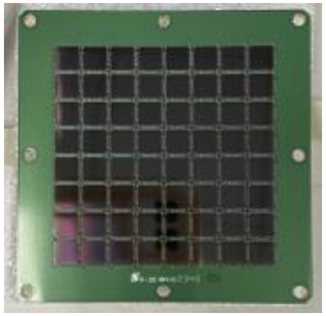
ZDC ECal 1st Prototype Analysis and MC Status

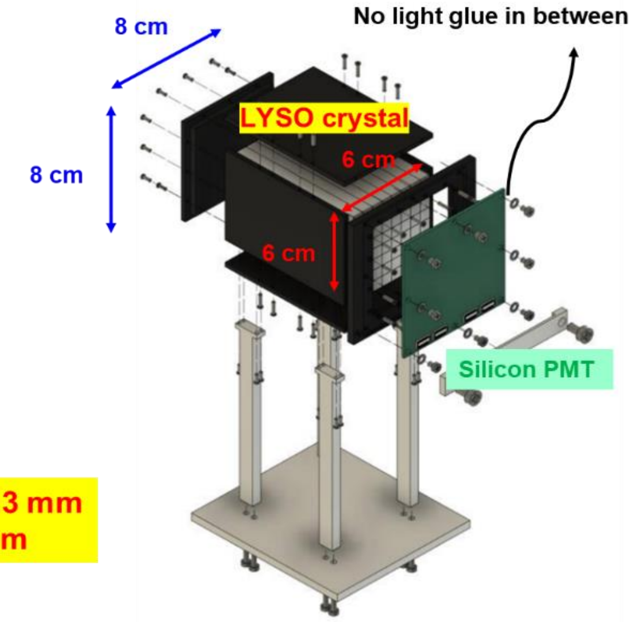
ZDC ECal 1st Prototype



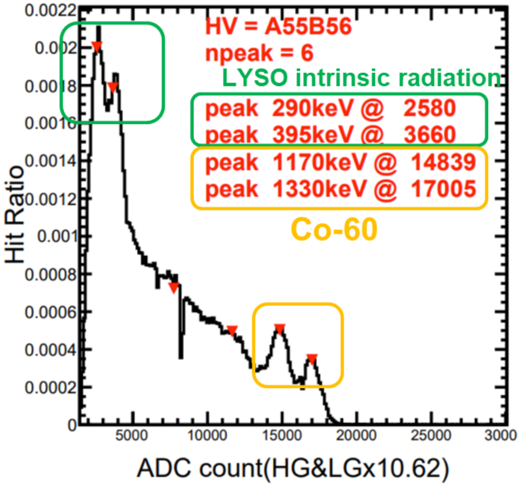
SiPM 8*8 array

LYSO crystal

one pixel = 7.12 mm x 7.12 mm x 88.3 mm
8 * 8 pixels = 56.96mm * 56.96mm



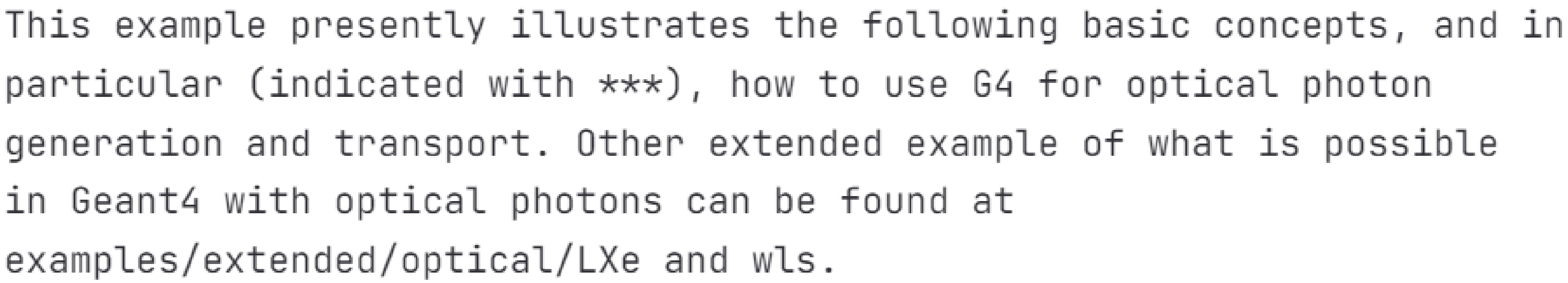
- SiPM array + LYSO crystal
- 8*8 channels
- One channel : 7mm * 7mm * 8.8cm
- All channels : 6cm * 6cm * 8.8cm (8X0)



MC Status

- Based on example :

https://gitlab.cern.ch/geant4/geant4/-/tree/master/examples/extended/optical/OpNovice



This example presently illustrates the following basic concepts, and in particular (indicated with ***), how to use G4 for optical photon generation and transport. Other extended example of what is possible in Geant4 with optical photons can be found at examples/extended/optical/LXe and wls.

- Steps :

Define crystal geometry

Implement parameters of crystal

Implement reflection surface

Observe energy dump and optical photons in crystal

not yet done :

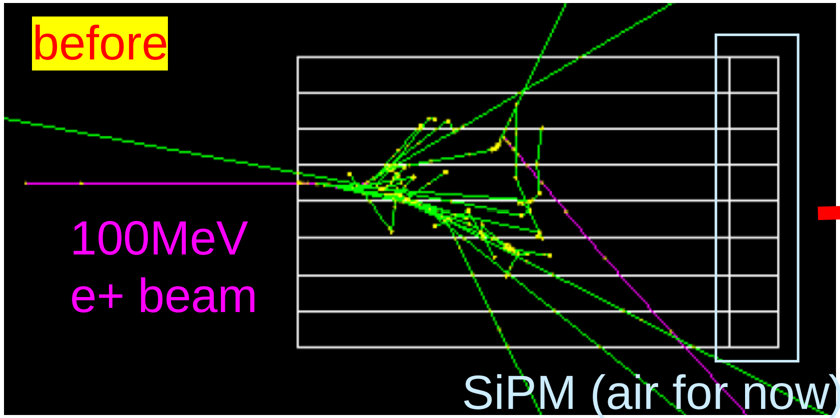
Implement detector (SiPM),

Implement SiPM parameters

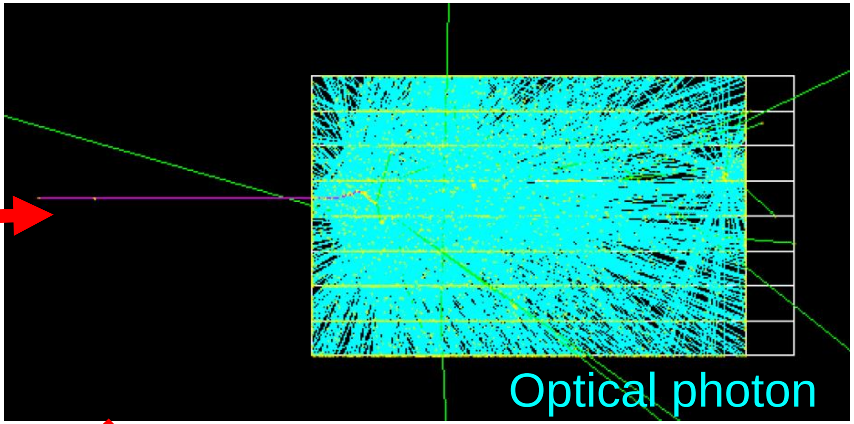
Read hits

MC Simulation of LYSO Crystal

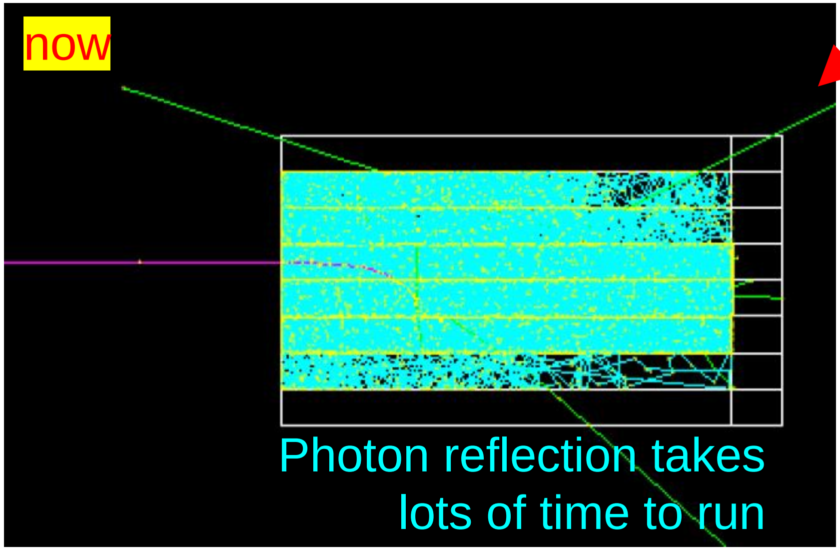
Only LYSO



LYSO + MPT(w/ Birk's)



LYSO + MPT(w/ Birk's) + Reflection Surface



Photon reflection takes lots of time to run

- Positron/Beam(purple)
- Electron(yellow)
- Gamma (green)
- Optical photon (cyan)
  - Scintillation
  - Cherenkov

- Beam energy 50MeV-800MeV simulated.
- SiPM not simulated.

Material Property Table of LYSO

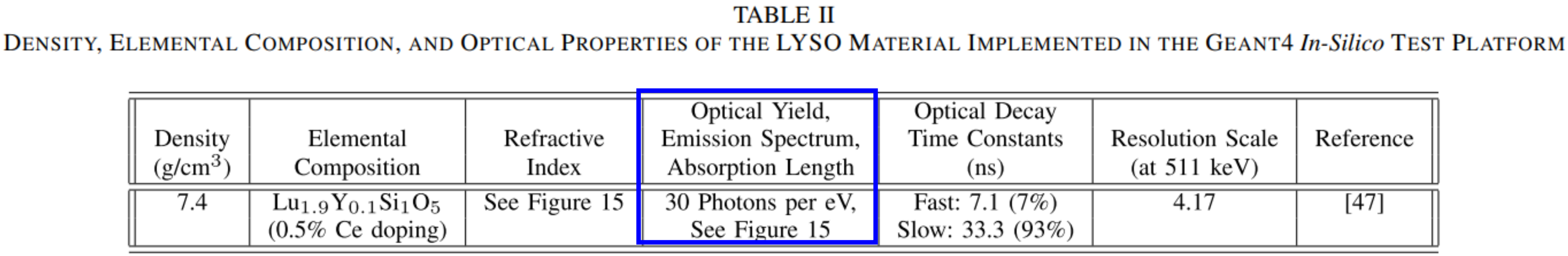


TABLE II

DENSITY, ELEMENTAL COMPOSITION, AND OPTICAL PROPERTIES OF THE LYSO MATERIAL IMPLEMENTED IN THE GEANT4 *In-Silico* TEST PLATFORM

