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

Design and Performance Studies of the Electromagnetic Calorimeter for Super Tau-Charm Facility

Yong Song (USTC)

On behalf of the STCF calorimeter working group

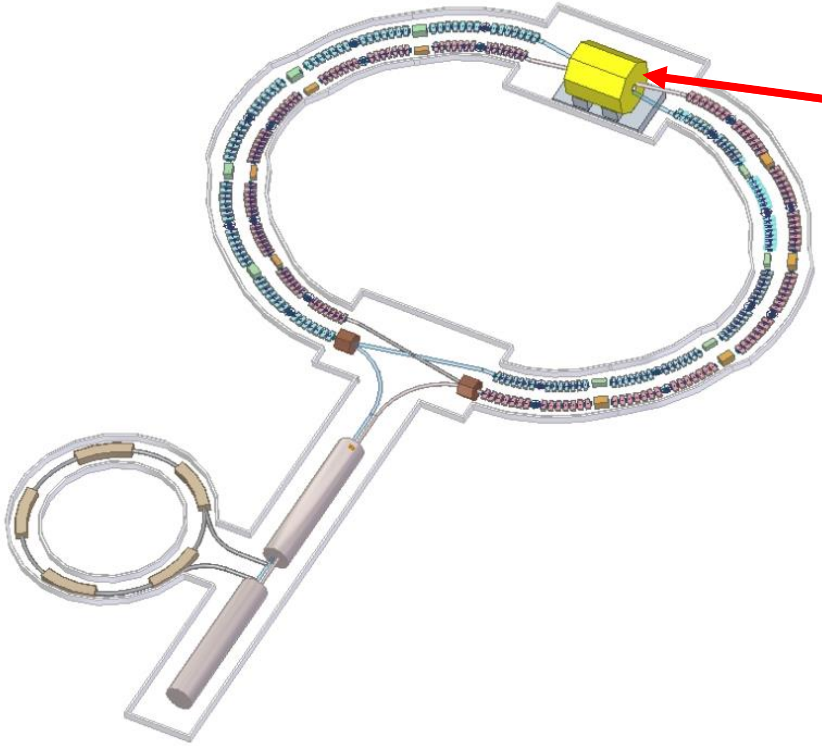
CALOR 2022
May 16, 2022

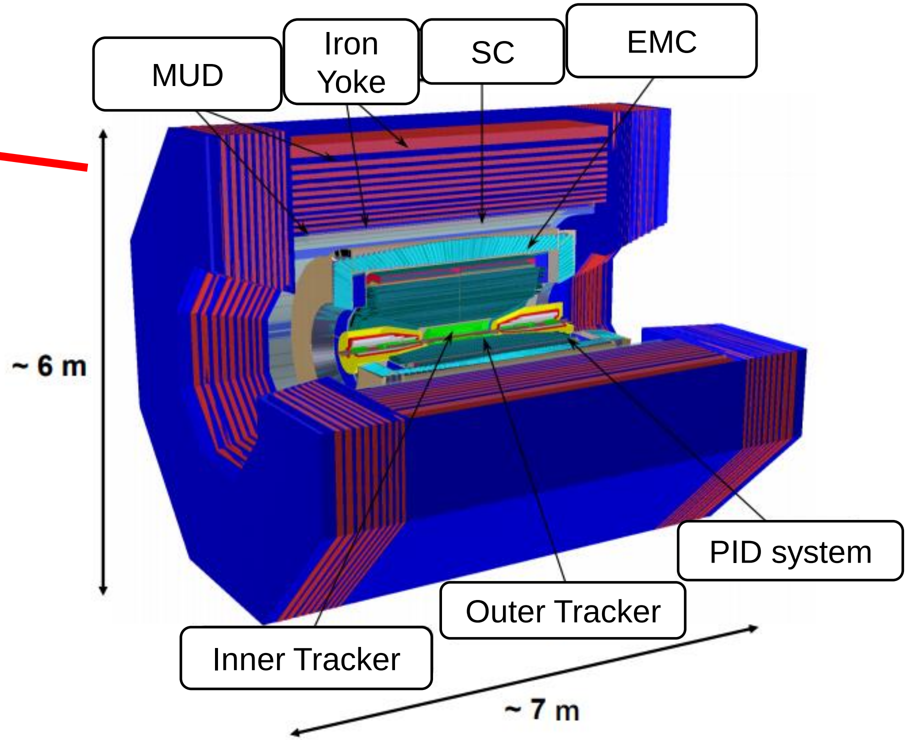
Outline

- **Research Background**
- **STCF EMC**
  - EMC Design
  - Performance Study
  - Some experimental Results
- **Summary**

Research Background

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





Research Background

● Requirements for Electromagnetic Calorimeter (EMC)

➢ Fast response

- ◆ Challenge of high Luminosity

  High event rate (400kHz)

  Extremely high background

➢ High precision

- ◆ Energy resolution

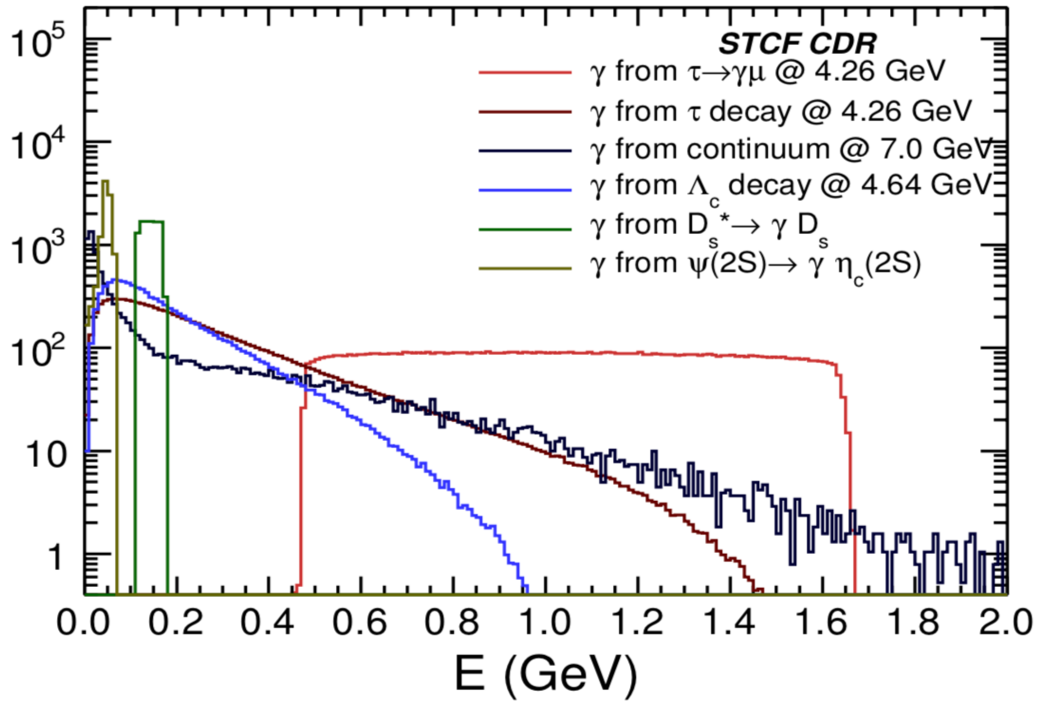
  Better than 2.5% @1 GeV

- ◆ Position resolution

  Better than 6 mm @1 GeV

- ◆ Time resolution

  Better than 300 ps @1 GeV



Energy distribution for photons

EMC Design —— Sensitive Unit

● Pure CsI crystal + APD photo-device

- Pure CsI (pCsI) crystal
  - Fast decay time (30 ns)
  - Good radiation hardness
  - Low light yield

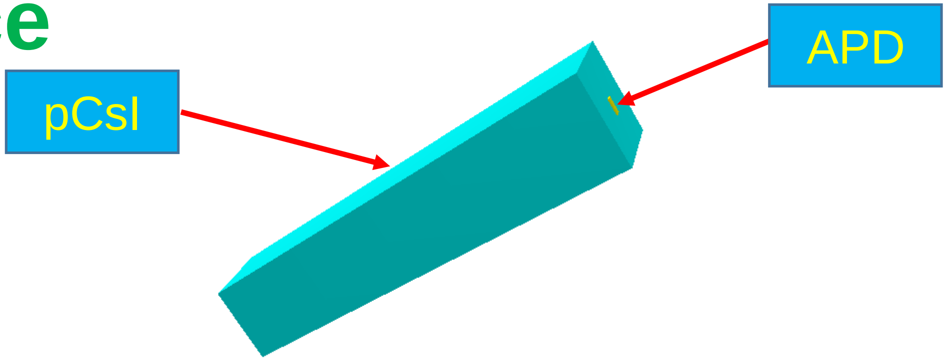
- Avalanche photodiode (APD)
  - Large area

