中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

# High-granularity Crystal Calorimeter: R&D status

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on behalf of the CEPC Calorimetry Working Group

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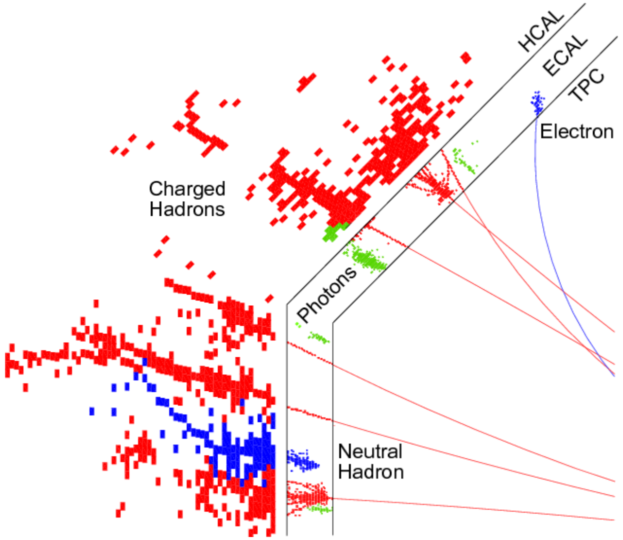
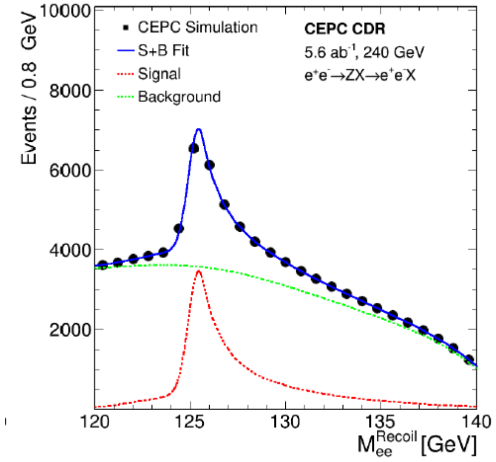
# Motivations

- Background: future lepton colliders (e.g. CEPC, ILC, etc. )
  - Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - Capability to trigger single photons
    - Flavour physics at Z-pole: precision $\gamma/\pi^0$ reconstruction
    - Potentials in search of BSM physics
- Finely segmented crystals
  - PFA capability for precision measurements of jets
  - Jet energy resolution aims for 3~4%



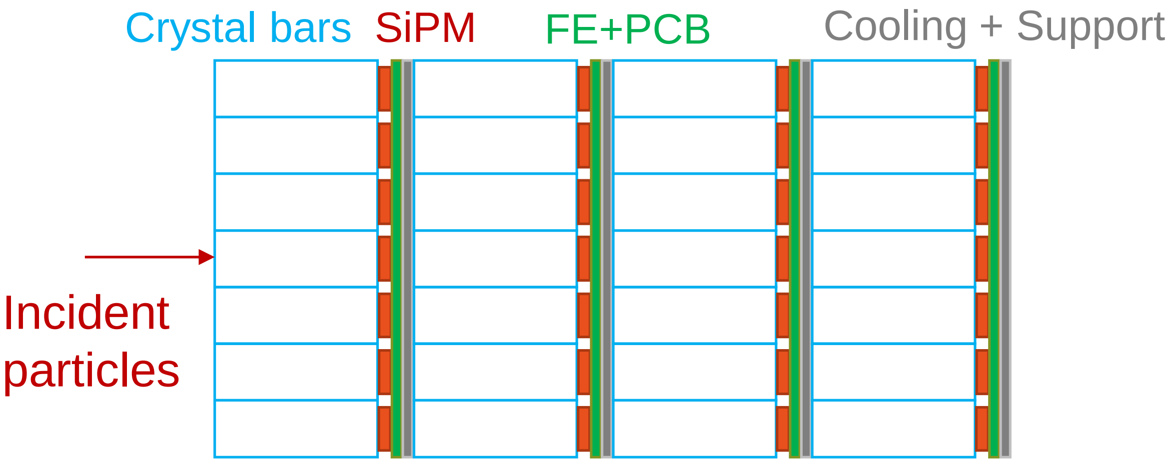


# R&D efforts targeting key issues and technical challenges

- Key issues: performance studies and optimization
  - Detector layout: crystal segmentation in longitudinal and lateral dimensions
  - Performance: single particles and jets with PFA
  - Fast timing
  - Impacts from dead materials: upstream tracker, services (cabling, cooling)
  - Potentials: dual-gated or dual-readout for better hadronic energy resolution
- Critical technical questions/challenges
  - Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)
  - Front-end electronics: cornerstone for instrumentation of high-granularity calorimetry
    - Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working mode, minimal dead time, etc.
  - Light-weight cooling and supporting mechanics
  - Calibration schemes and monitoring systems: SiPMs, crystals and ASICs
  - System integration: scalable detector design (modules), mass assembly, QA/QC

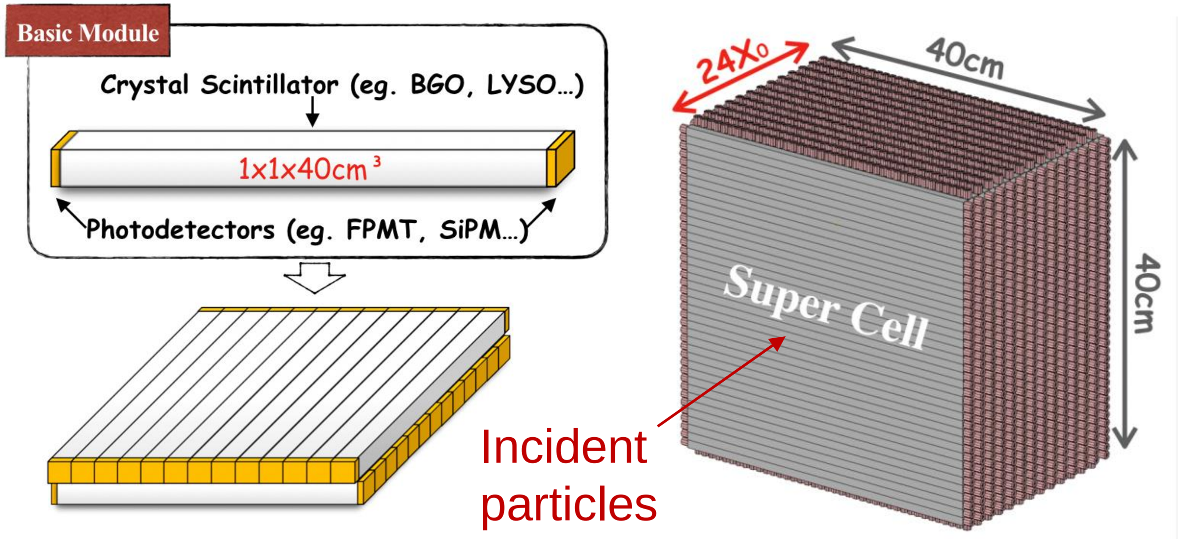
# High-granularity crystal ECAL: 2 major designs

## Design 1



- Fine segmentation
  - Both longitudinal and transverse
  - Single-ended readout with SiPM
- A natural design compatible with PFA

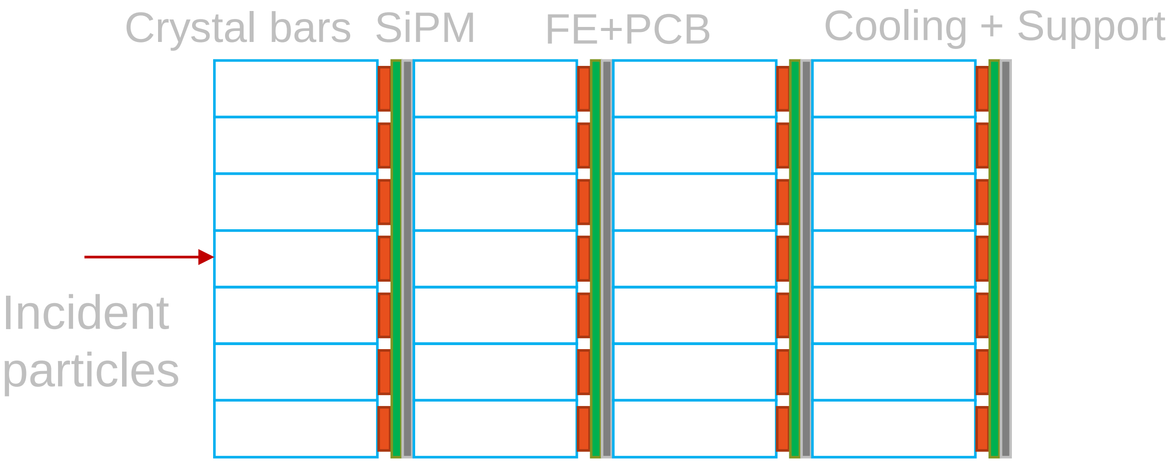
## Design 2 (current focus)



- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

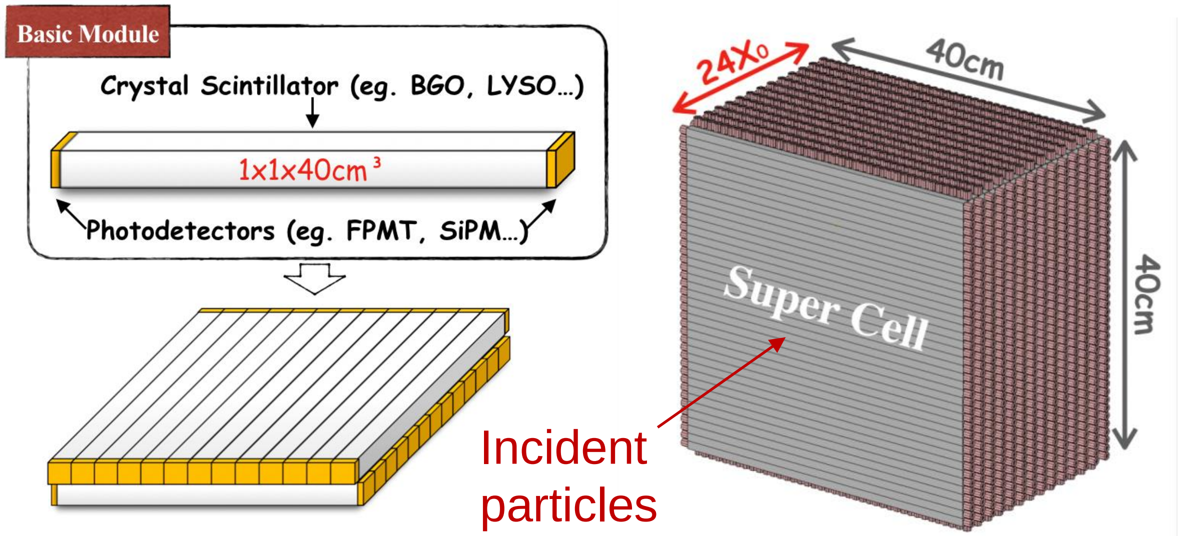
# High-granularity crystal ECAL: 2 major designs

## Design 1: short bars



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

## Design 2: long bars (current focus)



- **Advantages**
  - Longitudinal granularity
  - Save #channels (e.g. ~15 times less)
  - De facto 3D calorimeter: timing for hit positions for transverse granularity
- **Key issues**
  - Ambiguity: multiple incident particles within one super cell
  - Separation of nearby showers
  - Impact on the Jet Energy Resolution (JER)

# Recent progress presented in this talk

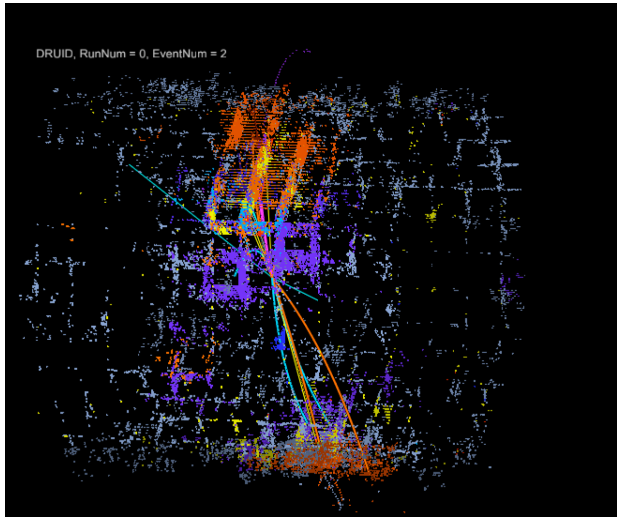
- Key issues: performance studies and optimization
  - PFA performance with jets with PFA: preliminary studies with crystals
  - Software development in the new framework CEPCSW
    - Geometry construction in DD4HEP
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting
    - Performance validation

