3D Crystal Calorimeter: R&D status

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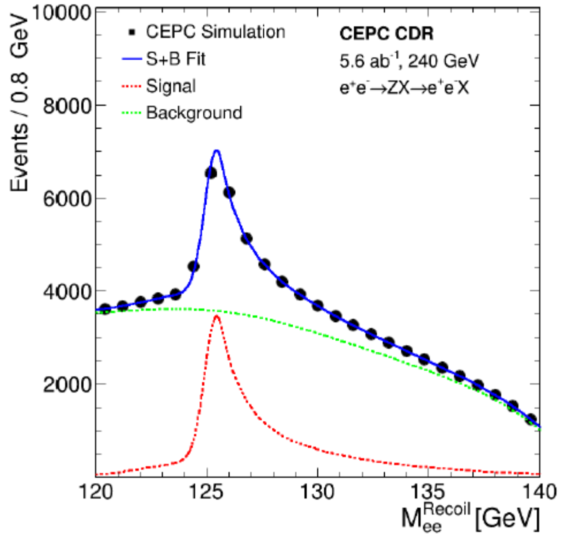
on behalf of the CEPC Crystal Calorimeter Team

CEPC Day
Dec. 28, 2020

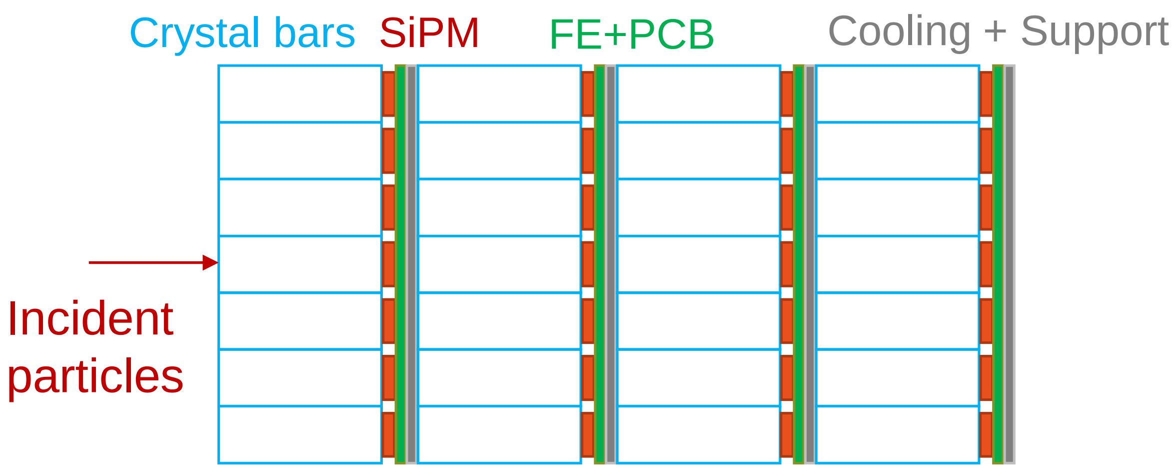
Motivations (reminder)

- Background: future lepton colliders (e.g. CEPC)
  - 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, potentials in search of new physics, …
- Fine segmentation
  - PFA capability for precision measurements of jets



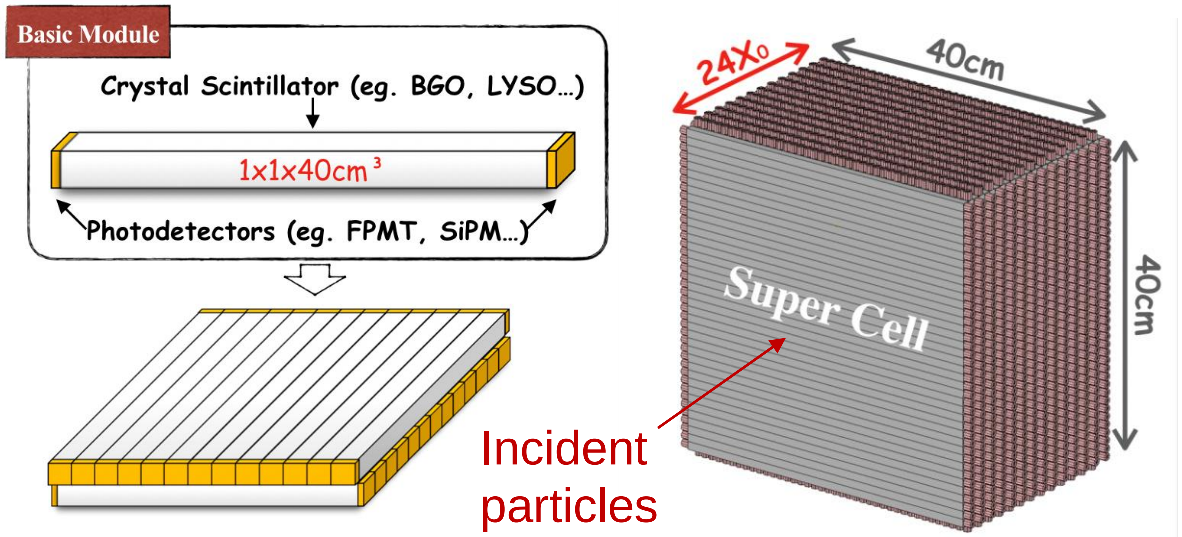
3D crystal ECAL: 2 major designs

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
- Single-ended readout with SiPM
- Potentials with PFA

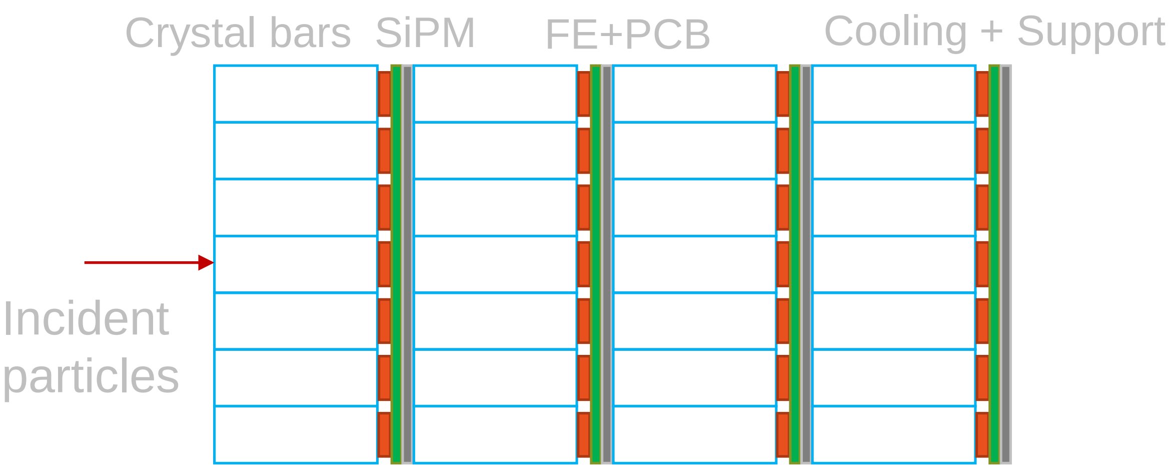
Design 2



- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm (24X0 depth)
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

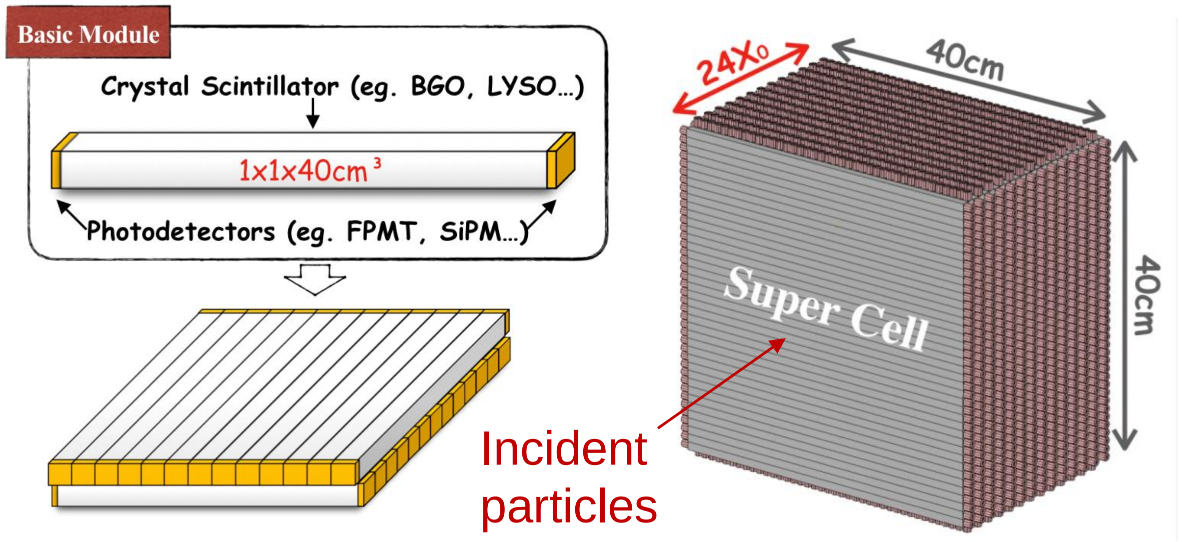
3D crystal ECAL: 2 major designs

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: e.g. 28 layers of BGO ,1cm per layer
  - 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)

General status

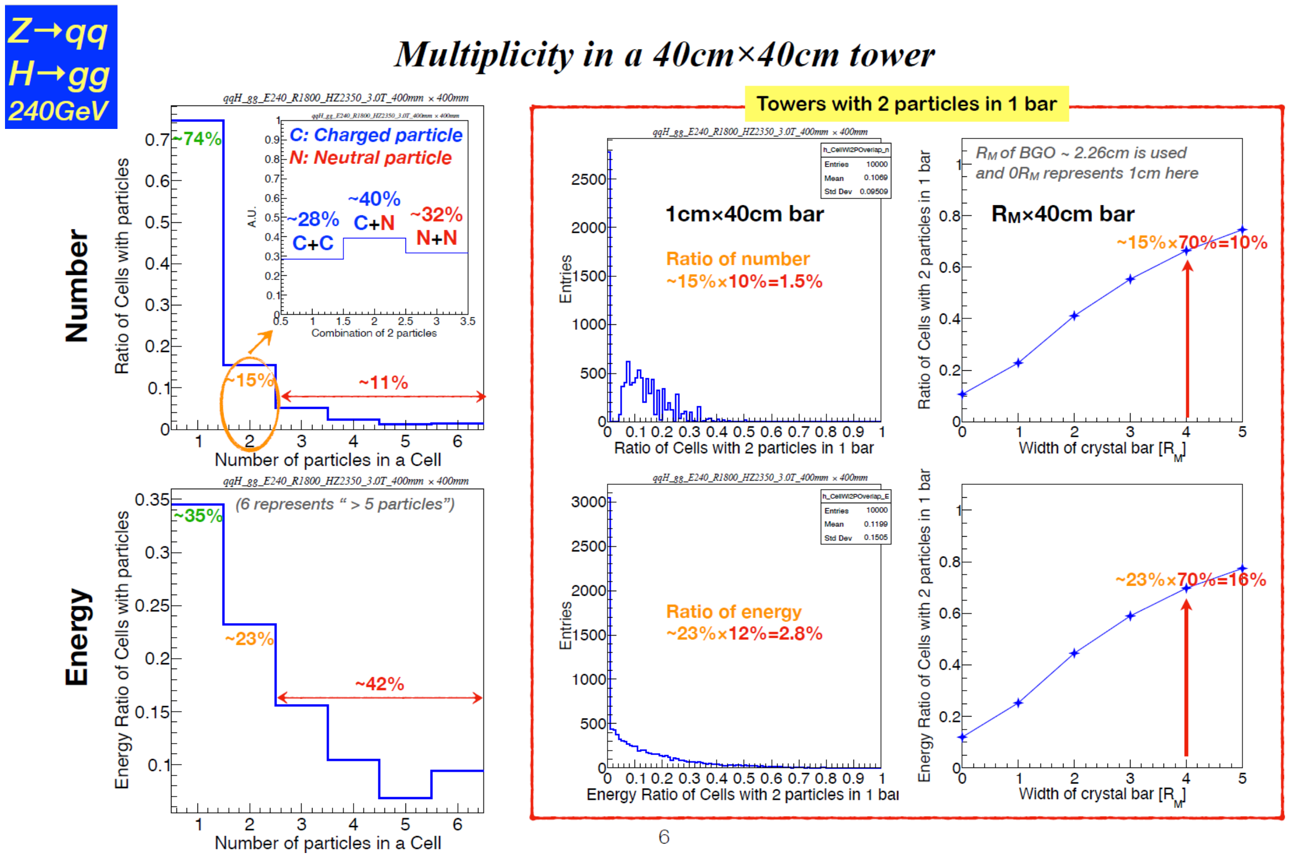
- Reminders from physics
  - Multiplicity with jets
  - Impressions about jets from event display

