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

Yong Liu (Institute of High Energy Physics, CAS),

on behalf of the CEPC Calorimetry Working Group

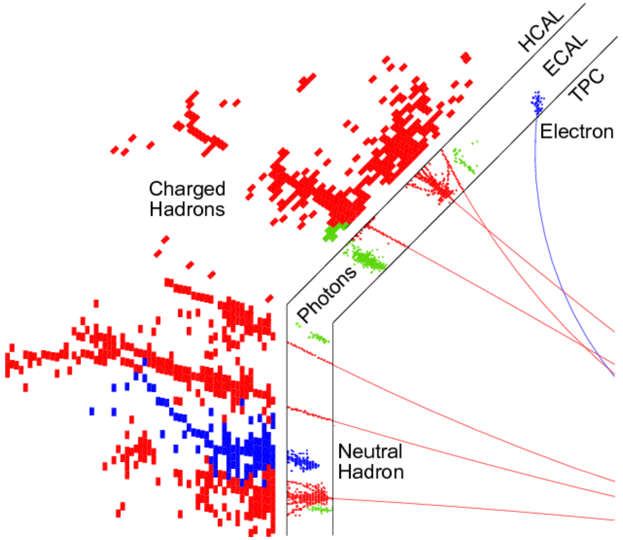
CEPC Physics and Detector Plenary Meeting

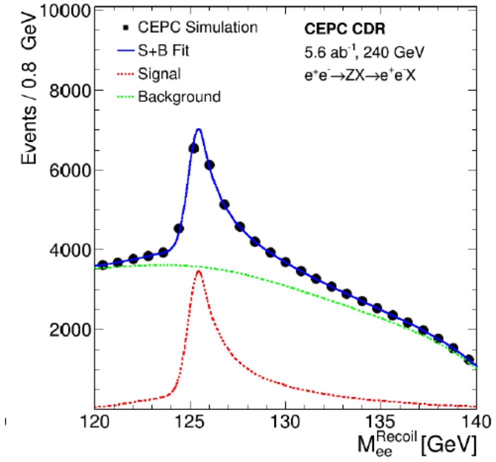
March 31, 2021

Mostly based on the talk presented in the [CALICE Collaboration Meeting] last week

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 γ/π^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%



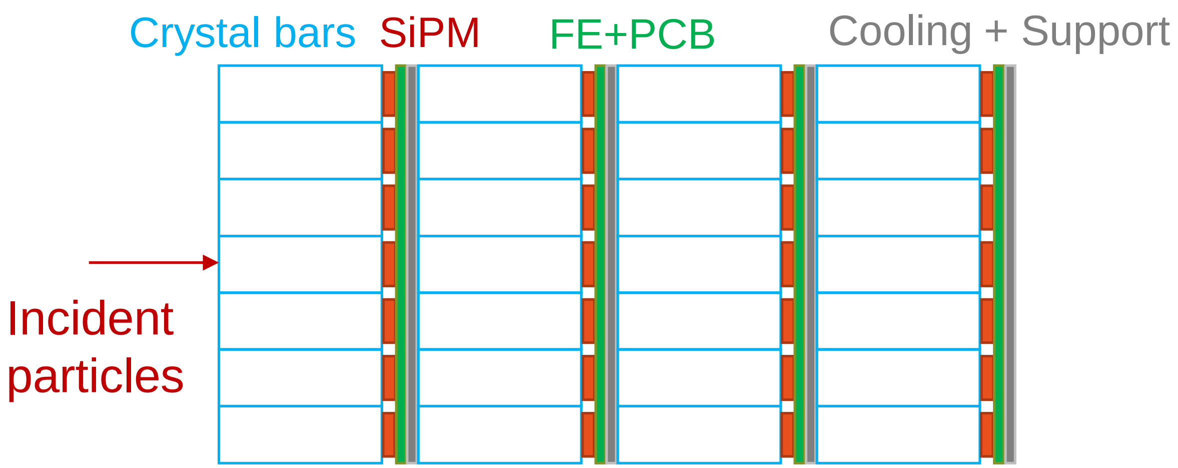


R&D efforts targeting key issues and technical challenges (reminder)

- 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 design: 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

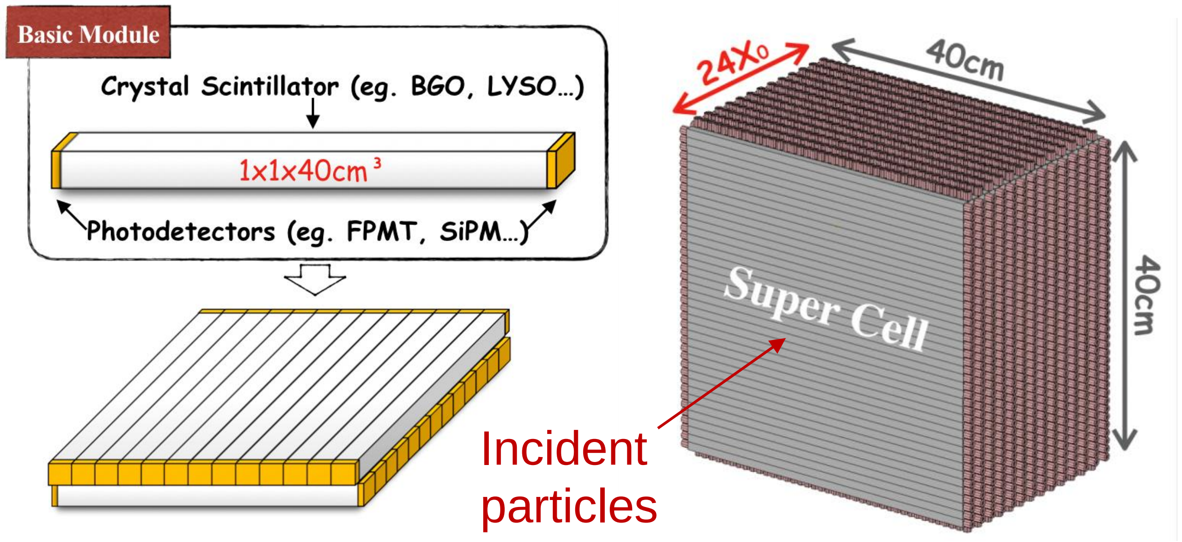
High-granularity crystal ECAL: 2 major designs

Design 1



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

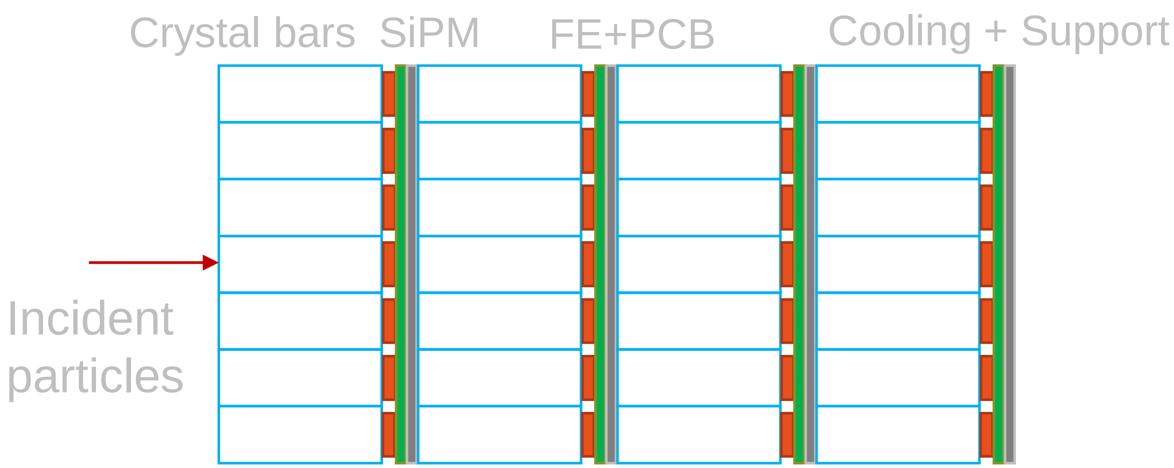
Design 2 (current focus)



- 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

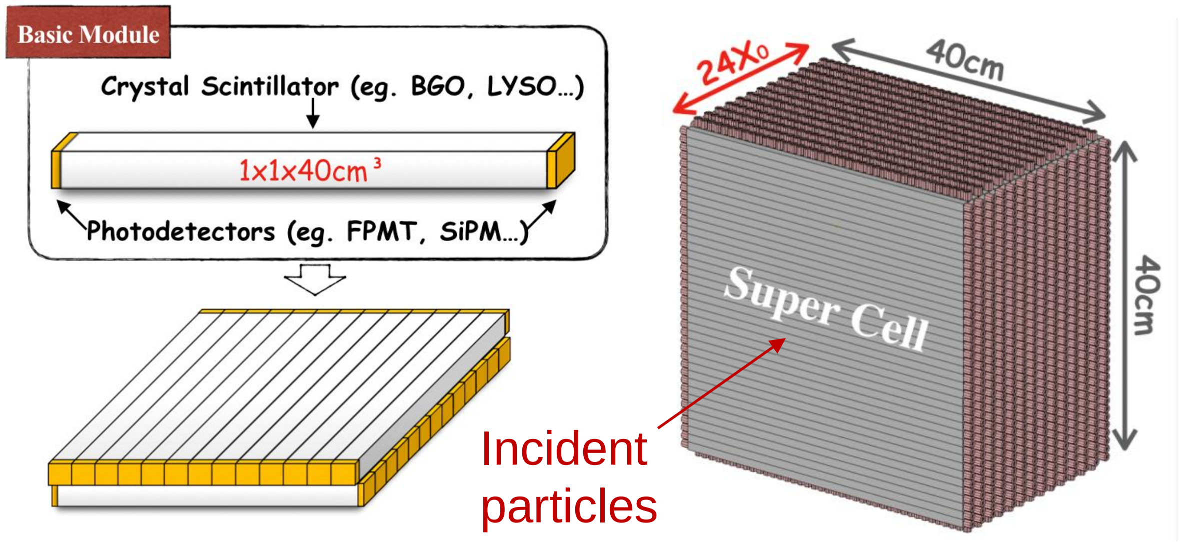
High-granularity crystal ECAL: 2 major designs

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

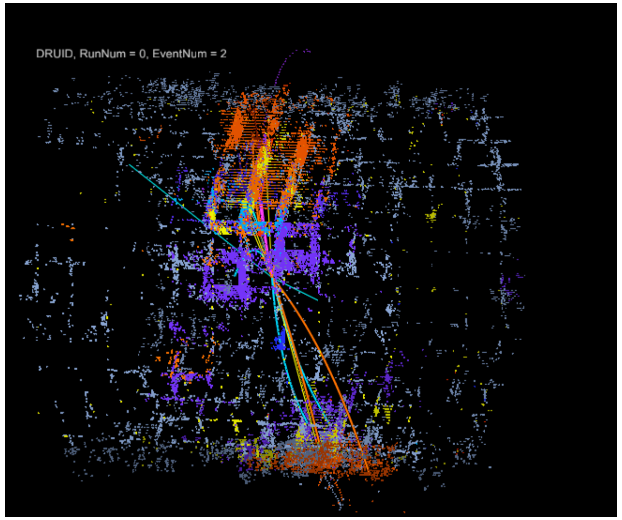
- Key issues: performance studies and optimization
  - PFA performance with jets with PFA: preliminary studies with crystals
  - Software development in the new framework CEPCSW
    - Geometry construction in DD4HEP
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting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

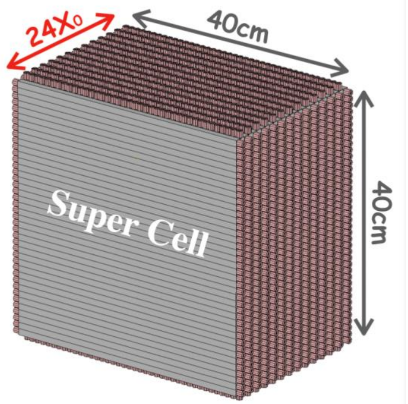
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

PFA performance: a first glance with crystals

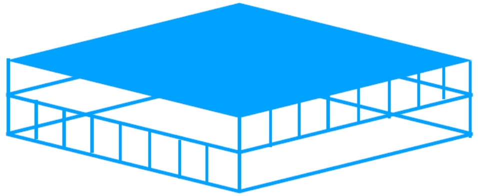
Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \to \nu\nu, H \to gg)$ 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)



