Reconstruction algorithms for the crystal bar ECAL

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on behalf of the CEPC Calo-software working group

2023年粒子物理实验计算软件与技术研讨会

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中国科学院高能物理研究所
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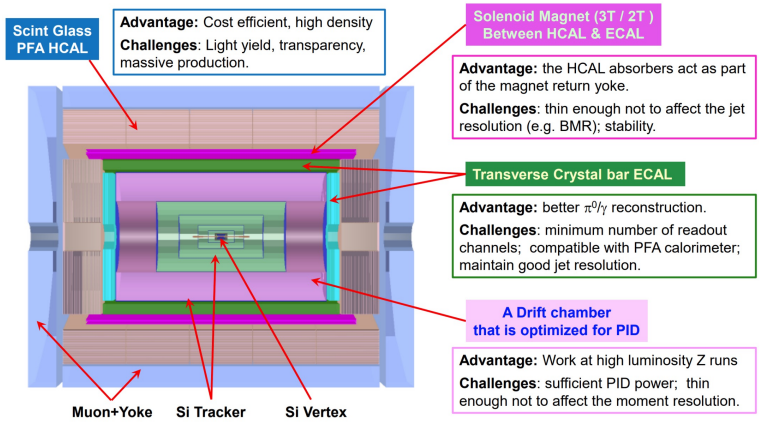
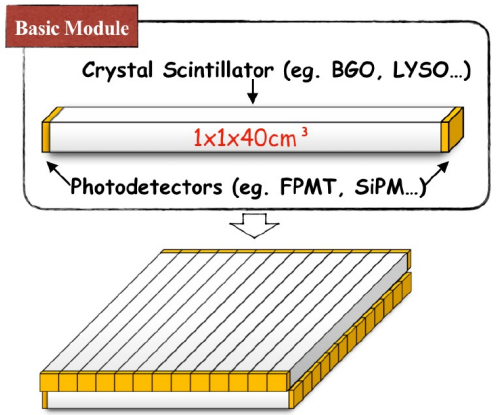
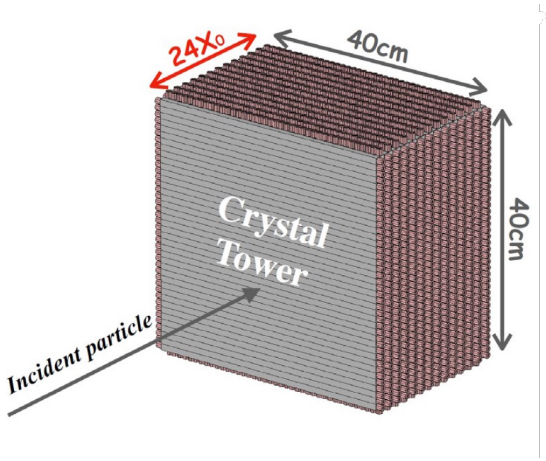
Introduction

- **Future lepton collider experiment:**
  - Precise measurement for Higgs, EW, top, etc.
  - Require excellent jet resolution: **Particle Flow Approach.**
    - $\sigma_{jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{EM} + \sigma^2_{Had} + \sigma^2_{Confusion}}$
  - Imaging calorimeter + Topological analysis



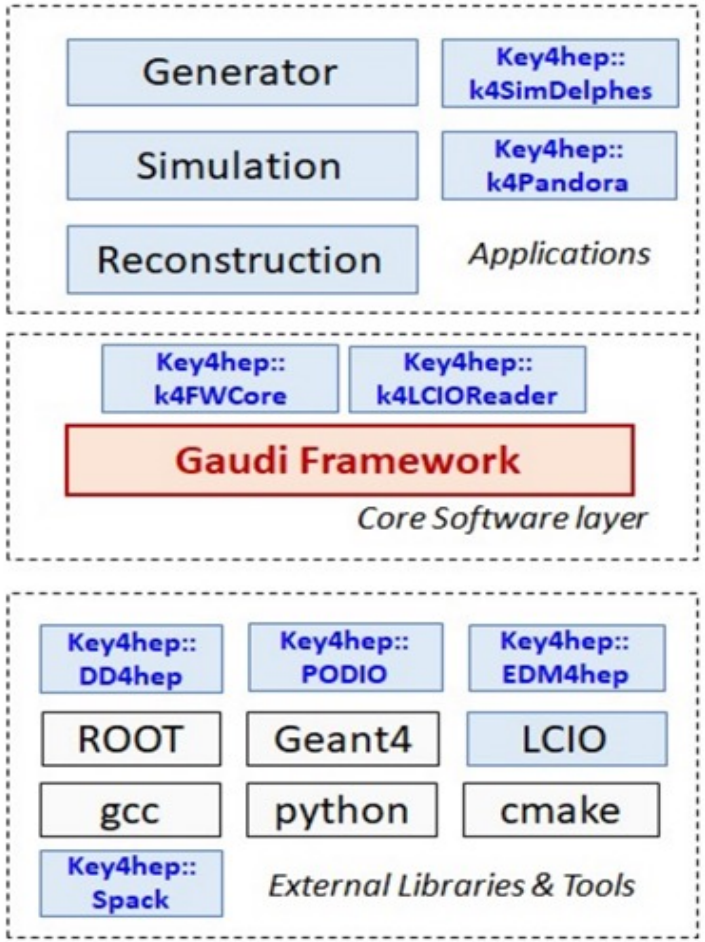
- **Crystal bar ECAL design for the CEPC 4th conceptual detector design:**
  - Long crystal bars, double-side readout with SiPM.
  - Crossed arrangement in adjacent layers + timing at 2 sides for positioning.
  - Better energy resolution, fewer #channels.
  - **Need specific reconstruction algorithms**.

