ECAL simulation for LHCb Upgrade II

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Collaborating with colleagues from Peking Univ., Tsinghua Univ. and IJCLab

Sim framework : Files · SiTiming · SPACAL-RD / spacal-simulation · GitLab (cern.ch)

Rec framework : Files · master · Jiale Fei / ECAL_Reconstruction · GitLab (cern.ch)

■ Outline

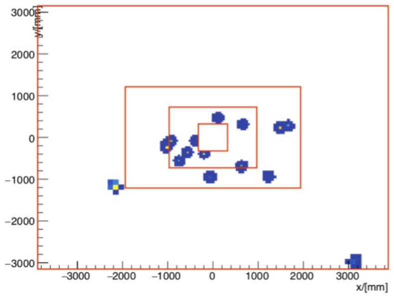
1. ECAL in upgrade II
2. ECAL modules
   - Standard double-ended readout SPACAL
   - SPACAL-Silicon
3. Detector performance
4. Simulation workflow and reconstruction software
5. Summary and outlook

■ ECAL in upgrade II

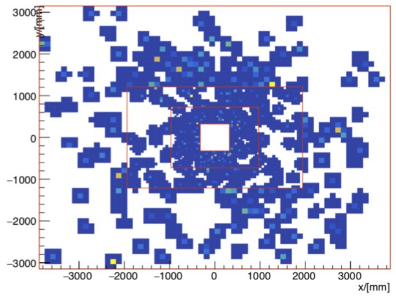
In order to ensure that the calorimeter can still guarantee at least similar performance under HL-LHC as at Run 1 and Run 2. The following requirements are presented :

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

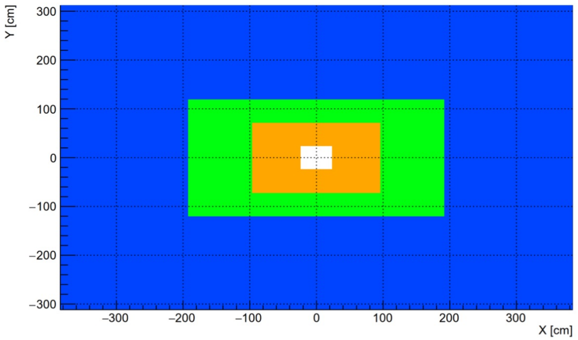


Upgrade II with $L = 1.5\times10^{34} cm^{-2}\cdot s^{-1}$

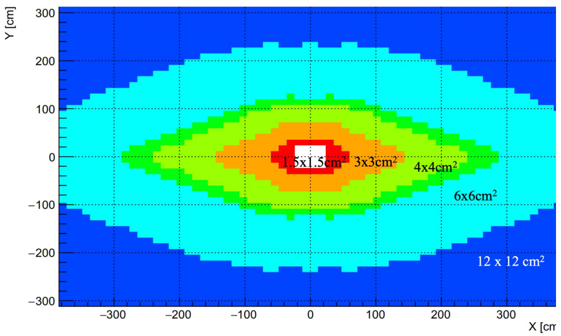


Current geometry:

Cell size

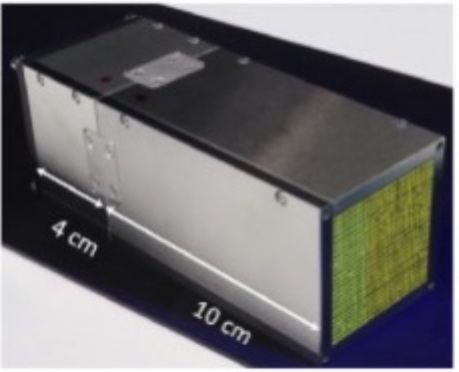


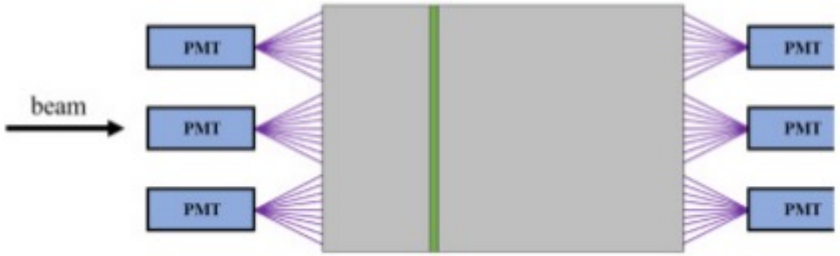
Upgrade 2



■ Standard double-ended readout SPACAL

- The SPACAL is a sampling calorimeter wherein scintillating fibres are inserted into a dense absorber.
- Consider two sets of materials GAGG-W（$R_m \approx 1.5cm$） and Polystyrene-Pb （$R_m \approx 3cm$）(Fibres-Absorber).
- Overall length approximately $25X_0$, double-ended readout.
- Setting the reflective surface at approximately $7X_0$ (shower maximum) splits the detector into two segments.



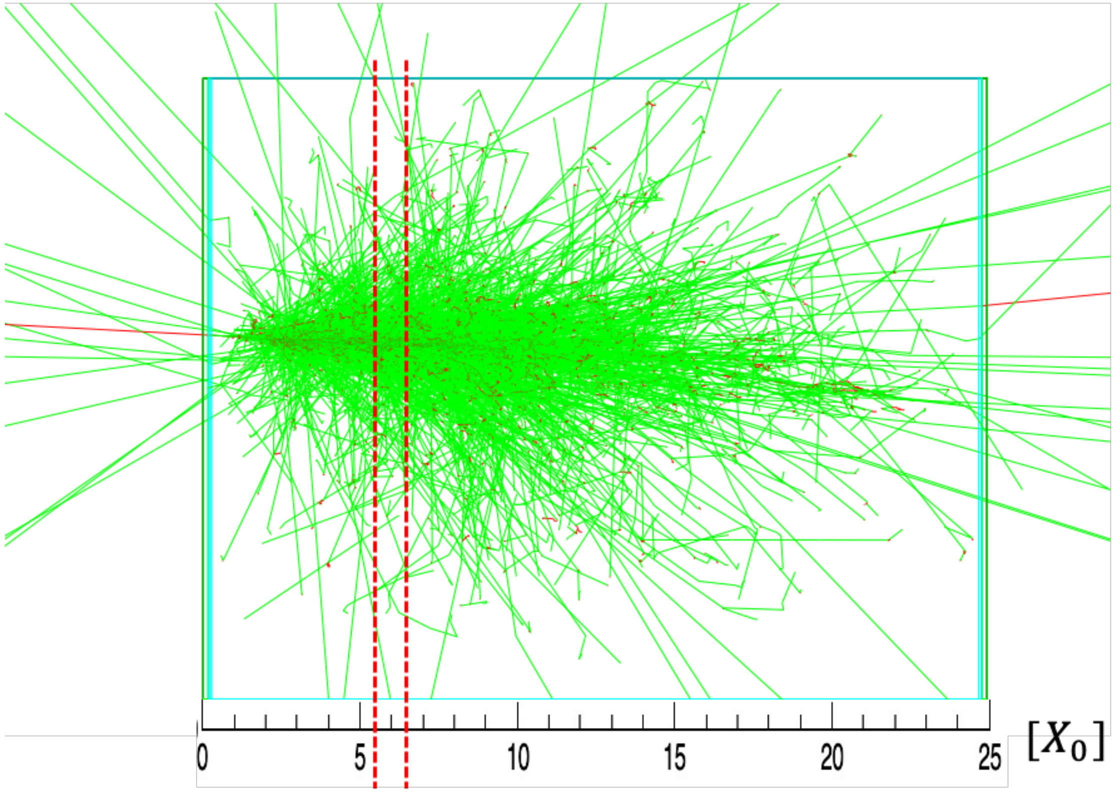


A SPACAL module

SPACAL Modules	GAGG-W	Polystyrene-Pb
Absorber	Tungsten	Lead
Active fibres	GAGG	Polystyrene
Radiation length	≈ 0.64 cm	≈ 1.1 cm
Moliere radius	≈ 1.5 cm	≈ 3 cm
Cell size	1.5*1.5 cm	3*3 cm
Sections	2(45mm+105mm)	2(80mm+210mm)

■ Adding silicon layers

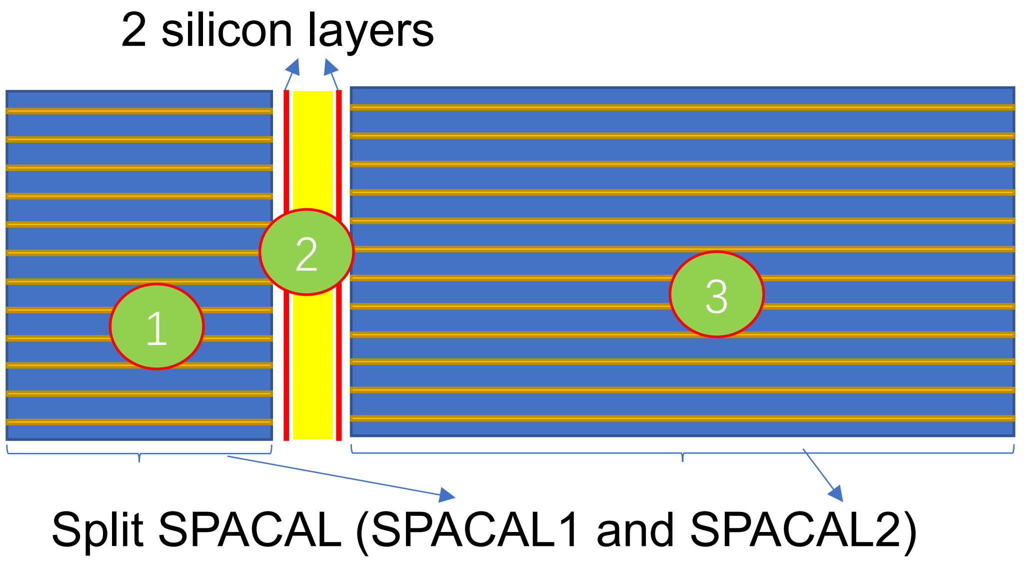
- Achieve high granularity to get the profile information of the clusters. For cluster segmentation or particle identification.
- The performance of the silicon detectors is related to the number of MIPs, which are added between the front and back SPACALs in order to ensure the performance of the silicon detectors.
- Good time response for additional time information.
- Increase longitudinal readout information.
- The placement should strike a balance between the density of MIPs (the closer to the shower maximum the larger) and the ability to split the clusters (the further away from the shower maximum the better).
- Two options
  - For Polystyrene-Pb， placed at 6.5 X_0.
  - For GAGG-W， placed at 5.5 X_0.



Cross section of 10GeV electron cluster

■ SPACAL-Silicon

- Compared to the standard SPACAL, the front SPACAL shortened by 0.5 X_0 for Polystyrene-Pb and 1.5 X_0 for GAGG-W.
- The goal is to add multi-dimensional information while ensuring similar or better basic performance (energy, time, position) than standard SPACAL, and explore the use of more dimensional information

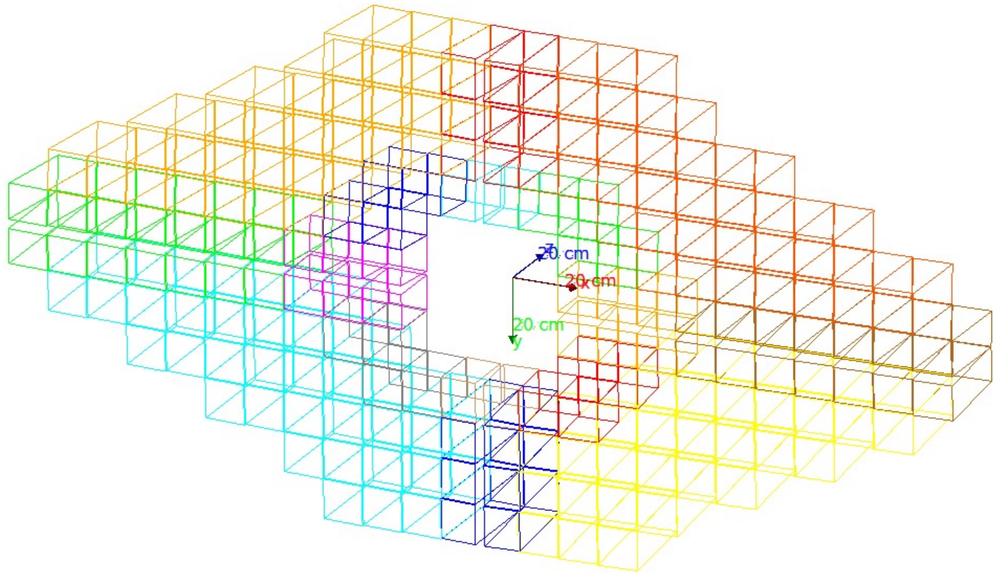


SPACAL Modules	GAGG-W($X_0 \approx 0.64, R_m \approx 1.5\ [cm]$)	Polystyrene-Pb ($X_0 \approx 1.15,\ R_m \approx 3\ [cm]$)
Absorber	Tungsten	Lead
Active fibres	GAGG	Polystyrene
Thickness of Silicon	0.5 mm	0.5 mm
Thickness of cooling layer	6 mm	6 mm
Silicon cell size	5mm	5mm
SPACAL cell size	15mm	30mm
Sections (SPACAL-Silicon)	4(35mm+2*Si+105mm)	4(75mm+2*Si+210mm)

■ Particle gun performance of SPACAL(-Silicon)

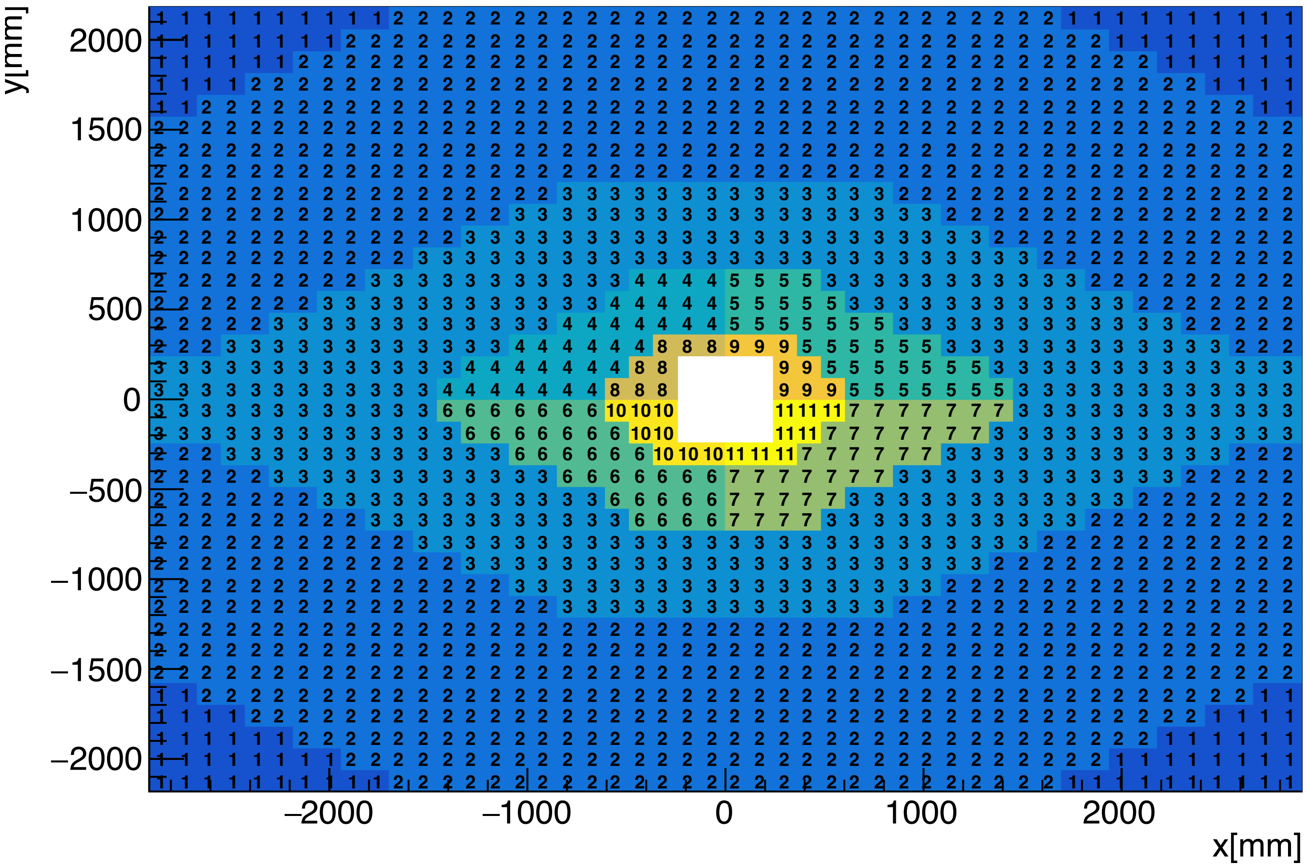
➢ Particle gun configuration:

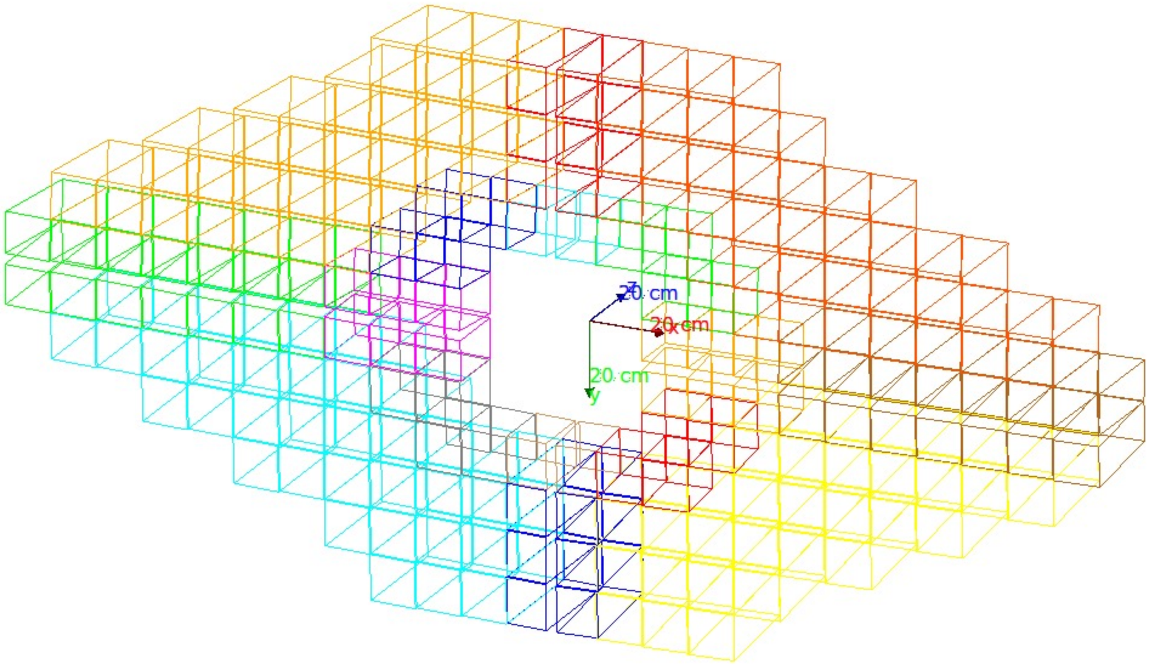
- Incident particle : photon
- Energy : 0-150 GeV
- Generation position : (0 mm,0 mm,-12835.54 mm)
- ECal installation position : (0 mm,0 mm,0 mm)



SPACAL Modules	GAGG-W	Polystyrene-Pb
Absorber	Tungsten	Lead
Active fibres	GAGG	Polystyrene
Sections (SPACAL)	2(45mm+105cm)	2(80mm+210mm)
Sections (SPACAL-Silicon)	4(35mm+2*Si+105mm)	4(75mm+2*Si+210mm)

■ Particle gun performance of SPACAL(-Silicon)





Region 4-7	Region 8-11
3 cm SPACAL(Polystyrene-Pb)	1.5 cm SPACAL(GAGG-W)

- ➢ The SPACAL module is installed by rotating it 3 degrees outwards in the x/y direction.
- ➢ The most inner region are GAGG-W modules, sub-inner region are Polystyrene-Pb modules

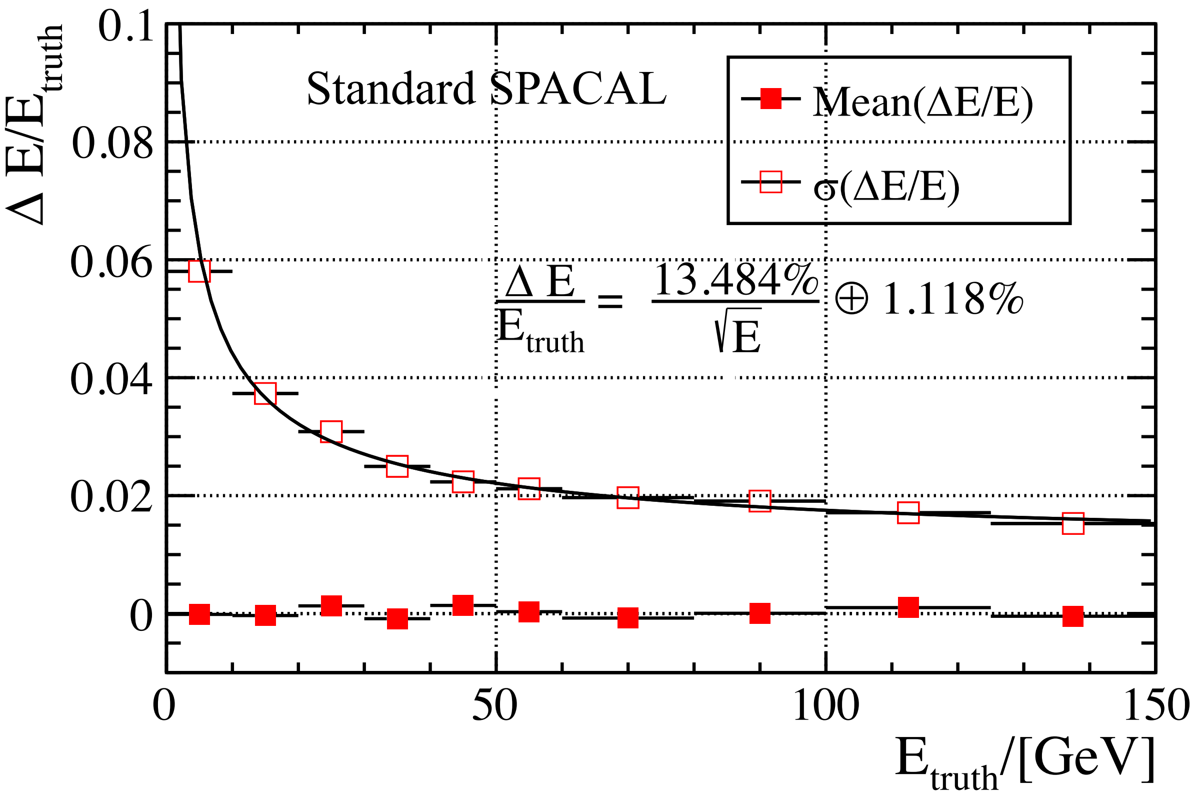
■ Particle gun performance of SPACAL(-Silicon)

