Segmented active absorber calorimeter development

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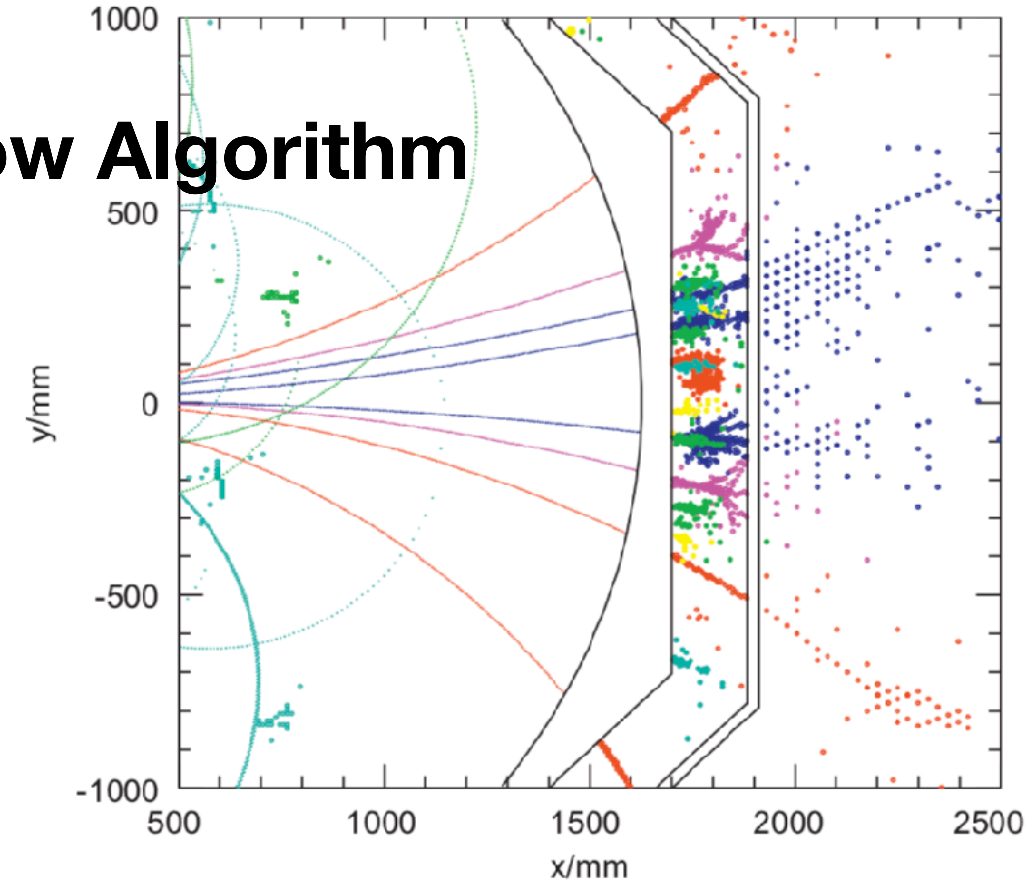
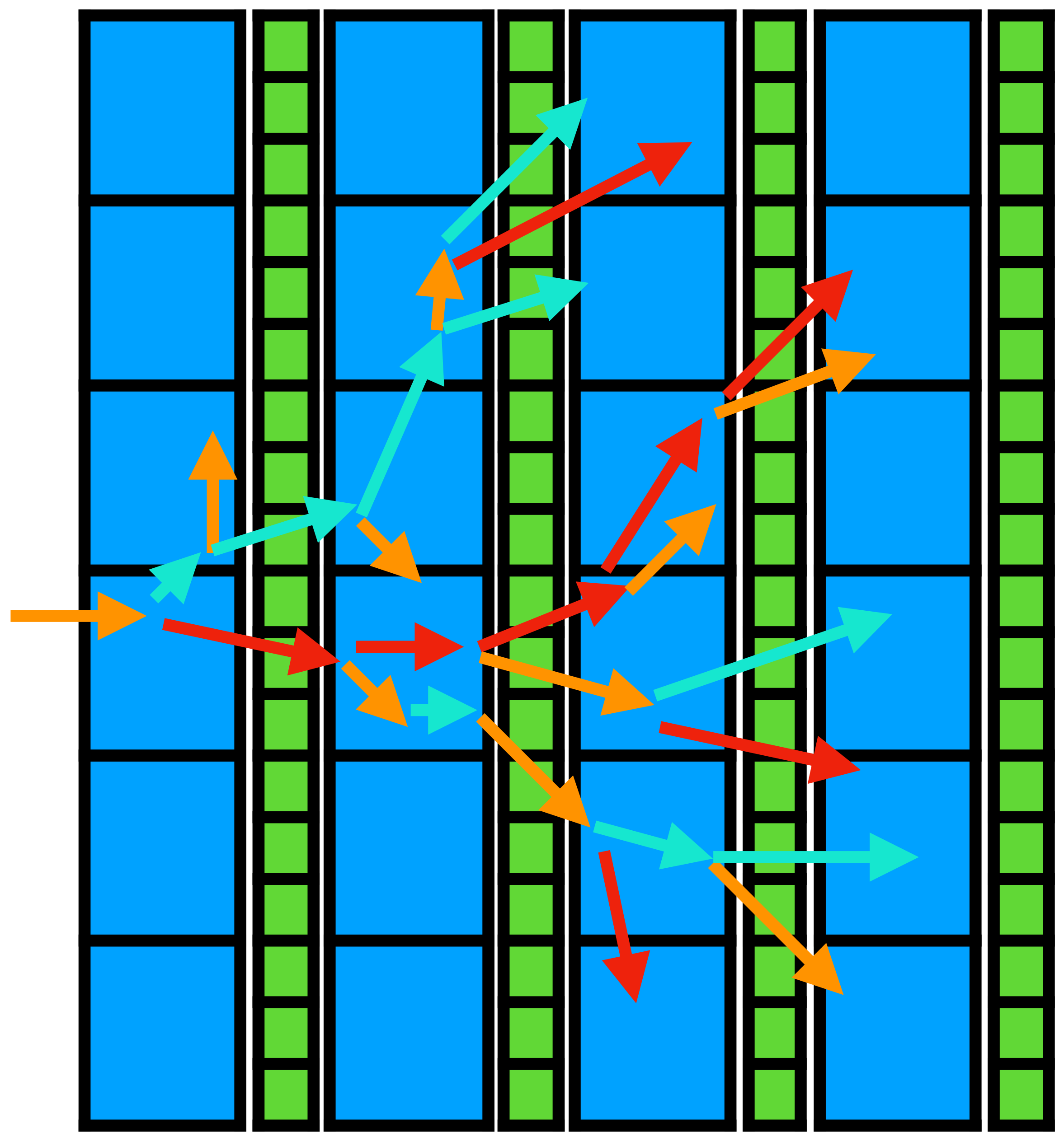
Segmented Active Absorver Calorimeter

Particle Flow Algorithm



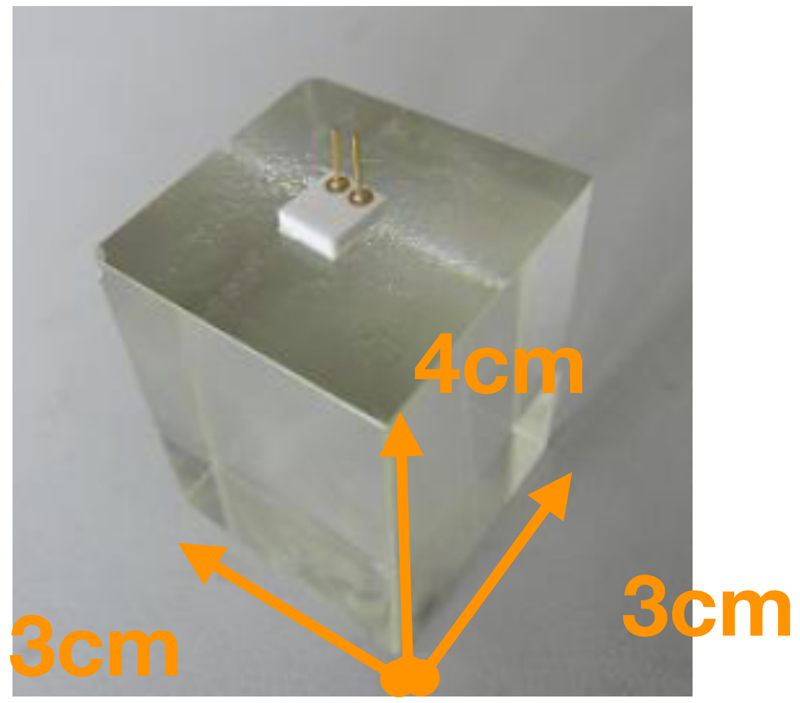
- Improving calorimeter performance is necessary for future high-energy frontier collider experiments.
- Particle Flow Algorithm is indispensable for future experiments.
- To use PFA, a sampling calorimeter is required.
- If the energy of the absorber layer is taken into account, the energy resolution can be improved.
- The active absorption layer should be subdivided accordingly for PFA.
- Therefore, we considered Segmented Active Absorber Calorimeter



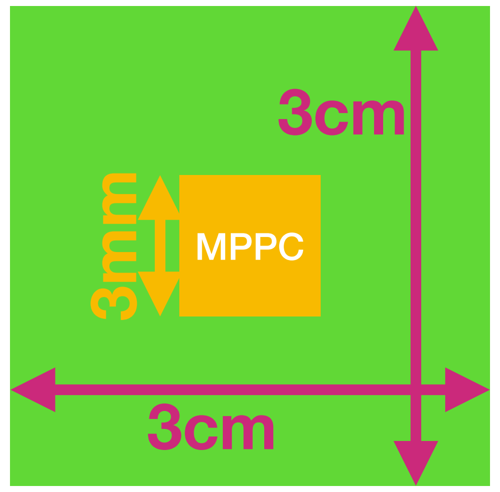
Energy Measurement: Absorber
Position Measurement: Detector

Segmented Lead Glass Absorber

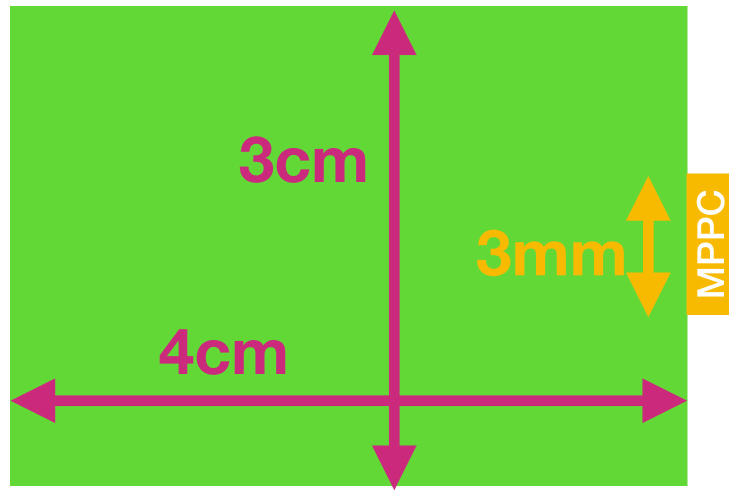
- One of the active absorber materials is lead glass.
- The lead glass is transparent.
  -> Cherenkov light can be measured with an optical sensor.
- MPPC is a thin photosensor.
  -> It can reduce dead volume.
  -> We use 3x3mm^2 sensor(S13360-3050CS, S13360-3075CS).
- Segmentation is necessary for PFA.
  -> 3 x 3 x 4 cm^3 size lead glass block
- To read out each lead glass independently for PFA
  -> Each block was enveloped with reflector.
- This one lead glass has 2.4X_0 (4cm thickness)
  (lead glass X_0 = 1.7 cm)
- 1 layer consists of 9 lead glass block array.
  (This array is enclosed by a 5 mm aluminum case.
- We manufactured 3 layers for the prototype.



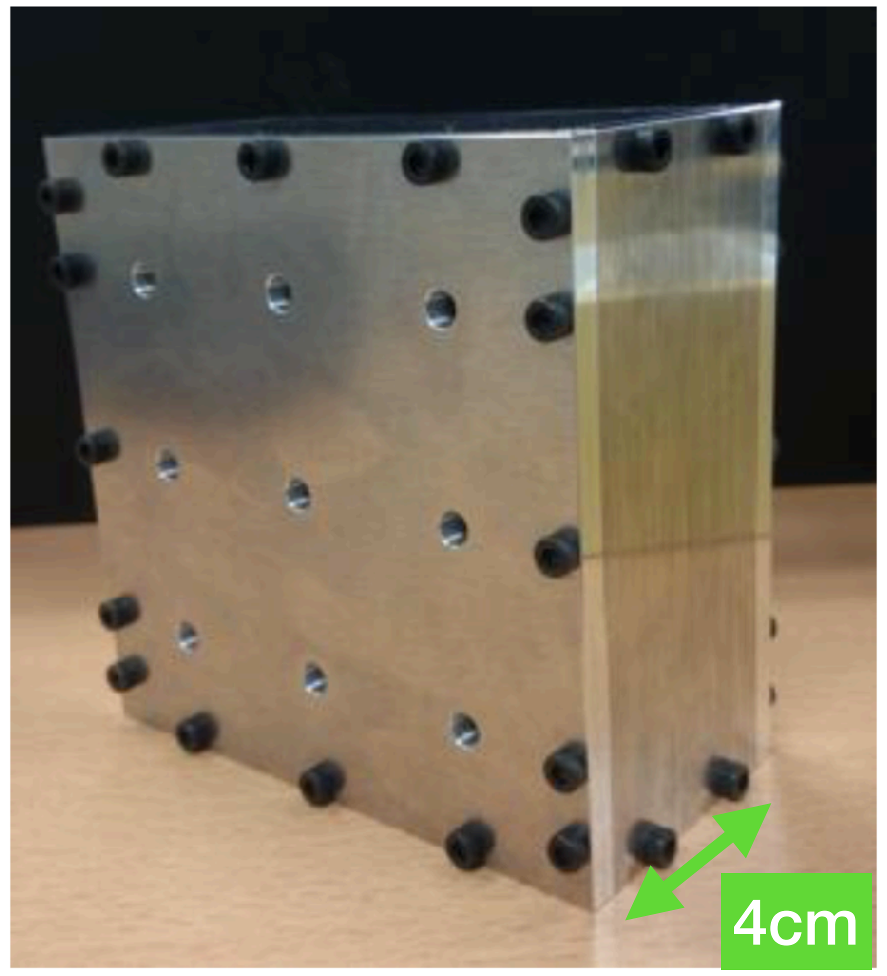
Lead glass block with optical sensor (MPPC)



Backend view



Top view

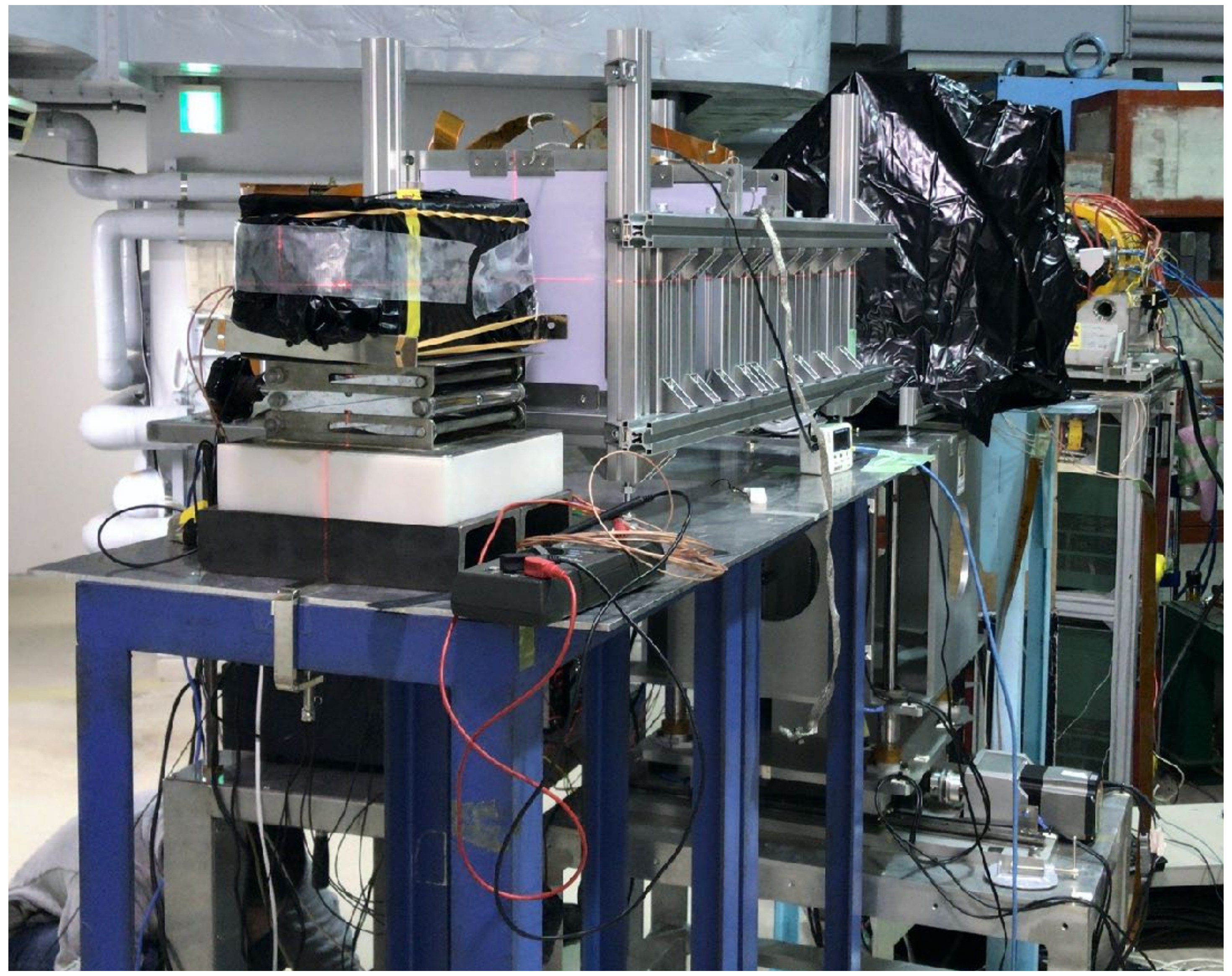


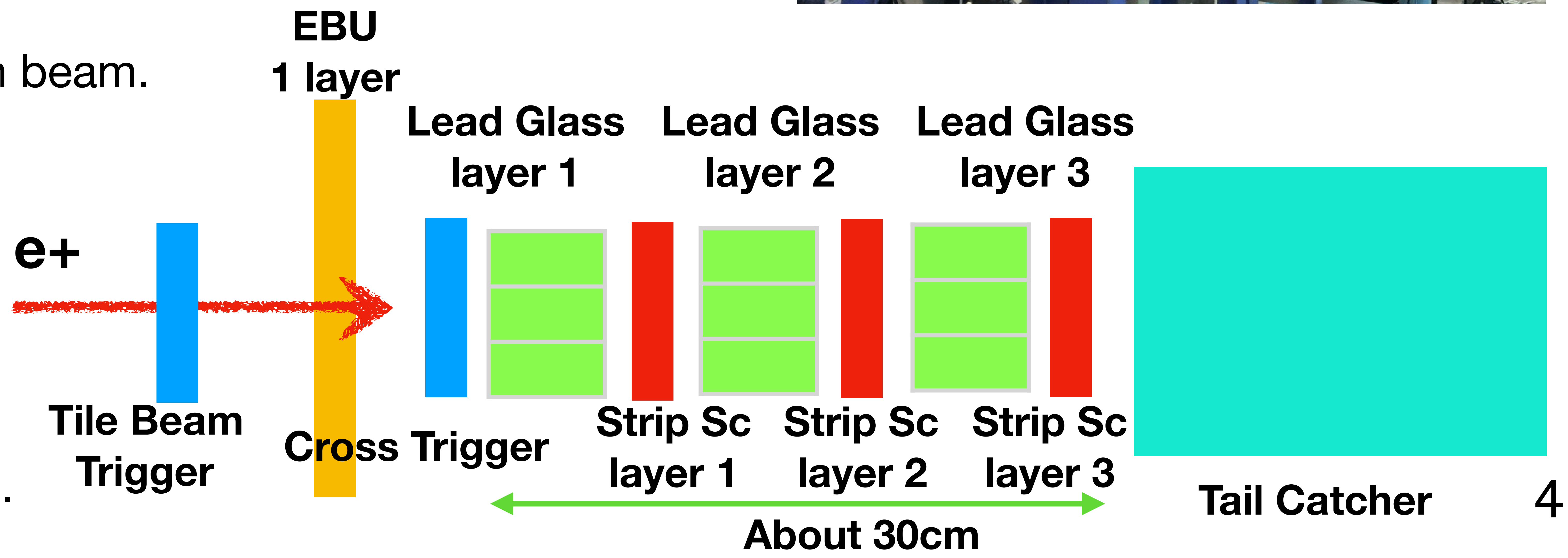
Active Absorber Layer


Lead Glass blocks Array

Prototype of active absorber ECAL

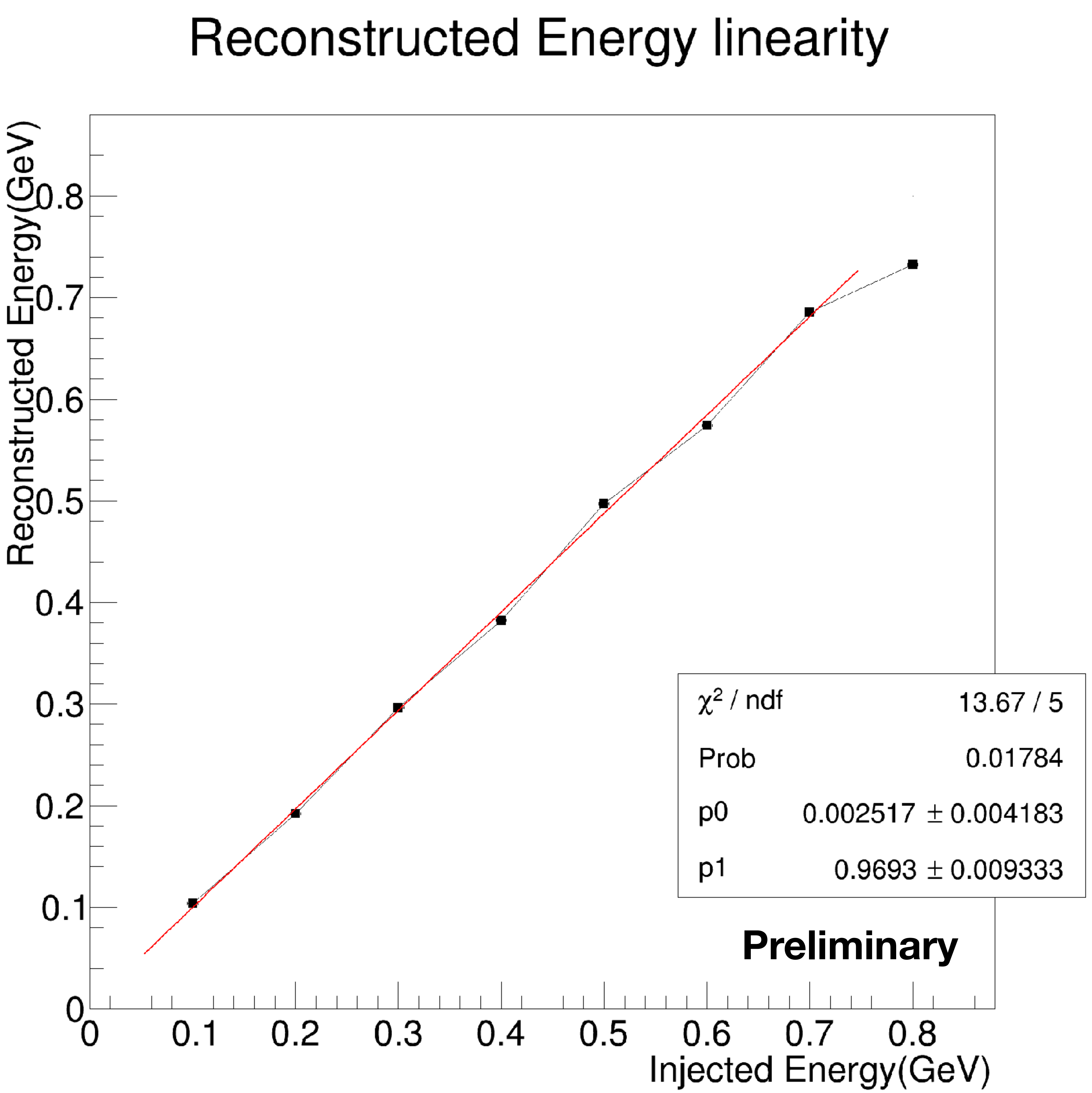
- We manufactured 3 layers sampling calorimeter as an active absorber ECAL.
  - **Active Absorber layer**: Segmented lead glasses with MPPCs
  - **Fine granulated detection layer**: Strip scintillators
  - **Tail catcher**: A large lead glass
- We performed test beam at ELPH at Tohoku University (ELPH: Research Center for ELectron PHoton Science
- Injection from 100MeV to 800MeV positron beam.
- The tests were performed in this order.
  - Tail catcher calibration
  - Lead glass block calibration
  - Entire prototype performance evaluation.





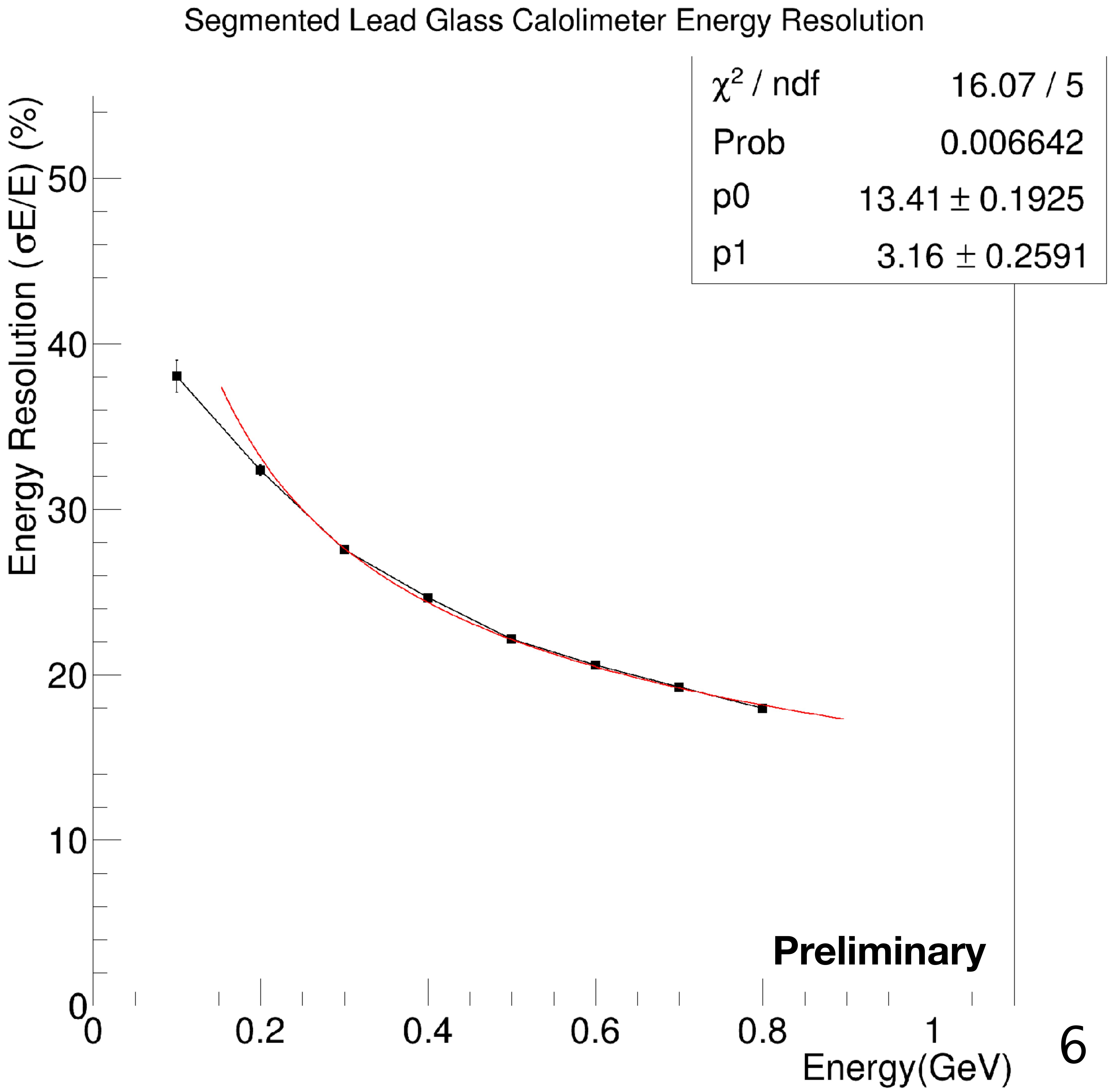
Energy linearity

- Linearity is calculated based on the result of energy reconstruction.
- Results up to 700MeV are linear enough.
  -> Slope is 0.970
- The intercept of 0.003GeV is small enough to be consistent with zero.
- At 800 MeV, it is not included in the fitting.
- This reason is also investigated using simulation.



