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Electromagnetic Calorimeter Software for Super Tau-Charm Facility

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(On behalf of the STCF ECAL working group)

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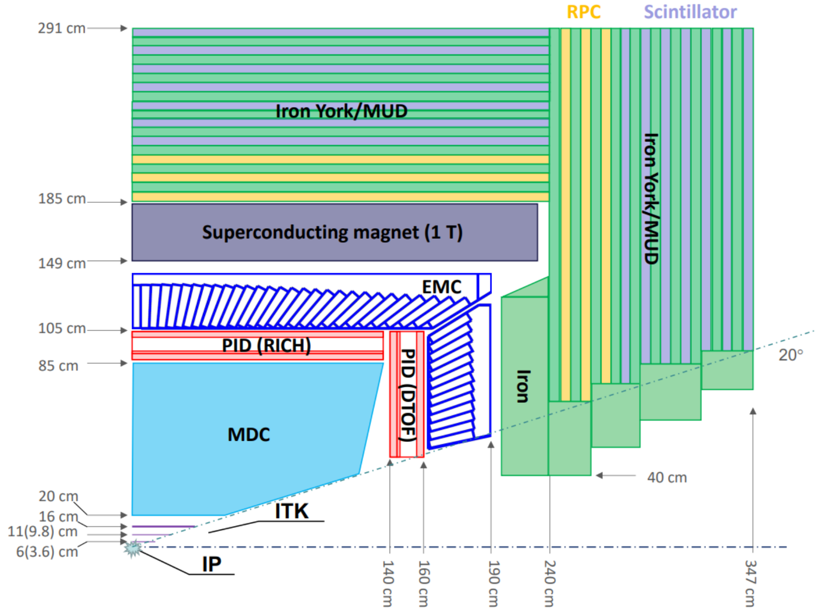
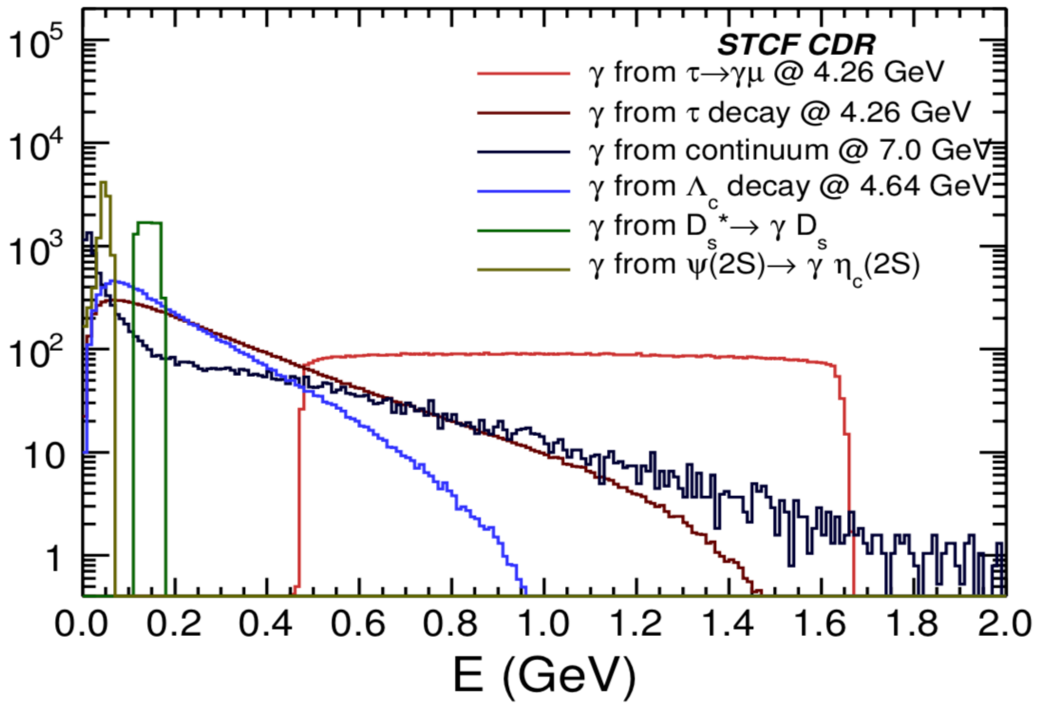
Super Tau-Charm Facility

- Electron-positron collider experiment
- High luminosity： beyond $0.5 \times 10^{35}\ cm^{-2} \cdot s^{-1}$ @ 4GeV
- Wide energy region： center-of-mass energy range of 2~7 GeV



Requirements for ECAL

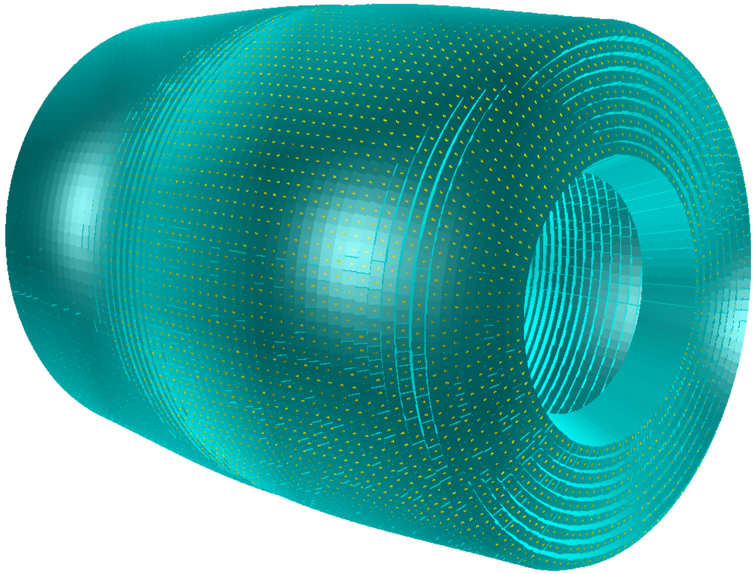
- **Fast response**
  - Challenge of high Luminosity
    - High count rate
    - Extremely high background
- **High precision**
  - Energy resolution
    - Better than 2.5% @1GeV
  - Position resolution
    - Better than 5mm @1GeV
  - Time resolution
    - Better than 300ps @1GeV

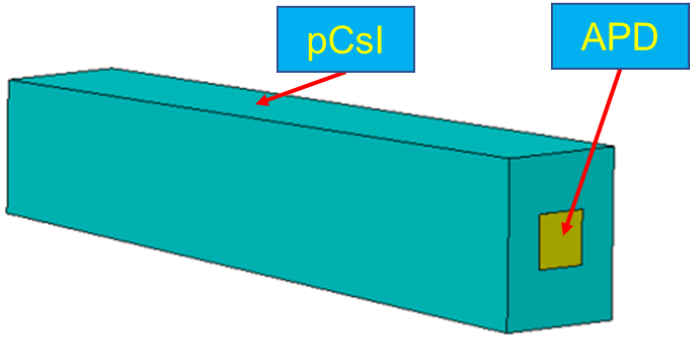


Energy distribution for photons

ECAL Design

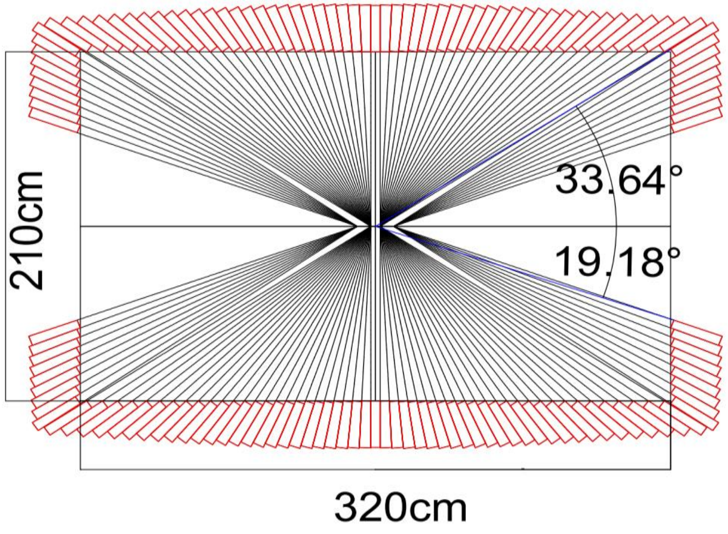
- Total absorption calorimeter
  - Barrel: $51 \times 132 = 6732$
  - Endcap: $3 \times (85 + 102 + 136) \times 2 = 1938$
  - Crystal Size:
    - $5 \times 5 \times 28(15X_0)\ cm^3$
- Sensitive Unit
  - Pure CsI (pCsI) crystal
    - Fast decay time (~30ns)
    - Good radiation hardness
    - Low light yield
  - Avalanche photodiode (APD)
    - Short wavelength type
    - Large area ($10 \times 10\ mm^2 \times 4$)

