Simulation and Reconstruction of the Electromagnetic Calorimeter for Super Tau-Charm Facility

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Outline

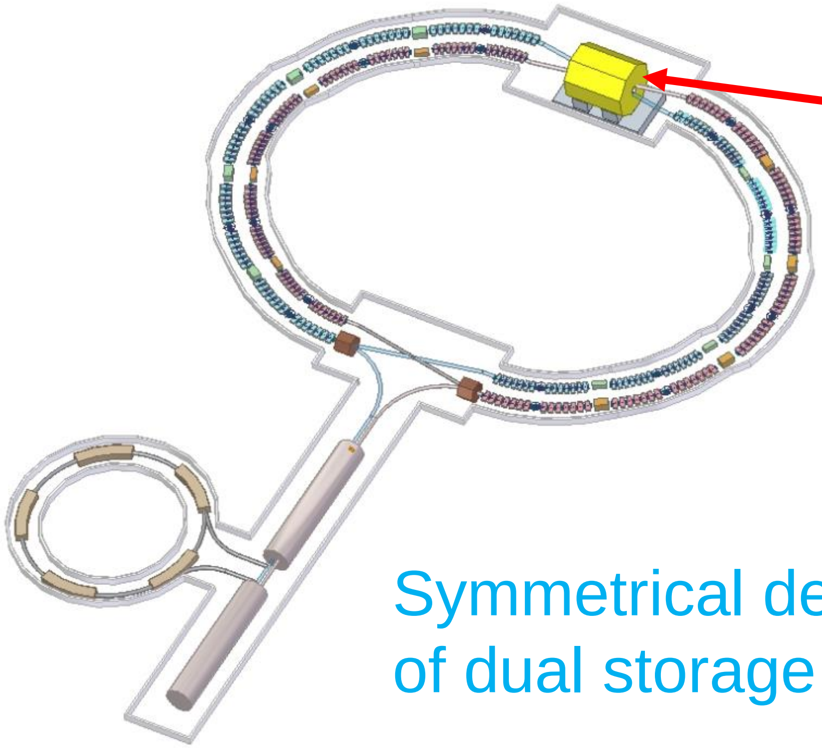
- **Research Background**

- **STCF ECAL**
  - ECAL Design
  - Performance Studies of ECAL
    - Reconstruction of Energy and Position
    - Time Simulation and Reconstruction
    - Background Simulation

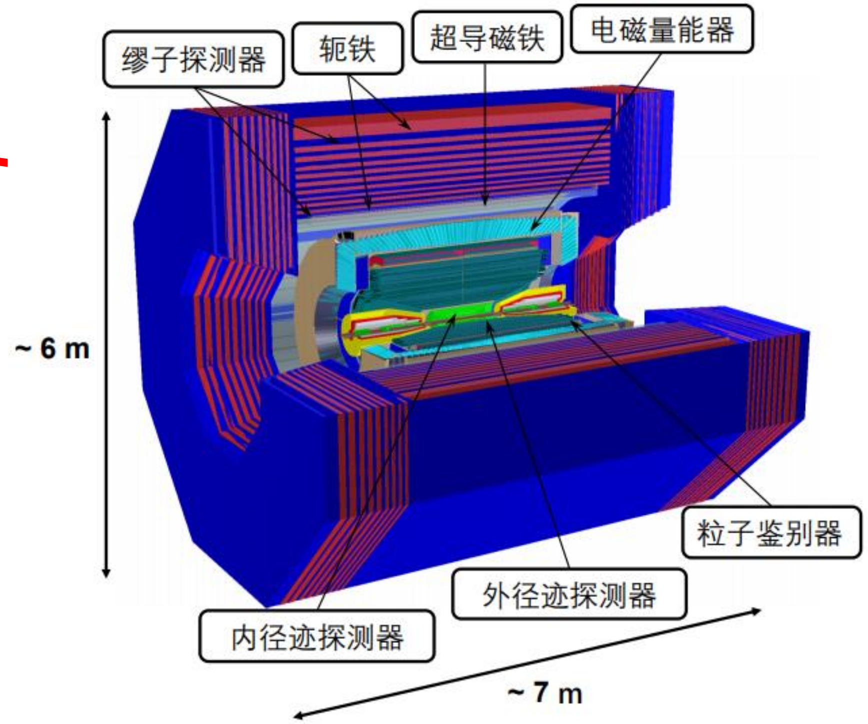
- **Summary**

Research Background

- **Super Tau-Charm Facility (STCF) is the next generation electron-positron collider experiment after BEPCII/BESIII**
  - High luminosity： beyond $0.5 \times 10^{35}\ cm^{-2} \cdot s^{-1}$@ 4 GeV
  - Wide energy region： center-of-mass energy range of 2~7 GeV



Symmetrical design
of dual storage ring



Research Background

● Requirements for Electromagnetic Calorimeter (ECAL)

➢ Fast response

◆ Challenge of high Luminosity

High event rate (400 kHz)