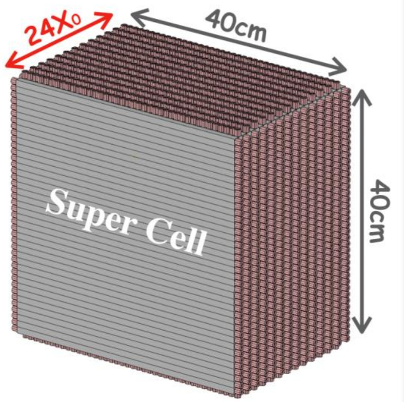
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

# PFA performance: a first glance with crystals

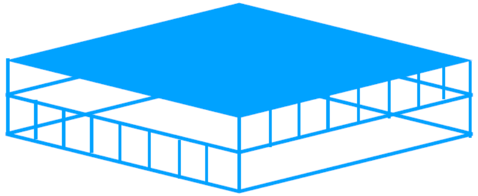
Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
- Simulation setup: a temporary layout for first studies
  - Crystal calorimeter with silicon layers
    - Use positioning info from silicon pads, energy from crystal bars
    - Reconstruction algorithm for crystals not ready yet
  - RPC-based semi-digital hadron calorimeter (SDHCAL)
  - Other subdetectors: CEPC CDR baseline





ECAL: 14 super-layers (24X0)



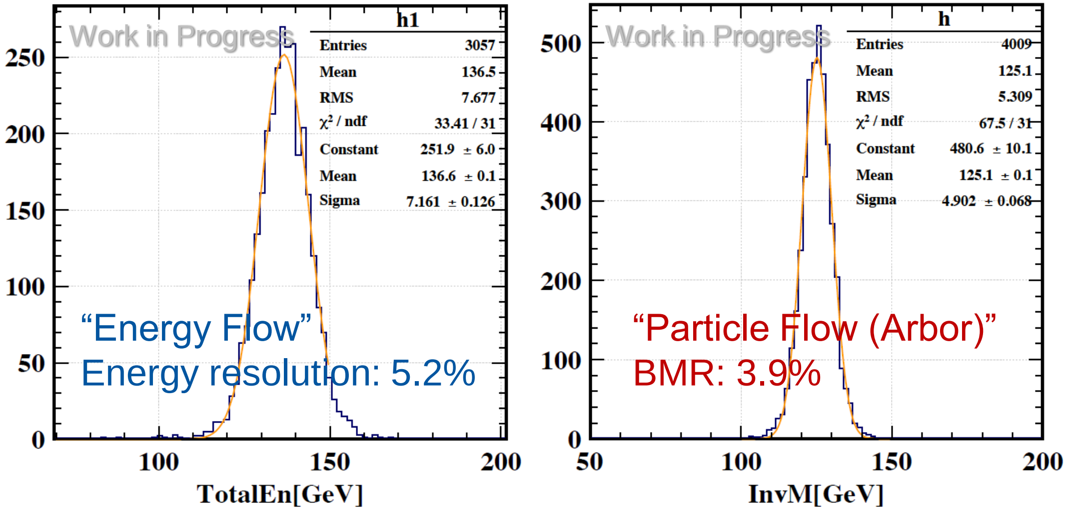
1 super-layer:
2 crystal layers (energy)
1 thin silicon layers (position)

# PFA performance with CDR baseline detector

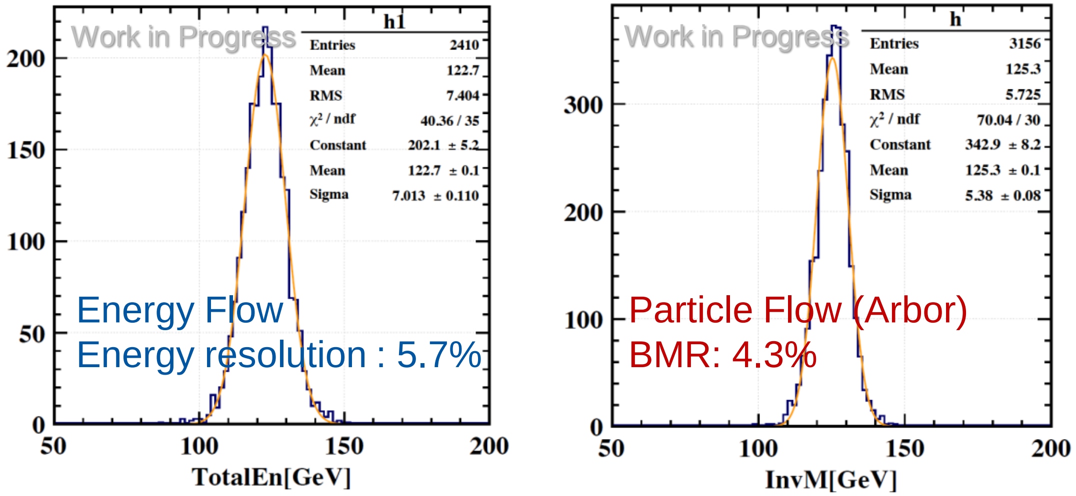
Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
  - Energy flow: combination of hits in calorimeters only
  - Boson mass resolution (BMR)
- PFA improves the resolution from 5.2% to 3.9%

ECAL: 28 SiW layers (24X0)



ECAL: 14 SiW layers (24X0)



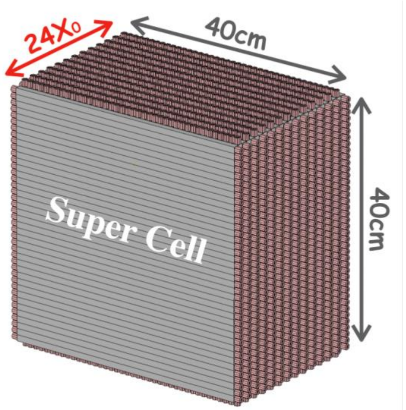
CEPC CDR baseline detector:
BMR improved to 3.9% with PFA

SiW ECAL with a factor of two lower sampling frequency:
to compare with crystals (next page)

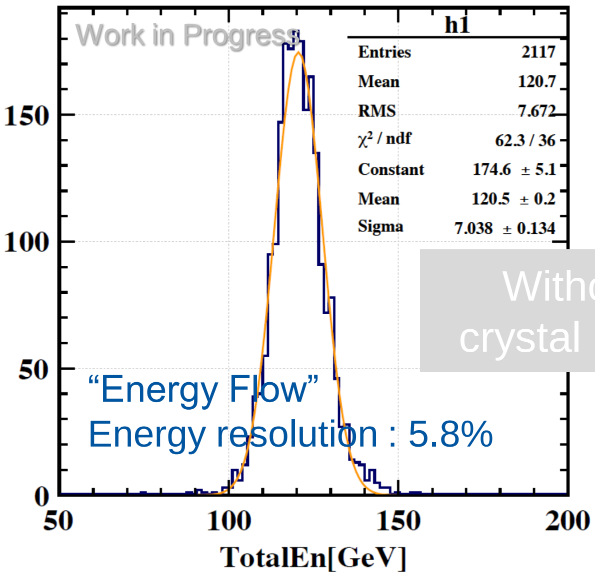
# PFA performance: a first glance with crystals

Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
- **14 layers** of crystal and silicon: use silicon for positioning
  - Without crystal information: PFA improves resolution to 5.0% from 5.8%
  - With crystal energy information only: energy resolution ~4.8%
- Plenty of room to improve PFA performance with crystals
  - Essential: reconstruction algorithm, PFA parameters tuning for crystals

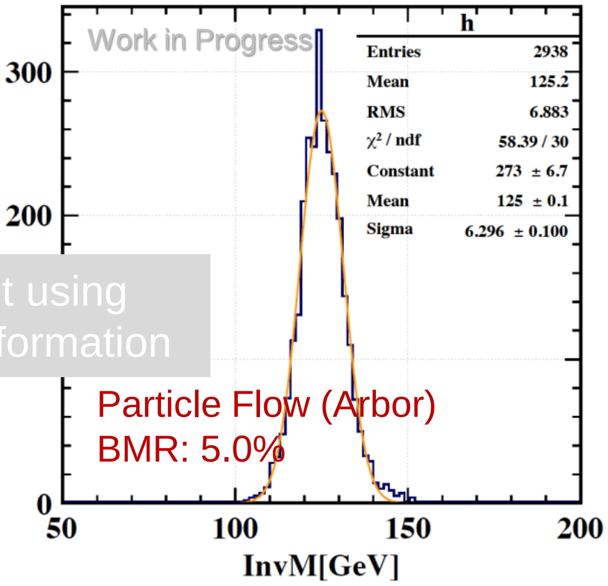


ECAL: 14 super-layers (24X0)

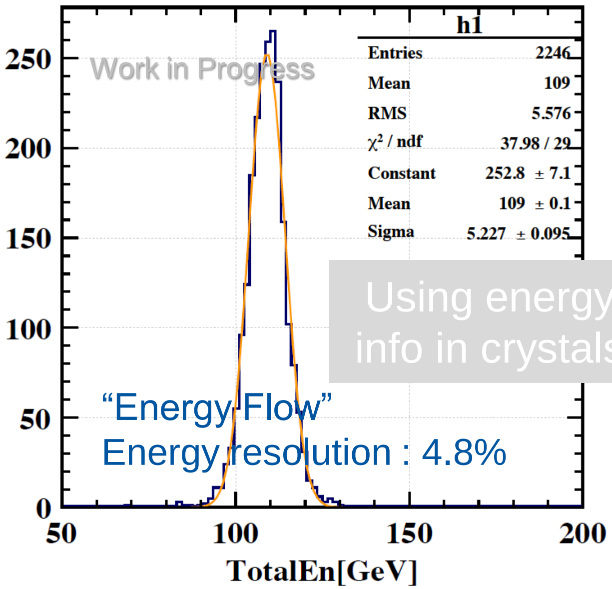


Without using crystal information

"Energy Flow"
Energy resolution : 5.8%

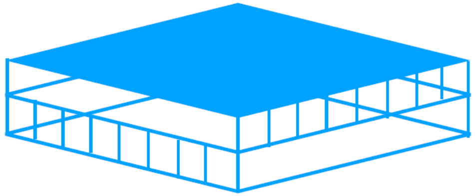


Particle Flow (Arbor)
BMR: 5.0%



Using energy info in crystals

"Energy Flow"
Energy resolution : 4.8%



1 super-layer:
2 crystal layers (energy);
1 thin silicon layers (position)

Note the Arbor PFA parameters not yet optimised for crystals: more overlaps in crystals expected (larger $X_0, R_M$ than tungsten)

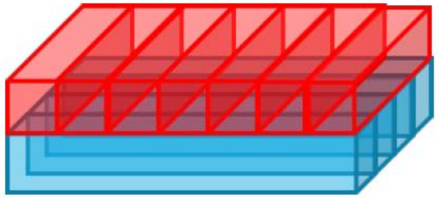
# Recent progress presented in this talk

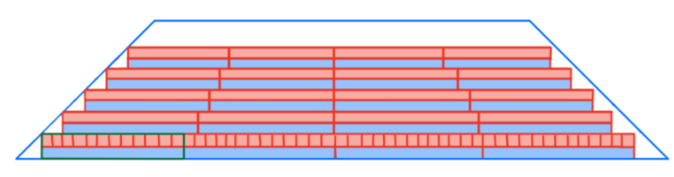
- Key issues: performance studies and optimization
  - PFA performance with jets with PFA
  - Software development in the new framework CEPCSW
    - Geometry construction in DD4HEP
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting
    - Performance validation

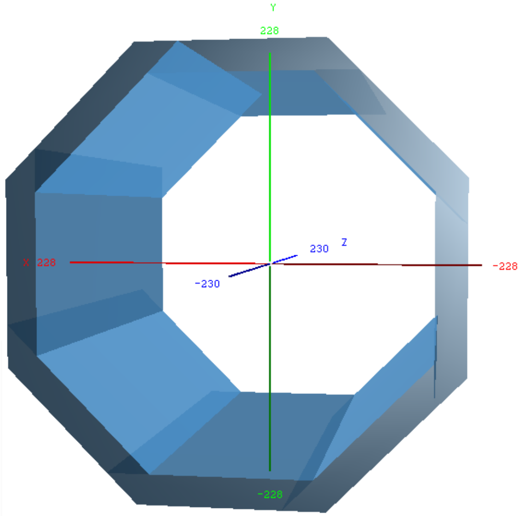
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