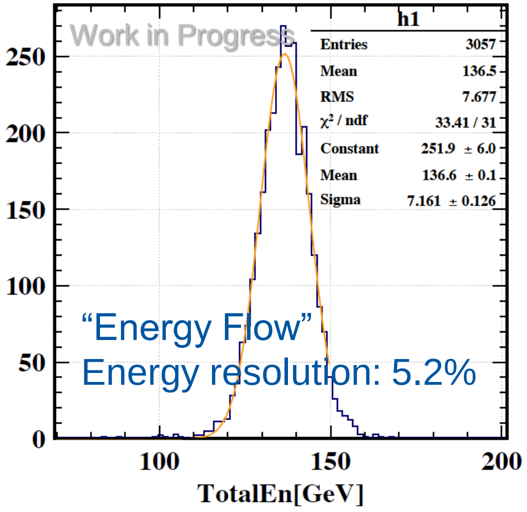
1 super-layer:
2 crystal layers (energy)
1 thin silicon layers (position)

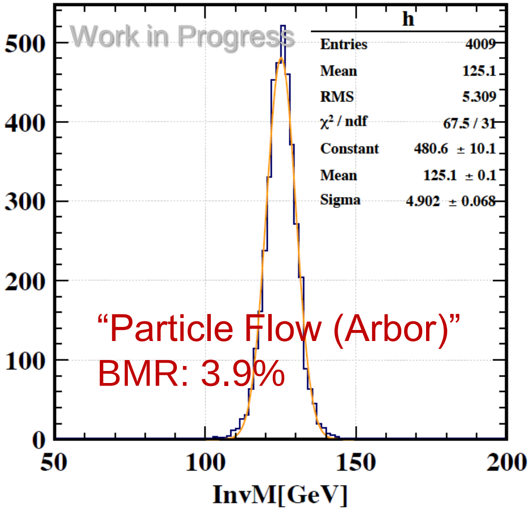
PFA performance with CDR baseline detector

Dan Yu (IHEP)

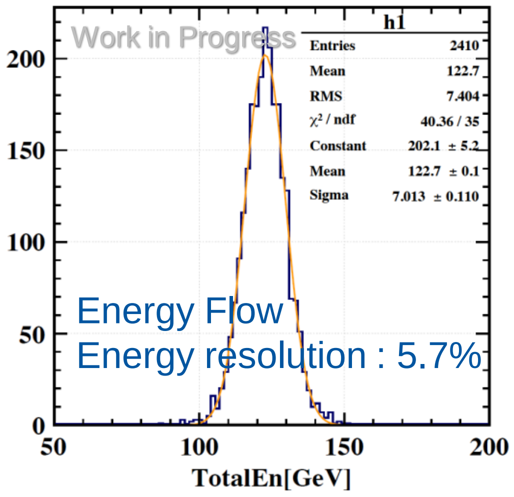
- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
  - Energy flow: combination of hits in calorimeters only
  - Boson mass resolution (BMR)
- PFA improves the resolution from 5.2% to 3.9%

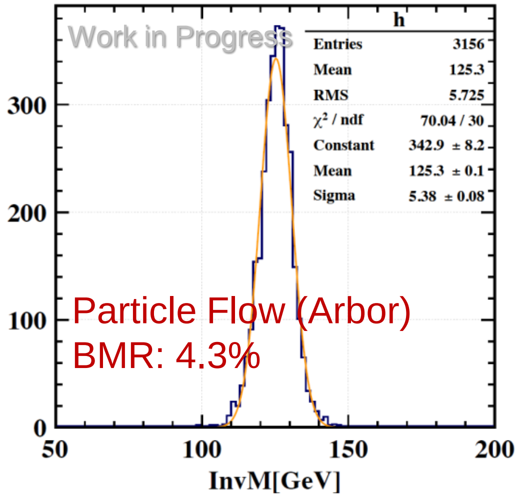
ECAL: 28 SiW layers (24X0)





ECAL: 14 SiW layers (24X0)





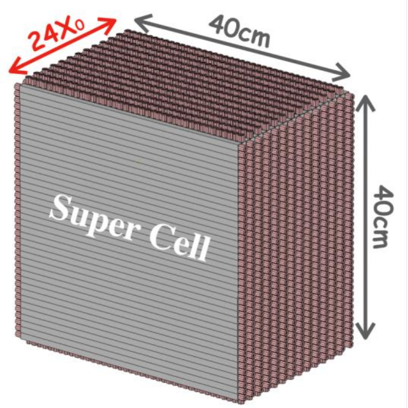
CEPC CDR baseline detector:
BMR improved to 3.9% with PFA

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

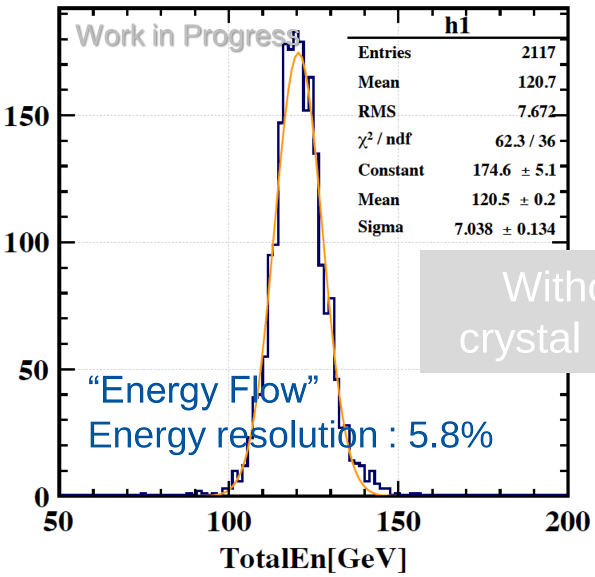
PFA performance: a first glance with crystals

Dan Yu (IHEP)

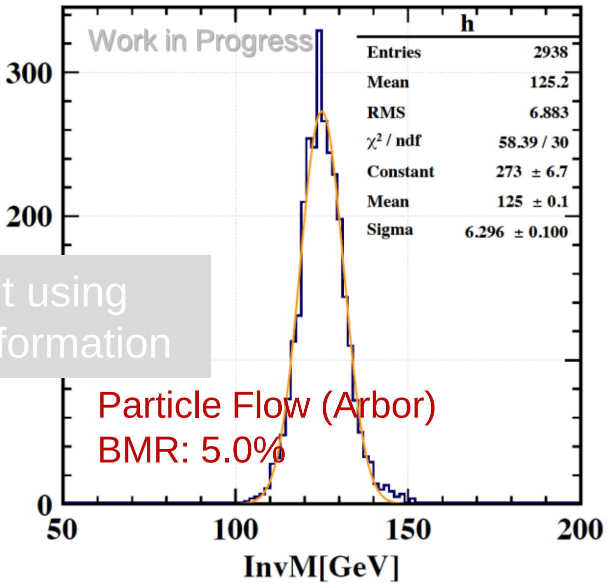
- 2-jet benchmark events in $ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV
- **14 layers** of crystal and silicon: use silicon for positioning
  - Without crystal information: PFA improves resolution to 5.0% from 5.8%
  - With crystal energy information only: energy resolution ~4.8%
- Plenty of room to improve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

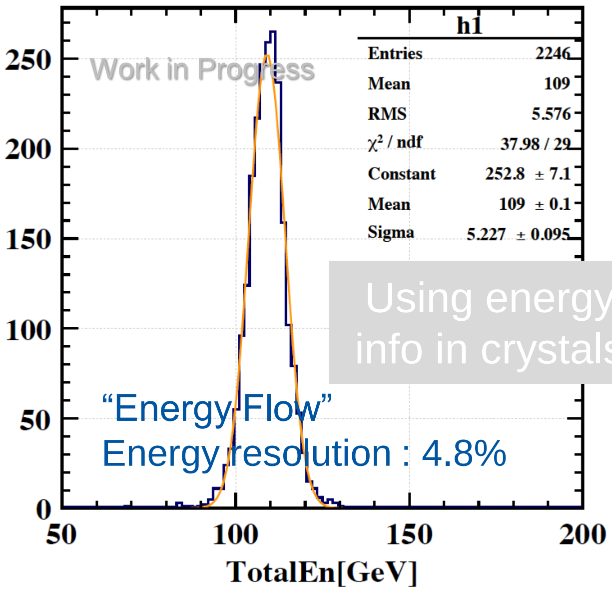


ECAL: 14 super-layers (24X0)

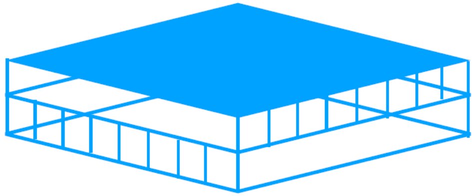


Without using crystal information





Using energy info in crystals

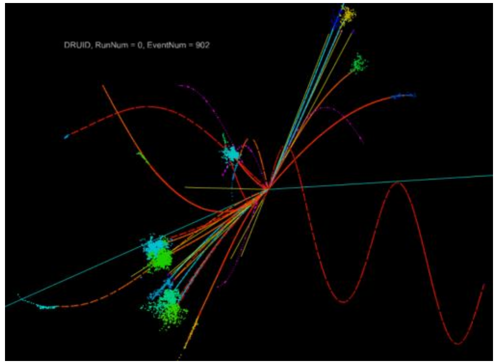


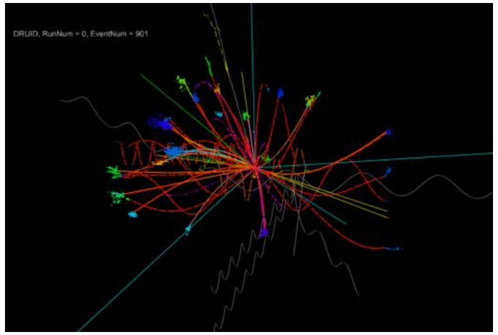
1 super-layer:
2 crystal layers (energy);
1 thin silicon layers (position)

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

PFA performance: ongoing studies

- Strategy/ideas
  - Quantify BMR in the physics benchmark: 2-jet events in $ZH(Z \to \nu\nu, H \to gg)$
  - First start with an ideal finely segmented crystal calorimeter
  - Change the crystal granularity → impacts → requirements on segmentation (e.g. BMR<4%) → compare with performance of design of long crystal bars
- Detector geometry CEPC_v4 (CDR), and replace SiW ECAL with crystal ECAL
  - ECAL geometry: first start with crystal cubes ($1\ \mathrm{cm}^3$)
- Ongoing studies and plans
  - BMR with “default” ArborPFA parameters (tuned for SiW)
  - ArborPFA paras tuning for crystals: e.g. clustering efficiency and separation power
    - Significantly wider shower profiles than in SiW, and more “isolated” hits
  - Calibration of crystal calorimeter to hadronic showers





2 gluon-jets in $ZH(Z \to \nu\nu, H \to gg)$: event display

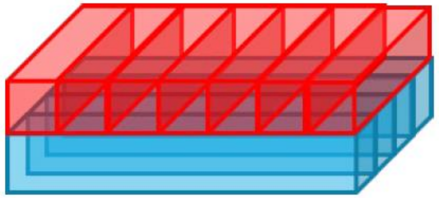
Recent progress presented in this talk

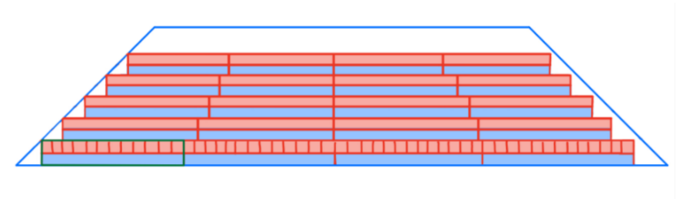
- Key issues: performance studies and optimization
  - PFA performance with jets with PFA
  - Software development in the new framework CEPCSW
    - Geometry construction in DD4HEP
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting
    - Performance validation