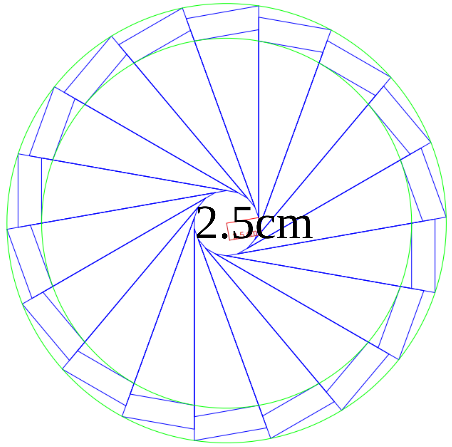




ECAL Setup

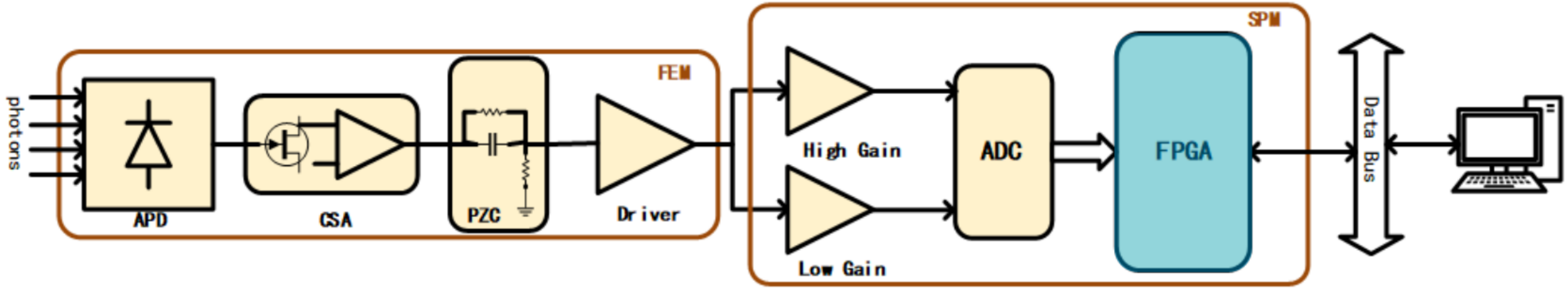
- "Dead Material"
  - 150-μm Teflon reflective film
  - 75-μm polyethylene insulating film
  - 75-μm Al electrostatic shielding film
  - No supporting material
- Light Yield: 100 p.e./MeV
- Light Collection Non-uniformity
  - collection efficiency: $\epsilon(l) = 95\% + l/L \times 5\%$
- $\sigma_{noise} = 1.0$ MeV
- $E_{hit\_thres} = 5.0$ MeV
- Secondary Particles Hit APD





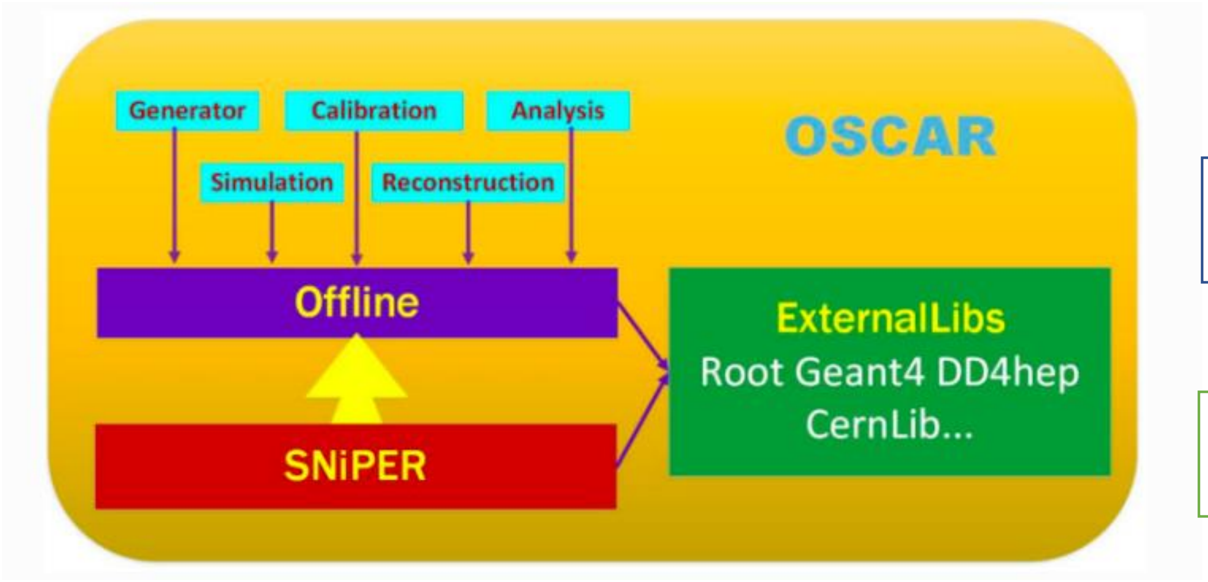
ECAL Electronics

- Charge sensitive amplifier and pole-zero cancellation with shaping time 100 ns
- High and Low Gain (300 MeV/3000MeV)
- 16-bit ADC (~16000 channels) with 80 MHz sampling rate