# Geometry construction

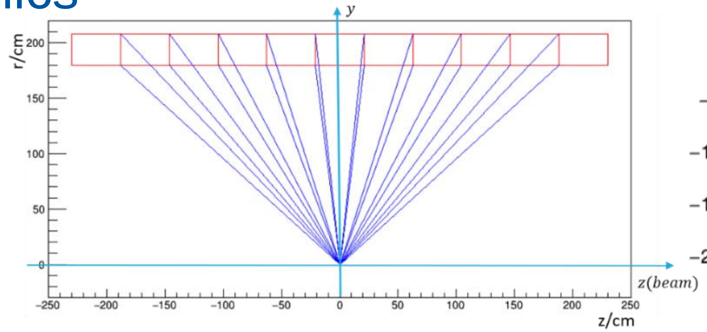
- General
  - BGO crystal bars: $1\text{cm} \times 1\text{cm} \times \sim 40\text{cm}$
  - Readout at two ends
- Basic detector unit: super cell
  - 2 layers of crossed bars
- Detector layout with DD4HEP
  - $\text{R} = 1.8\text{m}, \text{L} = 4.6\text{m}, \text{H} = 28\text{cm}$
  - Barrel ECAL implemented
  - 8 identical staves (trapezoids)
  - Avoid projectile cracks pointing to the IP
- Ideal layout: excluding electronics and mechanics
  - Gaps identified

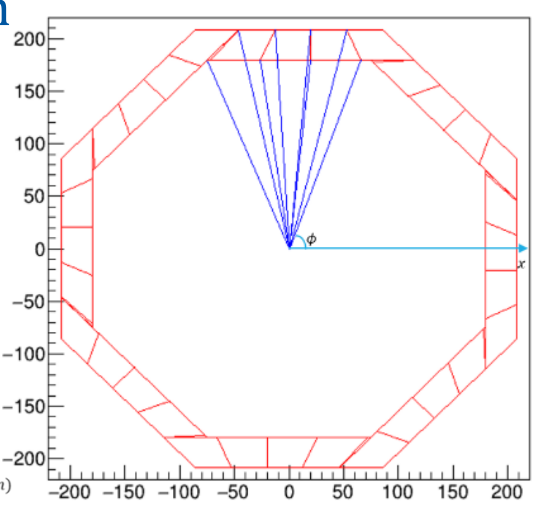






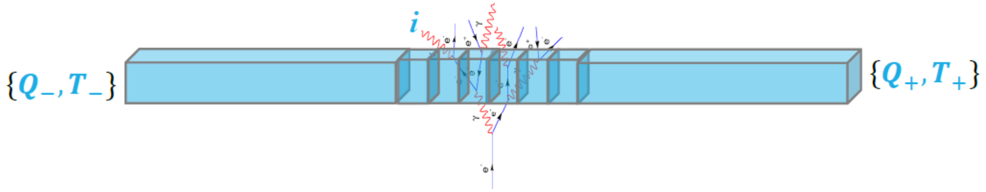
BGO: $\text{X}_0 = 1.1\text{cm}, \ \text{R}_\text{M} = 2.2\text{cm}$





# Simulation and digitisation

- G4 full simulation build to extract timing resolution
  - Optical photon processes: scintillation, Cherenkov, bulk absorption and boundary processes
- G4 Shower simulation: no optical processes
- Digitisation for each long bar
  - Contributions of i-th step in G4
  - Amplitude (or #photons)
    - $Q_{\pm}(i) \propto E_0 \exp(-\frac{L/2 \pm z(i)}{L_0})$
  - Time stamps
    - $T_{\pm}(i) = T_0 + Gaus(\frac{z(i)}{v}, \sigma_T)$
    - $\sigma_T$ extracted from full simulation



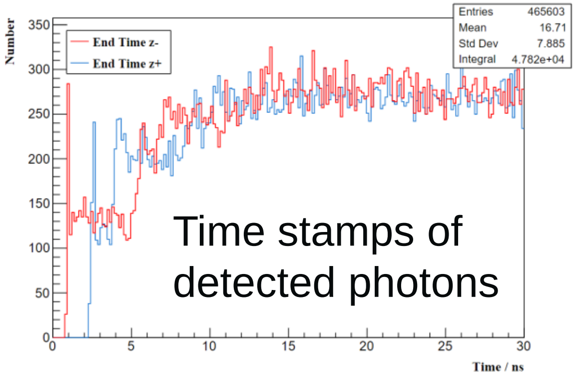
400×10×10 mm$^3$ BGO Crystal

SiPM1

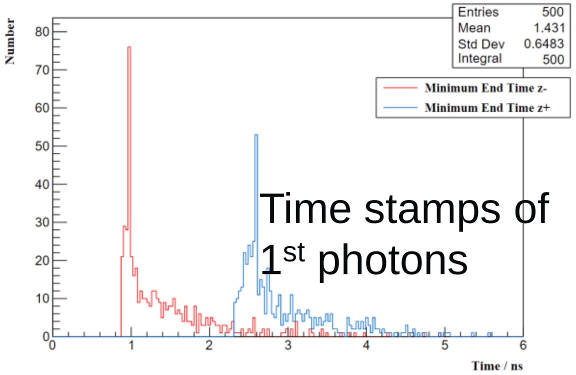
muon

ESR wrapping

SiPM2



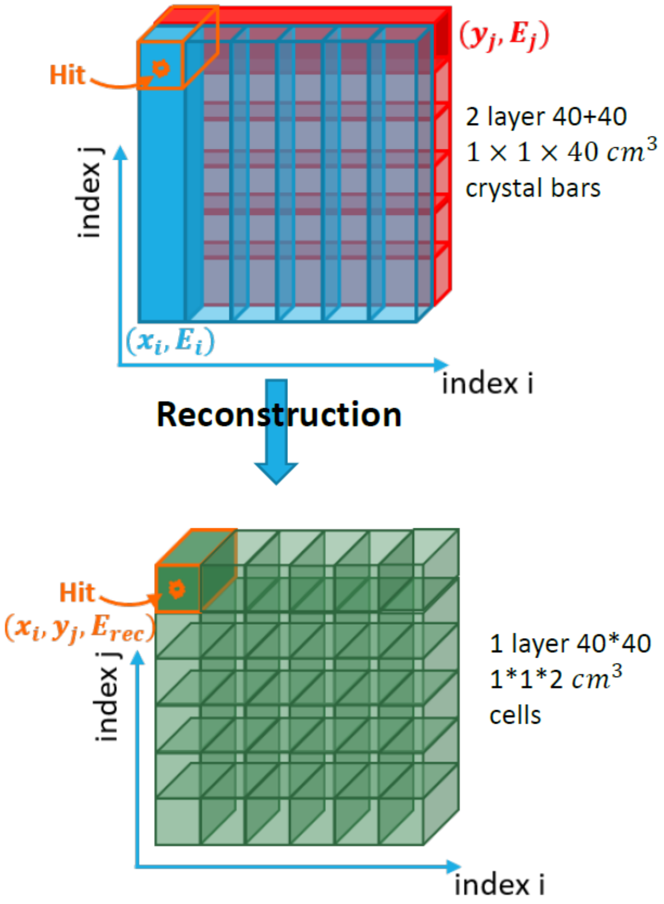
Time stamps of detected photons



Time stamps of 1st photons

**Geant4 full simulation established**

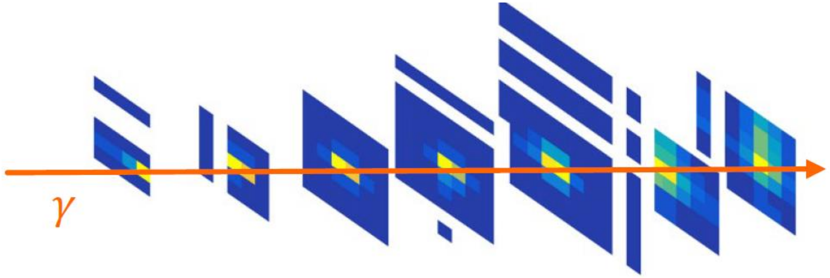
# Hit reconstruction

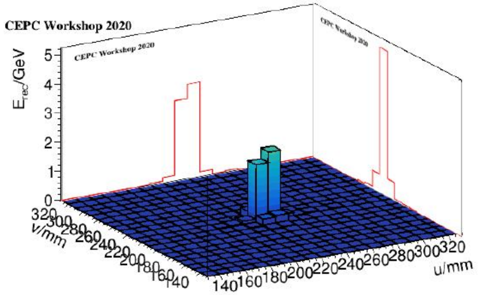


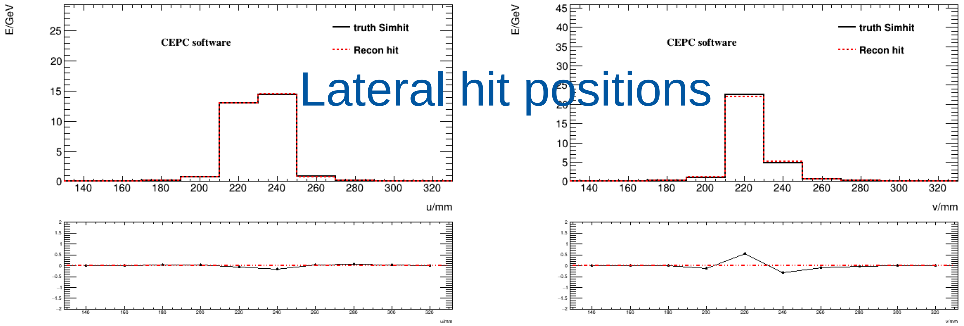
- Combine every two layers to determine
  - Hit positions in lateral plane
  - Energy sharing: energy deposition in the adjacent layer as weight

$$E_{rec}^{hit_{ij}} = E_i \times f_i + E_j \times f_j,$$

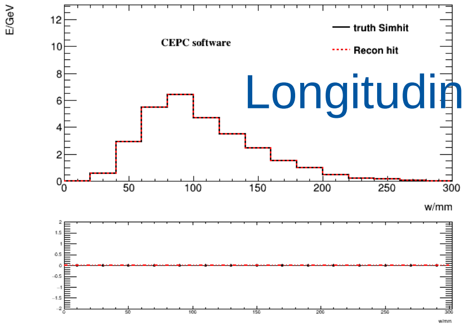
$$f_i = \frac{E_j}{\Sigma E_j}, \qquad f_j = \frac{E_i}{\Sigma E_i}$$







Lateral hit positions

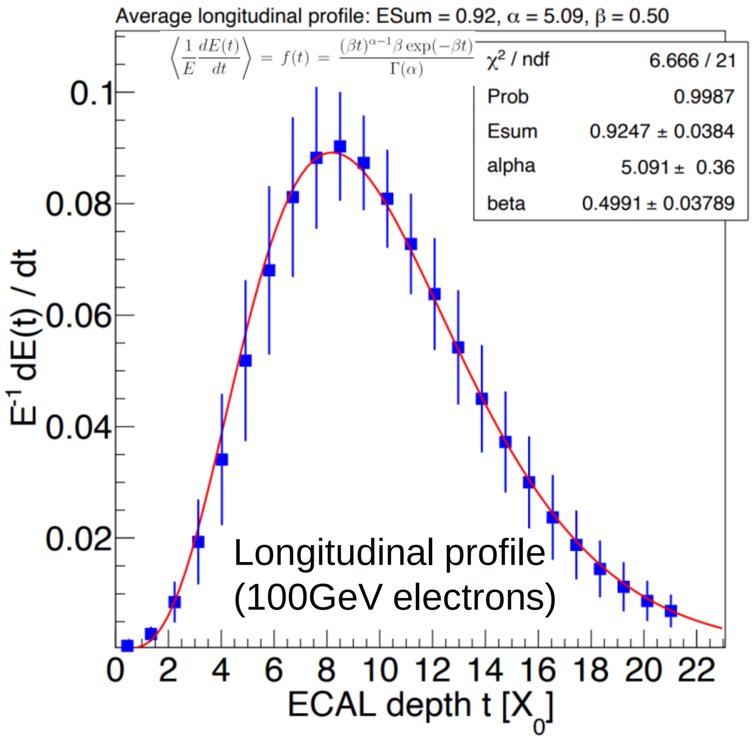


Longitudinal

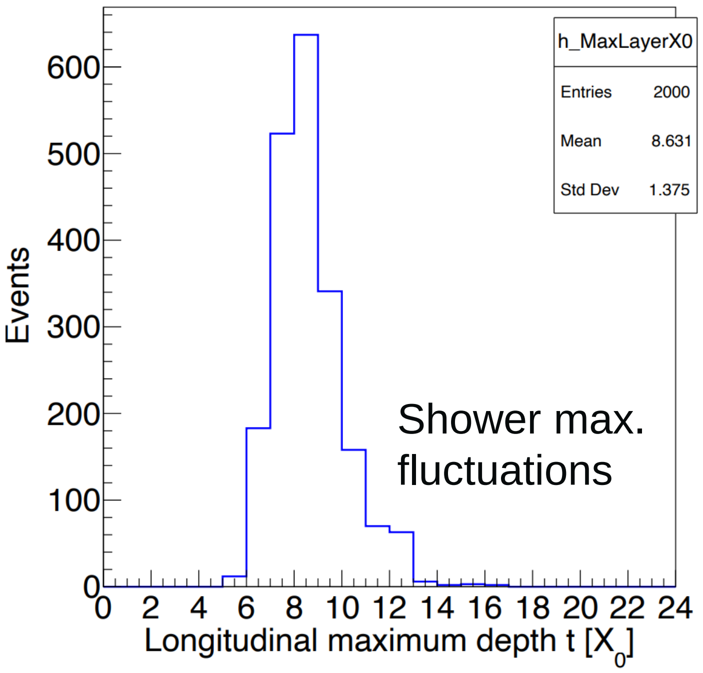
# Shower profiles studies in simulation

Yuexin Wang (IHEP)