- Crystal Size:
  - Total radiation length

    15 X_0 (28 cm)
  - End face size

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

    back end: $\sim 6.5 \times 6.5\ cm^2$

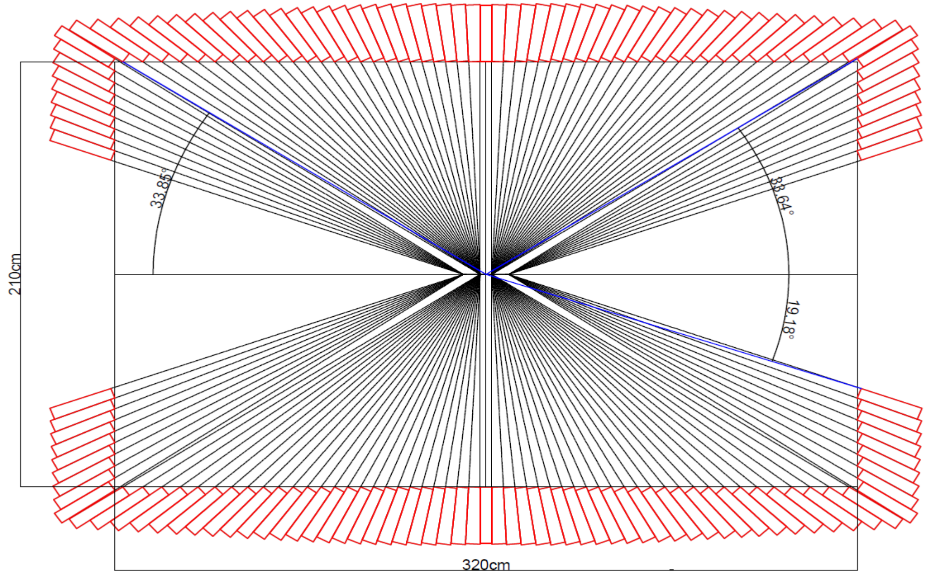


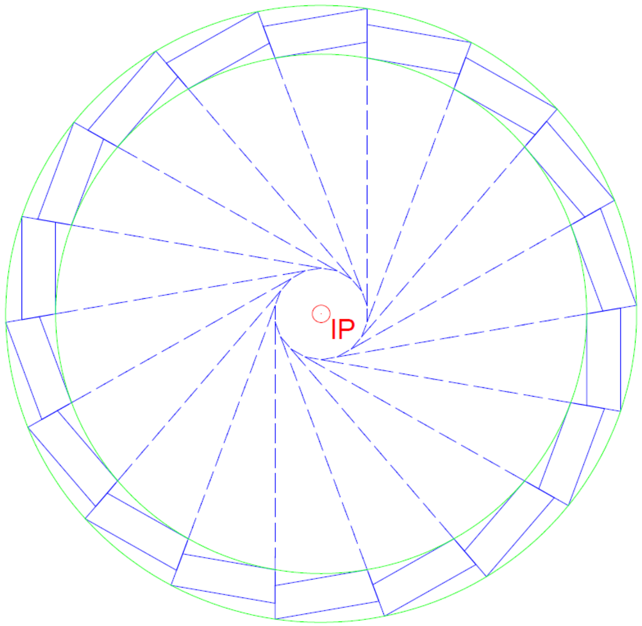
EMC pCsI crystal unit

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

EMC Design —— Geometry Model

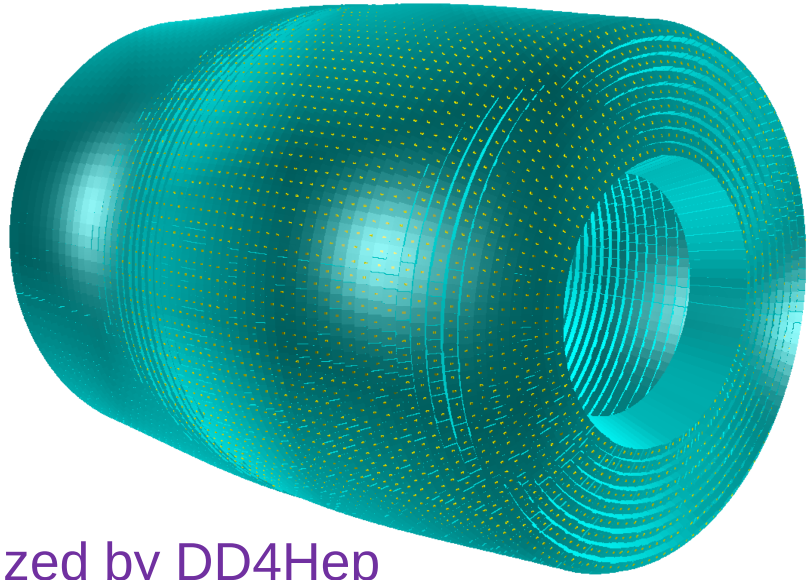
- **Total absorption calorimeter**
  - Barrel: $51 \times 132 = 6732$
  - Endcap: $3 \times (85 + 102 + 136) = 969$
  - The defocus operation is applied to both θ-directions and φ-directions





Defocus

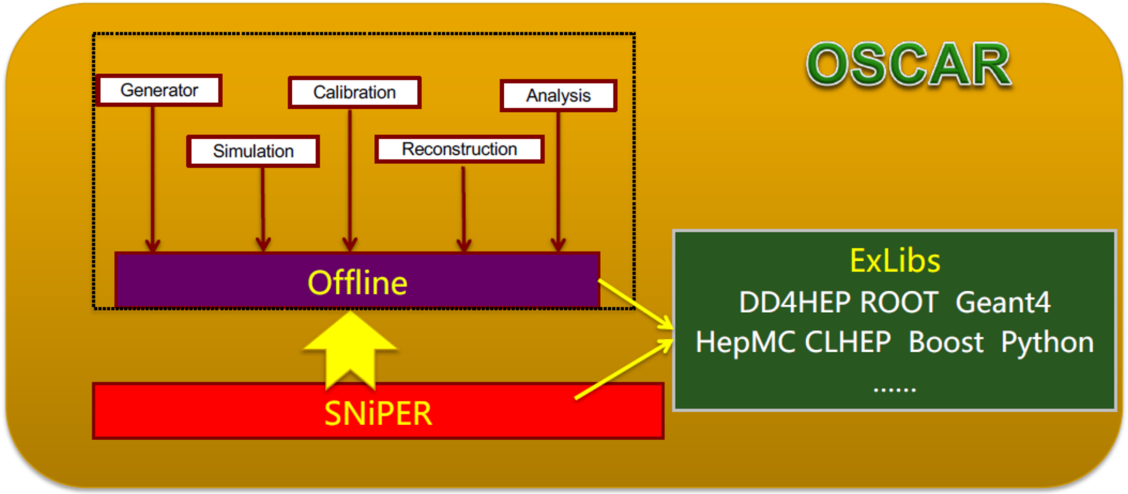
The Defocus operation **completely avoids** the particles passing directly between the crystals.