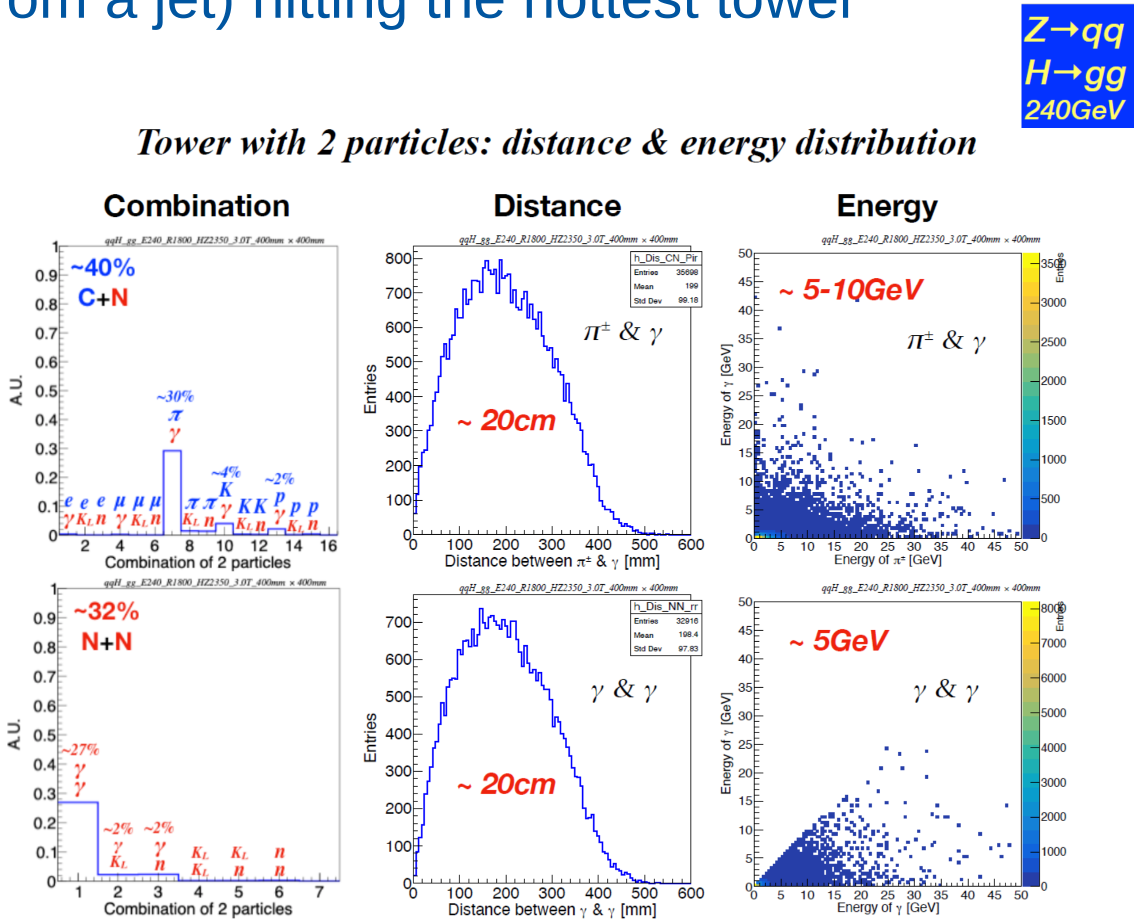
- R&D progress
  - Selected results from the weekly group meetings
    - https://indico.ihep.ac.cn/category/748/
  - Implementations in the new software framework CEPCSW
  - EM shower studies: comparison of bar geometry with cubes
  - Hardware progress
    - Preparations of a test stand for crystal-SiPM readout
    - Key question: timing resolution, digitization model

Studies on physics requirements: reminder

Yuexin Wang (IHEP)

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

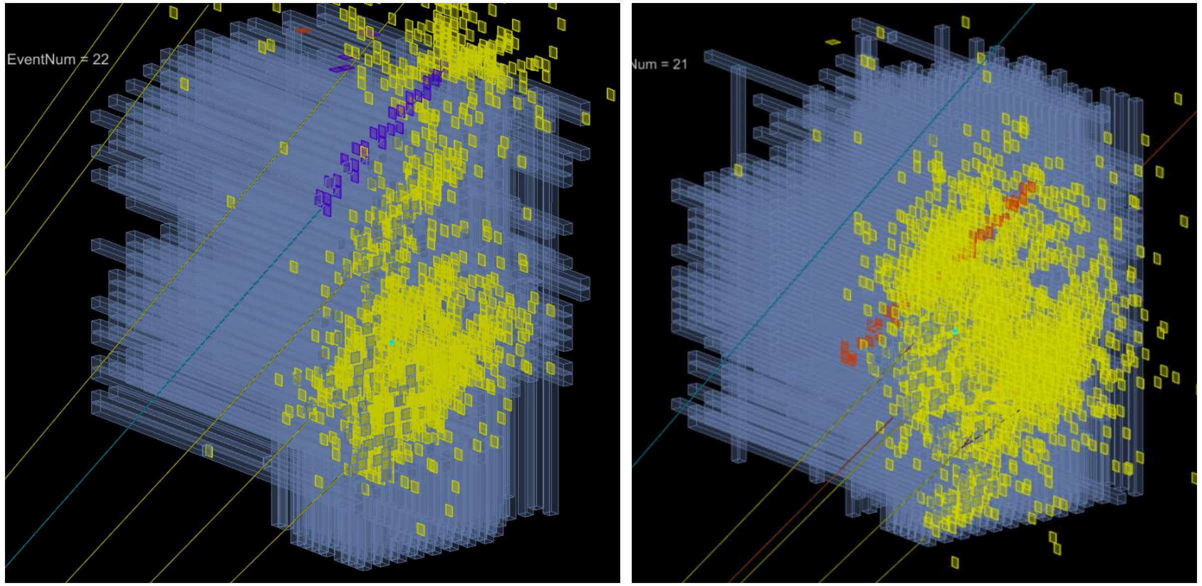




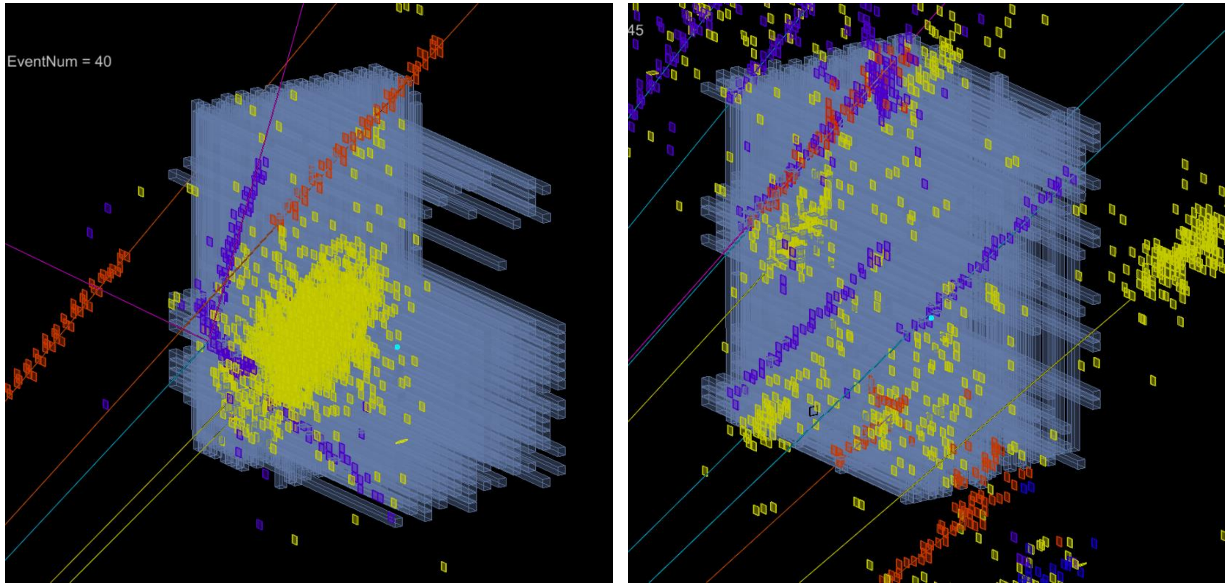
Jets in Event Display

Di-jet events from $Z \rightarrow qq$

- Impressions of topology of EM/hadron showers within jets
- Intuitive guidance for the reconstruction development
- Current strategy: first studies with (close-by) EM showers, then hadron showers (due to the intrinsic complexity)



Multiple gammas and a charged pion



Multiple gammas and hadrons

Crystal Calorimeter in CEPCSW

- Detector geometry implementation (done)
- Simulation and digitization (done)
- Reconstruction (under development)
  - Clustering of crystal bars and cluster splitting
  - Time/energy matching to veto ghost hits.
- Performance check (under development)

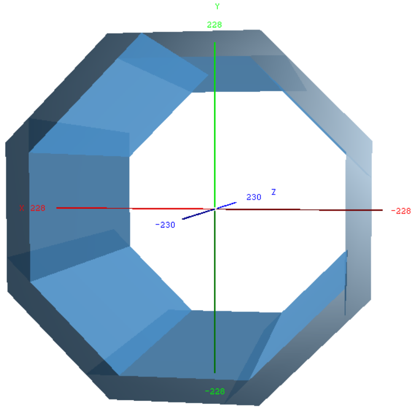
Geometry Construction in CEPCSW

Fangyi Guo (IHEP)

- A complete barrel ECAL implemented
  - BGO crystal bars: $1\text{cm} \times 1\text{cm} \times \sim 40\text{cm}$
  - Every 2 layers of vertically intersected bars
    - Readout at two ends

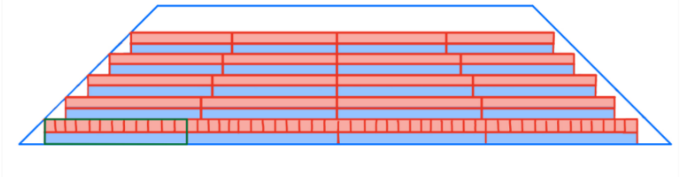
- General information
  - 8 identical staves (trapezoids)
  - Avoid projectile cracks pointing to the IP
  - Ideal layout: excluding electronics and mechanics
  - Gaps identified

