Simulation and Initial Tests of the Dual-Readout Electromagnetic Calorimeter

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Fudan University

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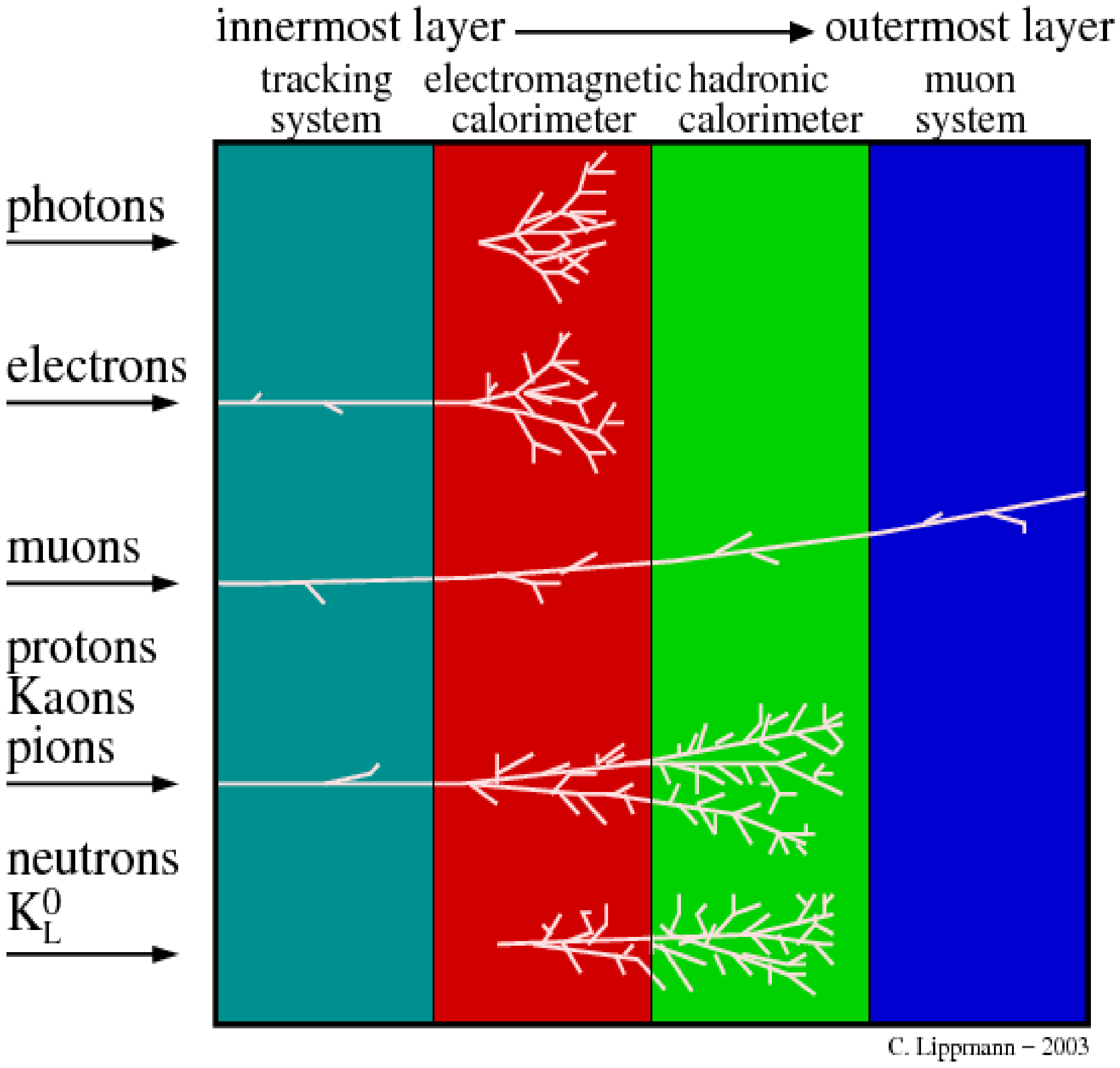
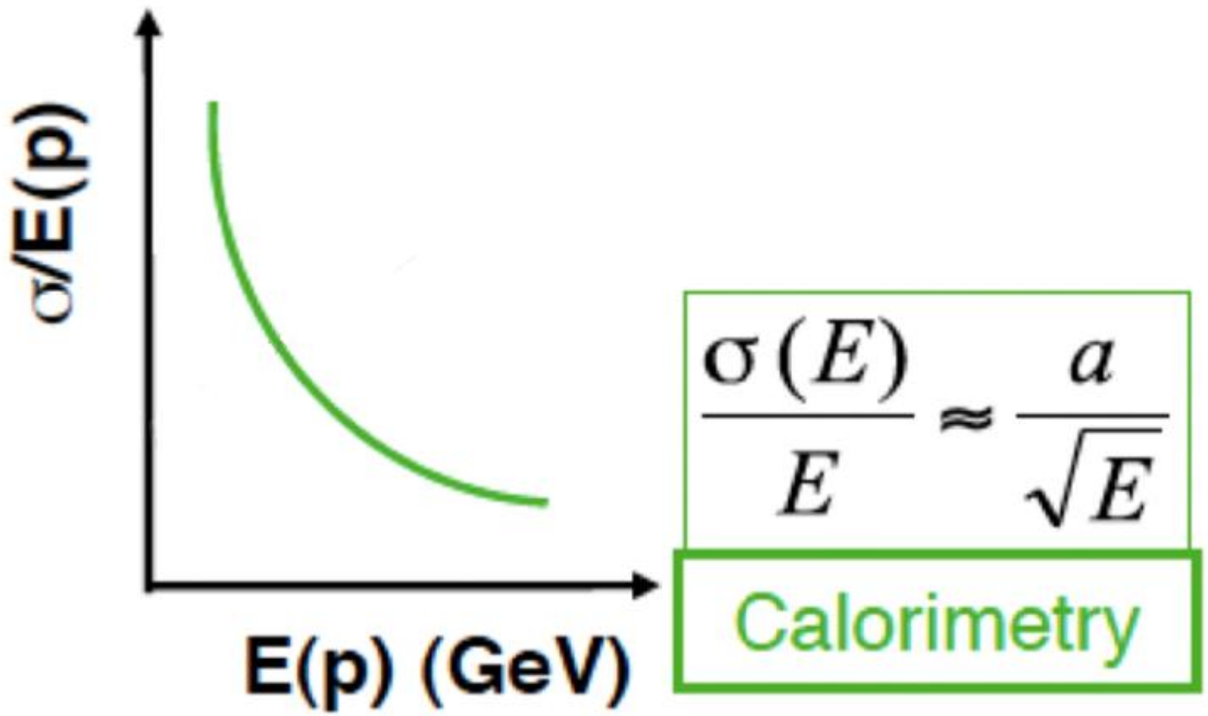
Contents

Application of Calorimeters in Spectrometer Detectors

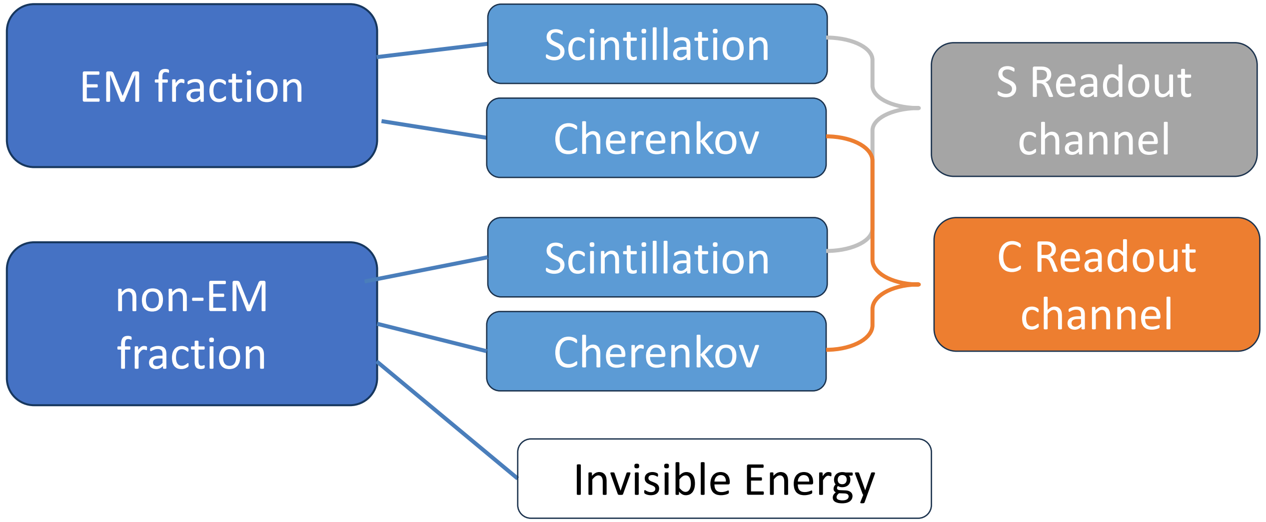


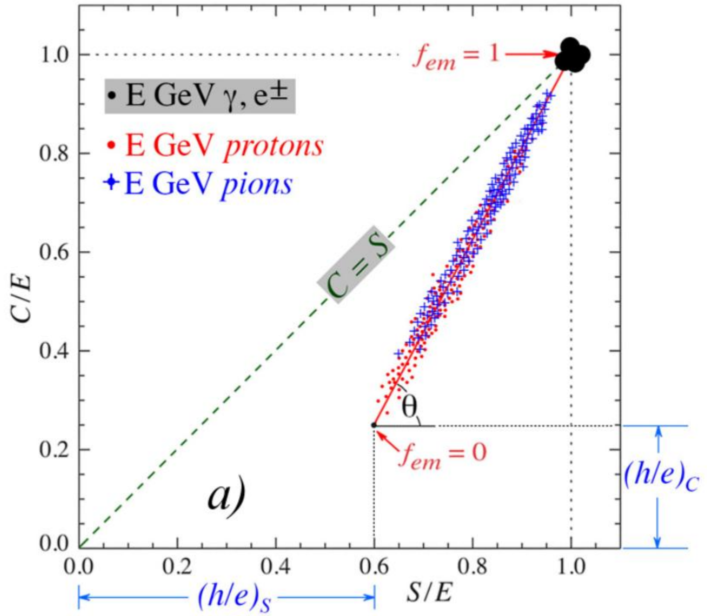
Electromagnetic calorimeter： $e^{\pm}, \gamma$

Hadronic calorimeter ： $\pi^{\pm}, p^{\pm}, K^{\pm}, K_L^0, n$



Advantages of the Dual-Readout Calorimeter

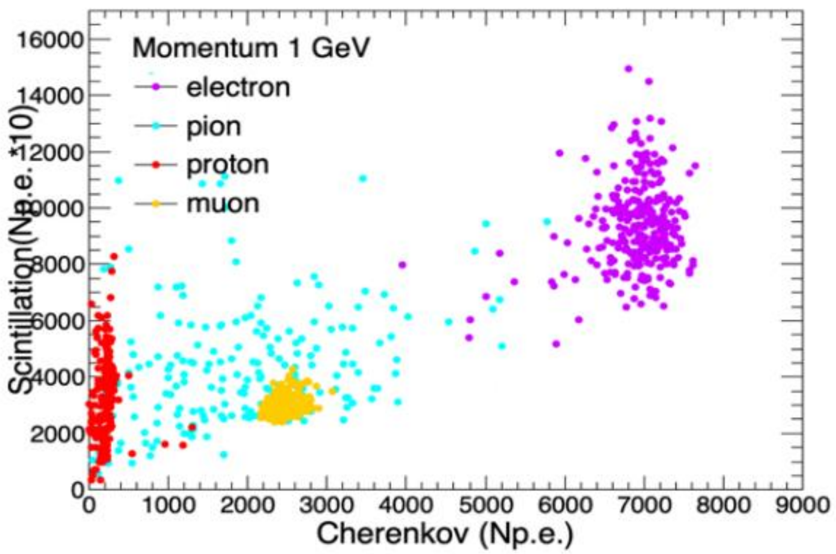


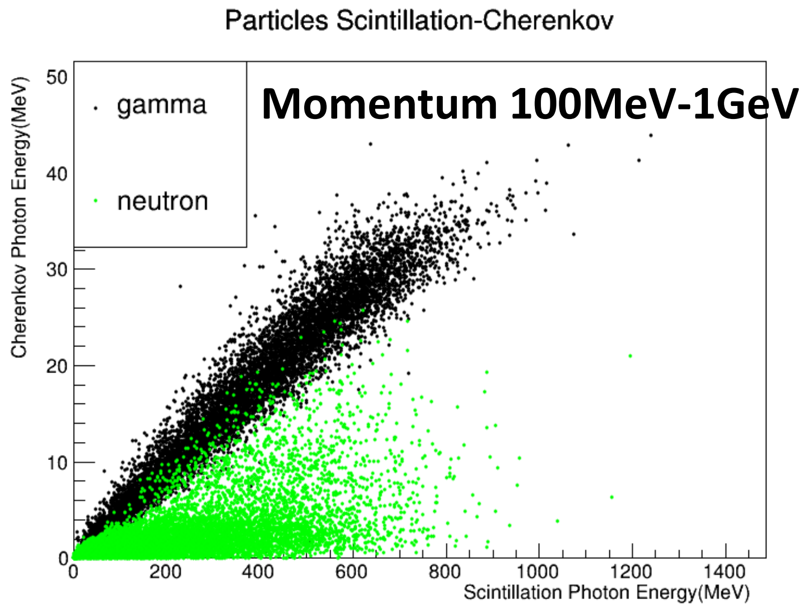


$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C}$$

$$E = \frac{S - cot\theta C}{1 - cot\theta}$$

PID performance

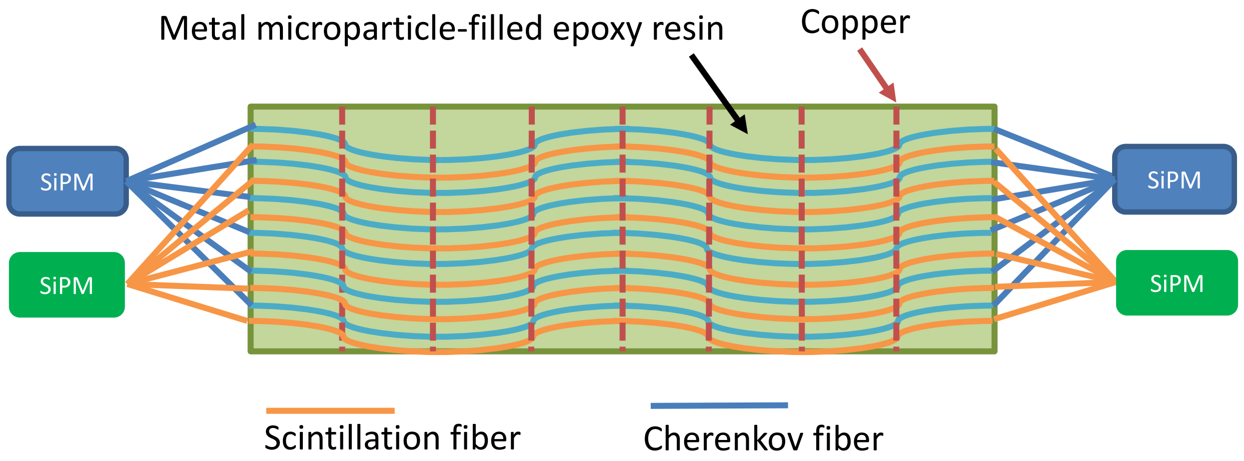


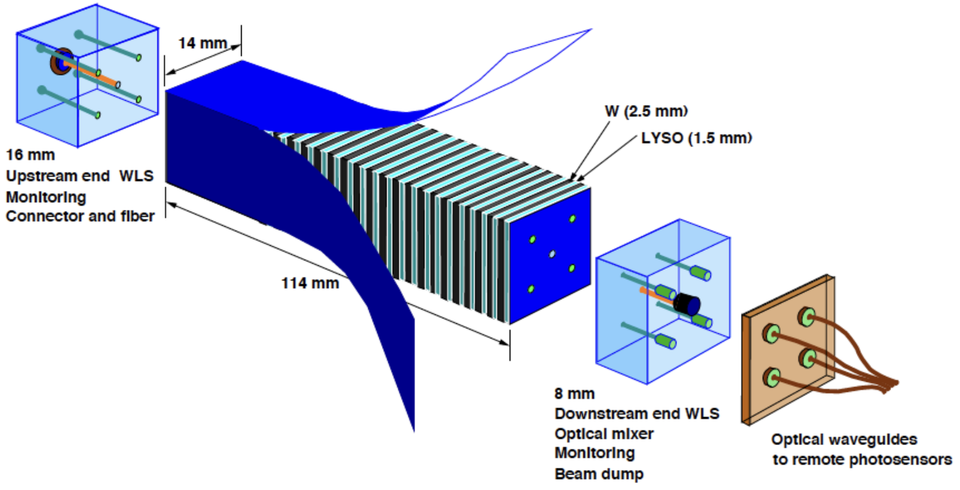


In **hadronic** measurements, the dual-readout method can correct energy calculations.

