Updates of the ECal: simulation and hardware

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On behalf of EicC ECal group

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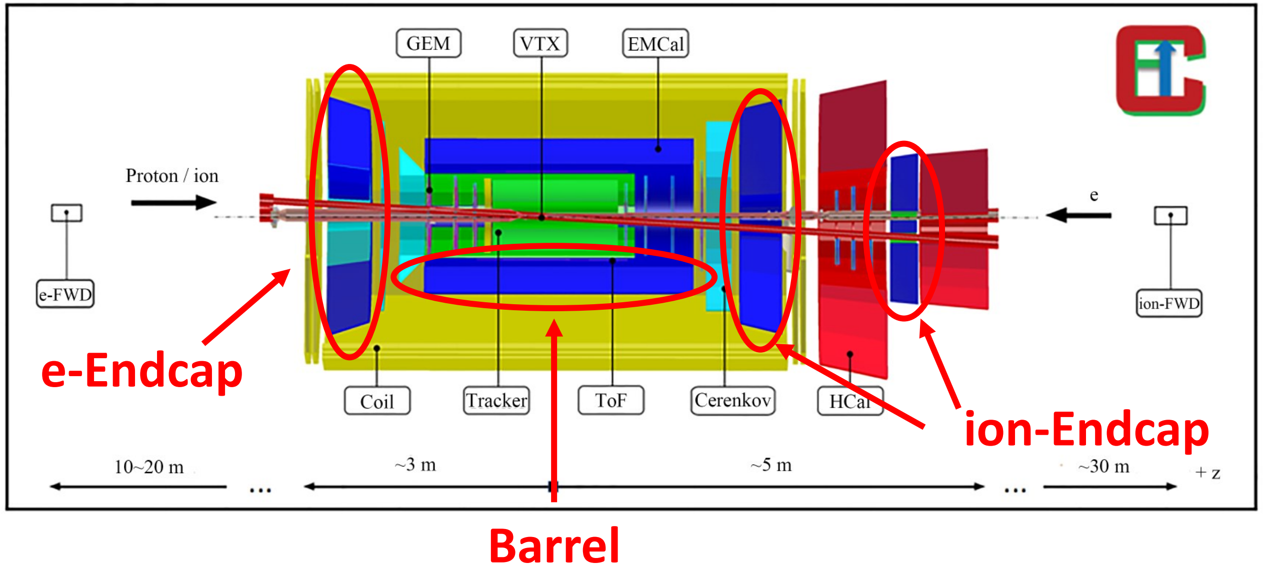
Outline

- ❖ EicC ECal detector introduction
- ❖ Module simulation work
  - Design of ECal module
  - Module performance
- ❖ Whole ECal detector simulation
- ❖ ECal simulation software and reconstruction framework
- ❖ Shashlik prototype hardware work

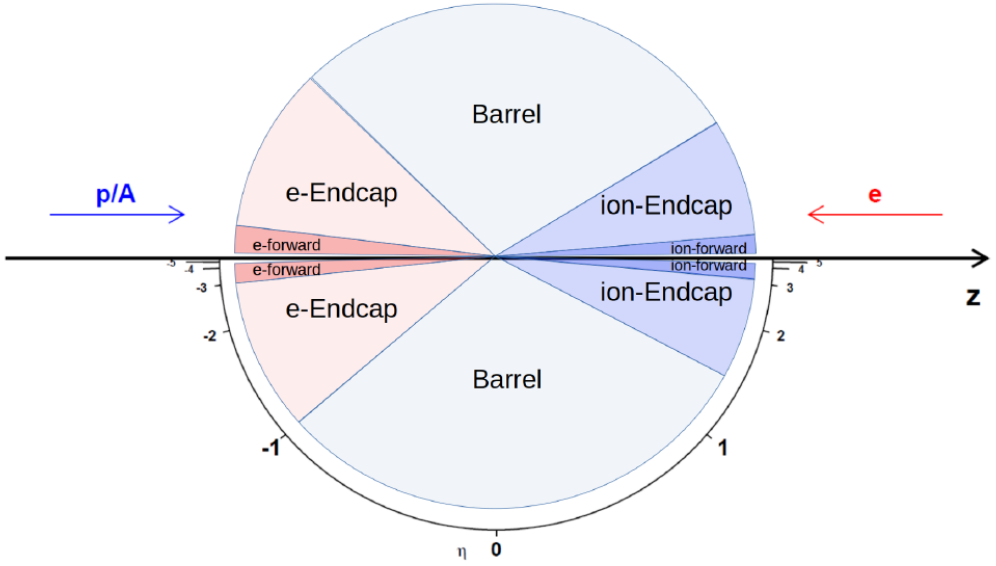
Design of the ECal for EicC

From EicC white paper



Basical ECal special requirement:

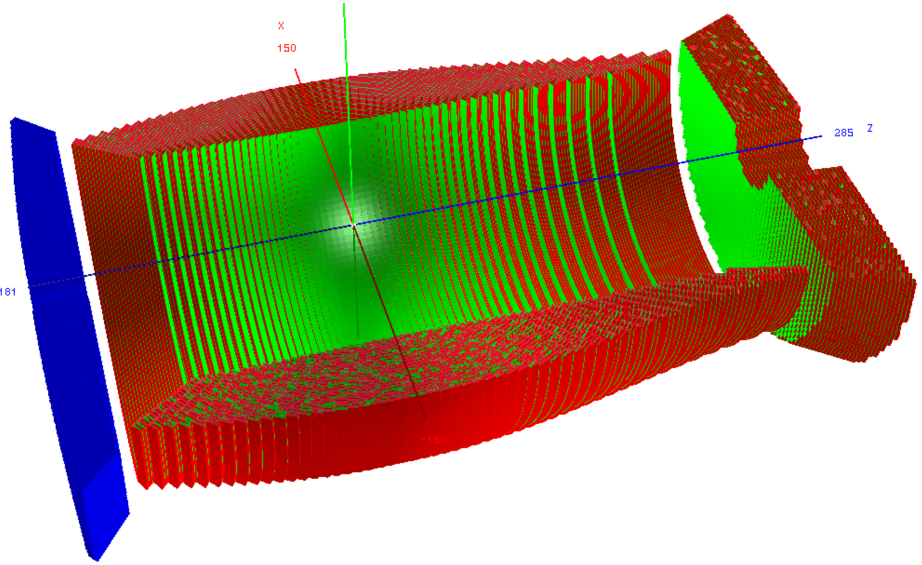
- **E-endcap:** good low energy resolution
- **Barrel:** short radius, good angle resolution
- **Ion-endcap:** angle resolution, π^0 reconstruction, PID. Need additional small angle detector.



Detector	Pseudorapidity	Angle(degree)
Ion-Endcap	3	5.7
	1.5	25.2
Barrel		
	-1	139.6
e-Endcap	-3	174.3

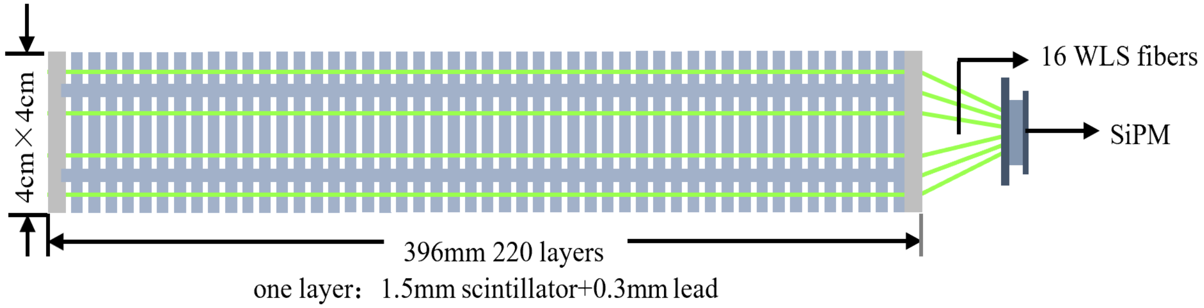
Whole Design in simulation

- General design of whole Ecal Detector.
- CsI is applied in e-endcap, Shashlik style is applied in both barrel and ion-endcap
- Two ion-endcap ECals combine to one in this simulation.
- **The actual distances** of the two endcaps to IP depend on the available space of the EicC design

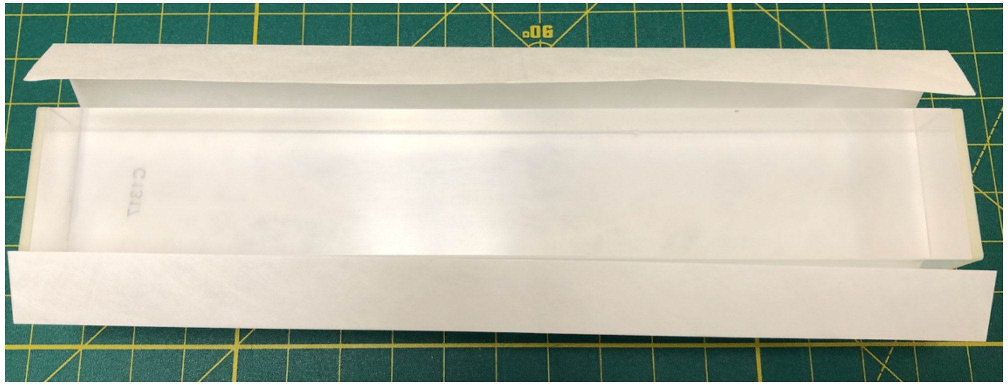


	EMC	type	z/r[m]	Length[cm],X_0	Coverage[cm]	pseudorapidity	Tower size
EicC	e-endcap	**CsI**	**Z=-1.5**	30, $16X_0$	15.0<r<127.6	(-3.0, -1.0)	4.0*4.0(front)
	barrel	**Shashlik**	**R=0.9**	50, $16X_0$	-105.8<z<187.5	(-1.0, 1.5)	4.0*4.0 (front)
	Ion-endcap	**Shashlik**	**Z=2.4**	50, $16X_0$	24.0<r<115.2	(1.5, 3.0)	

EicC ECal module optimization and simulation

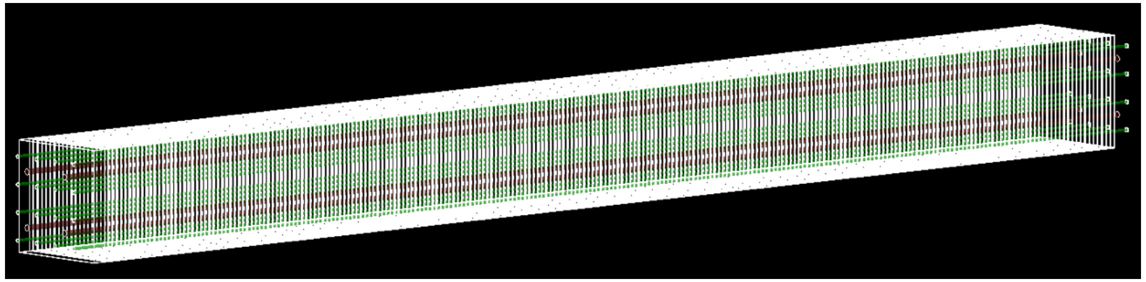


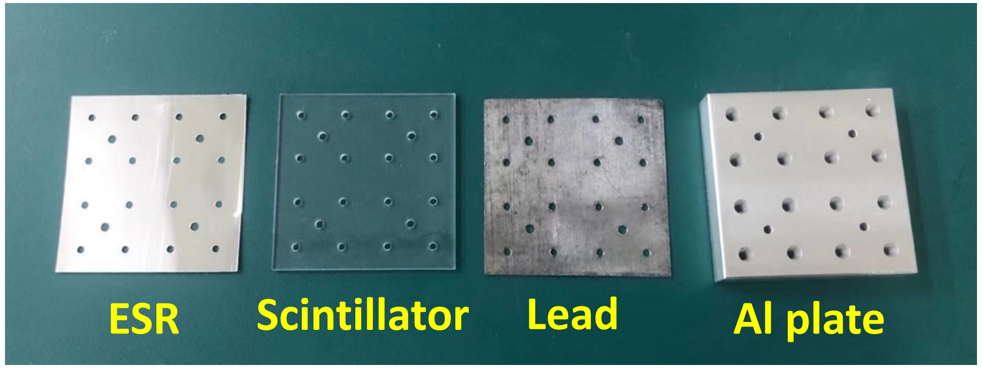
NIKA-MPD shashlik Ecal



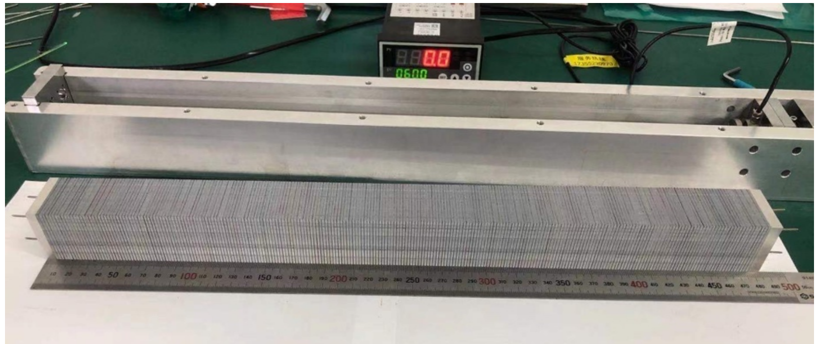
CsI Crystal

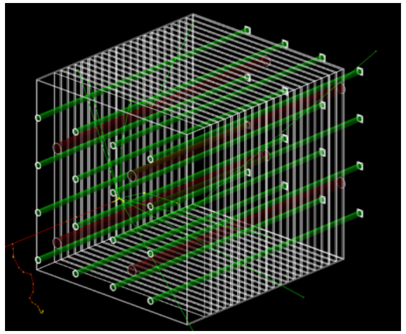
Shashlik ECal design





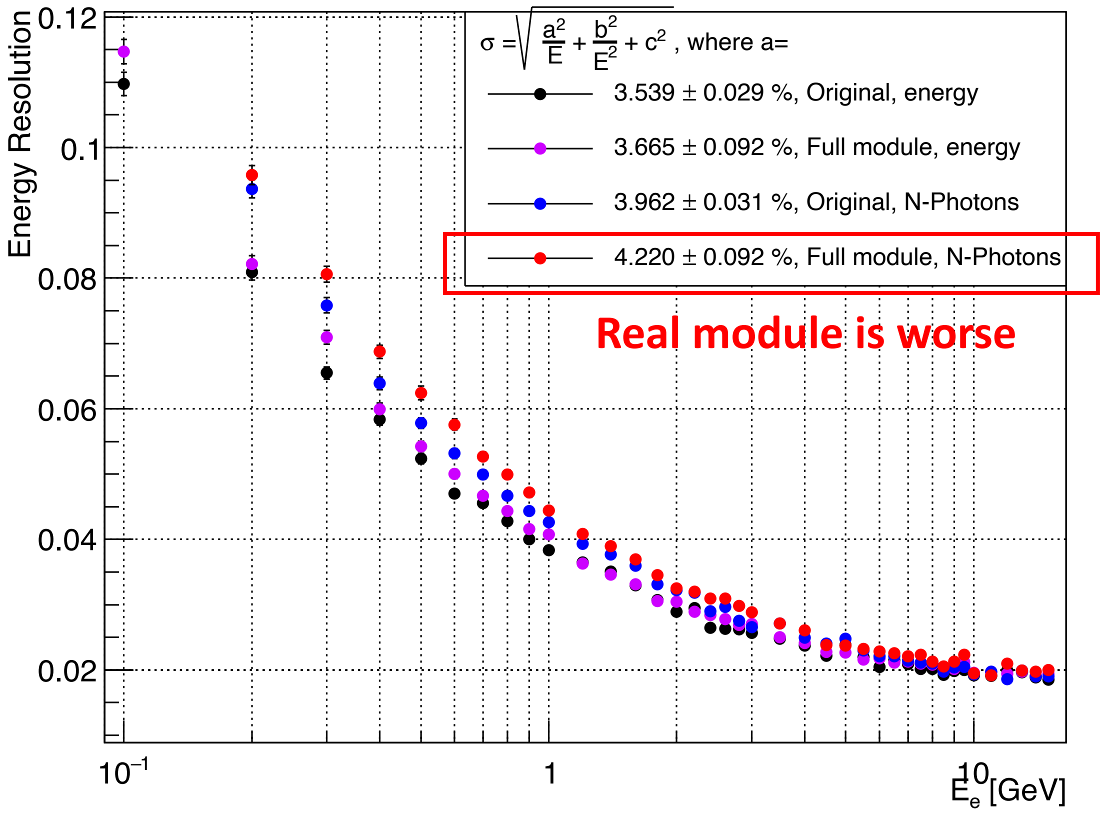
- **Longitudinal:**
  - (1.5 mm scintillator + 0.35 mm lead+ 65 μ m reflector *2) * 240 layers
  - Radiation length: total 16 X_0 (X_0: 2.81cm, Reflector not include)
  - **Length**: 15mm external fiber, 6mm Al Plate + 470mm + 8mm Al Plate + 45mm fiber bundle + 15mm SiPM readout = **560mm**
- **Lateral:**
  - 4.0×4.0 cm^2
  - 16×Φ1.2mm WLS fbers to collect light
  - 4× Φ 1.5mm steel rods as module support
- **Other supplyment**
  - ESR as fiber end reflector
  - 6.0×6.0 mm^2 S13360-6025 SiPM as readout
  - TiO2 coating