Extremely high background

➢ High precision

◆ Energy resolution

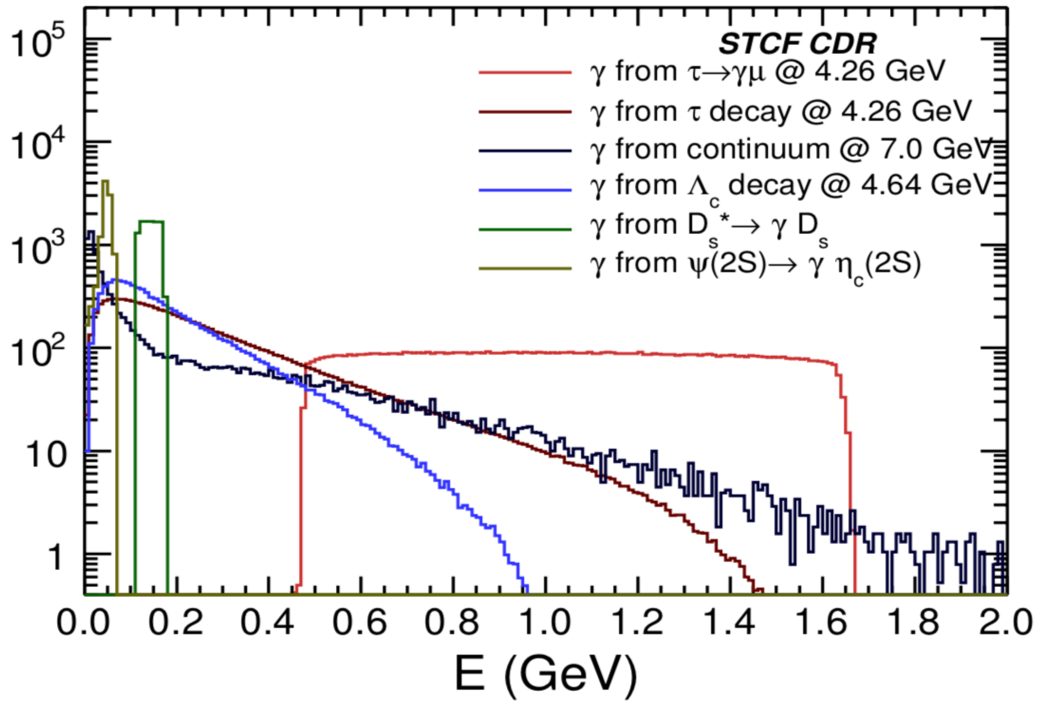
Better than 2.5% @1 GeV

◆ Position resolution

Better than 6 mm @1 GeV

◆ Time resolution

Better than 300 ps @1 GeV

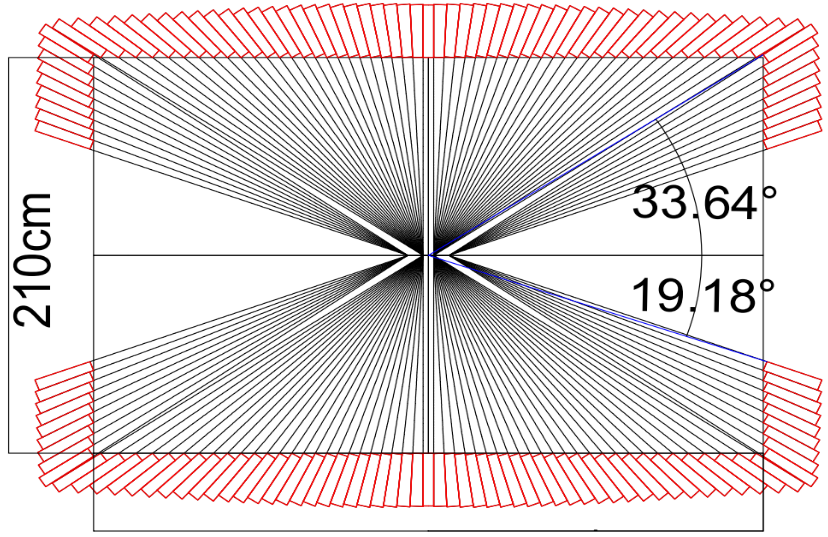


Energy distribution for photons

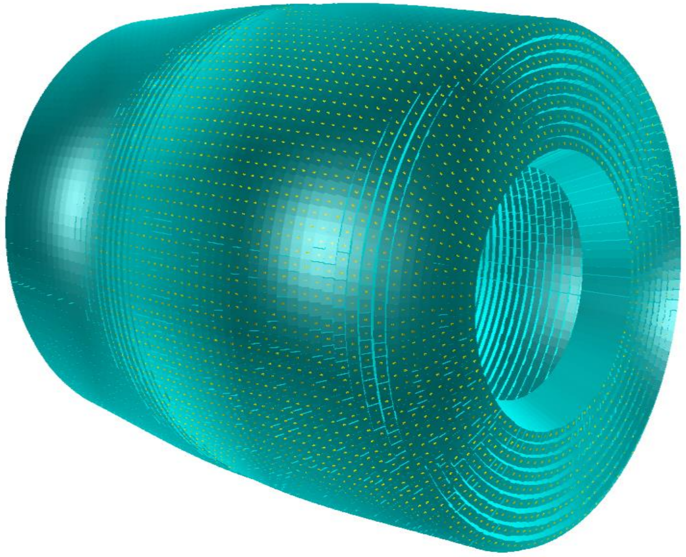
ECAL Design

Total absorption calorimeter

- Barrel: $51 \times 132 = 6732$
- Endcap: $3 \times (85 + 102 + 136) = 969$

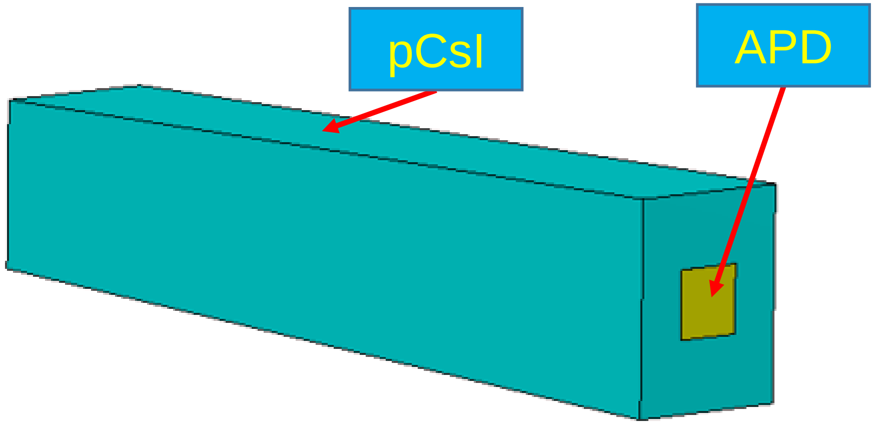


Crystal arrangement diagram



Visualized by DD4Hep

Sensitive Unit

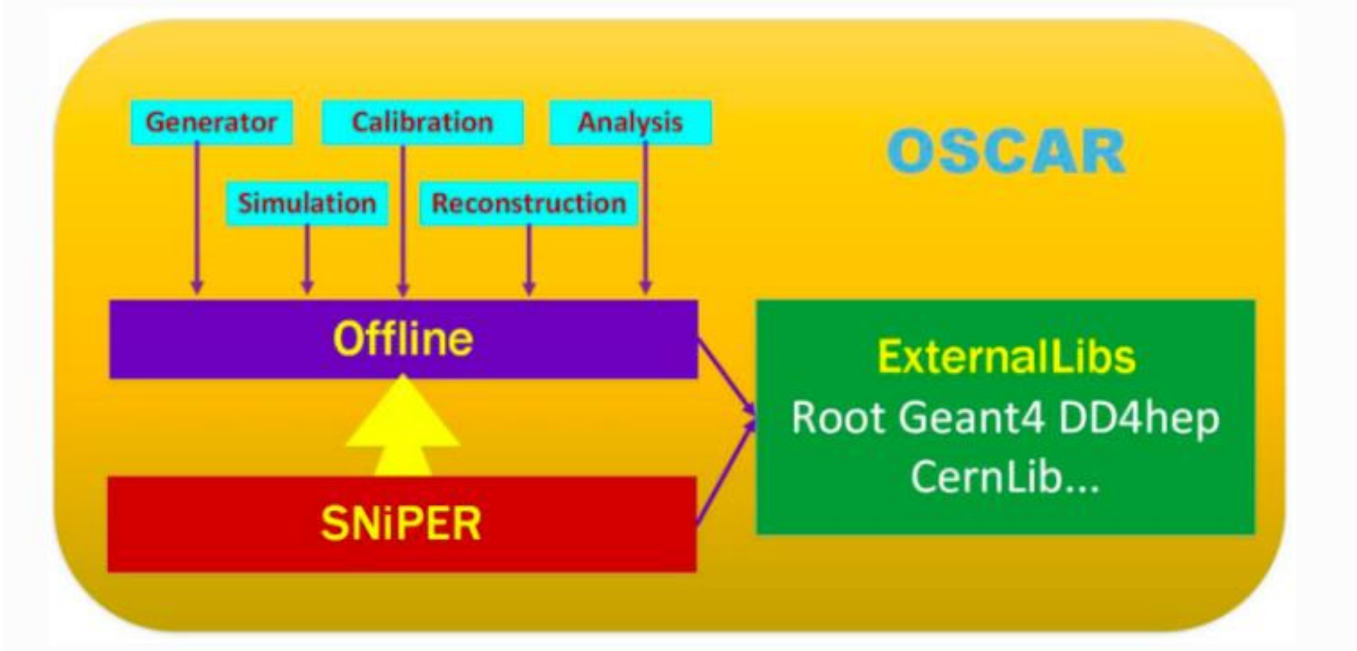


Pure CsI (pCsI) crystal + APD

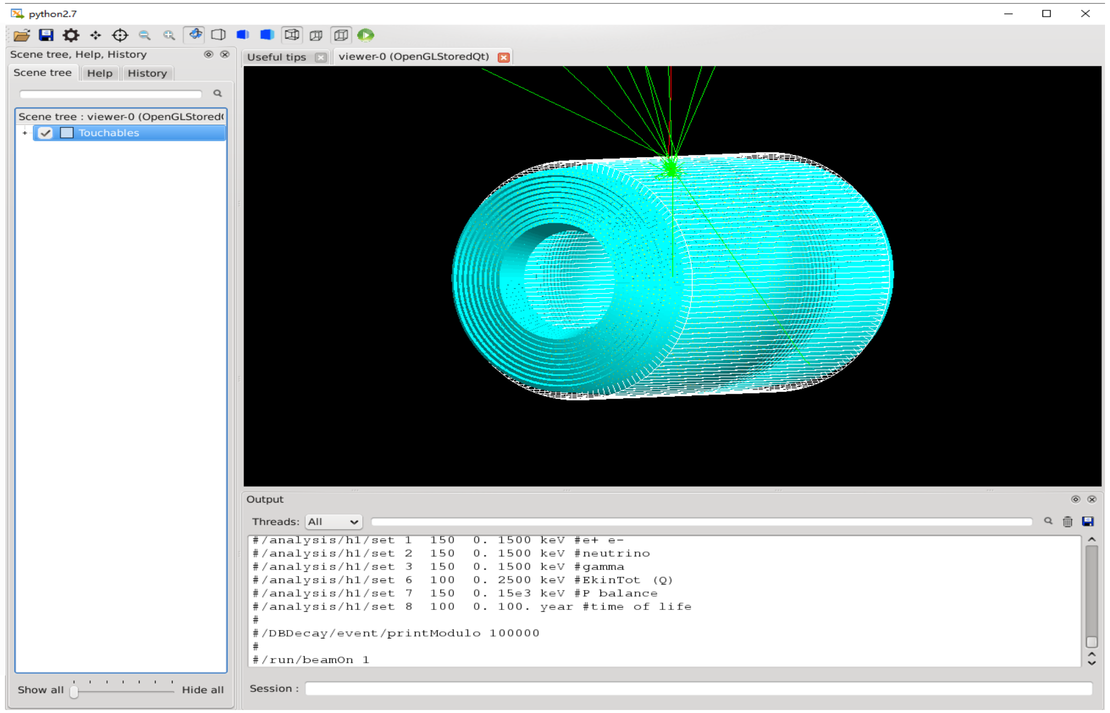
- Pure CsI (pCsI) crystal
  - Fast decay time
  - Good radiation hardness
  - Low light yield
- Avalanche photodiode (APD)
  - Short wavelength type
  - Large area $(10 \times 10\ mm^2 \times 4)$

Performance Studies Based on OSCAR

- **OSCAR: Offline Software of Super Tau-Charm Facility**



OSCAR Framework Composition



Photon Shower Visualization

Reconstruction Algorithm

- **A preliminary reconstruction algorithm of ECAL is developed**

ECALRecAlg

Cluster search

↓

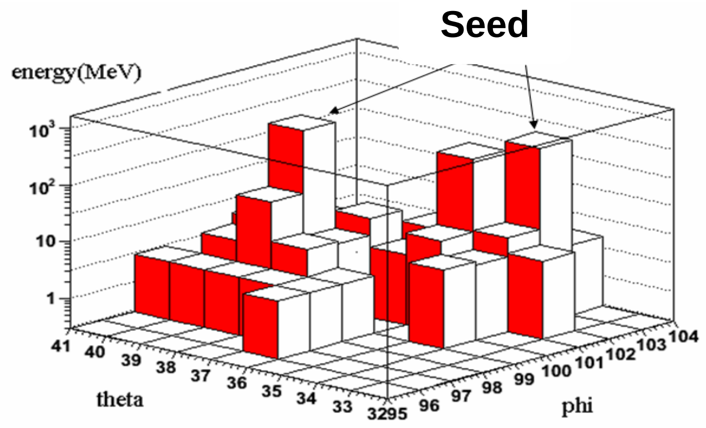
Seed search

↓

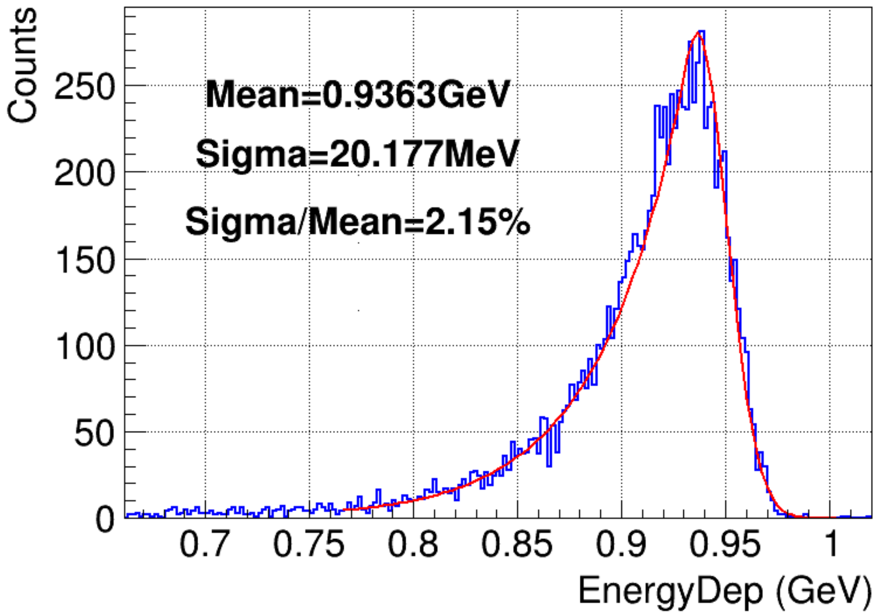
Clusters split into Showers

↓

Calculation and correction of shower energy and position



π^0 Cluster (two photons)