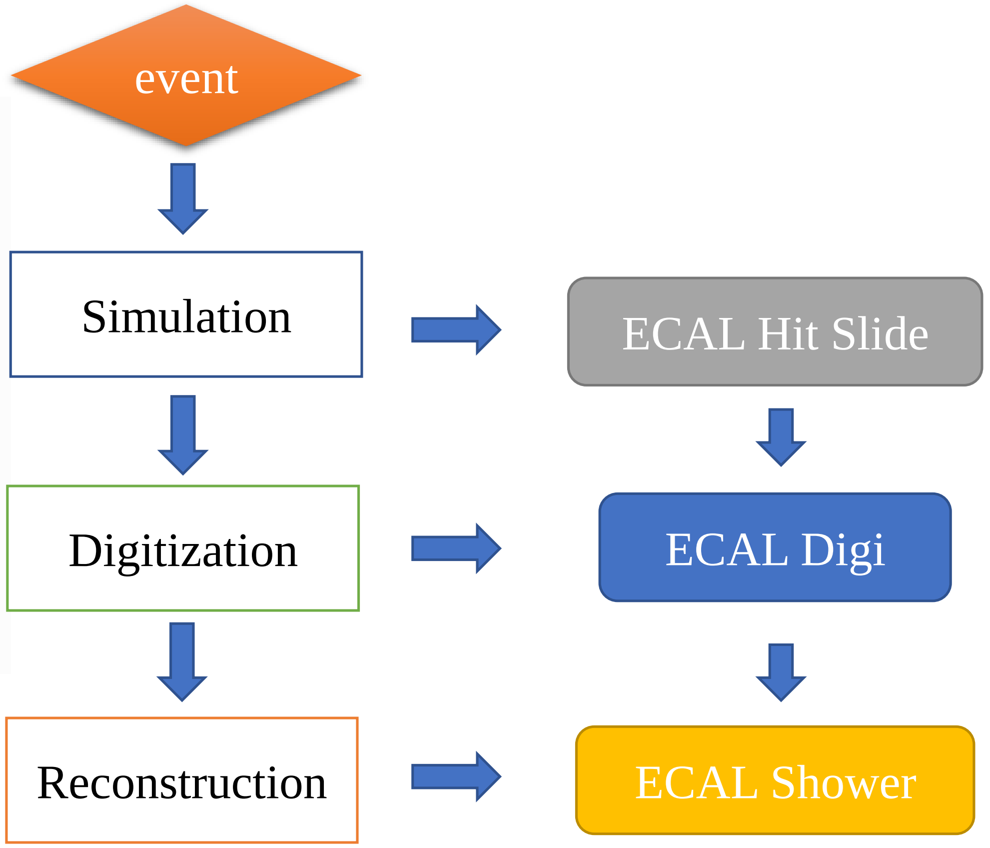


Based on OSCAR

- OSCAR: Offline Software of Super Tau-Charm Facility



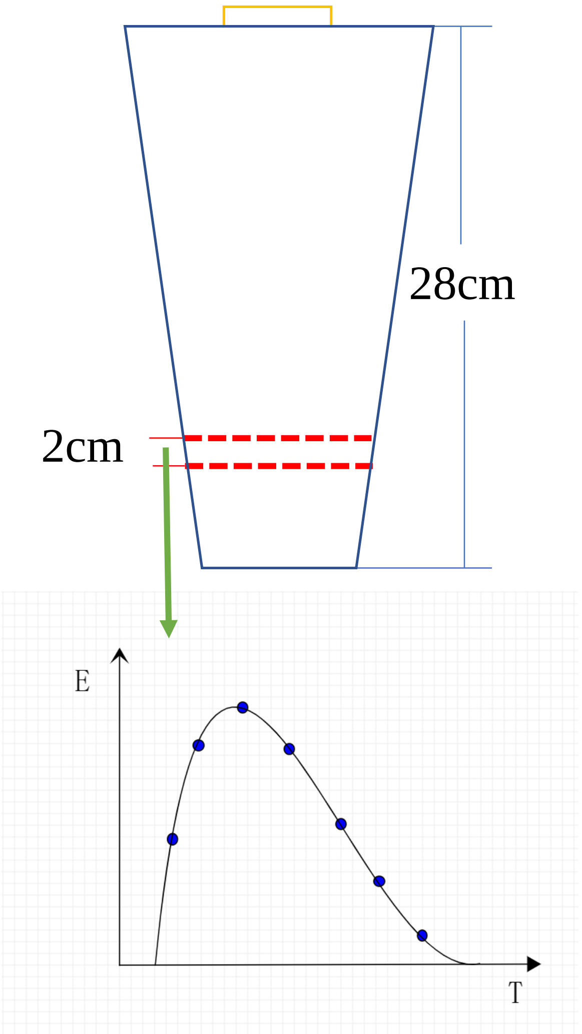
OSCAR Framework Composition



Simulation Algorithm

- Based on Geant4 Simulation
  - Process the information for each Geant4 step
- Data Model (layer as a unit)
  - Thickness 2cm as a layer unit
  - Each unit with a energy-time distribution: points with (E,T)
  - Bin width 500ps for energy-time distribution

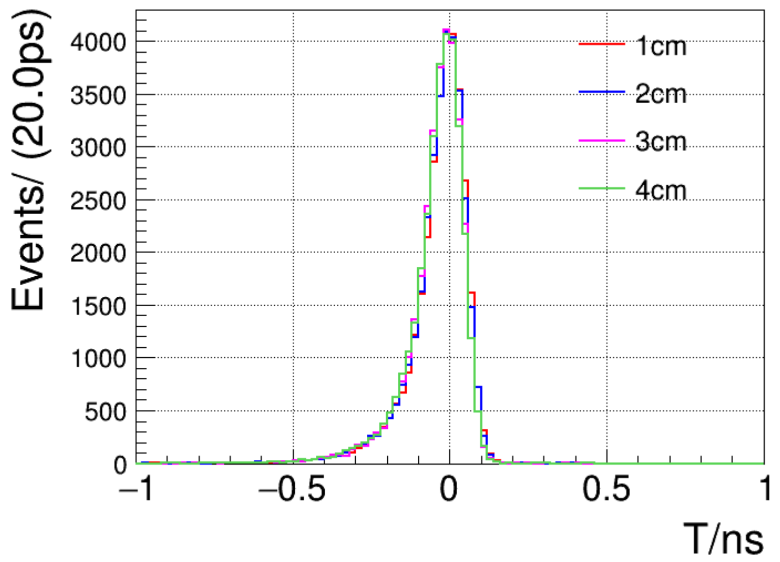
✓ Save storage space
✓ Minimal loss of information

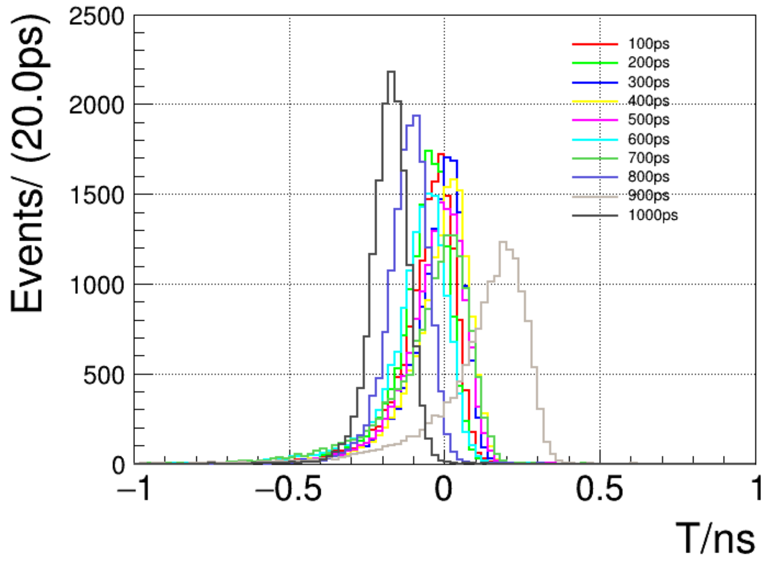


Simulation Algorithm

Data Model

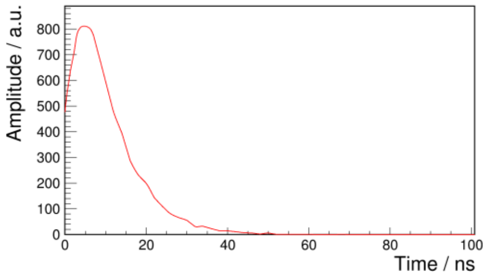
- **Sizes of thickness and time bin width have been optimized**
  - No large difference of time distribution for different thickness
    - Consider the non-uniformity may vary in the future : 2cm
  - Different time bin width with different time resolution and central value
    - Difference in central value approximately equivalent to a shift of the template
    - Consider the resolution and the similarity to the template: 500ps





Digitization Algorithm

Waveform shaping



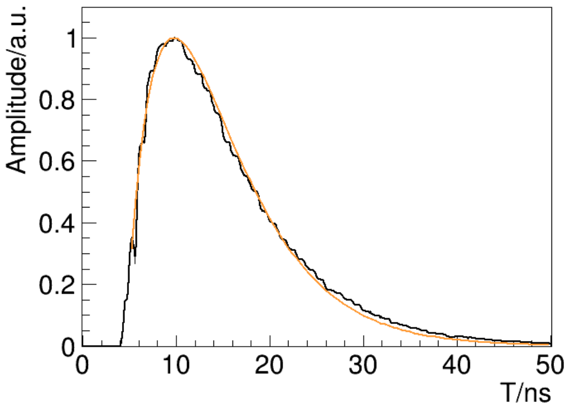
Geant4 optical simulation for each layer unit (standalone)

Sampling

Points (E-T) in each layer unit

Light output nonuniformity

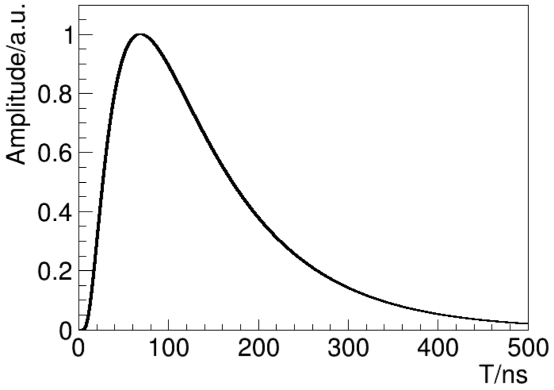
Fluorescence transfer parameterized simulation



convolution

Scintillation process

Electronics response function



Electronic noise

ADC (12.5ns)

Output waveform

Digitization Algorithm

Waveform fitting

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

  Where y_i and t_i are from readout waveform; the electronics foundation p in digitization is $p = 0$; A and τ are the amplitude and time from fitting result; S_{ij} is the noise covariance matrix.