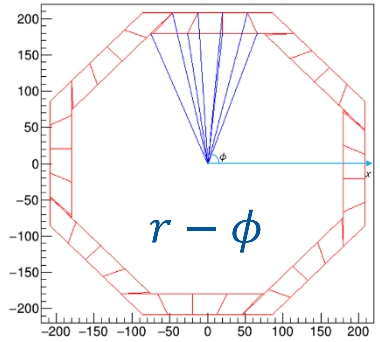
- DD4Hep used for geometry construction

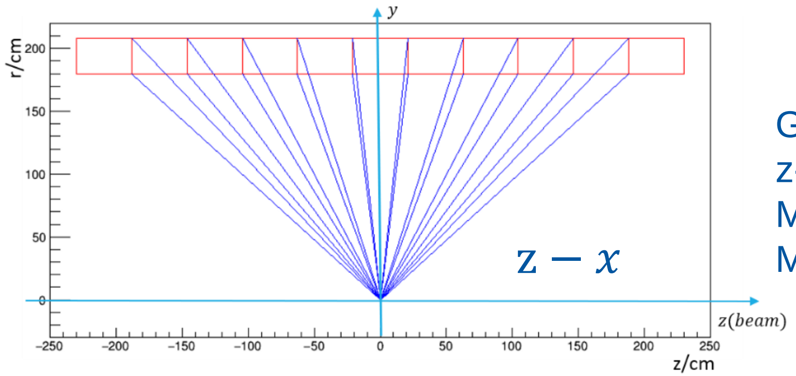


Inner radius $R = 1.8m$
Length along beam line $L = 4.6m$
Total depth $H = 28\ cm$

BGO: $X_0 = 1.12cm,\ R_M = 2.23cm$







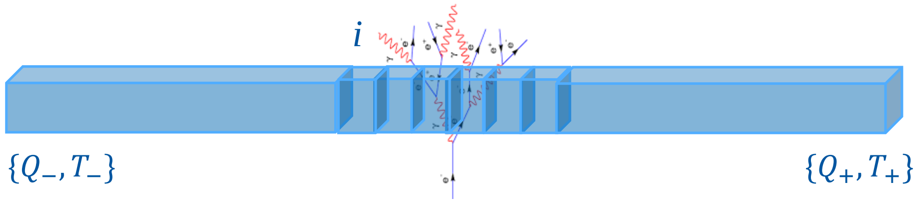
Gaps in $r - \phi$ and z-x planes
Minimum $\Delta\phi = 0.85°$
Minimum $\Delta\theta = 0.89°$

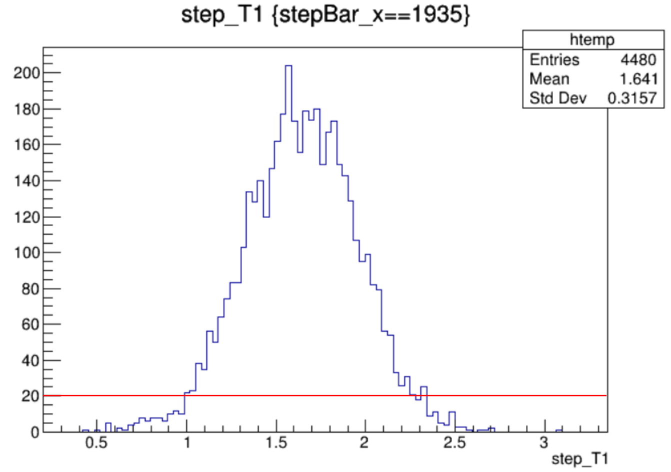
Crystal calorimeter: simulation and digitization

Fangyi Guo (IHEP)

- Simulation performed with Geant4 in CEPCSW
  - Electromagnetic interactions (current focus)

- Digitization for each long crystal bar
  - Readout at two ends: charge Q and time T
  - Contribution from the i-th G4step
    - $\mathrm{Q}_{\pm}^{i} = \mathrm{E}_0 \cdot \exp\left(-\frac{\frac{L}{2} \pm z_i}{L_{Att}}\right)$; $\mathrm{T}_{\pm}^{i} = \mathrm{T}_0 + \mathrm{Gaus}(z_{\pm}^{i}/v,\ \sigma_T)$
  - For a full bar:
    - $\mathrm{Q}_{\pm} = \sum_{step} \mathrm{Q}_{\pm}^{i}$
    - $\mathrm{T}_{\pm} = \mathrm{T}_{\pm}^{k} \mid \left(\sum_{i=1}^{k} \mathrm{Q}_{\pm}^{i} > \epsilon \mathrm{Q}_{\pm}^{tot}\right),\ \epsilon = 5\%.$
    - Considering a simplified scenario: no light attenuation along bars ($L_{Att} = \infty$), $Q_{\pm} \propto E_{tot}$

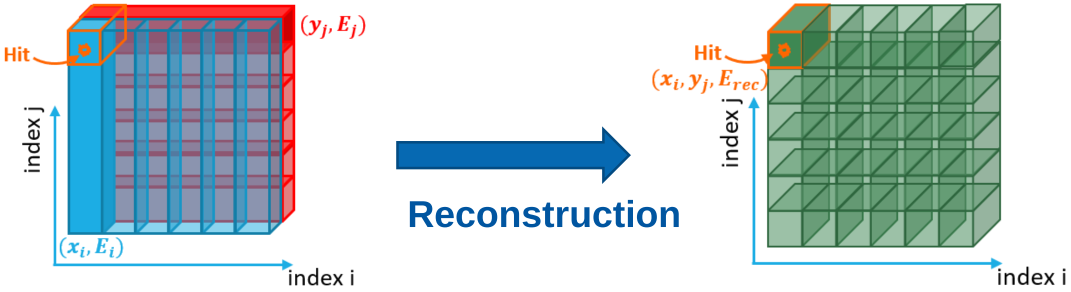




Hit reconstruction in CEPCSW

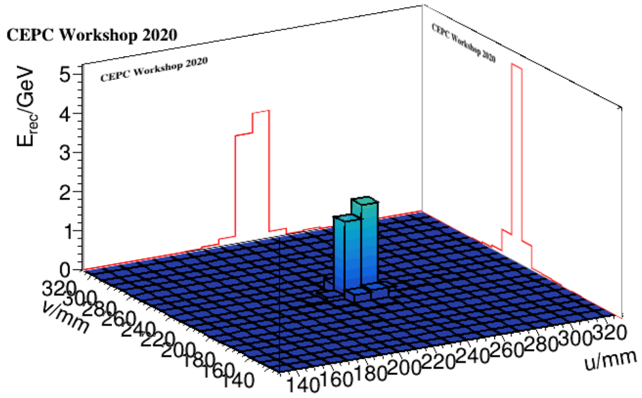
Fangyi Guo (IHEP)

- Hit reconstruction: locating hits in 2 crossed bars.
  - Position: $(x_i, y_j, \frac{(z_i+z_j)}{2})$
  - Energy: use energy distributed in crossed bars as a energy fraction:
    - $E_{rec} = E_i \times f_i + E_j \times f_j,$ where $f_i = \frac{E_j}{\Sigma E_j}, \quad f_j = \frac{E_i}{\Sigma E_i}$
- MC-Truth level hits: merge G4steps in each 1*1*1 cm^3 cube as a truth hit.
- Time information: $x_T = x_{bar} + \frac{T1-T2}{2} v$.
  - Match x_T with x_i to veto ghost hits.



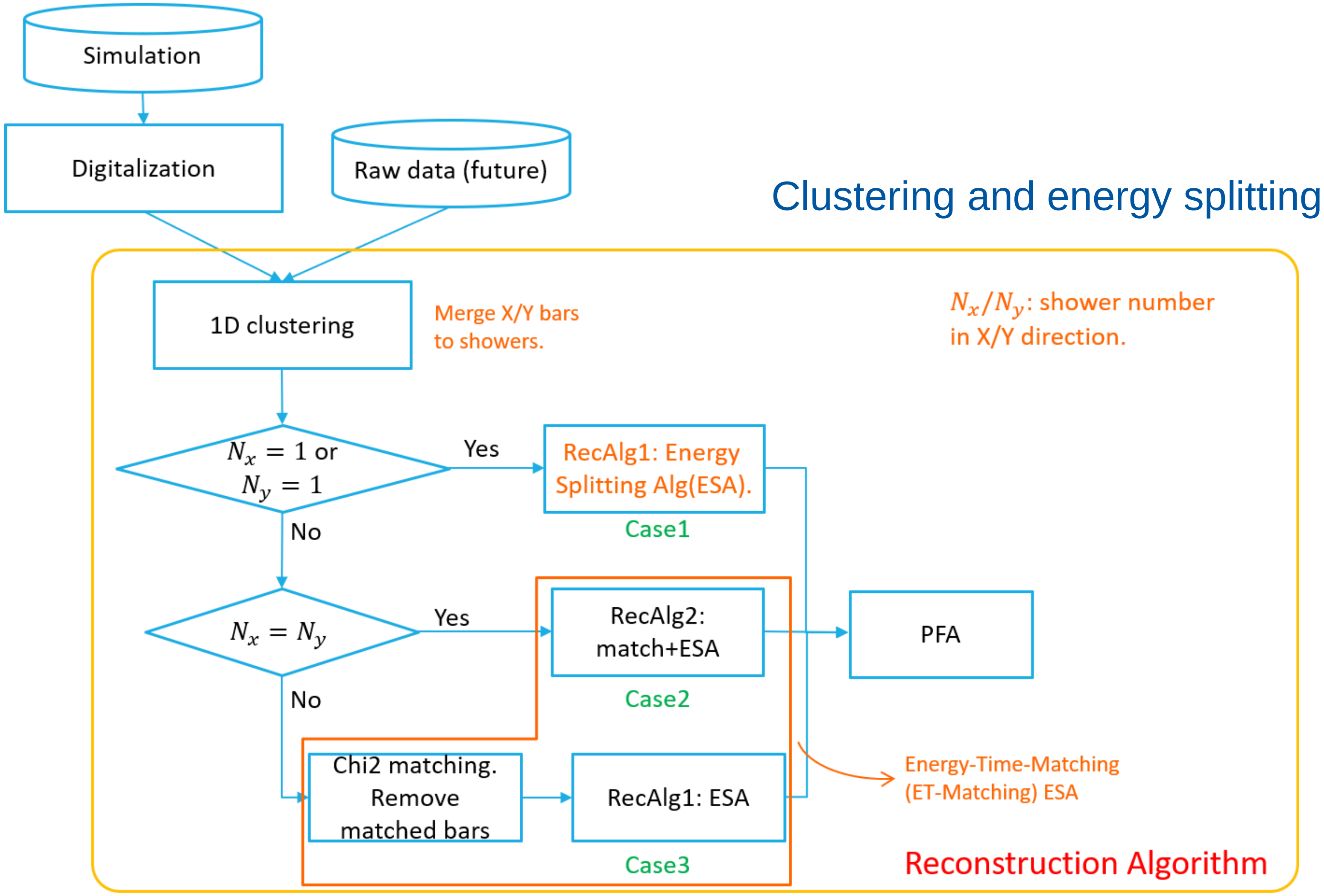
2 layers of $1 \times 1 \times 40\ \mathrm{cm}^3$ crystal bars (40+40)

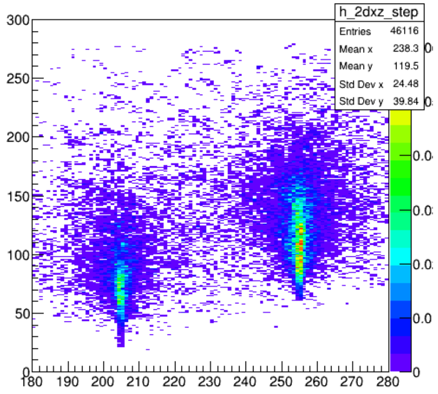
1 layer of $1 \times 1 \times 2\ cm^3$ crystal cells (40×40)