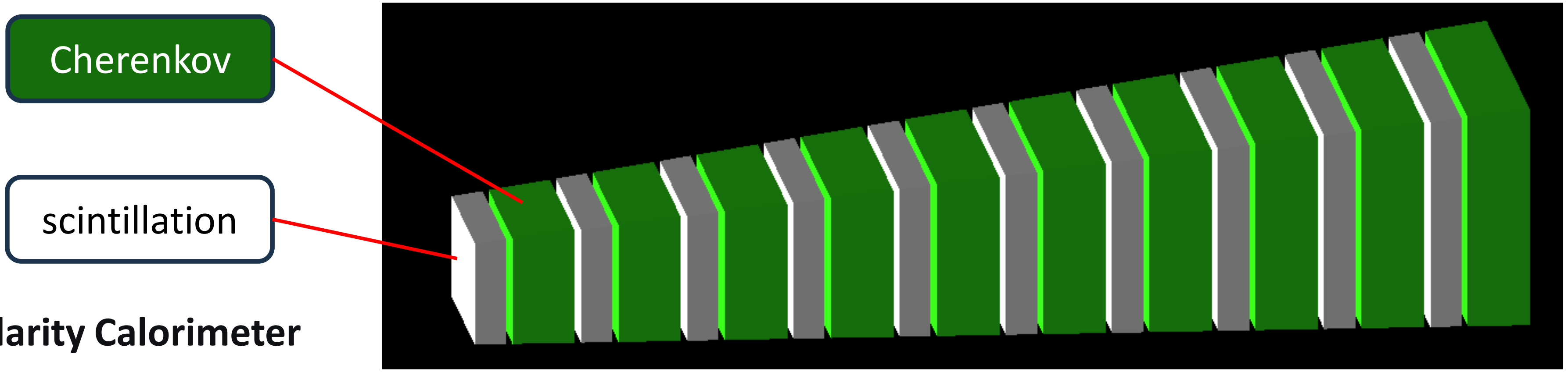
Dual-Readout Calorimeter Structure

Scintillation： CsI， PbWO4， Plastic Scintillator…
Cherenkov Radiation： PbF2， Lead Glass， Aerogel…



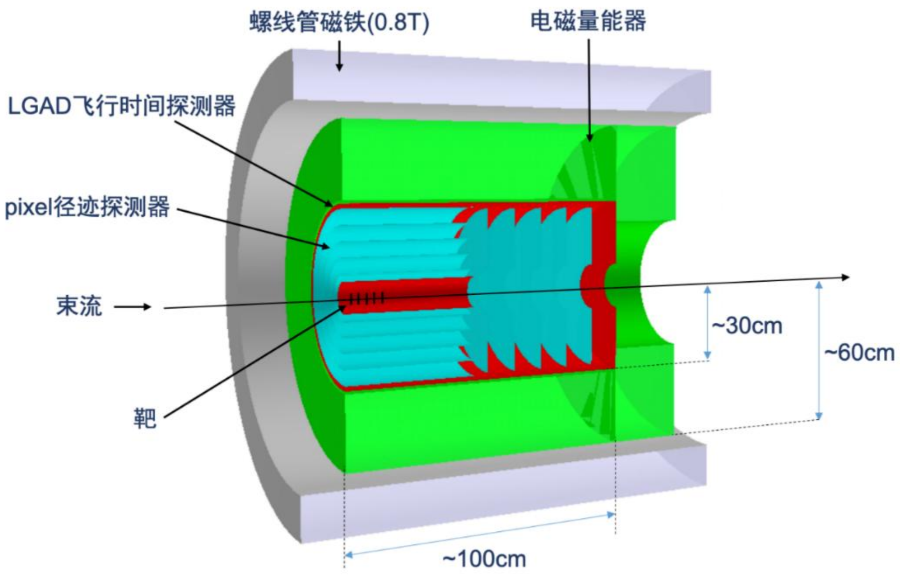


With segmentation along the length, photon loss during transportation can be reduced.

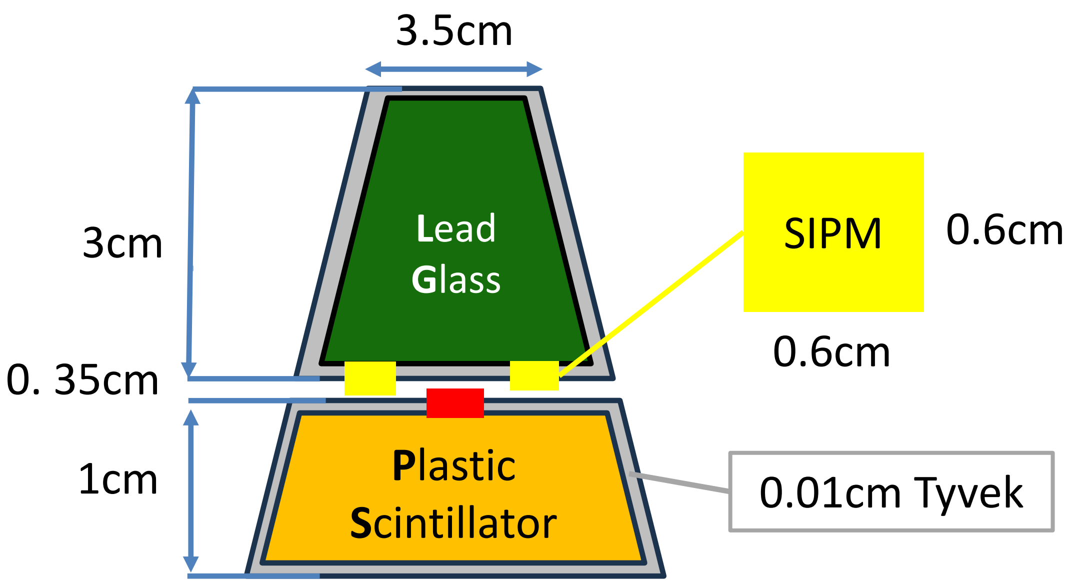


High-Granularity Calorimeter

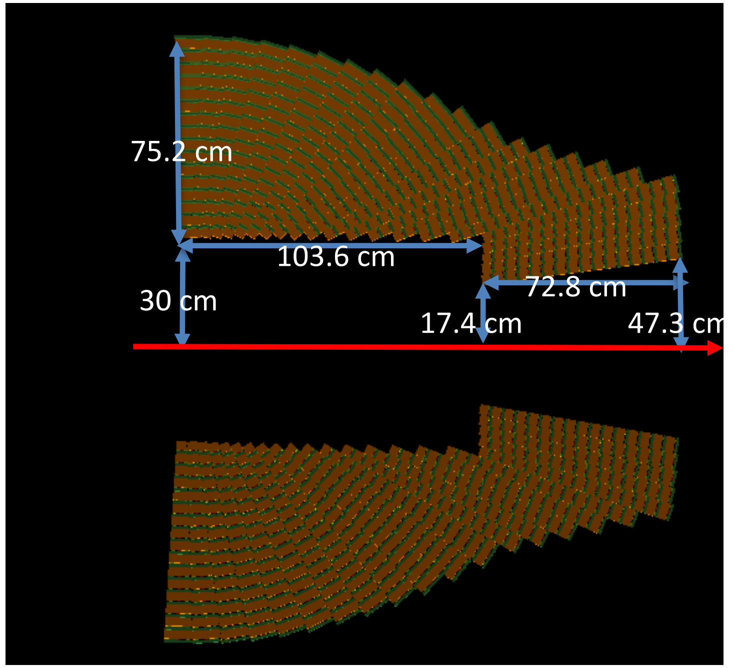
EMC Basic Structure

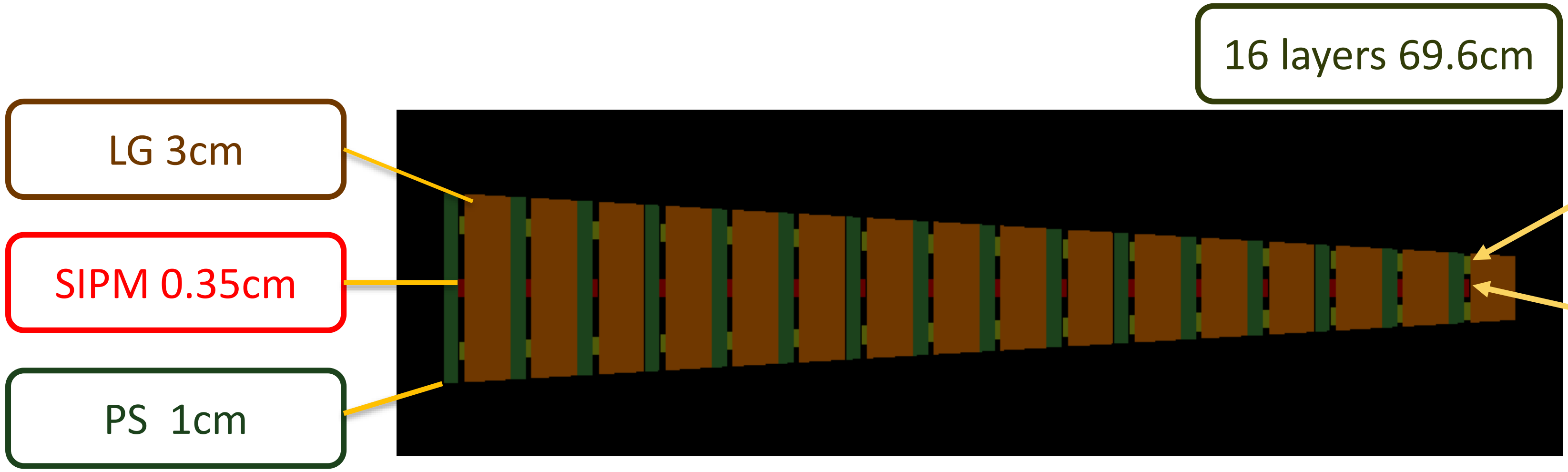


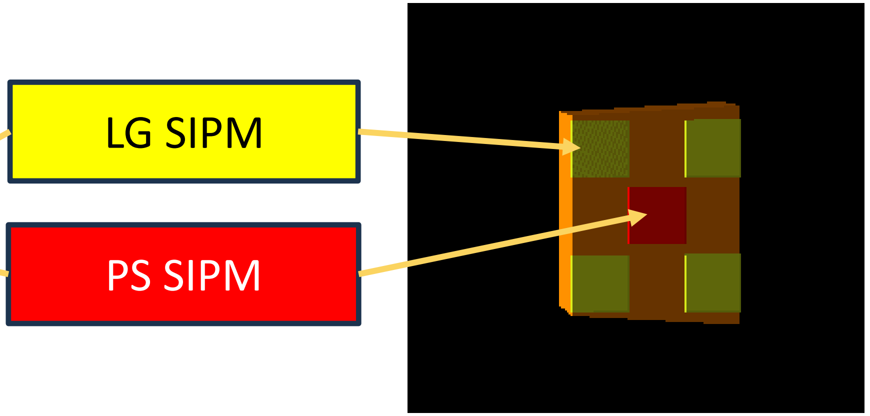
HHaS basic structure



Single module

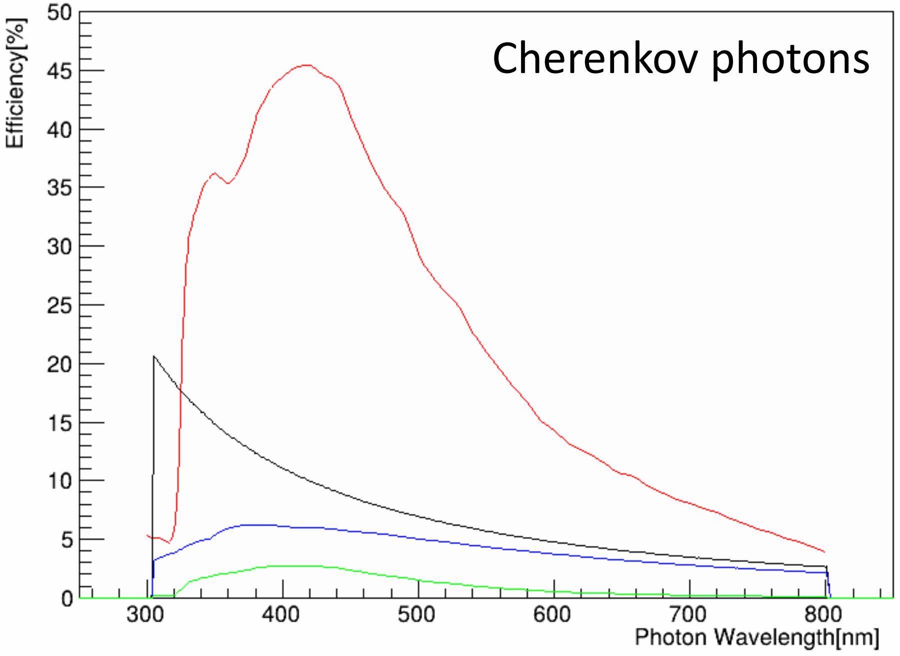


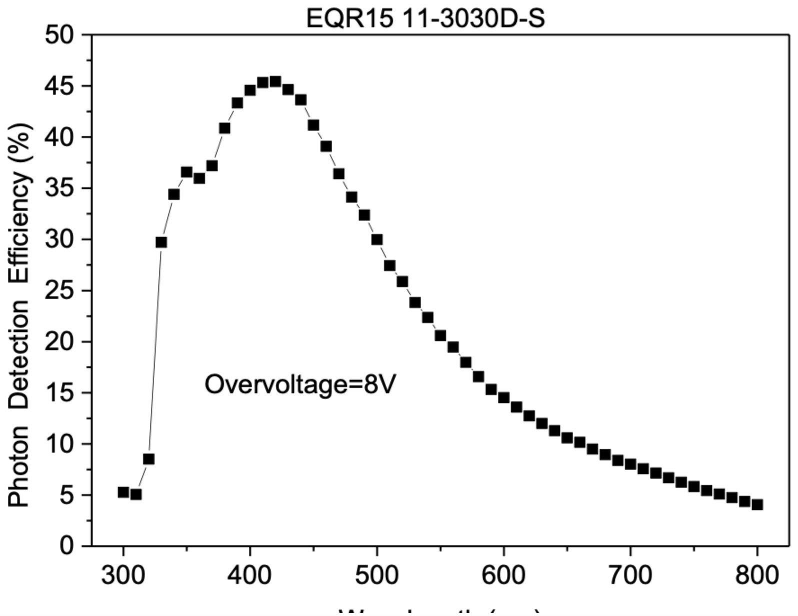


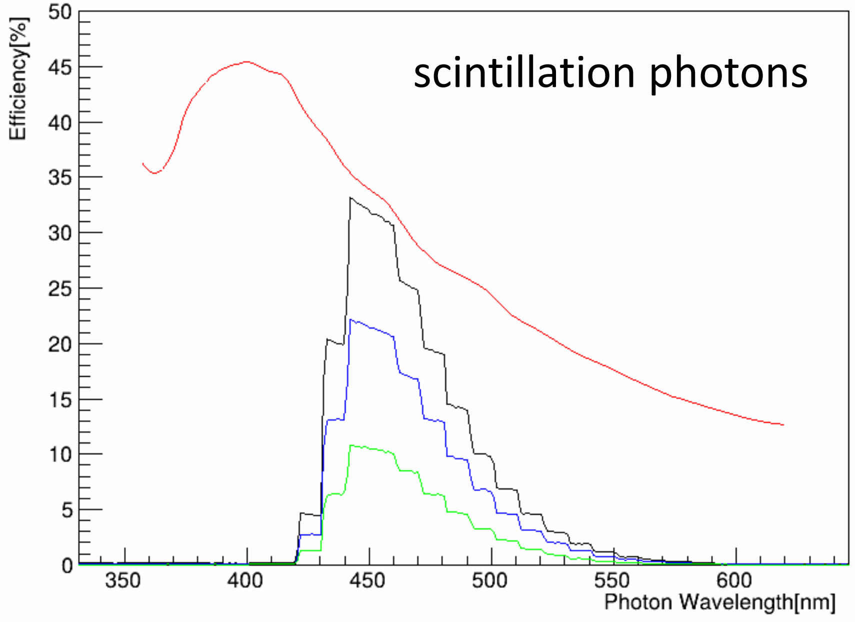


Simulation Parameters

Based on the wavelength range of the SiPM efficiency spectrum, the photon wavelength range has been set to 300 nm – 800 nm.