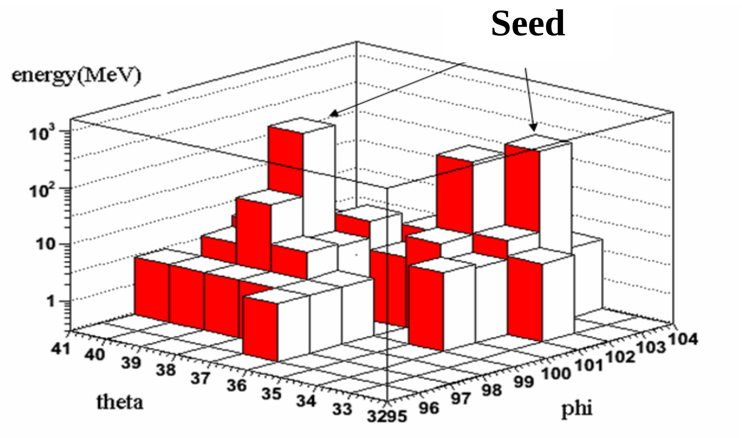
- **Multi-template fitting to study the capability for pile-up recovery**

Reconstruction Algorithm

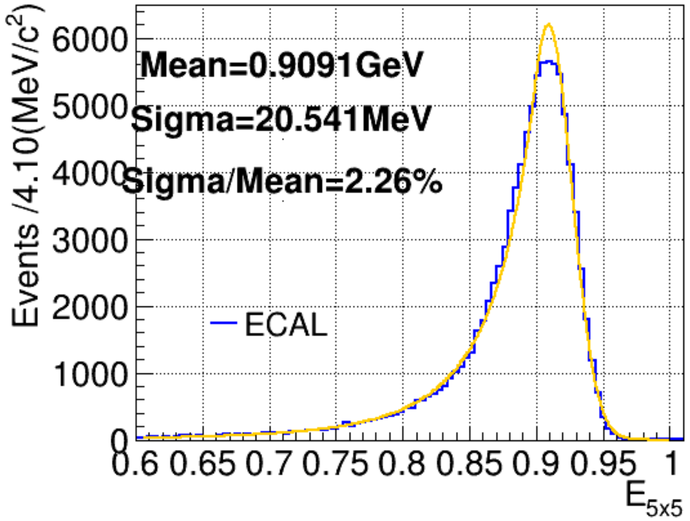
- A complete reconstruction algorithm of ECAL is developed

ECALRecAlg

1. **Cluster search**
2. **Seed search**
3. **Clusters split into Showers**
4. **Calculation and correction of shower energy and position**



π^0 Cluster (two photons)



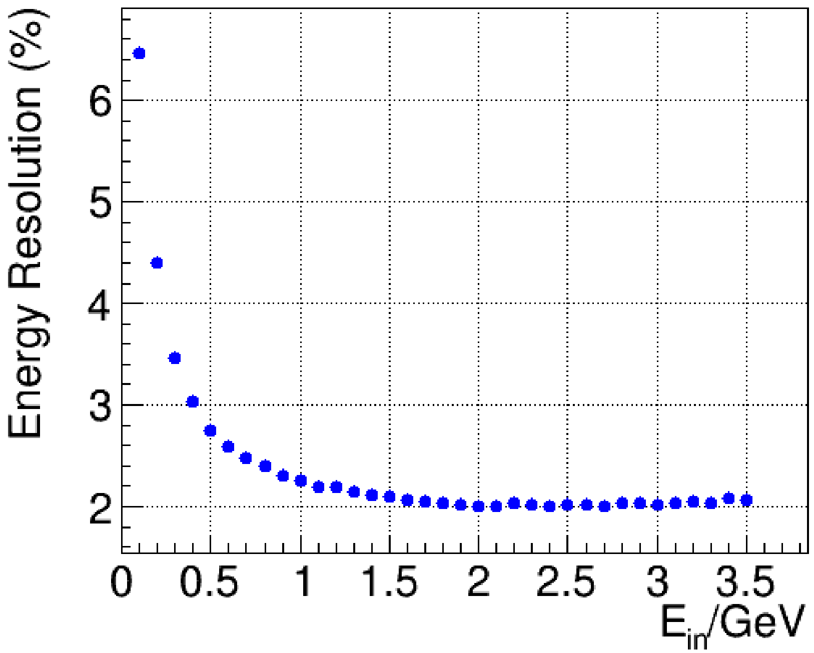
Energy distribution of 1GeV γ

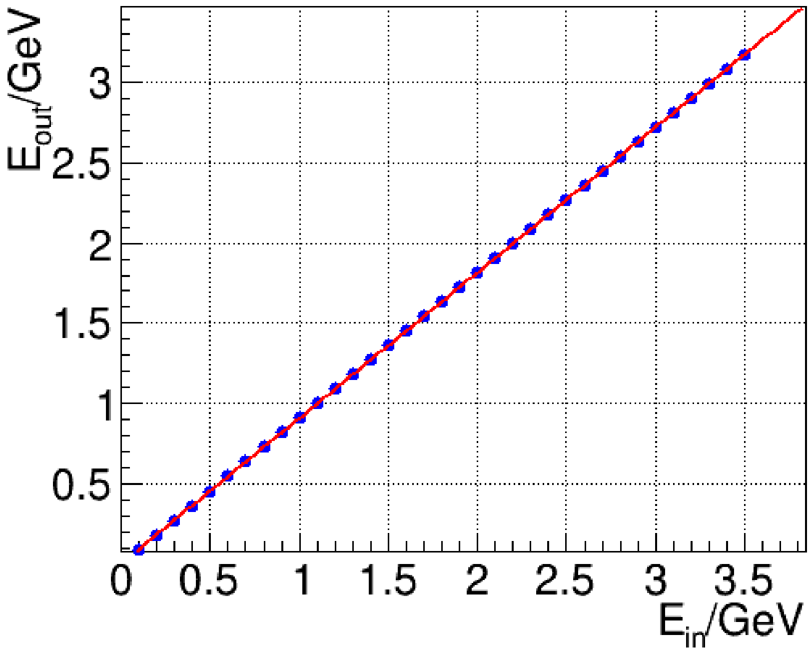
- Fitted by Crystal Ball function
- Energy resolution defined by

$$\sigma_E = \frac{FWHM}{2.355}$$

Reconstruction Performance

Energy Reconstruction



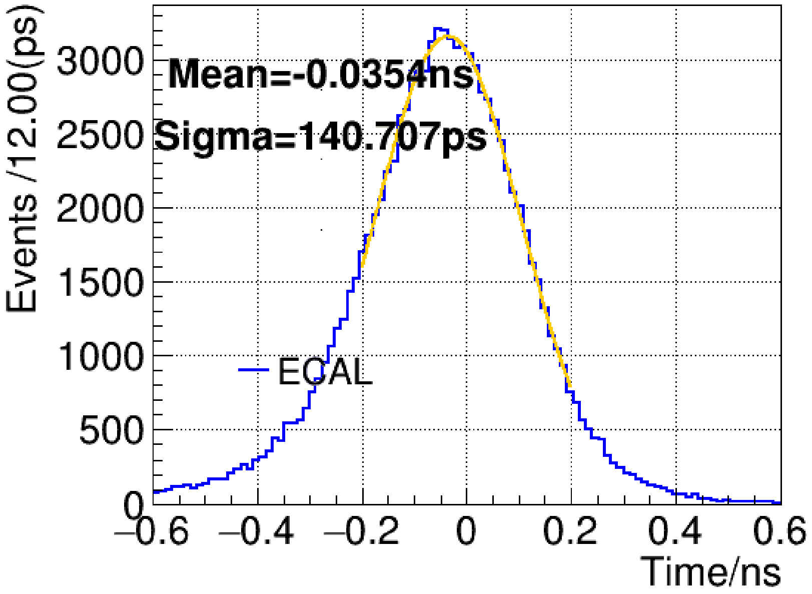


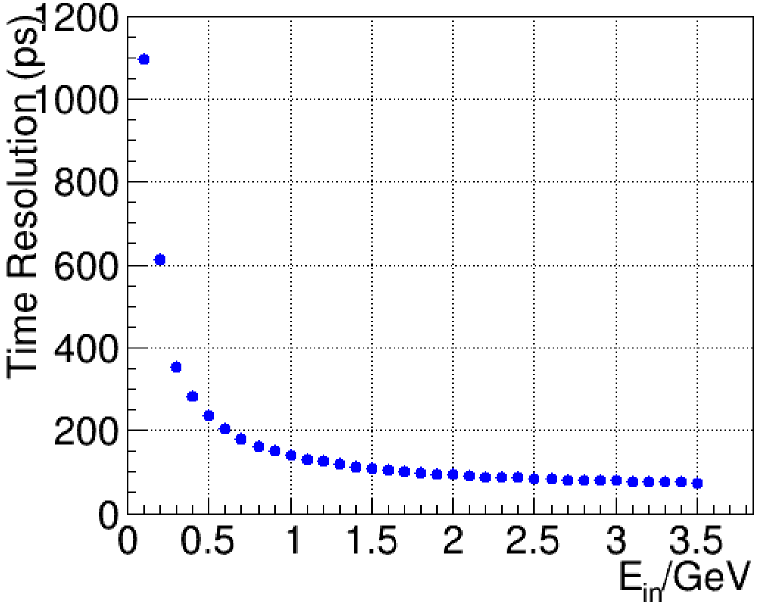
- ✓ $\sigma_E = 2.26\%$ @ 1 GeV
- ✓ $\sigma_E = 6.44\%$ @ 0.1 GeV
- ✓ Meet the requirement

