Simulation and Reconstruction in ECAL

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Representing CEPC Software Group

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Introduction

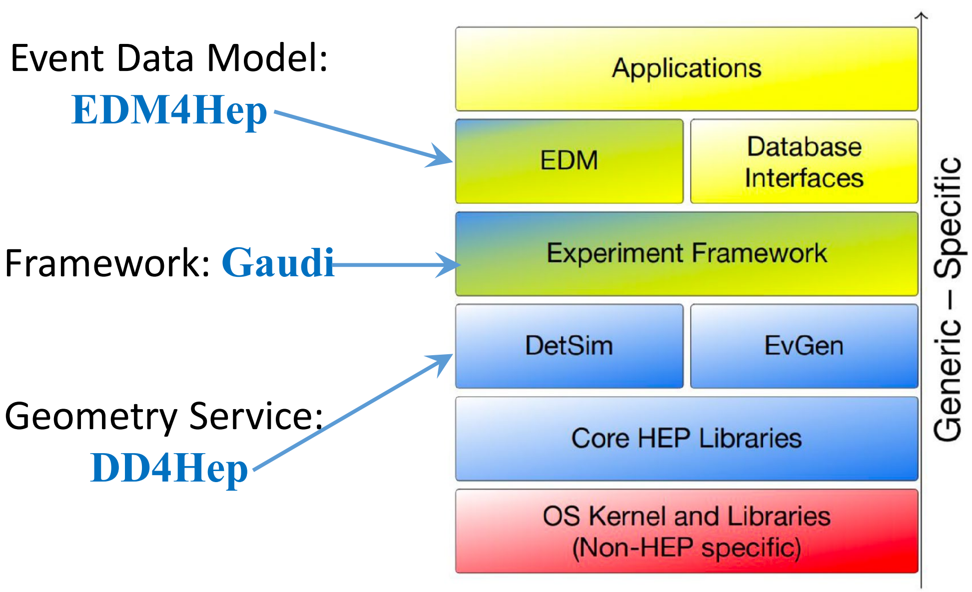
- Constraints on the detector performance from CEPC high precision physics programs.

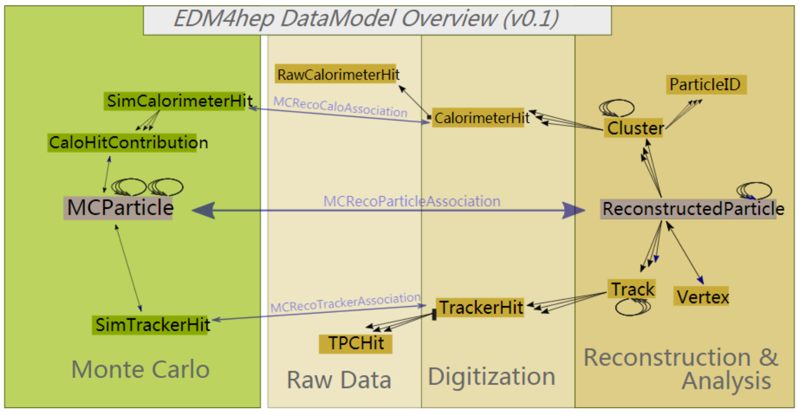
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

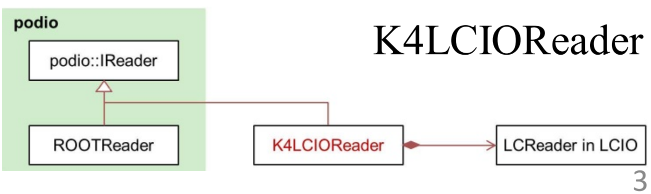
- To achieve a jet energy resolution of 3-4%, one approach is calorimeter system based on particle flow approach.
- Future detector studies critically reply on simulation to model detector concepts and to understand the detector's limitations and physics reach.
- A silicon-tungsten ECAL with high granularity is adopted into the full detector simulation.
  - ➢ Porting simulation and digitization into CEPCSW.
- Particle flow approach oriented reconstruction library Pandora.
- A frozen shower method for fast simulation of ECAL.
- A reference detector design: a long crystal bar ($\sim 1 \times 1 \times 40cm^3$) solution for the ECAL.
  - ➢ Explore the technical feasibility of PFA oriented long crystal bar design.

CEPCSW

- CEPC software originally started from the iLCSoft (many thanks) used for CDR study
  - —LCIO, Marlin, MokkaC, Gear, ……
- Reached consensus among ILC, CLIC, FCC, CEPC, … to develop a common turnkey software stack: Key4Hep
- EDM4Hep: official and common event data model in Key4Hep.
- Unified geometry service used by simulation and reconstruction.



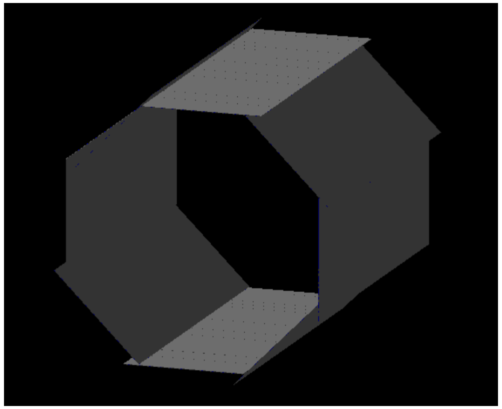




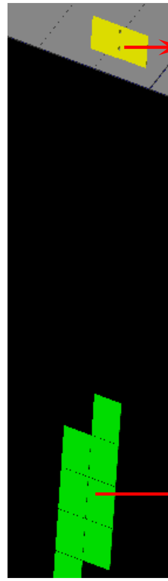
Porting ECAL Simulation into CEPCSW

- Status: SiW-ECAL is available in the CEPCSW.
- The detector description is available for both simulation and reconstruction.
  - ➢ Detector parameters (XML, based compact file): Detector/DetCEPCv4/compact
  - ➢ Detector constructor (C++ based): Detector/DetCEPCv4/src/calorimeter
- Detector response simulation for ECAL is done.
  - ➢ Package Simulation/DetSimSD is created for geant4 simulation.
    - —CalorimeterSensDetTool: integrated with Gaudi
    - —CaloSensitiveDetector: integrated with Geant4
    - —DDG4SensitiveDetector: integrated with DDG4 to get VolumeID/CellID
- EDM4Hep based calo hit objects and McTruth information are saved.
  - ➢ SimCalorimeterHitCollection (cellID, energy, position…)
  - ➢ CaloHitContributionCollection (Particles'PDG, energy, time, position…)

Detector Description & Detector Responses



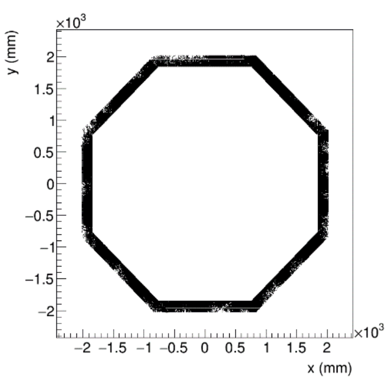
One layer (Si+W+Si) is shown
- 8 staves
- 5 modules per stave
- 5 towers per modules



Note: other wafers in this layer are not displayed.