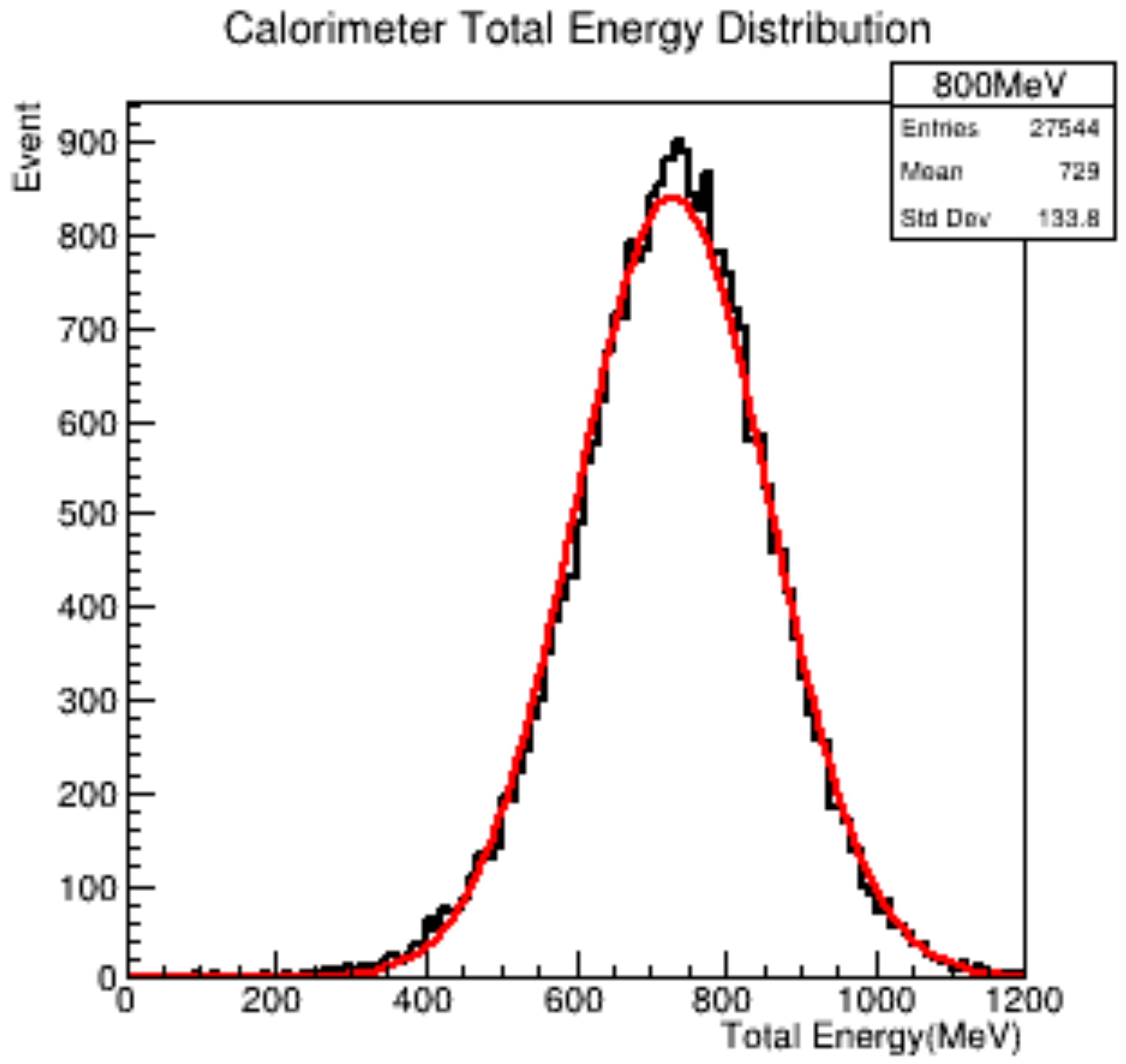
Energy resolution

- The energy resolution was calculated from the energy reconstruction results.
- Excluding 100 MeV, the results are in good agreement with $1/\sqrt{E}$ fit results
- From the result, the resolution results is 13.5%$/\sqrt{E}$
- The constant term is as large as 3%
- We are checking 100MeV data and large constant term.
- This resolution is greatly influenced by photon statistics and aluminum case.
- We are investigating the effect of photon statistics and material effect by simulation



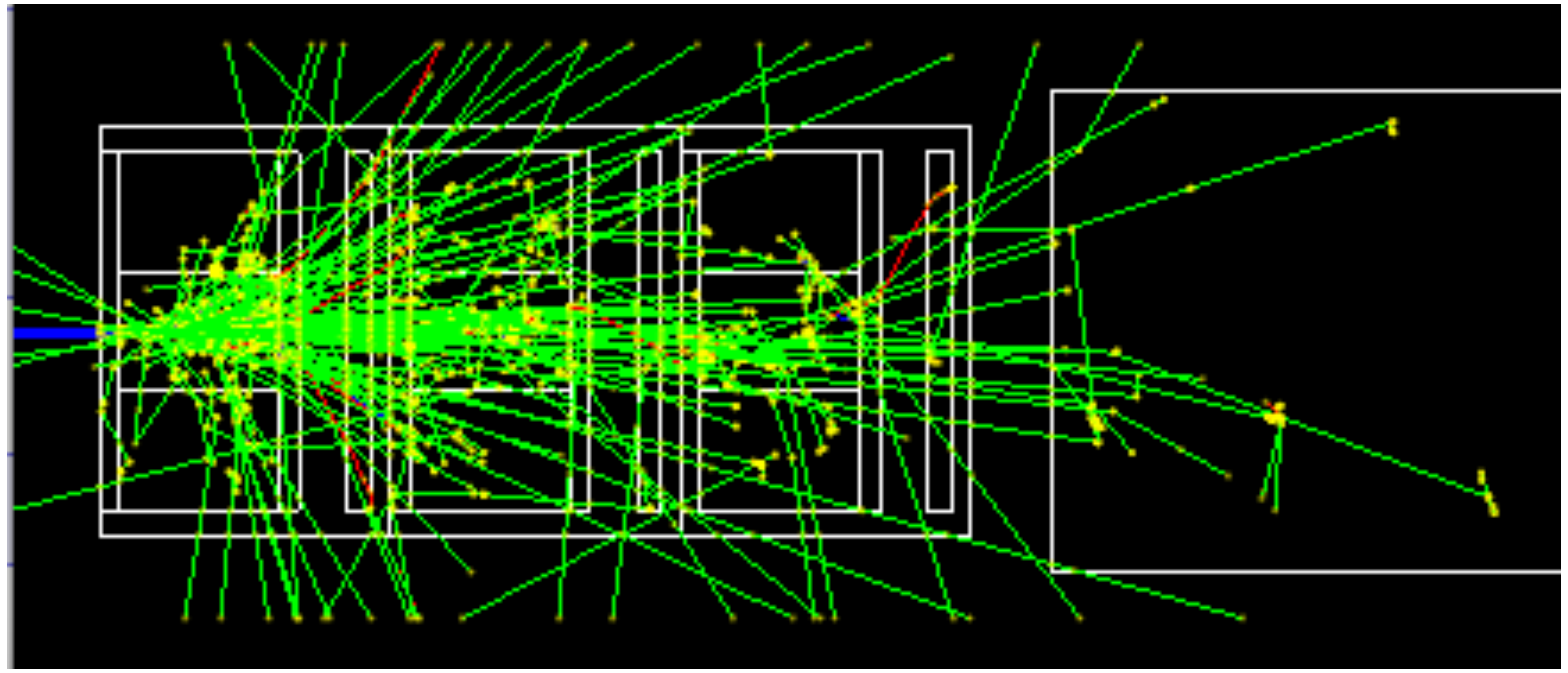
Current problem

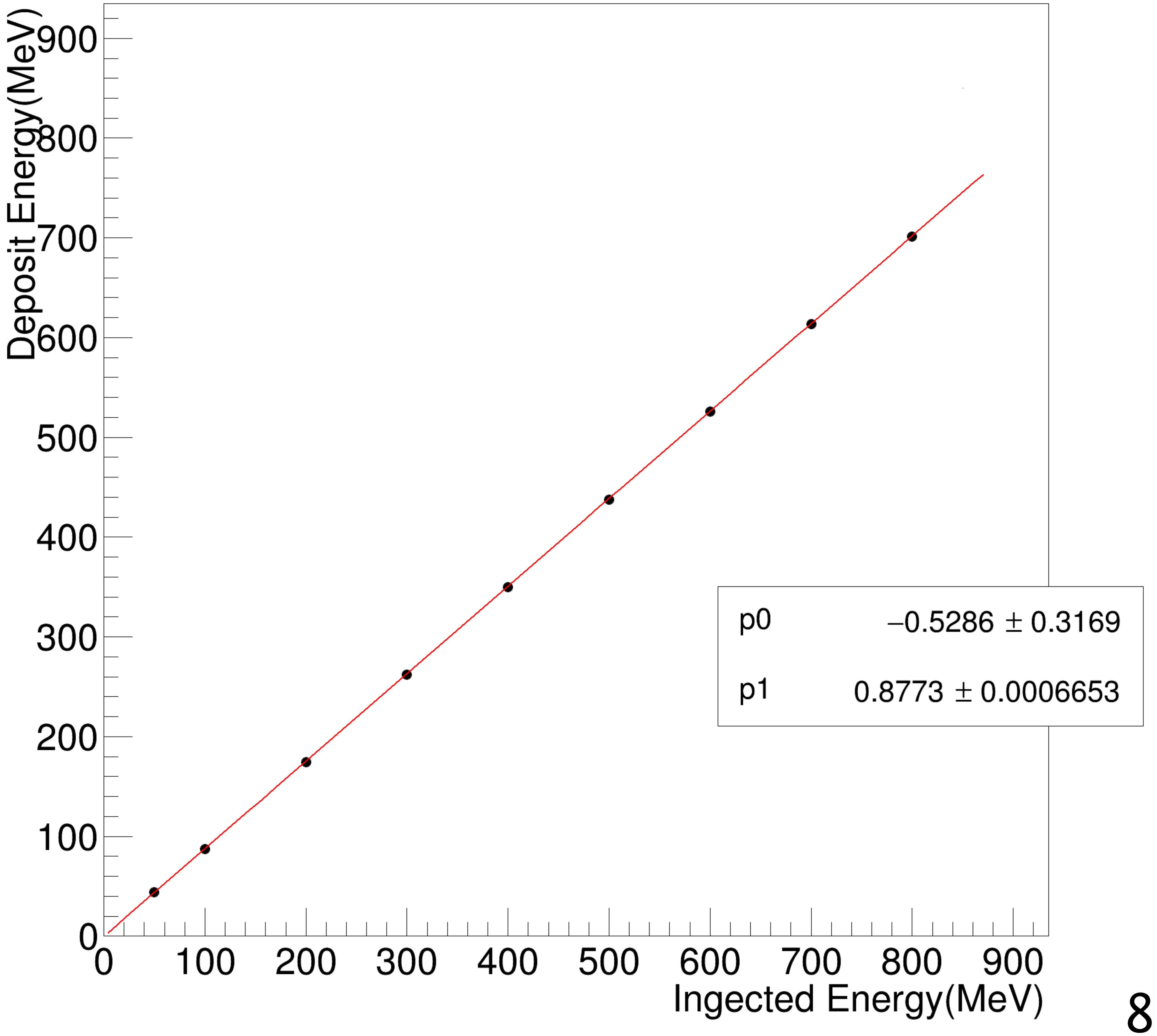
- We have three big problems.
  - Energy deviation from the linearity of the reconstruction at 800 MeV.
  - Overall energy resolution is not as high as expected.
  - Why there is a large constant of 3% in energy resolution.
- For example, 800 MeV data alone is no problem.
- Think about other factors that are not the calorimeter itself.
- We are trying to determine the cause of this problem in simulation.
- We are also trying to improve the calorimeter itself.



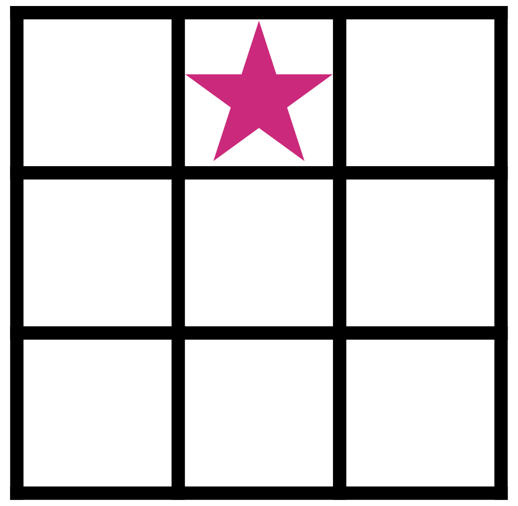
Energy leak

- The total radiation length of this calorimeter is about $22X_0$ (37cm thickness lead glass)
- Since it is not a large calorimeter, it is necessary to check the amount of leakage.
- According to simulations, the energy leak is about 12%.
- Shower is leaking side and diagonally backward.





Effect of dead channel



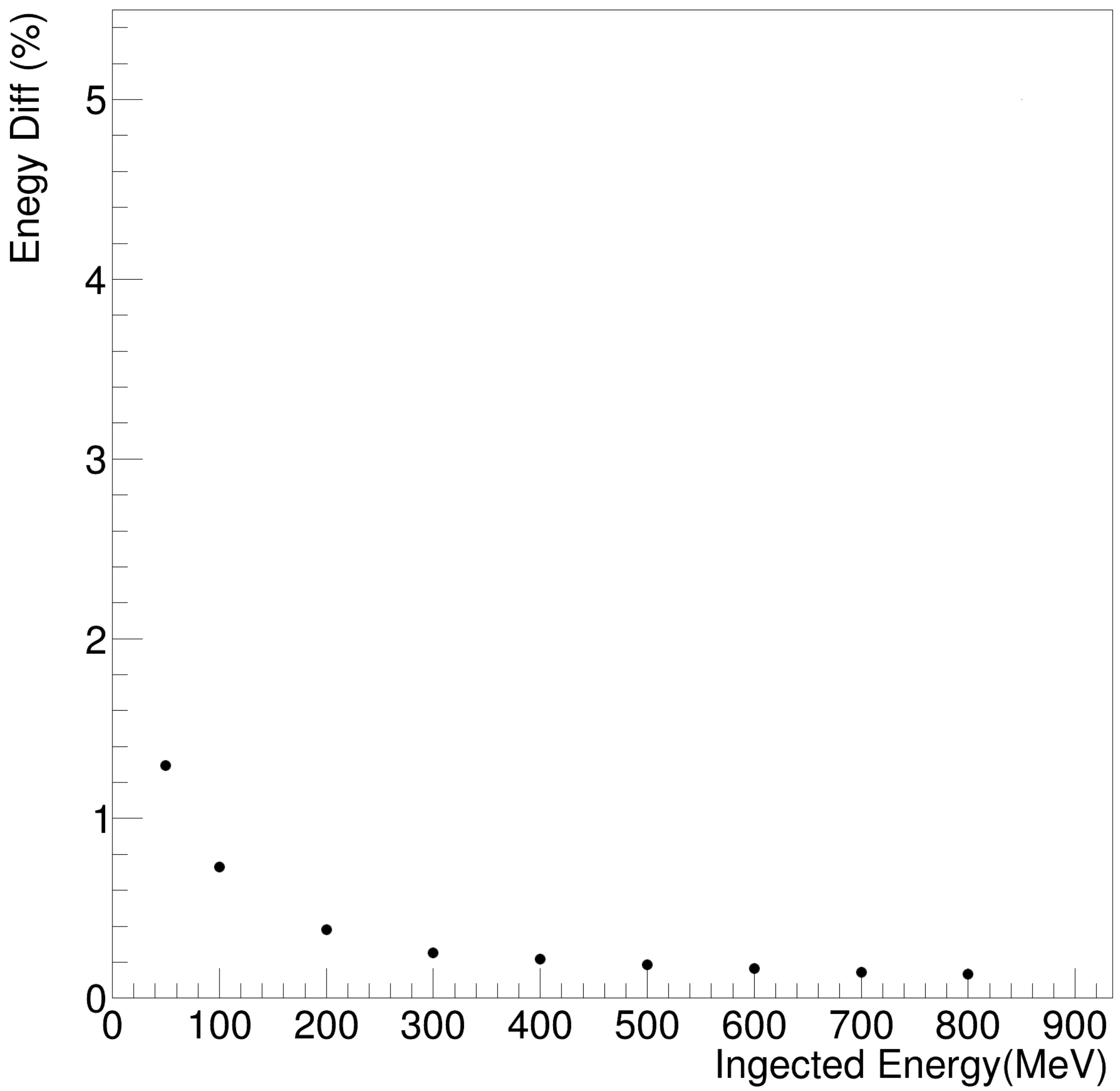
- The adjustment range of EASIROC was not enough and the center left channel of the first layer was dead.

- Since the shower is generated from the center, not important first layer except for the central channel

- This was actually confirmed by simulation

- In most cases, it was about 1% and above 300 MeV it was 0.2%.

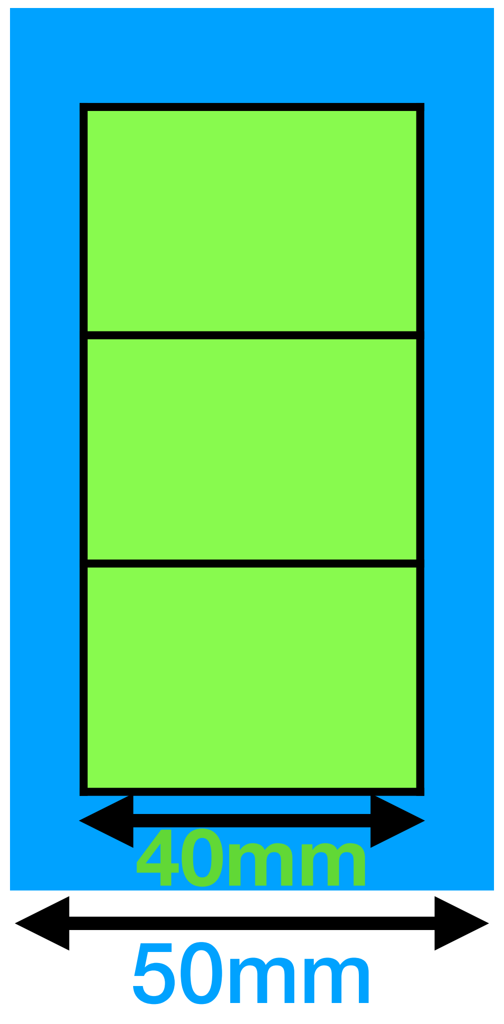
$$(1 - E_{w/o1ch}/E_{all}) \cdot 100$$

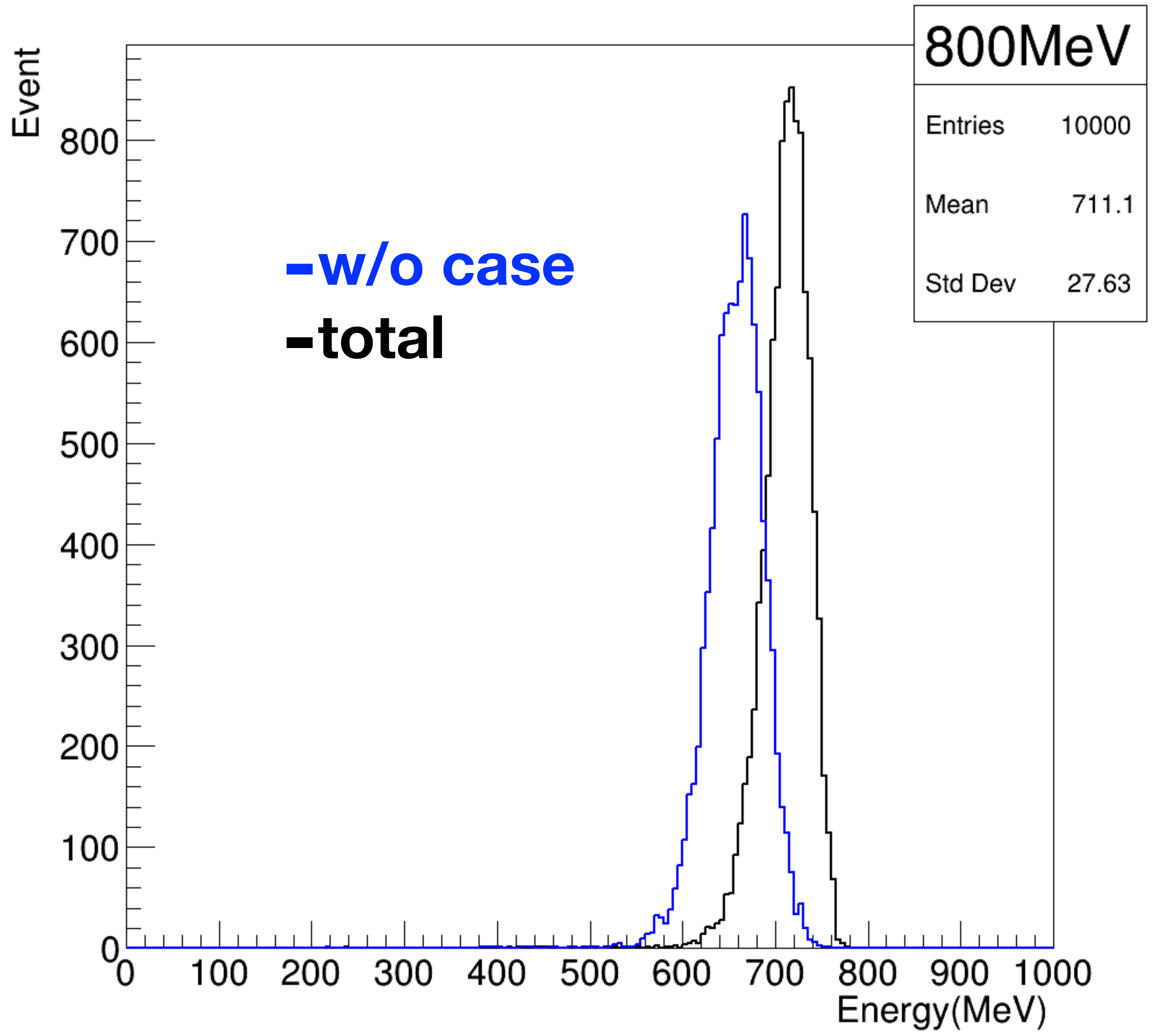


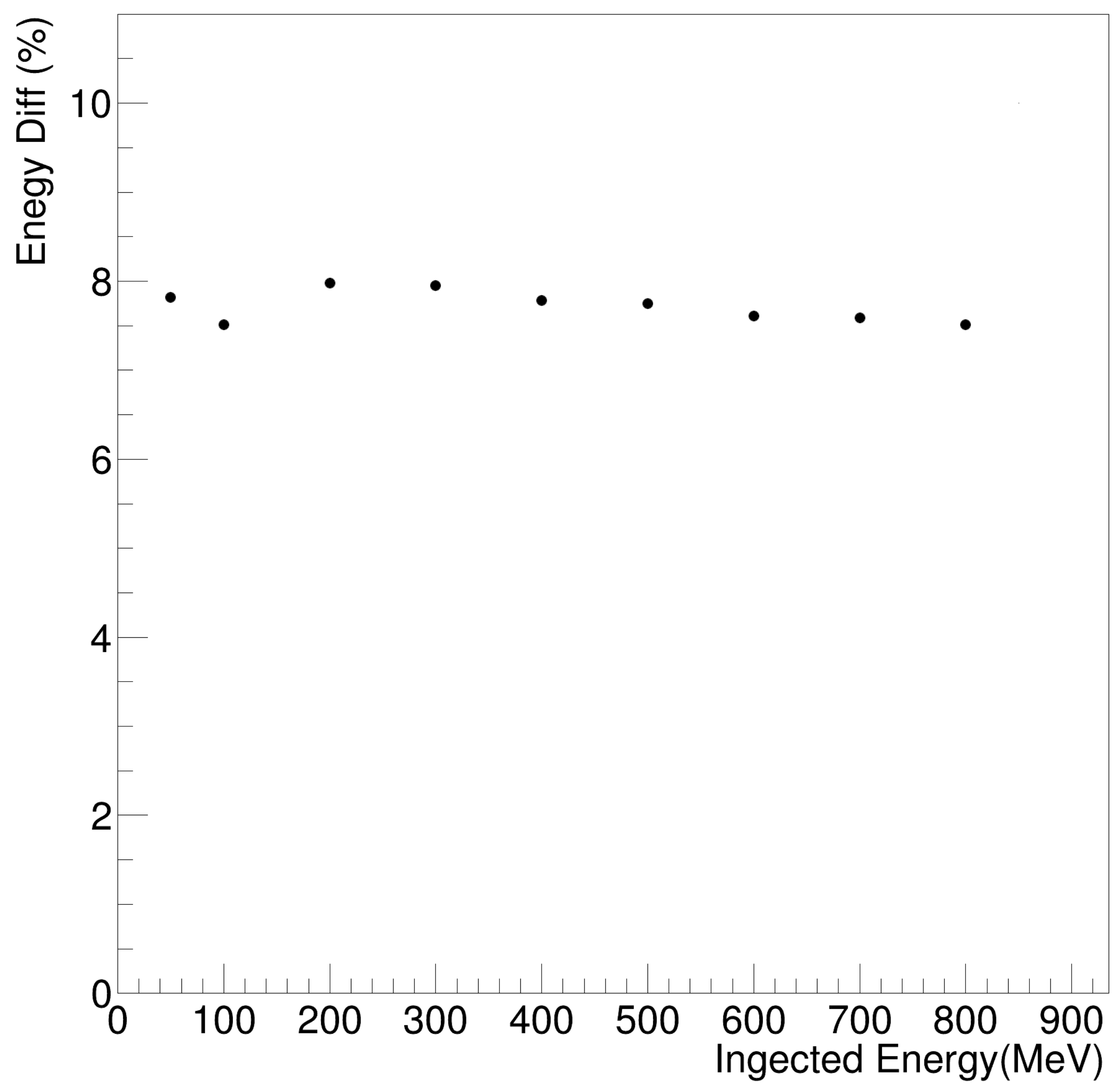
Effect of aluminum case

- Covered with aluminum case to hold lead glass blocks.
- The thickness is 10 mm per layer and 30 mm for three layers.
- Therefore, the corresponding energy is deposited here.
- The energy deposit of the case is about 8%.

