中国科学技术大学
University of Science and Technology of China

Design and R&D of the Electromagnetic Calorimeter for the Super Tau-Charm Facility

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On behalf of the STCF calorimeter working group

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Outline

- **Research Background**
- **STCF ECAL Conceptual Design**
- **STCF ECAL R&D**
- **Summary**

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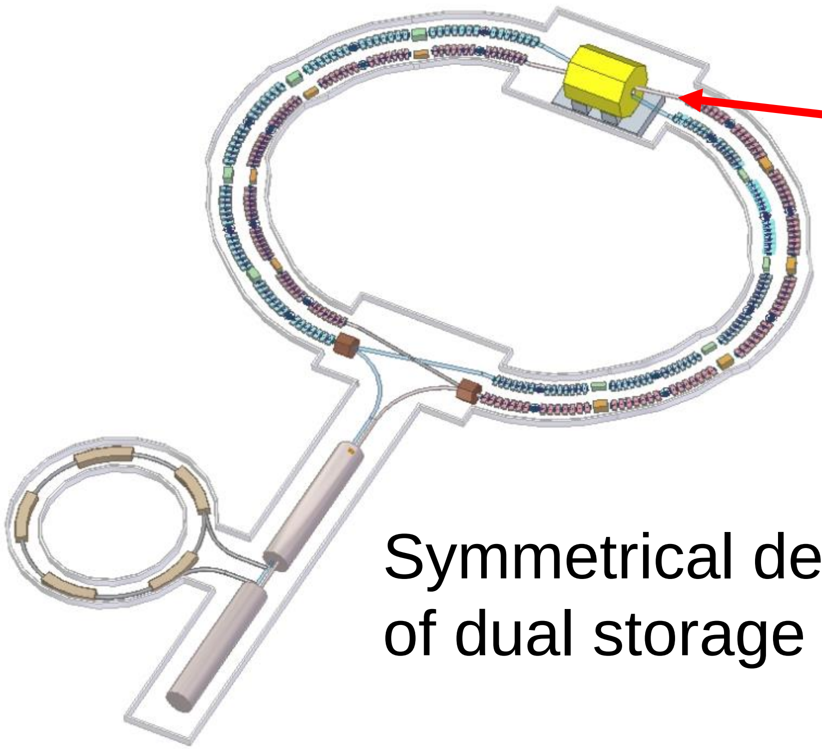
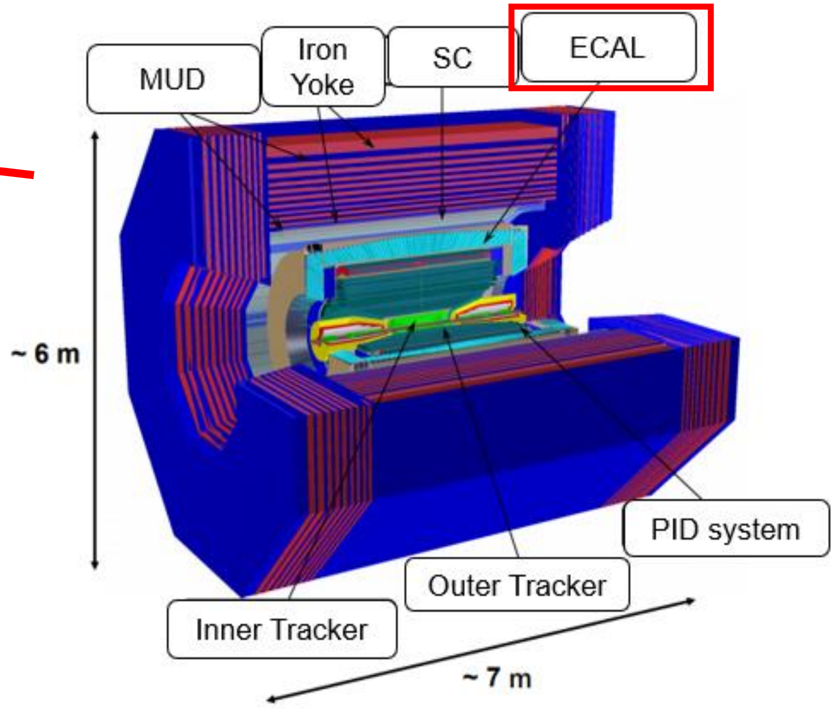
Super Tau-Charm Facility

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



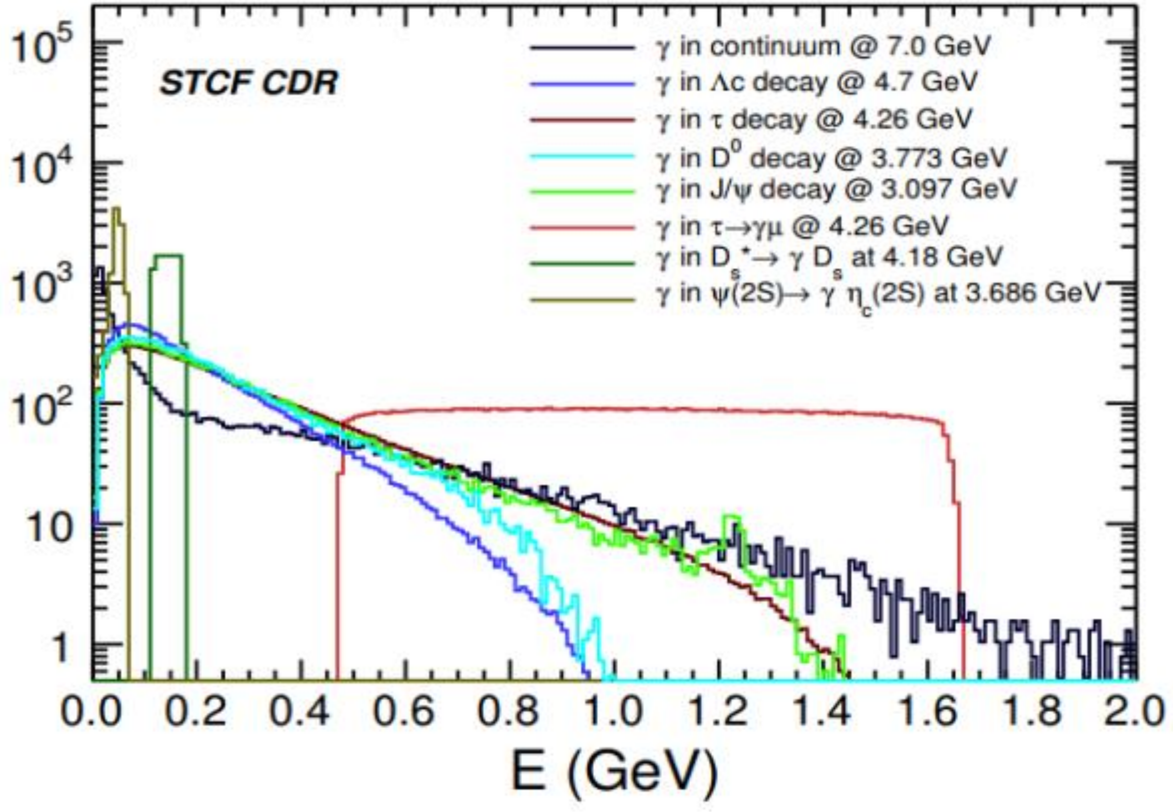
Symmetrical design of dual storage ring



Requirements for Electromagnetic Calorimeter(ECAL)

- **Fast response**
  - Challenge of high Luminosity
    - High event rate (400 kHz)
    - High background level
    - (~MHz for single crystal unit)

- **High precision**
  - Energy resolution
    - Better than 2.5% @1 GeV
  - Position resolution
    - Better than 5 mm @1 GeV
  - **Time resolution**
    - Better than 300 ps @1 GeV



Energy distribution of photons

For more specific details, please refer to the STCF CDR.

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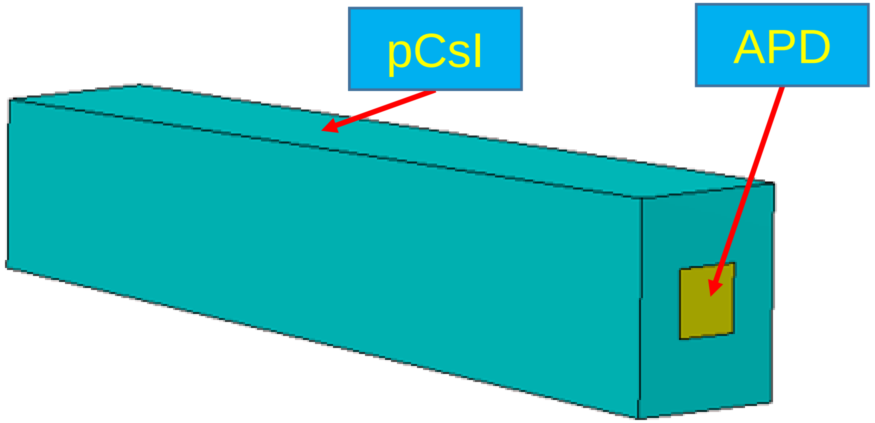
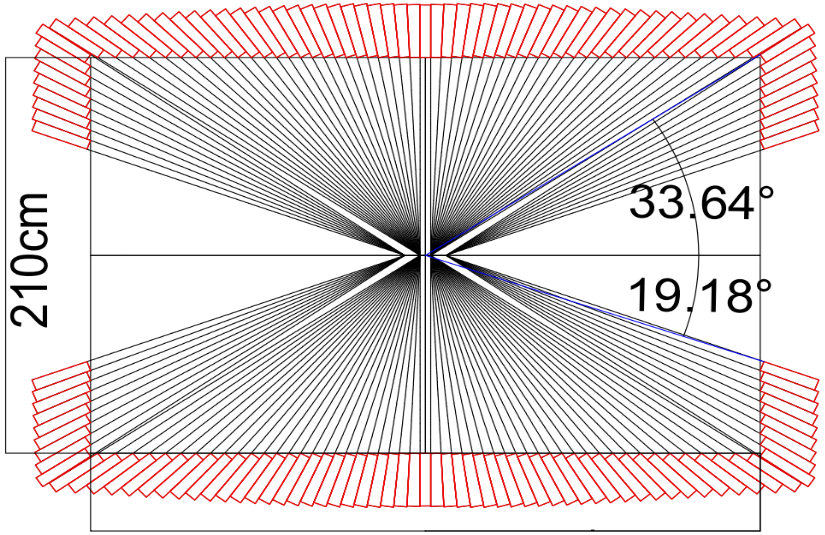
ECAL Conceptual Design— crystal calorimeter

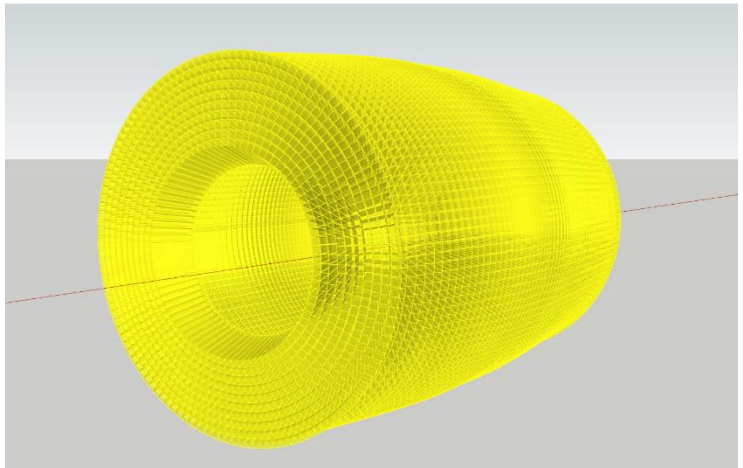


Pure CsI (pCsI) crystal + APD

- Pure CsI (pCsI) crystal
  - Fast decay time (~30 ns)
  - Good radiation hardness
  - Low light yield
- Avalanche photodiode (APD)
  - Large area

