NPS Energy Resolution Simulation using GEANT4

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This is a note of a NPS(Neutral Particle Spectrometer) energy resolution simulation results using GEANT4.10.03. The optical properties of the crystals and their wrapping material are put in order to observe more realistic resolution of the detector. By changing the distance between the crystals from 0mm to 2mm with 0.5mm increment, we checked the effect in resolution. Gamma with energy of range from 1GeV to 10GeV with 2.25GeV increment and 500MeV were used as a primary source. We have obtained the energy resolution of ∼1.5% for the calorimeter with 1% miscalibration in 6 to 8 GeV energy range.

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Introduction

The Neutral Particle Spectrometer(NPS) is made of 1116 $PbWO_4$ crystals and its final design is yet to be decided. The energy resolution of the detector is one of the most important parts to be considered in the design of the calorimeter. For the detector to be structurally safe and relatively easier to maintain, it is better to use supporting structures between the crystals. However, since we do not want to give up too much on the energy resolution of the detector, the simulation of the NPS depending on the size and material of the gap between the crystals is necessary. Here we describe the geometry of the detector in the simulation and the results. In this paper there are two results presented, one with air between the crystals and one with carbon structure between the crystals. Additionally, we suggest other methods of building the NPS' structure in appendix C. We summarise the NPS energy resolution dependency on the distance and material between the crystals in conclusion.

Detector Geometry

NPS

The 1116 $PbWO_4$ crystals are stacked in the form of 31×36 matrix. Each of the crystals are wrapped with VM2000. The PMTs are attached at the backside of each of the crystals. Each of the crystals are supported by carbon frame with density of 1.55g/cm^3. To make a reference, we also present the result with gap filled with air between the crystals.

Crystal

The crystals have $20.5\times20.5\times200.5$mm^3 and the wrapper has a thickness of 65μm. Each of the crystals has optical properties of the $PbWO_4$ measured by R.Y. Zhu et al. [1]. The detail of the implementation of the optical properties of the crystals into the simulation is described in Ref. [2]. The PMTs' dimensions are $20.5 \times 20.5 \times 20.5 mm^3$ in order to make no light leaks when photons travel from crystal to PMT. The PMT is a volume made of SiO_2 covered with thin aluminium. The aluminium cover counts the number of the photons arrived and the numbers are used to determine the energy deposited in the crystal.

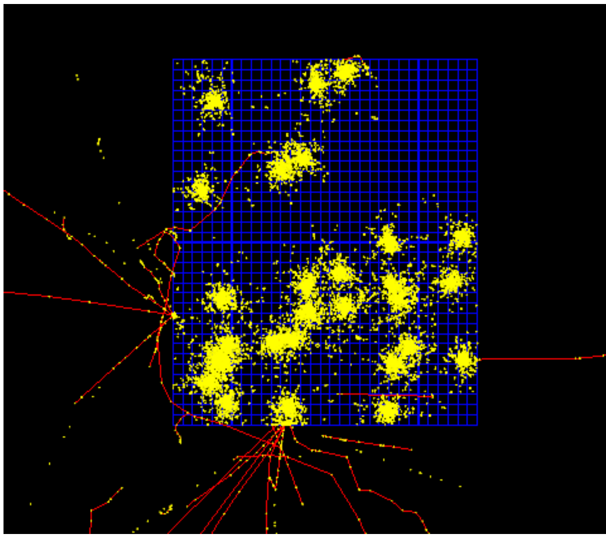
Simulation

In the simulation, the user puts light yield which controls the number of photons produced per energy of the particles in the crystal. The light yield in the simulation was 15/MeV as can be seen from Figure 2. The variables of the runs which are the energy of the primary source and the size of the gap between the crystals are described in the Table 1.

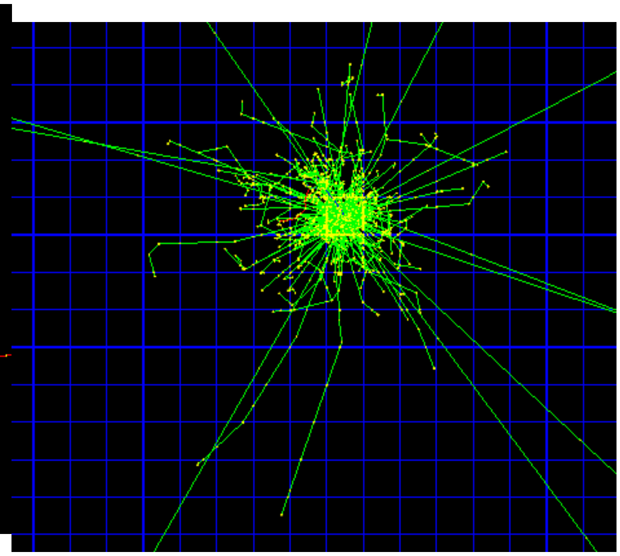
The gammas were used as primary sources and distributed on the surface of the calorimeter as can be seen from Figure 1 (a). In order to achieve near 5,000 events, about 10,000 primary events were needed. For the case of 1GeV gamma as a primary source with 250 events, the simulation took 3 hours to finish.

Table 1: Variables in the simulations.

Energy [GeV]	0.5	1	3.25	5.5	7.75	10
Gap [mm]	0	0.5	1	1.5	2	



(a) 1GeV gammas distributed on the surface of the NPS



(b) 1GeV gamma creating a shower

Figure 1: Visualisation of the simulation.
Red : negatively charged particle track, Green : gamma track

Results

Energy deposition in the NPS

Figure 2 is the number of optical photons collected at the PMTs from 5000 of 1GeV gammas with no gaps between the crystals. Since the energy deposition histogram is not a sharp peak nor a Gaussian, because of combined effects of Compton scatterings, non full absorptions of energies and etc., the histogram is broad and makes a longer tail on the left side from the peak. To quickly and simply extract the mean number of the optical photons, i.e. mean energy and the resolution, we carefully fit the histogram with Gaussian as shown in Figure 2.

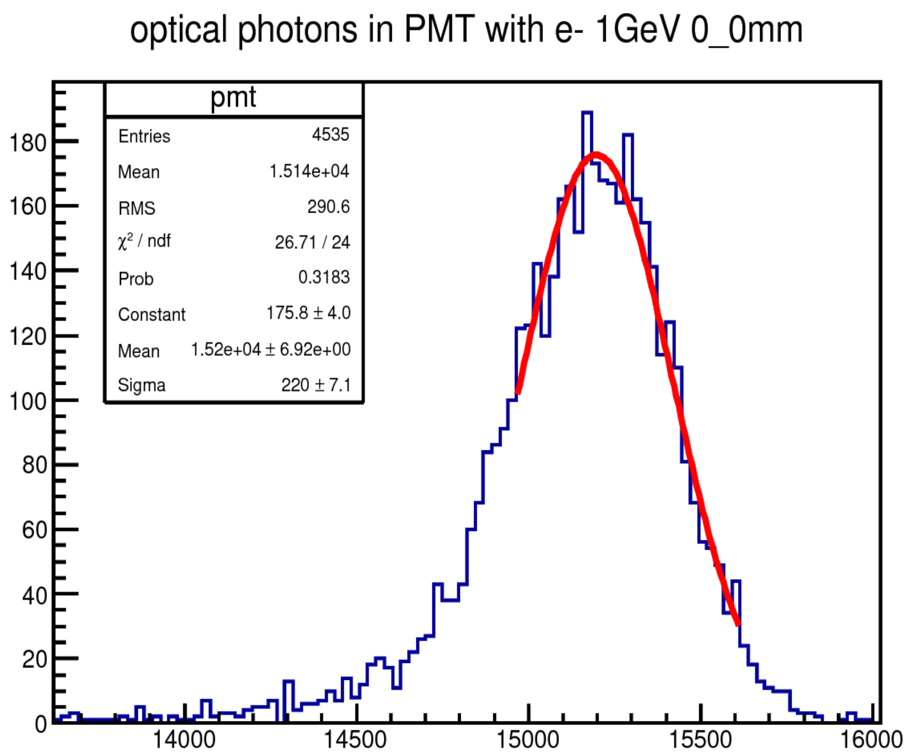


Figure 2: Histogram of number of optical photons collected at the PMTs. Gaussian fitted. Light yield : $\sim$ 15/MeV, Gap : 0mm, Energy of the gammas : 1GeV.