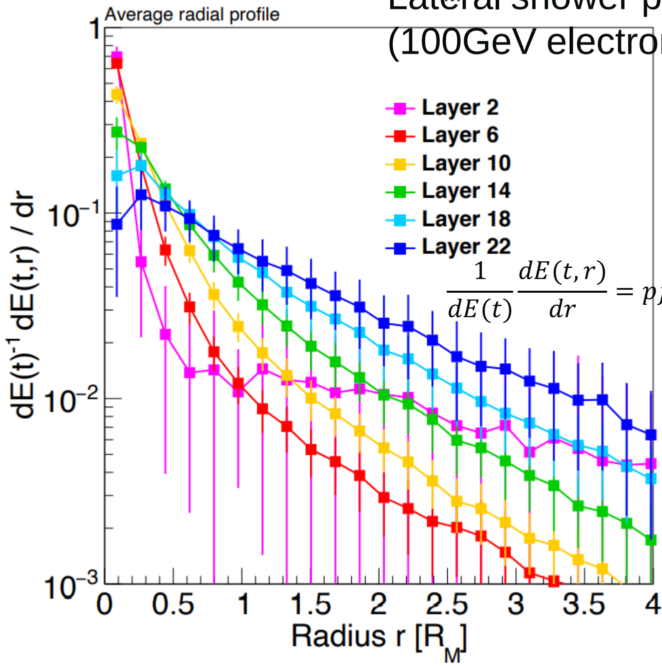
- Key question: how to separate two close-by EM showers
- EM shower profiles in 3D with highly granular cells: ongoing studies
  - Input to the weights for energy splitting in reconstruction
  - Working progress to implement this in software



Longitudinal profile (100GeV electrons)



Shower max. fluctuations

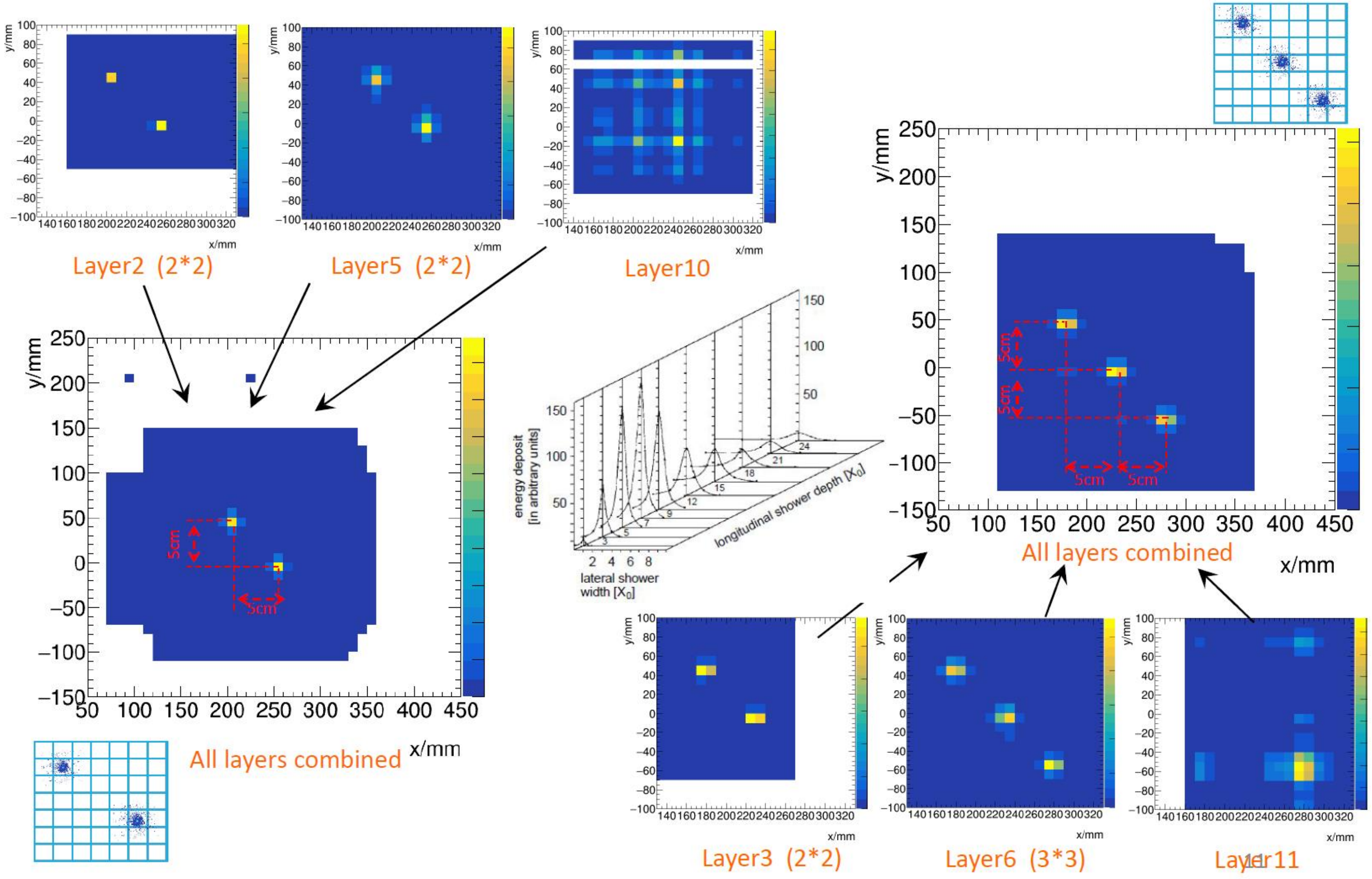


Lateral shower profile (100GeV electrons)

$$\frac{1}{dE(t)}\frac{dE(t,r)}{dr} = p f_C(r) + (1-p) f_T(r)$$

Distance along radial direction from shower axis (scaled in Moliere radius)

# Validation: ongoing studies



- Use close-by gammas
- “Ghost hits” can mostly cleaned by the layer-wise clustering
    - Exceptions in layers far away from shower max.
    - Tried to combined all layers

# Recent progress presented in this talk

- Key issues: performance studies and optimization
  - PFA performance with jets with PFA
  - Software development in the new framework CEPCSW
    - Geometry construction in DD4HEP
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting
    - Performance validation

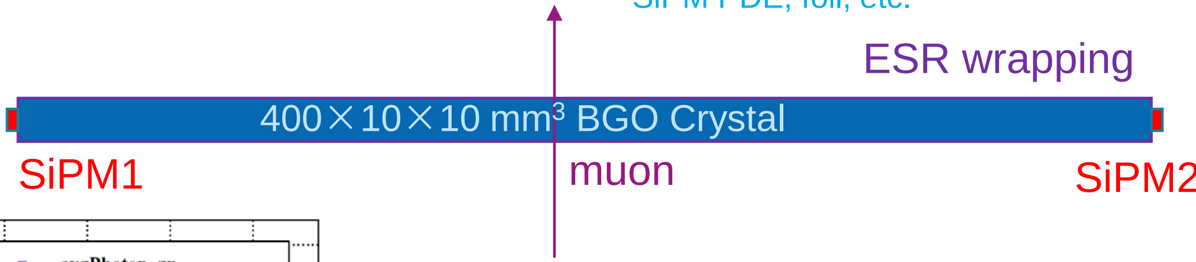
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

# Crystal bar: length impacts and uniformity scan

Baohua Qi (IHEP)

- G4 full simulation of MIP response
  - BGO and PWO crystals (varying lengths): photons detected at each SiPM
  - Also scanned different hit positions: response uniformity
- Hints for calibration; need to improve MIP response of PWO (e.g. larger SiPM)
- Measurements in plan to validate the simulation

Wavelength dependent parameters implemented in the simulation: scintillation and transmission spectra, SiPM PDE, foil, etc.



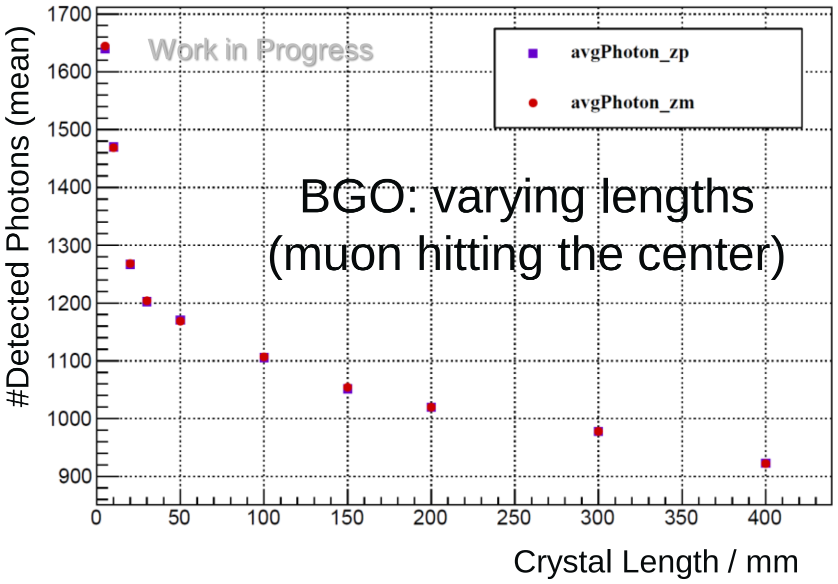
ESR wrapping

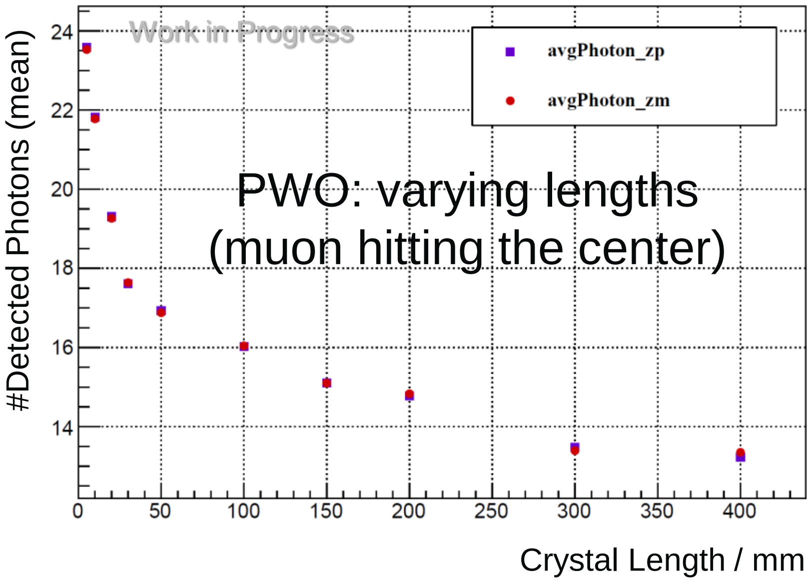
400×10×10 mm³ BGO Crystal

SiPM1

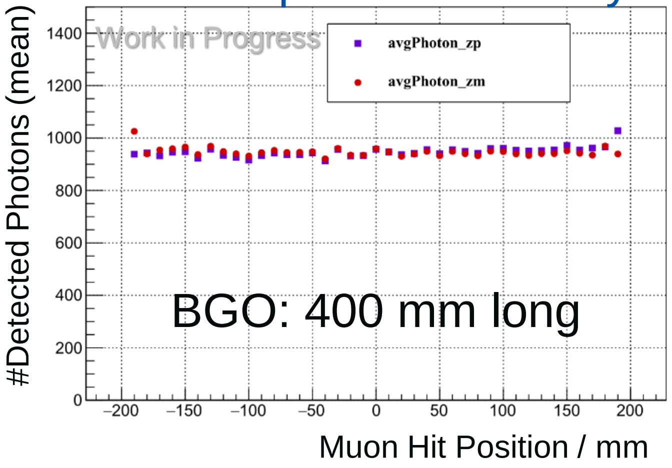
muon

SiPM2





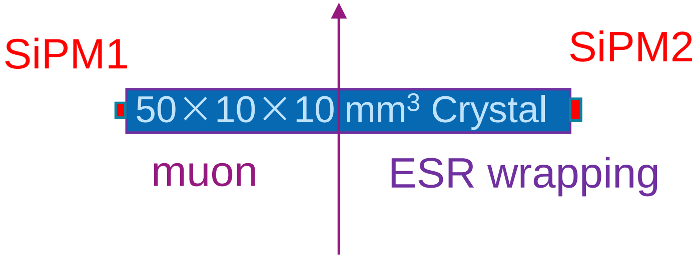
MIP Response uniformity



# Crystal bar: timing studies

Baohua Qi (IHEP)