Density (g/cm^3)	Elemental Composition	Refractive Index	Optical Yield, Emission Spectrum, Absorption Length	Optical Decay Time Constants (ns)	Resolution Scale (at 511 keV)	Reference
7.4	$Lu_{1.9}Y_{0.1}Si_1O_5$ (0.5% Ce doping)	See Figure 15	30 Photons per eV, See Figure 15	Fast: 7.1 (7%) Slow: 33.3 (93%)	4.17	[47]

energy dependent

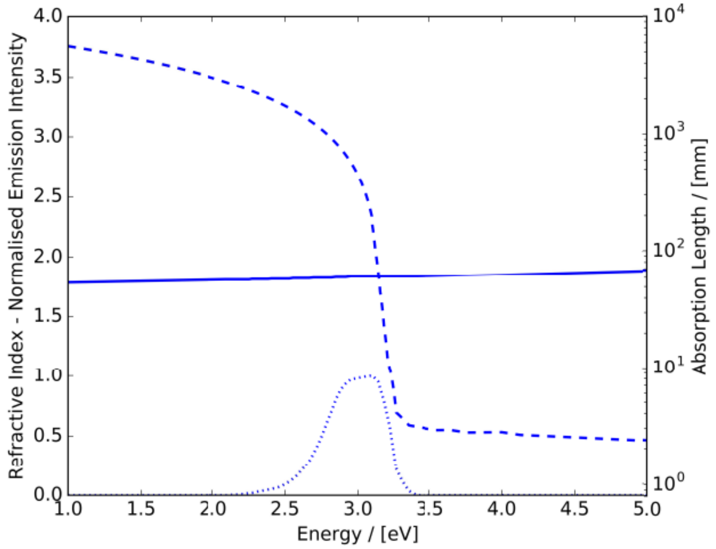
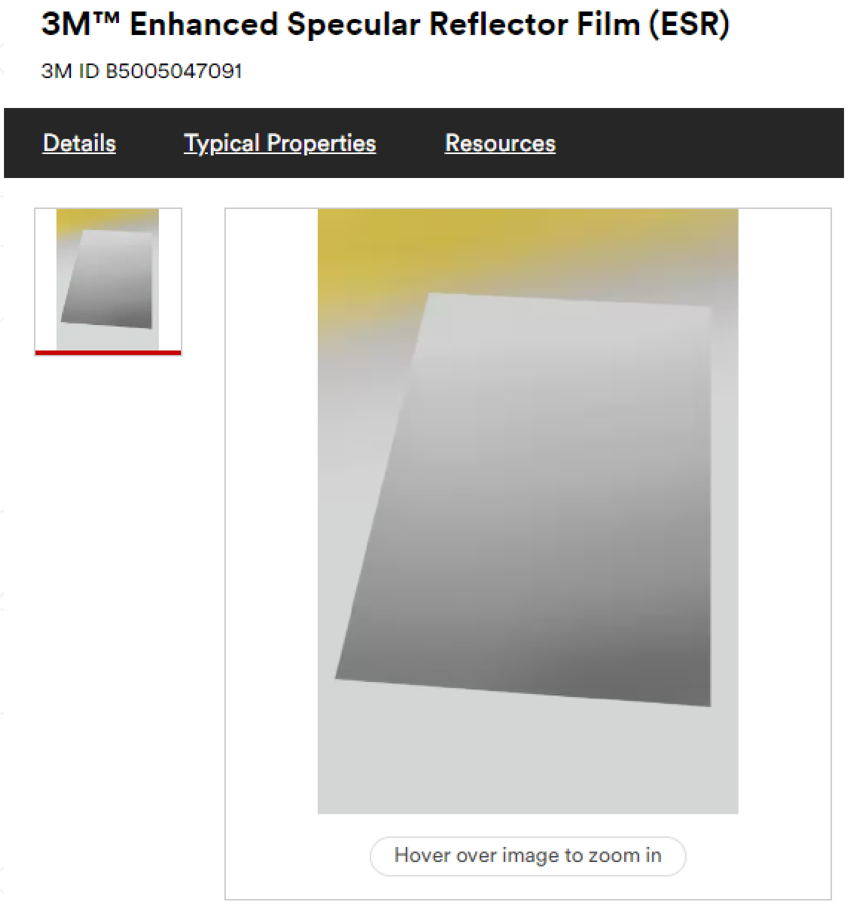


Fig. 15. LYSO scintillator crystal material refractive index (solid line), attenuation length (dashed line), and normalized scintillation photon emission intensity (dotted line) data sets implemented in the Geant4 *in-silico* test platform.

- Reference paper
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8876605

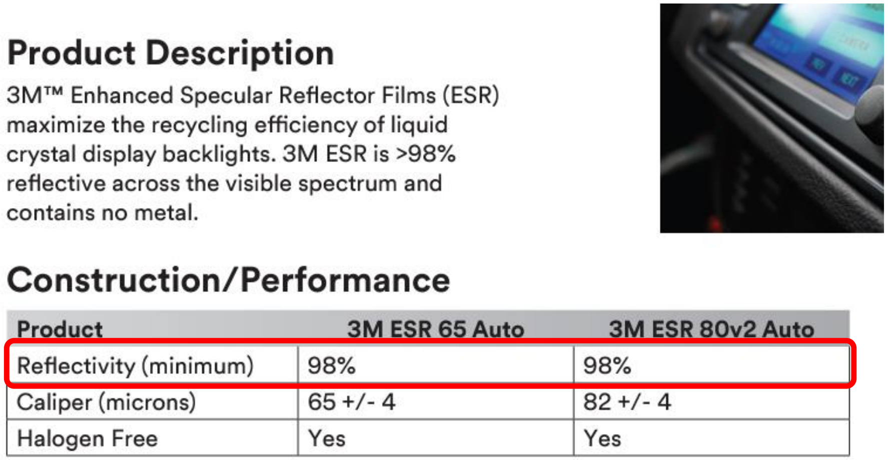
- Reference code
https://github.com/JunhaoWang511/MLCsimulation/blob/master/src/MLCDetectorConstruction.cc

Reflection Surface with 3M ERS



3M™ Enhanced Specular Reflector Film (ESR)

3M ID B5005047091



Product Description

3M™ Enhanced Specular Reflector Films (ESR) maximize the recycling efficiency of liquid crystal display backlights. 3M ESR is >98% reflective across the visible spectrum and contains no metal.

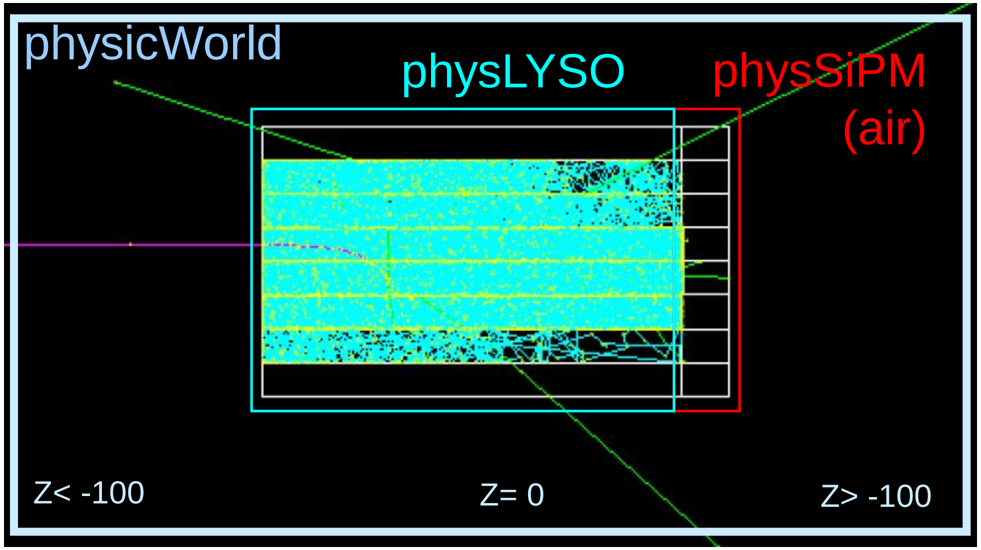
Construction/Performance

Product	3M ESR 65 Auto	3M ESR 80v2 Auto
Reflectivity (minimum)	98%	98%
Caliper (microns)	65 +/- 4	82 +/- 4
Halogen Free	Yes	Yes

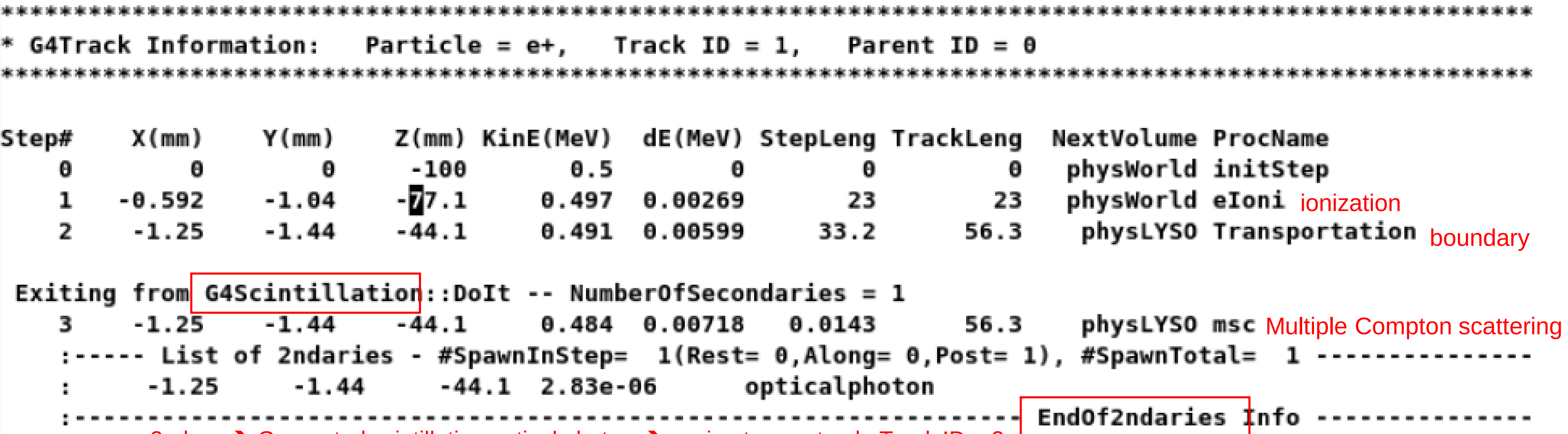
Reflectivity = 0.98

https://www.3m.com/3M/en_US/p/d/b5005047091/

Tracking and Steps in MC



- Positron/Beam(purple)
- Electron(yellow)
- Gamma (green)
- Optical photon (cyan)
  - Scintillation
  - Cherenkov