Resolution of the NPS

Resolution

From all the fitting results from simulations varying with the size of the gaps between the crystals and the energy of the gammas, we can get the resolution of the detector using the equation (1).

$$\frac{\sigma}{E} = A \oplus \frac{B}{\sqrt{E}} \oplus \frac{C}{E} \tag{1}$$

The symbol $'\oplus'$ in the equation is to add quadratically. $\boldsymbol{A}$ is a term that concerns the geometry of the detectors, $\boldsymbol{B}$ is a term that is coming from the statistics of the events and $\boldsymbol{C}$ is a term that comes from the electronic readout noise. When using this equation to fit the resolution results, the parameter $\boldsymbol{C}$ was fixed to 0. When the parameter $\boldsymbol{C}$ was introduced, all three parameters were unconstrained and it seemed reasonable to fix $\boldsymbol{C}$ to 0 since the electrical noise was not simulated.

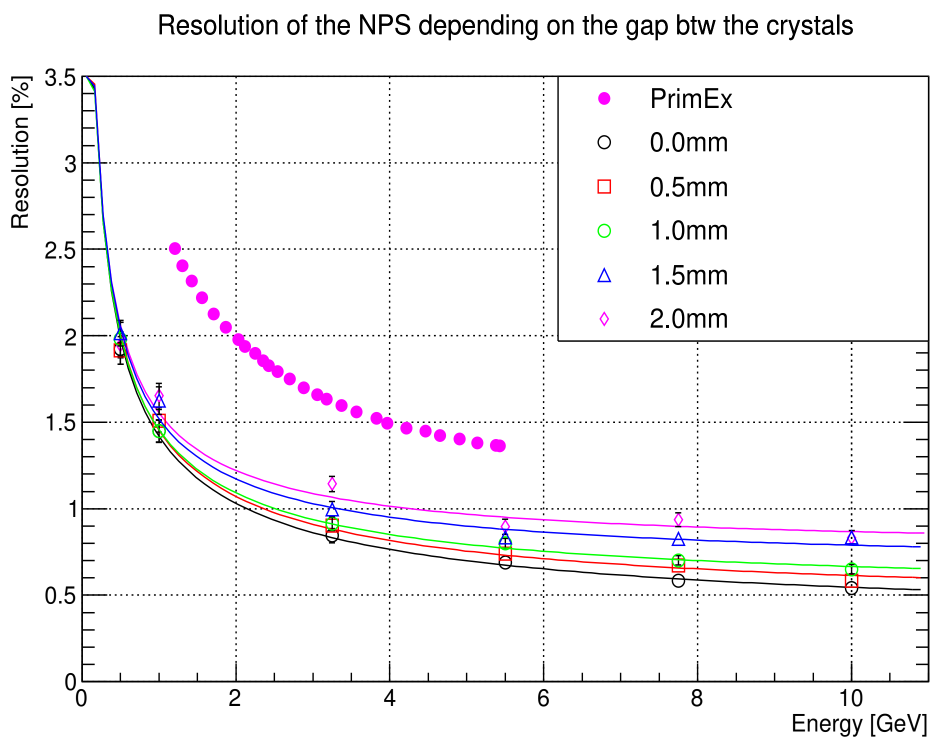


Figure 3: Resolution of the detector. Gap : air.
The resolutions are fitted using the function (1) with $\boldsymbol{C} = 0$.

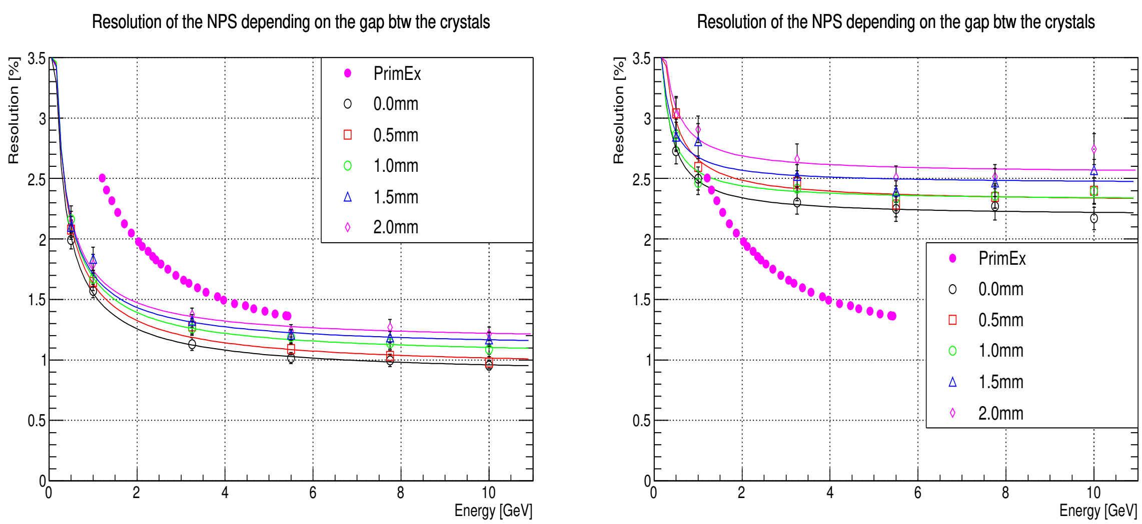
The results with air gap between the crystals are presented in Figure 3 with the resolution of the PrimEx which also used 1152 $PbWO_4$ blocks with the combination of 576 lead glass blocks [3]. In the area of interest which in our case is the DVCS region, around 6 to 8 GeV range, the resolution increases almost linearly to the size of the gap between the crystals from 0.6% to 0.9% near 7 GeV.