$$(1 - E_{w/ocase}/E_{all}) \cdot 100$$

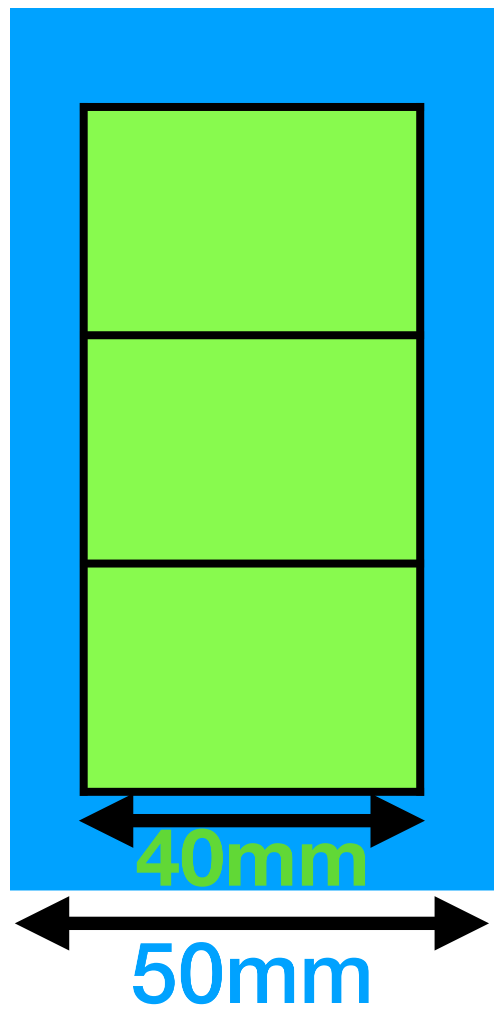


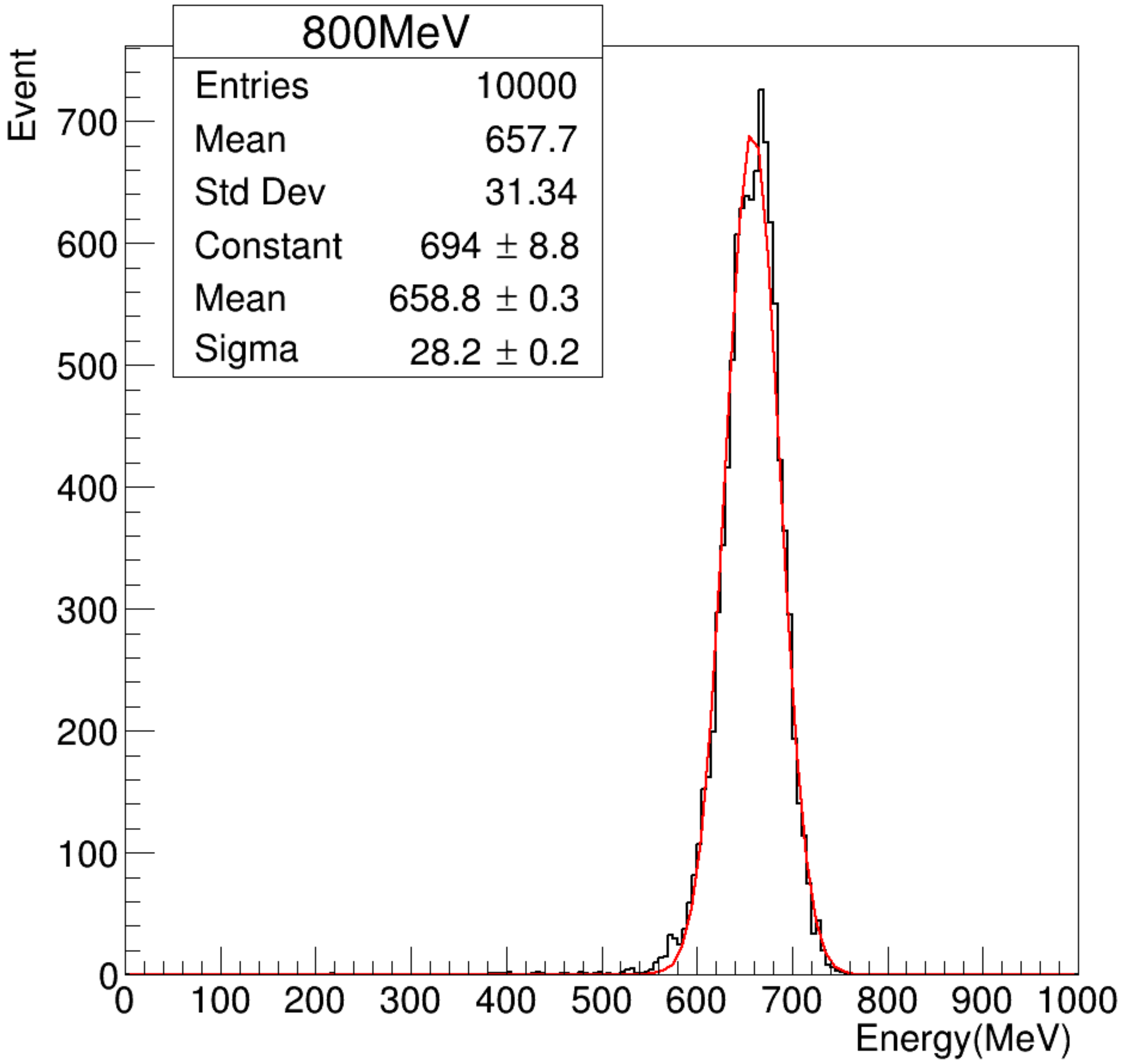


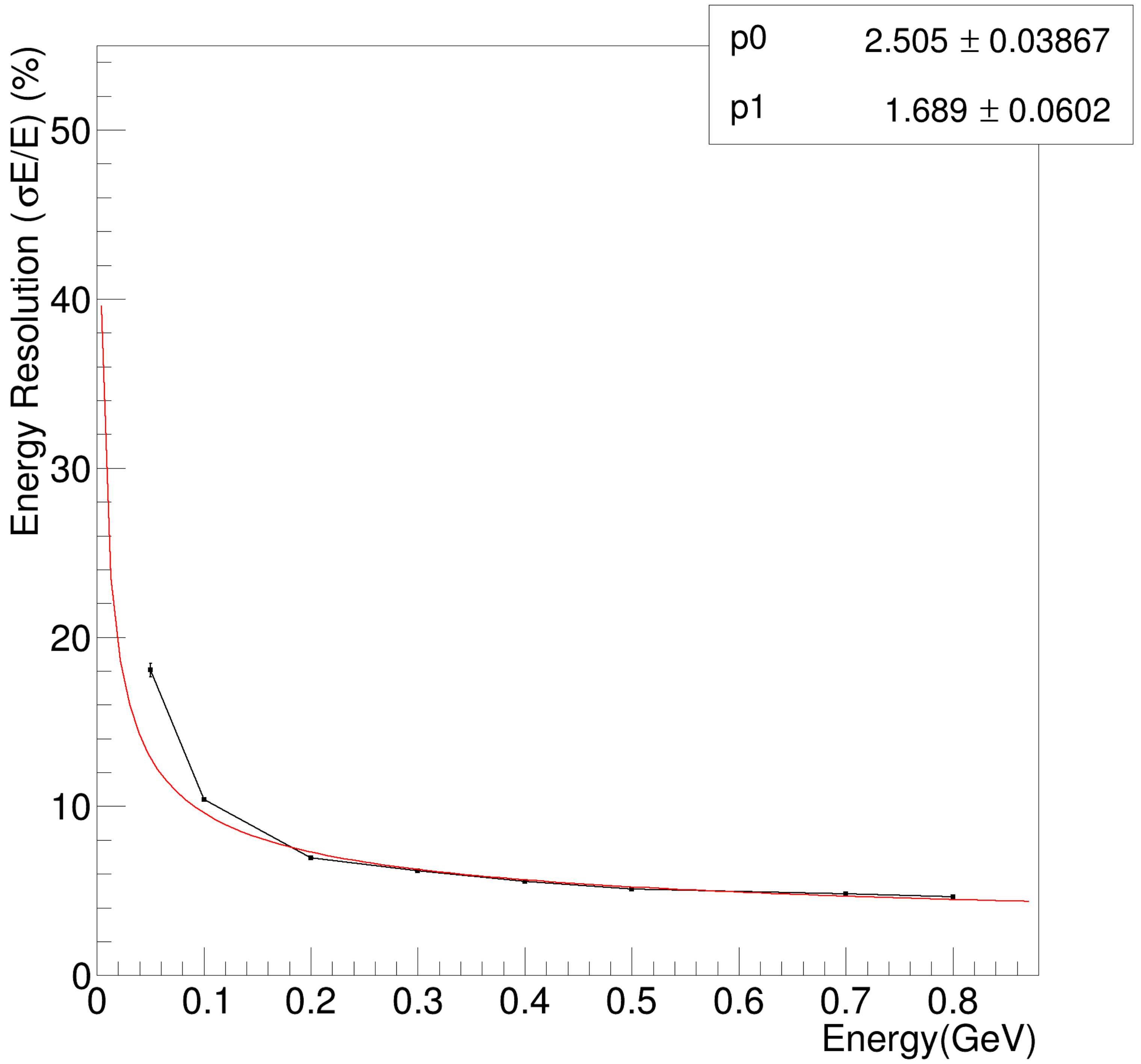


Effect of aluminum case

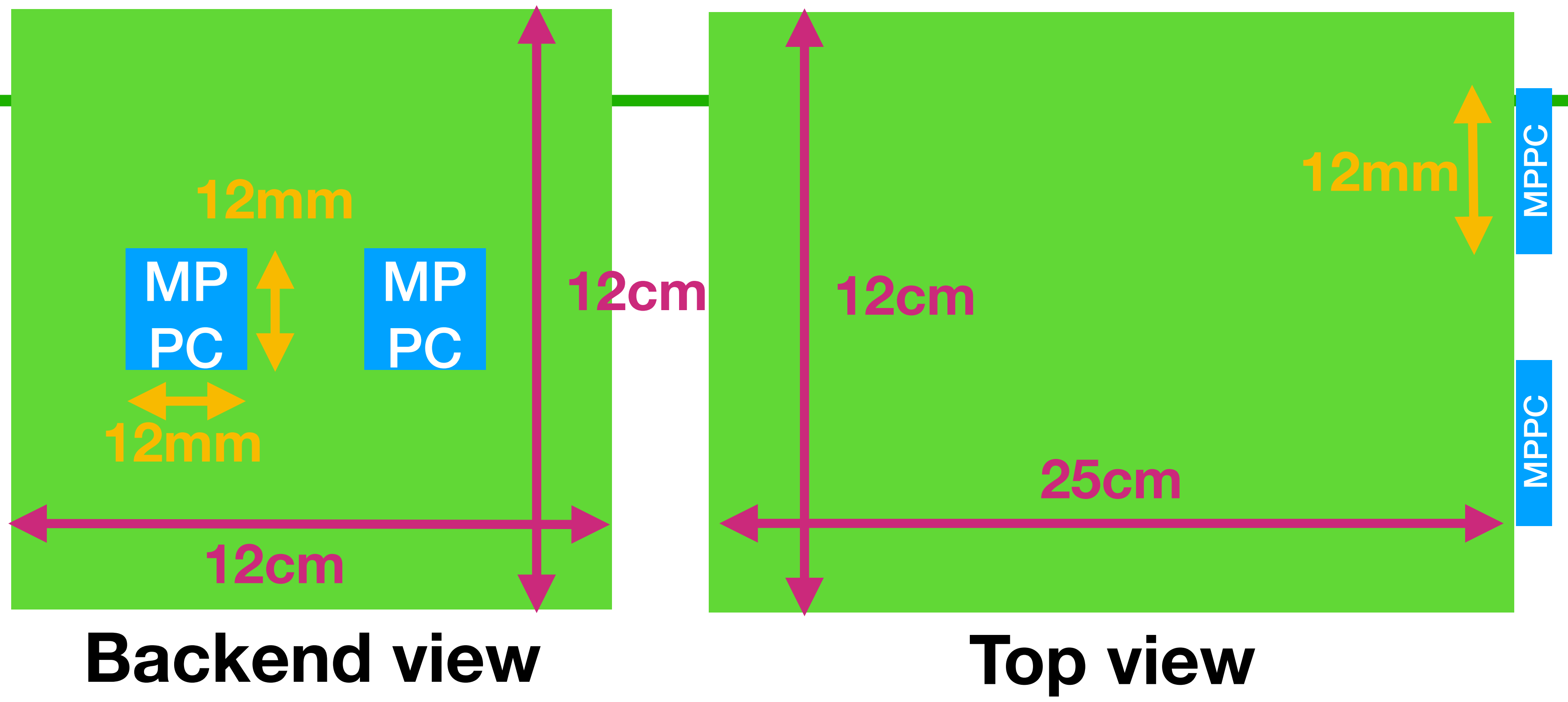
- This effect also affects energy resolution
- The case behaves like a normal calorimeter inactive absorption layer.
- From this we can see that the effect of this case is not small.
-



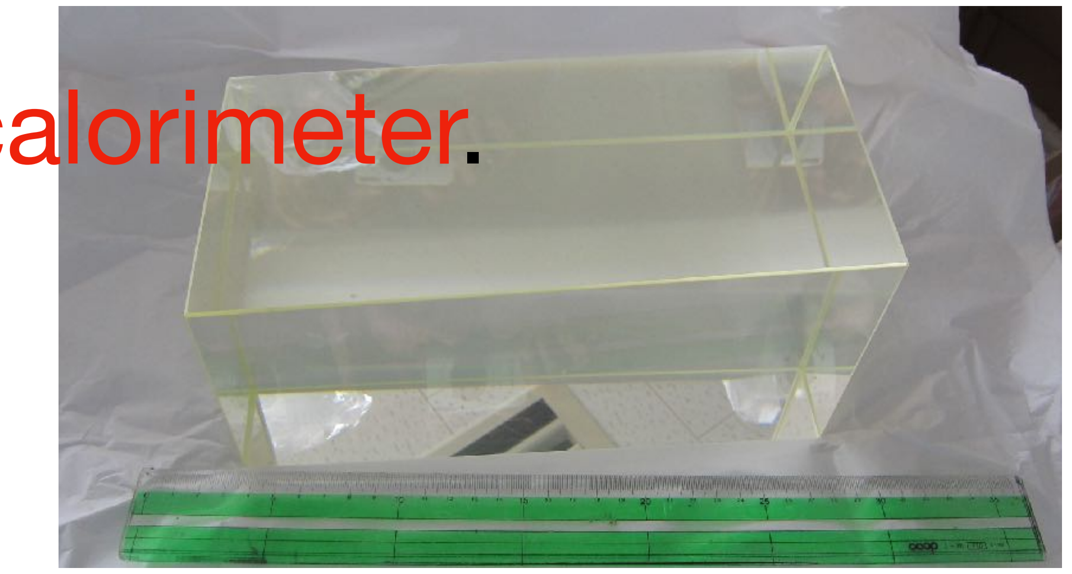




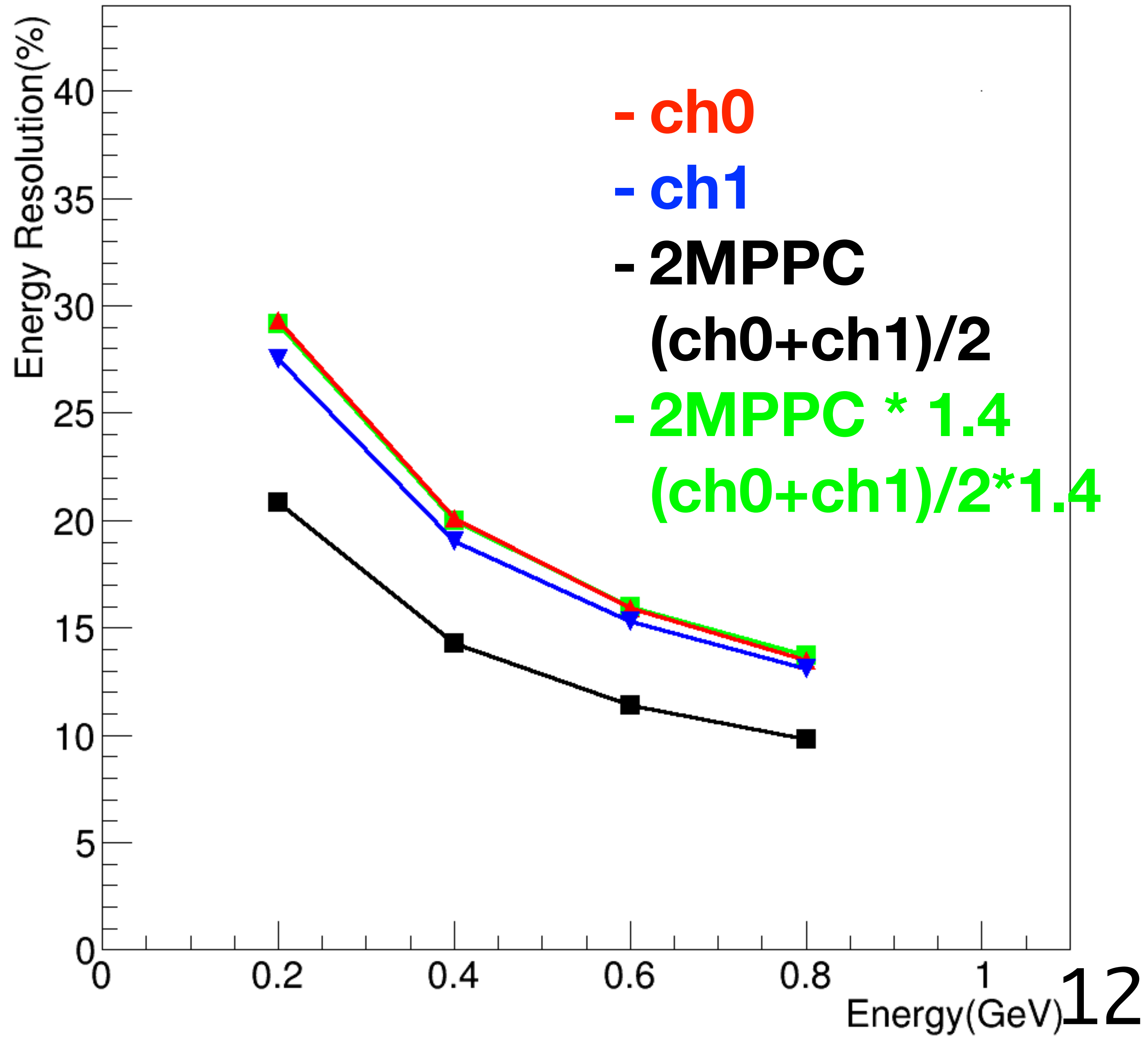
Effect of photon statics to energy resolution



- The resolution of the tail catcher measured in this experiment was about $9\%/\sqrt{E}$ (use MPPC.
- In previous experiments, it was $5\%/\sqrt{E}$ (use large PMT.
- This resolution comes from photon statics.
- This is because doubling the number of MPPCs used increases the resolution by a factor of 1.4.
- It is considered that the same occurs in a lead glass block having the same sectional area and area ratio of the light receiving surface.
- It also affects the energy resolution of the entire calorimeter.
- Light collection efficiency needs to be improved.

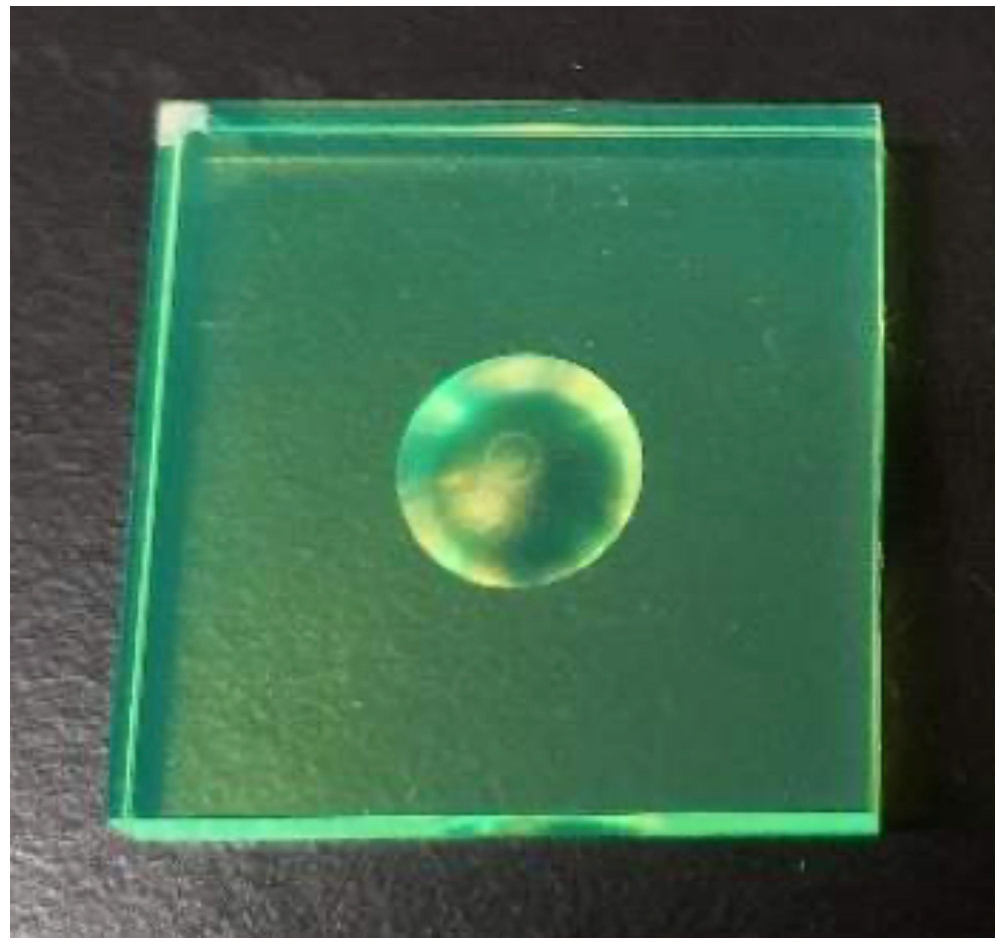


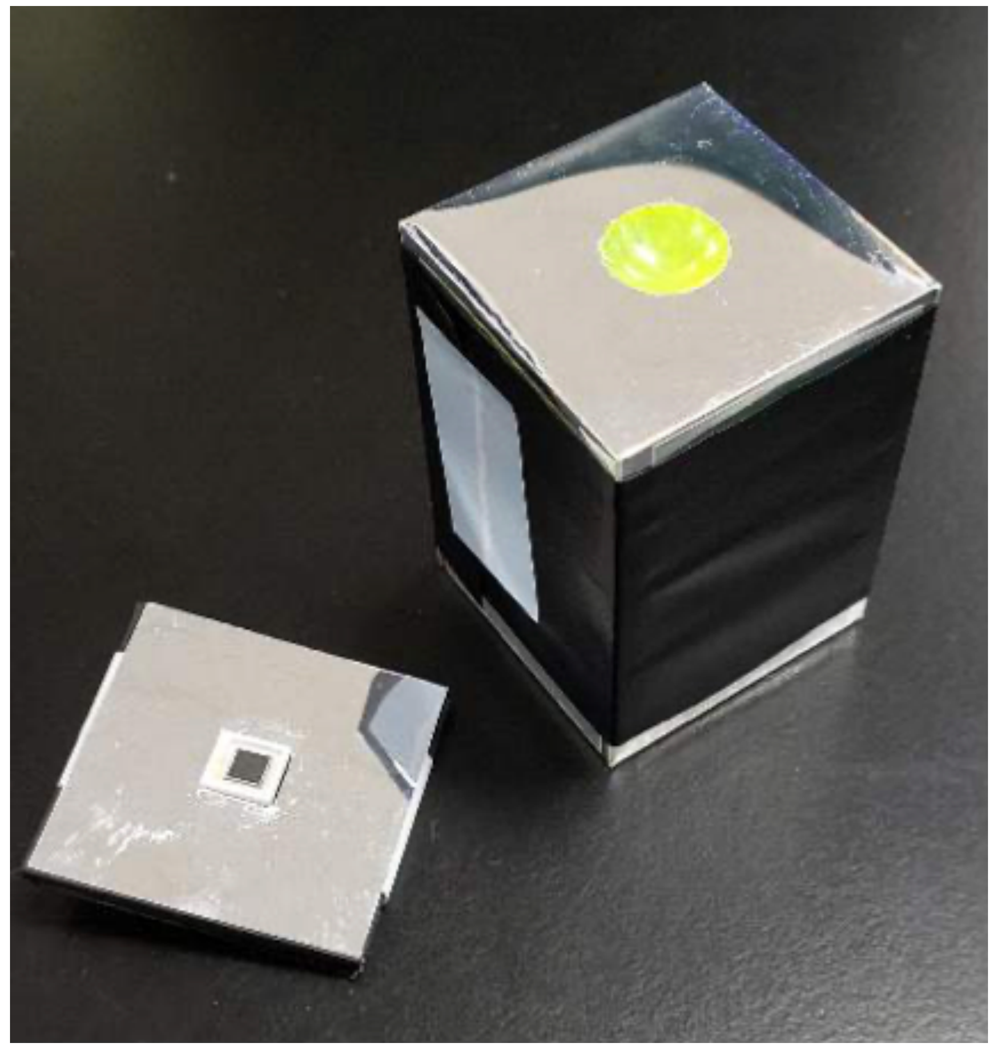
Tail Catcher energy resolution



Improvement of light collection efficiency using WLS

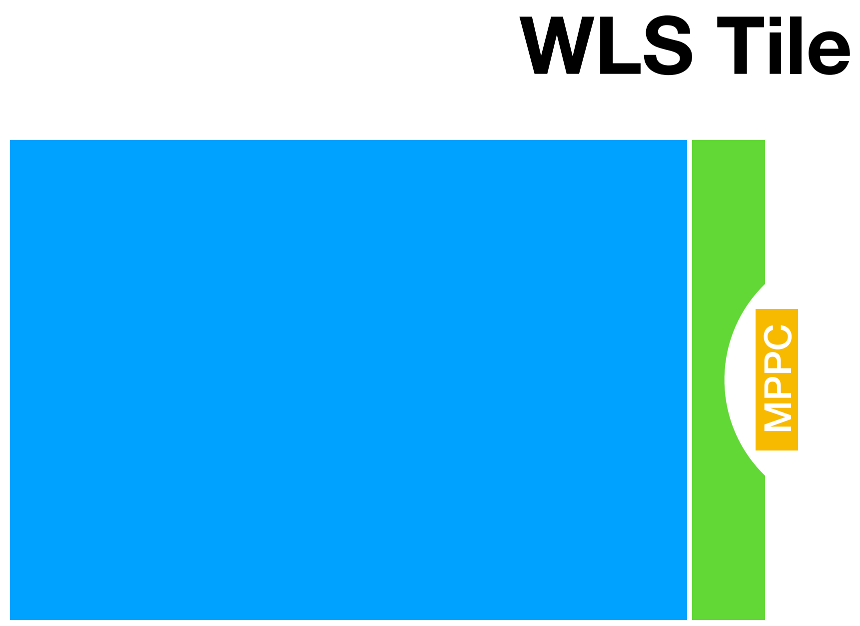
- There are ways to increase MPPC, but it affects cost.
- We converted the wavelength of the Cherenkov light using WLS and tested the improvement of the light collection efficiency.
- We tested a WLS tile with the same shape as the analog HCAL scintillator.





Current type
Directory one MPPC readout

Simple method
Several MPPCs readout

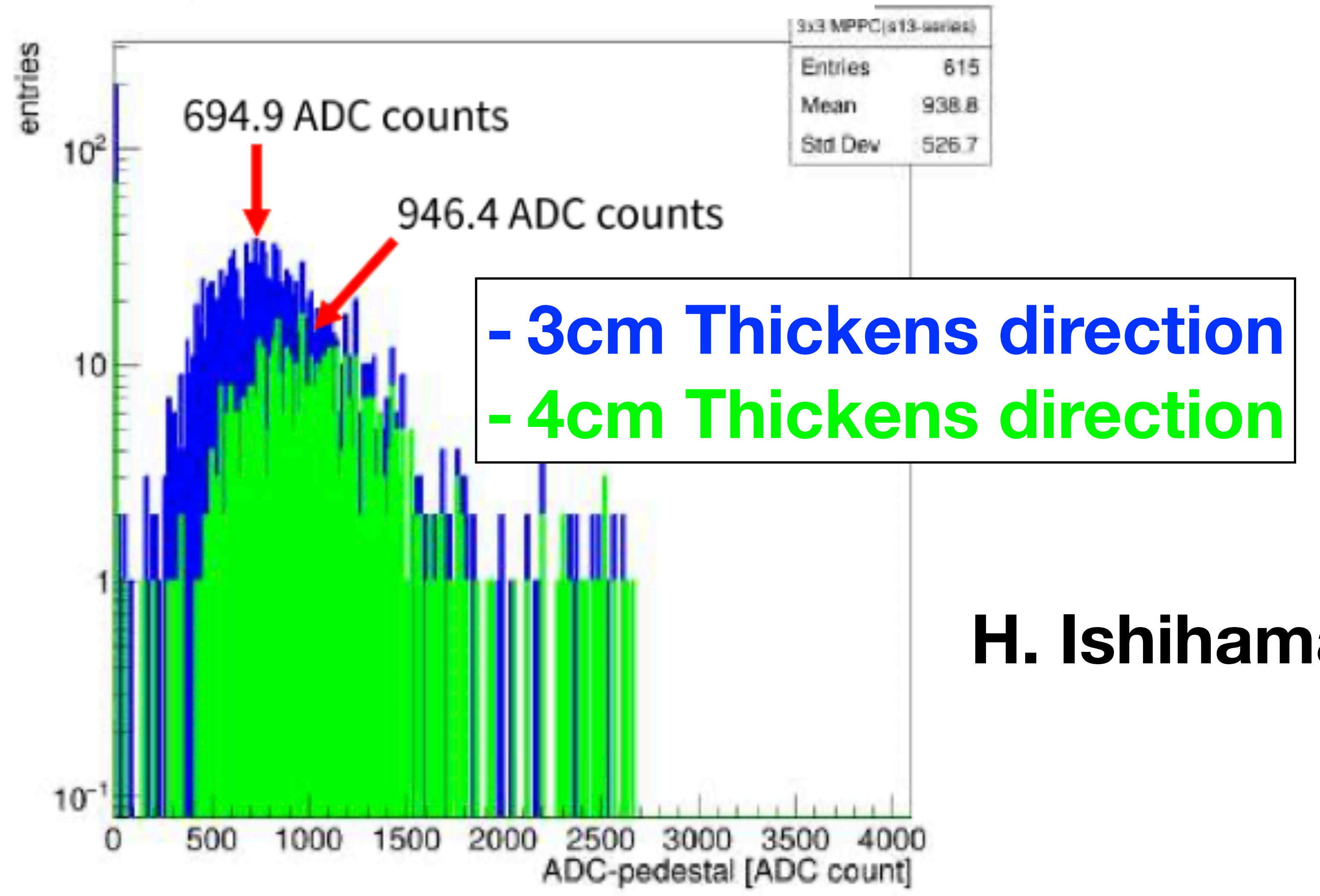


Use WLS Tile
One MPPC readout

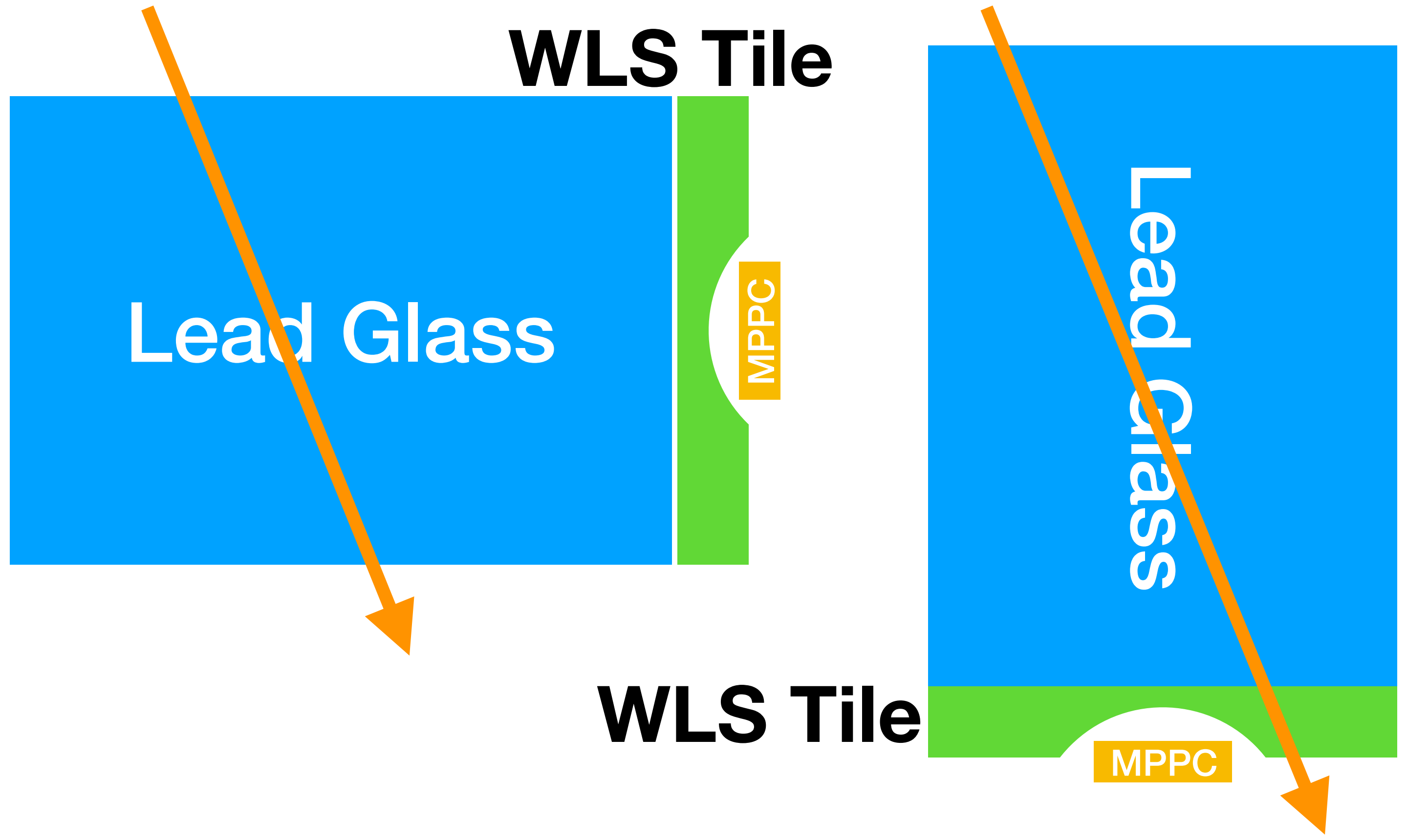
Cosmic muon test

- Tested with and without WLS tiles.
- The number of photoelectrons at the MPPC was confirmed by LEDs.
- Using WLS, it was confirmed that the light yield was doubled.
- Also, by changing the installation direction, we confirmed the difference in the amount of light depending on the thickness.
- At 3mm, light yield became 11 p.e.
- At 4mm, light yield became 15 p.e.