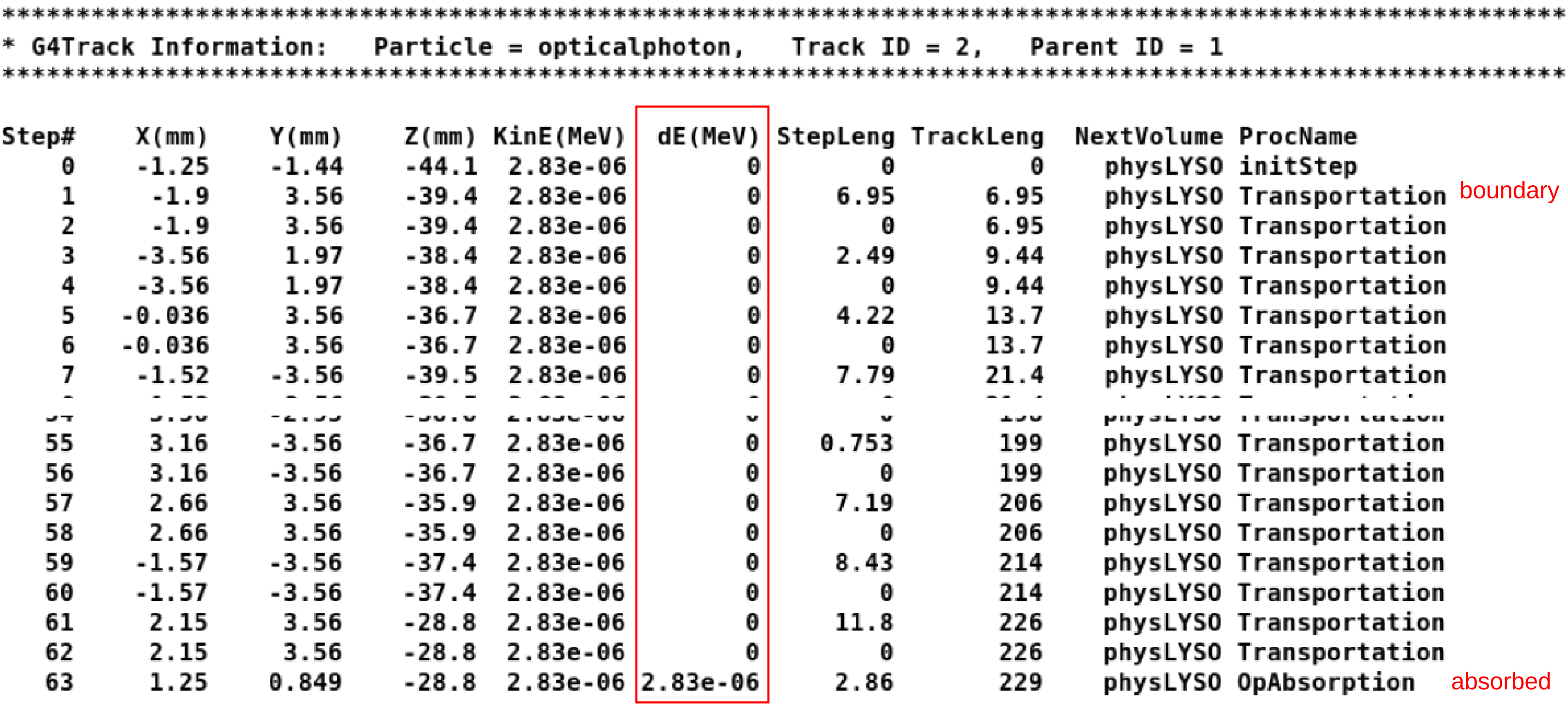
```
****************************************************************************************
* G4Track Information:   Particle = e+,   Track ID = 1,   Parent ID = 0
****************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0     -100       0.5        0        0         0   physWorld initStep
    1   -0.592    -1.04    -77.1     0.497  0.00269       23        23   physWorld eIoni
    2    -1.25    -1.44    -44.1     0.491  0.00599     33.2      56.3    physLYSO Transportation

 Exiting from G4Scintillation::DoIt -- NumberOfSecondaries = 1
    3    -1.25    -1.44    -44.1     0.484  0.00718   0.0143      56.3    physLYSO msc
    :----- List of 2ndaries - #SpawnInStep=  1(Rest= 0,Along= 0,Post= 1), #SpawnTotal=  1 ---------------
    :      -1.25      -1.44      -44.1   2.83e-06      opticalphoton
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------
```

ionization

boundary

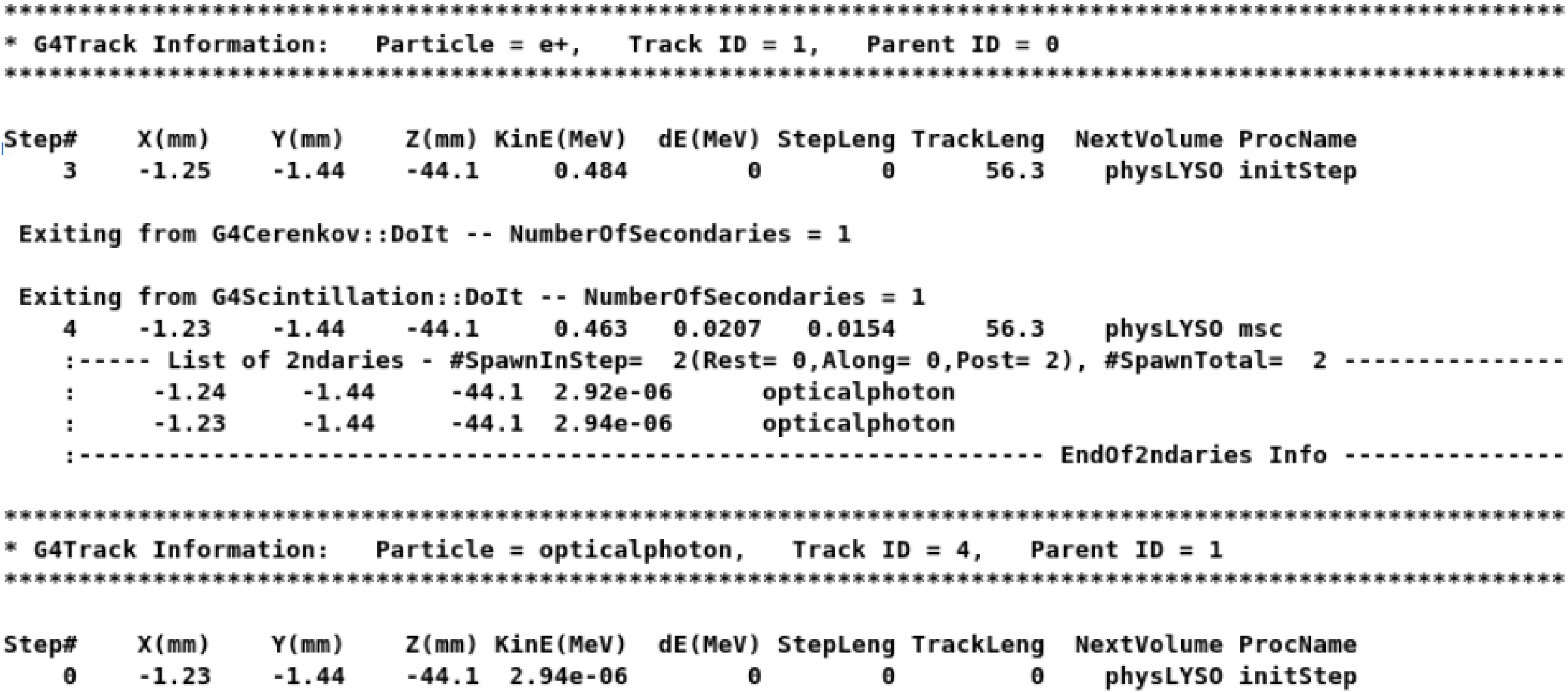
Multiple Compton scattering

msc 2ndary ➔ Generated scintillation optical photon ➔ assign to new track, Track ID = 2



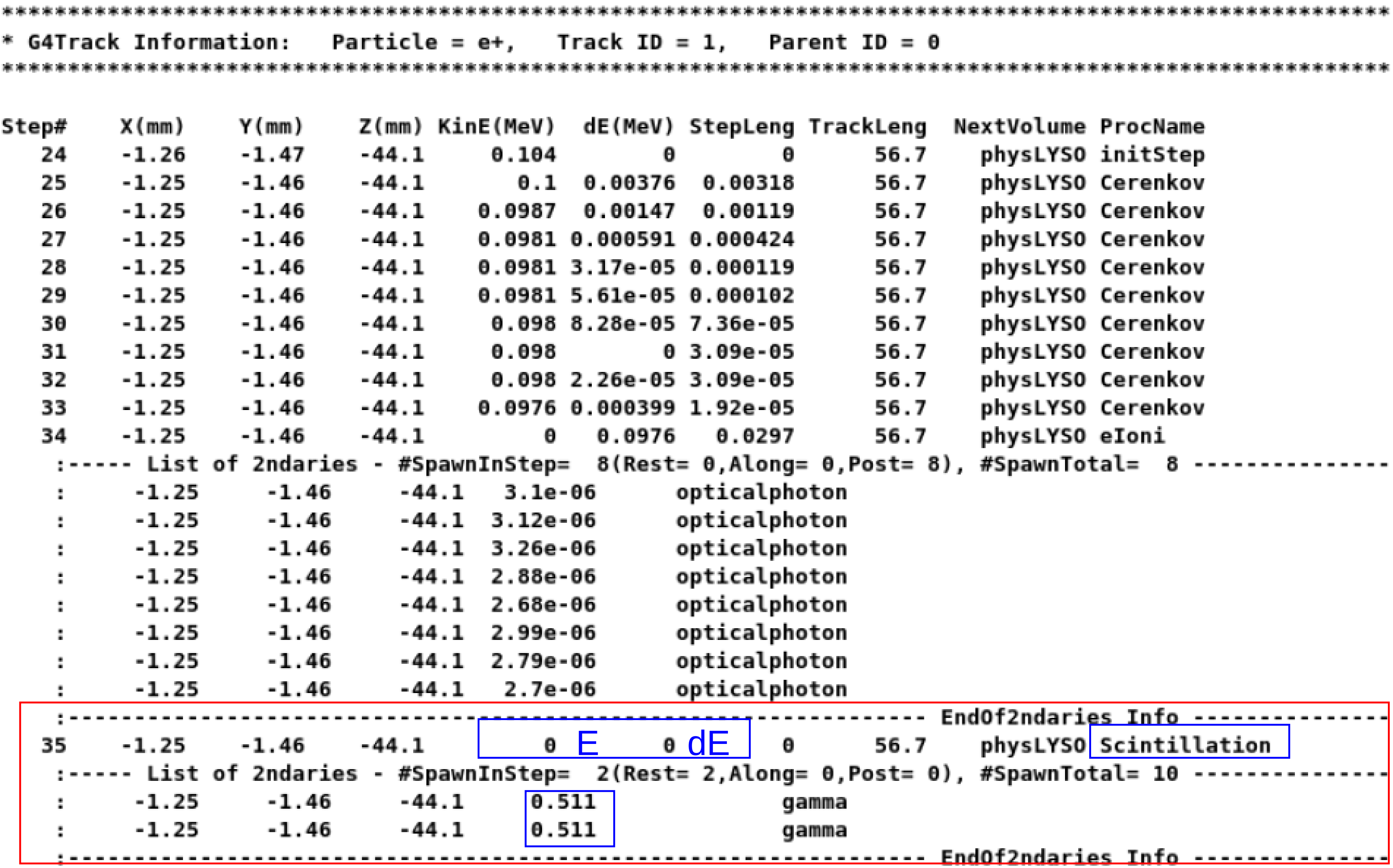
```
*******************************************************************************
* G4Track Information:   Particle = opticalphoton,   Track ID = 2,   Parent ID = 1
*******************************************************************************

Step#     X(mm)     Y(mm)     Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -1.25     -1.44     -44.1  2.83e-06         0        0         0   physLYSO initStep
    1      -1.9      3.56     -39.4  2.83e-06         0     6.95      6.95   physLYSO Transportation
    2      -1.9      3.56     -39.4  2.83e-06         0        0      6.95   physLYSO Transportation
    3     -3.56      1.97     -38.4  2.83e-06         0     2.49      9.44   physLYSO Transportation
    4     -3.56      1.97     -38.4  2.83e-06         0        0      9.44   physLYSO Transportation
    5    -0.036      3.56     -36.7  2.83e-06         0     4.22      13.7   physLYSO Transportation
    6    -0.036      3.56     -36.7  2.83e-06         0        0      13.7   physLYSO Transportation
    7     -1.52     -3.56     -39.5  2.83e-06         0     7.79      21.4   physLYSO Transportation
   55      3.16     -3.56     -36.7  2.83e-06         0    0.753       199   physLYSO Transportation
   56      3.16     -3.56     -36.7  2.83e-06         0        0       199   physLYSO Transportation
   57      2.66      3.56     -35.9  2.83e-06         0     7.19       206   physLYSO Transportation
   58      2.66      3.56     -35.9  2.83e-06         0        0       206   physLYSO Transportation
   59     -1.57     -3.56     -37.4  2.83e-06         0     8.43       214   physLYSO Transportation
   60     -1.57     -3.56     -37.4  2.83e-06         0        0       214   physLYSO Transportation
   61      2.15      3.56     -28.8  2.83e-06         0     11.8       226   physLYSO Transportation
   62      2.15      3.56     -28.8  2.83e-06         0        0       226   physLYSO Transportation
   63      1.25     0.849     -28.8  2.83e-06  2.83e-06     2.86       229   physLYSO OpAbsorption
```