Miscalibration

In real situation, each crystals will have a calibration coefficient that will only be known to a few %. In some crystals, we will be systematically overestimating the energies, and in some others, underestimating them. To consider those effect, the user can modify the energies in the crystals with Gauss random with mean value of 1 and sigma of preference. In this report, the sigma was 0.01 and 0.03 to consider the miscalibration effect of 1% and 3%.

$$\text{Modified energy} = \text{Originally deposited energy in each crystals} \times \text{Gauss Random(mean : 1, } \sigma \text{ : 1 or 3)} \tag{2}$$

The resolution with miscalibration effects are shown in Figure 4

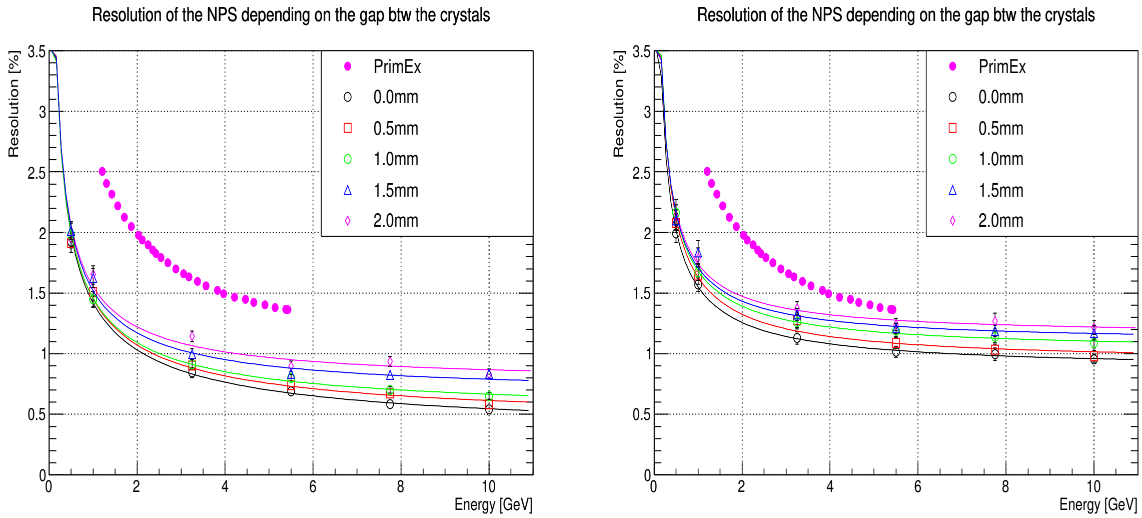


(a) 1% Miscalibration

(b) 3% Miscalibration

Figure 4: Resolution of the detector with miscalibration effect. Gap : air.

Since 3% miscalibration gives too much of an effect, we will compare 1% miscalibration effect with the original in Figure 5.

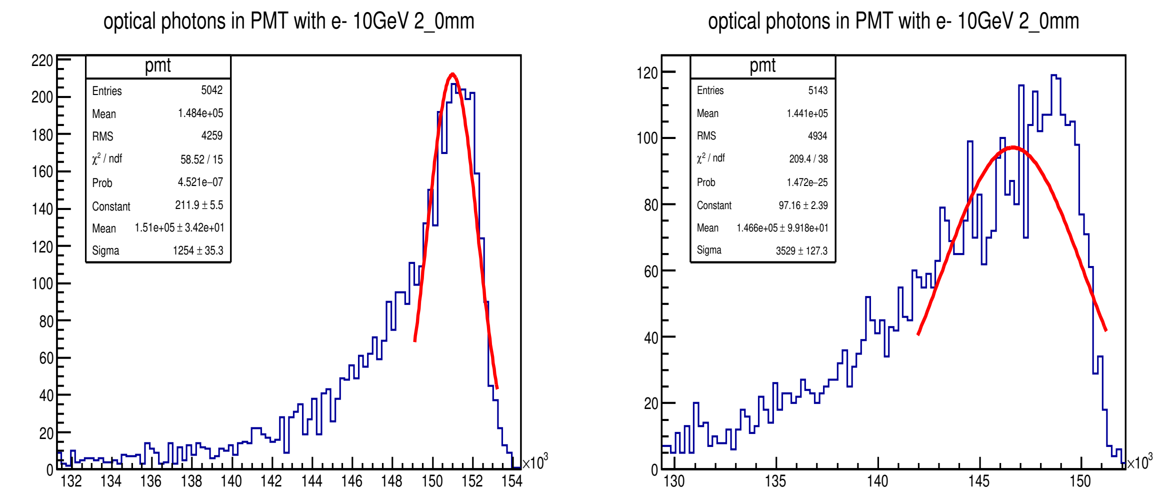


(a) No Miscalibration

(b) 1% Miscalibration

Figure 5: Comparison between the original and with 1% miscalibration. Gap : air.

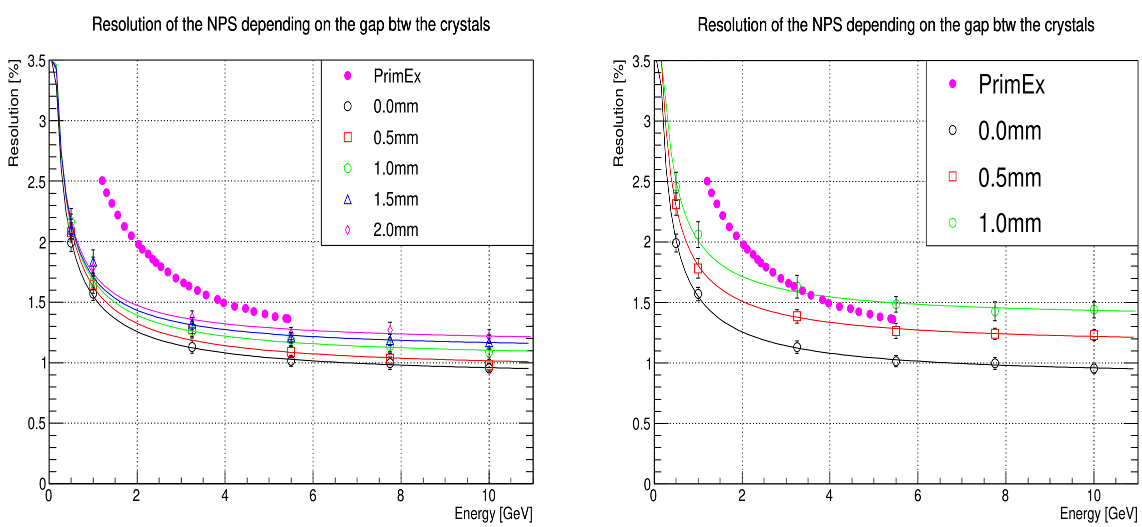
When carbon is introduced as a dead material between the crystals the energy deposition is too broad to use one Gaussian fitting (See Figure 6). For this reason, the resolution for the case of carbon dead material, we only show you the resolution results with gap size of 0.5mm and 1mm between the crystals. The comparison of the resolution results between the air gap between the crystals and the carbon between them in Figure 7.



(a) Air gap

(b) Carbon gap

Figure 6: Comparison of the 10GeV gamma energy deposition histogram
Gap : 2mm



(a) Air gap

(b) Carbon gap

Figure 7: Comparison between the air gap & carbon gap. 1% miscalibration.

Resolution Parameters

The resolutions fitting functions' fitting parameters are presented in this section. For the reference, PrimEx has the value of the parameter $\boldsymbol{A}$ = 0.9%, $\boldsymbol{B}$ = 2.5% and $\boldsymbol{C}$ = 1% [3].