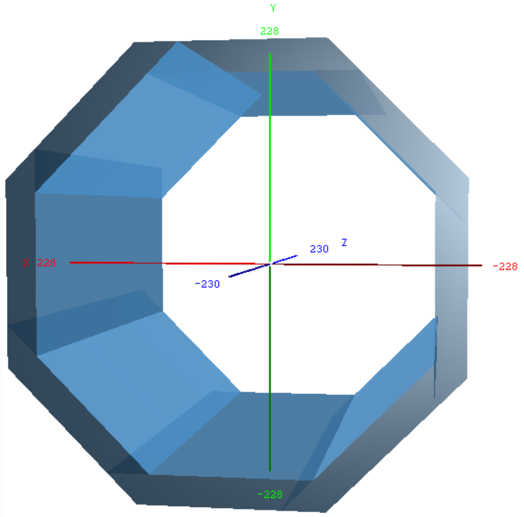
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

Geometry construction

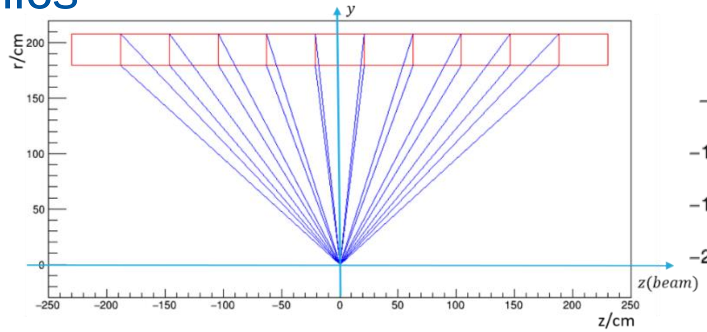
- General
  - BGO crystal bars: $1\text{cm} \times 1\text{cm} \times {\sim}40\text{cm}$
  - Readout at two ends
- Basic detector unit: super cell
  - 2 layers of crossed bars
- Detector layout with DD4HEP
  - $\mathrm{R} = 1.8\mathrm{m}, \mathrm{L} = 4.6\mathrm{m}, \mathrm{H} = 28\mathrm{cm}$
  - Barrel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

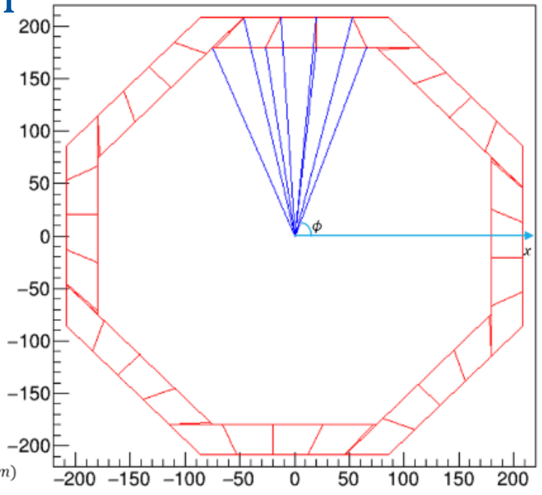






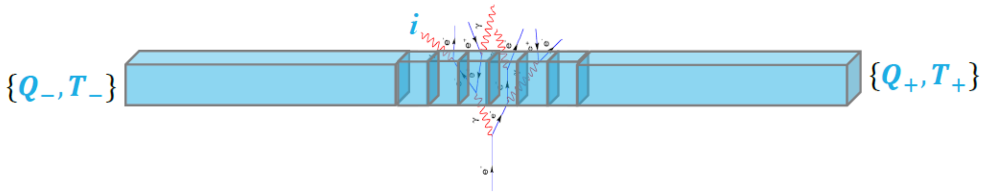
BGO: $\mathrm{X_0} = 1.1\mathrm{cm},\ \mathrm{R_M} = 2.2\mathrm{cm}$

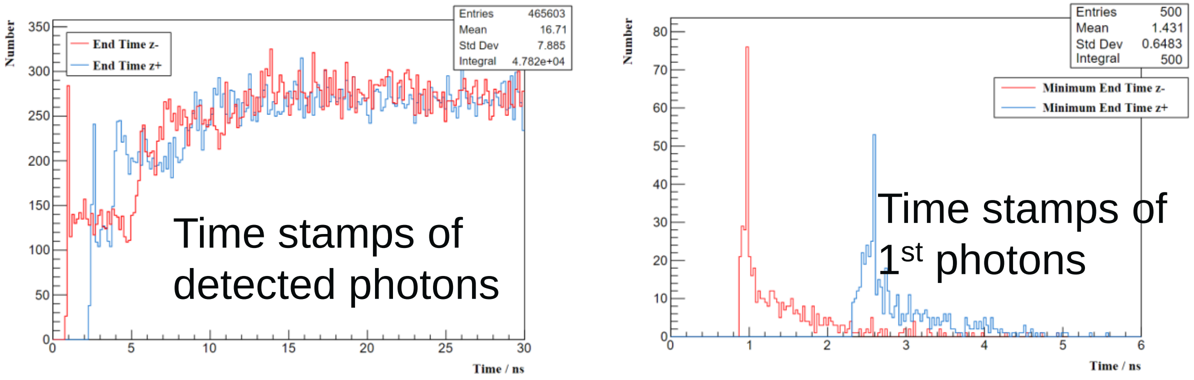




Simulation and digitisation

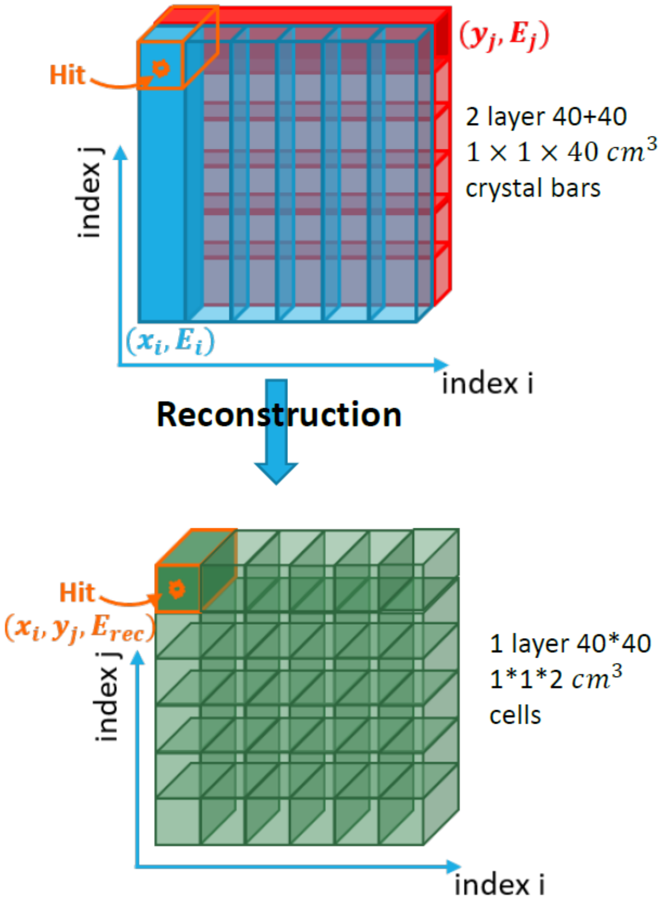
- G4 full simulation build to extract timing resolution
  - Optical photon processes: scintillation, Cherenkov, bulk absorption and boundary processes
- G4 Shower simulation: no optical processes
- Digitisation for each long bar
  - Contributions of i-th step in G4
  - Amplitude (or #photons)
    - $Q_{\pm}(i)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





Geant4 full simulation established

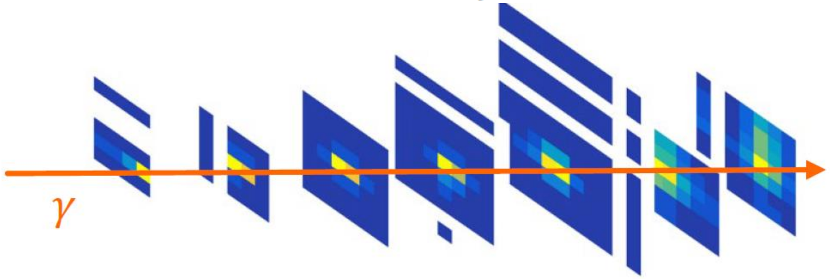
Hit reconstruction

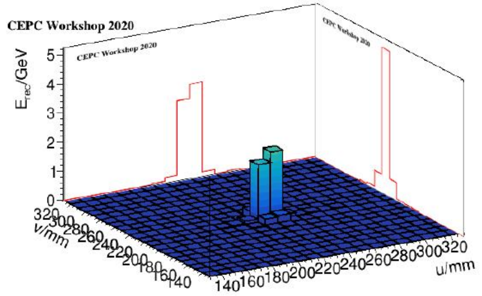


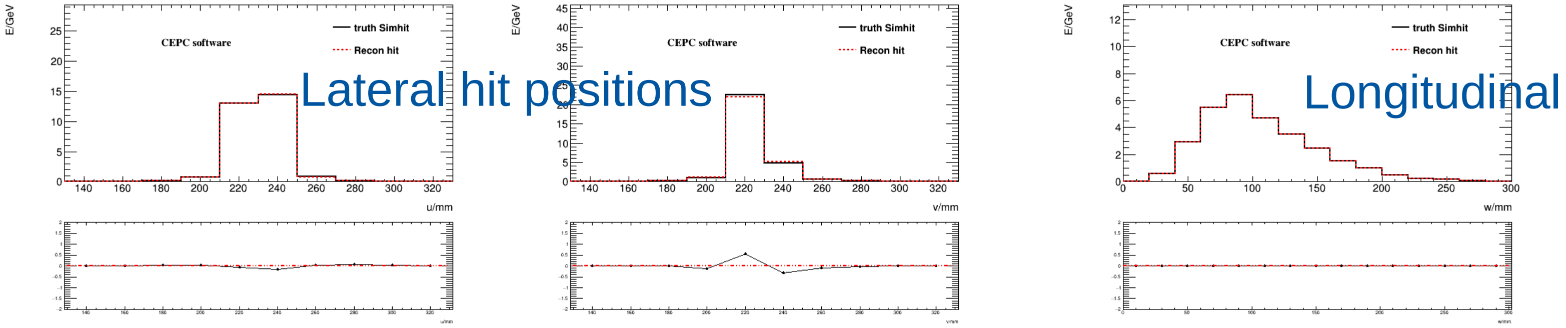
- Combine every two layers to determine
  - Hit positions in lateral plane
  - Energy sharing: energy deposition in the adjacent layer as weight

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

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



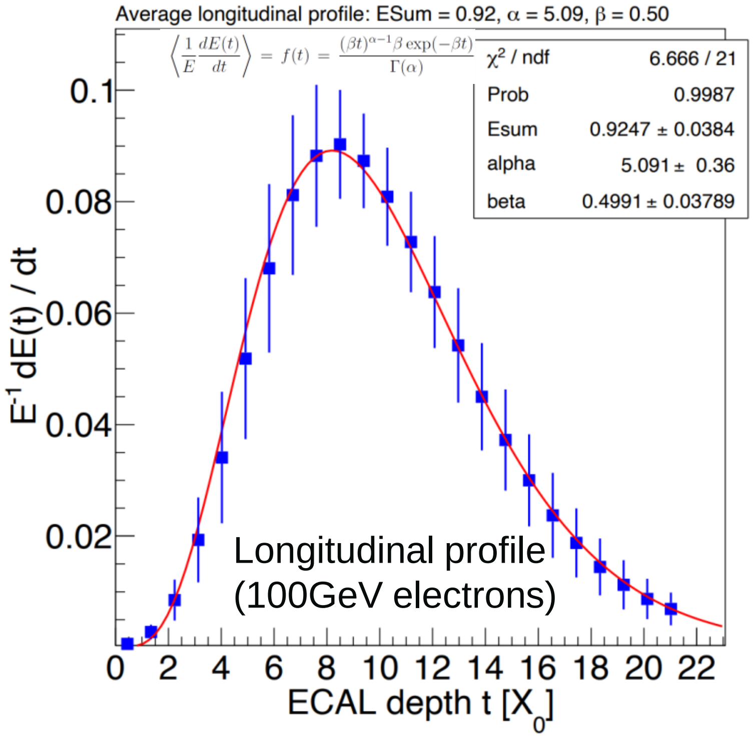




Shower profiles studies in simulation

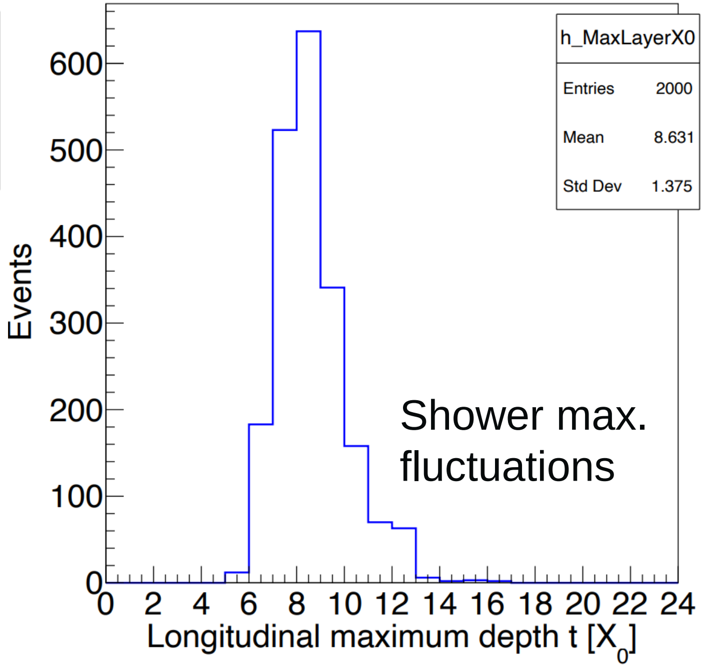
Yuexin Wang (IHEP)