For optical photons : no energy dump during the transportation steps until it is absorbed.



```
*********************************************************************************************************
* G4Track Information:   Particle = e+,   Track ID = 1,   Parent ID = 0
*********************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    3    -1.25    -1.44    -44.1     0.484        0        0      56.3    physLYSO initStep

 Exiting from G4Cerenkov::DoIt -- NumberOfSecondaries = 1

 Exiting from G4Scintillation::DoIt -- NumberOfSecondaries = 1
    4    -1.23    -1.44    -44.1     0.463   0.0207   0.0154      56.3    physLYSO msc
    :----- List of 2ndaries - #SpawnInStep=  2(Rest= 0,Along= 0,Post= 2), #SpawnTotal=  2 ---------------
    :     -1.24     -1.44     -44.1  2.92e-06      opticalphoton
    :     -1.23     -1.44     -44.1  2.94e-06      opticalphoton
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------

*********************************************************************************************************
* G4Track Information:   Particle = opticalphoton,   Track ID = 4,   Parent ID = 1
*********************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0    -1.23    -1.44    -44.1  2.94e-06        0        0         0    physLYSO initStep
```

Optical photons are generated as positron passes through LYSO



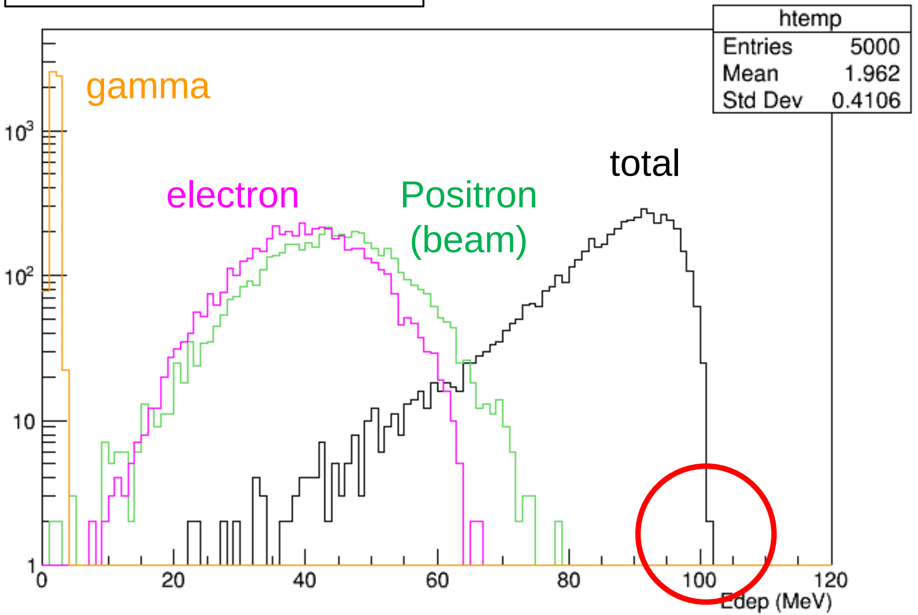
```
*********************************************************************************************
* G4Track Information:   Particle = e+,   Track ID = 1,   Parent ID = 0
*********************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
   24    -1.26    -1.47    -44.1     0.104        0        0      56.7    physLYSO initStep
   25    -1.25    -1.46    -44.1       0.1  0.00376  0.00318      56.7    physLYSO Cerenkov
   26    -1.25    -1.46    -44.1    0.0987  0.00147  0.00119      56.7    physLYSO Cerenkov
   27    -1.25    -1.46    -44.1    0.0981 0.000591 0.000424      56.7    physLYSO Cerenkov
   28    -1.25    -1.46    -44.1    0.0981 3.17e-05 0.000119      56.7    physLYSO Cerenkov
   29    -1.25    -1.46    -44.1    0.0981 5.61e-05 0.000102      56.7    physLYSO Cerenkov
   30    -1.25    -1.46    -44.1     0.098 8.28e-05 7.36e-05      56.7    physLYSO Cerenkov
   31    -1.25    -1.46    -44.1     0.098        0 3.09e-05      56.7    physLYSO Cerenkov
   32    -1.25    -1.46    -44.1     0.098 2.26e-05 3.09e-05      56.7    physLYSO Cerenkov
   33    -1.25    -1.46    -44.1    0.0976 0.000399 1.92e-05      56.7    physLYSO Cerenkov
   34    -1.25    -1.46    -44.1         0   0.0976   0.0297      56.7    physLYSO eIoni
    :----- List of 2ndaries - #SpawnInStep=  8(Rest= 0,Along= 0,Post= 8), #SpawnTotal=  8 --------------
    :       -1.25      -1.46      -44.1    3.1e-06        opticalphoton
    :       -1.25      -1.46      -44.1   3.12e-06        opticalphoton
    :       -1.25      -1.46      -44.1   3.26e-06        opticalphoton
    :       -1.25      -1.46      -44.1   2.88e-06        opticalphoton
    :       -1.25      -1.46      -44.1   2.68e-06        opticalphoton
    :       -1.25      -1.46      -44.1   2.99e-06        opticalphoton
    :       -1.25      -1.46      -44.1   2.79e-06        opticalphoton
    :       -1.25      -1.46      -44.1    2.7e-06        opticalphoton
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------
   35    -1.25    -1.46    -44.1         0        0        0      56.7    physLYSO Scintillation
    :----- List of 2ndaries - #SpawnInStep=  2(Rest= 2,Along= 0,Post= 0), #SpawnTotal= 10 --------------
    :       -1.25      -1.46      -44.1      0.511                gamma
    :       -1.25      -1.46      -44.1      0.511                gamma
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------
```

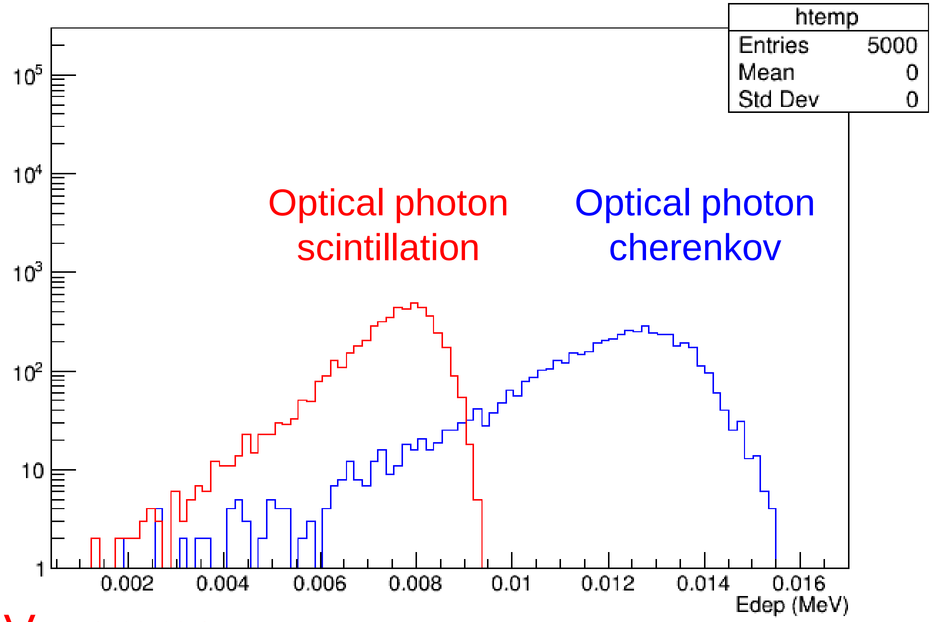
Scintillation generates extra energy doesn’t come from beam = 0.511MeV (mass of electron)