Shashlik array simulation result

Energy resolution



$$E = \left(\sum E_i\right) \cdot w_{sampling\_ratio}$$

$$E = \left(\sum NPhotons_i\right) \cdot w_{photon\_to\_energy}$$

W0 parameter optimization for position reconstruction

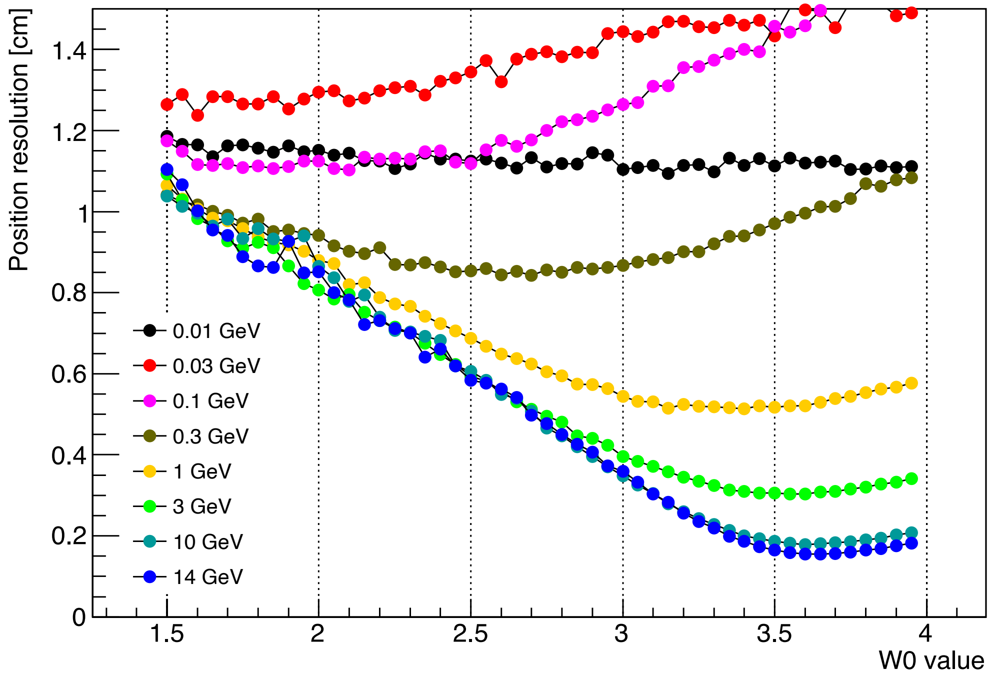
The hit position is reconstructed by

$$x = \frac{\sum(x_i \cdot W_i)}{\sum W_i}$$

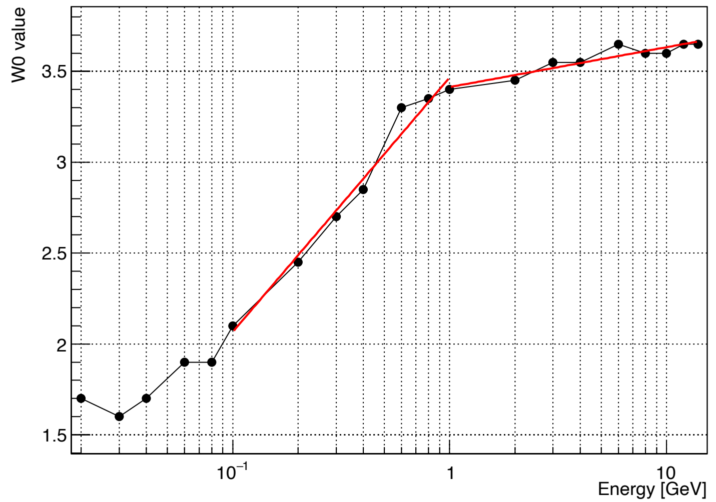
Where $W_i = W_0 + \log\left(\frac{E_i}{\sum E}\right)$, W_0 is a constant that related to the energy.

W_0=3.5 equivalent to $E_i/E>3\%$

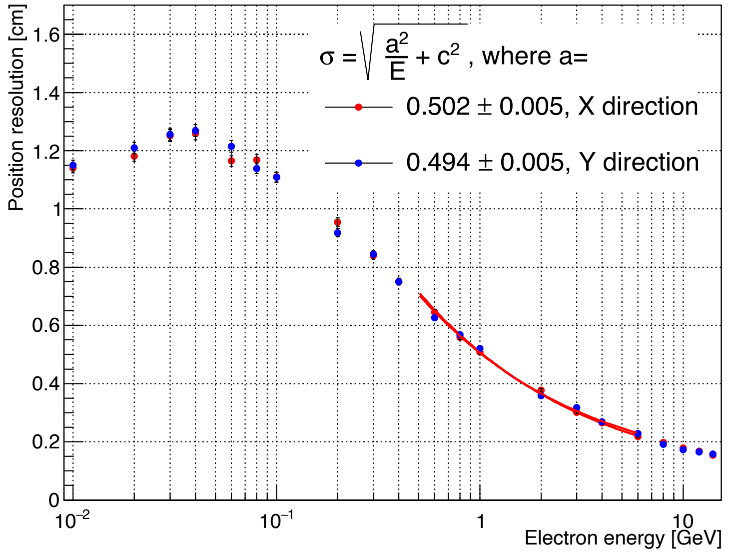
Position resolution v.s. W0 for different e- energy



Fitting of W0 value with e- energy

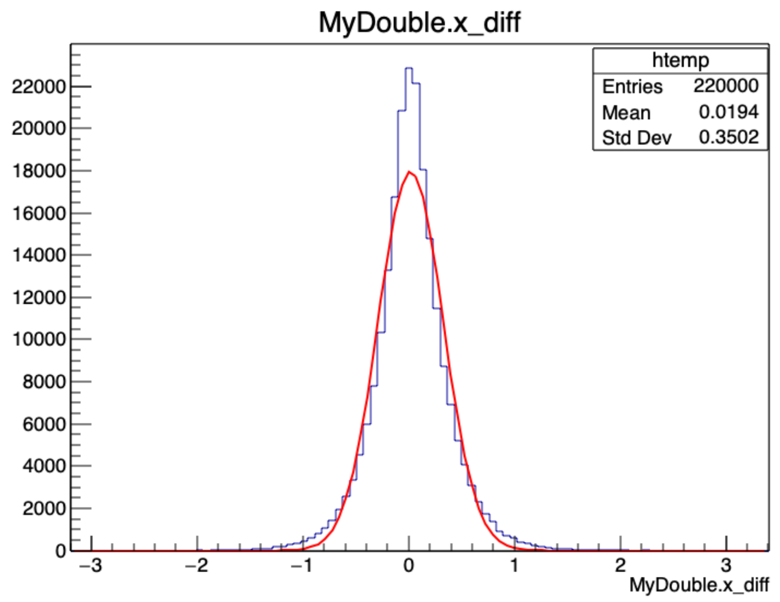


Position resolution result with e- energy



Position resolution with NN method (0.5-5 GeV)

Train input: N.P.E. of 49 modules, energy range: 0.5-5 GeV
Output： reconstructed position



Use NN trained model to test single energy data: [mm]

- **0.6 GeV: 5.77**
- **1 GeV: 4.6**
- **2 GeV: 3.1**
- **4 GeV: 2.52**

Compared with **the W0 method**: [mm]

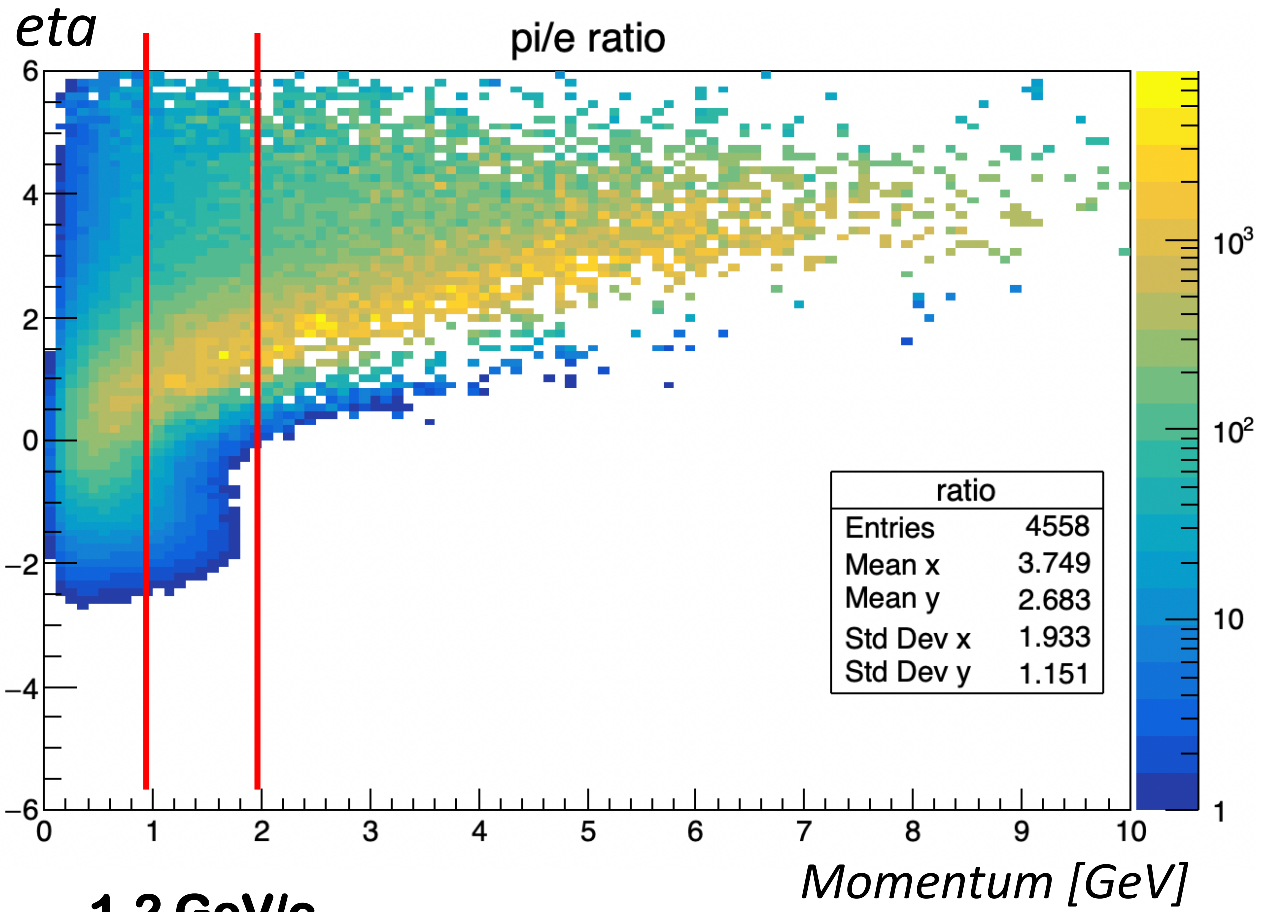
- 0.6 GeV: 6.2
- 1 GeV: 5.3
- 2 GeV: 3.65
- 4 GeV: 2.7

- NN method for position reconstruction is much better than W_0 method.
- May exist other better "theoretical calculation" method!

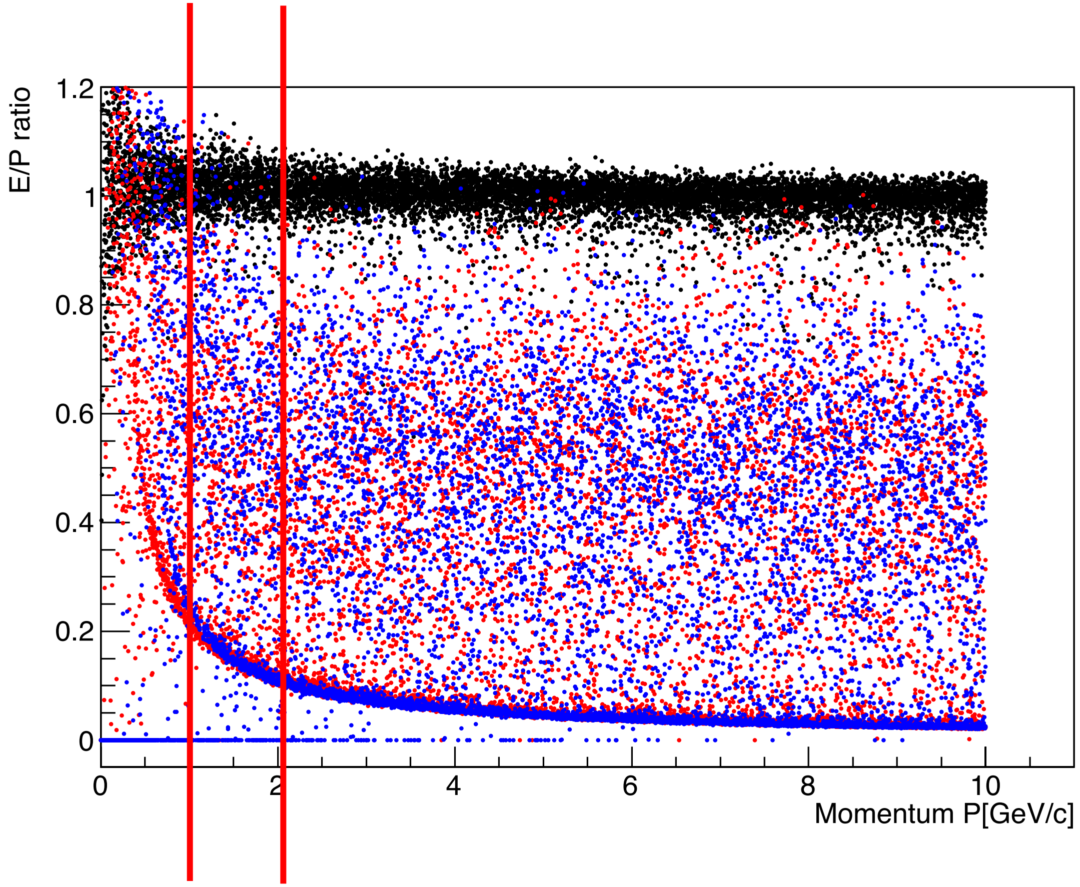
- NN method is also applied for energy reconstruction and PID, but not work well as ordinary method

PID: e/π separation of ECal (Shashllik)

Ratio from pythia

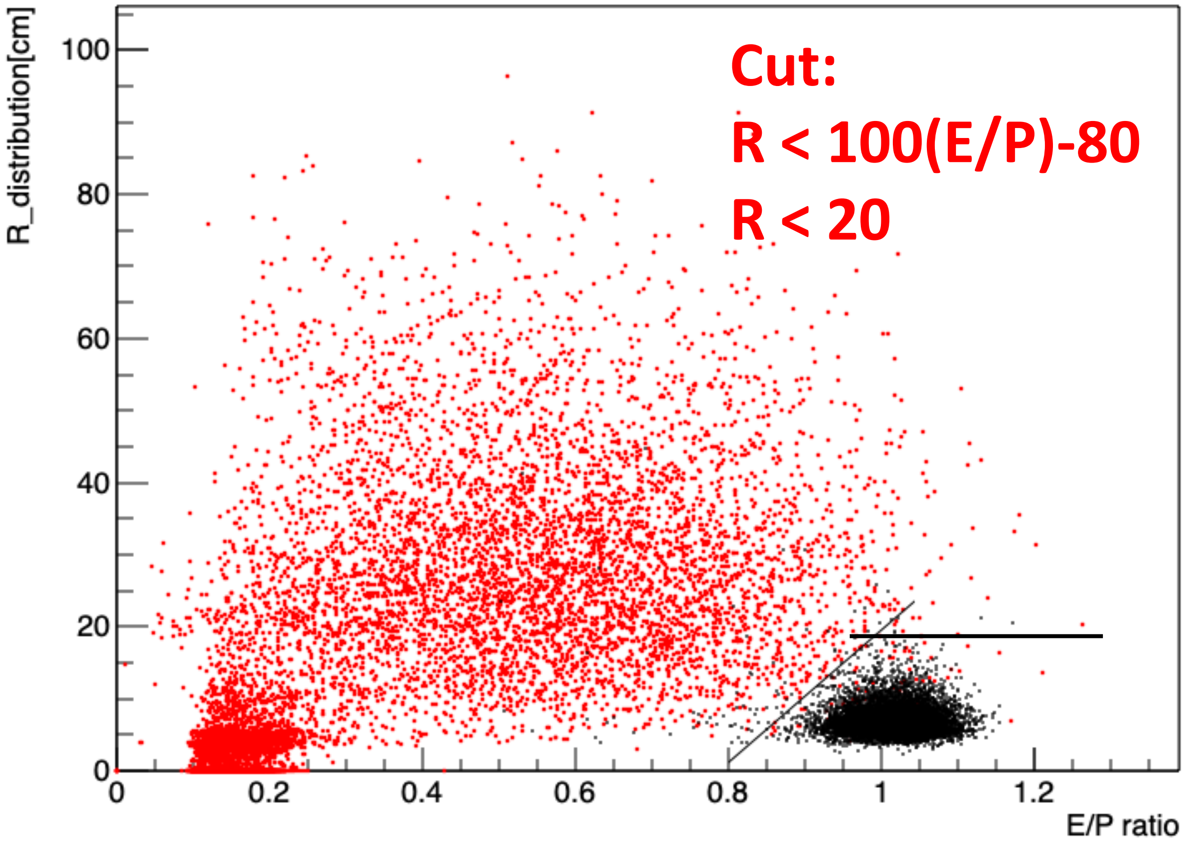


1-2 GeV/c



e-
Pi-
K-

Artificial cut selection and PID result (1-2 GeV/c)



Two cut: **E/P ratio** and **R(r)**:

$$R(x) = \sum (x_i - x_{re})^2 \frac{w_i}{w_{all}}$$

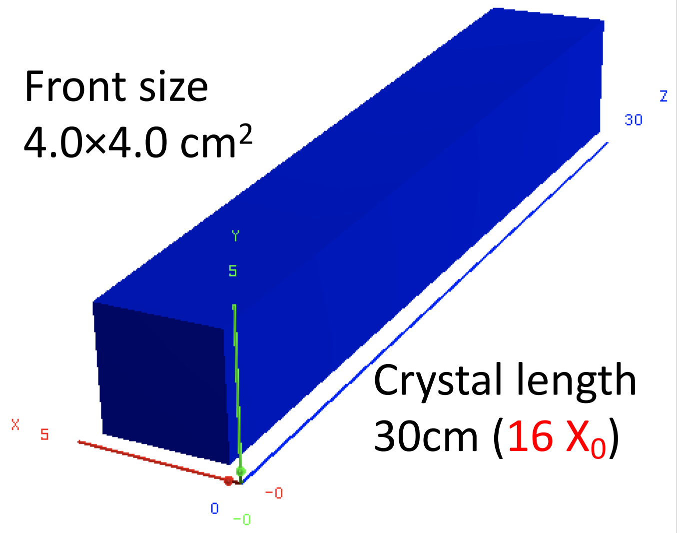
$$R(r) = \sqrt{R(x)^2 + R(y)^2}$$

Percentage (%) (200k events)		Real PID	
		e	π
PID result	e	99.25	0.70
	π	0.75	99.30