- 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



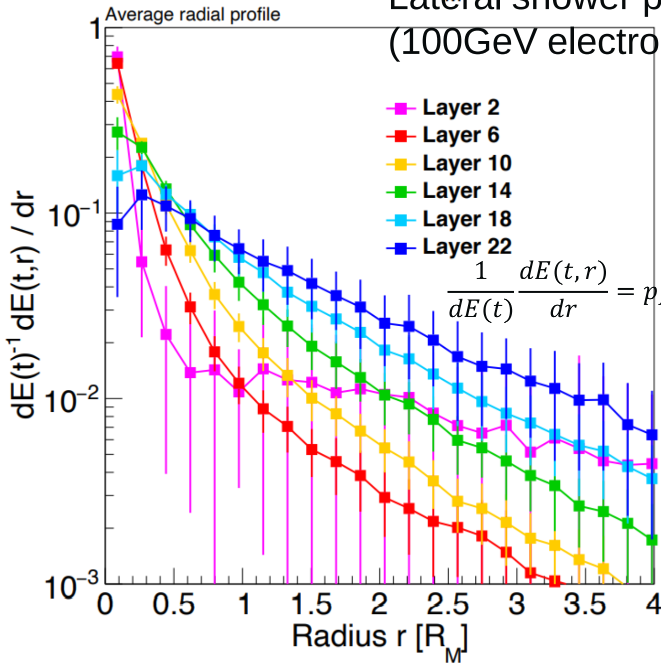
$$\left\langle \frac{1}{E}\frac{dE(t)}{dt} \right\rangle = f(t) = \frac{(\beta t)^{\alpha-1}\beta\exp(-\beta t)}{\Gamma(\alpha)}$$

Longitudinal profile (100GeV electrons)



Shower max. fluctuations

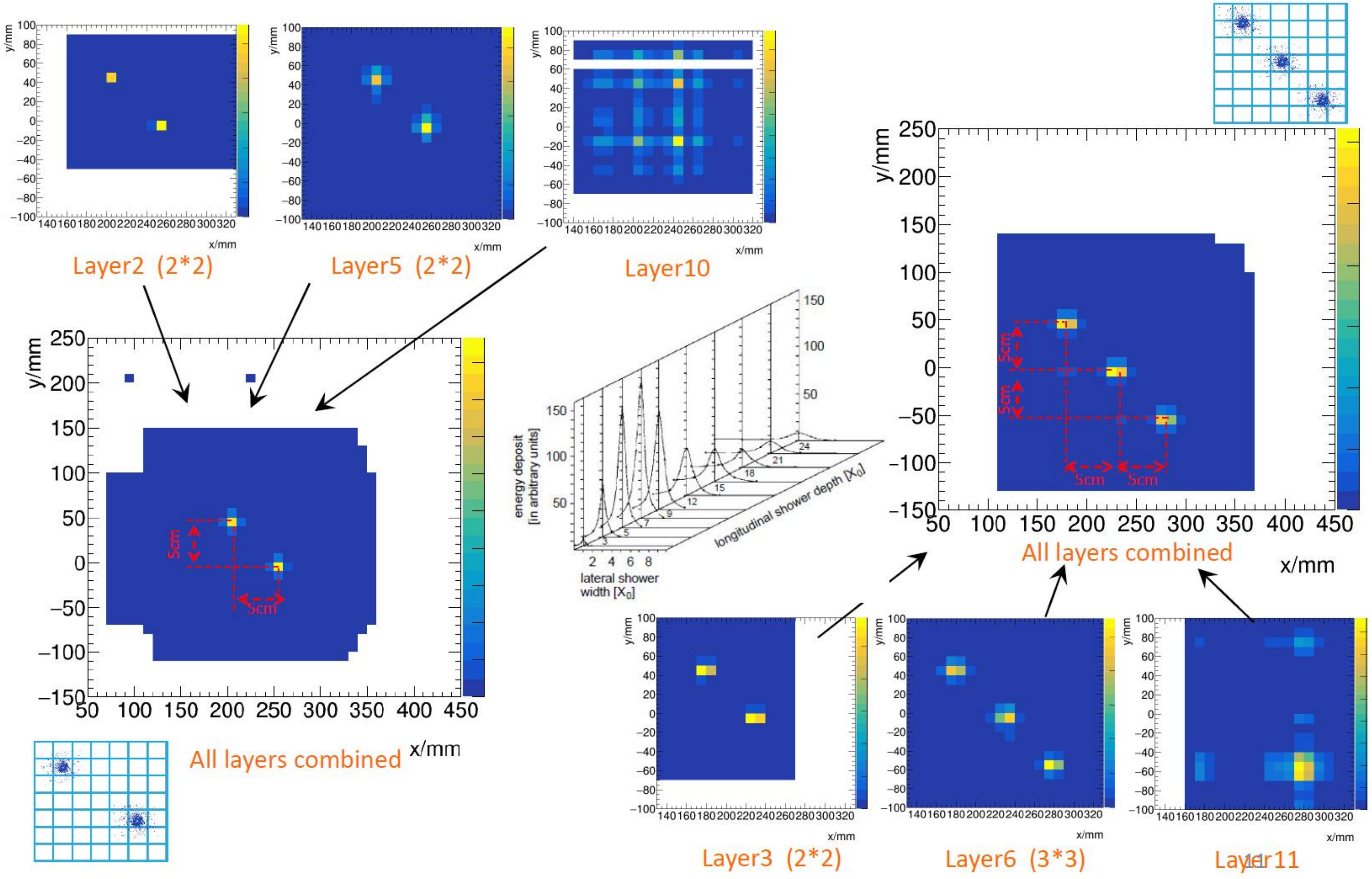
Lateral shower profile (100GeV electrons)



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

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

Ongoing studies: validation and performance



- 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
- Other ongoing studies

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 design (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

Detector unit: general considerations

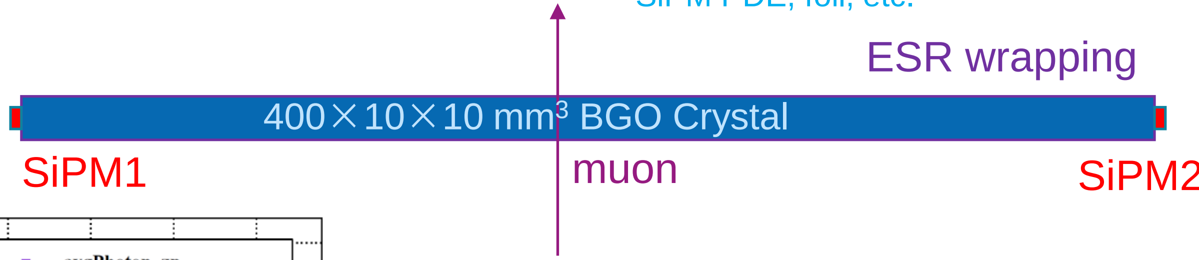
- Key parameters
  - MIP response (#p.e./MIP)
    - Photon statistics: significant impact to the stochastic term (<3%)
    - Energy threshold: sensitivity to low-energy photons
  - Dynamic range
    - Orders of magnitude: o(1MeV ~ 30 GeV) per crystal cell
      - Dependent on crystal dimensions
    - Impact from non-linearity effects of photosensors and electronics
      - SiPM: e.g. limited amount of pixels on a given sensitive area
      - Electronics: e.g. Time-over-Threshold technique
  - Fast timing
    - To explore potentials of <100ps and understand possible limitations

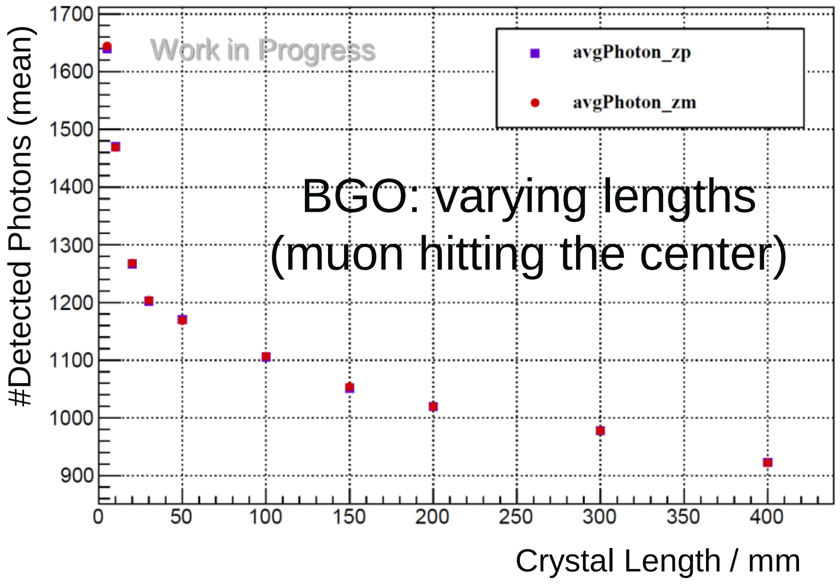
Crystal bar: length impacts and uniformity scan

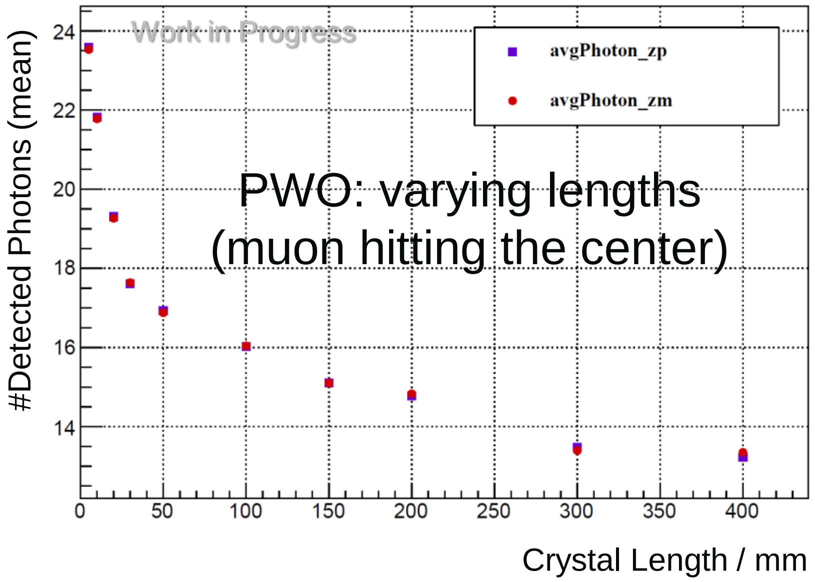
Baohua Qi (IHEP)

- 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

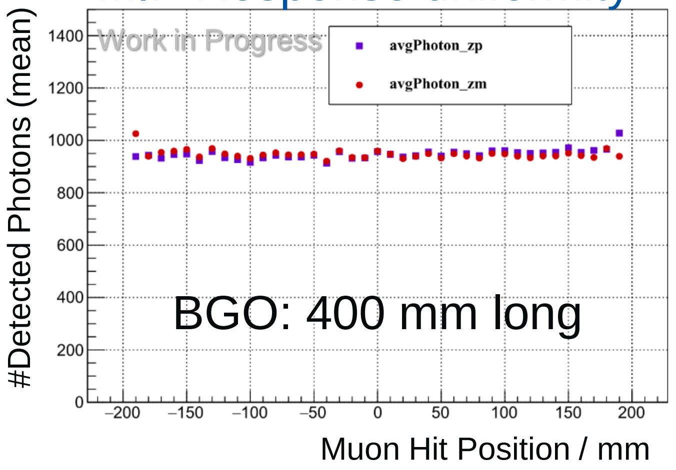
Wavelength dependent parameters implemented in the simulation: scintillation and transmission spectra, SiPM PDE, foil, etc.