Energy Deposition

100 MeV positron
LY = 50/MeV

Energy deposition per event



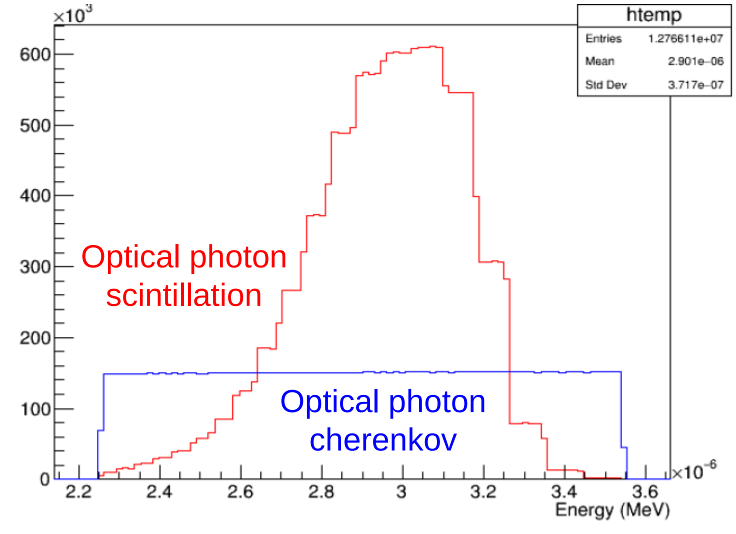


Edep>100MeV, gamma

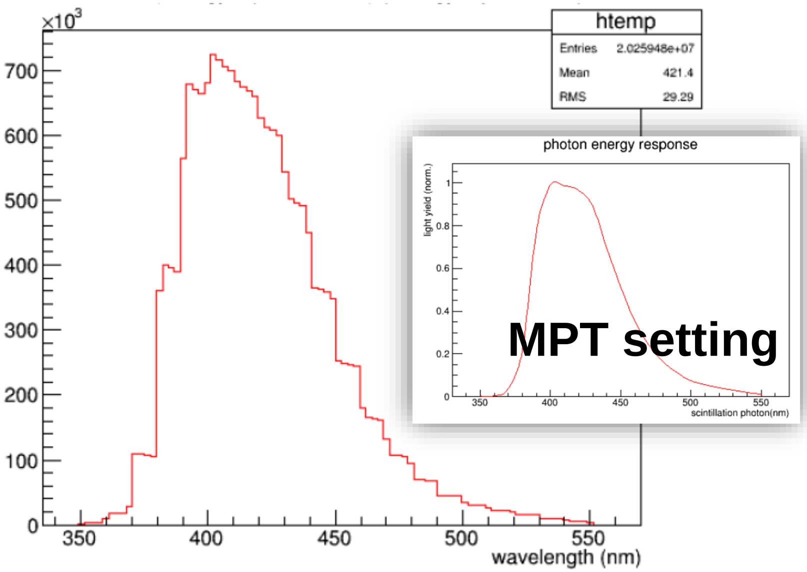
- Most energy are carried by beam and electron.
- Extra energy contribution from gamma.
- Optical photons carry very small amount of energy, ~0.01%.

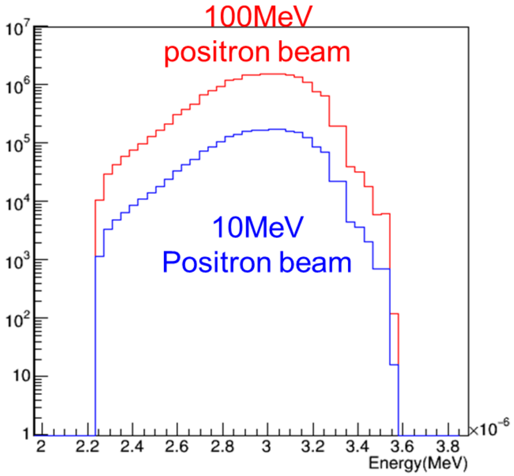
Optical Photons

100 MeV positron, LY = 50/MeV



$$\lambda(nm) = \frac{1240}{E(eV)}$$

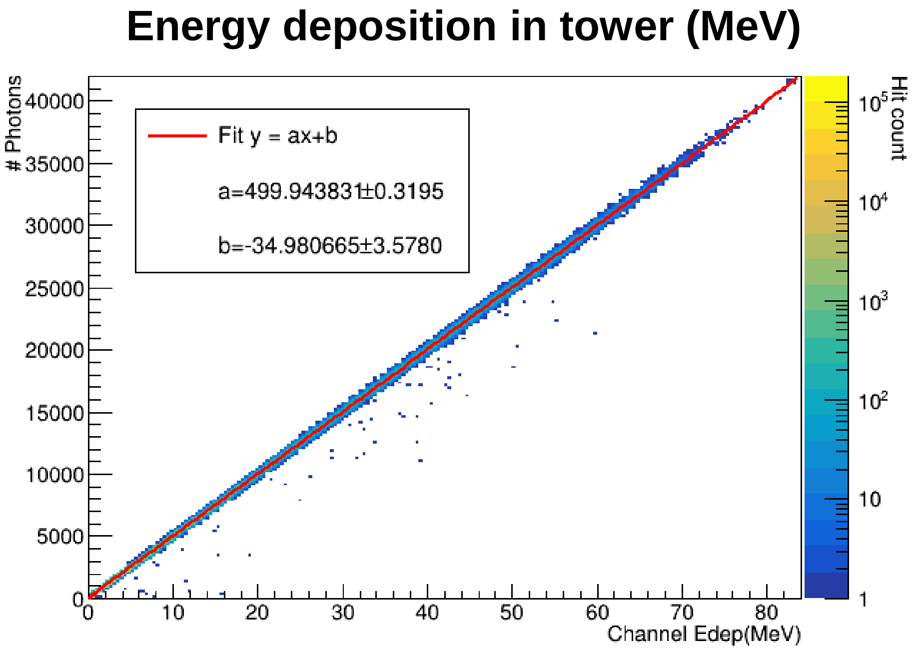




- Energy spectrum of scintillation photons is the same as the setup in MPT.
- Energy spectrum of Cherenkov photons is flat.
- Energy spectrum of optical photons doesn’t change w/ the injected beam energy.
- Increase beam energy only increase number of scintillation photons and total energy deposition of scintillation photons, not their energy spectrum.

Energy and Optical Photons

100 MeV positron, LY = 500/MeV

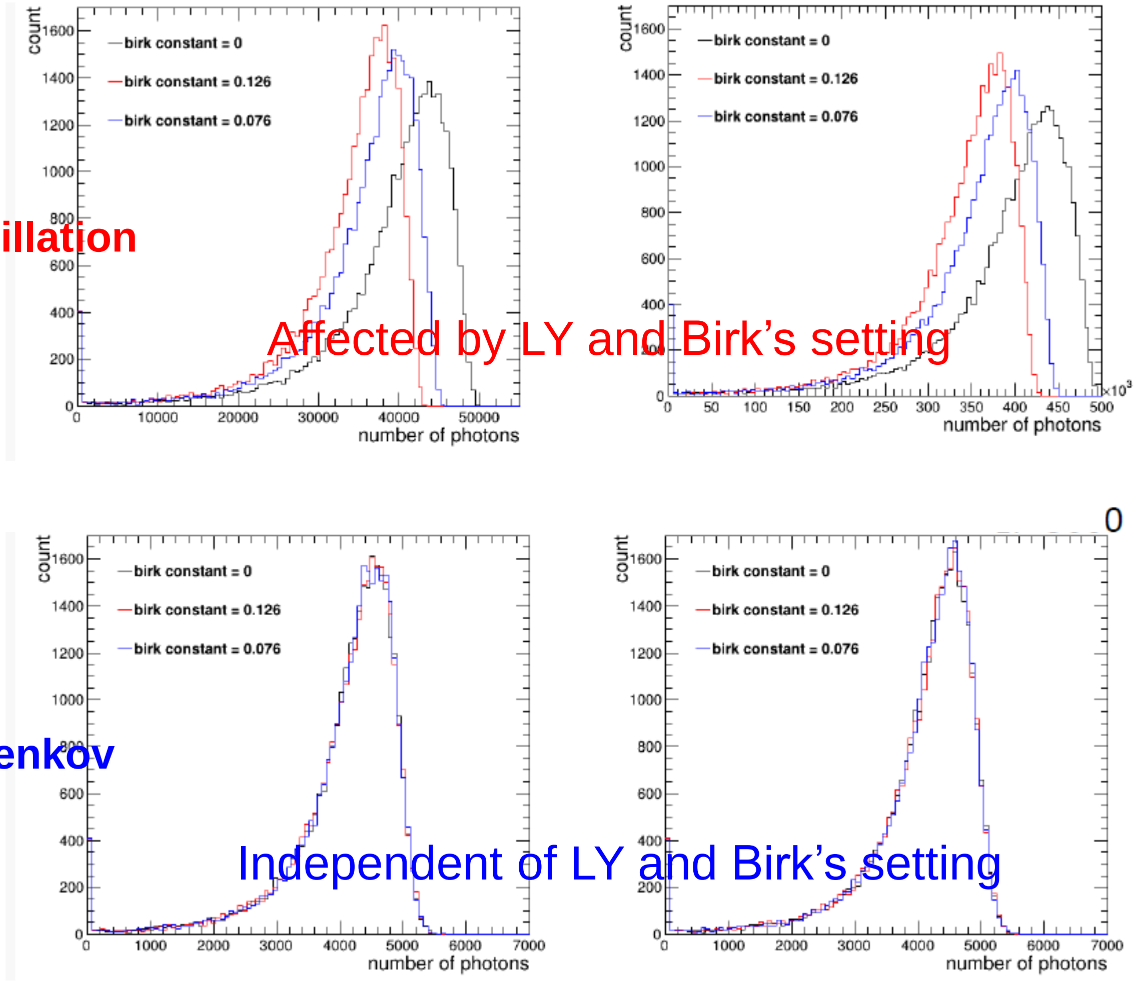


Energy deposition in crystal is linear with number of photons generated when E<100MeV.

Effects of Light Yield Setting and Birk’s Law

100MeV positron

LY = 500 **LY = 5000**

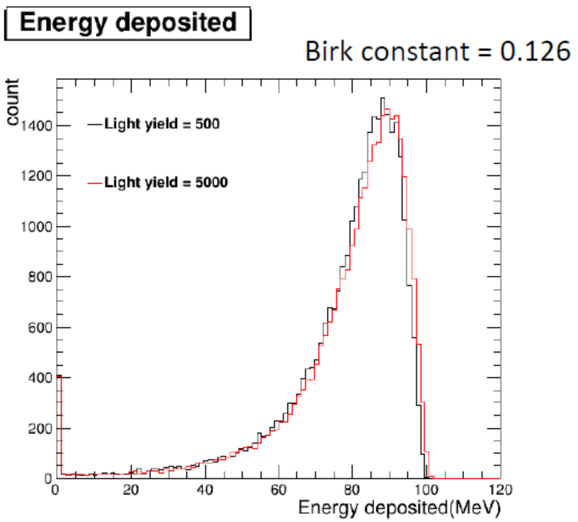


Scintillation

Affected by LY and Birk’s setting

Cherenkov

Independent of LY and Birk’s setting

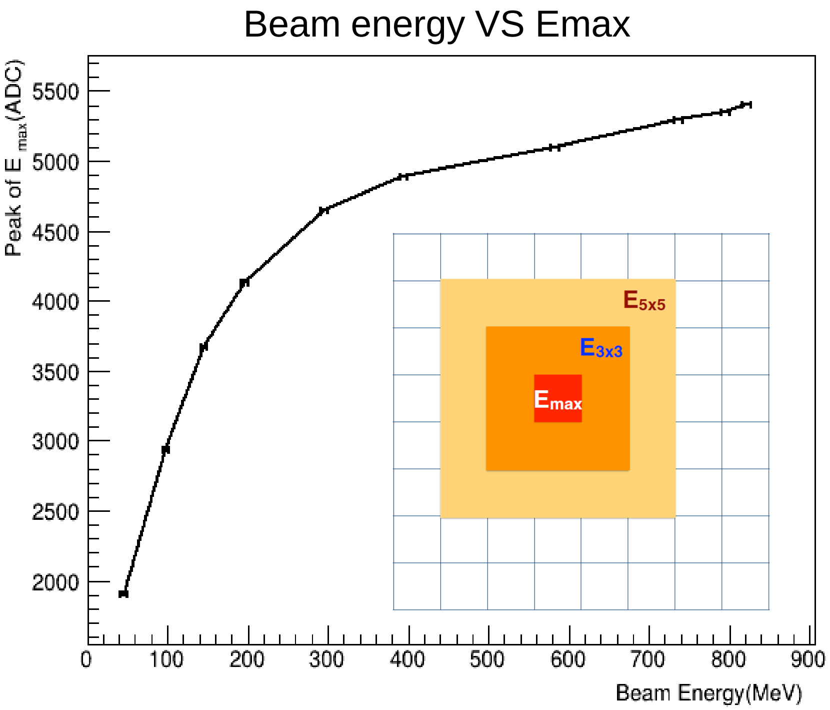


Birk constant = 0.126

- Total energy deposition in crystal doesn’t change w/ the setting of LY and Birk’s law.
- Currently we were still using the distribution of energy deposition of to fit data. We will switch to optical photons.