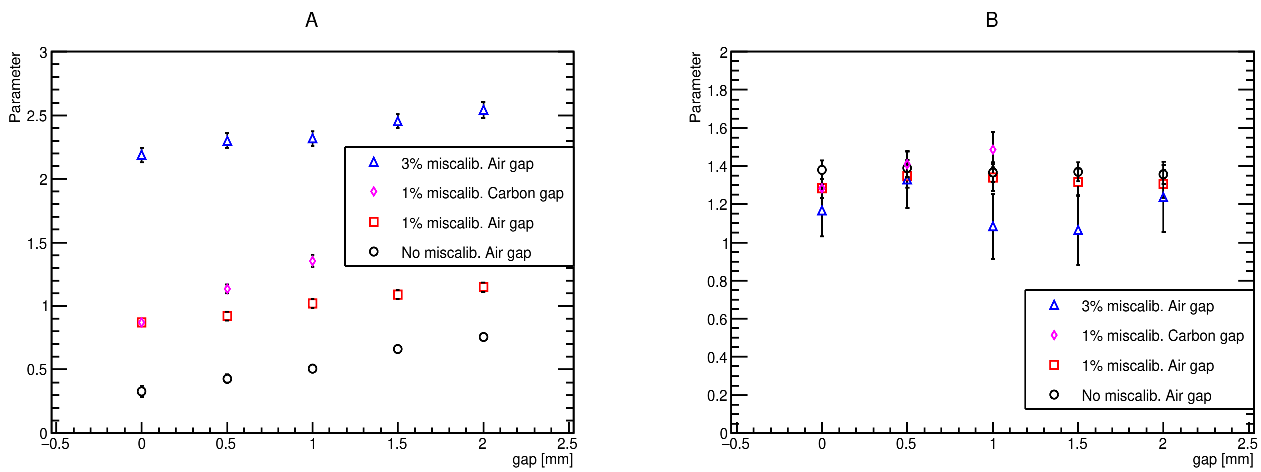


Figure 8: Parameter $\boldsymbol{A}$ and $\boldsymbol{B}$ form the fitting function (1) with $\boldsymbol{C}$ = 0.

As can be seen from Figure 8, the gap between the crystals and the miscalibrations mostly affect on the parameter $\boldsymbol{A}$. And as the size of the gap increases, the value also increases almost linearly. Additionally, the increasing speed becomes larger when carbon gap is used. However, parameter $\boldsymbol{B}$ gets less effect from the gap size changes and the miscalibration effect and the value is about 50% lower than that of the PrimEx.

Convoluted Function Fitting

Since we have introduced carbon frame as a dead material between the crystals, the histogram of the energy deposition in the calorimeter has been not apt to use Gaussian as a fitting function. Considering the definition of energy resolution is Δ/E ($\Delta : FWHM$), it is better to obtain FWHM(Full Width Half Maximum) of the energy deposition peak. To reliably obtain the FWHM, Gaussian convoluted with exponential function is suitable to fit the histogram(see Figure 9).

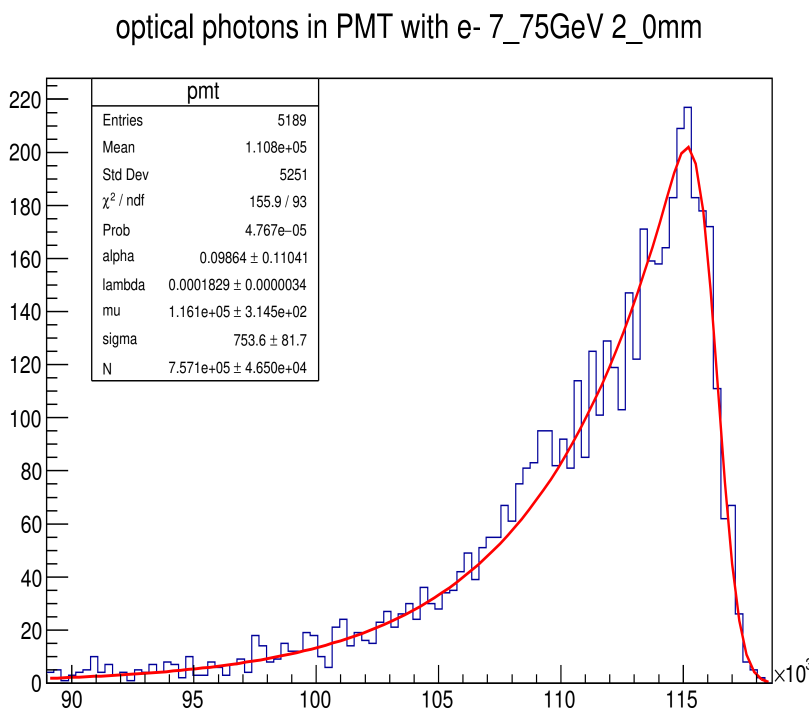


Figure 9: Exponential ⊗ Gaussian fitting of the energy deposition histogram.
Gap : 2mm, Energy of the gamma : 7.75GeV.

Conclusion

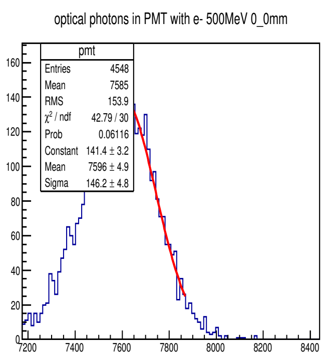
The Geant4 simulation using optical photons physics process with realistic light yield for NPS energy resolution has been done. When 1% miscalibration effect is applied, the resolution changes by 30% from 1% to 1.3% when the air gap changes from 0mm to 2mm at 7 GeV. However, the resolution changes around 40%∼ 60% at 7 GeV when miscalibration of 1% is introduced. Therefore, the crystal-to-crystal calibration has a bigger effect than the air gap size effect on the resolution of the calorimeter.

Finally, with 1% miscalibration, the resolution changes by 50% from 1% to 1.5% at 7GeV when there is no gap between the crystals to when there is 1mm carbon structure with density of 1.55g/cm^3 between the crystals.

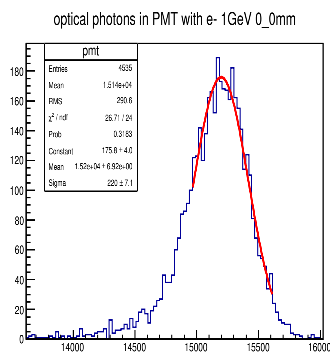
Appendices

Energy deposition in the NPS with air gap

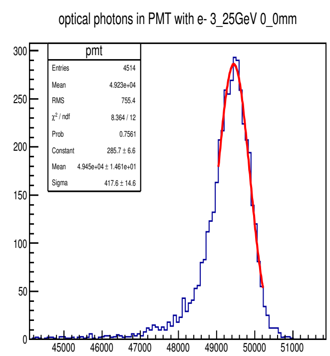
In this section, the histograms of energy deposition in the detector with air gaps by a source of gamma with various energies and distances between the crystals are shown.



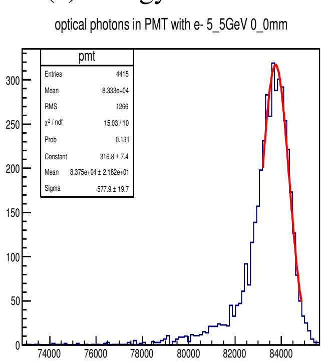
(a) Energy : 500MeV



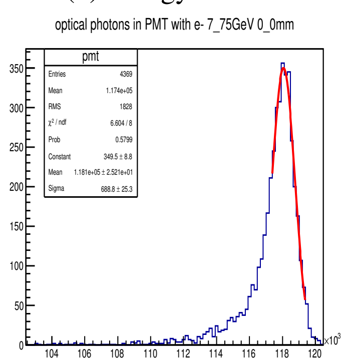
(b) Energy : 1GeV



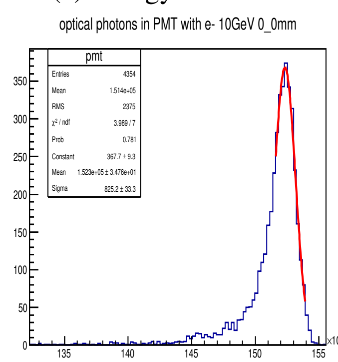
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

