JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAMME

Soft Photon study in hadron and nuclear interactions

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Introduction

As a result of the passage of high-energy particles through the scintillator crystal, cascade processes arise, such as electromagnetic and hadron showers. These phenomena are well described and studied. However, the question of the appearance of so-called soft photons (SPh) in such processes still remains unresolved. The characteristic energy for SPh is less than 50 MeV and they are not decay product of secondary particles.

About 30 years ago it was also experimentally confirmed that in hadronic and nuclear interactions there is excess yield of SPh. Such phenomena was observed only in the hadron channels. It was absent in the lepton channel: $e^+e^- \to \mu^+\mu^-$. The existing theoretical calculations based on the QED can not predict and explain this excess.

Nowadays, the nature of soft photons remains obscure and physics only offer various phenomenological models taking into account quantum chromodynamics and experimental data. The most successful model is based on hypothesis of the cold quark-gluon plasma (QGP) formation. This model supposes formation of a quark-gluon system which consists of a few quarks, antiquarks and gluons (about 40 partons). These partons are encountering with each other and reradiate soft photons because it is not enough of their energy to produce hadrons. The main reactions are the Compton scattering: $q + g \to q + \gamma$, and annihilation: $q + \bar{q} \to \gamma$.

Project objectives

- Get experience in Geant4 toolkit and Root data-analysis framework
- Designing of "shashlik" elctromagnetic calorimeter with GaGG and YAP scintillators

1 Calorimetry

Calorimetry is a fairly common detection method in high-energy physics. Calorimeters are devices that consists of blocks with detecting material in which the passing particles are completely absorbed and their energy is converted into a measured signal. The interaction of an incident particle with a calorimeter (by means of electromagnetic or strong interactions) creates a stream of secondary particles (cascade shower) with gradually decreasing energy. The particle energy is recorded in the form of scintillations or in the form of a electric signal.

Calorimeters can be divided into electromagnetic calorimeters, which are used to measure the characteristics of mainly electrons and photons through their electromagnetic interactions (e.g. bremsstrahlung, pair production), and hadron calorimeters, which are used to measure the characteristics of hadrons through their strong and electromagnetic interactions.

The next classification of calorimeters is according to the type of their construction. These are heterogeneous calorimeters and homogeneous calorimeters. Heterogeneous calorimeters consist of alternating layers of absorber and detecting volume, this design is used to improve spatial resolution. Homogeneous calorimeters, on the other hand, are built from only one type of material that performs both tasks of absorber and detector.

1.1 Electromagnetic showers

Electrons and positrons lose energy by the bremsstrahlung and ionization. The second process prevails for low particle energy, the first – for high energy (∼10 MeV).

Critical energy E_c for solid materials (or gases), at which ionization losses and bremsstrahlung losses are equal:

$$E_c = \frac{610(710)}{Z + 1.24(0.92)}\ \text{MeV}. \tag{1}$$

For compound materials with N elements:

$$E_c = \frac{550}{Z_{eff}}, \tag{2}$$

where Z_{eff} is given by:

$$Z_{eff} = \frac{\sum_{i=1}^{N} Z_i f_i}{\sum_{i=1}^{N} f_i}, \tag{3}$$

finally, the mass fraction of i-th element f_i calculated by:

$$f_i = \frac{A_i v_i}{\sum_{k=1}^{N} A_k v_k}, \tag{4}$$

where A – atomic mass in g/mole, v – element valence.

Photons interact with matter by the photoelectric effect, Compton scattering, or the production of electron-positron pairs (PP). The photoelectric effect dominates at low energies, PP at high energies. The cross sections of these processes also depend on the Z of the medium. For example, the cross section for the photoelectric effect is proportional to Z^5 and to the energy of the γ-quantum as E^{-3}, while the cross section for PP gradually increases, both with Z and with E, and reaches its saturation around ∼1 GeV.

For describe the electromagnetic shower development, the concepts of radiation length (for calculating longitudinal profiles) and the Molière radius (for calculating transverse dimensions) are introduced. The radiation length X_0 depends on the calorimeter material properties:

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln{(287/\sqrt{Z})}} \text{ g/cm}^2. \tag{5}$$

For N elemental material X_0 can be calculated approximately:

$$X_0 \approx \frac{1}{\sum_{i=1}^{N} f_i/X_0^i}, \tag{6}$$

where X_0^i – radiation length for i-th element in compound.