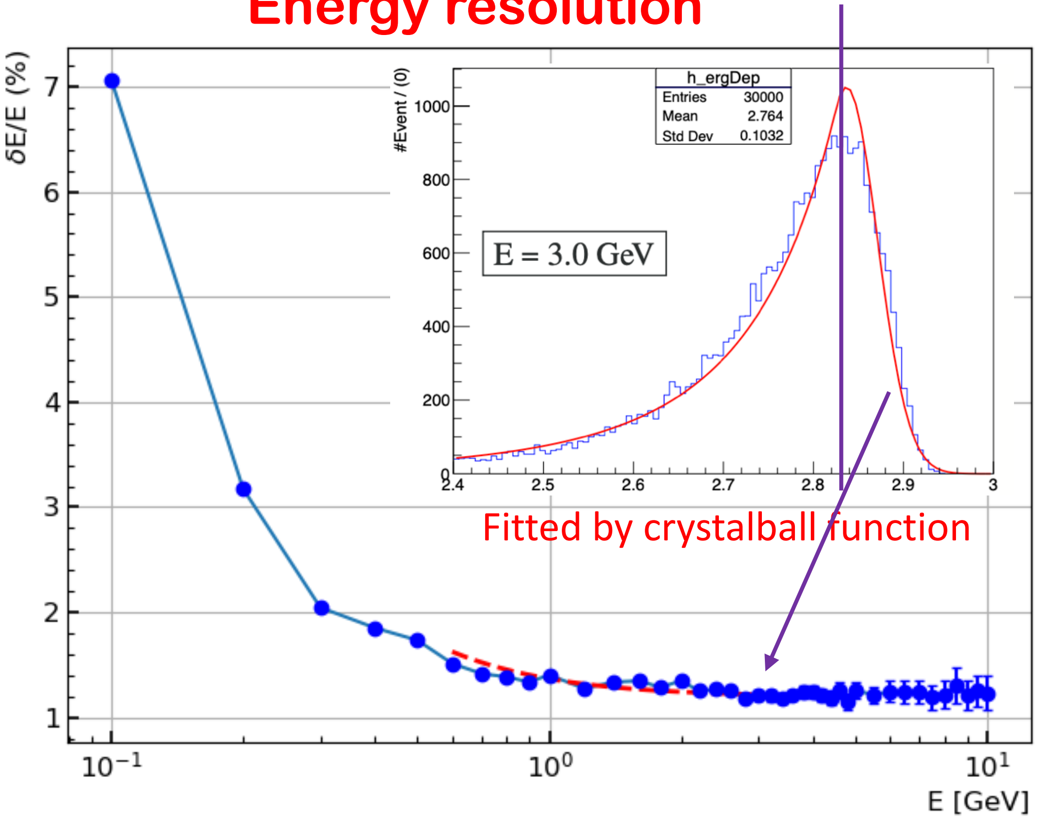
- Good result for PID: e efficiency > 99%, π rejection ~ 100:1
- If considering the real e/π ratio, cut selection and PID result will be much different
- Shower method and MIP/time method result for e/π is independent

CsI module array simulation result

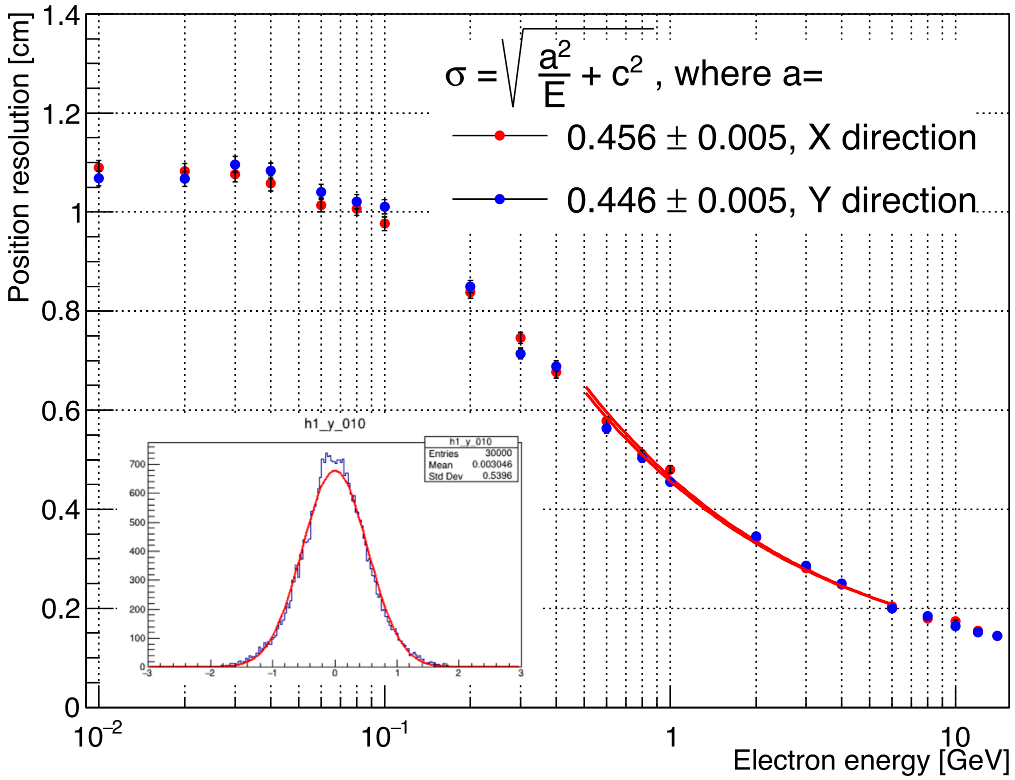
- Very good energy resolution: 1.5%@1GeV
- Better position resolution(0.48cm@1GeV) than shashlik(0.53cm@1GeV)



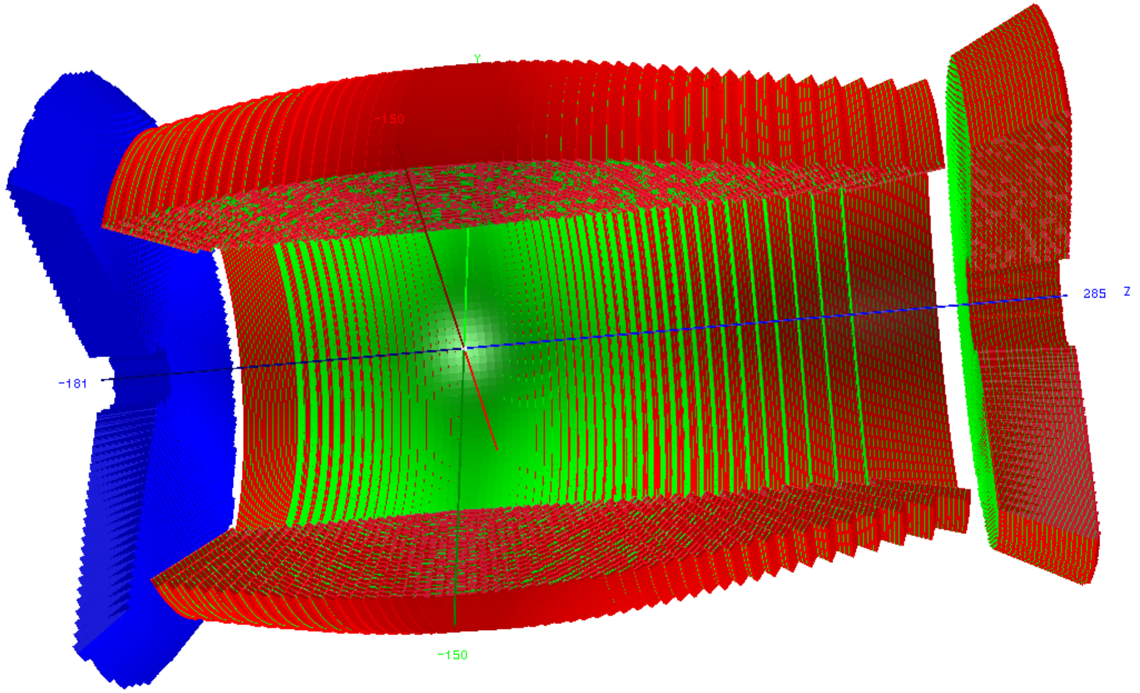
Energy resolution



Position resolution

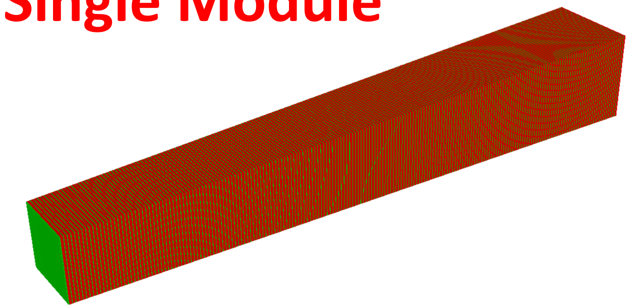


Whole ECal simulation

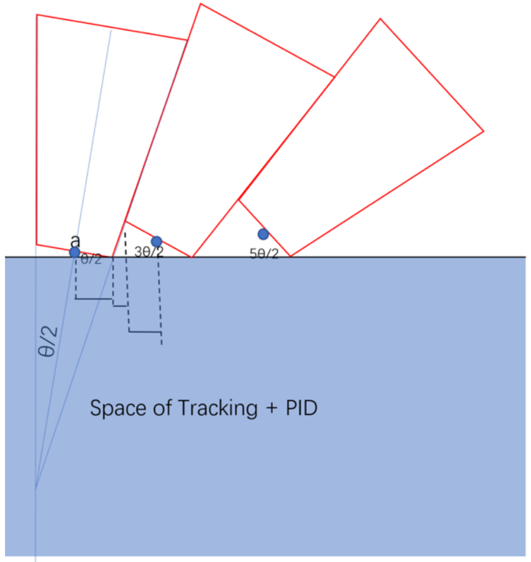


Shashlik barrel and ion-endcap configuration for the EMC

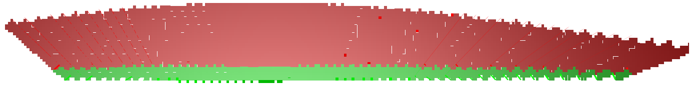
Single Module

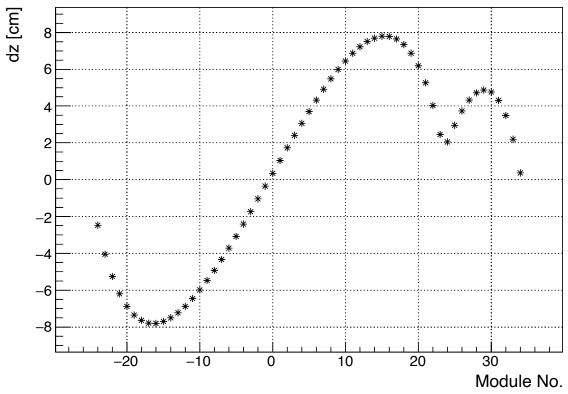


240 layers * (1.5 mm scintillator + 0.35 mm Lead) (16 X_0)



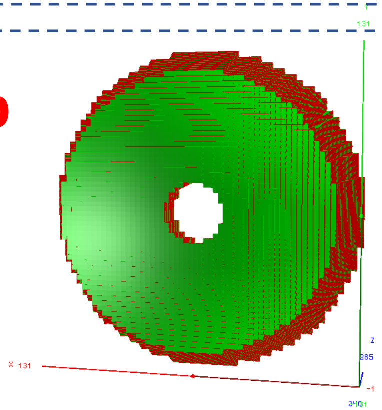
Barrel

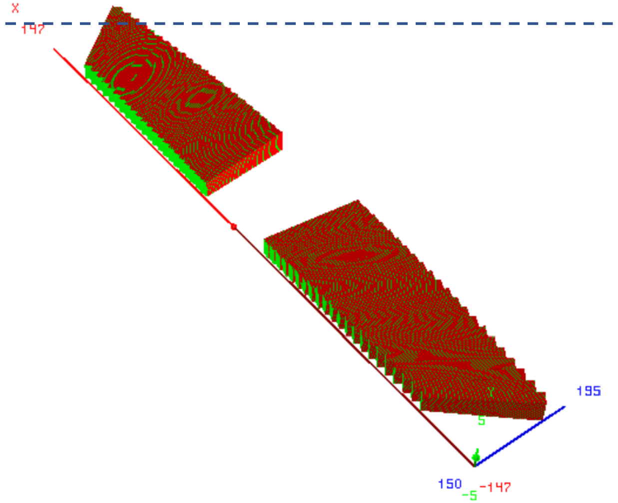




- Trapezoid shape module
  - $4.0 \times 4.0\ cm^2$ front size
  - $5.7 \times 5.7\ cm^2$ rear size
- **Use two modules with different angle: 2.1 + 1.35**
- Each module roughly point to the IP (Interaction Point)

Ion-endcap





- Trapezoid shape module
  - $4.0 \times 4.0\ cm^2$ front size
  - $4.7 \times 4.7\ cm^2$ rear size
- Each module point to the IP (Interaction Point)

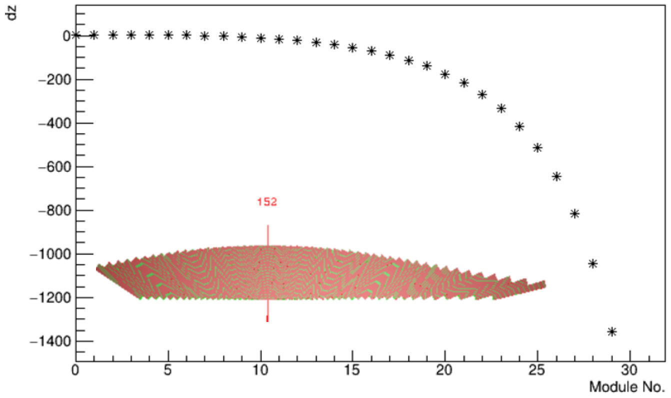
Module θ optimization for barrel

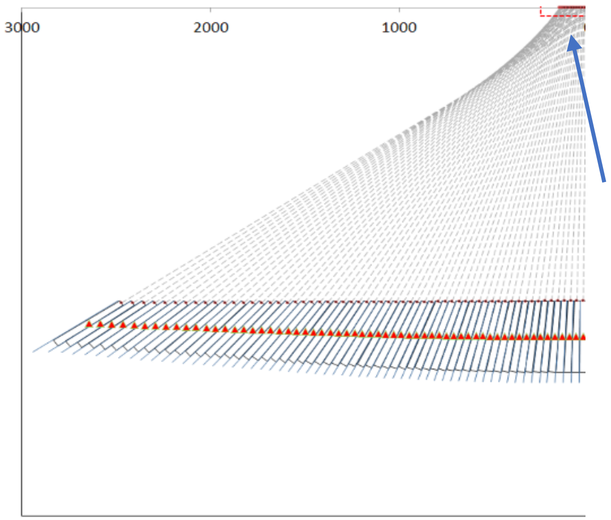
The trapezoid module angle is optimized for two angles:

24 + 24 + 10 with 2.1° + 2.1° + 1.3°

to minimize the dz and the energy leakage between barrel and endcap.