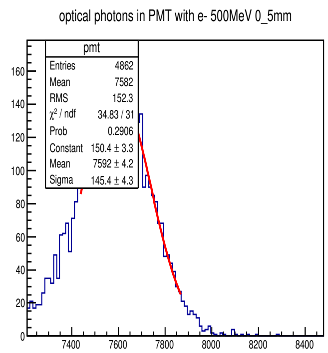


(e) Energy : 7.75GeV

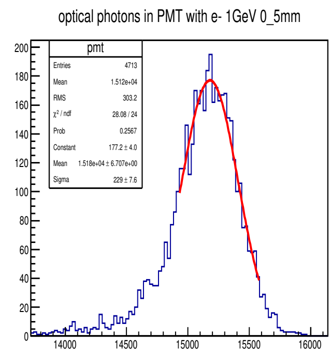


(f) Energy : 10GeV

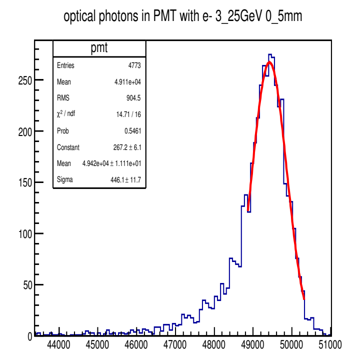
Figure A.1: Energy deposition. Number of photons collected at the PMT. Gap : 0mm



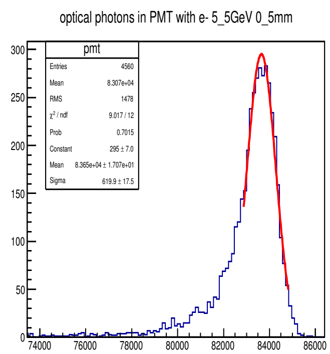
(a) Energy : 500MeV



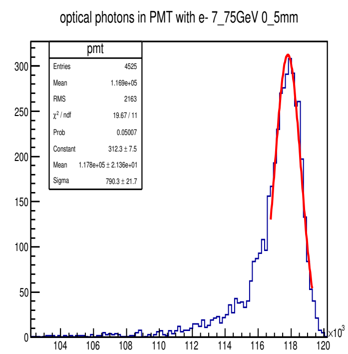
(b) Energy : 1GeV



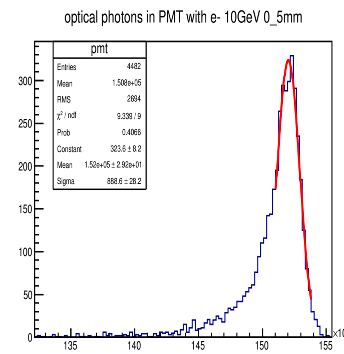
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

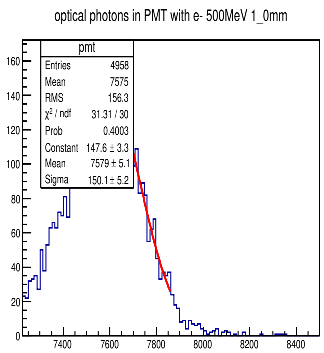


(e) Energy : 7.75GeV

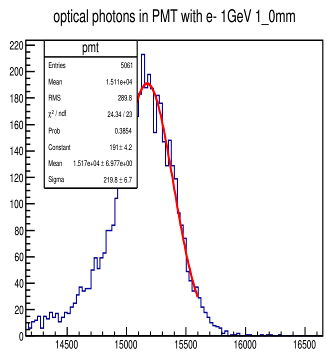


(f) Energy : 10GeV

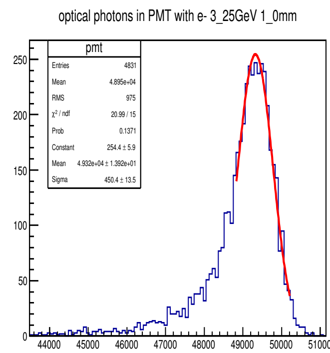
Figure A.2: Energy deposition. Number of photons collected at the PMT. Gap : 0.5mm



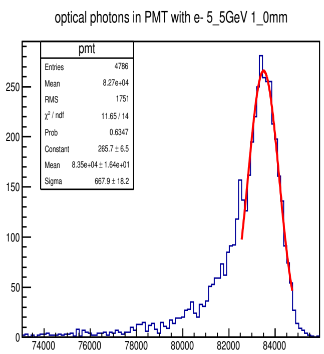
(a) Energy : 500MeV



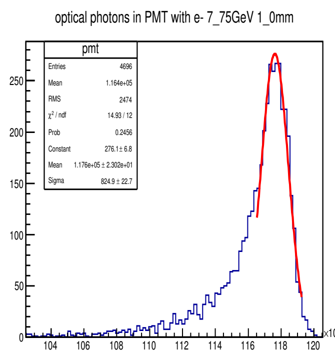
(b) Energy : 1GeV



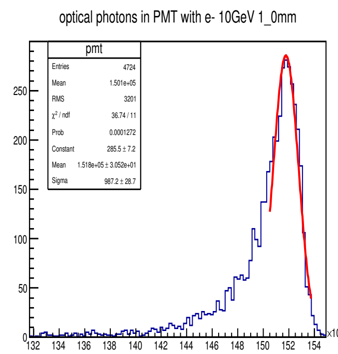
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

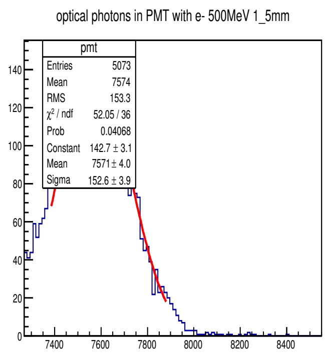


(e) Energy : 7.75GeV

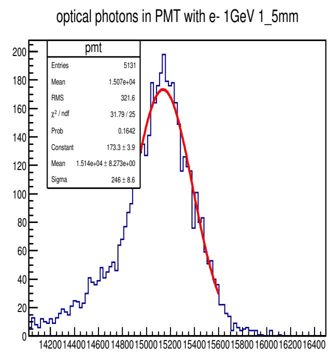


(f) Energy : 10GeV

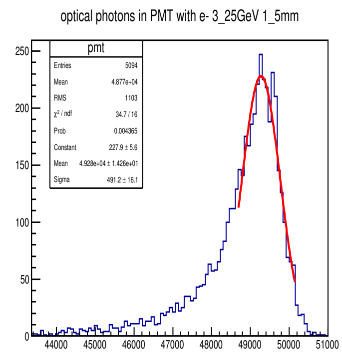
Figure A.3: Energy deposition. Number of photons collected at the PMT. Gap : 1mm



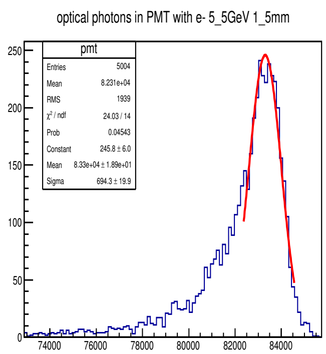
(a) Energy : 500MeV



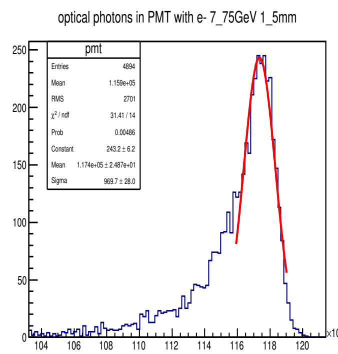
(b) Energy : 1GeV



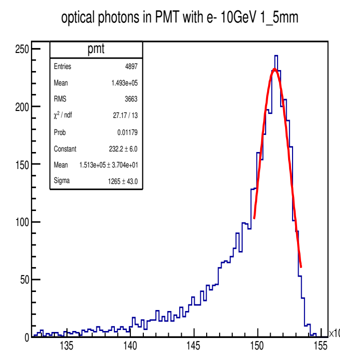
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