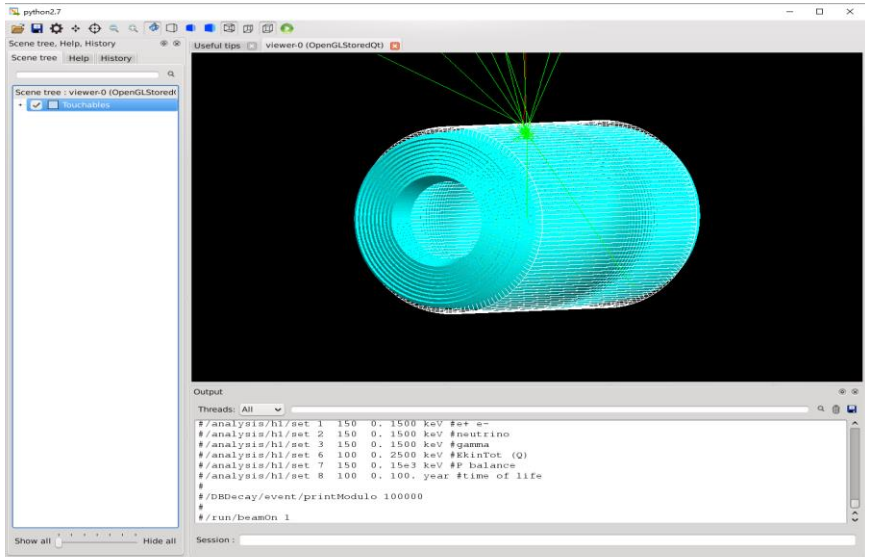


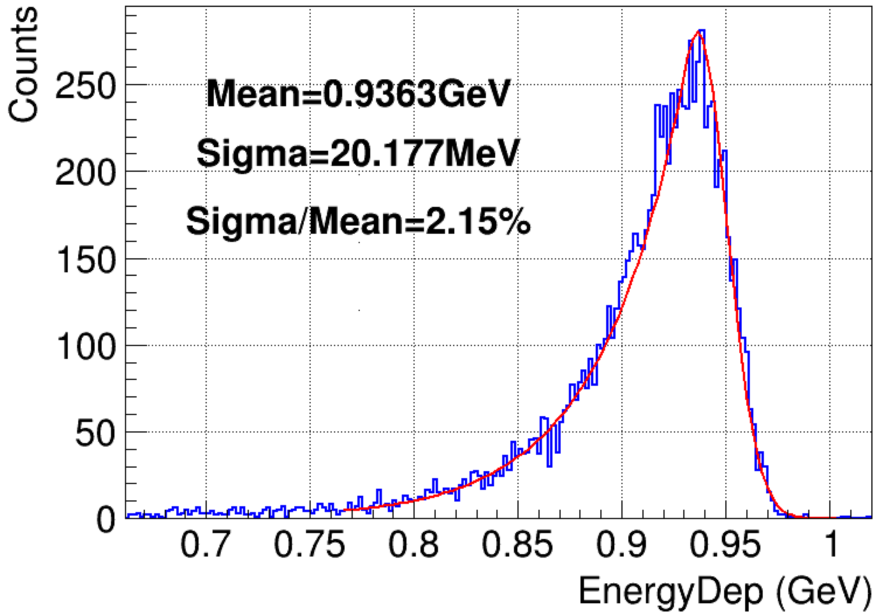
Visualized by DD4Hep

Performance Study Based on OSCAR

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







Energy reconstruction of 1GeV γ

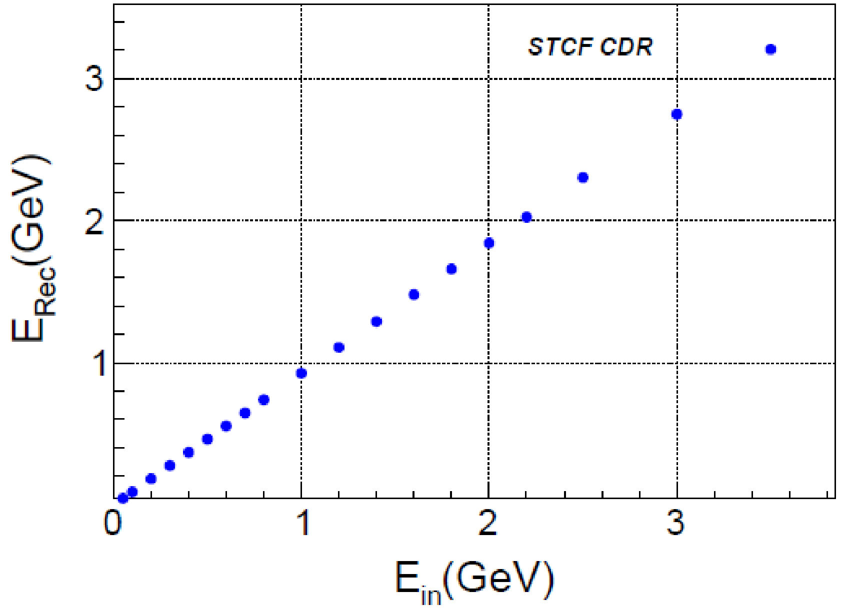
The energy spectrum is fitted by Crystal Ball function, and the energy resolution is defined by

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

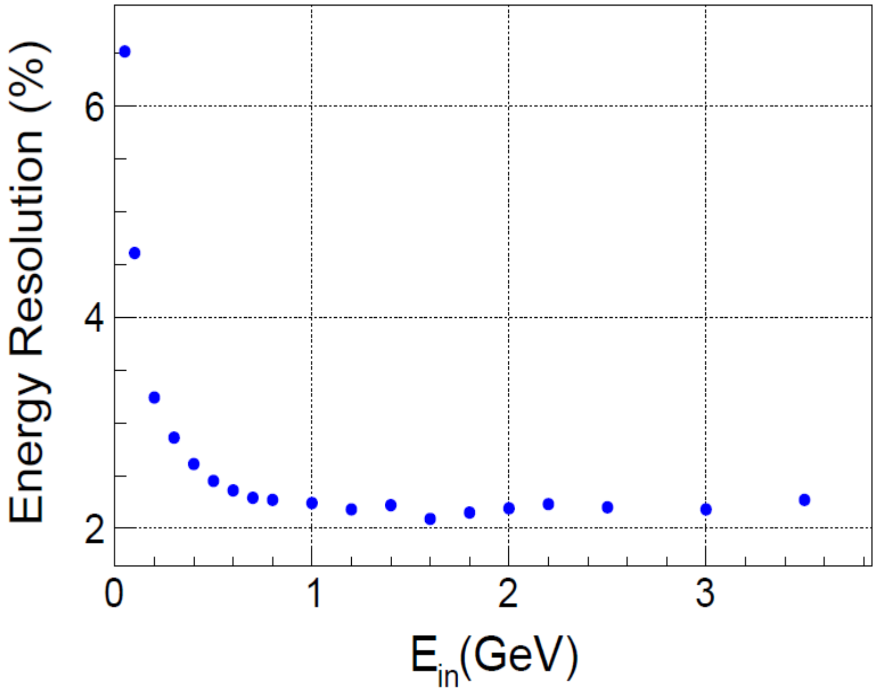
Performance Simulation

●Study of energy resolution

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



Good energy linearity is maintained in the energy range of 50MeV~3.5GeV



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

Performance Simulation

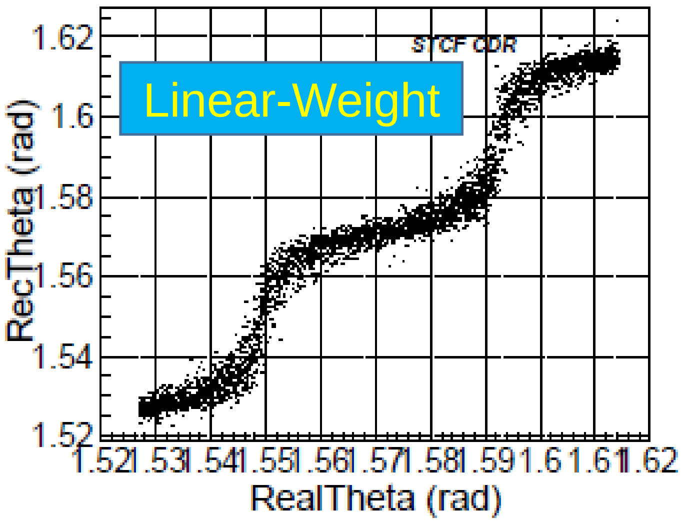
●Study of position resolution

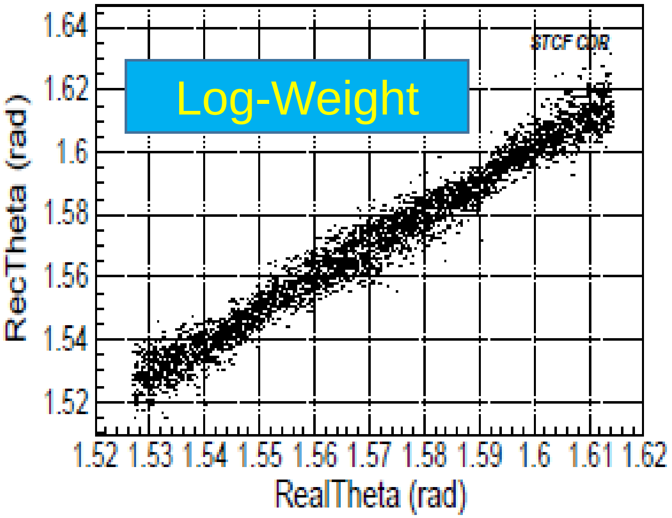
- Barycenter method with logarithmic weight

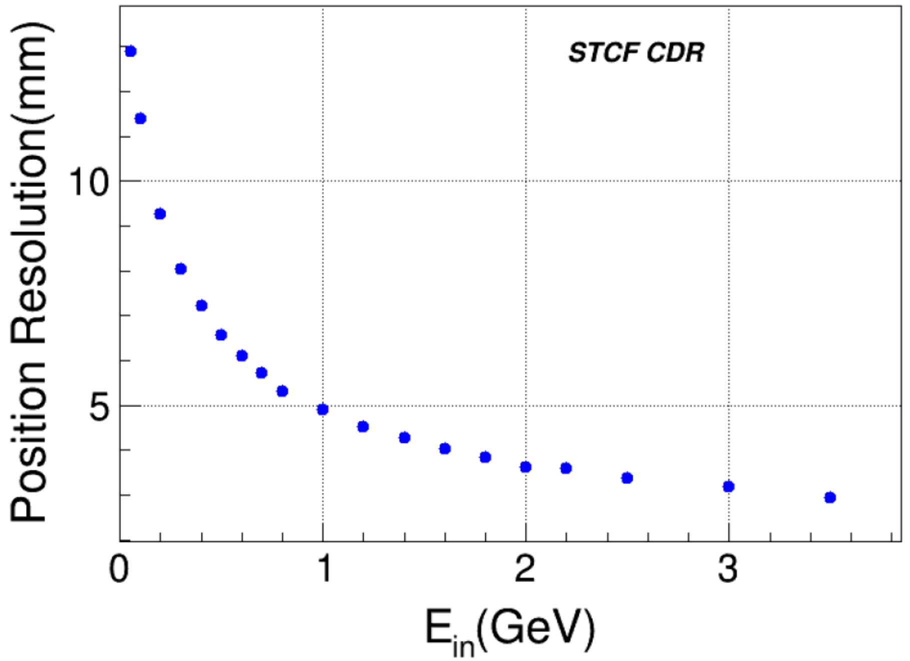
$$X_c = \sum_j^N W_j(E_j) \cdot X_j / \sum_j^N W_j(E_j)$$

Where:

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





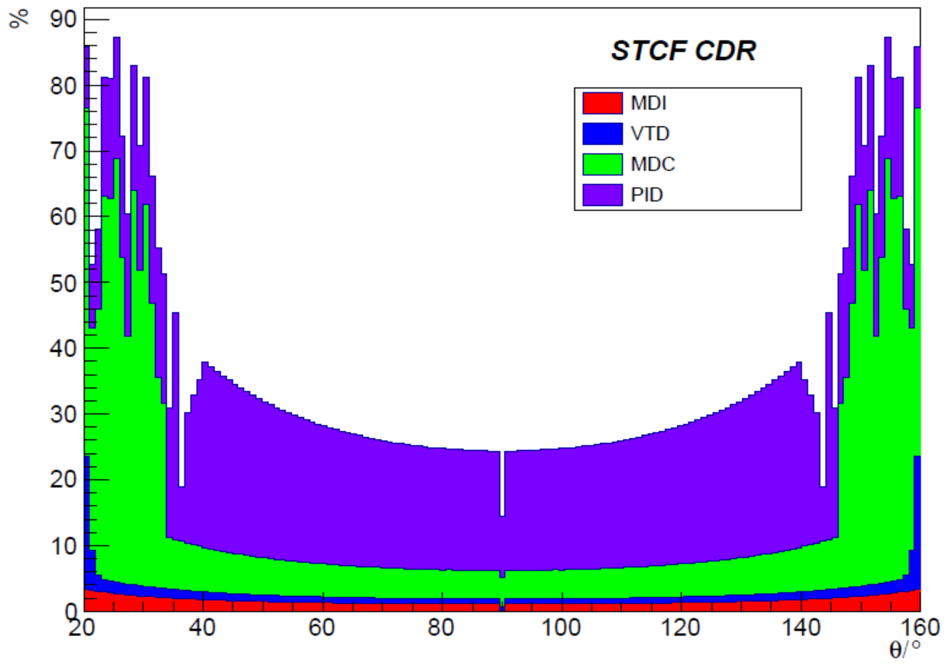


The position resolution is 4.9 mm @ 1 GeV ,which meets the performance requirement.

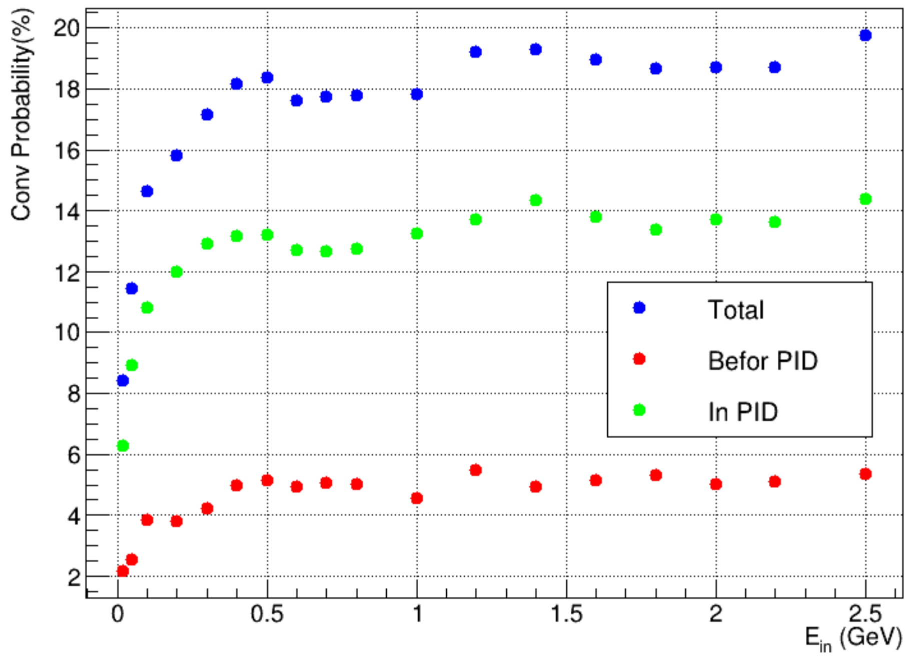
Performance Simulation

●Material budget in front of the EMC

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



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

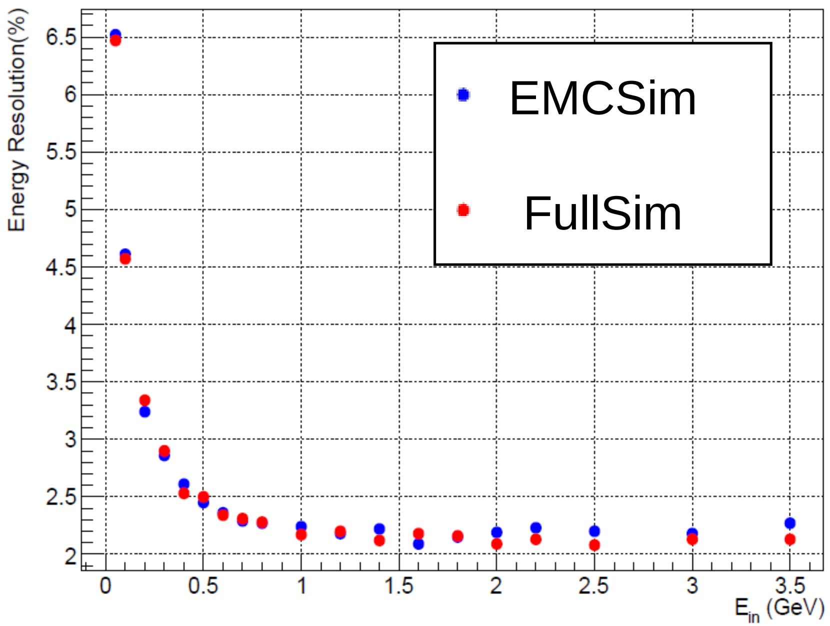


γ conversion probability in front of EMC

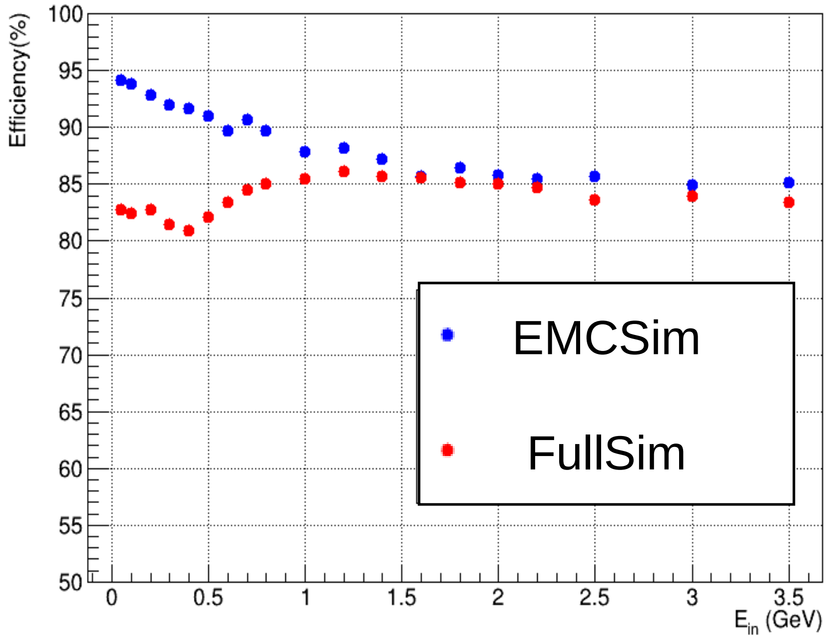
Performance Simulation

Impact of materials in front of EMC

- A full STCF detector simulation study was carried out, and the simulation results are compared with EMC 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 $\frac{N_{rec}}{N_{MC}}$,

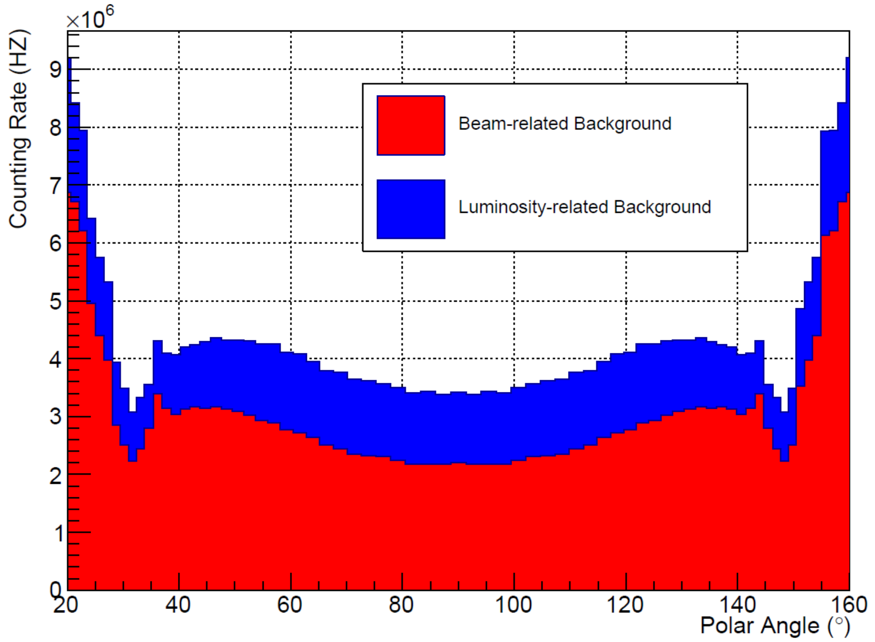
N_{rec} satisfy: $E_{peak} - 4\sigma_E < E_{rec} < E_{peak} + 2\sigma_E$.