- ✓ Good energy linearity in the energy range of 100 MeV ~ 3.5 GeV

Reconstruction Performance

Time Reconstruction





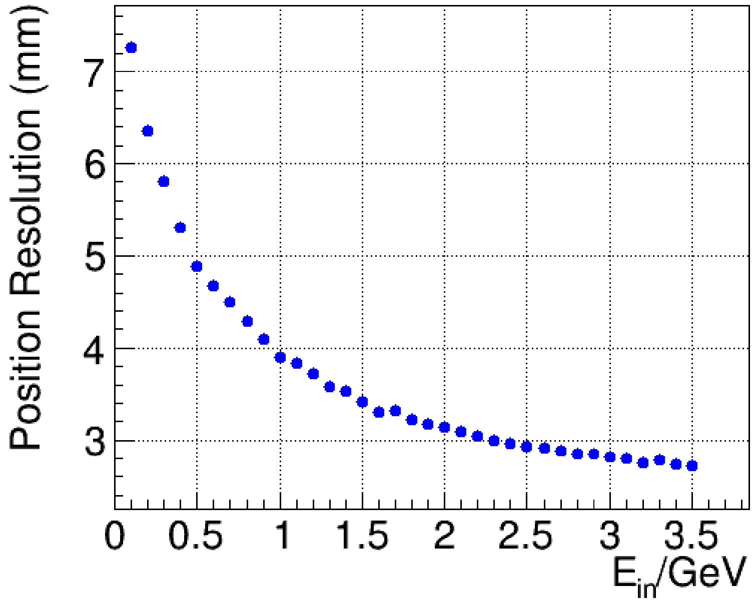
- ✓ σ_T = 140 ps @ 1 GeV
- ✓ Fitted with Gaussian function
- ✓ Meet the requirement

Reconstruction Performance

Position Reconstruction

- Splitting algorithms (used by BESIII and Panda)
  - $a_{ik} = \frac{E_k \times \exp(c \times \frac{r_{ik}}{R_M})}{\sum_{j=1}^{m} E_j \times \exp(c \times \frac{r_{ij}}{R_M})}$
- Barycenter method
  - $X_c = \sum_j^N W_j(E_j) \cdot X_j / \sum_j^N W_j(E_j)$

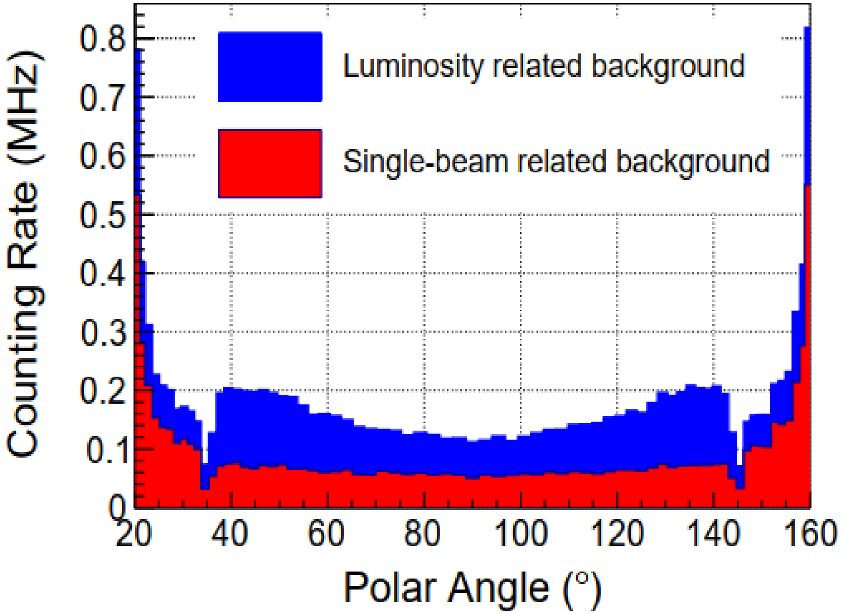
Where $W_j(E_j) = \max\{0, a - \sqrt{-\ln\left(E_j / \sum_j^N E_j\right)}\}$



- ✓ $\sigma_{pos} = 3.9$ mm @ 1 GeV
- ✓ Meet the requirement

Challenges of high background

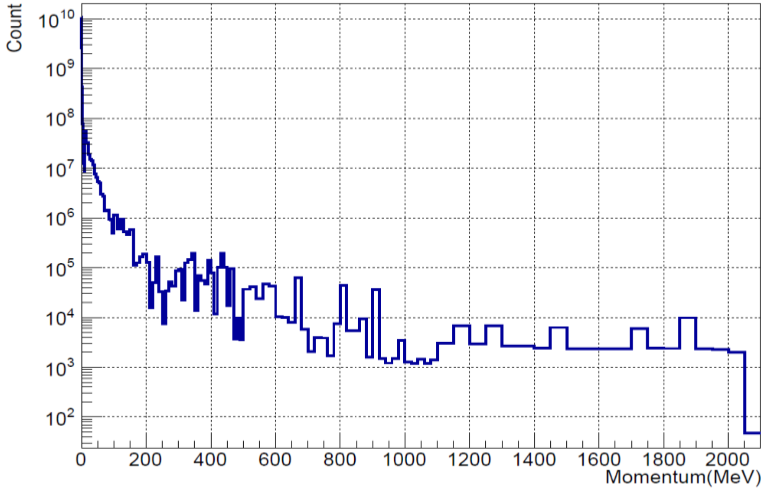
- **Luminosity-related Background**
  - Radiative BhaBha Scattering (RBB)
  - Two Photon Process



Variation of the background counting rate with polar angle

Counting rate reaches the order of MHz

- **Single-beam related Background**
  - Thouschek Effect
  - Coulomb Scattering
  - Bremsstrahlung



Momentum distribution of background particles

Most background particles concentrate in the low momentum region

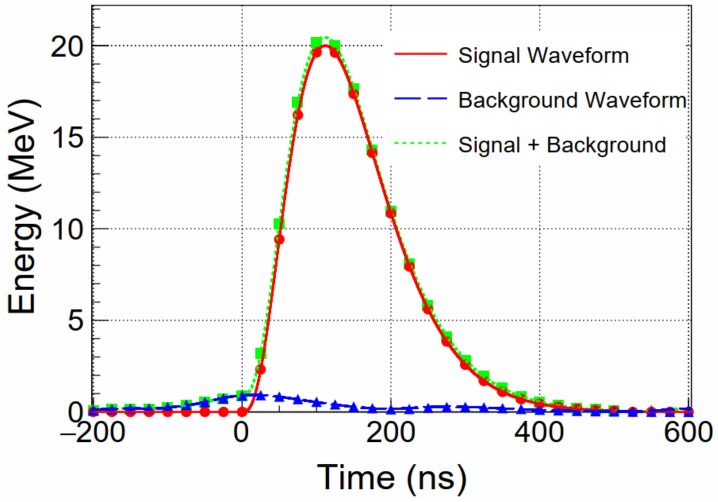
Pile-up Recovery

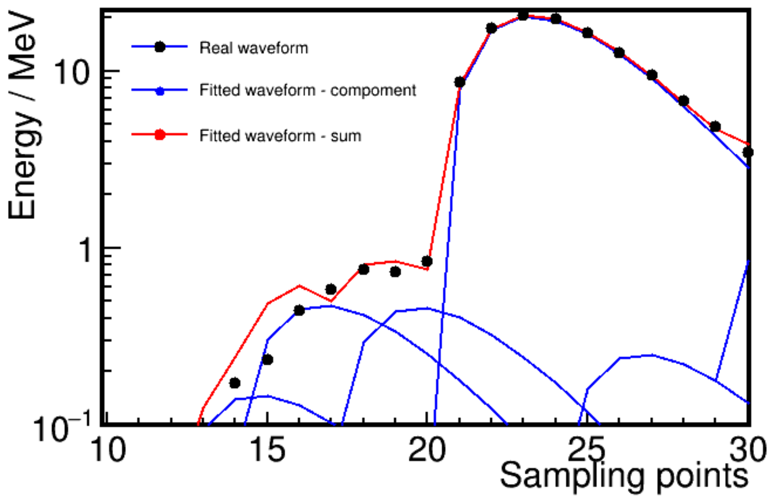
Multi-template fit

- Fit all the potential waveforms with template
- Isolate signals by time
- The fit minimizes the χ^2 defined as:

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

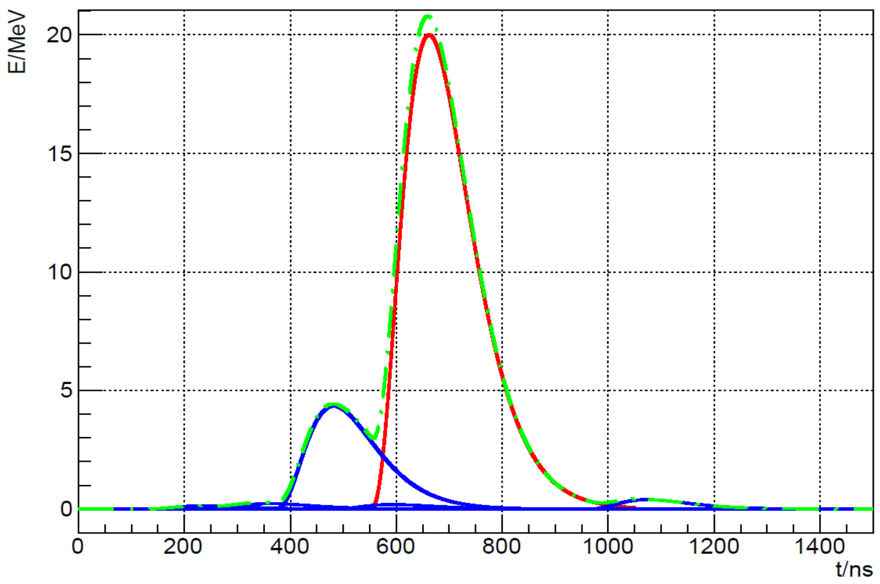
Where:
N is the number of templates;
vector $\vec{S}$ comprise the readout samples;
vector $\overrightarrow{p_j}$ is the waveform template;
A_j are the amplitudes, which are obtained by the fit;
C is the noise covariance matrix.



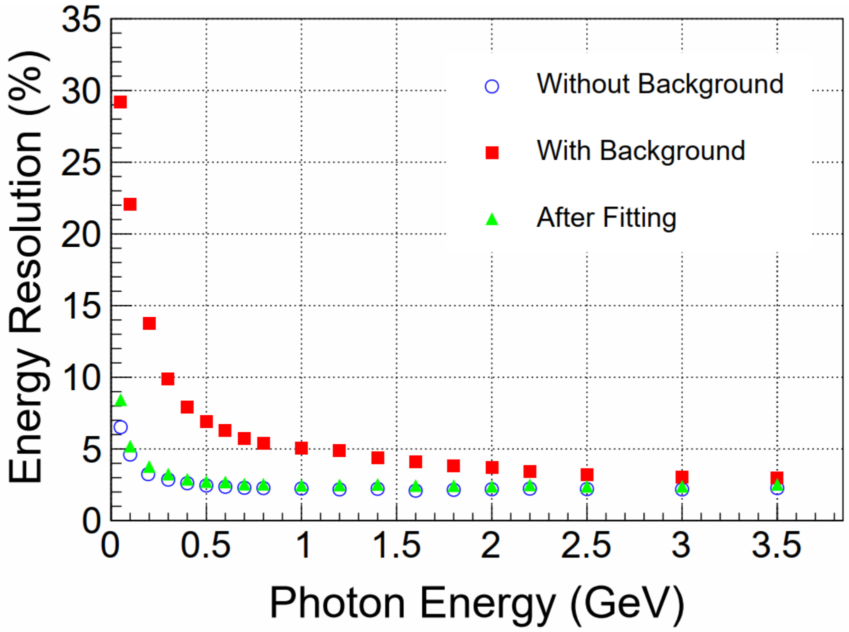


Pile-up Recovery

- Background waveform is superimposed on the signal waveform
- The impact of the background is devastating
- Energy Resolution is greatly recovered



The amplitude of signal is distorted



Summary

- The software of ECAL has been established based on OSCAR
- The simulated performance of ECAL meets requirements.
  - ✓ Energy measurement with 2.26% @ 1 GeV
  - ✓ Position measurement with 140 ps @ 1 GeV
  - ✓ Time measurement with 3.9 mm @ 1 GeV
  - ✓ A general algorithm shows good performance on pile-up recovery

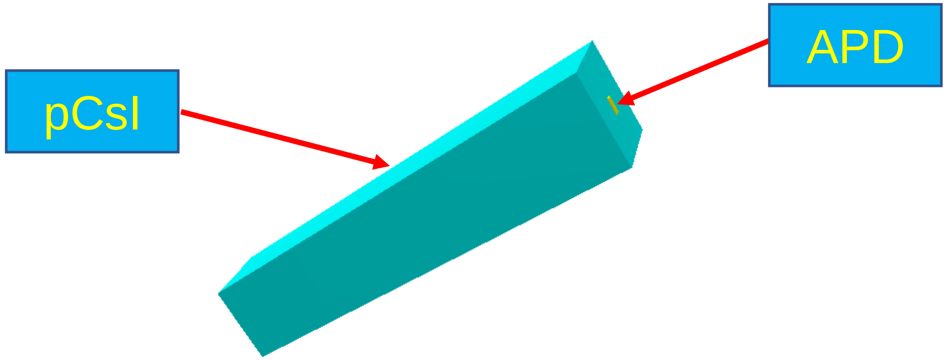
- The difference between simulation and the real electronics response, and signal processing method to be updated
- The online pile-up recovery method to be updated

Thanks for your listening!

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 ($10 \times 10\ mm^2 \times 4$)



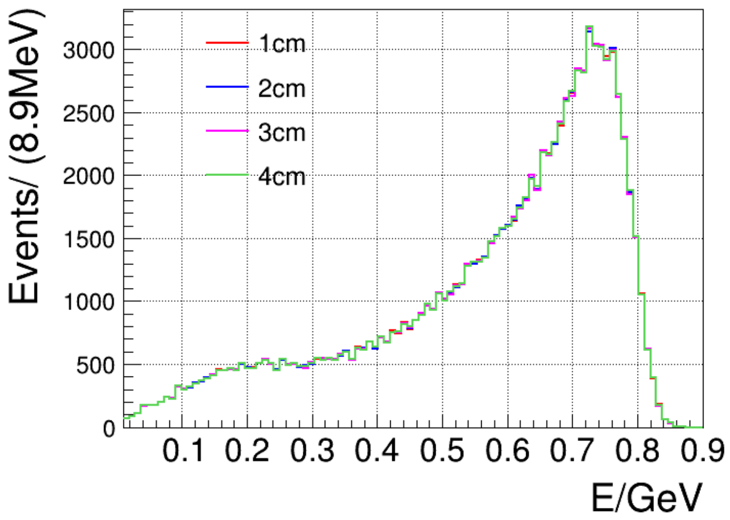
ECAL pCsI crystal unit

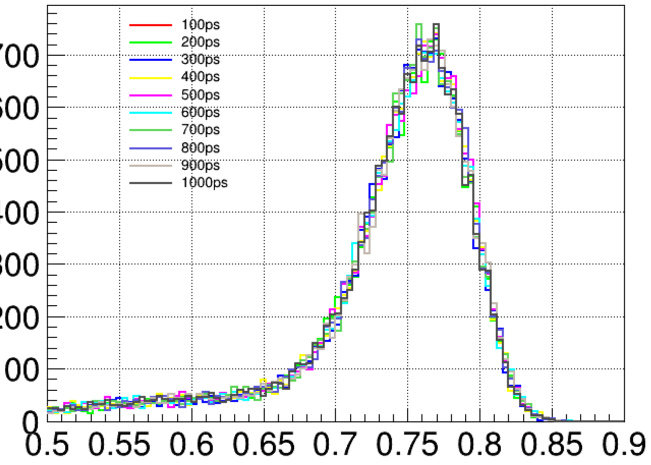
Crystal	Pure CsI
Density (g/cm³)	4.51
Melting Point (°C)	621
Radiation Length (cm)	1.86
Moliere Radius (cm)	3.57
Refractive index	1.95
Hygroscopicity	Slight
Luminescence (nm)	310
Decay time (ns)	30 6
Light yield (%)	3.6 1.1
Dose rate dependent	No
D(LY)/dT (%/°C)	-1.4
Experiment	KTeV Mu2e