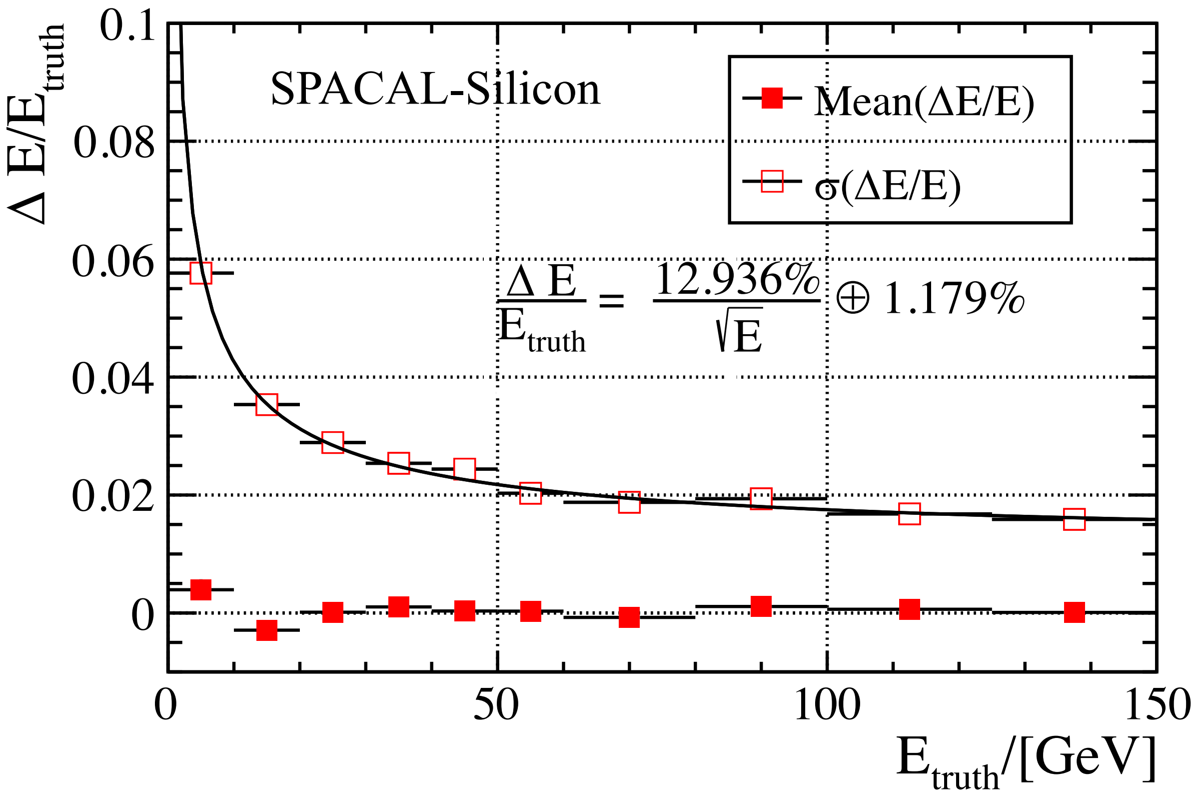
- Polystyrene-Pb
  - Combined
  - Layer by layer(backup)

- GAGG-W

■ Particle gun performance of SPACAL(-Silicon)

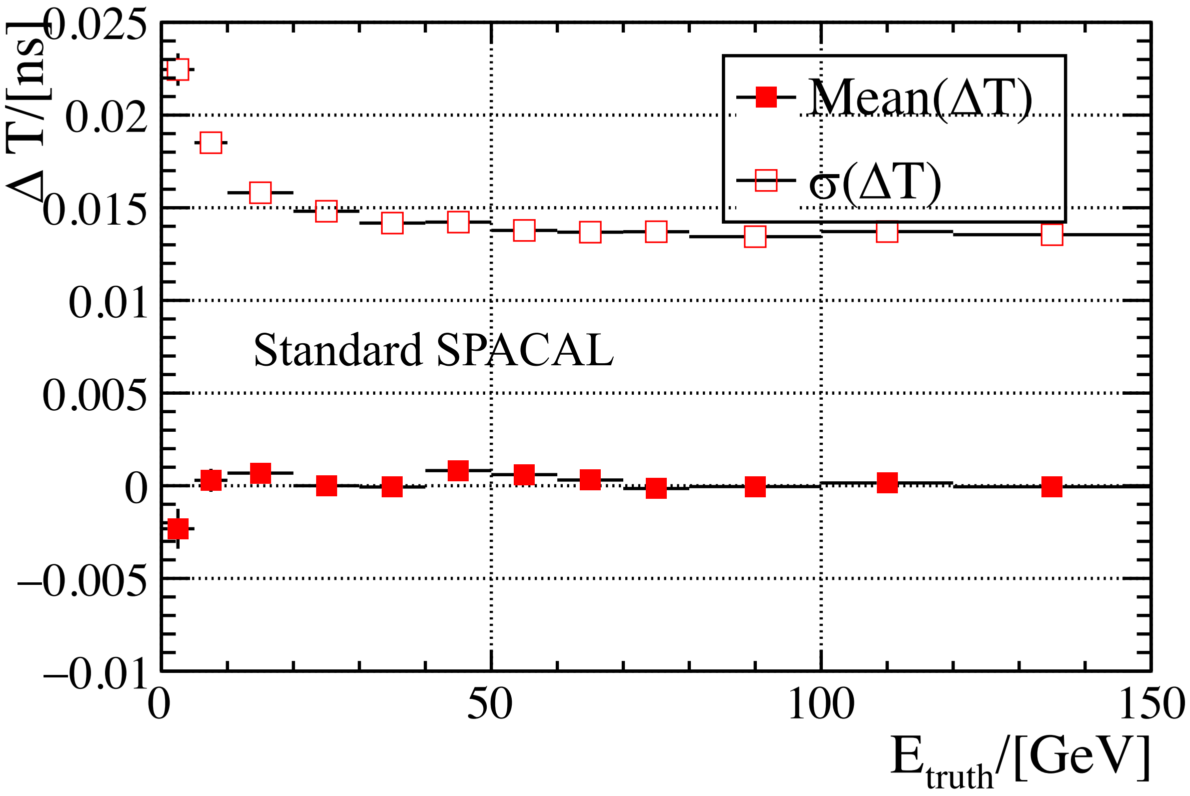
➢ Energy resolution（Polystyrene-Pb；3*3 cm）

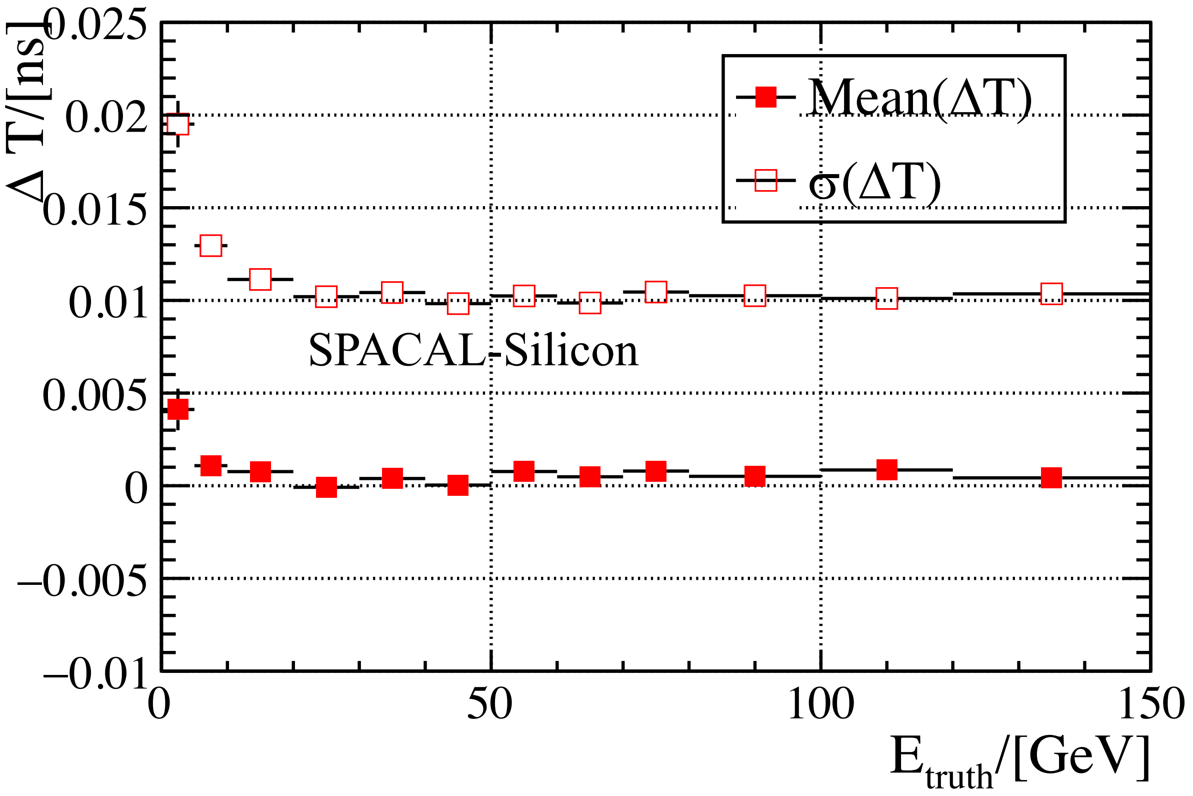




■ Particle gun performance of SPACAL(-Silicon)

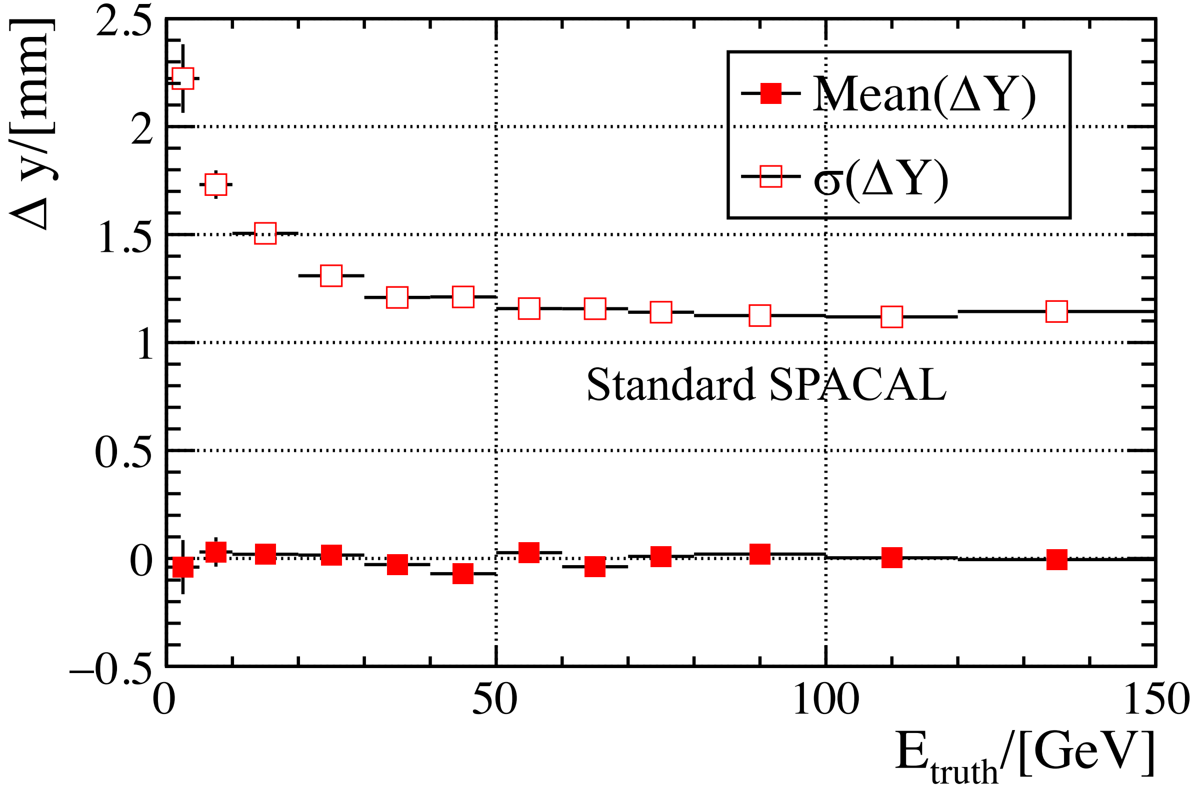
- Time resolution（Polystyrene-Pb；3*3 cm）

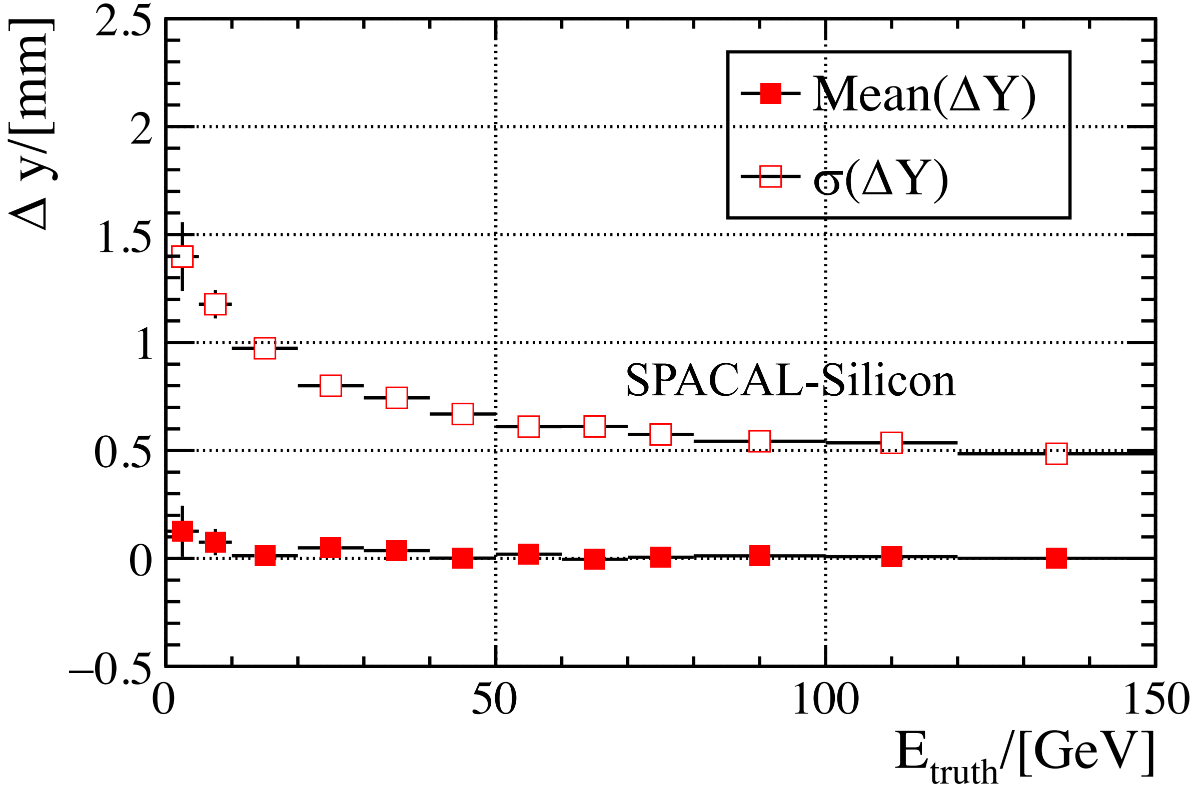




■ Particle gun performance of SPACAL(-Silicon)

➢ Position resolution（Polystyrene-Pb；3*3 cm）





■ Particle gun performance of SPACAL(-Silicon)

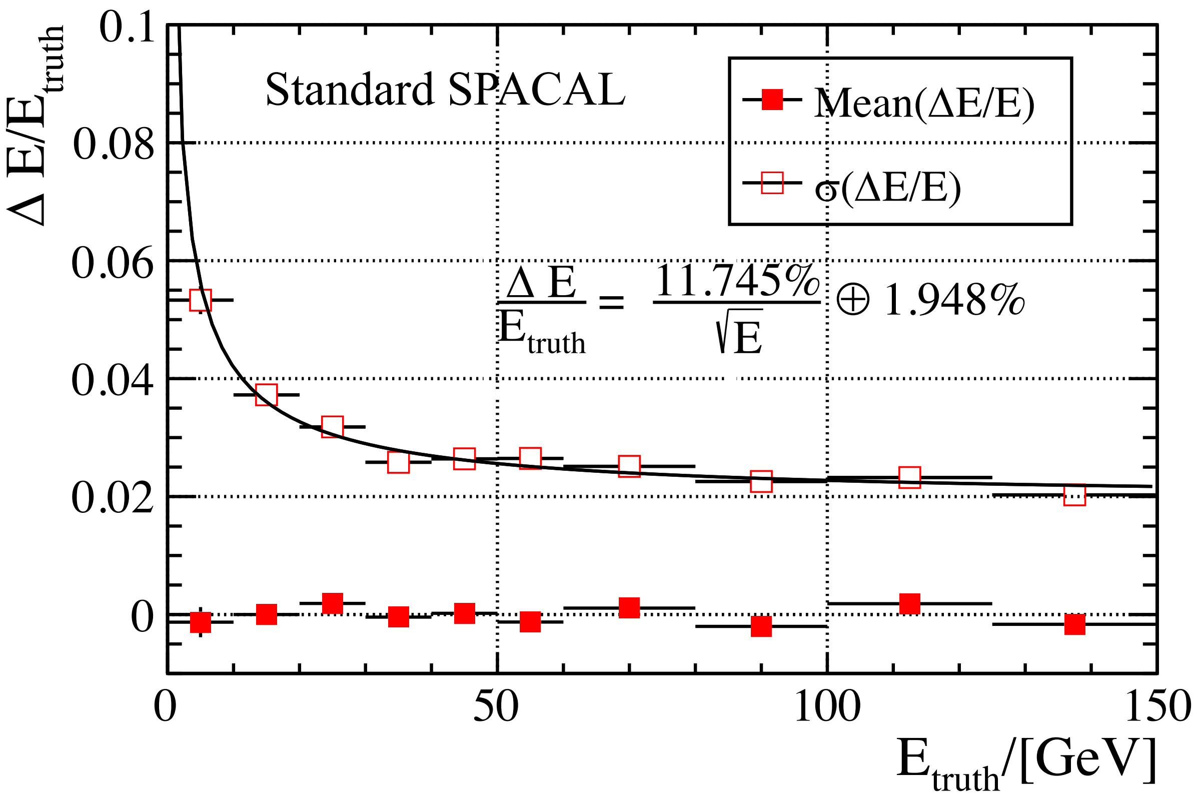
➢Polystyrene-Pb

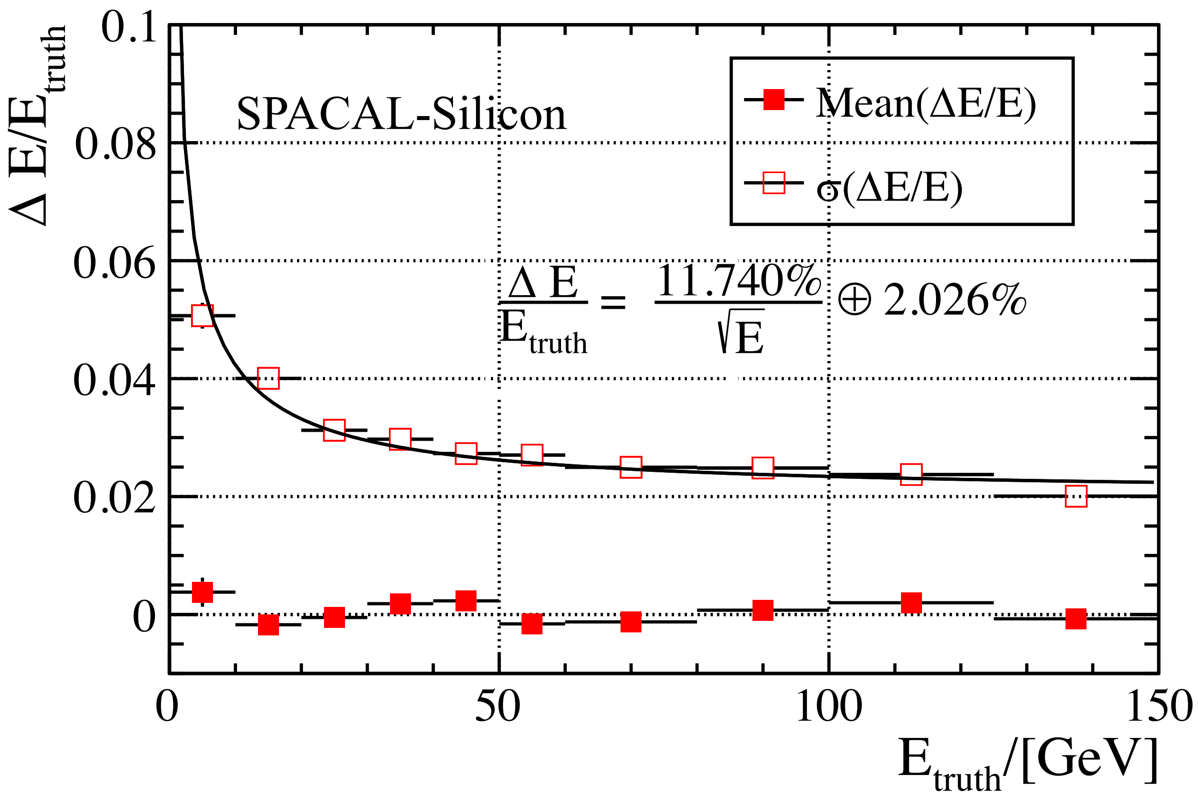
➢GAGG-W

- Combined
- Layer by layer(backup)

■ Particle gun performance of SPACAL(-Silicon)