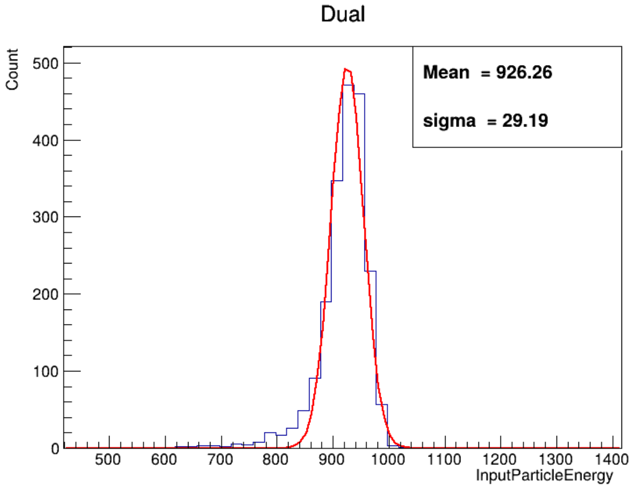




Red: SiPM detection efficiency
Black: Spectrum of generated Cherenkov photons
Blue: Spectrum of Cherenkov photons received by the SiPM
Green: Spectrum of Cherenkov photons detected by the SiPM

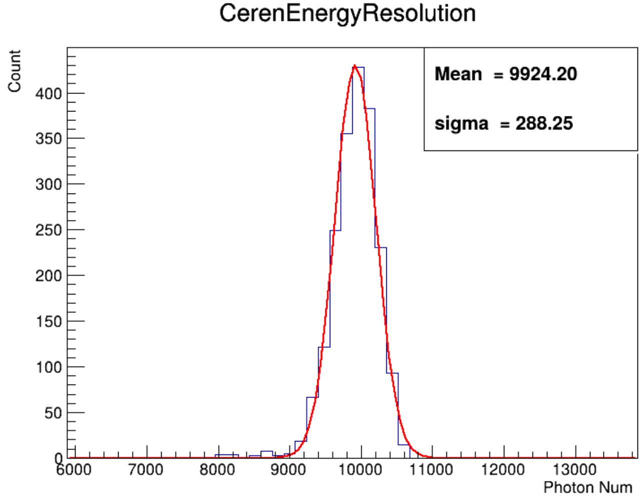
Incident particle 1GeV γ

3cm PS 1cm LG blocks 16 layers



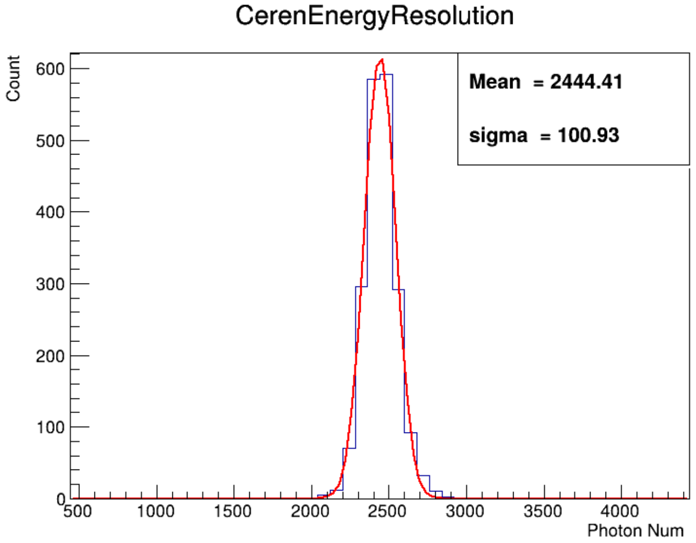
$$\sigma/E = 3.15\%/\sqrt{E}$$

3cm LG 1cm LG blocks 16 layers



$$\sigma/E = 2.90\%/\sqrt{E}$$

64cm Lead glass bar



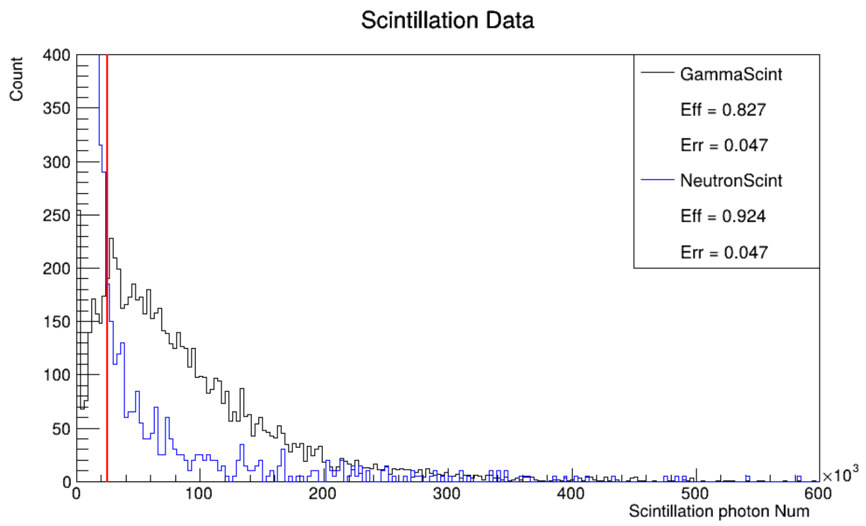
$$\sigma/E = 4.12\%/\sqrt{E}$$

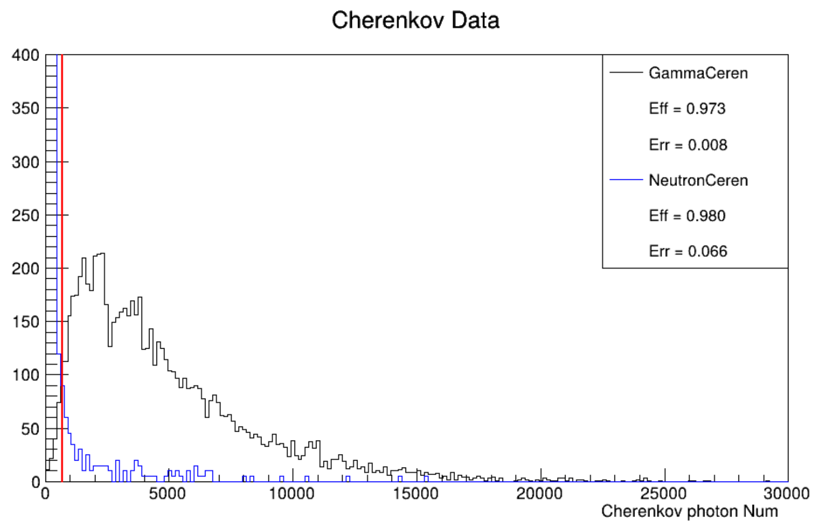
Cherenkov Photon Count

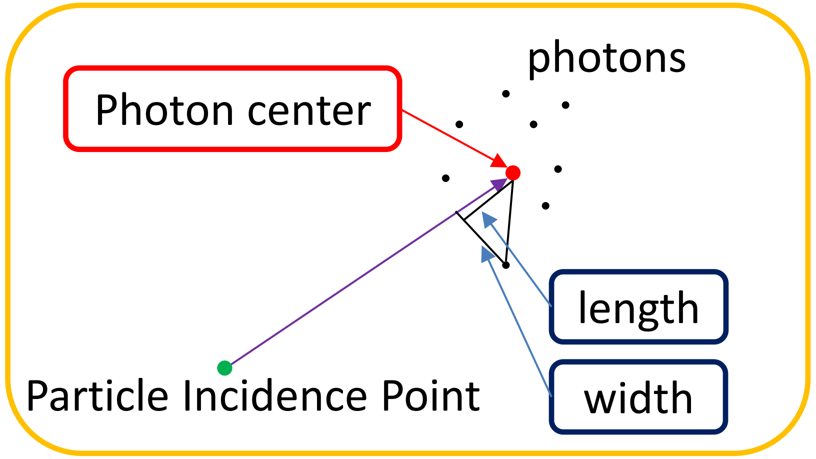
Calorimeter Structure	Generate	Module Absorb	Reflective Loss	SiPM received	SiPM detected
PS-LG block only Cherenkov	45312	15419	8777	21355	9341
(%)	100%	34.0%	19.3%	47.1%	20.6%
Lead glass block	50690	18120	10662	22597	9877
(%)	100%	35.7%	21.0%	44.5%	19.4%
Lead glass bar	51631	34550	11344	5737	2441
(%)	100%	66.9%	21.9%	11.1%	4.27%

PID Performance

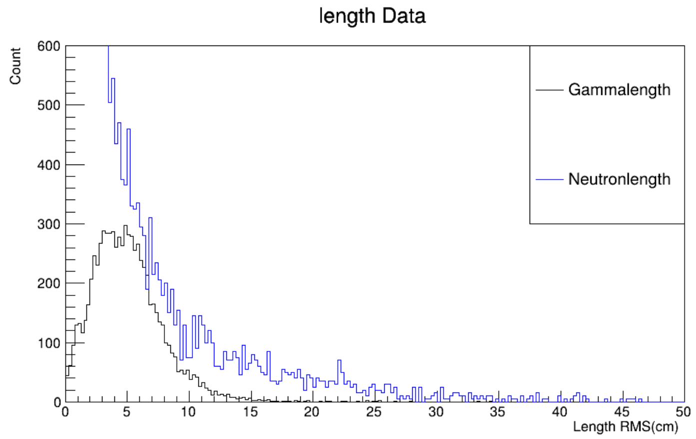
Using event generators based on 1.8 GeV kinetic energy protons hitting a Li target.

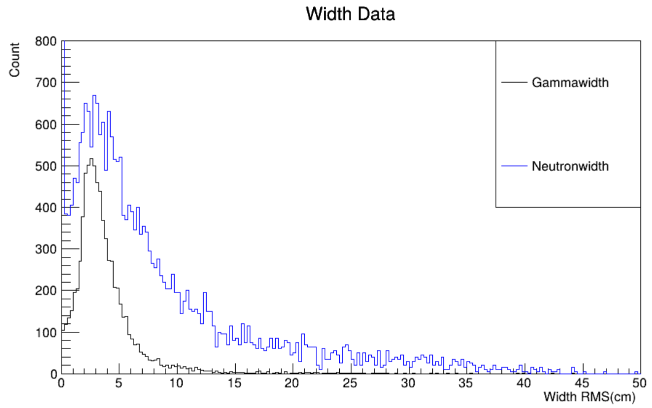


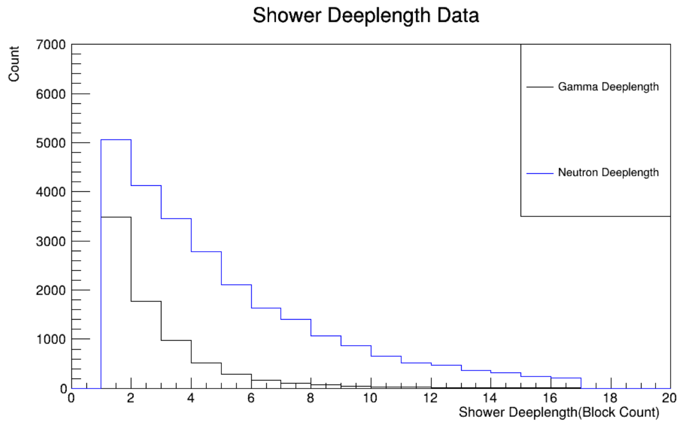




For each event, we calculate the RMS of the photon distributions' length and width, and take the block number with the deepest shower as the depth.

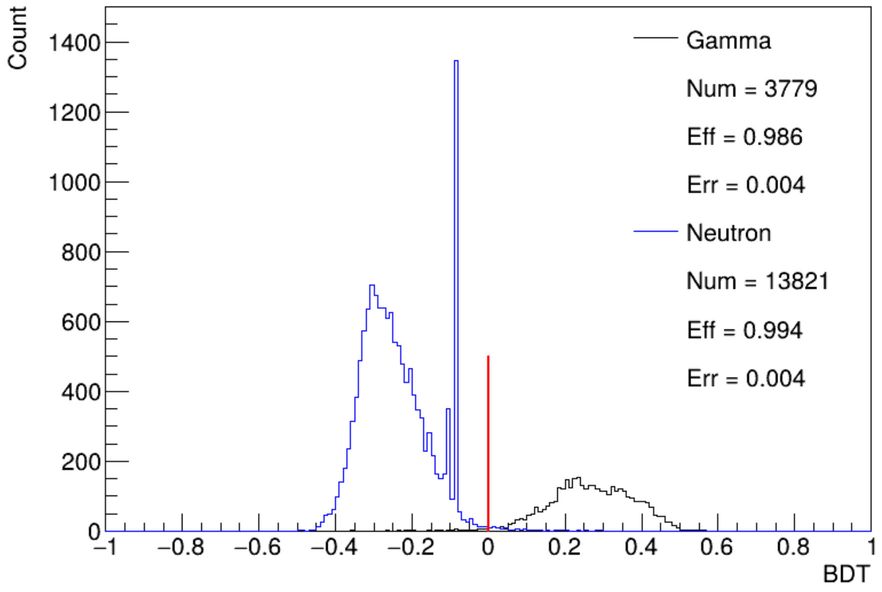




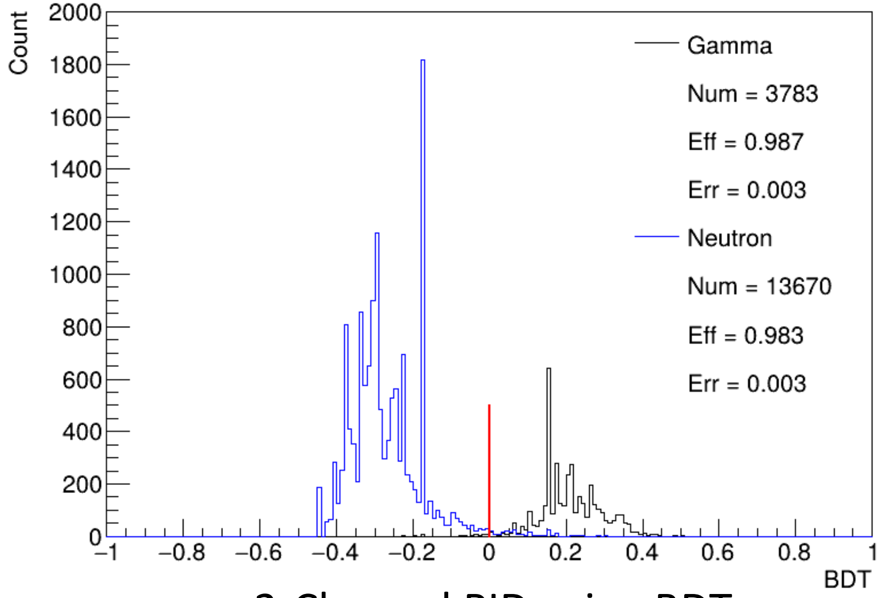


PID Performance

Using the Boosted Decision Tree (BDT) algorithm to PID, with data from multiple channels serving as input.



5-Channel PID using BDT



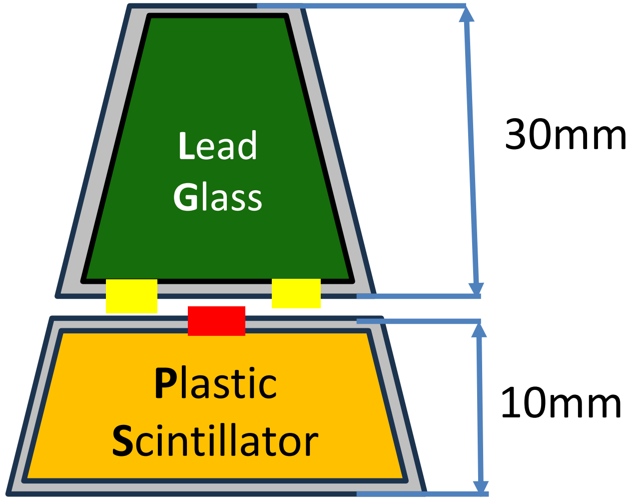
2-Channel PID using BDT

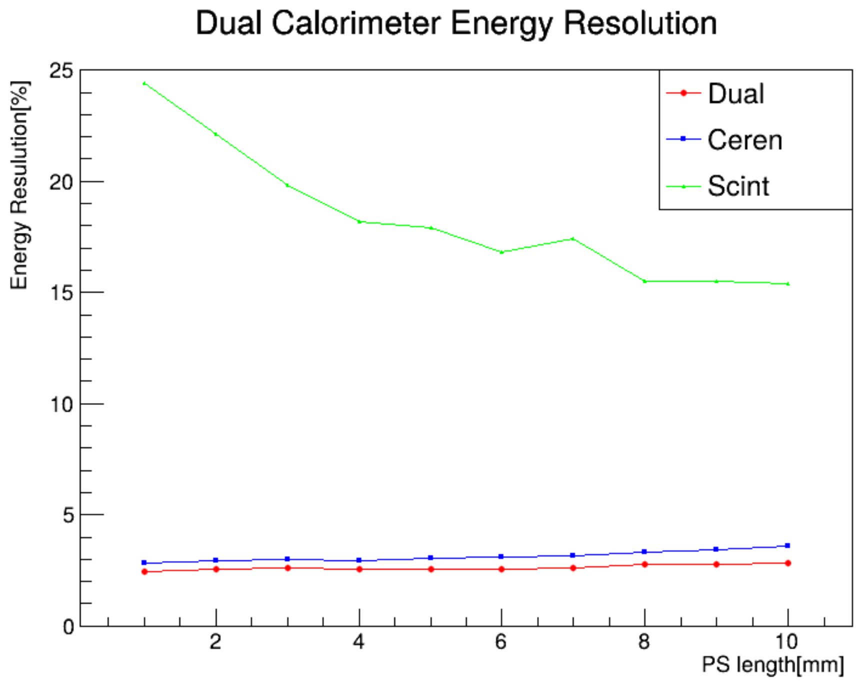
Compared to the 5-channel system, the 2-channel system shows no significant drop in PID efficiency, while the read-out cost is substantially reduced.

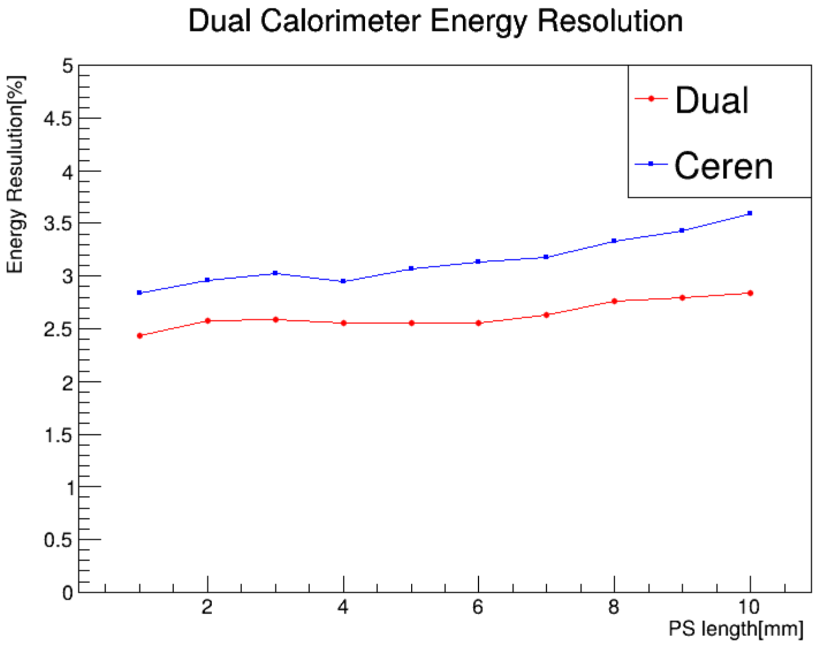
After applying the BDT algorithm for γ/n identification, the PID efficiency for both particle types exceeded 98%.