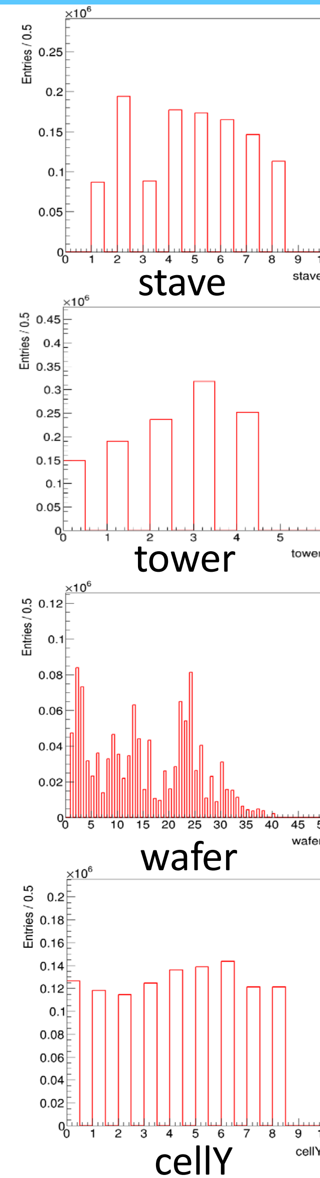
One sensitive layer in a tower

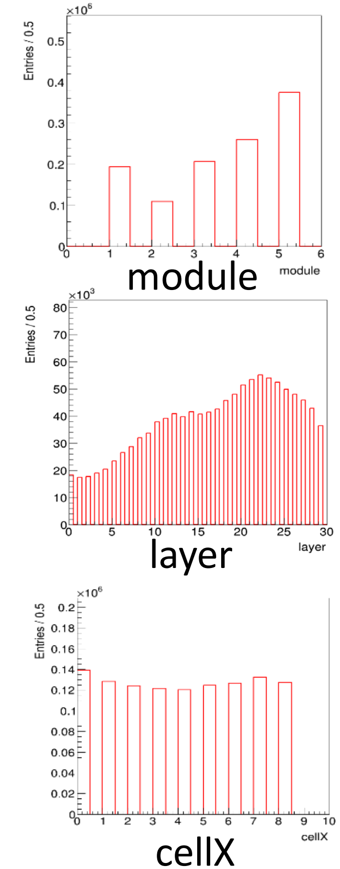
All the information are stored in ROOT for further validation:
- EcalBarrelCollection, EcalBarrelContributionCollection
- EcalEndcapsCollection, EcalEndcapsContributionCollection
- EcalEndcapRingCollection, EcalEndcapRingContributionCollection



Hit position (x:y)

π^+(E=100GeV, $\theta = 0 - 180^{\circ}$, $\phi = 0 - 360^{\circ}$), no B filed



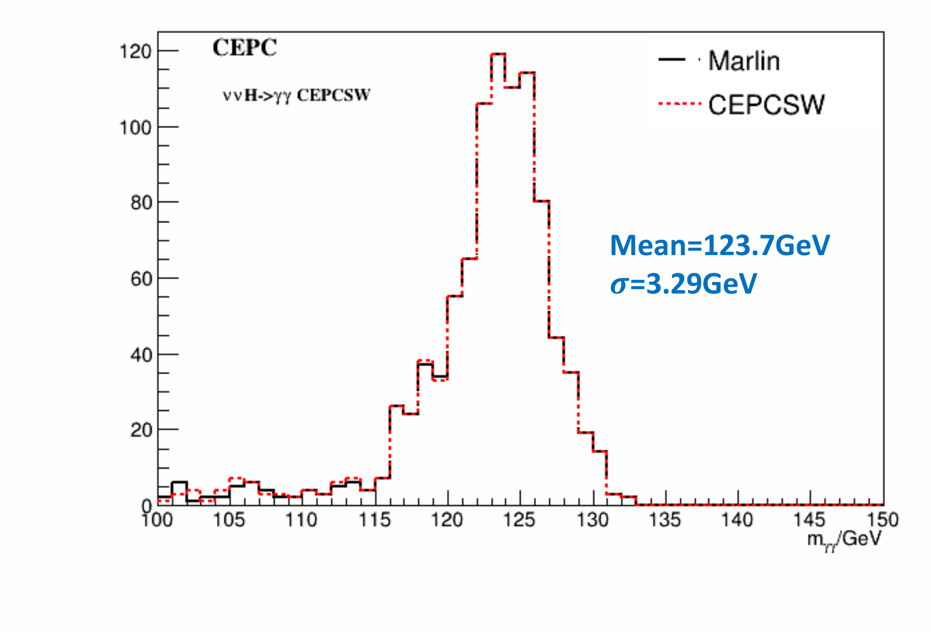


The ID is based on VolumeID (detector) and CellID (segmentation) in DD4hep

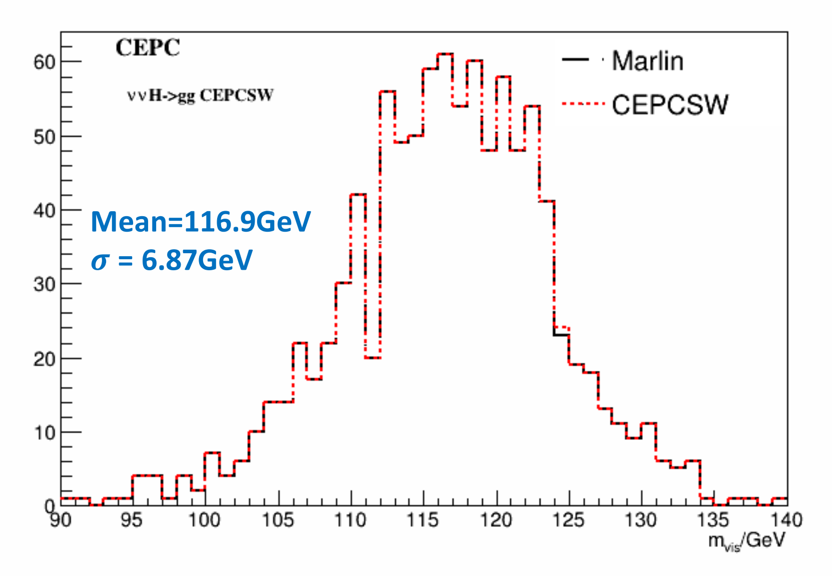
Migration of Calorimeter Digitization

- Calorimeter digitization has been migrated from Marlin to CEPCSW
- Validation shows the results in CEPCSW are consistent with that in Marlin