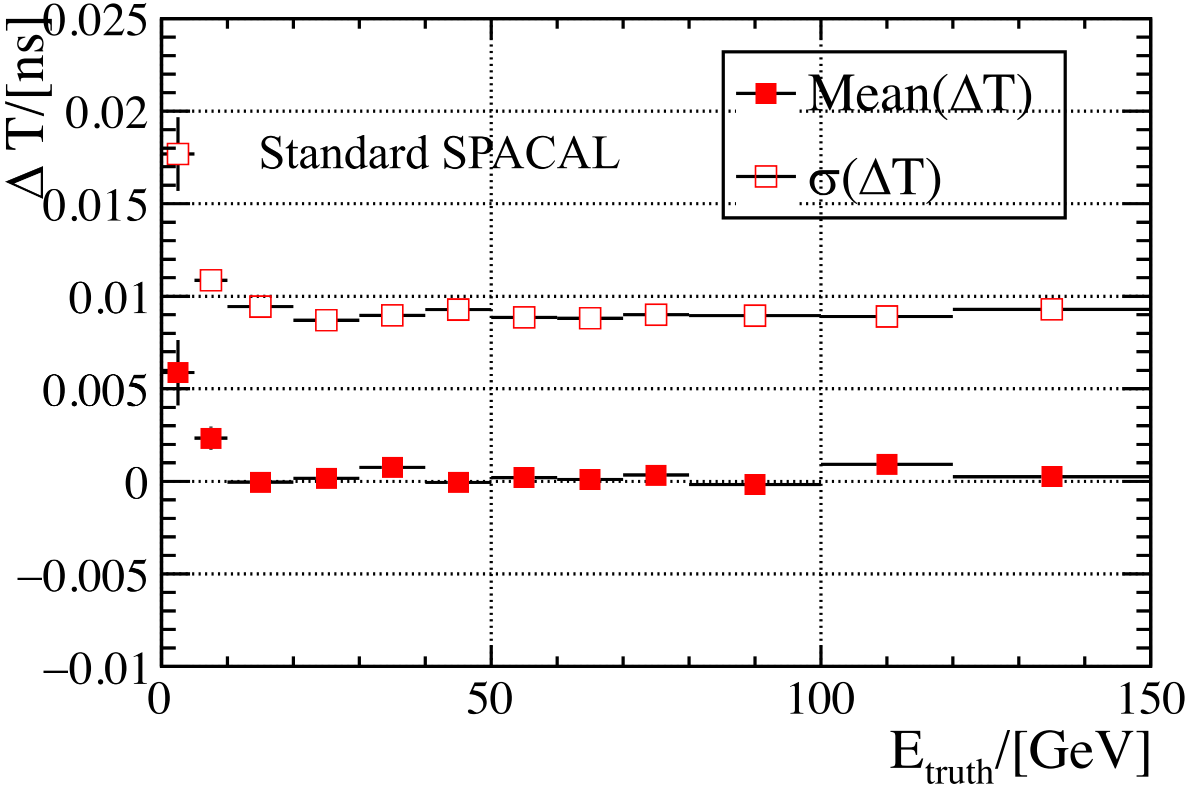
➢ Energy resolution （GAGG-W； 1.5*1.5 cm）

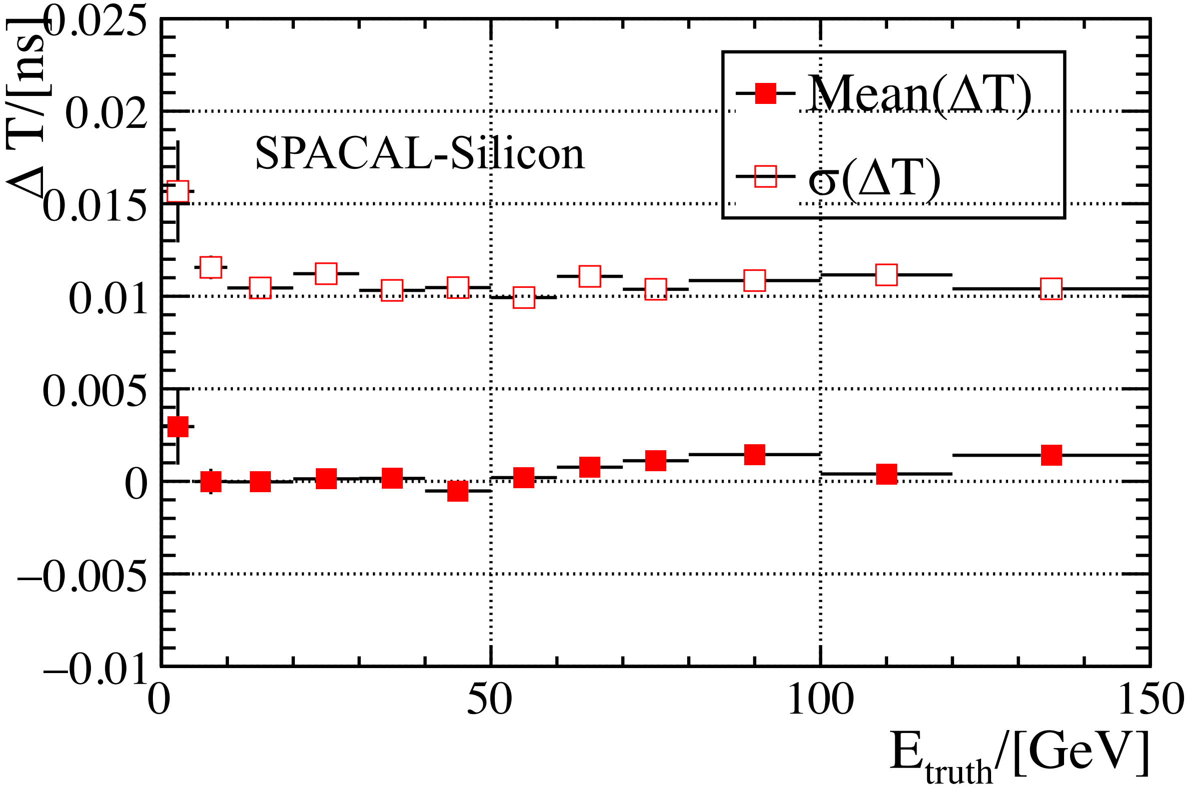




■ Particle gun performance of SPACAL(-Silicon)

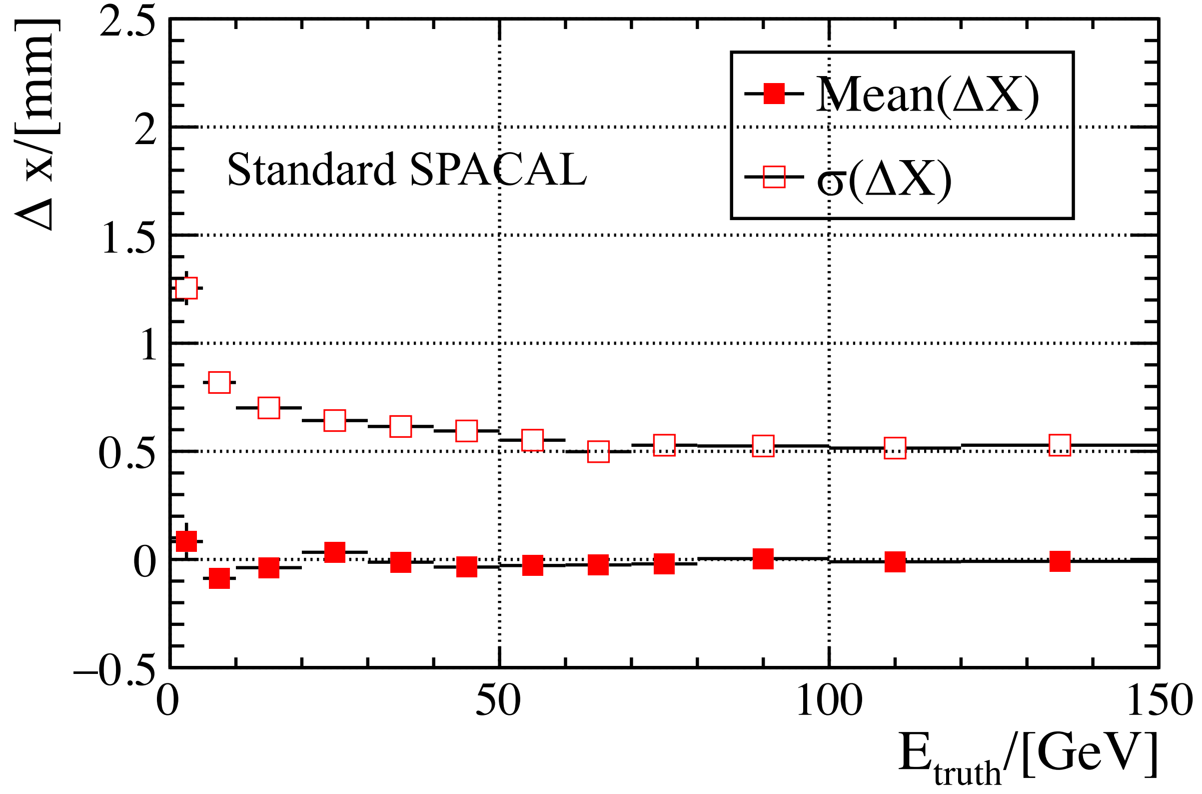
➢ Time resolution （GAGG-W；1.5*1.5 cm）

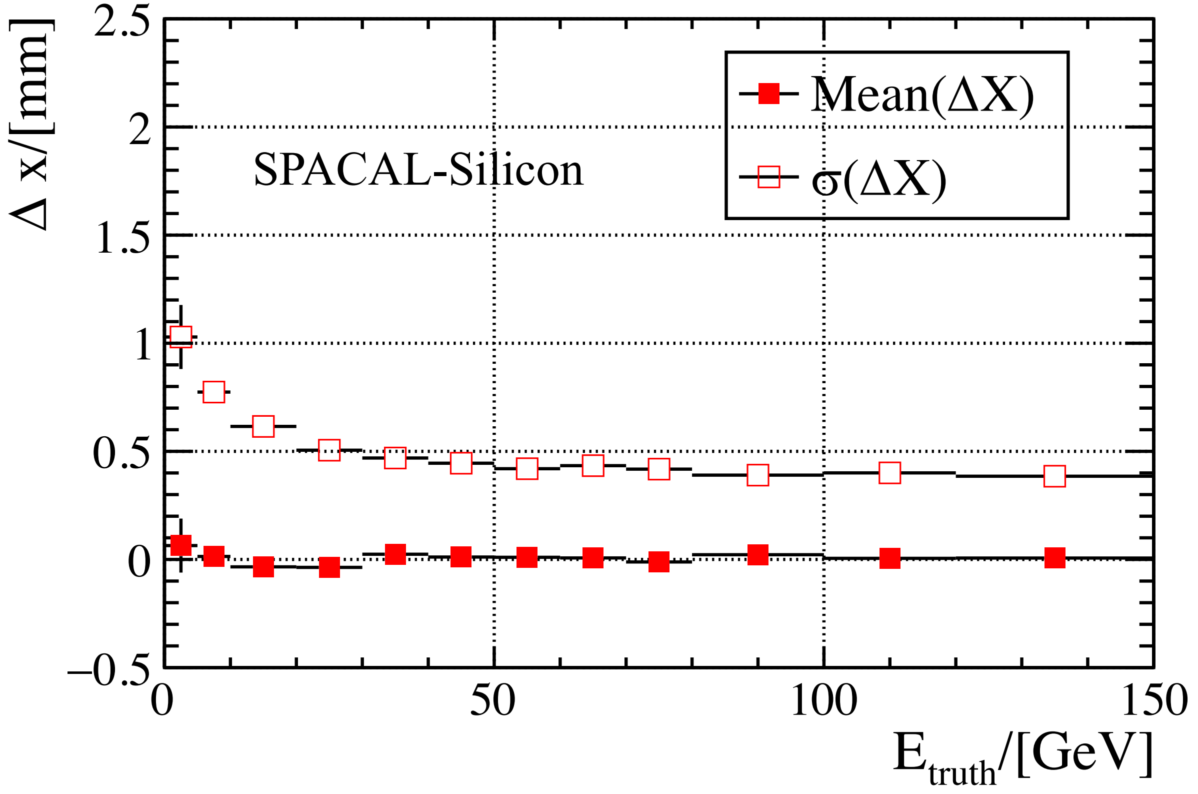




■ Particle gun performance of SPACAL(-Silicon)

➢ Position resolution（GAGG-W； 1.5*1.5 cm）



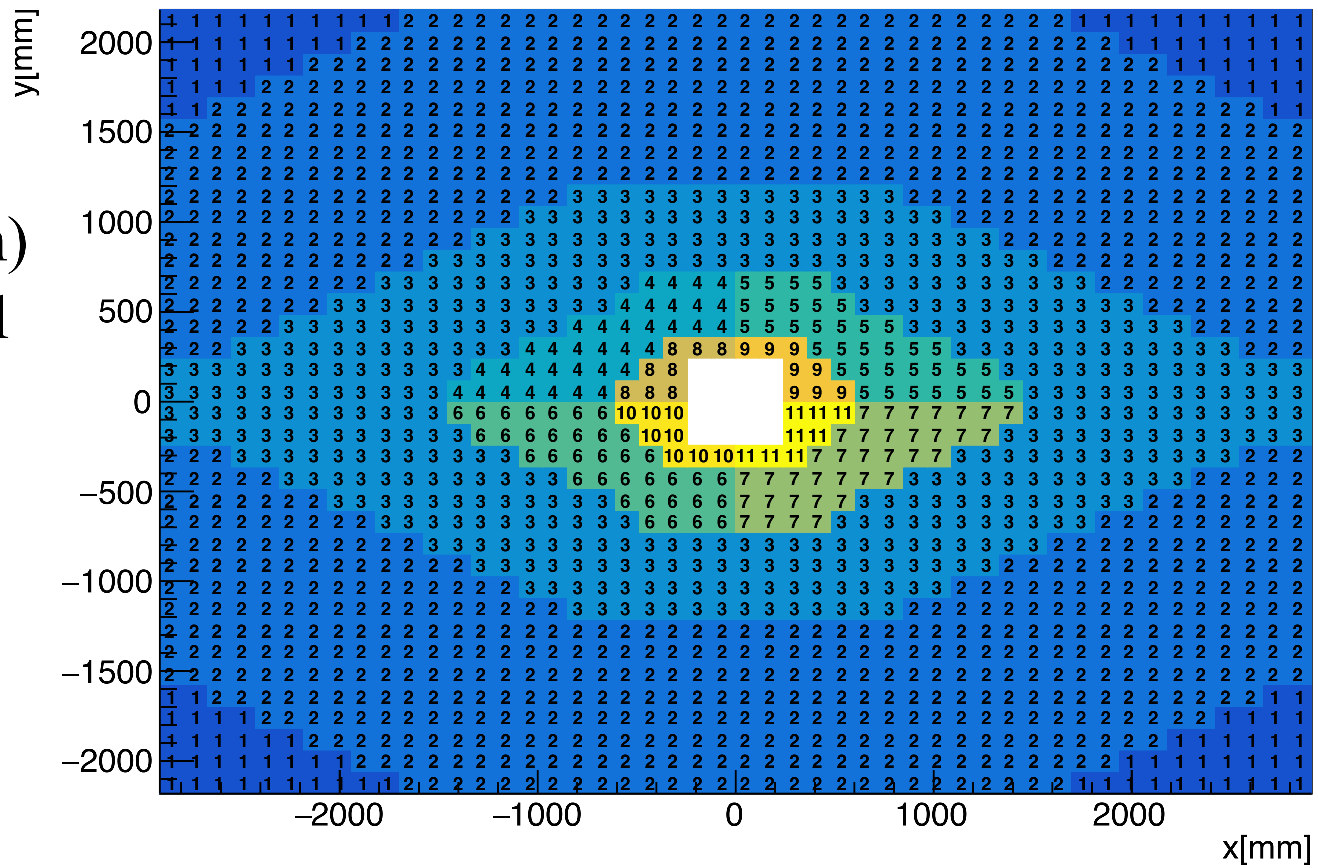


SPACAL-Silicon achieved our Expectations in basic performance : similar or better basic performance than standard SPACAL.

■ Performance of SPACAL(-Silicon) in simulation

➢ Check the performance of SPACAL(-Silicon) for different physical channels in region 4-11 (SPACAL regions).

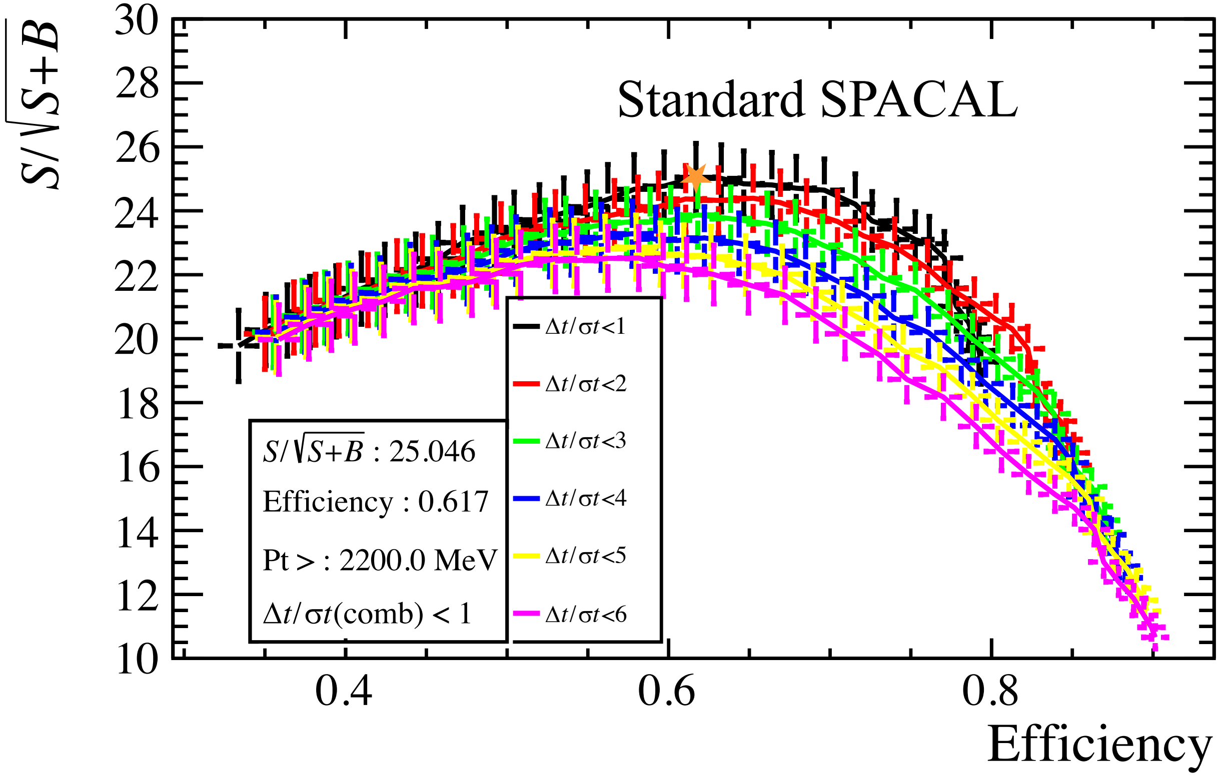
- $B^0 \to K^*(K\pi)\gamma$
- $B^\pm \to D^*(D\gamma)\pi^\pm$

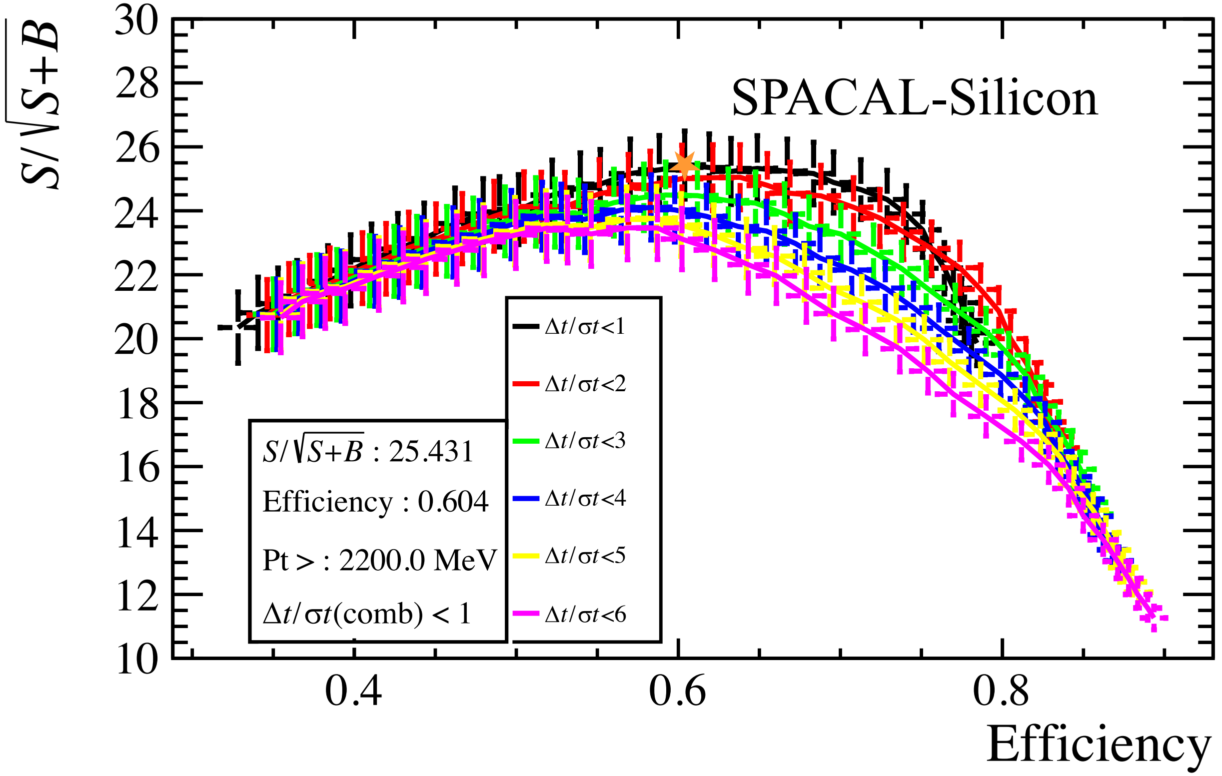


Region 4-7	Region 8-11
3 cm SPACAL(Polystyrene-Pb)	1.5 cm SPACAL(GAGG-W)

■ Performance of $B^0 \to K^*(K\pi)\gamma$

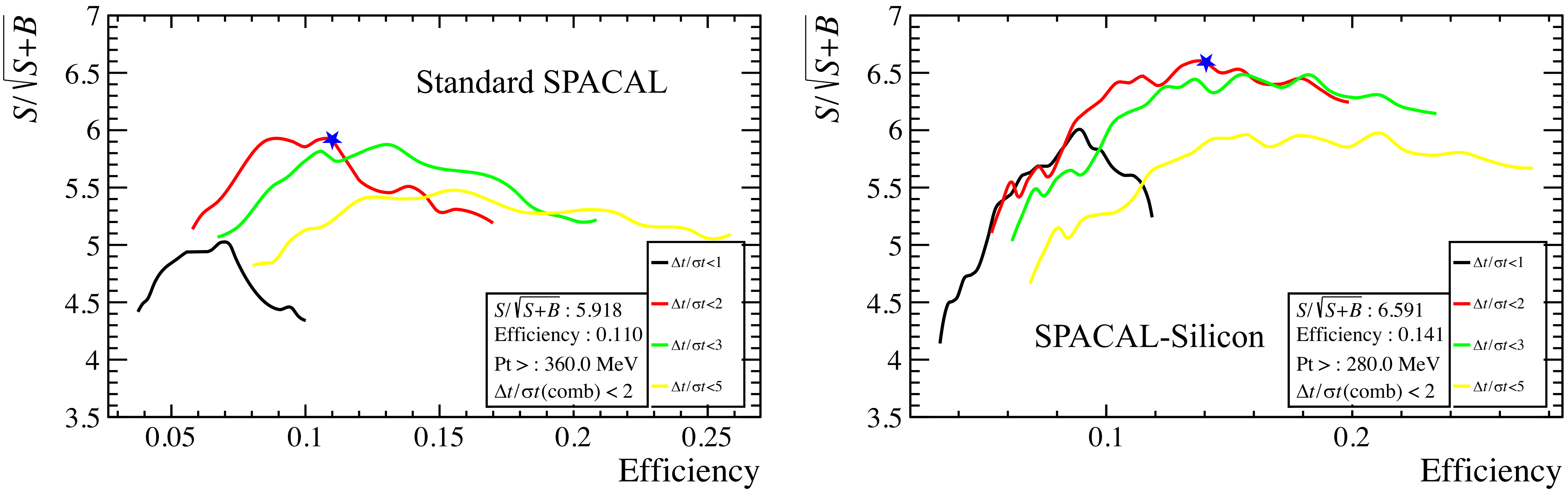
- In high energy photon channel, the energy resolution will dominate the performance.





