Electromagnetic calorimeter simulation for the LHCb Upgrade II

CLHCP 2021

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■ Outline

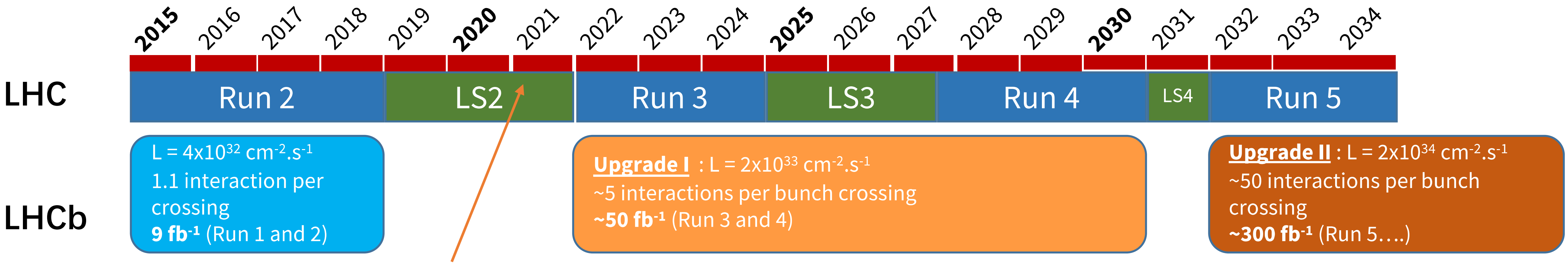
1. Introduction

2. ECAL scheme
    - SPACAL detector
    - Si-W detector
    - SPACAL-SiTiming

3. Performance study

4. Summary and outlook

■ LHCb Upgrades



- Currently ‘Upgrade I’ is under installation and commissioning, and is the next challenge for LHCb
- Upgrade II is another major upgrade planned for 2032:
  - since LS3 will be a long stop (3 years), some of the upgrade II activities may be advanced to 2025 = Upgrade Ib

■ Introduction

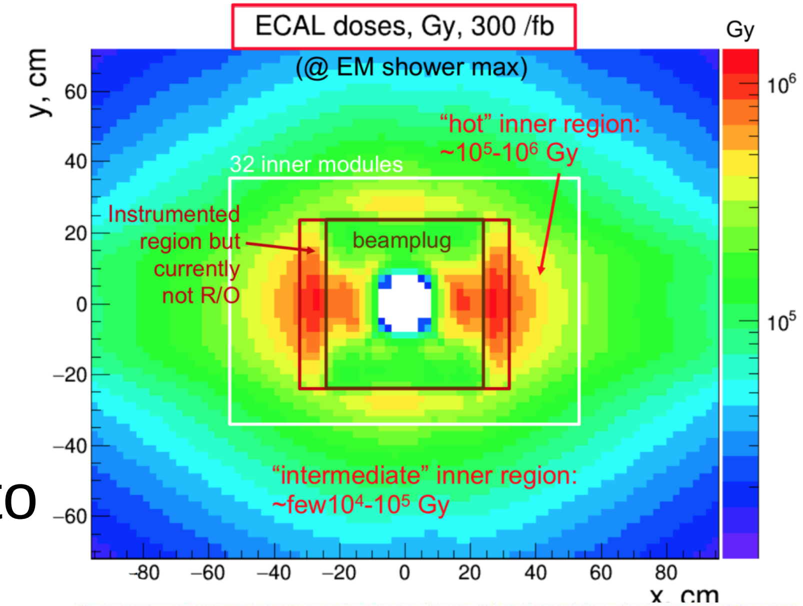
Why we should Upgrade :

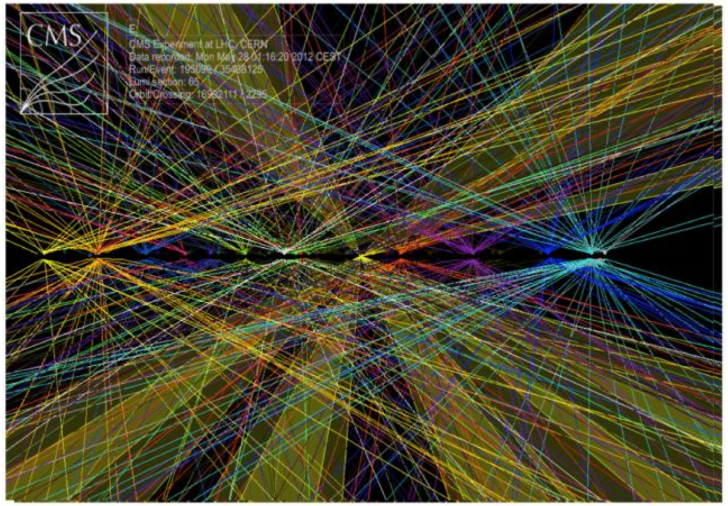
◆ Some hints of New Physics in LHC Runs 1 & 2

◆ High Luminosity up to $1.5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ is desired to achieve the precision to probe new physics

- Upgrade is needed for the challenges of serious pile-up and radiation damage at high lumi

ECAL upgrade is very important



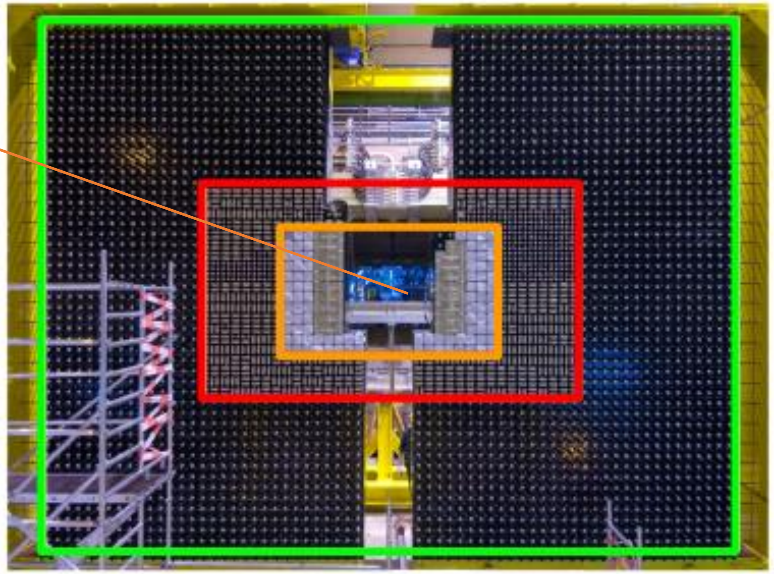


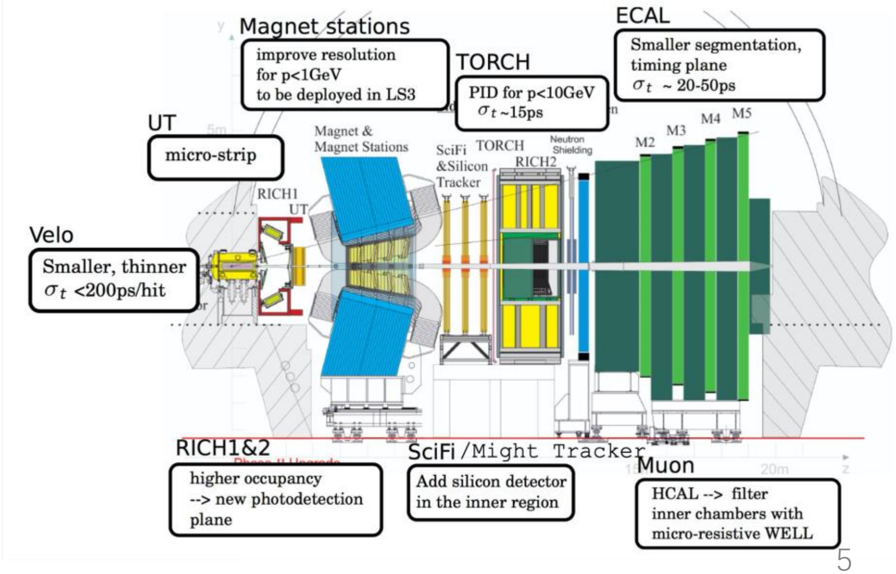
■ Calorimeter

◆Calorimeter in Upgrade Ib & II :

- HCAL will be removed
- Electromagnetic Calorimeter essential for physics program
- Current ECAL modules will have to be replaced in the most inner part for Upgrade Ib because of radiation damages
- Small the Moliere Radius and X0 of the material

Inner part



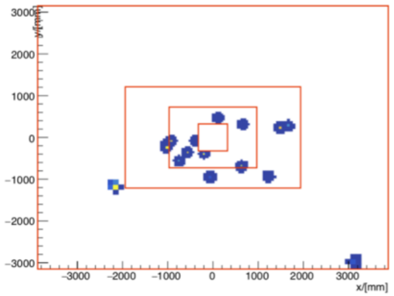


■ Requirements of ECAL upgrade

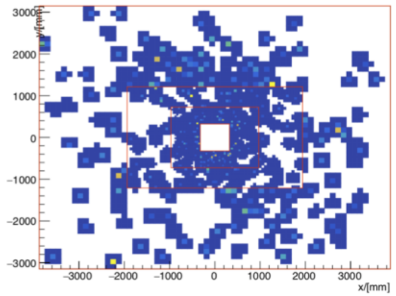
Requirements :

- Better energy and position resolution
- Radiation resistance
  - To deal with the high radiation
- Precision time information
  - To deal with the pile-up
- High granularity
  - To reduce the occupancy due to the high luminosity

Present $L = 2\times10^{32} cm^{-2}\cdot s^{-1}$

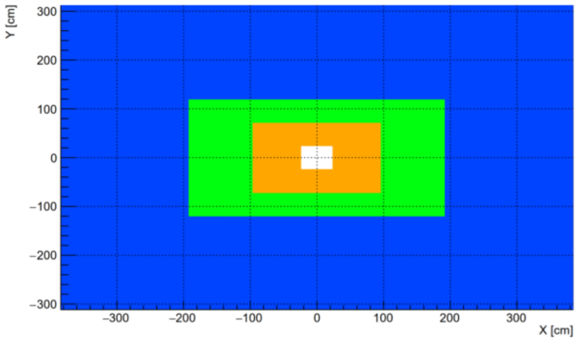


Upgrade II with $L = 1.5\times10^{34} cm^{-2}\cdot s^{-1}$

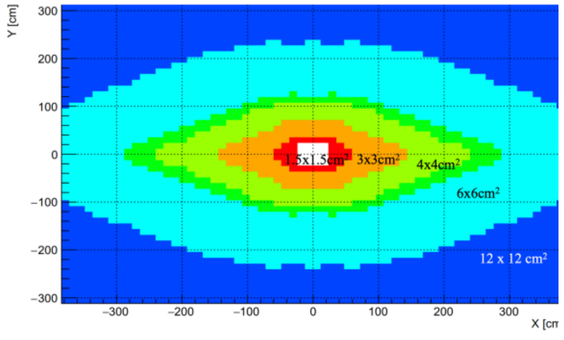


Current geometry:

Cell size



Upgrade 2

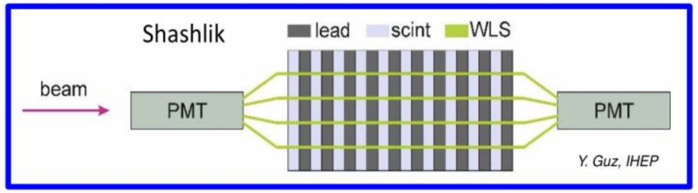


■ ECAL proposal for Upgrade II

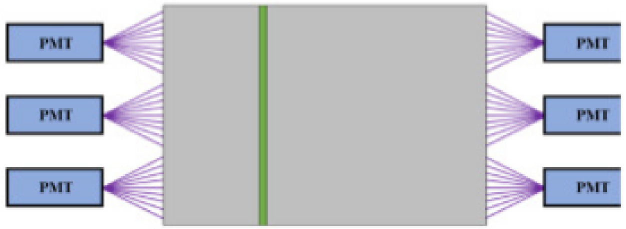
The FTDR is under LHCC review

◆Refurbish current Shashlik modules, adding double readout and faster wavelength shifting fibers

Shashlik



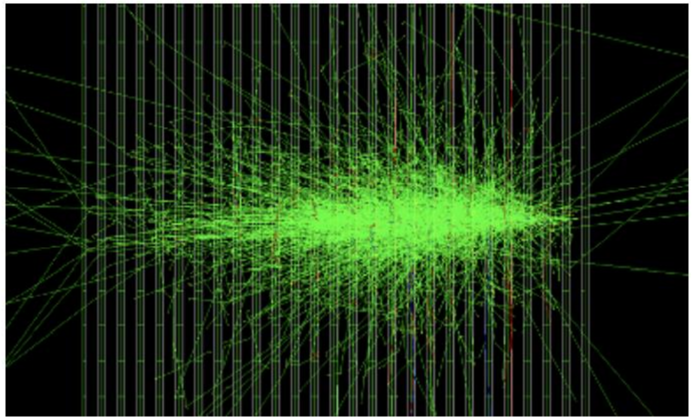
◆SPACAL modules, reading light from scintillators directly, with longitudinal segmentation