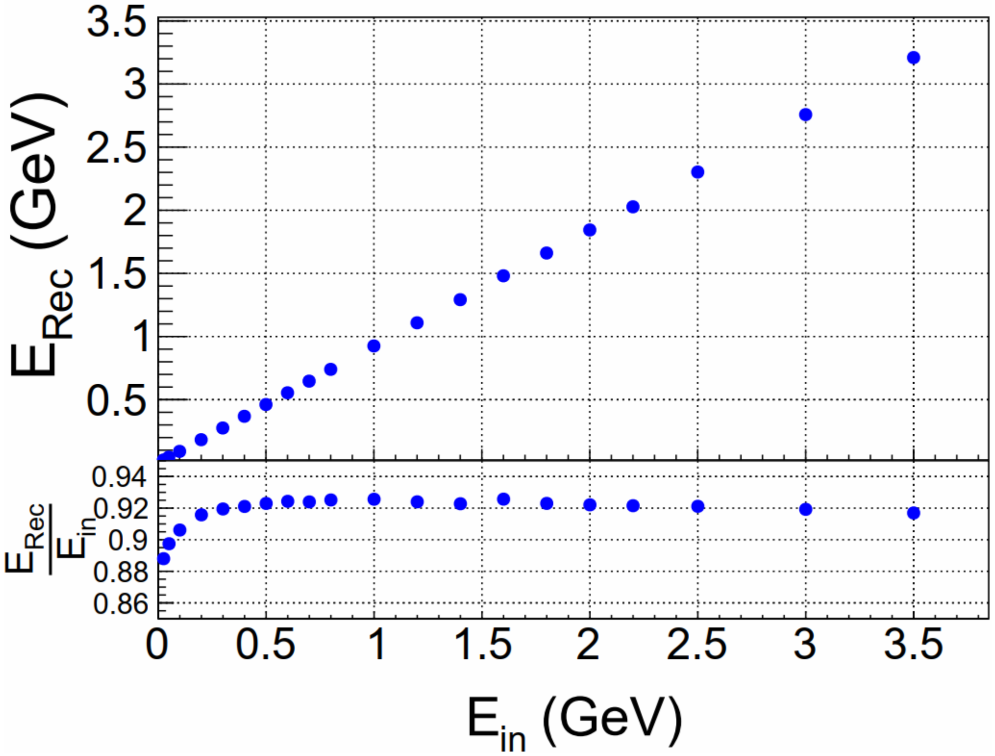
Energy reconstruction of 1GeV γ

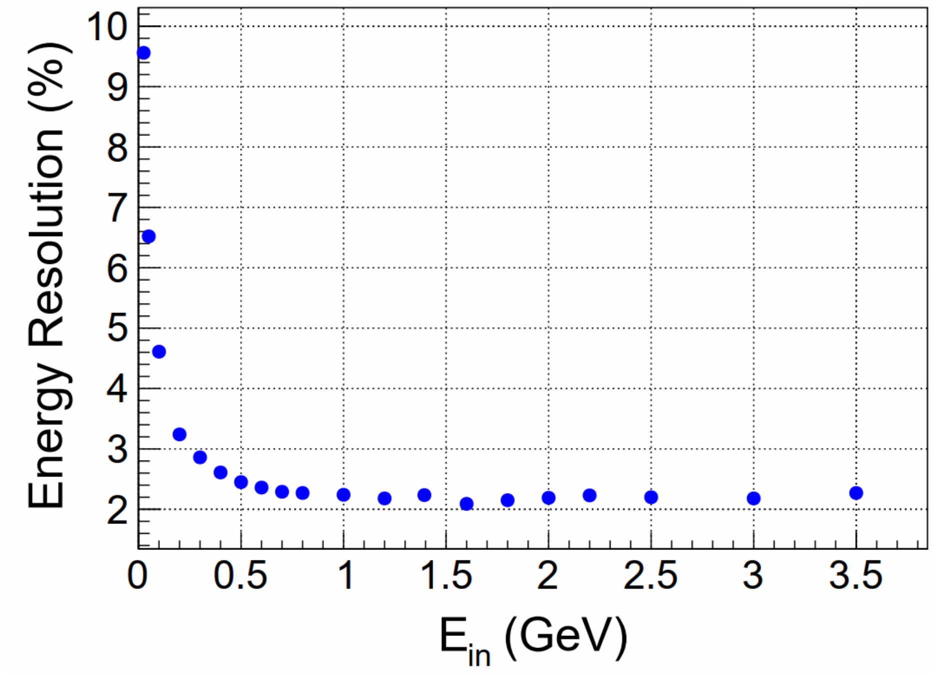
The energy spectrum is fitted by Crystal Ball function, and the energy resolution is defined by $\sigma_E = \frac{FWHM}{2.355}$.

Reconstruction of Energy and Position

●Energy Reconstruction

1. “Dead Material”
2. Light Yield (L.Y. = 100 p.e./MeV)
3. Light Collection Non-uniformity
4. Secondary Particles Hit APD
5. Electronics Noise





Good energy linearity is maintained in the energy range of 25MeV~3.5GeV

The energy resolution is 2.15% @ 1 GeV ,which meets the performance requirement.

Reconstruction of Energy and Position

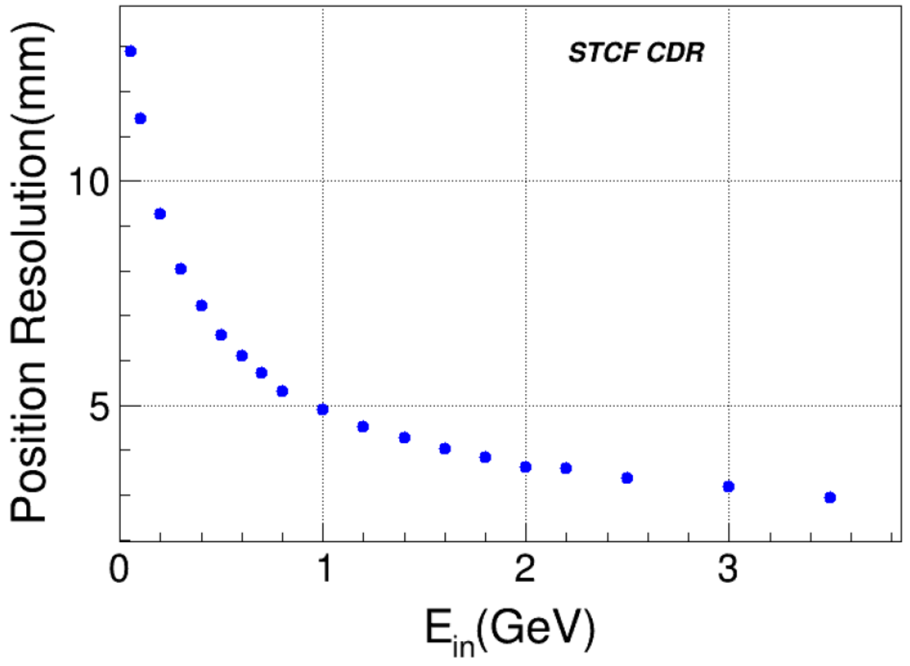
●Position Reconstruction

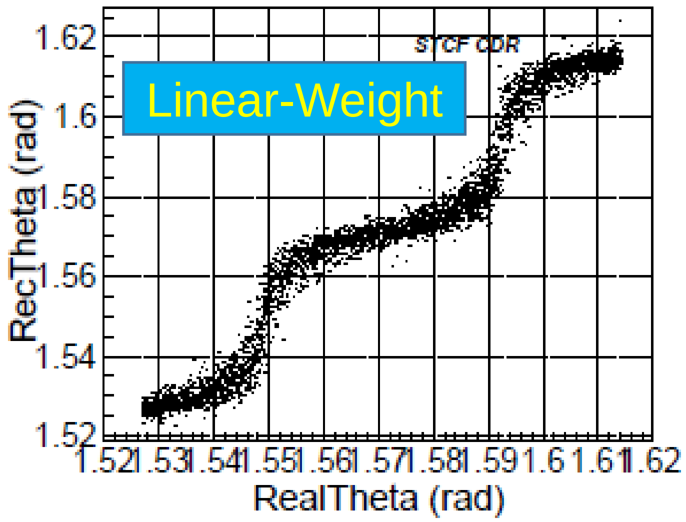
- Barycenter method with logarithmic weight

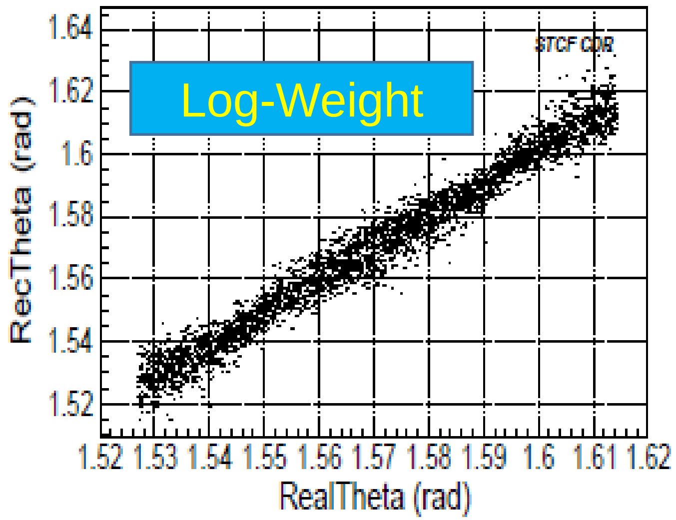
$$X_c = \sum_{j}^{N} W_j(E_j) \cdot X_j / \sum_{j}^{N} W_j(E_j)$$

Where:

$$W_j(E_j) = \max\{0, a + \ln(E_j / \sum_{j}^{N} E_j)\}$$





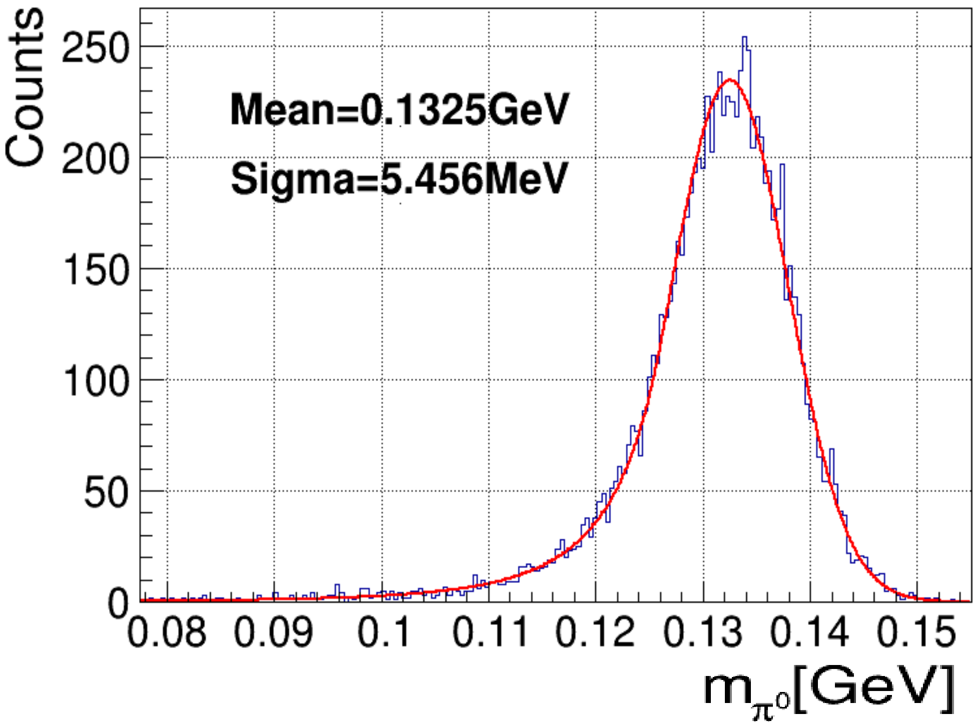


The position resolution is 4.9 mm @ 1 GeV ,which meets the performance requirement.