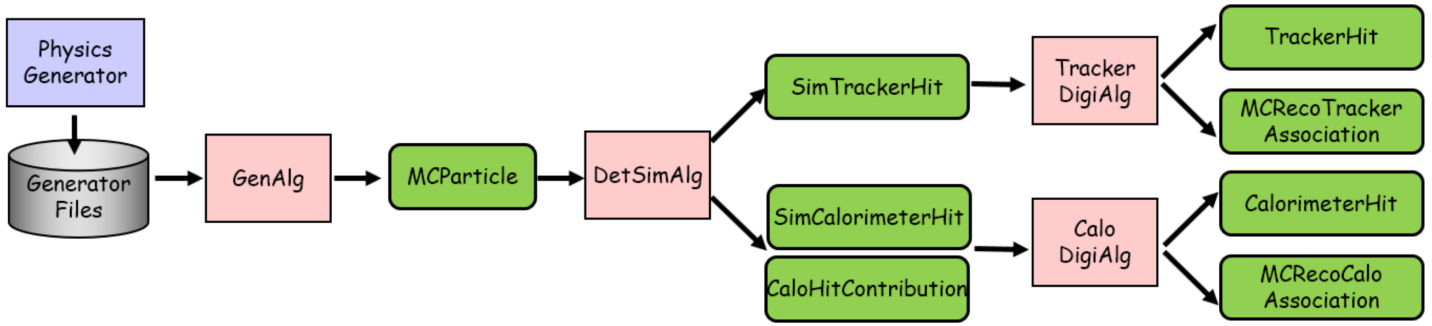




CEPCSW framework

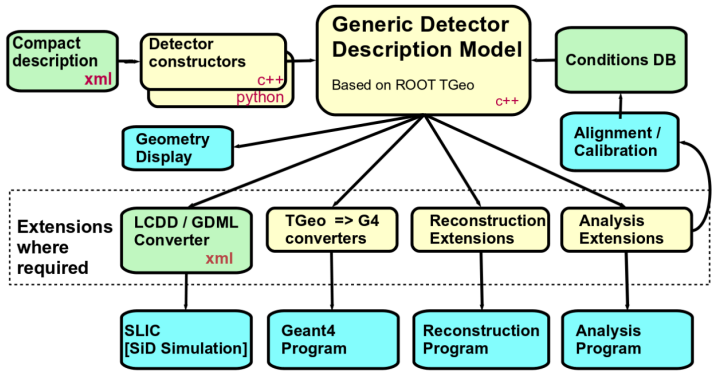
- **Common software stack: Key4HEP**
  - CEPCSW: Gaudi-based framework.
    - including core software, applications, external libraries, etc.
  - Event Data Model: EDM4HEP.
  - Detector description: DD4HEP.
  - ECAL software is developed under CEPCSW.



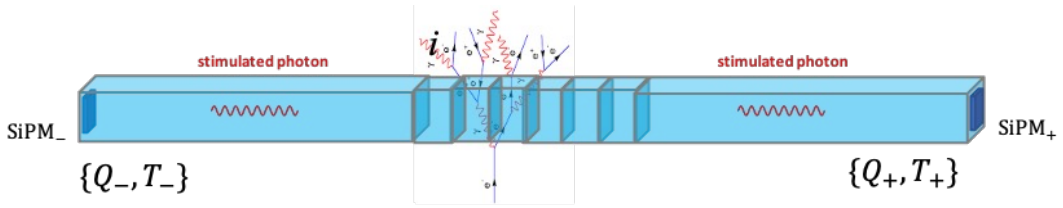


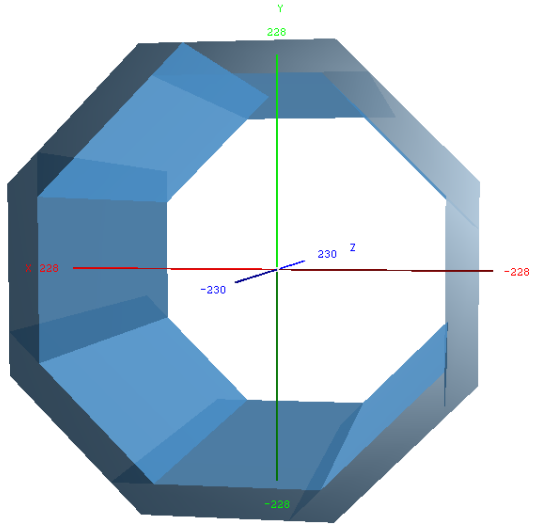
Simulation and digitization

- **Detector description:**
  - Unit: BGO crystal bar, size $1\times1\times40\sim60\ \mathrm{cm}^3$.
  - Octangular barrel structure, $\mathrm{R} = 1.86\ \mathrm{m}, \mathrm{L} = 6.6\ \mathrm{m}, \mathrm{H} = 28\ \mathrm{cm}$.
  - DD4HEP for geometry construction.



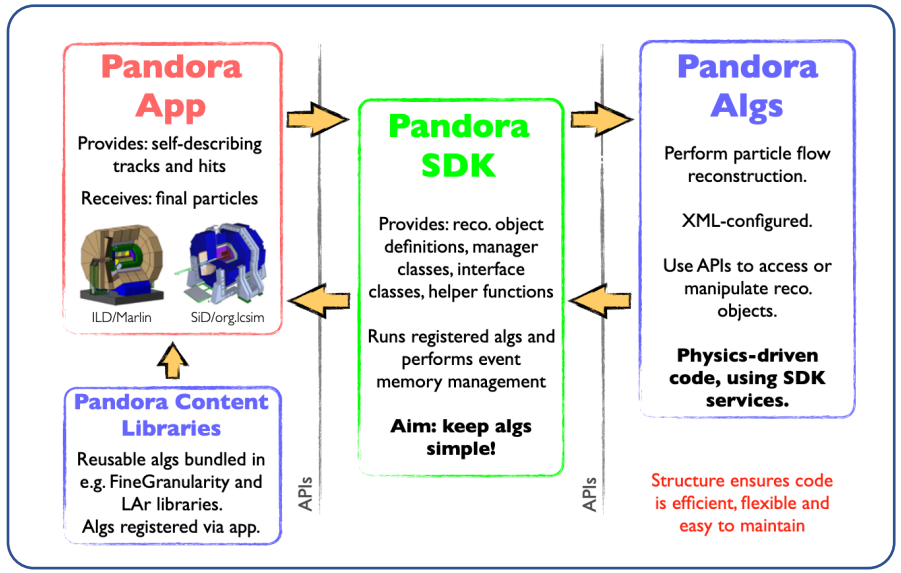
- **Unit digitization:**
  - For step i: $Q_{\pm}^{i} = E_0 \cdot e^{-\frac{L/2 \pm z_i}{L_{Atten}}}, \quad T_{\pm}^{i} = T_0 + Gaus(z_{\pm}^{i}/v, \sigma_T)$
  - For each bar: $Q_{\pm} = \sum_{step} Q_{\pm}^{i}, \quad T_{\pm} = T_{\pm}^{k} \mid (\sum_{i=1}^{k} Q_{\pm}^{i} > thres).$