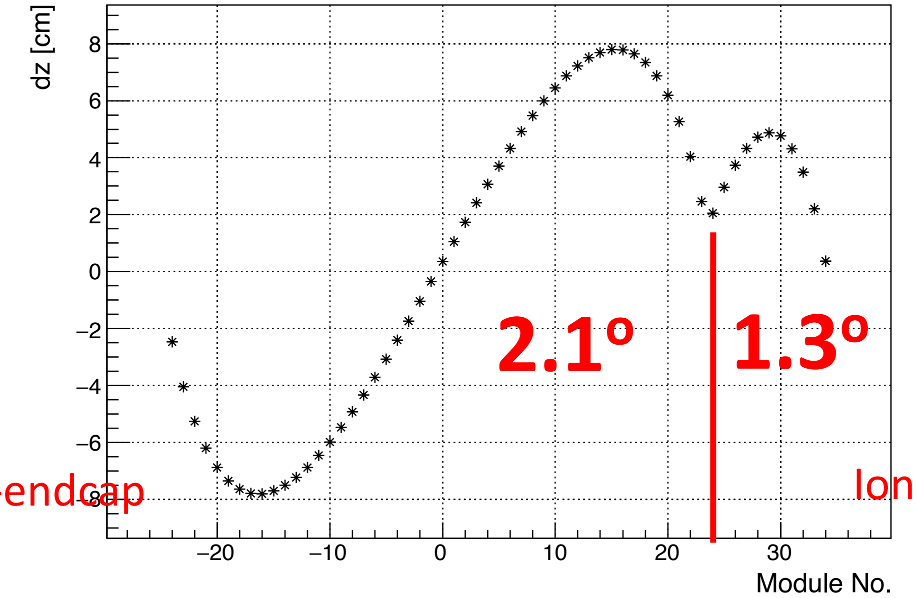
Initial



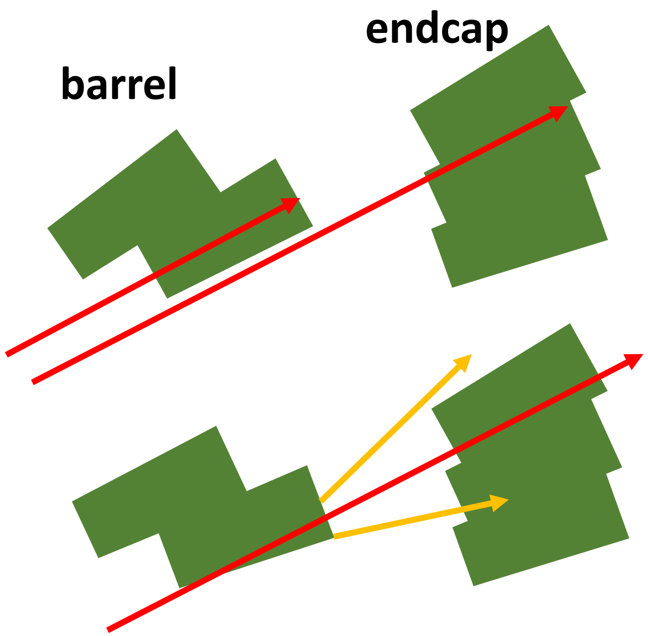


dz(cm): the distance bettween IP and the module point to z axis

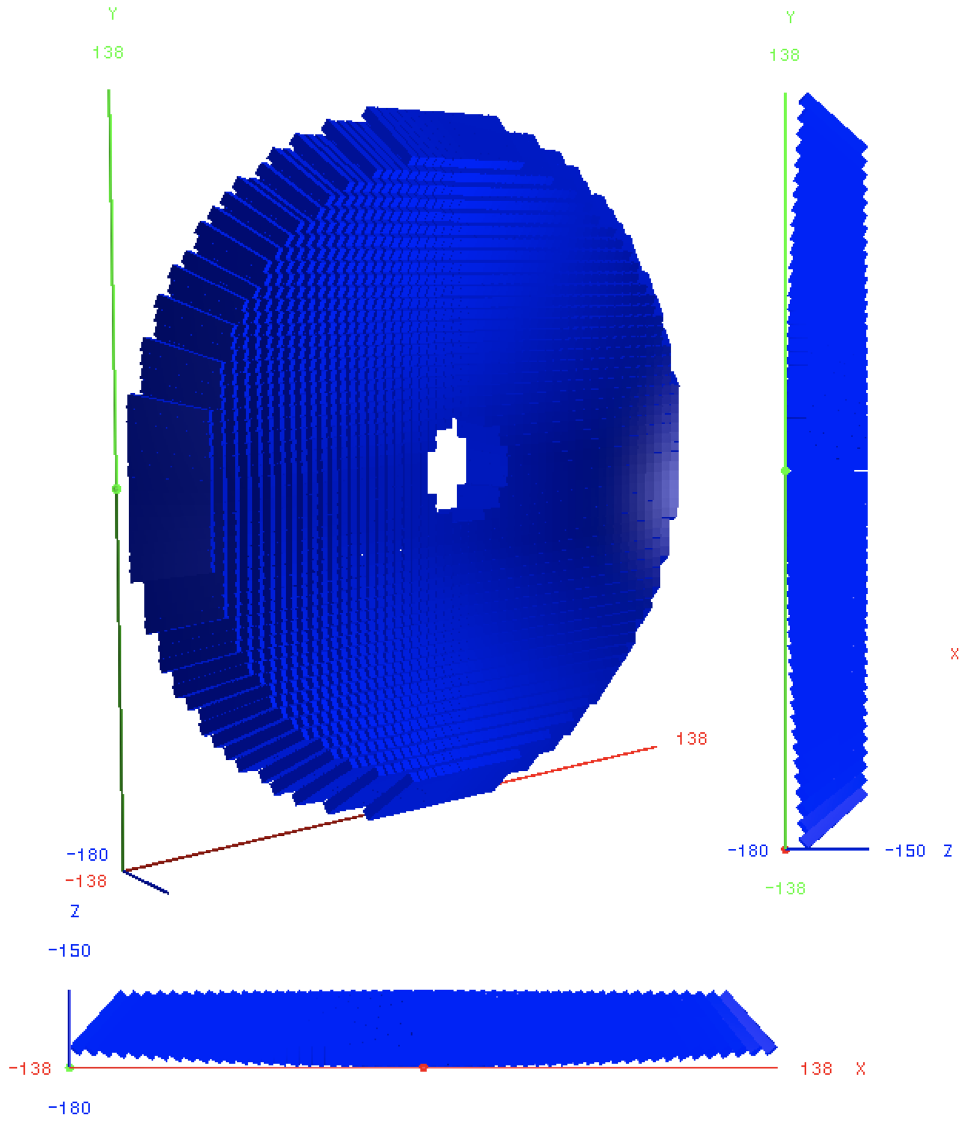
Two angles



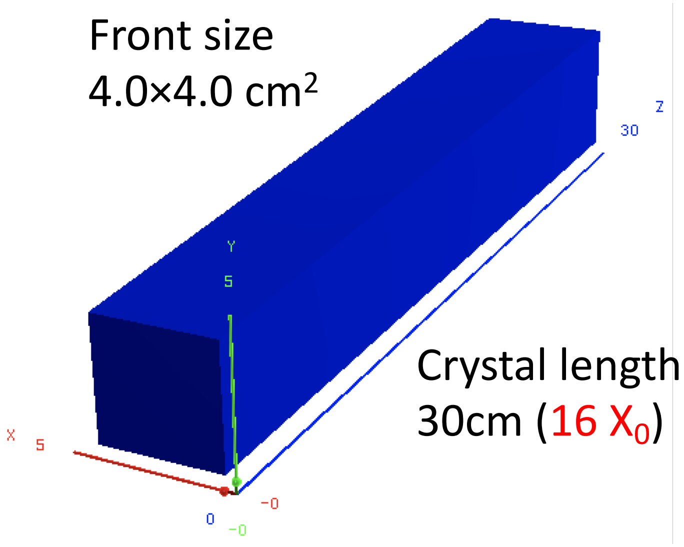
Advantage of two angles design



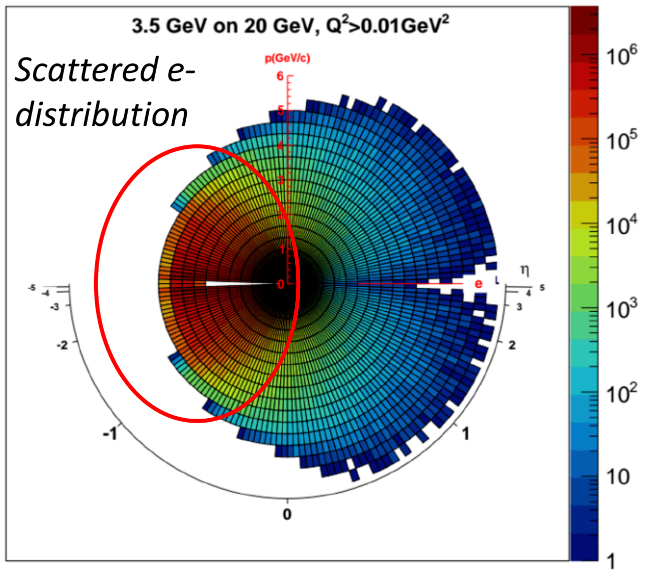
Electron Forward Endcap Configuration for the ECal



Front size
4.0×4.0 cm^2

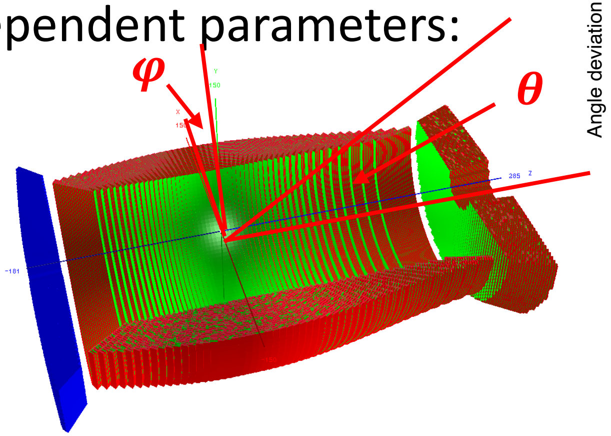


Crystal length
30cm (16 X_0)

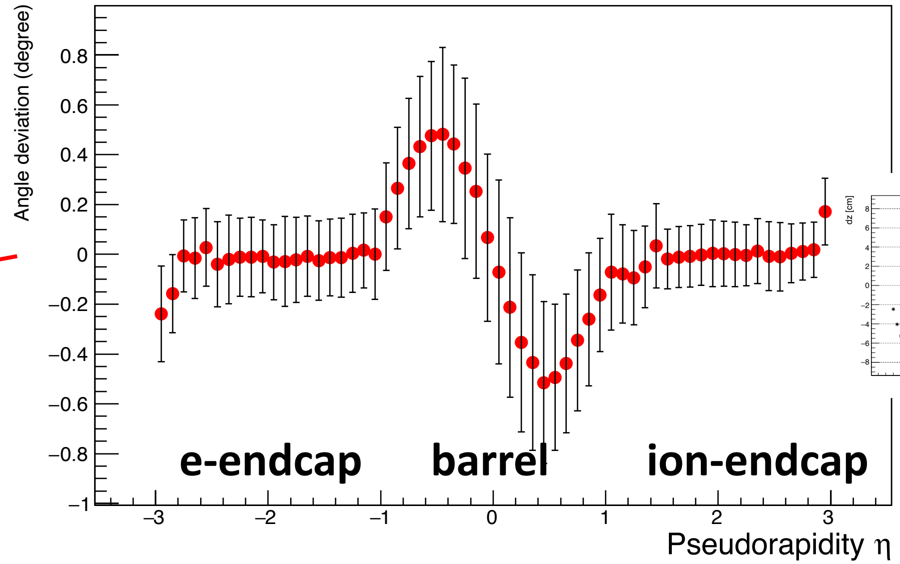


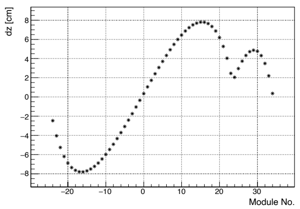
Single e⁻ reconstruction

- Reconstruction based on 3-independent parameters:
  - Energy
  - Two angles (θ and φ).
- Δ = Reco – Real
- **Need extra calibration for bais**

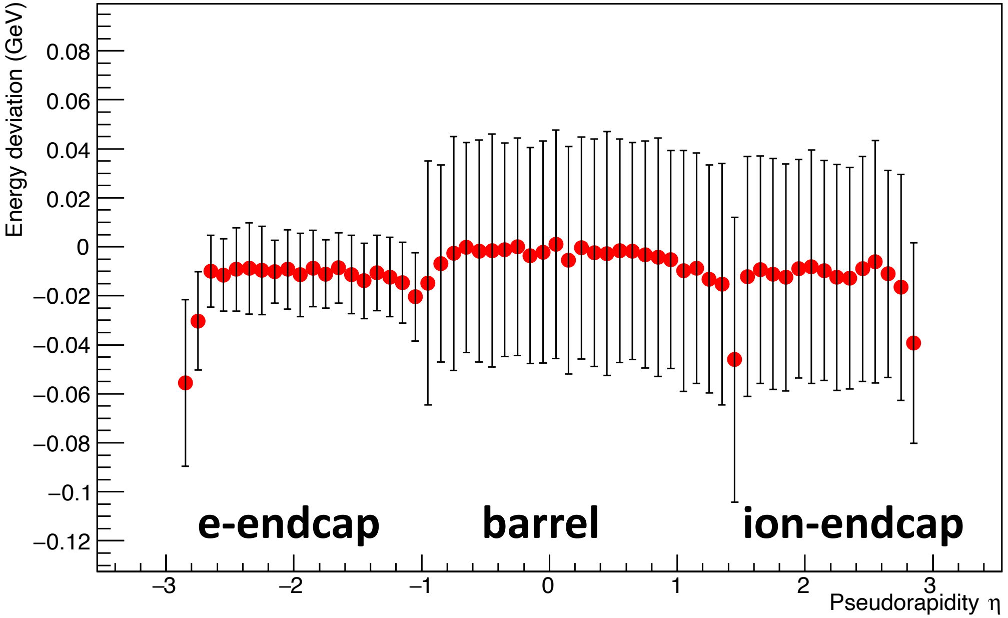


Reconstructed angle $\Delta\theta$ vs. Pseudorapidity η

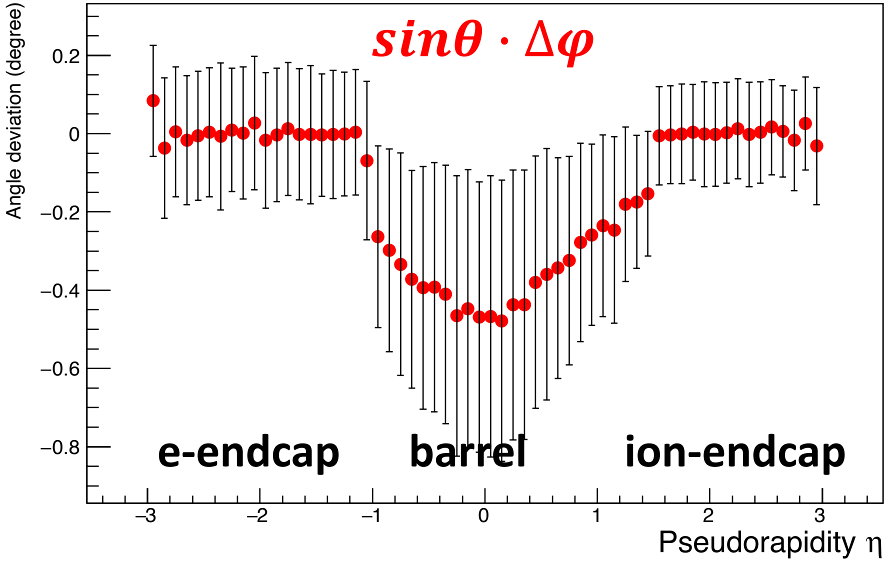


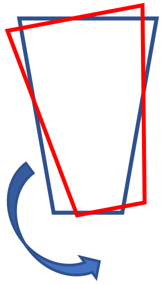


1GeV e- energy ΔE & resolution v.s. Pseudorapidity



Reconstructed angle $\Delta\varphi$ vs. Pseudorapidity η





Ecal simulation in EiccRoot

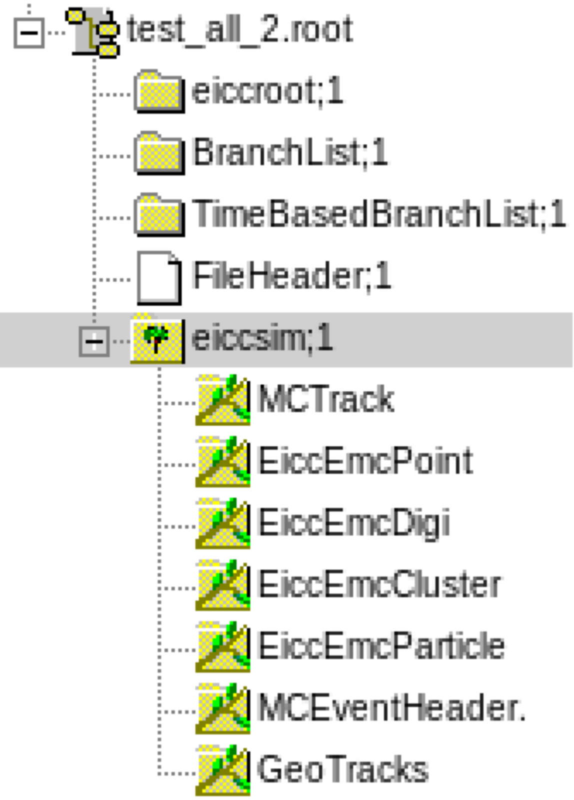
- Refer to **PandaRoot** and **MpdRoot(NIKA)** EMC software structure.
- Perform both **simulation and reconstruction** with one script(”run_sim.c”).
- **Input:**
  - **Generator setting and other detectors**
  - **Geometry root file: E-endcap, barrel and ion-endcap, or** 7*7 array.
  - **Parameters for reconstruction**
- **Main task: ECal simulation, module digitization, cluster reconstruction, particle reconstruction**
- **Output:**
  - Tree contains the result of each task
  - Final result: 4-V of reconstructed particles and PID

CPU/MEM/Disk performance: (linear to energy)

- Time consuming: ***0.06s/(1GeV*1event)***
- Low memory consuming
- Disk usage:
  - Normal: 52k byte/ 1 GeV(e-)
  - Minimum: 8.5k byte / 1 GeV(e-)

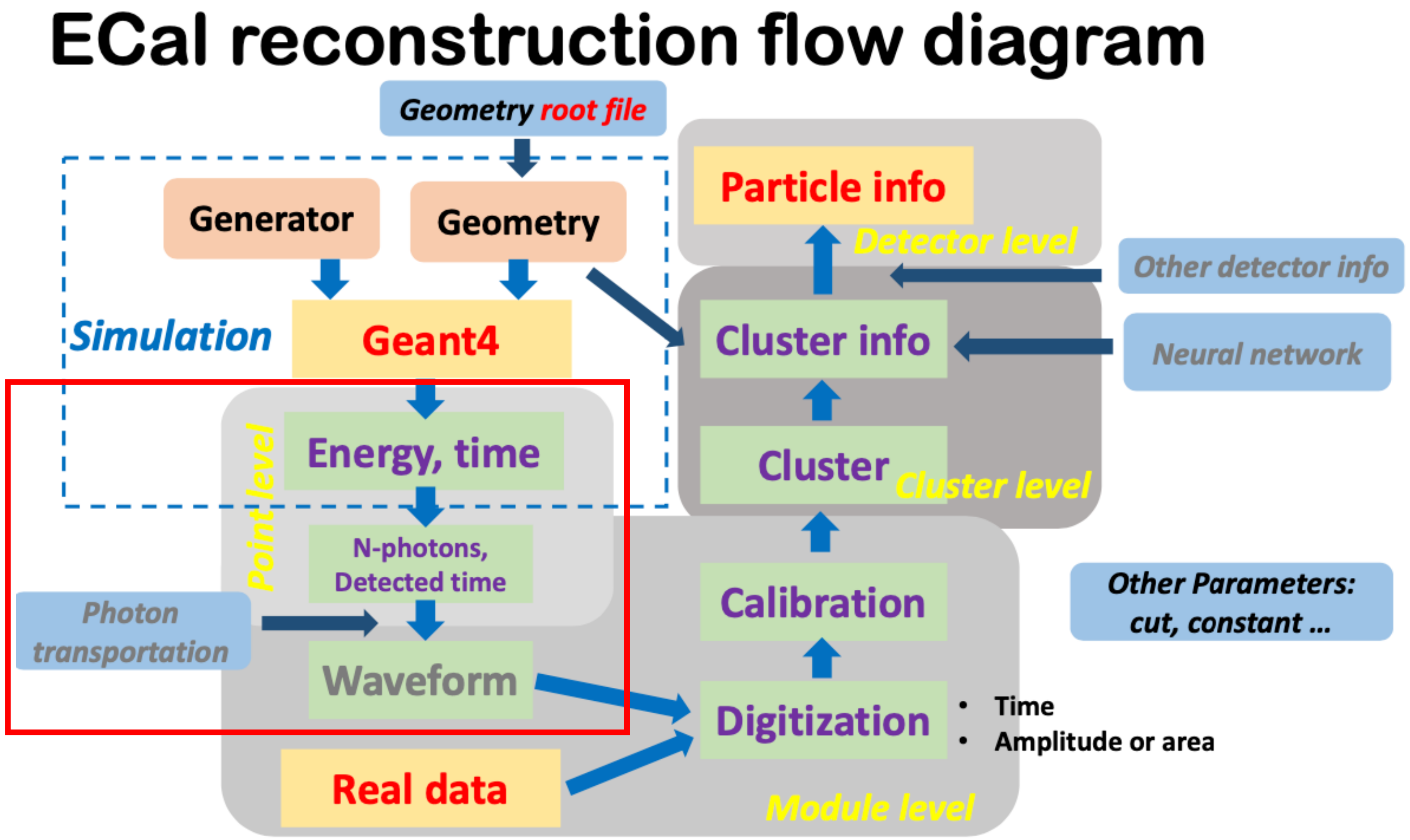
Released on IMP farm!