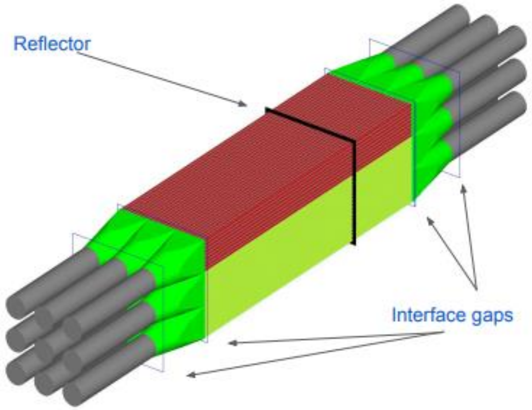
◆Si-W modules containing 26 layers of tungsten as absorber, interleaved with 26 silicon layers as the active material

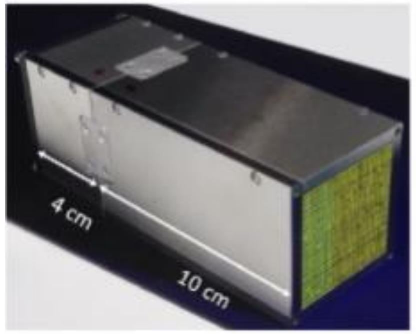
◆Mixture modules to take advantages from different modules by mixing them

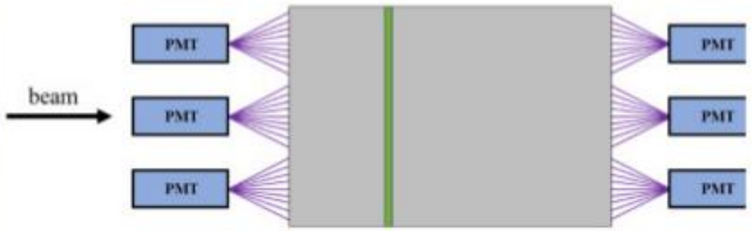
What we are interested in

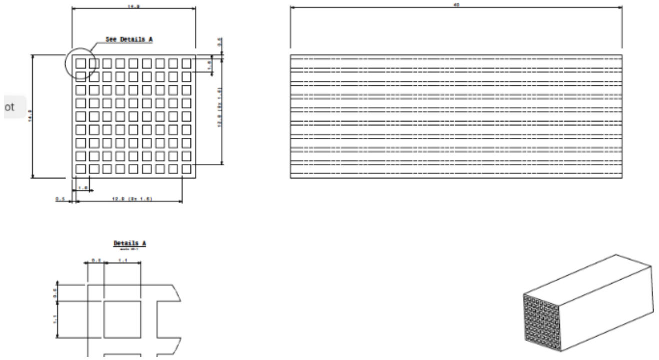


■ Pure SPACAL Detector





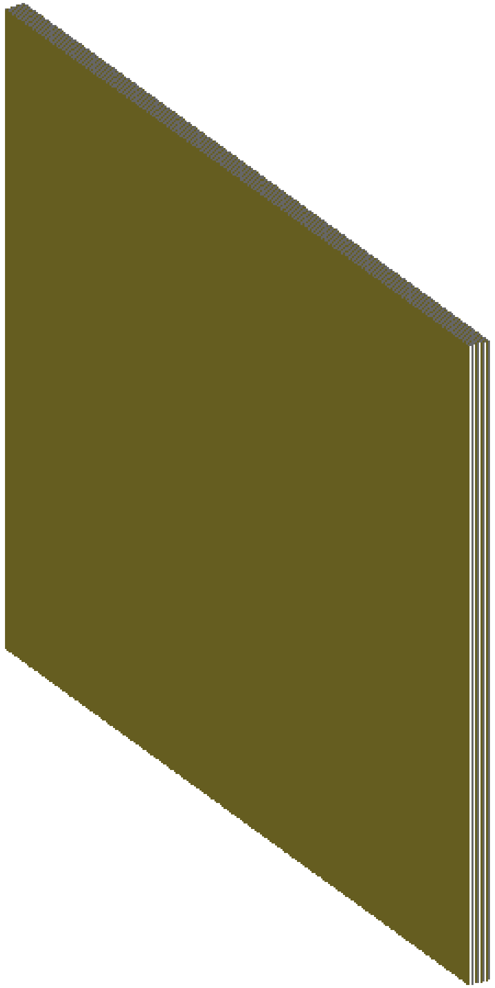


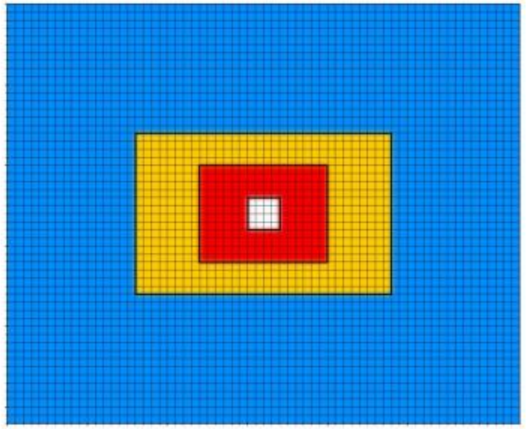


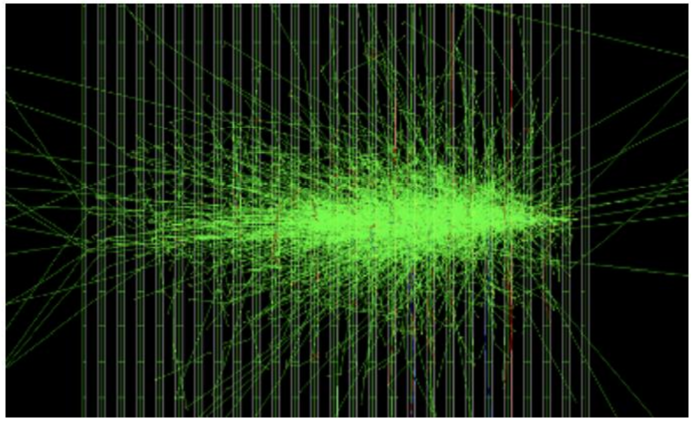
◆Spaghetti Calorimeter (SPACAL) , a detector consists of scintillating plastic fibers embedded in a lead matrix. And the signal will be amplified and readout by PMT located at both ends of the detector.

- Great performance both in time and energy resolution
- But due to the large Moliere radius, a very small cell size cannot be achieved.

■ Pure Si-W Detector



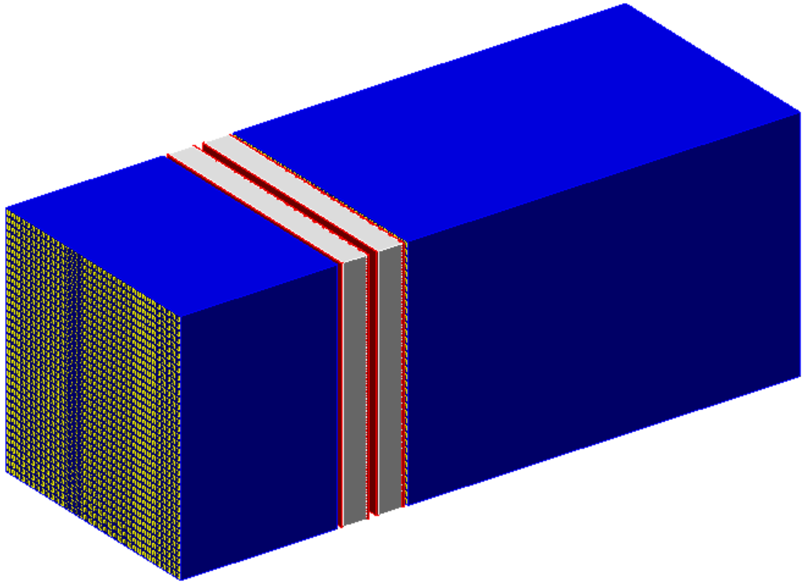


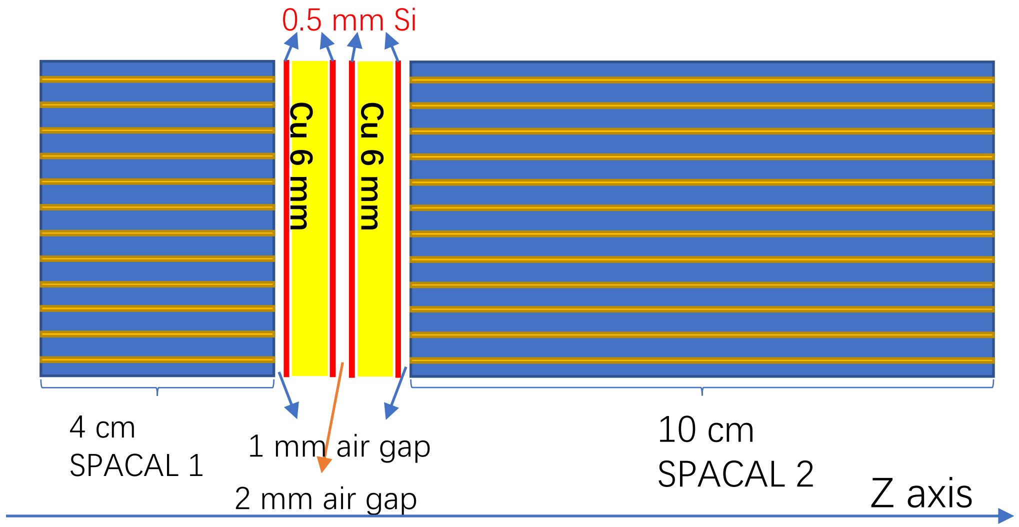


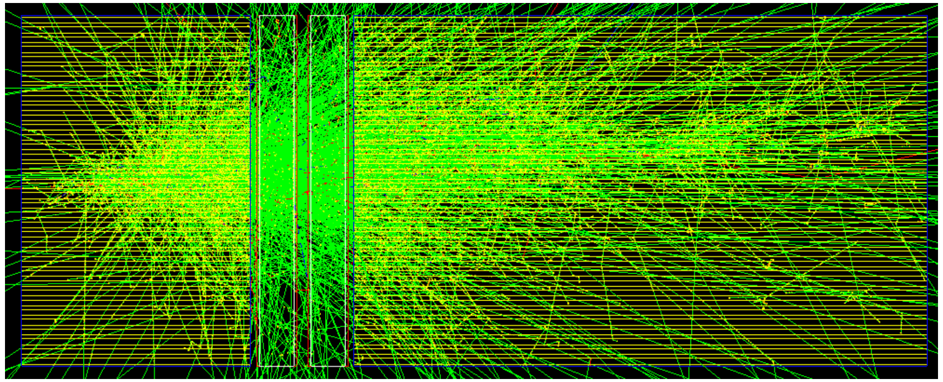
◆Greater granularity performance

- This technique was adopted by CMS for the CMS phase-2 upgrade endcap calorimeter called HGCAL (High granularity Calorimeter).
- A lot of R&D activities are carried out because the HLLHC introduces challenges in radiation resistance and good time resolution.
- CMS HGCAL beam test show promising results of the prototype silicon modules .
- The energy resolution will be worse when the silicon layer number is too small. But large layer number means huge cost.