- Barrel: $51 \times 132 = 6732$
- Endcap: $3 \times (85 + 102 + 136) = 969$
- Crystal Size: $\sim 5 \times 5 \times 28(15X_0)\ cm^3$





Crystal arrangement diagram and geometry model

Simulation Studies Based on Geant4

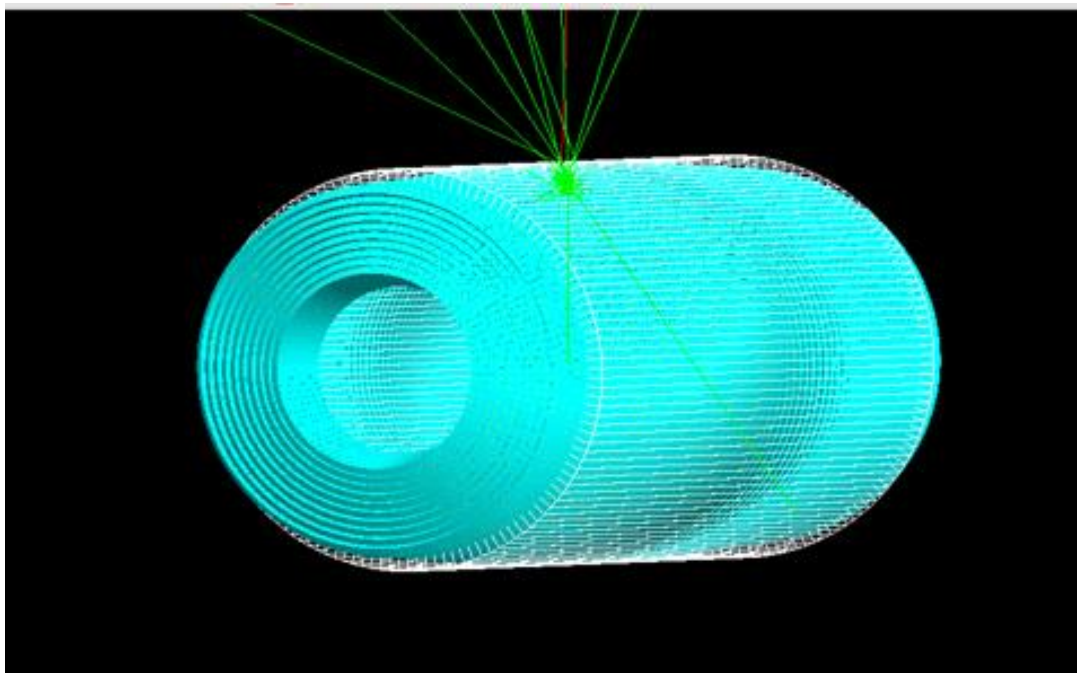
Geant4 Simulation Setup

1. **"Dead Material"**
   a. 150-µm Teflon reflective film
   b. 75-µm polyethylene insulating film
   c. 75-µm Al electrostatic shielding film
   d. 200-µm-thick carbon fiber
2. **Light Yield (100 p.e./MeV)**
3. **Light Collection Non-uniformity**

   collection efficiency:

   $$\varepsilon(l) = 95\% + l/L \times 5\%,$$

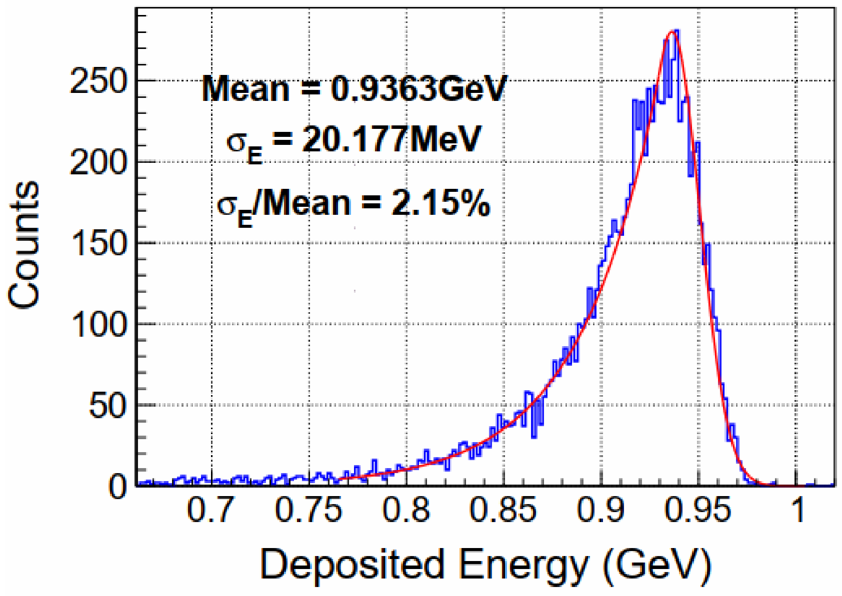
   where L is the length of the crystal,
   l is the distance from APD.
4. **Secondary Particles Hit APD**
5. **Electronics Noise (1 MeV)**



Photon Shower Visualization

Reconstruction of Energy

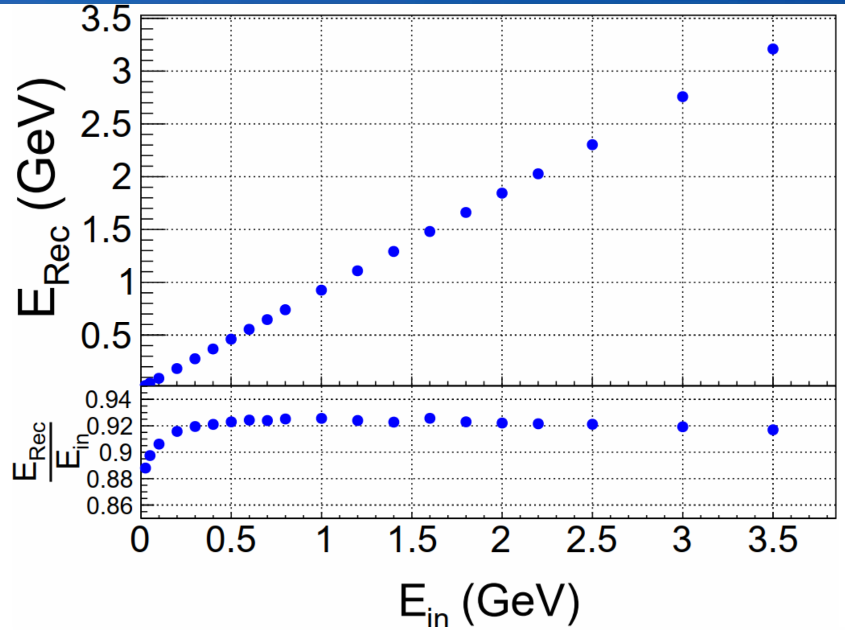
- The photon energy is reconstructed by summing energy deposition of a 5×5 crystal array

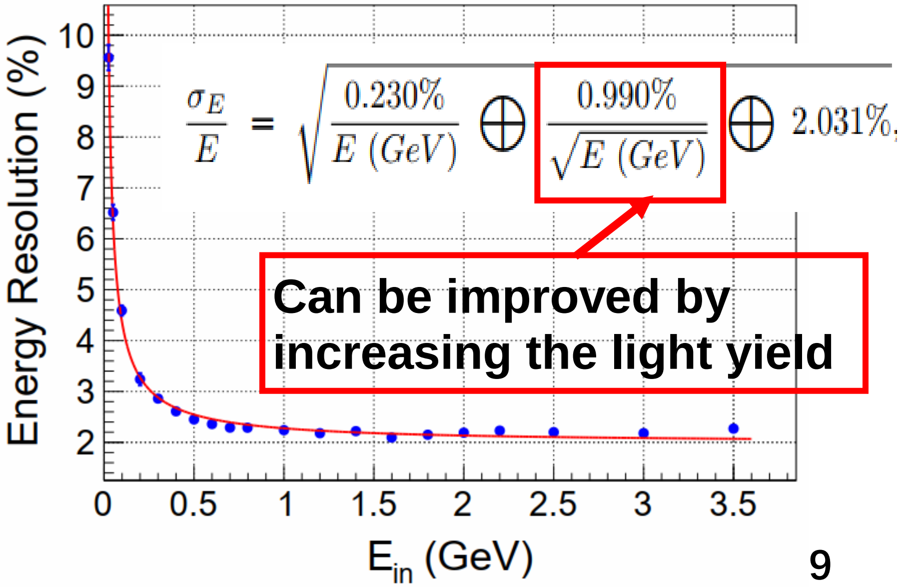


Energy reconstruction of 1GeV γ

The energy spectrum is fitted by Crystal Ball function, and the energy resolution is defined by

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





Reconstruction of Position

- Barycenter method with logarithmic weight

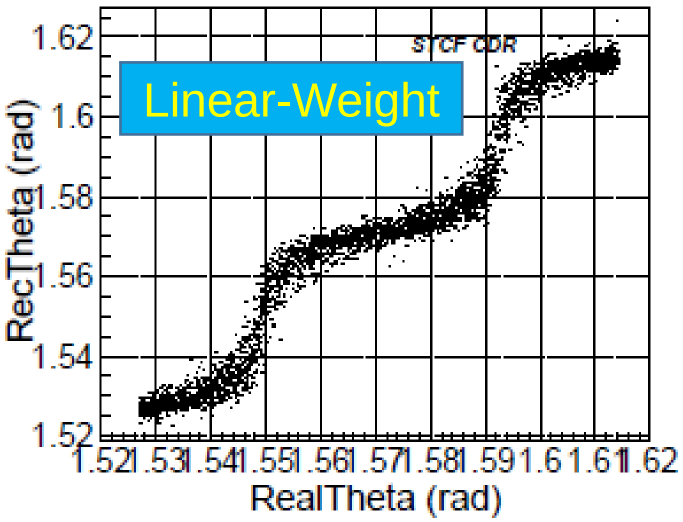
$$X_c = \sum_{j}^{N} W_j(E_j) \cdot X_j / \sum_{j}^{N} W_j(E_j)$$

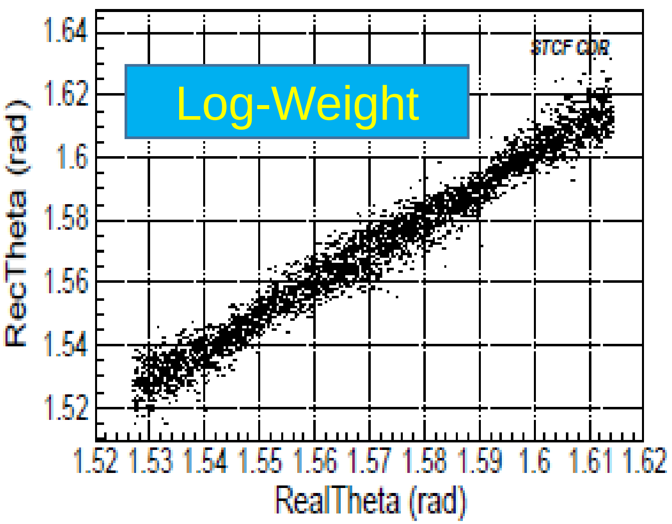
Where:

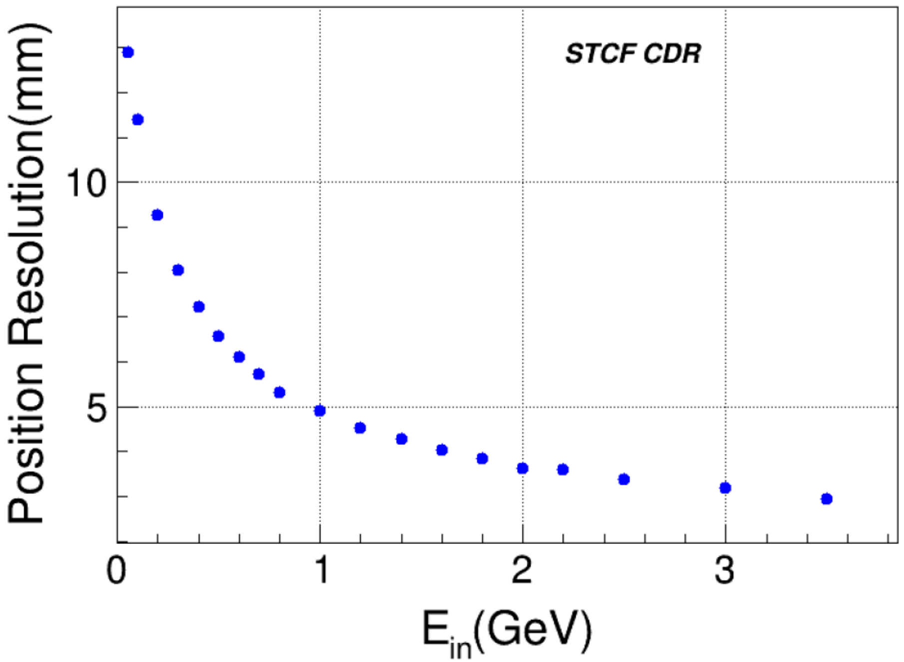
Linear-Weight: $W_j(E_j) = E_j$,

Log-Weight: $W_j(E_j) = \max\{0, a + \ln(E_j / \sum_j^N E_j)\}$,

E_j is the deposited energy in the j_{th} crystal.



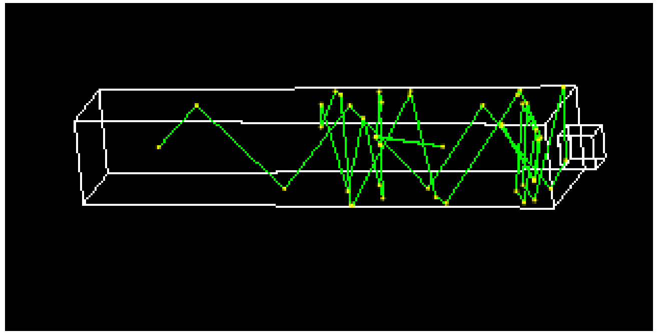




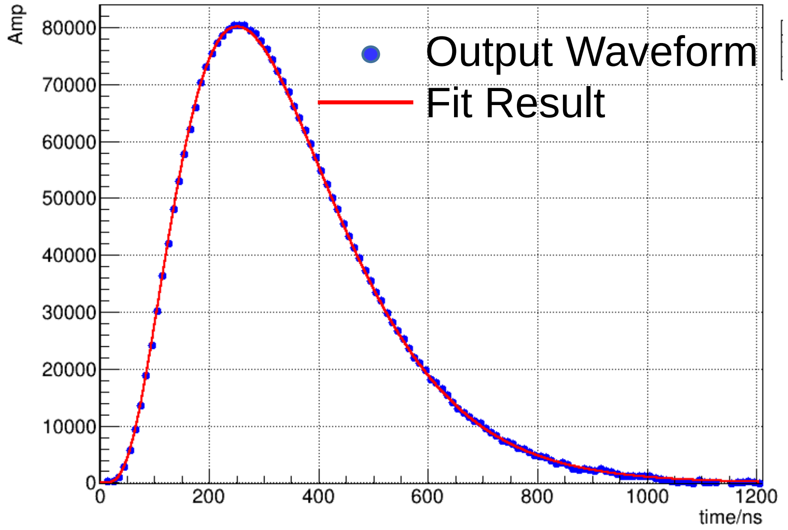
Position resolution of the ECAL

Timing Performance Simulation

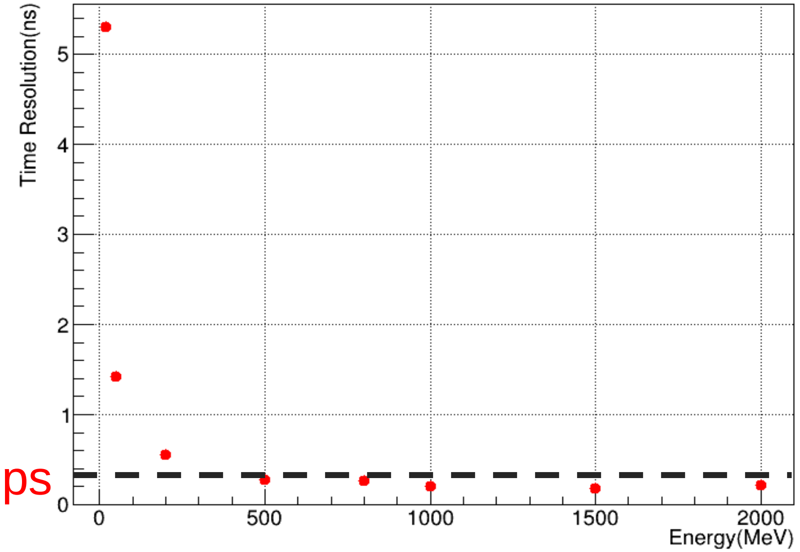
- Time distribution of photoelectron was convolved with the electronic impulse response function
- Timing was performed using waveform fitting method.
- The main factor limiting timing performance is electronic noise, especially at low energy.
- Performance can be improved by increasing the light yield to reduce the equivalent noise energy



Light transmission



Fit the waveform

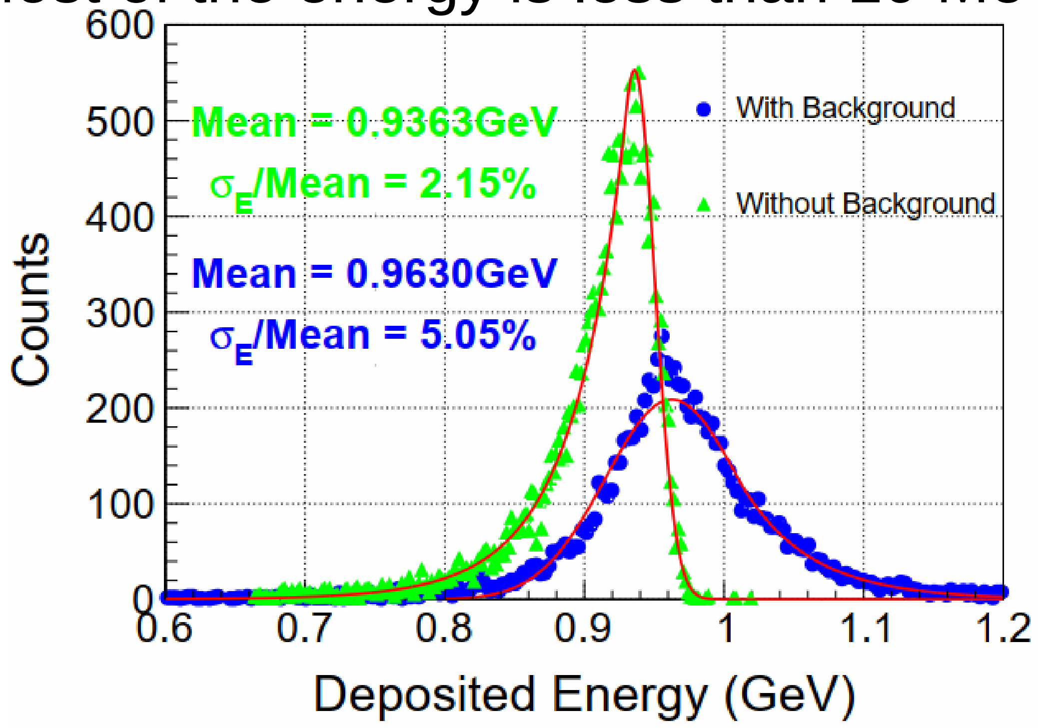


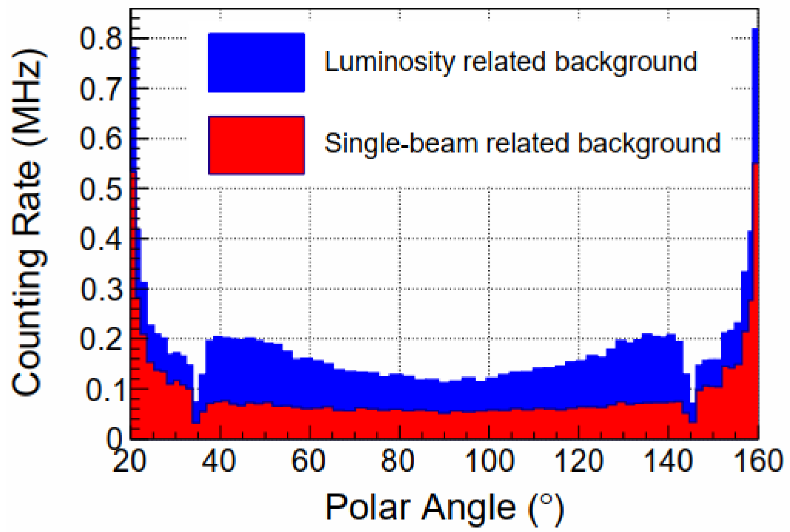
Time resolution of photons

Impact of Background on ECAL Performance

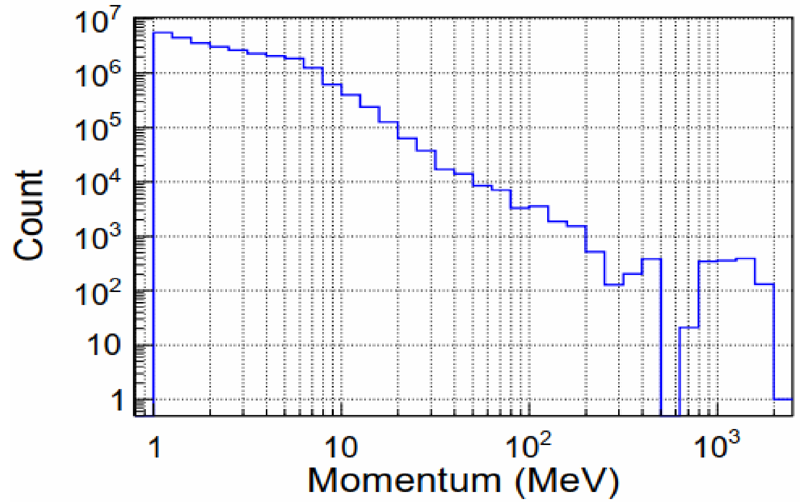
Challenges of high background level

- High luminosity introduces high background, which will cause pileup and affect energy reconstruction
- The background counting rate of single crystal unit is close to MHz
- Most of the energy is less than 10 MeV