WLS Tile result



H. Ishihama



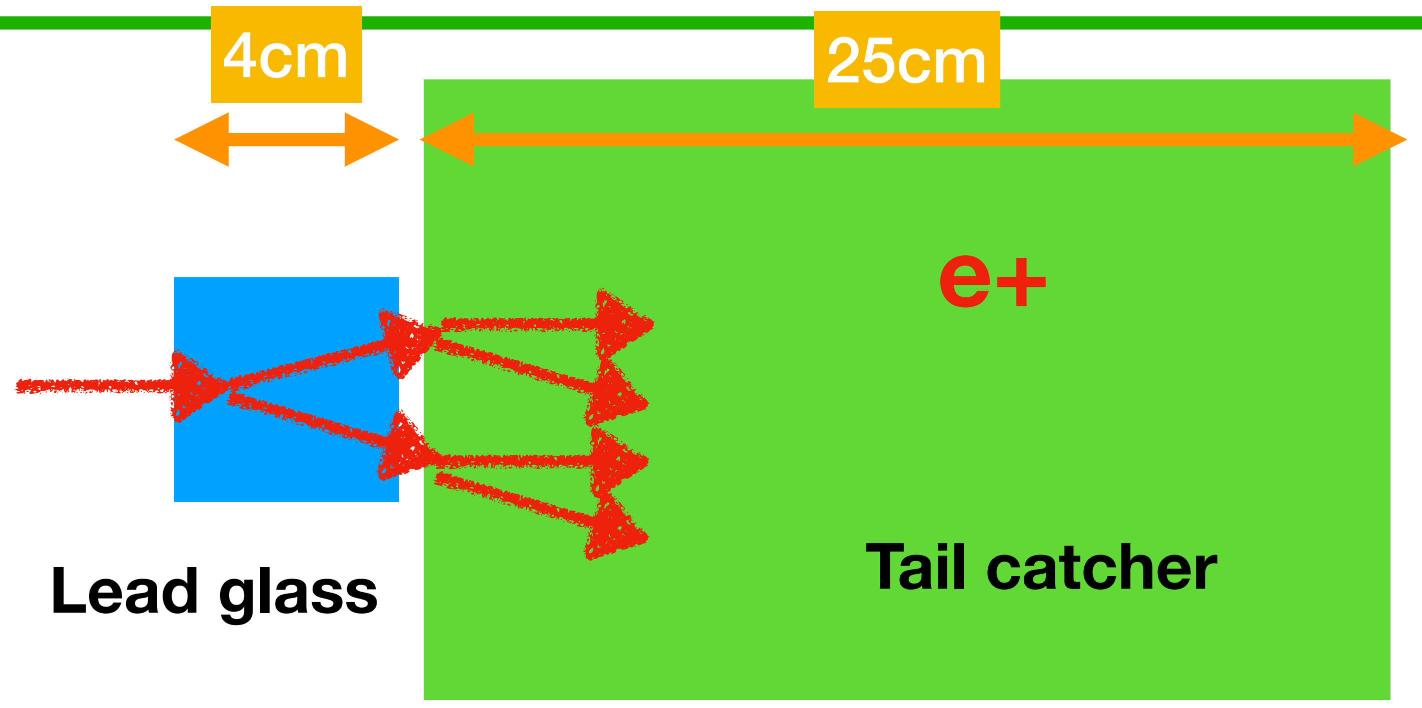
Summary

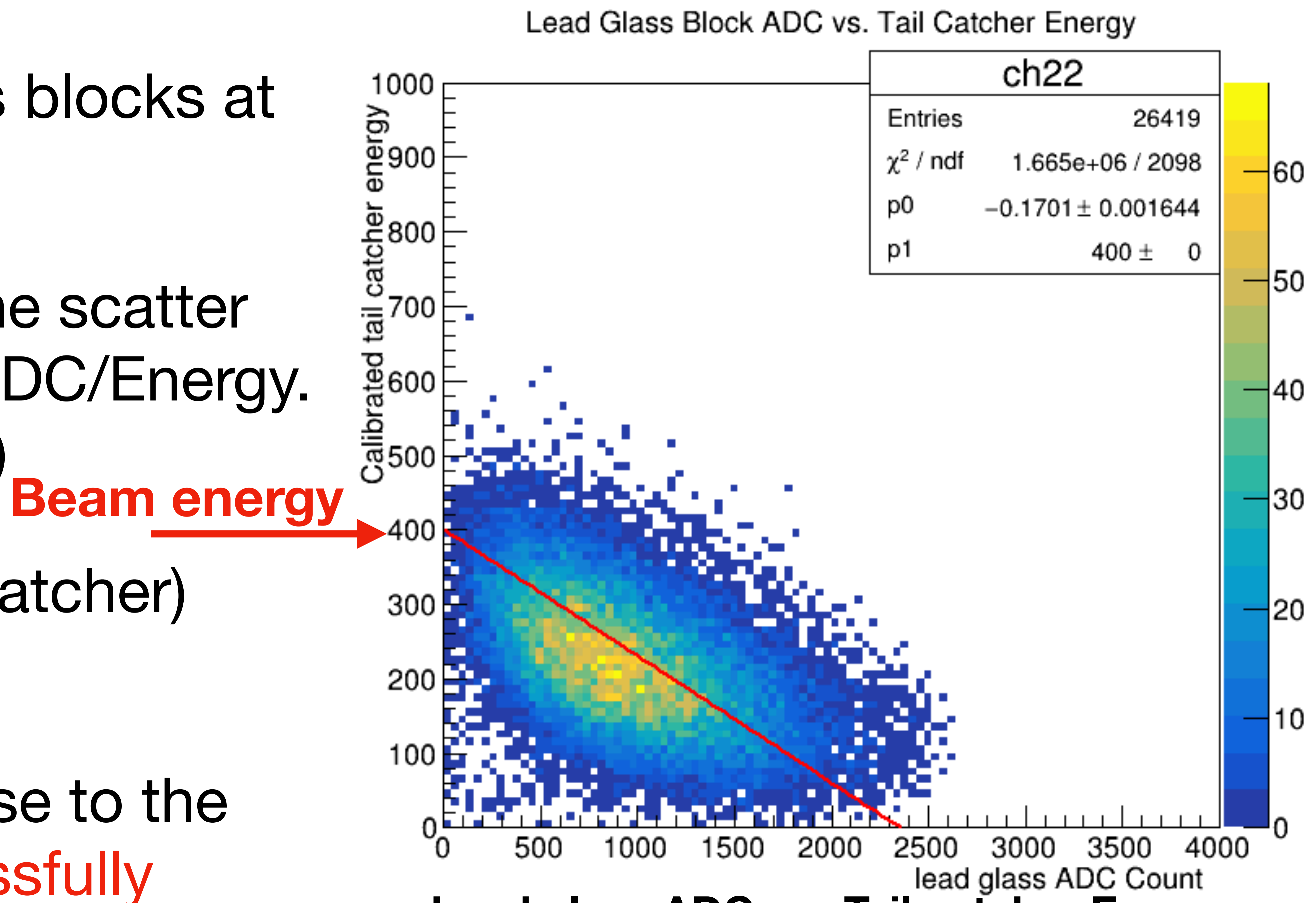
- Performance improvement of the calorimeter is expected for future high-energy frontier collider experiments.
- We are developing and testing segmented active absorber lead glass calorimeter.
- The beam was used to verify the performance of the 3layer prototype.
- The linearity is as high as 97%, and the current resolution is 13%.
- Simulations have identified some issues.
    - There is a 12% energy leak.
    - The effects of dead channels are less than 1% and are almost nonexistent.
    - The 30mm aluminum case has an 8% effect, affecting resolution.
- It has been confirmed that the light collection efficiency is one of the reasons for degrading the energy resolution.
- It was found that using WLS tiles doubled the amount of light.
- Future Plan
    - More realistic simulation and more analysis(energy resolution and photon statics)

Backup

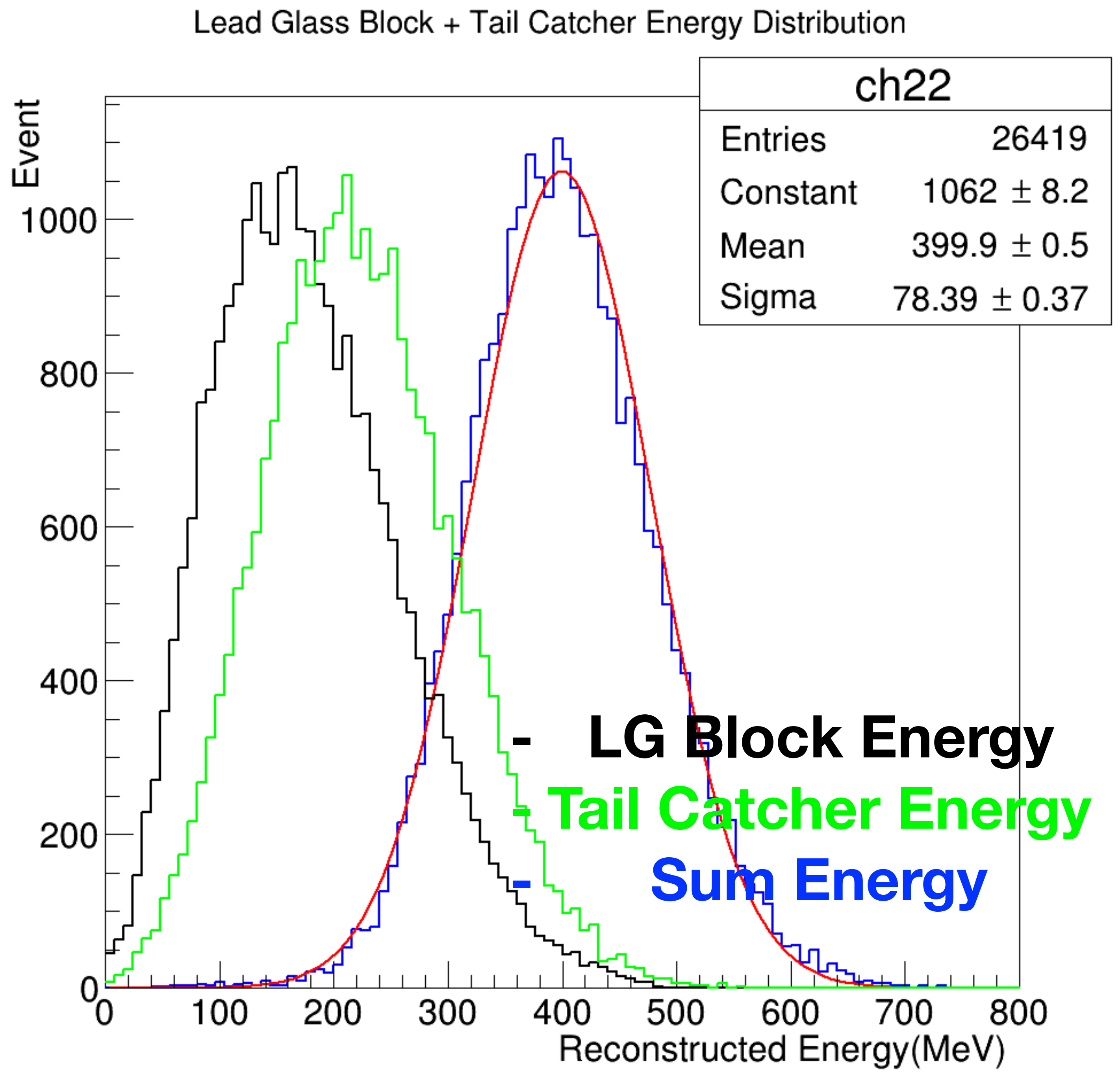
Energy calibration of lead glass block

- Calibration of each small lead glass blocks.
- Since the single block is small and energy leaks.
  -> Measurement was performed with a tail catcher.
- We did calibrate all the lead glass blocks at 400MeV positron.
- We get a slope parameter from the scatter plot by linear fitting to be 0.170 ADC/Energy. (This is ch22 calibration constant)
- Sum (the lead glass block + tail catcher) energy distribution is Gaussian.
- Reconstructed energy is very close to the injected energy (400MeV), successfully calibrated.





Lead glass ADC v.s. Tail catcher Energy

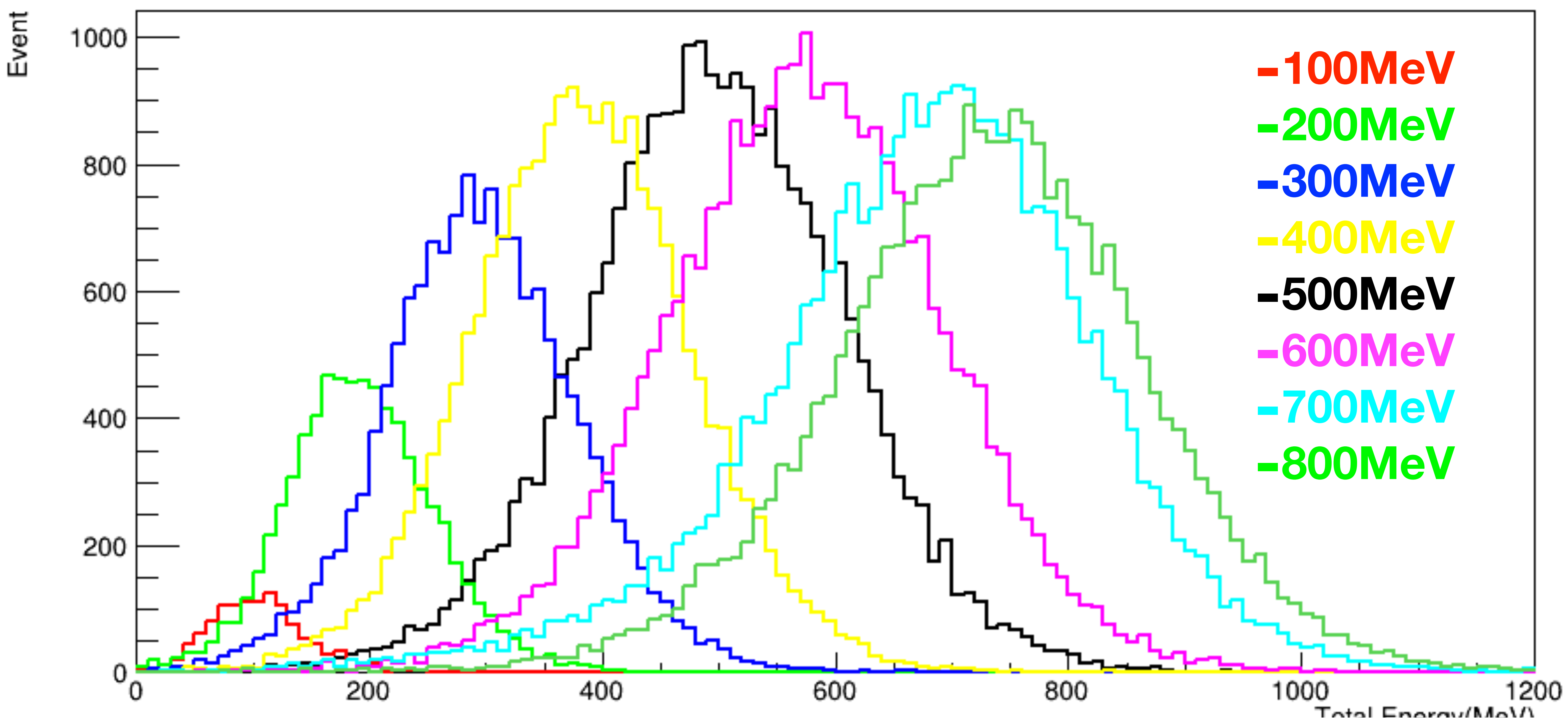


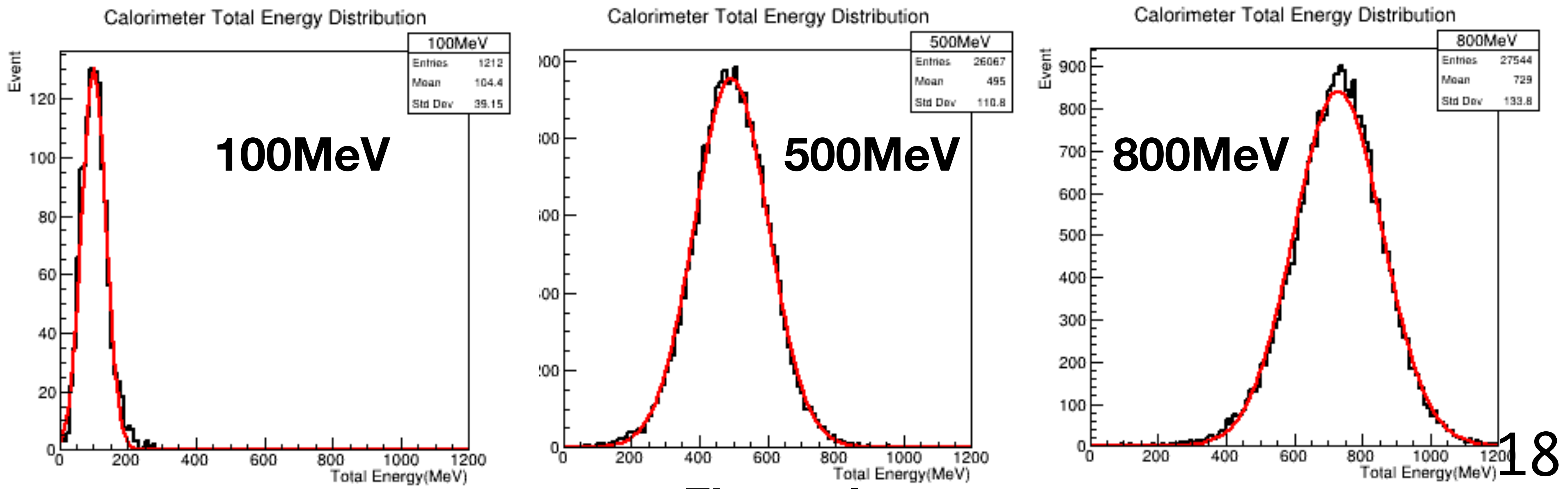
Energy Distribution of reconstructed

Energy reconstruction

- After all lead glass channel calibration, we reconstructed calorimeter energy. (Results of 3 lead glass absorber layers and tail catcher without Scintillator)
- Incident energy entered 100-800 MeV in 100MeV increments
- The energy distribution is in good agreement with the Gaussian distribution
- Up to 700 MeV, energy can be reconstructed well.
- At 800 MeV, the peak position of 800MeV data is about 10% smaller than expected.
  -> Checking now

Reconstructed energy

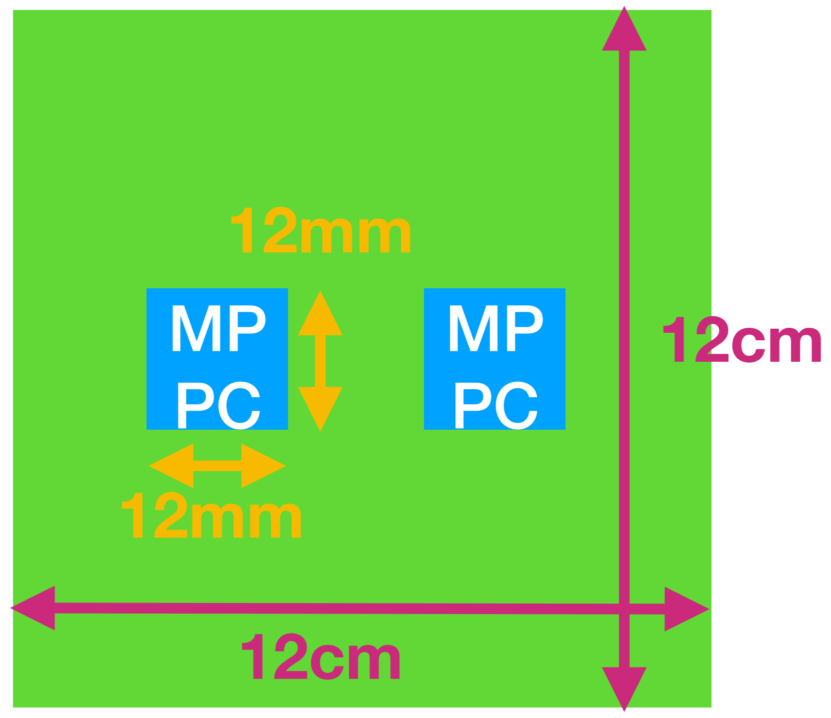




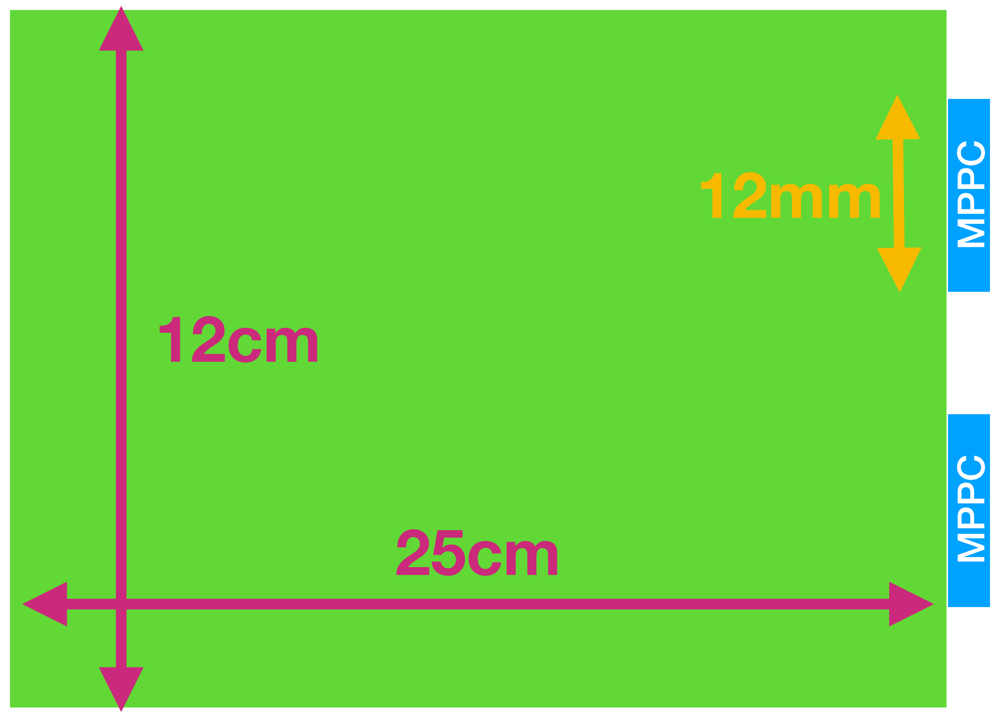
Fit result

Tail Catcher

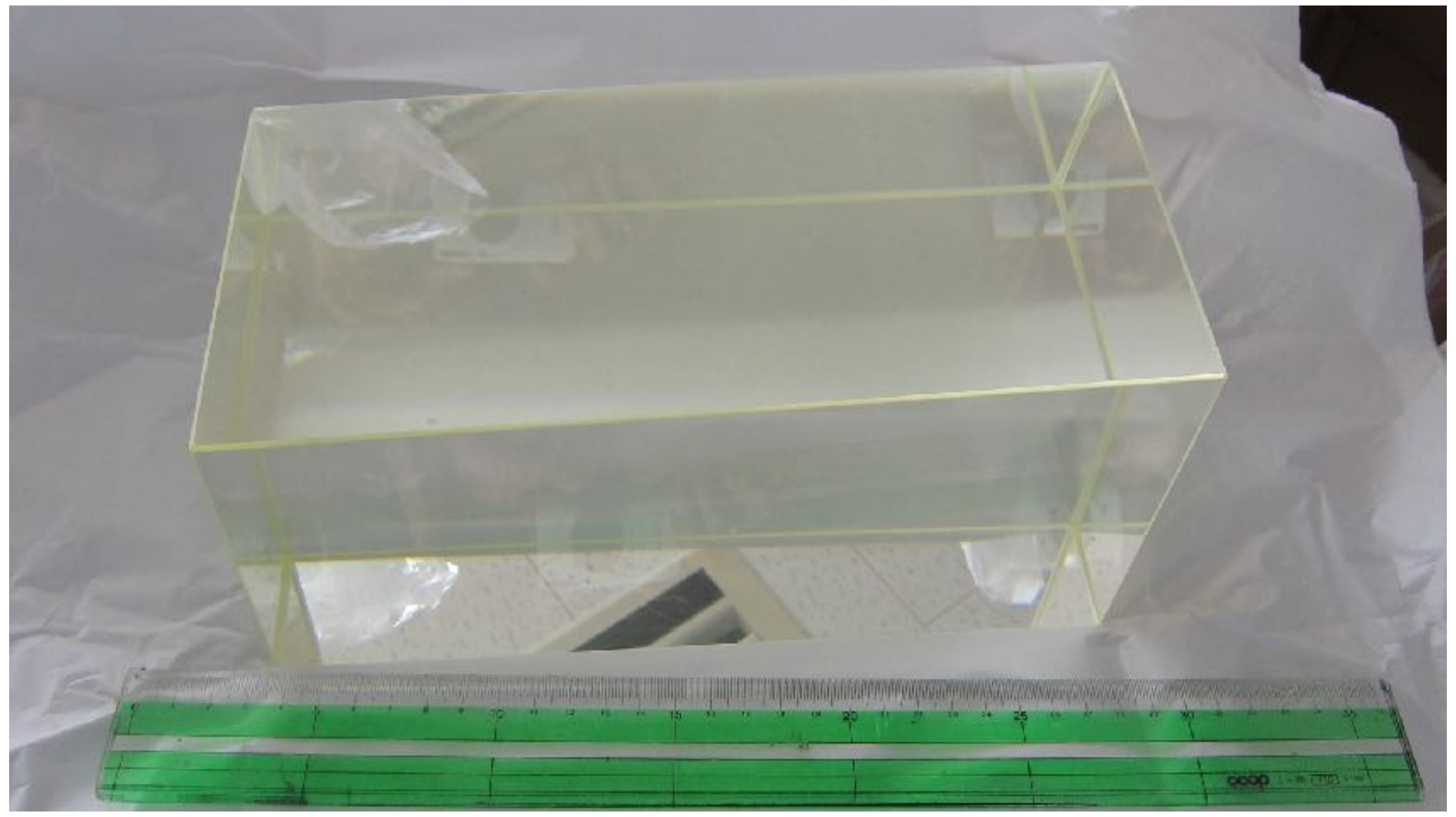
- Put most downstream at the beamline, to detect the leakage energy.
- Single large lead glass bock (12x12x25cm^3) (14.7X_0)
- The optical readout is done by two MPPCs of 12 x12 mm^2.
- Two MPPCs are glued directory on the backend of the tail catcher.
- Area radio is 100:1 (Lead glass surface:MPPC)
- Energy calibration with the beam.