■ SPACAL-SiTiming Detector





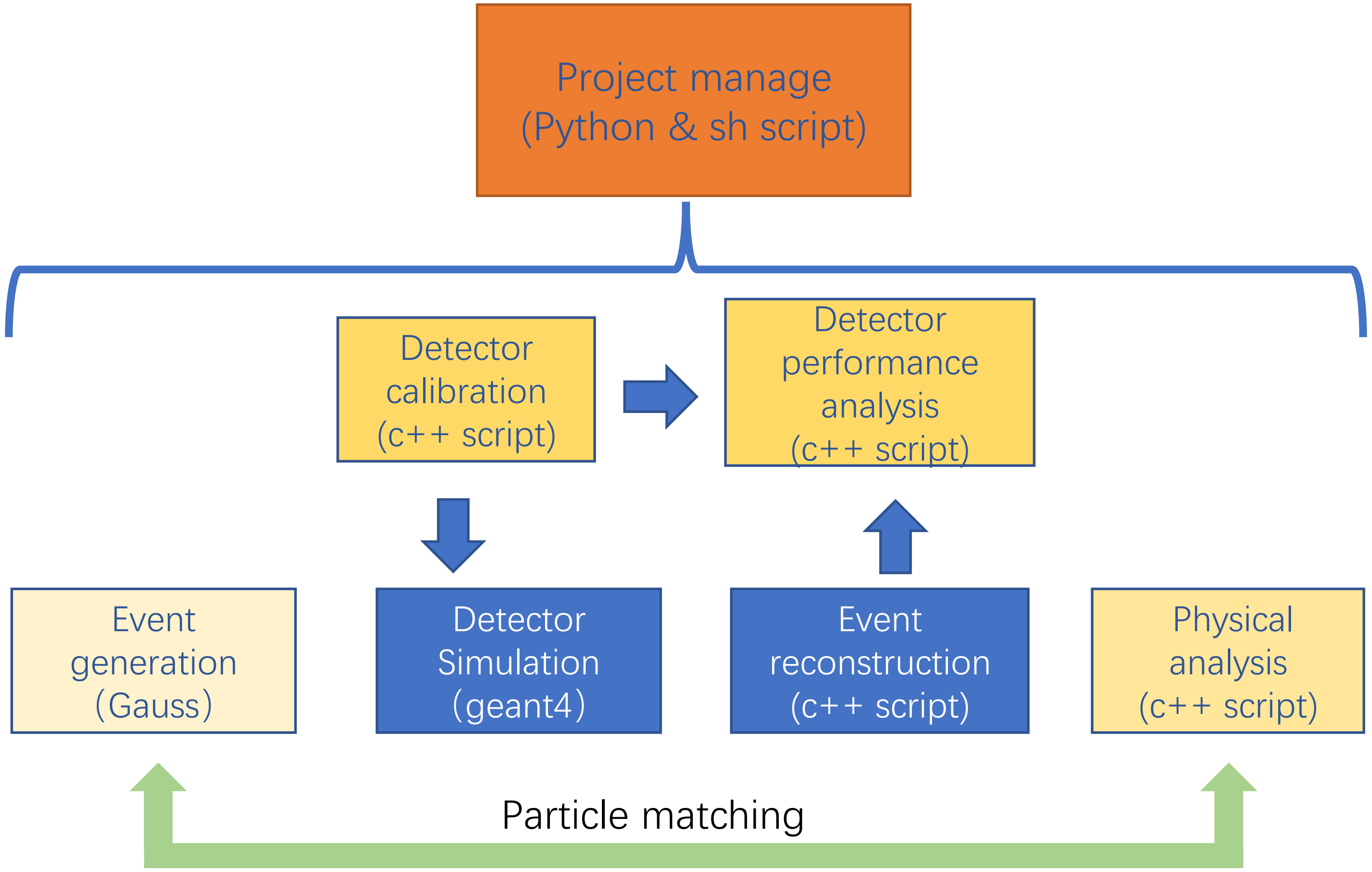


◆Feasible scheme taking into account both time energy resolution and high granularity

- Cost of the pure silicon detector with 26 layers is too expensive to afford.
- We can carry out research on the basis of SPACAL people without from sketch.
- Adding Silicon Timing layer in SPACAL Detector is a natural way for us to try to get better performance.

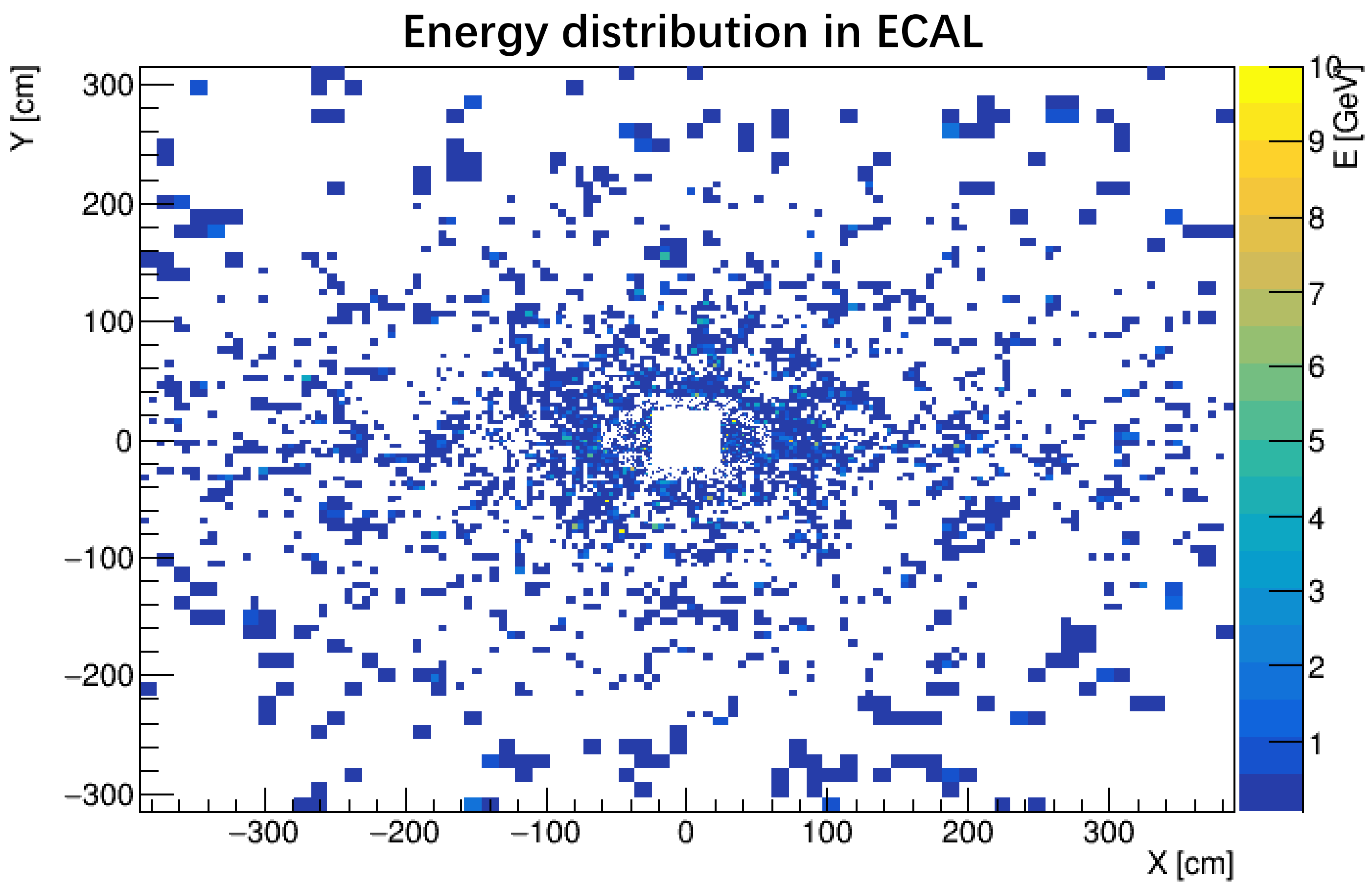
■ Simulation study framework

- ✓ Event generation
- ✓ Simulation software
- ✓ Detector performance study
- ✓ Calibration and reconstruction algorithm
- ✓ Physical channel analysis script



■ Performance to be studied

- Energy resolution
- Position resolution
- Time resolution
- Physical channel performance



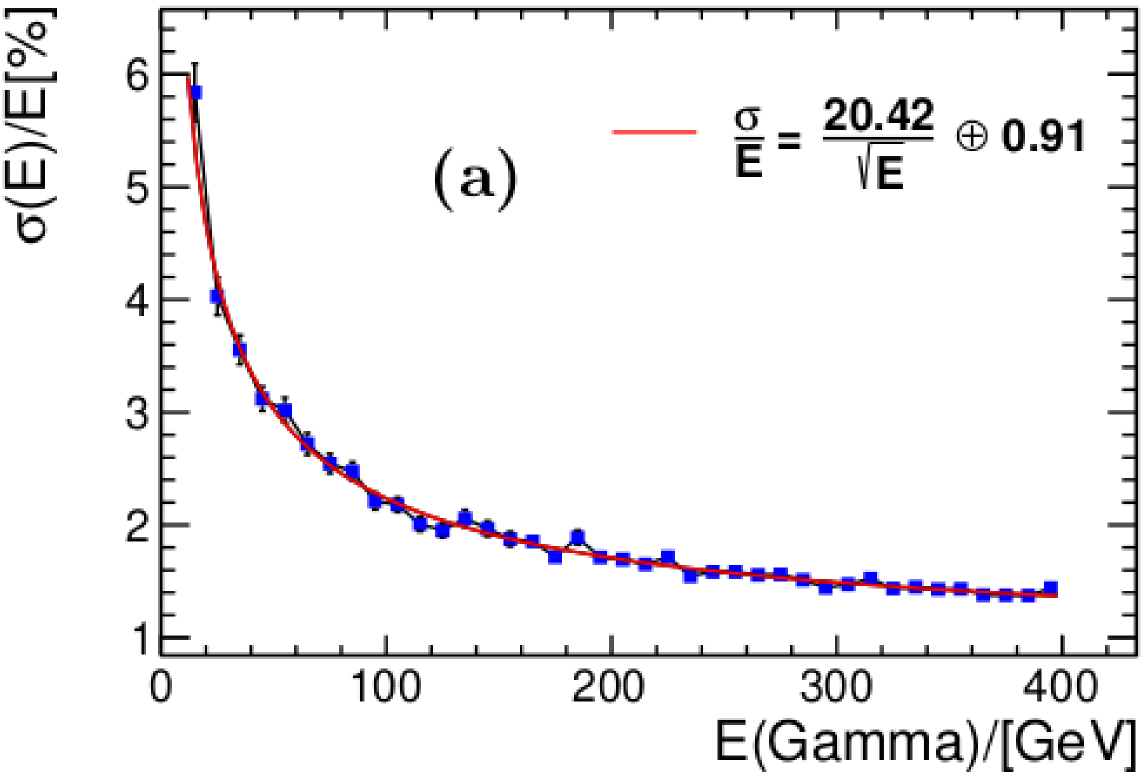
■ Simulation result

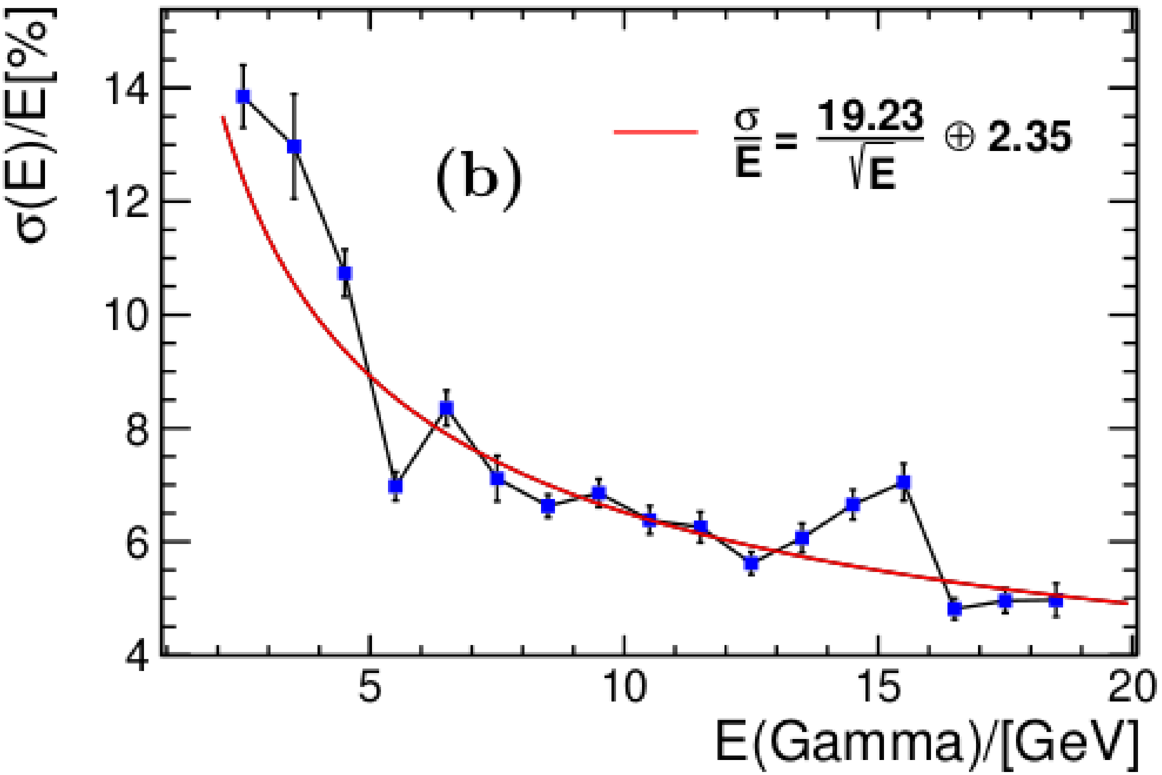
Some simulation result for Si-W and SPACAL-SiTiming will be shown

