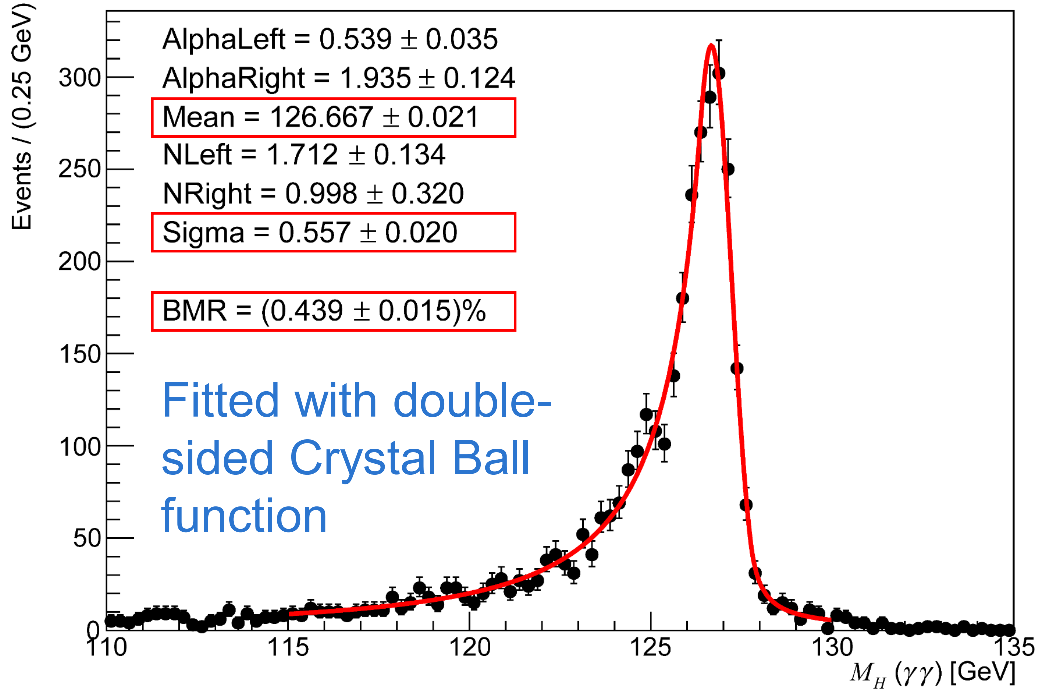






Invariant Mass in $H \to \gamma\gamma$ Process

- **Motivation:** a golden channel for precision measurements of Higgs properties.
- **Conclusion:** **BMR = (0.439 ± 0.015)%**.
- **Remark:** the performance of CyberPFA reconstruction is still being studied.



Summary & Outlook

- **Summary:**
  - Tests of SiPMs and crystals display the rationality of using crystals for ECAL.
  - Beam tests of crystal modules show the room for improvement of digitisation models.
  - Simulation within CEPCSW reveals the potential of crystal ECAL in studying physical processes with photon final states.

- **Outlook:**
  - Further studies of single SiPMs and crystals will be carried out.
  - Using beam test data, simulation and digitisation models will be better validated.
  - Performance of reconstruction with crystal ECAL in CEPCSW will be improved, and more physical processes will be studied.

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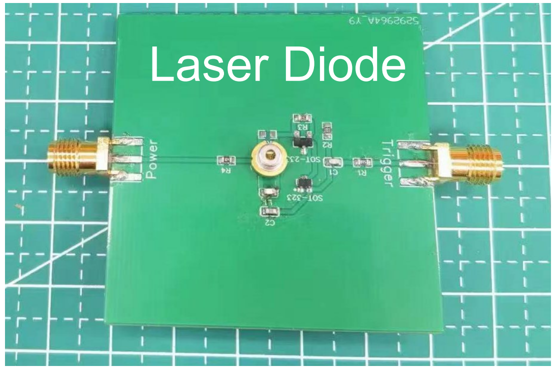
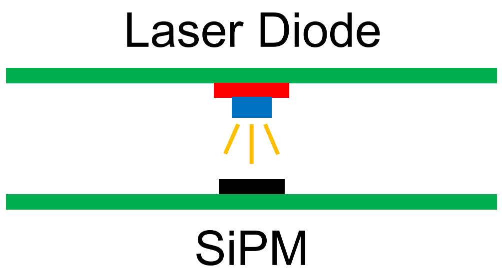
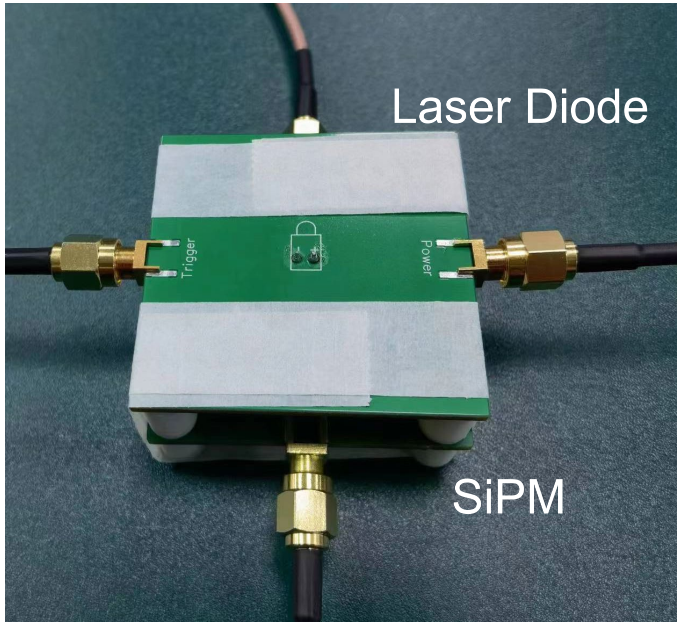
Appendix

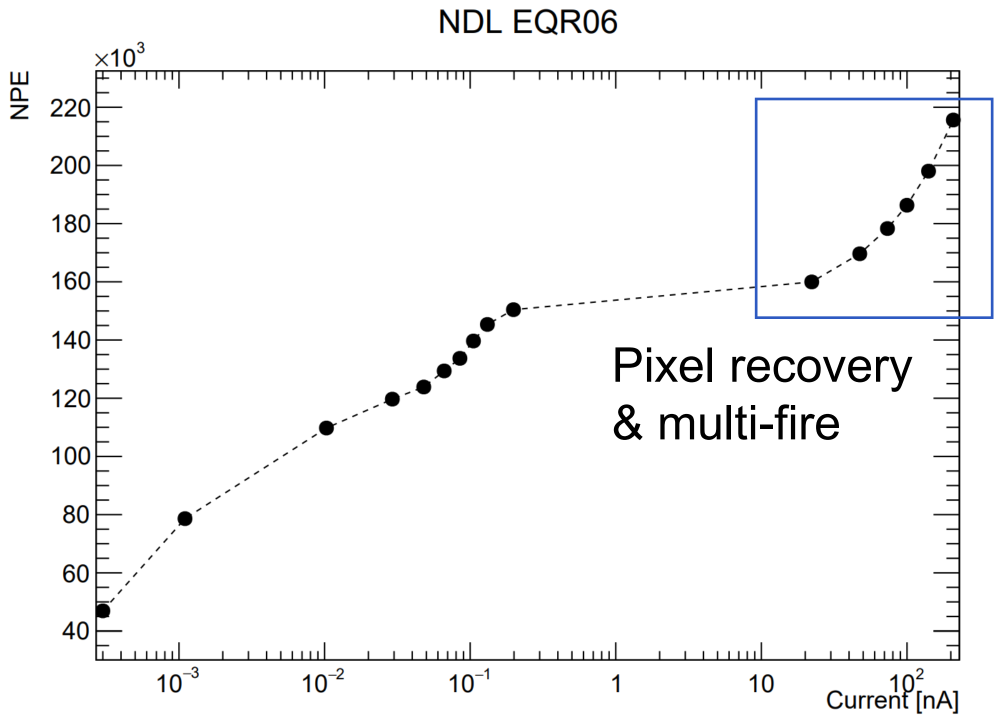
Measurements with Laser Diode

- **Laser diode** with a driver circuit: 1.6 W diode, 450 nm peak wavelength, < 5 ns pulse width, kHz trigger rate (by AWG), (0–30) V power supply.
- The pulse duration is longer than pixel recovery time.
- The number of detected pe may exceed the saturation value.