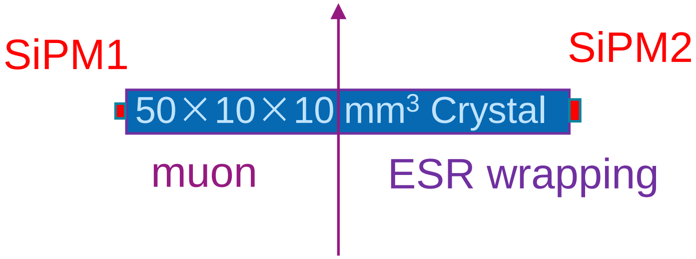
MIP Response uniformity

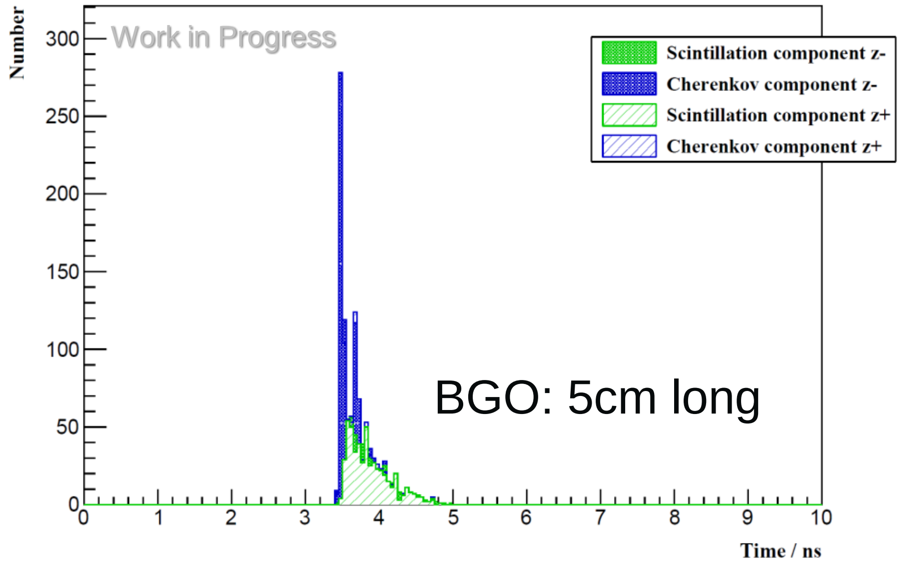


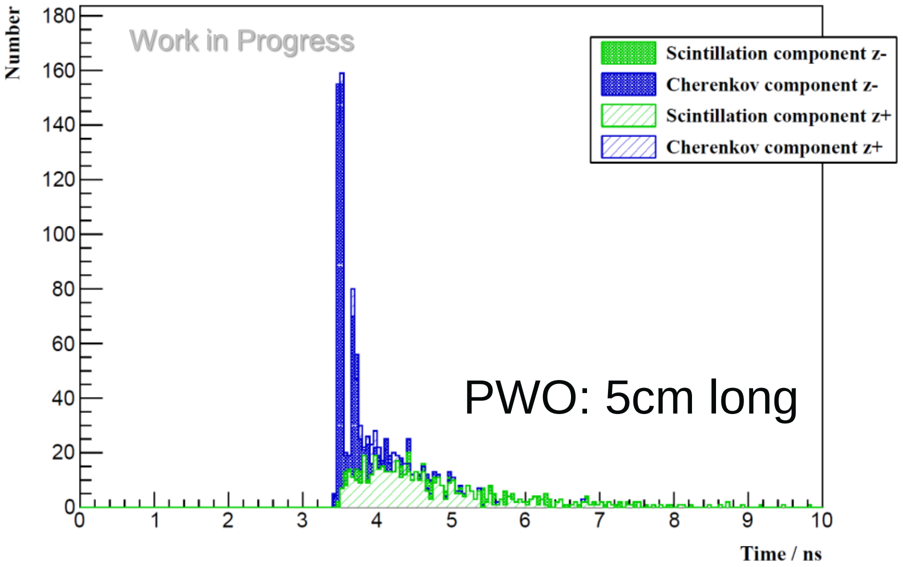
Crystal bar: timing studies

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



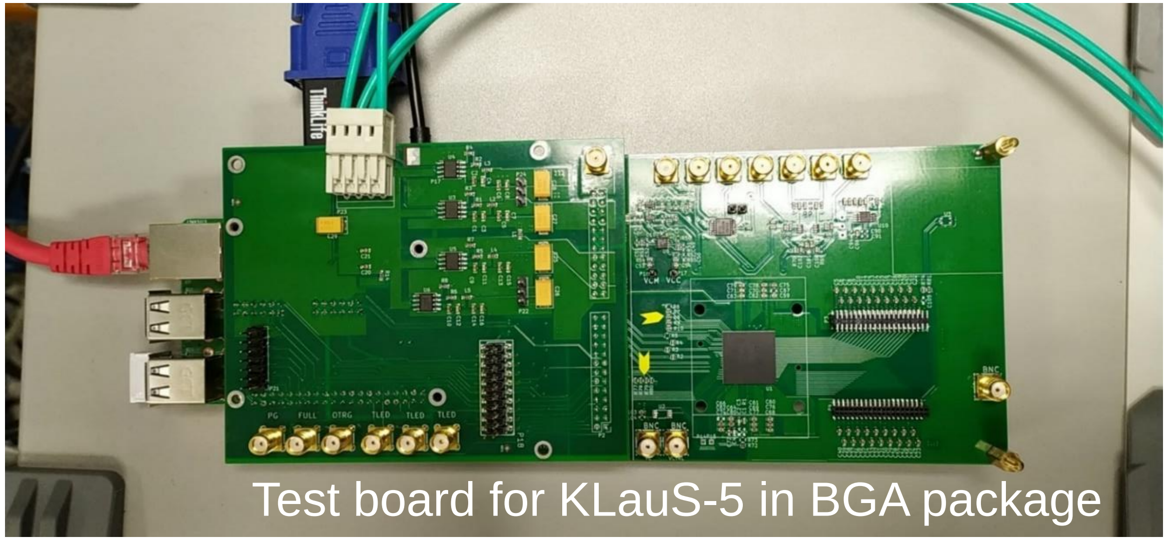




Front-end electronics for SiPM readout

- 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

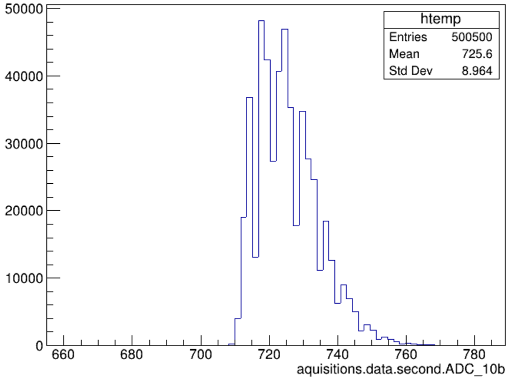

Test board for KLauS-5 in BGA package

Joint efforts with the JUNO-TAO team

Klaus5 tests with NDL-SiPM (reminder)