Background Level

● Challenges of high background

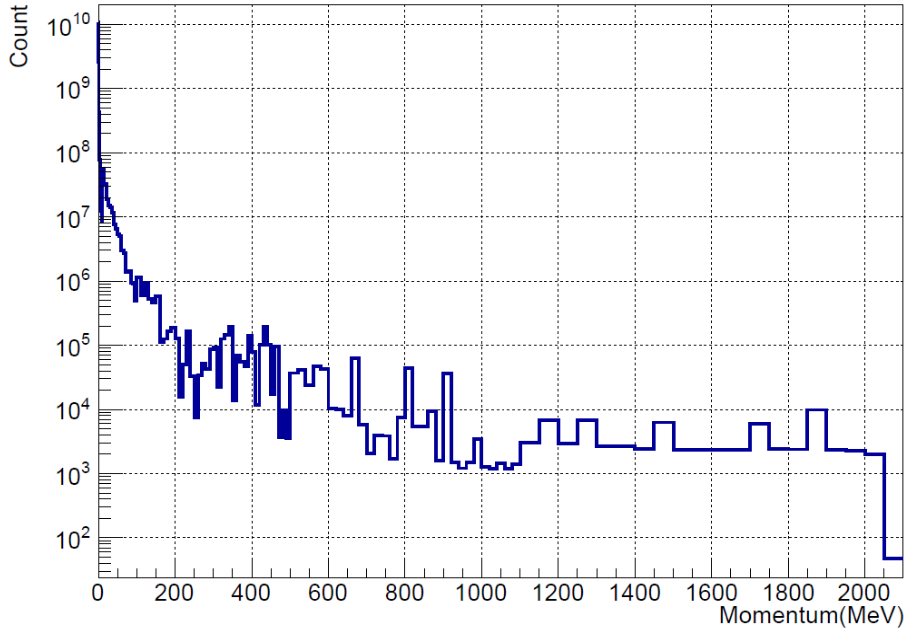
➢ Background Source

1. Luminosity-related Background
2. Beam-related Background



The background counting rate varies with polar angle.

Counting rate reaches the order of MHz



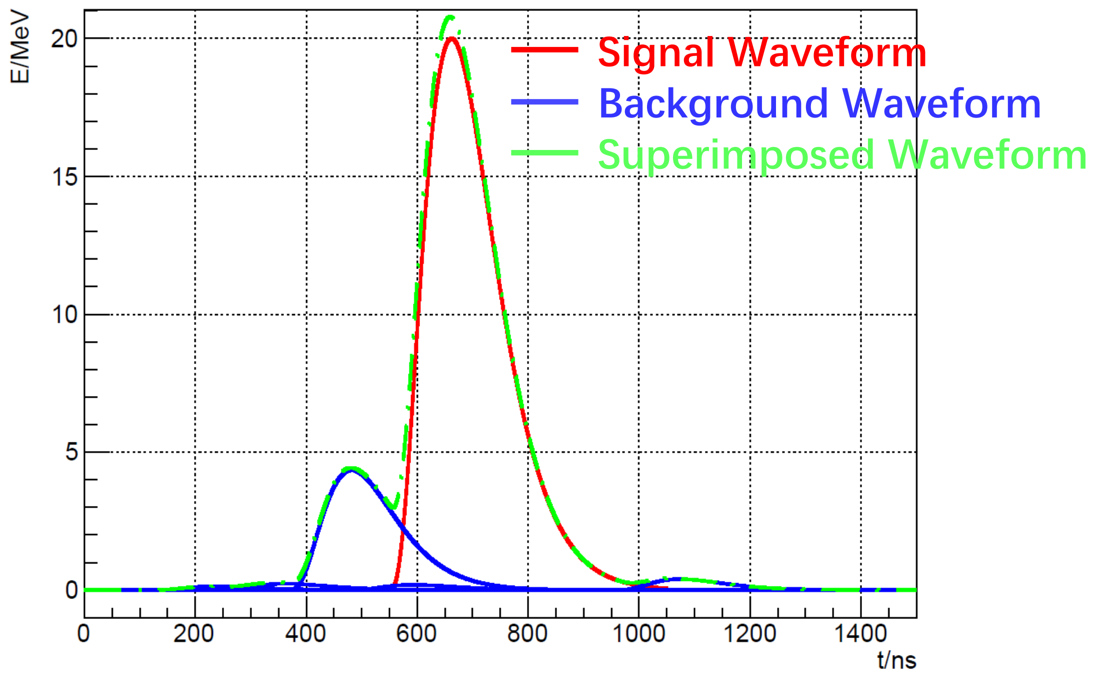
The momentum distribution of background particles.

Most background particles have very low momentum (<1MeV)

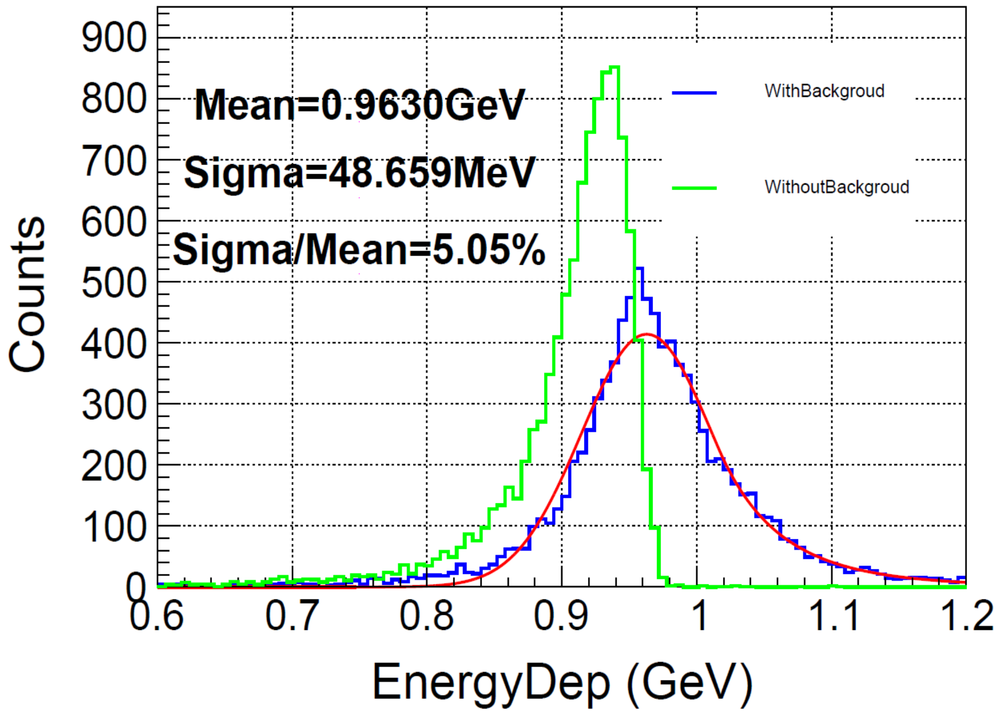
Background Level

● Challenges of high background

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



The amplitude and time of signal are distorted.



The energy spectrum of 1 GeV photons before and after introducing background.

Waveform Fitting Method

Multi-template fitting

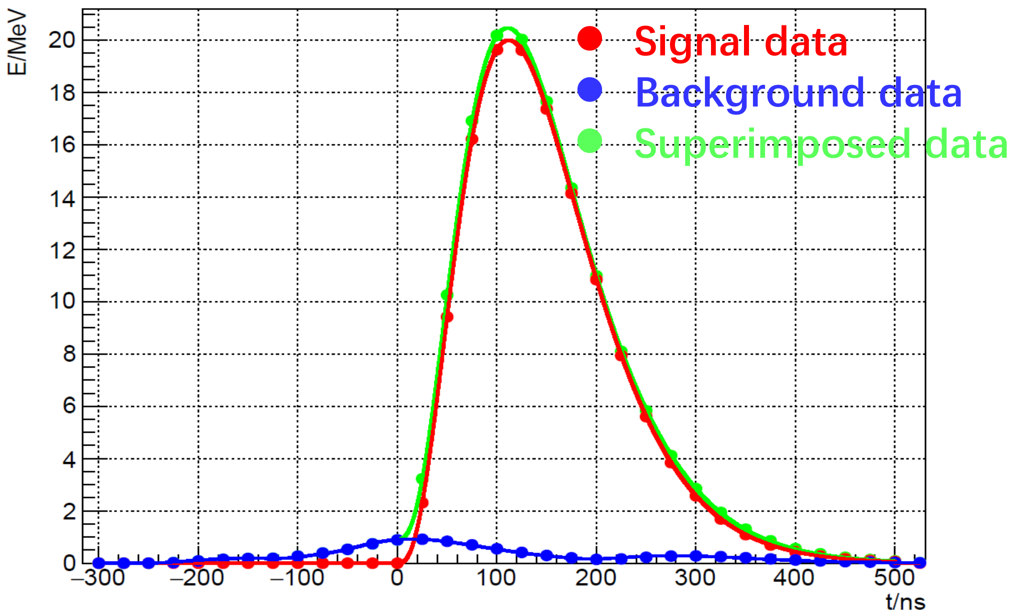
- The waveform template is obtained by convoluting the pure CsI fluorescence signal with the electronics impulse response function
- The fit minimizes the χ^2 defined as:

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

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.