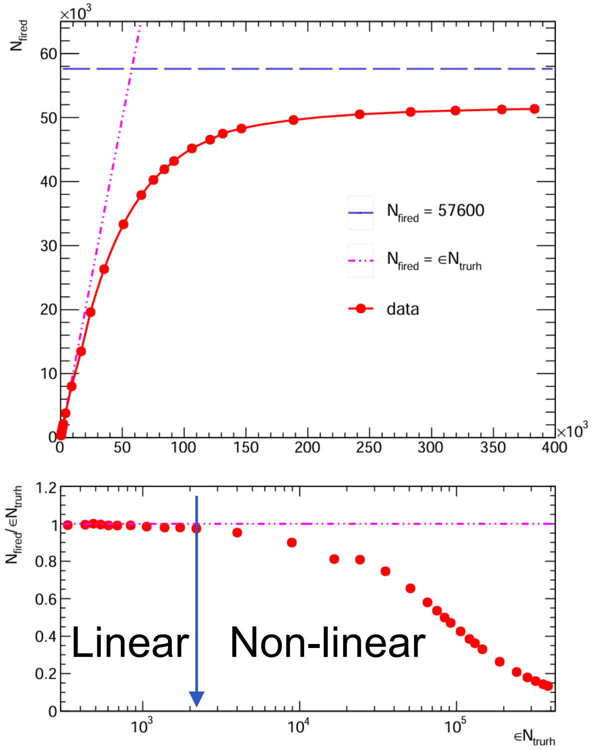




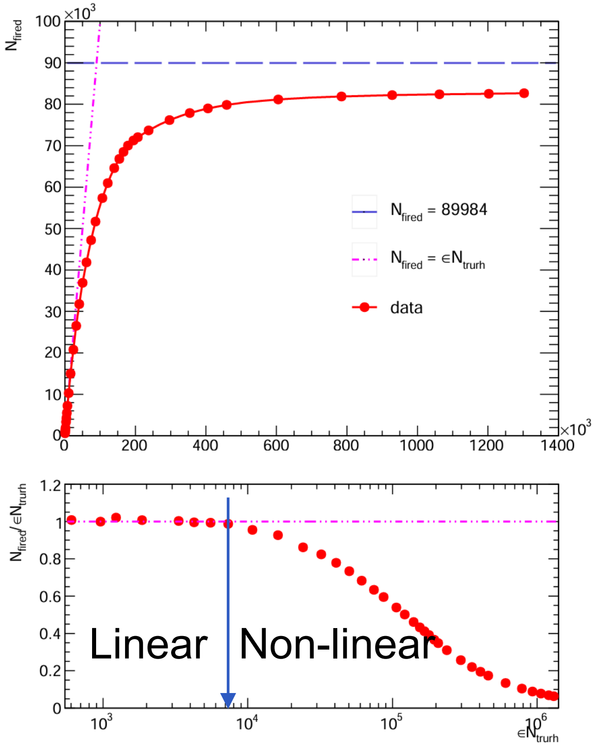


Dynamic Range and Linearity of SiPMs

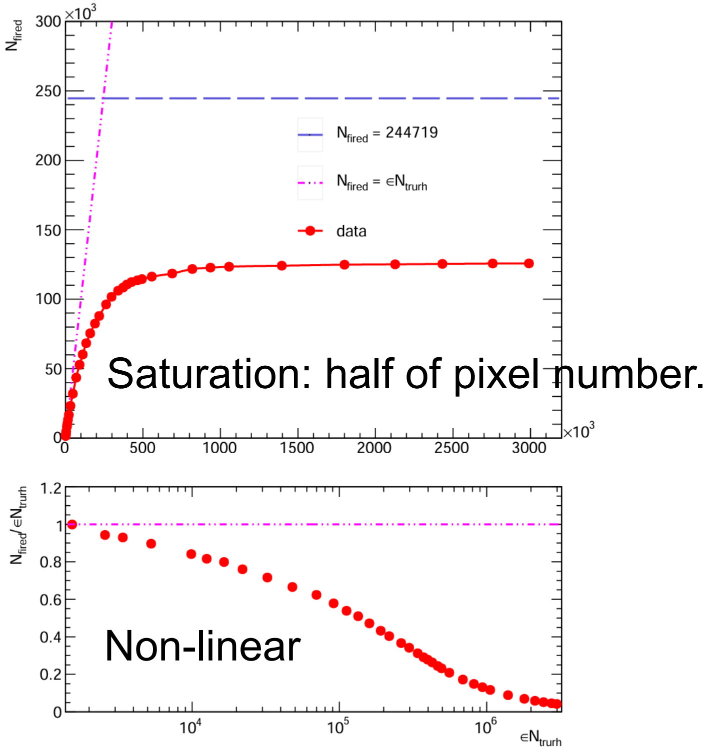
Type of SiPM	Active Area / mm^2	Pixel Pitch / μm	Pixel Number
HPK S13360-6025PE	6×6	**25**	57,600
HPK S14160-3010PS	3×3	**10**	89,984
NDL EQR06 11-3030D-S	3×3	**6**	244,719



HPK S13360-6025PE



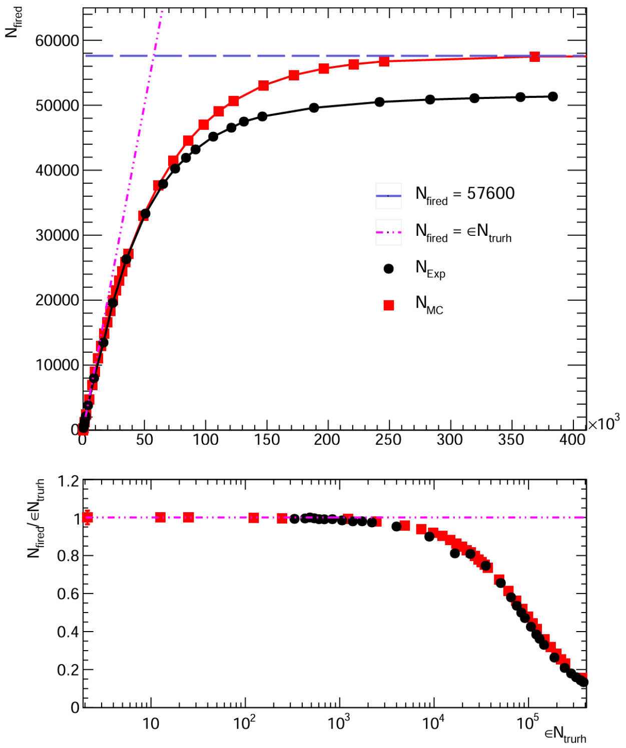
HPK S14160-3010PS



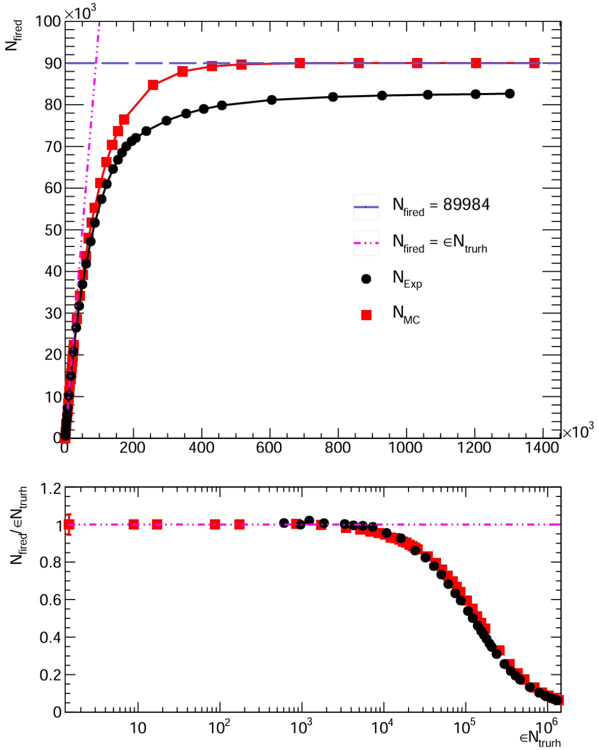
NDL EQR06 11-3030D-S

Simulation of SiPMs — Laser

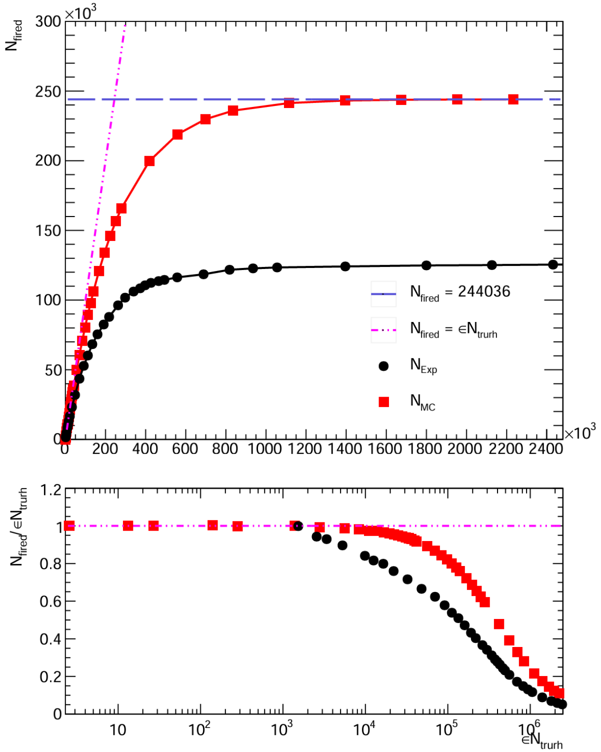
- Toy MC model with SiPM pixel density, PDE spectrum, cross-talk and BGO emission spectrum.
- MC strictly saturates to pixel number, different from experimental results; but the results reveal the trends of the experiments.