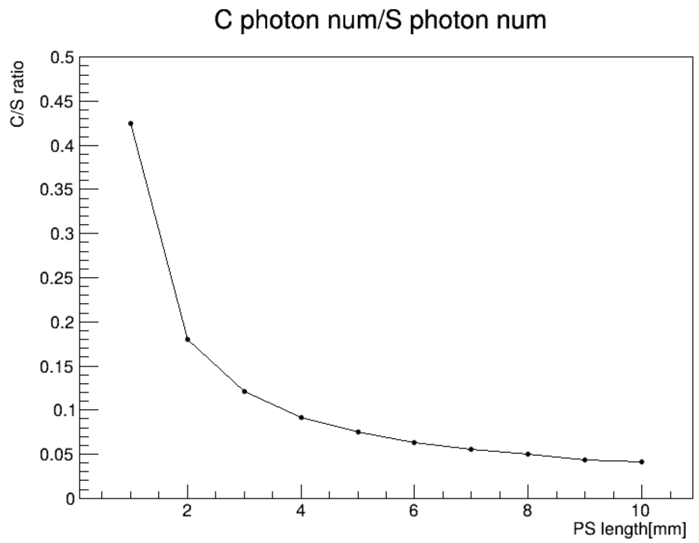
We keep the total length of each module at 4 cm,

while adjust the ratio of PS to LG from 1 mm:39 mm up to 10 mm:30 mm.





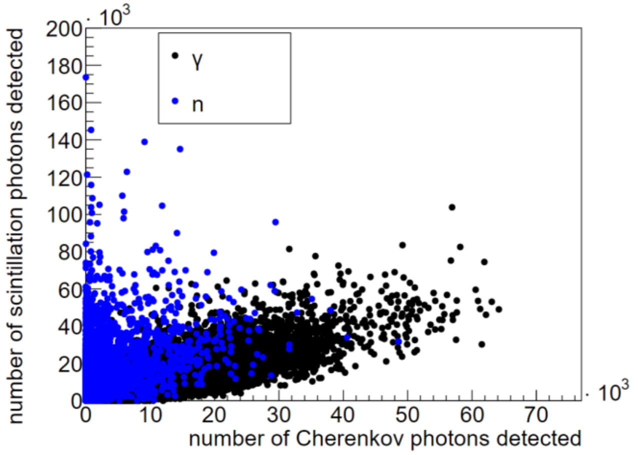


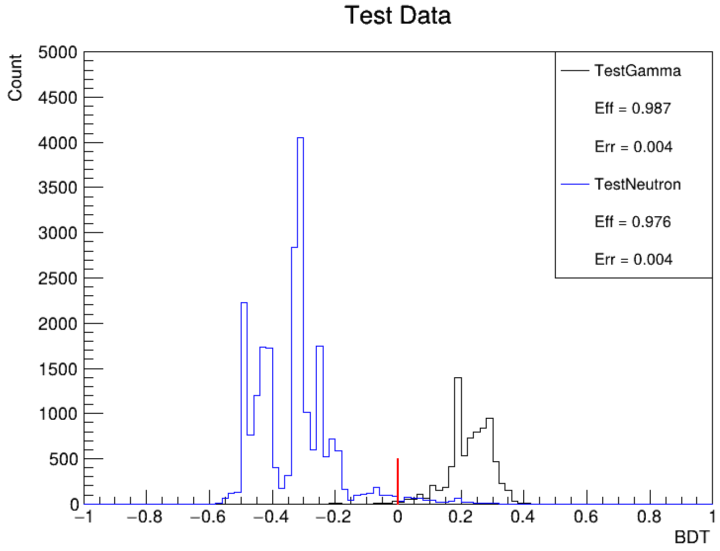


When the PS length was 1 mm, the ratio of scintillation photons to Cherenkov photons reached 0.44, achieving the best dual-readout resolution of 2.43%.

PID Performance for 1-mm Structure

1mmPS 39mmLG gamma neutron compare





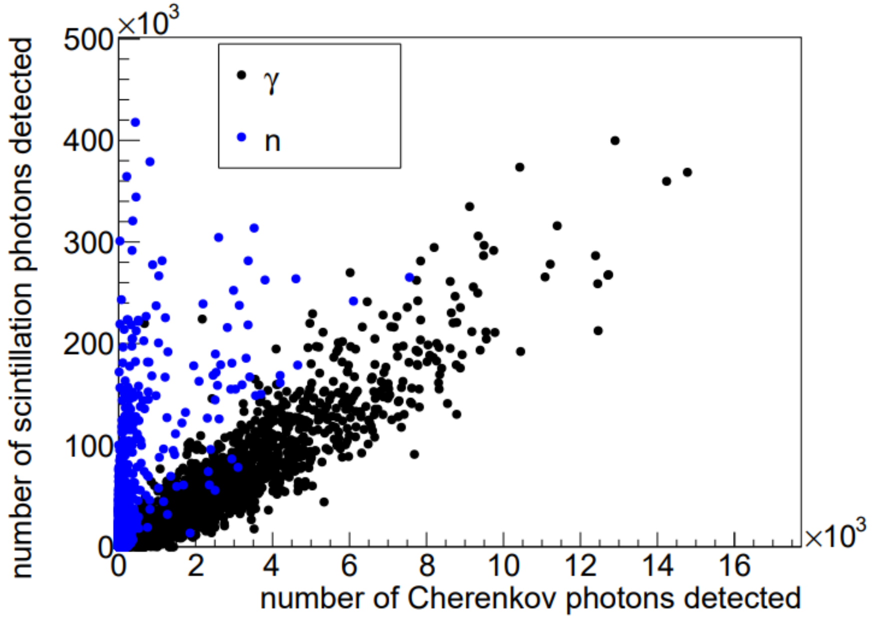
Scintillation–Cherenkov 2D scatter plot

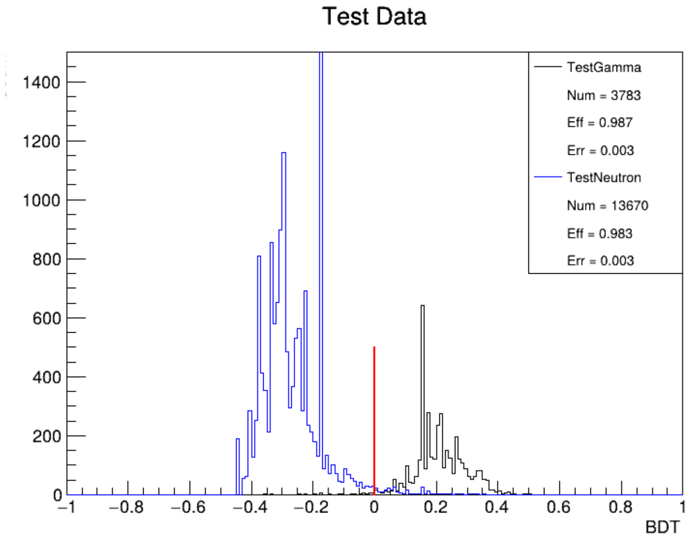
The data was classified using the BDT algorithm with BDT=0 as the cut threshold.

Gamma identification efficiency: 98.7%

Neutron identification efficiency: 97.6%

10mmPS 30mmLG





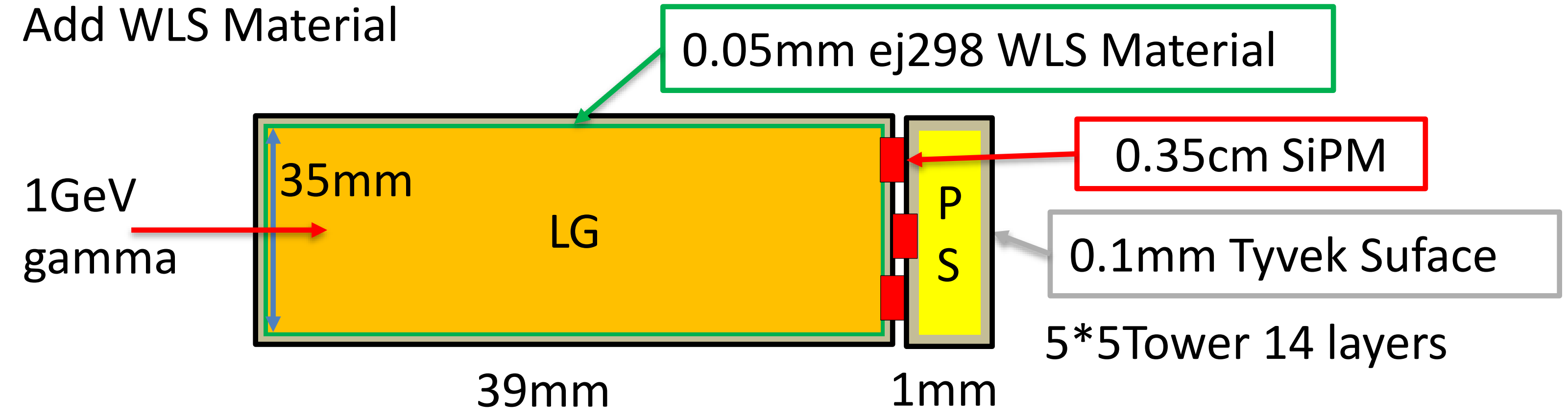
Gamma identification efficiency: 98.7%

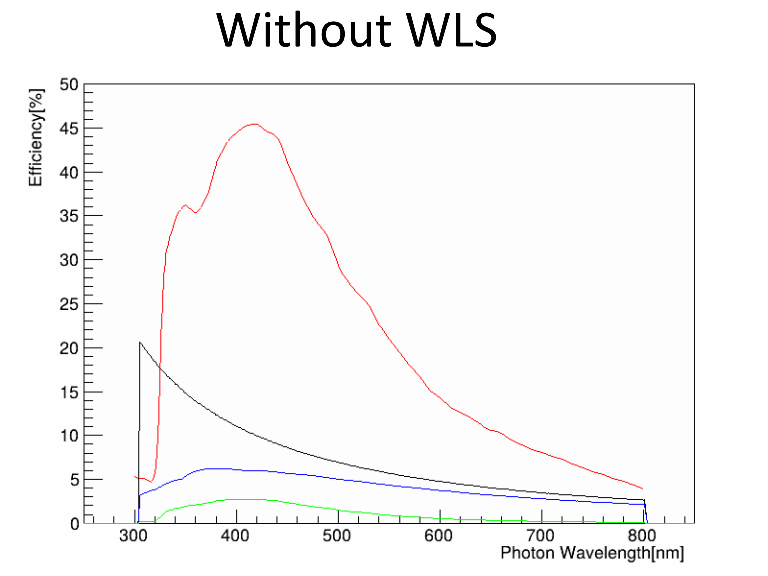
Neutron identification efficiency: 98.3%

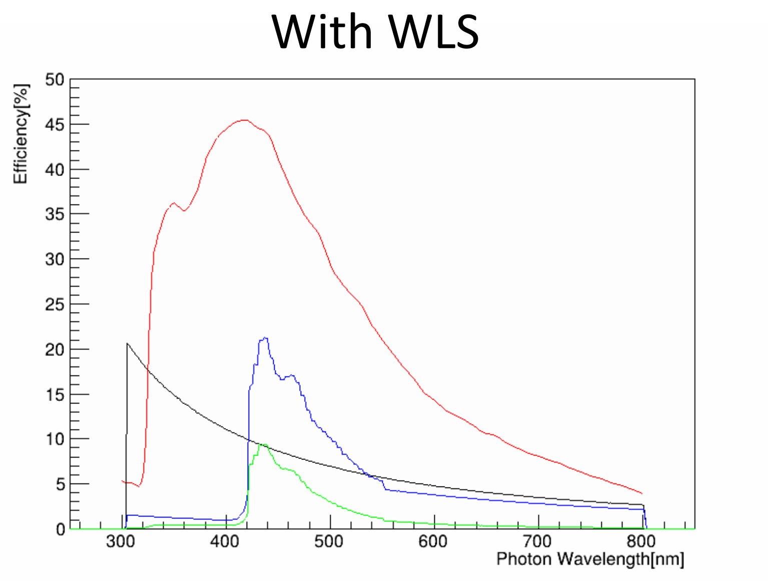
The PID performance is **consistent**.

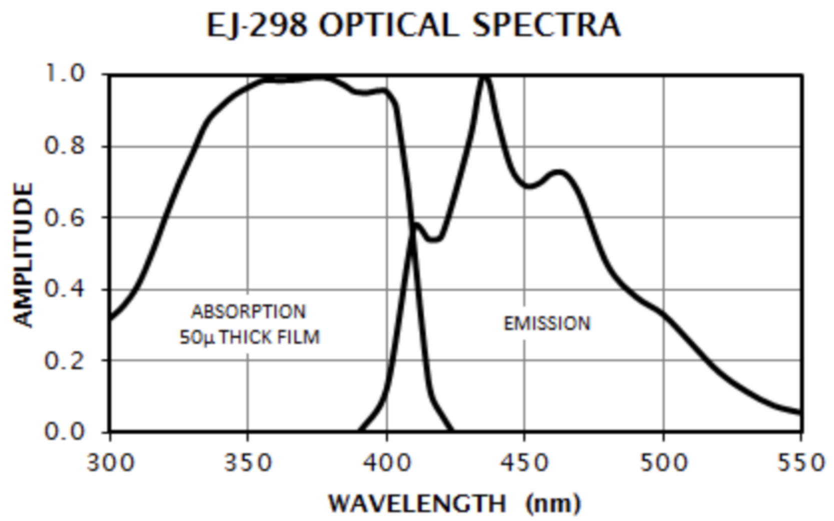
WLS Simulation Results

Add WLS Material

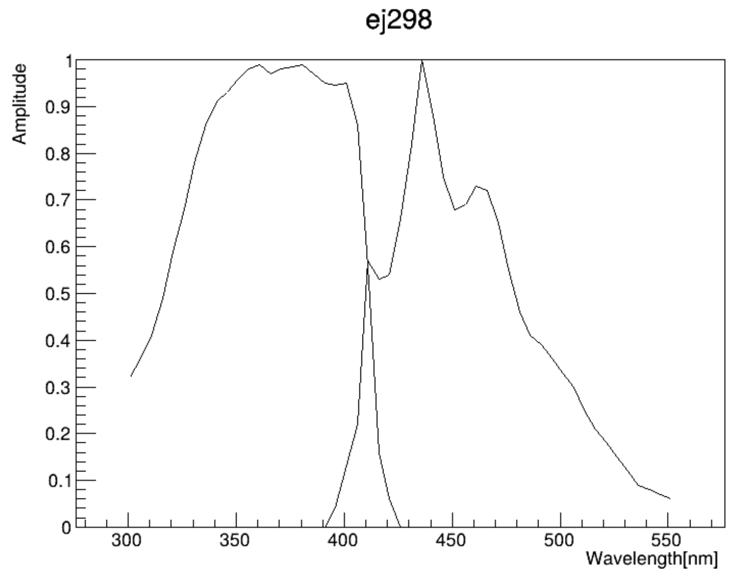








Parameters in G4 simulation



Red: SiPM detection efficiency

Black: Spectrum of generated Cherenkov photons

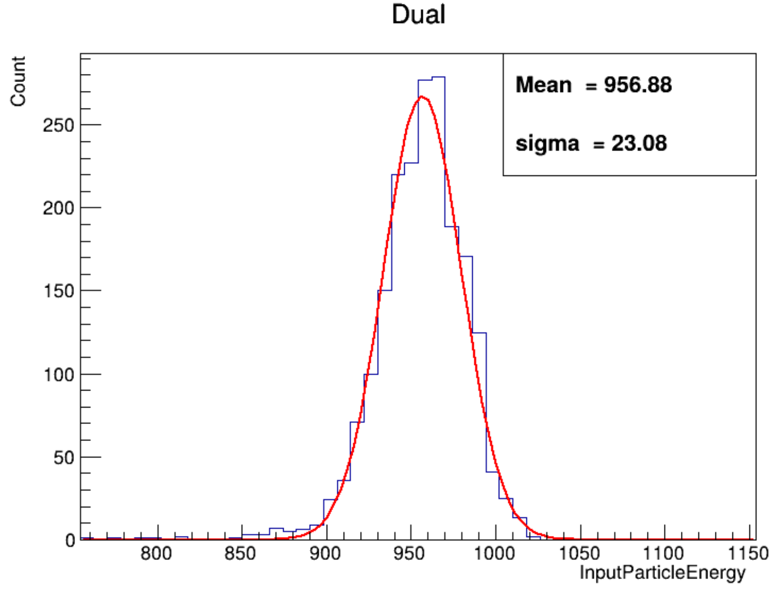
Blue: Spectrum of Cherenkov photons received by the SiPM