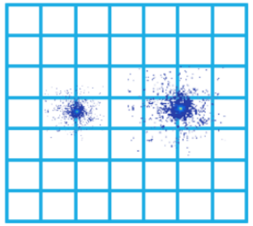


Reconstruction algorithm in CEPCSW

Fangyi Guo (IHEP)



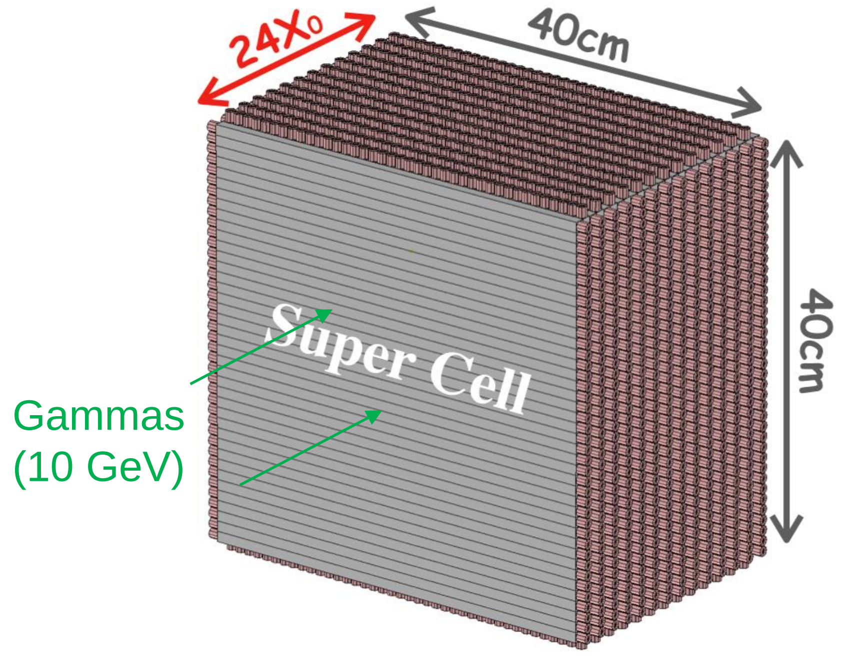




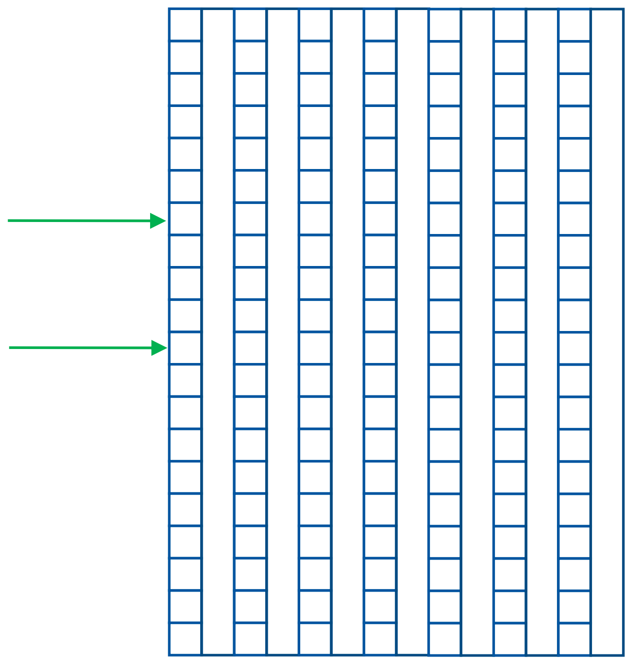
- Sort out information to feed PFA
- Used the knowledge on the traditional crystal calorimeter (e.g. BESIII EMC)
- Working on the implementation in CEPCSW
- Performance check to be done

EM shower studies with crystal bars in Geant4

- Two sets of reconstructed positions
  - Hits (energy weights) and timing difference



2 gammas separated by 40mm in both X and Y



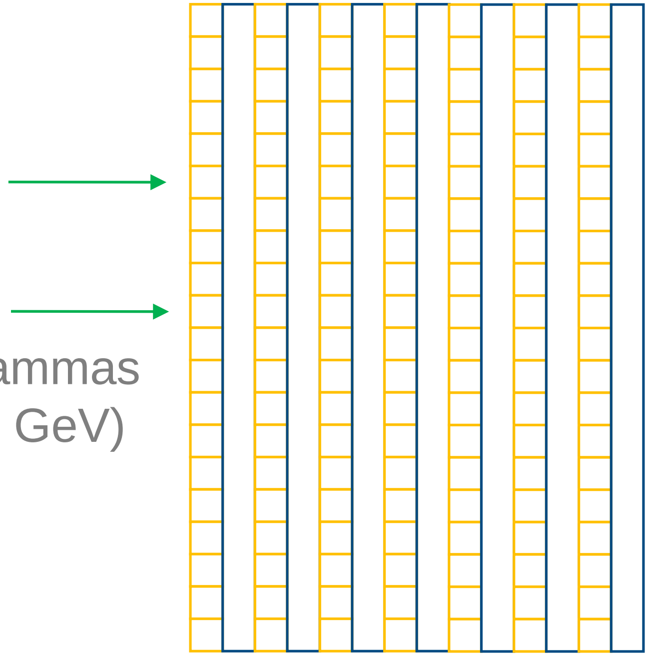
Side View
(one quarter)

- Reconstructed positions from hits
  - Fine granularity: 10mm
  - Even layers: Y
  - Odd layers: X
- Reconstructed positions from timing
  - Complementary to hit positions
  - Even layers: X
  - Odd layers: Y
  - Constraints from timing resolution

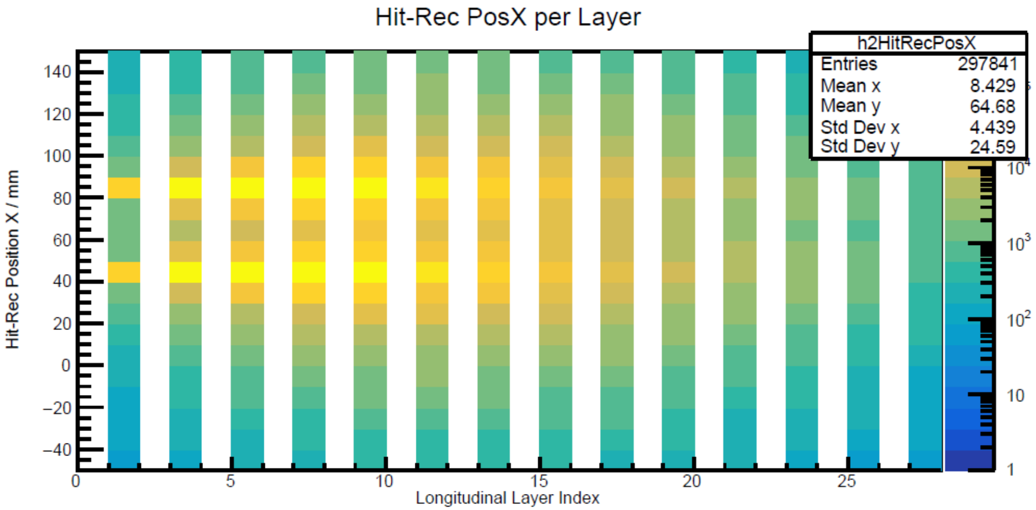
Reconstructed positions from hits

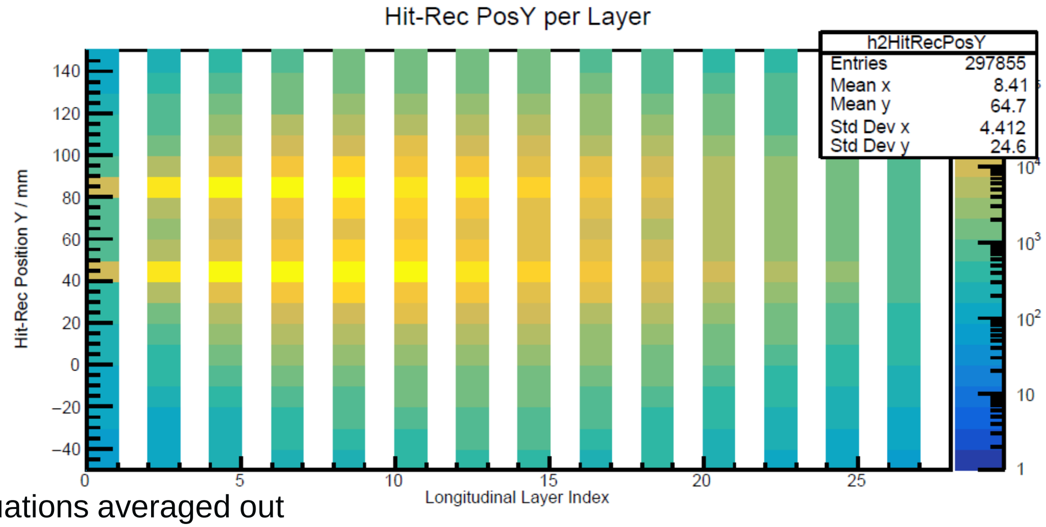
2 gammas separated by 40mm in both X and Y

2 gammas (10 GeV)