Validation of ECAL



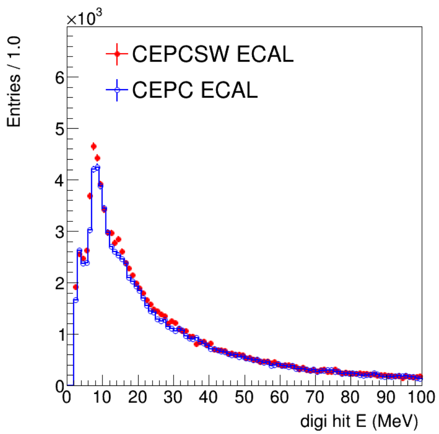
Validation of HCAL

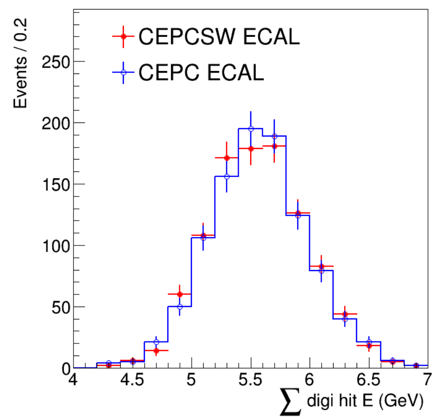


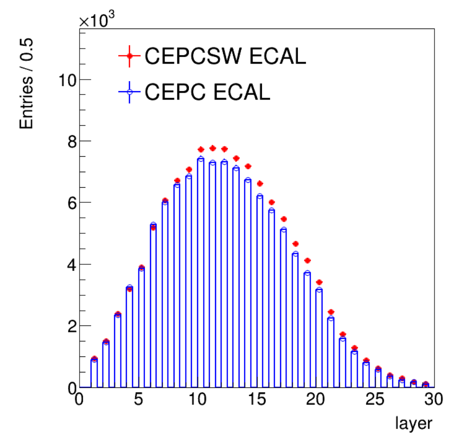
LCIO data as input

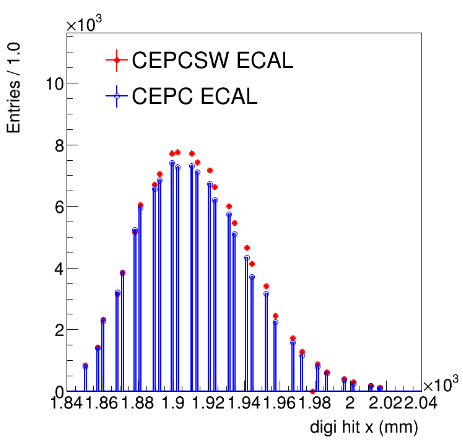
ECAL Simulation and Digitization

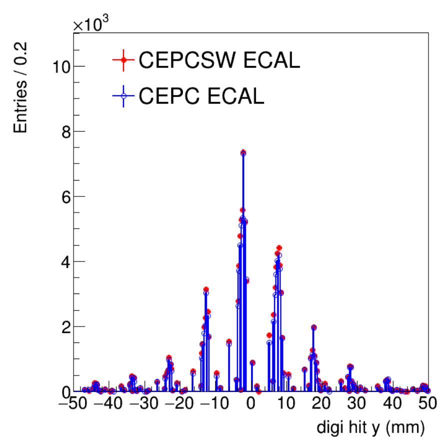
- 1000 Single γ events (E=5GeV, $\theta = 60^{\circ}, \phi = 0$).
- Preliminary results of digi hit distributions.

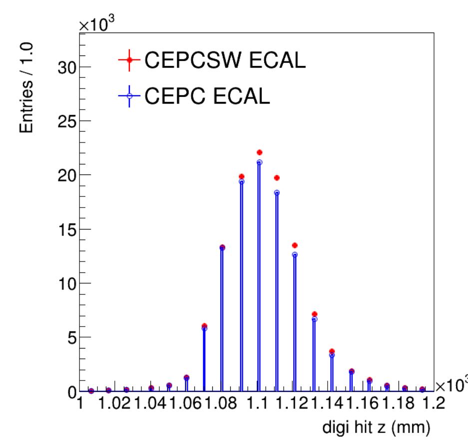








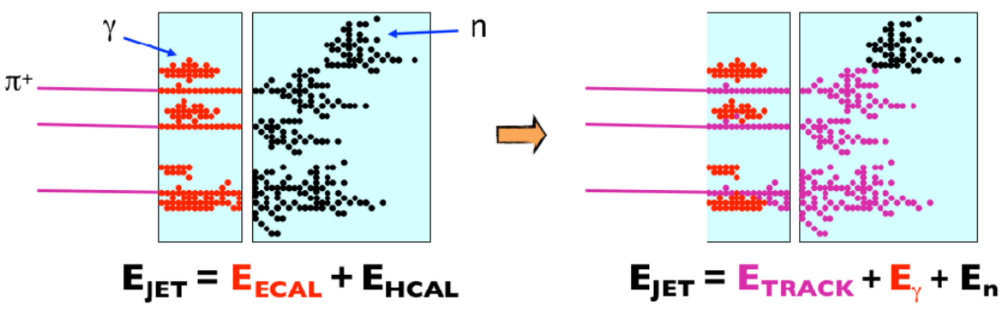


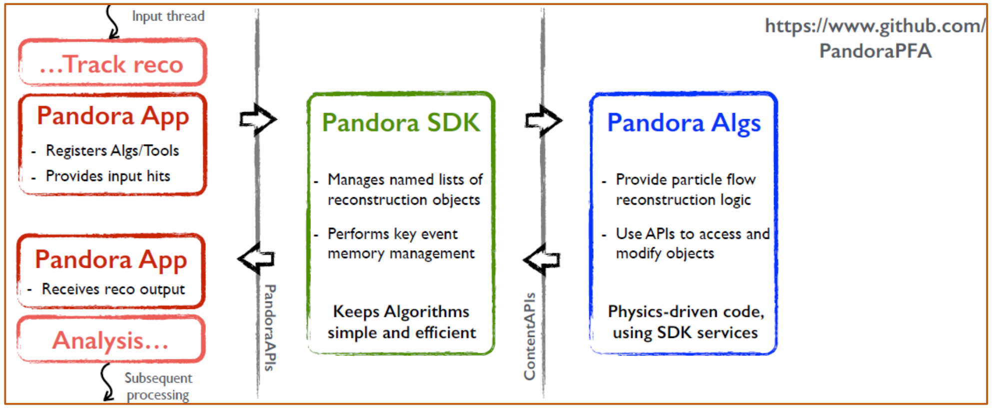


Pandora

- The majority of the Higgs, W, and Z bosons decay into multi-jets final states.
  - ➢ 3-4% jet energy resolution gives decent 2.6—2.3 σ W/Z separation.
  - ➢ Particle flow approach is a promising strategy to reach the goal.

- Pandora is a general pattern recognition algorithm developed to study PFA calorimeter.
- Applications of Key4Hep

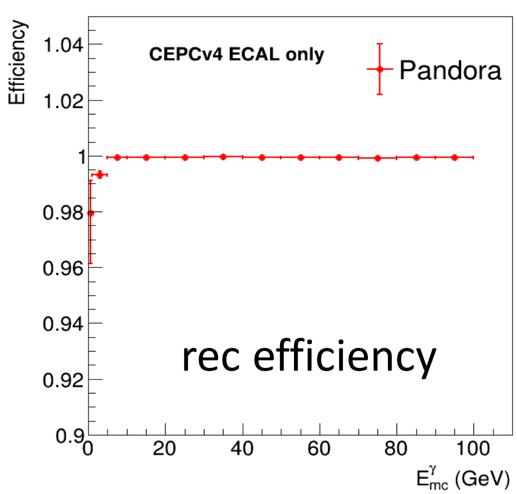


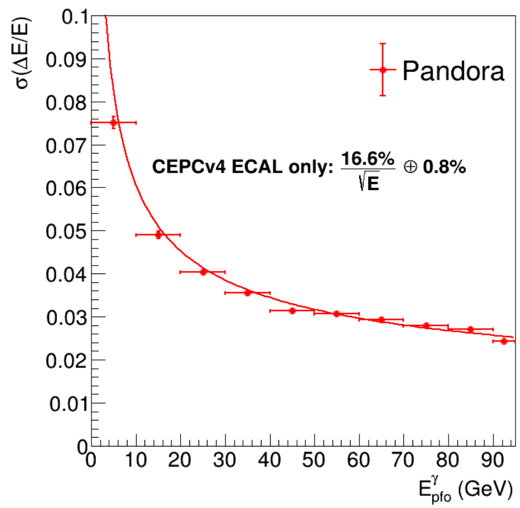


- Pandora App: a Gaudi algorithm in CEPCSW. It provides input objects and receive reconstructed objects.
- Pandora SDK: managing pandora objects.
- Pandora Algs: reconstructing objects.