Green: Spectrum of Cherenkov photons detected by the SiPM

WLS Simulation Results

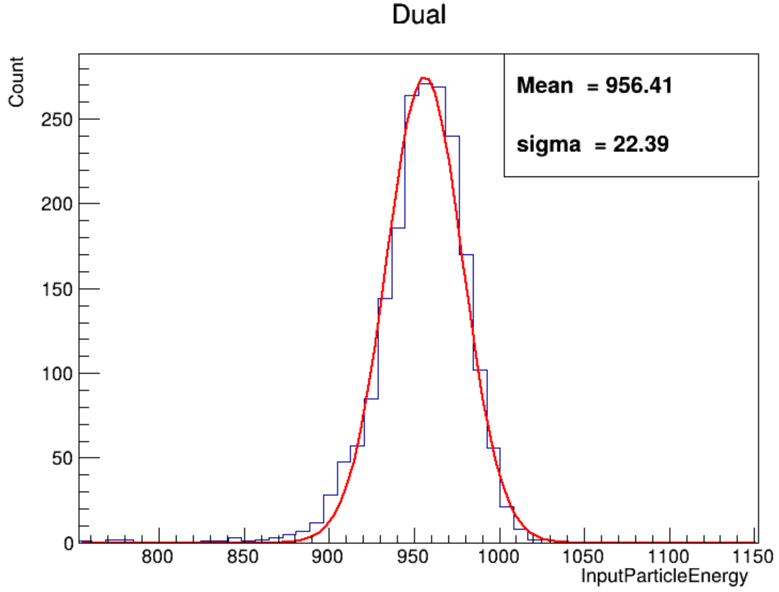
Energy Resolution

Without WLS



$\sigma/E = 2.41\%/\sqrt{E}$

With WLS



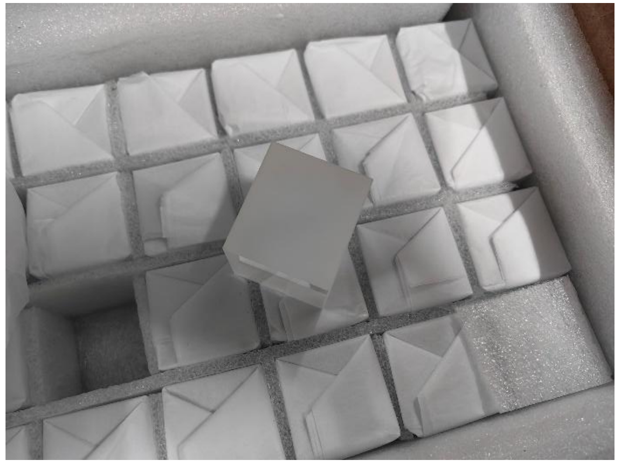
$\sigma/E = 2.34\%/\sqrt{E}$

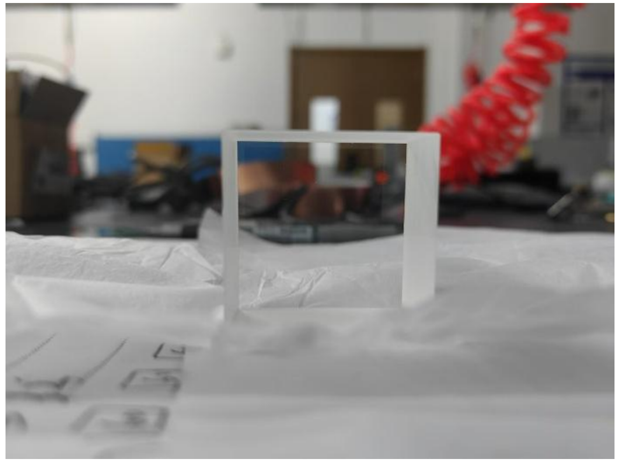
Number of Cherenkov photons

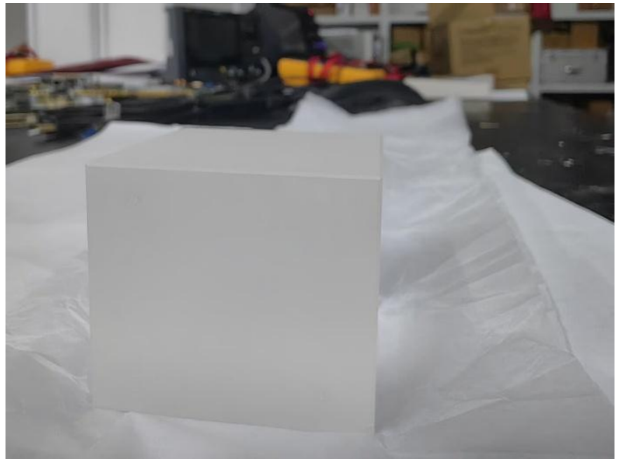
WLS Surface	Generate	Module Absorb	Reflective Surface Absorb	SiPM received	SiPM detected
Without WLS	89544	26278	11771	52616	13357
(%)	100%	29.3%	13.1%	58.7%	14.9%
With WLS	89123	12575	8120	62759	17849
（%）	100%	14.1%	9.11%	70.4%	20.1%

Since the original detected photon was already high, the improvement of resolution is not too much.

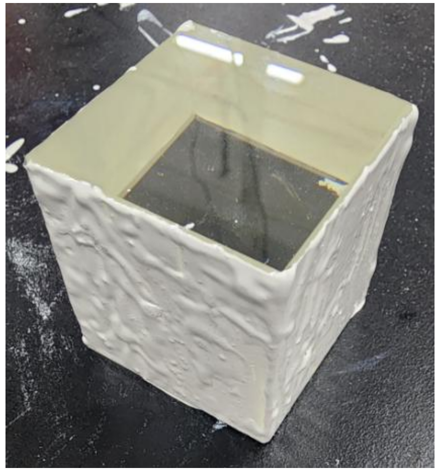
Lead Glass





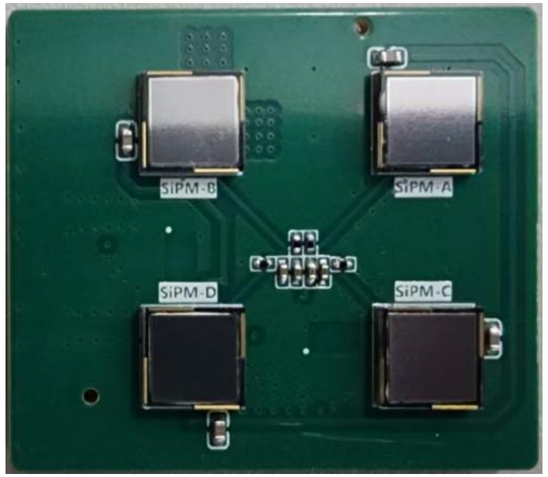


Lead Glass block
Its dimensions are 3.5 × 3.5 × 3.9 cm^3, and the end faces have been polished.



Coating the surface of the lead glass with a reflective layer made of TiO_2

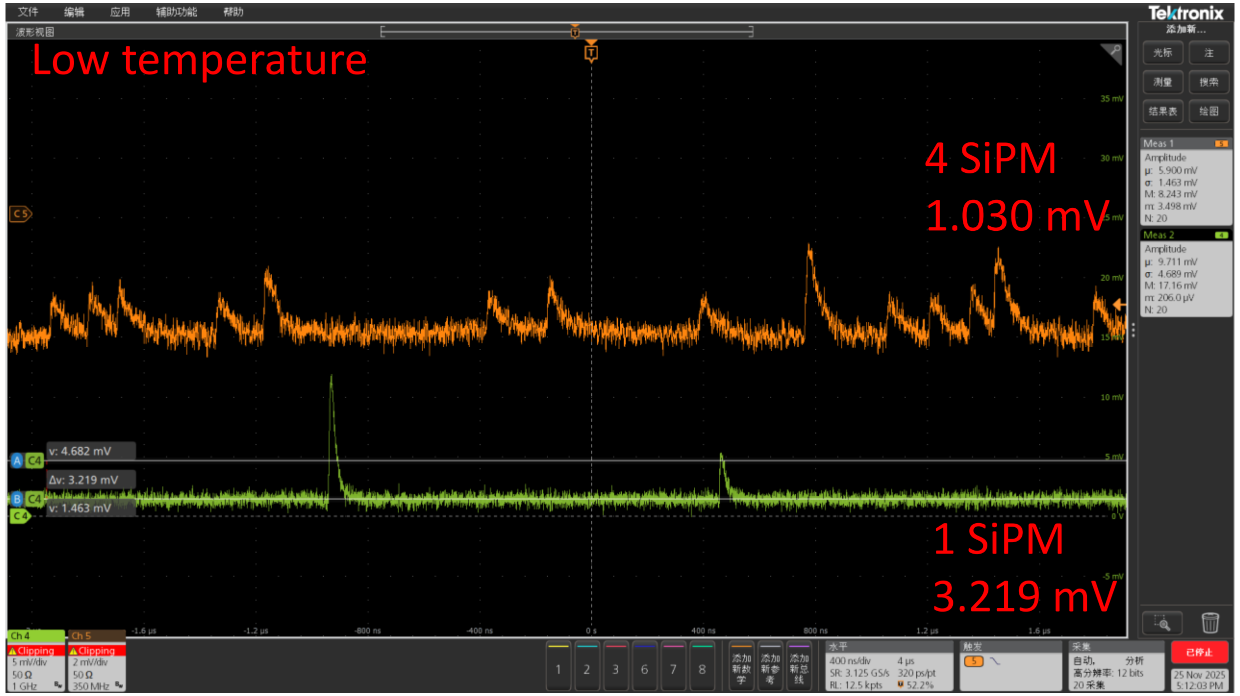
Cosmic Ray Test

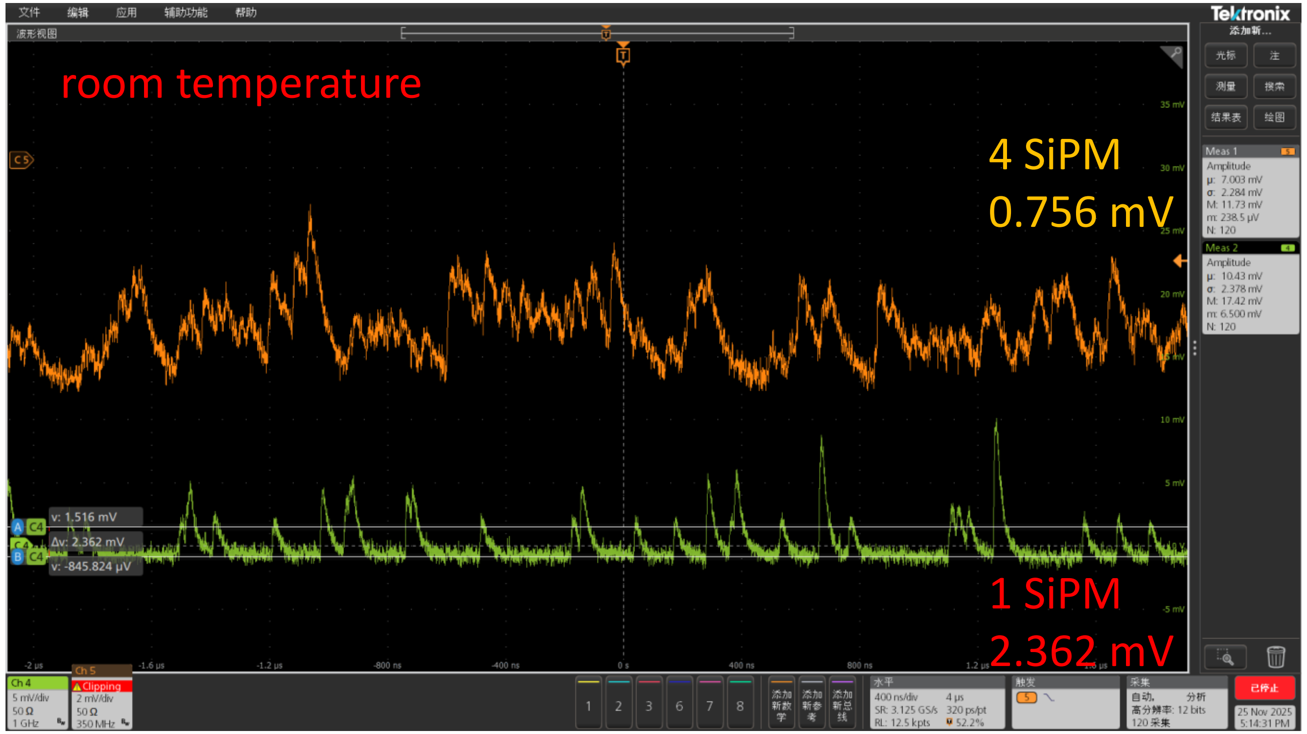


The four-channel SiPM has a high dark count, so single photon-electron is hard to see. It was detected using a cold environment.

At low temperature, the single pe Voltage of the SiPM will increase.

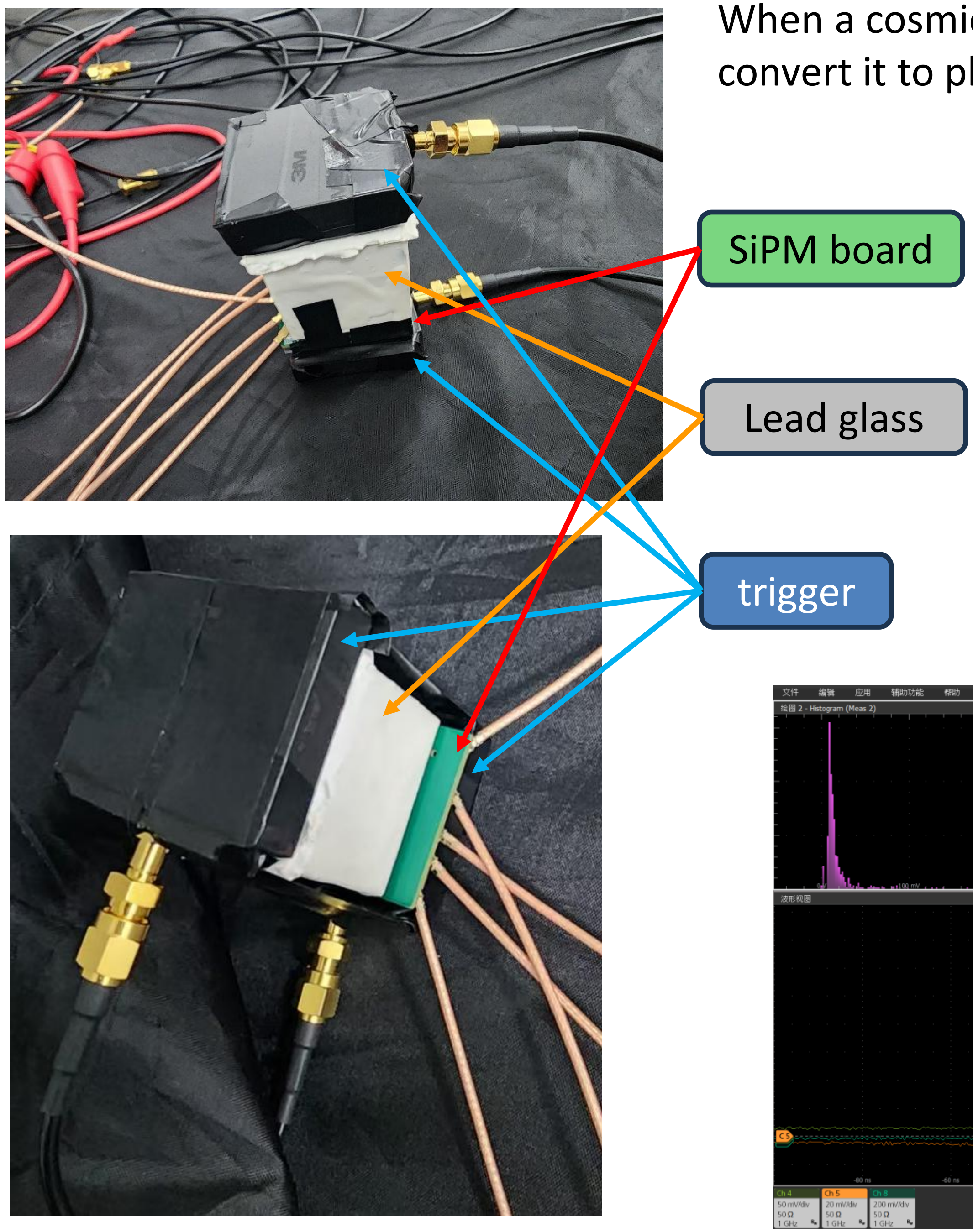
Use the single pe voltage at low temperature to estimate the four channels' single pe Voltage at room temperature.