(Side View)
Fine granularity: hit positions

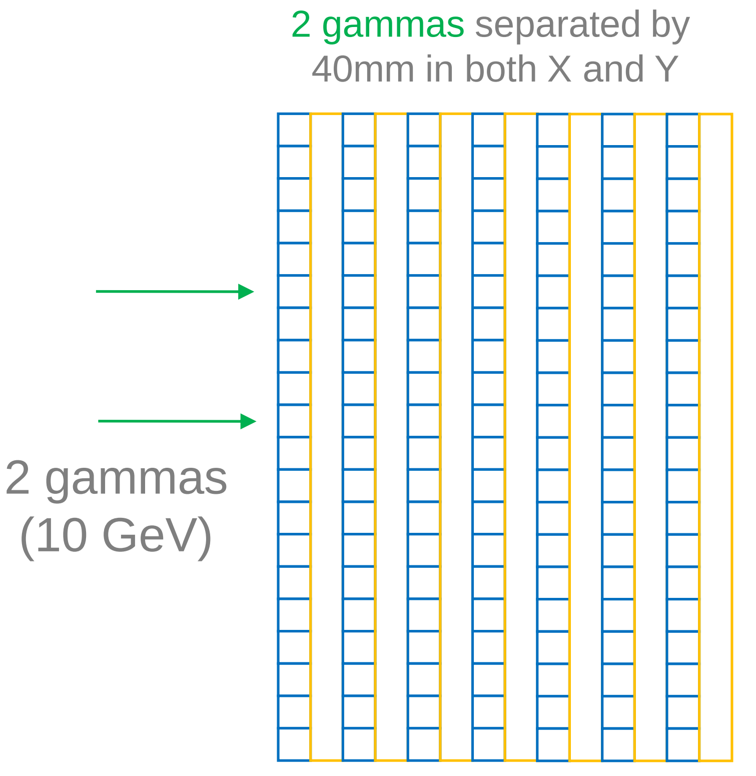


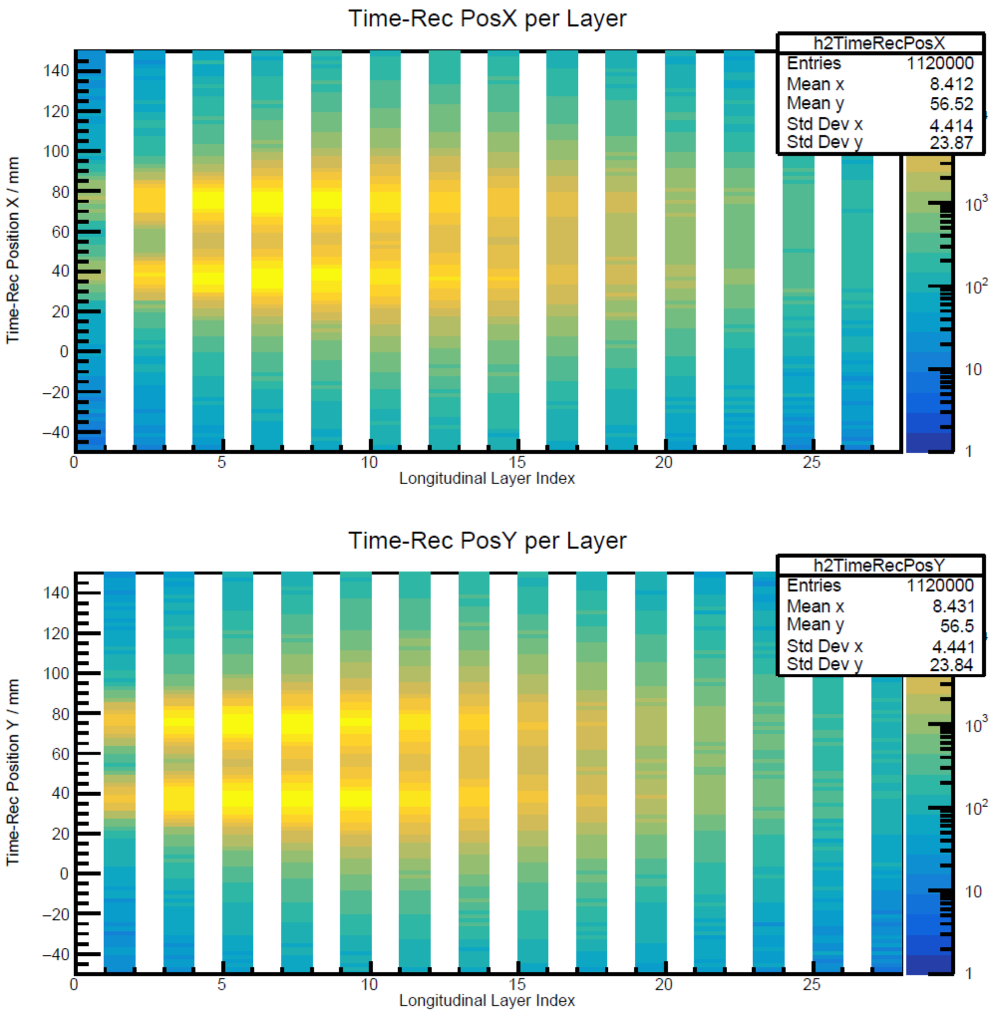


- Reconstructed positions from hits
  - Fine granularity: 10mm
  - Even layers: pos. Y
  - Odd layers: pos. X
  - Energy-weights applied

Note that all events summed up; event-by-event fluctuations averaged out

Reconstructed positions from timing





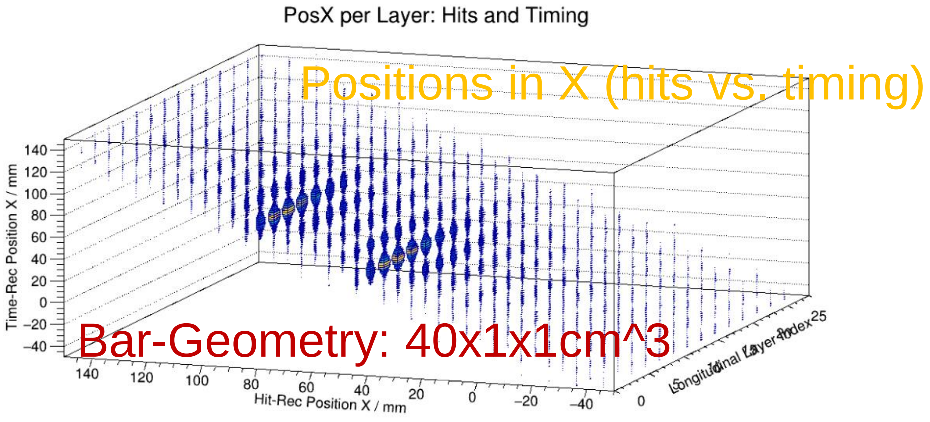
- Reconstructed positions from timing
  - Complementary to hit positions
  - Even layers: X
  - Odd layers: Y
  - Constraints from timing resolution: to be studied

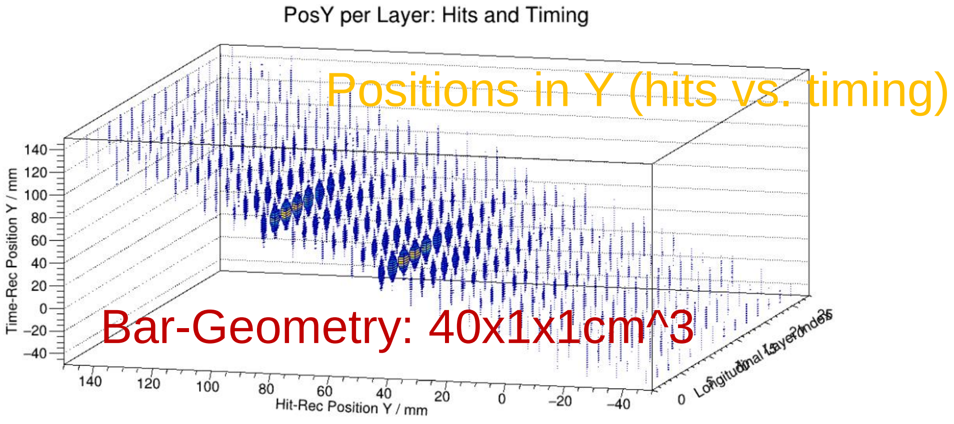
PosX,Y = $\frac{(t1-t2)}{2v}$;
t1, t2 are the timing at two ends;
v is the effective velocity

Note that all events summed up; event-by-event fluctuations averaged out

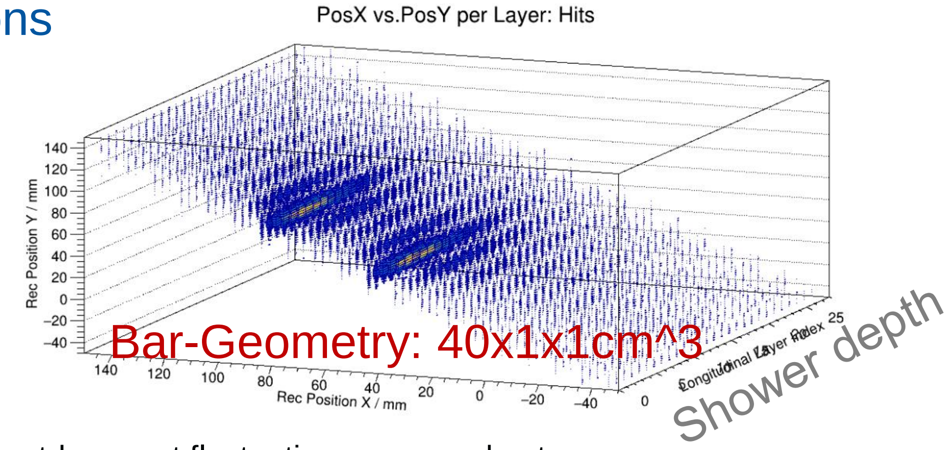
EM shower studies with crystal bars in Geant4

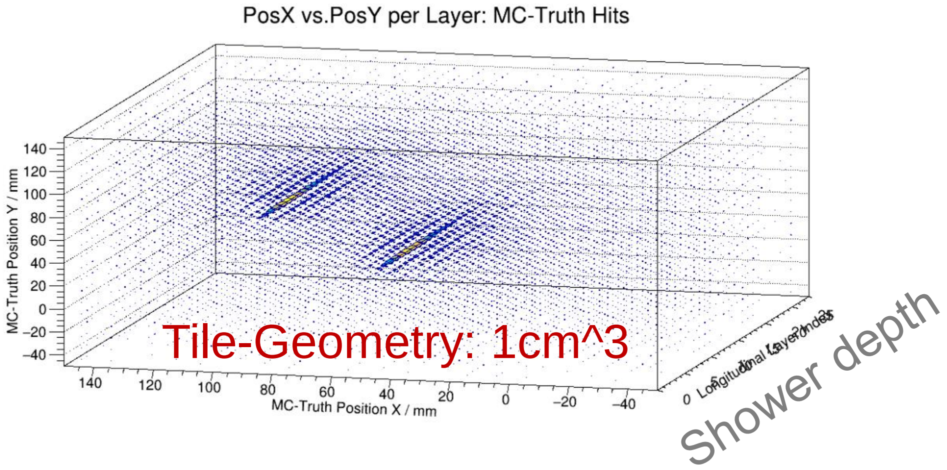
- Reconstructed positions: combined hits and timing of crystal bars
  - Comparison with MC-Truth (cubic-cm crystals), to understand the impact from geometry