■ Energy resolution for pure Si-W

The energy resolution close to 8% at 5 GeV and 1.5% when large than 100 GeV

Silicon Cell size : 1 cm^2

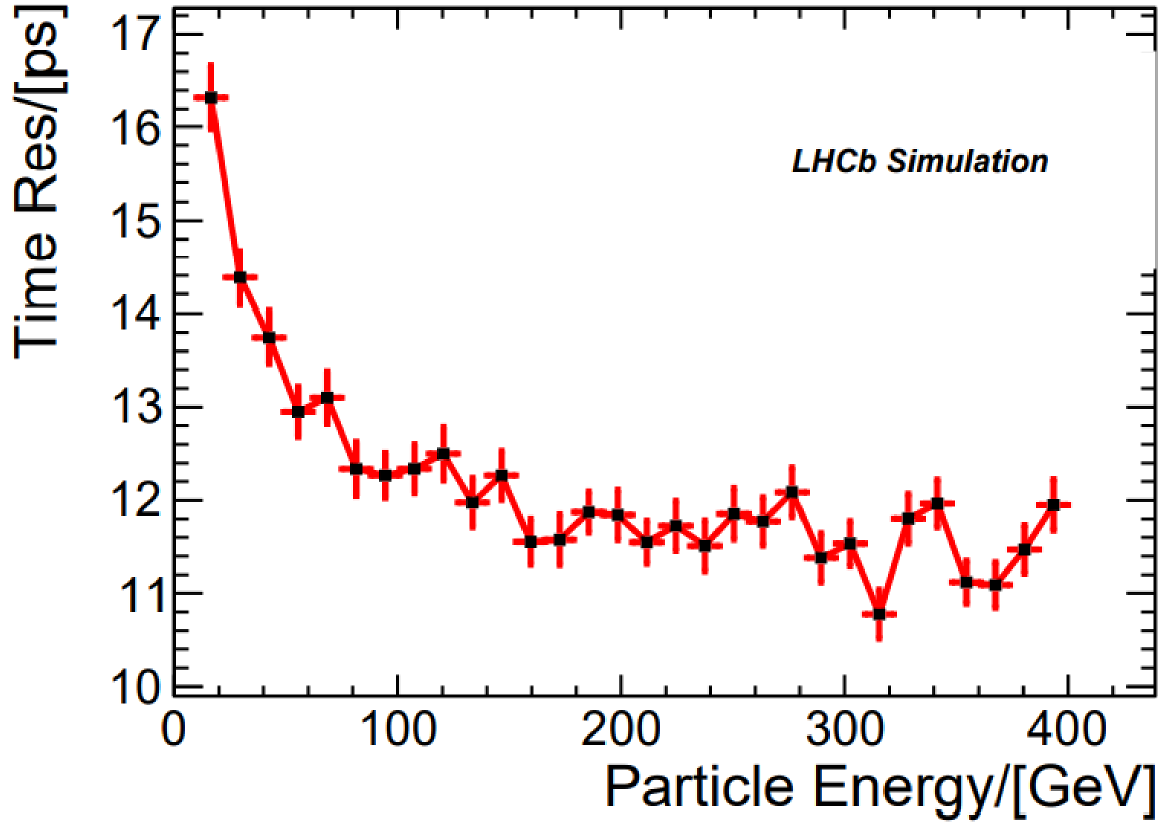


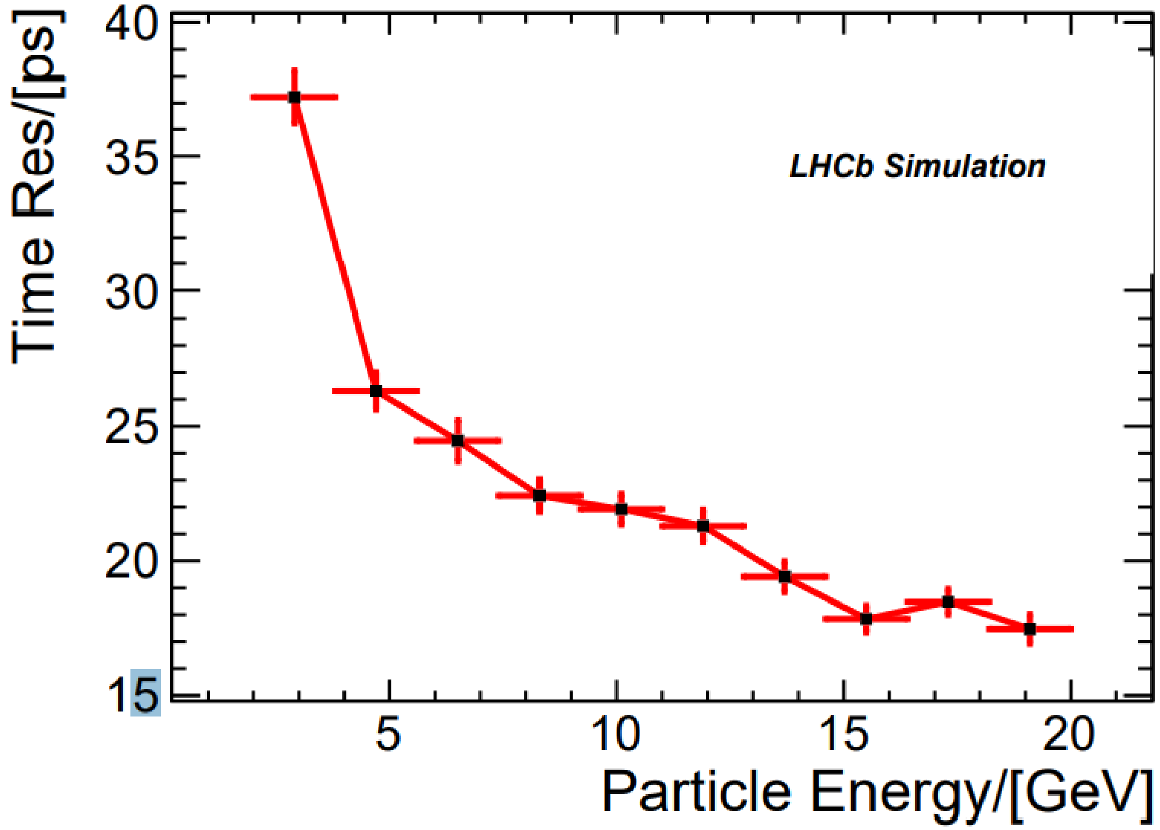


■ Time resolution for Pure Si-W

The time resolution close to 27 ps at 5 GeV and less than 12 when large than 100 GeV

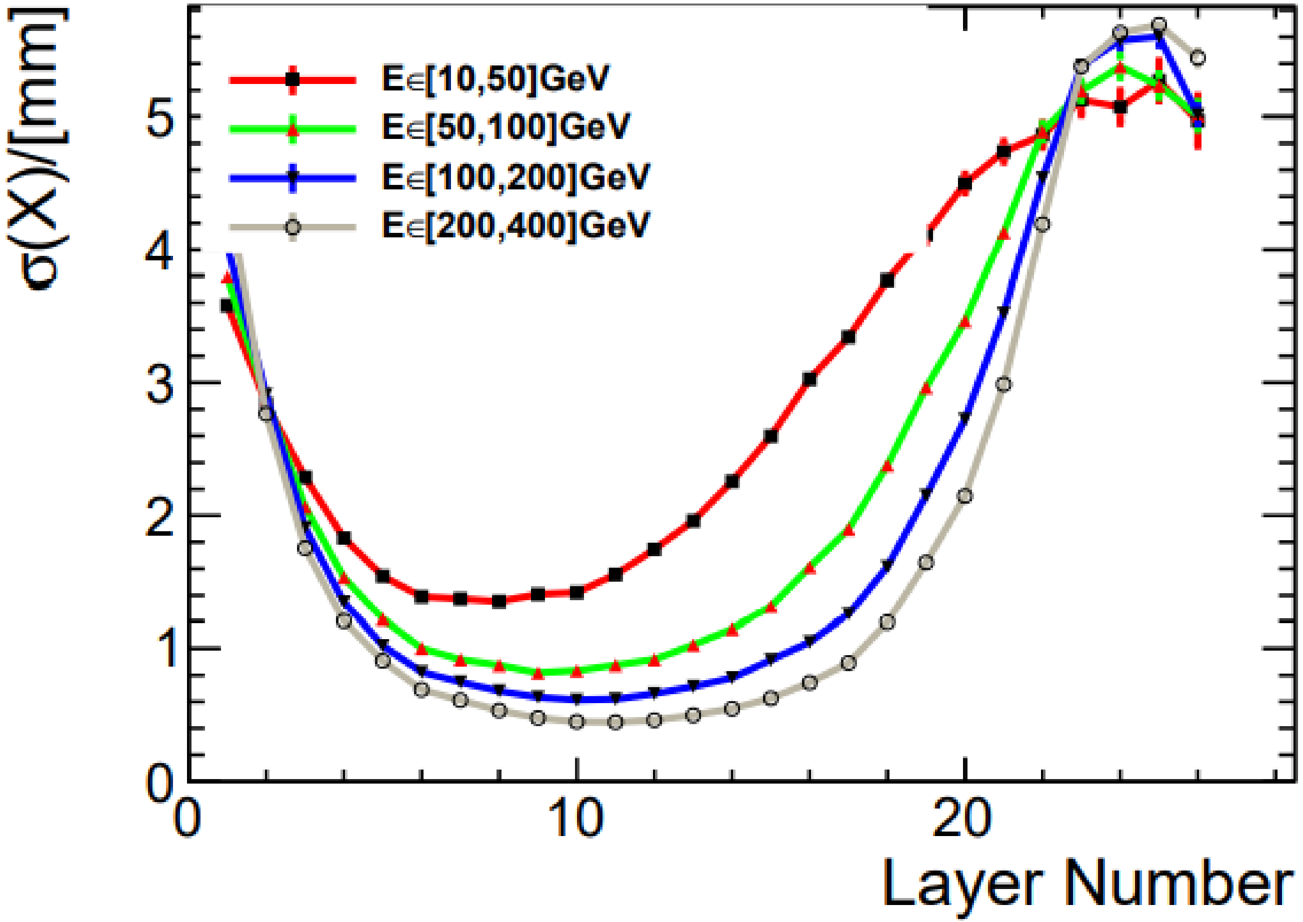
Silicon Cell size : 1 cm^2





■ Position resolution versus Layer Number for Pure Si-W

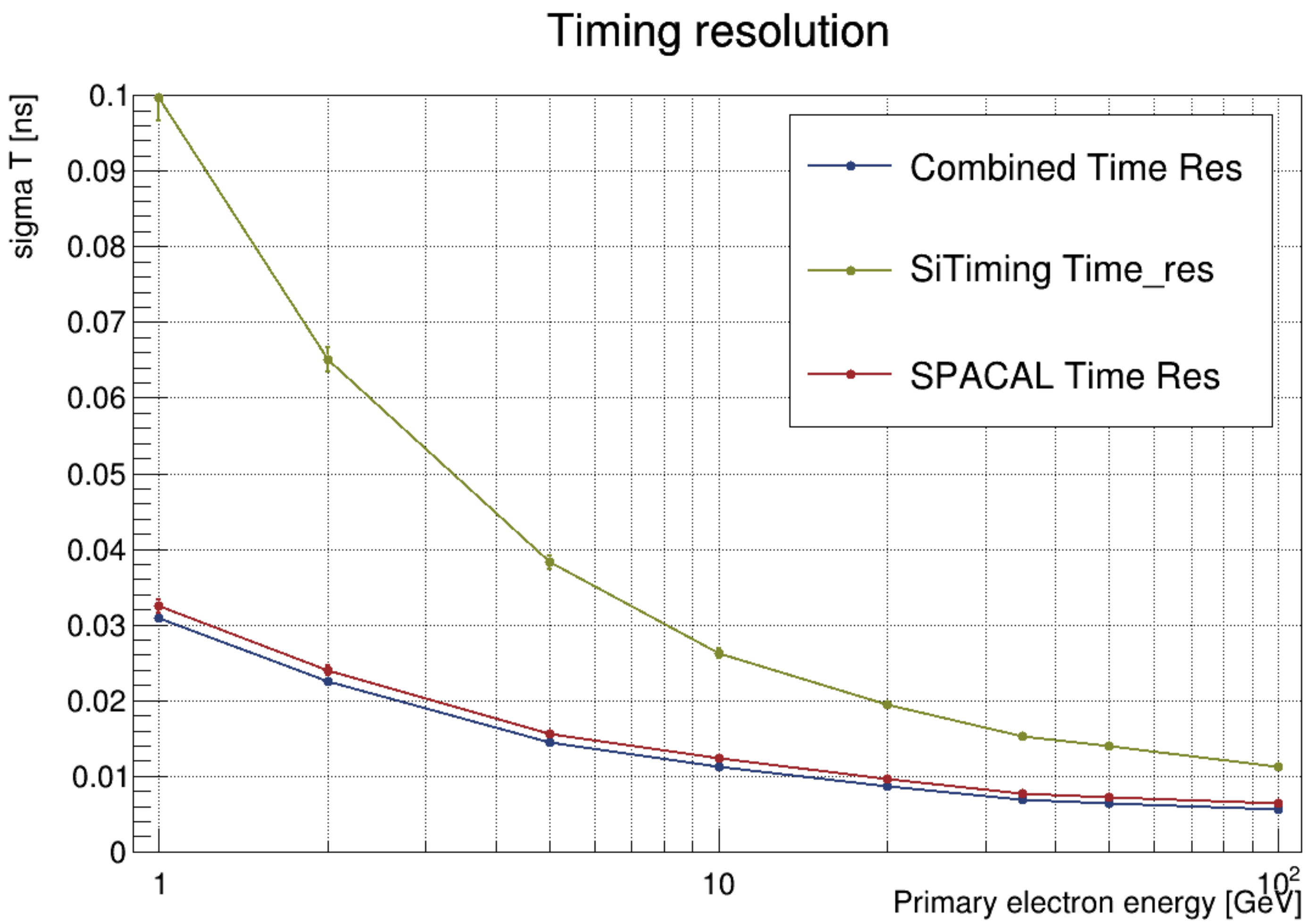
Position resolution



Silicon Cell size : 1 cm^2

The silicon can get great position resolution in the $1cm^2$ cell size with layer number from 4 to 16 . And silicon is easily to get smaller cell size which means higher granularity and better position resolution.