Pandora in CEPCSW

- Single γ events are used for performance check of Pandora algorithm.
  - The reconstruction efficiency >99% for energy above 1GeV, which fulfills the CDR requirement.
  - Energy resolution $\frac{16.6\%}{\sqrt{E}} \oplus 0.8\%$, consistent with CDR intrinsic $\frac{15.1\%}{\sqrt{E}} \oplus 1.3\%$

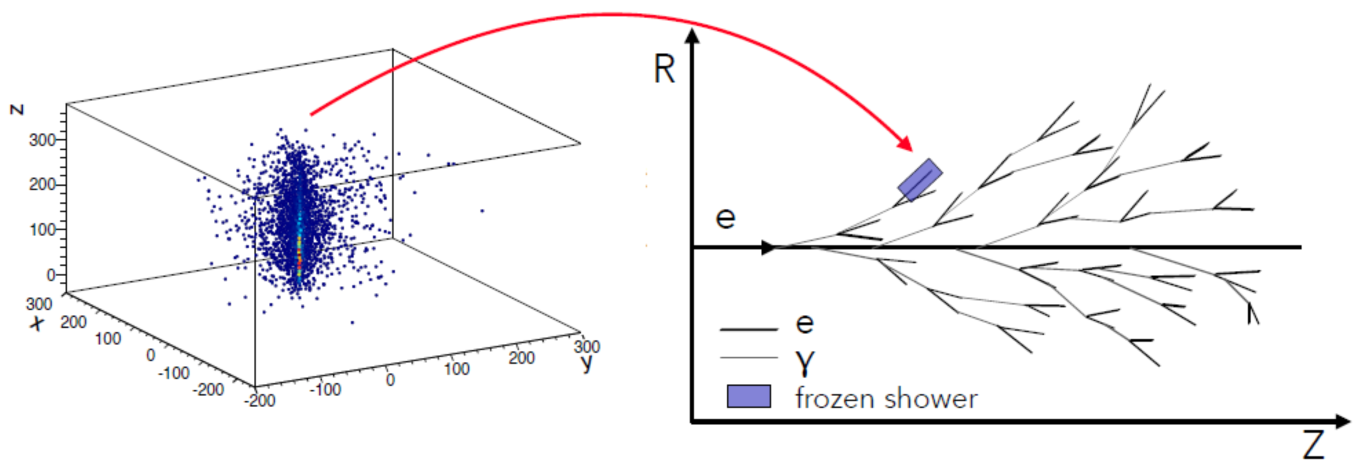




- Plan: performance checks of hadrons and jet energy resolutions, optimization towards CEPC detector.

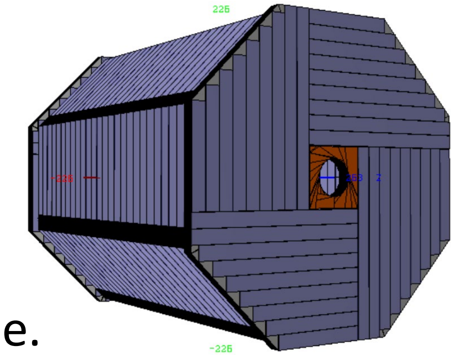
ECAL Fast Simulation: Frozen Shower

- A large number of computing resources are used for MC simulation, calorimeter simulation is one of bottlenecks.
- In full simulation, a shower development produce a large amounts of secondary particles. For certain low energy secondary particle (energy, direction), the subsequent shower development follow a similar stochastic distribution.
- In frozen shower simulation, the low energy showers are substituted by the pre-generated showers from the library.
  - FS Library Generation: pre-generated low energy showers and their properties.
  - FS Library Access (Fast Simulation): Showers stored in library are accessed to replace the fully simulated showers.

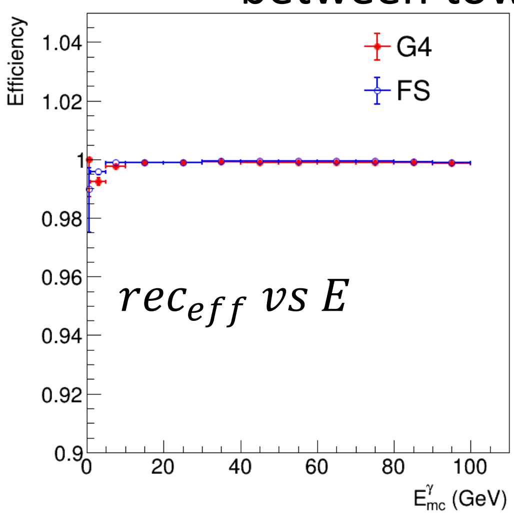


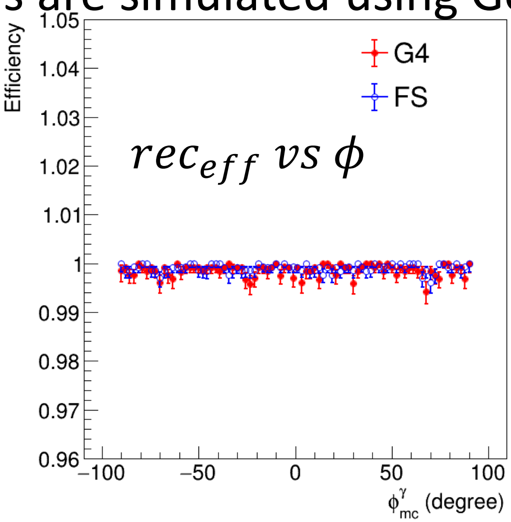
Frozen Shower Simulation

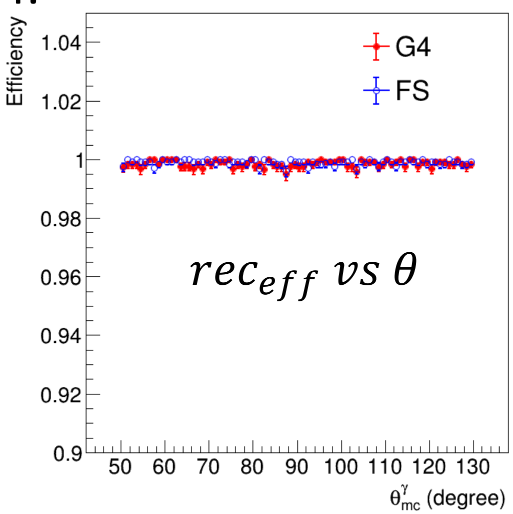
- Frozen Shower library generation:
  - ➢ Electron/positron for barrel ECAL
    - – Energy range: 150MeV — 1GeV
    - – θ range: 50° to 90°, ϕ range: -20° to 20°
    - – Longitudinal range: 1850 — 2000 mm
  - ➢ Library size ~ 20 GB, saved in uncompressed ROOT file.
  - ➢ Currently the FS work is under LCIO CEPC software framework.