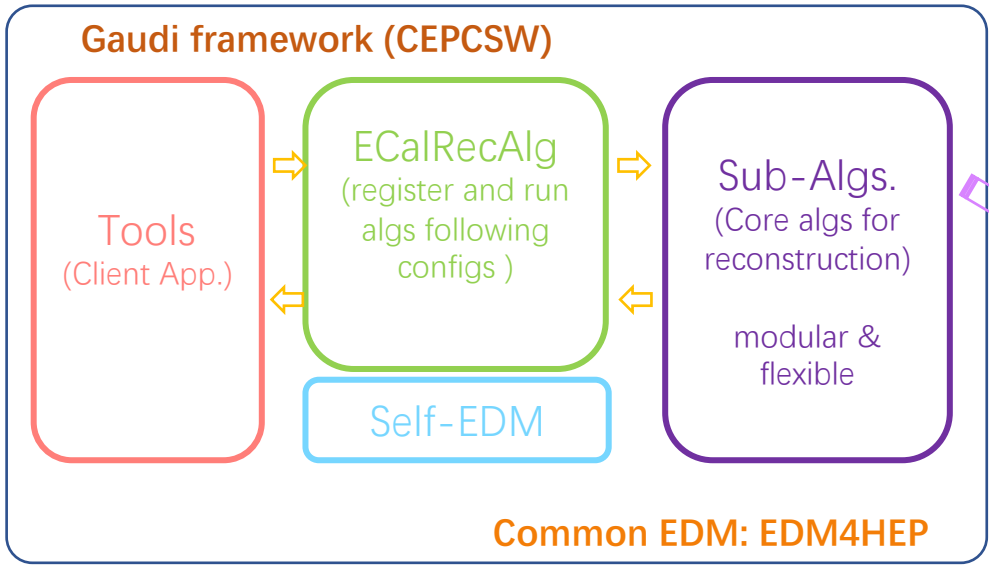


Reconstruction software

- **A proto-PFA reconstruction software for the ECAL:**
  - Follow the idea of PandoraSDK: flexible, reusable, modular.
  - Develop within CEPCSW: based on the common HEP software stack Key4HEP.



J.S.Marshall, CHEF 2013

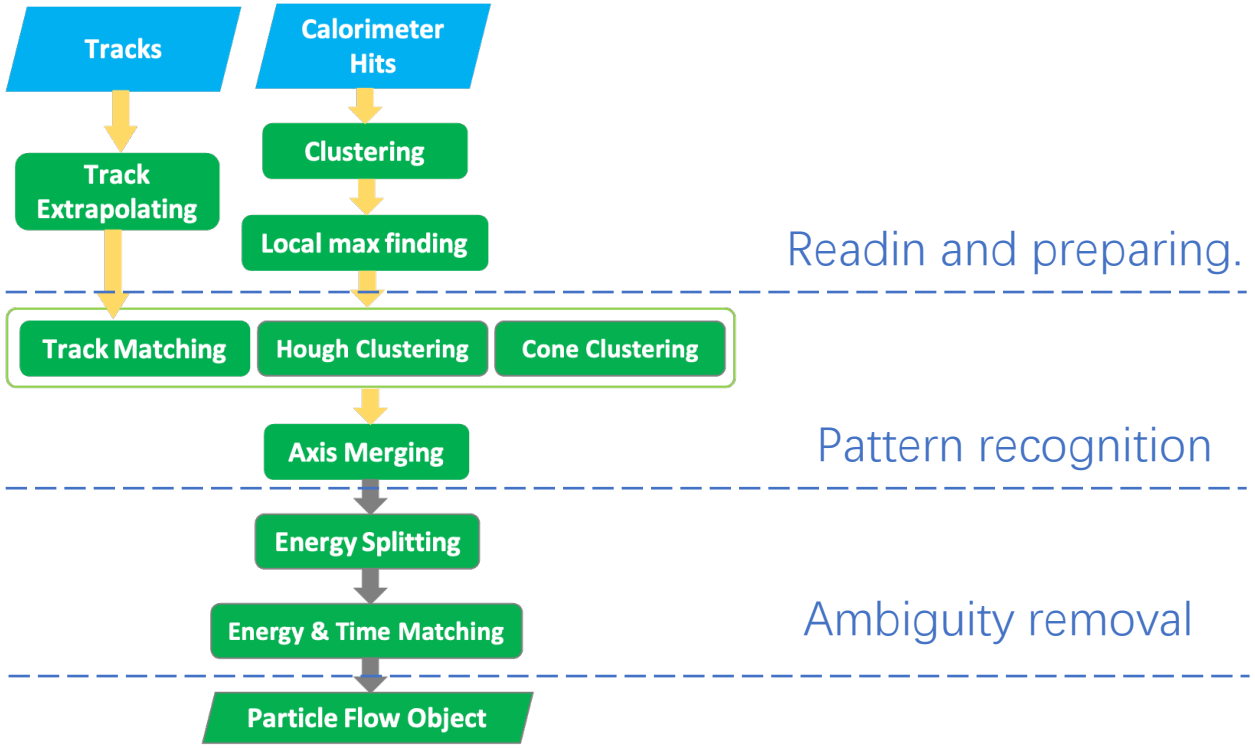


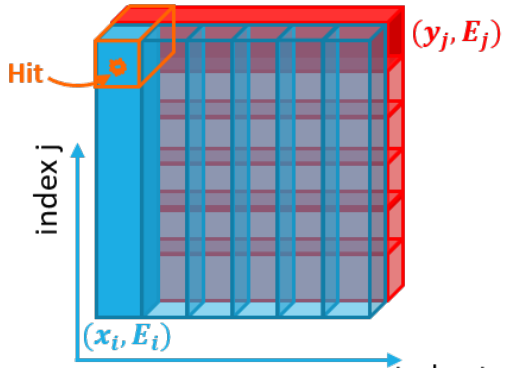
Work in progress

Reconstruction flow:
- Clustering
- Shower Recognition:
  LocalMaxFinding,
  HoughClustering,
  TrackExtrapolatin,
  TrackingMatching.
- EnergySplitting
- EnergyTimeMatching