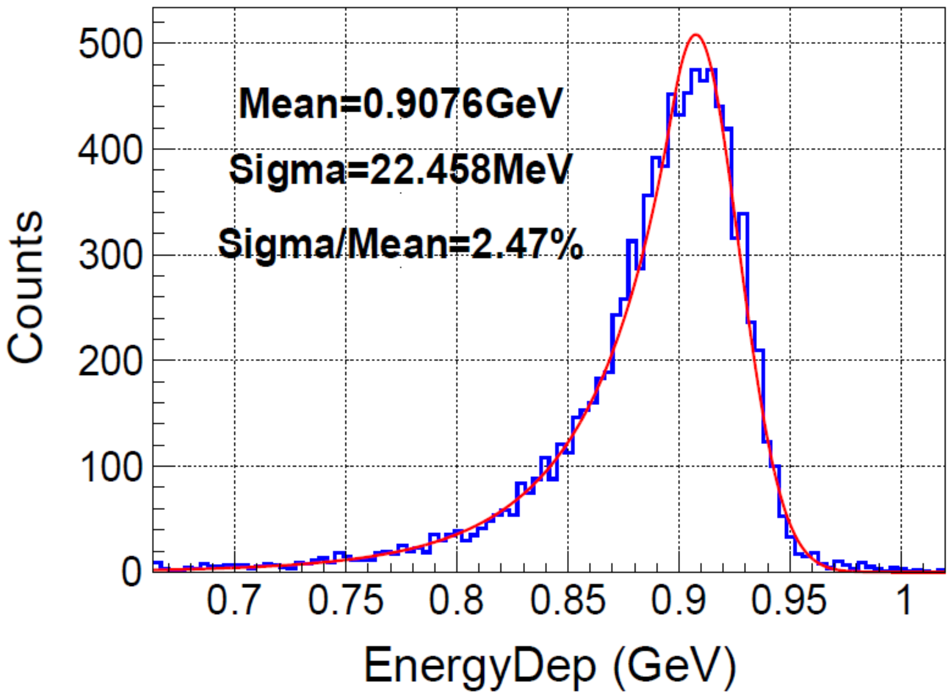
An example of the multi-template fitting result.



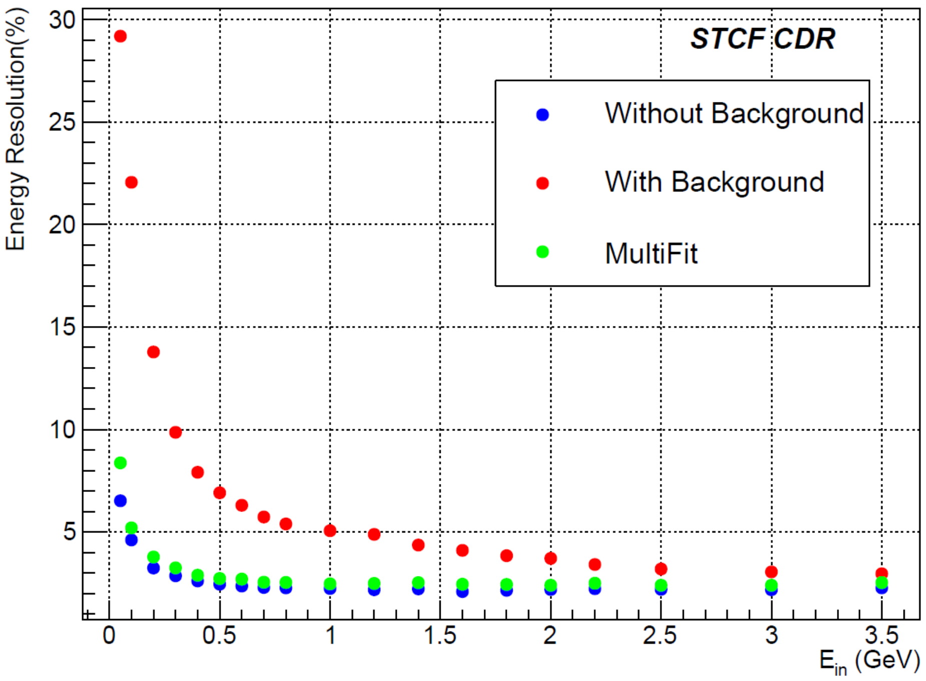
- The green line is the fitting result of the data, which is the sum of total templates.
- The red line is the template represents the signal.
- The blue line represents the background, which is the sum of the remaining templates.

Waveform Fitting Method

- **The effect of waveform fitting method**



The energy spectrum of 1 GeV photons after waveform fitting.



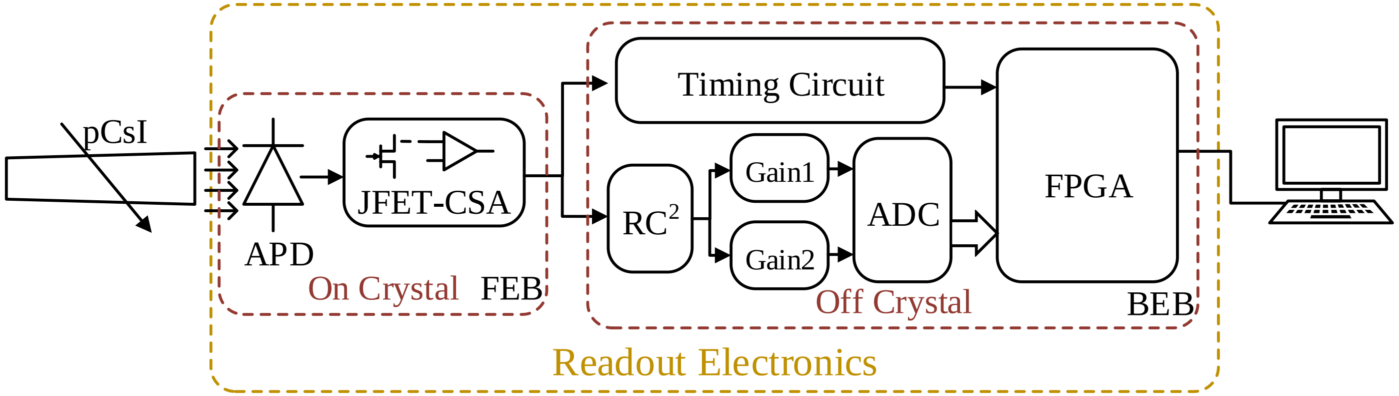
The energy resolution under three different situation.

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

pCsI Light Yield Test

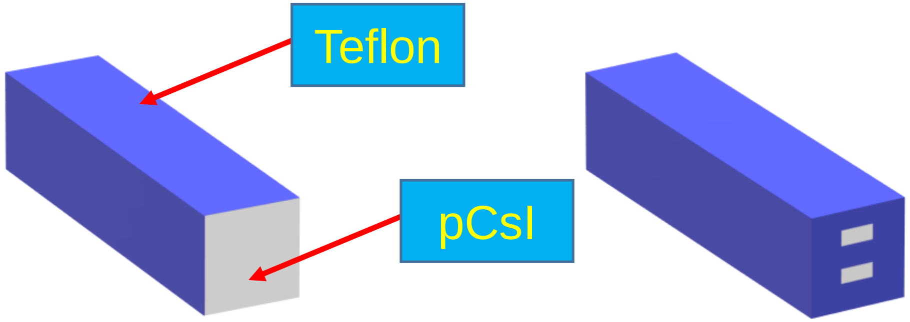
●pCsI + 4 APD

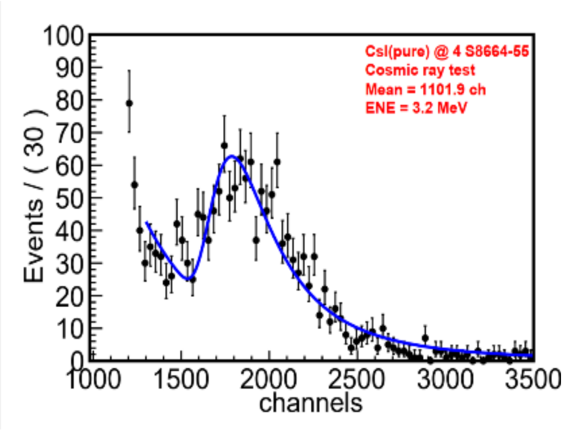
- ➢ Using cosmic ray to test sensitive unit
- ➢ 4 APDs for high light yield
- ➢ FEB: CSA-based readout design
- ➢ BEB: CR-RC^2 shaper