HPK S13360-6025PE



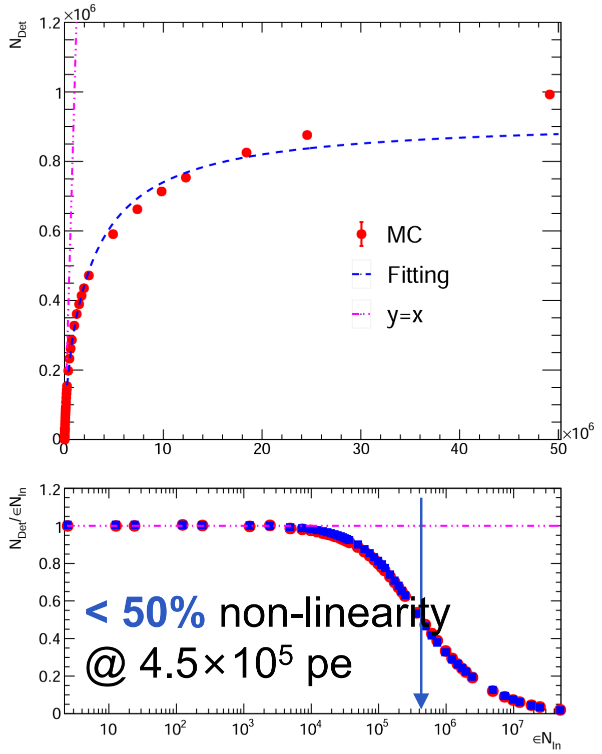
HPK S14160-3010PS



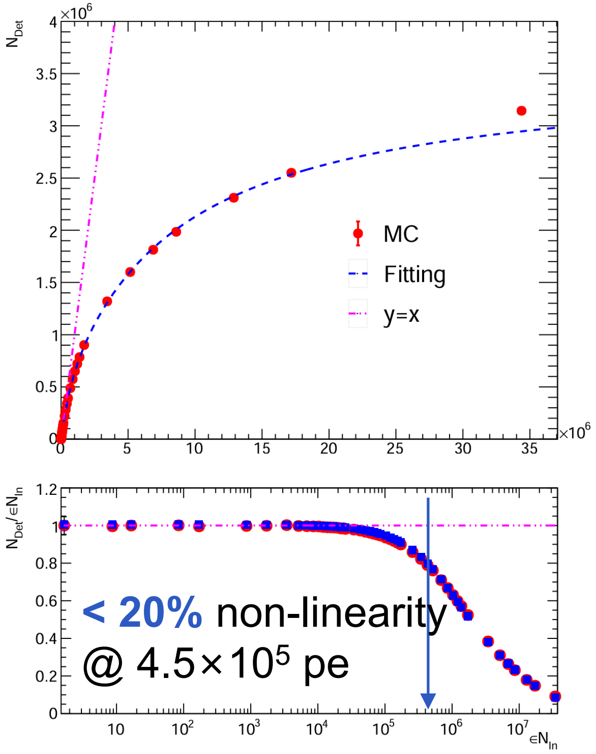
NDL EQR06 11-3030D-S

Simulation of SiPMs — BGO Scintillation

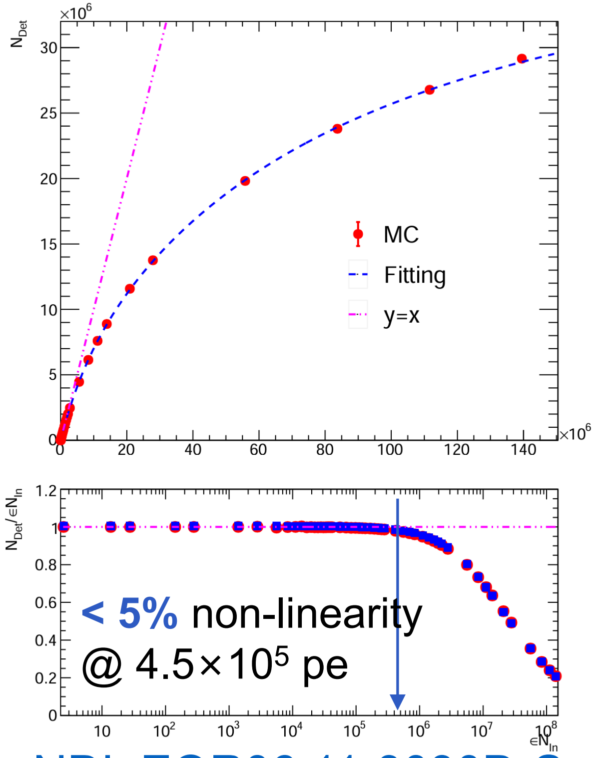
- Toy MC model with SiPM pixel density, PDE spectrum, cross-talk, waveform properties, multi-fire effect of pixels, BGO emission spectrum and detection time of scintillation photons.
- NDL EQR06 11-3030D-S shows enough dynamic range for ECAL specification.



HPK S13360-6025PE



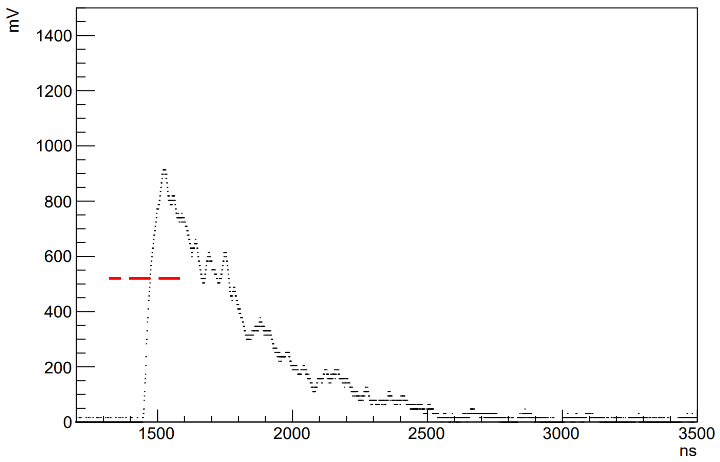
HPK S14160-3010PS



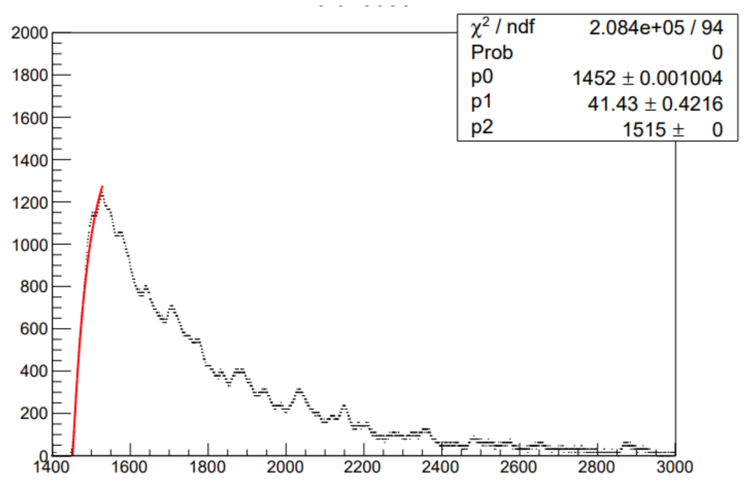
NDL EQR06 11-3030D-S

Timing Methods

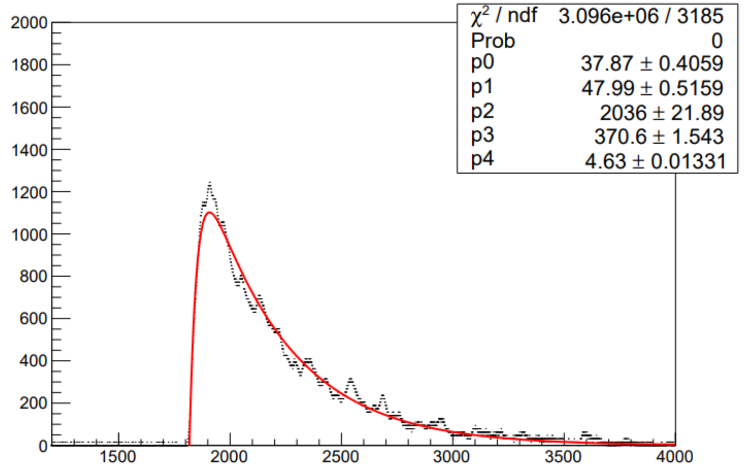
- Leading-edge fitting: $y = \left[1 - \exp\left(-\frac{x - p_0}{p_1}\right)\right] \cdot p_2$.
- Waveform fitting: $y = \left[1 - \exp\left(-\frac{x}{p_0} + 1\right)\right] \cdot p_2 \cdot \exp\left(-\frac{x}{p_3} + p_4\right)$.
- **Leading-edge fitting** yields the best time resolution.