Reconstructed positions (X, Y) in each layer



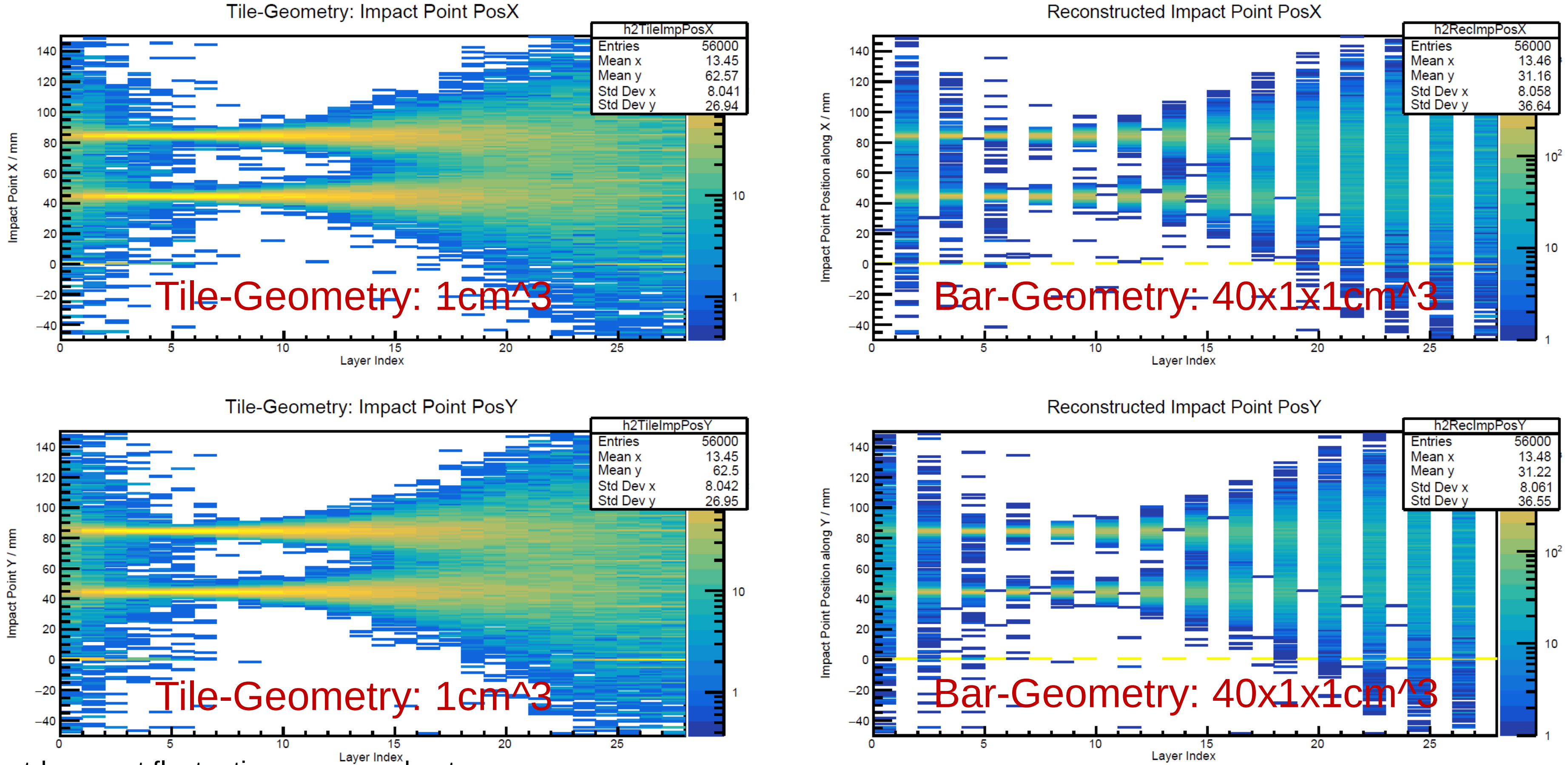


Note that all events summed up; event-by-event fluctuations averaged out

EM shower studies: to understand impacts from geometry

- Center-of-Gravity (COG): layer-wise
  - Important information to determine each shower axis (before energy splitting)

Reconstructed COG (X, Y) in each layer

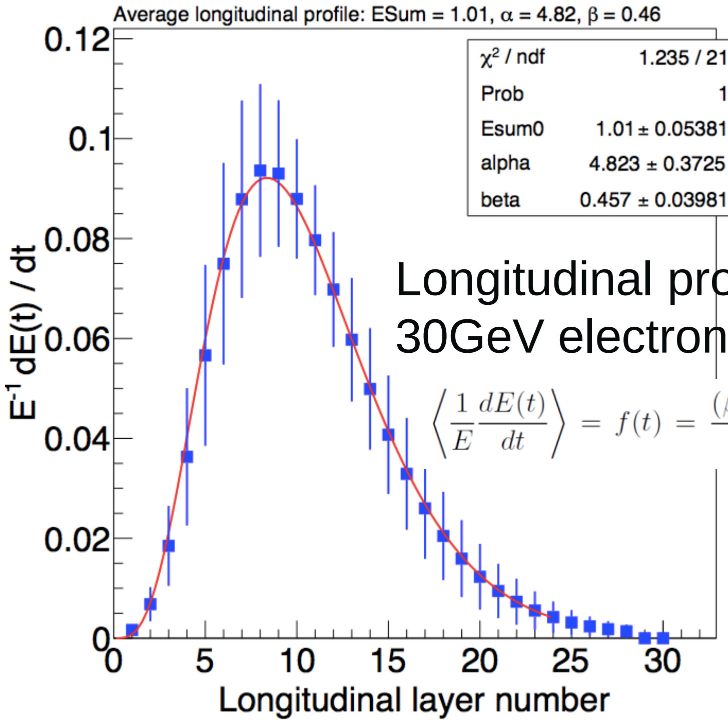


Note that all events summed up; event-by-event fluctuations averaged out

Shower profiles

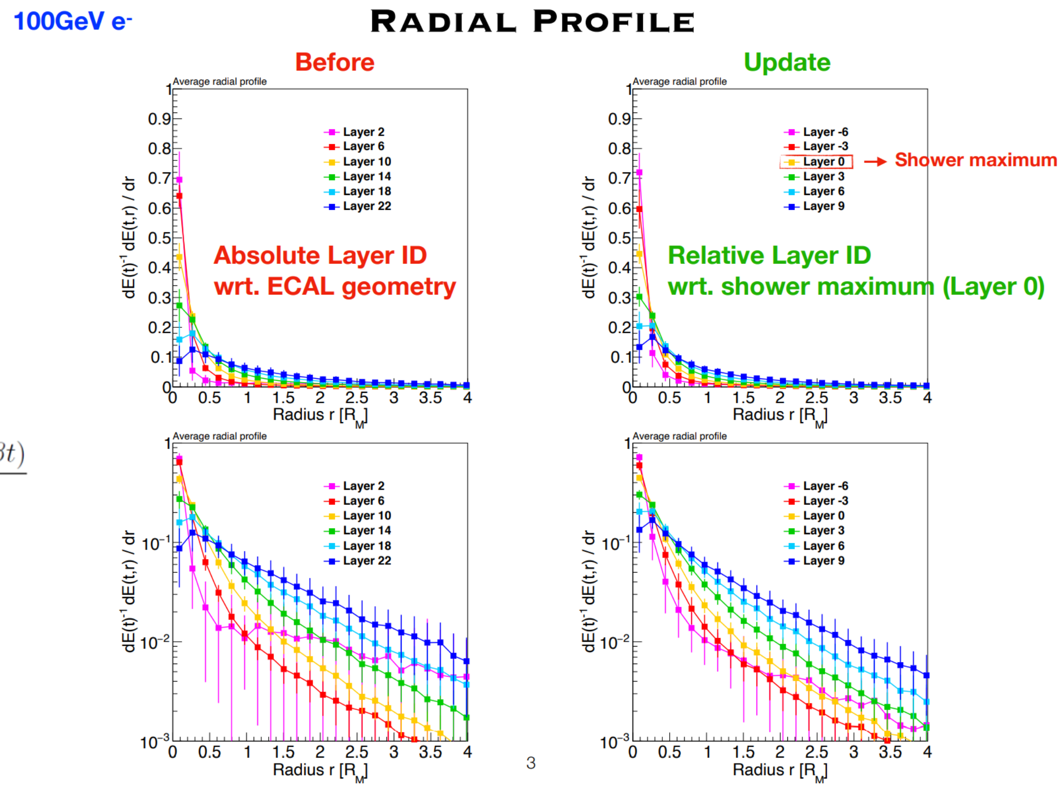
Baohua Qi, Yuexin Wang

- EM shower profiles in 3D
  - Information obtained and stored in ROOT files
  - Input to the weights for energy splitting of close-by showers



Longitudinal profile:
30GeV electrons

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

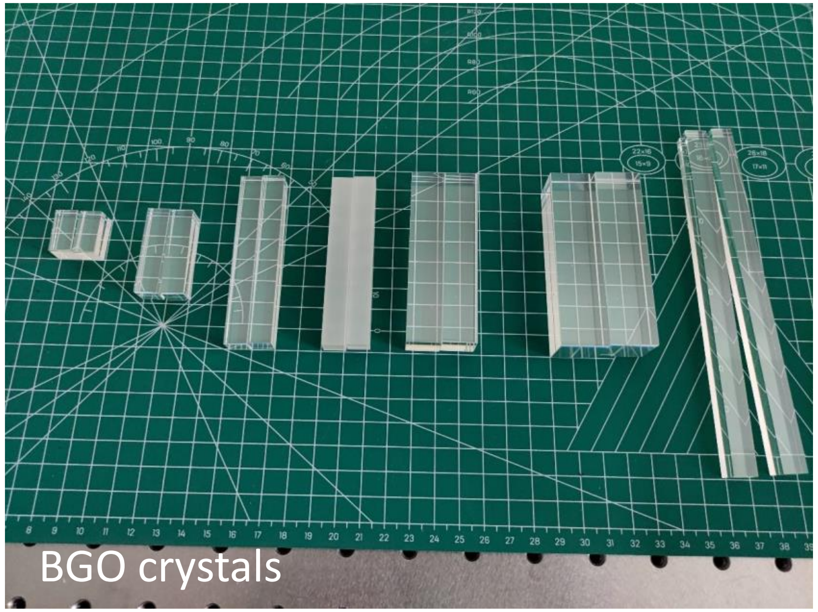


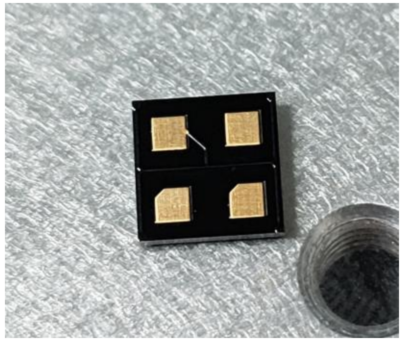
Test stand for crystal-SiPM

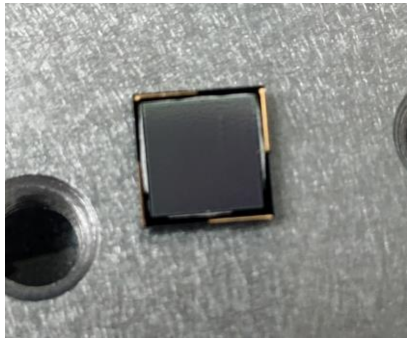
- Key questions
  - To quantify timing resolution of crystal bars and SiPMs
  - Validation of Geant4 full simulation, which is used for digitization
- Infrastructure
  - Ready: optical table, dark box, oscilloscope
  - To be tested/commissioned: UV LEDs, XYZ stage, digitizer (PXI crate/module)

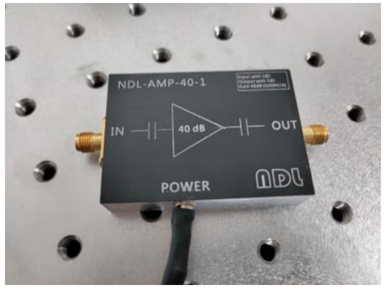
Scintillating crystals and SiPMs

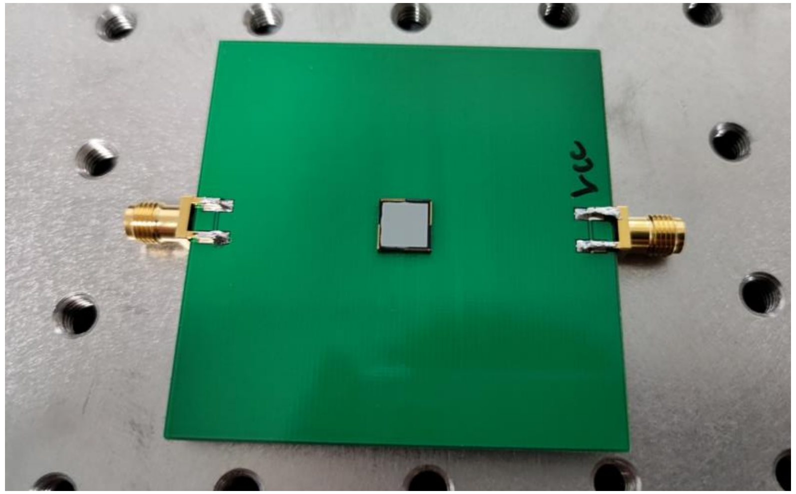
- Crystal samples from SIC: ready
  - Various: lengths, transverse sizes, surface treatments
- Wrapping foil: specular (ESR), diffuse (Teflon, Tyvek), to be done
- Silicon photomultipliers
  - From 2 major vendors: NDL (China) and HPK (Japan)
  - Adapter PCB and preamplifier