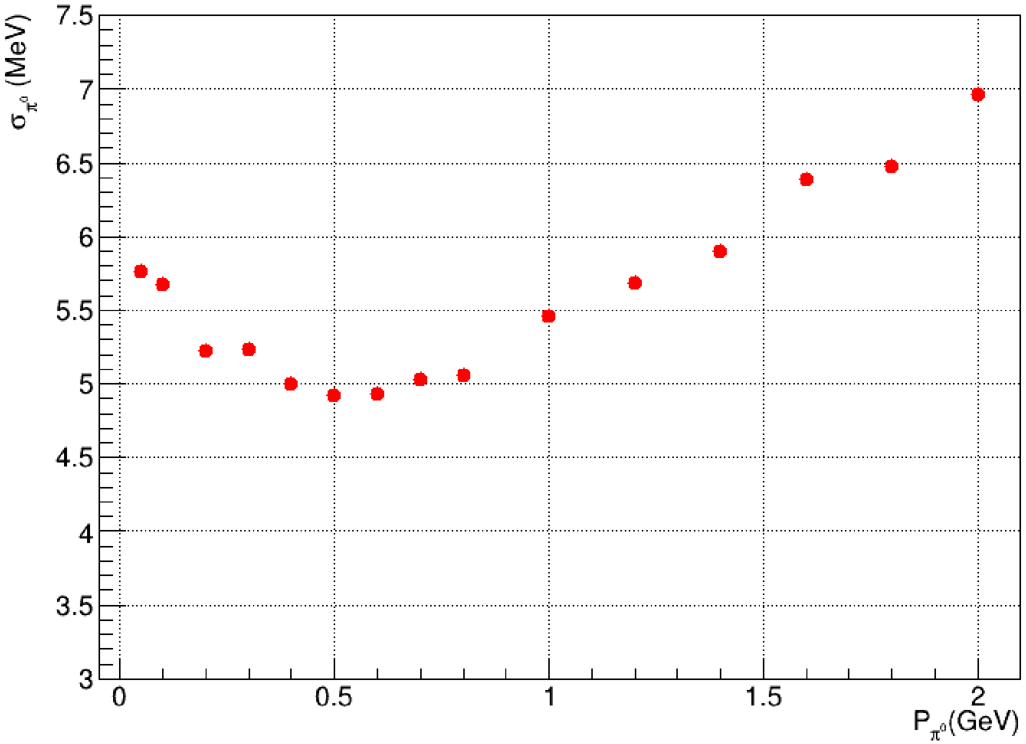
Reconstruction of Energy and Position

●Reconstruction of π^0

$$m_{\pi 0} = \sqrt{2E_1E_2(1 - cos\alpha)}$$



Mass reconstruction of π^0 (P = 1GeV)