Constant Fraction



Leading-Edge Fitting

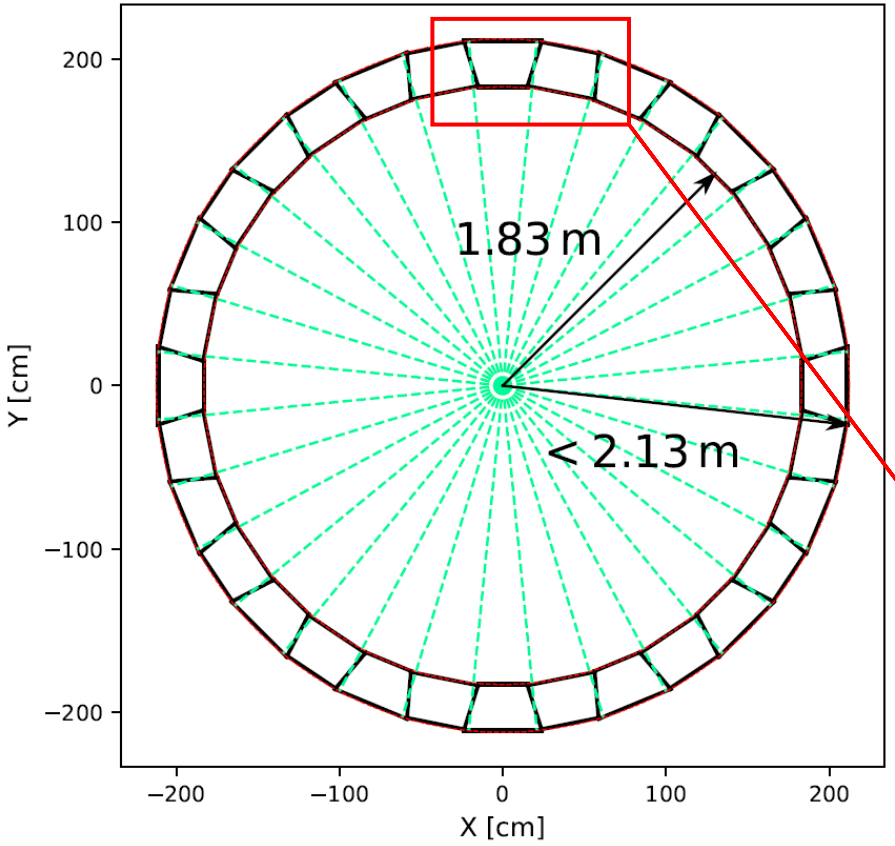


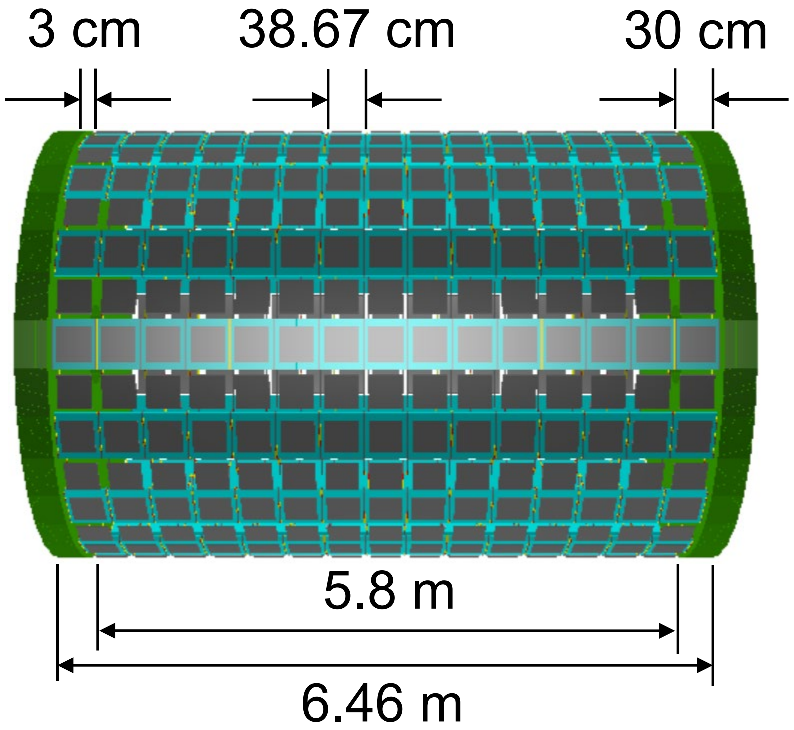
Waveform Fitting

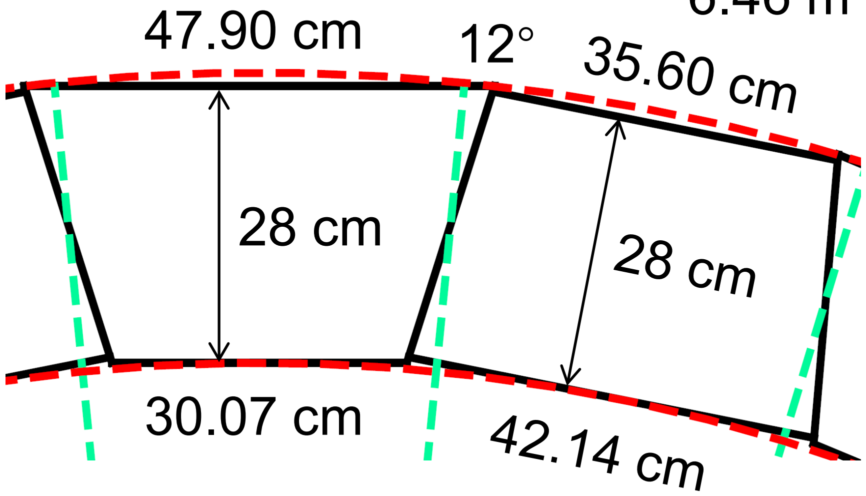
Characterising Digitisation Parameters

Category	Parameter	Value	Note	Value from the Module
Scintillation	Intrinsic Light Yield	8,200 ph/MeV	Property of BGO, (8,000–10,000) ph/MeV	8,200 ph/MeV
	Effective Light Yield	200 pe/MIP	$\mathrm{LY_{int}} \cdot \mathrm{LCE} \cdot \mathrm{PDE}$, 1×1×40 cm^3 BGO	760 or 1,340 pe/MIP (module 1 or 2)
	MIP Energy	8.9 MeV	5 GeV μ^- penetrate 1 cm BGO	17.8 MeV (2 cm BGO)
	Non-Uniformity Along Bar	0.03%	$[(\mathrm{Ch1}+2)_{\mathrm{max}} - (\mathrm{Ch1}+2)_{\mathrm{min}}]/(\mathrm{Ch1}+2)_{\mathrm{min}}$	— (< 1% in measurement)
	Difference Between Two Ends	5%	$(\mathrm{Ch1_{max}} - \mathrm{Ch2_{min}})/\mathrm{Ch2_{min}}$	— (< 1% in measurement)
	Light Collection Efficiency	1.1%	To ensure the effective light yield	3.1% or 5.4%
	Photon Detection Efficiency	25%	SiPM, NDL EQR06	17% or 30% (HPK S14160-3010/15PS)
SiPM	Active Area	3×3 mm^2	SiPM, NDL EQR06	3×3 mm^2 (HPK S14160-3010/15PS)
	Pixel Pitch	6 μm	SiPM, NDL EQR06	10 or 15 μm
	Pixel Number	244,719	SiPM, NDL EQR06	89,984 or 57,600
	DCR	2.5 MHz	SiPM, NDL EQR06	0.7 MHz
	Gain Fluctuation	8%	SiPM, NDL EQR06	5%
	Cross-Talk	12%	SiPM, NDL EQR06	0.5%
ADC	Time Window	2 μs	Assumption, depends on shaping time	87.5 ns
	Number of Gain Modes	3	Assumption	2 (CAEN A5202, Citiroc-1A)
	Dynamic Range	(0.1–4,885) MIP	Accurately measured within 30 GeV	(0.1–80) MIP
	Vertical Accuracy	13-bit, 8,192 ADC	Citiroc-1A	13-bit, 8,192 ADC
	Switching Point	8,000 ADC	Citiroc-1A	7,900 ADC
	Pedestal Position	50 ADC	Citiroc-1A	(40–80) ADC
	Pedestal Width	4 ADC	SiPM dark noise is not included	(3–10) ADC, with dark noise