Reconstruction software

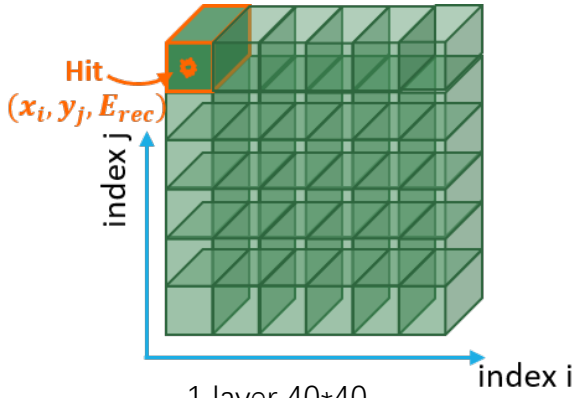
- **A proto-PFA reconstruction software for the ECAL:**
  - Combine 2 layers to mimic a high-granularity ECAL.
  - Use time + similar energy in adjacent layer for cross-location.
- **Reconstruction algorithm flow:**





2 layer 40+40
$1\times1\times40\ cm^3$
crystal bars

Reconstruction



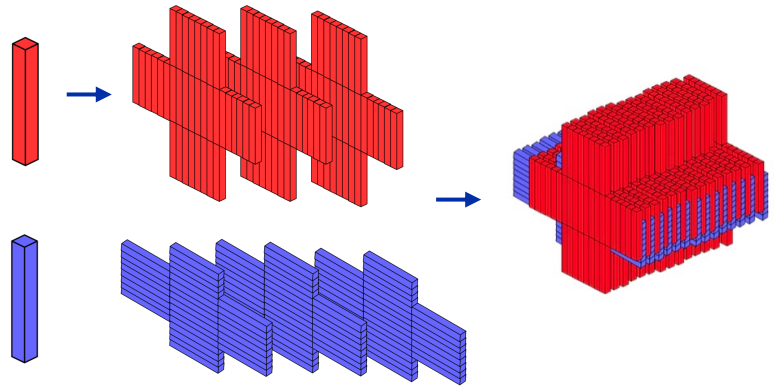
1 layer 40*40
$1*1*2\ cm^3$ cells

Reconstruction software

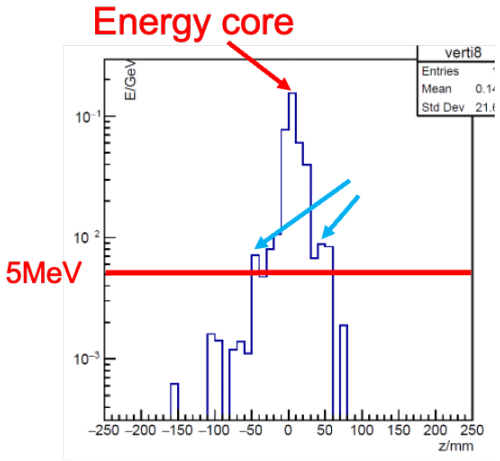
Weizheng Song, IHEP

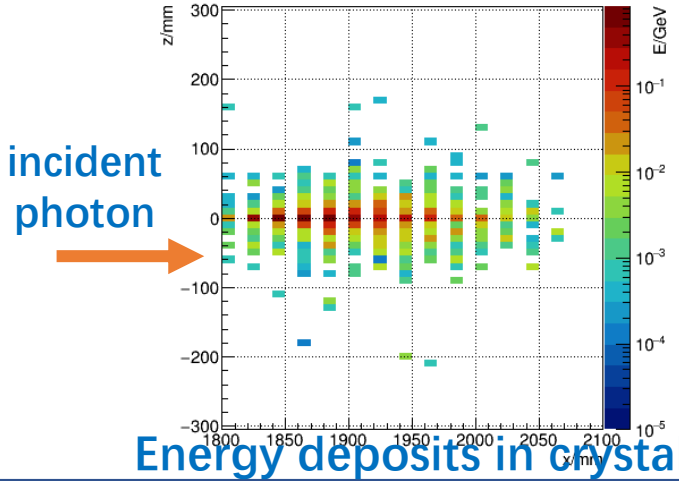
- **Global clustering**
  - Neighbor clustering based on geometry.
    - Define “neighbor” for each EDM with:

      template<T1, T2> StatusCode Clustering();
  - Vertical and horizontal units are clustered respectively.

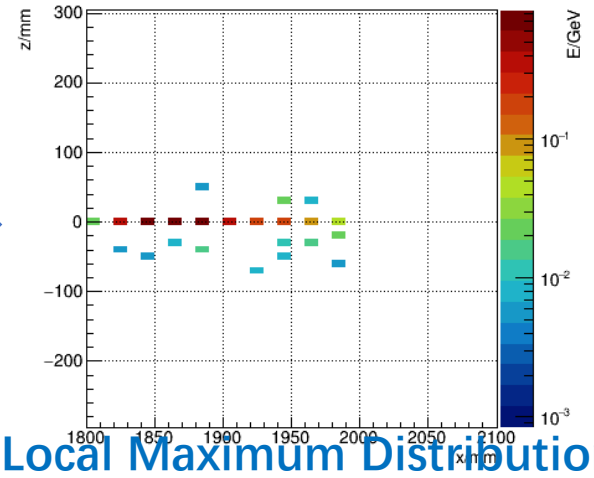


- **Local maxima finding**
  - Recognize energy core in this homogeneous crystal ECAL.