- Timing performance to MIPs in G4 full simulation: ongoing
  - BGO and PWO crystals (varying lengths): time stamp of the first photon detected at each SiPM
  - Use Cherenkov light in the slow scintillator such as BGO?
    - Then need to consider dependence to incident angles
  - Different transversal section: other than current 10mmx10mm
  - Need to digest the fresh results for further hints
  - Will look at other crystal options for fast timing: e.g. LYSO



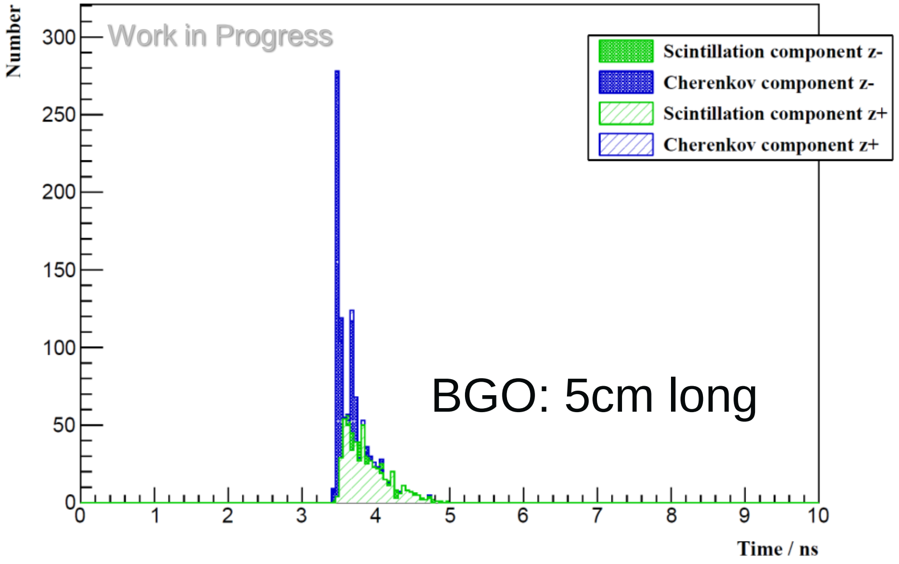
SiPM1

SiPM2

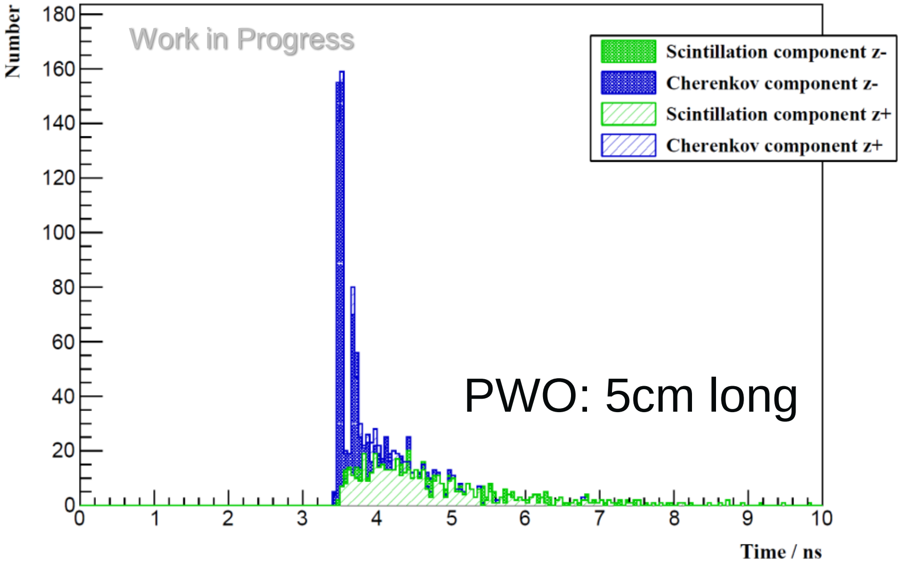
$50\times10\times10$ $mm^3$ Crystal

muon

ESR wrapping



BGO: 5cm long

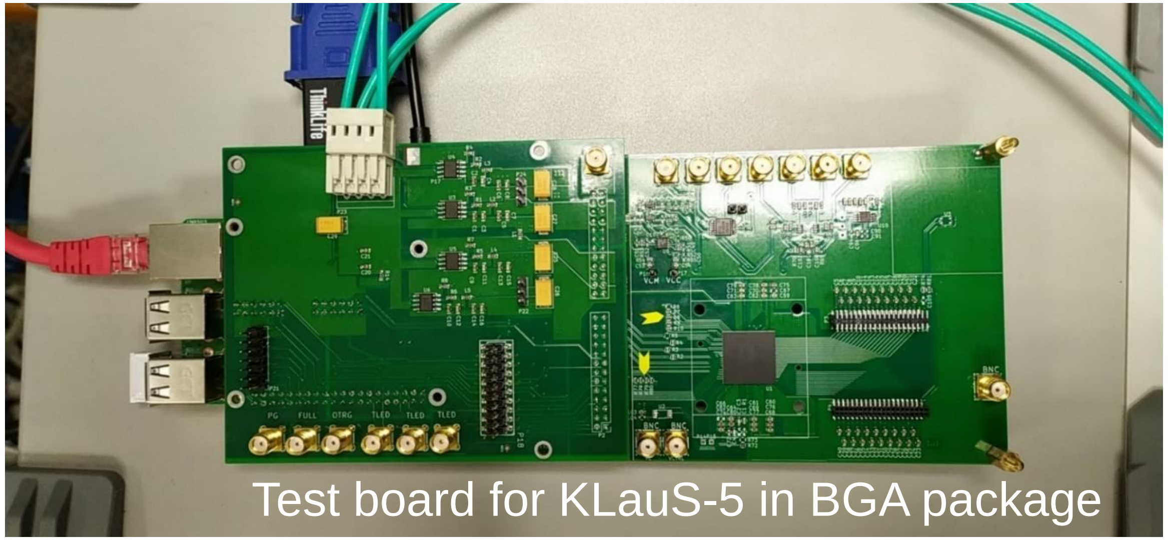


PWO: 5cm long

# Front-end electronics for SiPM readout

- Designed by KIP, U. Heidelberg
  - Originally for CALICE AHCAL (scintillator-SiPM)
- Promising candidate: 36-channel, low-power
  - Excellent S/N ratio: stringently required by high-dynamic SiPMs (small pixels)
  - Continuous working mode: crucial for circular colliders (no power pulsing)
- Need to quantitatively verify its performance and power consumption

Klaus5 in BGA



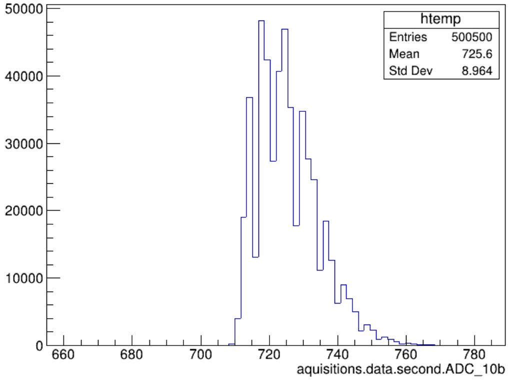
Test board for KLauS-5 in BGA package

Joint efforts with the JUNO-TAO team

# Klaus5 tests with NDL-SiPM (reminder)

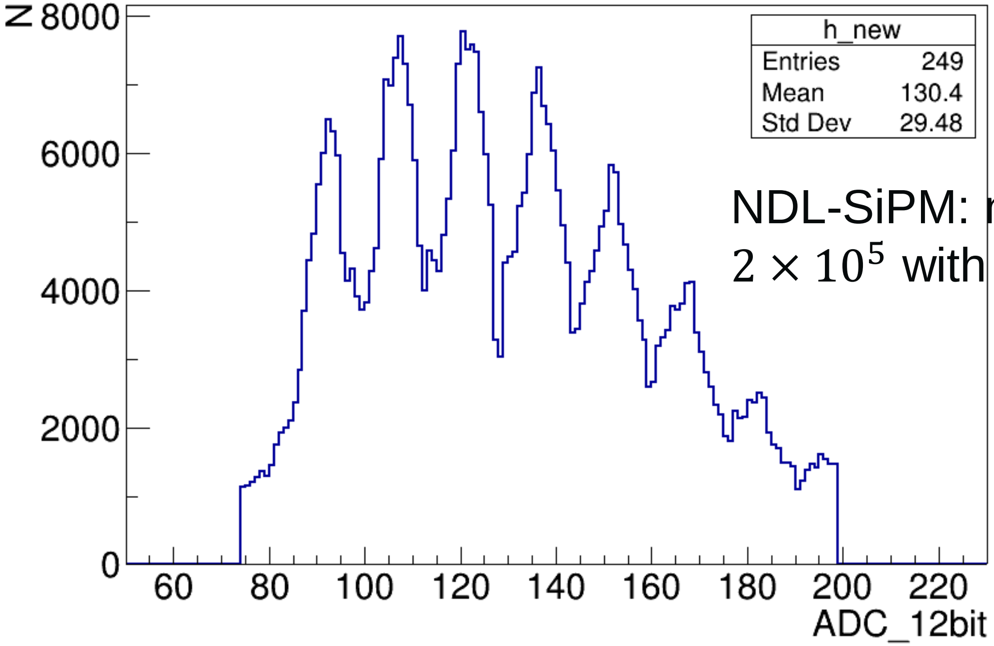
Single photon calibration

- NDL-SiPM features: small pixel pitch (10μm or smaller), high PDE
  - Requires high S/N ratio in electronics to resolve single photons (small gain)
- Klaus5 proved to be able to resolve the single photons (32fC/p.e.)
  - Benefits from its high S/N ratio and high resolution