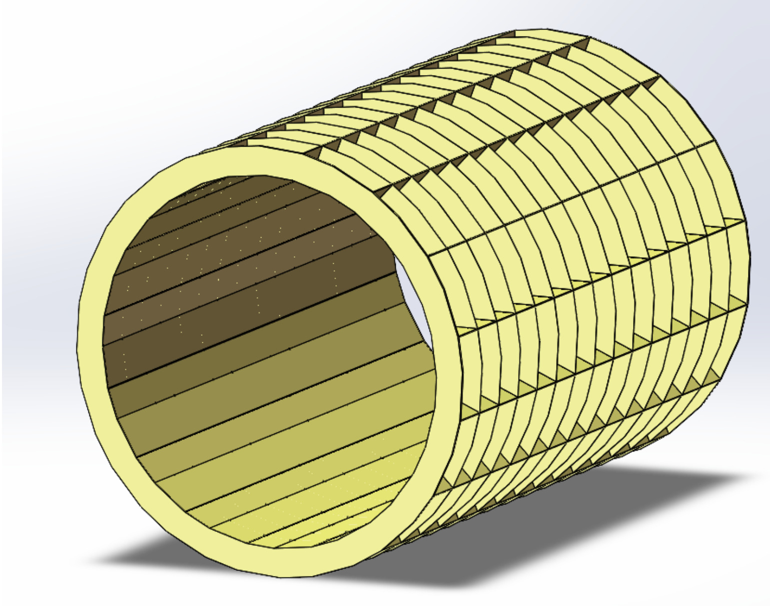
Crystal ECAL in CEPCSW — Parameters

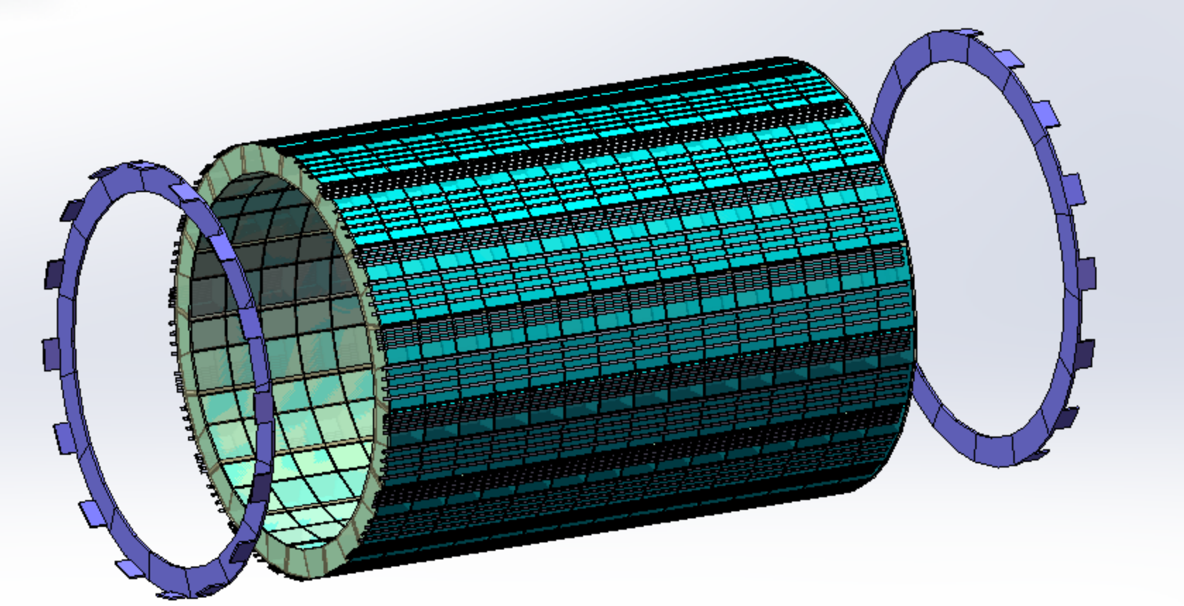


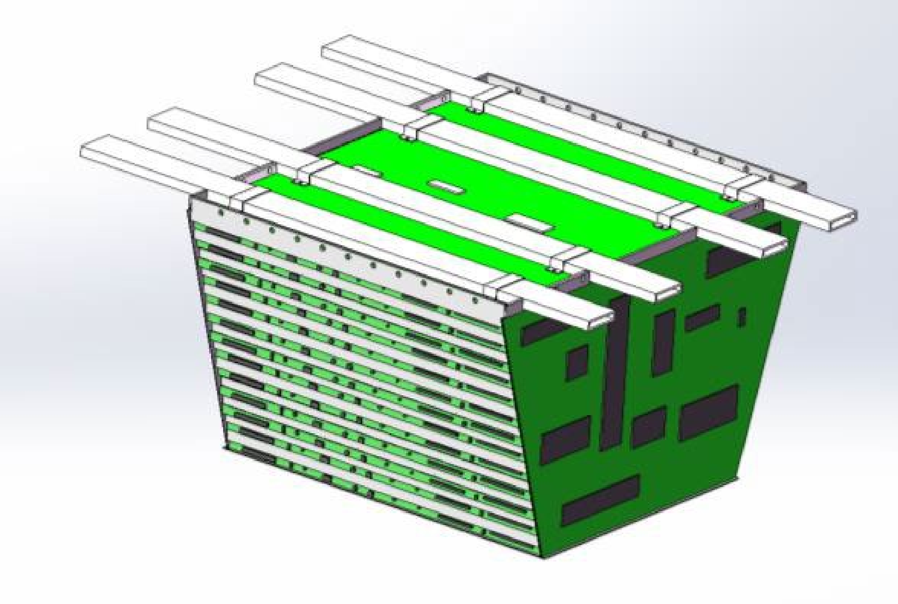


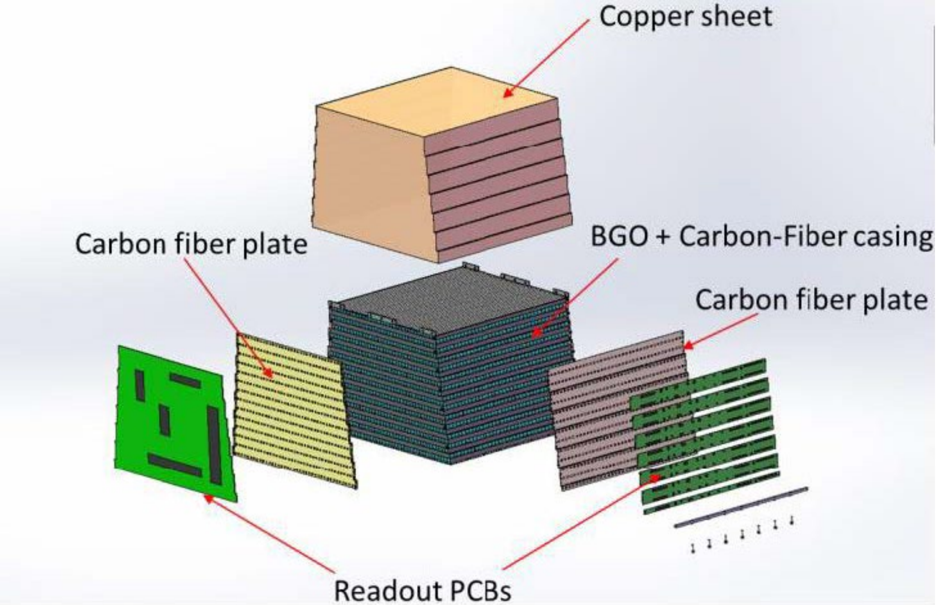


Mechanical Design of Barrel ECAL

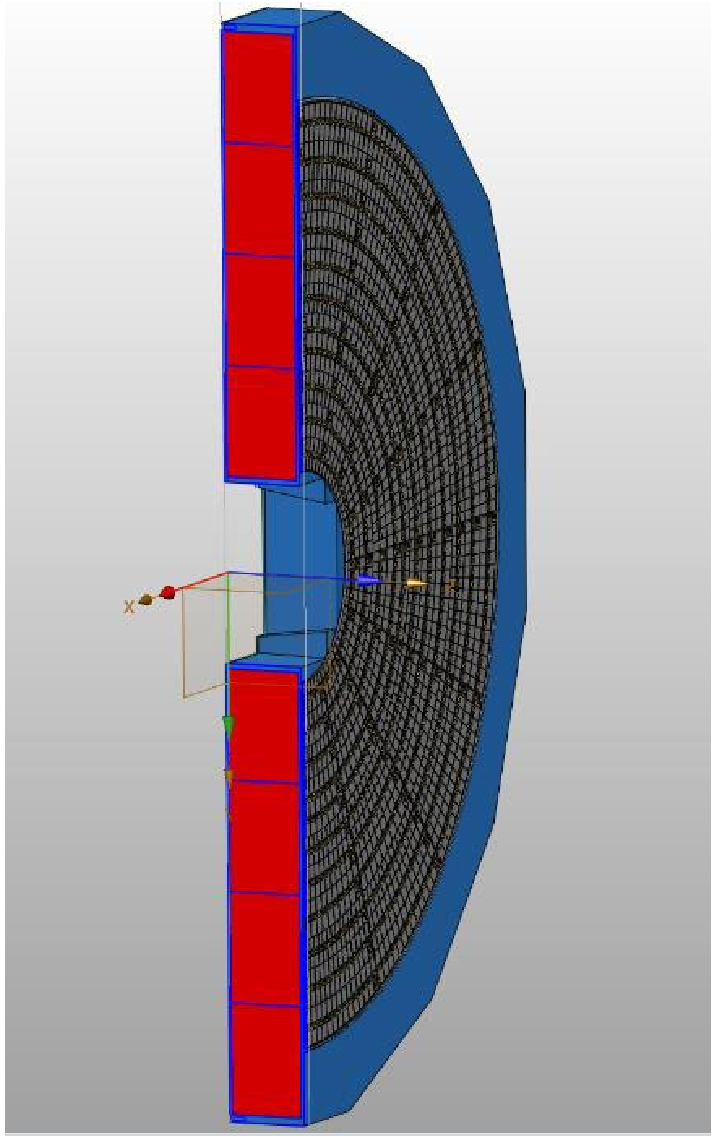


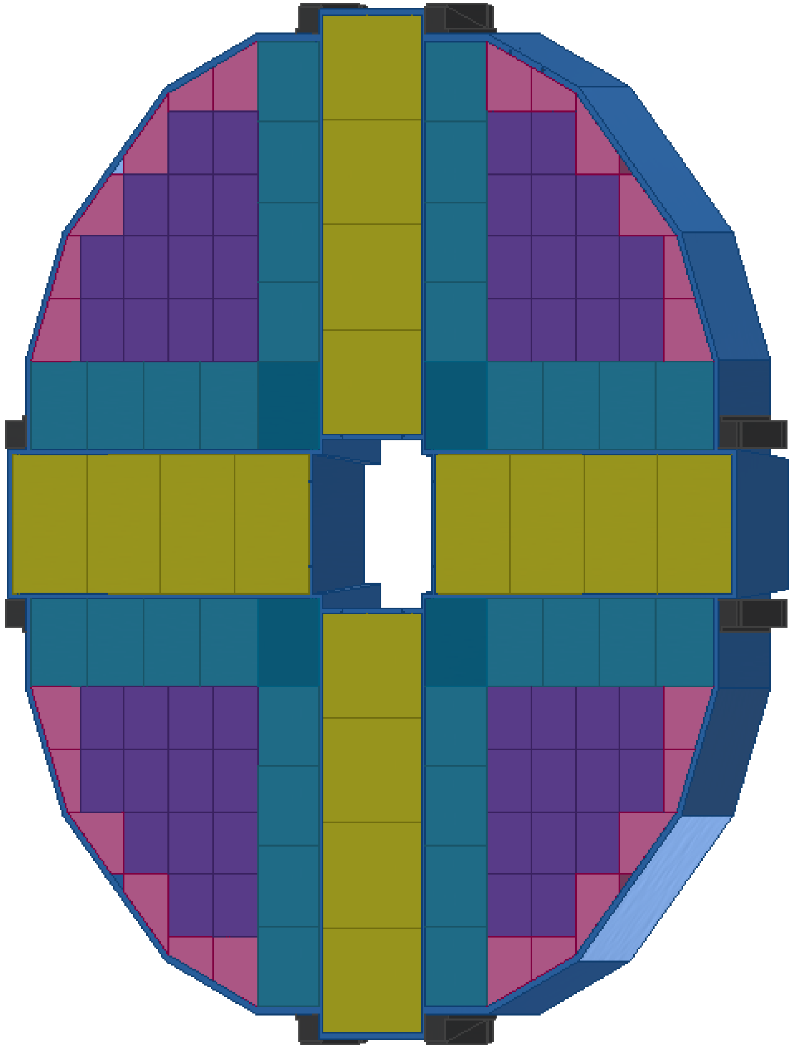


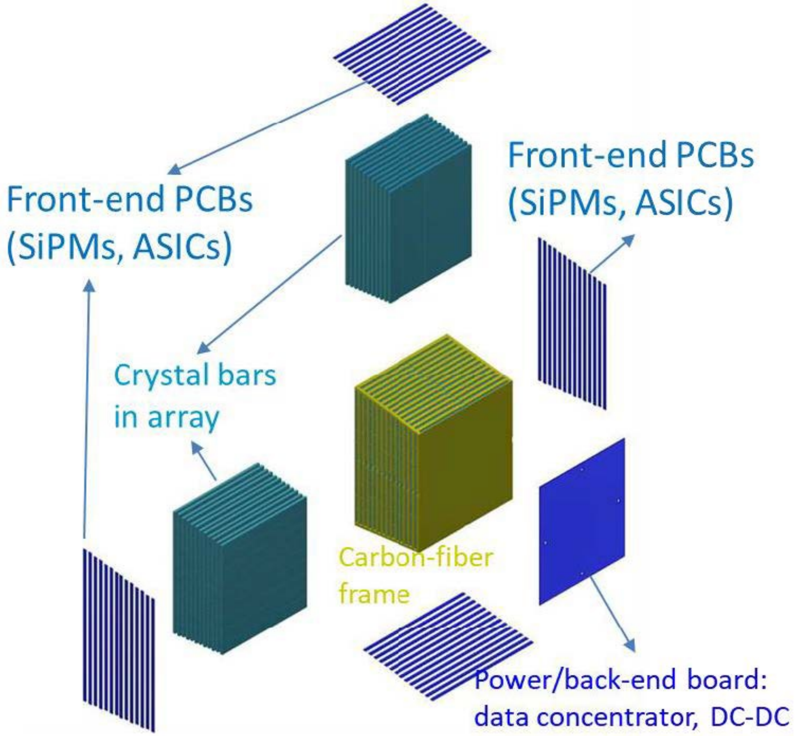




Mechanical Design of End-Cap ECAL



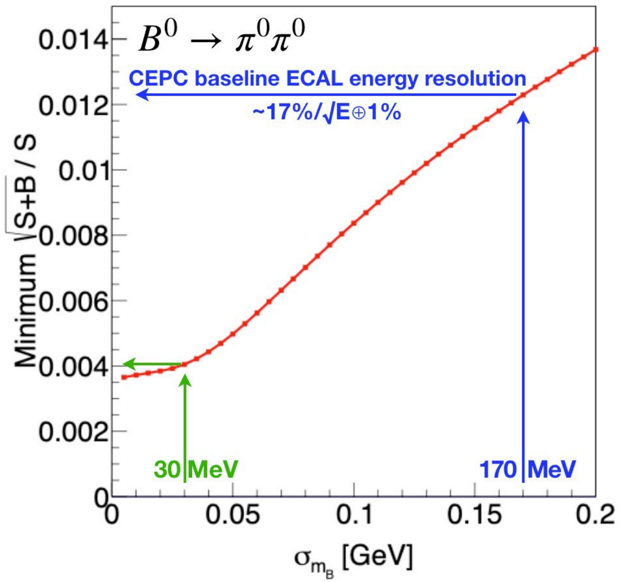


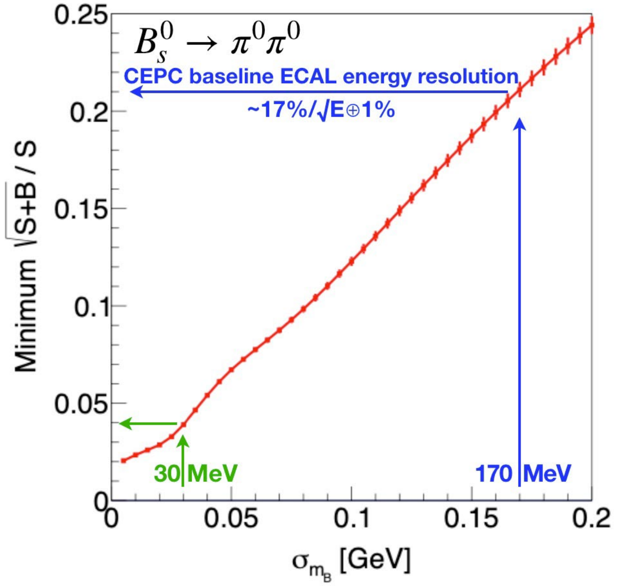


Potential of Crystal ECAL in Flavour Physics