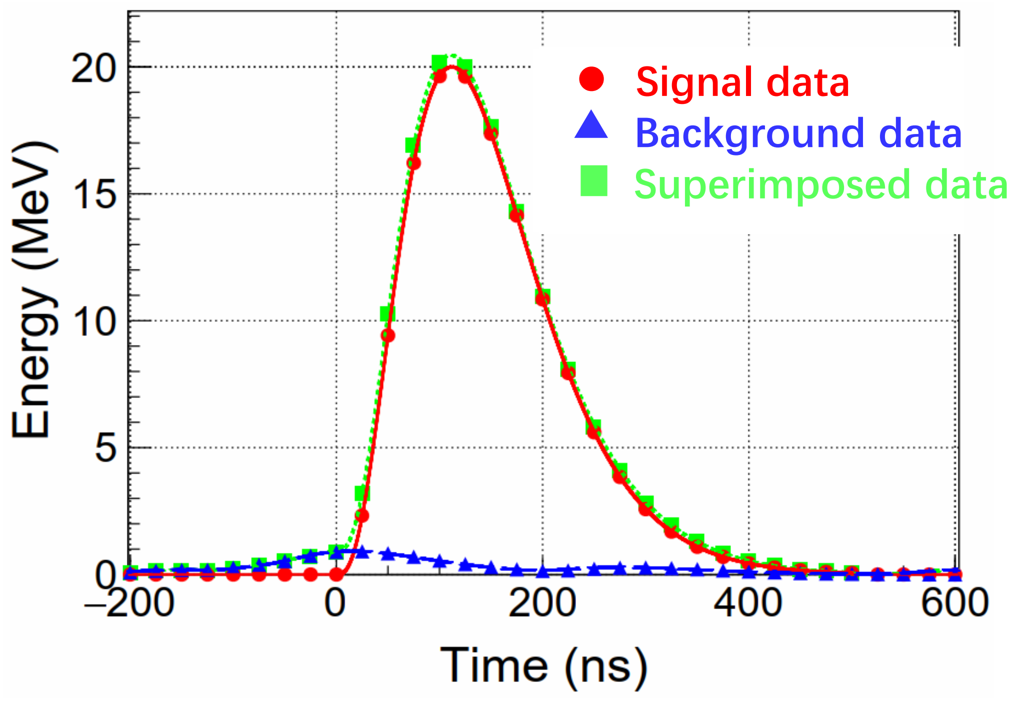
Background counting rate

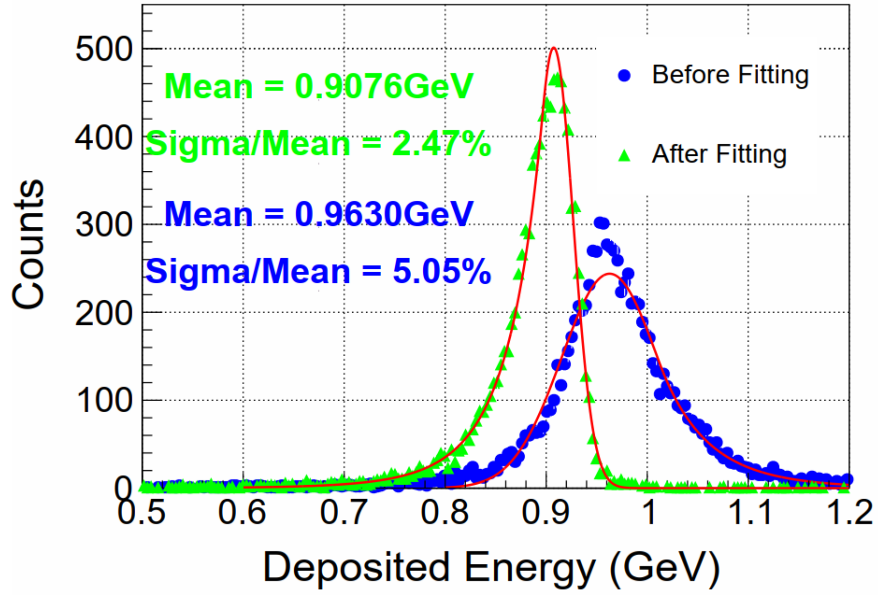


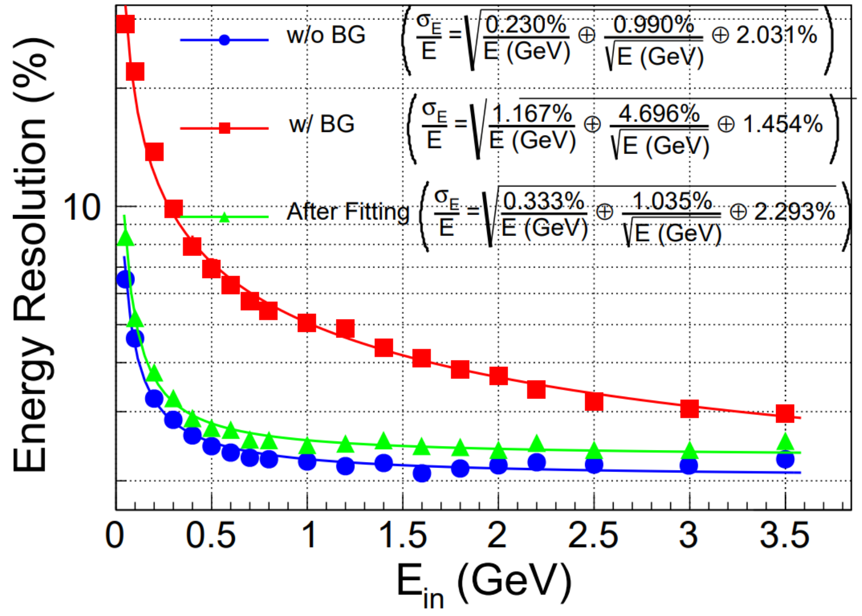
Background momentum distribution

Waveform Fitting Method

- **Multi-template fitting**







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

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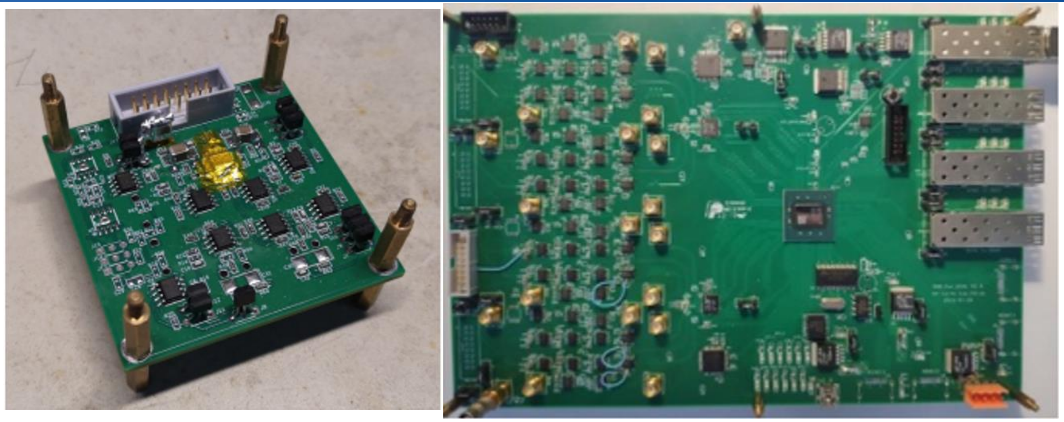
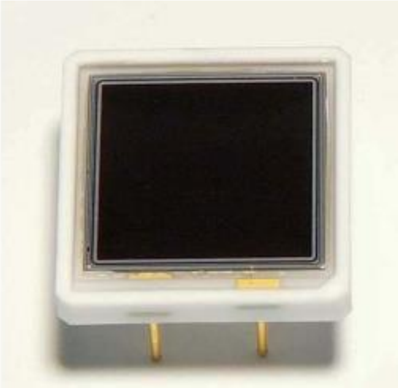
Detector Element and Electronics

- pCsI crystal
  - The fluorescence main peak is at about 310 nm
  - The transmission is about 40% @ 310 nm
- The reflection coefficient of reflective film
  - Teflon material is close to 100% @ 310 nm
- APD type
  - HAMAMATSU, S8664-1010
- Electronics
  - CSA-based readout design

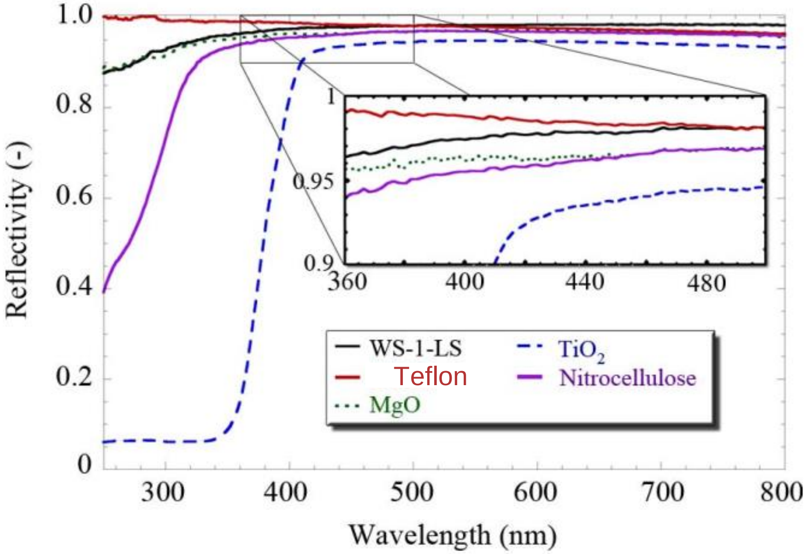


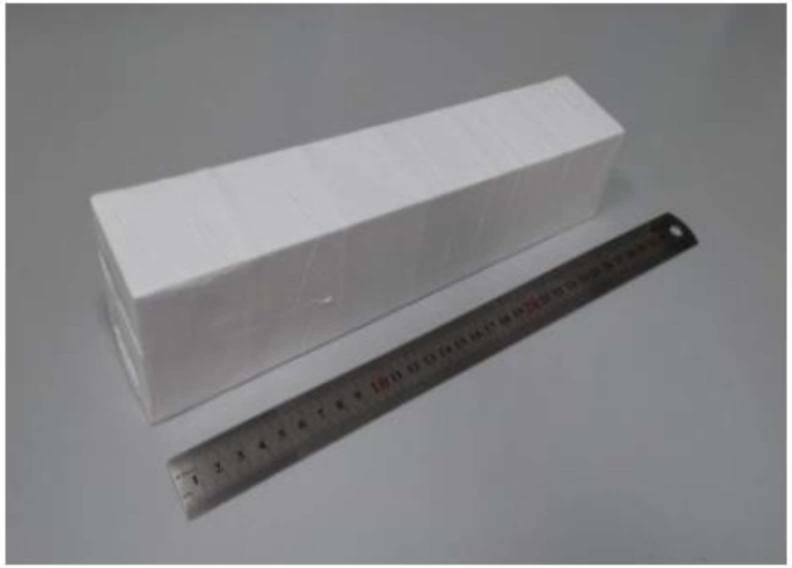
Front End Board & Back End Board

For more specific details, please refer to the Electronics for STCF ECAL.