Energy deposits in crystals



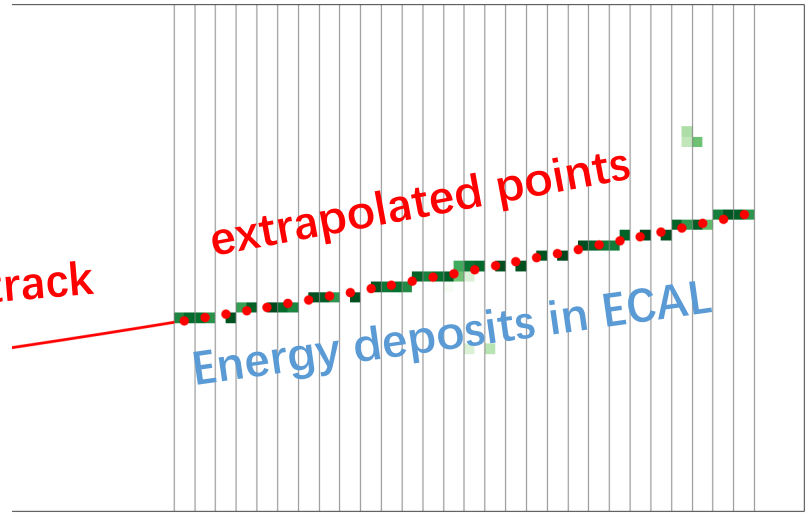
Local Maximum Distribution

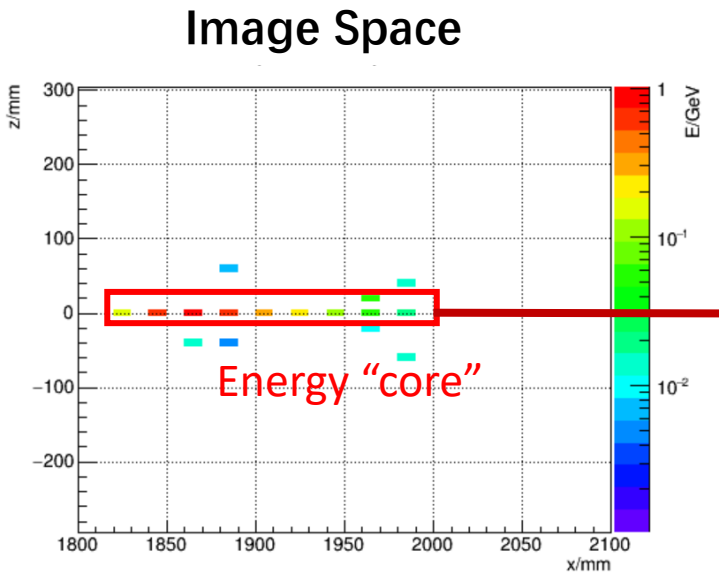
Reconstruction software

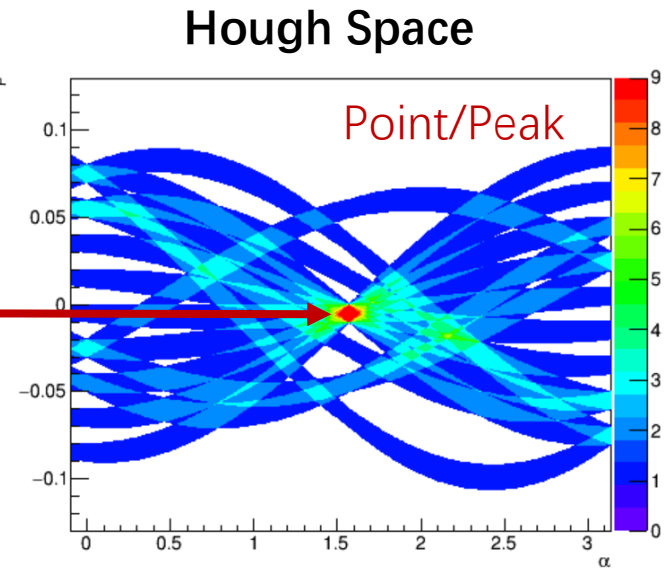
Yang Zhang, IHEP

- **Shower recognition:**
  - Charged particle: track-match.
  - EM shower: Hough transformation.
  - Fragment: cone-clustering.

Controlled with AlgorithmManager: flexible to implement new algorithms.