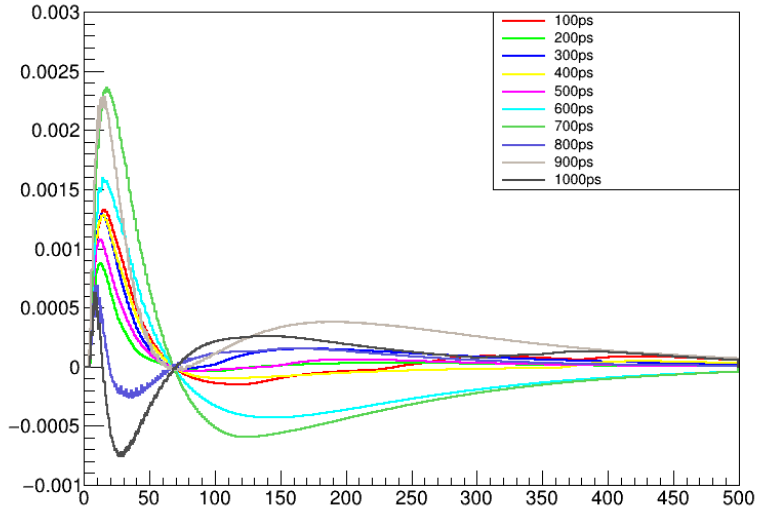
Simulation Algorithm

Data Model

- Energy distribution and comparison with template

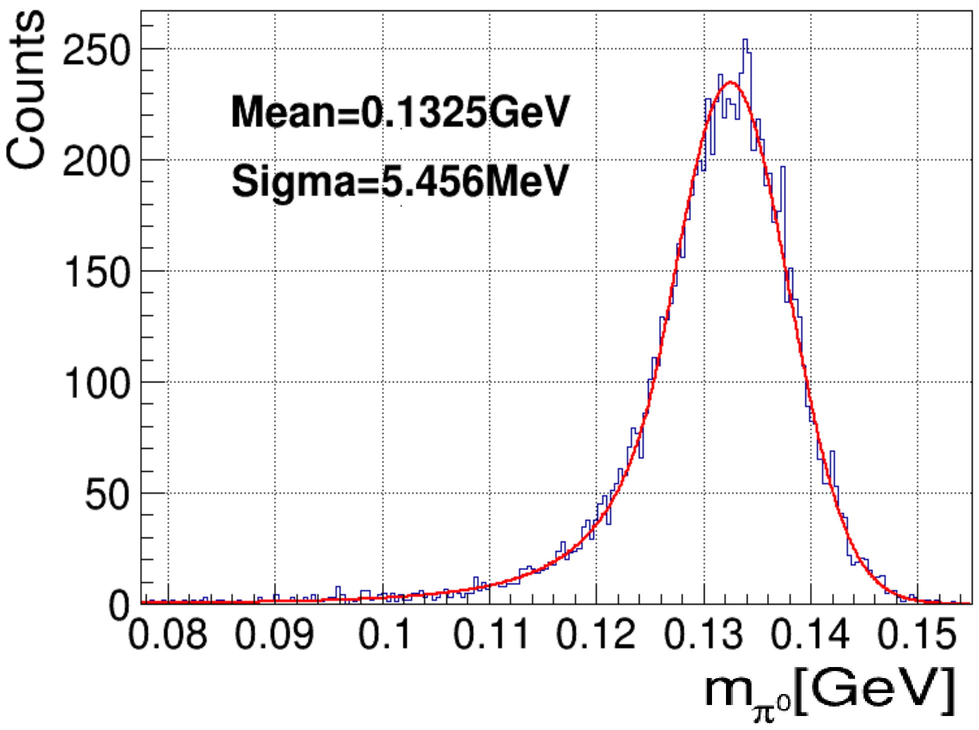




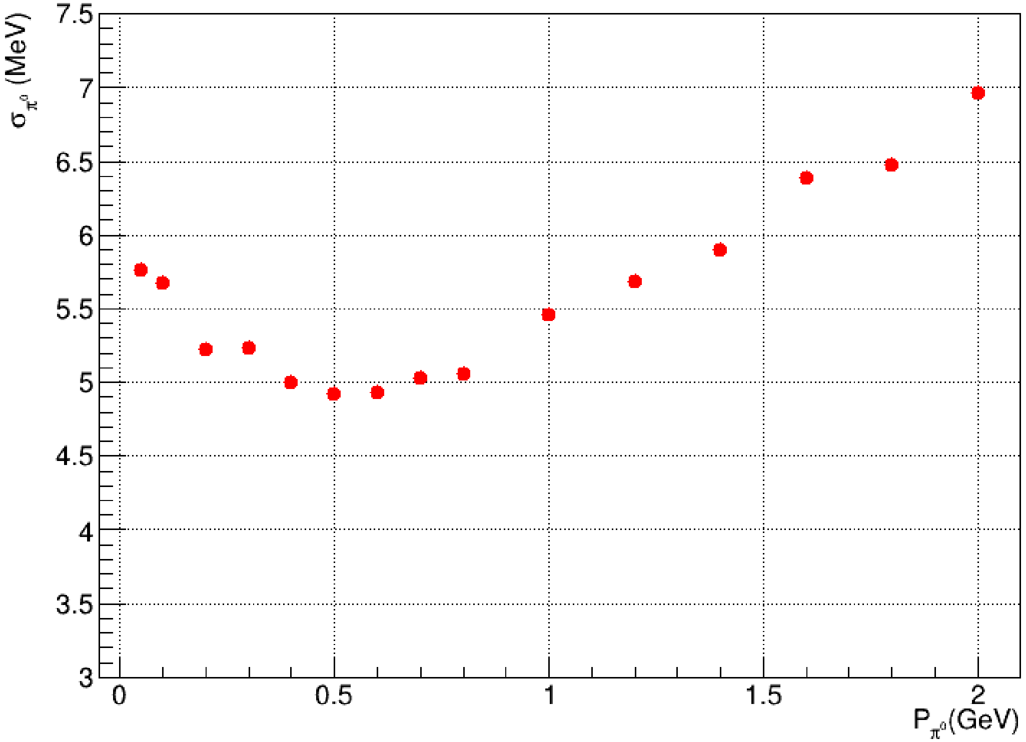


π^0 Reconstruction

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

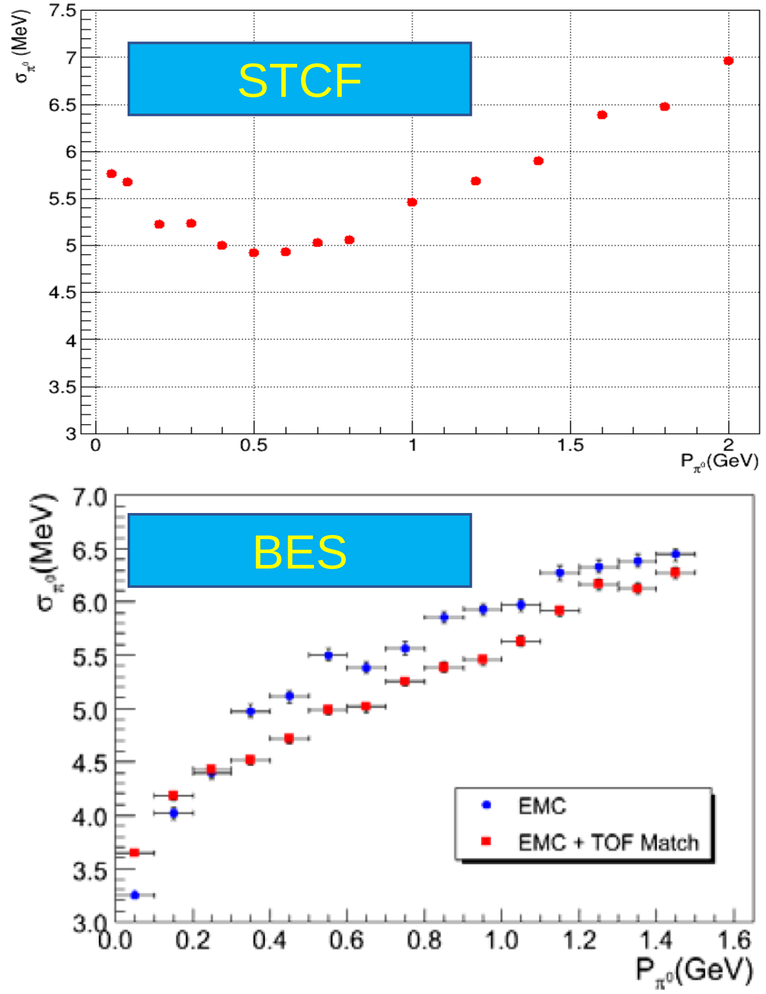


Mass reconstruction of π^0 (P = 1GeV)