Full output tree



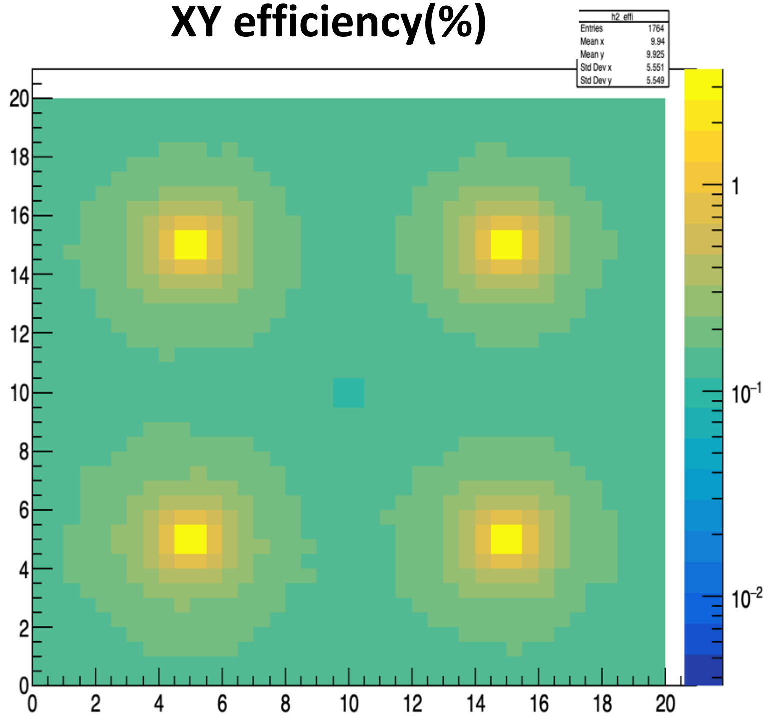
Complement the simulation work

1. Parametrization from energy to N-Photons detected in SiPM.
2. N-Photons + time -> Waveform
3. Extract energy and time from waveform.

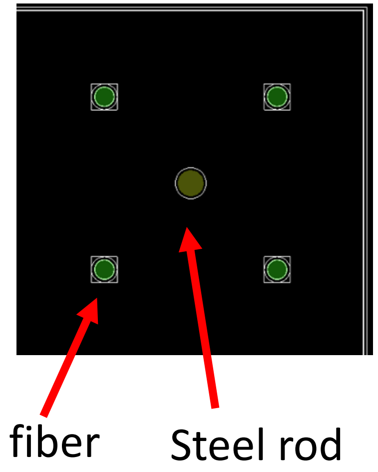


Shashlik 3D efficiency

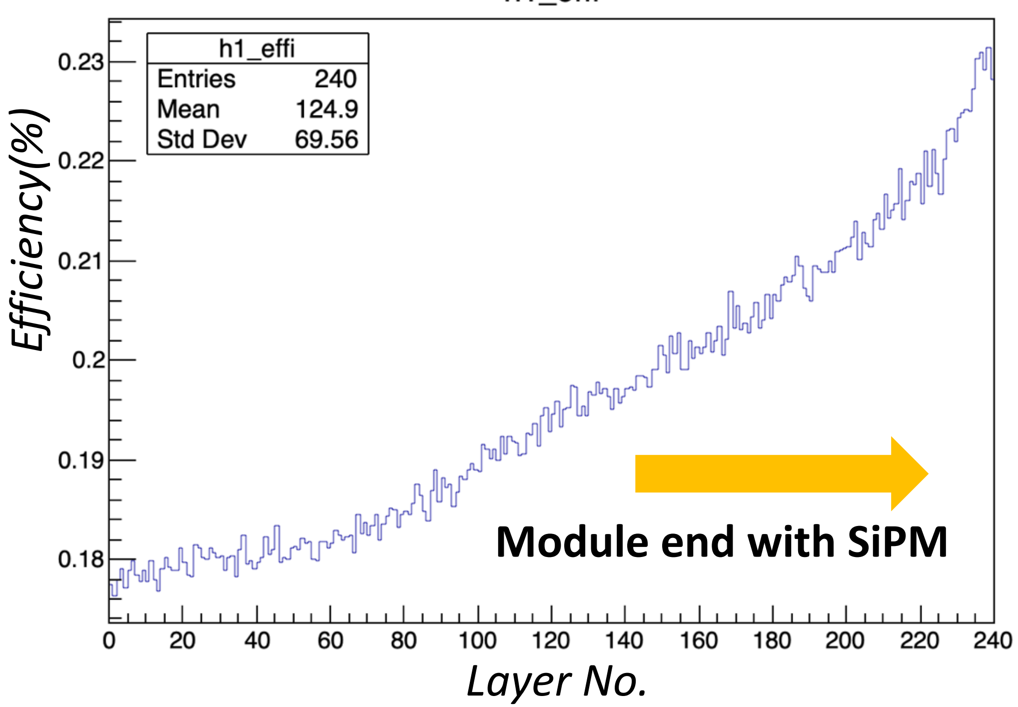
XY efficiency(%)



¼ of module



Z(N layer) direction efficiency

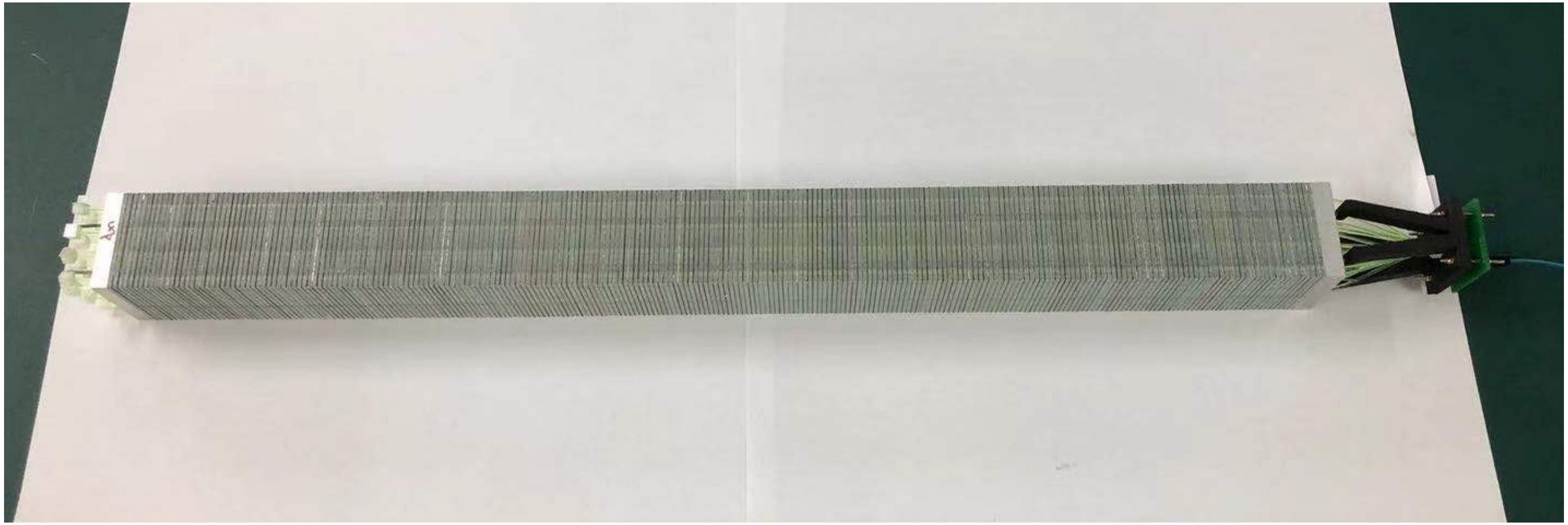


- 3D photon collection efficiency(x, y, NLayer): 1. evaluate the uniformity of module; 2. light yield simulation with 3D parametrization.
- 3D photon collection efficiency extraction method:

$$effi = \frac{Nphotons\ hit\ on\ SiPM}{Nphotons\ generated\ initially}$$

- Each bin is 0.5mm for X and Y direction, for geometry symmetry, ¼ of area is considered in final result

Shashlik ECal hardware work



NPE simulation comparison between beam test(e) and comsic ray(muon)

	Energy deposit (MeV) in Scintillator (Landau fit)	N.P.E simulation	N.P.E /MeV	Normalized to 1GeV e- 4000N.P.E/360MeV (11.1/MeV) (NIKA beam test)
1GeV e-	224 (gaus fitting)	3297(gaus)	14.7	2486(=224MeV *11.1/MeV) (Single module)
3GeV mu- (vertical)	73.9	1014	13.7	**820**
3GeV mu- (horizontal)	5.62	90.3	16.0	**63*1.09(16/14.7)=68.7**

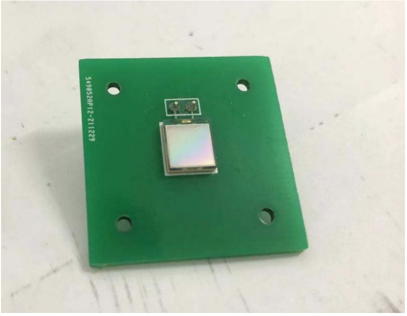
PMT test

- To evaluate the NPE value of prototype module, ordinary PMT is used, and read out by a FADC, which could acquire both waveform and work as precise QDC.

PMT in test (ET 9814B)

SiPM test

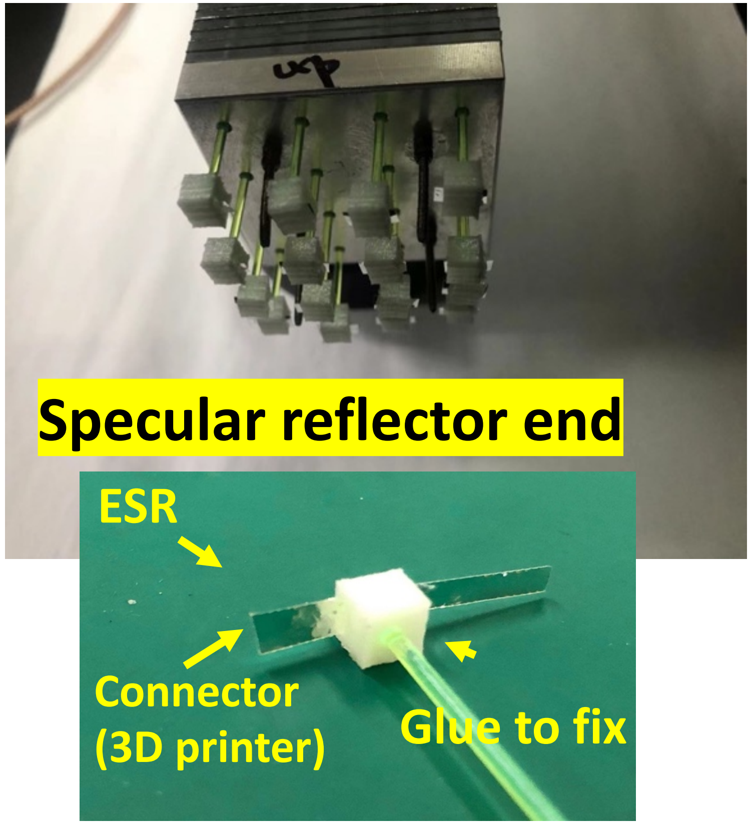
- The SPE of SiPM could not be calibrated now in our Lab.



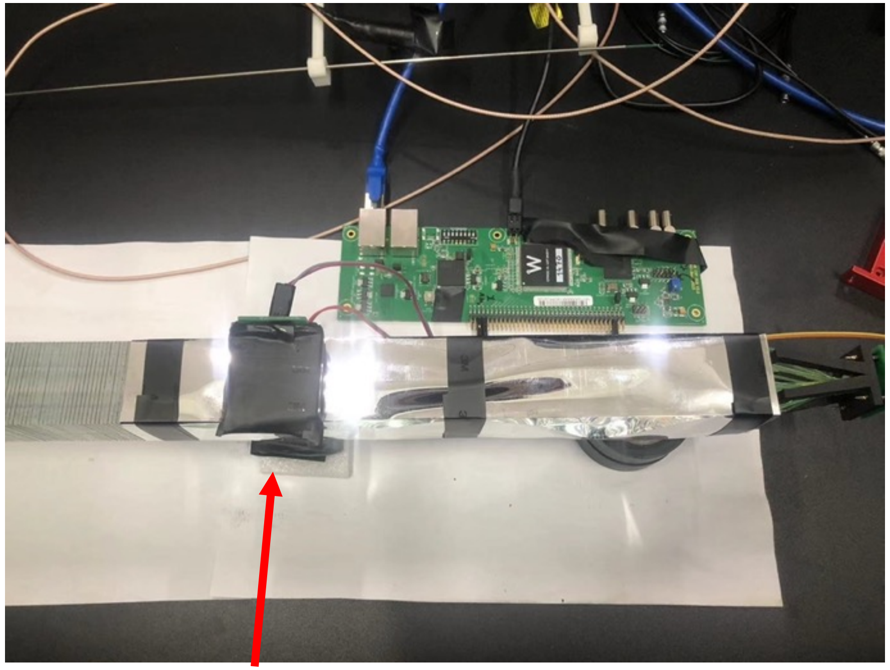
SiPM readout electronic: CAEN DT5702

Horizontal cosmic ray test setup

Add fiber end mirror

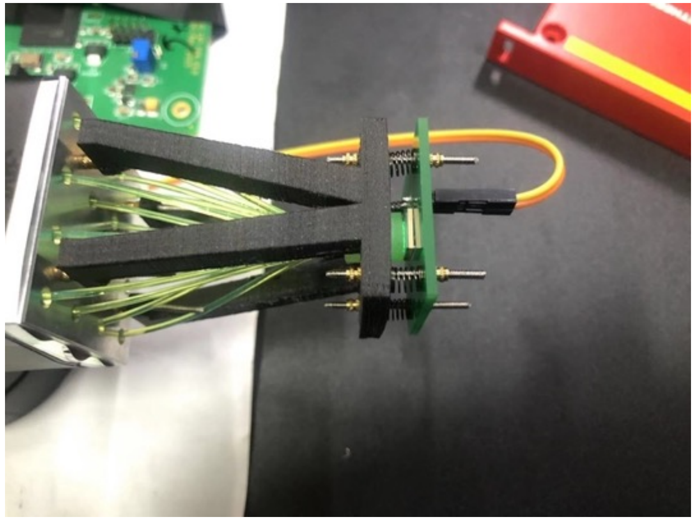


ESR coating(temporary)

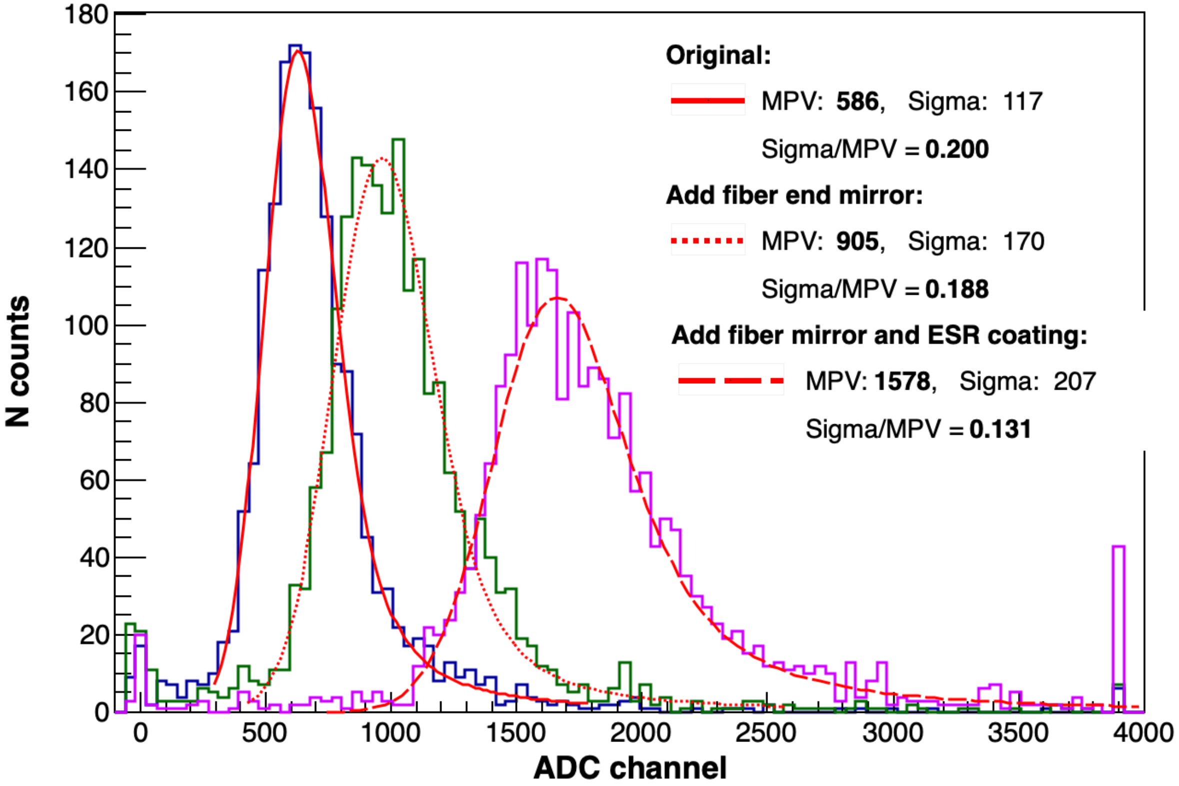


Trigger scintillator that places at the center of module has the same size as module laterral size.