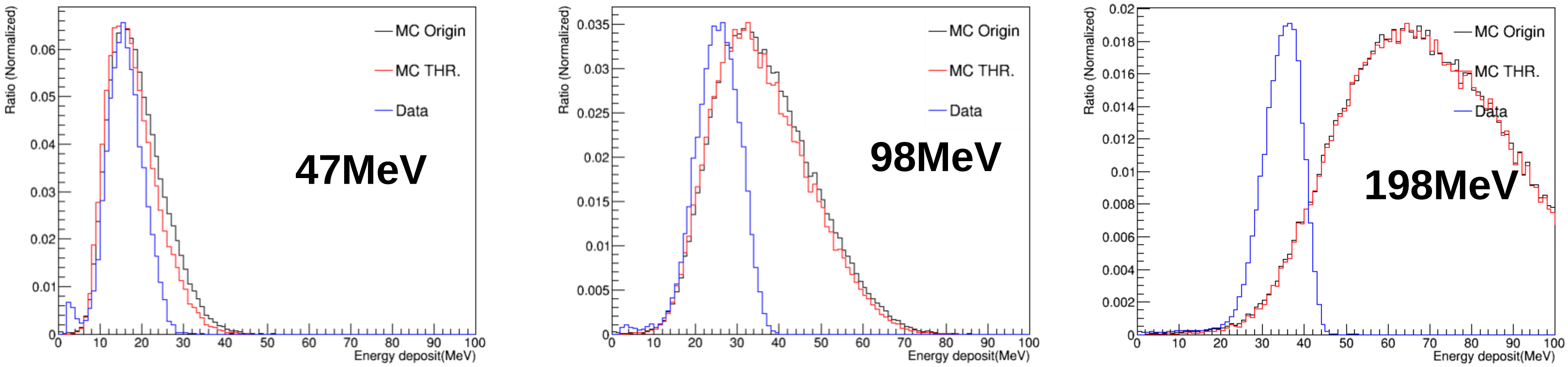
Data and MC comparison

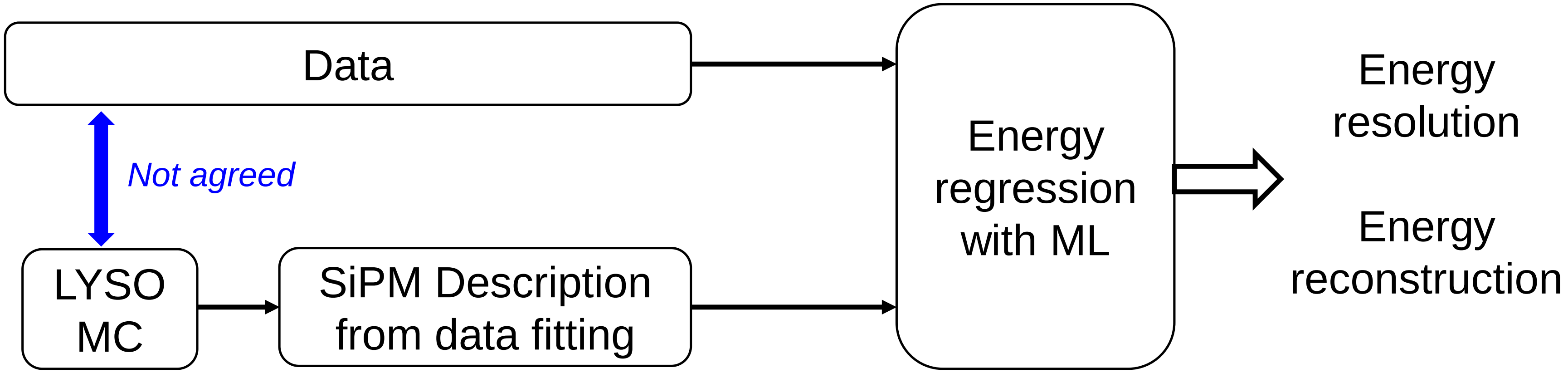
Beam Test



- We performed beam test w/ 1st prototype at ELPH on Feb, 2024.
- Positron beam w/ beam energy 50MeV to 800MeV
- Nonlinearity between beam and measured energy is observed.

Data and MC Comparison





Data

Not agreed

LYSO
MC

SiPM Description
from data fitting

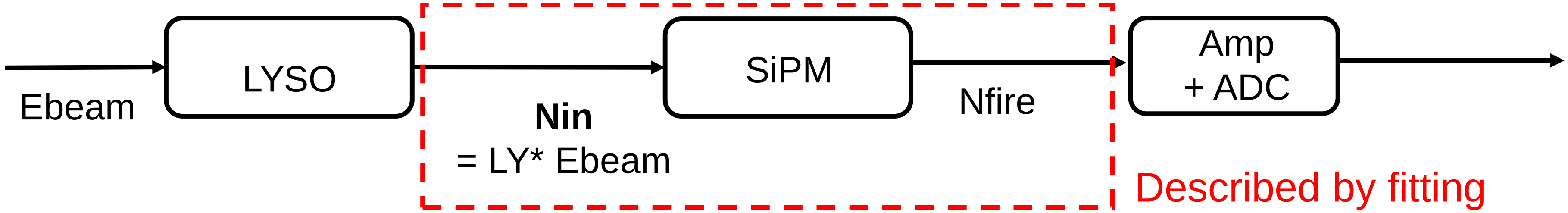
Energy
regression
with ML

Energy
resolution

Energy
reconstruction

- MC only simulates LYSO crystal (Compare w/ energy deposited).
- Saturation effect of SiPM is important and should be described.

Description of SiPM



Ebeam

LYSO

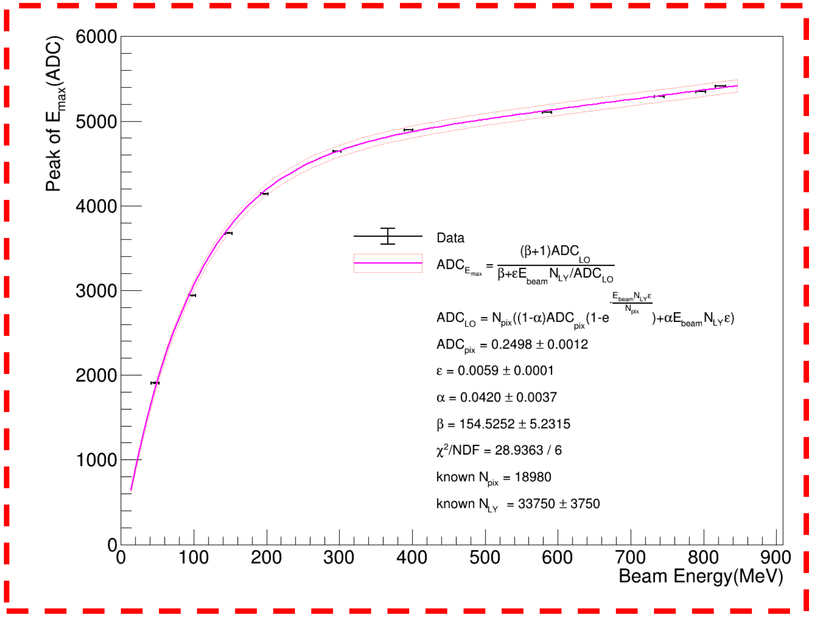
Nin
= LY* Ebeam

SiPM

Nfire

Amp
+ ADC

Described by fitting



$$ADC_{Emax} = \frac{(\beta+1)ADC_{LO}}{\beta+\varepsilon N_{in}/ADC_{LO}}$$

$$ADC_{LO} = N_{pix}\left[(1-\alpha)ADC_{pix}\left(1-exp\left(\frac{\varepsilon N_{in}}{N_{pix}}\right)+\alpha\varepsilon N_{in}\right]\right.$$

ADC_{pix} = 0.2498 ± 0.0012

ε = 0.0059 ± 0.0001 Photon detection efficiency of SiPM

α = 0.0420 ± 0.0038 average charge contribution of remaining photons

β = 154.5352 ± 5.2206 charge contributiondecrease as the increase of Nphoton

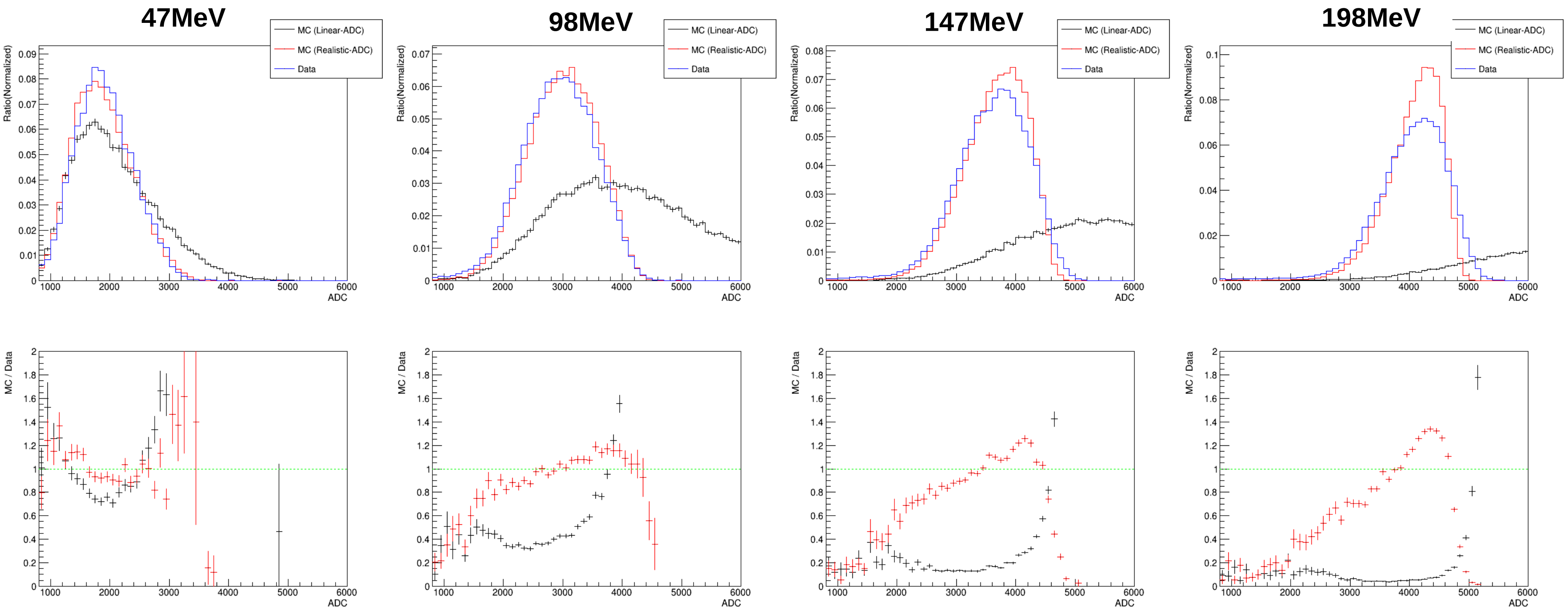
χ^2/NDF = 28.9377 / 6

known N_{pix} = 18980 Num. pixel of SiPM (fix)