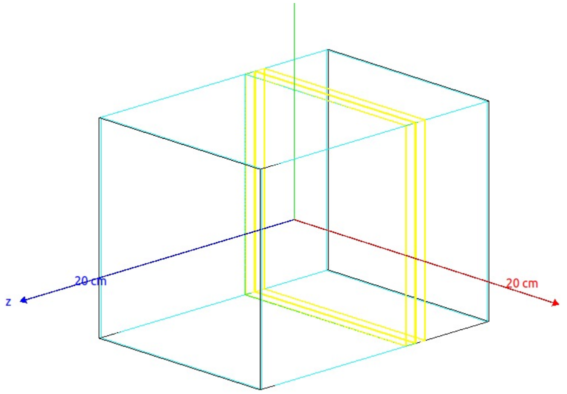
■ Performance of $B^{\pm} \to D^{*}(D\gamma)\pi^{\pm}$

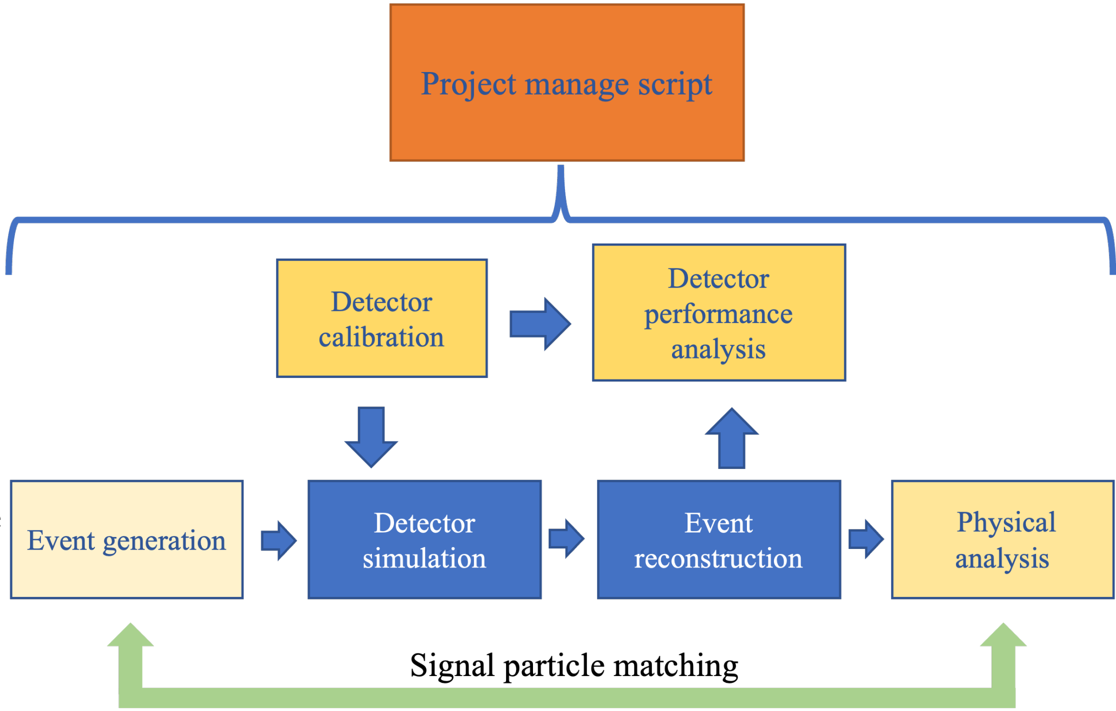
- This channel is a soft γ channel, so we check the performance of ECal by the mass distribution of $D^{*}(D^{0}\gamma)$.



■ Simulation and reconstruction framework

- In order to obtain the above resolution and physical channel benchmark performance. Relevant software and algorithms were developed to simulate, calibrate, and reconstruct events for the above detectors.
- Simulation(Files · SiTiming · SPACAL-RD / spacal-simulation · GitLab (cern.ch)) : New branch "SiTiming" based on V2.0 of "**spacal-simulation**" which is a ECal simulation framework developed by group of CERN.
- Reconstruction(Files · master · Jiale Fei / ECAL_Reconstruction · GitLab (cern.ch)) : An independently developed multi-layer calorimeter reconstruction framework with ease of use and good generalisability.

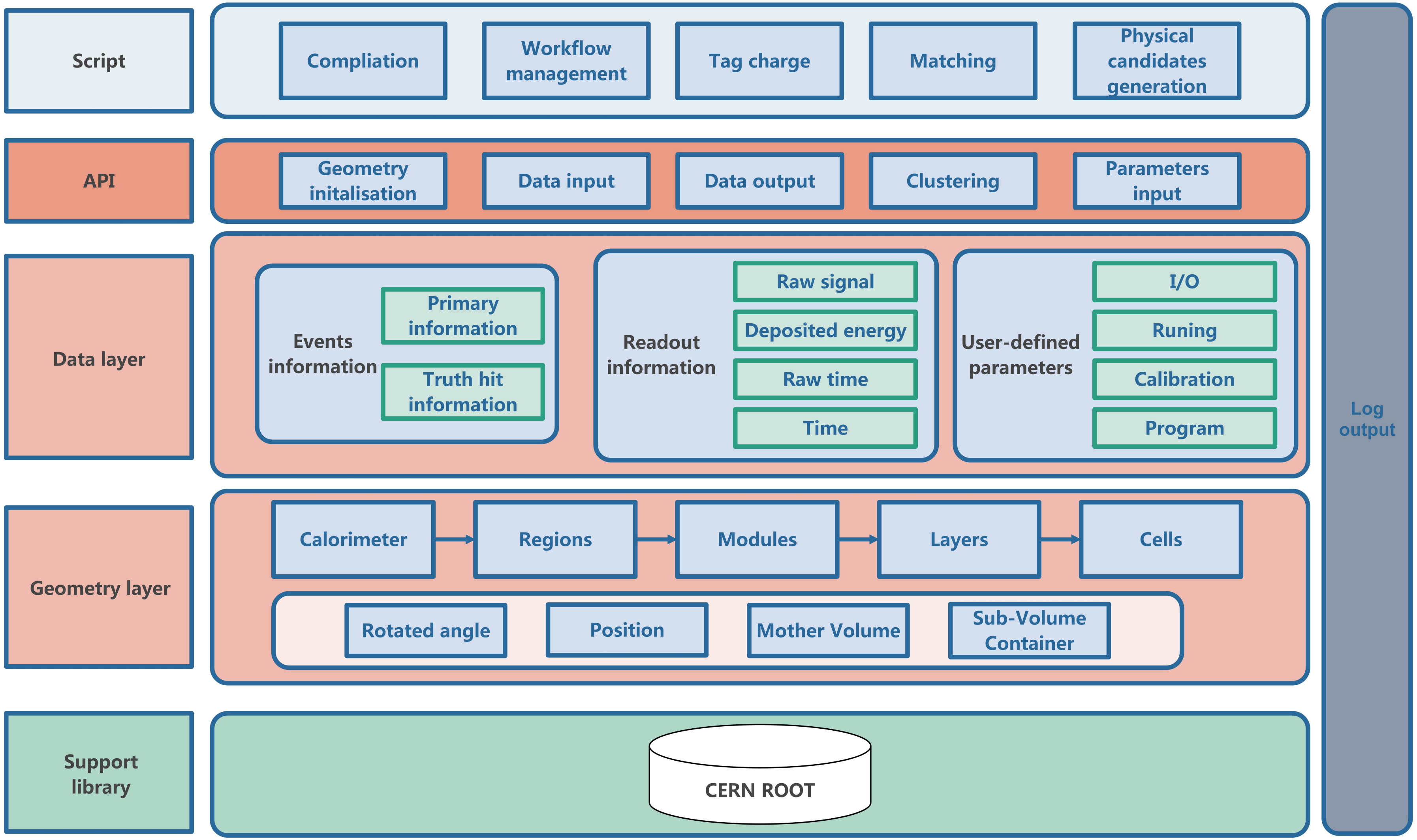




Workflow of our project

■ Reconstruction framework

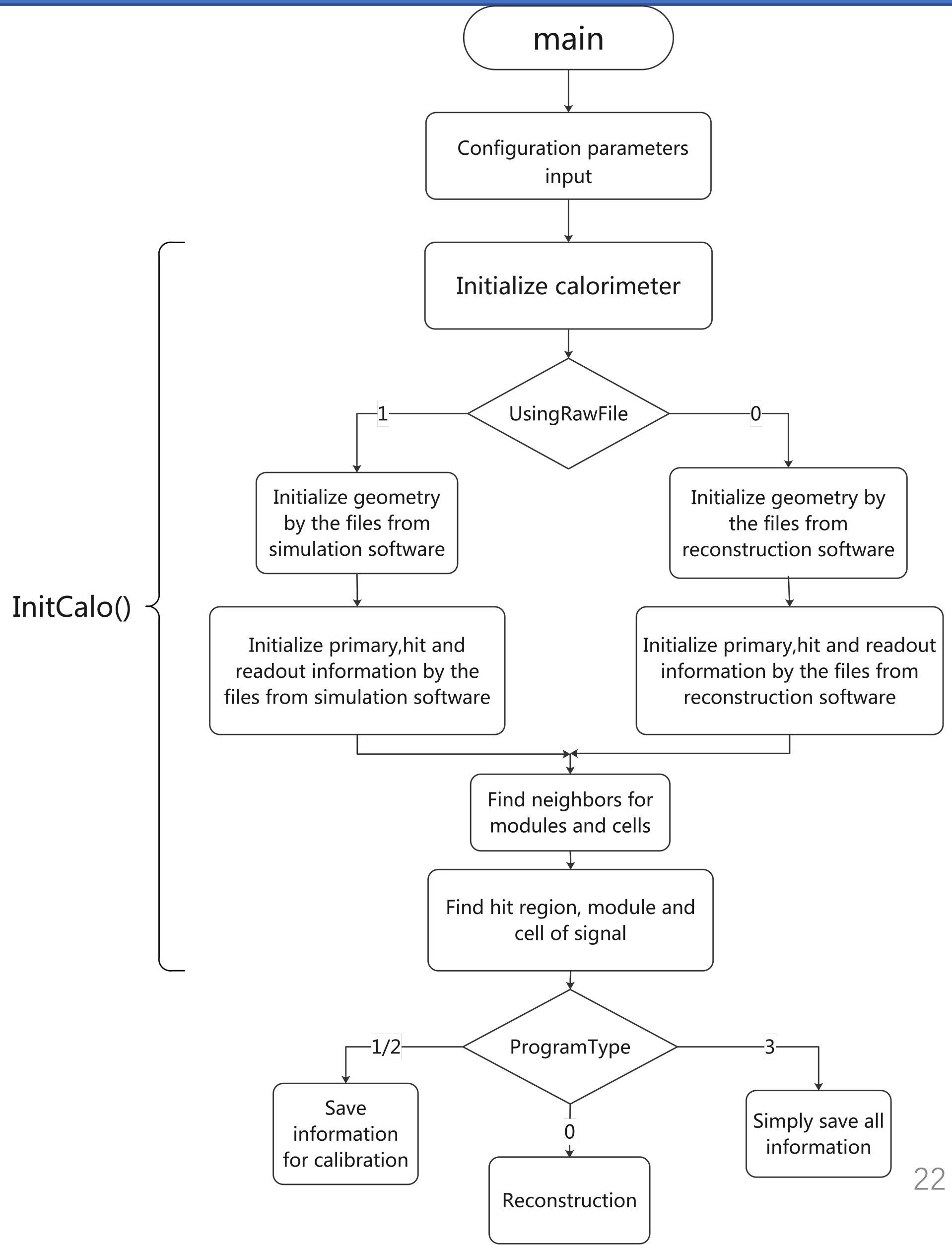
- ➢ Deal with multi-layer and rotated calorimeter.
  - Shashlik
  - SPACAL
  - Si-W
  - SPACAL-Silicon
  - SPACAL-LAPPD
  - ……
- ➢ User friendliness
  - A lot of scripts are provided.
  - Compatible with “spacal-simulation”



■ Program selection

- The running program will be determined by configuration parameter "ProgramType" (int).
- Different values corresponding to different cases :
  - 0 : Reconstruction
  - 1 : Save information for cell calibration.
  - 2 : Save information for cluster correction.
  - 3 : Simply save all information.

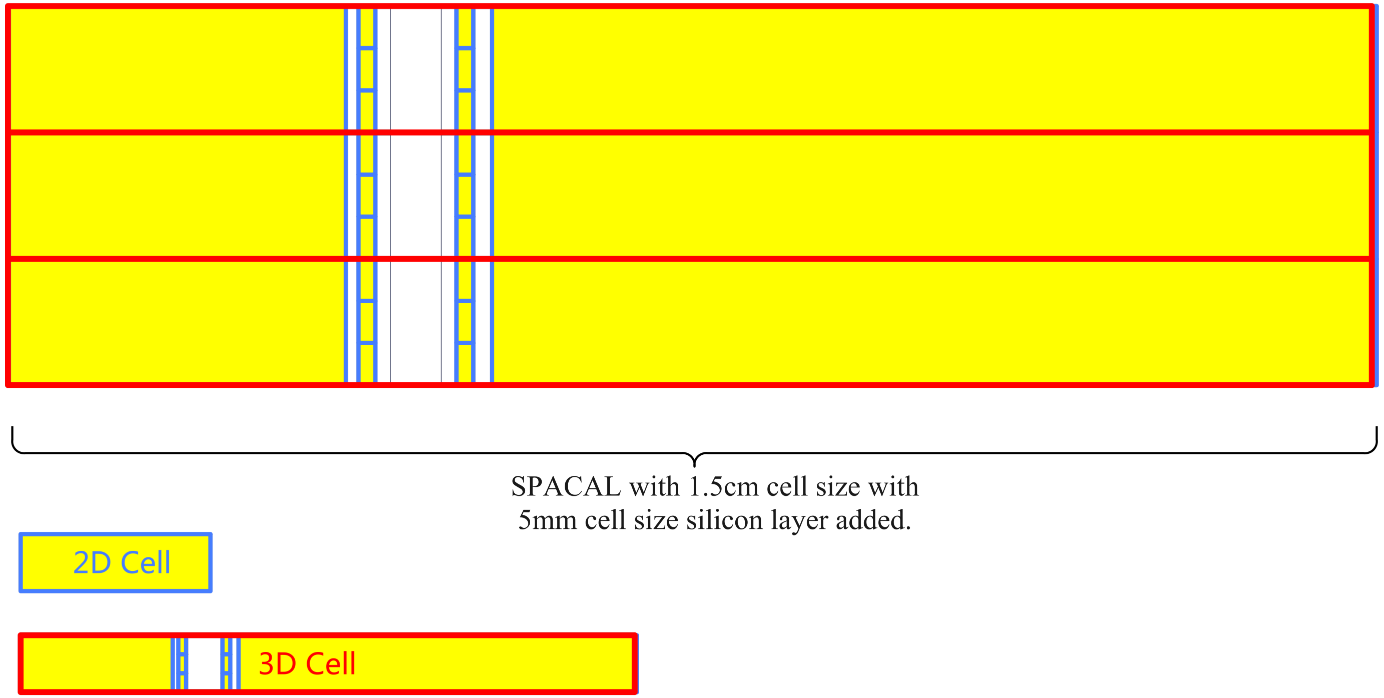
- https://gitlab.cern.ch/jfei/ecal_reconstruction/



■ Definition of 2D and 3D

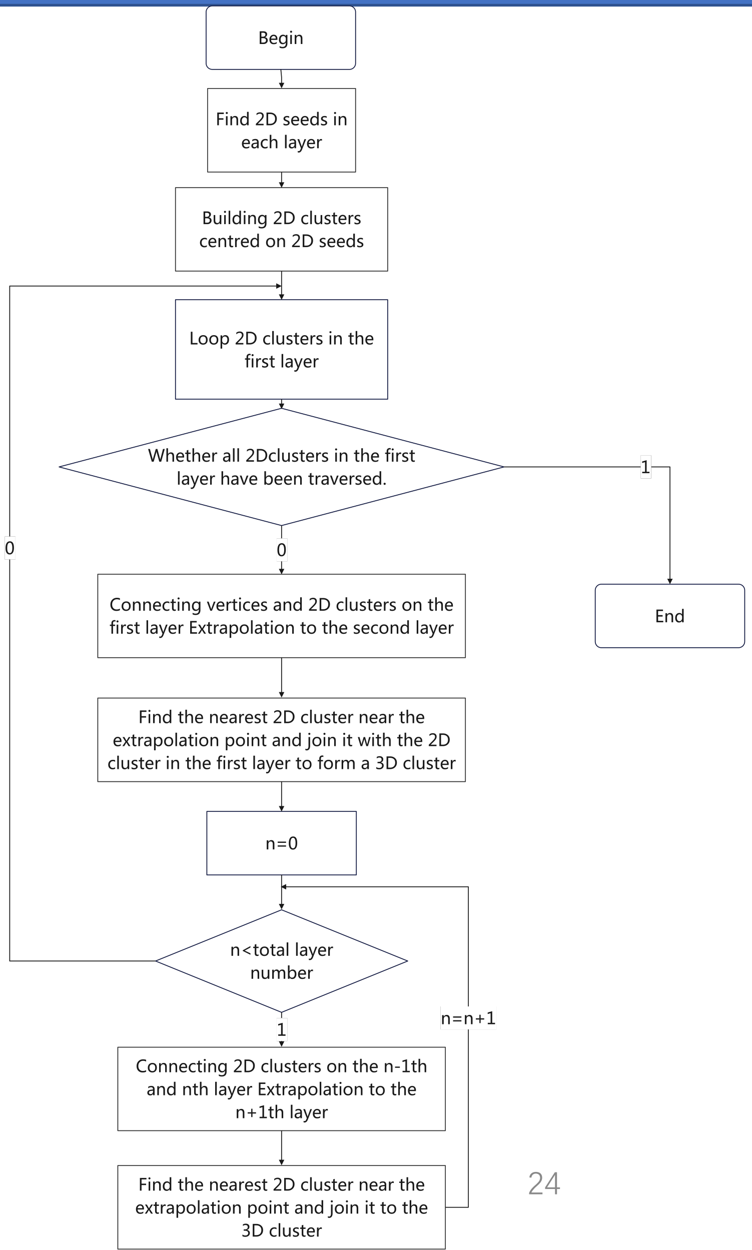
- ➢ For the cell, the 3D cell consists of multiple 2D cells. The energy of the 3D cell is the sum of the energy of the 2D cells. The coordinate of a 3D cell is its geometric centre.

- ➢ For the cluster, the 3D cluster consists of multiple 2D clusters.