BGO crystals





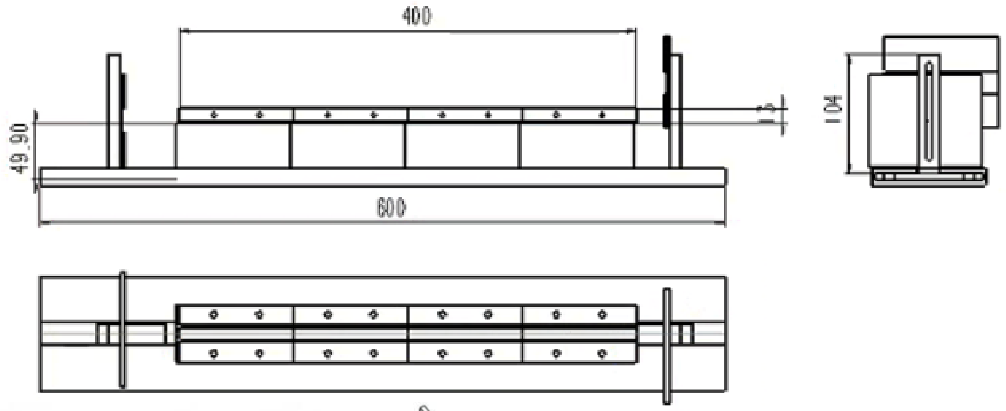


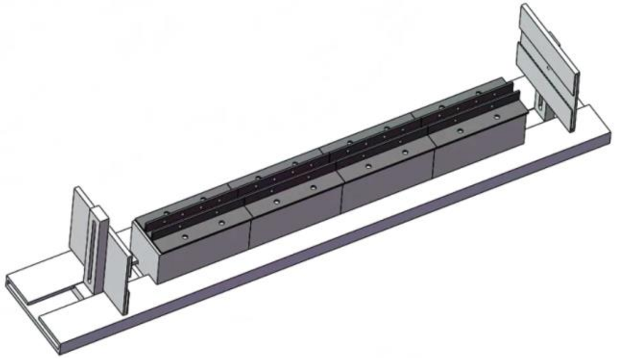


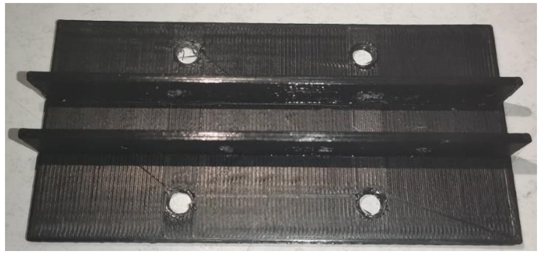
Test stand: mechanics for crystal bars

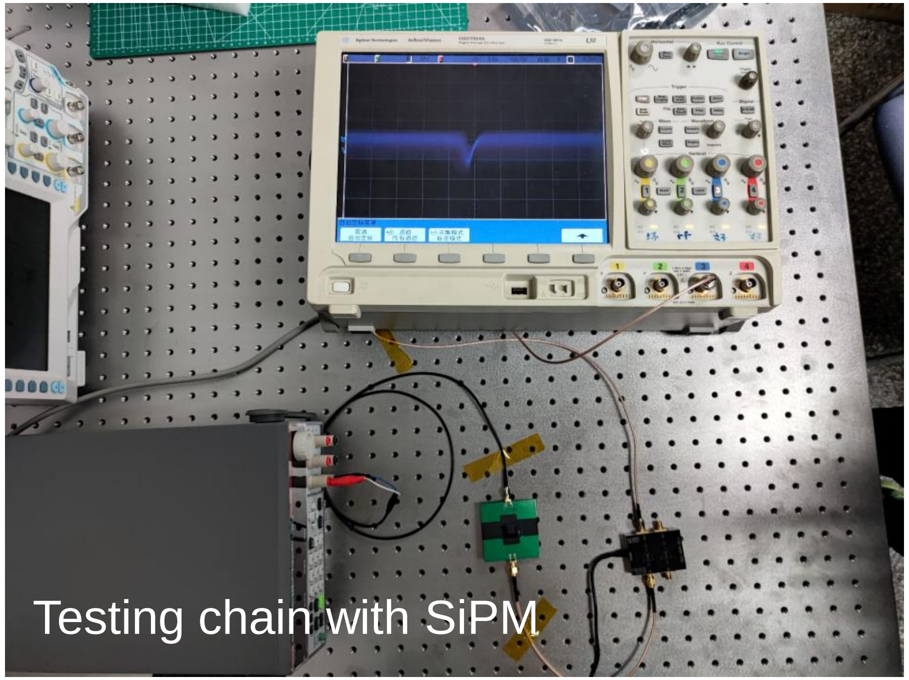
Jiechen Jiang, Baohua Qi

- Custom (flexible) design to support crystal bars with different lengths
  - Parts from 3D printing (tested) + aluminum from machining (to be done)








Testing chain with SiPM

Summary

- Progress on the 3D crystal calorimeter
  - Geometry and digitization implemented in CEPCSW
  - Working on the reconstruction algorithm in CEPCSW
  - EM shower studies in Geant4
    - To understand impacts from geometry
    - Information for energy splitting: ready
  - Test stand for crystal-SiPM: under development

- Plans
  - Reconstruction algorithm in CEPCSW
    - Performance check for close-by EM showers
  - Hadronic showers in crystal ECAL (guided by event display with jets)
  - Timing performance of crystal-SiPM

Backup slides

Studies on physics requirements

Yuexin Wang (IHEP)

- Estimate the multiplicity level of jets: fast simulation
  - Mean ~4 particles within the hottest tower

Multi-jet events at generator level:

☞ *Calculate the impact point of visible final states on the inner surface of ECAL*

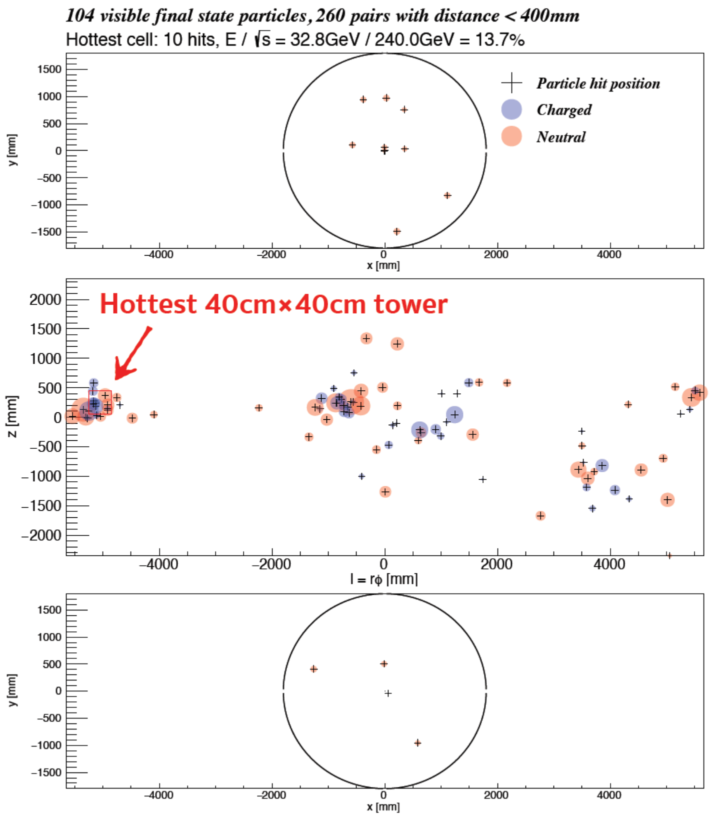
☞ *240GeV, ZH (Z→qq, H→gg) (4-jet event)* as an *example*

Parameters in calculation:

- *A simple cylinder ECAL*
- *Inner Radius, R=1800mm*
- *Barrel Length, L=4700mm*
- *Magnetic Field, B=3T*

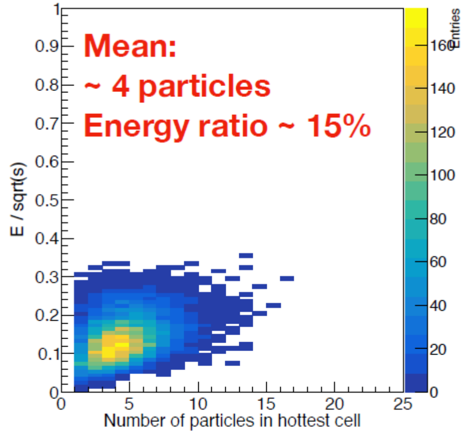
Analysis level:

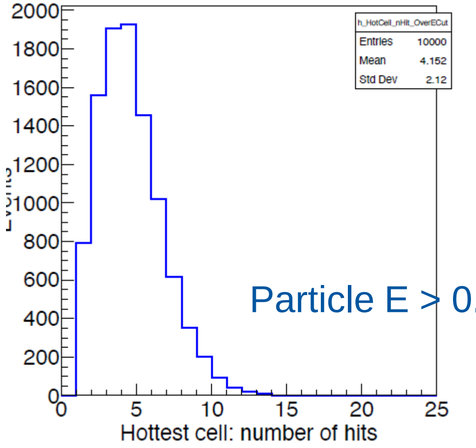
- *Hottest tower (with maximum energy)*
  - *multiplicity and energy ratio to √s*
- *Average proportion of towers with multi-particle*



Unfolded cylindrical ECAL

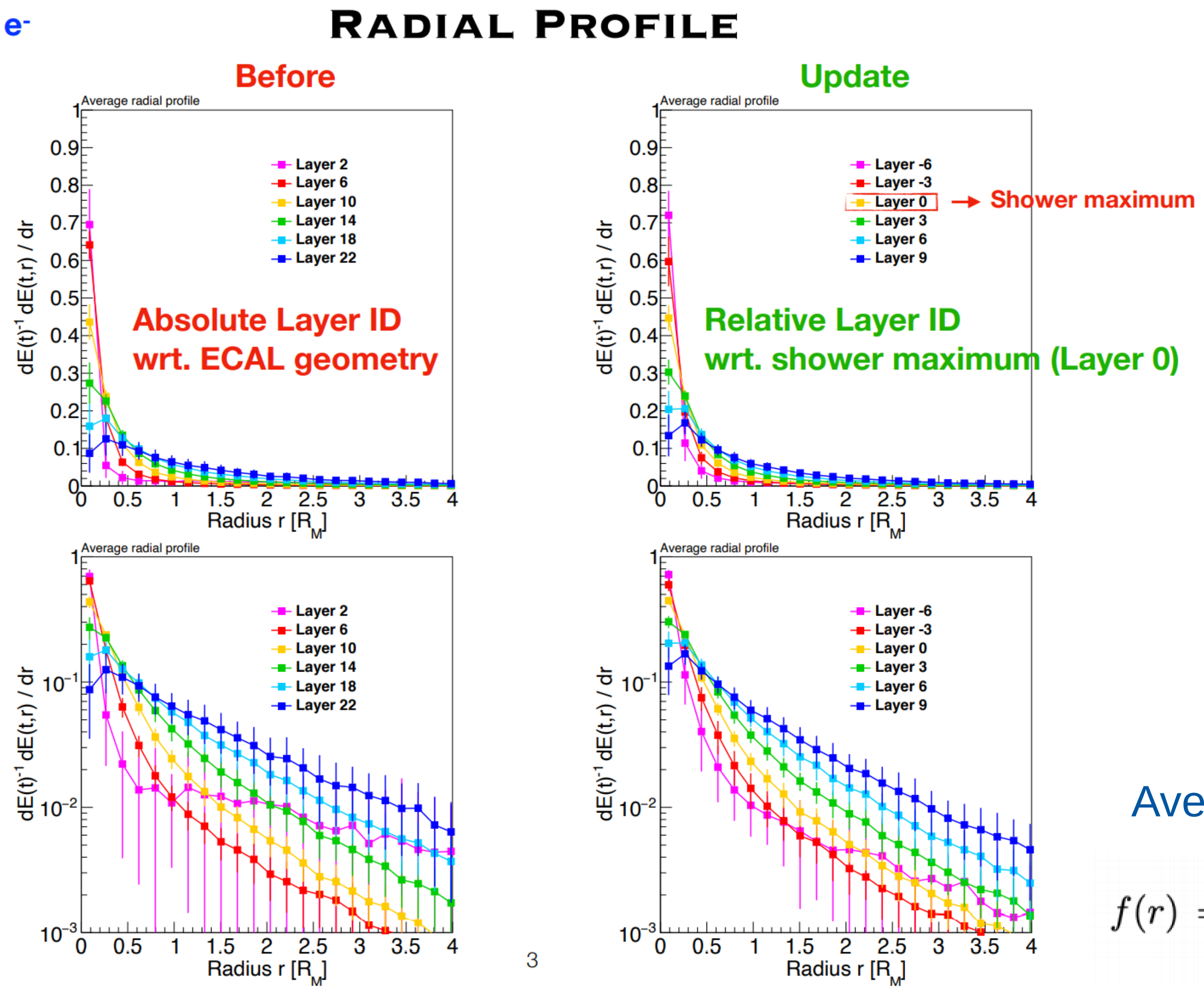
Hottest 40cm×40cm tower





Shower lateral profile: layer-wise

100GeV e-



EM shower lateral profiles

- Histograms stored for each longitudinal layer
- "Normalised" to the shower maximum
- Need to locate the shower axis beforehand
- Assign weights for energy splitting in the same bar