Single photon spectrum in 10-bit ADC mode: can not be resolved

Single photon spectrum in 12-bit ADC mode: after corrections

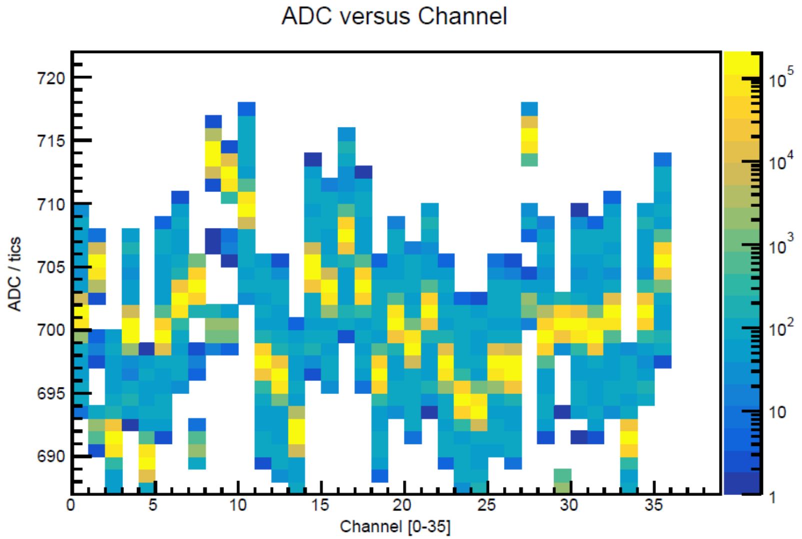


NDL-SiPM: nominal gain $2 \times 10^5$ with 10μm pixels

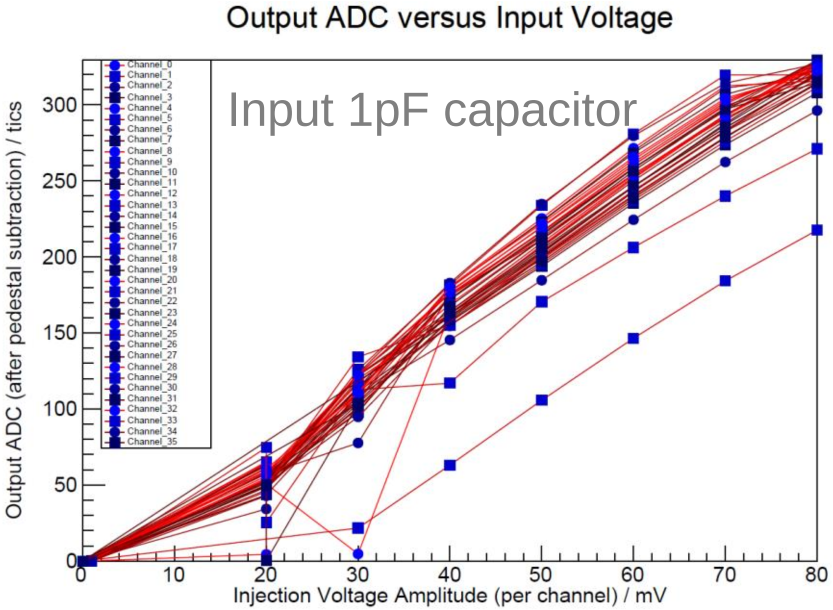
# Klaus5 tests with charge injection

**Dynamic Range**

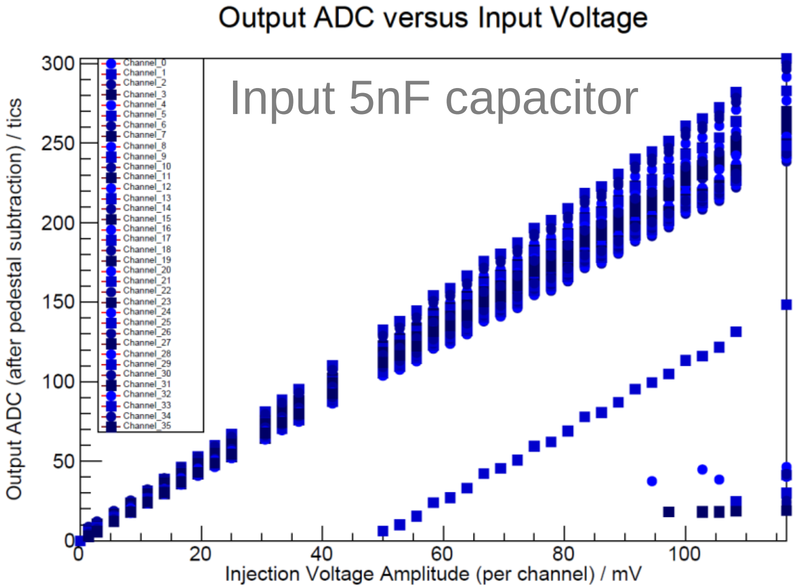
- Testing of all 36 channels
  - Good linearity in different working modes (high gain and low gain)
  - Small equivalent noise charge (ENC) ~4.5fC
  - Dynamic range: ~550pC as the maximum charge (preliminary)



Pedestals in mid High Gain mode



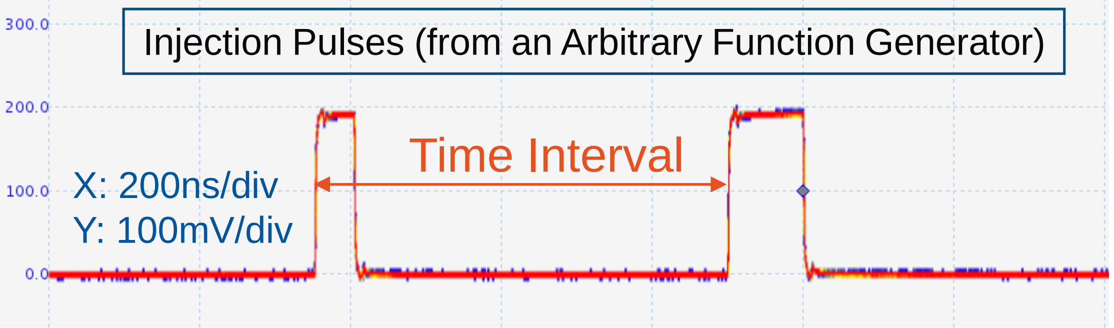
ADC in mid High Gain mode
(after pedestal subtraction)



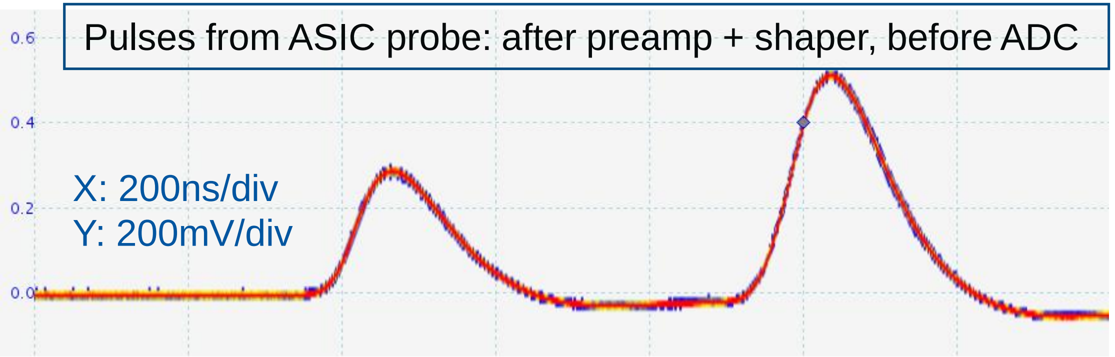
ADC in Ultra Low Gain mode
(after pedestal subtraction)

# Klaus5 dead time measurements (reminder)

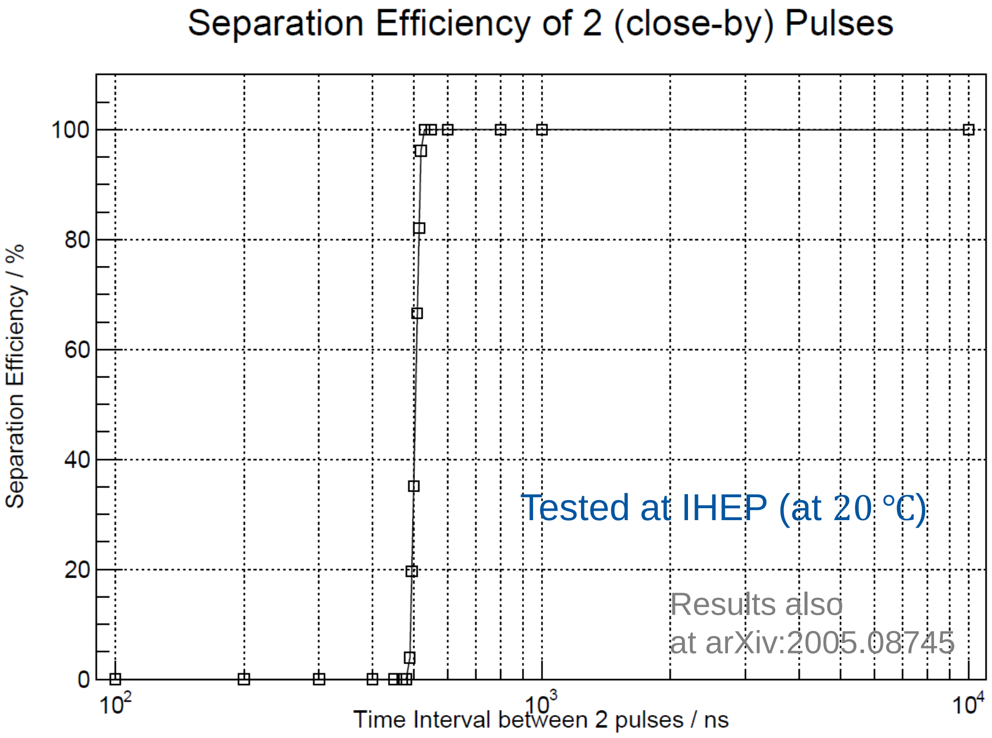
**Potential for continuous mode**



Injection Pulses (from an Arbitrary Function Generator)



Pulses from ASIC probe: after preamp + shaper, before ADC



Separation Efficiency of 2 (close-by) Pulses

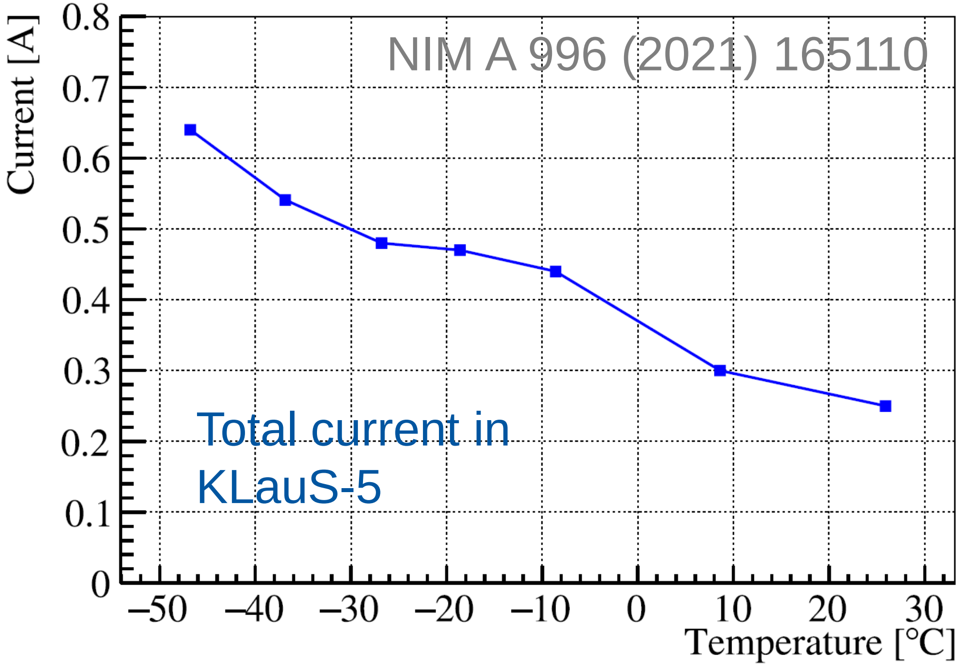
Tested at IHEP (at 20 ℃)

Results also at arXiv:2005.08745

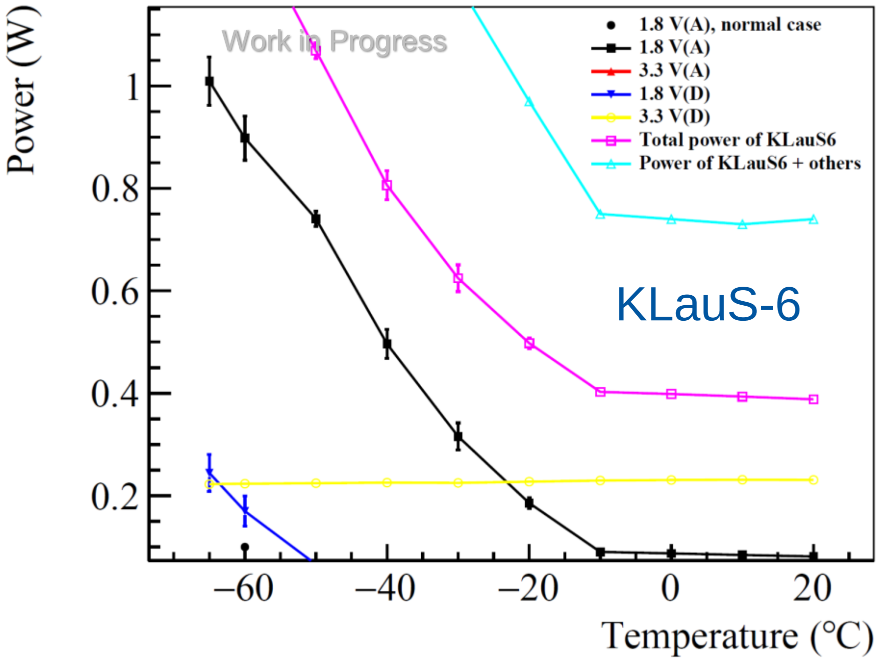
- Varying time interval between 2 injection pulses: 100ns - 10µs
- When time interval > 500ns, 100% efficiency of separating the two pulses
  - Promising feature for 100% duty cycle ( required by circular colliders)