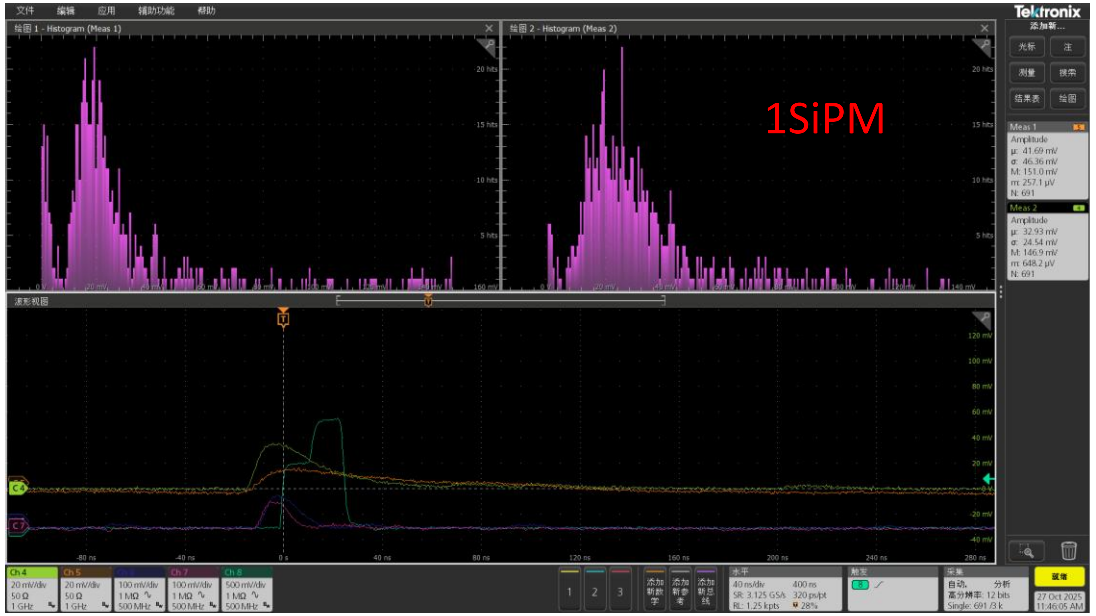


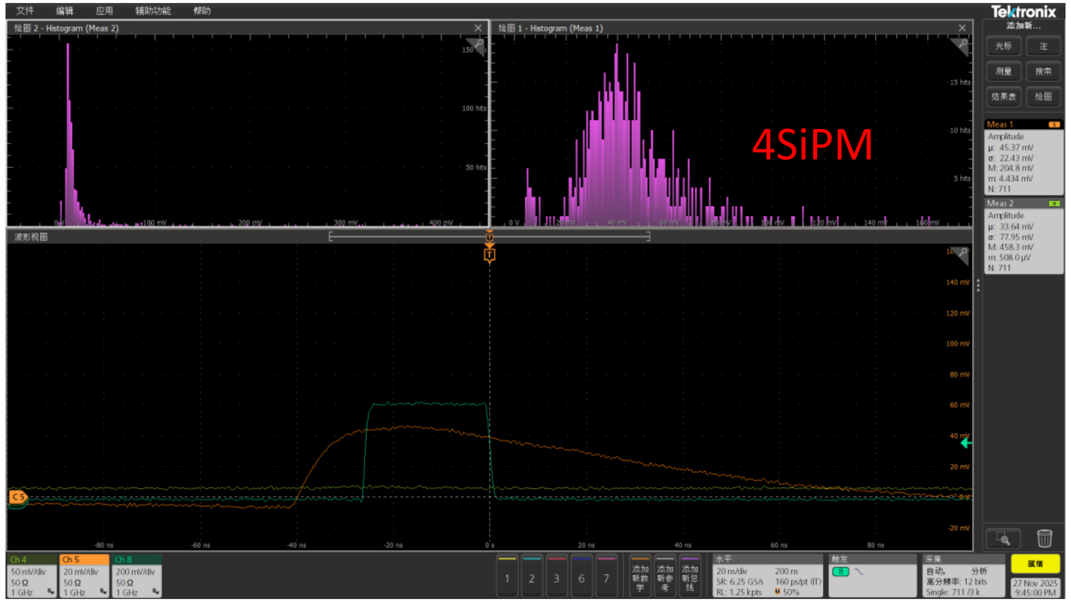


Test Results

When a cosmic ray passes both triggers, we record the SiPM signal and convert it to photon count using the single pe.



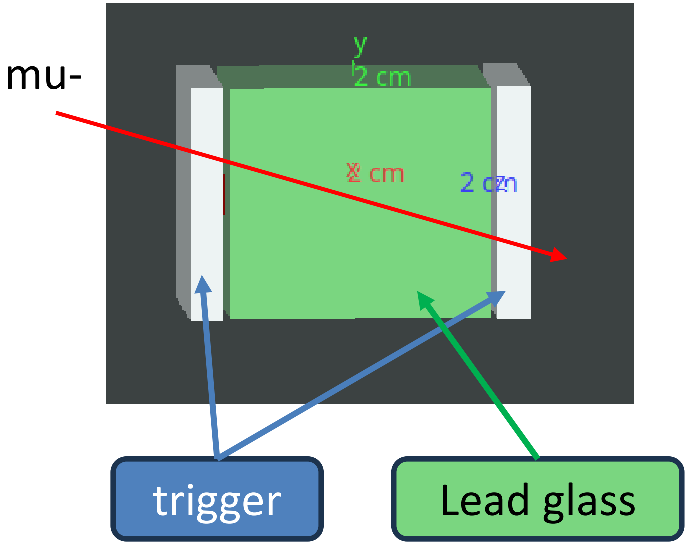




Cherenkov photons 1 SiPM
Single pe 2.362mV
Mean photons: 15.23

Cherenkov photons 4 SiPM
Single pe 0.756mV
Mean photons: 59.31

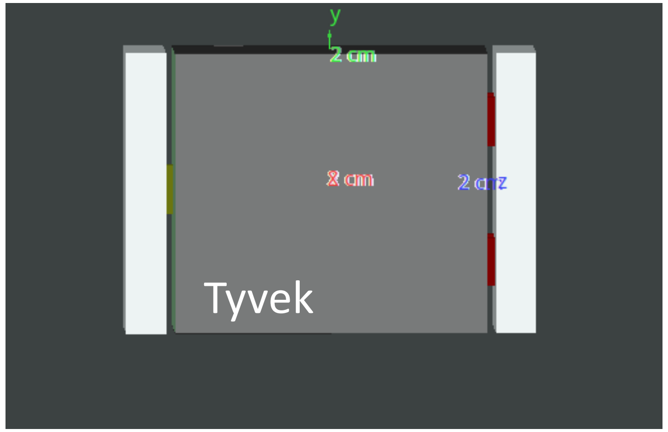
Simulation Results



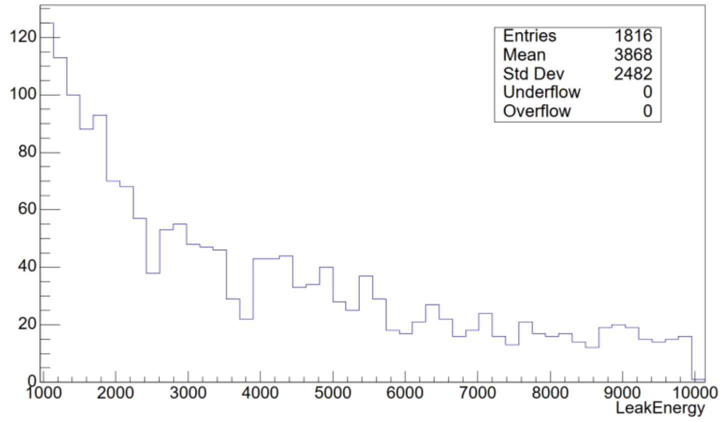
The trigger material is plastic scintillator.

SiPMs was placed at the center of the lead glass to collect signals.

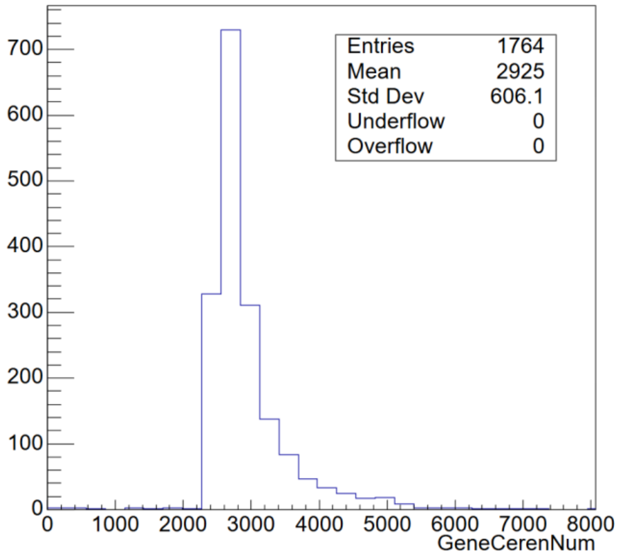
When both triggers produce signals ,the photons detected by the SiPM will be recorded



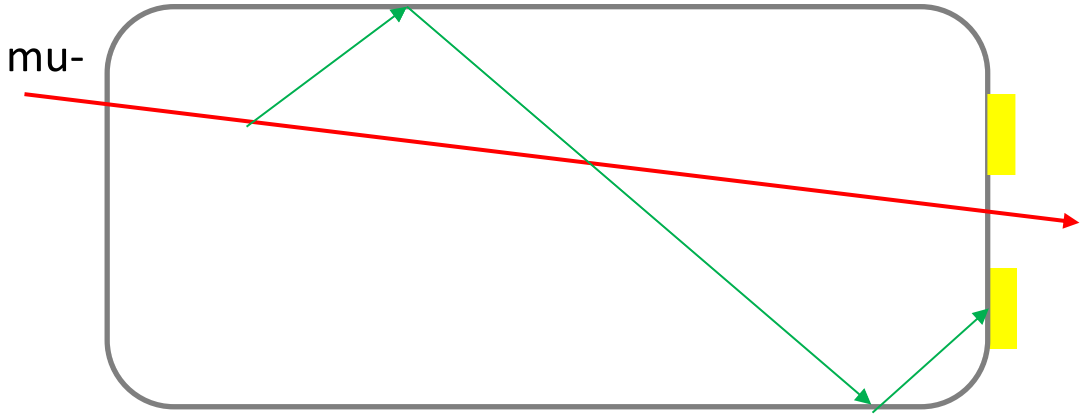
Using Tyvek as a reflective layer with 96% reflectivity.



Cosmic ray energies are sampled log-uniformly from 1 to 10 GeV.

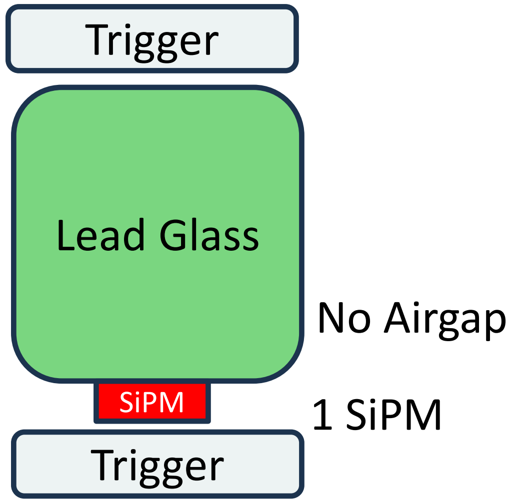


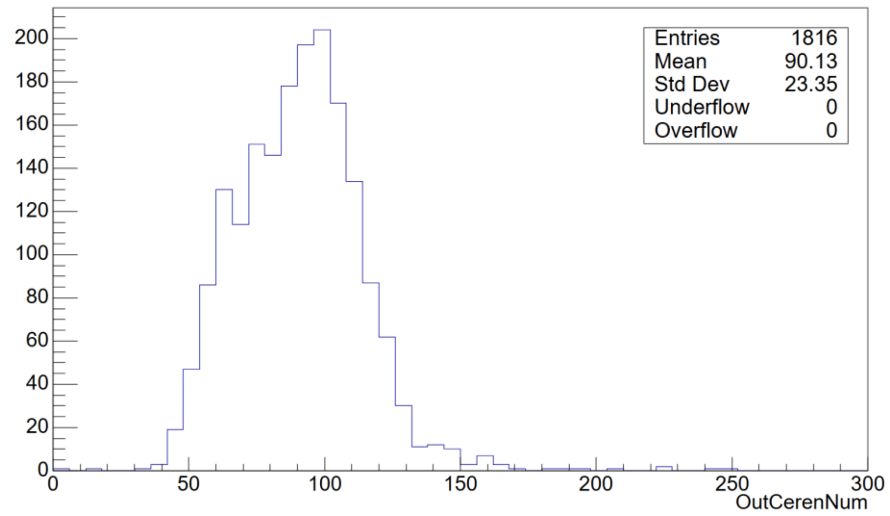
Cherenkov photons emitted by cosmic rays



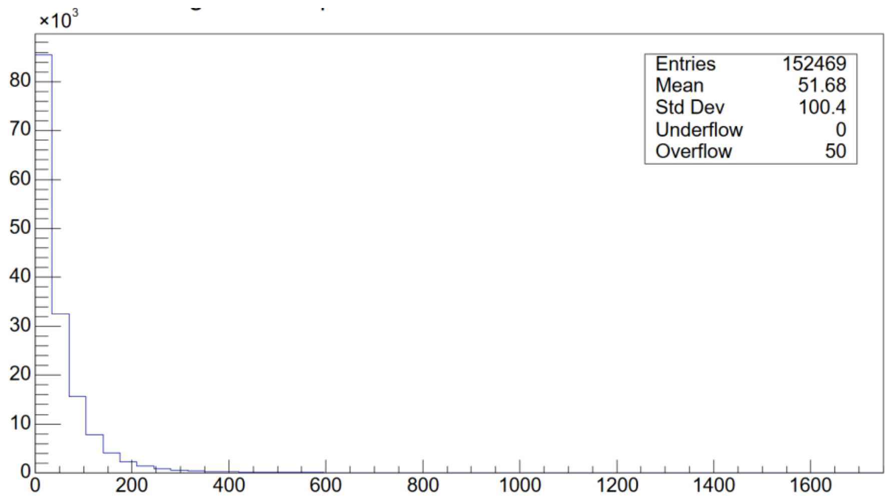
Record the number of **photons collected by SiPM**.
Record **these photons' reflection count**.

Simulation Results

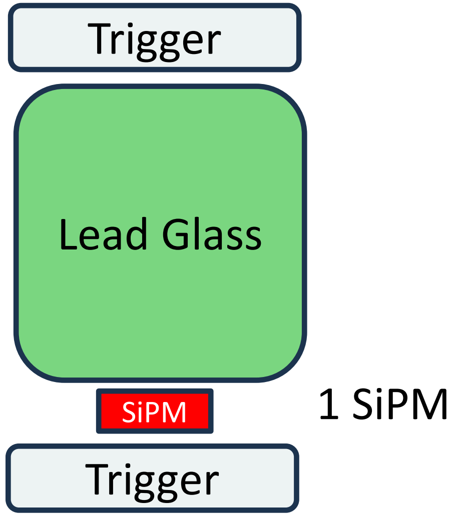


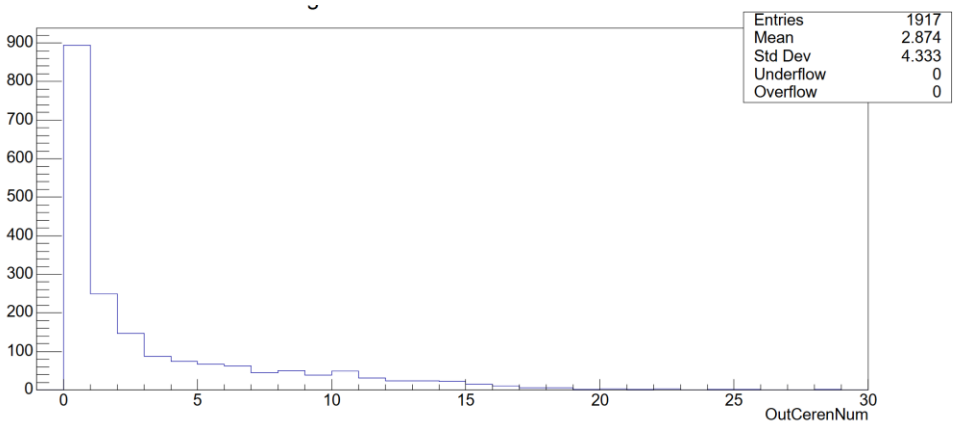


Mean photons 90

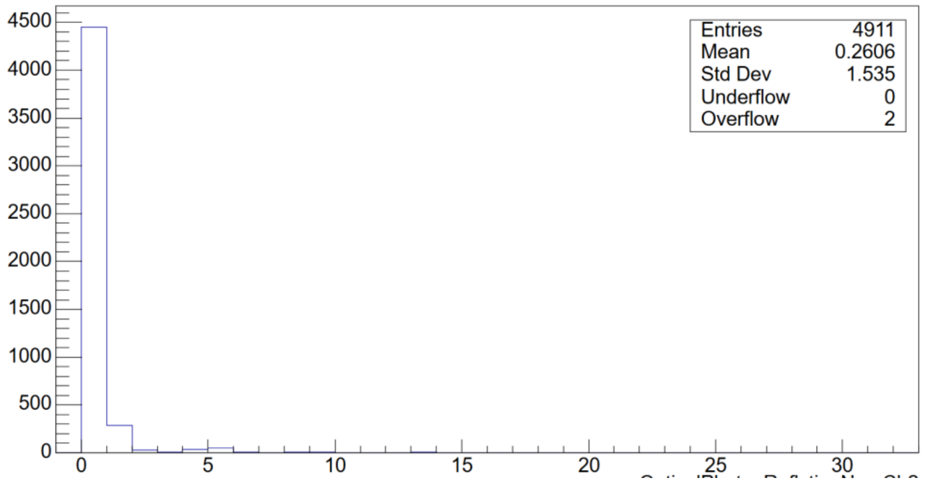


Photons Mean Reflection Times 51





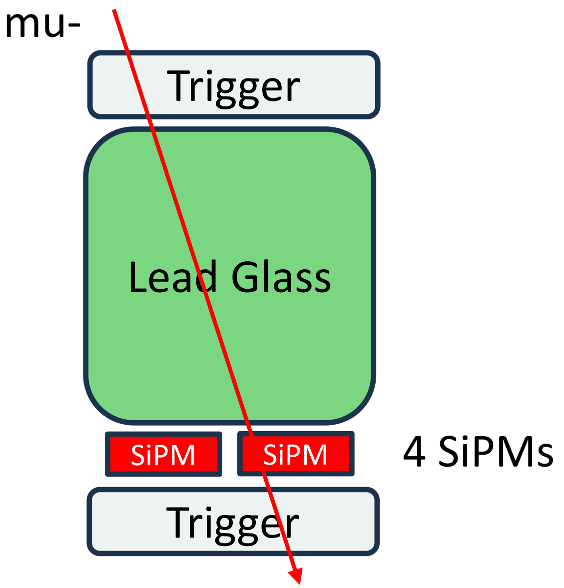
Mean photons 2.6

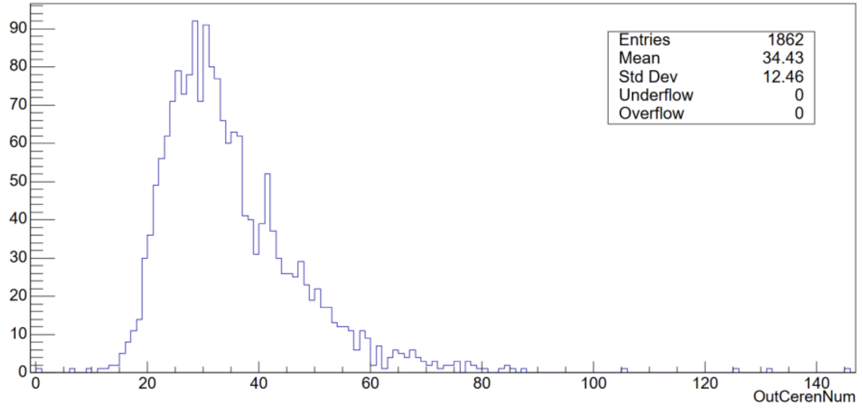


Photons Mean Reflection Times 0.2

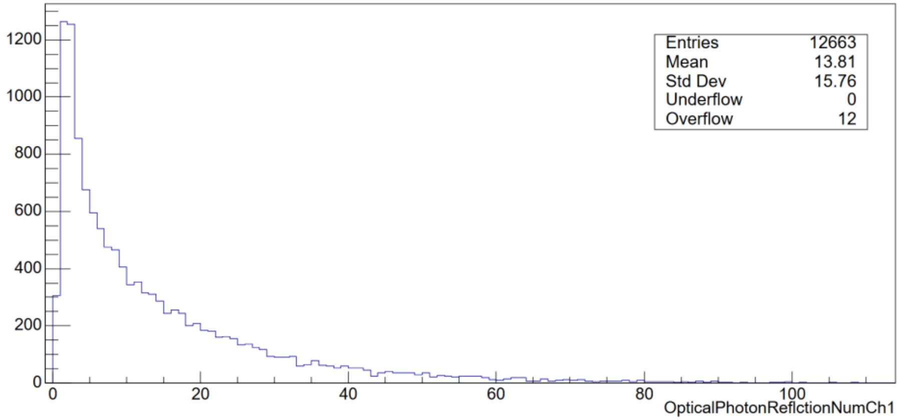
Add 0.05mm Air gap
between Lead Glass and SiPM