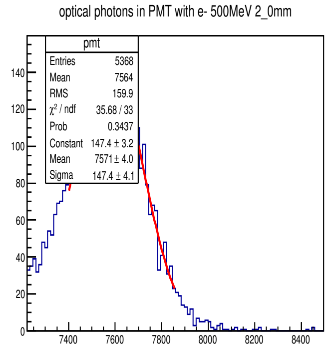


(e) Energy : 7.75GeV

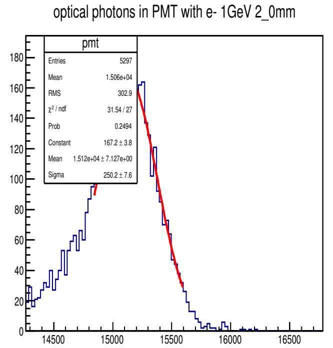


(f) Energy : 10GeV

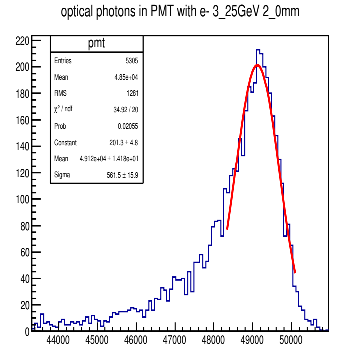
Figure A.4: Energy deposition. Number of photons collected at the PMT. Gap : 1.5mm



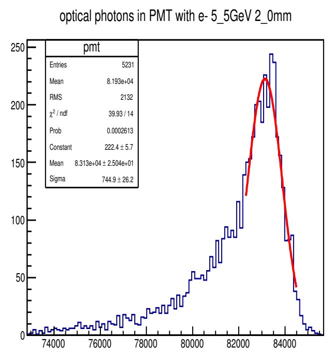
(a) Energy : 500MeV



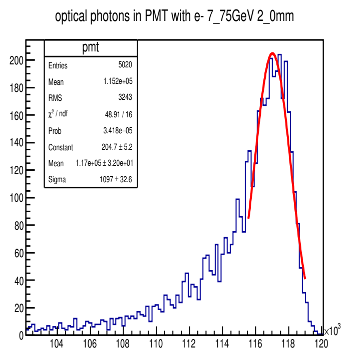
(b) Energy : 1GeV



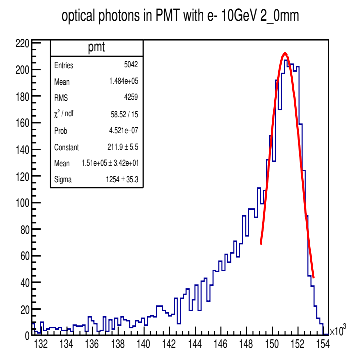
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV



(e) Energy : 7.75GeV

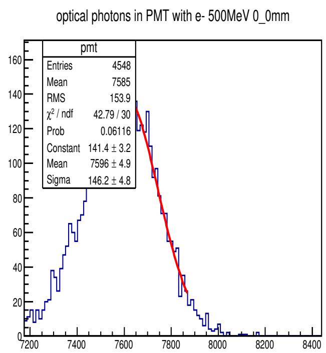


(f) Energy : 10GeV

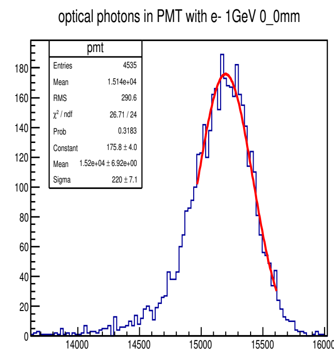
Figure A.5: Energy deposition. Number of photons collected at the PMT. Gap : 2mm

Energy deposition in the NPS with carbon structure

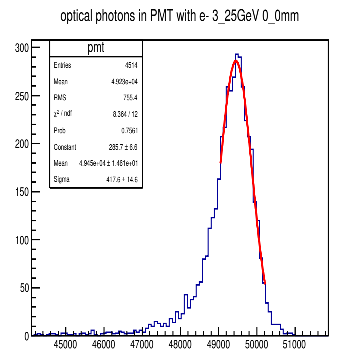
In this section, the histograms of energy deposition in the detector with carbon structure by a source of gamma with various energies and distances between the crystals are shown.



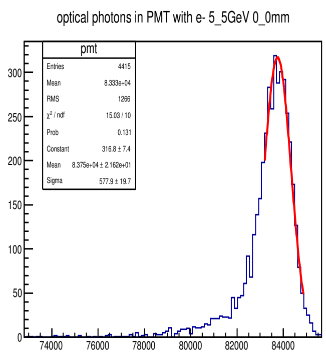
(a) Energy : 500MeV



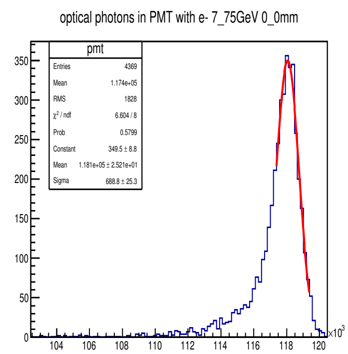
(b) Energy : 1GeV



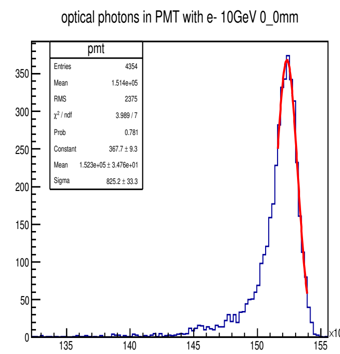
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

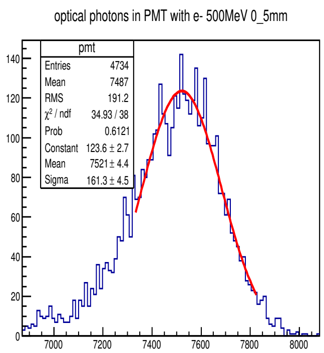


(e) Energy : 7.75GeV

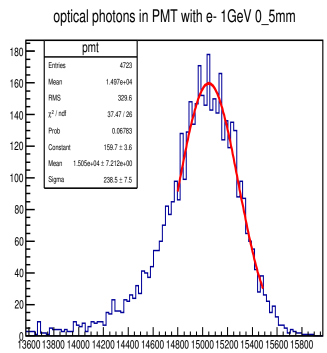


(f) Energy : 10GeV

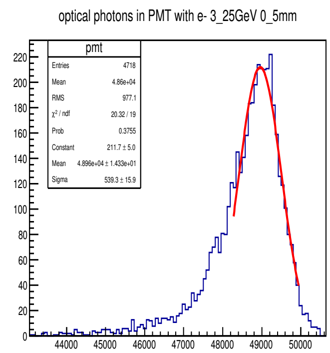
Figure B.1: Energy deposition. Number of photons collected at the PMT. Gap : 0mm