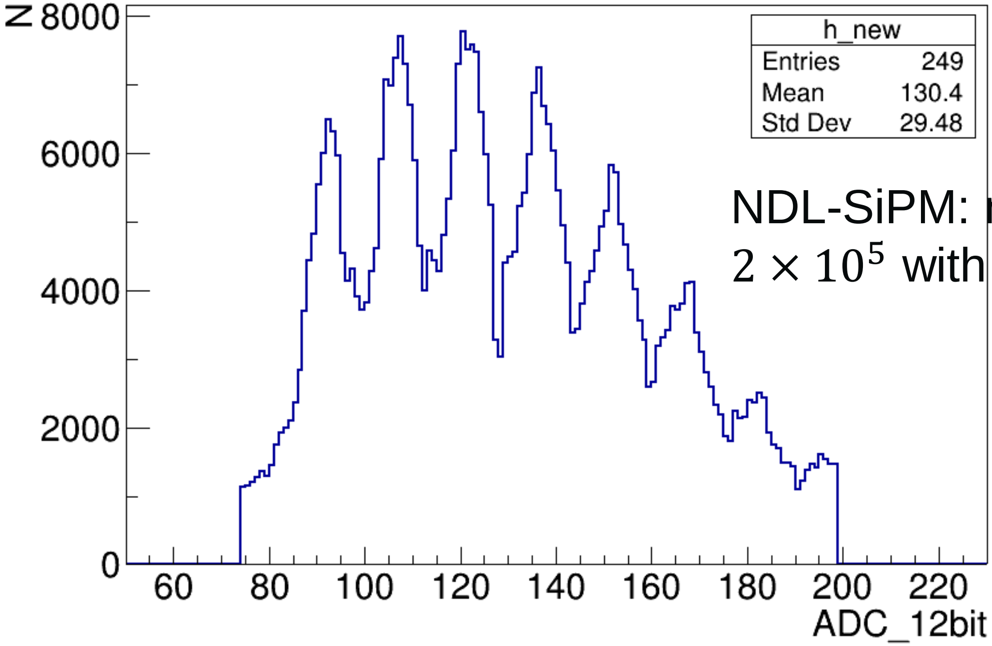
Single photon calibration

- 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

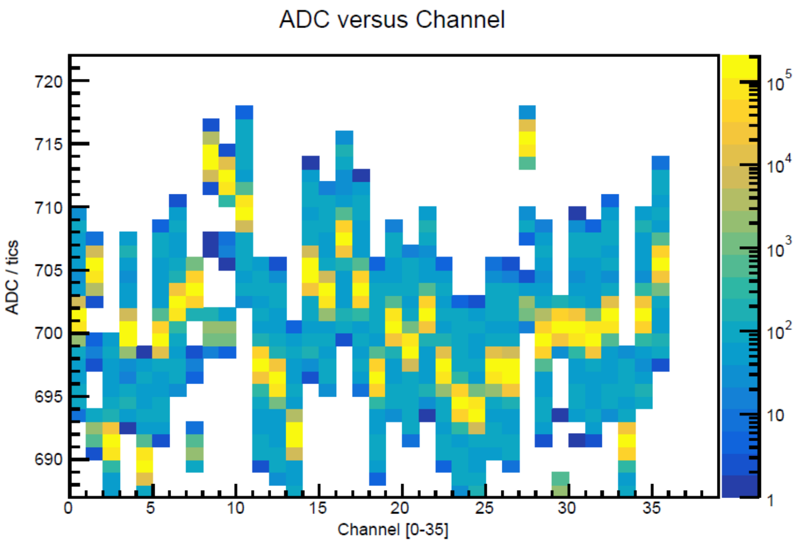


NDL-SiPM: nominal gain 2×10^5 with 10µm pixels

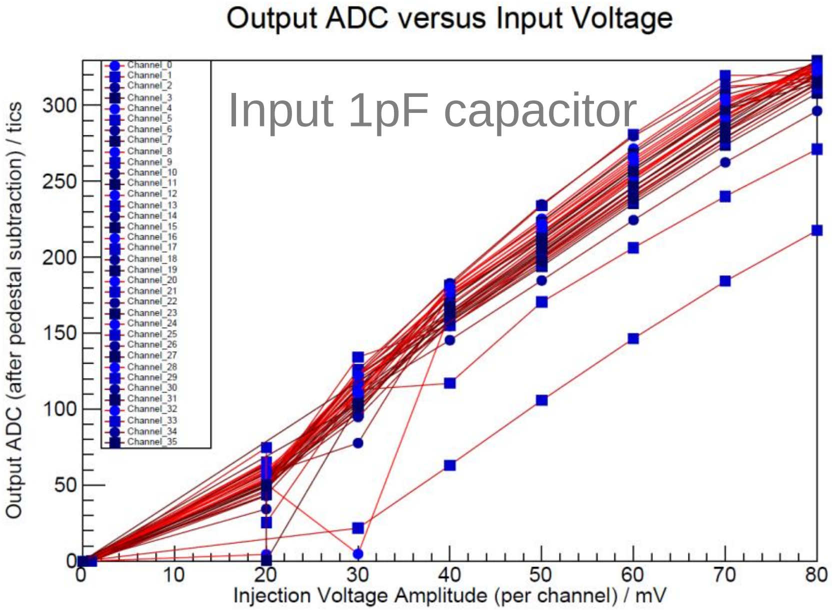
Klaus5 tests with charge injection

Dynamic Range

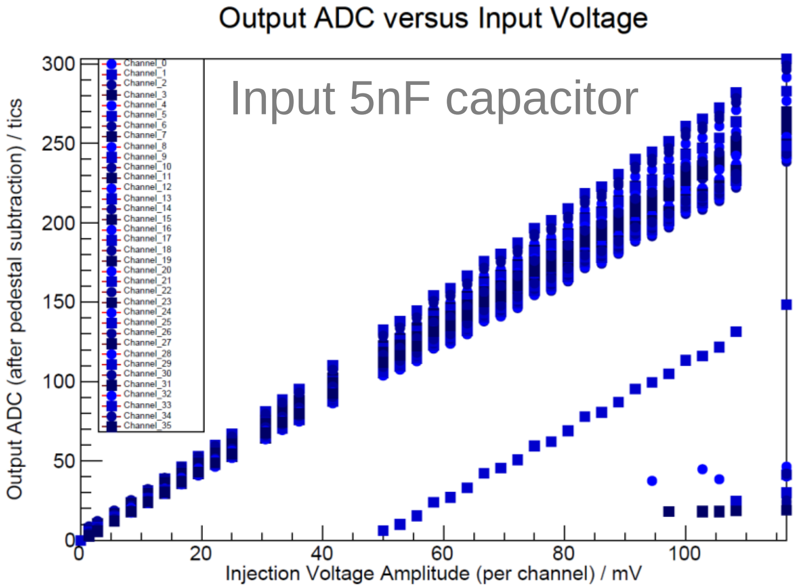
- Testing of all 36 channels
  - Good linearity in different working modes (high gain and low gain)
  - Small equivalent noise charge (ENC) ~4.5fC
  - Dynamic range: ~550pC as the maximum charge (preliminary)



Pedestals in mid High Gain mode



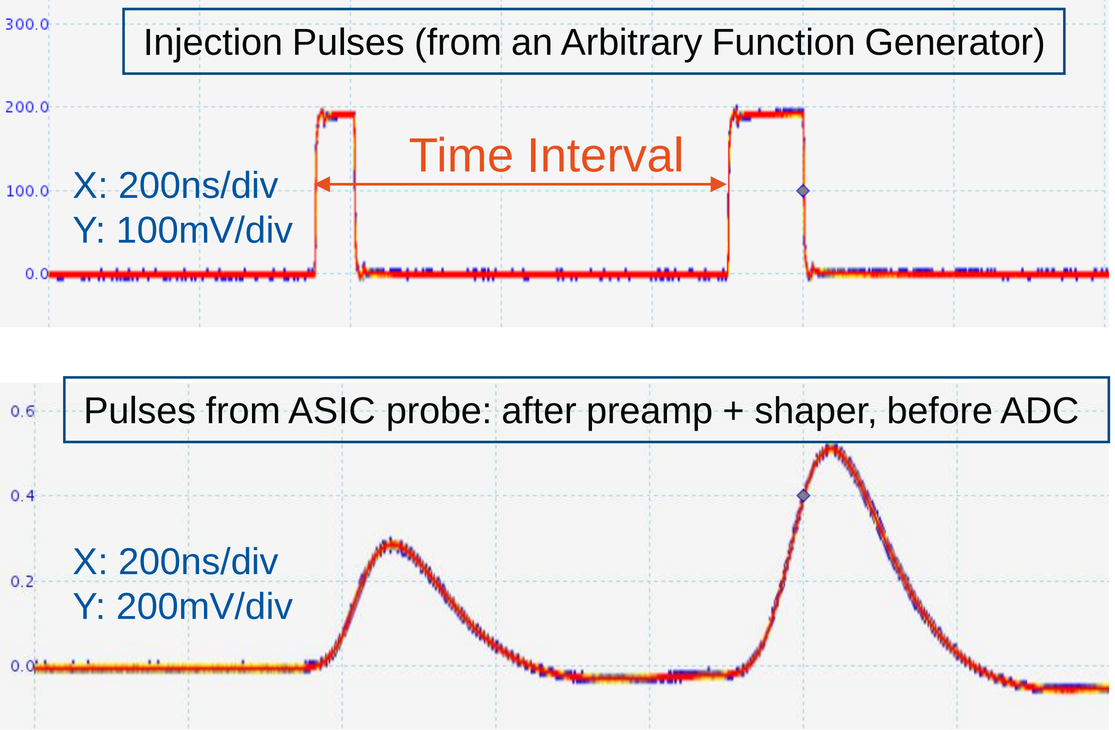
ADC in mid High Gain mode (after pedestal subtraction)

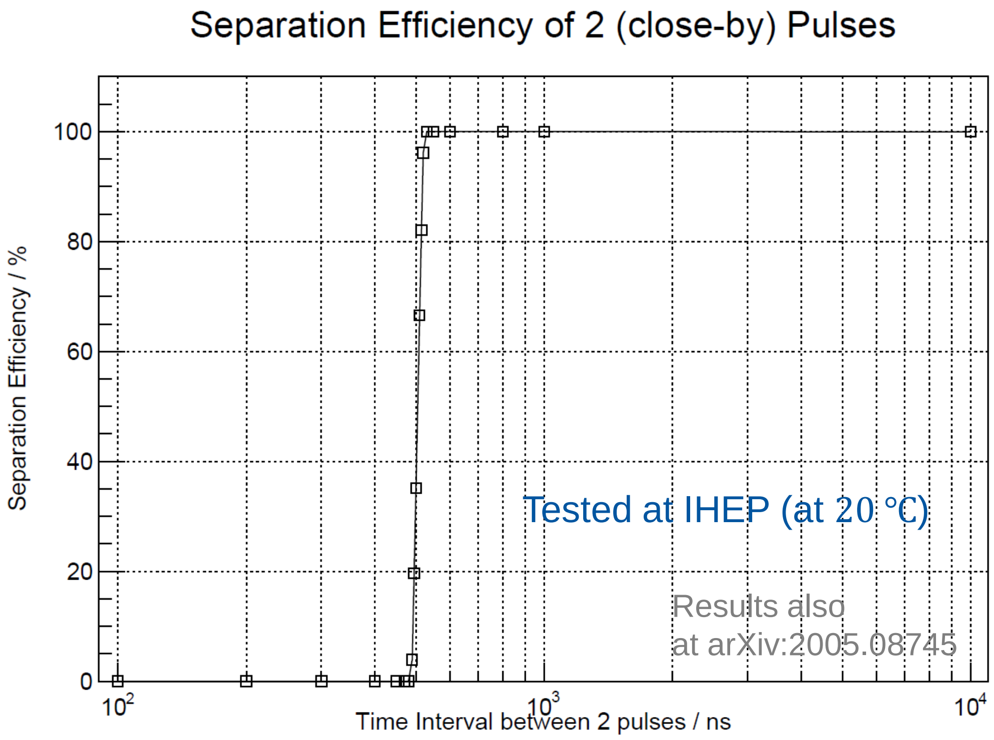


ADC in Ultra Low Gain mode (after pedestal subtraction)

Klaus5 dead time measurements (reminder)

Potential for continuous mode

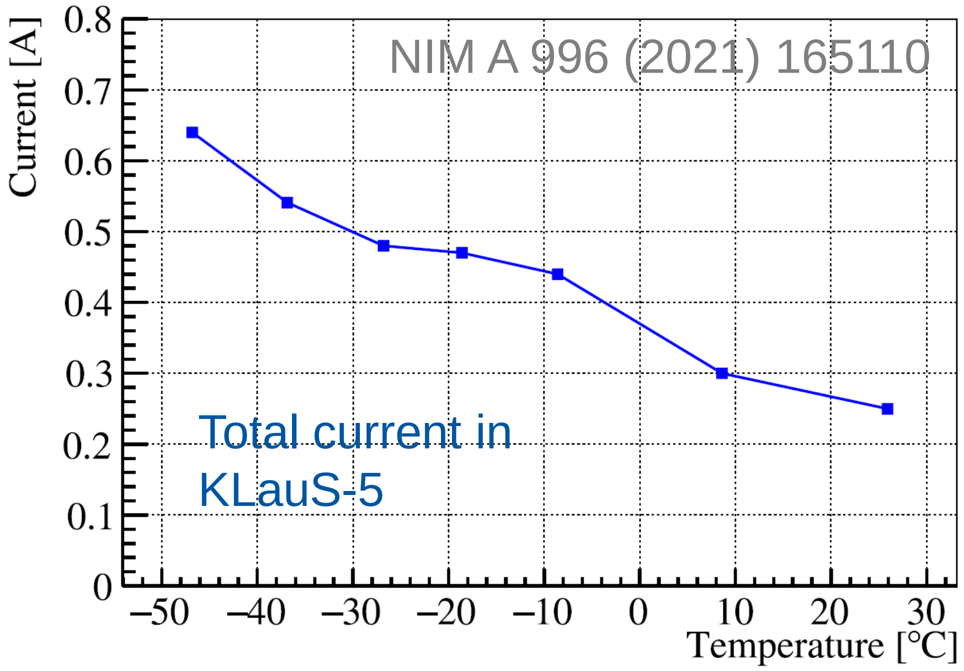


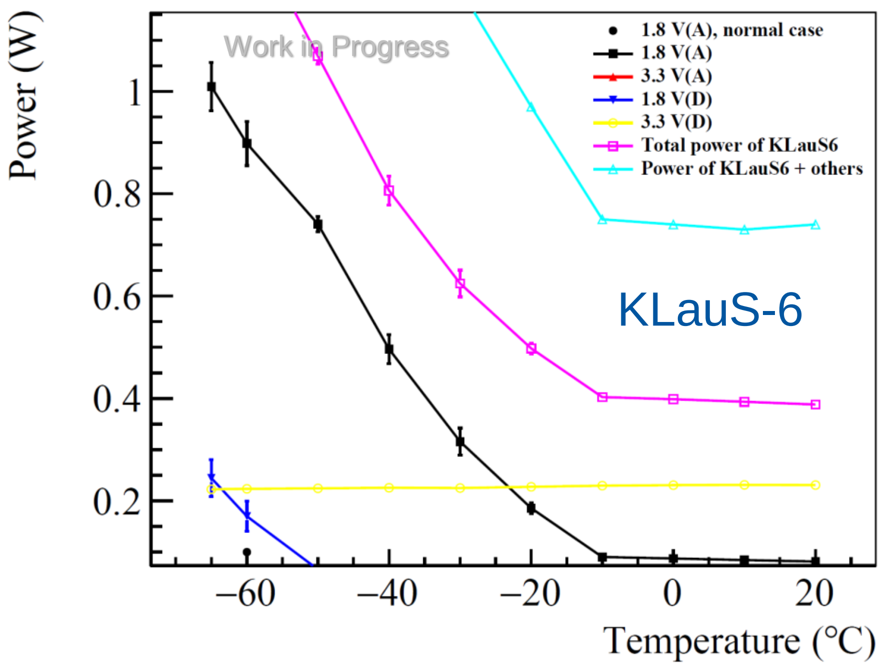


- Varying time interval between 2 injection pulses: 100ns - 10µs
- When time interval > 500ns, 100% efficiency of separating the two pulses
  - Promising feature for 100% duty cycle (required by circular colliders)

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)