■ Time resolution for SPACAL-SiTiming



Crystal Material : GFAG

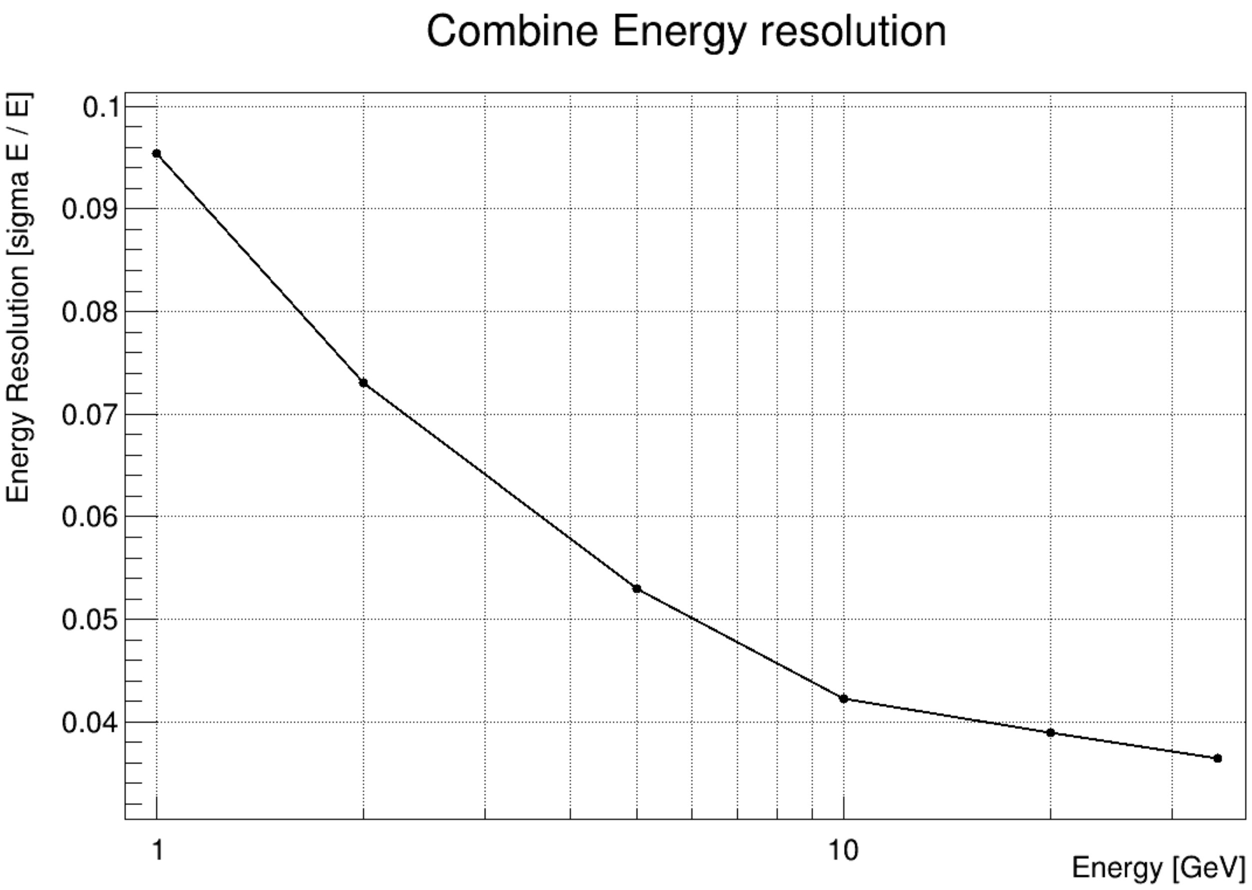
Absorber Material : Tungsten

SPACAL Cell size : 1.5 cm^2

Silicon Cell size : 1 cm^2

Silicon thickness : 0.5 mm

■ Energy resolution for SPACAL-SiTiming



Adding Cu as cooling layer between SPACAL will worsen the energy resolution of SPACAL part.

The energy resolution is similar with that of pure SPACAL after combing information from silicon and SPACAL

■ How to use time information

We use $B^- \to D^*\pi^- \to (D^0, \gamma)\pi^-$ as an example:

We can get the hit time of each cell and reconstruct the ToA (time of arrive) of a cluster (γ candidate). We named it ToA_{rec}.

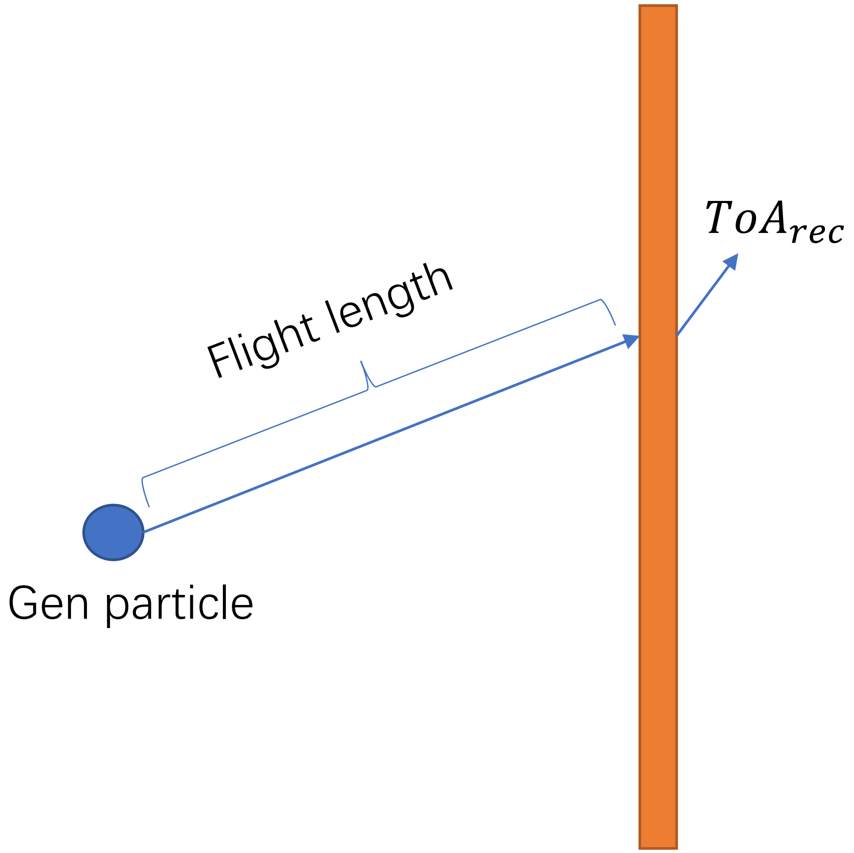
Another assumption is we have a D^0 candidate with its Generation vertex time V_{time} and Position.

Then we can predict the ToA by the flight length (f_{length}) and the V_{time}.

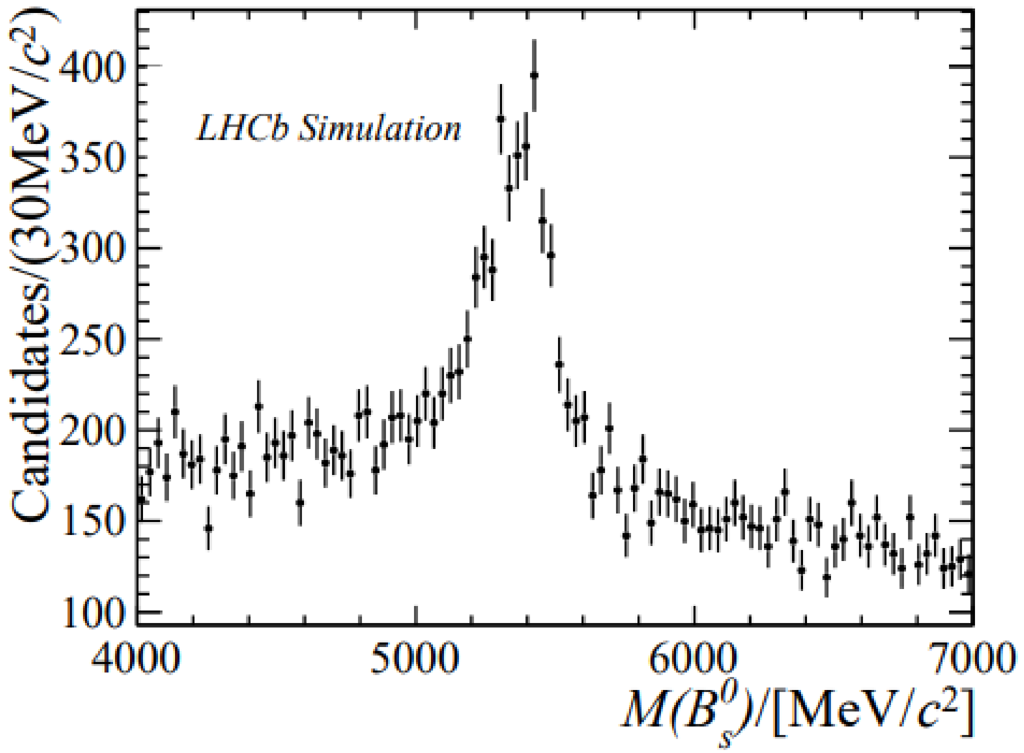
$$ToA_{prediction} = f_{length}/c + V_{\text{time}}$$

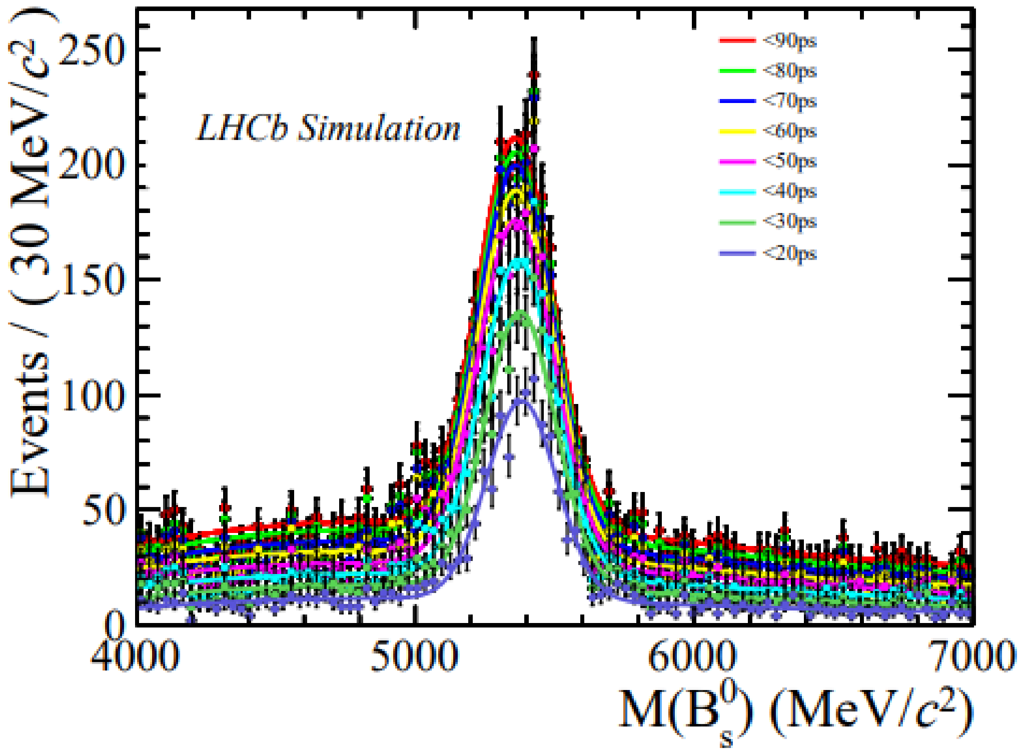
We define the Δt :

$$\boldsymbol{\Delta t = abs(ToA_{rec} - ToA_{prediction})}$$



■ $B_s^0 \to \phi\gamma$ (Si-W)