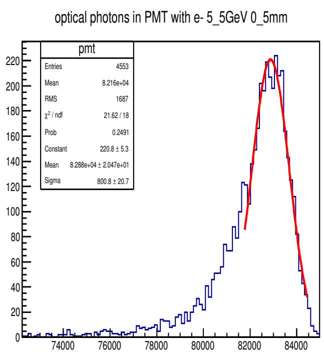
(a) Energy : 500MeV



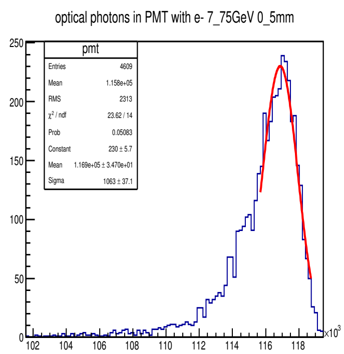
(b) Energy : 1GeV



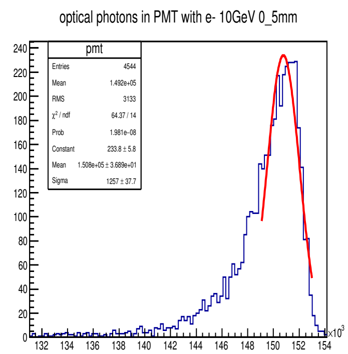
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

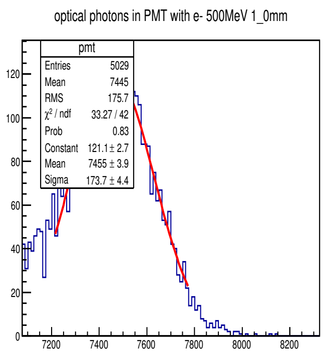


(e) Energy : 7.75GeV

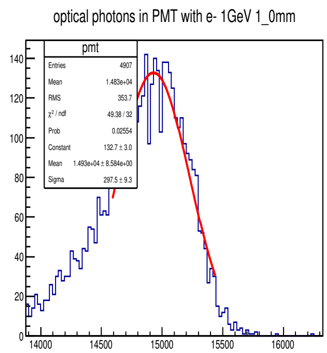


(f) Energy : 10GeV

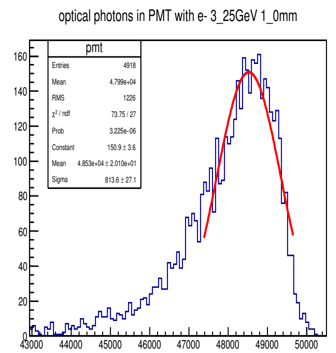
Figure B.2: Energy deposition. Number of photons collected at the PMT. Gap : 0.5mm



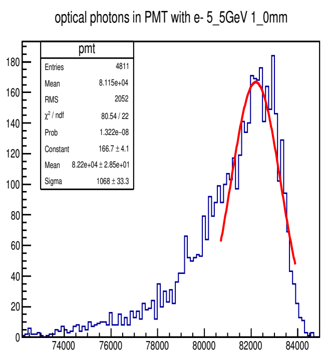
(a) Energy : 500MeV



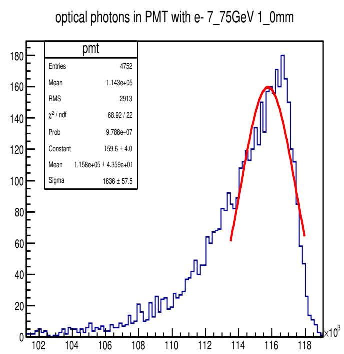
(b) Energy : 1GeV



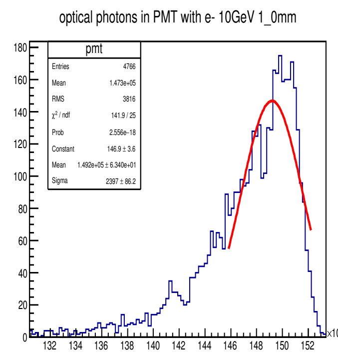
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

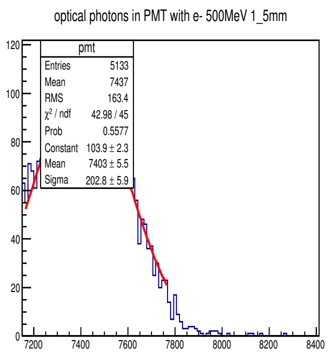


(e) Energy : 7.75GeV

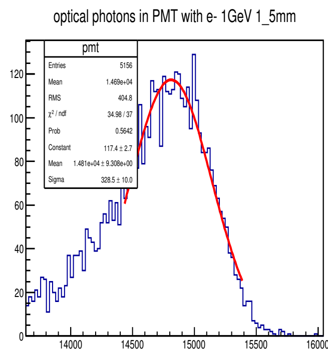


(f) Energy : 10GeV

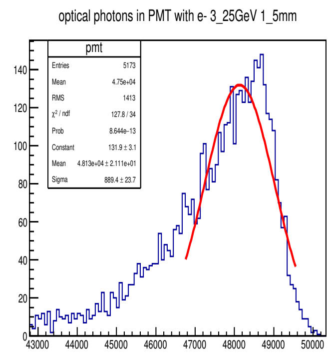
Figure B.3: Energy deposition. Number of photons collected at the PMT. Gap : 1mm



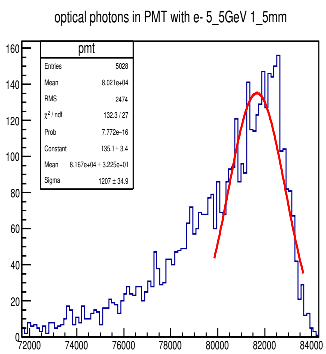
(a) Energy : 500MeV



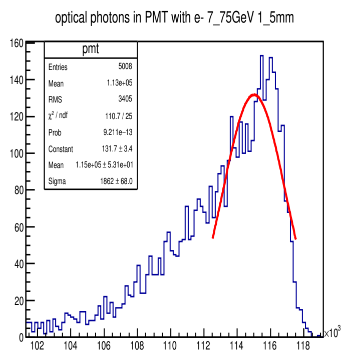
(b) Energy : 1GeV



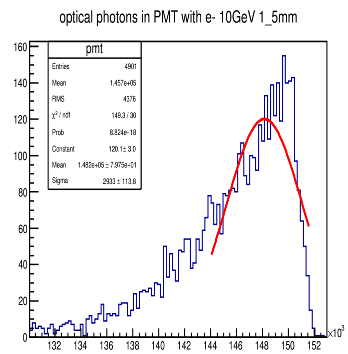
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV

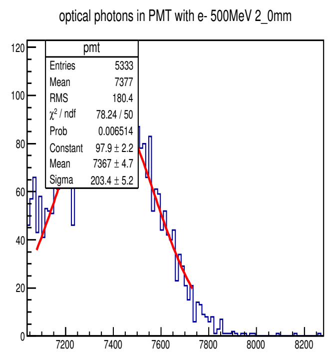


(e) Energy : 7.75GeV

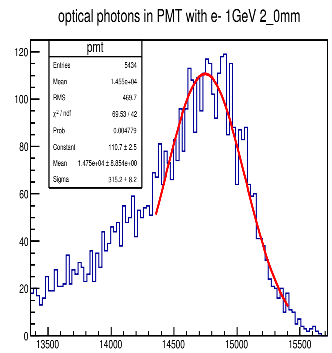


(f) Energy : 10GeV

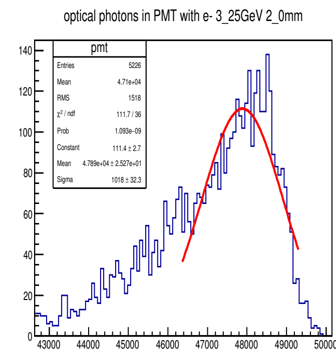
Figure B.4: Energy deposition. Number of photons collected at the PMT. Gap : 1.5mm