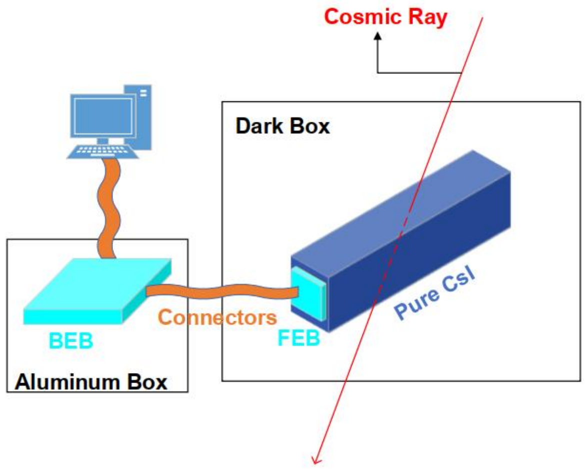
S8664-1010 APD



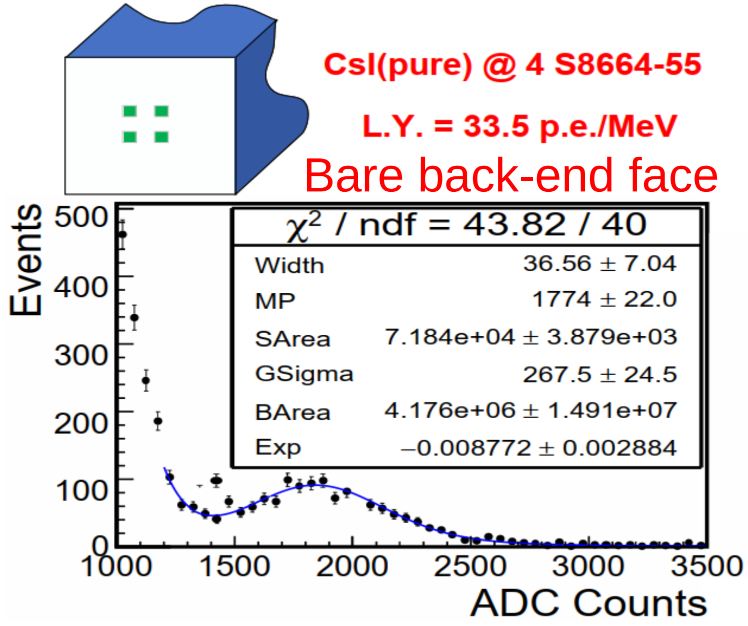


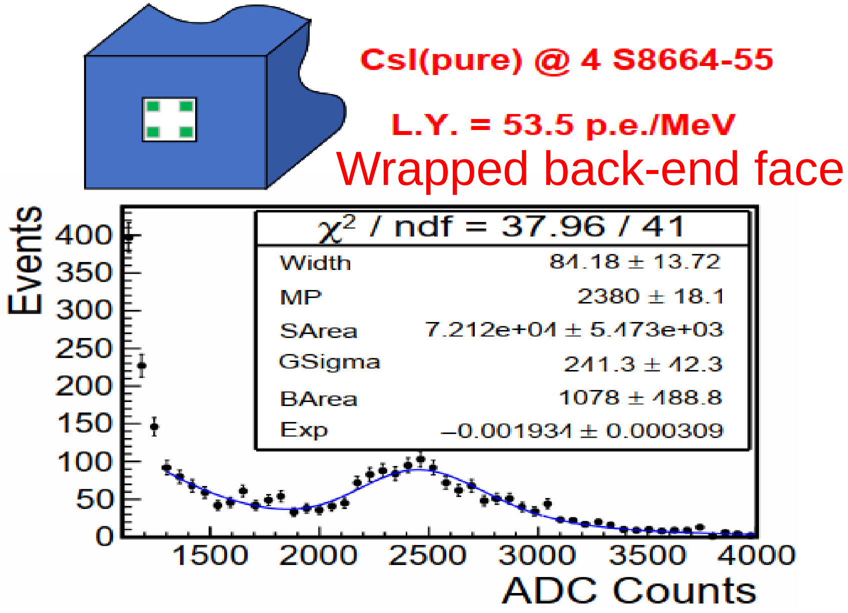
Light yield measurement by a cosmic ray test

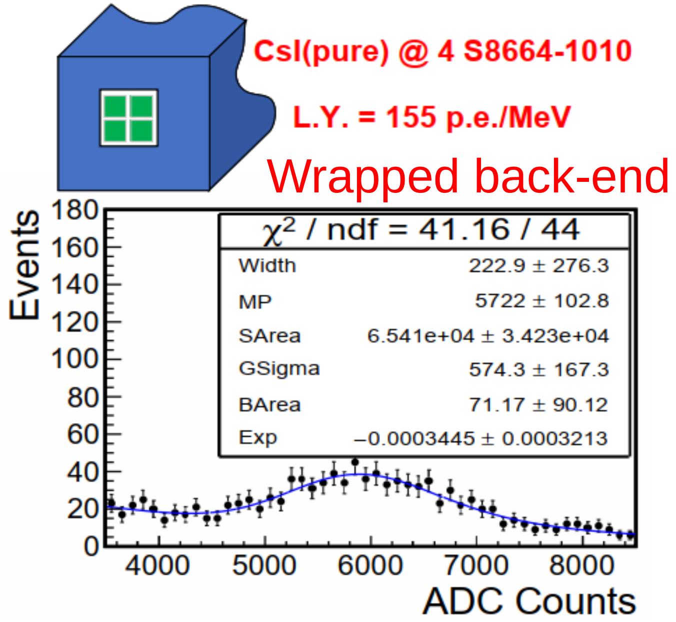
- Different packaging method
  - Bare or wrapped back-end face
- Different APD size
  - Four S8664-55 APDs ($5 \times 5\, mm^2 \times 4$)
  - Four S8664-1010 APDs ($10 \times 10\, mm^2 \times 4$)



Schematic diagram and photo of the cosmic ray test setup

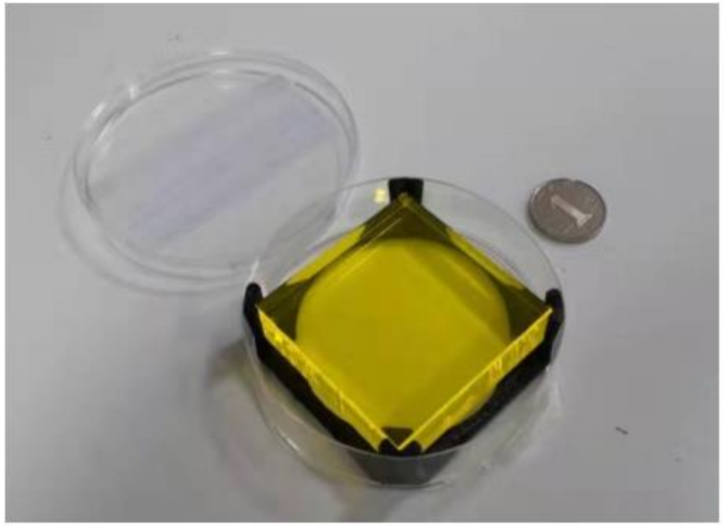


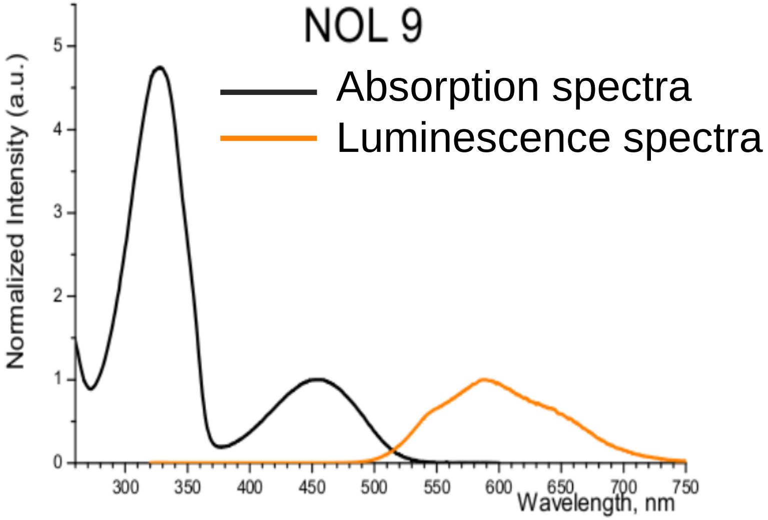


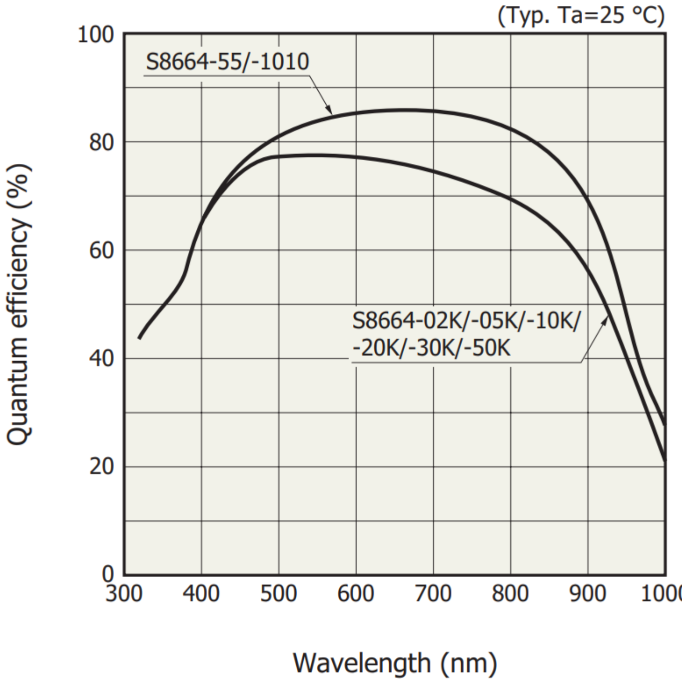


Wavelength Shifter(WLS)

- The quantum efficiency(QE) of APD is approximately 40% at 310nm.
- NOL-9 is a type of wavelength-shifting material that can convert short wavelengths into longer wavelengths.