- Frozen Shower ECAL fast simulation:
  - ➢ Performance check: γ
  - ➢ Using Pandora for the reconstruction of ECAL and HCAL
  - ➢ The concatenate regions for different staves and the gap regions between towers are simulated using Geant4.

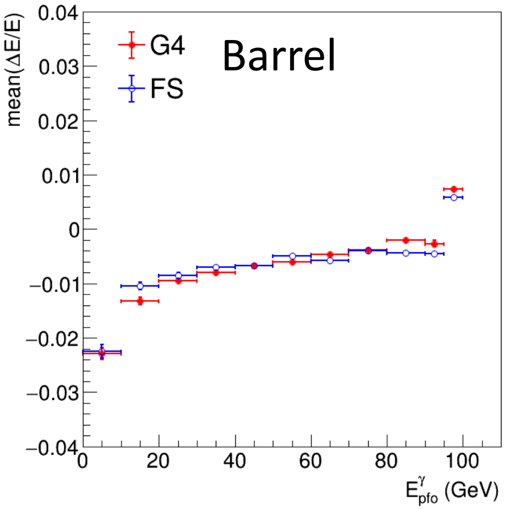




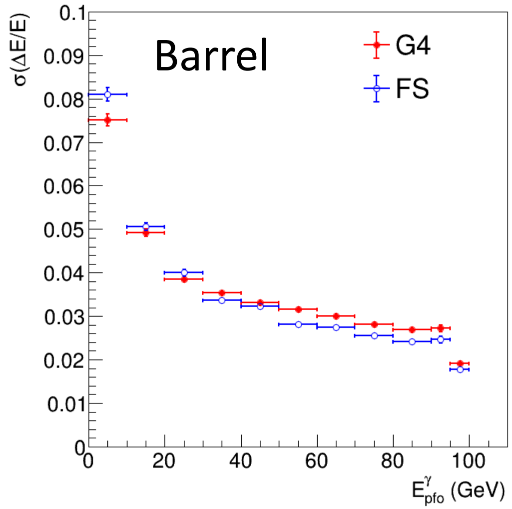


Performance check of Frozen Shower Sim

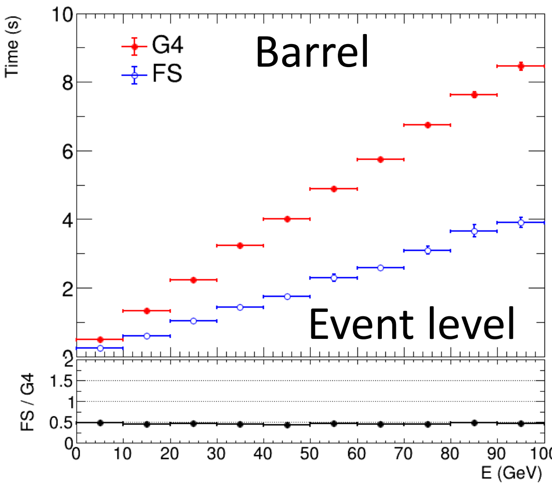
- Single γ simulation is used for performance check
- Using Pandora for reconstruction



$\text{mean}\left(\frac{\Delta E}{E}\right)$ vs E



$\sigma\left(\frac{\Delta E}{E}\right)$ vs E



time vs E

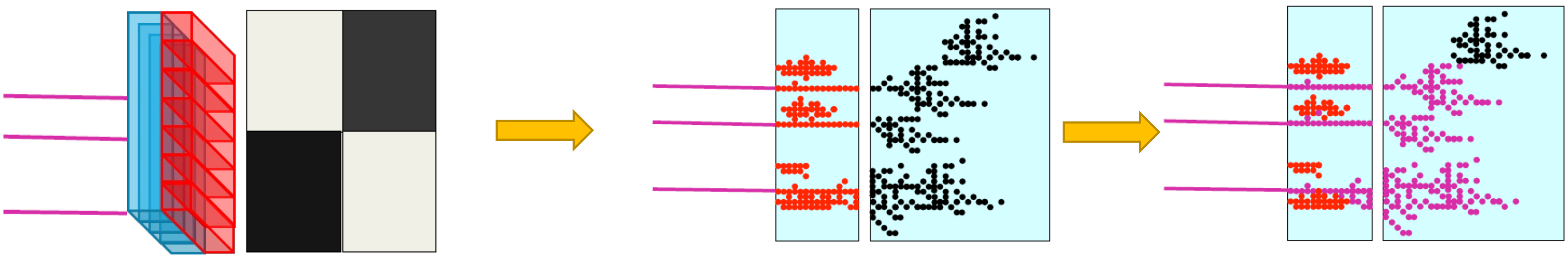
- Good agreement between G4 simulation and FS simulation.
- Around one time speed up can be obtained.
- Optimization of FS method for further acceleration of the simulation.

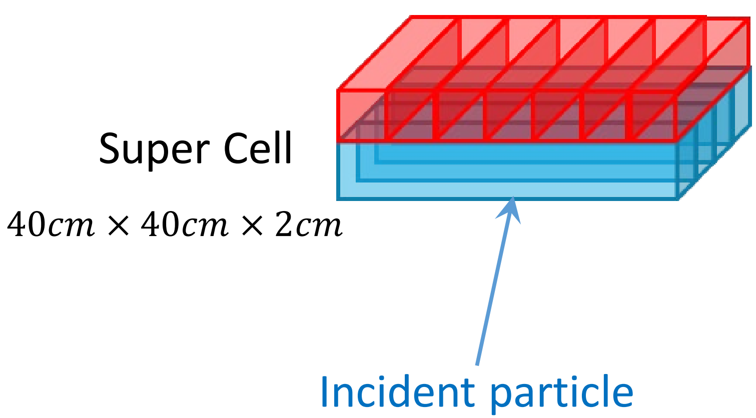
A Crystal Bar Solution for the ECAL

- Jet Energy Resolution: combination of detector and software performances
  - ➢ Hardware: resolve *E* from different particles.
  - ➢ Software: identify *E* from each individual particle.

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

- Confusion is the limiting factor, the crucial aspect is the ability to correctly assign calorimeter energy deposits to the correct particles.