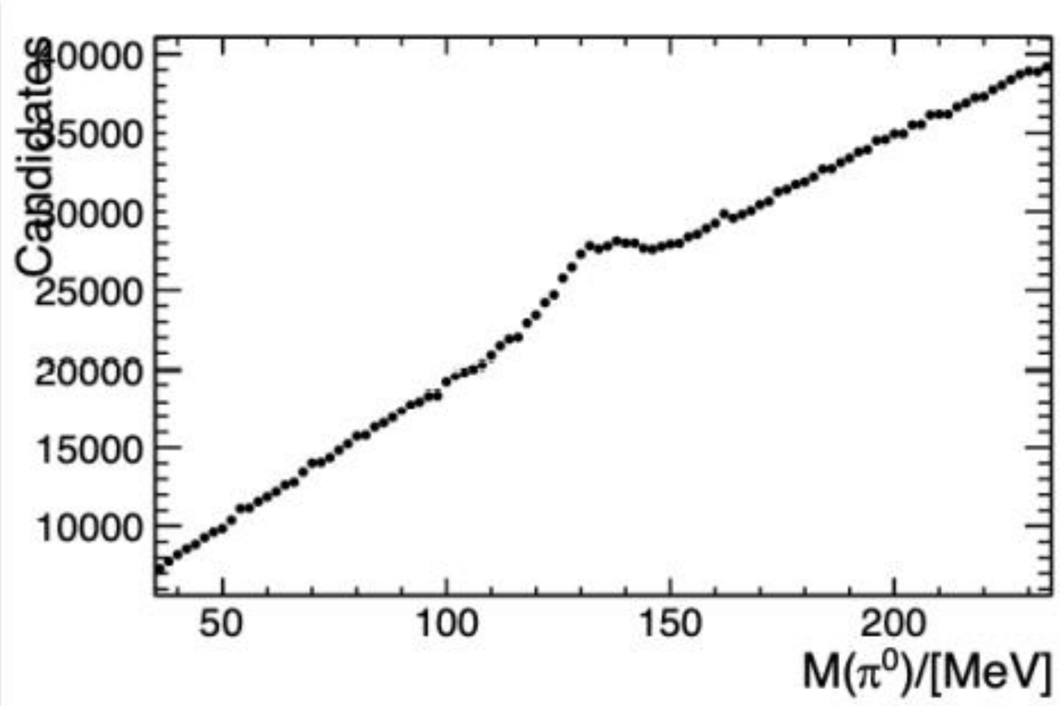


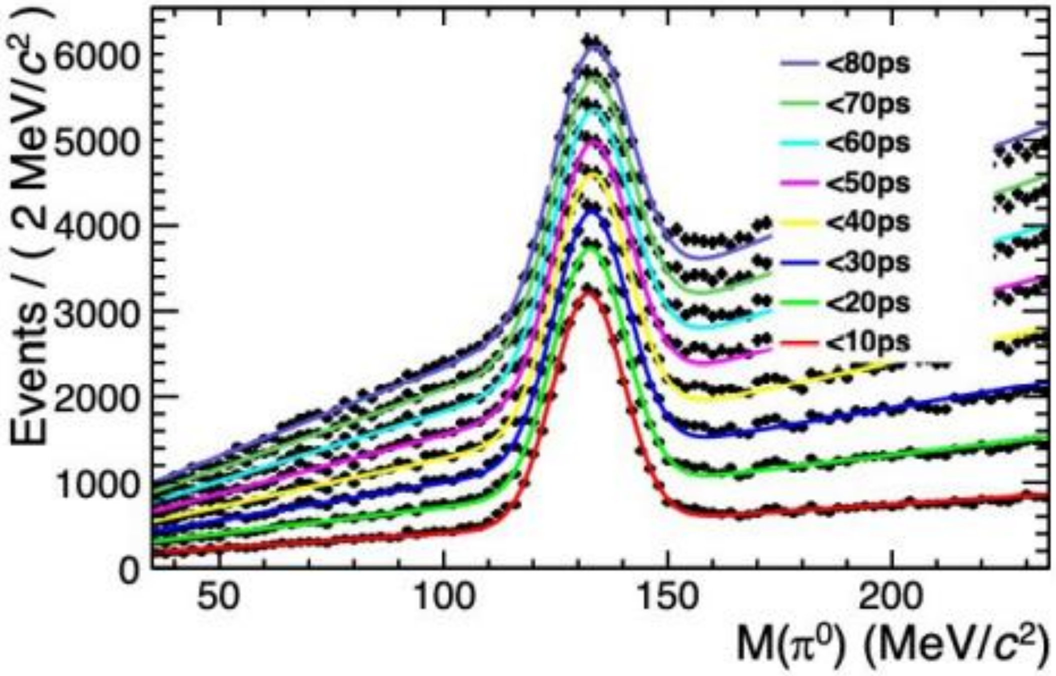
Adding Time information to the analysis can significantly improve the signal-to-noise ratio.

■ $B_s^0 \to J/\psi\pi^0$ (Si-W)

$B_s^0 \to J/\psi\pi^0$

This channel is a good example to test the ability separating the γ/π^0 of a detector



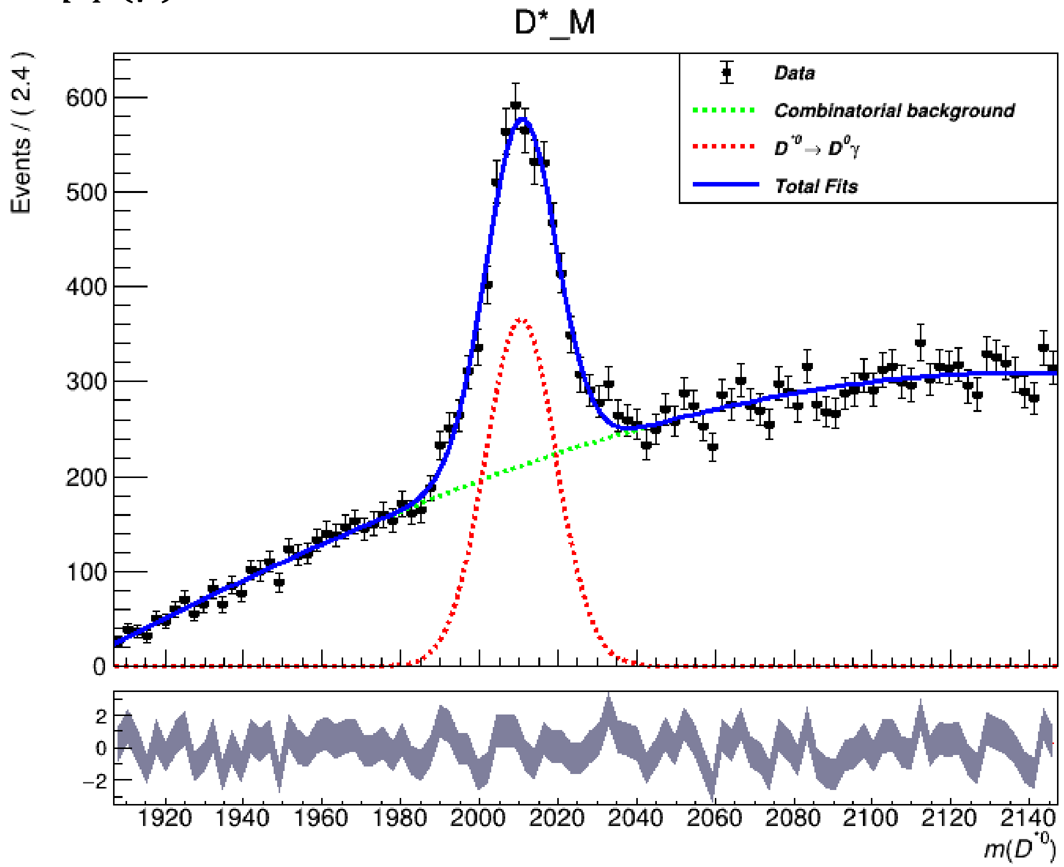


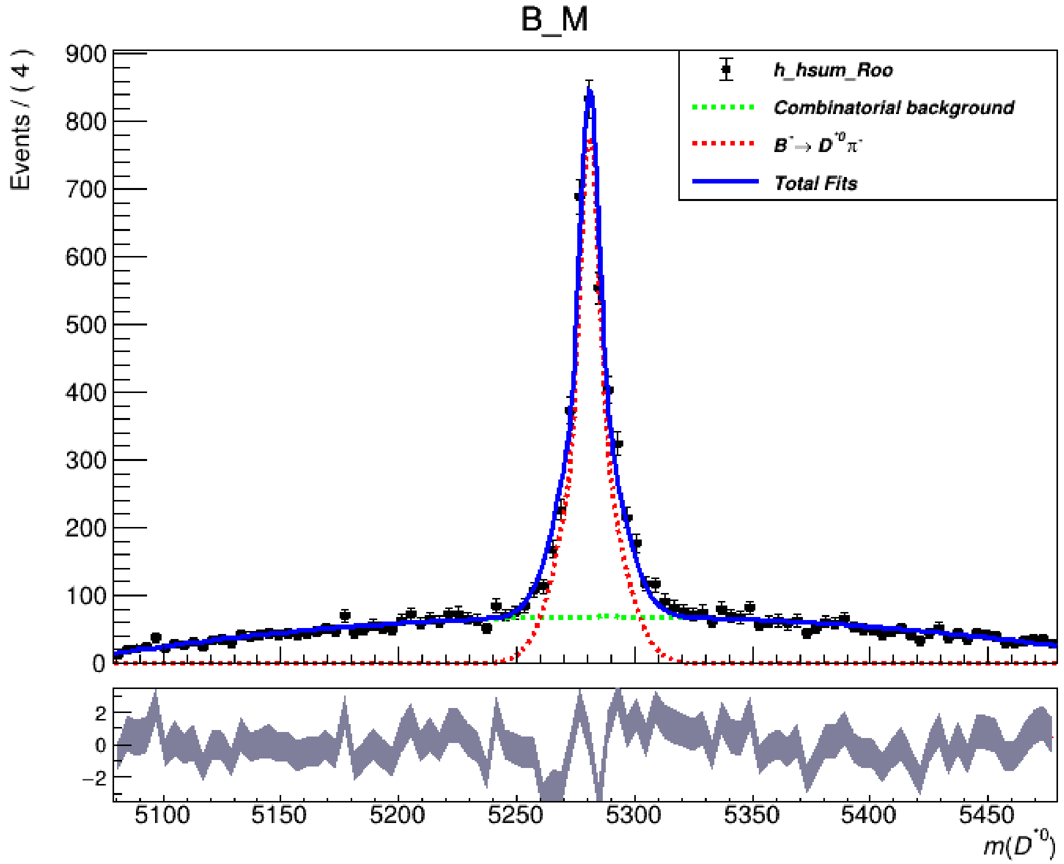
Time information is helpful to separate γ/π^0.

$B^- \to D^*\pi^- \to (D^0,\gamma)\pi^-$ (SPACAL-SiTiming)

$B^- \to D^*\pi^- \to (D^0,\gamma)\pi^-$ Luminosity : $4 \times 10^{32}\ cm^{-2}.s^{-1}$