Backend view



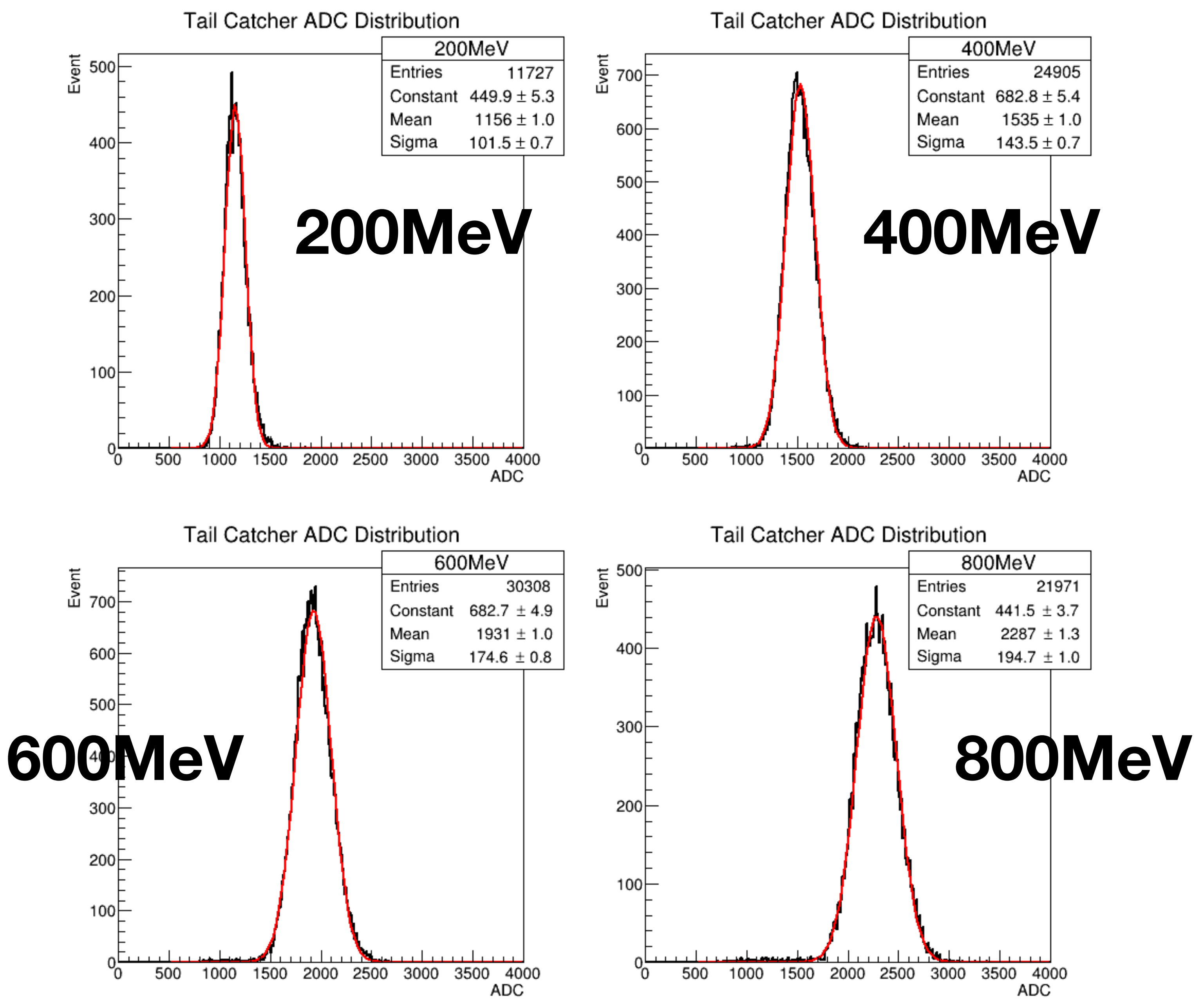
Top view


12x12x25cm^3 lead glass block

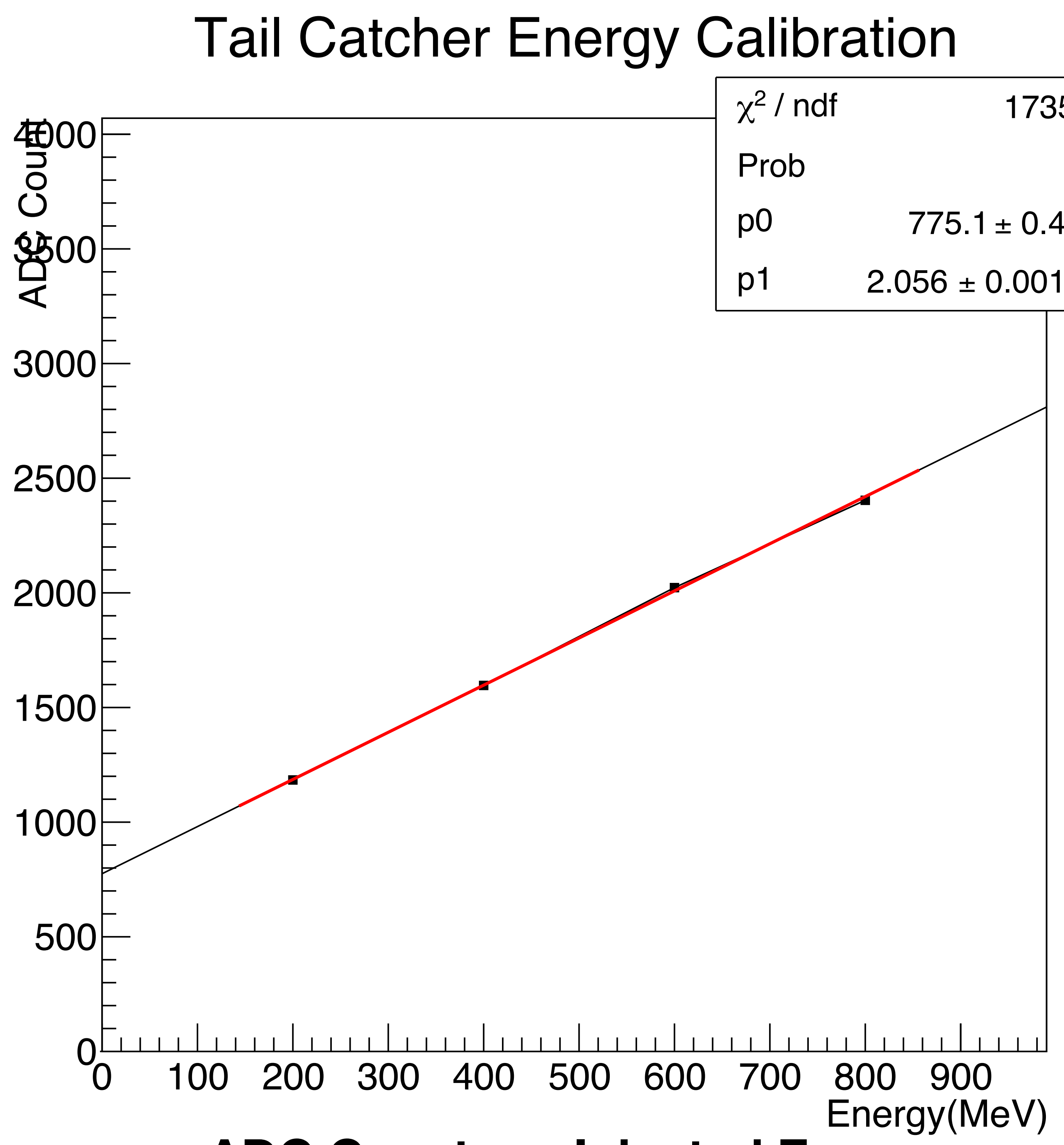

Tail Catcher

Tail Catcher energy calibration and resolution

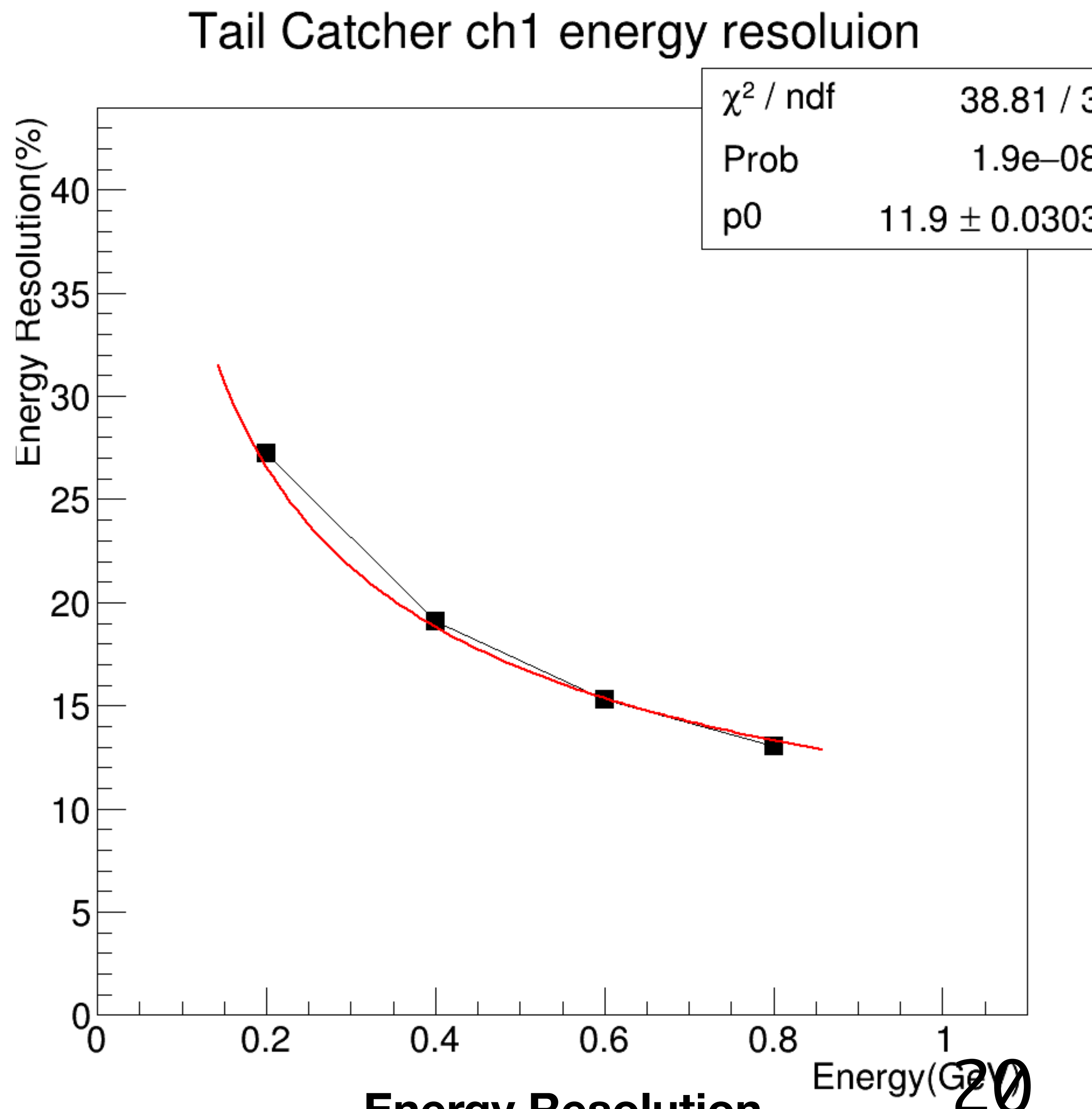
- First, we calibrated the tail catcher with an MPPC of 12 x 12 mm^2.
- The gaussian response was measured with several beam energies.
- A sufficiently linear response to the injected energy was confirmed.
- The Energy resolution of σ/E is fitted with $1/\sqrt{E}$.
- Tail catcher energy resolution resulted in $12\%/\sqrt{E}$.



ADC Distribution of e+ injected



ADC Count v.s. Injected Energy



Energy Resolution

Parameter of Lead Glass

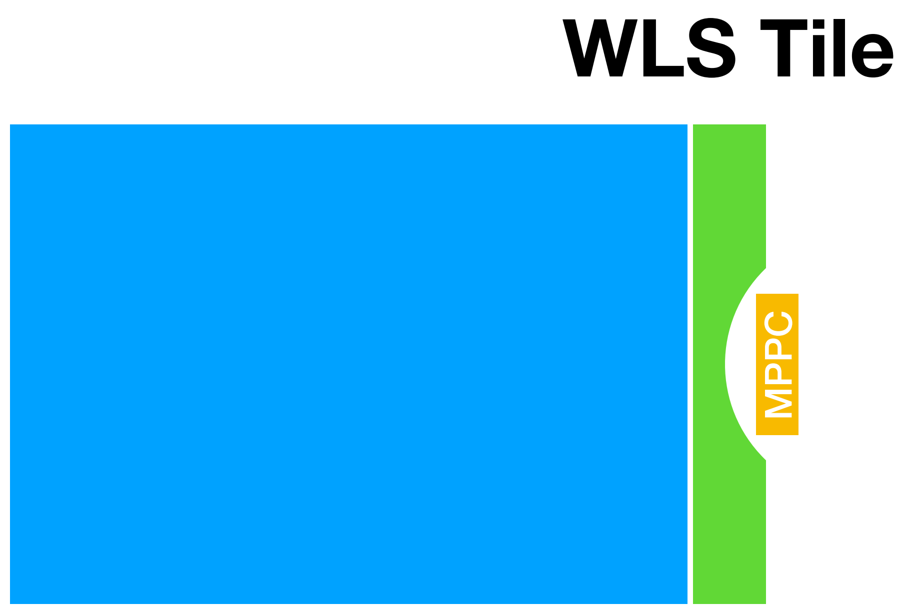
Chemical composition (wt%)	
SiO_2	27.3
PbO	70.9
K_2O	0.9
Na_2O	0.6
Sb_2O_2	0.3
Radiation length (cm)	1.7
Refractive index	1.8
Density (g/cm_3)	5.2
Critical energy (MeV)	12.6
Molière unit (X_0)	1.7

Light yield improvement structure

Now testing

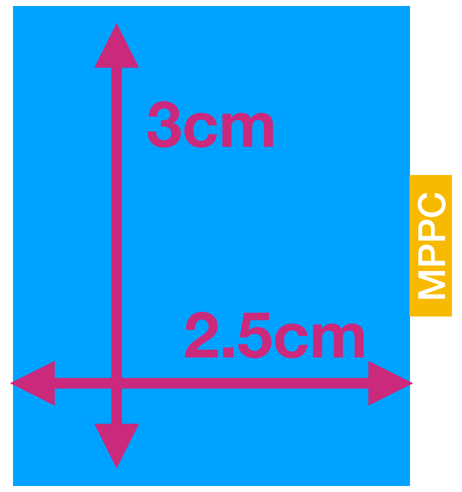
Current type
Directory one MPPC readout

Simple method
Several MPPCs readout

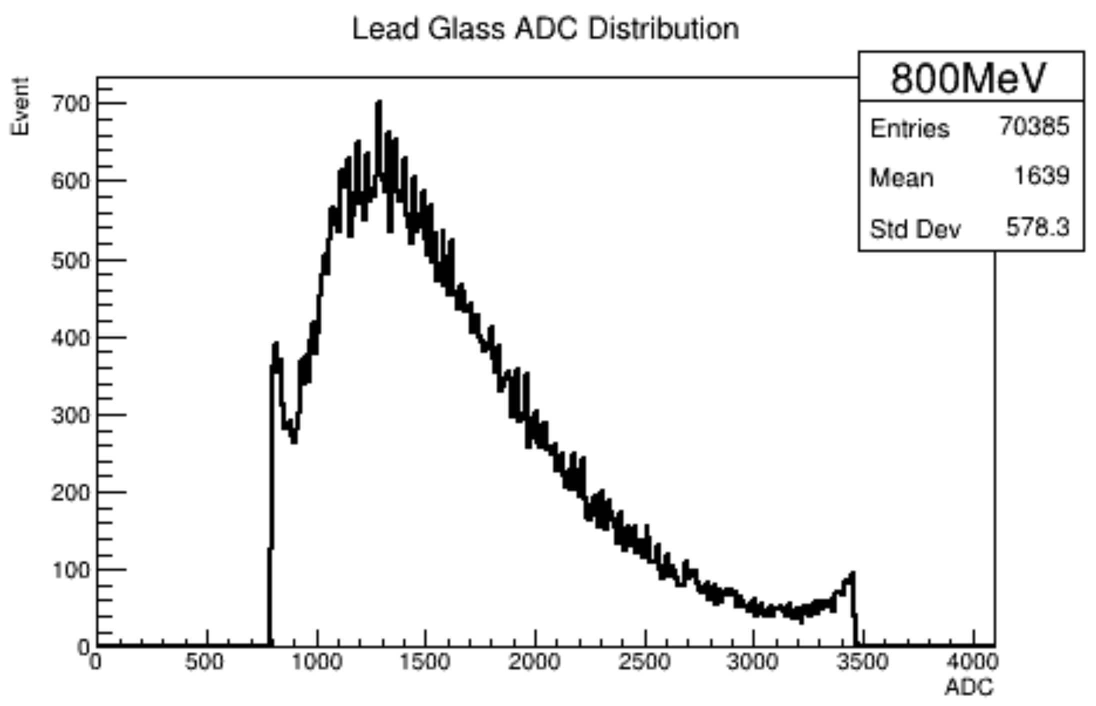


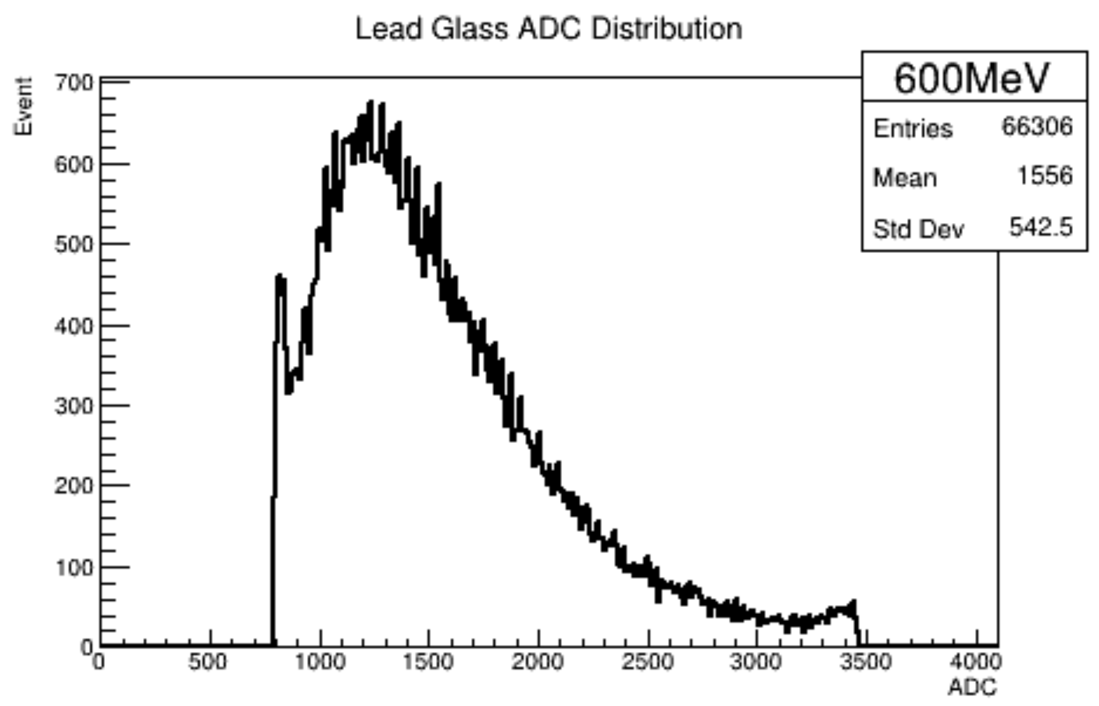
Use WLS Tile
One MPPC readout

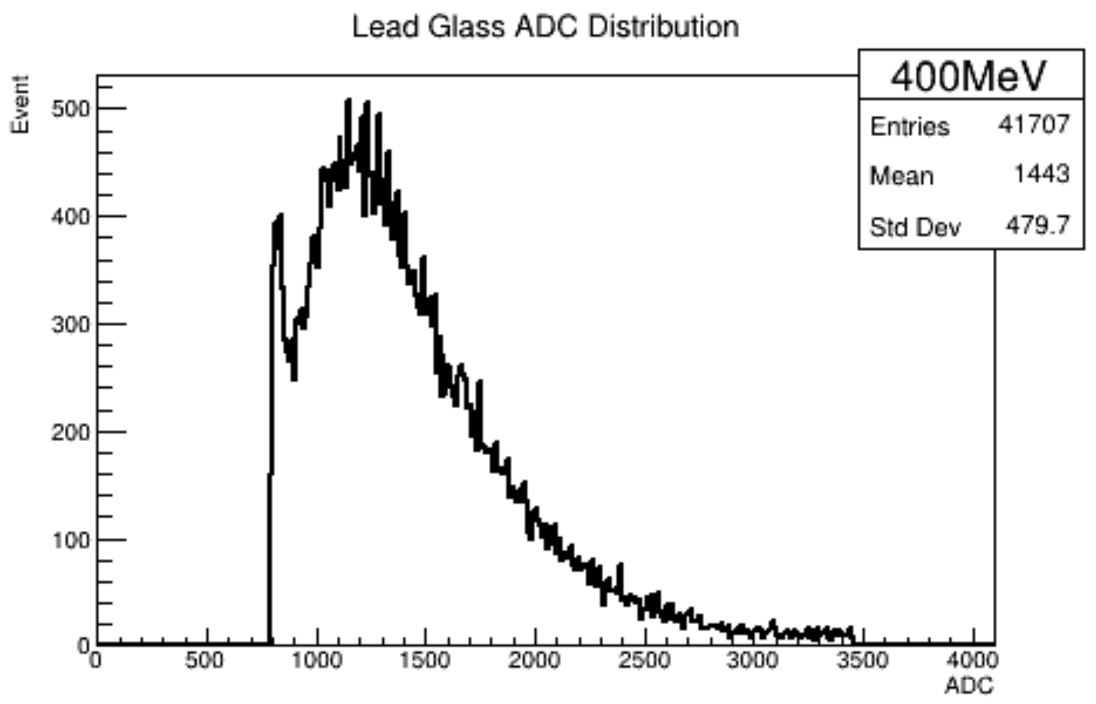
2.5cm thickness lead glass

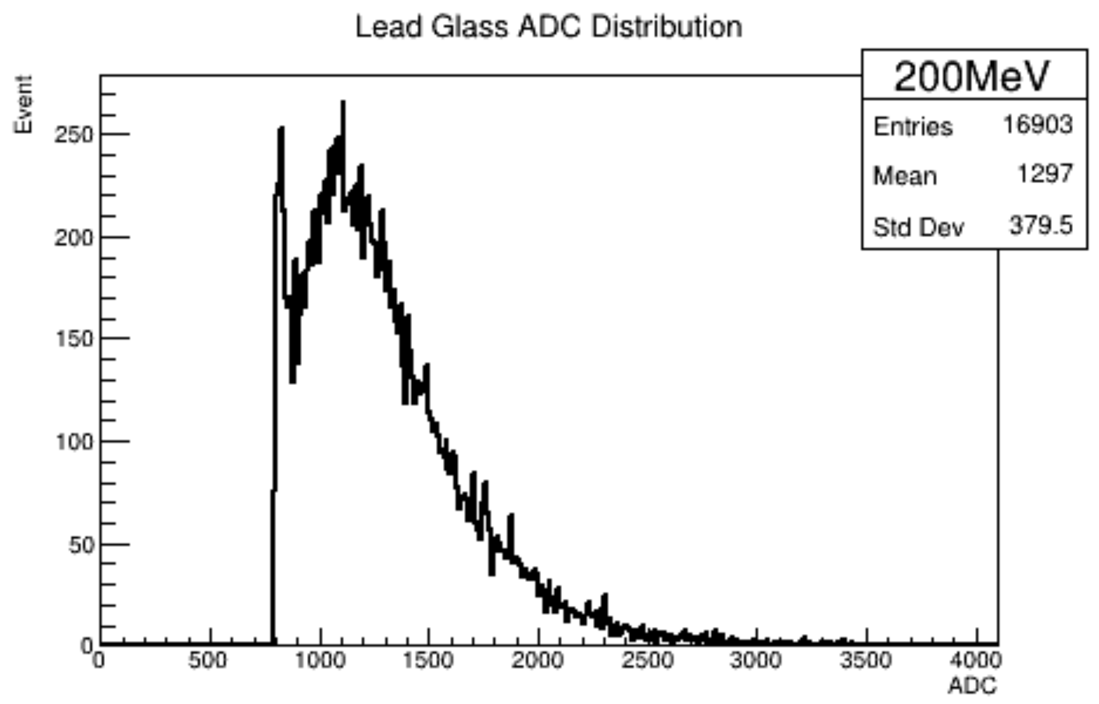


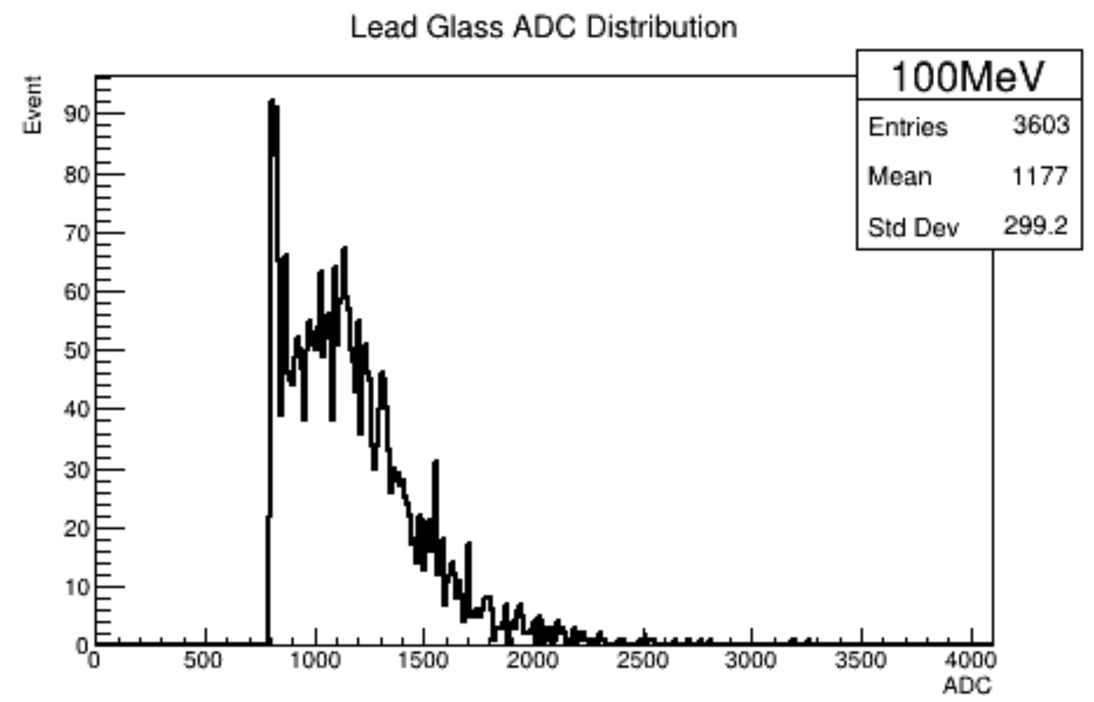
2.5cm thickness lead glass





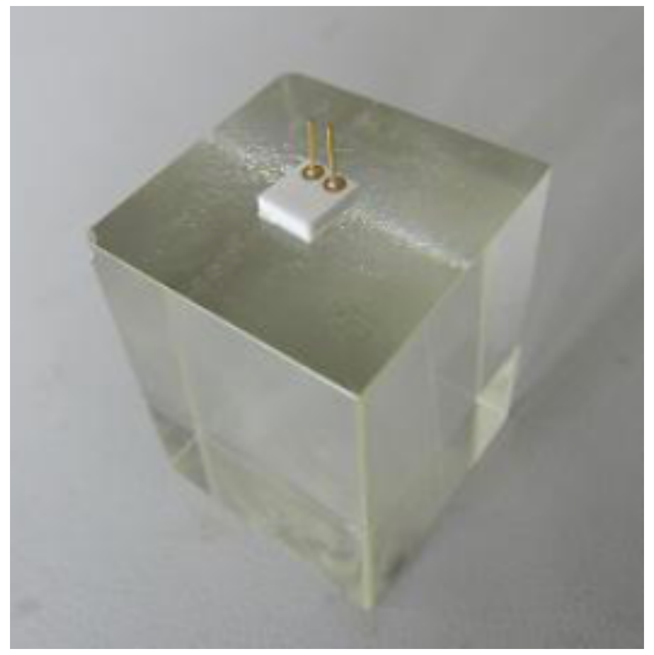




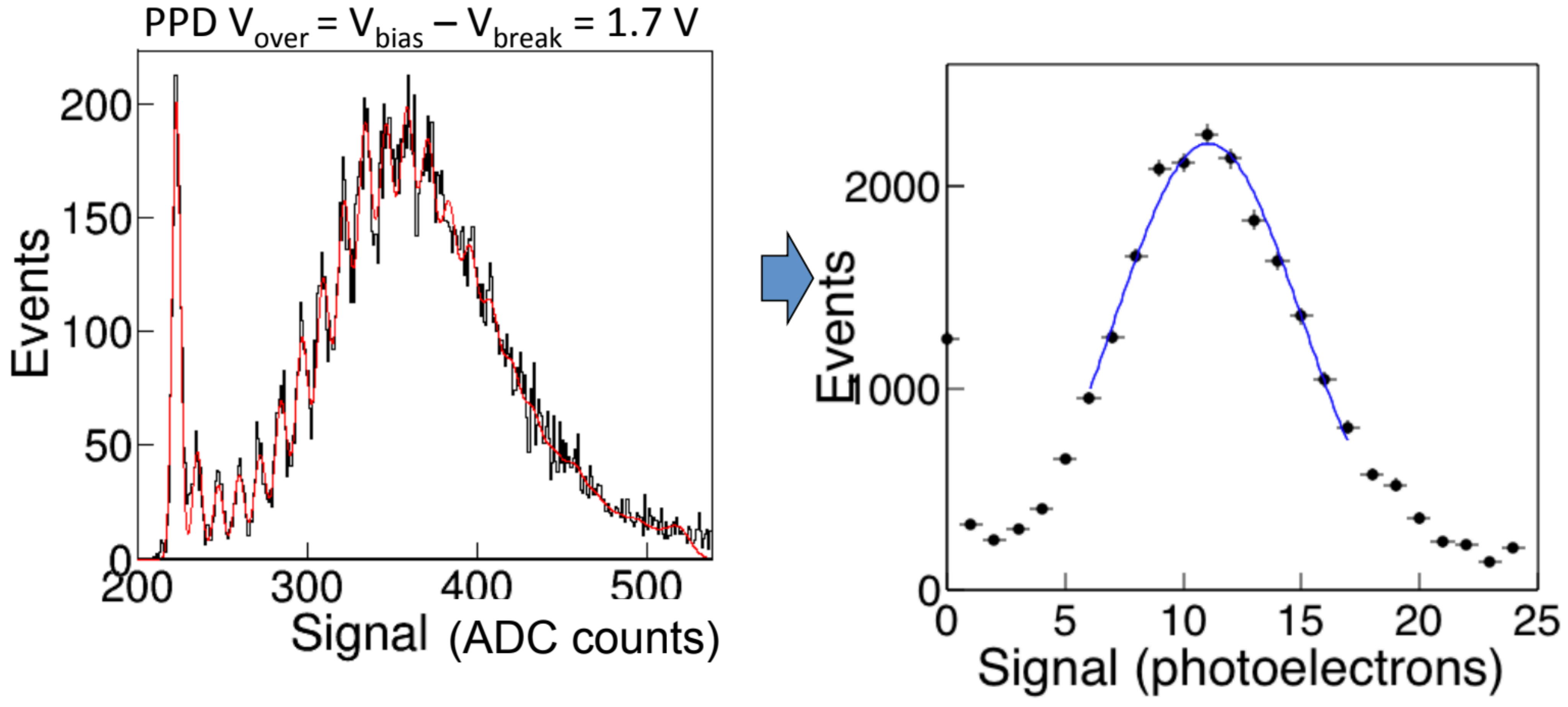


Readout Cherenkov light

- Lead glass block surface is 3x3cm^2 but MPPC sensor area is very small (3x3mm^2) (1/100).
- We want to avoid dead volume increase, we try directory readout (no optical guide)
- Cherenkov light can be read under 350nm if air gap Cherenkov light is totally reflected because of heavy lead glass density.
- This problem was solved by putting in optical grease between the lead glass and MPPC
- Cherenkov light is very small but can be read 12 p.e. by cosmic muon