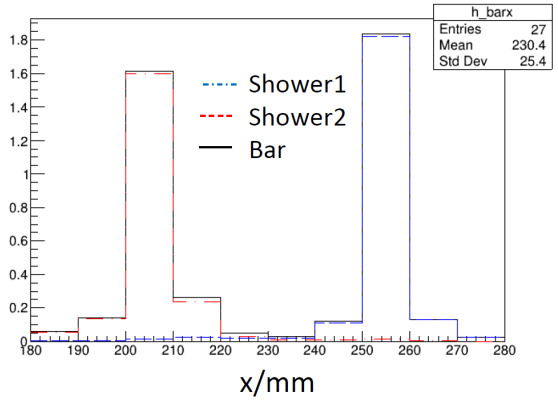




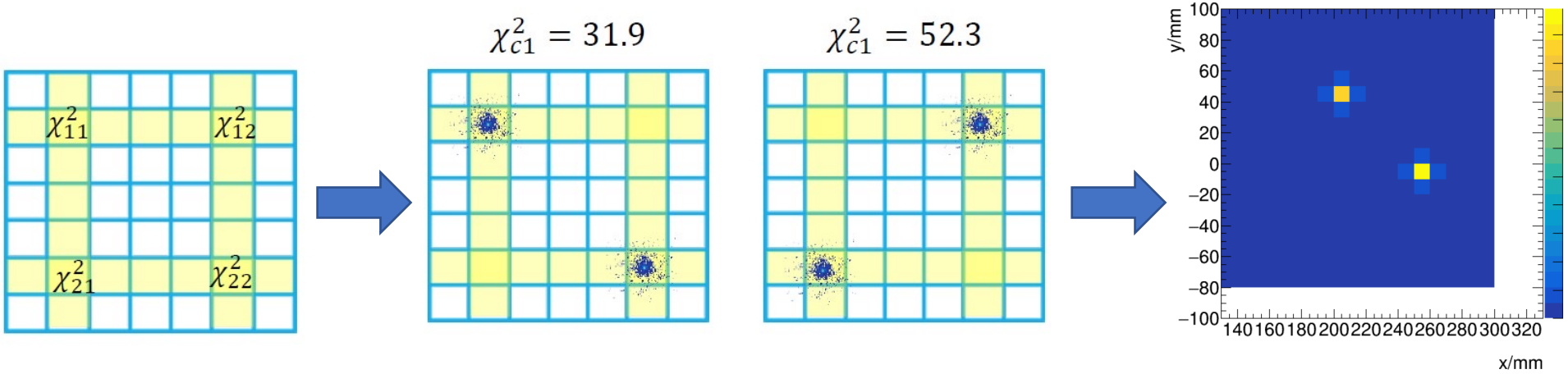


Reconstruction software

- **Energy splitting and pattern matching:**
  - Larger R_M for crystal ➡ severer shower overlap ➡ shower splitting.
  - Calculate the expected energy deposition from EM profile.
    - Expected energy $E_{i\alpha}^{exp} = E_{seed\,\alpha} \times f(x)$,
    - Assigned weight $w_{i\alpha} = E_{i\alpha}^{exp} / \Sigma_\alpha E_{i\alpha}^{exp}$

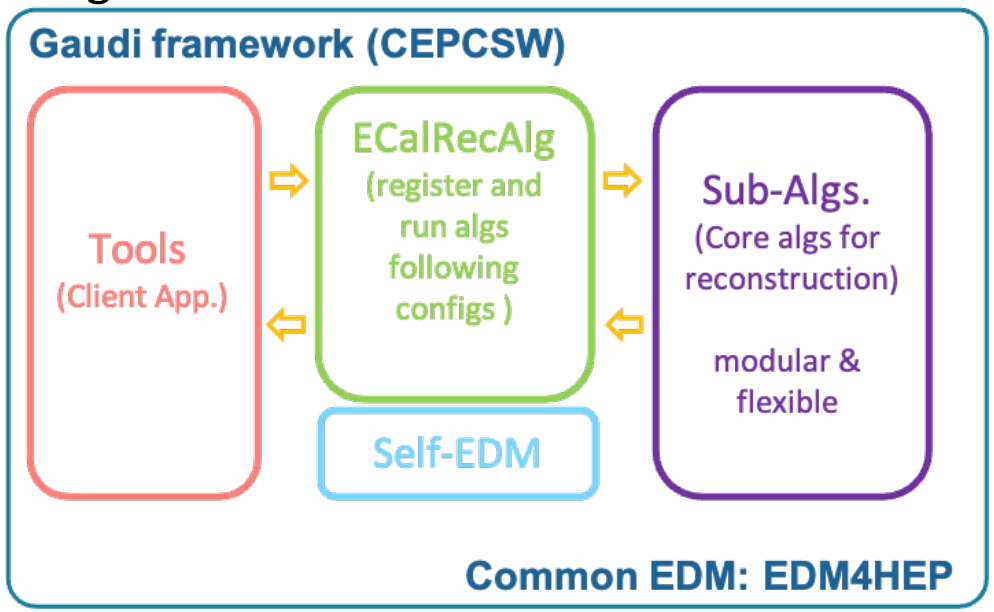


- **Orthogonal bar to granular hit:**
  - Combine U/V info, split the bar with adjacent layer profile. Ghost-hit problem!
  - Define χ^2 value with energy and time info to reject the wrong combination.



Reconstruction software

- **Software configuration**
  - **Self-EDM**: CaloUnit (bar), 1D/2D/3DCluster, HalfCluster, Track, etc.
  - **Client App**: manage input/output objects, e.g. MCParticleCreator, CaloHitCreator,
  - **Algorithm Manager**: Register and run algorithms.



Algorithm 2: 重建算法 EcalRecAlg

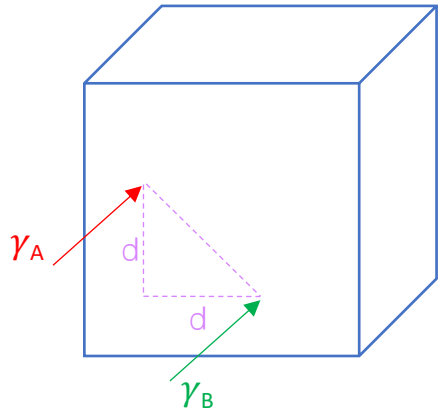
Input: 数字化后晶体条 edm4hep::CalorimeterHitCollection;

Output: 重建后的粒子流对象 PFO
（edm4hep::ReconstructedParticleCollection）

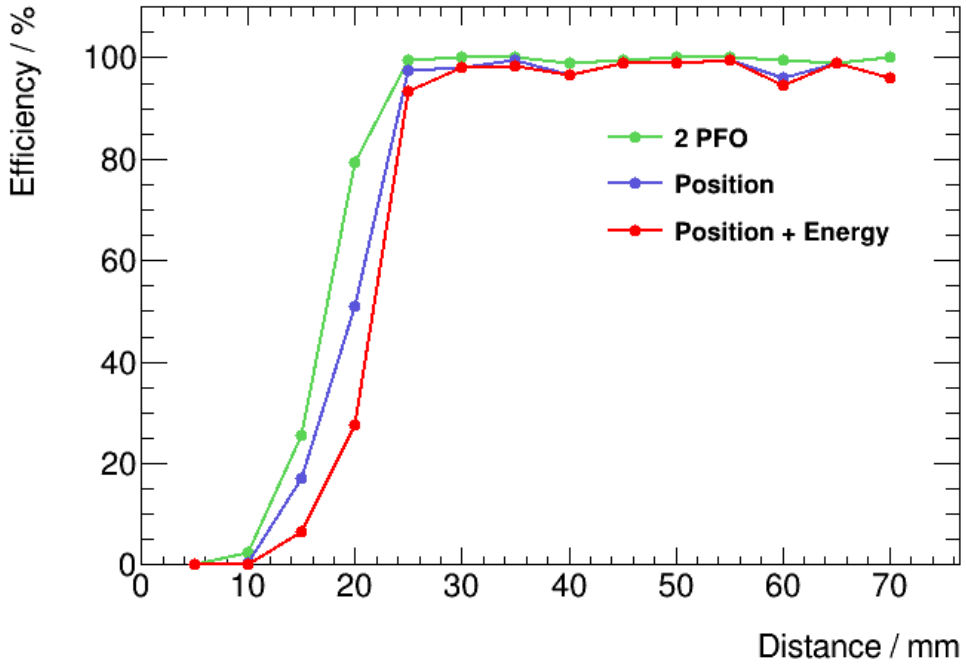
初始化：设置全局参数 GlobalSettings；
初始化：初始化接口函数 ObjectCreators，从配置文件中读取对象名,；
初始化：算法管理函数 AlgorithmManager 注册算法；
初始化：AlgorithmManager 配置算法调用顺序，从配置文件中为每个算法配置执行参数；
初始化：初始化几何服务 GeoService、探测器解码器 Decoder；
初始化：注册分析文件 ntuple；
foreach Event **do**
    ObjectCreators 读取对象数据，暂存在 DataCol；
    AlgorithmManager 按配置调用算法执行计算，结果储存进 DataCol；
    OutputCreater 读取 DataCol 中数据，写出重建后对象 ReconstructedParticleCollection；
    写入 ntuple；
    DataCol 清空内存；
写出所有数据，清空内存；