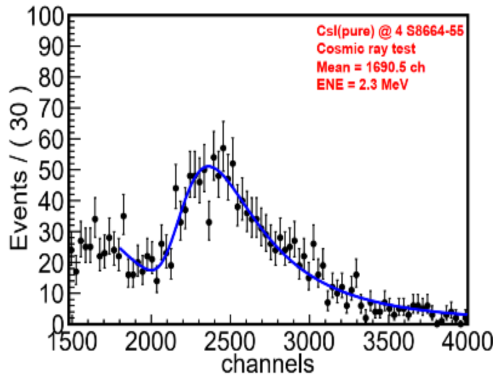
pCsI Light Yield Test

- **Wrapping method**



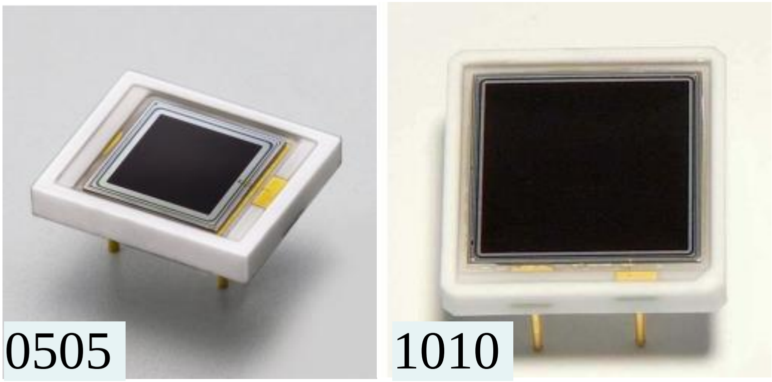


~35 p.e./MeV



~54 p.e./MeV

- **Size of APD**



Hamamatsu S8664-0505/1010

Size: $5 \times 5\, mm^2 / 10 \times 10\, mm^2$

APD	Light Yield (p.e./MeV)
S8664-0505	54
S8664-1010	156

Whether the back end face is wrapped has a great impact.

Time Resolution Test

- **Demand for time performance**
  - ➢ Background suppression
  - ➢ Gamma-neutron discrimination
  - ➢ Event identification
  - ➢ ……

Better than 300ps @ 1 GeV is required for EMC.

- **Time performance test**
  - ➢ LED + APD
  - ➢ Timing method based on waveform fitting (1-template fitting)

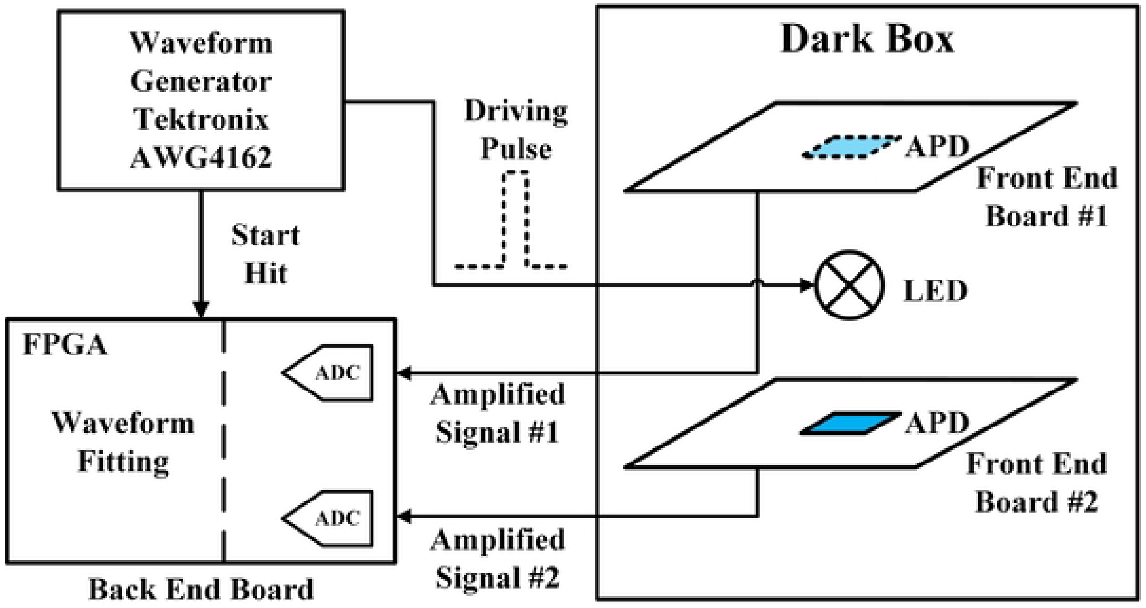
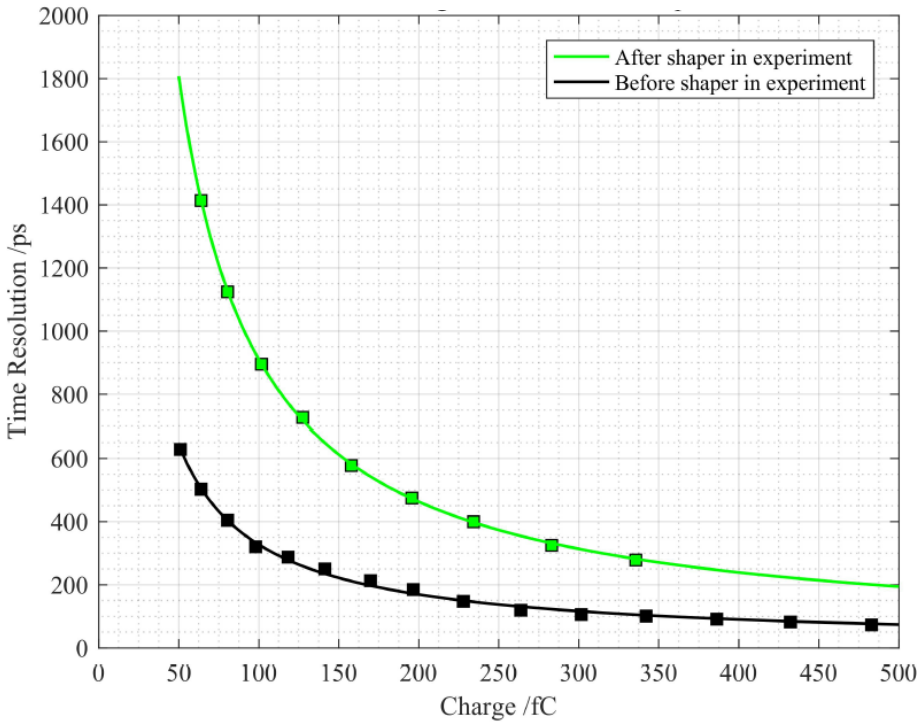


Diagram of the time performance test

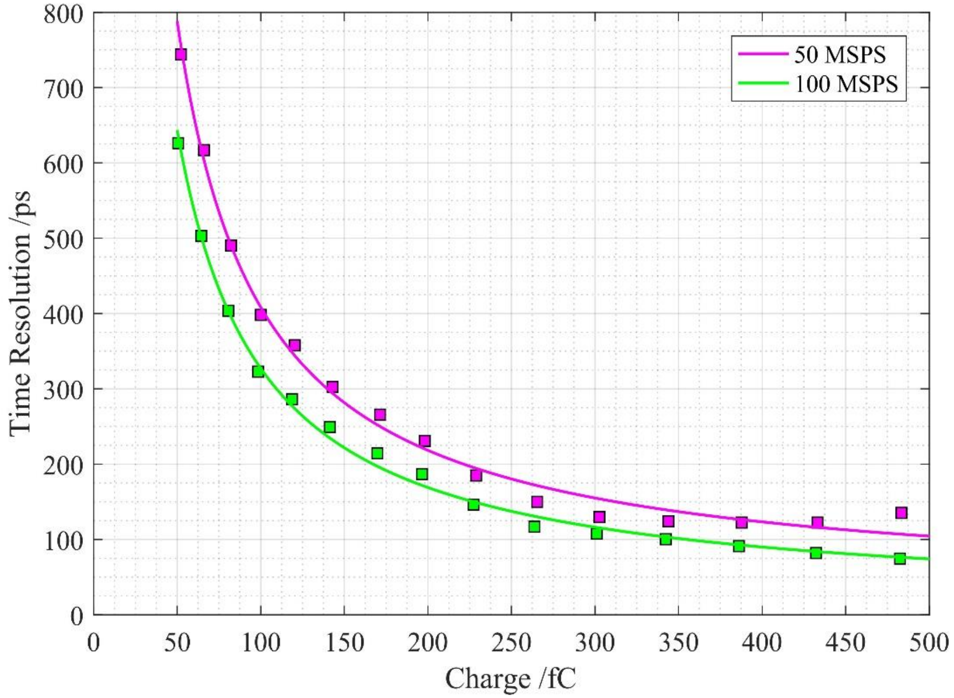
Time Resolution Test

● Time Performance

- ➢ Unfiltered signal have better performance
- ➢ Increasing the sampling rate helps improve performance



After Shaper: 464 ps ; Before Shaper: 169 ps
@ 200 fC (equivalent deposition energy of 1GeV)



50 MSPS: 219 ps ; 100 MSPS: 169 ps
@ 200 fC (equivalent deposition energy of 1GeV)

Summary

- **High precision EMC with fast response characteristics**
  - **High luminosity, good energy resolution, good time resolution**
- **The baseline design of EMC was done**
  - **pCsI + APD**
  - **A Compact design of EMC geometry model with defocus operation was completed**
- **The key performance of EMC was studied based on OSCAR**
  - **The MC results shows that the design of EMC could meet the requirements**
  - **The waveform fitting method is helpful in solving the problem of high background rate**
- **Some test results**
  - **pCsI + 4 1010-APD : 156 p.e./MeV**
  - **LED + APD : 169 ps @ 1GeV**

Thanks!