Fiber bundle – SiPM coupling



Horizontal cosmic ray test result



Fitted by covolution of landau and gaus:

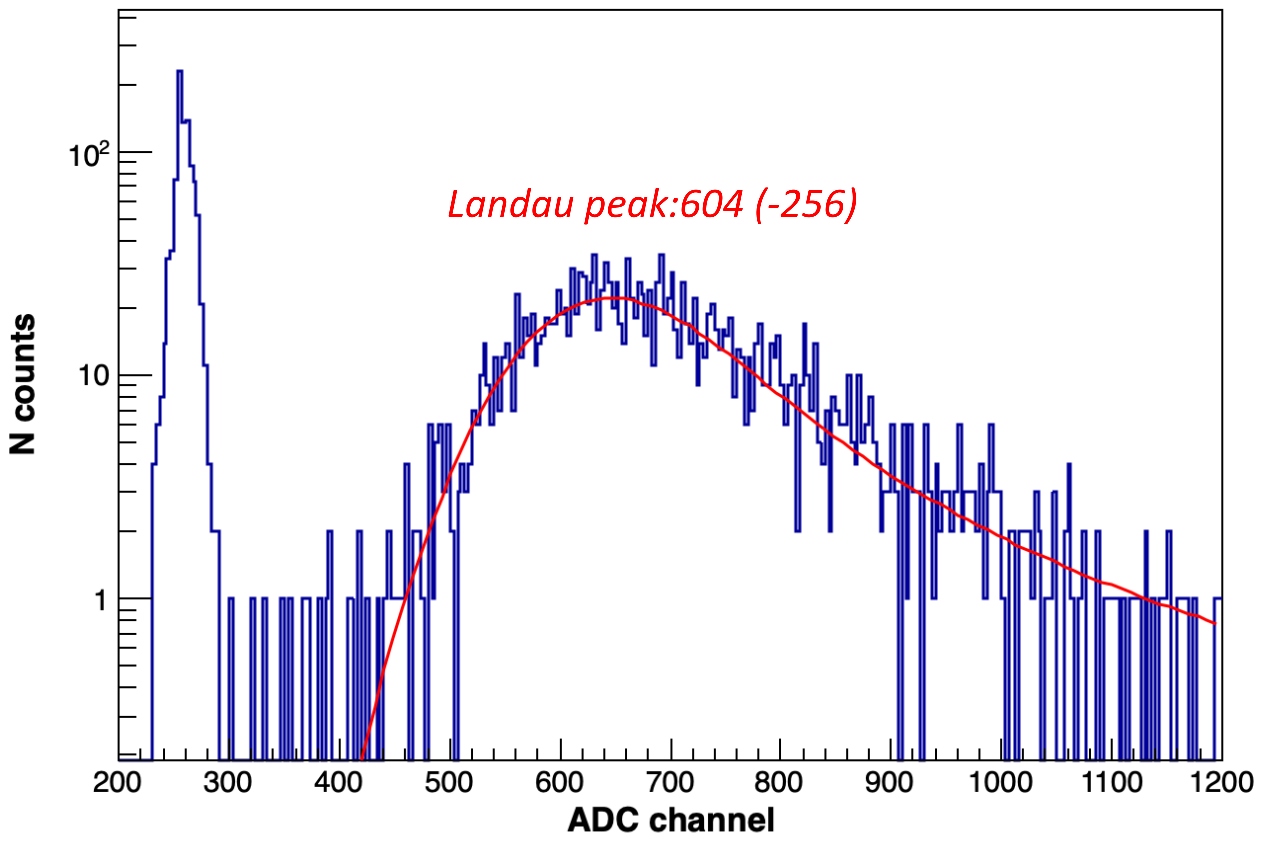
```
EXT PARAMETER
NO.   NAME        VALUE          ERROR
 1  Width       8.21287e+01   6.02676e+00
 2  MP          1.57781e+03   1.00396e+01
 3  Area        8.71232e+04   1.94861e+03
 4  GSigma      2.07478e+02   1.07888e+01
```

landau : width, MP
gaus : GSigma

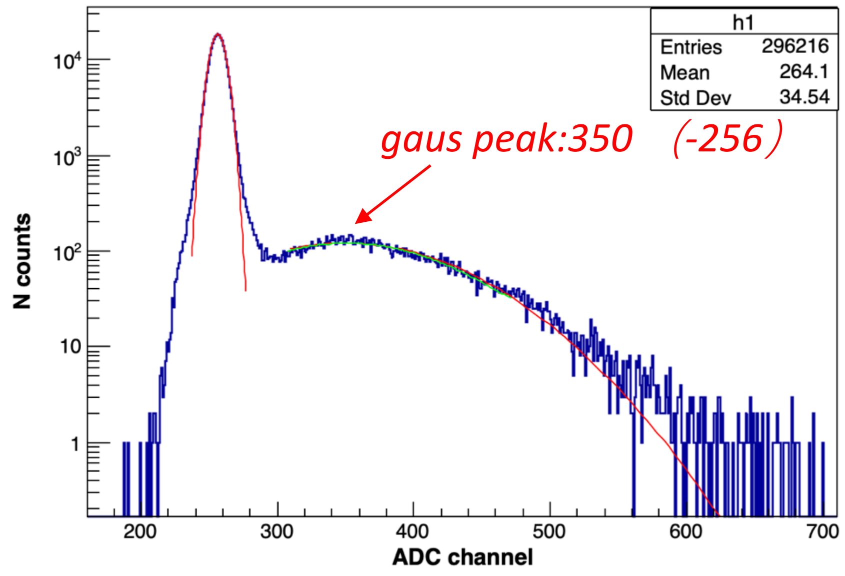
Test setup	ADC count	Relative improvement	Simualtion result	
			N.P.E	Relative improvement
original	586		59	
Add fiber end mirror	905	0.54	68	**0.15**
Fiber end mirror + coating	1578	0.74	90.3	**0.33**

Horizontal NPE result （**PMT test**）

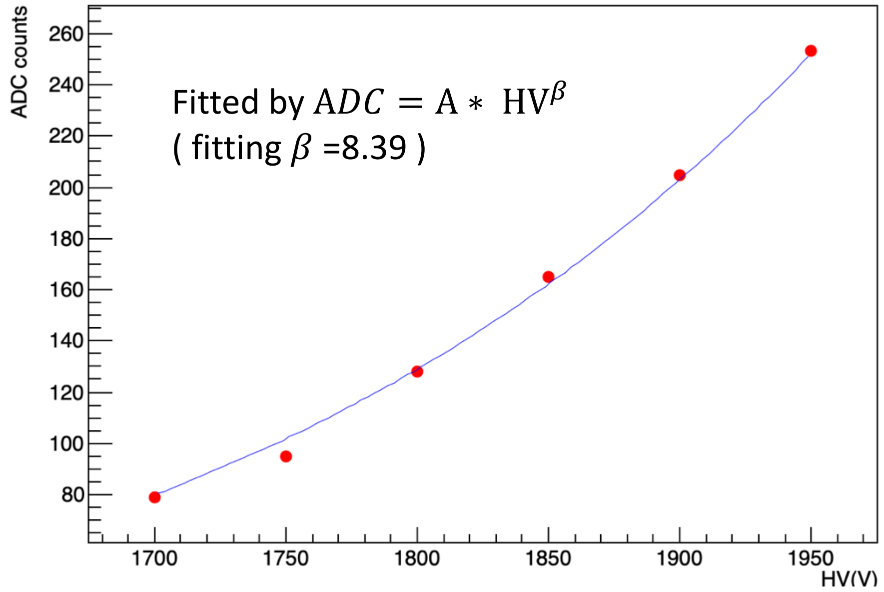
Horizontal cosmic ray ADC spectrum



1750V SPE spectrum



ADC v.s. HV

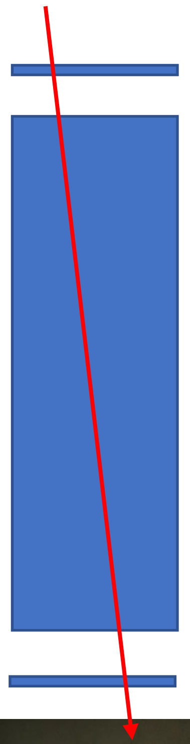


- For SPE spectrum, 94 LSB with **10** fC/LSB
- For cosmic ray test, 344 LSB with **160** fC/LSB
- Finally, **58.6** NPEs is acquired.

Next shashlik prototype test plan

- Perform both precise **horizontal and verticle** module cosmic ray test by PMT, and evaluate the NPE value.
- Update the test **electronics plug-in for SiPM**.
- Use low range type SiPM for cosmic ray test.
- Test the performance of all materials.
- Optimize the scintillator performance by improving the component.

Cosmic ray test sketch map



Conclusion and outlook

- ✓**Module and detector optimization** is perfromed
- ✓Improved performance for **energy, position and PID**
- ✓**ECal simulation and reconstruction software frame** is built, work well for the Ecal detector
- ✓**Test setup and prototype** is built and starting cosmic ray test

Work in hand:

- ➢Go on waveform simulation and reconstruction for more precise simulation
- ➢More work on prototype assembly, test and Lab setup
- ➢Time reconstruction and performance

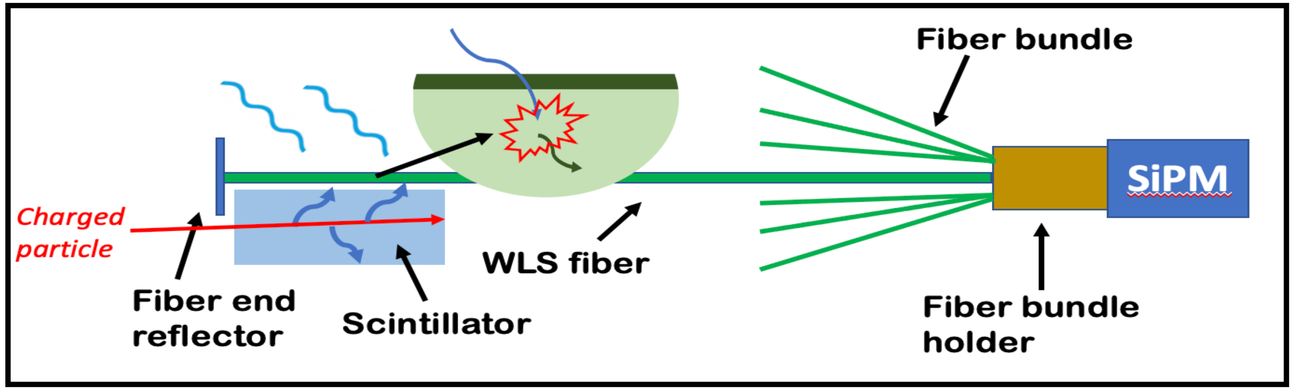
Future work

- ➢Cooperate with other detectors
- ➢Physics requirement
- ➢Re-consider the module design after the whole software frame is finished
- ➢More other work……ANN……

THANK YOU!

Geant4 optical photon simulation

Takes into account the effects of **light generation** and **propagation** inside the scintillator tiles and in the WLS fibers.

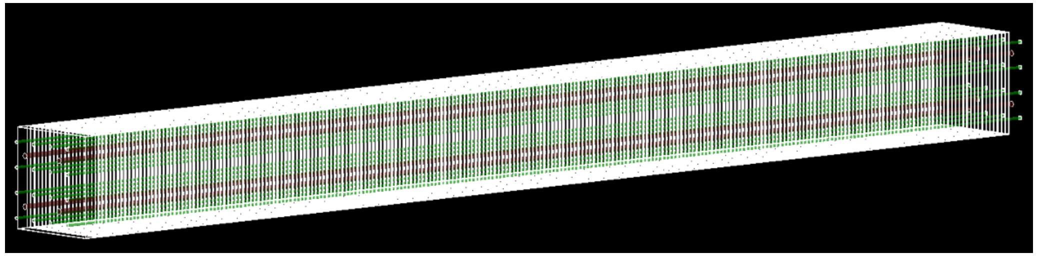


***OpticalPhysics* physics list**

- Generation processes through scintillation for both the slow and fast components;
- Exponential light attenuation processes;
- Wave-length-shifting processes;
- Reflection and refraction processes between materials with different refractive index.

➢ **Time consuming**

➢ **Important to extract parameters for the simplified simulations**



Cluster algorithm for photon reconstruction

- Photon energy deposited in few blocks of ECal
- Build cluster with cellular automaton algorithm:

Step 1: Select block above energy threshold

0	0.01	0.02	0.01	0	0
0	0.05	0.05	0.1	0.4	0.1
0.02	0.2	0.5	0.3	1.9	0.1
0	0.3	3.0	0.3	0.3	0
0	0.2	0.2	0.1	0.03	0

0	0.01	0.02	0.01	0	0
0	0.05	0.05	0.1	0.4	0.1
0.02	0.2	0.5	0.3	1.9	0.1
0	0.3	3.0	0.3	0.3	0
0	0.2	0.2	0.1	0.03	0

0	0.01	0.02	0.01	0	0
0	0.05	0.05	0.1	0.4	0.1
0.02	0.2	0.5	0.3	1.9	0.1
0	0.3	3.0	0.3	0.3	0
0	0.2	0.2	0.1	0.03	0

Step 2: Maximum peak contaminates the blocks around it

			0.01		
	0.05	0.05	0.1	0.4	0.1
0.02	0.2	0.5	0.3	1.9	0.1
	0.3	3.0	0.3	0.3	
	0.2	0.2	0.1	0.03	

Problem: can't split these blocks to the adjacent two clusters, **need ANN.**

			0.01		
	0.05	0.05	1.9	1.9	1.9
0.02	3.0	3.0	3.0	1.9	1.9
	3.0	3.0	3.0	1.9	
	3.0	3.0	3.0	0.03	

			1.9		
	3.0	3.0	1.9	1.9	1.9
3.0	3.0	3.0	3.0	1.9	1.9
	3.0	3.0	3.0	1.9	
	3.0	3.0	3.0	3.0	

Two clusters are reconstructed

Then, the energy, time and position information of photon cluster could be reconstructed through these pulses.

Module array simulation *(first preliminary result)*

Performed by **Xiaoyu Peng(彭肖宇)**, supervisor: **Prof. Xiaodong Wang**(USC)

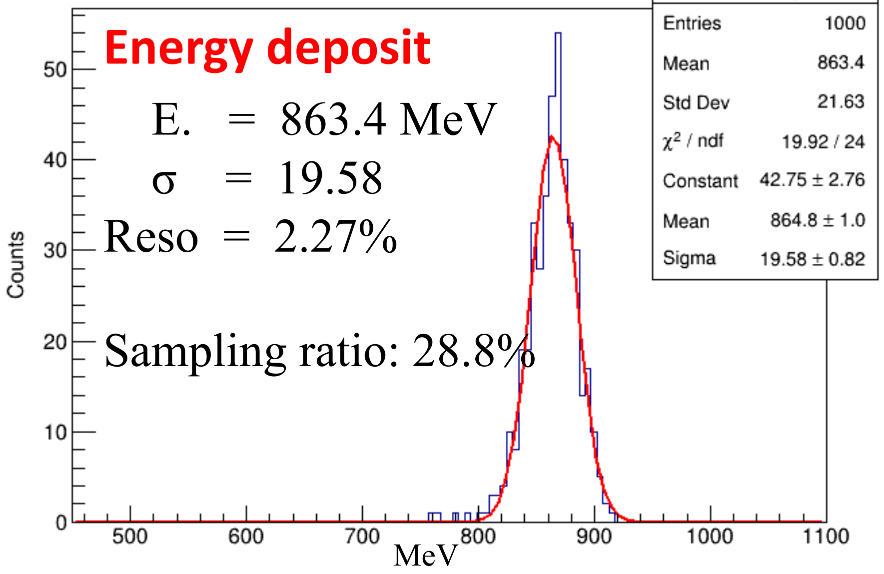
- **3GeV e- vertical incident**
- **7×7 module array**

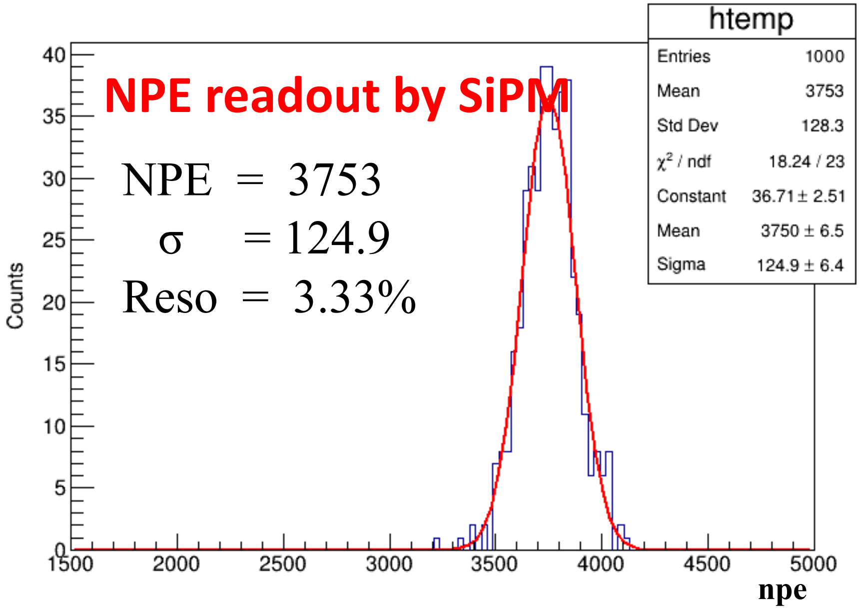
Considering 20% resolution of SPE signal, the total energy resolution @3GeV could be evaluated as:

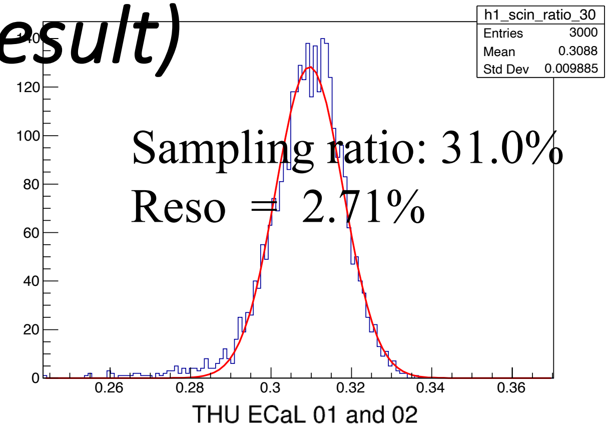
$$\sigma_{all} \approx \sqrt{\sigma_{NPE}^2 + \left(\frac{\sigma_{SPE}}{\sqrt{N_{mean}}}\right)^2}$$