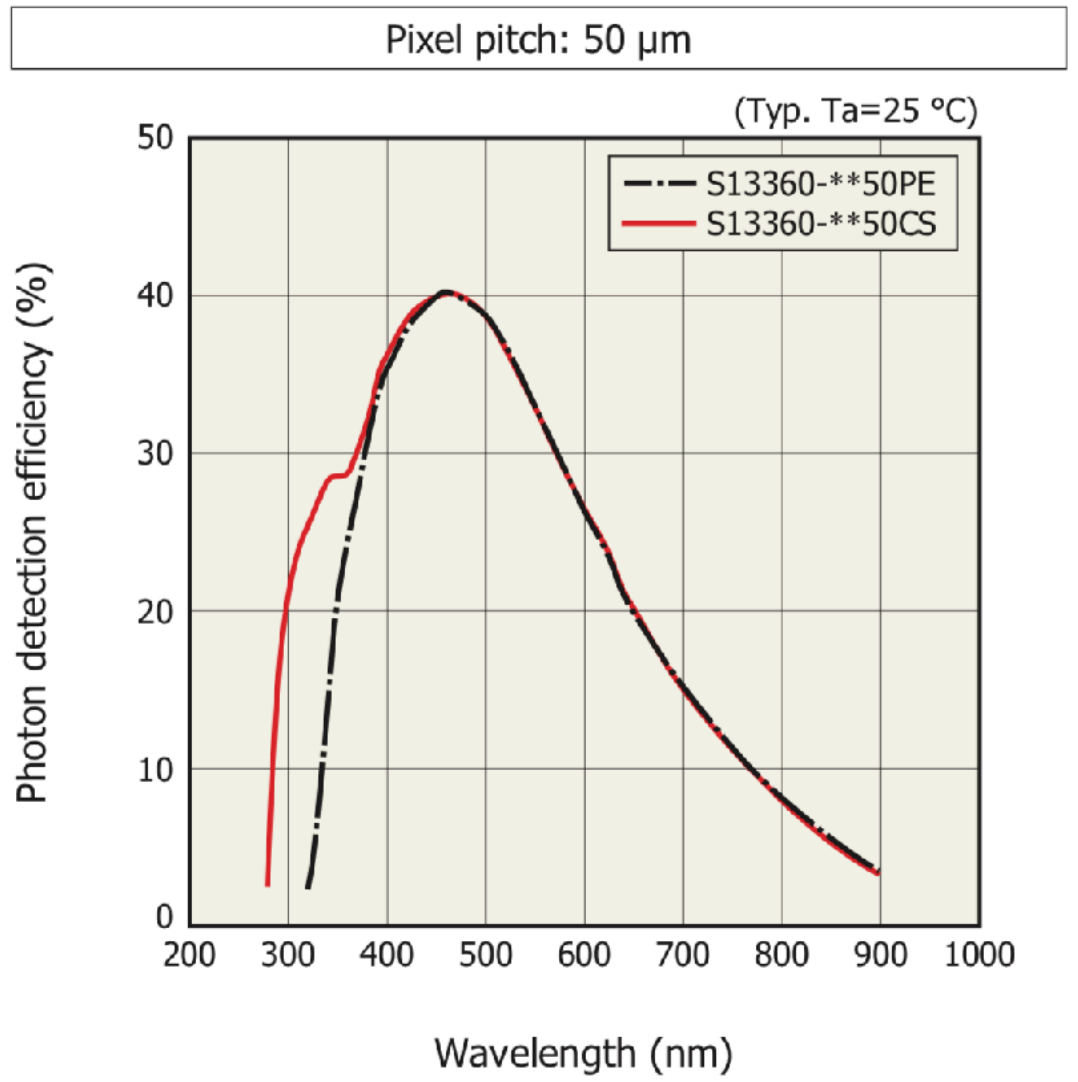
Lead glass block and MPPC



Muon signal

By Uozumi

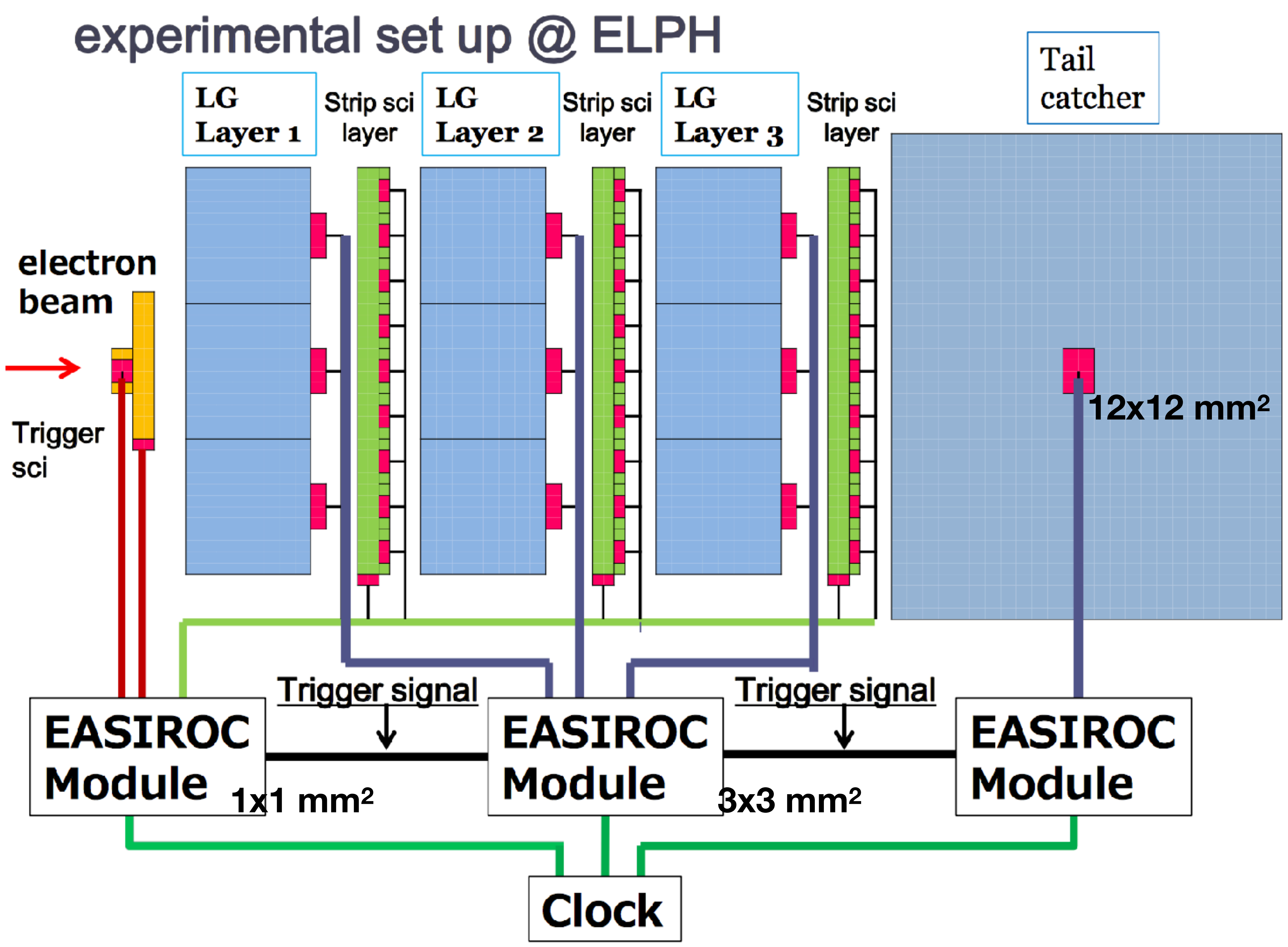
Optical coupling of Lead glass block and MPPC



Dependence of wavelength

Read out and Trigger system

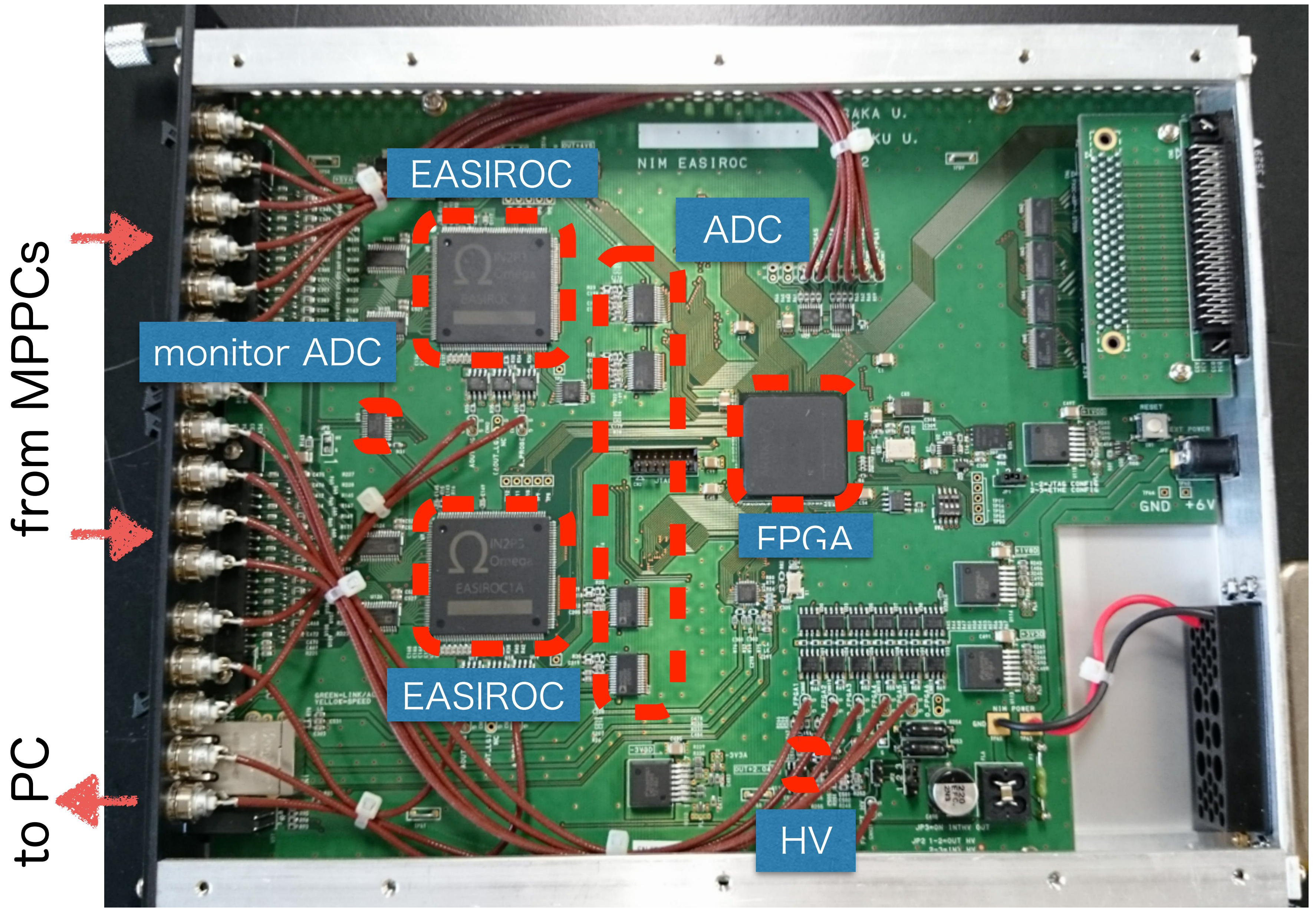
- This prototype has 83 MPPCs.
  - Active absorber layers have 27 MPPCs
  - Strip scintillator layers have 54 MPPCs
  - The tail catcher has 2 MPPCs
- 3 EASIROC Modules to read out MPPC signals for 3 types of MPPCs as different breakdown voltages. (1 x 1 mm^2, 3 x 3 mm^2, 12 x 12 mm^2)
- Trigger signals are made by one EASIROC Module -> 2 trigger scintillators coincidence.
- Trigger signals are fed into the other modules.
- All EASIROC Modules are read out with 250kHz and 40MHz synchronized clocks.



Read Out and Trigger system

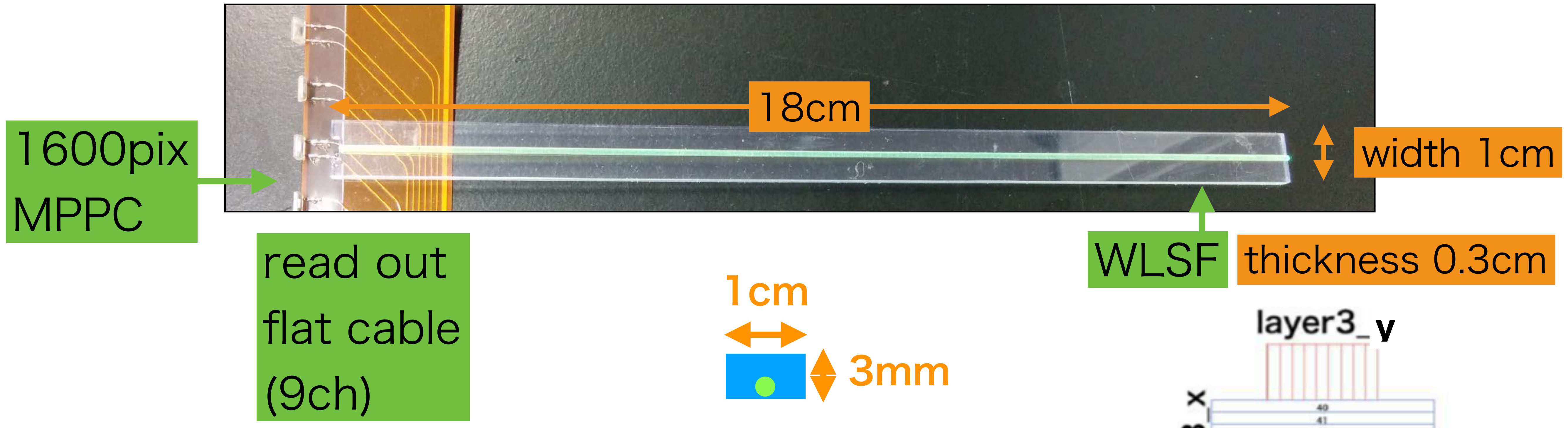
EASIROC Module

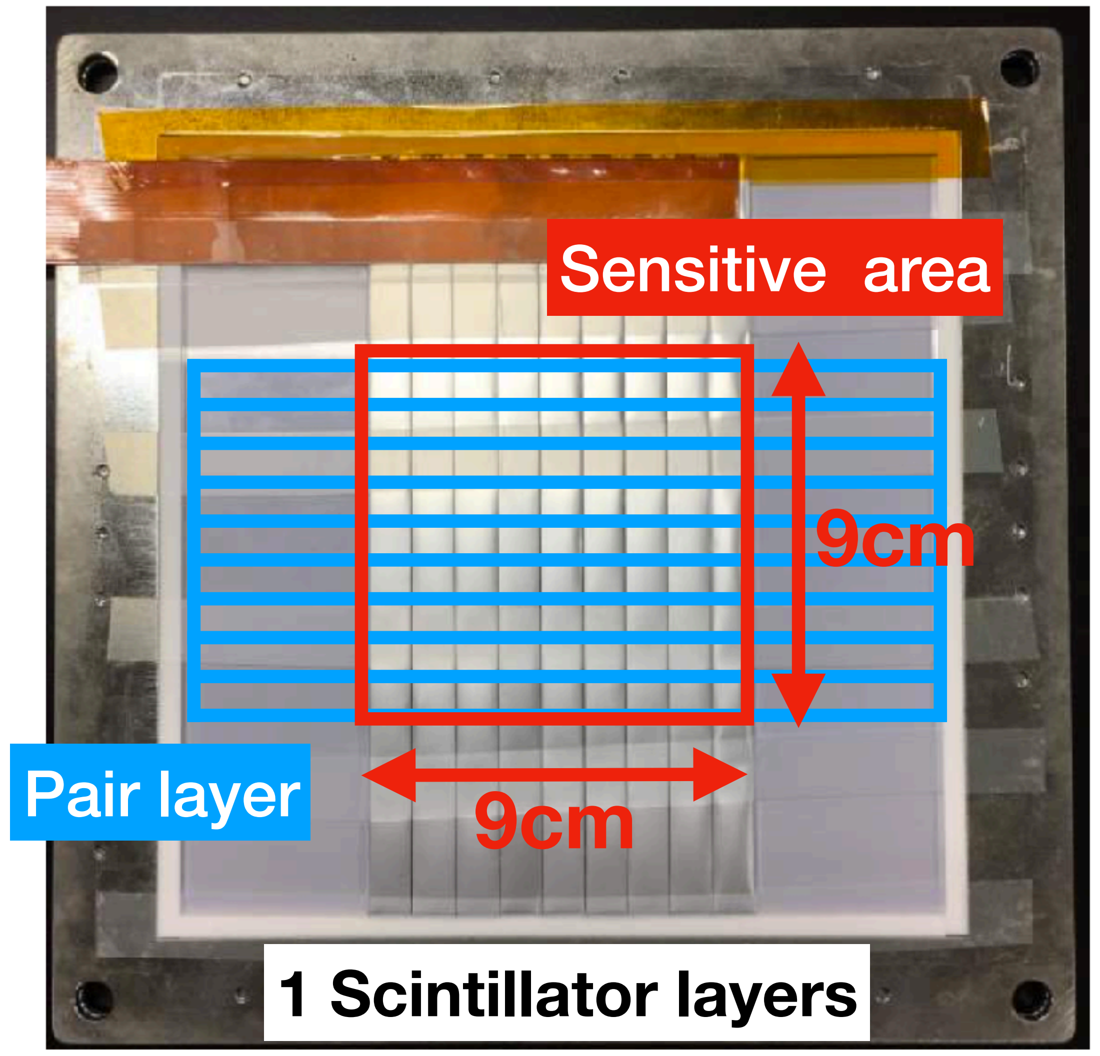
- DAQ system uses EASIROC Modules
- Developed by KEK and OSAKA University for MPPC
- We have modified the FPGA firmware and added TDC and coincidence functionality
- Multiple modules can be synchronized by the external clock
- A module equips two EASIROC chips (developed by Omega) for 64 channels
- Includes ADC, TDC and HV power supply
- Controlled by PC via Ethernet

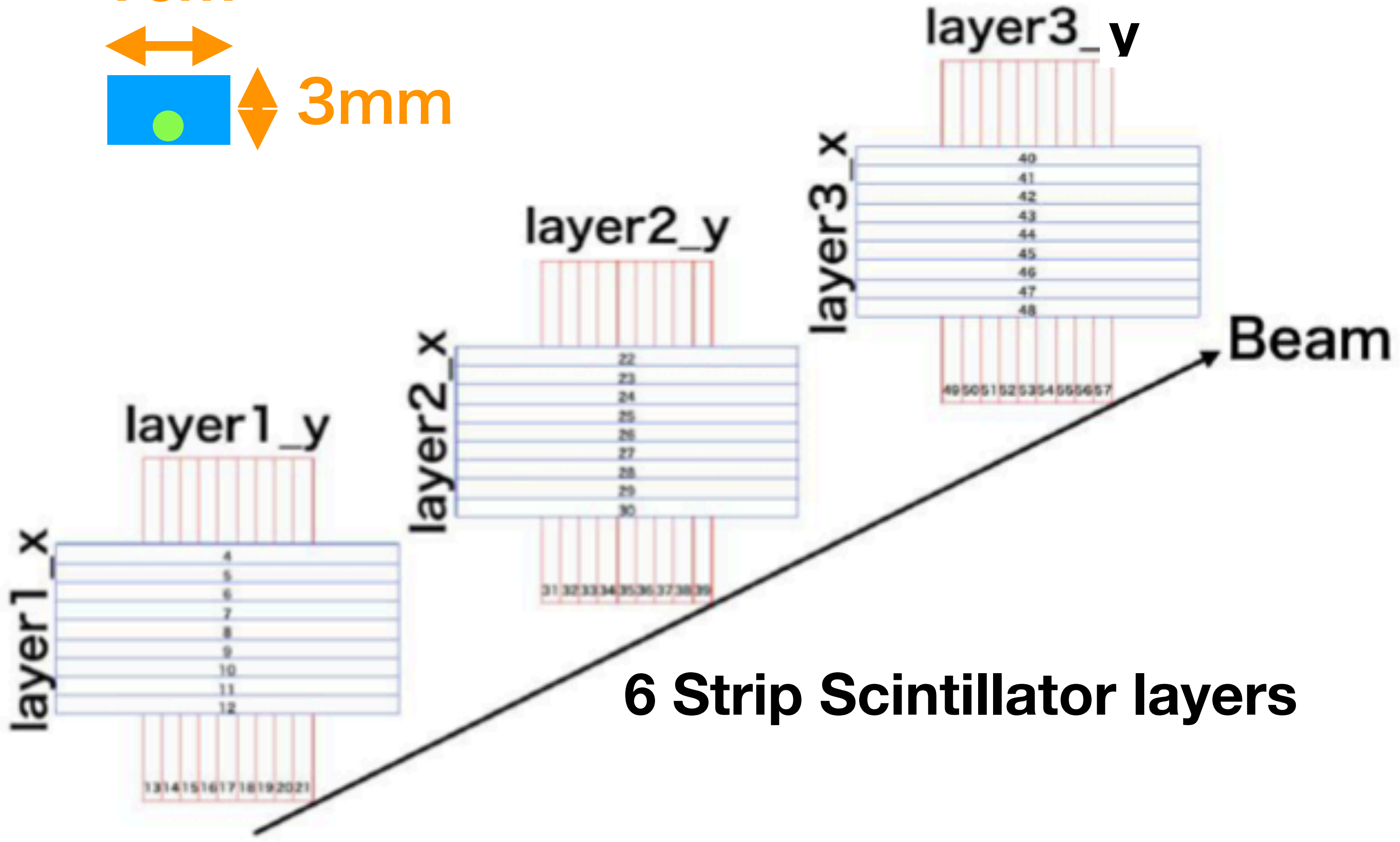


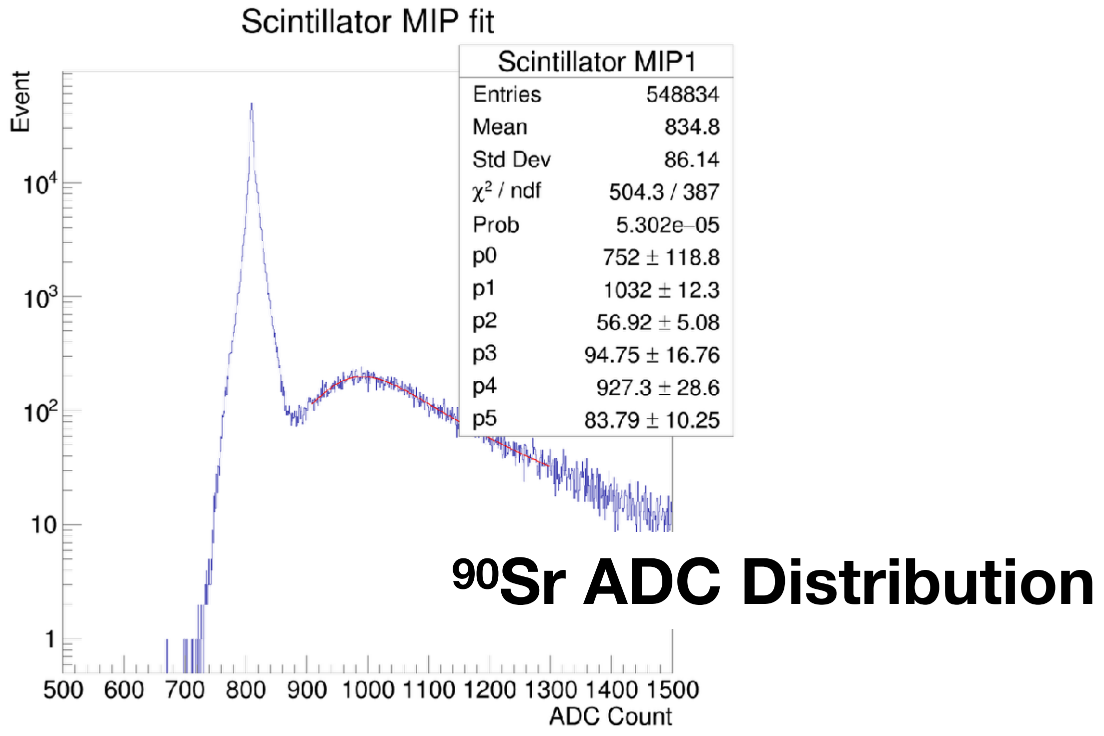
Detection layer (strip scintillator)

- A scintillator layer: 9 x 9 cm^2 sensitive area
- Same sizes as the lead glass layer.
- Component
  - 9 strip scintillator in one layer
  - Strip scintillators (EJ-204) with 18 x 1 x 0.3 cm^3
  - Wavelength shifting fiber (Y-11).
  - 1 x 1 mm^2, 25μm pitch, 1600pixel MPPC
  - Enveloped with 3M reflector film.
- We manufactured 6 layers.
- Pre-calibration of the layer at the bench test was done with cosmic muons and ^{90}Sr.





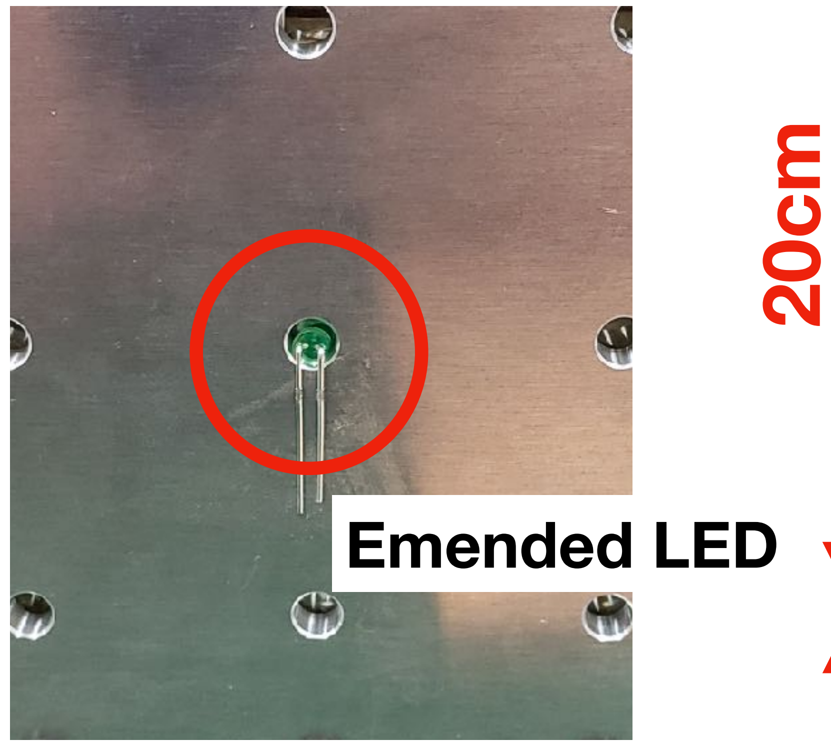


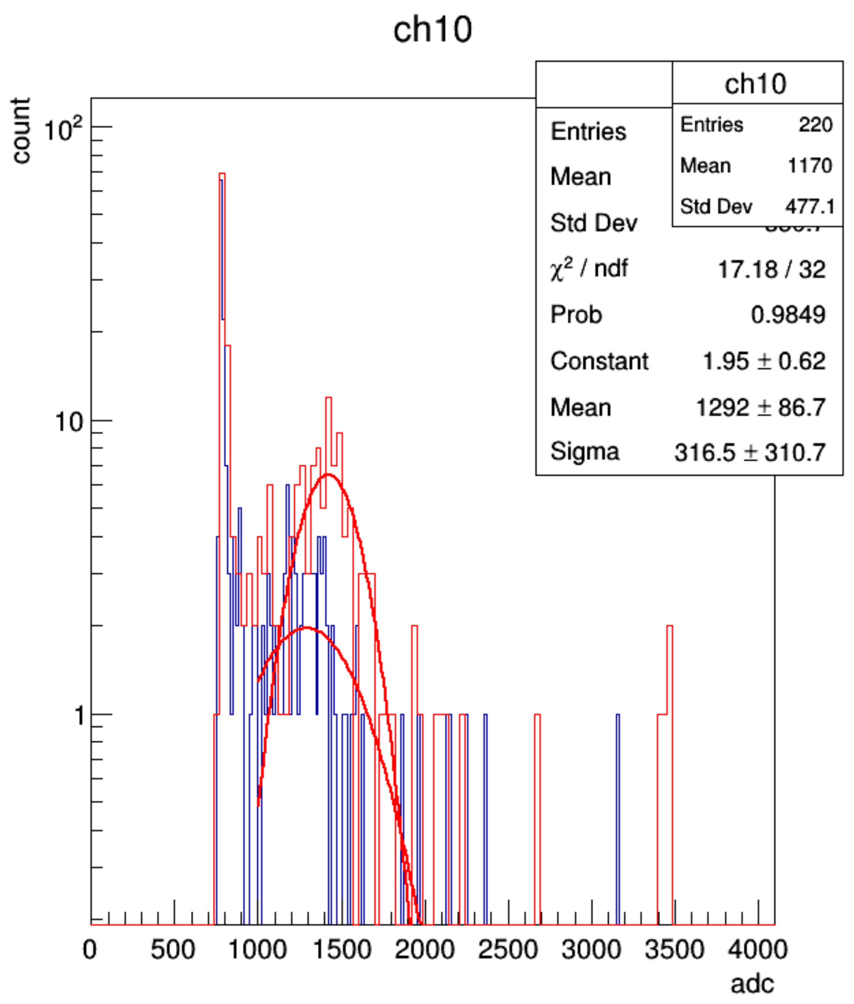


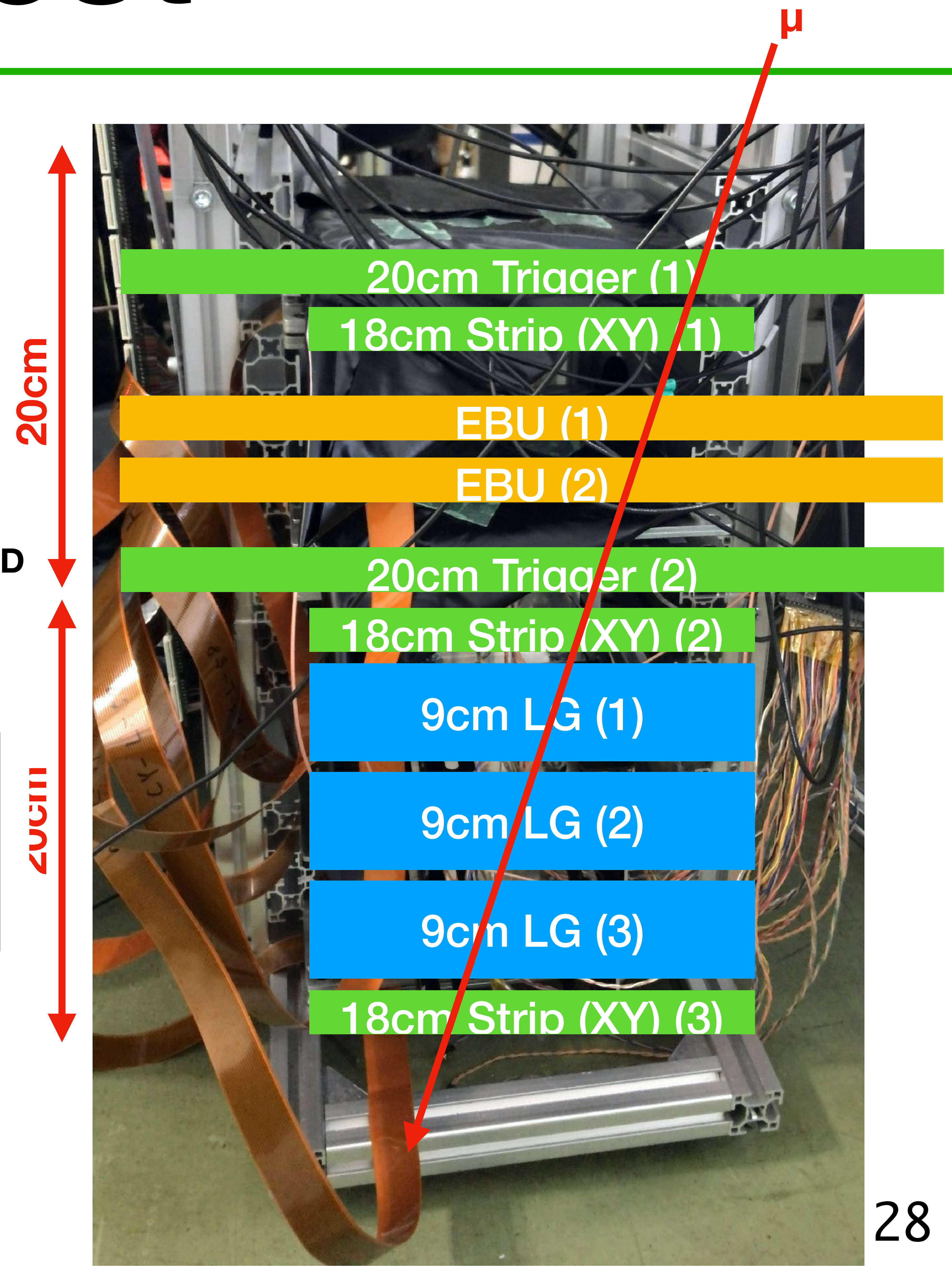
^{90}Sr ADC Distribution

Cosmic ray test

- Operation check of the whole detector by cosmic muons
- We also pre-calibrate lead glass blocks by cosmic muons
- For calibration lead glass blocks, it is necessary to inject particles energetic enough to emit Cherenkov light (eg. cosmic muon)
- The energy deposit by a cosmic muon with 4cm thickness lead glass is estimated at 50 MeV
- The position can be detected by using the information of the strip scintillator layers
- We can see through muon peak and move peak different bias voltage
- Read line peak is 22 p.e (compare with LED calibration result)