Reconstruction software

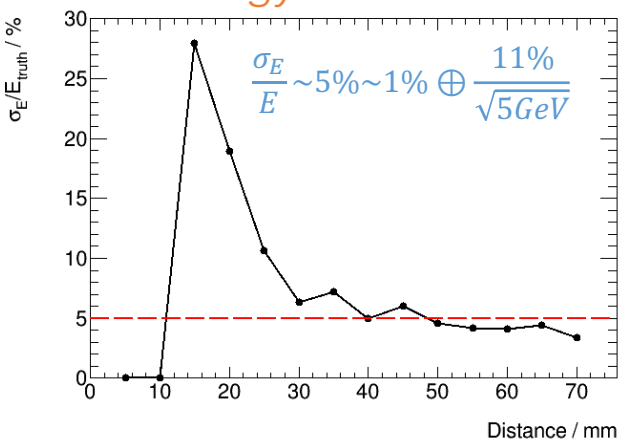
- **Preliminary performance**
  - Particle gun events simulation for two 5GeV photons in parallel.
  - Scan the distance between photons, check the successful reconstruction efficiency and energy resolution. **Key for PFA.**



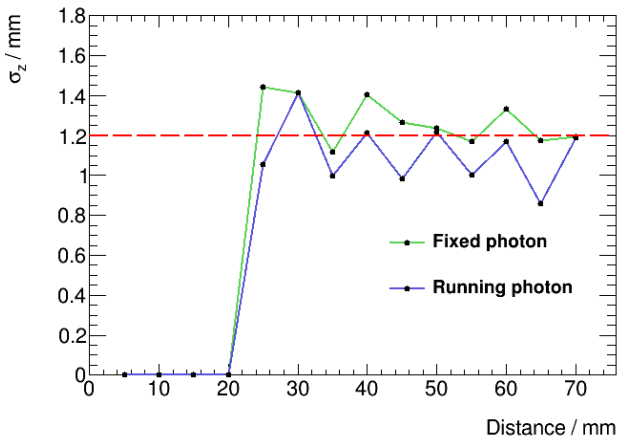
Separation efficiency



Energy resolution



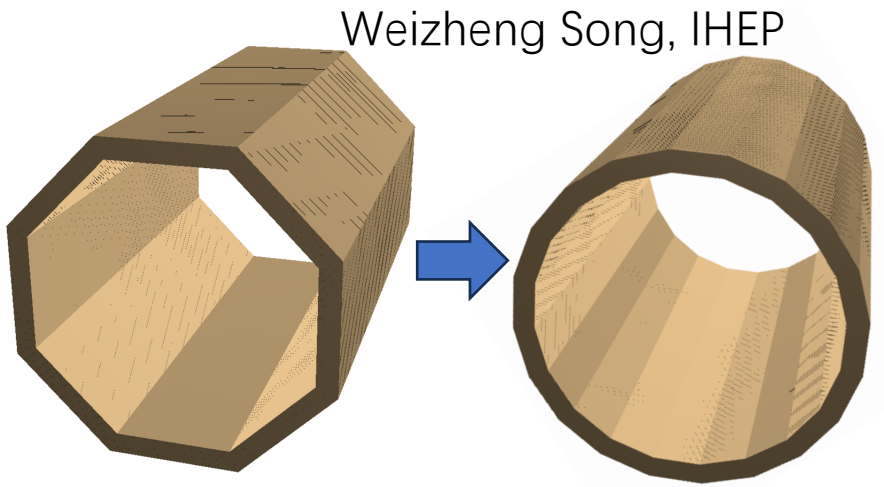
Position resolution



Cylindrical ECAL geometry

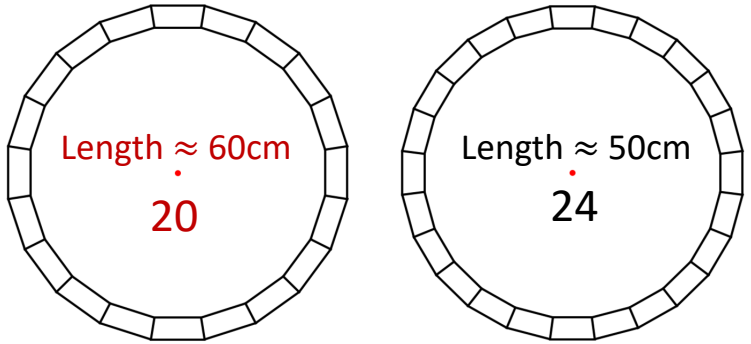
- **New geometry option: cylindrical ECAL**
  - Decrease the outer radius, reduce HCAL budget.
  - Consider the cracks and supporting.

Ideal ——– – – – – – – → Real



- **Geometry description with DD4HEP**
  - Configurable with xml: bar length, module number, dead space, etc.