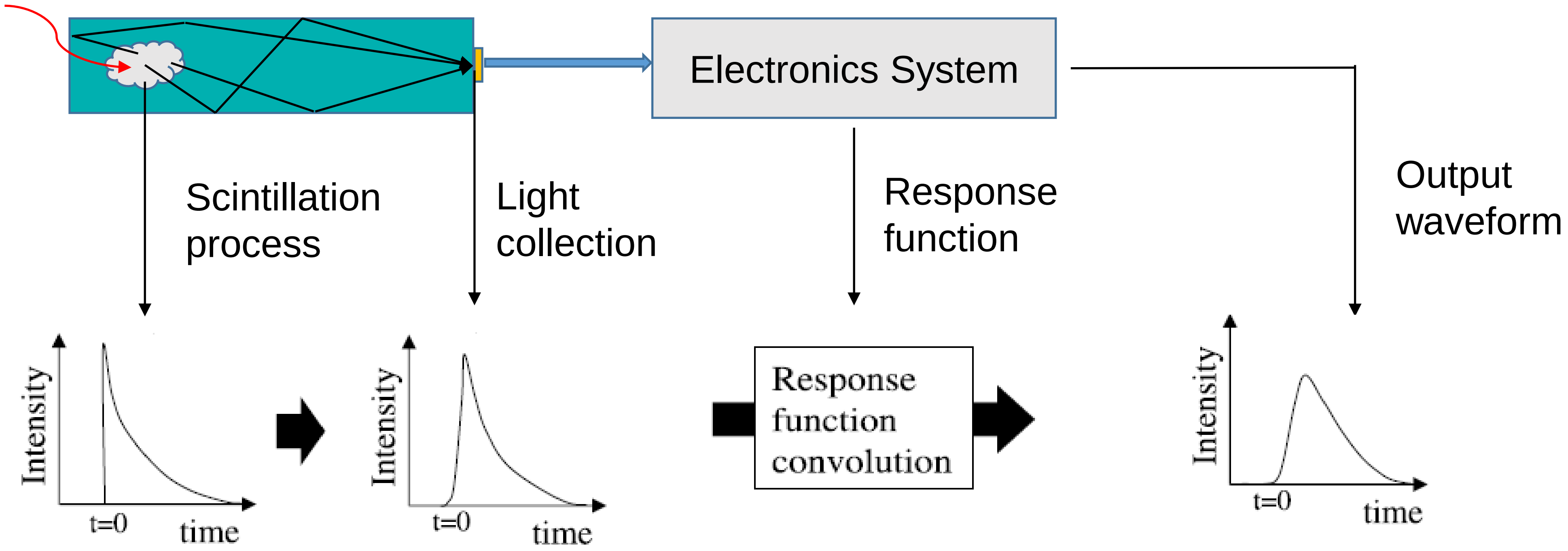


Mass resolution of π^0

Time Simulation and Reconstruction

●Time Simulation

- ➢ Based on Geant4 Optical Simulation

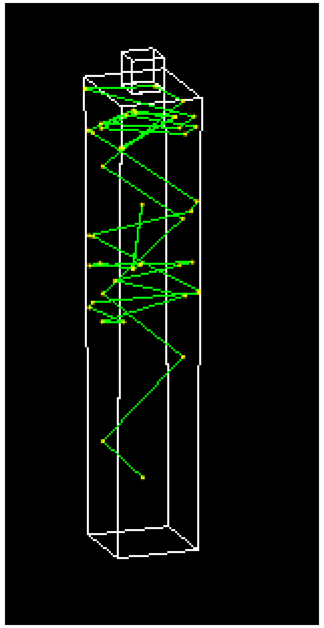


Schematic diagram of the time simulation method

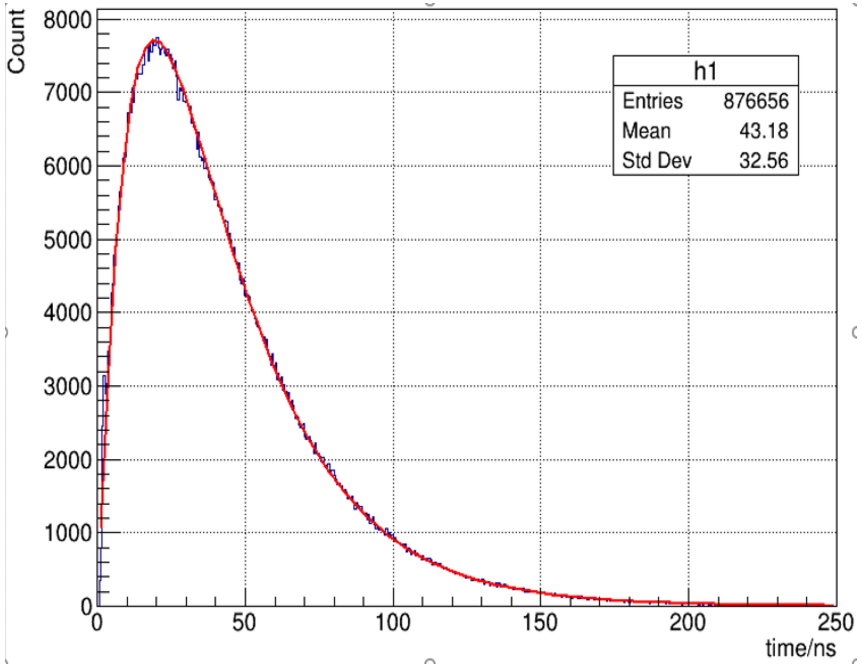
Time Simulation and Reconstruction

●Time Simulation

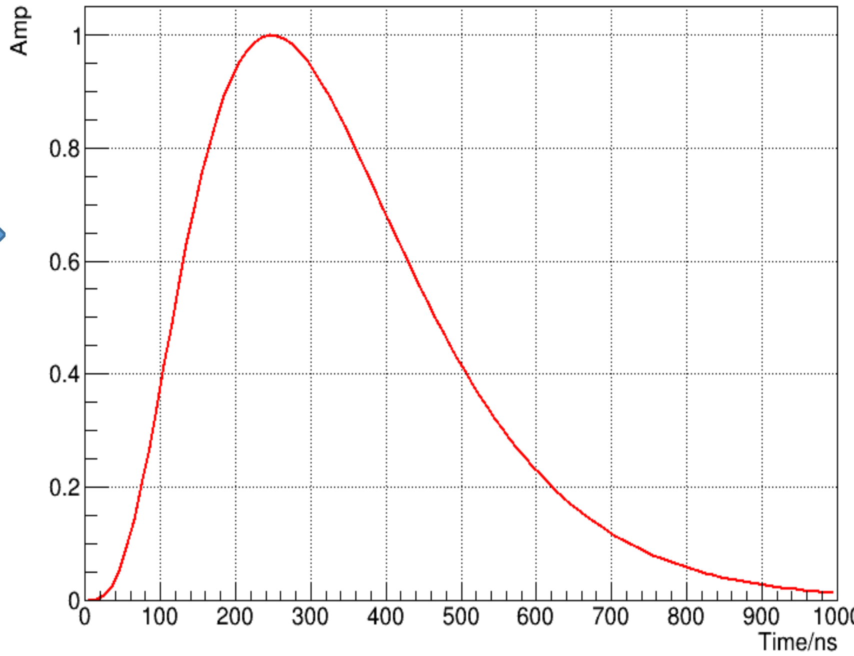
- ➢ Based on Geant4 Optical Simulation



Transmission of fluorescent photons in crystal



The time distribution of fluorescent photons being collected

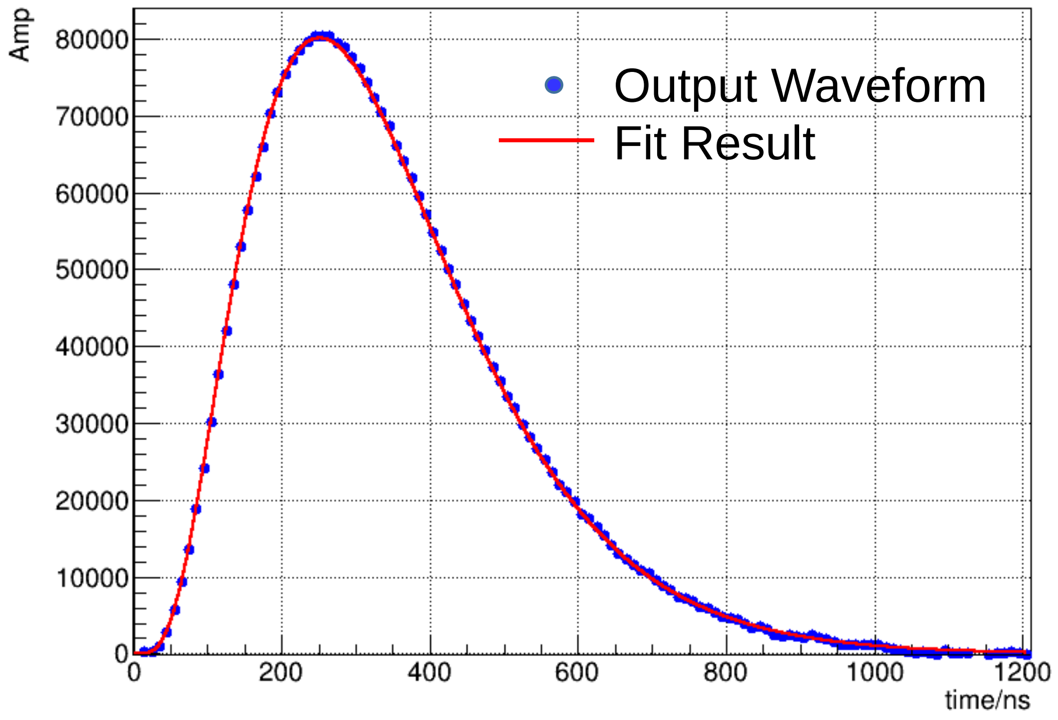


Output waveform template

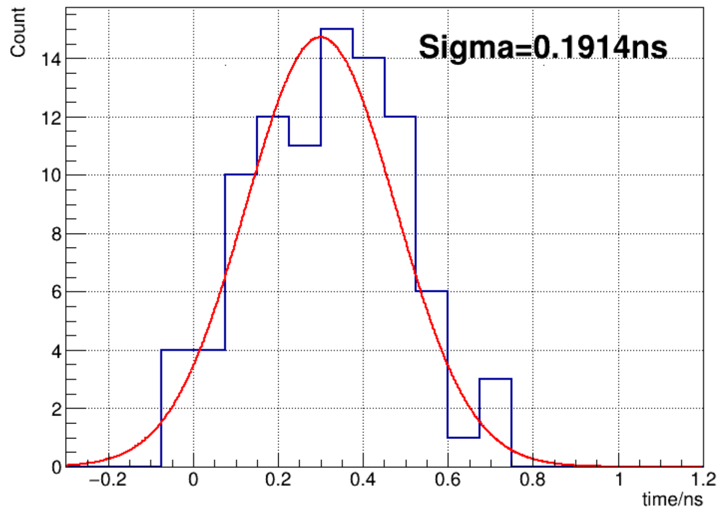
Time Simulation and Reconstruction

●Time Reconstruction

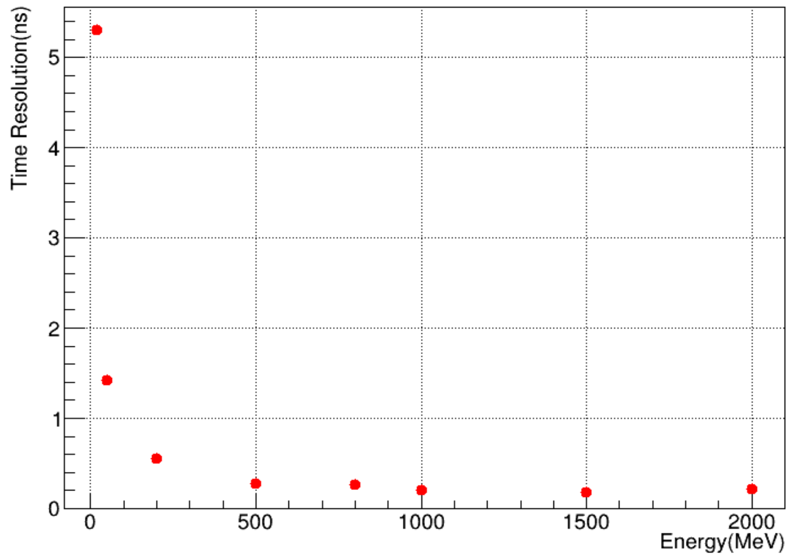
- ➢ Based on waveform fitting



Example of fit result



Time reconstruction of photon (E = 1GeV)

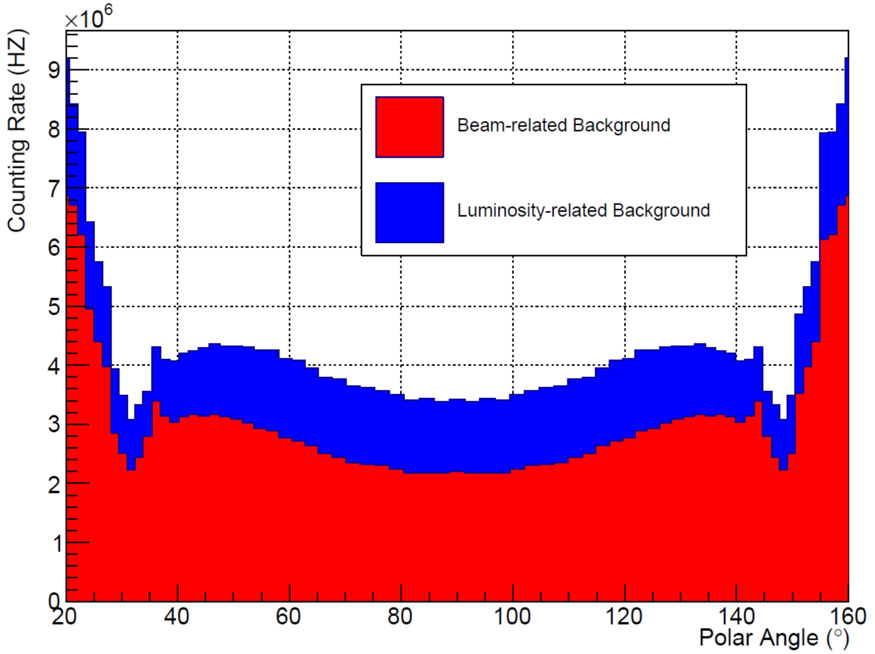


Time resolution of photons at different energies

Background Simulation

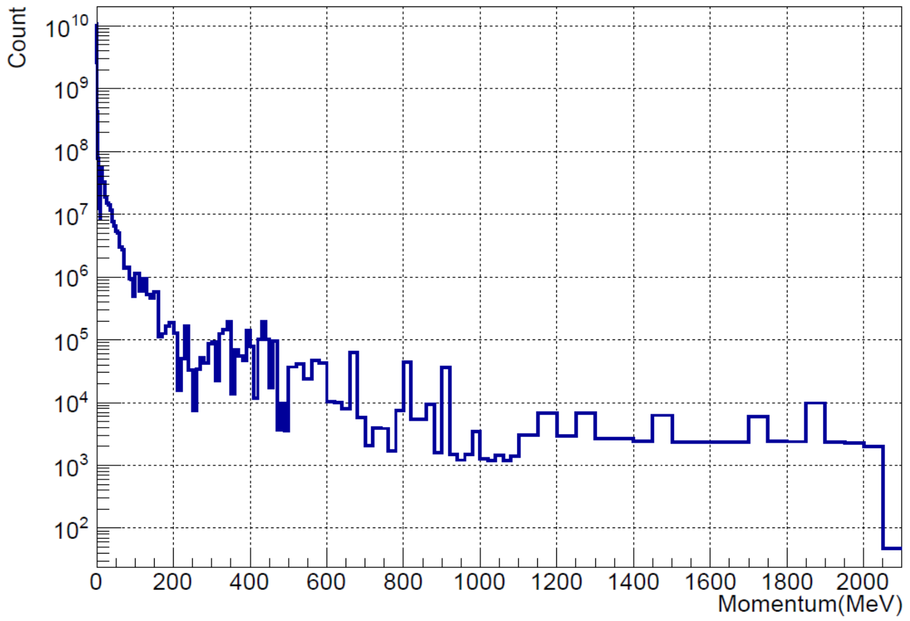
Challenges of high background

- Luminosity-related Background
  1. Radiative BhaBha Scattering (RBB)
  2. Two Photon Process
- Single-beam related Background
  1. Thouschek Effect
  2. Coulomb Scattering
  3. Bremsstrahlung



Variation of the background counting rate with polar angle

Counting rate reaches the order of MHz



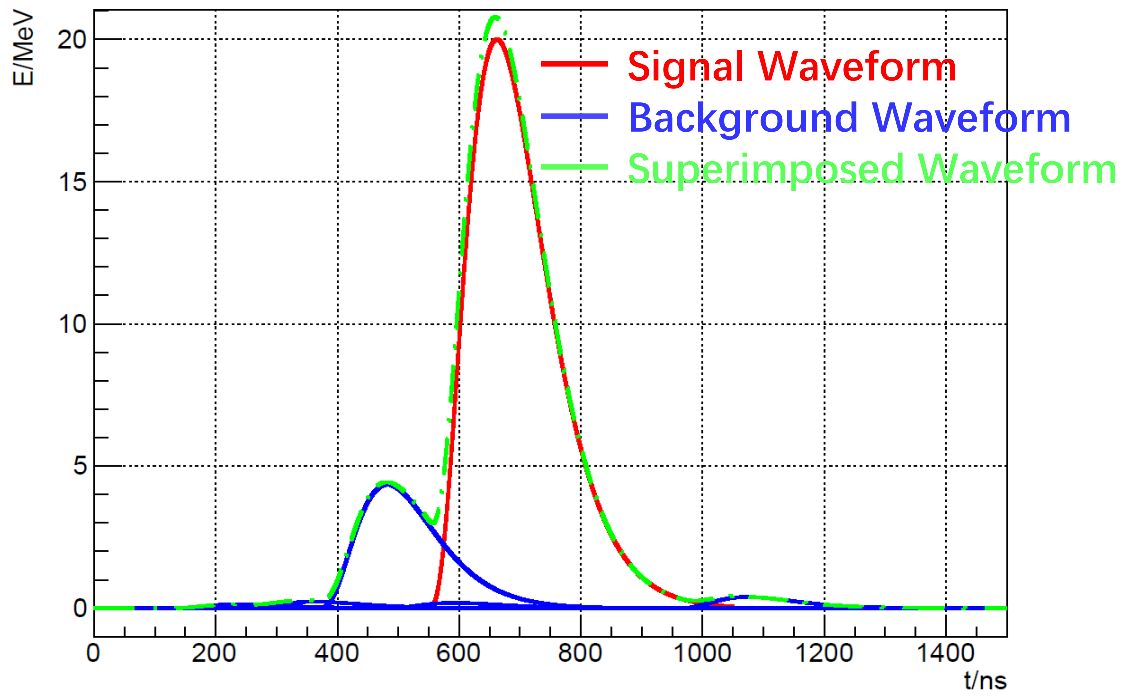
Momentum distribution of background particles