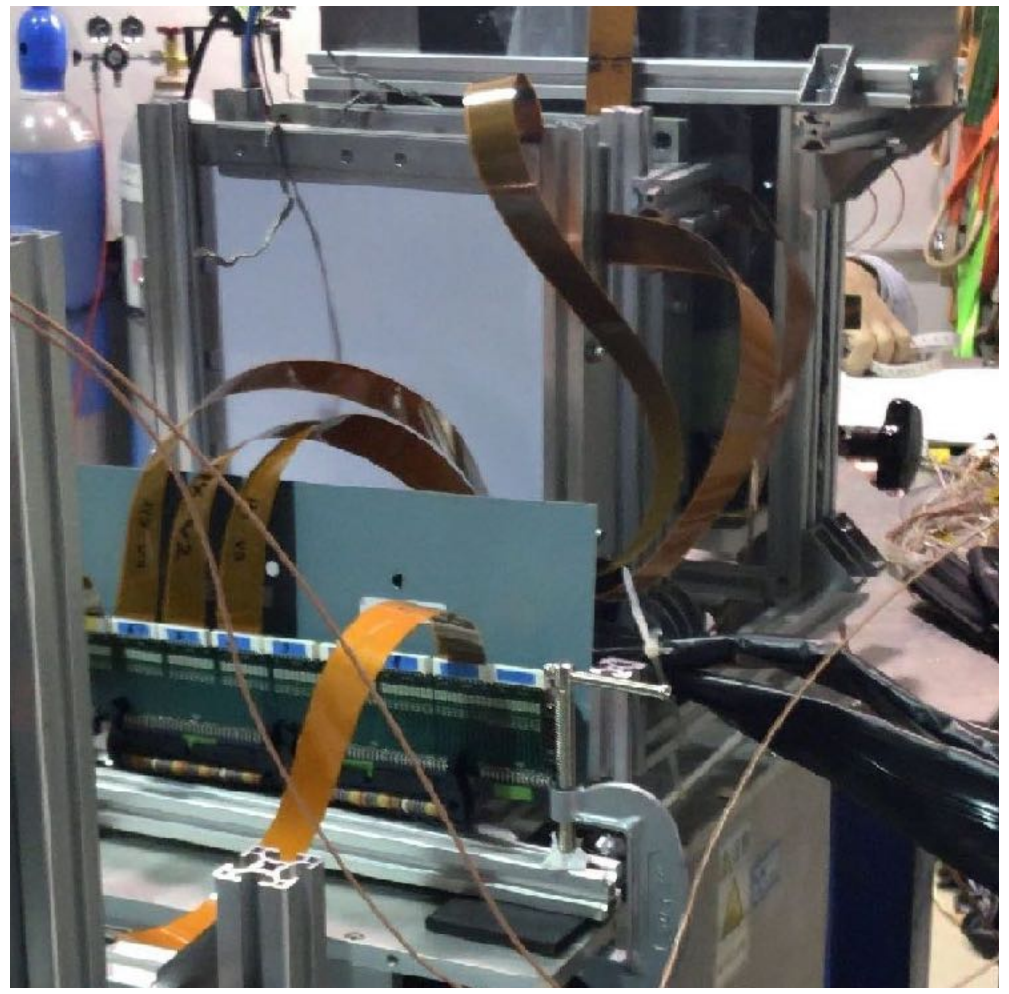




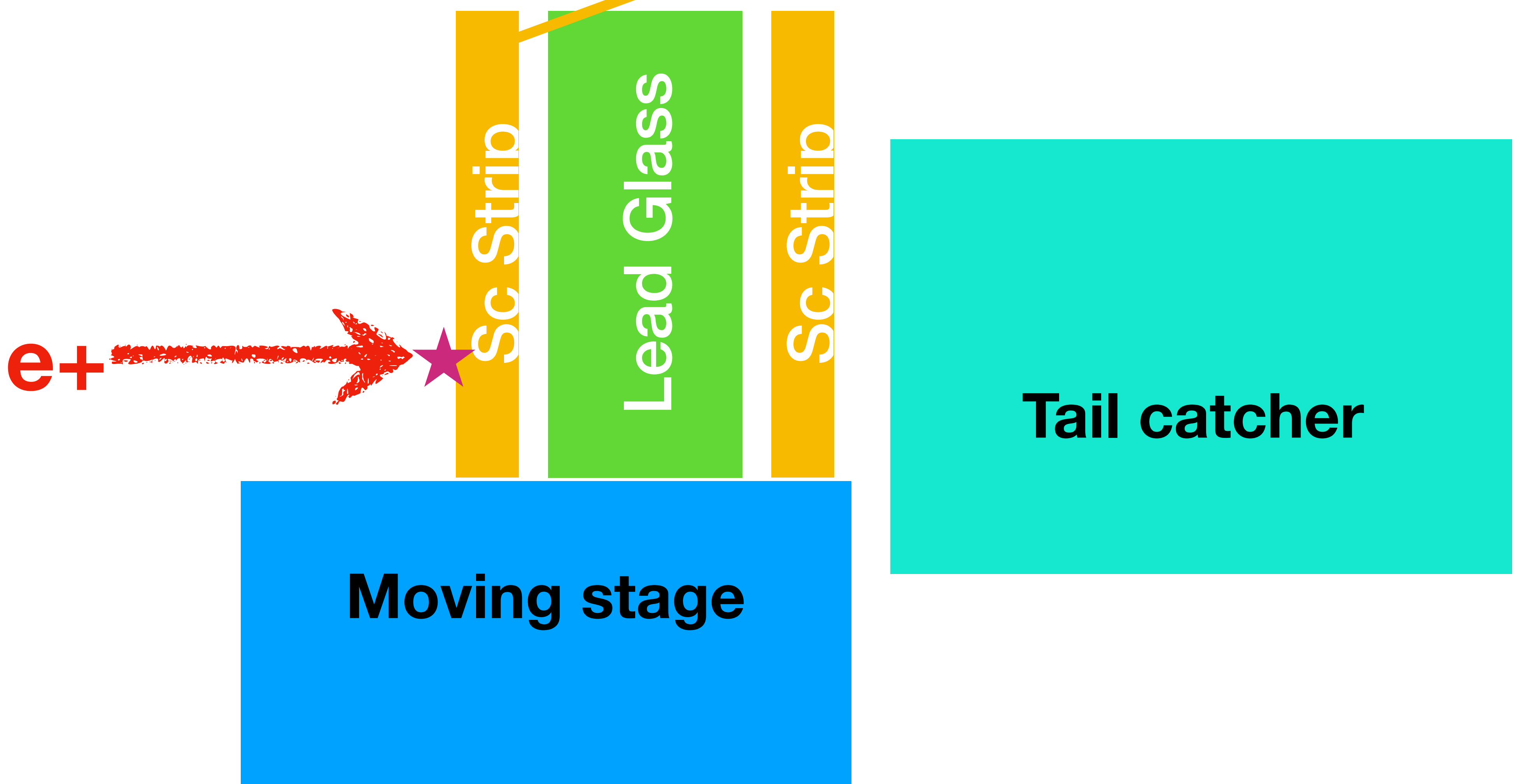


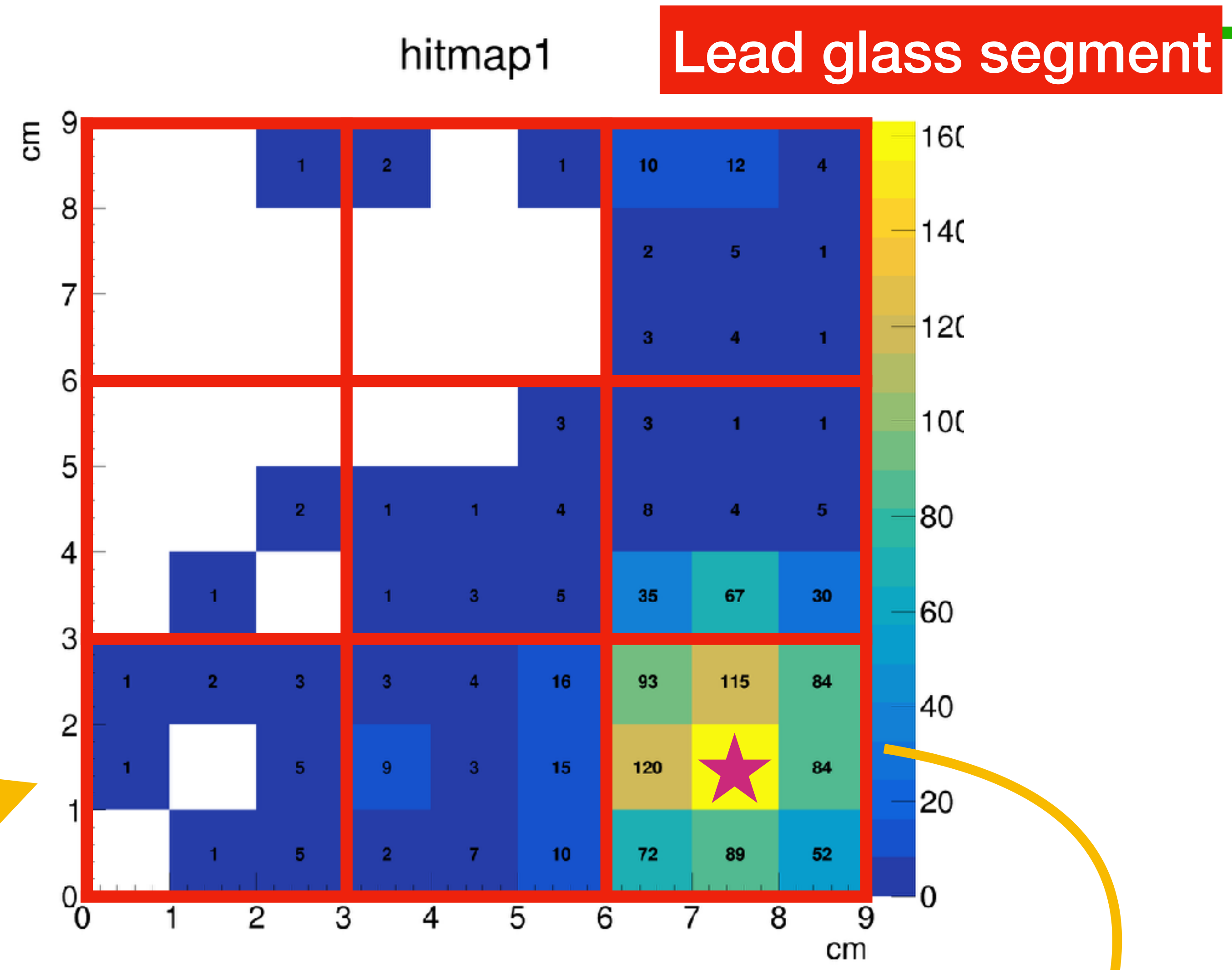
Set Up of Energy Calibration

- We did calibration all Lead Glass block channels with 400MeV beam.
- We moved the position of the detector using an electric moving stage by remote control
- Beam position was confirmed by using strip layer in front of the lead glass layer
- Lead glass at the center of the layer confirmed the response by changing incident energy(100, 200, 400, 600, 800MeV)

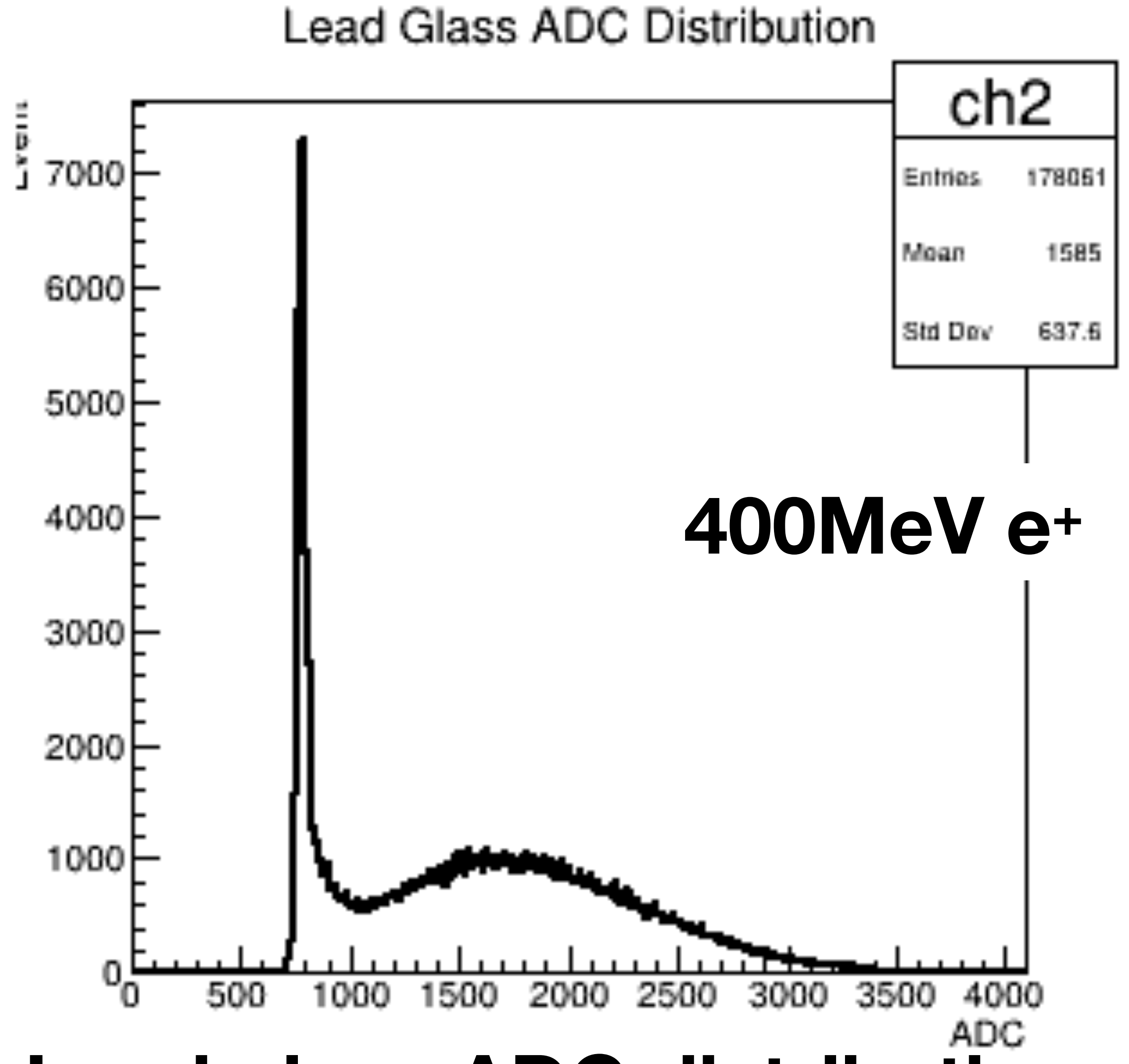


Set up of energy calibration



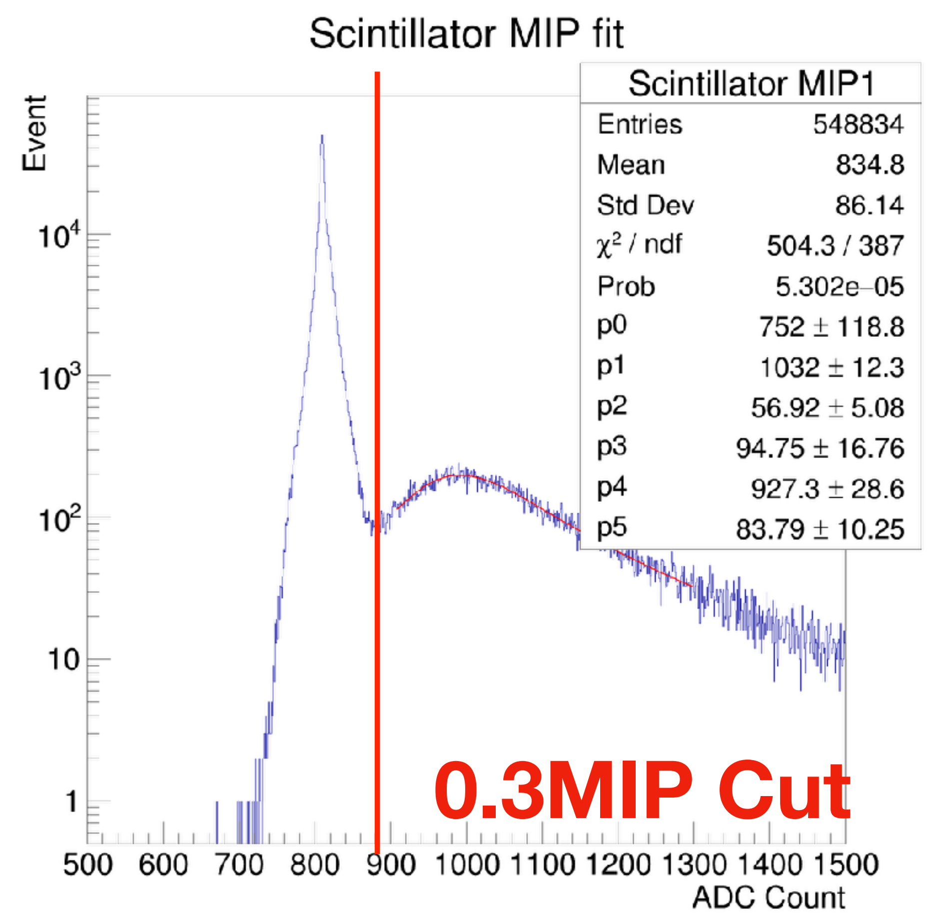


Sc hitmap for Beam position



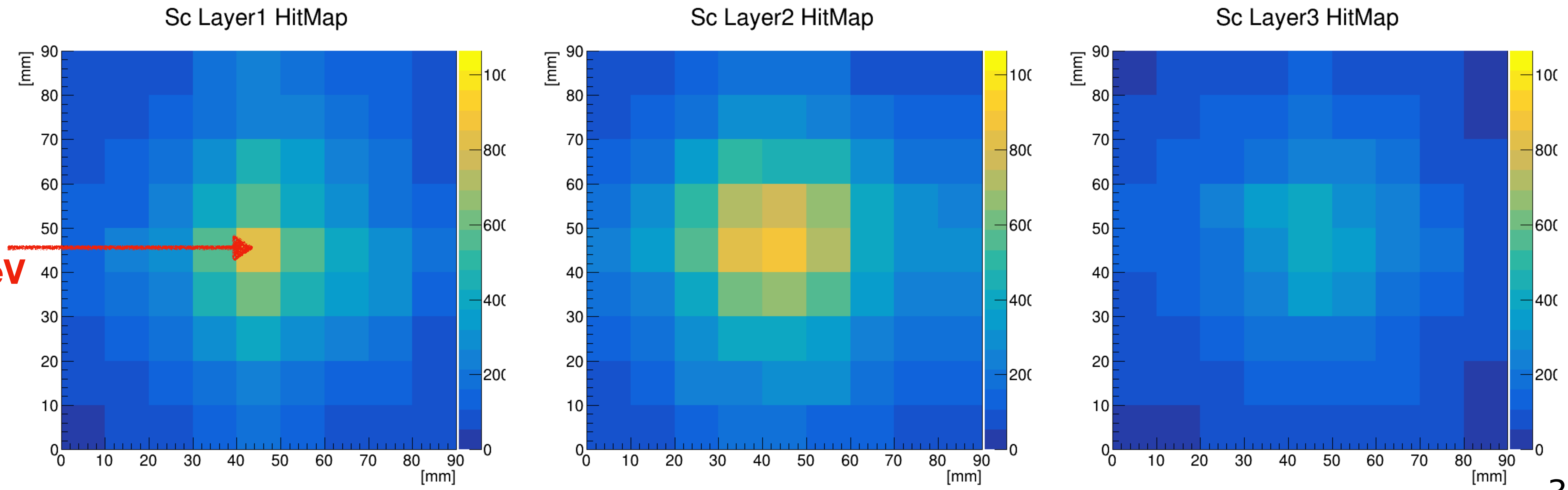
Lead glass ADC distribution

Scintillator Hitmap (2017)



- Injection 800MeV positron
- Cut at 0.3 MIP and took the coincidence of X and Y layers
- We can see the development of EM shower
- All strip scintillator channels work well

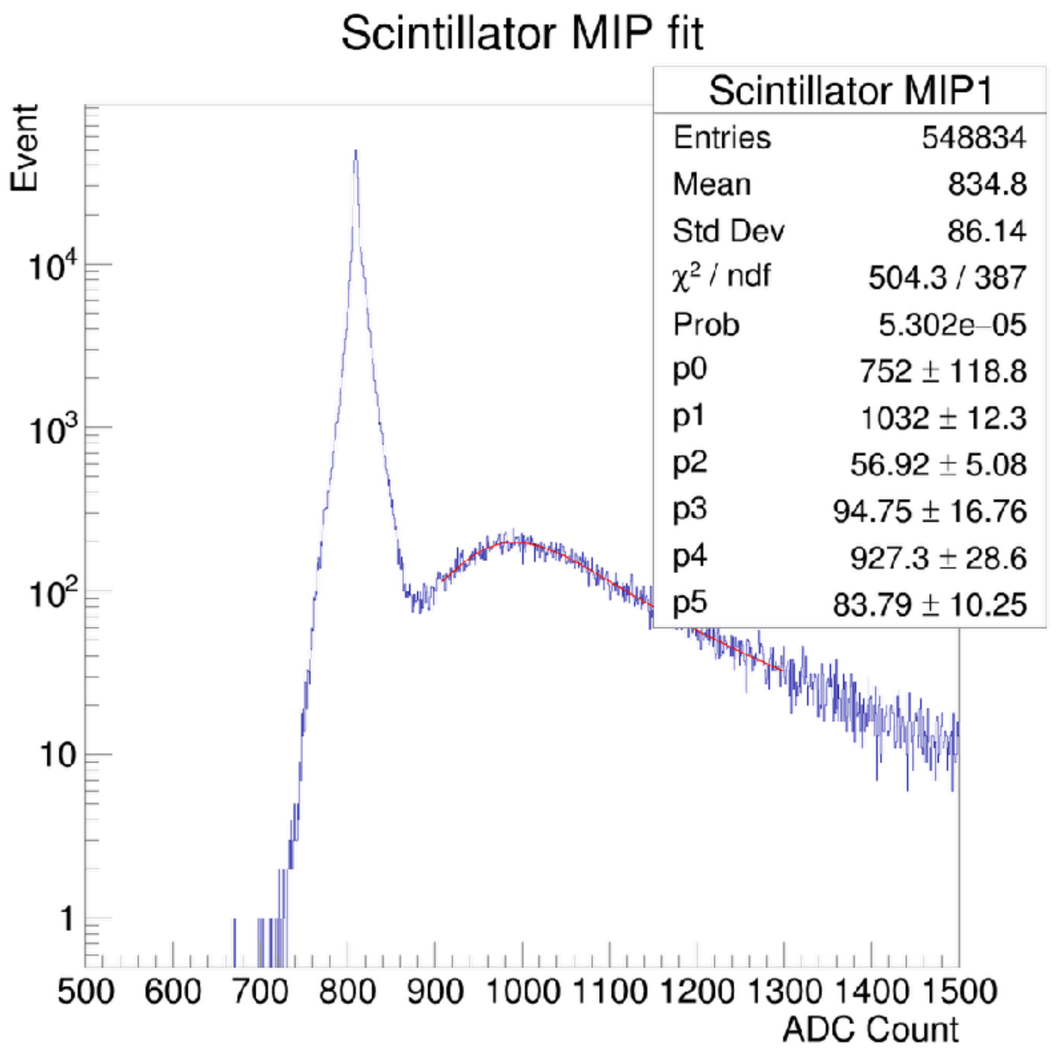
e+ 800MeV

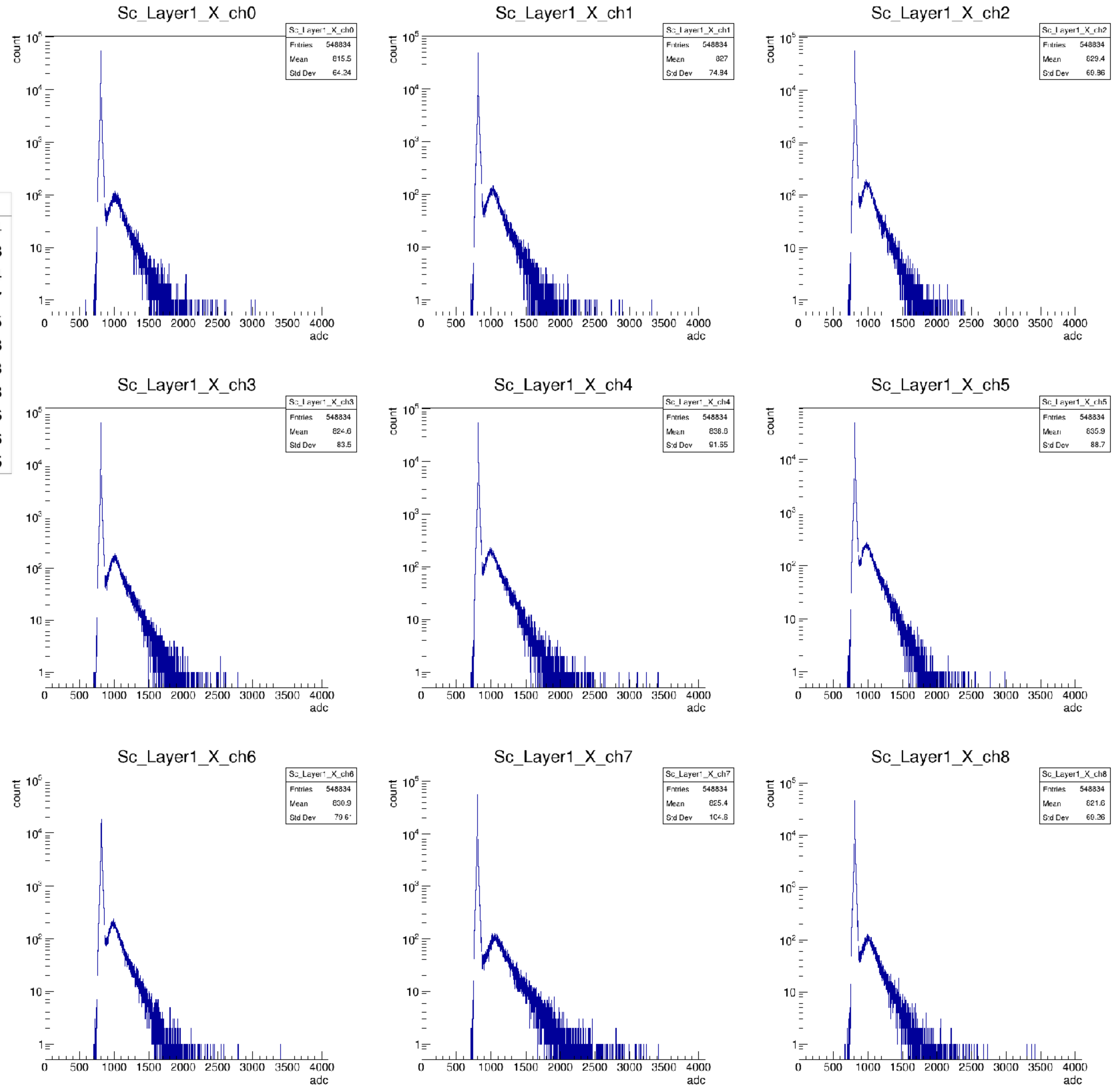


800MeV Sc Hitmap

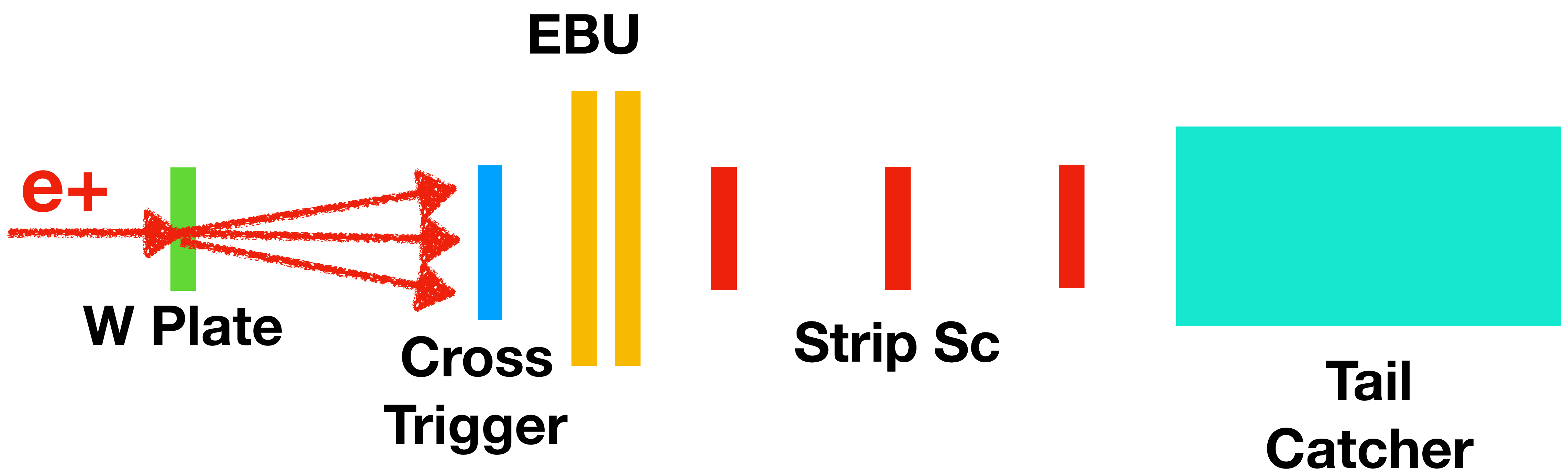
Scintillator Calibration

- Injection 800MeV positron
- Makes shower by W plate set at most upstream
- The trigger is using tail catcher signal at most downstream
- All Channels can see MIPs, and work well (2016 test, 2 channels were dead)
- Calibrate scintillator using MIP fit result