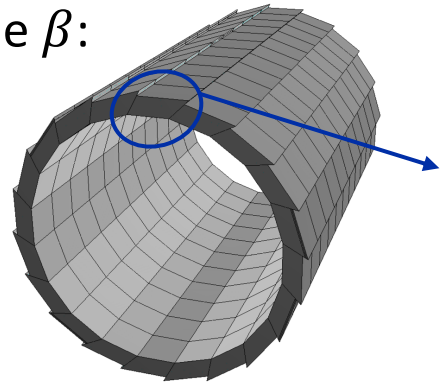
```
<define>
  <constant name="ecalbarrel_inner_radius"        value="Ecal_barrel_inner_radius"/>
  <constant name="ecalbarrel_thickness"           value="Ecal_barrel_thickness"/>
  <constant name="ecalbarrel_zlength"             value="Ecal_barrel_half_length*2"/>
  <constant name="ecalbarrel_crystal_size"        value="15*mm" />
  <constant name="ecalbarrel_phimodule_number"    value="20" />
  <constant name="ecalbarrel_Zmodule_number"      value="11"/>
  <constant name="ecalbarrel_module_ratation"     value="15*degree" />
  <constant name="ecalbarrel_length_deadspace"    value="8.5*mm"/>

</define>
```



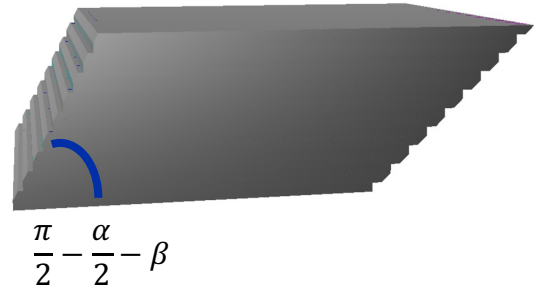
Cylindrical ECAL geometry

Weizheng Song, IHEP

- **Preliminary simulation:**
  - Study the impact of crack region and module rotate angle β:
    - $\beta = 0$: cracks towards the IP.
    - Larger β: larger R_{outer}.
  - Check energy leakage with single photon events:
    - 10 GeV, $\phi \in [0°, 360°]$.

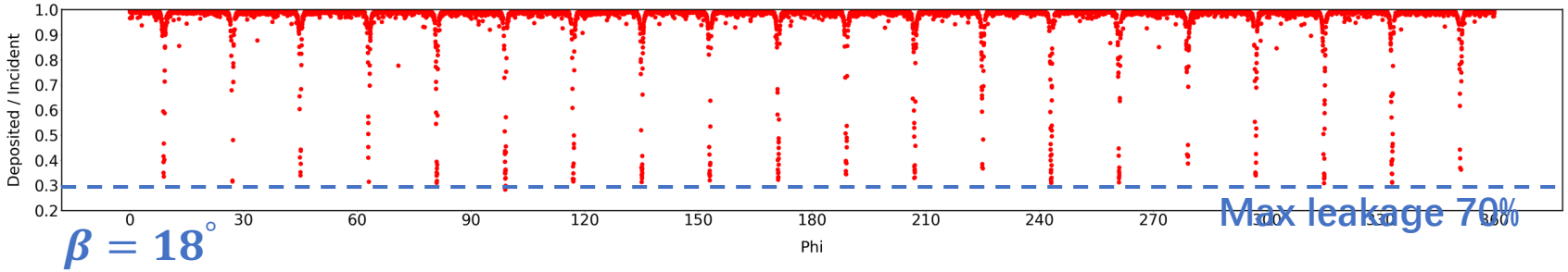


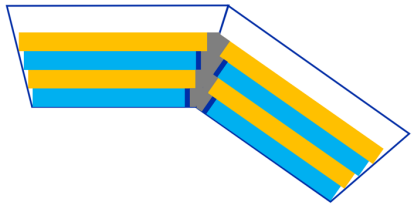
module



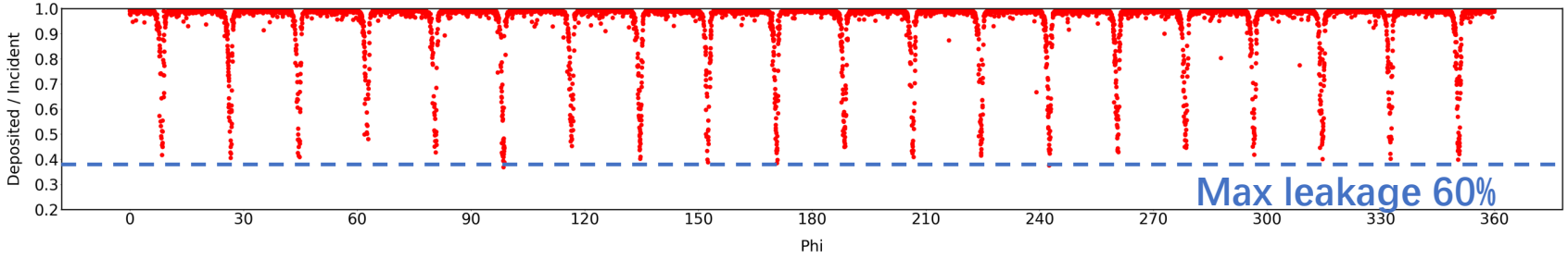
$\frac{\pi}{2} - \frac{\alpha}{2} - \beta$

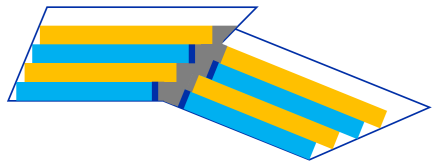
No tilt ($\beta = 0°$)





$\beta = 18°$





Summary

- **Crystal bar ECAL is a novel and challenging ECAL design.**
  - Detector geometry description is constructed with DD4HEP.
    - Configurable cylindrical ECAL geometry is built for optimization.
  - Digitization and reconstruction software are developed within Gaudi framework.
    - Addressed several pattern recognition algorithms with full 5D info (x, y, z, E, T) is processing.
    - Flexible and modular proto-PFA software is on-going. More individual algorithms are expected to be independently developed and easily implemented.
  - Next: performance test.
    - Shown preliminary result for the separation.
    - Targeting the full PFA reconstruction and CEPC physical benchmark: Boson Mass Resolution.