- The performance of ECAL is characterised by $B^0_{(s)}$ **mass resolution**.
- Crystal ECAL improves the accuracy in $B^0_{(s)} \to \pi^0\pi^0$ by a factor of **3–5**.

Type of ECAL	EM Energy Resolution	σ_{m_B}/MeV	Accuracy in $B^0 \to \pi^0\pi^0$	Accuracy in $B^0_s \to \pi^0\pi^0$
SiW-ECAL	$17\%/\sqrt{E\ [\mathrm{GeV}]} \oplus 1\%$	170	~1.2%	~21%
Crystal ECAL	$3\%/\sqrt{E\ [\mathrm{GeV}]} \oplus 0.3\%$	30	~0.4%	~4%

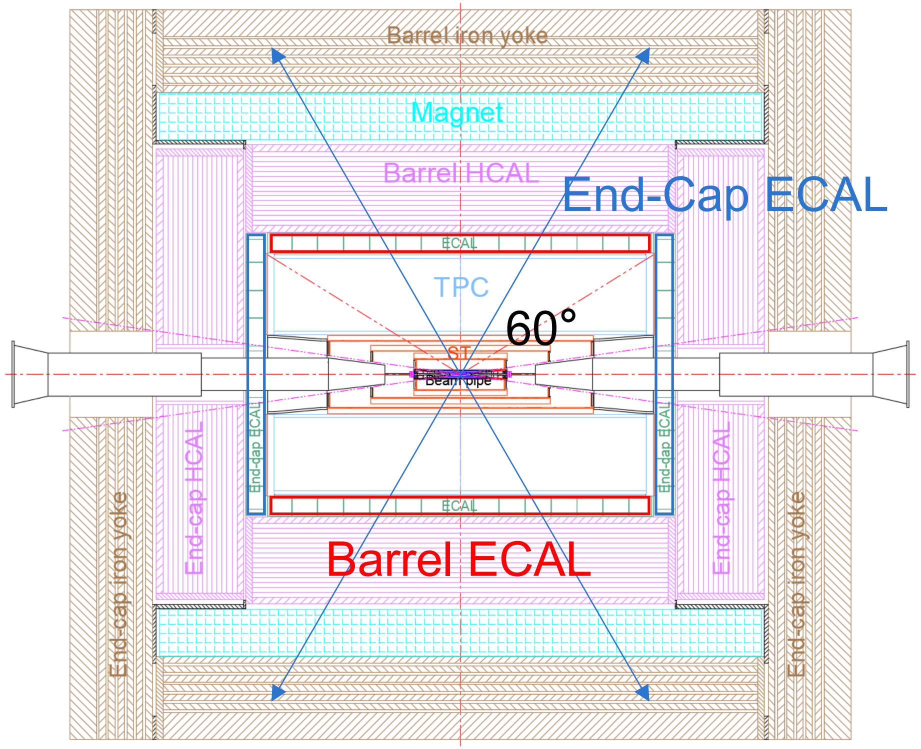




https://indico.ihep.ac.cn/event/19839/contributions/138701/attachments/71081/85973/Yuexin_CKMalpha_20230814.pdf