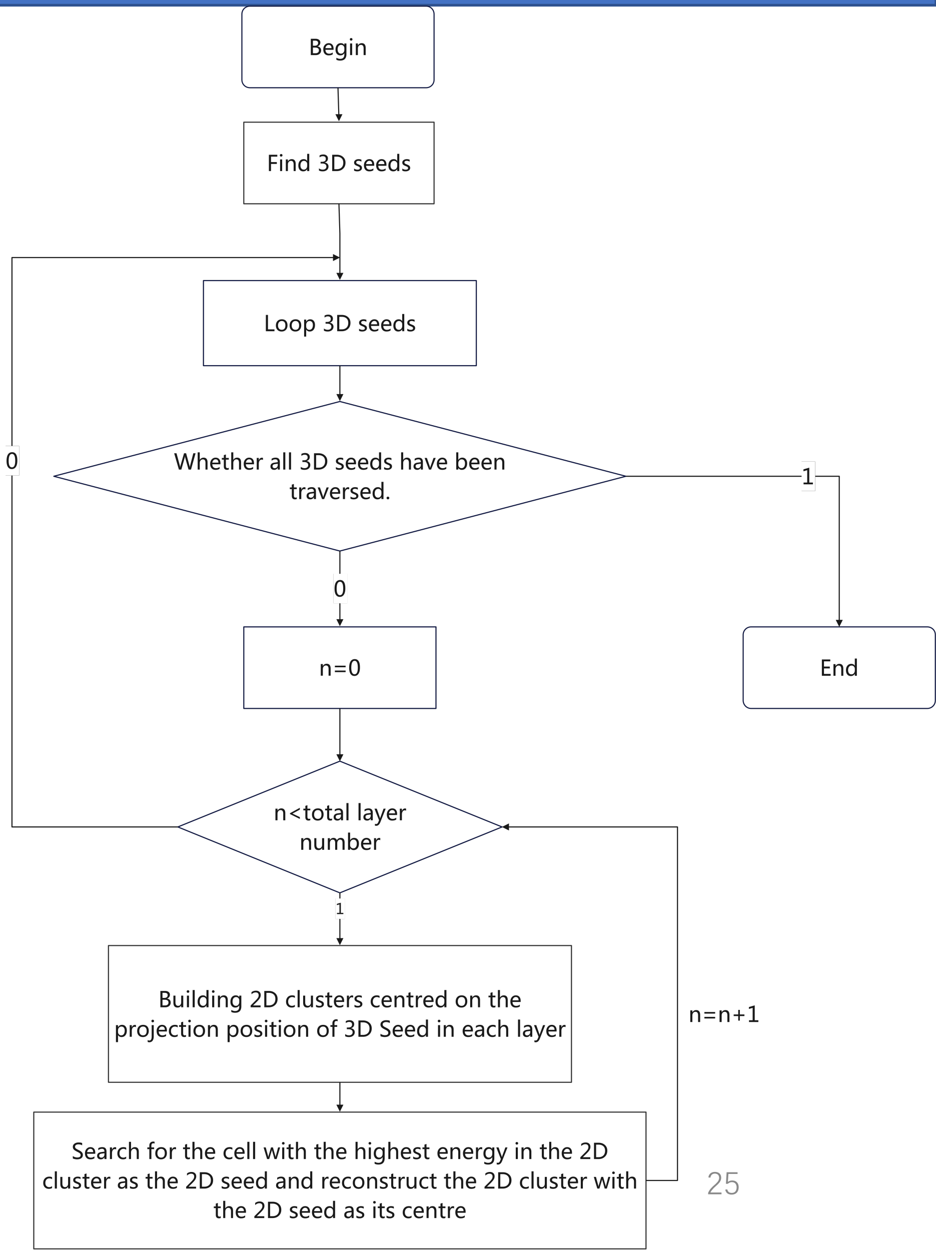
■ Reconstruction

- Method 1 to build 3D cluster
  - Search for a local maximum as a 2D seed in the readout cell of the calorimeter in each layer. construct a 2D cluster with the 2D seed as the centre, connect the initial vertex with the 2D cluster in the first layer, extrapolate it to the second layer, and search for the most correlated 2D cluster in the second layer within a certain error range. Connect the 2D clusters of the first layer with the second layer extrapolated to the third layer. And so on until all layers are traversed. All connected 2D clusters will form 3D clusters



■ Reconstruction

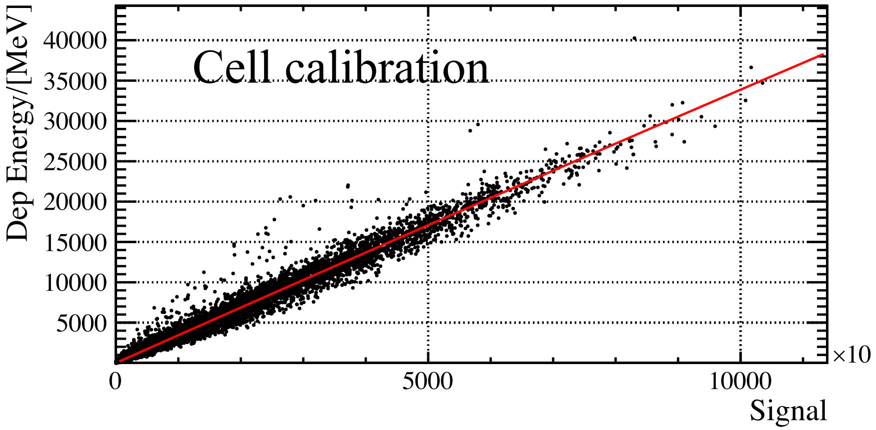
- Method 2 to build 3D cluster
  - Merge multi-layer readout cells to construct a 3D readout cell with the same size as the module Moliere radius. Search for local maximum in the 3D readout cell as 3D Seed, construct 2D clusters in each layer centred on the projection position of 3D Seed in each layer, and merge all the 2D clusters corresponding to 3D seed to obtain 3D clusters. Then re-search the Cell with the largest energy in each 2D Cluster as the 2D seed of each 2D Cluster. and reconstruct each 2D Cluster of the 3D Cluster centred on the 2D seed.

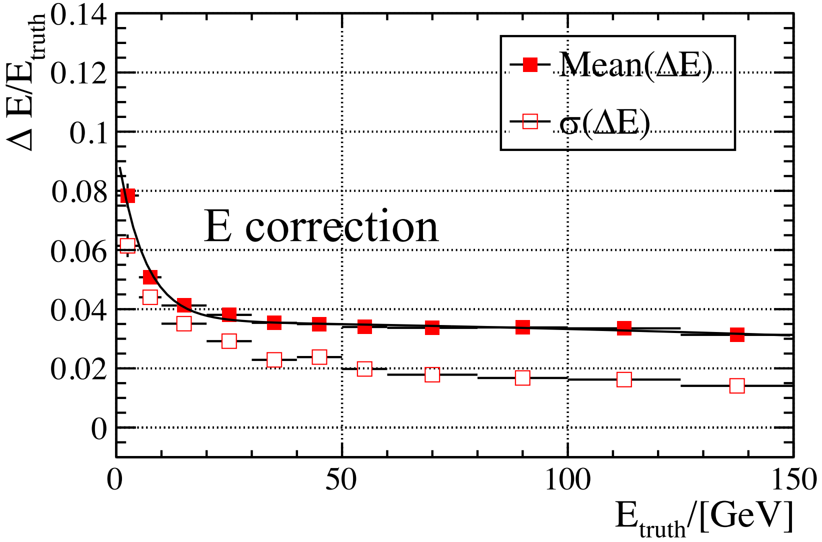


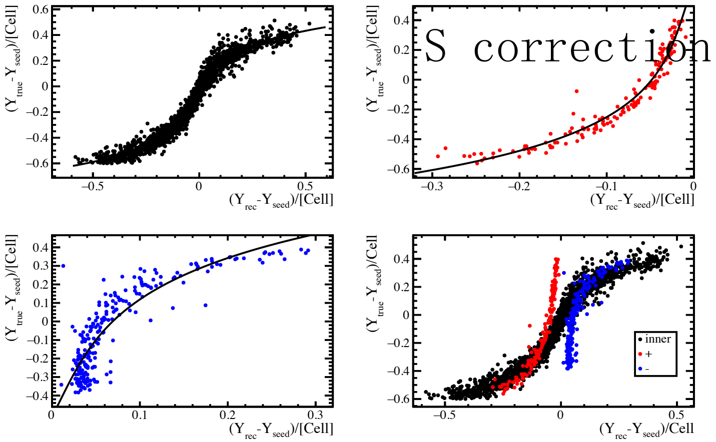
■ Calibration and correction

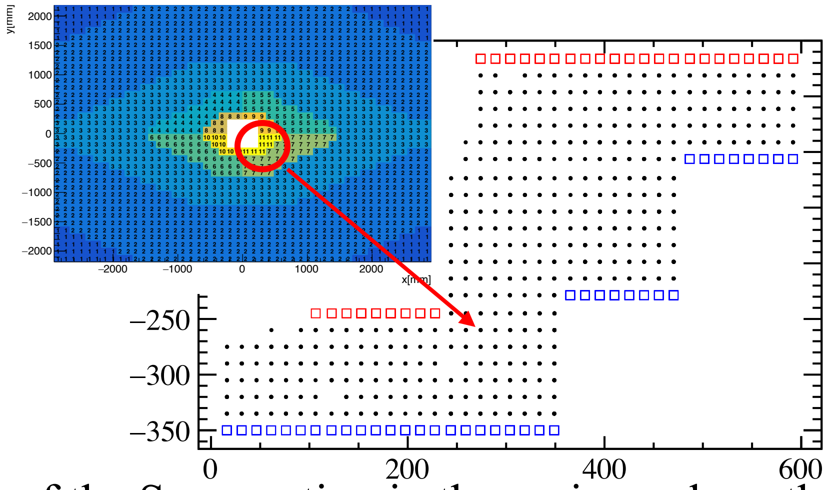
➢

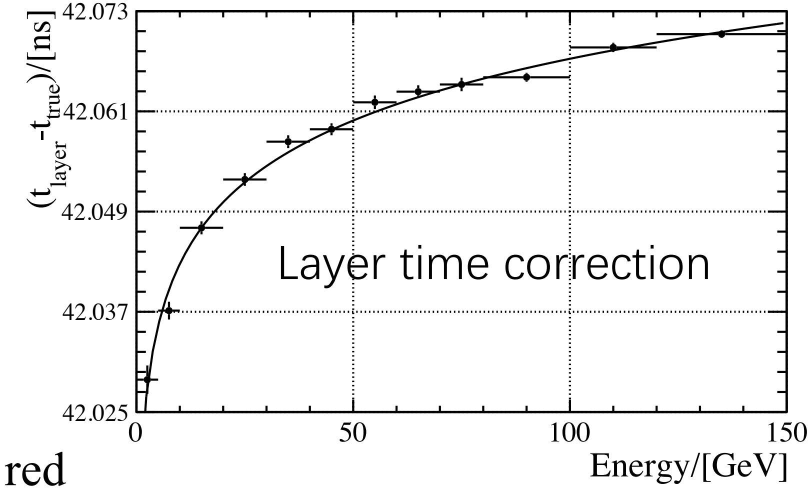
- Cell calibration
- Cluster E correction
- S and L correction
- Layer time correction







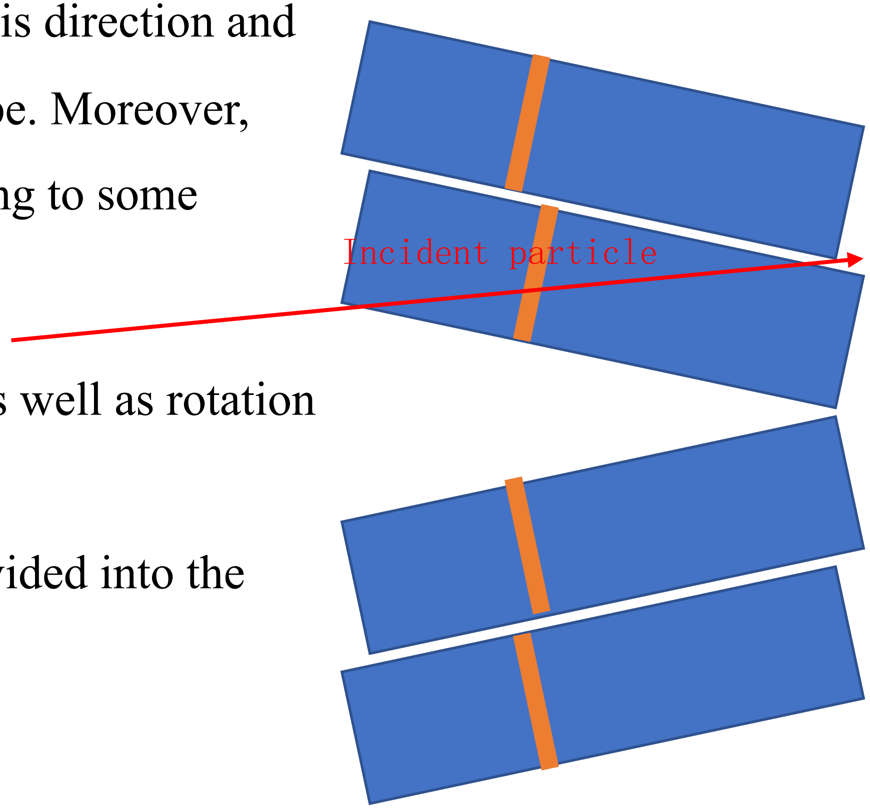




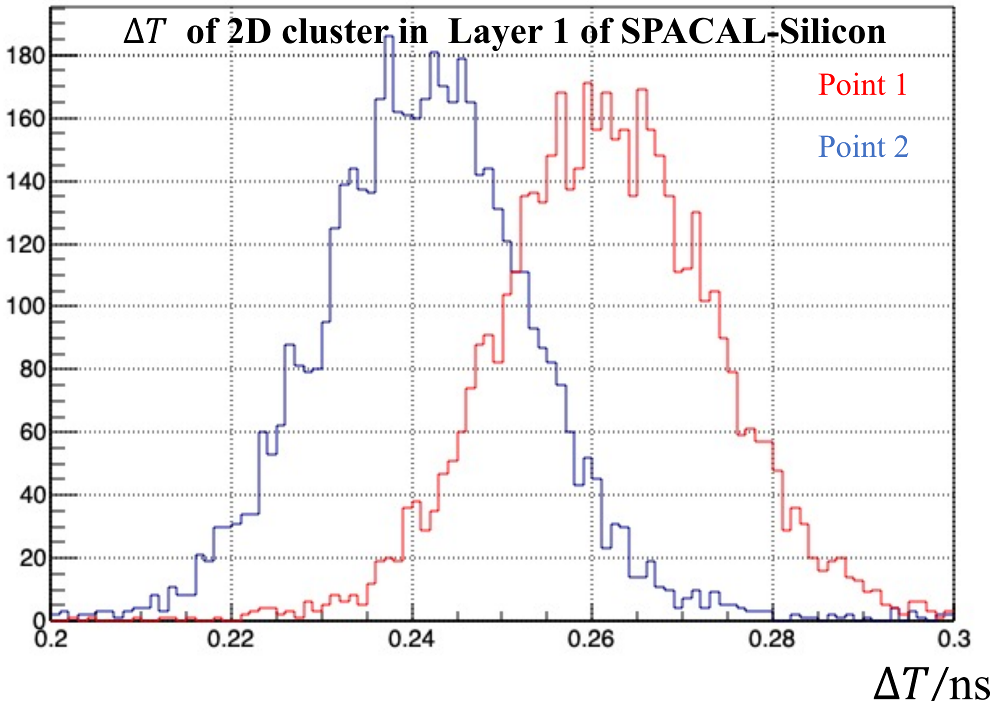
Position of the different components of the S-correction in the region, where the red and blue components are located at the edges of the region.

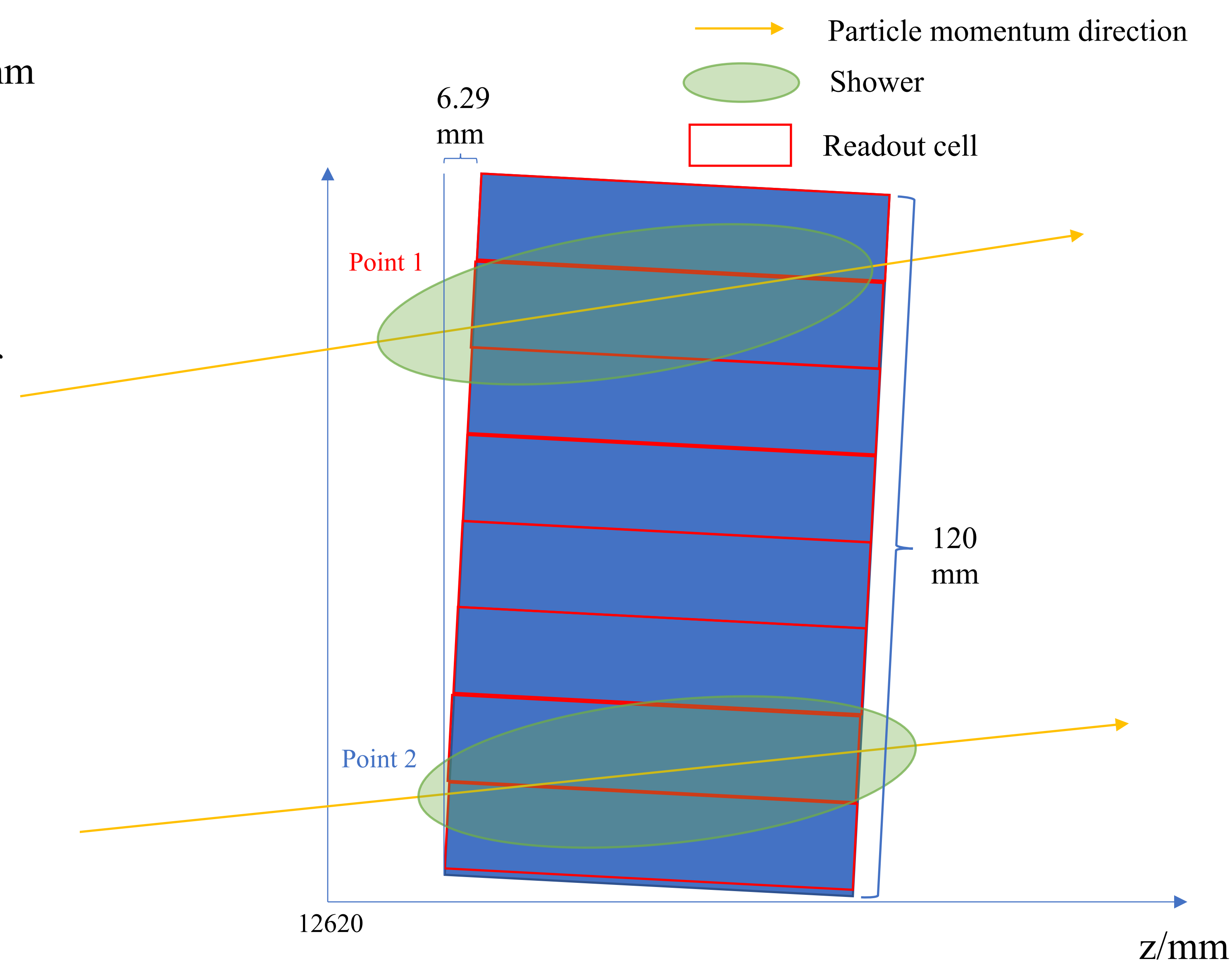
■ Rotated case

- Due to the rotation of the modules, the modules are no longer parallel to the Z-axis direction and the layers are no longer aligned with each other between modules of the same type. Moreover, there will be large gaps between modules with different rotation directions, leading to some energy leakage.
  - Consider global and relative coordinates (relative to the module) for cells, as well as rotation angles.
  - Cells with the same relative z-coordinate and the same rotation angle are divided into the same layer.
  - Compensates for energy losses caused by seams.
  - Compensation based on rotation angle and relative position of 2D clusters when performing time calibration (next page)



- T_{Tru} : truth time of particle in plane z=12620 mm
- $\Delta T = T_{clu2D} - T_{Tru}$
- Consider two 2D clusters (right figure),one point in the upper part of the module, another point in the lower part of the module , about $6/299.79 \approx 20$ ps bias will induced to the ΔT of those two points





- **Using point 1 to correct the time of point 2 will induce the bias of ΔT !**

Summary and outlook

- Completed the development of a general reconstruction framework for multi-layer calorimeters, providing a complete workflow configuration script for simulation and reconstruction, which allows flexible simulation and reconstruction of different calorimeters.

- In particle gun simulation, the SPACAL-Silicon module achieve similar energy resolution and better time and position resolution than standard SPACAL which meets our design expectations.

- Based on same reconstruction process, the SPACAL-Silicon perform similarly to standard SPACAL on $B^0 \to K^*(K\pi)\gamma$ and better than standard SPACAL on $B^\pm \to D^*(D\gamma)\pi^\pm$

- SPACAL-Silicon provides more dimensional information both vertically and horizontally, and in the future it is hoped to design a series of algorithms to utilise those information. This would expect large performance gains in the soft γ channel and the π^0 physical channel.

Backup

Reconstruction

- The event reconstruction of the calorimeter is divided into three steps
  - Calibrate cells
  - Clustering
  - Correct clusters

- In our framework, instead of directly calibrating 3D clusters, we calibrate the 2D clusters that make up the 3D clusters. The information of the 3D clusters is then computed from the information of the 2D clusters.

Will be useful to utilize longitudinal and transverse information on clusters

- Weight for each layer related the resolution of each layer.