4 Side Surfaces Rough



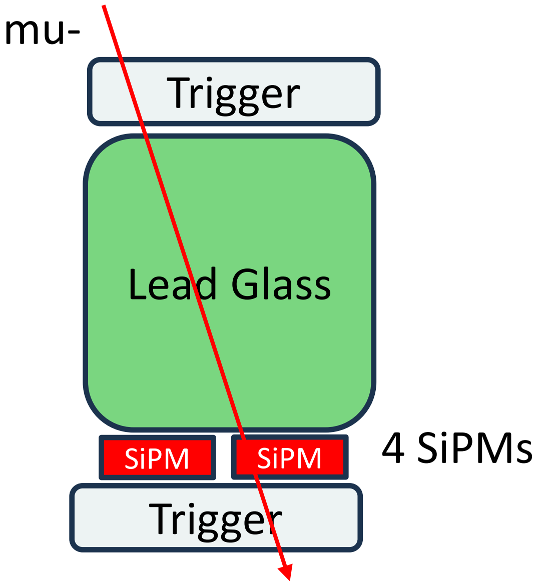


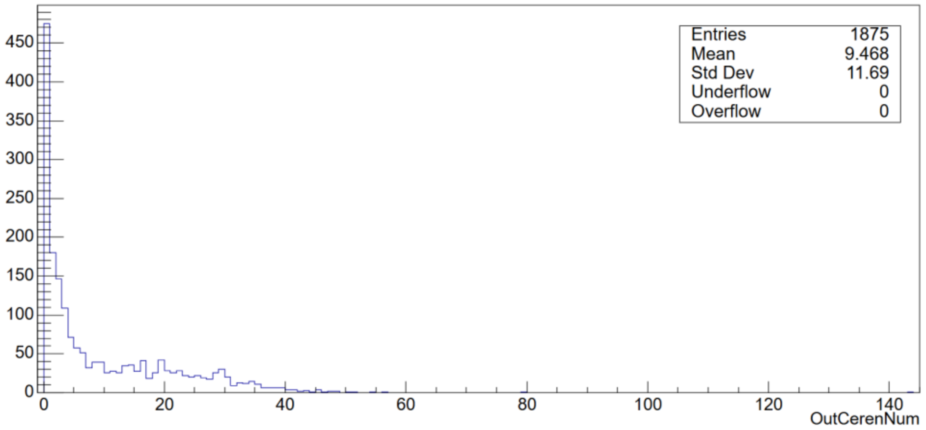
Mean collected photons: 34.3



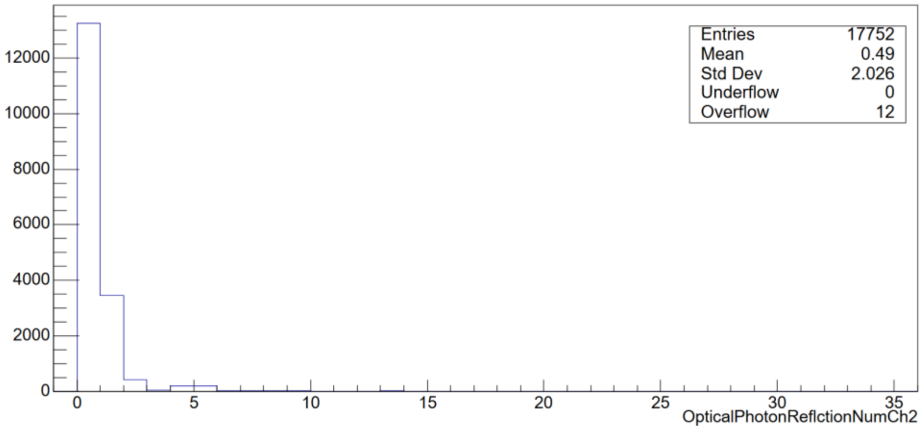
Mean reflection times: 13.81

No Surfaces Rough





Mean photons 9.4



Photons Mean Reflection Times 0.49

Simulation Results

Cherenkov photons count

Airgap	Generate	Module Absorb	Reflection Loss	SiPM(top) received	SiPM(top) detected	SiPM(bottom) received	SiPM(bottom) detected
No Airgap	2904	1391	713	390	85	410	90
(%)	100%	47.8%	24.5%	13.4%	2.92%	14.1%	3.09%
with Airgap	2942	2207	722	1.78	0.45	11.35	2.87
(%)	100%	75.0%	24.5%	0.06%	0.02%	0.38%	0.09%

After adding the air gap, the number of absorbed photons increased a lot.

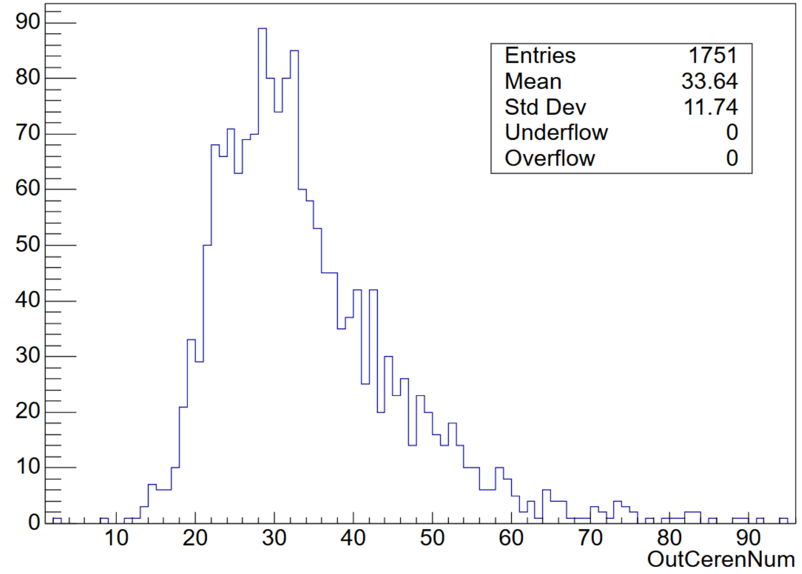
Rough Surface	Generate	Module Absorb	Reflection Loss	SiPM(top) received	SiPM(top) detected	SiPM(bottom) received	SiPM(bottom) detected
Rough Surface	2964	945.6	1858	26.56	6.8	134.2	34.43
(%)	100%	31.90%	62.69%	0.90%	0.23%	4.53%	1.16%
No Rough Surface	2954	2210	706	1.54	0.38	36.81	9.46
（%）	100%	74.81%	23.90%	0.05%	0.01%	1.25%	0.32%

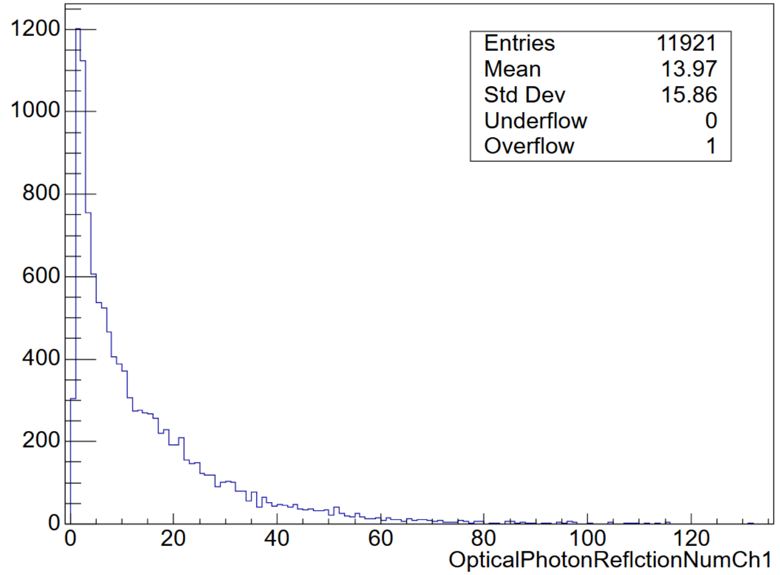
After adding the rough surface, the reflection loss increased and absorption decreased,
indicating that more photons indeed escaped form the lead glass.

Simulation Results

Four side surfaces rough

Four Side Surface Cover

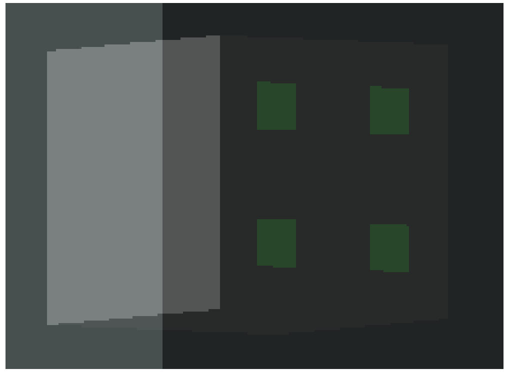


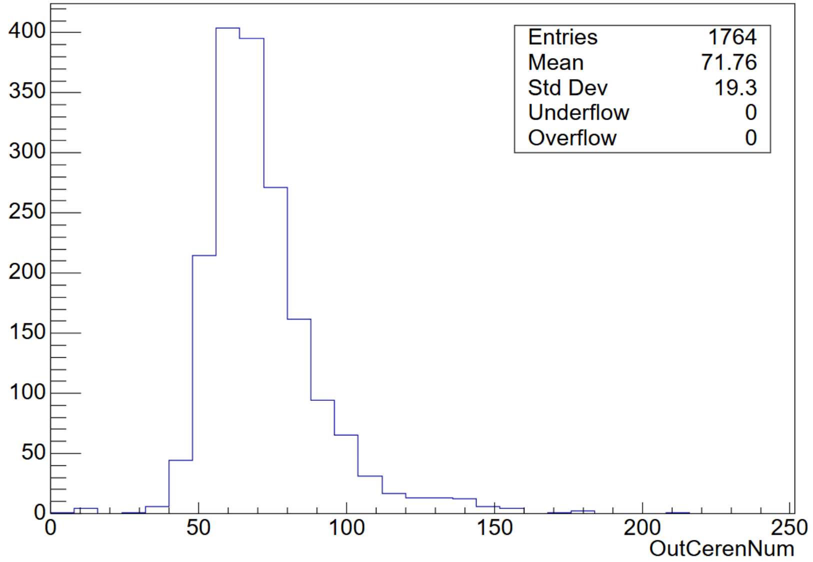


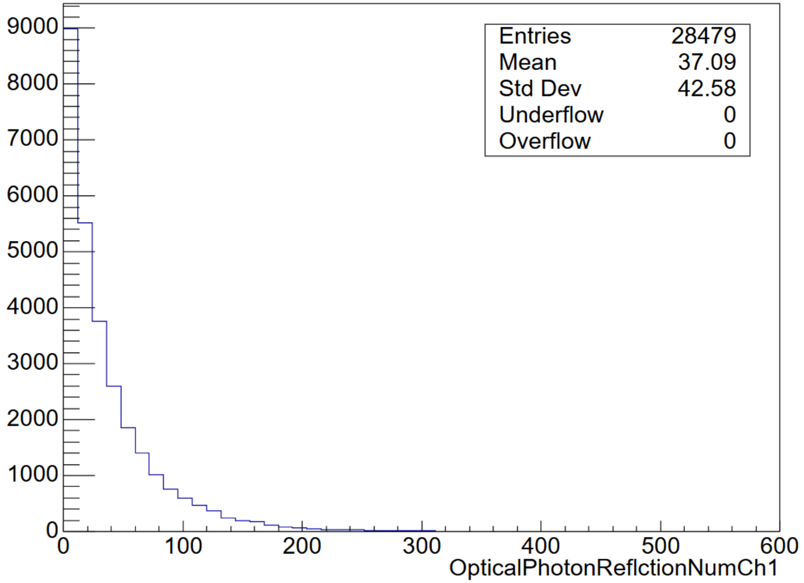
Mean collected photons: 33.64

Mean reflection times: 13.97

Full Surface Cover except SiPM window







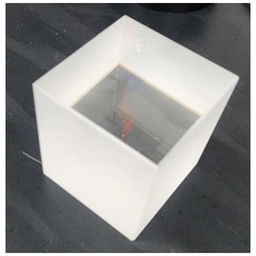
Mean collected photons: 71.76

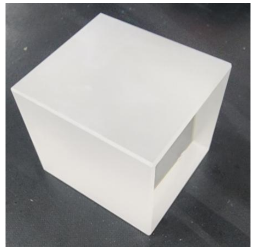
Mean reflection times: 37.09

Comparison of Test and Simulation Results

Based on the simulation results, we also performed tests on the available lead-glass blocks, including different wrapping design and different readout surfaces.

Using 4 SiPMs to collect photons





Cherenkov photons Num

Read-out Surface	Test/Simulation	No Cover	Cover 4 Side Surfaces	Cover 5 Surfaces	Cover all Surfaces except SiPM window
Polish	Cosmic ray test	33.72	59.31	85.11	95.42
	Simulation	14.88	34.3	52.02	71.76
Rough	Cosmic ray test	40.2	57.58	79.70	
	Simulation	18.56	33.79	54.95	

The simulation results are slightly lower than the actual test, but remains consistent in scale.

This is because the airgap in reality is smaller than in the simulation.

Summary

The dual-readout EMC has an energy resolution of 2.43% for 1 GeV γ.

It also has an identification efficiency higher than 97% for both γ and n.

The measured cosmic-ray response agrees well with the simulation.

Future Work

We will use cosmic rays to conduct further tests on the Lead Glass.

Assembly of the entire tower will begin in early 2026 for beam tests.

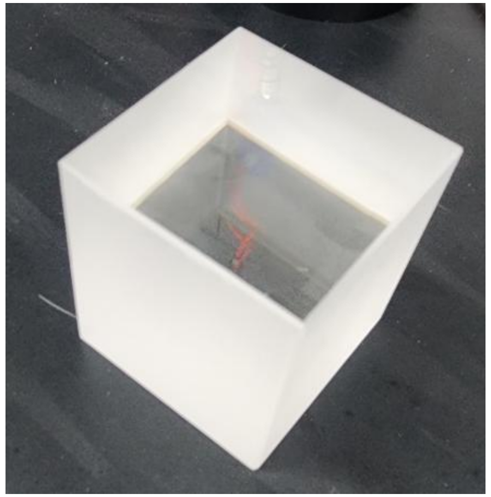
Based on the experimental results, the EMC structural design will be refined, followed by updated simulations of the full EMC system.