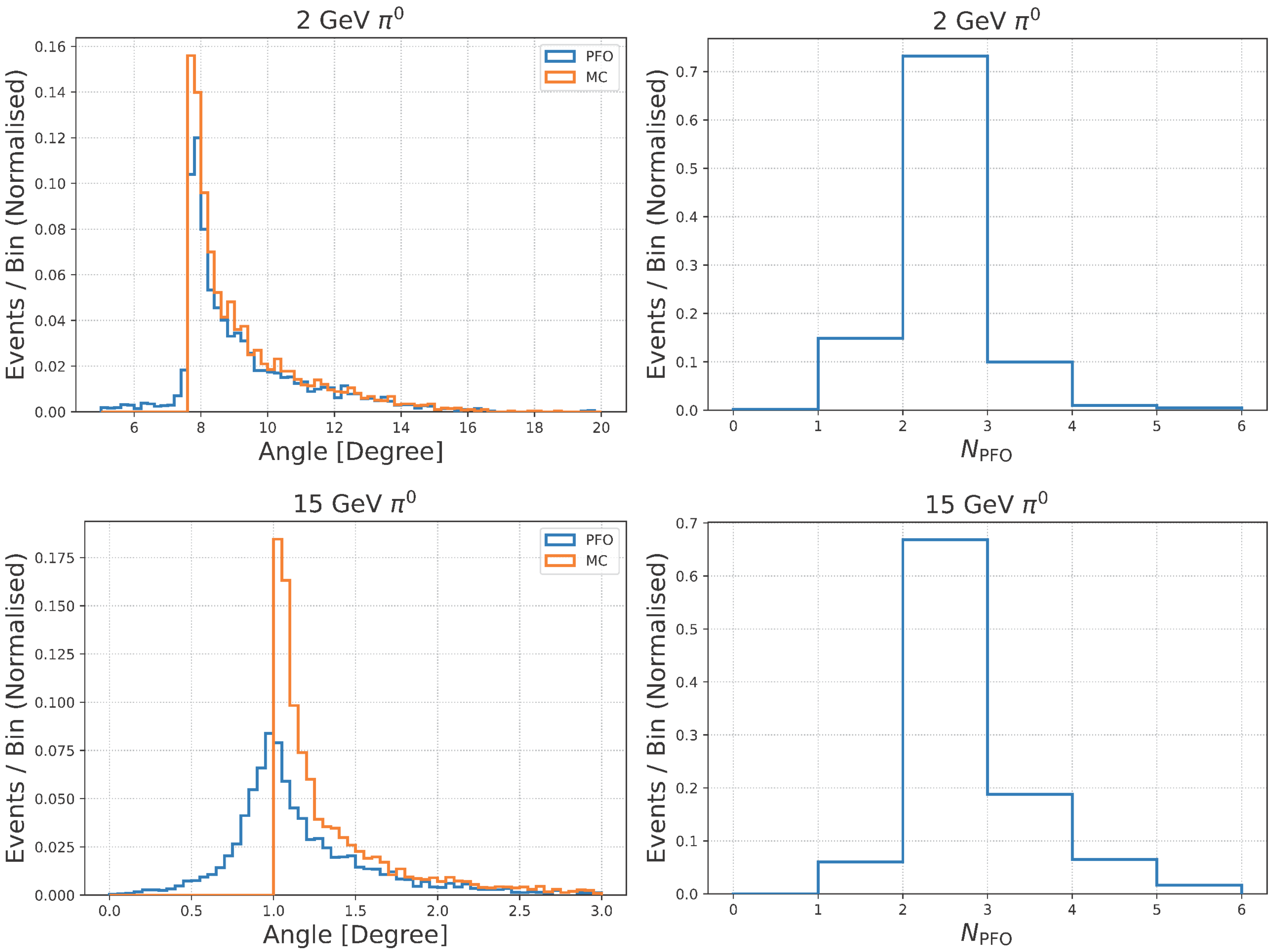
Event Selection of $\pi^0 \to \gamma\gamma$ Process

- **Selection of MC photons:**
  - An event has two and only two photons (**PDGID = 22**);
  - Both photons satisfy $\boldsymbol{\theta} \in [\mathbf{60°}, \mathbf{120°}]$.
- **Selection of particle flow objects (PFOs):**
  - Discard PFOs with $E \leq 0$ at first.
  - > 2 PFOs: iterate all combinations, then select the two PFOs that correspond to an invariant mass **closest to** $\boldsymbol{m_{\pi^0}} = 134.9768\ \mathrm{MeV}$.
- **Remark:** with current CyberPFA, if an event has only 1 PFO, then it corresponds to two merged photons and is mis-identified as one photon (cannot be used for reconstruction).



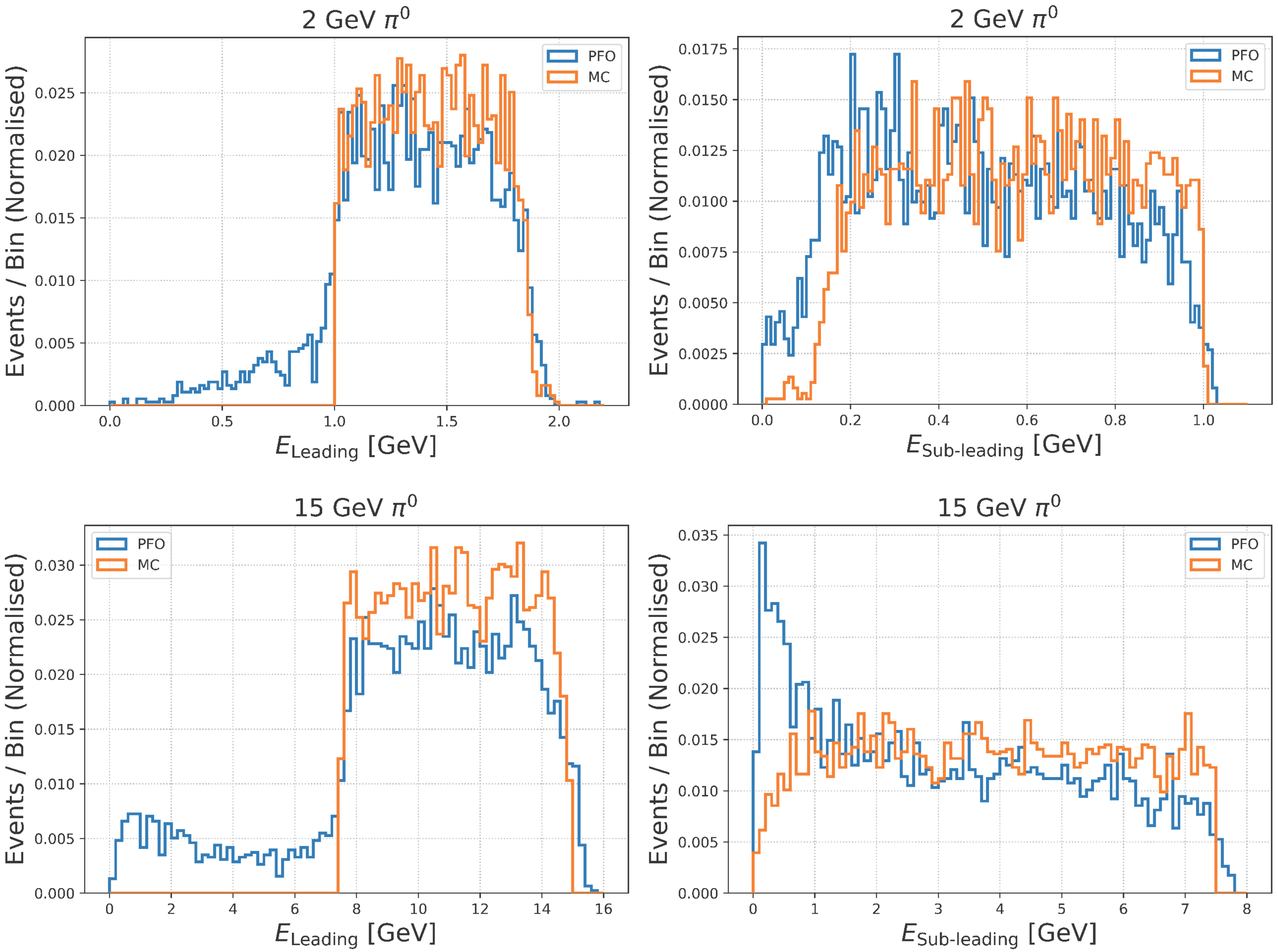
Reconstruction of $\pi^0 \rightarrow \gamma\gamma$ Process

- Lorentz boost dominates, especially at high energies ($E_{k,\pi^0} \gg m_{\pi^0}$), making two photons difficult to separate.
- Few minor clusters are formed, since E_{total} **is not too high**.