$$W_{layer_i} = \frac{1}{(\sigma_{layer_i}^{t/pos}(E))^2}$$

■ Performance in simulation

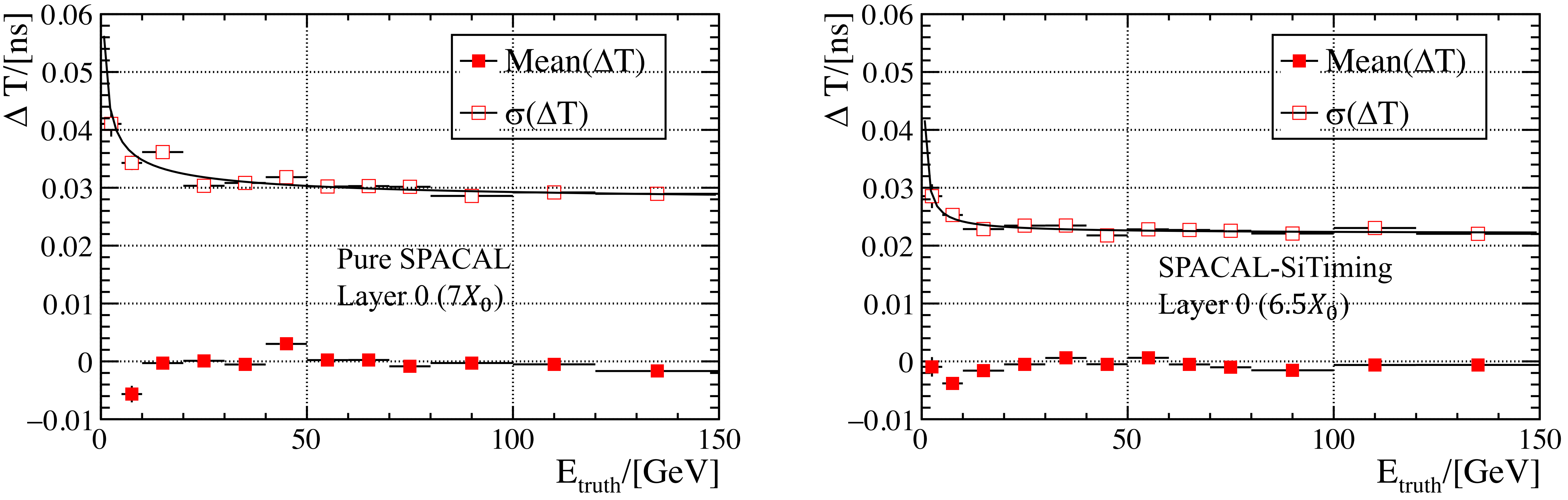
- ➢GAGG-W
  - Layers
  - Combined

- ➢Polystyrene-Pb

■ SPACAL与SPACAL-SiTiming的性能对比

➢ 前段SPACAL的时间分辨率

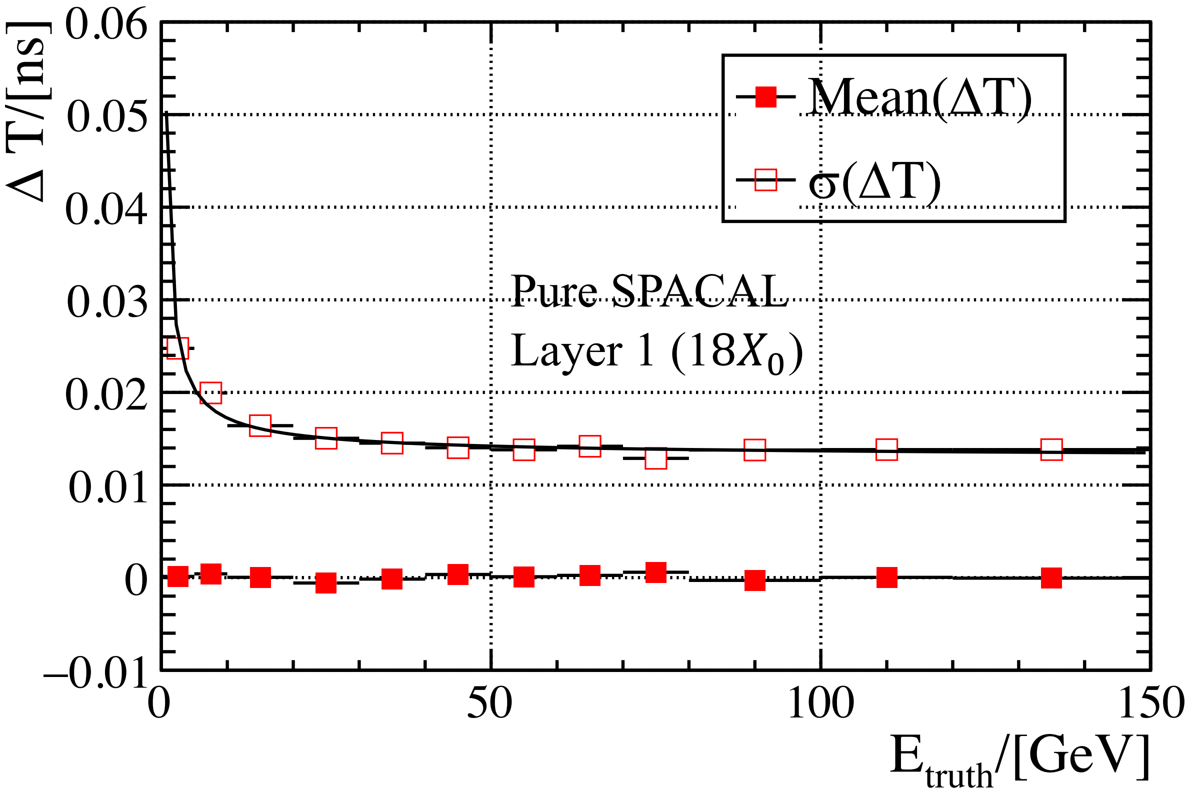
Polystyrene-Pb

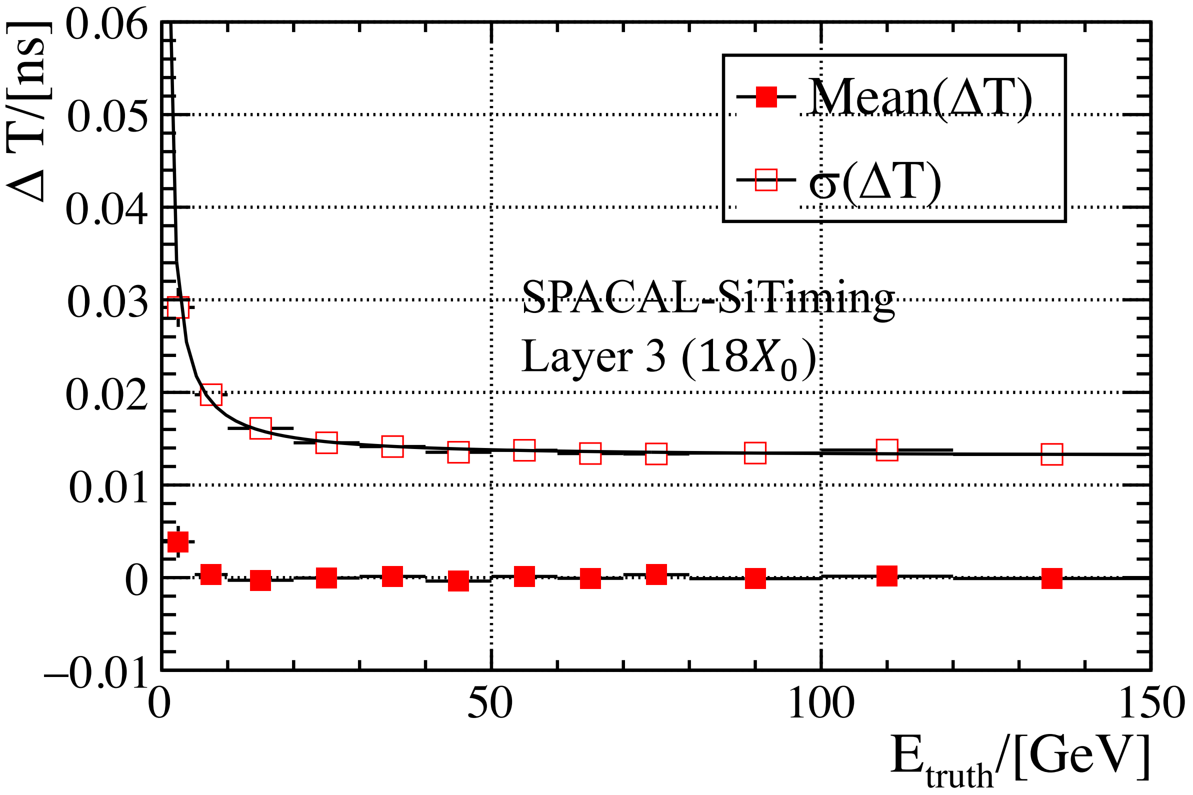


■ SPACAL与SPACAL-SiTiming的性能对比

➢ 后段SPACAL的时间分辨率

Polystyrene-Pb

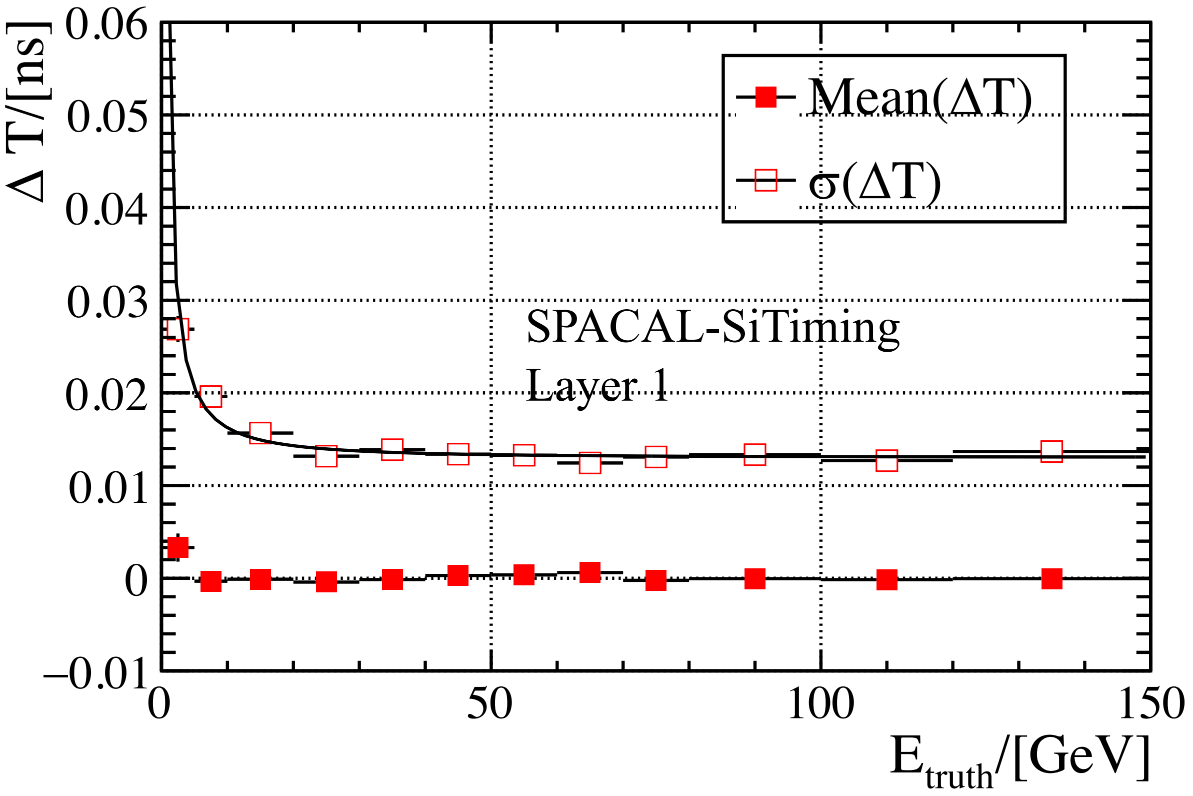


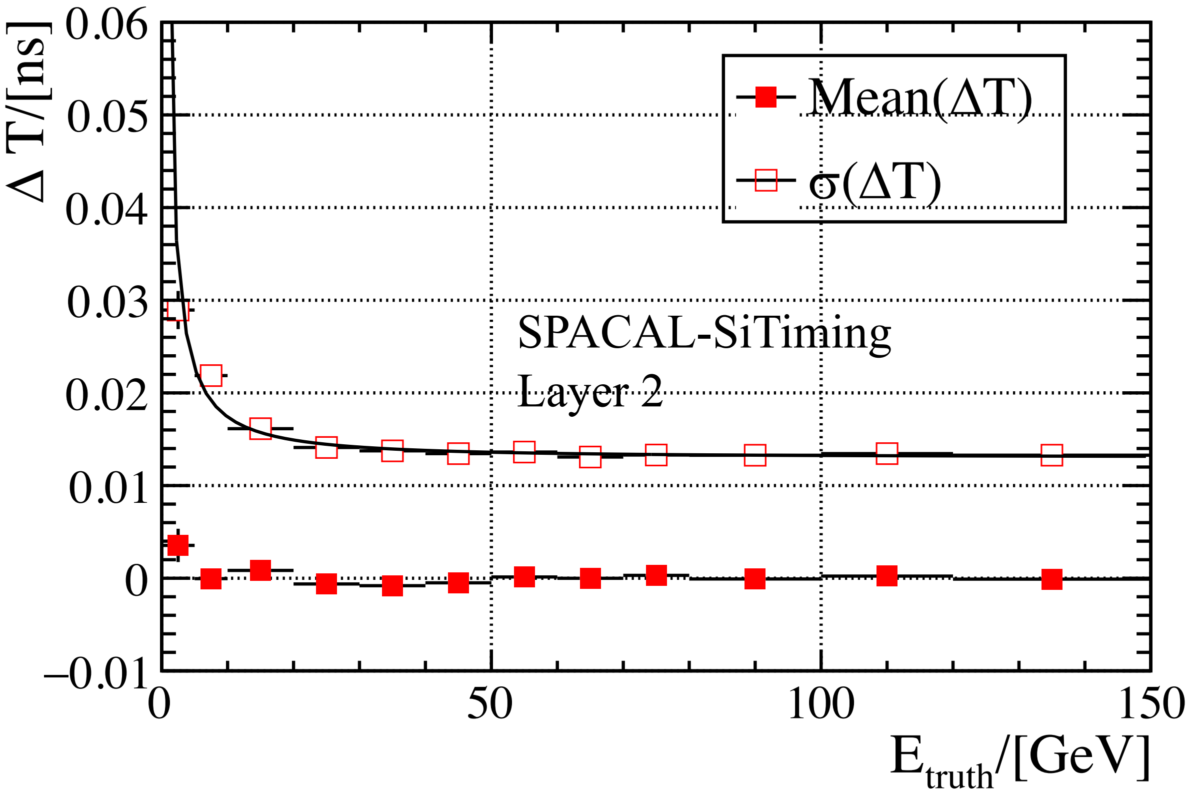


■ SPACAL与SPACAL-SiTiming的性能对比

➢ SPACAL-SiTiming的Silicon的时间分辨率

Polystyrene-Pb

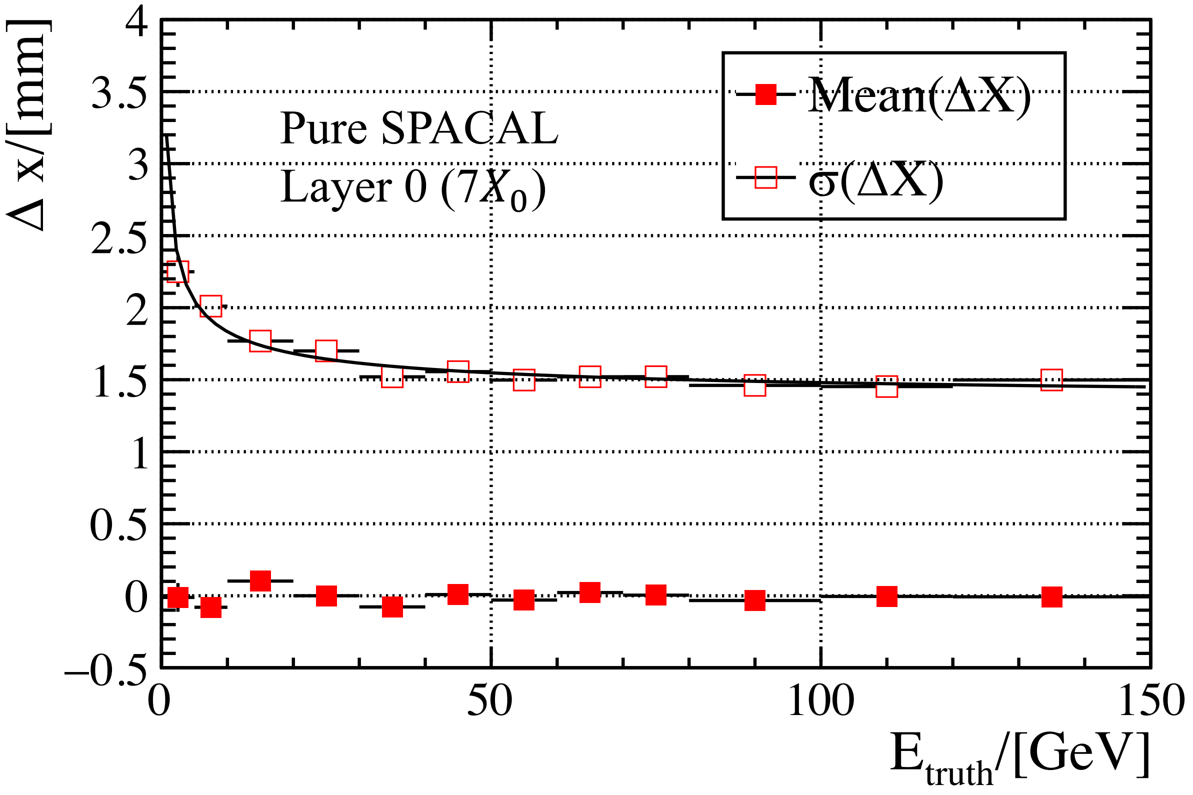