Most background particles concentrate in the low momentum region

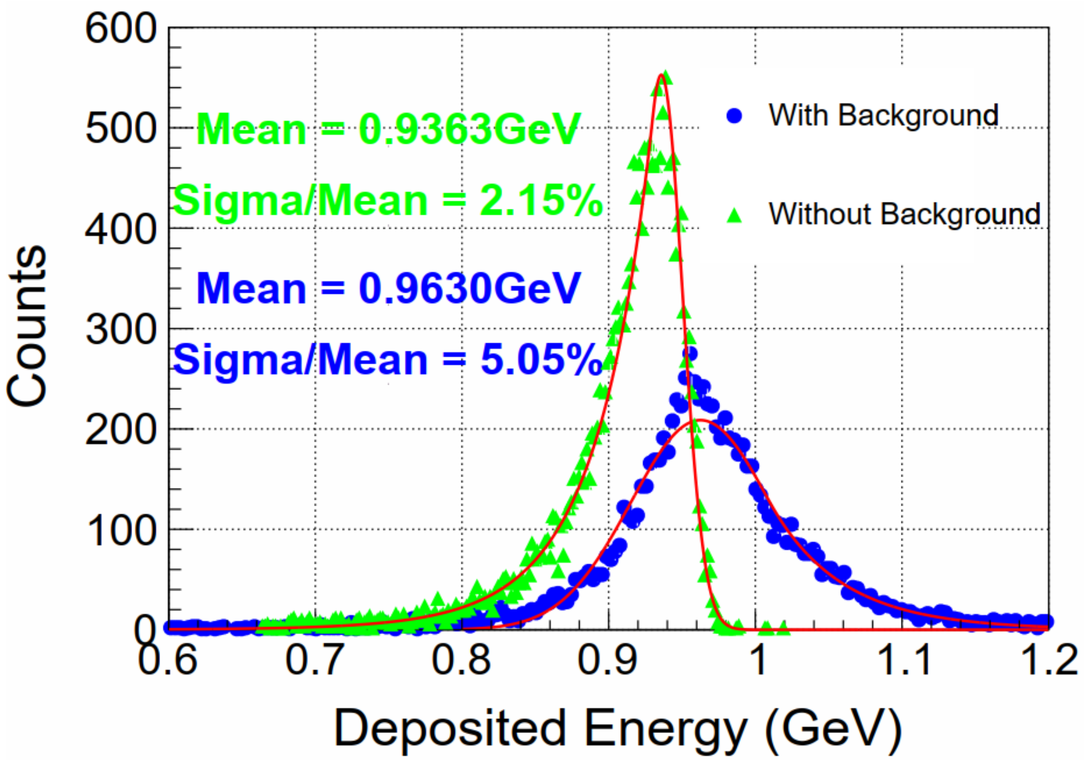
Background Simulation

● Challenges of high background

- ➢ Background waveform is superimposed on the signal waveform
- ➢ The impact of the background is devastating.



The amplitude of signal is distorted



The energy spectra of 1 GeV photons before and after introducing background

Waveform Fitting Method

Multi-template fitting

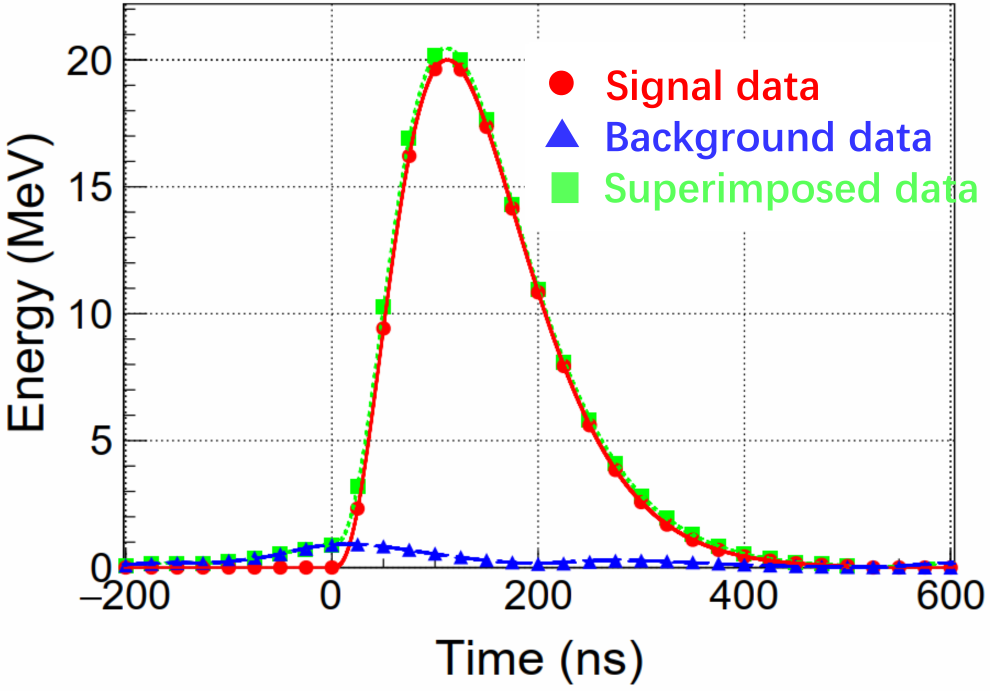
- The waveform template is obtained by convoluting the pure CsI fluorescence signal with the electronics impulse response function.
- The fit minimizes the χ^2 defined as:

$$\chi^2 = \left(\sum_{j=1}^{N} A_j \vec{p_j} - \vec{S}\right)^T C^{-1} \left(\sum_{j=1}^{N} A_j \vec{p_j} - \vec{S}\right)$$

Where:

N is the number of templates;
vector $\vec{S}$ comprise the readout samples;
vector $\vec{p_j}$ is the waveform template;
A_j are the amplitudes, which are obtained by the fit;
C is the noise covariance matrix.

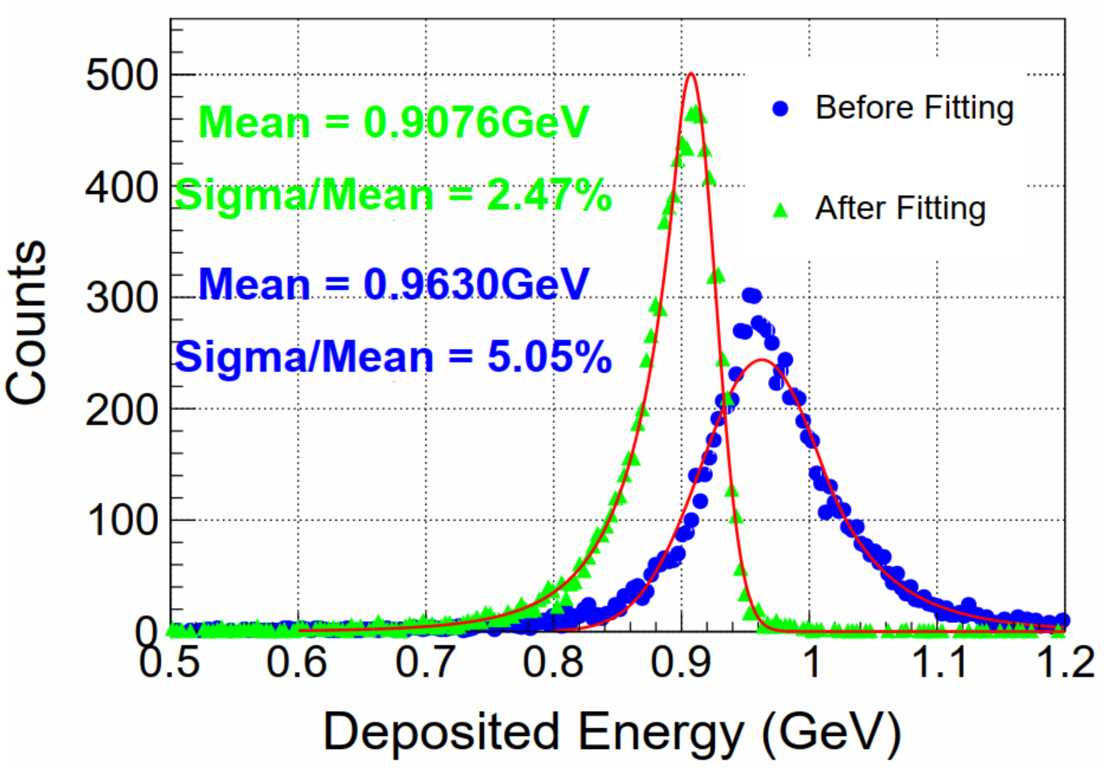
An example of the multi-template fitting result.



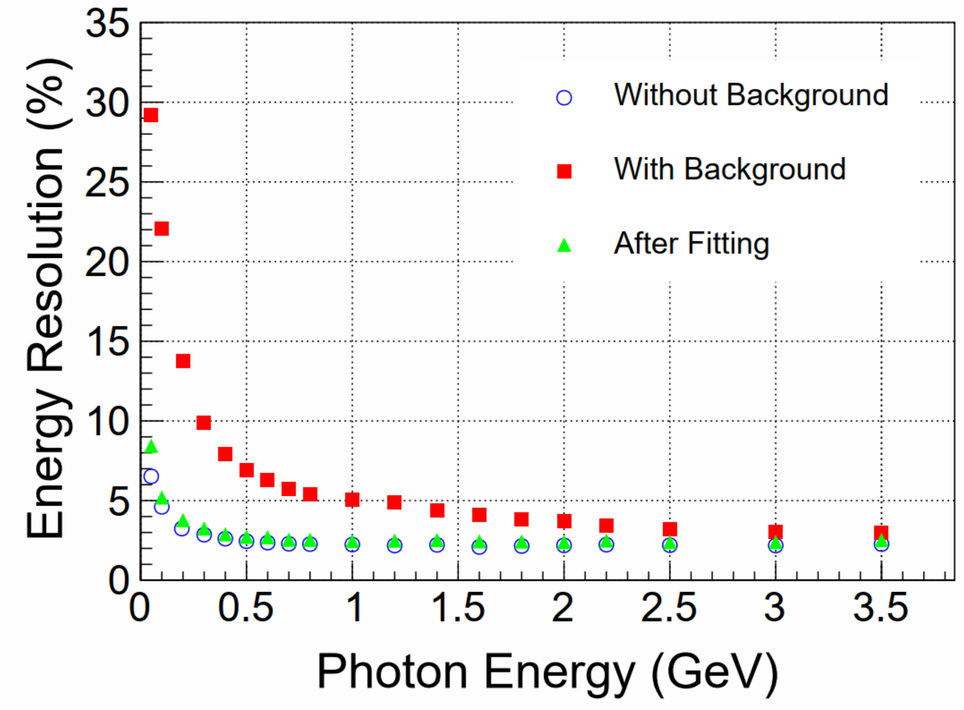
- The green line is the fitting result of the data, which is the sum of total templates.
- The red line is the template represents the signal.
- The blue line represents the background, which is the sum of the remaining templates.