# KLauS: power consumption

- Power consumption measurements with varying temperatures
  - KLauS chips (version 5, 6) and peripherals
  - KLauS6: ~0.4W/chip measured around room temperature
    - At threshold=0 (high trigger rate expected ~2MHz)



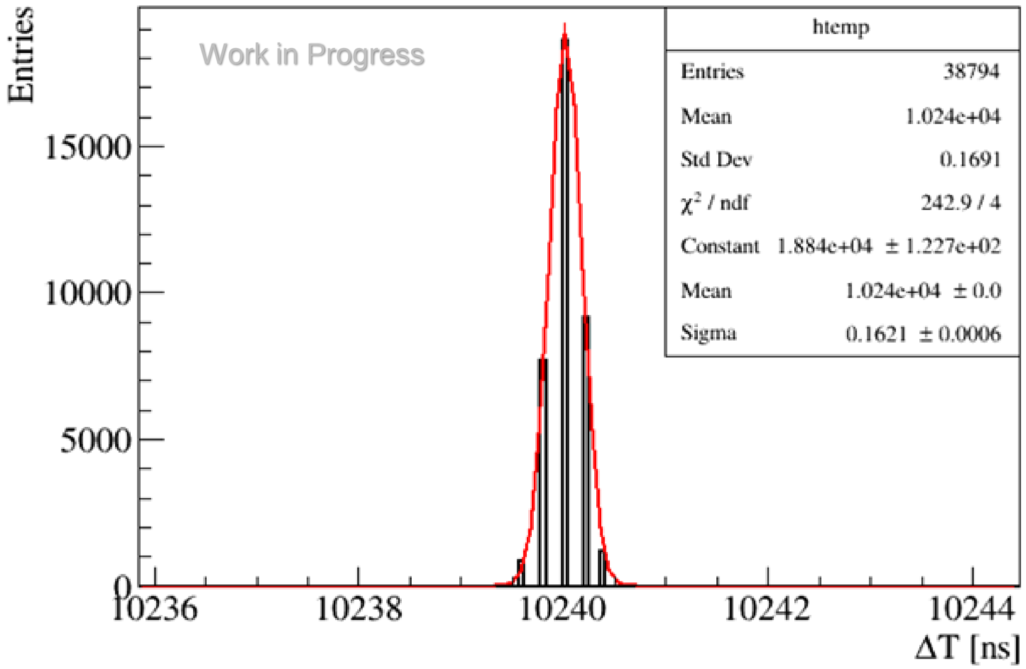
Typical 3.3mW/ch for Klaus5



With JUNO-TAO team

# KLauS6: timing performance

- KLauS6: tested with a pulse generator
  - KLauS6 TDC bin 200 ps: theoretical resolution ~58 ps
  - Time intervals between 2 pulses
  - Timing resolution measured ~160ps
    - Still quite some room for improvement



Pulse generator settings
- 100kHz repetition rate
- 40mV pulse height
- 3ns rising edge
- 3ns rising falling edge

With JUNO-TAO team

# Summary

- High-granularity crystal ECAL
  - Aim to achieve optimal EM energy resolution and PFA capability
  - Steady R&D progress targeting key issues (performance and technical)
    - PFA performance: preliminary studies with crystals
    - Software developments in CEPCSW
      - Geometry, simulation, reconstruction (hits, clustering), validation
    - Technical studies
      - SiPM and crystal: uniformity and timing potentials in simulation
      - Characterisations of SiPM-dedicated readout ASIC (KLauS)

- Welcome broader collaborations: synergies expected
  - Early R&D stage, many open issues
  - In the common software framework (Gaudi, Key4HEP, DD4HEP, …)

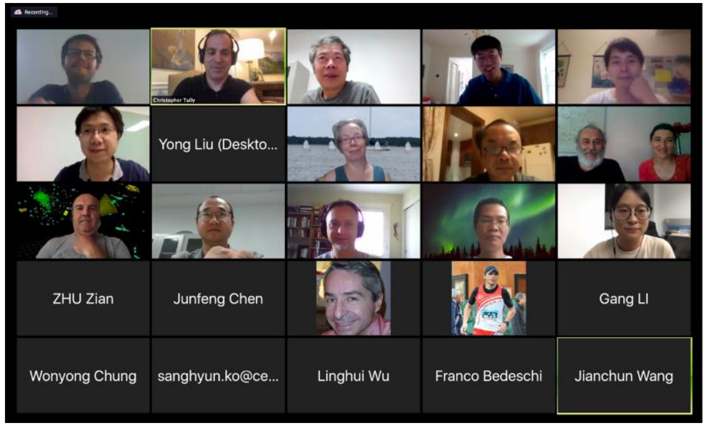
Thank you!

# Backup slides

# High-granularity Crystal Calorimeter: past workshops

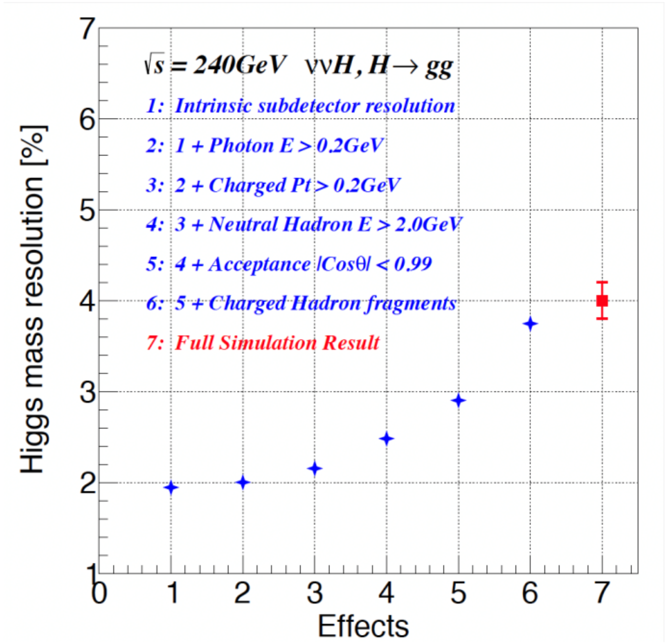
- Ideas firstly proposed: CEPC calorimetry workshop (March 2019)
- Follow-up workshop: Mini-workshop on a detector concept with a crystal ECAL
  - R&D efforts targeting key issues and technical challenges

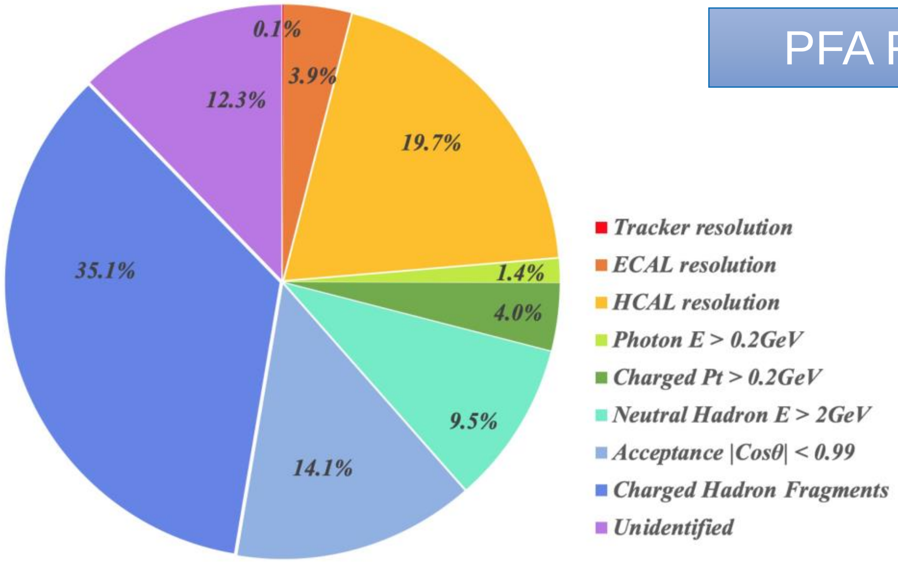
Virtual mini-workshop on a detector concept with a crystal ECAL, July 22-23, 2020, https://indico.ihep.ac.cn/event/11938/



# Impacts to Higgs mass resolution: reminder

Yuexin Wang (IHEP)





PFA Fast Simulation

- Full simulation with SiW-ECAL via the benchmark Higgs to 2 gluons
  - 10 longitudinal layers or more in ECAL can help achieve better than 4% of BMR
  - Expect small impact from ECAL intrinsic energy resolution (PFA fast simulation)
- Guidance for the longitudinal segmentation
  - Will perform more benchmark studies for crystal ECAL in the CEPC detector simulation

# Crystal and SiW options

Crystal ECAL: $BGO$

- Optimal energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
  - Better jet energy resolution $0.17\sqrt{E_J}$
- Larger $R_M$ ➔ larger lateral width of a shower
  - Increase probability of showers' overlap
- Larger $\lambda_I/X_0$ ➔ longitudinal development is determined by $\lambda_I$
  - Increase probability of hadronic shower in ECAL

$$\sigma_{Jet} = \sqrt{\sigma_{Track}^2 + \sigma_{Had}^2 + \sigma_{em}^2 + \sigma_{Confusion}^2}$$

*Confusion* is the limiting factor in PFA.

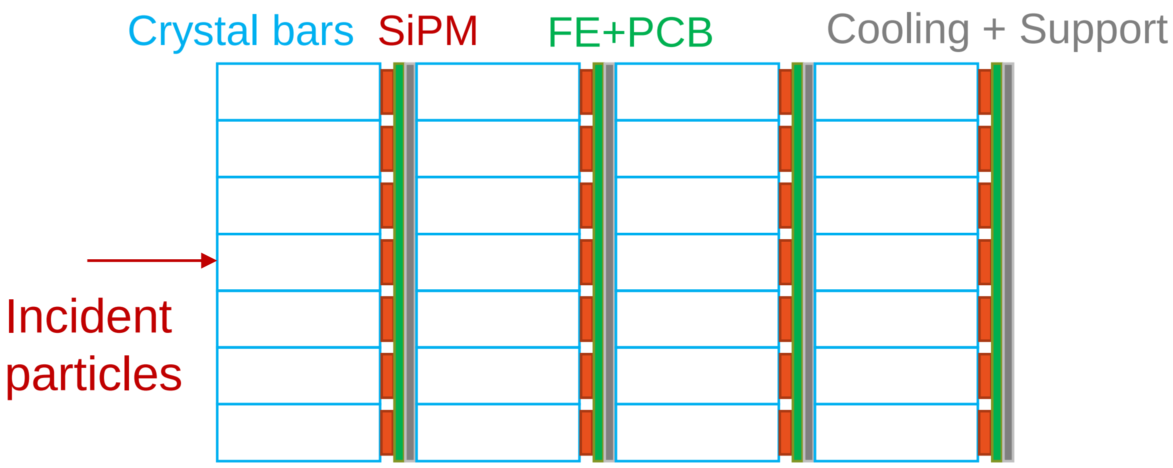
- Avoid double counting of same particle
- Separate energy from different particles

| Material | $X_0$ /cm | $R_M$ /cm | $\lambda_I$ /cm | $\lambda_I/X_0$ |
|---|---|---|---|---|
| W | 0.35 | 0.93 | 9.6 | 27.4 |
| BGO | 1.12 | 2.23 | 22.8 | 20.3 |
| Ratio | 3.2 | 2.4 | 2.4 | 0.74 |

| Component | Detector | Energy Fraction | Energy Resolution | Jet Energy Resolution |
|---|---|---|---|---|
| Charged Particles ($X^\pm$) | Tracker | $\sim 0.6\ E_J$ | — | — |
| Photons ($\gamma$) | ECAL | $\sim 0.3\ E_J$ | $0.15\sqrt{E_\gamma}$ | $0.08\sqrt{E_J}$ |
| | | | $0.03\sqrt{E_\gamma}$ | $0.016\sqrt{E_J}$ |
| Neutral Hadrons ($h^0$) | HCAL | $\sim 0.1\ E_J$ | $0.55\sqrt{E_{h^0}}$ | $0.17\sqrt{E_J}$ |