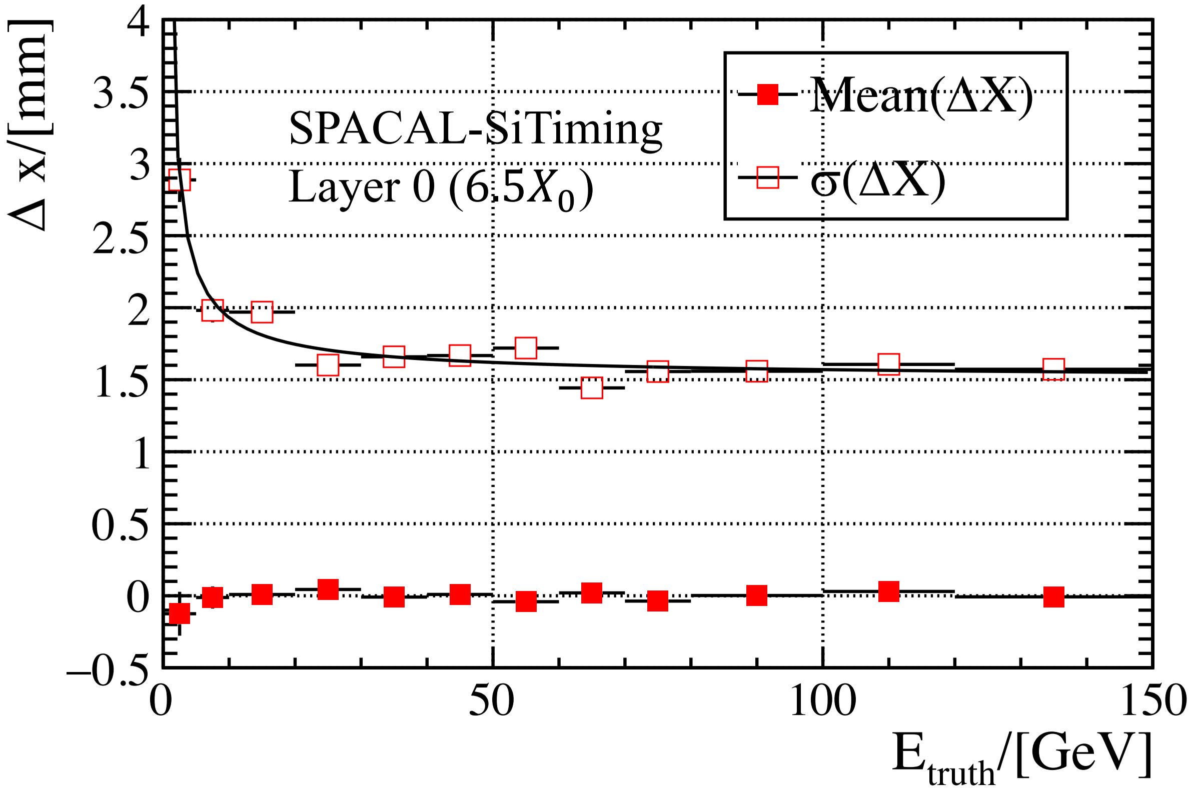


■ SPACAL与SPACAL-SiTiming的性能对比

➢ 前段SPACAL的位置分辨率

Polystyrene-Pb

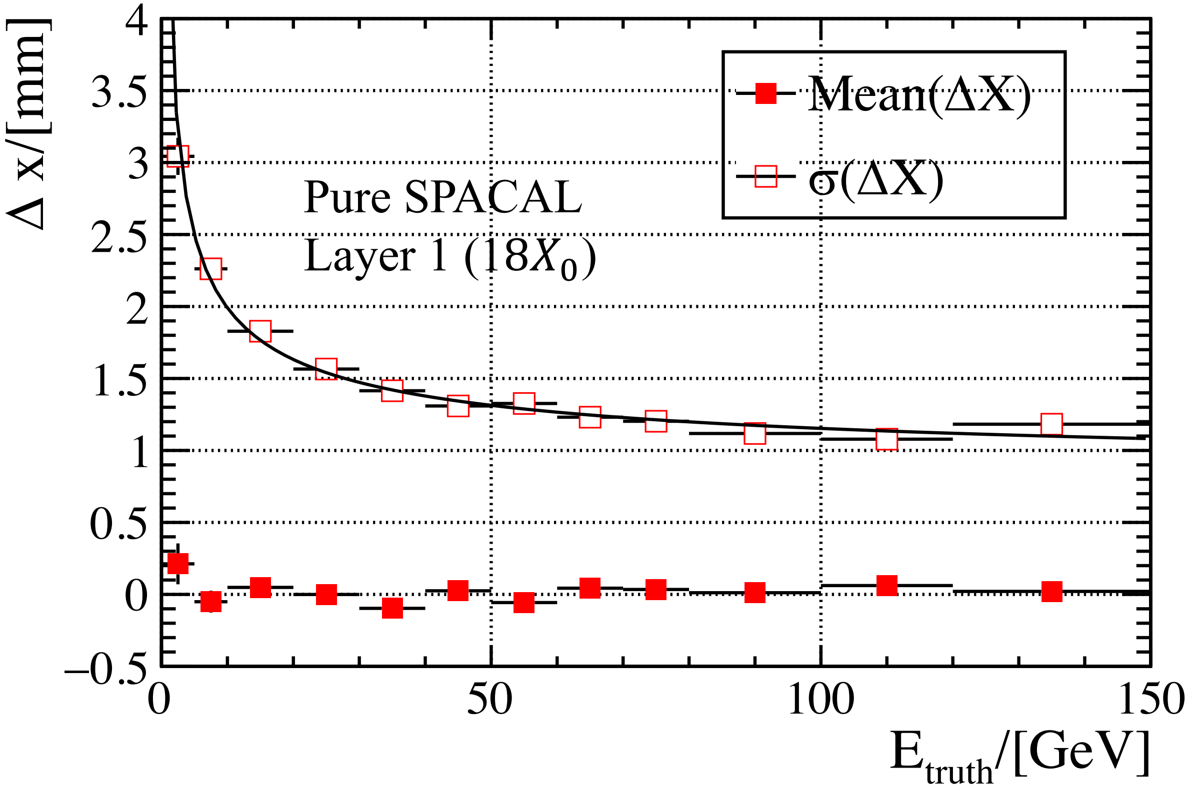


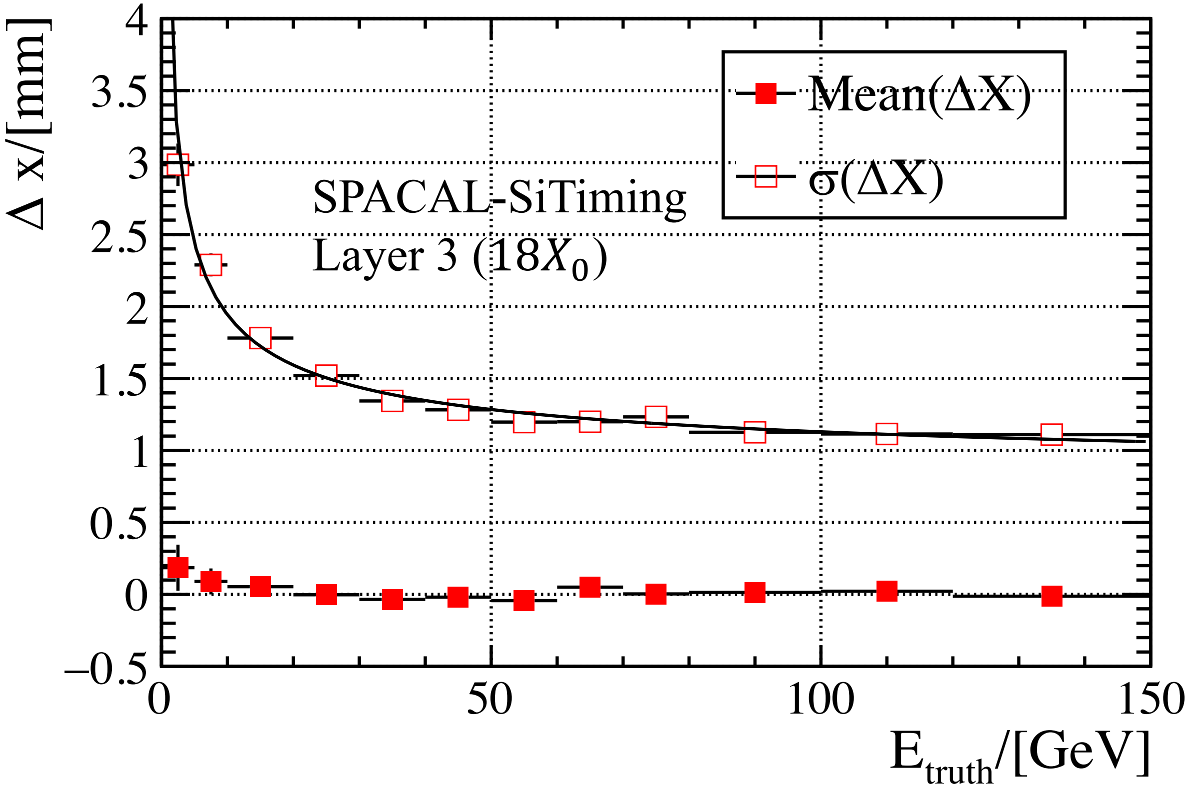


■ SPACAL与SPACAL-SiTiming的性能对比

➢ 后段SPACAL的位置分辨率

Polystyrene-Pb

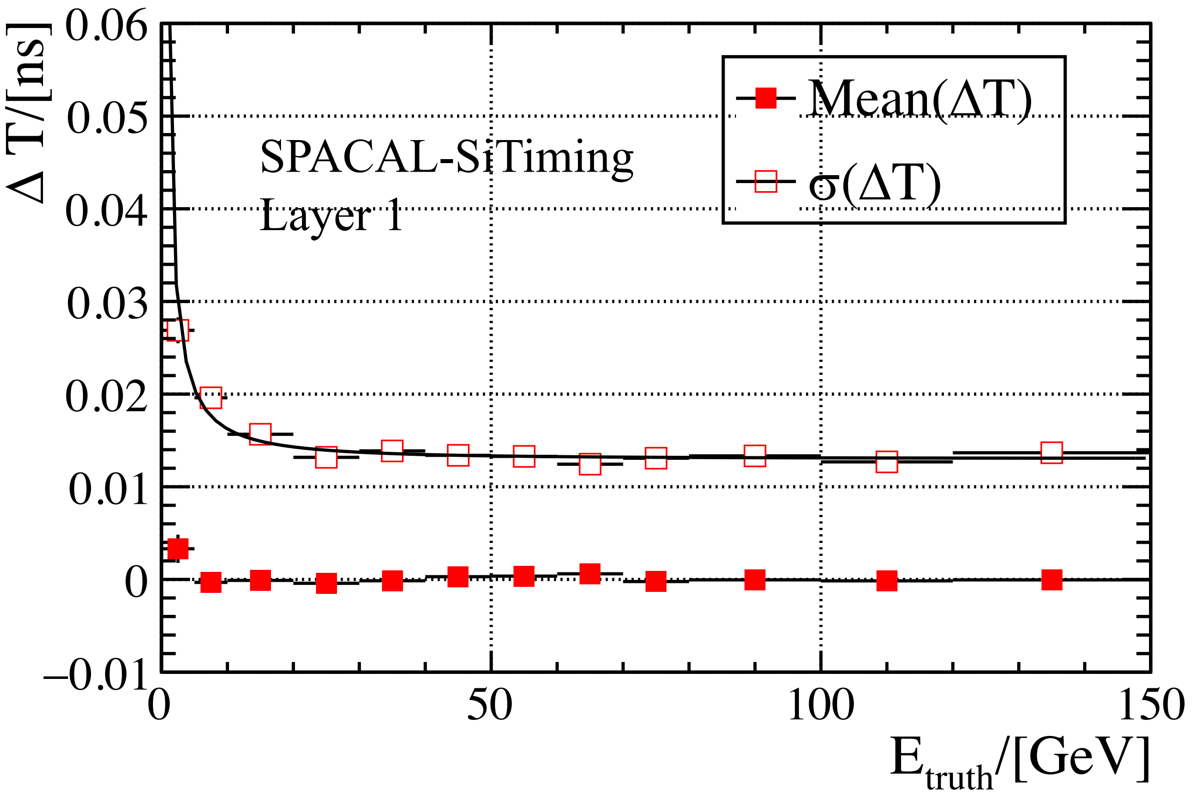


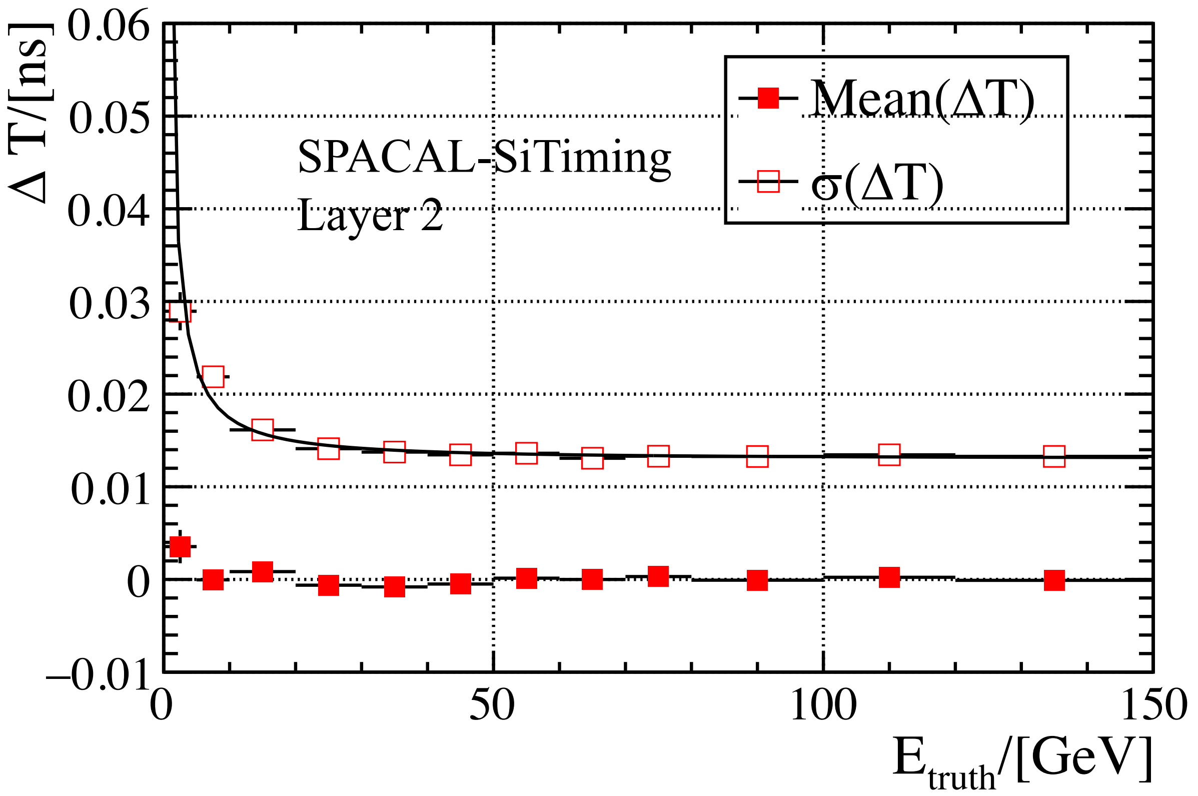


■ SPACAL与SPACAL-SiTiming的性能对比

➢ SPACAL-SiTiming的Silicon的位置分辨率

Polystyrene-Pb





■ Performance in simulation

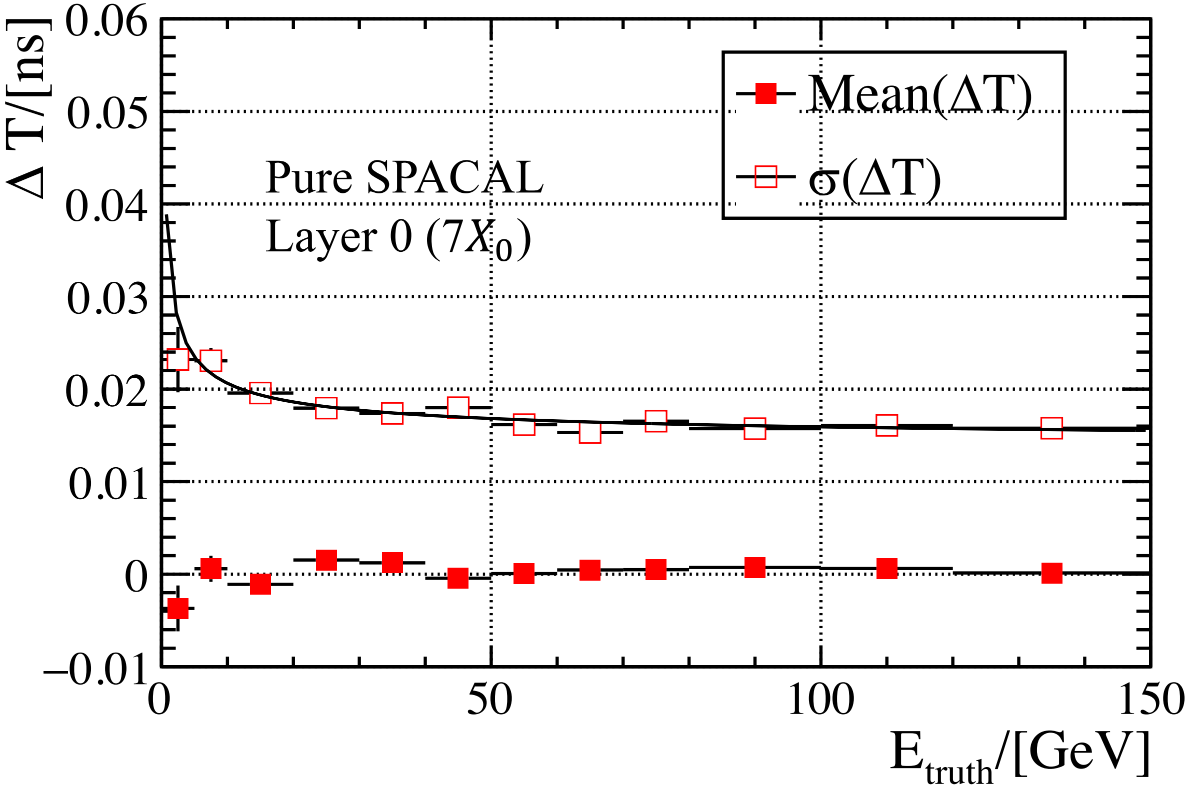
- GAGG-W

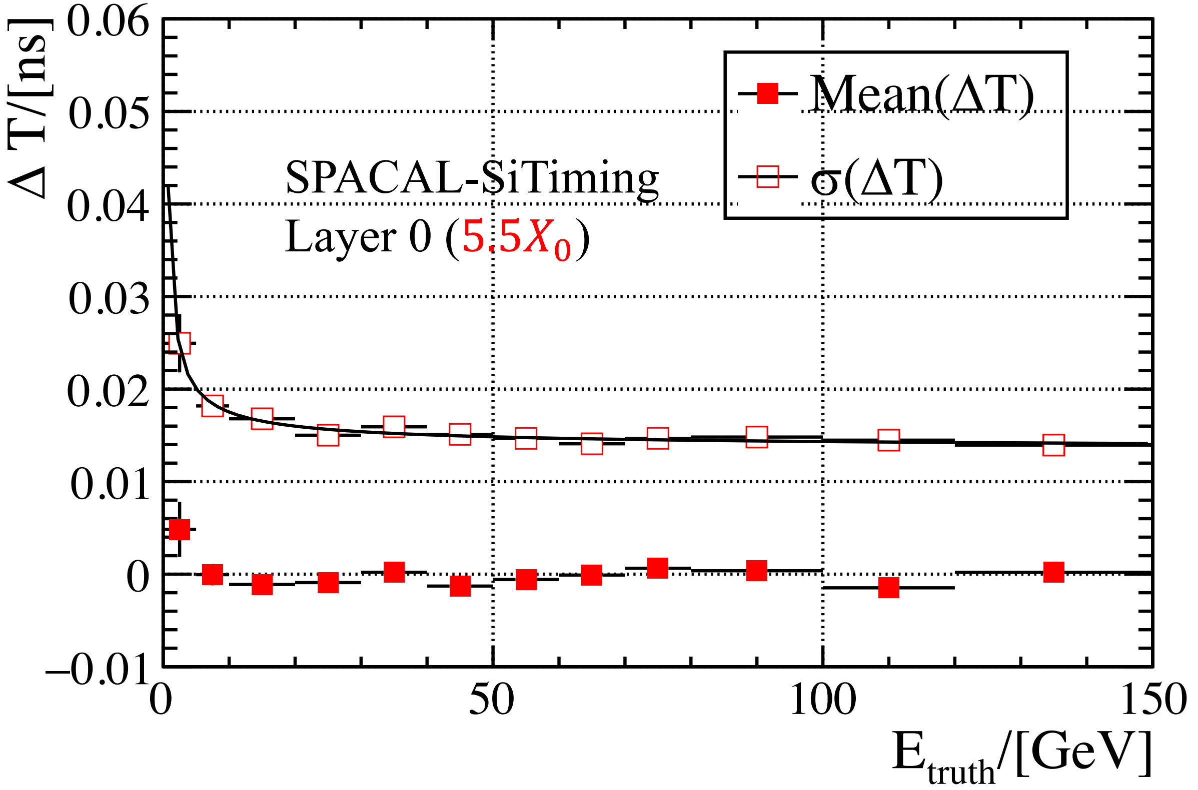
- Polystyrene-Pb
  - Layers
  - Combined