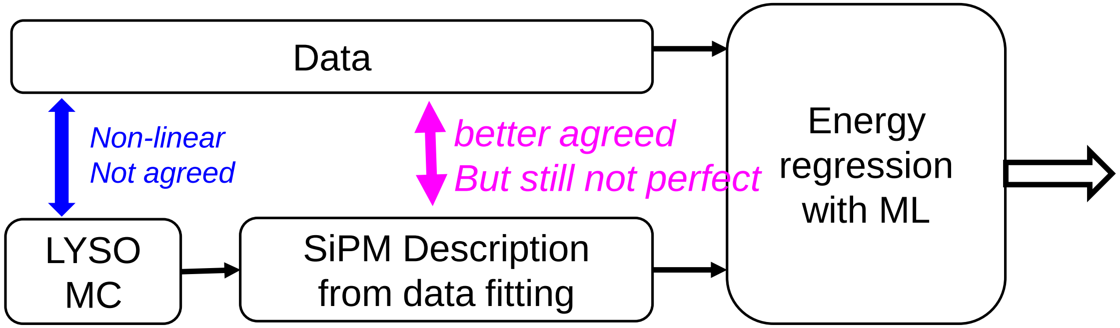
known N_{LY} = 33750 ± 3750 Light yield of SiPM (fix)

https://arxiv.org/abs/1510.01102

Data and MC Comparison after applying SiPM Behavior Curve to MC



- **Data**
- **LYSO MC**
- **LYSO MC * SiPM**



Data

Non-linear
Not agreed

better agreed
But still not perfect

LYSO MC

SiPM Description from data fitting

Energy regression with ML

Energy resolution
Energy reconstruction

Energy Regression

Energy Regression Calibration with Machine Learning Method

- **Purpose of energy regression : Energy deposited in the calorimeter may not always be directly proportional to the energy of the incident particle** due **leakage**, noise, etc. By accurately estimating the particle energy, energy regression **improves the energy resolution and energy reconstruction.**

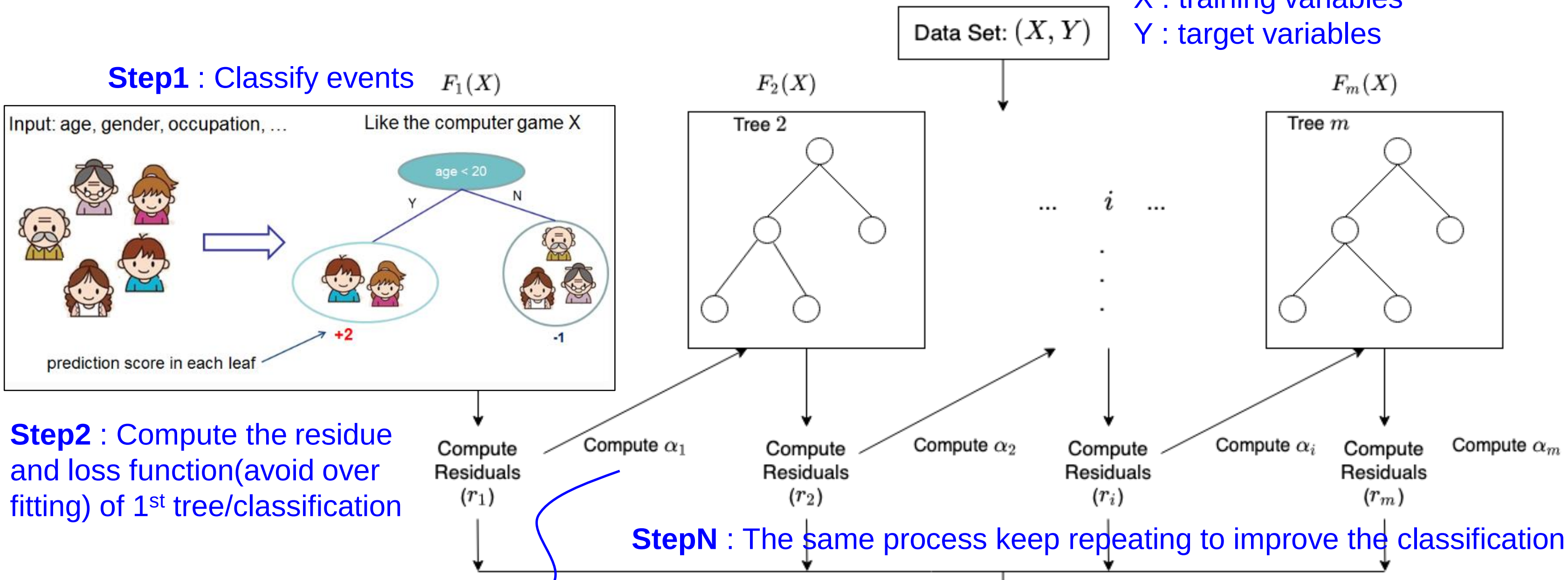
- **Machine learning techniques** can be used as a method to perform the energy regression.

(1) Collect large MC sample and **select training parameters (Emax, E3x3, E5x5)**
target parameters (ratio of Ebeam/E5x5).
(1) Model training with large MC sample.
(2) Validate trained model with separated MC sample.
(3) Apply the trained MC to data.

Attention : One have to make sure **MC and data are agreed at certain level. We are still working on it!**

XGBoost (Extreme Gradient Boosting)

Step0 : Data set
X : training variables
Y : target variables



Step1 : Classify events

Step2 : Compute the residue and loss function(avoid over fitting) of 1st tree/classification

Step3 : The 1st tree is usually not the best classification. The 2nd tree/classification add a parameter obtained from the 1st tree, $\alpha 1$, to improve the classification.

StepN : The same process keep repeating to improve the classification.

$$\boxed{F_m(X) \; = \; F_{m-1}(X) + \alpha_m h_m(X, r_{m-1}),}$$

where α_i, and r_i are the regularization parameters and residuals computed with the i^{th} tree respectfully, and h_i is a function that is trained to predict residuals, r_i using X for the i^{th} tree. To compute α_i we use the residuals computed, r_i and compute the following: $arg \min_{\alpha} \; = \sum_{i=1}^{m} L(Y_i, F_{i-1}(X_i) + \alpha h_i(X_i, r_{i-1}))$ where $L(Y, F(X))$ is a differentiable loss function.

➔ Final output :
The predictions of all trees/classifications are combined to produce the final output.

Reference : https://xgboost.readthedocs.io/en/stable/tutorials/model.html
https://docs.aws.amazon.com/zh_tw/sagemaker/latest/dg/xgboost-HowItWorks.html

Training Conditions

- **XGBoost in Python**

- **Training MC sample**

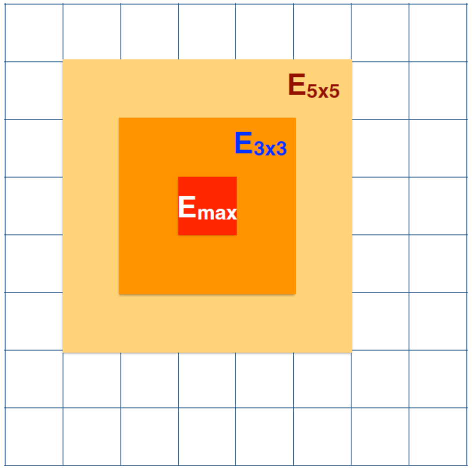
① 197MeV
② 30k events
(20% test, 80% training)

- **Training variables (X):**

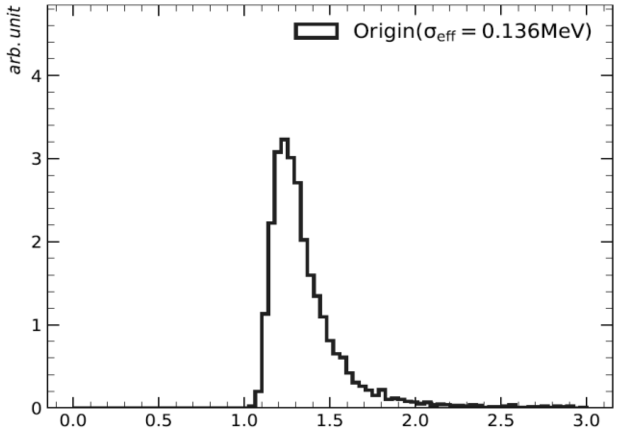
① E1x1
② E3x3
③ E5x5
④ E1x1/E5x5
⑤ E1x1/E3x3
⑥ E3x3/E5x5