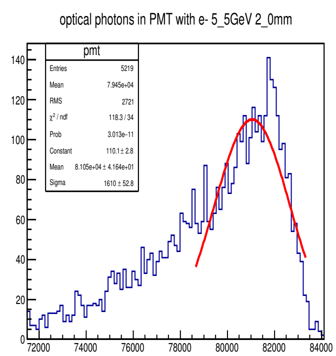
(a) Energy : 500MeV



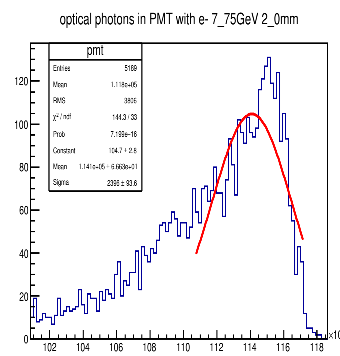
(b) Energy : 1GeV



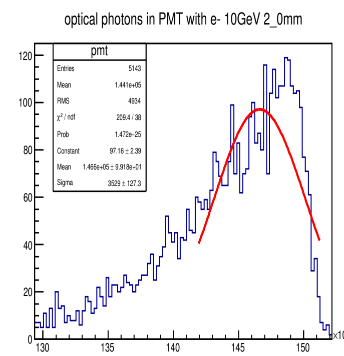
(c) Energy : 3.25GeV



(d) Energy : 5.5GeV



(e) Energy : 7.75GeV



(f) Energy : 10GeV

Figure B.5: Energy deposition. Number of photons collected at the PMT. Gap : 2mm

Clustering Structure for the NPS

We also tried two different structures and checked the resolution. One of the structure is 2-by-2 clustering of the crystals and the other is 3-by-3 clustering of them. There were also similar problem in fitting the histogram of the energy deposition in high energy range. By slightly changing the fitting range, the resolution changed largely enough to switch the order of the resolution against the size of the gap between the crystals. For this reason, we ex clued the resolution of the detector in the case of 10GeV as a primary source energy. The resolution results of 2-by-2 clustering is presented in Figure C.1 and 3-by-3 is in Figure C.2.

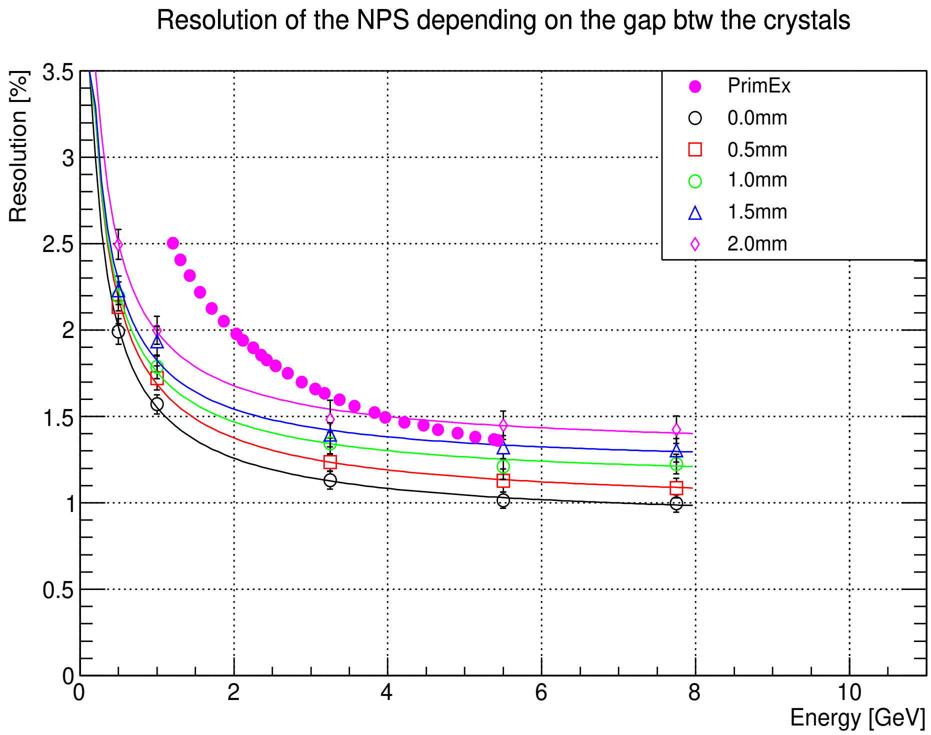


Figure C.1: Resolution of the 2-by-2 clustered detector.

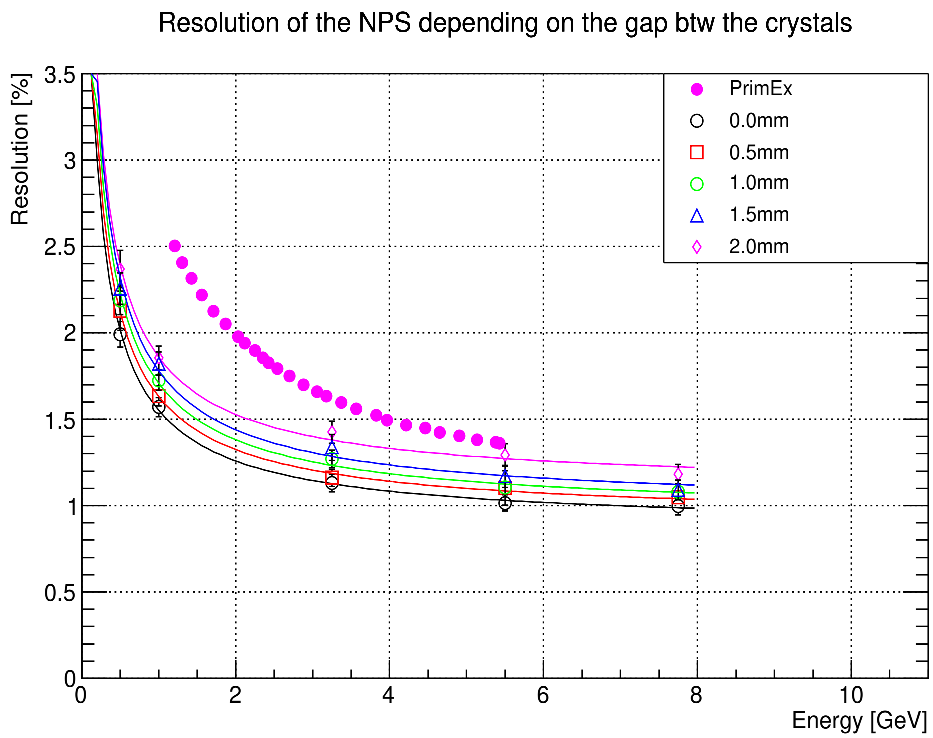


Figure C.2: Resolution of the 3-by-3 clustered detector.

References

[1] Zhu, *A study on the properties of lead tungstate crystals* Nucl. Inst. Meth. Phys. A 376 (1996) 319-334

[2] Ko, *Geant4 Optical Photon Simulation of the PbWO4 crystals for the NPS* Internal Note

[3] Kubantsev, *Performance of the PrimEx Electromagnetic Calorimeter* `arXiv:physics/0609201v1`