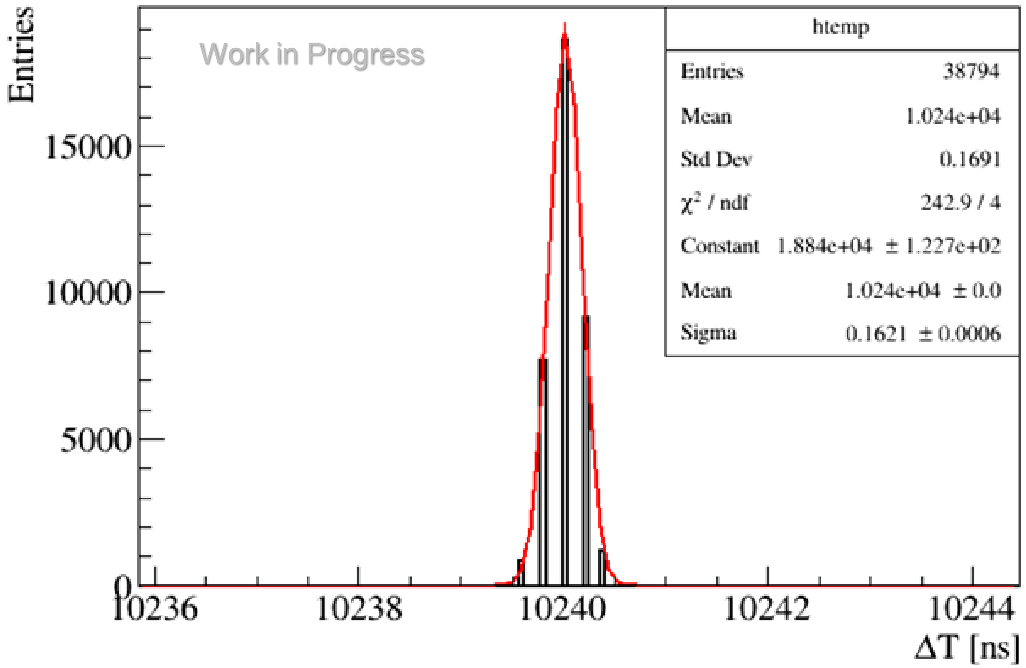


Typical 3.3mW/ch for Klaus5

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

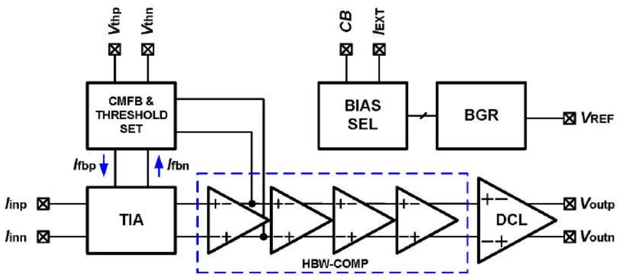
With JUNO-TAO team

Electronics: ongoing R&D

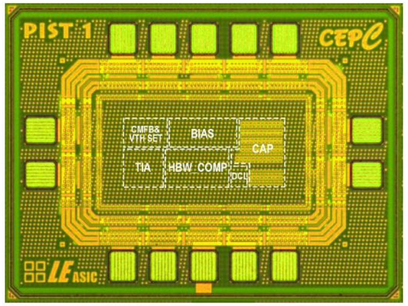
Bo Lu (IHEP), et al.

- PIST ASIC prototype for fast timing and TOT

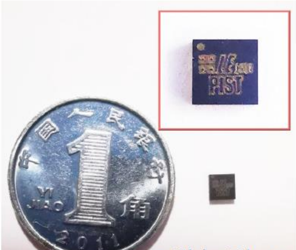
A Glance at the PIST ASIC



■ ASIC System Architecture

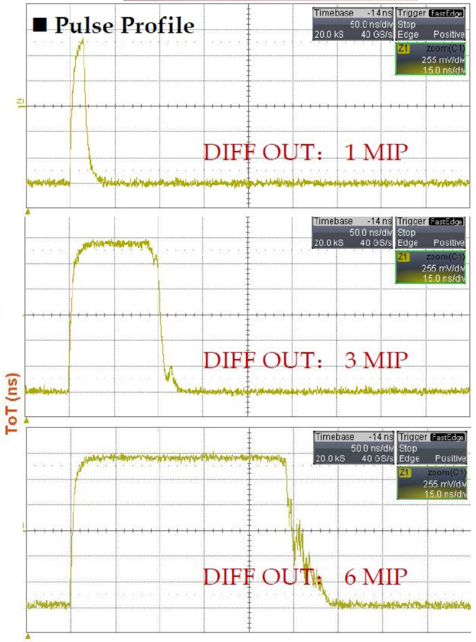


■ Micrograph



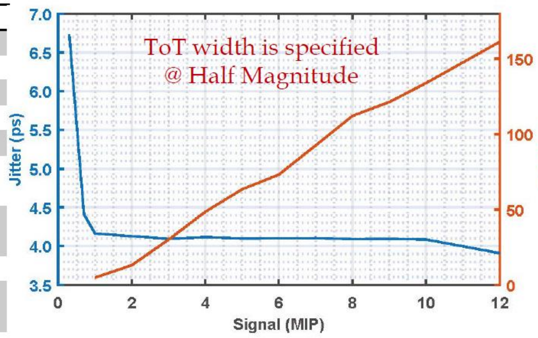
■ Chip Photo

■ Pulse Profile



■ PIST v.s. NINO

Param.	Value	
ASIC	PIST	NINO
Technology	SMIC 55 nm CMOS	IBM 0.25 μm CMOS
Power Supply	1.2 V	2.5 V
Area	~ 220×125 μm^2	~ 460×210 μm^2
Signal Range	1~12 MIP	0.1 ~ 2 pC
Detector Capacitance (C_{DET})	55 pF	10 pF
Leading Edge Jitter	4 ps @ 1 MIP	> 20 ps ~70 ps @ 100 fC
ToT Linearity	-2.70 %/3.95 %	NA
Differential Input Impedance	30 ~ 60 Ω	40 ~ 75 Ω
Power Dissipation	18 mW/Channel	30 mW/Channel
Output Interface	DCL	DCL



■ Jitter and ToT performances

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 readout ASIC

- Welcome broader collaborations: synergies expected
  - In the common software framework (Gaudi, Key4HEP, DD4HEP, …)

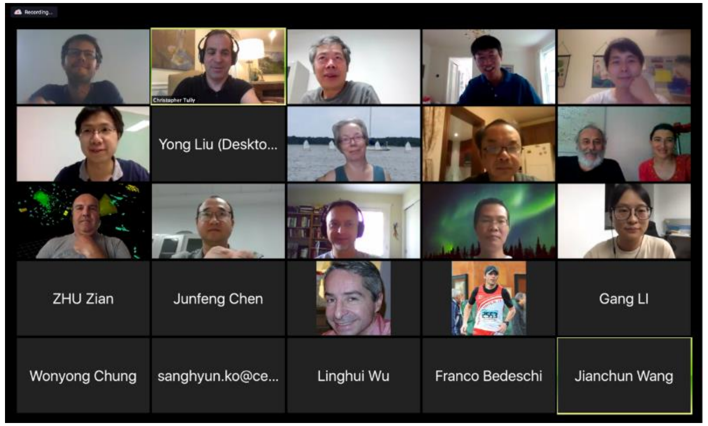
Thank you!

Backup slides

High-granularity Crystal Calorimeter: past workshops

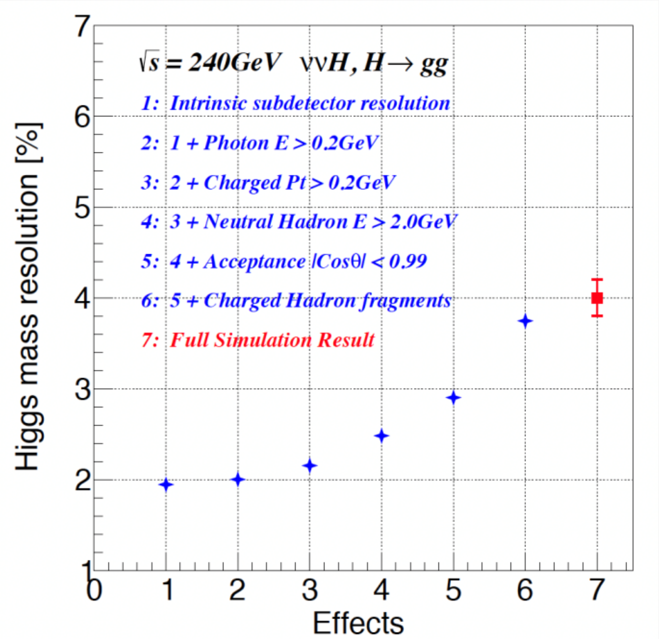
- Ideas firstly proposed: CEPC calorimetry workshop (March 2019)
- Follow-up workshop: Mini-workshop on a detector concept with a crystal ECAL
  - R&D efforts targeting key issues and technical challenges

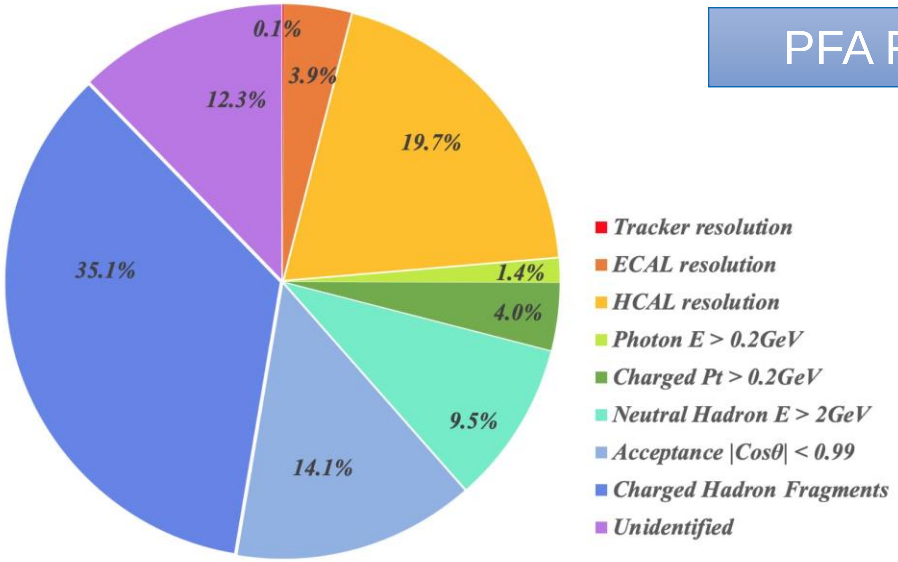
Virtual mini-workshop on a detector concept with a crystal ECAL, July 22-23, 2020, https://indico.ihep.ac.cn/event/11938/



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 λ_I / X_0 ➔ longitudinal development is determined by λ_I
  — Increase probability of hadronic shower in ECAL

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

Confusion is the limiting factor in PFA.