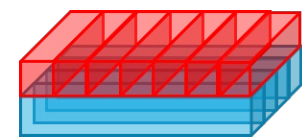


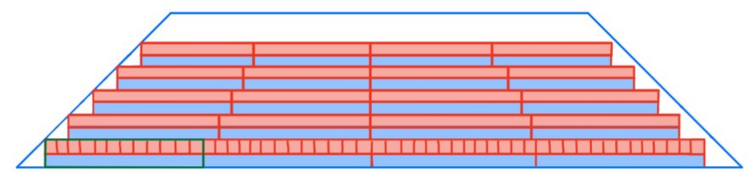
- Motivations:
  - ➢ Optimal EM energy resolution: $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
  - ➢ #channels, over an order magnitude less
- Key issues:
  - ➢ 2D measurements provide 3D information
  - ➢ Multiplicity of incident particles (in plan)

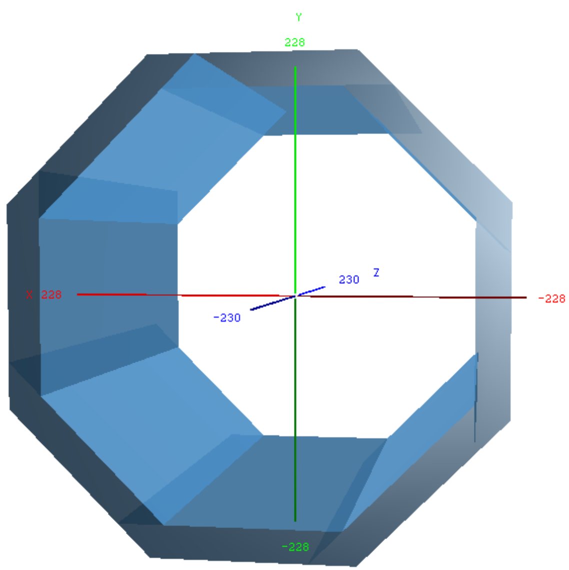
Geometry Construction

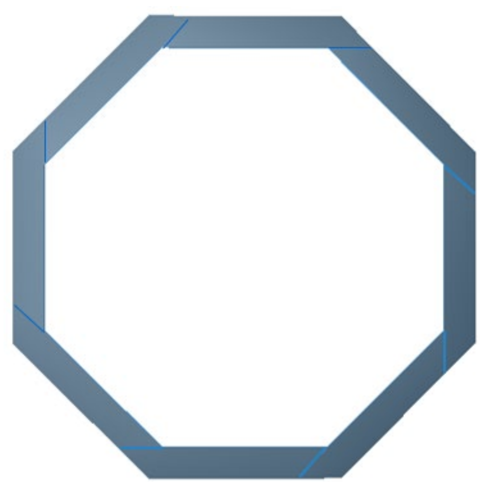
A full BGO crystal barrel ECAL

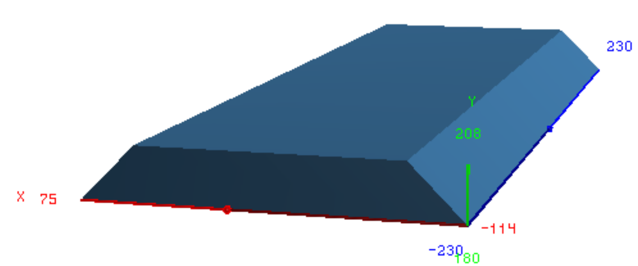
- Crystal bar:
  - BGO: $X_0 = 1.12cm$, $R_M = 2.23cm$
  - Size: $1cm \times 1cm \times \sim 40cm$
  - Dual-end readout
- Basic Unit — Super Cell
  - 2 layers of vertically intersected crystal bars
  - Size: $\sim$40cm $\times$ $\sim$40cm $\times$ $2cm^2$
- Detector
  - $R = 1.8m$, $L = 4.6m$, $H = 28cm$
  - 8 same trapezoidal staves
- Ideal detector without electronics, supporting, etc.
- DD4Hep is used for geometry construction.











Simulation and Digitization

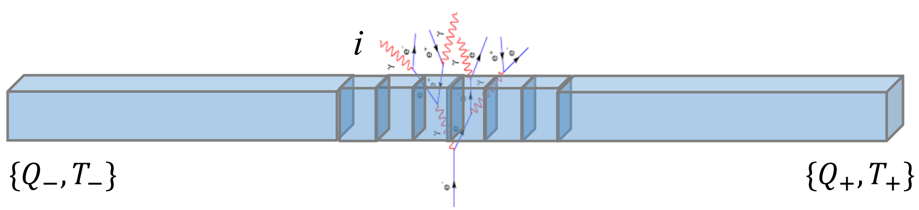
- Simulation is performed with Geant4 in CEPCSW.
  - Electromagnetic interactions
- Digitization for one long crystal bar:
  - Readout information: 2-end Q and T.
  - Contribution from G4step i:

$$Q_{\pm}^{i} = E_0 \cdot e^{-\frac{\frac{L}{2} \pm z_i}{L_{Att}}}, \quad T_{\pm}^{i} = Gaus(z_{\pm}^{i}/v,\ \sigma_T).$$

  - For the full bar:

$$Q_{\pm} = \sum_{step} Q_{\pm}^{i},\ T_{\pm} = \min(T_{\pm}^{i})$$

  - Simplified condition: $L_{Att} = \infty$, so $Q_{\pm} = E_{tot}$.



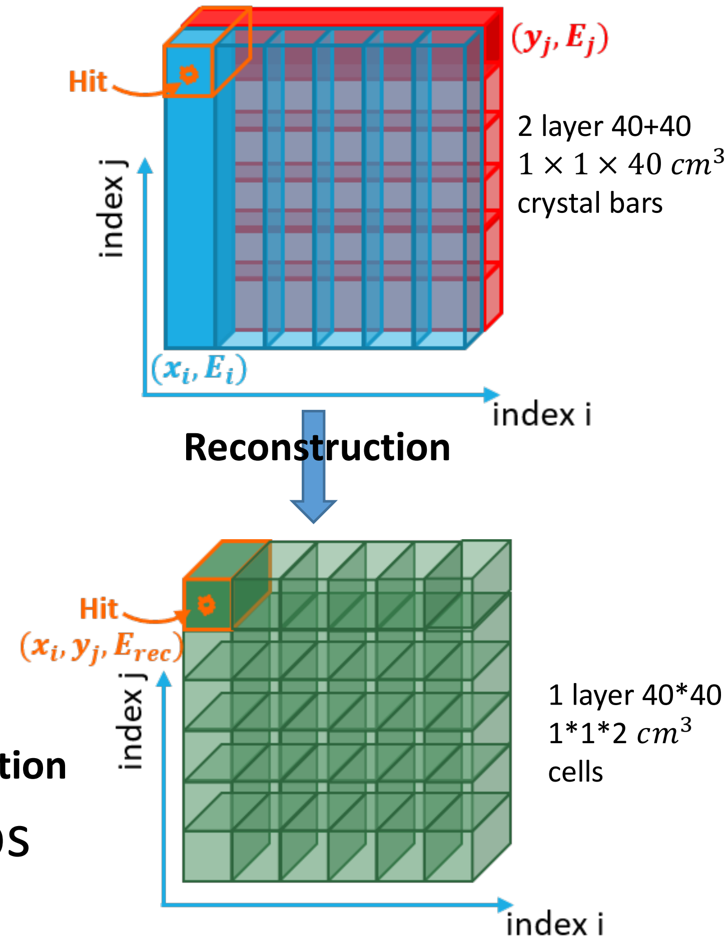
Hit Reconstruction

- Hit reconstruction: cross locating of bars.
  - Position: $(x_i, y_j, \frac{(z_i+z_j)}{2})$
  - Energy: use energy distribution in cross bars as fraction:

$$E_{rec} = E_i \times f_i + E_j \times f_j,$$
$$f_i = \frac{E_j}{\Sigma E_j}, \quad f_j = \frac{E_i}{\Sigma E_i}$$

  - Position from time:
    - $x_T = x_{bar} + \frac{T1-T2}{2} v, \sigma_x = \frac{\sigma_T}{\sqrt{2}} v.$
    - If($|x_T - x_{rec}| > N\sigma_x$) remove this hit.