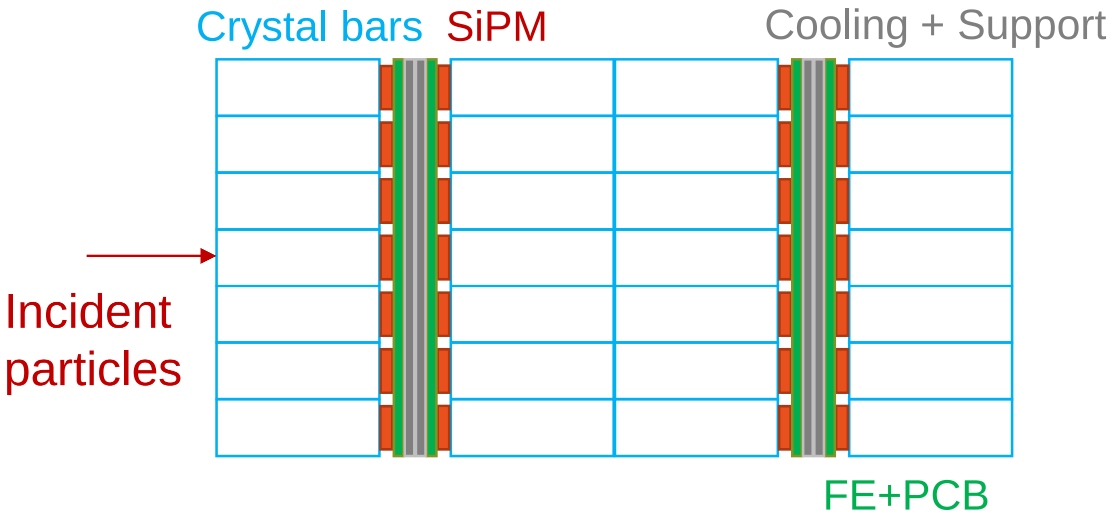
# Considerations on detector layouts

## Layout 1: same module for each layer



- Pros
  - Modular design
  - Uniform structure (easy calibration)
- Cons
  - Material budgets (cooling, mechanics)

## Layout 2: every two layers share the same cooling service and mechanics



- Pros
  - Save material budget (e.g. a factor of two)
- Cons
  - Non-uniform sampling structure: will need specific considerations for calibration

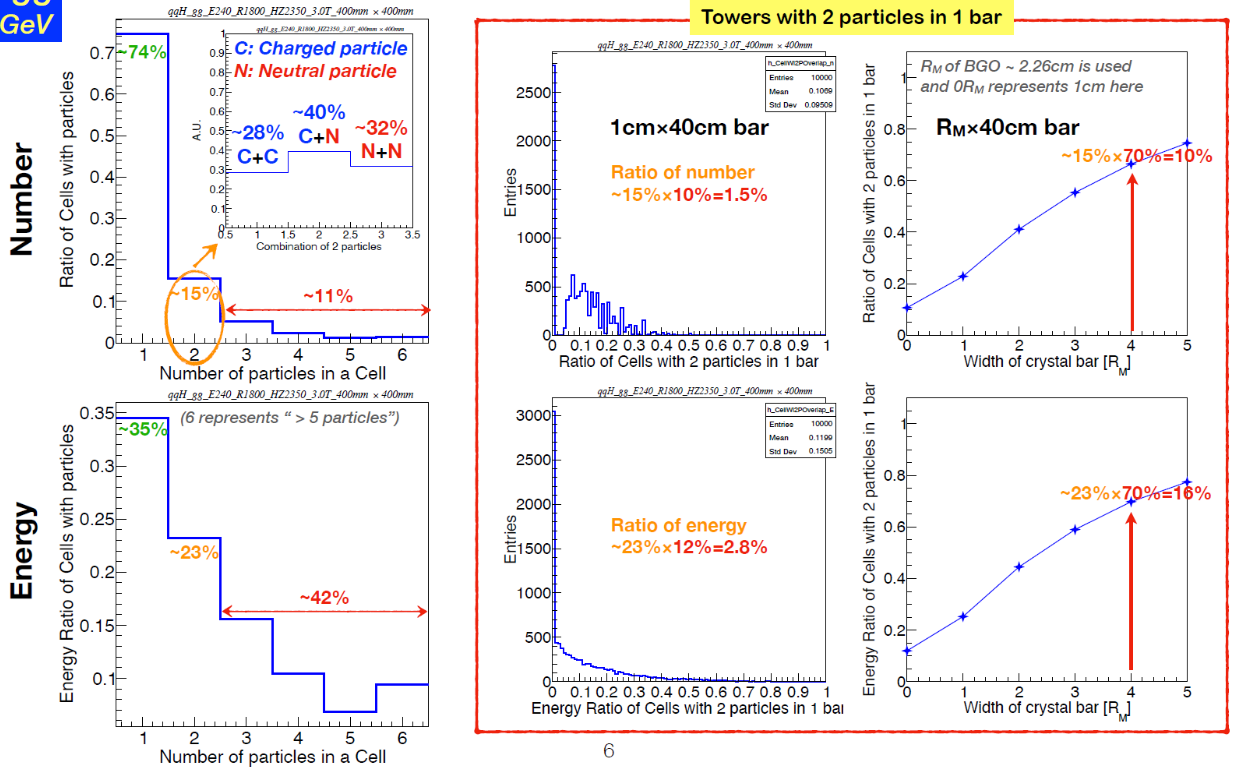
# Studies on physics requirements

Yuexin Wang (IHEP)

- Estimate the multiplicity level of jets: fast simulation
  - Detailed studies with 2 incident particles (from a jet) hitting the hottest tower

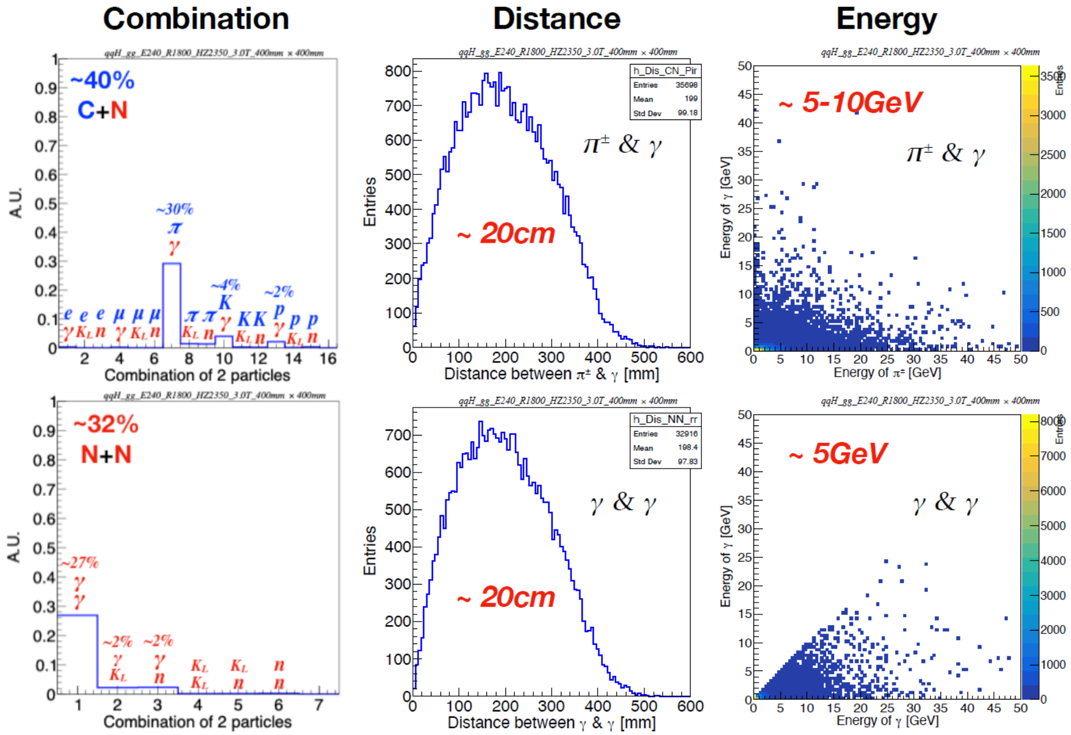
*Z→qq*
*H→gg*
*240GeV*

*Multiplicity in a 40cm×40cm tower*



*Z→qq*
*H→gg*
*240GeV*

*Tower with 2 particles: distance & energy distribution*

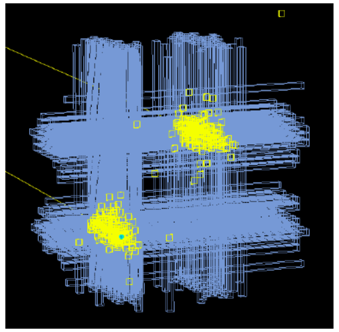


# Reconstruction: ongoing studies

Yuexin Wang (IHEP)

## Patterns in event display: 2 photons

## Shower profiles: 2 photons

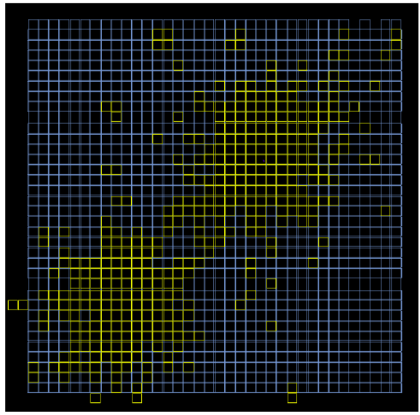


**2 parallel 5GeV γ**

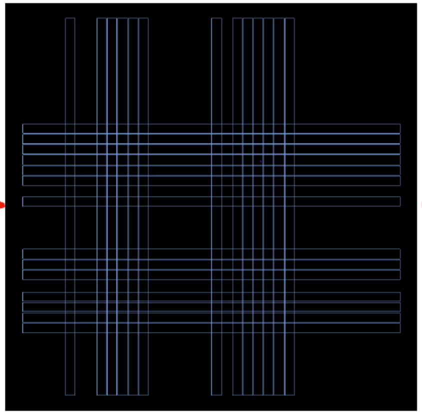
*distance ~20cm along the diagonal*

*→ can be separated.*

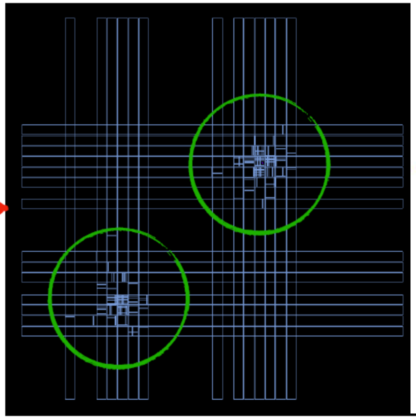
**Simulated Hits (yellow cells)**

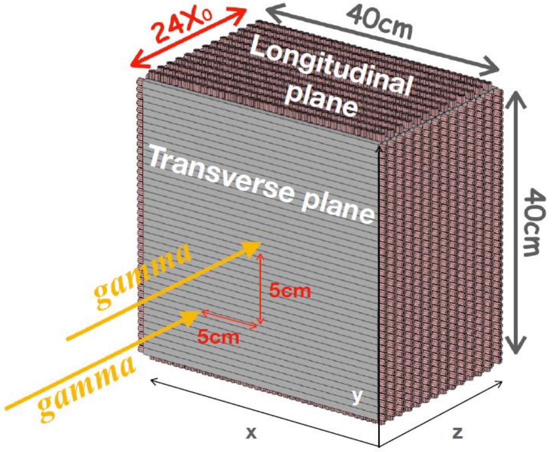


**Digitized Long Bar Hits ($E_{dep}$ > 1 MIP)**

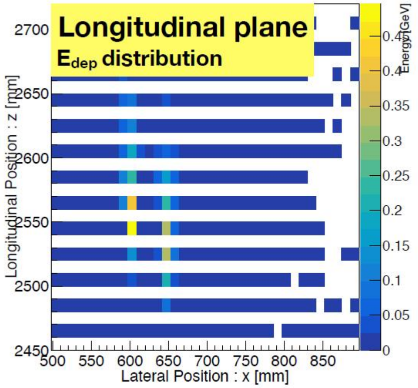


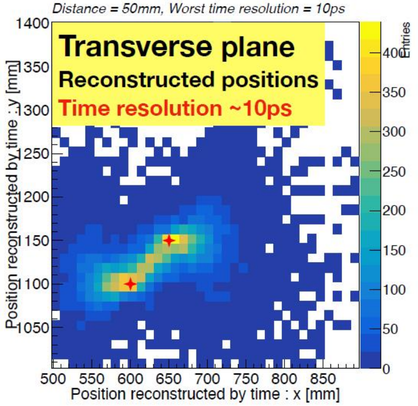
**Reconstructed positions using time difference of 2 ends**





5cm ~ 2R$_M$ for BGO (R$_M$=2.26cm)





# Pattern studies using Event Display

- Patterns for first impression, but still complex
- Need further studies on positioning and energy splitting