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

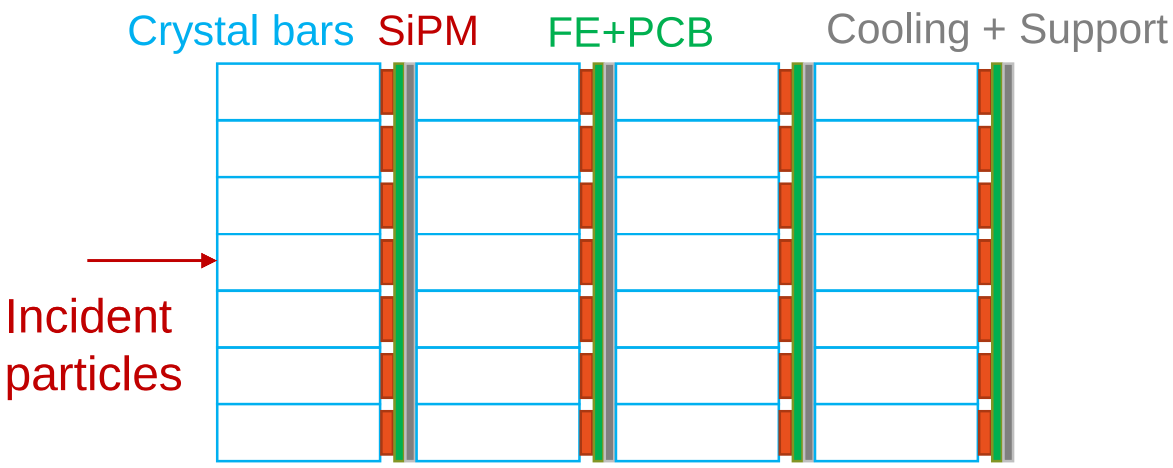
Material	X_0 /cm	R_M /cm	λ_I /cm	λ_I / X_0
W	**0.35**	**0.93**	**9.6**	**27.4**
BGO	**1.12**	**2.23**	**22.8**	**20.3**
Ratio	3.2	2.4	2.4	0.74

Component	Detector	Energy Fraction	Energy Resolution	Jet Energy Resolution
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\ E_J$	—	—
Photons (γ)	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	$\sim 0.1\ E_J$	$0.55\sqrt{E_{h^0}}$	$0.17\sqrt{E_J}$

3

Considerations on detector layouts

Layout 1: same module for each layer



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

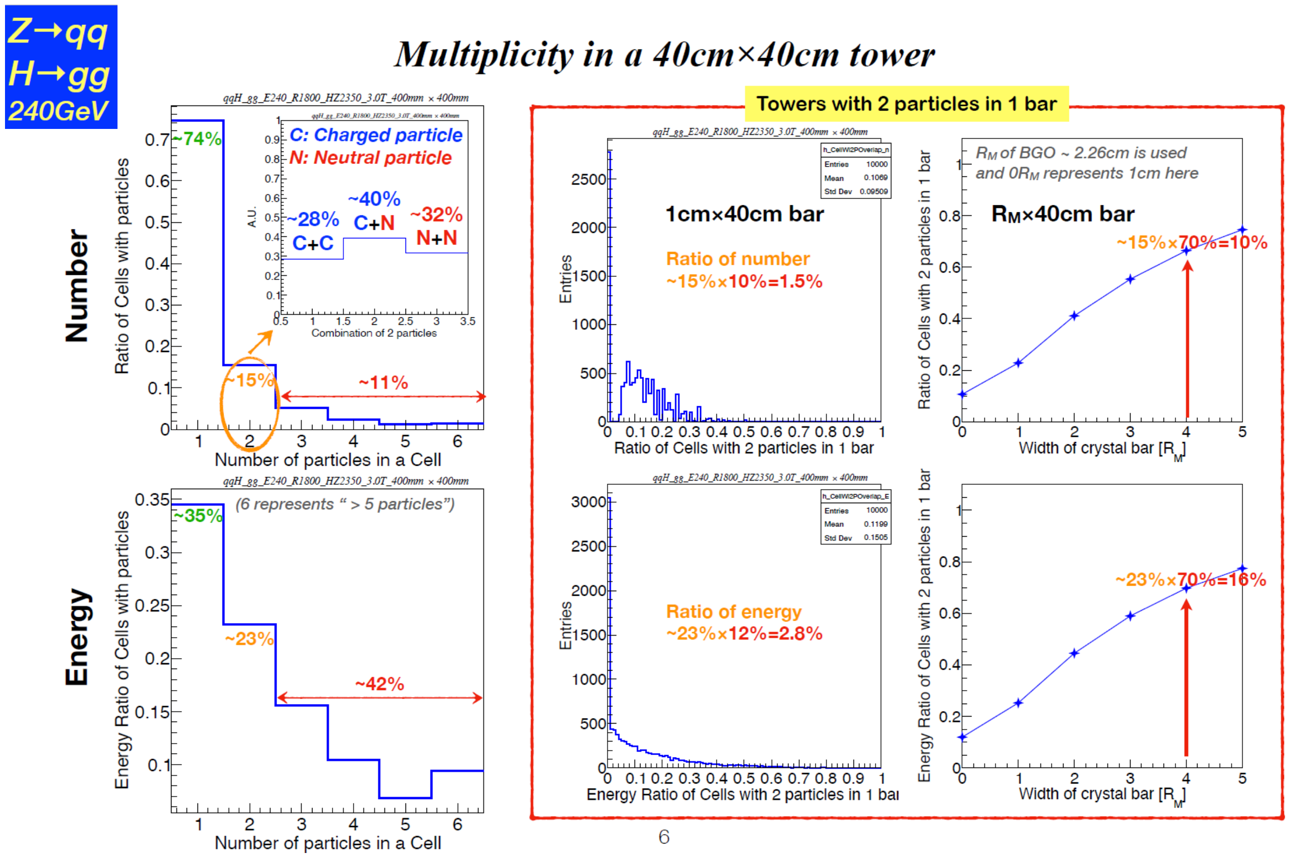
Layout 2: every two layers share the same cooling service and mechanics

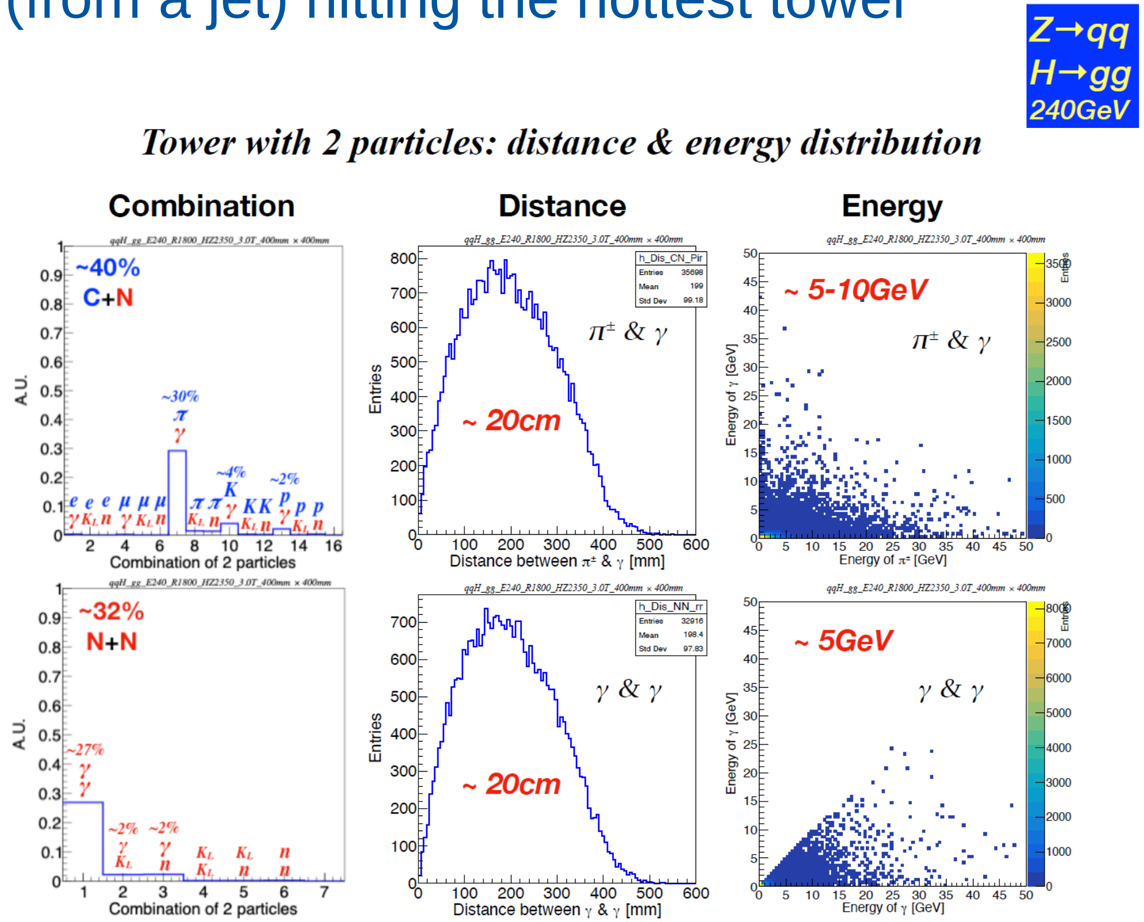
- Pros
  - Save material budget (e.g. a factor of two)
- Cons
  - Non-uniform sampling structure: will need specific considerations for calibration

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

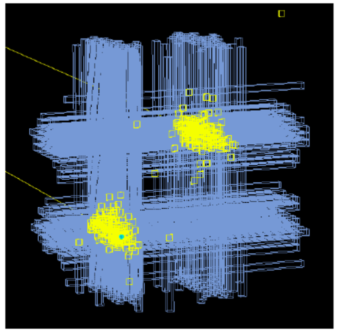




Reconstruction: ongoing studies

Yuexin Wang (IHEP)

Patterns in event display: 2 photons



2 parallel 5GeV γ

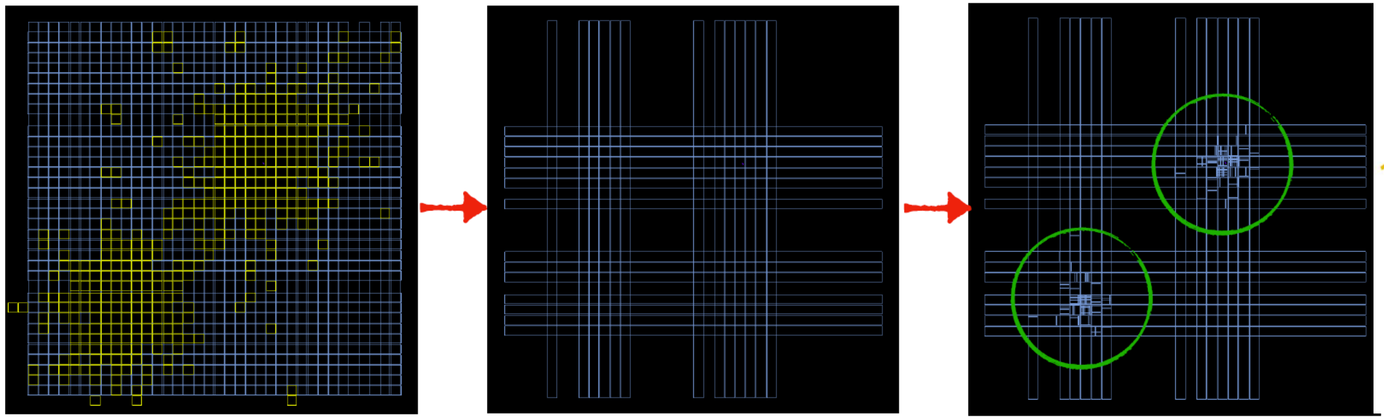
distance ~20cm along the diagonal

→ can be separated.

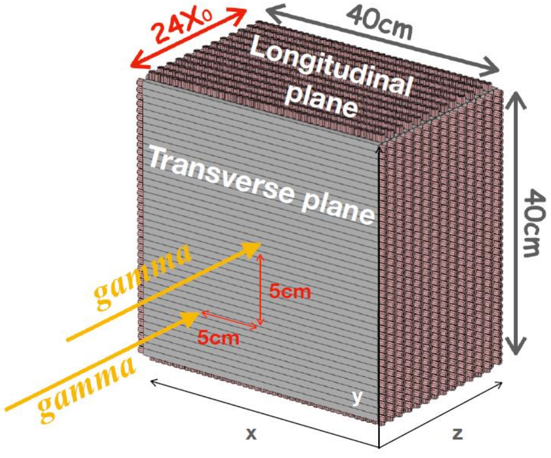
Simulated Hits (yellow cells)

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

Reconstructed positions using time difference of 2 ends

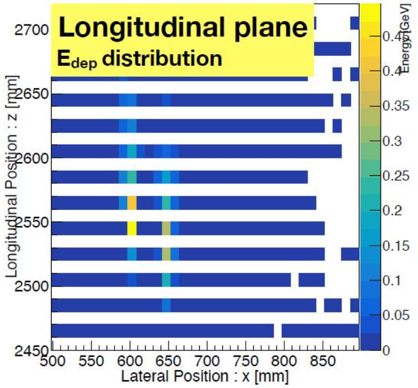


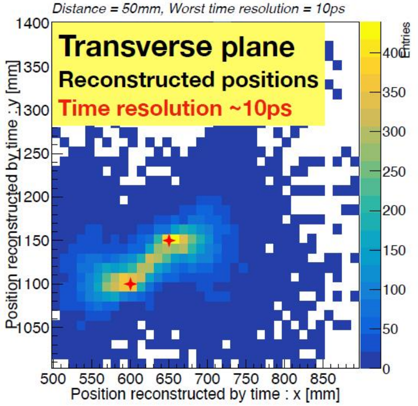
Shower profiles: 2 photons



5cm ~ $2R_M$ for BGO (R_M=2.26cm)

10





Pattern studies using Event Display

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