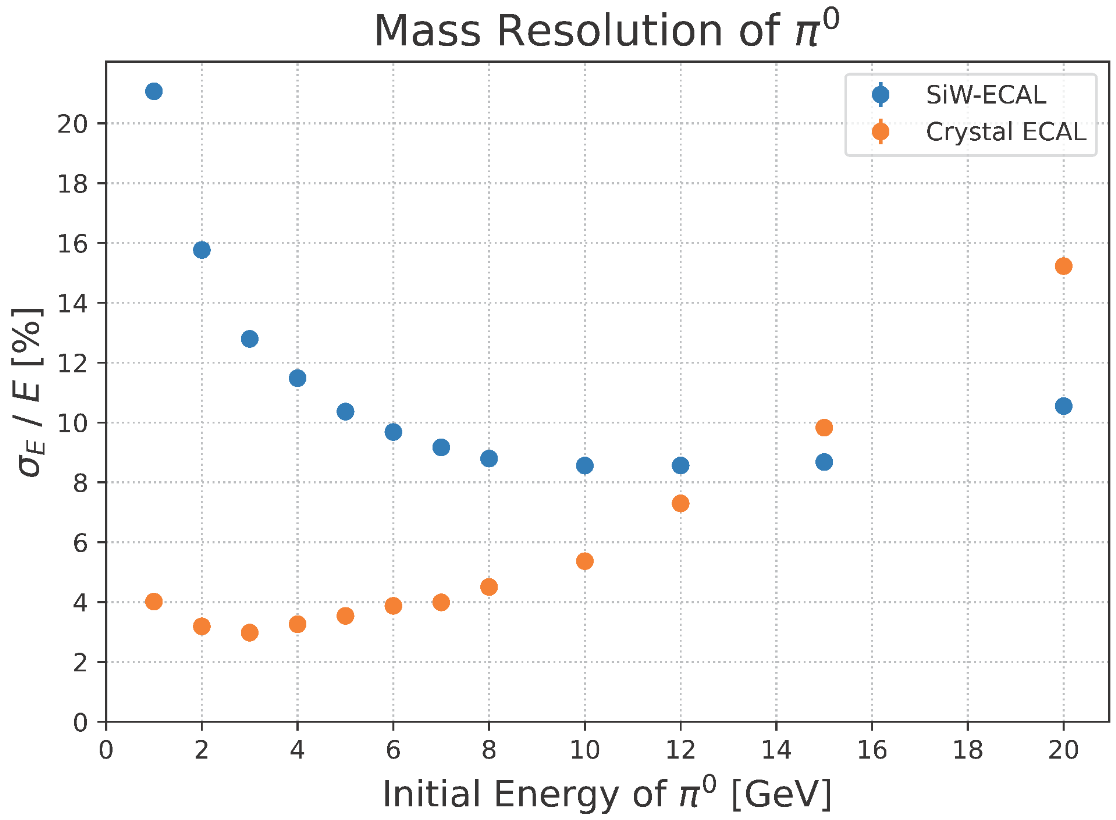
Kinematics in $\pi^0 \to \gamma\gamma$ Process

- The energy of the MC photons cannot be effectively reconstructed at high energies.
- Minor clusters result in the long tails on the left.



Invariant Mass in $\pi^0 \to \gamma\gamma$ Process

- **Motivation:** $B^0_{(s)} \to \pi^0\pi^0$ help determine CKM angle α (ϕ_2).
- **Conclusion:** crystal ECAL achieves a π^0 mass resolution of **~3%** at 3 GeV.
- **Remark:** the distributions of invariant mass become irregular at high energies.

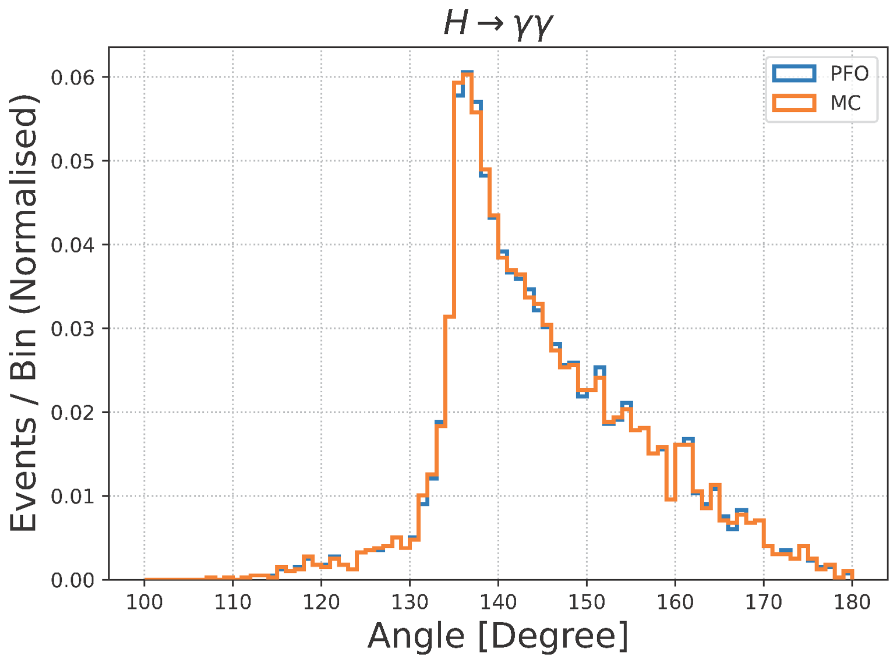


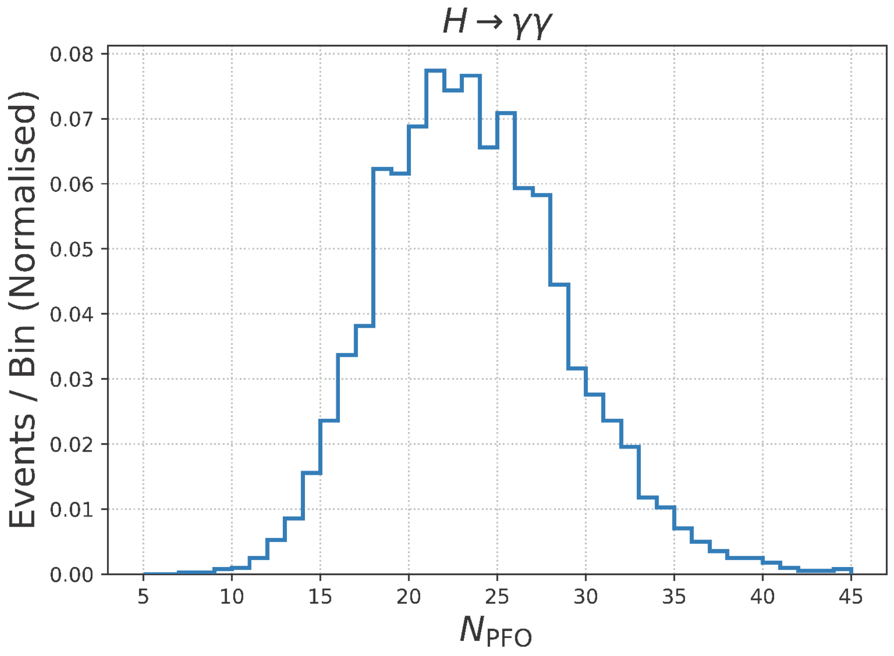
Event Selection of $H \to \gamma\gamma$ Process

- **Selection of MC photons:**
  - An event has two and only two photons (**PDGID = 22**), and their mother particle is the Higgs boson ($\boldsymbol{p_\gamma \geq 30\ \mathrm{GeV}}$); 9,573/9,600 = 99.72%
  - Both photons satisfy $\boldsymbol{\theta \in [60°, 120°]}$; 4,840/9,600 = 50.42%
  - Shower begins at $\boldsymbol{r = \sqrt{x^2 + y^2} \geq 1,830\ \mathrm{mm}}$. 3,980/9,600 = 41.46%
- **Selection of PFOs:** similar to Event Selection of $\pi^0 \to \gamma\gamma$, but select the pair with an invariant mass **closest to $\boldsymbol{m_H}$** $= 125.25\ \mathrm{GeV}$. 3,980/9,600 = 41.46%
- **Remark:** with current CyberPFA, if photon conversion happens within the tracker, more than one PFOs will be reconstructed.

Reconstruction of $H \to \gamma\gamma$ Process

- $E_{\mathrm{k},H} \ll m_H$, Lorentz boost does not significantly affect the angle between two MC photons, and the photons can be separated effectively.
- Scattered hits form a large number of minor clusters.





Kinematics in $H \to \gamma\gamma$ Process

- In general, the energy of the MC photons can be effectively reconstructed.
- Minor clusters result in the long tails on the left.
- Energy leakage to HCAL is mainly **below 10%**.