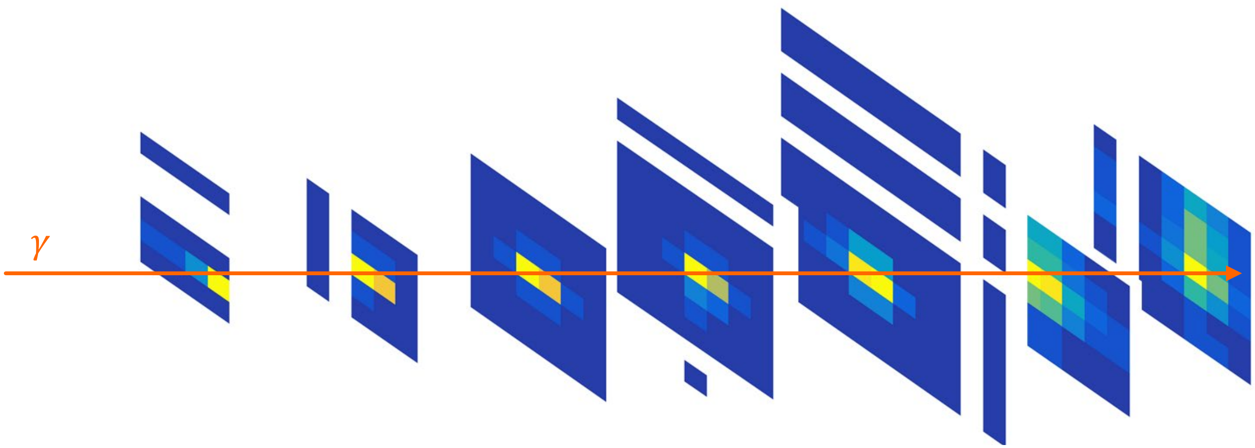
Ghost hit removal.
$N = \infty \Rightarrow$ No time information

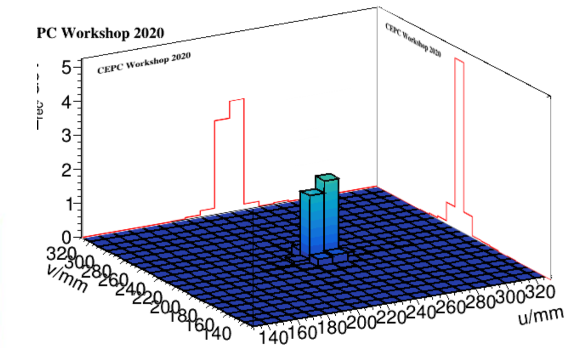


- Truth-level Simulated hit: merge G4steps in each 1*1*1 cm^3 cube as a truth hit.

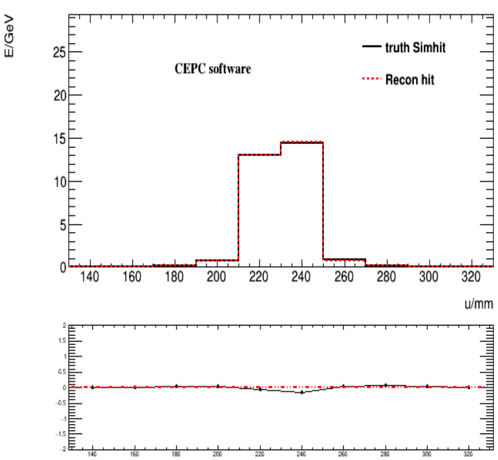
Hit Reconstruction

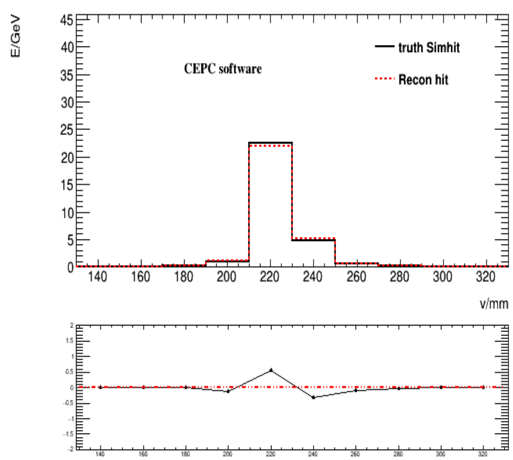
- Performance of a 30GeV single photon.
  - $L_{Att} = \infty, \mathrm{N} = \infty$
  - Energy threshold for each crystal bar: 3MeV.
  - Vertical shoot at the central of one super cell in first super-layer.

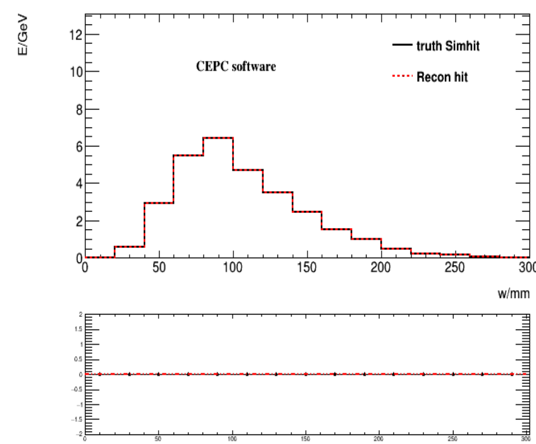




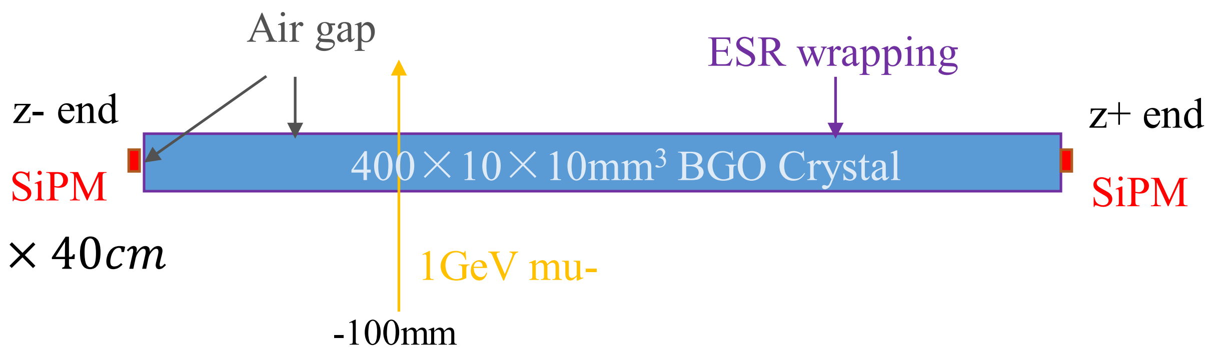
E_{rec} and projection in one super-layer