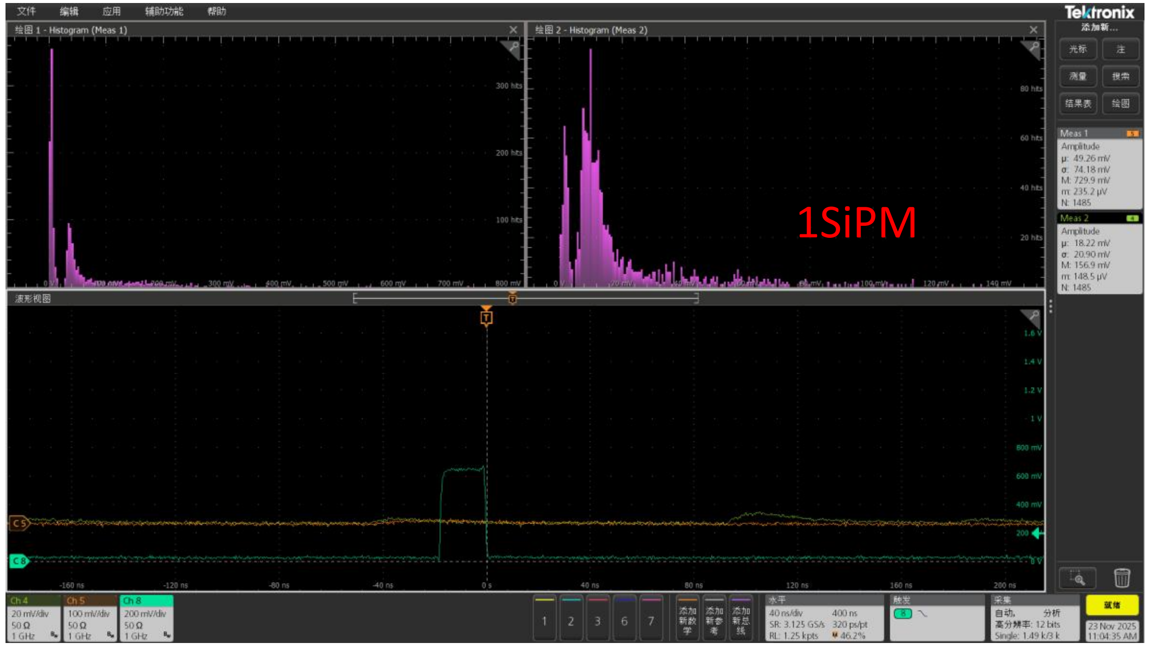
THANKS

Backup

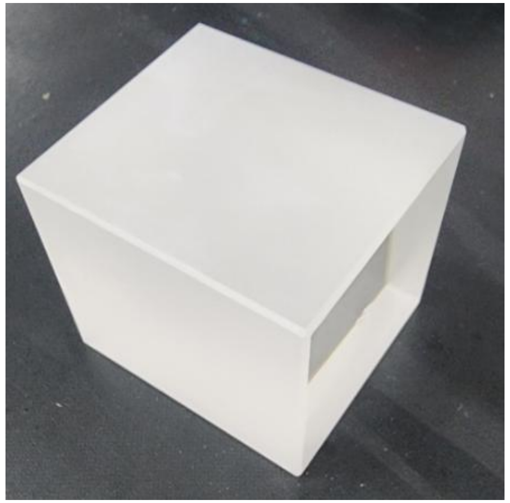
Test Results

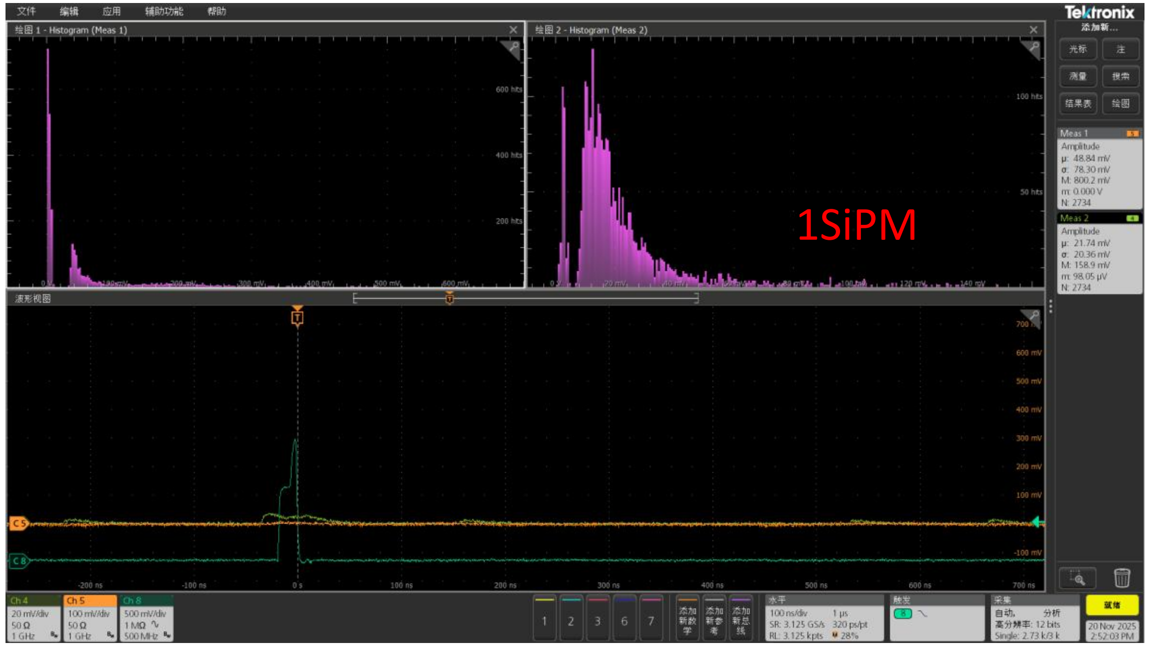
No coating Surface





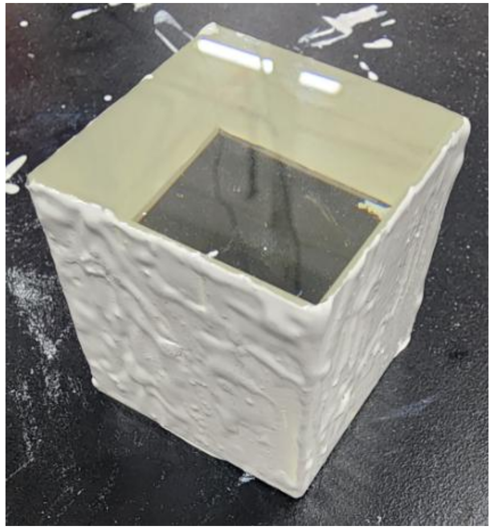
Polish Surface
1 SiPM
Mean photons: 8.43

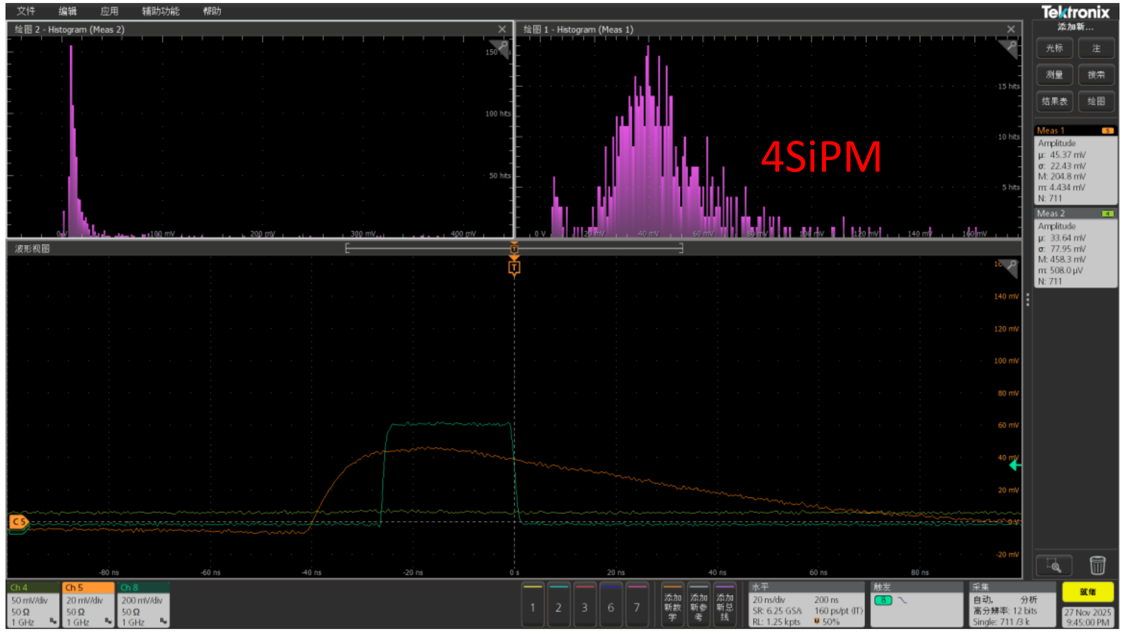




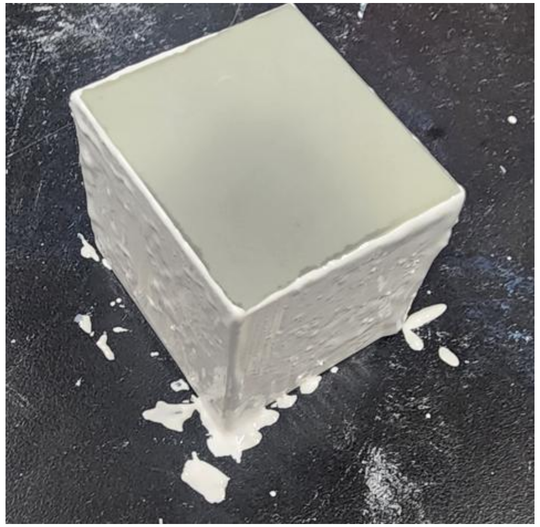
Rough Surface
1 SiPM
Mean photons: 10.05

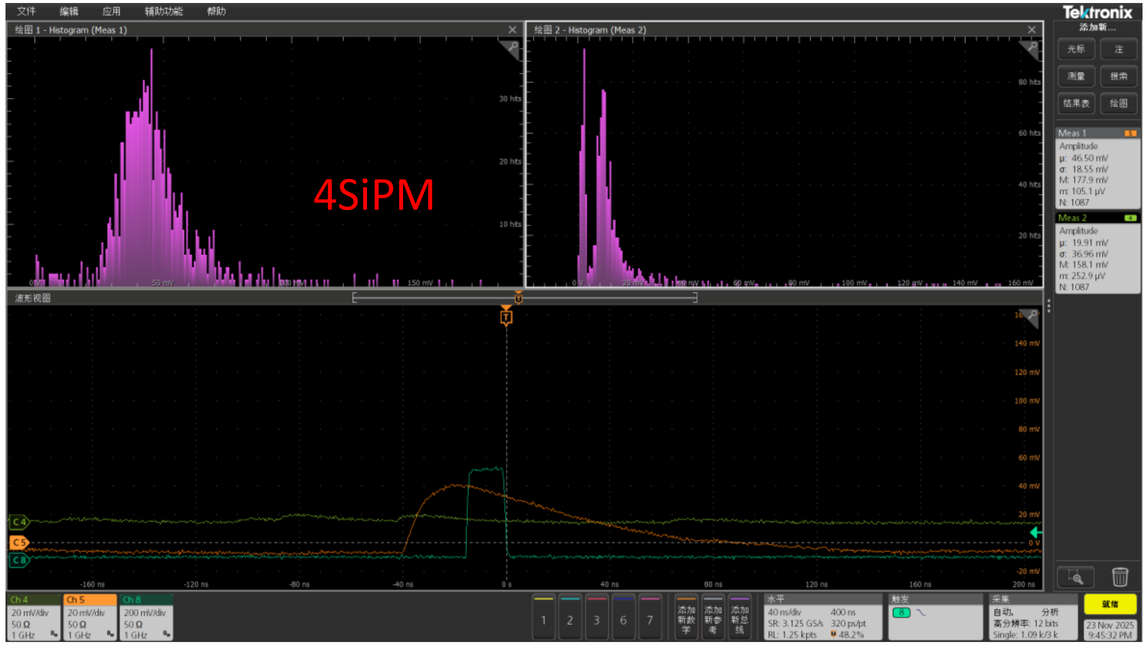
Test Results





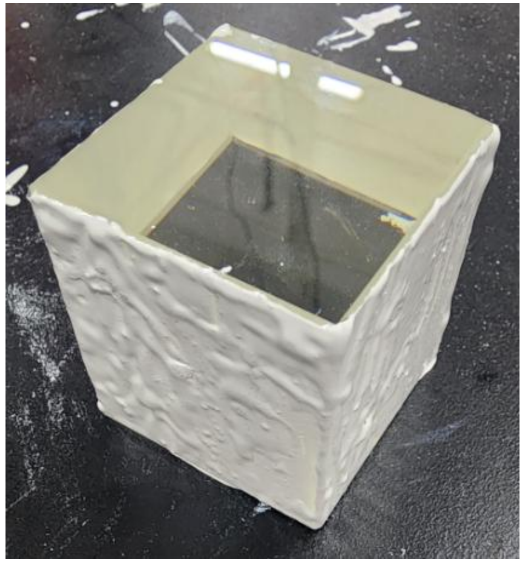
Polish Surface
4 SiPM
Mean photons: 59.31

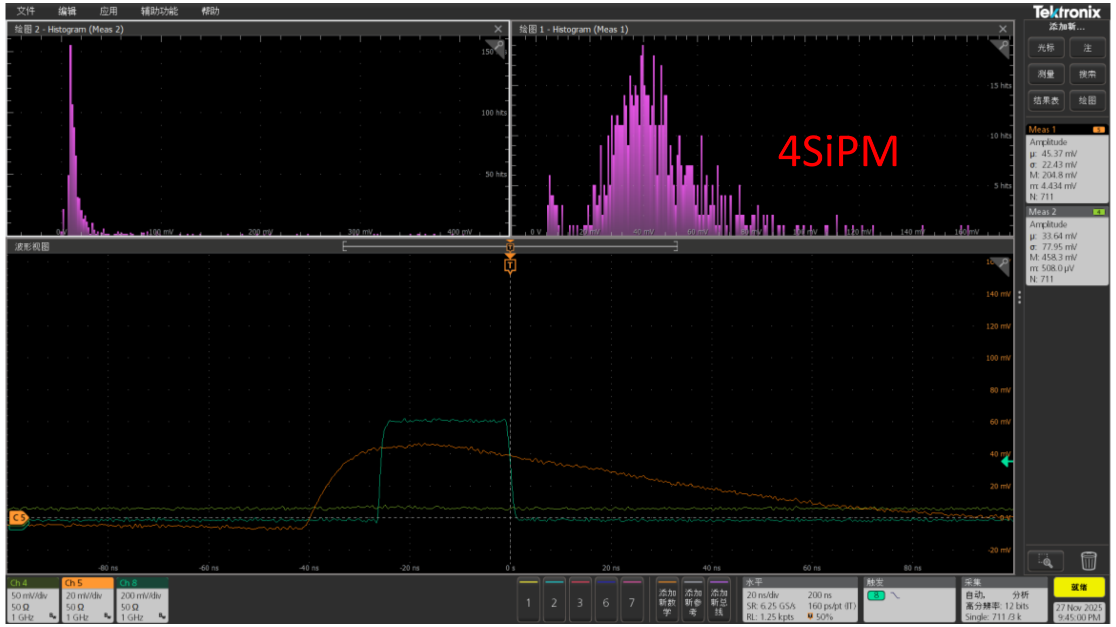




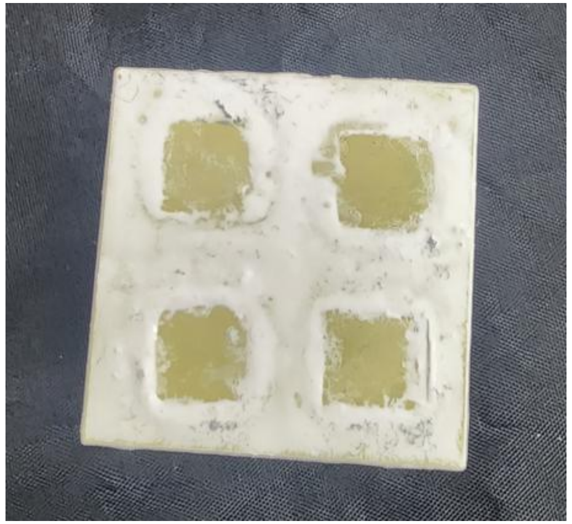
Rough Surface
4 SiPM
Mean photons: 57.58

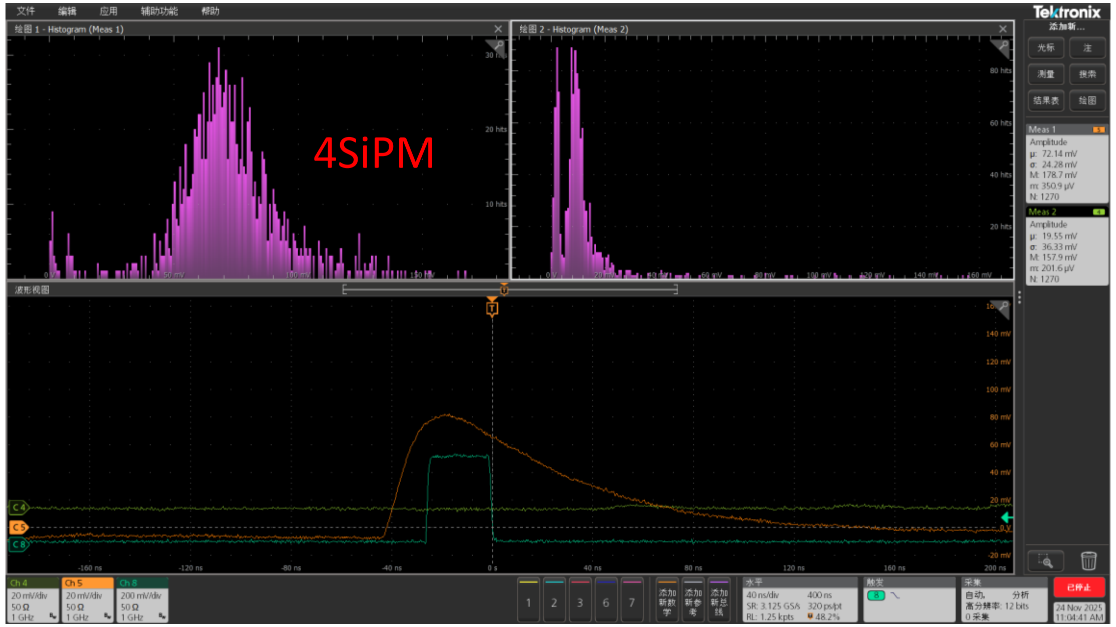
Test Results





4 Sides Coating
Polish Surface
4 SiPM
Mean photons: 59.31





Full Coating
4 SiPM
Mean photons: 89.83