Mass resolution of π^0

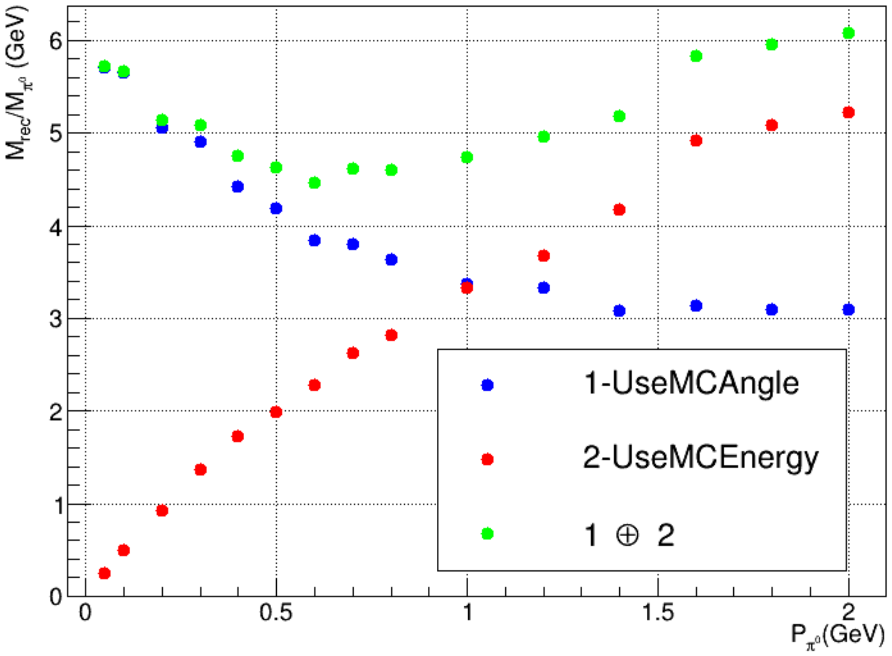
Reconstruction of Energy and Position



Mass resolution of π^0

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

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



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

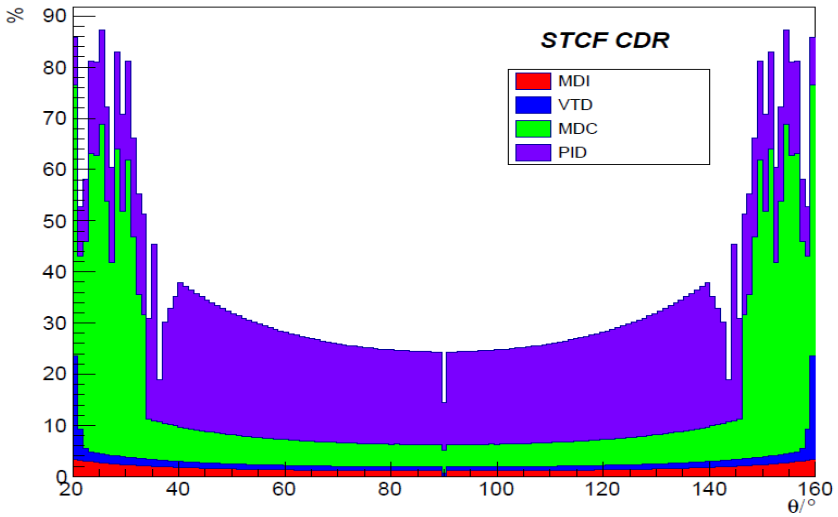
Algorithm *fnnls* **:**

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

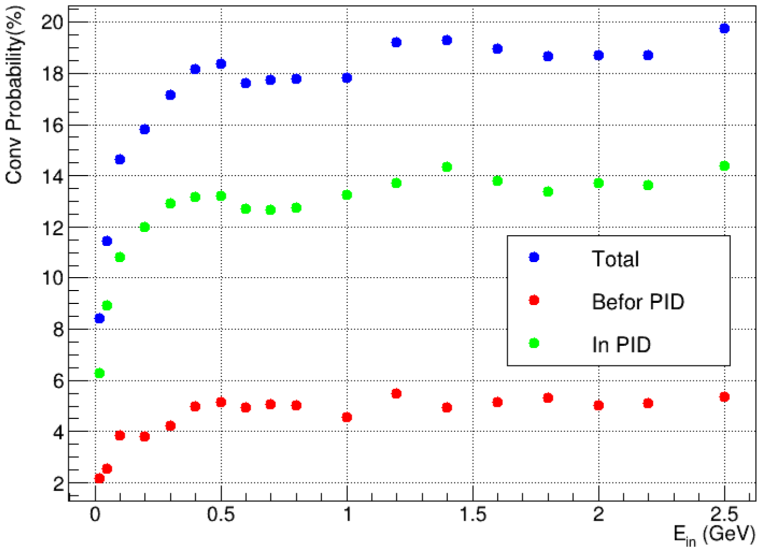
1. Proceed if $R \neq \varnothing \wedge [\max_{i\in R}(w_i) > tolerance]$
2. $j = \arg\max_{i\in R}(w_i)$
3. Include the index j in P and remove it from R
4. $\mathbf{s}^P = [(\mathbf{A}^T\mathbf{A})^P]^{-1}(\mathbf{A}^T\mathbf{b})^P$
   - 4.1. Proceed if $\min(\mathbf{s}^P) \leq 0$
   - 4.2. $\alpha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

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.



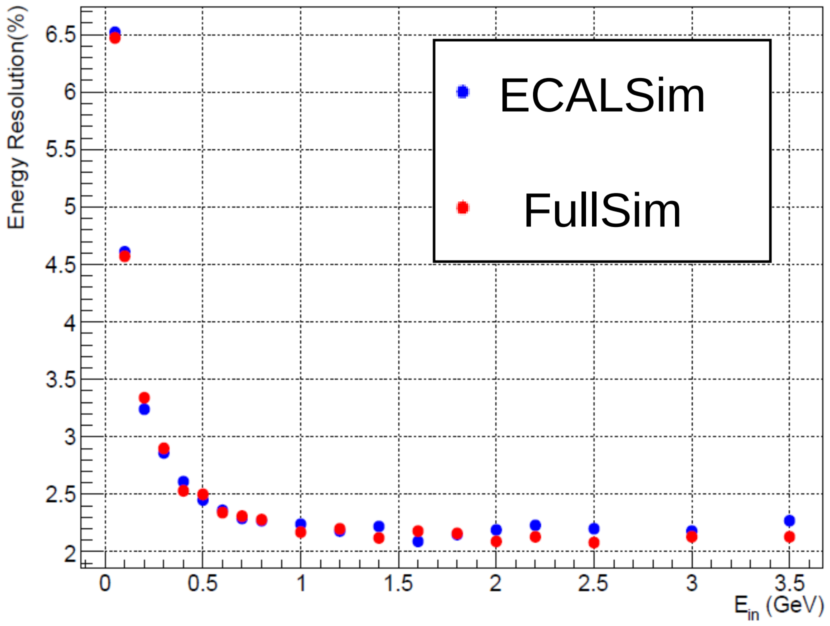
Materials in front of the ECAL in units of a radiation length X_0



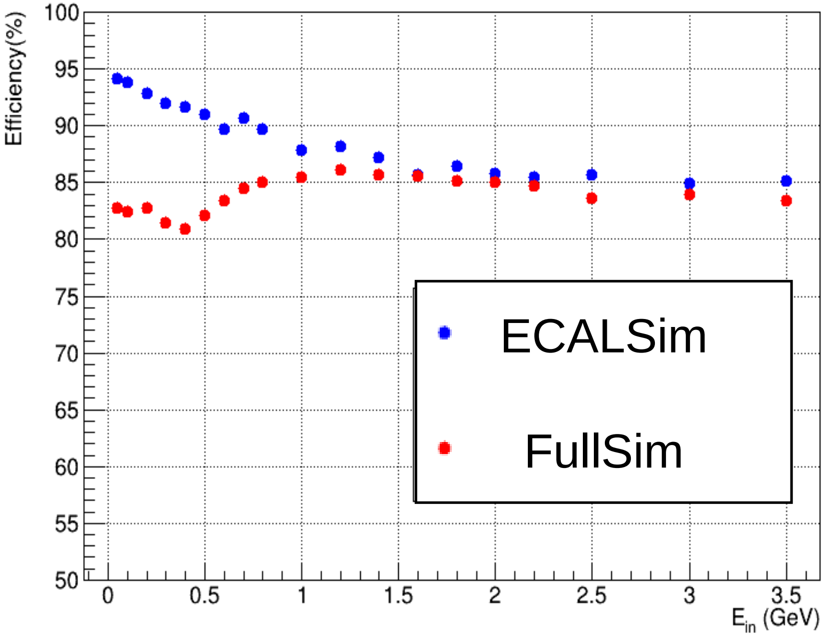
γ conversion probability in front of ECAL

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

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

- Little effect on the energy resolution
- Great effect on reconstruction efficiency.