$p_T(\gamma)$>180MeV



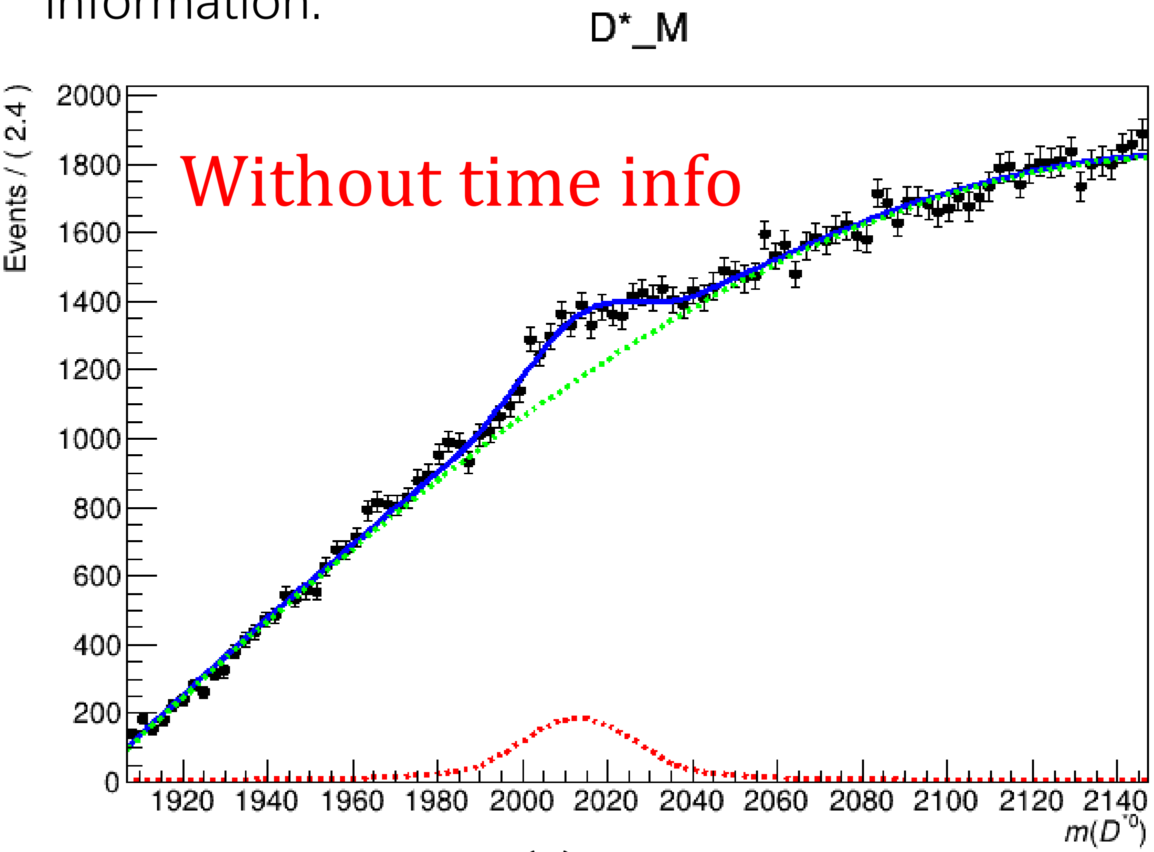


This channel contains a soft photon which can test the performance at low energy

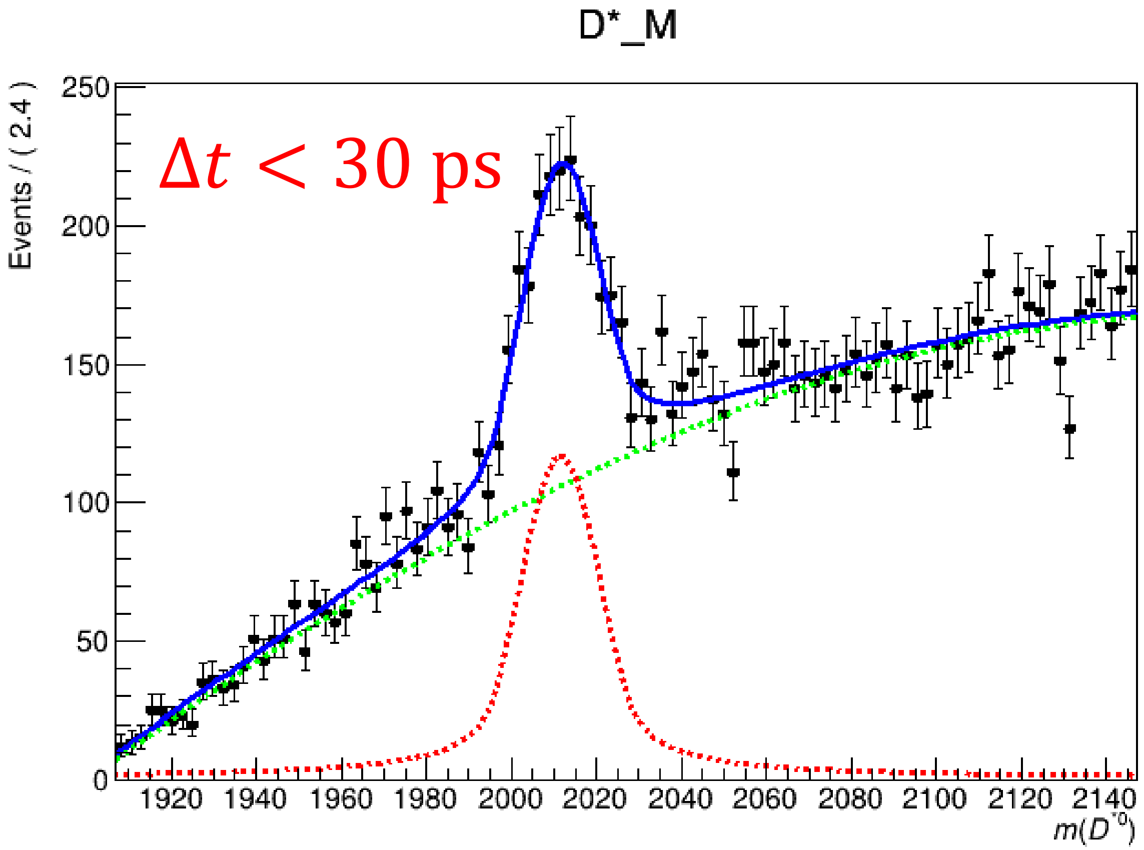
■ $B^- \rightarrow D^*\pi^- \rightarrow (D^0,\gamma)\pi^-$ (SPACAL-SiTiming)

$B^- \rightarrow D^*\pi^- \rightarrow (D^0,\gamma)\pi^-$

In high luminosity condition($1.5 \times 10^{34}\ cm^{-2}.s^{-1}$), signal can hardly to be distinguished without time information.



$p_T(\gamma)$>180MeV



$p_T(\gamma)$>180MeV

$\Delta t = abs(ToA_{rec} - ToA_{prediction})$

■ Summary & Outlook

- LHCb upgrade I is under installation , upgrade II FTDR is under LHCC review
- The ECAL upgrade is important for LHCb physics program
- Si-W, SPACAL, SPACAL-SiTiming are proposed, and simulation study performed with different physics channels
- Further study is still on going

Thank you

Backend

■ Clustering

To adapt to the new geometric layout, a slide-window-based clustering algorithm is proposed.

The algorithm can be be divided into three steps:

1) Find seed in the cell matrix:

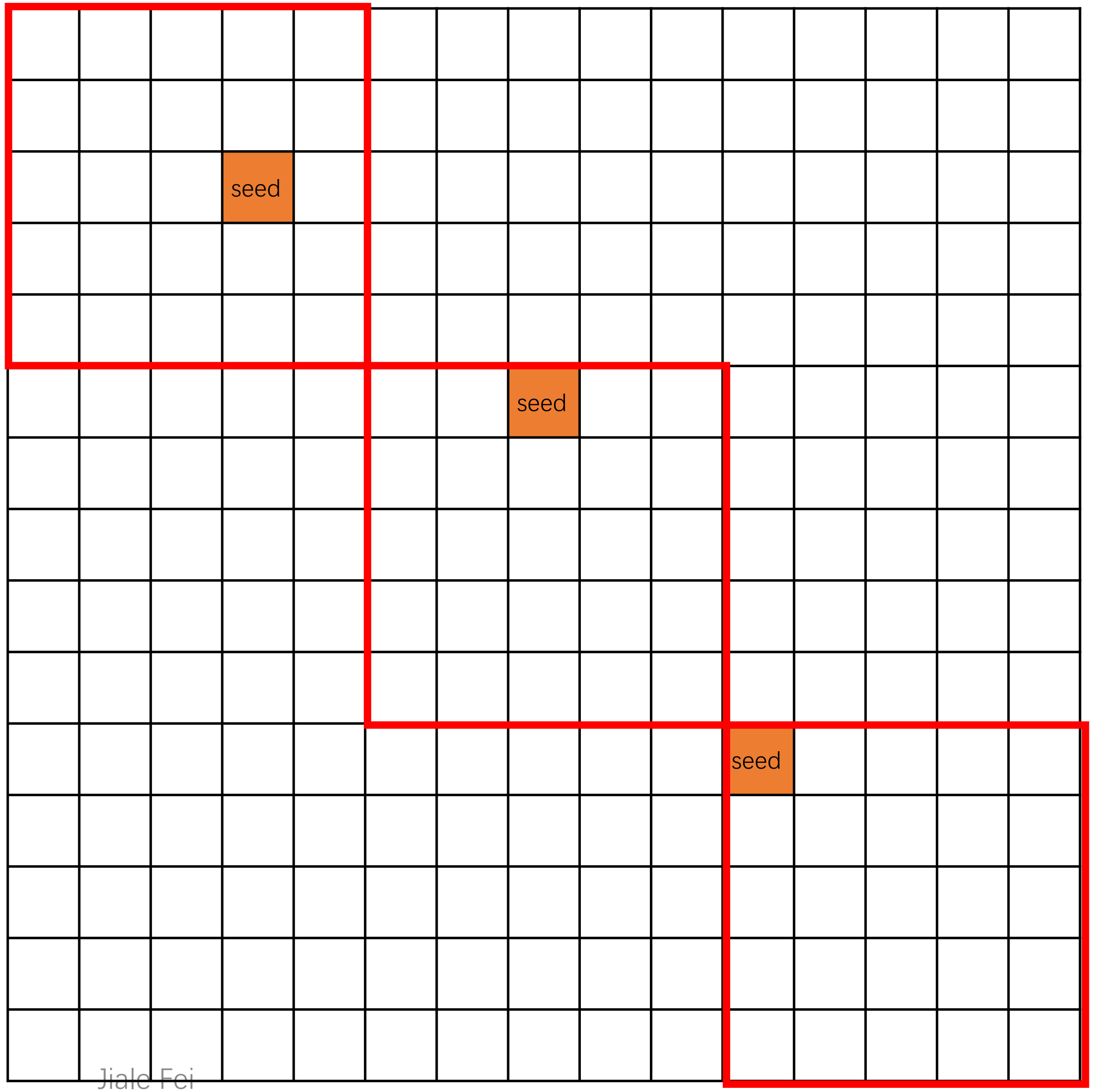
2) Assign cells to the seed:

3) Combining clusters in different layers:

■ Clustering

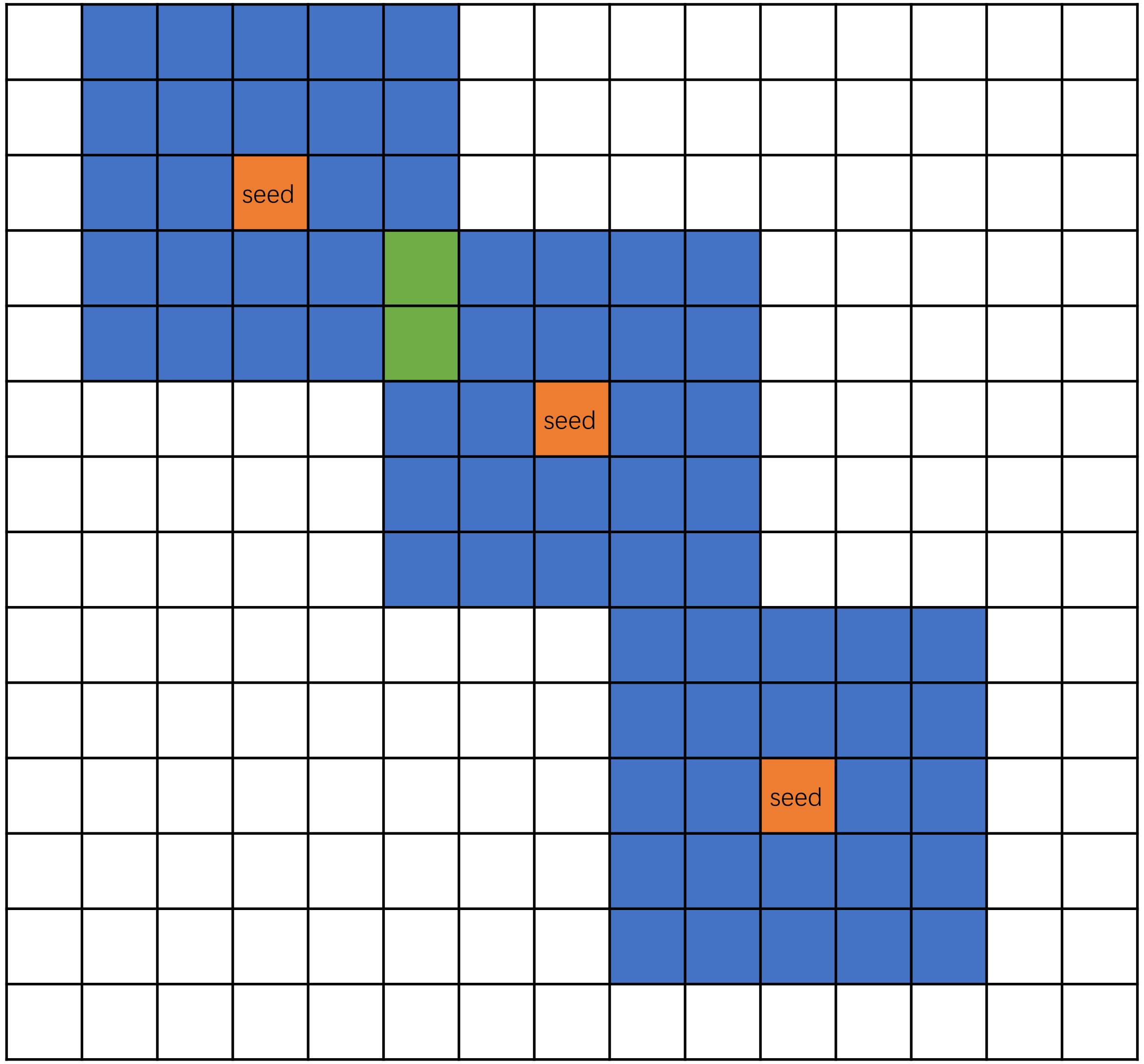
Traverse all cells from the top left of the Cell array by 5*5 size window.