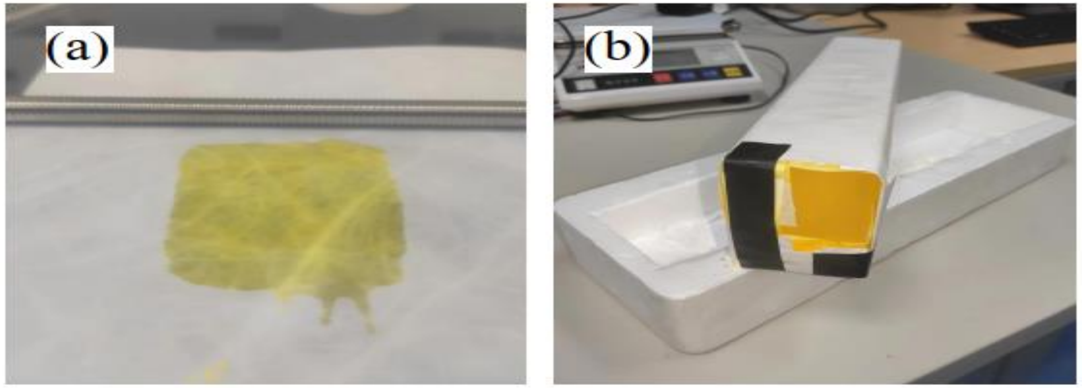




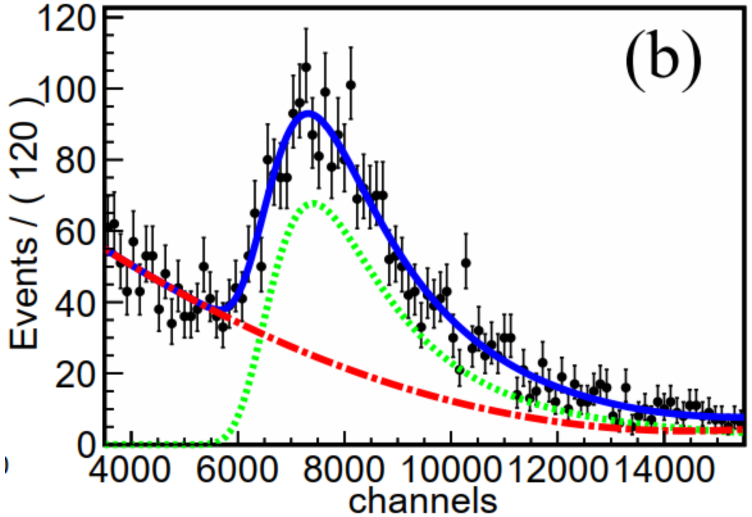
APD QE

Light yield increment by using WLS

- **Coating the WLS on packaging materials**

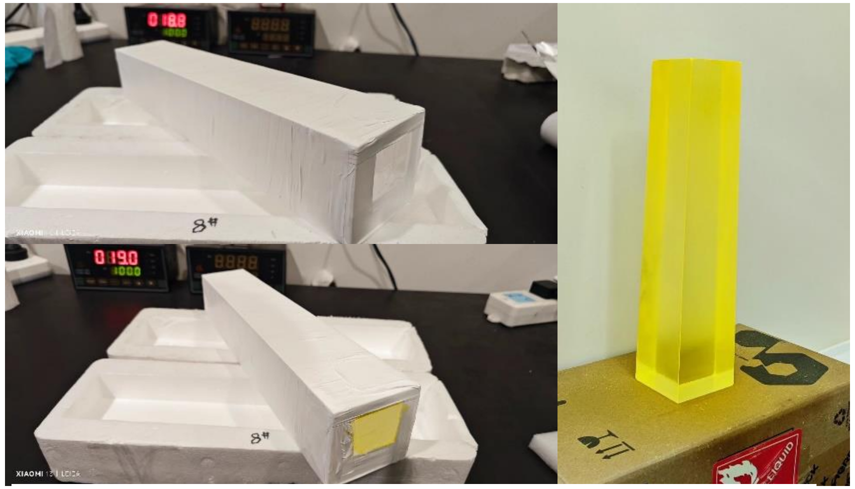


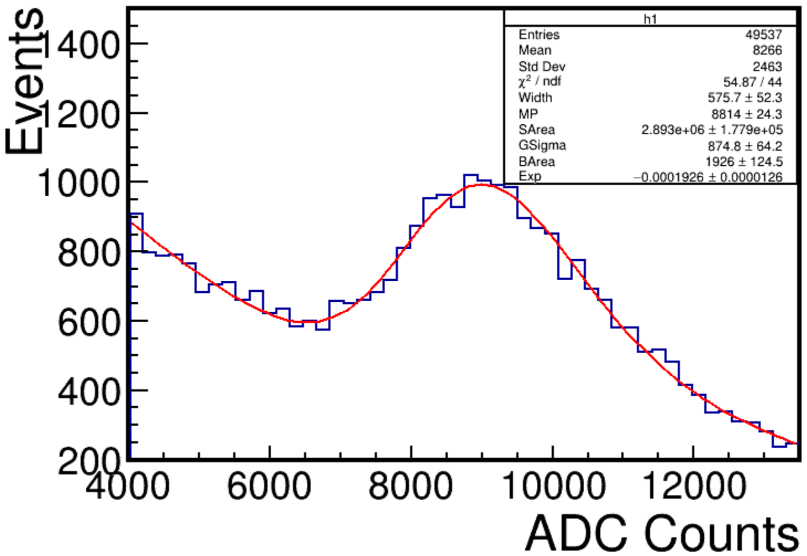
WLS coated on packaging materials and a assembled module



The light yield is increased by 60%, ~240 p.e./MeV

- **Coating the WLS on crystal**



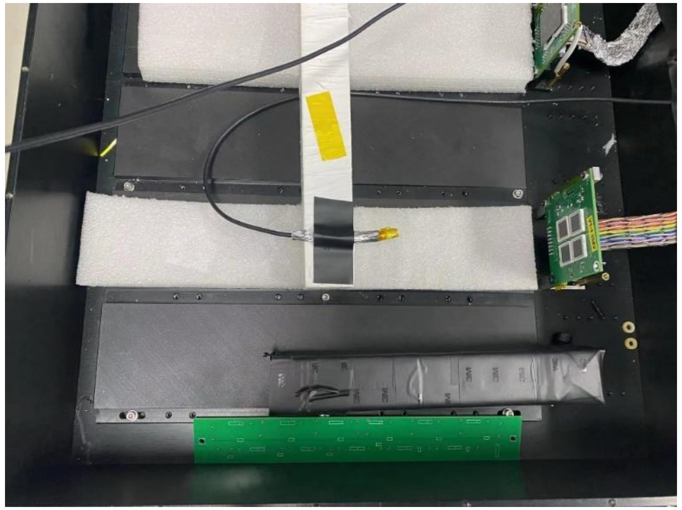


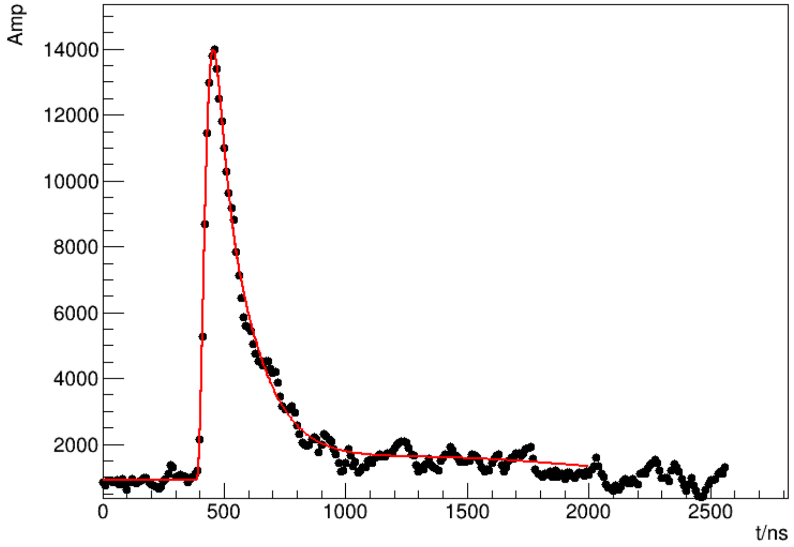
The light yield is increased by 100%, ~300 p.e./MeV

Time measurement by LED

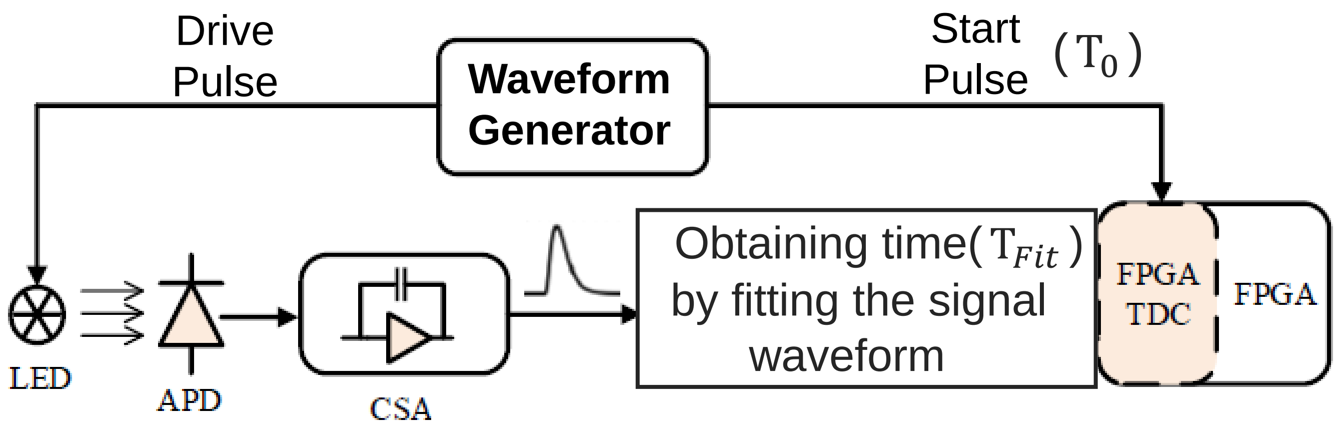
- **Contribution of electronics to time resolution**

  - Using LED to simulate crystal luminescence
  - Using waveform fitting method for timing