Other trials

- Tried to use models to fit the curves

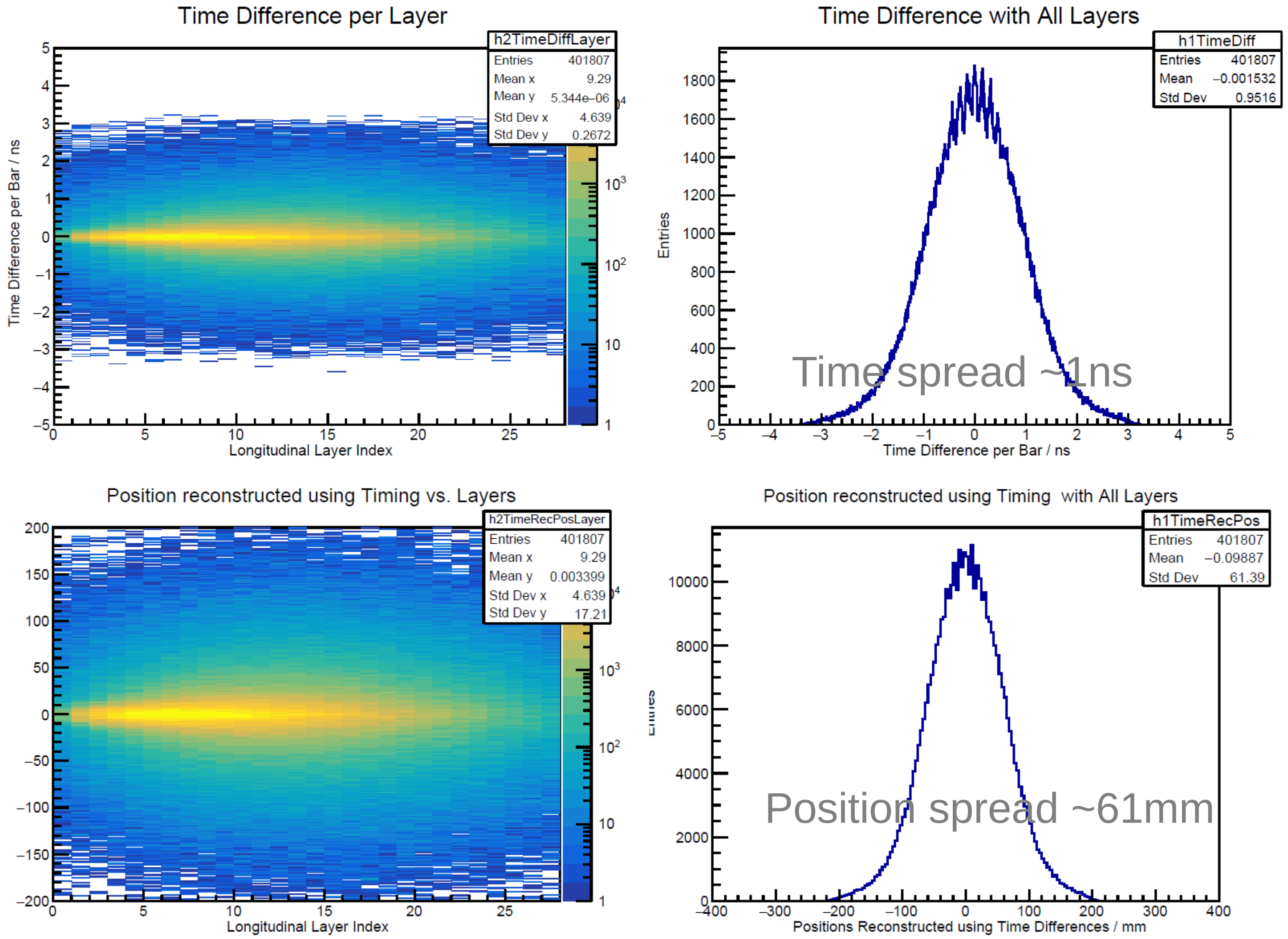
Average radial energy profiles

$$f(r) = \frac{1}{dE(t)} \frac{dE(t,r)}{dr}$$

$$\begin{aligned} f(r) &= p f_C(r) + (1-p) f_T(r) \\ &= p \frac{2 r R_C^2}{(r^2 + R_C^2)^2} + (1-p) \frac{2 r R_T^2}{(r^2 + R_T^2)^2} \end{aligned}$$

Reconstructed positions from timing

10 GeV gamma

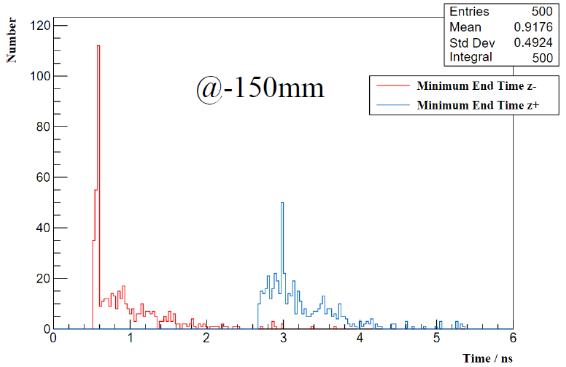


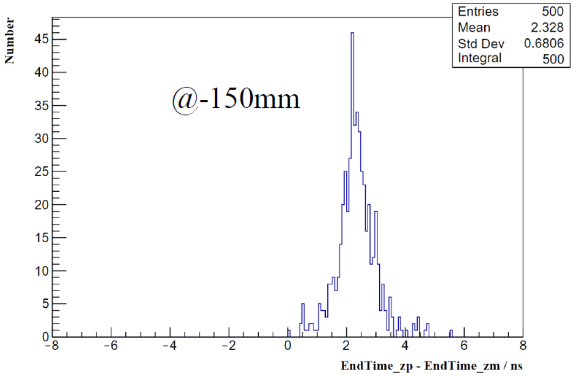
- Timing spread per bar: ~1ns
- Uncertainty of rec. positions from timing: ~60mm
- With energy weights, narrow down positioning precision ~10mm (preliminary)
  - Need to set energy cuts to quantify this precision

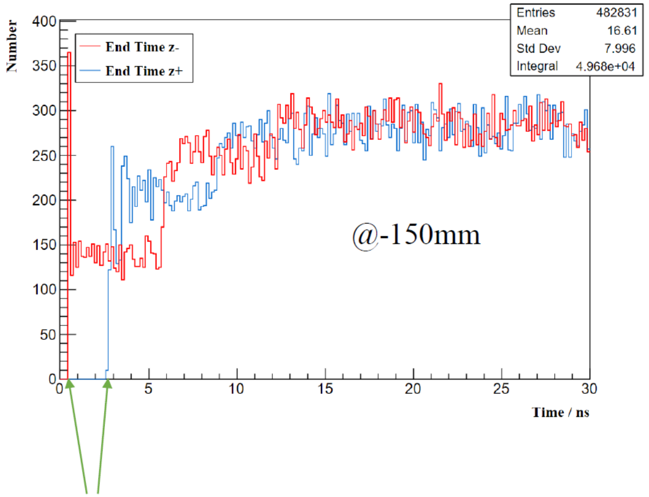
Geant4 full simulation for a single crystal bar

Baohua Qi (IHEP)

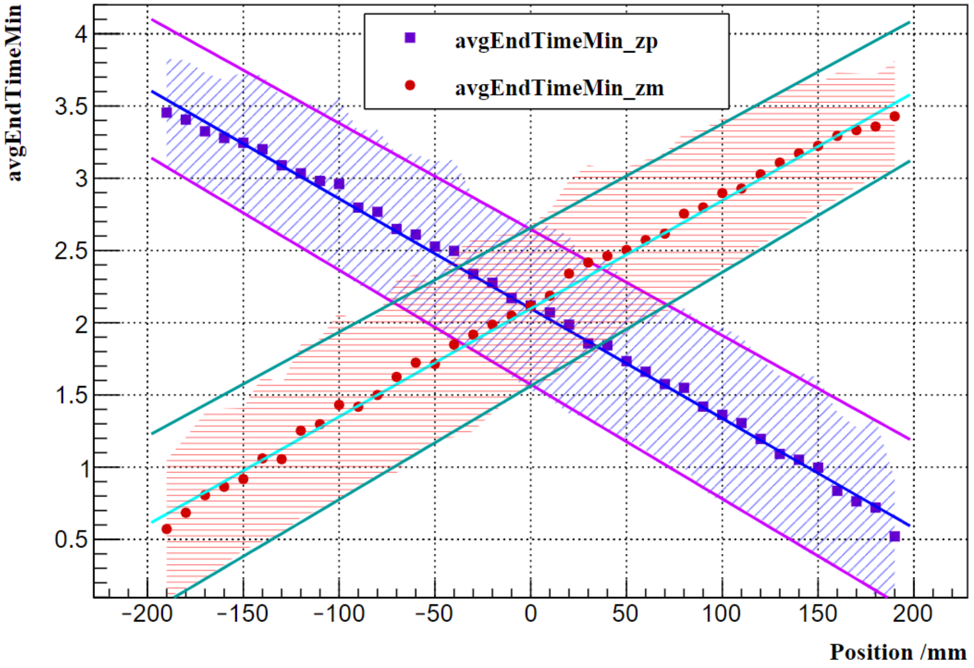
- To quantify the timing resolution at different hitting positions
- To provide input for the digitization model in CEPCSW







1st photon, percentage of Cherenkov photon ~ 30%



Geant4 full simulation for a single crystal bar

Baohua Qi (IHEP)

- Information extracted from G4
  - Energy deposition: mean ~10 MeV/MIP, determined by crystal thickness
  - #scintillation photons
  - #detected photons at either SiPM
  - Time stamp of each detected photon
    - T0: shooting of the primary particle (muon)
    - Included: scintillation time (~hundreds ns), propagation time (a few ns) within the crystal bar
    - **Excluded: timing uncertainties from SiPMs and electronics**
- Digitization
  - Timing: Choose the time stamp of the 1st photon detected at each SiPM
  - #detected photons : proportional to energy deposition