Single Crystal Bar Simulation Studies: Timing Performance

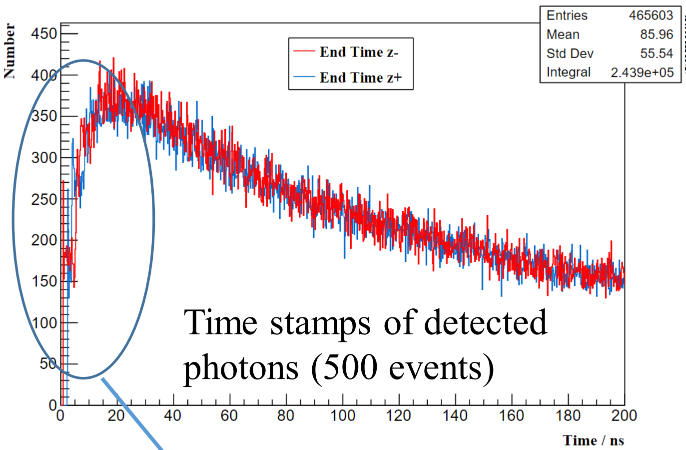


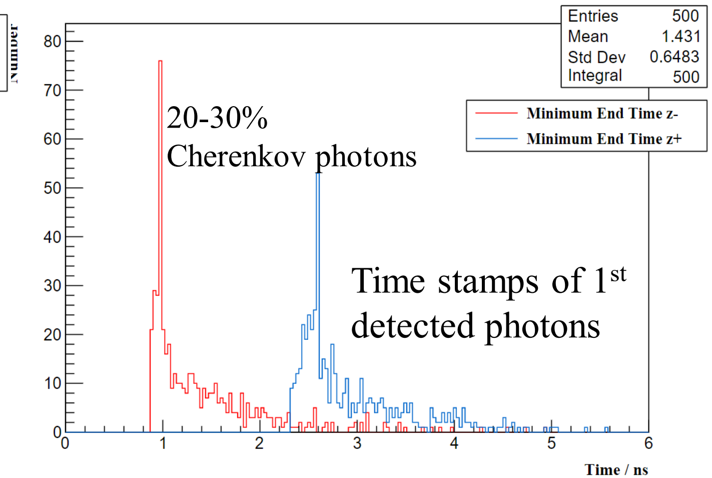
Geant4 full simulation

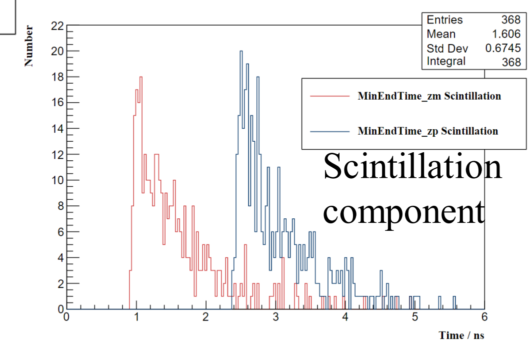
- Geometry
  - A crystal bar: $1cm \times 1cm \times 40cm$
  - Read out by two SiPMs
- Properties
  - BGO: light yield, decay times(fast and slow), refractive index, transmission (absorption length)
  - Wrapping: ESR foil (~99% reflectivity) with air gaps (total reflections)
  - SiPM: 6x6 or 10x10 mm2 sensitive area, Photon Detection Efficiency (PDE), realistic SMD package.
- Primary particle: 1GeV muon (for MIP calibration)
- Optical photon processes:
  - Scintillation, Cherenkov, absorption, refraction/reflection at boundaries

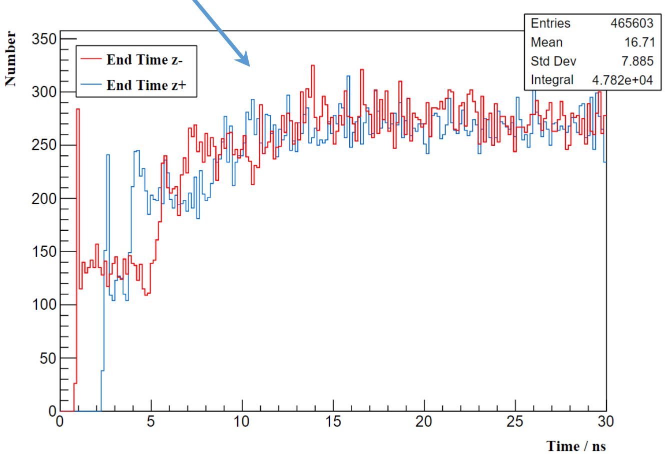
- Information extracted from G4
  - Energy deposition: mean ~10MeV/MIP
  - #detected photons
  - Time stamp of each detected photon
  - Include: scintillation, propagation time
  - Excluded: time uncertainties from SiPMs and electronics
- Digitization
  - Timing: time stamp of 1st photon detected
  - #detected photons: proportional to energy deposition
- Crystal measurements in plan.

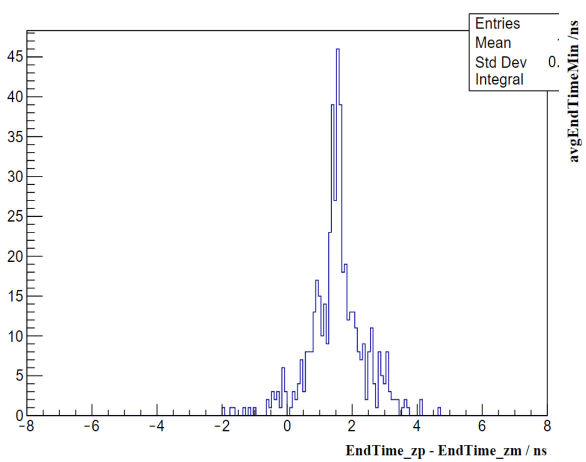
Single Crystal Bar Simulation Studies: Timing Performance

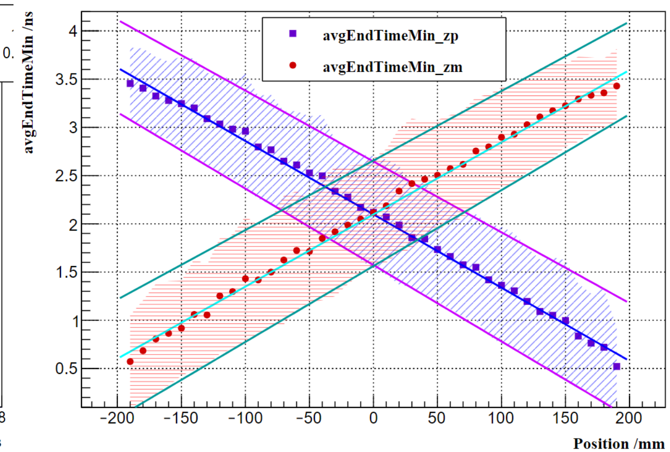












Summary and Plan

- Porting of simulation and digitization algorithms for ECAL from Marlin to CEPCSW is almost finished, preliminary result is promising.
- Integration of Pandora to CEPCSW and validation with single γ events.
- A frozen shower method for ECAL fast simulation is developed to speed up the simulation of electromagnetic shower.
- The crystal bar ECAl has been implemented in CEPCSW, and simplified/parameterized simulation digitization algorithms have been developed.
- Preliminary results show that 3D showers profiles can be extracted from 2D measurements of a single high-energy γ. Major focus in the plan: multiple incident particles hitting one super cell (e.g. ambiguity, energy splitting)

Thank you!