And find the local maximum energy cell in 5*5 Cells as the seed.



■ Clustering

A seed-centered 5×5 range cell is then added to the cluster， if a cell belong to more than one seed, than we should split the cell energy by the distance it from the seed.



■ Cluster(2D)

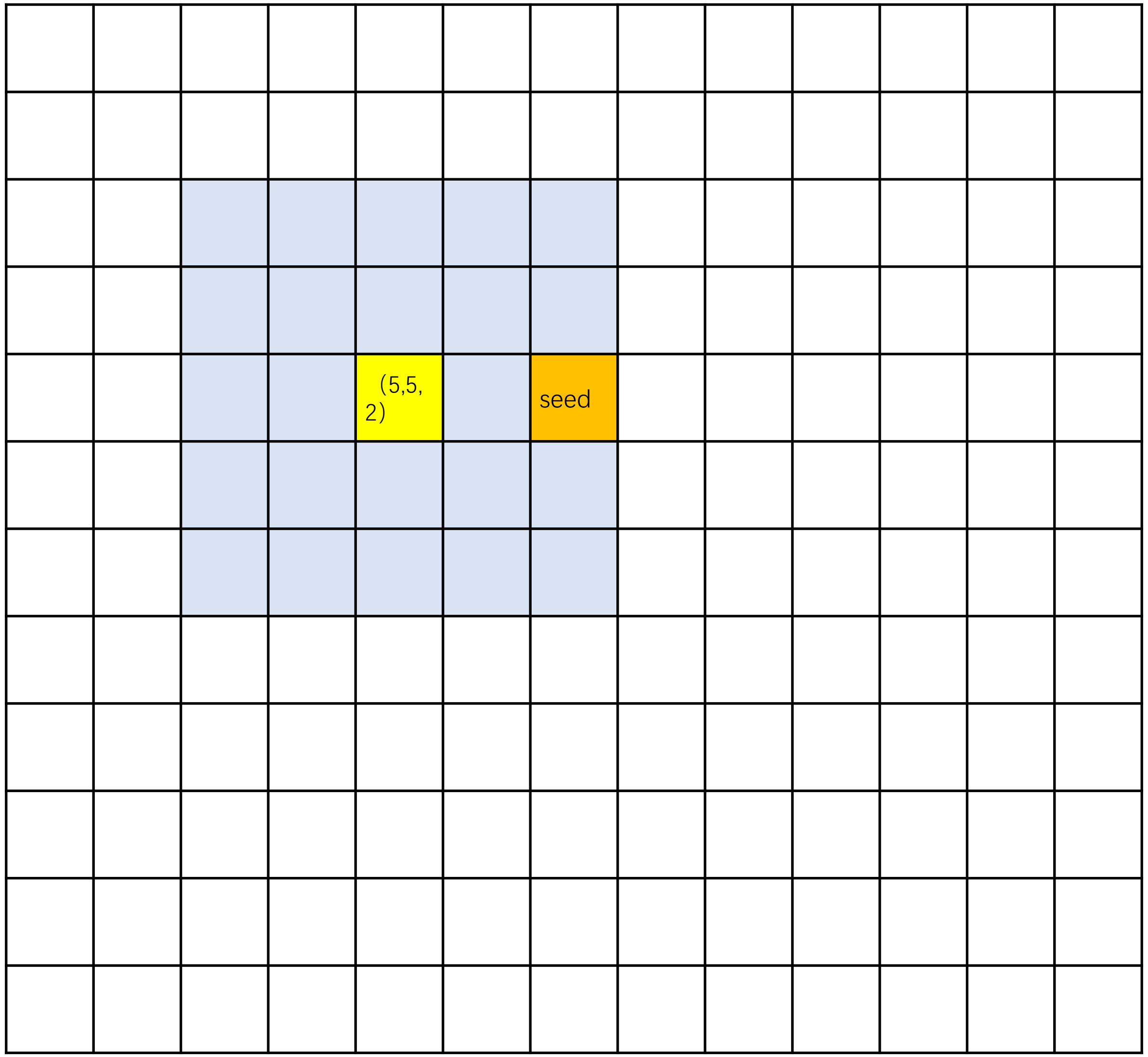
After we cluster the cell by seed, we get a Cluster(2D). it has those parameters:

- A container of Cell
  - Contain the Cell in this cluster
- Position(x,y,z)
  - The energy weighted average of the central coordinates of each cell
- Energy
  - Accumulate the energy of each cell
- Time
  - The energy weighted average of the time of each cell

■ Combining clusters in different layers

For example, if we have a cluster with seed in the first layer with xyz id : (5,5,1)。

Then we find cluster in range 5*5 cells centering on cell (5,5,2) in the second layer.
If we can find a cluster in this range , then we combine those two cluster.

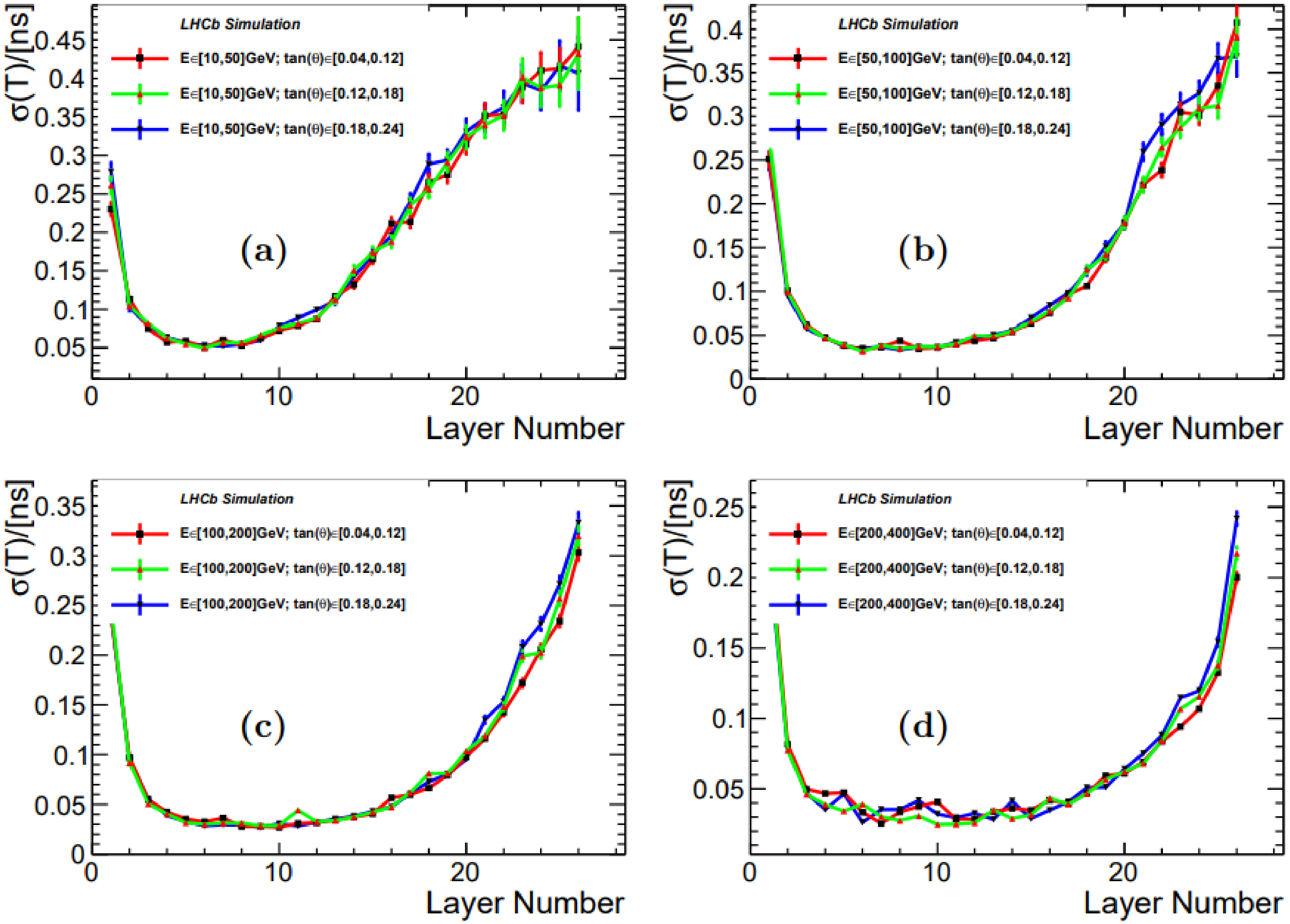


■ Cluster(3D)

After we combine cluster(2D) in different layers, then we get a Cluster(3D), it has those parameters:

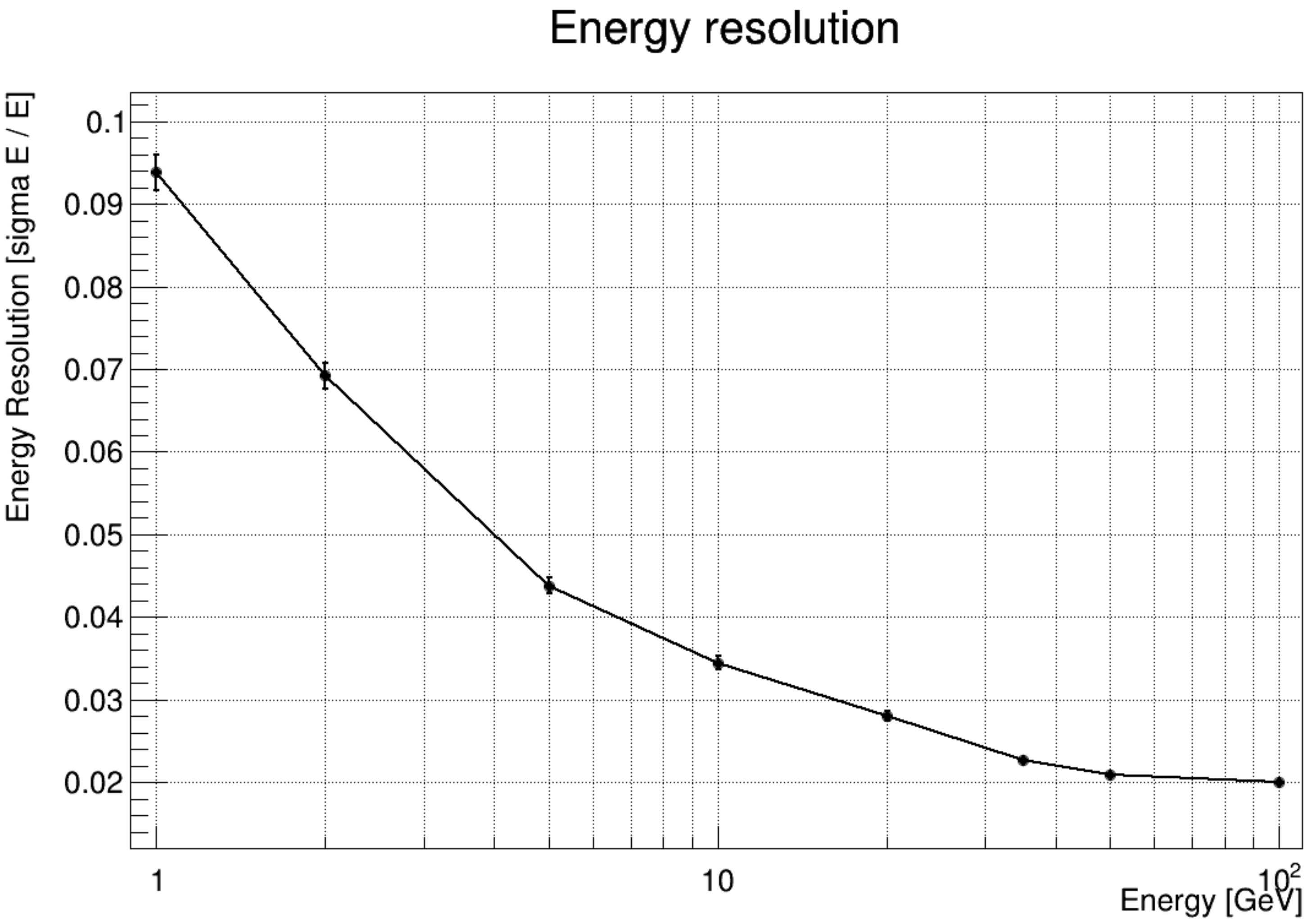
- A container of Cluster(2D)
  - Contain the Cluster(2D) in this Cluster(3D)
- Position(x,y,z)
  - The Position of Cluster(2D) in layer5 (SPACAL2)
- Energy
  - Accumulate the energy of each Cluster(2D)
- Time
  - The energy weighted average of the time of each Cluster(2D)

■ Detector Performance(Pure Si-W)



Silicon Cell size : 1 cm

The time resolution is close to the minimum when the number of Si layers reaches the four. That the reason we add four silicon layers between SPACAL in SPACAL-SiTiming.



Energy resolution
Energy Resolution [sigma E / E]
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
1
10
10^2
Energy [GeV]