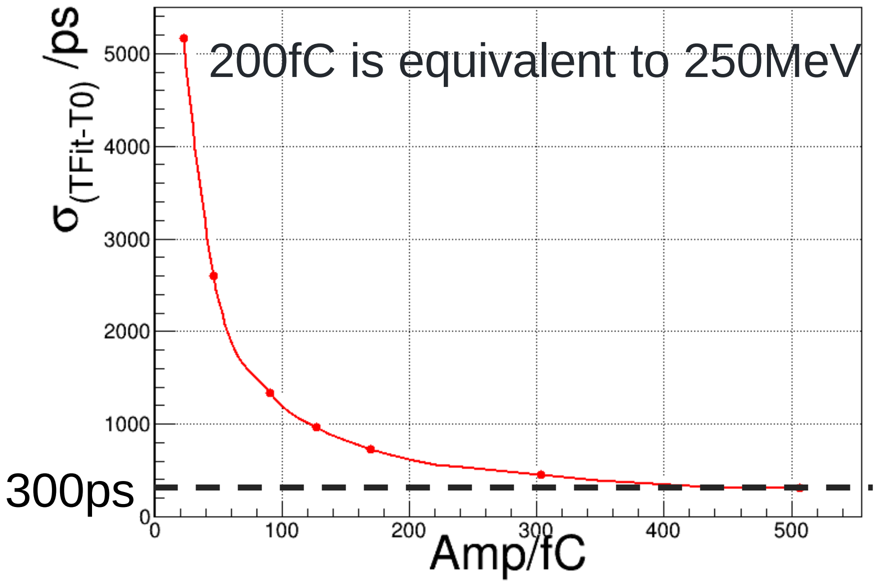




A fit result of signal waveform



LED test system

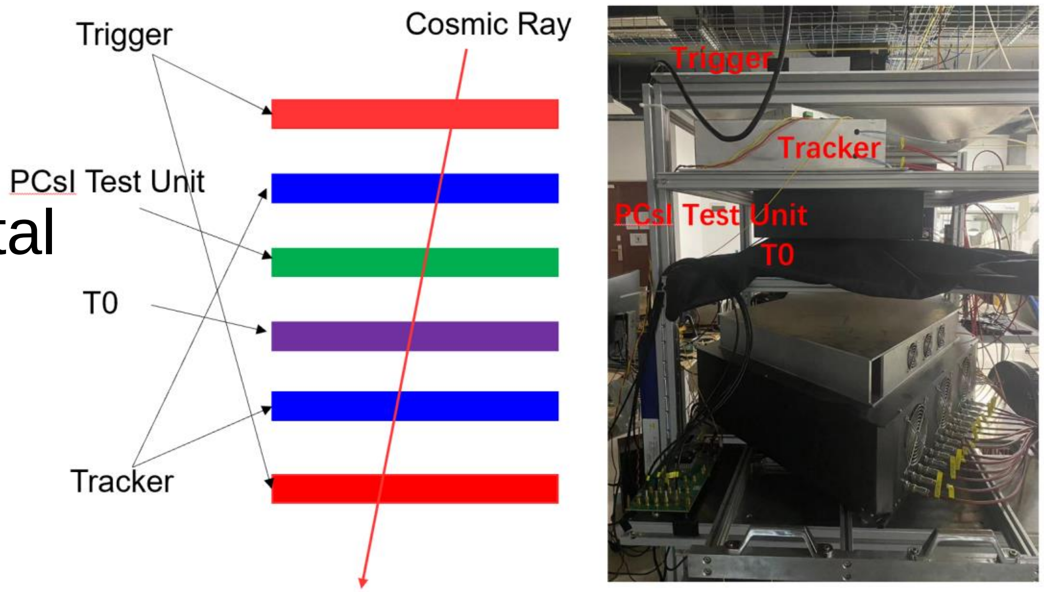


Time measurement by cosmic ray

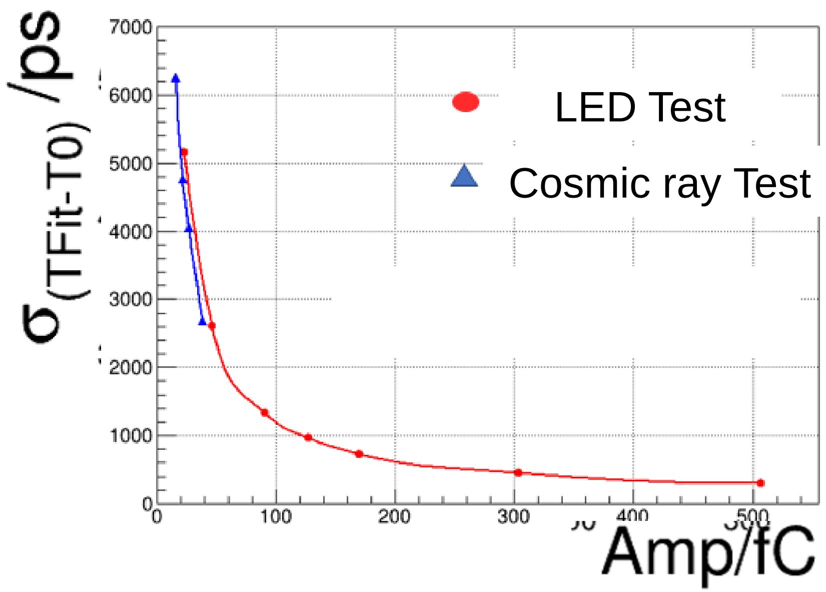
- **Other contributions to time resolution**

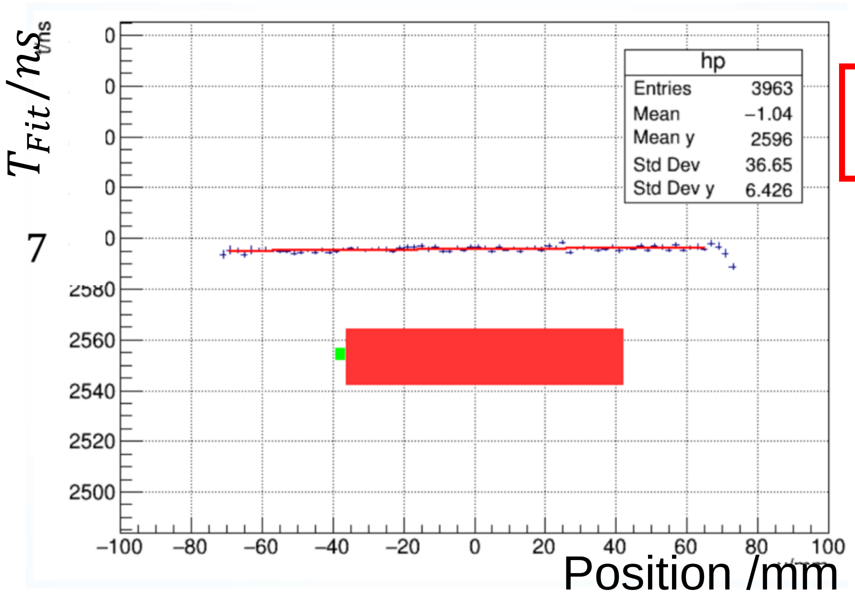
1. Light transmission
2. Fluctuations in the emission location of a crystal

The test result of cosmic ray is close the LED result indicate that the main contribution to time resolution comes from electronics at low energy.



Cosmic ray test system





$$T_{Fit} = 0.01(ns/mm) \times l\ (mm) + C$$

Where l is the distance from the APD, C is a constant. The fluctuation of photon shower positions is a few centimeters at high energy, the contribution of the 2nd point is about 50 to 100 ps.

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- **We illustrate the design of ECAL detector for the future STCF**
  - ✓ pCsI + APD + CSA electronics
  - ✓ The preliminary MC results show that this design could meet STCF requirements
- **The WLS was used to enhance the light yield, the result showed that the L.Y. could reach to 300 p.e./MeV**
- **The results from both the simulation and the test indicate that the timing performance of ECAL could meet the requirements of STCF**

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- **The WLS was used to enhance the light yield, the result showed that the L.Y. could reach to 300 p.e./MeV**
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Thanks!

Back Up

ECAL Design —— Crystal Selection

- Total absorption calorimeter
  - pCsI crystal + APD photo-device

Crystal	Pure CsI	LYSO	GSO	YAP	PWO	BaF:Y
Density (g/cm^3)	4.51	7.40	6.71	5.37	8.30	4.89
Melting Point (°C)	621	2050	1950	1872	1123	1280
Radiation Length (cm)	1.86	1.14	1.38	2.70	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	3.10
Refractive index	1.95	1.82	1.85	1.95	2.20	1.50
Hygroscopicity	Slight	No	No	No	No	No
Luminescence (nm)	310	402	430	370	425 420	300 220
Decay time (ns)	30 6	40	60	30	30 10	600 1.2
Light yield (%)	3.6 1.1	85	20	65	0.3 0.1	1.7 4.8
Dose rate dependent	No	No	TBA	TBA	Yes	No
D(LY)/dT (%/°C)	-1.4	-0.2	-0.4	TBA	-2.5	TBA
Experiment	KTeV Mu2e				CMS ALICE PANDA	

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 $\frac{\partial \chi^2}{\partial A} = 0, \frac{\partial \chi^2}{\partial \tau} = 0, \frac{\partial \chi^2}{\partial p} = 0$:

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

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

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

Waveform Fitting Method

● Multi-template fitting

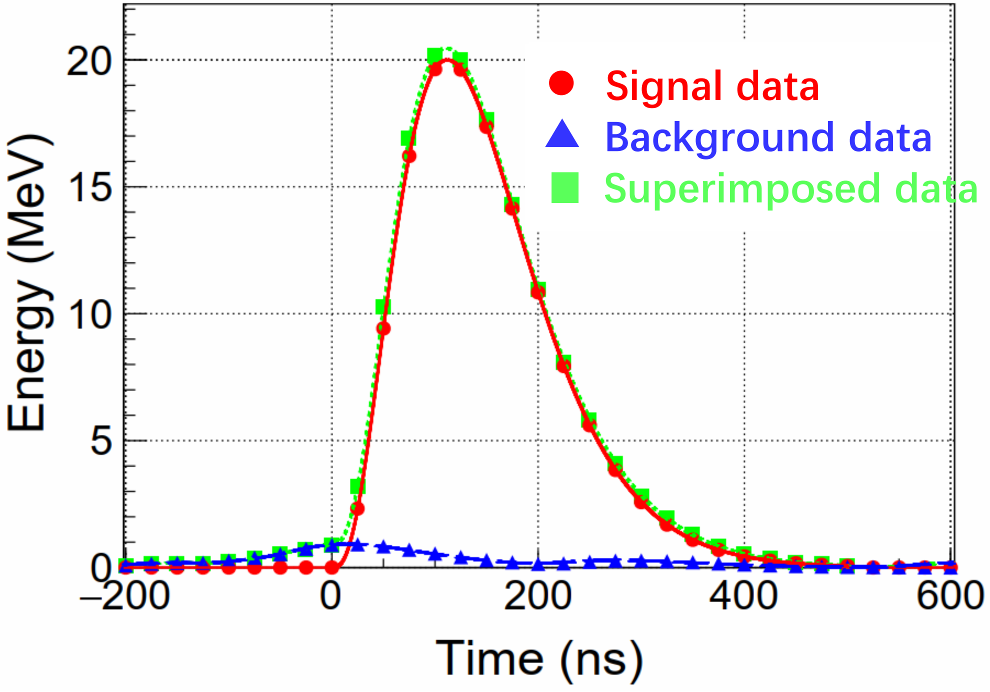
- ➢ The waveform template is obtained by convoluting the pure CsI fluorescence signal with the electronics impulse response function.
- ➢ The fit minimizes the χ^2 defined as:

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

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.

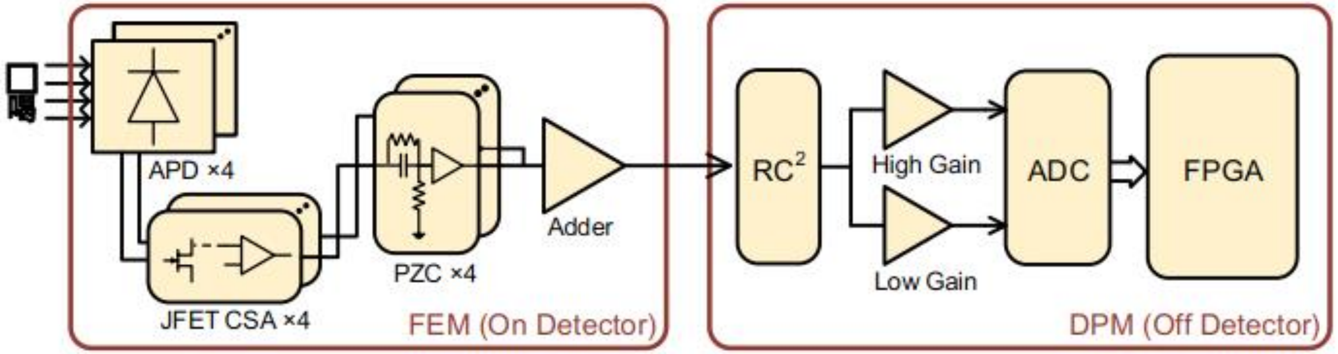


- ☐ The green line is the fitting result of the data, which is the sum of total templates.
- ☐ The red line is the template represents the signal.
- ☐ The blue line represents the background, which is the sum of the remaining templates.