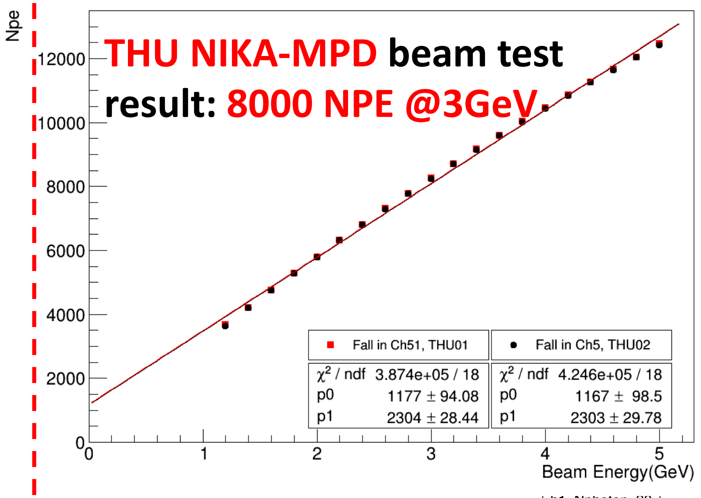
$$= \sqrt{0.03328^2 + \left(\frac{0.2}{\sqrt{3753}}\right)^2}$$

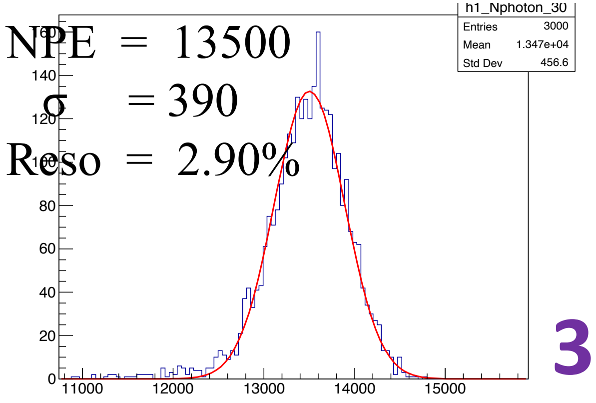
=3.343%









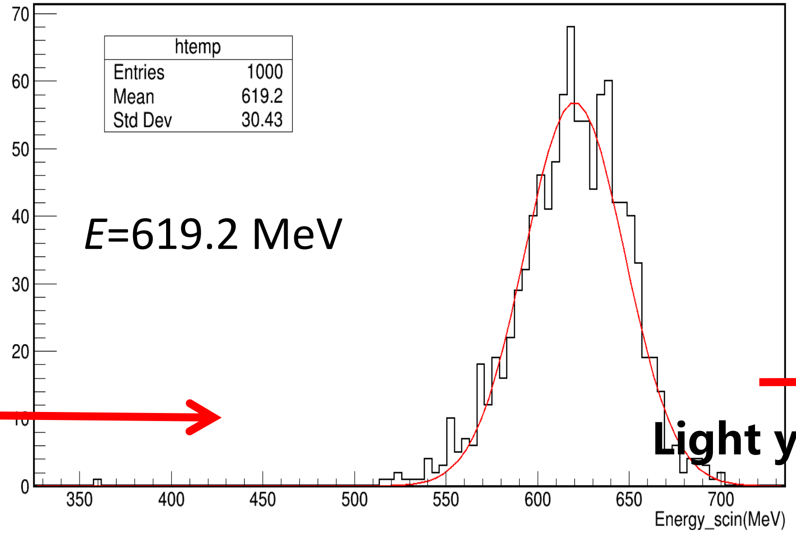


Photon collection efficiency in each step

Performed by **Xiaoyu Peng(彭肖宇)**

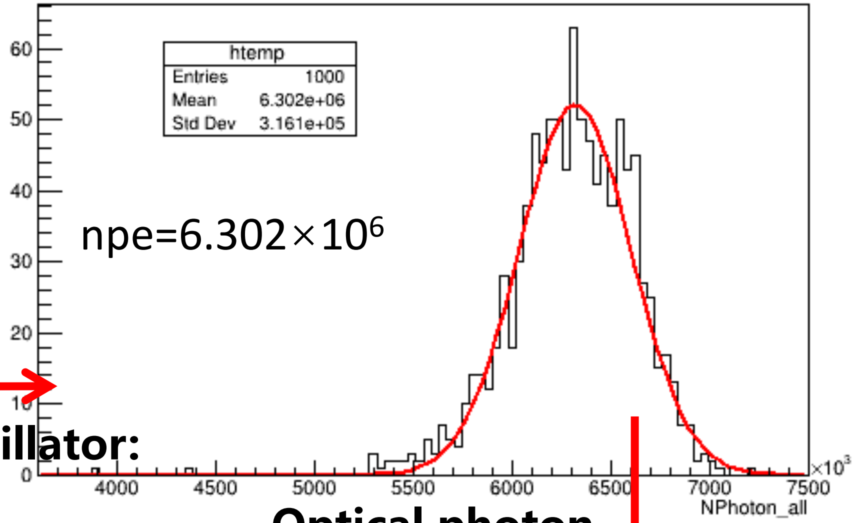
- **3GeV e-**
- **Single module**

3GeV e- incident to single module



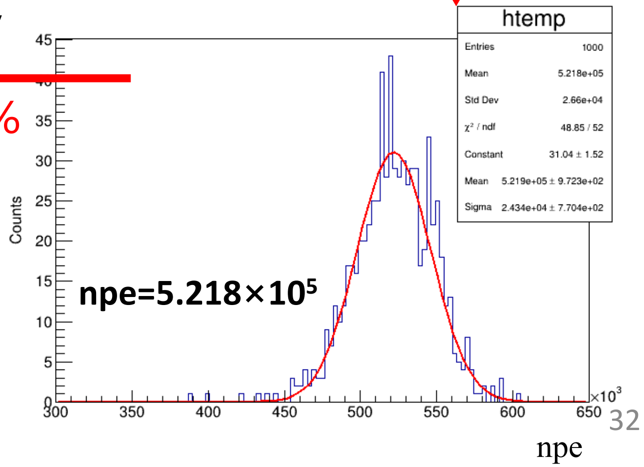
101.78%* *E*

Light yield in scintillator: 10npe/keV



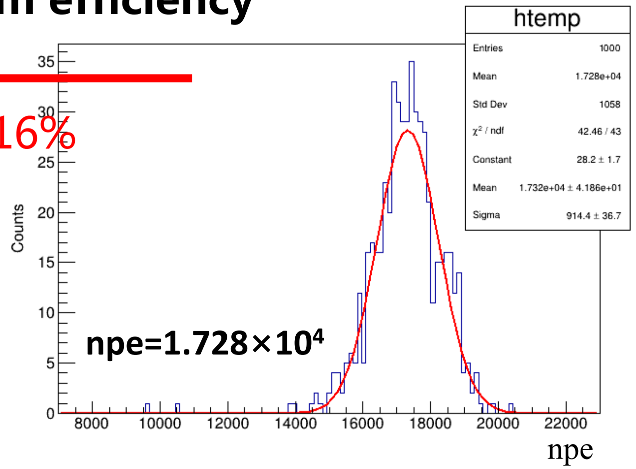
Optical photon entering WLS fiber

8.28%



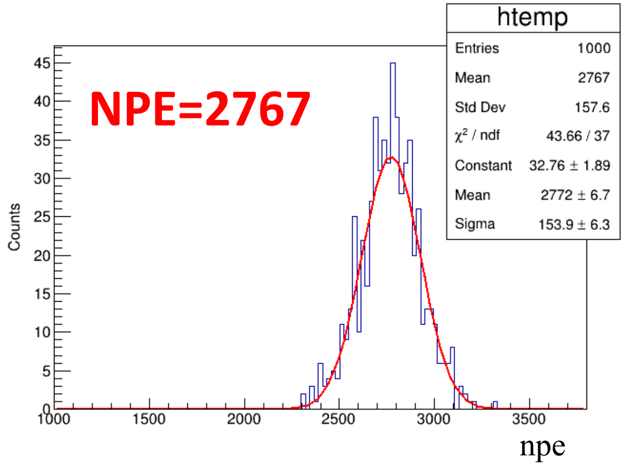
Trapped by fiber and transportation efficiency

3.31%



Considering SiPM quantum efficiency

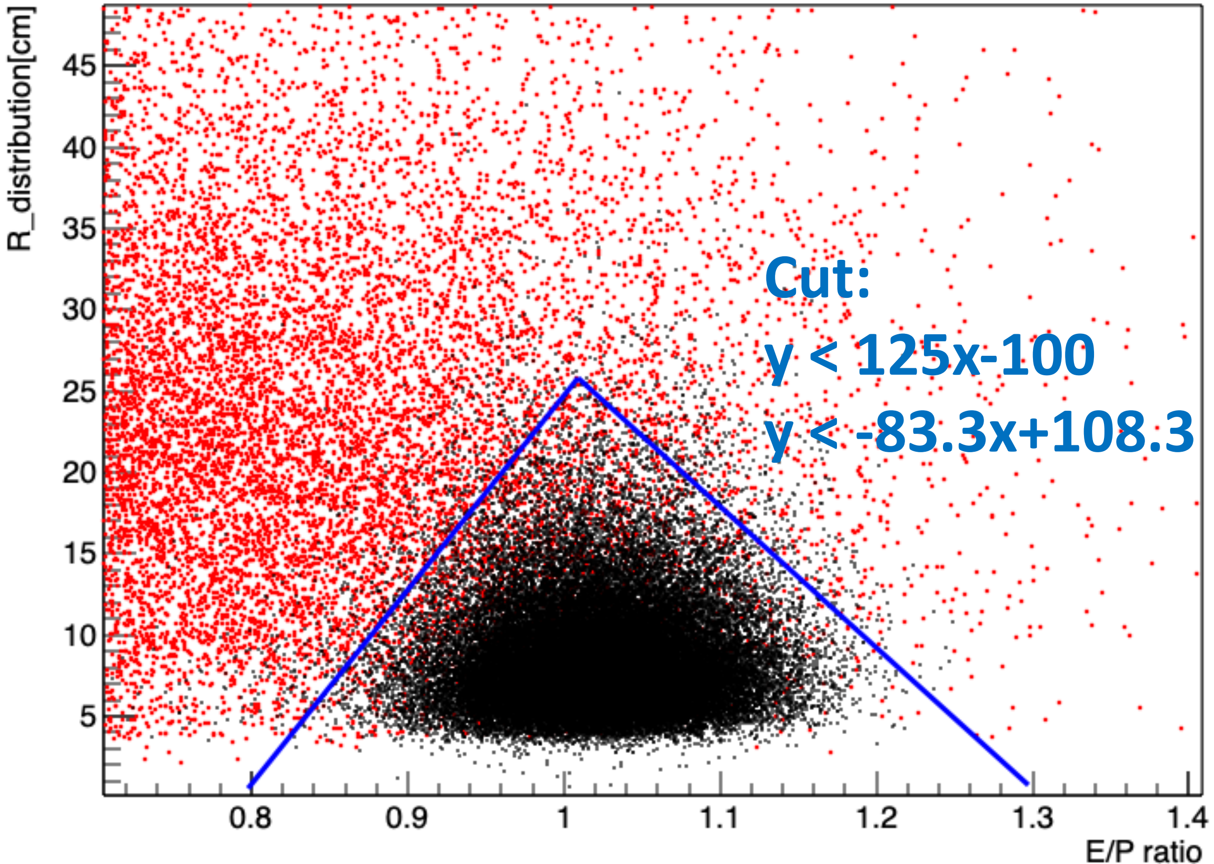
16%



Considering both E/P and R cut for 0.5-1 GeV/c e/π

$$P_{\perp min} = r * H * \frac{\frac{e}{c}}{P \to m} = 0.45 * 1.5 * \frac{\frac{1.6}{3}}{1.78} = \mathbf{0.202} \, \frac{\mathbf{GeV}}{\mathbf{c}}$$

If a particle has $P_{\perp}$ less than 0.202 GeV/c, it will never hit barrel, but could hit the endcap.



Percentage (%) (210k events)		Real PID	
		e	π
PID result	e	97.4	3.5
	π	2.6	96.5

Low momentum PID get worse, but not too worse.

π^0 in EicC

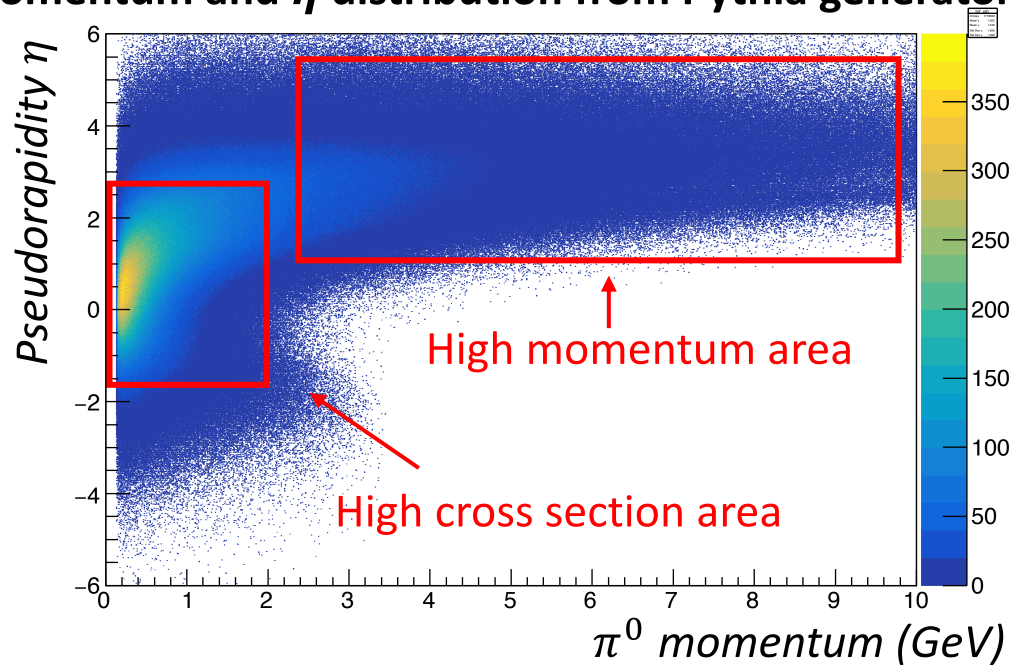
- Two photons ➤ π^0 reconstruction
- **π^0 Detection efficiency:**

π^0 Kinematic distribution → **energy cut** → detector acceptance → reconstruction efficiency