Back Up

EMC Design —— Crystal Selection

●Total absorption calorimeter

➢ **Pure CsI crystal + APD photo-device**

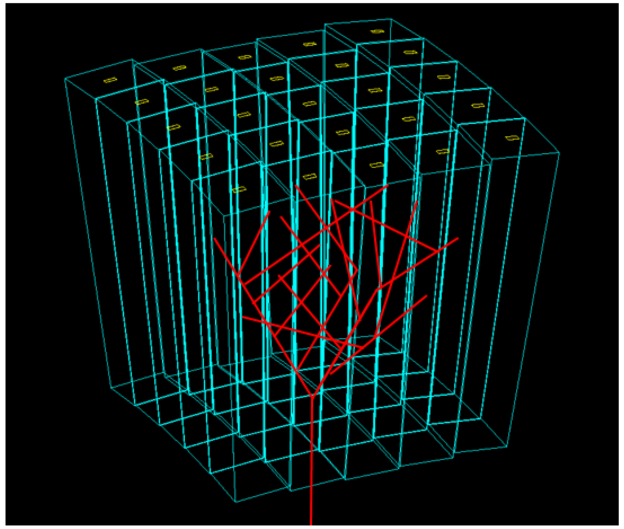
Crystal	Pure CsI	LYSO	GSO	YAP	PWO	BaF:Y
Density (g/cm^3)	4.51	7.40	6.71	5.37	8.30	4.89
Melting Point (°C)	621	2050	1950	1872	1123	1280
Radiation Length (cm)	1.86	1.14	1.38	2.70	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	3.10
Refractive index	1.95	1.82	1.85	1.95	2.20	1.50
Hygroscopicity	Slight	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	

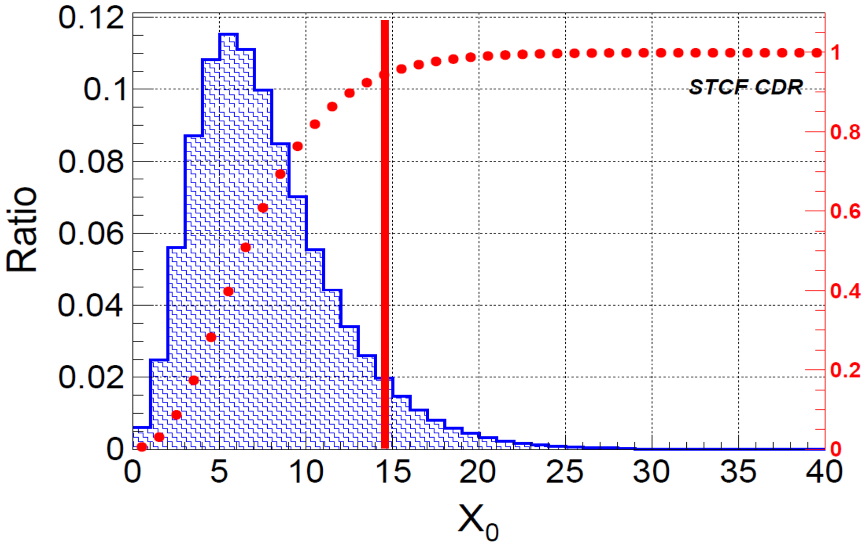
EMC Design —— Crystal Size Design

● Total radiation length

- **Absorb the electromagnetic shower as much as possible**
- **About 95% of energy will deposit in EMC with 15X_0**
- **When the length is increased after 15X_0, the "cost performance" decreases rapidly**

Thickness	10X_0 (18.6cm)	12X_0 (22.3cm)	15X_0 (27.9cm)	20X_0 (37.2cm)
Ratio (%)	76.3	86.3	94.3	98.7



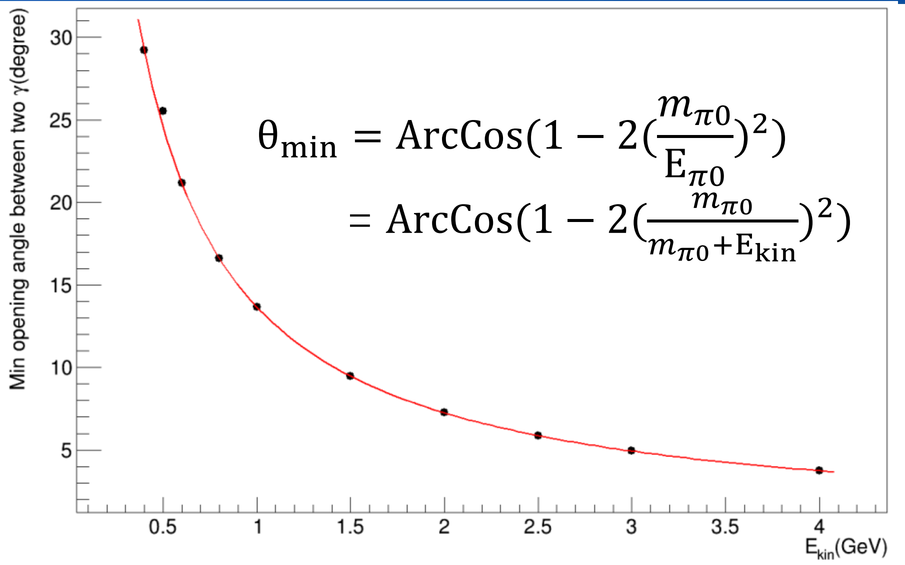


3 GeV γ-ray Shower profile

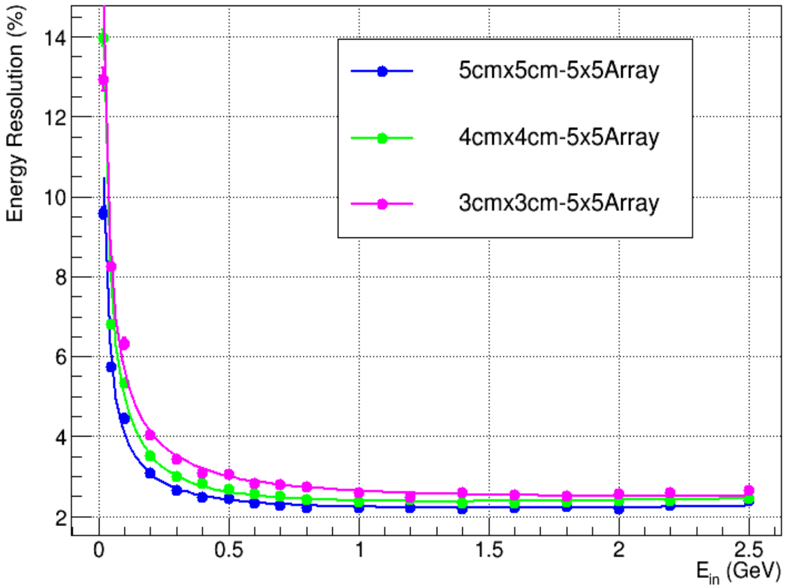
EMC Design —— Crystal Size Design

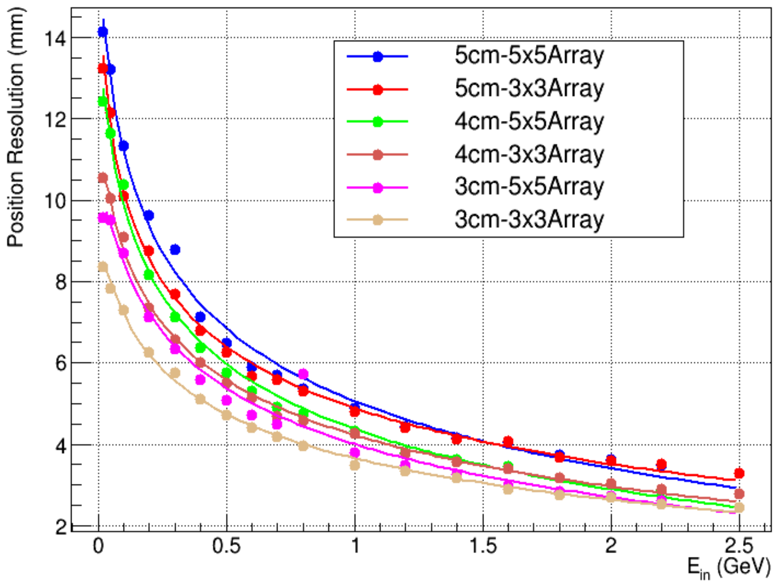
●End face size

- ➢ **The minimum angle between the two γ produced by the decay of π^0 decreases with the increase of the energy of π^0**
- ➢ **For 1.5GeV π^0, the minimum angle is about 10°, which require the end face size is not greater than $5.5\times 5.5\ cm^2$**



Minimum opening angle vs. $E_{\pi 0}$





The cell size of $5\times 5cm^2$ can meet the performance requirement well.

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 $\mathbf{x}^* = \arg\min \|\mathbf{A}\mathbf{x} - \mathbf{b}\|^2$.
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 $R \neq \varnothing \wedge [\max_{i \in R}(w_i) > \mathit{tolerance}]$
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. $\mathbf{w} = \mathbf{A}^T(\mathbf{b} - \mathbf{A}\mathbf{x})$