■ SPACAL与SPACAL-SiTiming的性能对比

➢ 前段SPACAL的时间分辨率

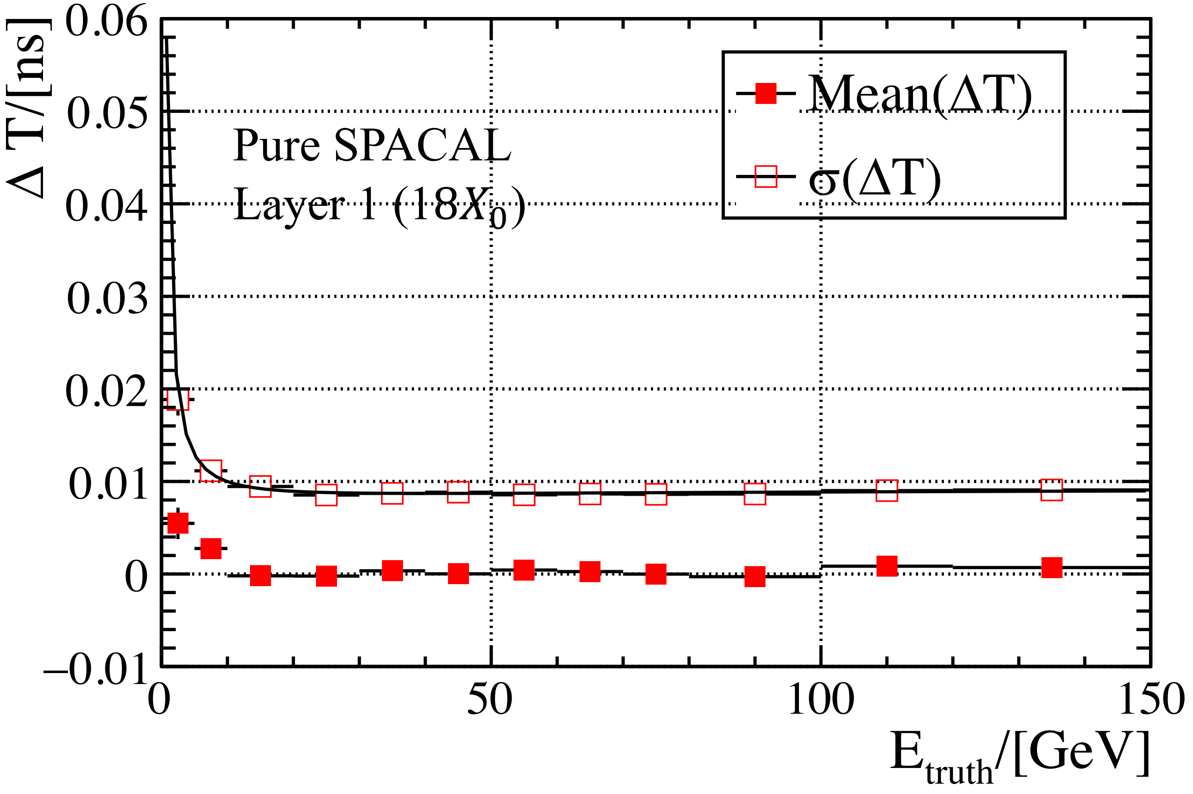
GAGG-W



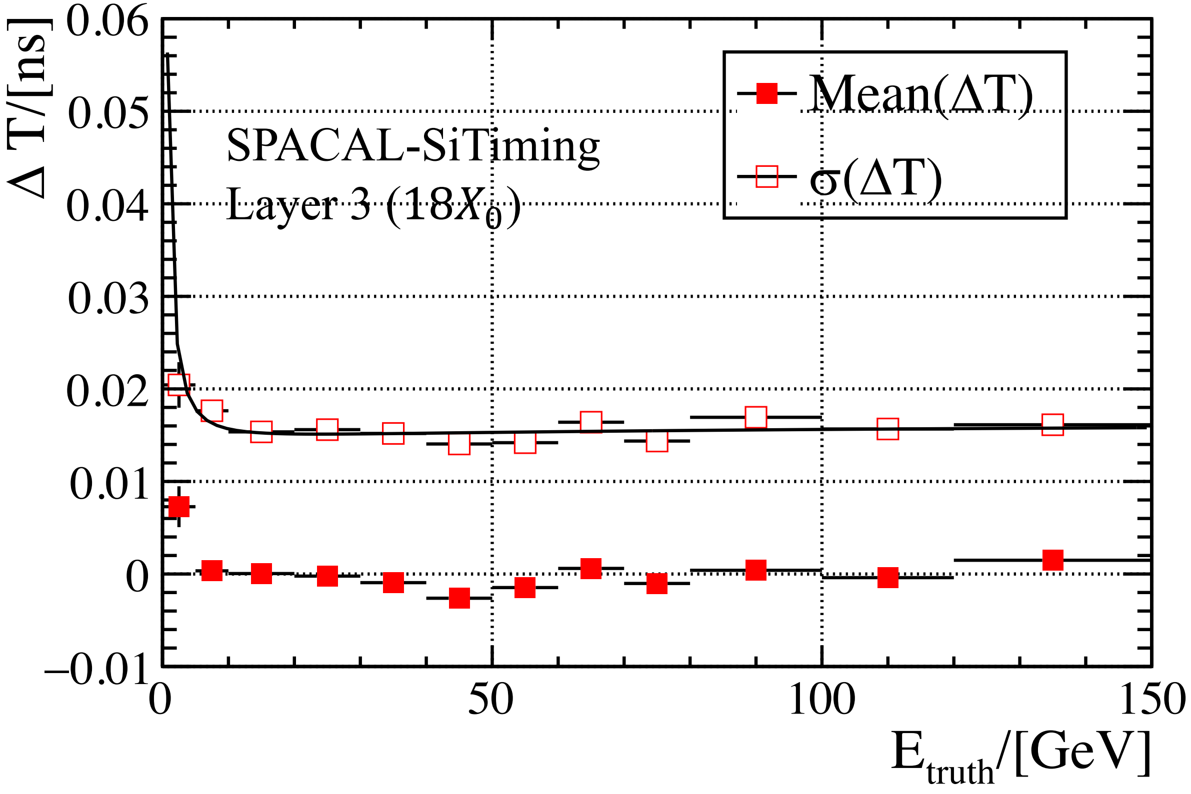


■ SPACAL与SPACAL-SiTiming的性能对比

➢ 后段SPACAL的时间分辨率



GAGG-W

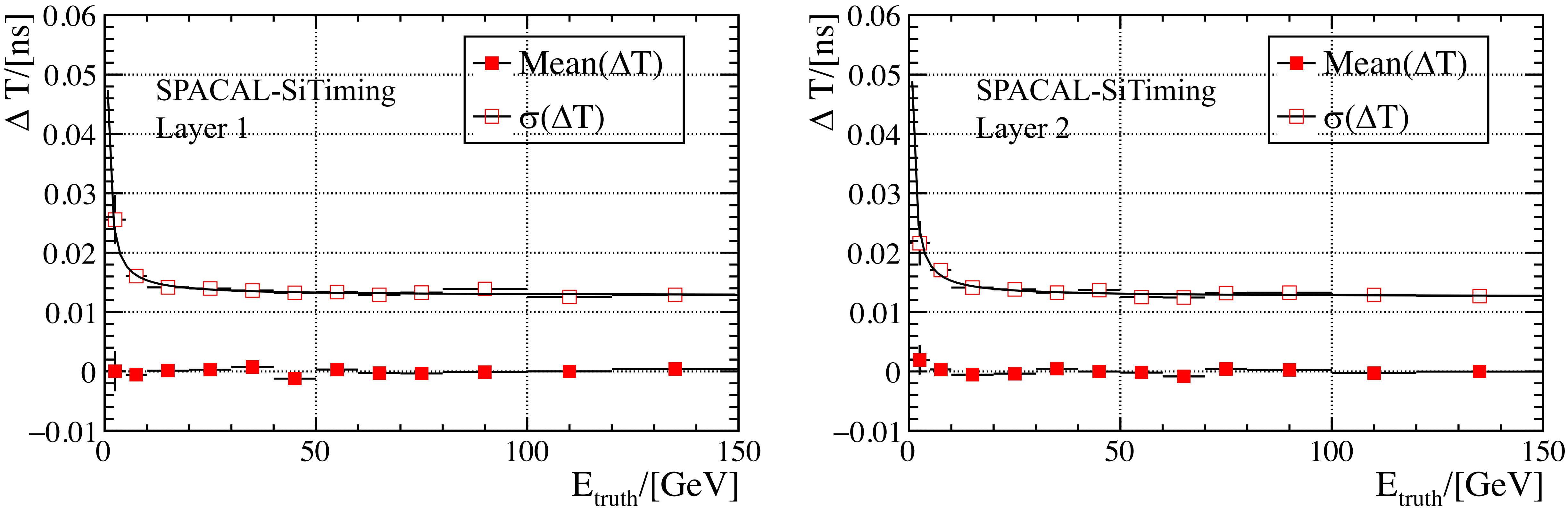


➢ 在SPACAL-SiTiming模块中由于前段SPACAL的缩短（$7X_0$ -> $5.5X_0$），后段SPACAL的时间分辨率受到了较大影响。

■ SPACAL与SPACAL-SiTiming的性能对比

➢ SPACAL-SiTiming的Silicon的时间分辨率

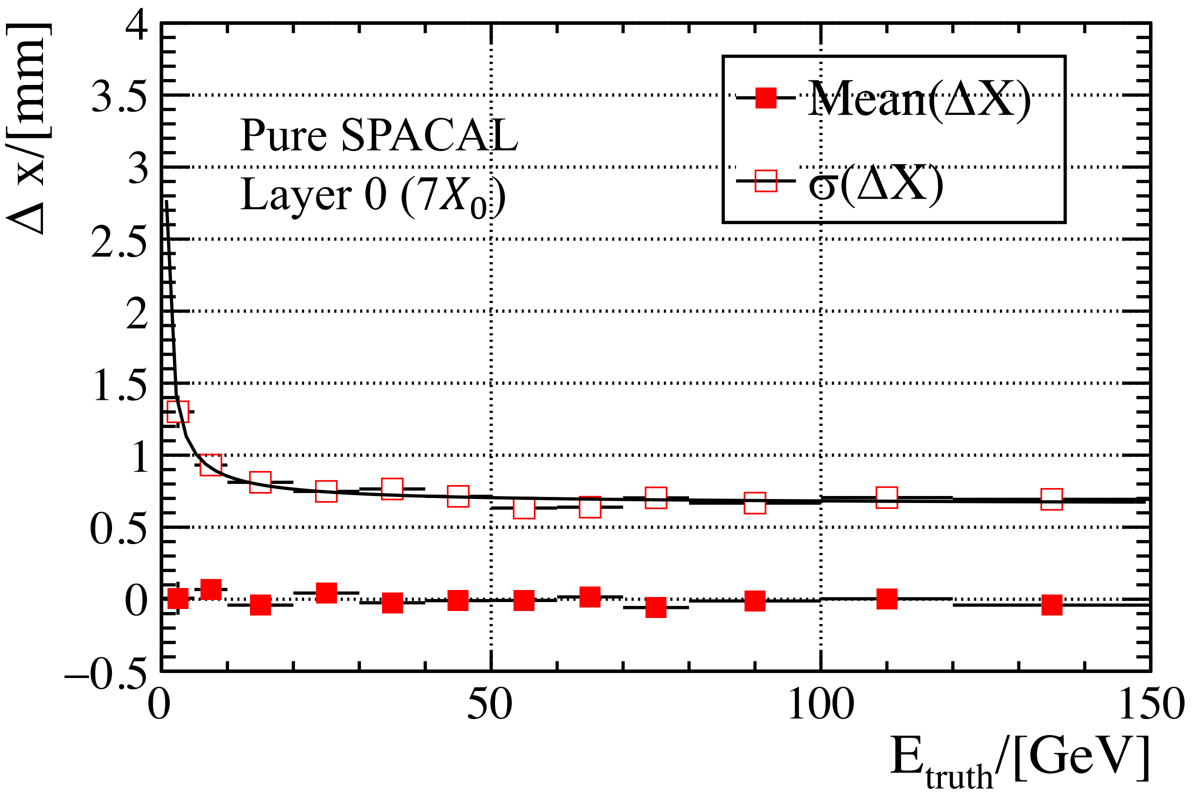
GAGG-W

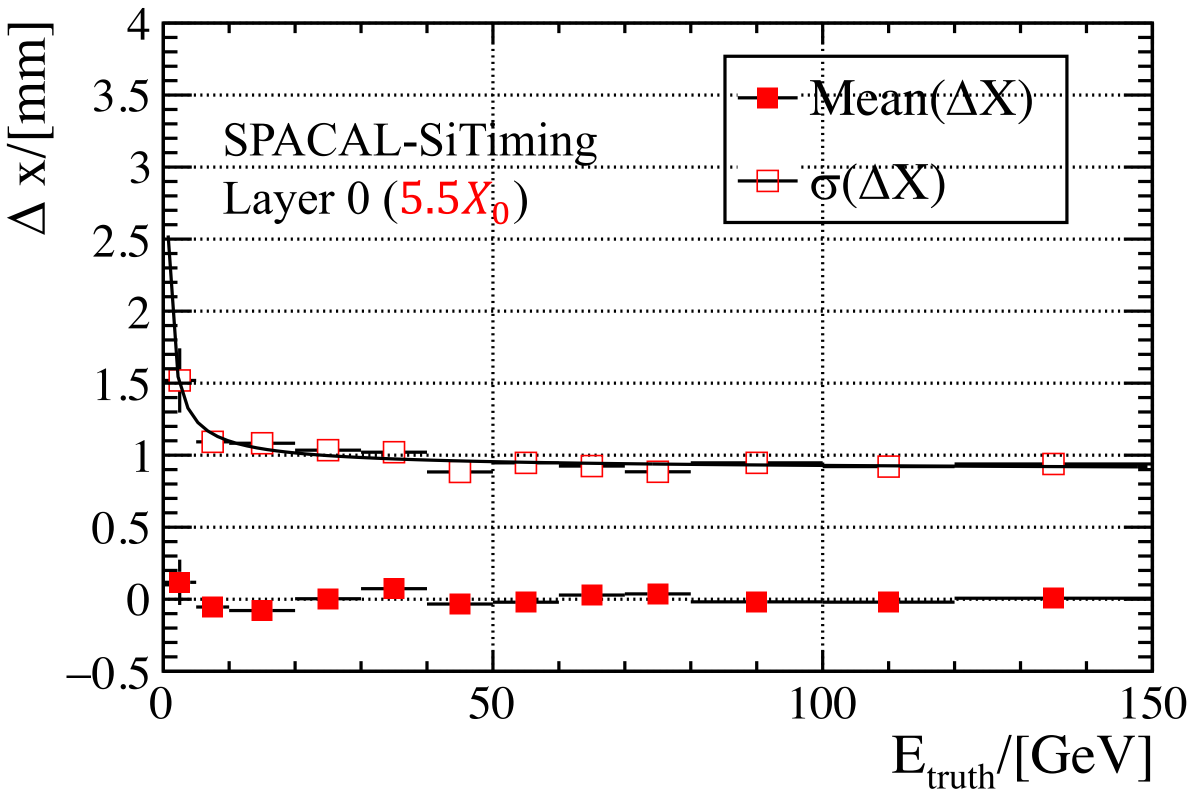


■ SPACAL与SPACAL-SiTiming的性能对比

➢ 前段SPACAL的位置分辨率

GAGG-W



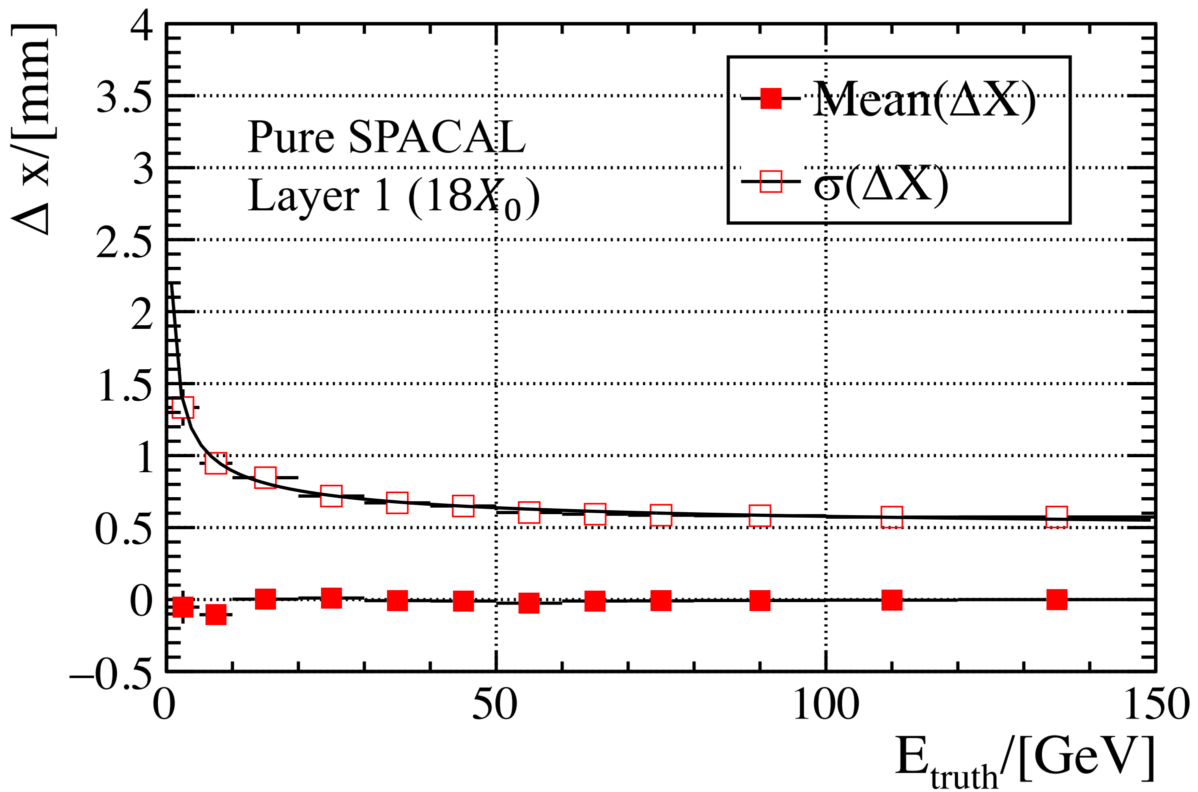


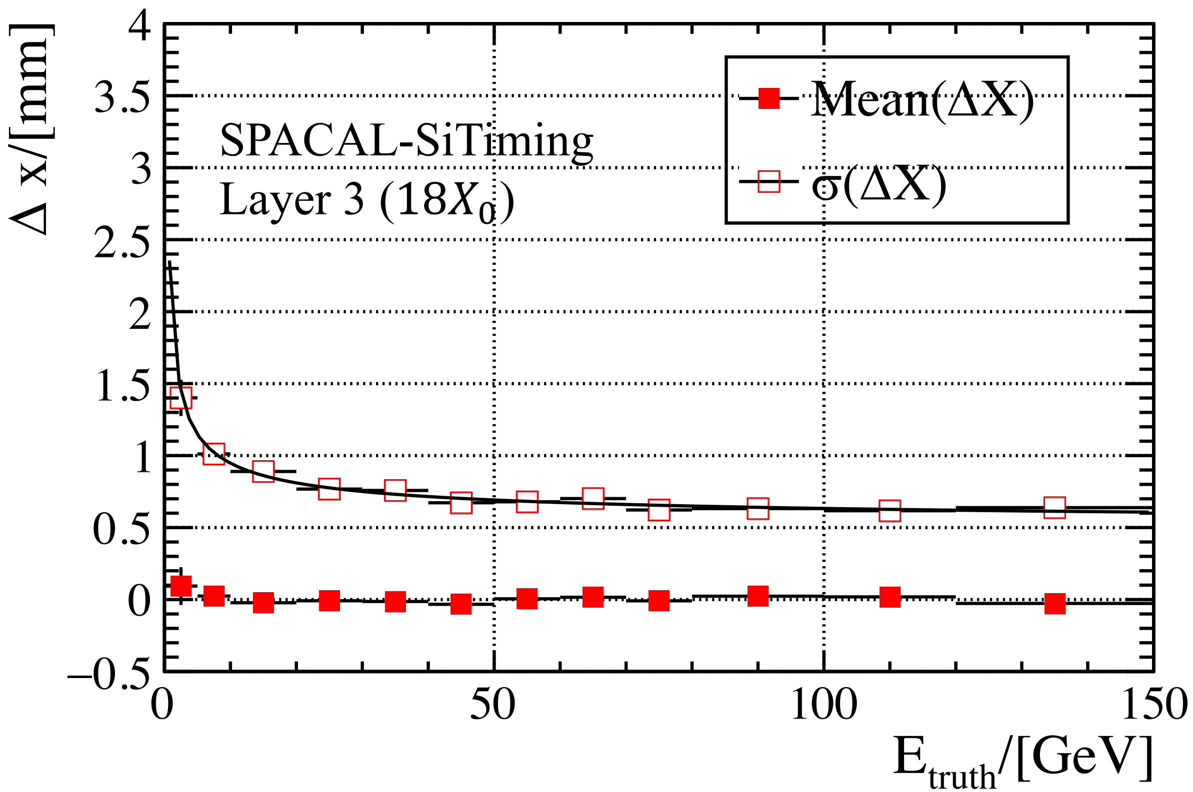
➢ 在SPACAL-SiTiming模块中由于前段SPACAL的缩短（7X_0 -> 5.5X_0），其能量沉积减少，位置分辨率受到了较大影响。

■ SPACAL与SPACAL-SiTiming的性能对比

➢ 后段SPACAL的位置分辨率

GAGG-W

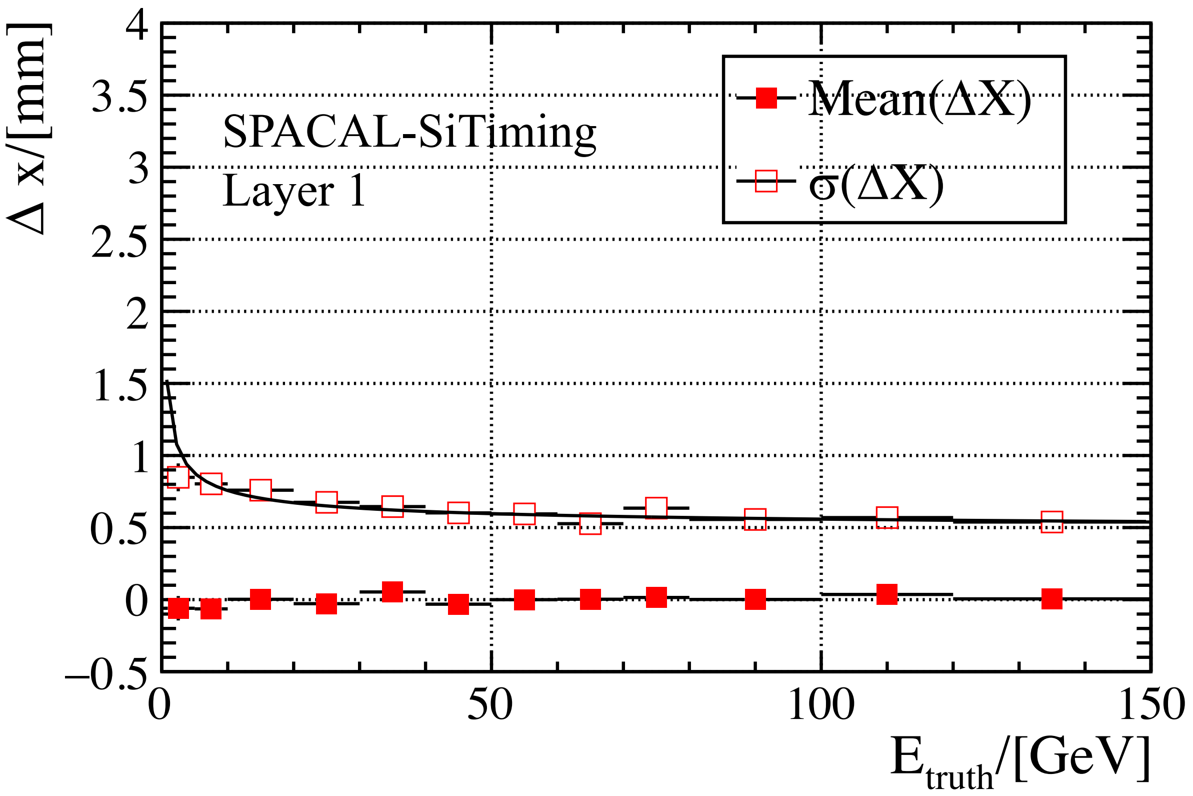


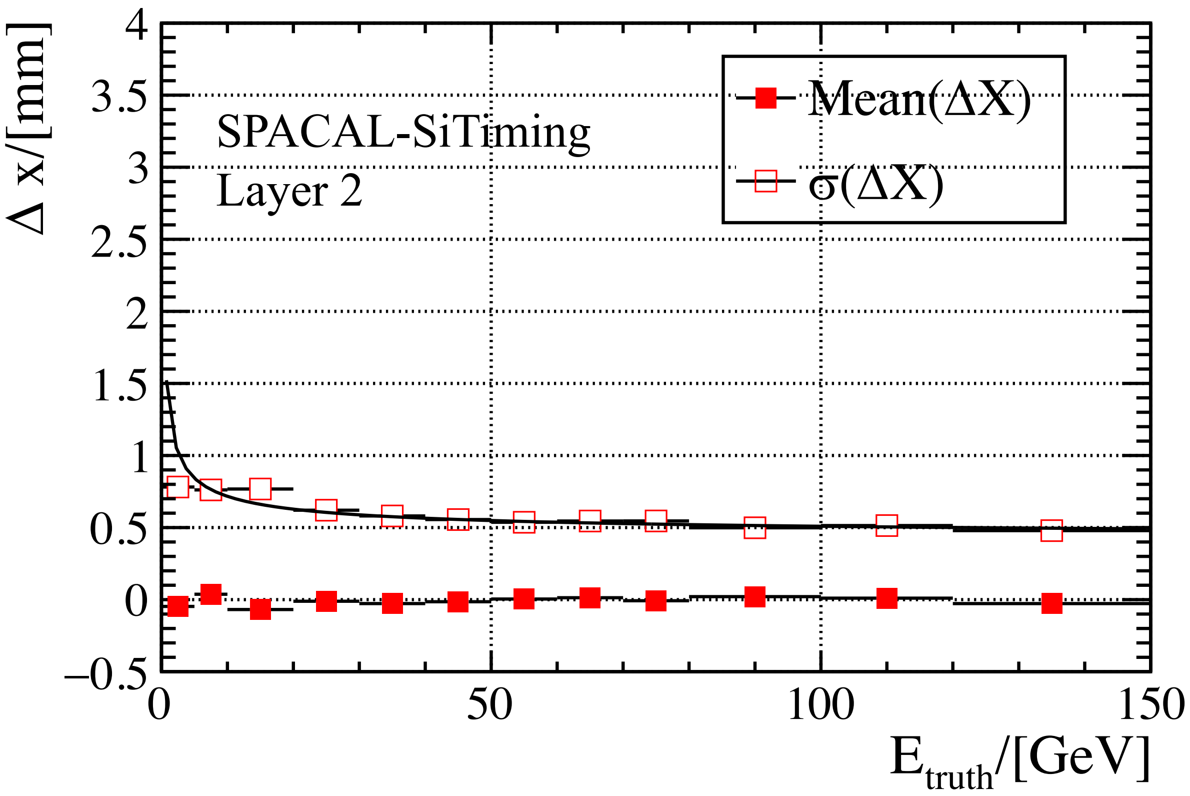


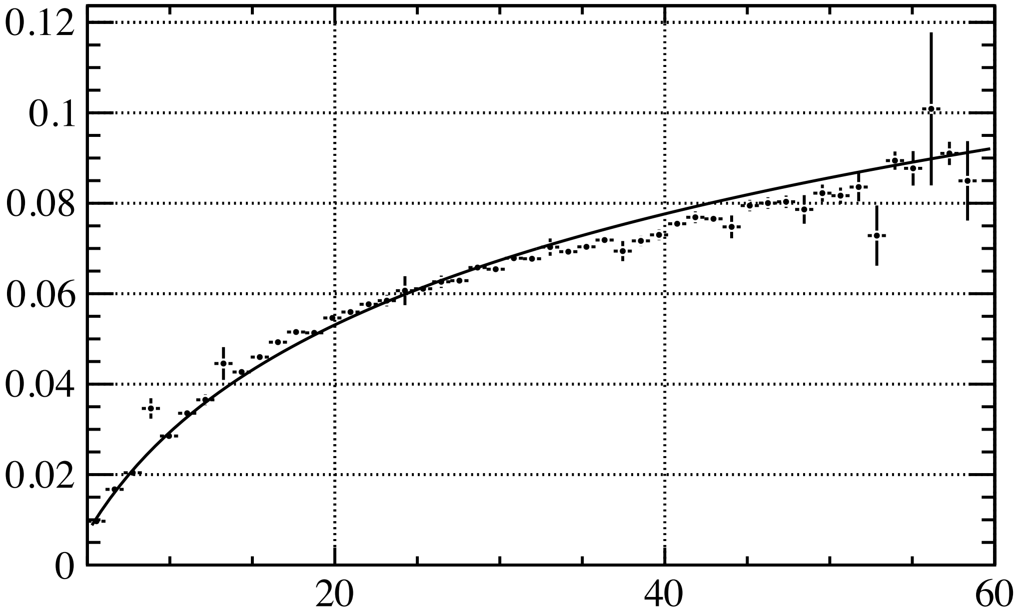
■ SPACAL与SPACAL-SiTiming的性能对比

➢ SPACAL-SiTiming的Silicon的位置分辨率

Polystyrene-Pb



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0.08
0.06
0.04
0.02
0
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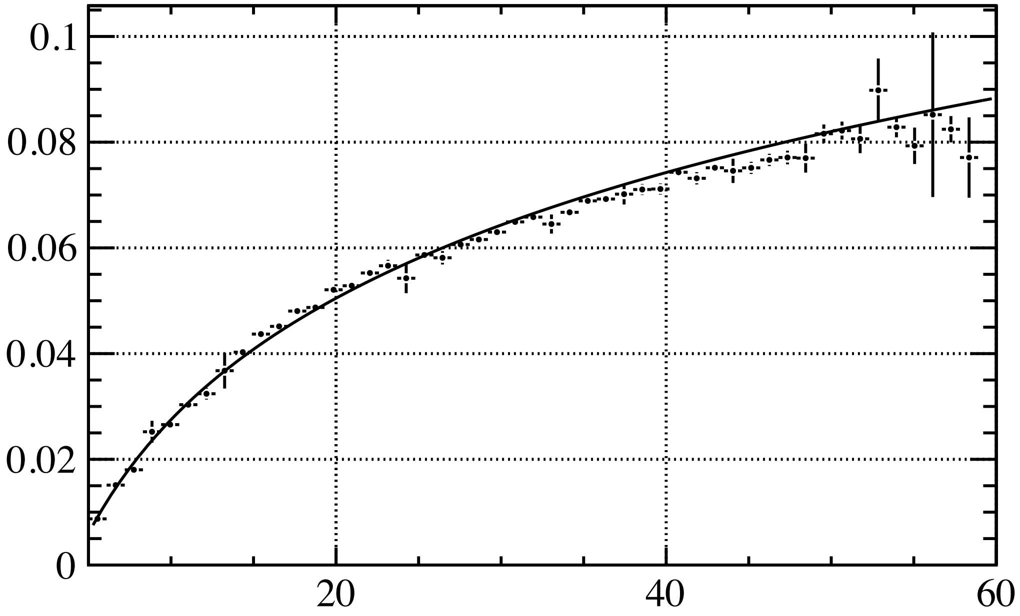
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60