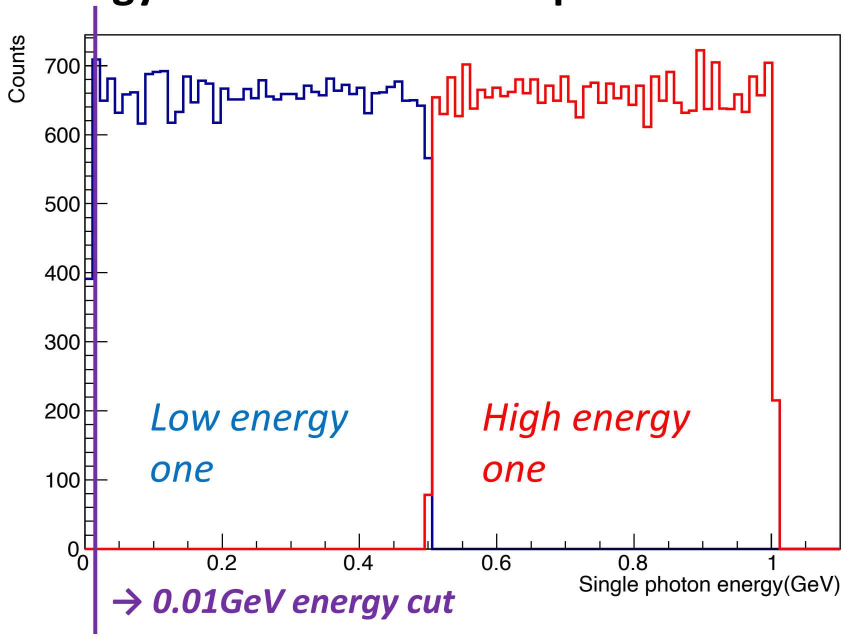
Intrinsic

Design and algorithm

π^0 momentum and η distribution from Pythia generator



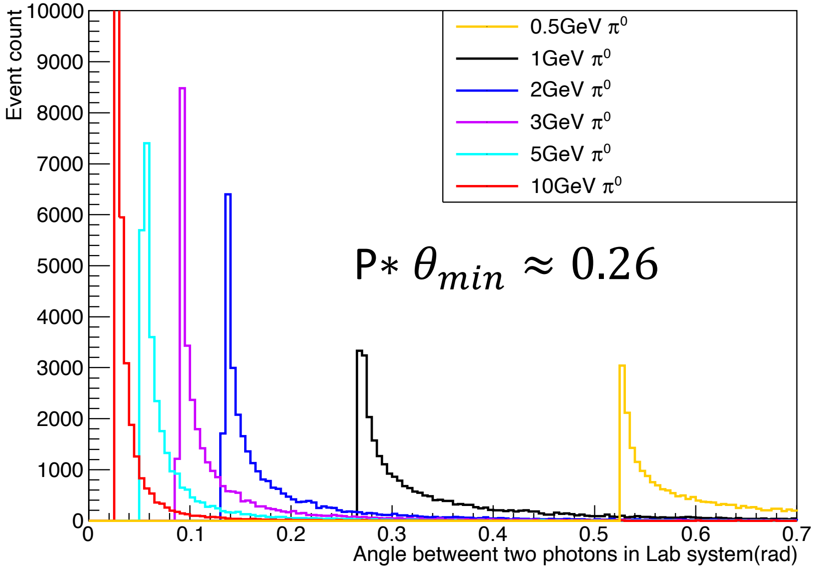
Energy distribution of two photons



1GeV π^0

Eifficiency >99%

Angle of two photon in Lab system



π^0 reconstruction

- π^0 **Detection efficiency:**

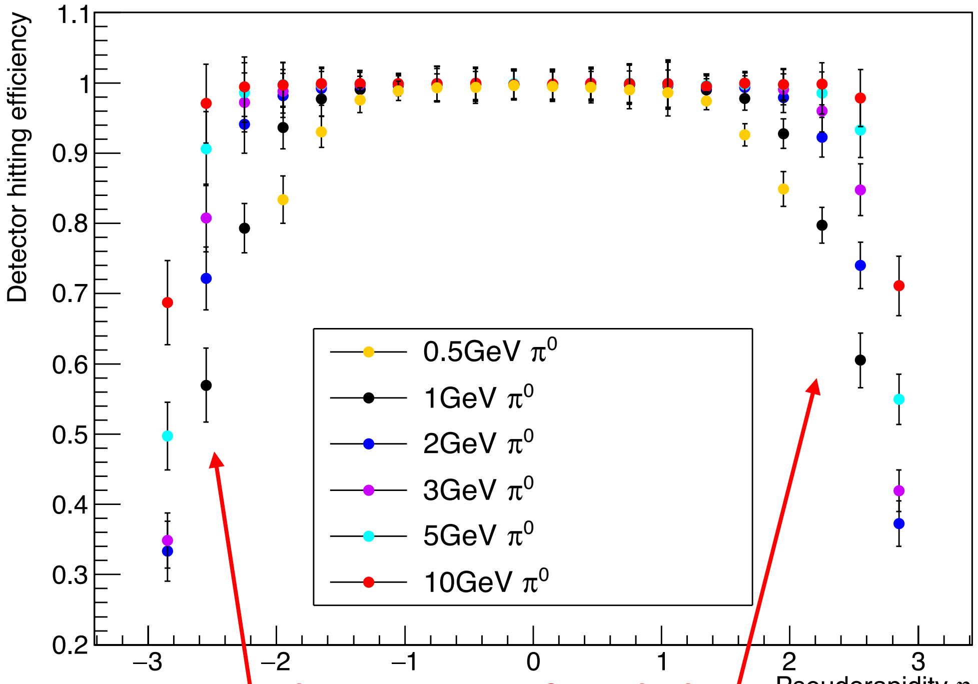
π^0 Kinematic distribution

energy cut

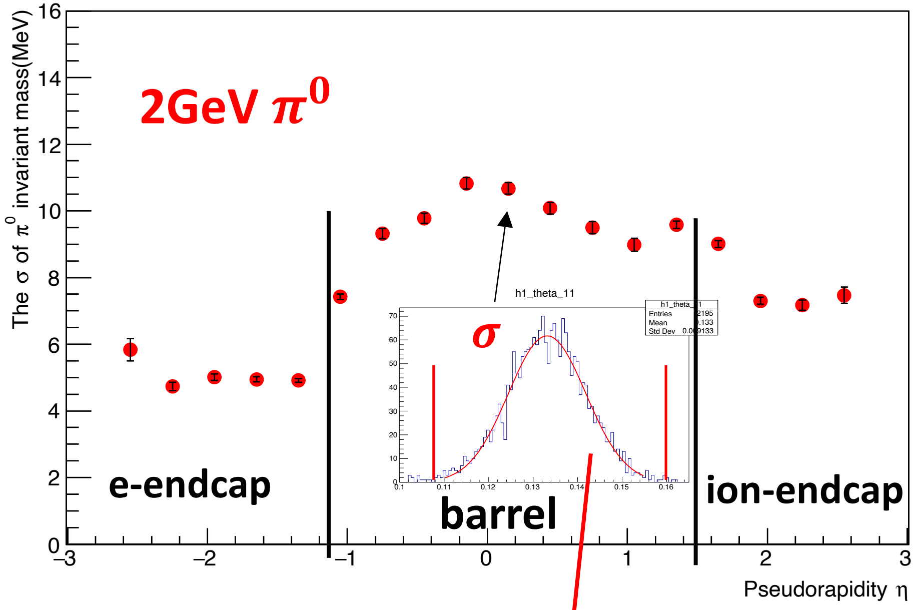
detector acceptance

reconstruction efficiency

ECal intrinsic geometry acceptance of π^0

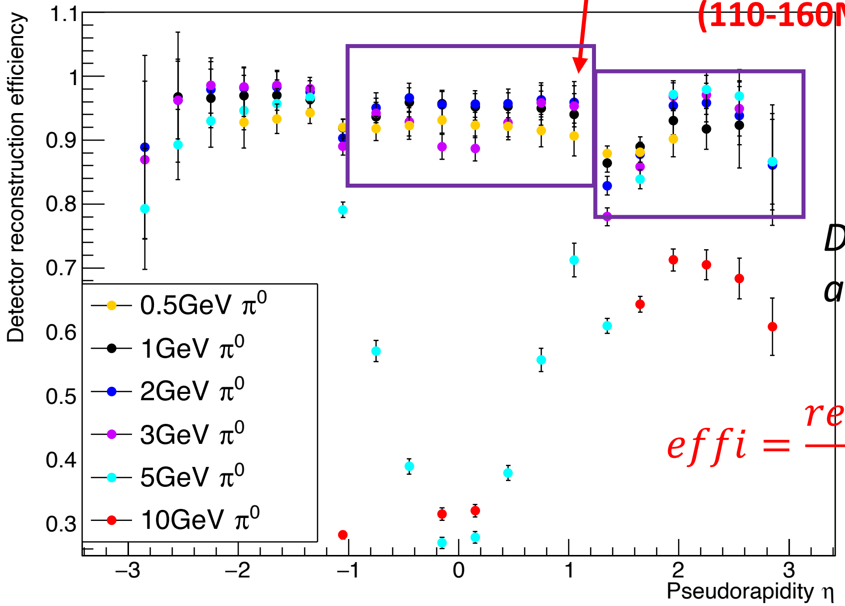


π^0 invariant mass resolution v.s. Pseudorapidity



π^0 reconstruction efficiency

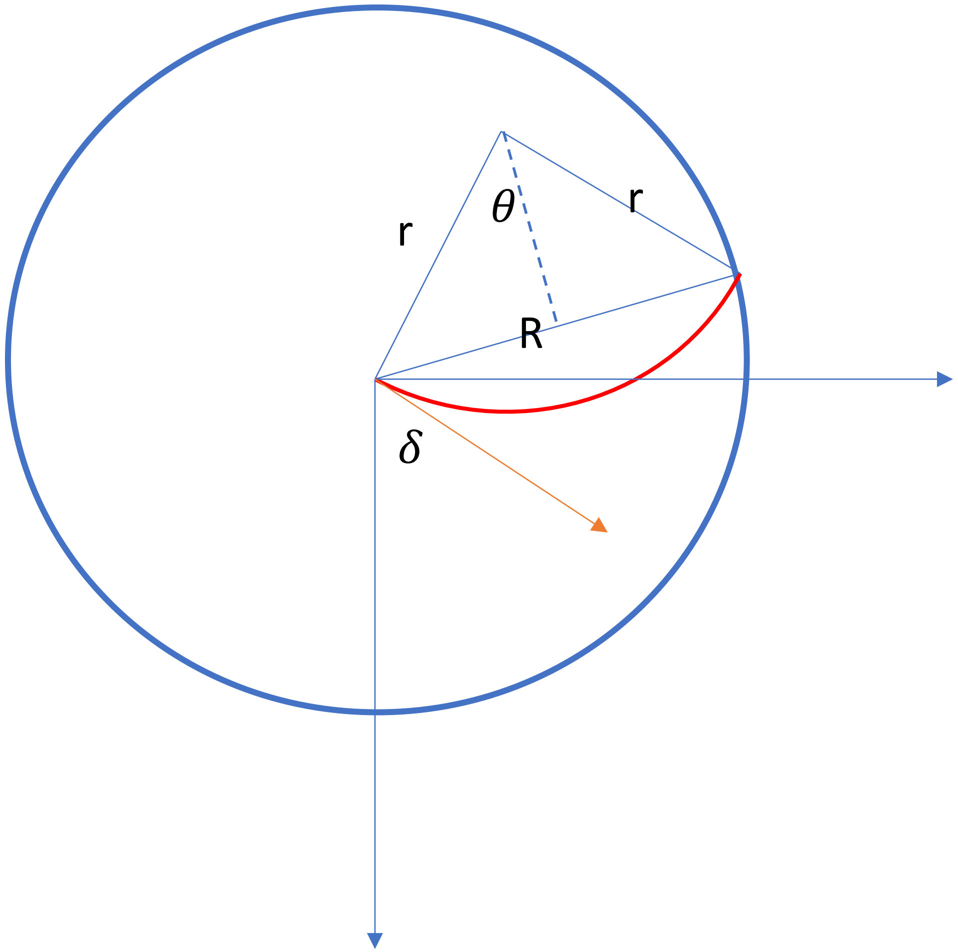
✓ π^0 invariant mass cut (110-160MeV)

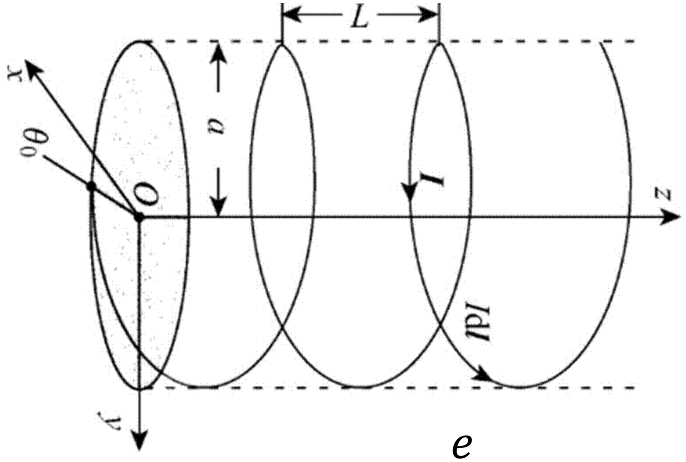


Dependent on the angle of two photons

$$effi = \frac{reconstructed\ \pi^0}{hitted\ \pi^0}$$

Add megnetic field





实际转动
不到半圈

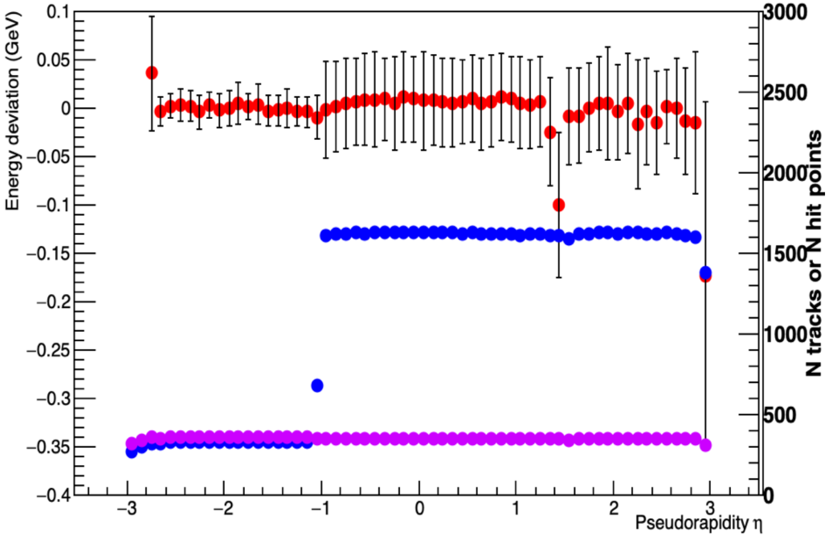
$$P_{\perp min} = r * H * \frac{\frac{e}{c}}{P \to m} = 0.45 * 1.5 * \frac{\frac{1.6}{3}}{1.78} = \mathbf{0.202\ \frac{GeV}{c}}$$

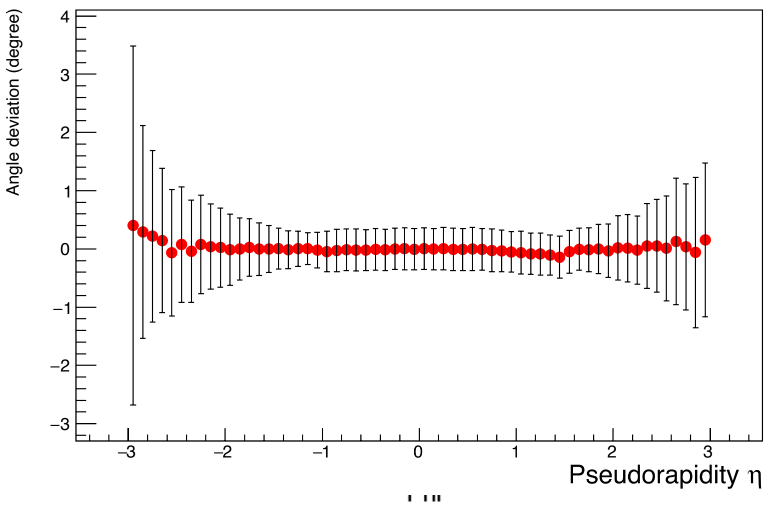
If a particle has $P_{\perp}$ less than 0.202 GeV/c, it will never hit barrel, but could hit the endcap.

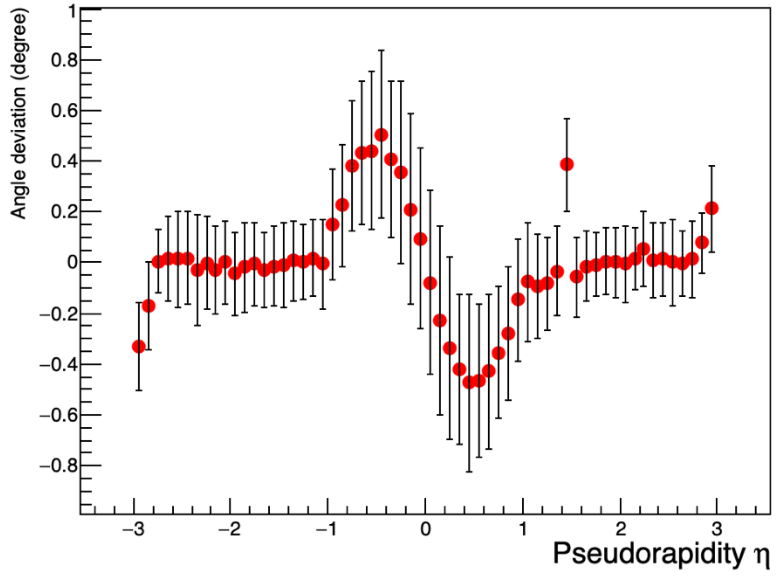
- 加入磁场后，粒子飞行时间增加，XY平面会增加一定角度入射，z-theta平面，粒子击中时的|z|距离增加。
- 量能器可以得到的击中信息（E, x, y, z)
- 除了能量E，其它三个参数均无法直接推算粒子的信息。

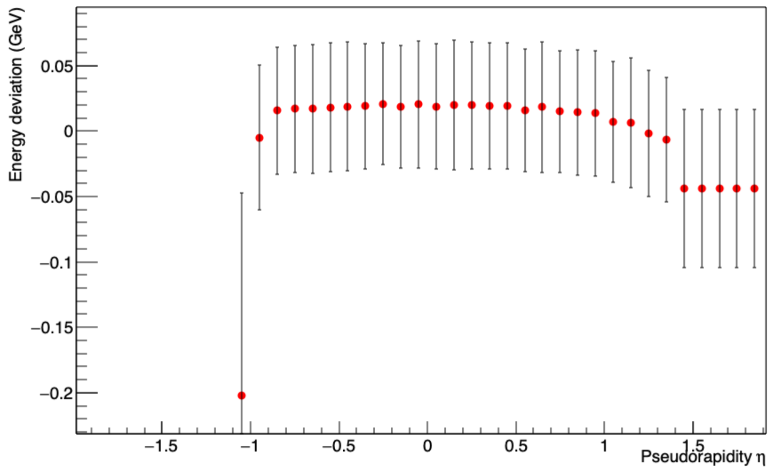
- 电子，能量1GeV
- 磁场1.5T
- 只考虑桶部击中

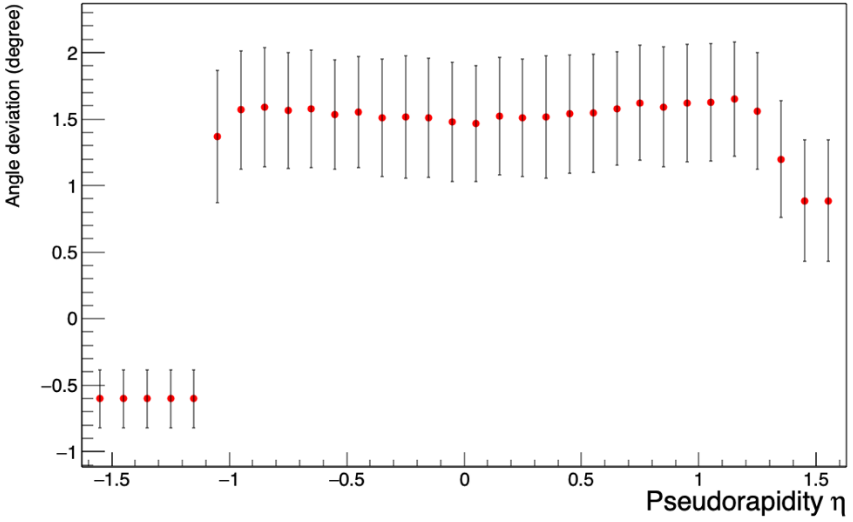
Comparison w/ and w/o magnetic field (barrel)

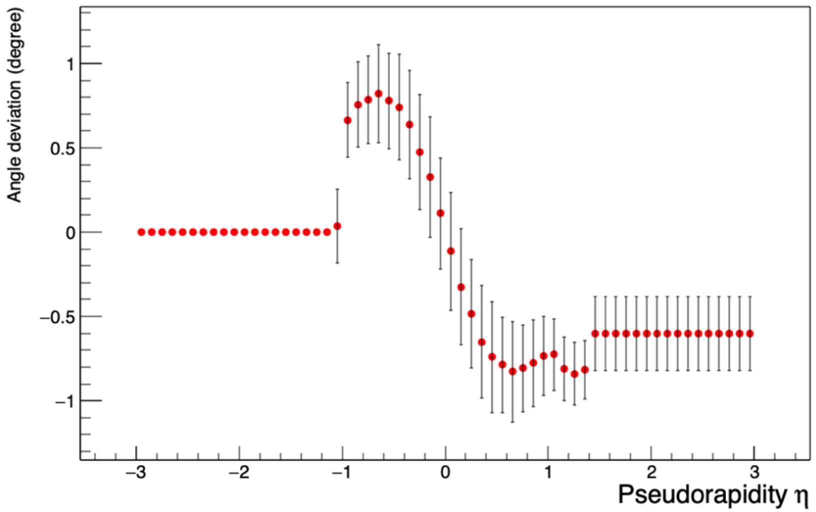












Beam test results