Waveform Fitting Method

- **The effect of waveform fitting method**



The energy spectra of 1 GeV photons before and after waveform fitting



The energy resolution under three different situations.

With the help of the waveform fitting method, the energy resolution is greatly improved, which meets the requirements of STCF ECAL.

Summary

- **High precision ECAL with fast response characteristics**
  - **High luminosity**
  - **good energy and position resolution**
  - **good time resolution**

- **The performance of ECAL was studied based on OSCAR**
  - **The Geant4 simulation results shows that the design of ECAL could meet the performance requirements.**
  - **Based on optical simulation, the time performance of ECAL was simulated and reconstructed.**
  - **The waveform fitting method is helpful in solving the problem of high background level.**

Thanks!

Back Up

ECAL Design —— Sensitive Unit

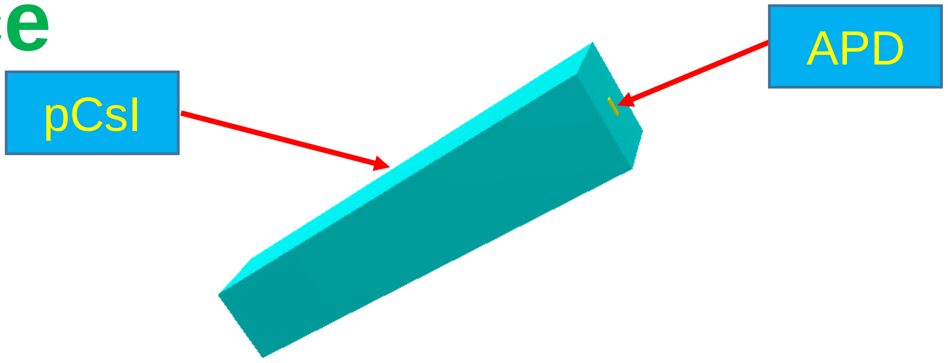
●Pure CsI crystal + APD photo-device

- ◆ Pure CsI (pCsI) crystal
  - ➢ Fast decay time
  - ➢ Good radiation hardness
  - ➢ Low light yield
- ◆ Crystal Size:
  - ➢ Total radiation length

    15 X_0 (28 cm)
  - ➢ End face size

    front end: $\sim 5 \times 5\ cm^2$

    back end: $\sim 6.5 \times 6.5\ cm^2$
- ◆ Avalanche photodiode (APD)
  - ➢ Short wavelength type
  - ➢ Large area $(10 \times 10\ mm^2 \times 4)$



ECAL pCsI crystal unit

Crystal	Pure CsI
Density (g/cm^3)	4.51
Melting Point (°C)	621
Radiation Length (cm)	1.86
Moliere Radius (cm)	3.57
Refractive index	1.95
Hygroscopicity	Slight
Luminescence (nm)	310
Decay time (ns)	30 6
Light yield (%)	3.6 1.1
Dose rate dependent	No
D(LY)/dT (%/°C)	-1.4
Experiment	KTeV Mu2e

Splitting Algorithm

$$E_k = \sum_{i=1}^{n} a_{ik} E_i$$

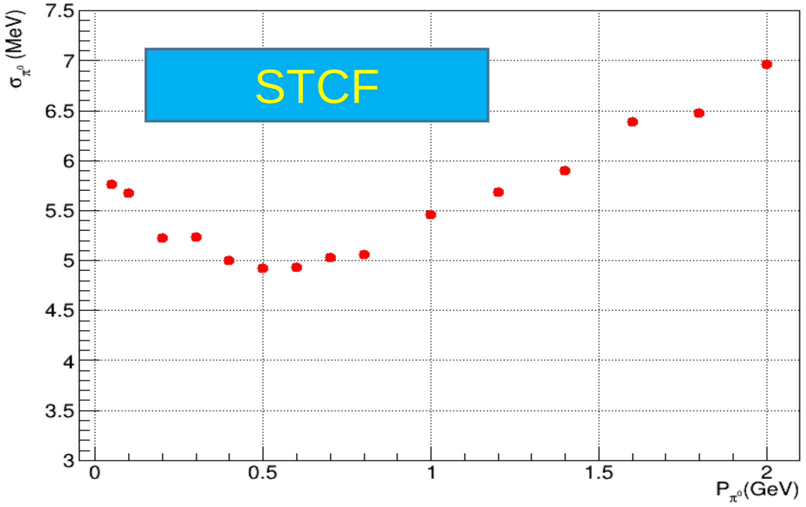
Splitting algorithms used by BES III and Panda:

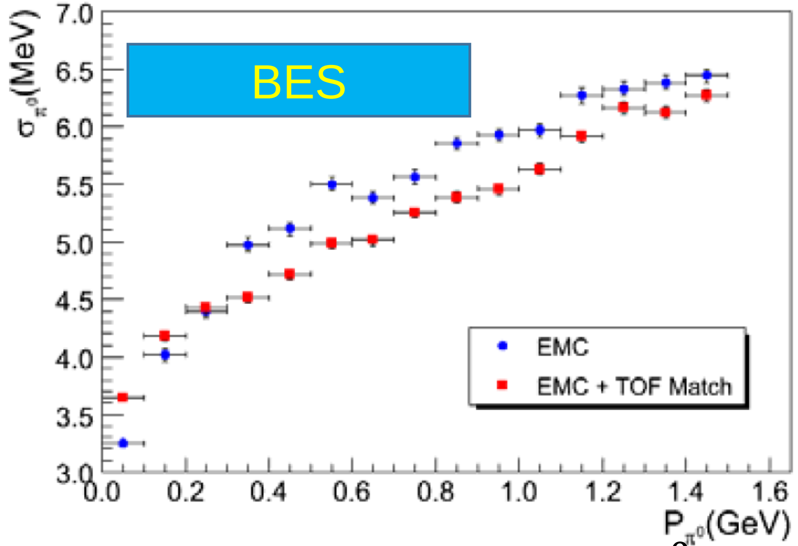
$$\mathrm{a}_{ik} = \frac{E_k \times \exp(c \times \frac{r_{ik}}{R_M})}{\sum_{j=1}^{m} E_j \times \exp(c \times \frac{r_{i\mathrm{j}}}{R_M})} \quad ,$$

where R_M is the Moliere radius, c is a constant, $r_{i\mathrm{j}}$ is the distance from the center of the i-th crystal to the location of the j-th shower center, and m is the number of showers, E_j is the energy of j-th seed.

Reconstruction of Energy and Position

- **Reconstruction of π^0**

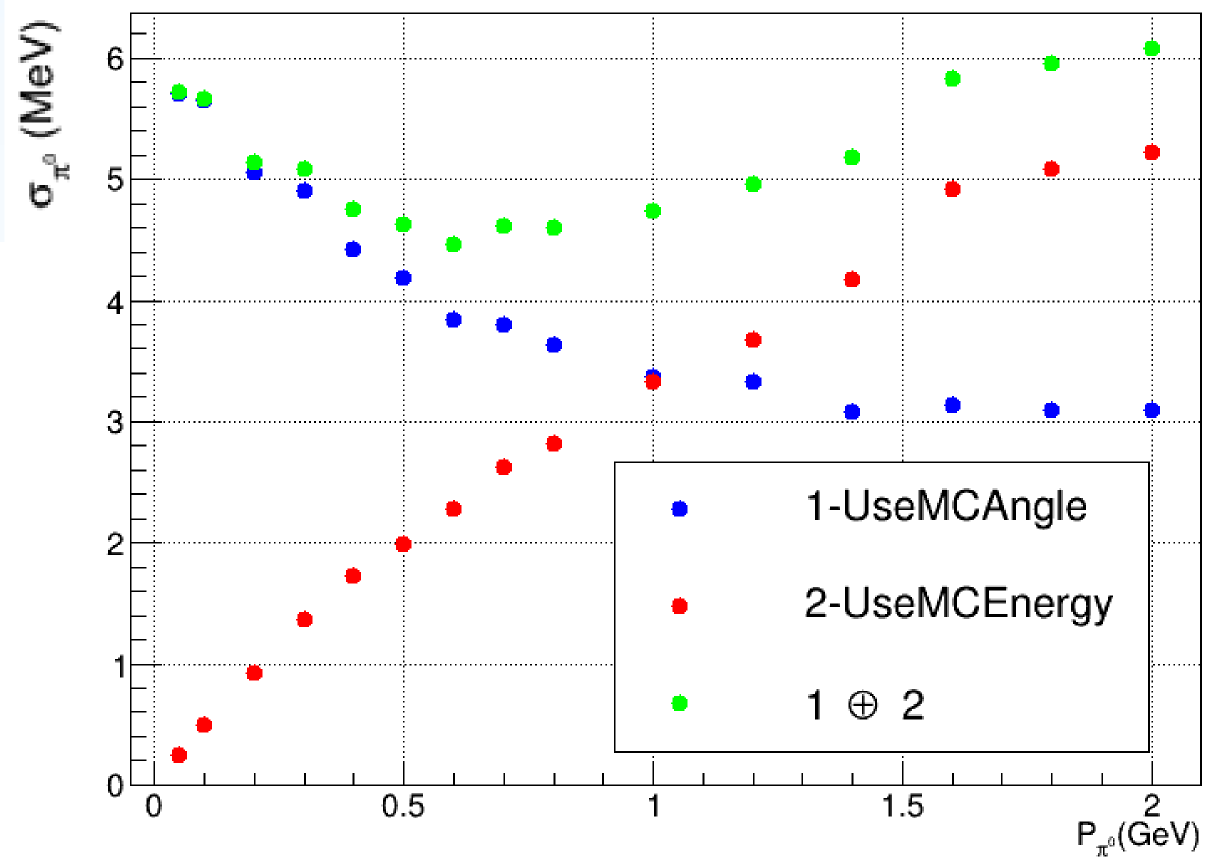




Mass resolution of π^0

$$\sigma_m^2 = \sigma_1^2 + \sigma_2^2$$

$$\sigma_1 \sim E(1-\cos\alpha)\sigma_E \qquad \sigma_2 \sim E^2 \sin\alpha\, \sigma_\alpha$$



1-Template Fitting

- Template shape function： $f(t) = A \times f(t-\tau) + p$
- $\chi^2 = \sum_{i,j}(y_i - A\cdot f(t_i-\tau) - p)\cdot S_{ij}^{-1}\cdot\left(y_j - A\cdot f\left(t_j-\tau\right)-p\right)$
- Apply $\frac{\partial\chi^2}{\partial A} = 0, \frac{\partial\chi^2}{\partial\tau} = 0, \frac{\partial\chi^2}{\partial p} = 0$:

$$\begin{cases} \sum_{i,j} f_{ki}\cdot S_{ij}^{-1}\cdot\left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \\ \sum_{i,j} f'_{ki}\cdot S_{ij}^{-1}\cdot\left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \\ \sum_{i,j} 1\cdot S_{ij}^{-1}\cdot\left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \end{cases}$$

$$\begin{pmatrix} \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \\ \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \\ \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \end{pmatrix}\cdot\begin{pmatrix} A \\ B \\ p \end{pmatrix} = \begin{pmatrix} \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \\ \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \\ \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \end{pmatrix}$$

$$\begin{pmatrix} A \\ B \\ p \end{pmatrix} = \begin{pmatrix} \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \\ \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \\ \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k^T & \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{F}_k'^T & \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{I} \end{pmatrix}^{-1}\cdot\begin{pmatrix} \boldsymbol{F}_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \\ \boldsymbol{F}'_k\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \\ \boldsymbol{I}\cdot\boldsymbol{S}^{-1}\cdot\boldsymbol{Y} \end{pmatrix}$$