Electronics

- High precise energy measurement
  - CSA-based readout design
- Wide dynamic range
  - dual gain readout
- Time measurement
  - waveform fitting

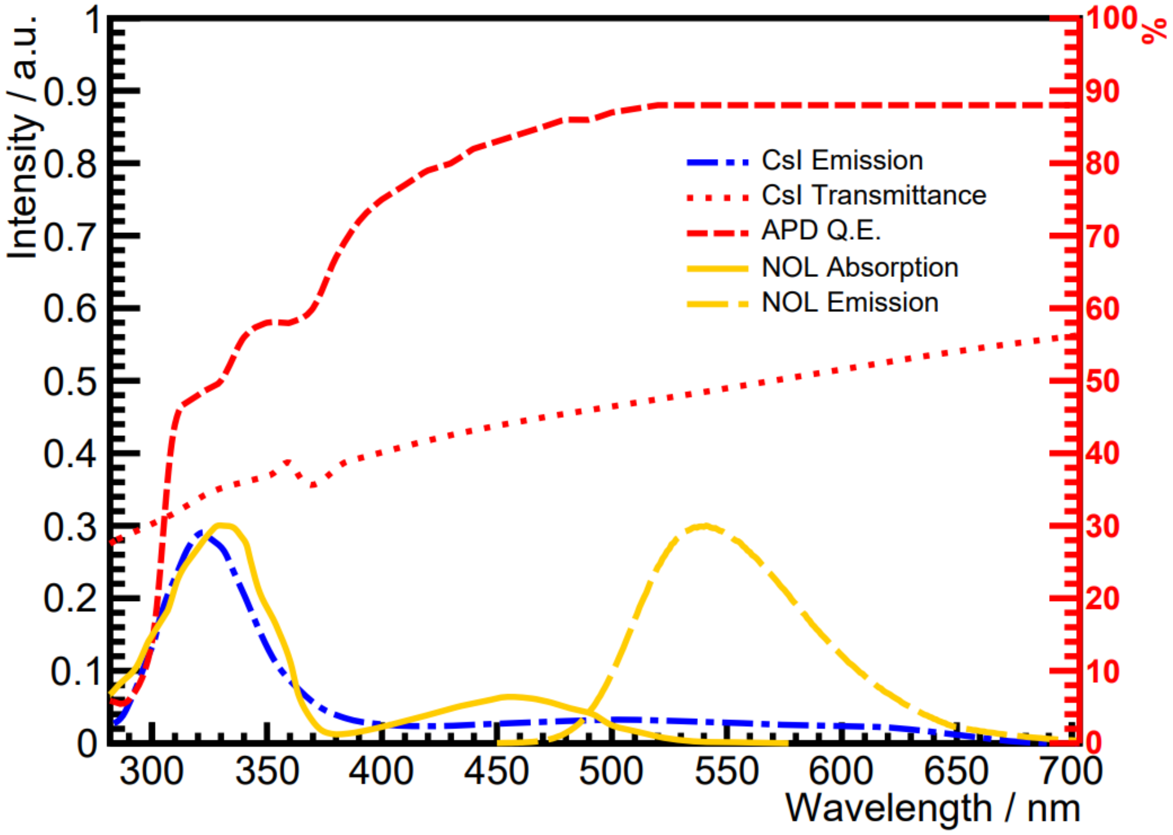
Front end board



Electronics design

Back end board

WLS



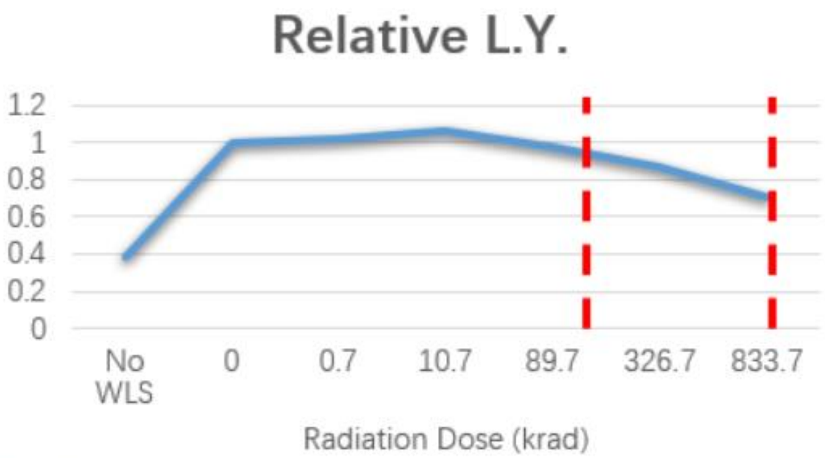
quantum yield of 95 %

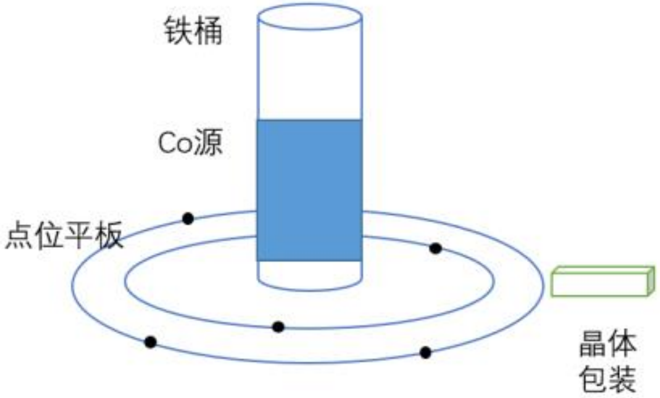
luminescence decay time of 7.17 ns

Wavelength shifter material study

- Radiation resistance test of WLS film using ^{60}Co
- The irradiated WLS film coated crystals were tested by cosmic rays：
  - 100 krad: No significant change
  - 1000 krad: close to 40% degradation

Radiation test

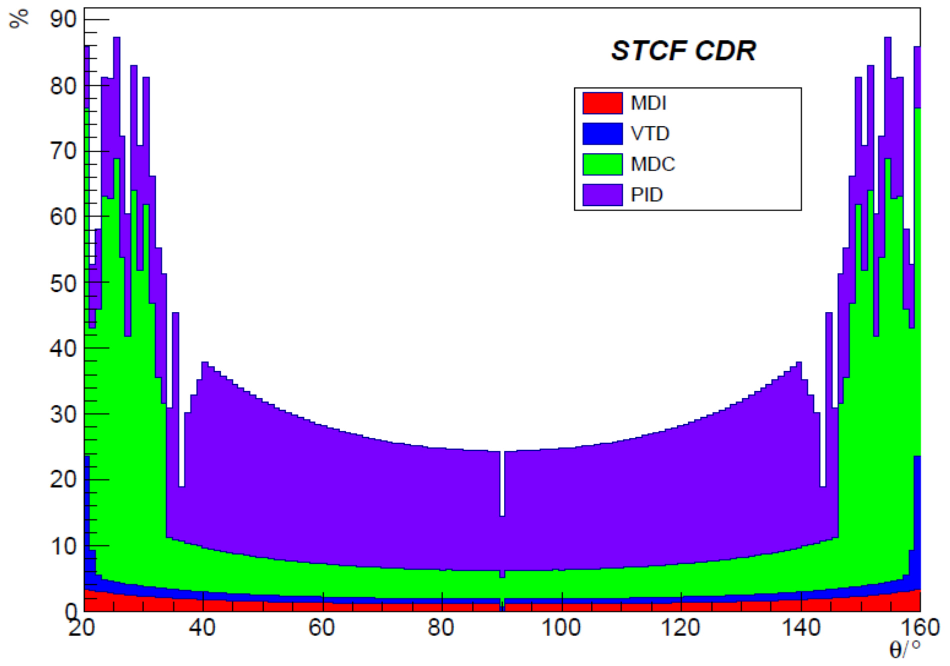




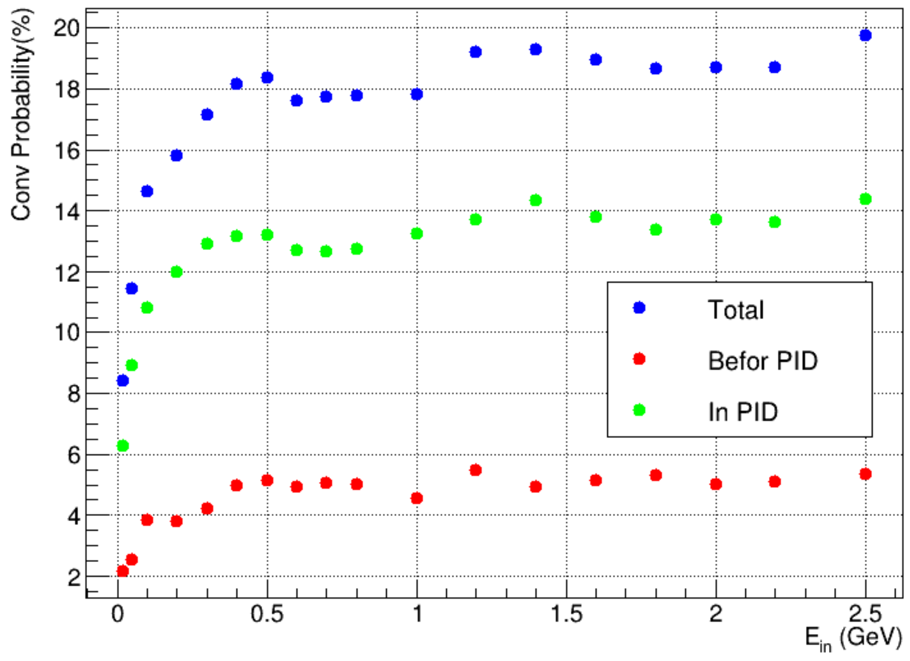
Performance Simulation

●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

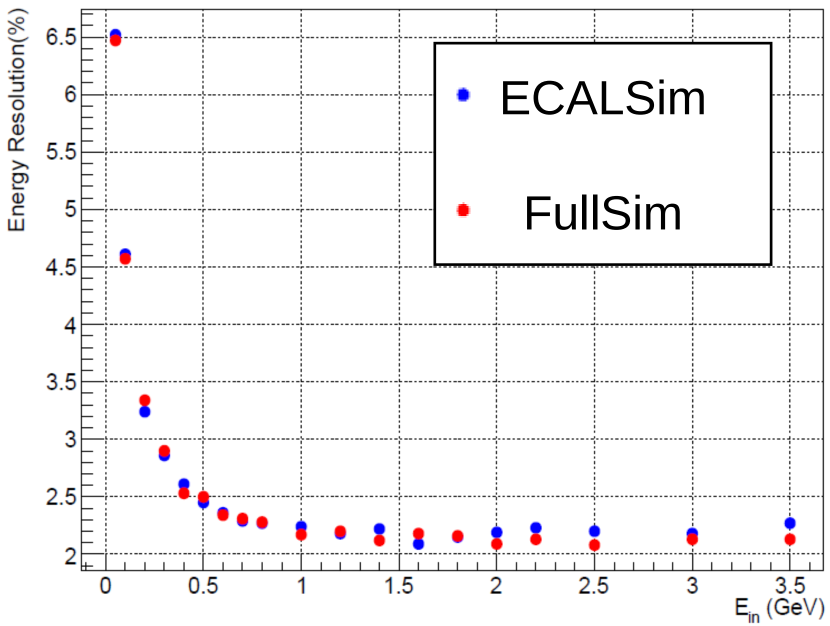


γ conversion probability in front of ECAL

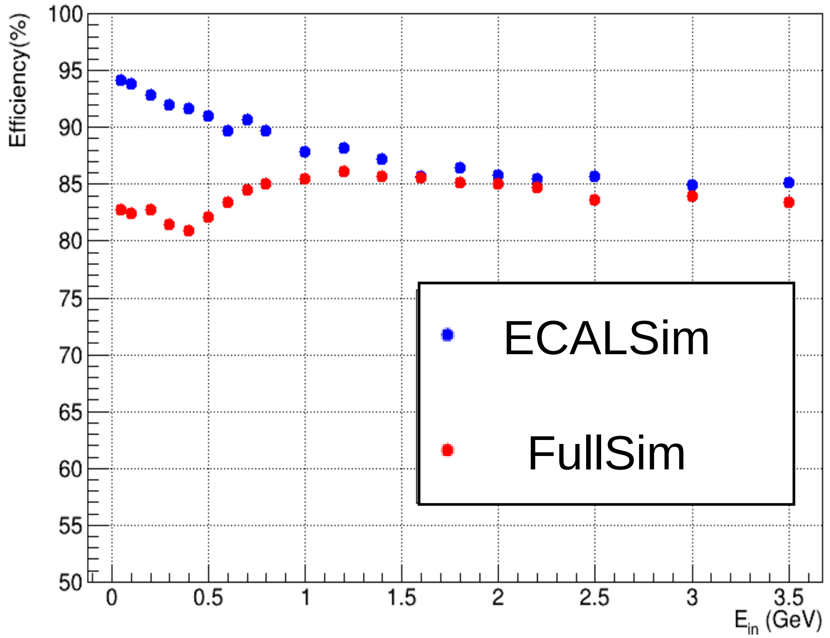
Performance Simulation

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