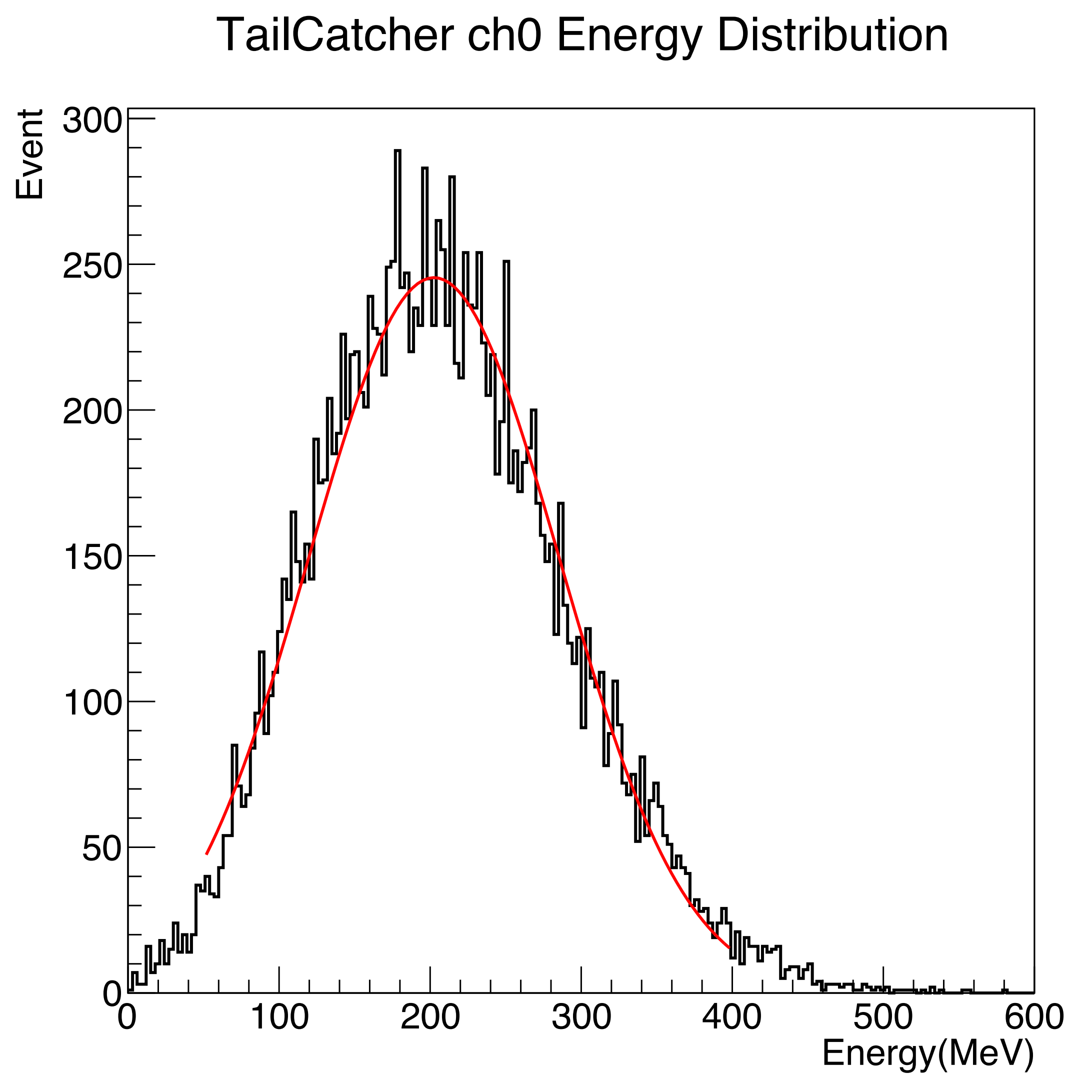
Layer 1 X direction ADC distribution at calibration run (2017)



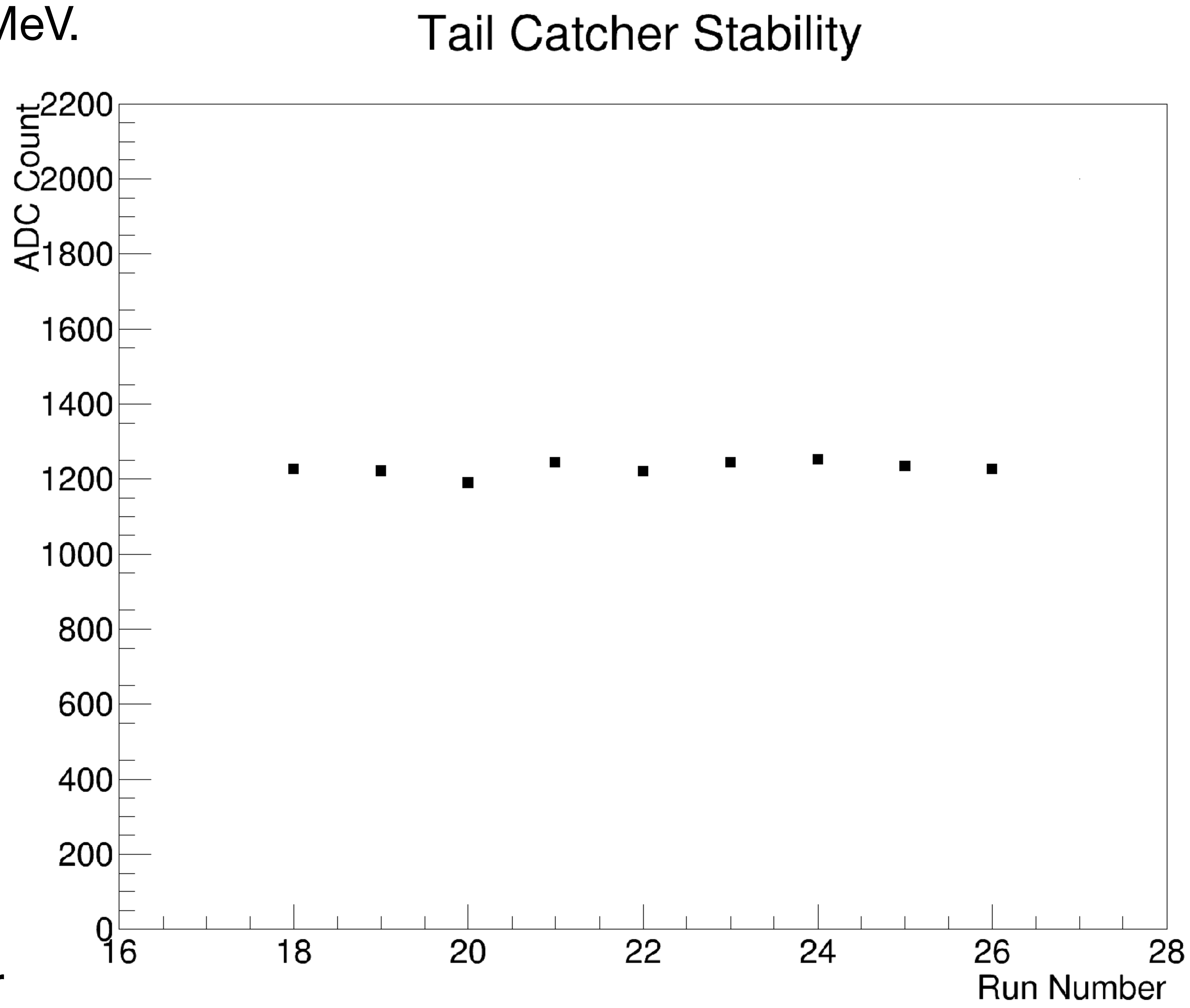
scintillator calibration setup (remove active absorber)

Tail catcher stability

- When evaluating the performance of this calorimeter, all lead glass blocks must be calibrated.
- At 400MeV injection, put one layer tail catcher detected 200MeV.
- If beam energy stable, this energy is not changed.
- We checked the stability of the tail catcher.



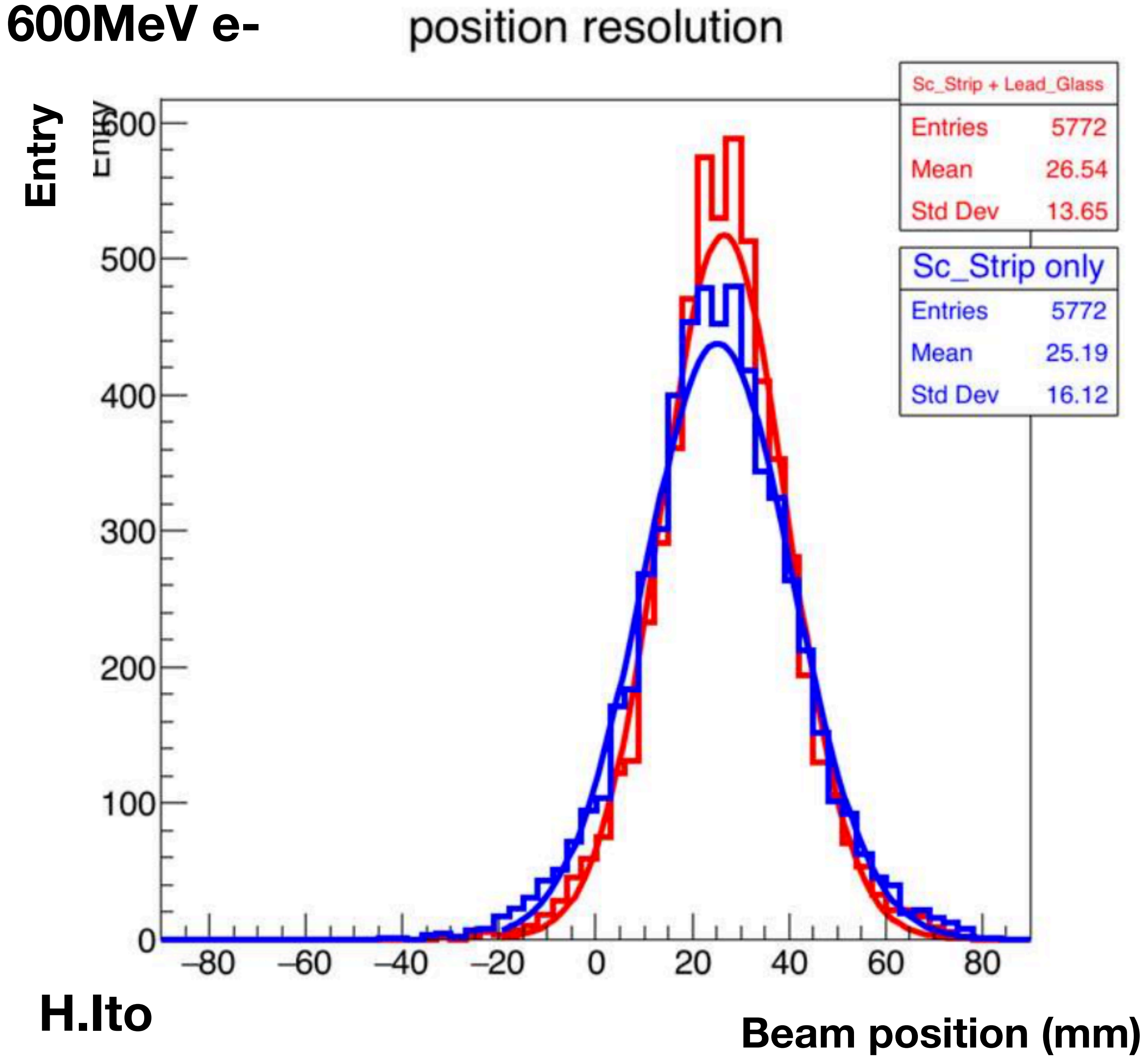
Tail catcher ADC Distribution of 400MeV e+ injected behind one LG Layer



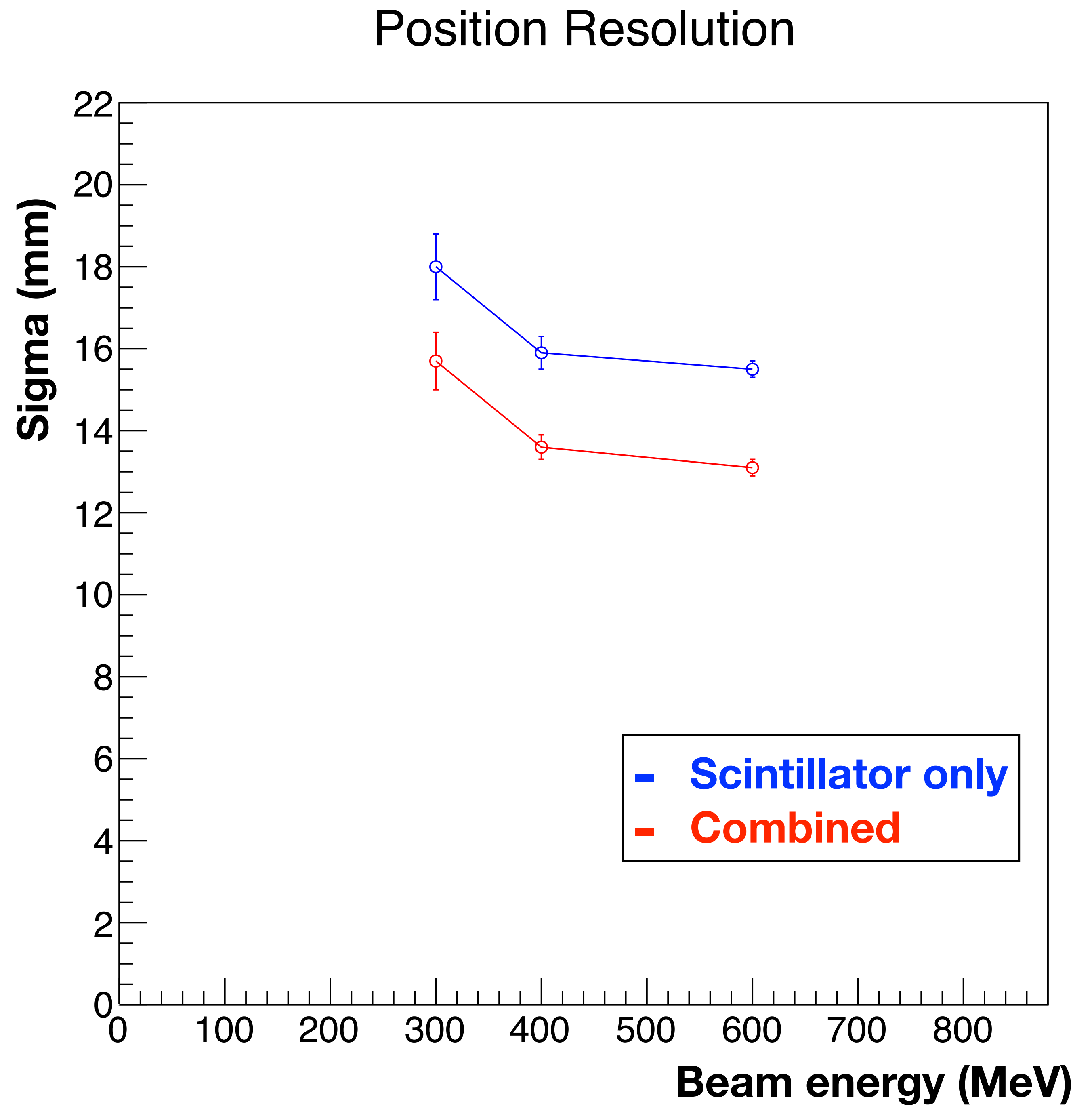
Position Resolution

- The beam was shifted 30 mm in parallel at beam line
- The position distribution results for the scintillator layer only (blue) and with lead-glass information combined (red)
- The beam position is reconstructed by calculating centroid in each layer and fitted with a straight line
- Results with absorber and scintillator layers are 10% better than those with scintillator only

600MeV e-

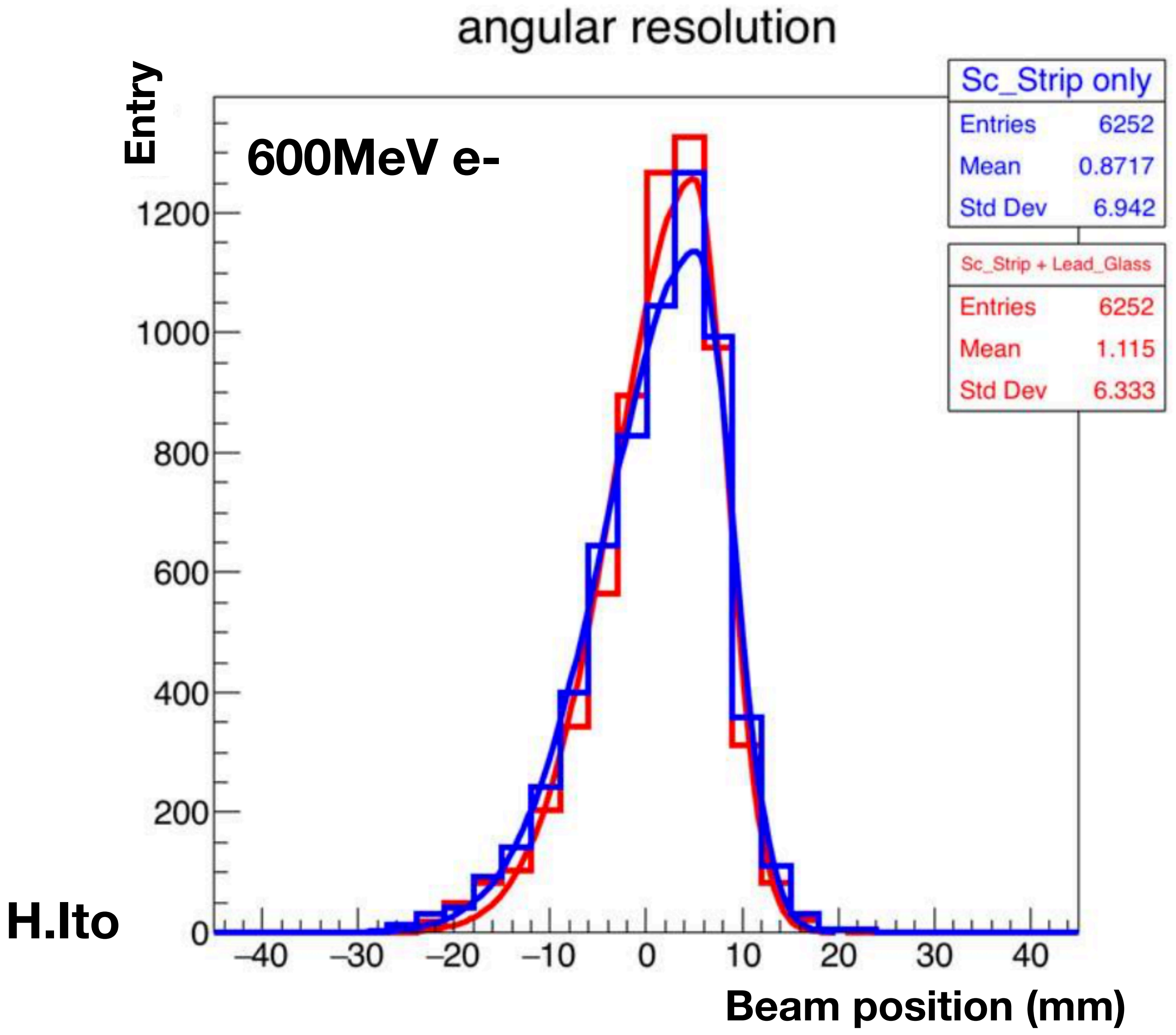


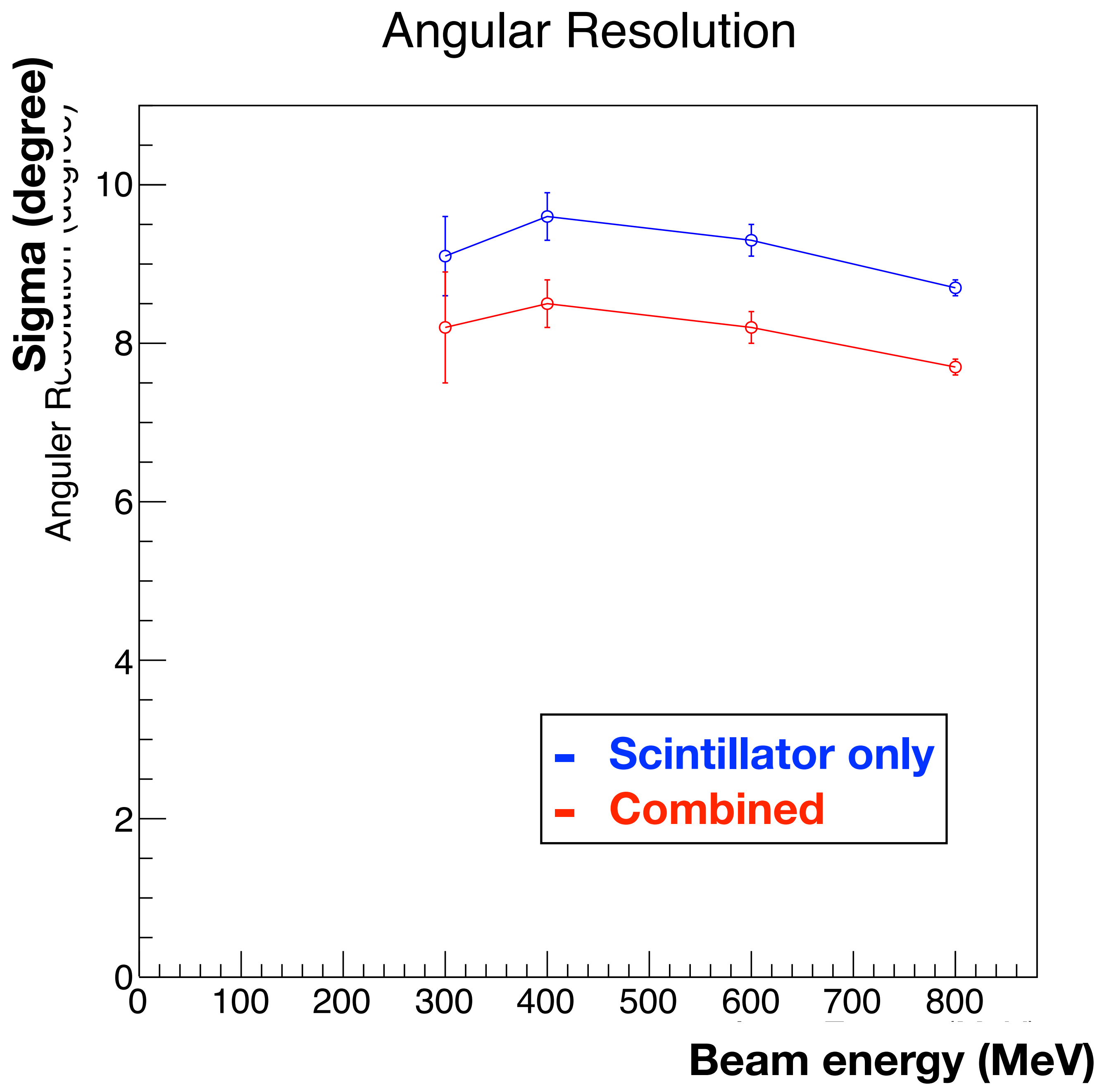
H.Ito



Angular Resolution

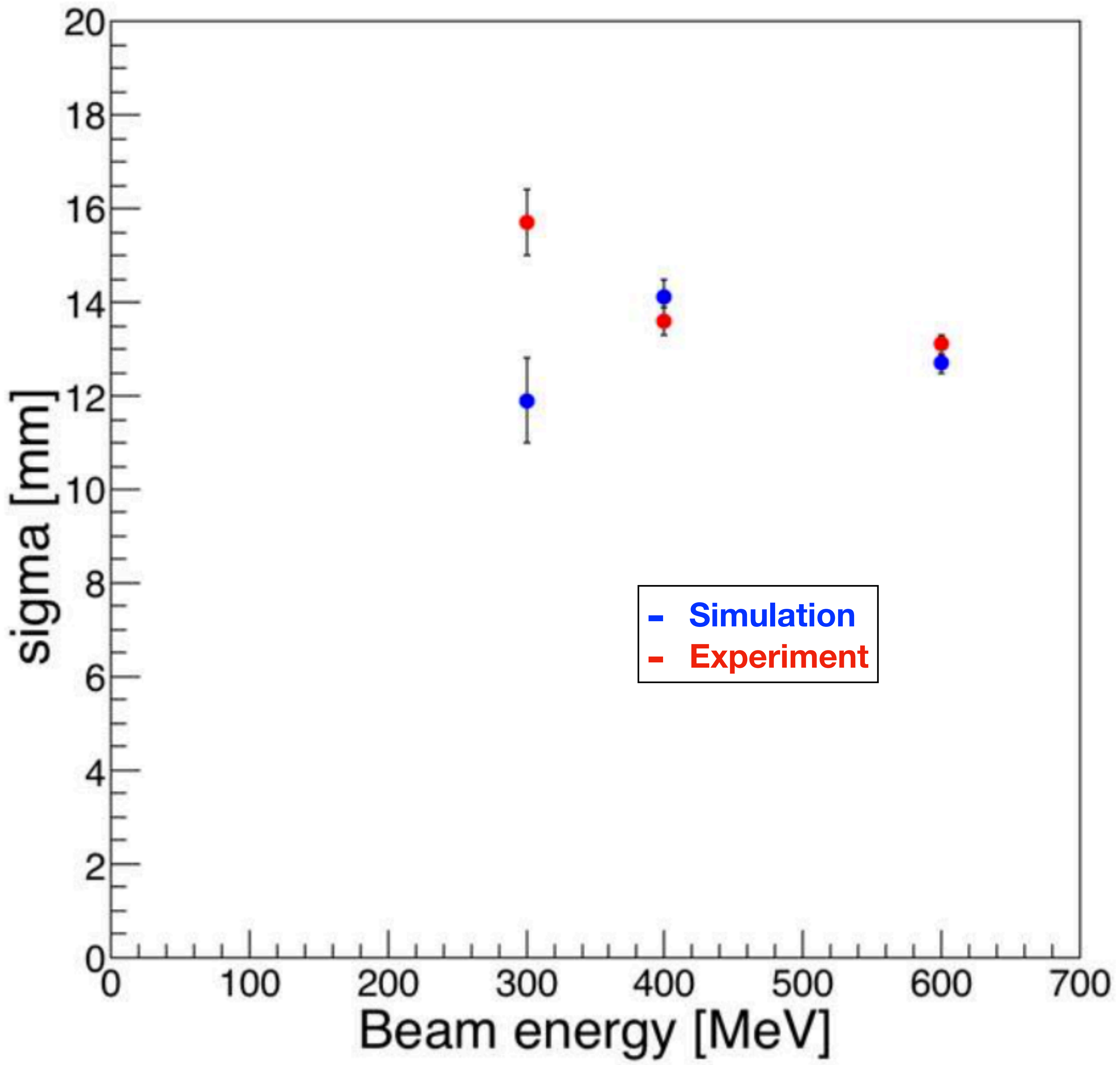
- The beam was injected at an angle of 5 degrees with the center axis of the calorimeter setup
- The angular distribution results for the scintillator layer only (blue) and with lead-glass information combined (red)
- The beam angle is reconstructed by calculating centroid in each layer and fitted with a straight line
- Results of absorber and scintillator layers are 10% better than scintillator only





Position and angular resolution (simulation vs experiment)

Position Resolution



Angular Resolution