- **Target variable (Y) :**

① **Ebeam/E5x5**



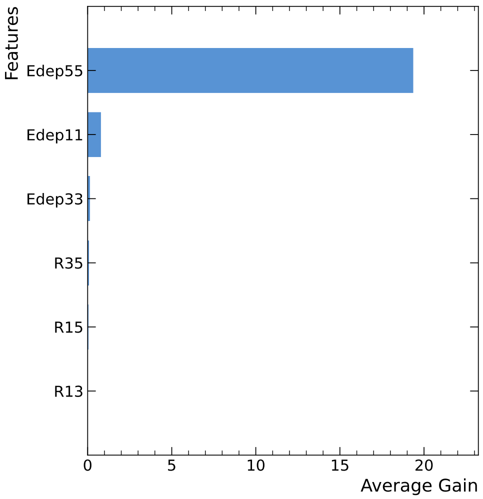
197MeV positron beam



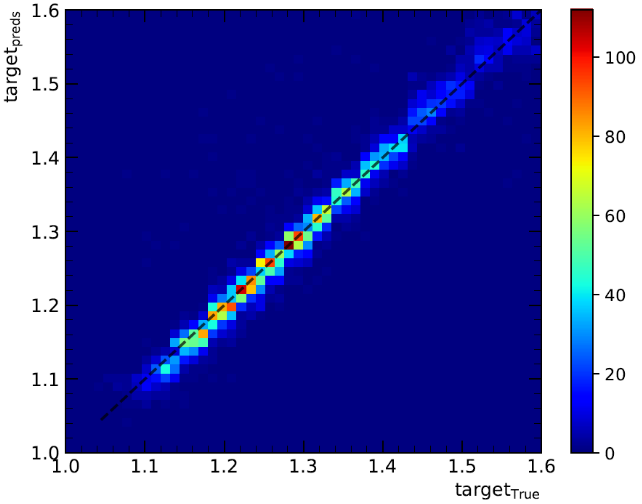
Target : Ebeam/E5x5

Validate ML Model

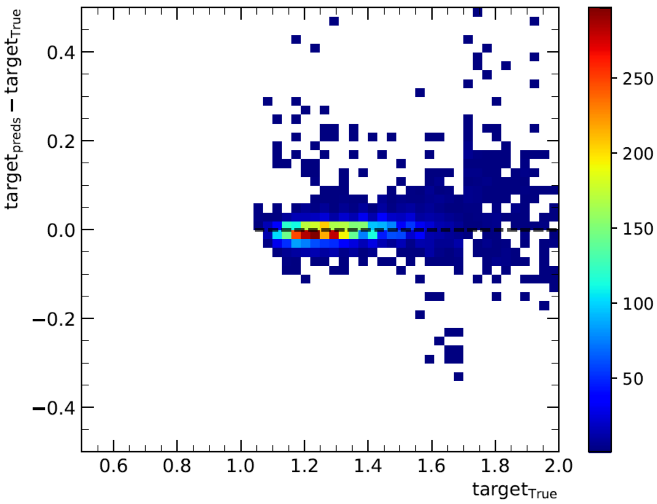
Importance of train variables, X



Target = Ebeam/E5x5
True VS predicted



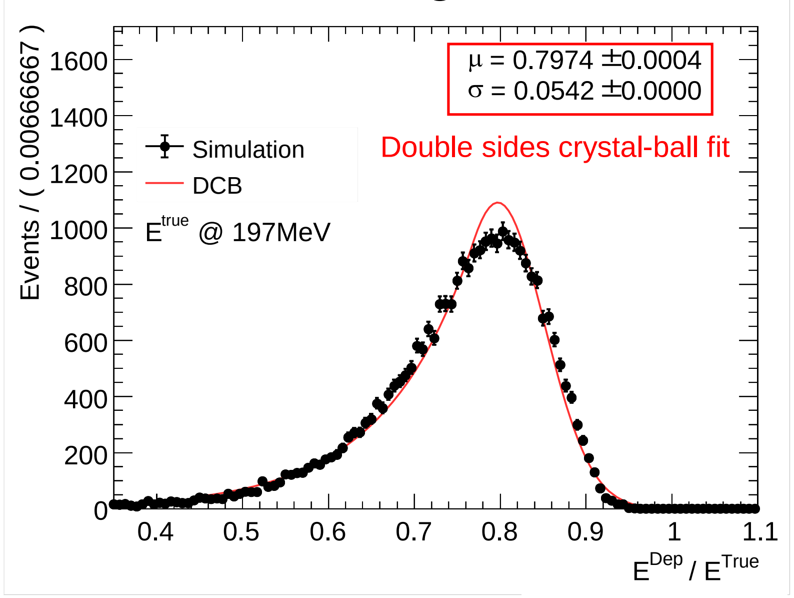
Target = Ebeam/E5x5
uncertainty



- Among all the training variables, E5x5 is the most important one.
- The training output shows reasonable prediction of target variable, Ebeam/E5x5, with less than 5% uncertainty.

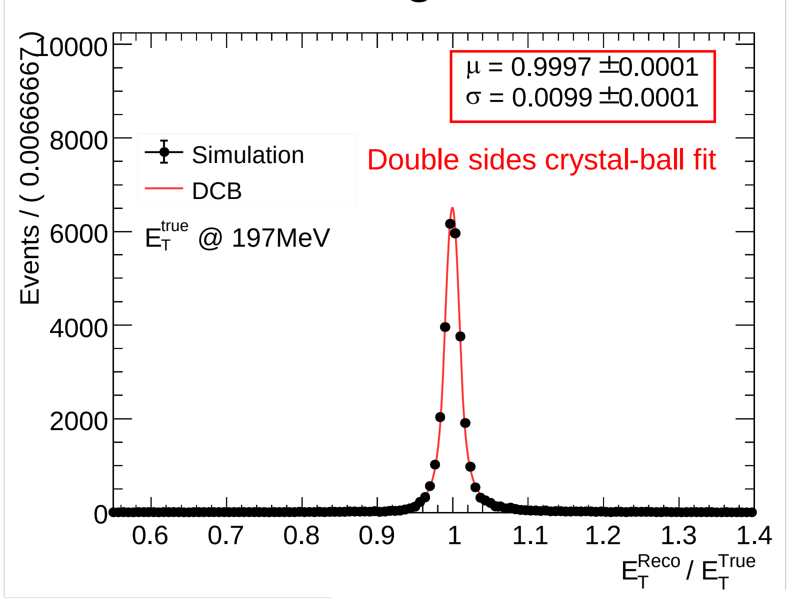
Impact of Energy Regression

Before regression



(E_{5x5}/E_{beam})

After regression

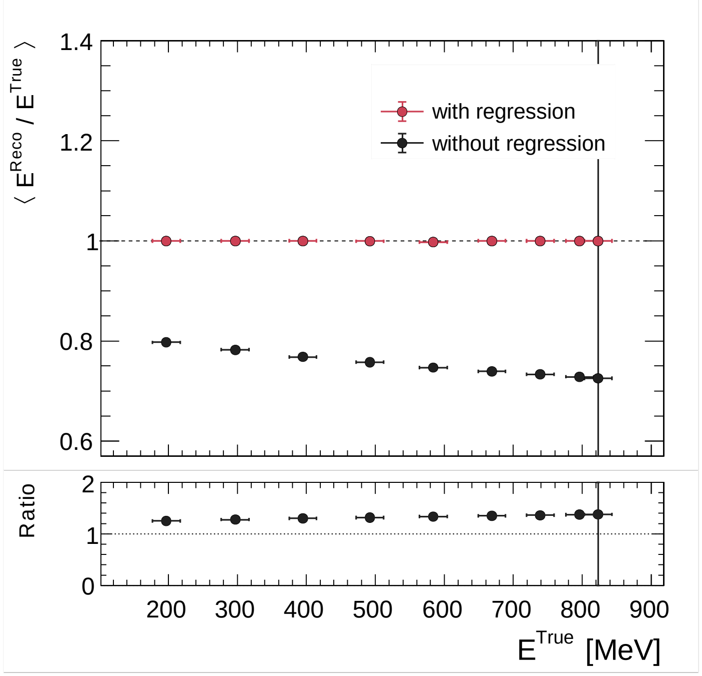


$(E_{beam}$: $E_{predicted}/E_{true})$

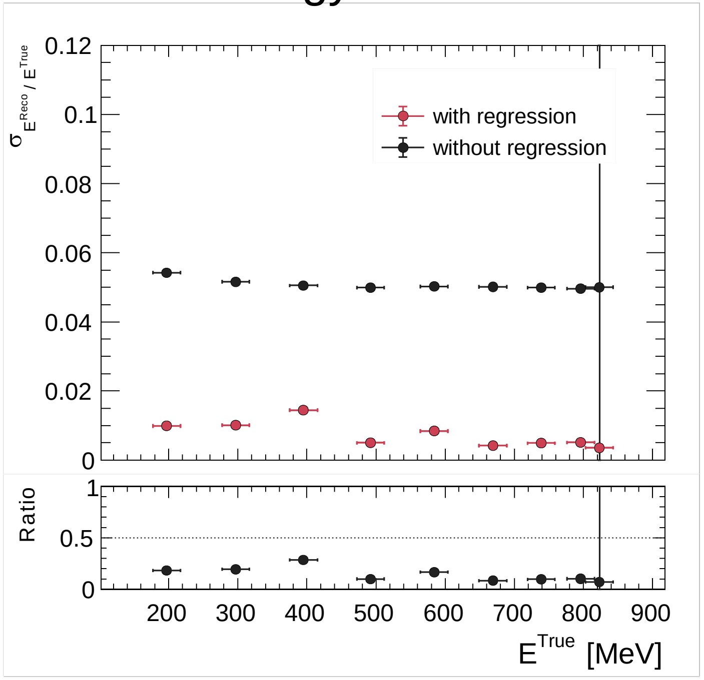
- A **new** MC sample generated w/ 197MeV positron beam w/ 30k events.
- After applying energy regression, the beam energy is will reconstructed by ML model and energy resolution improved from 5% to 1%.

Impact of Energy Regression

Reconstructed energy

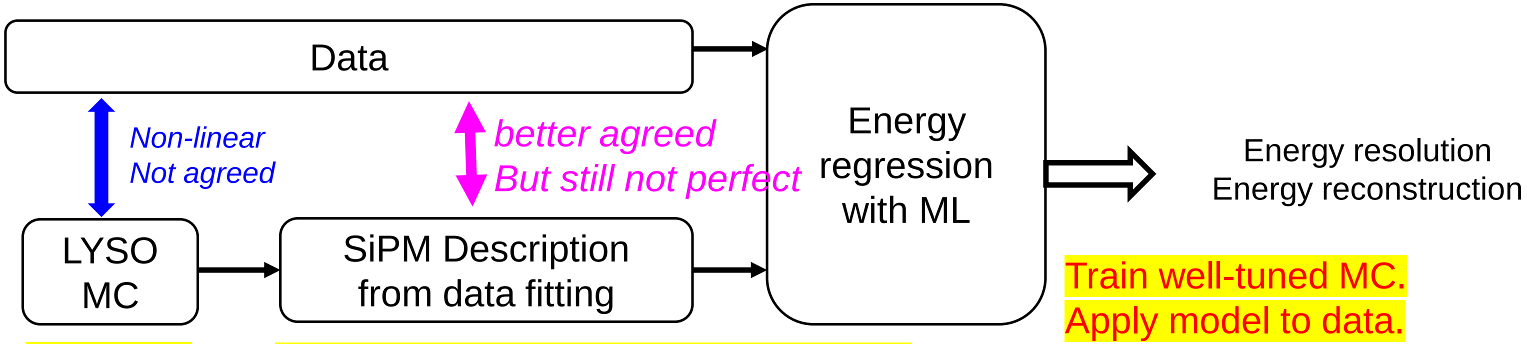


Energy resolution



- New MC samples with energy beam = 197MeV to 823 MeV are tested.
- Ebeam is well predicted and energy resolution is also improved after regression regardless the beam energy.

Summary and To Do



Data

Non-linear
Not agreed

better agreed
But still not perfect

LYSO
MC

SiPM Description
from data fitting

Energy
regression
with ML

Energy resolution
Energy reconstruction

Train well-tuned MC.
Apply model to data.

still tuning

Fit more data with higher beam energy
Fit data with not only Emax, also E3x3, E5x5