Nonnegative Least Square (NNLS)

Convention:

- b: A real pulse with m points
- x: fitted amplitudes for n pulses
- A: the ith column of A represents the template for the ith pulse and of course each template has m points.
- P: passive set – currently not fixed amps
- R: active set – currently fixed amplitudes

Algorithm *fnnls* **:**

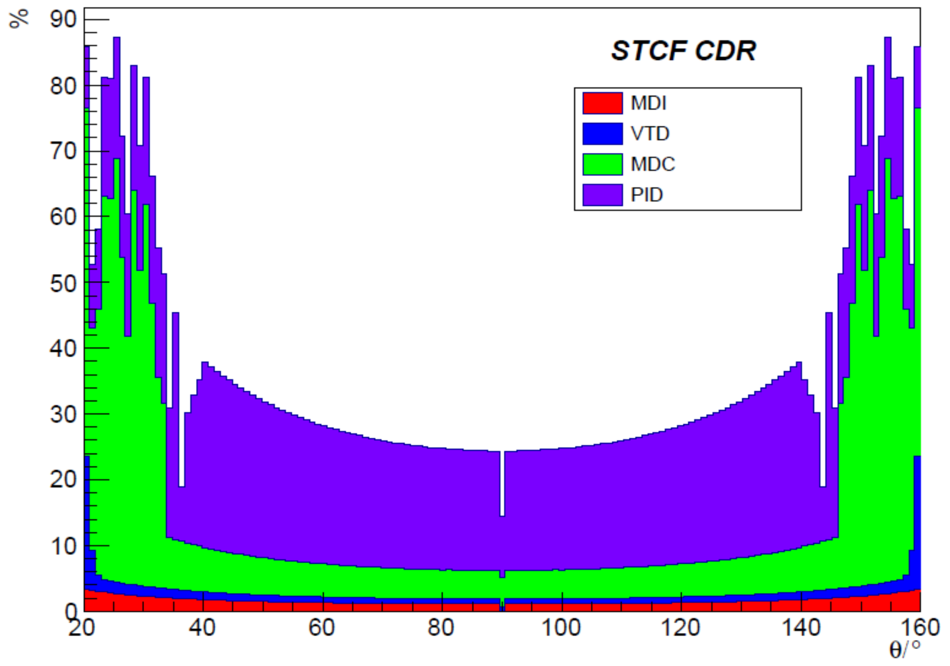
Input: $\mathbf{A} \in \mathbf{R}^{m \times n}$, $\mathbf{b} \in \mathbf{R}^{m}$
Output: $\mathbf{x}^* \geq 0$ such that $\mathbf{x}^* = \arg\min \|\mathbf{Ax} - \mathbf{b}\|^2$.
Initialization: $P = \varnothing, R = \{1, 2, \cdots, n\}, \mathbf{x} = \mathbf{0}, \mathbf{w} = \mathbf{A}^T\mathbf{b} - (\mathbf{A}^T\mathbf{A})\mathbf{x}$
repeat

1. Proceed if $R \neq \varnothing \wedge [\max_{i \in R}(w_i) > tolerance]$
2. $j = \arg\max_{i \in R}(w_i)$
3. Include the index j in P and remove it from R
4. $\mathbf{s}^P = [(\mathbf{A}^T\mathbf{A})^P]^{-1}(\mathbf{A}^T\mathbf{b})^P$
   - 4.1. Proceed if $\min(\mathbf{s}^P) \leq 0$
   - 4.2. $\alpha = -\min_{i \in P}[x_i/(x_i - s_i)]$
   - 4.3. $\mathbf{x} := \mathbf{x} + \alpha(\mathbf{s} - \mathbf{x})$
   - 4.4. Update R and P
   - 4.5. $\mathbf{s}^P = [(\mathbf{A}^T\mathbf{A})^P]^{-1}(\mathbf{A}^T\mathbf{b})^P$
   - 4.6. $\mathbf{s}^R = \mathbf{0}$
5. $\mathbf{x} = \mathbf{s}$
6. $\mathbf{w} = \mathbf{A}^T(\mathbf{b} - \mathbf{Ax})$

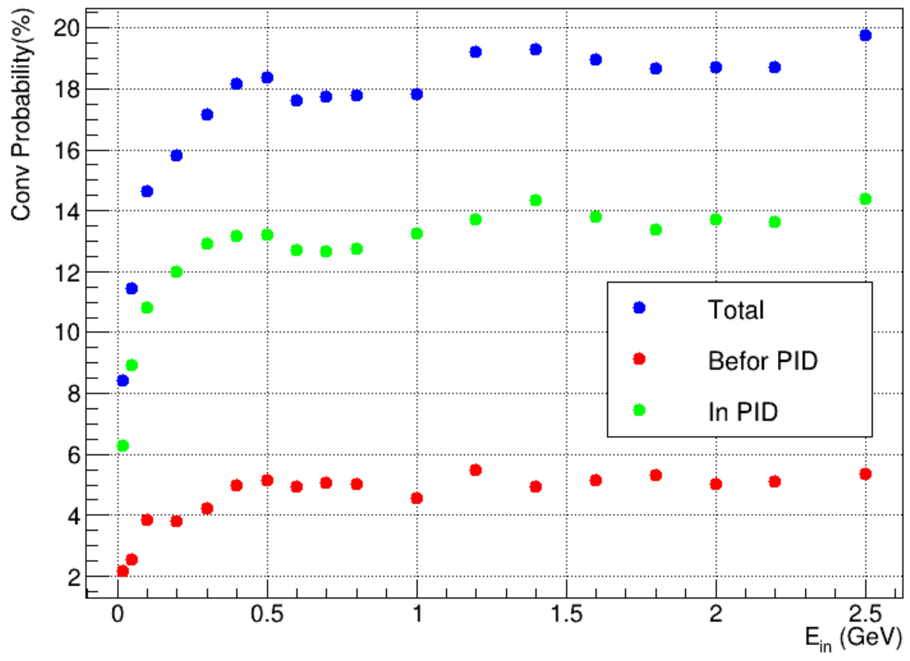
Performance Simulation

●Material budget in front of the ECAL

- ➢ The performance is affected by the interaction of photons with materials in front of the ECAL.
- ➢ The dominant interaction process for photons in the energy range of interest is gamma conversion.



Materials in front of the ECAL in units of a radiation length X_0

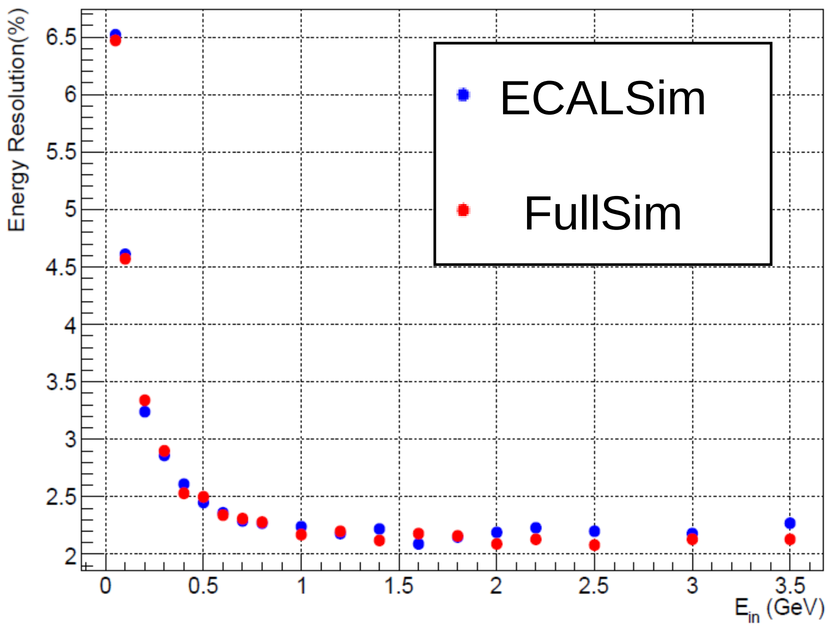


γ conversion probability in front of ECAL

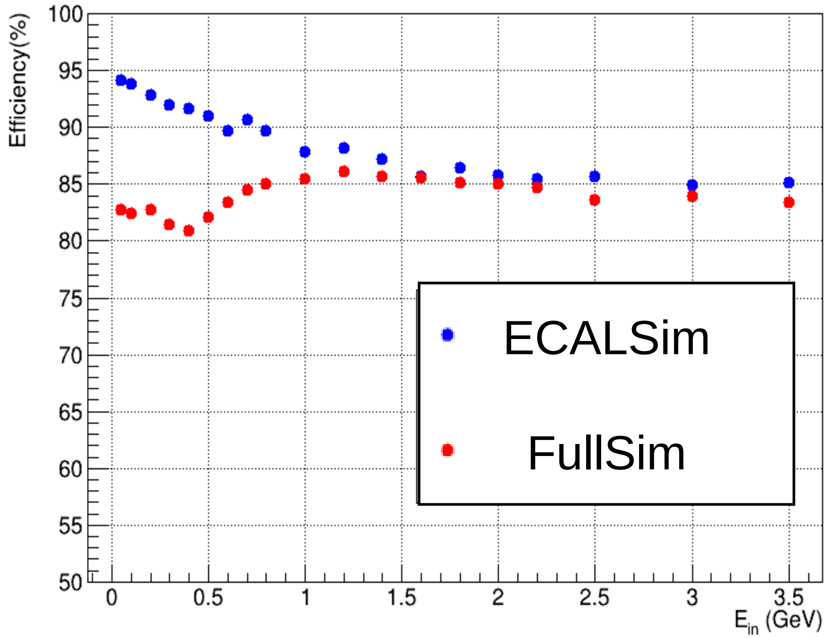
Performance Simulation

Impact of materials in front of ECAL

- A full STCF detector simulation study was carried out, and the simulation results are compared with ECAL only simulation results.



The energy resolution varies with γ energy.



The reconstruction efficiency varies with γ energy.

- ☐ have little effect on the energy resolution
- ☐ have great effect on reconstruction efficiency.

The reconstruction efficiency is defined by $\frac{N_{rec}}{N_{MC}}$,

N_{rec} satisfy: $E_{peak} - 4\sigma_E < E_{rec} < E_{peak} + 2\sigma_E$.