The radiation length determines the rate at which charged particle lose energy due to bremsstrahlung. For example, a high-energy electron loses on average 63% (e^{-1}) of its initial energy E_0, when passing a distance of $1X_0$ in the medium.

The Molière radius R_M is defined by the ratio of radiation length and critical energy as:

$$R_M = 21 \text{ MeV } \frac{X_0}{E_c} \text{ g/cm}^2. \tag{7}$$

About 90% of the shower energy is absorbed in a cylinder with a radius of $1R_M$. Because most calorimeters has a Molière radius of the order in a few centimeters – electromagnetic showers are quite narrow in cross section.

1.2 Hadron showers

In hadron cascades the strong interaction brings additional complexity:

1. Hadron production in a shower. The 90% of the particles are pions. Neutral pions π_0 decay into two gamma-quants, which leads to the formation and development of electromagnetic showers.
2. Nuclear reactions. In these processes, neutrons and protons are released from atomic nuclei. Part of the energy is spent on the binding energy of nucleons ~8 MeV and does not converted to the calorimeter signals. This is the so-called phenomenon of invisible energy.

Electromagnetic showers produced by π_0 mesons developed in the same way as showers corresponding to high-energy photons. Similarly to the radiation length for an electromagnetic shower, the nuclear interaction length λ_I can be introduces as well, i.e. the average distance that hadrons travel before causing a nuclear interaction. The λ_I can be roughly estimated as:

$$\lambda_\text{I} \approx 35 \text{ g/cm}^2 A^{1/3}. \tag{8}$$

In most detector materials nuclear interaction length is much larger than the radiation length, especially in materials with high Z. This fact can be successfully used to distinguish between electromagnetic and hadron showers.

2 Geant4 simulations

Based on the project objectives a heterogeneous calorimeter of "shashlik" type was simulated in Geant4 toolkit.

2.1 GaGG scintillator

Gadolinium-gallium garnet, $Gd_3Al_2Ga_3O_{12}$, is a newly developed inorganic scintillator. It is one of the brightest available scintillators with an emission peak at 520 nm. GaGG has good stopping power – density 6.67 g/cm^3, is physically rugged and and well suited to a broad range of applications.

The calorimeter model consists of 28 GaGG plates with dimensions 100×100×3 mm^3 and 27 plates of W/Cu absorber (100×100×2 mm^3).

Table 1. Component properties of the GaGG scintillator

Element	Z	A, g/mole	υ_i	ρ_i, g/cm^3	f_i	X_0^i, g/cm^2	X_0^i, cm
Ga	31	69.723	3	5.91	0.225669	12.77	2.1607
Gd	64	157.25	3	8.64	0.50896	7.5642	0.8754
Al	13	26.9816	2	2.7	0.05822	24.26468	8.9869
O	8	16	12	0.00143	0.207146	34.46	24097.9

Using formula (6) we get:

$$X_0^{GaGG} = 1.44 \text{ cm}.$$

For critical energy from formula (2):

$$E_c^{GaGG} = 13.1 \text{ MeV}.$$

Finally, using formula (7), the Molière radius is:

$$R_M^{GaGG} = 2.32 \text{ cm}.$$

We consider that the absorber is made of 50 % W and 50 % Cu. Composite density is 11.187 g/cm^3 and radiation length is 0.56 cm.

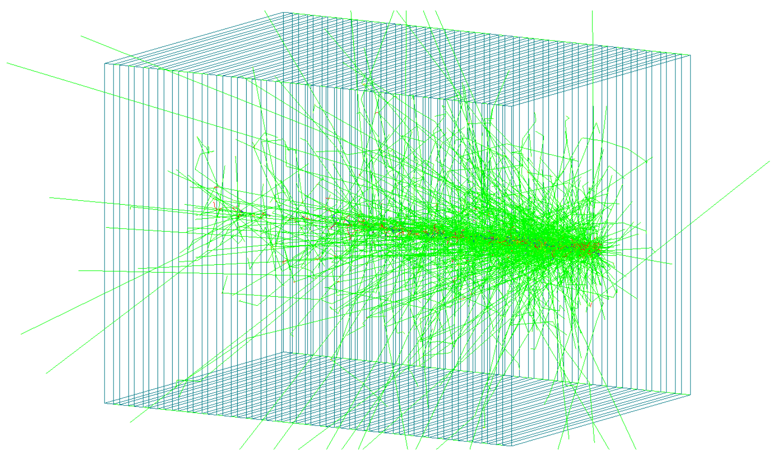
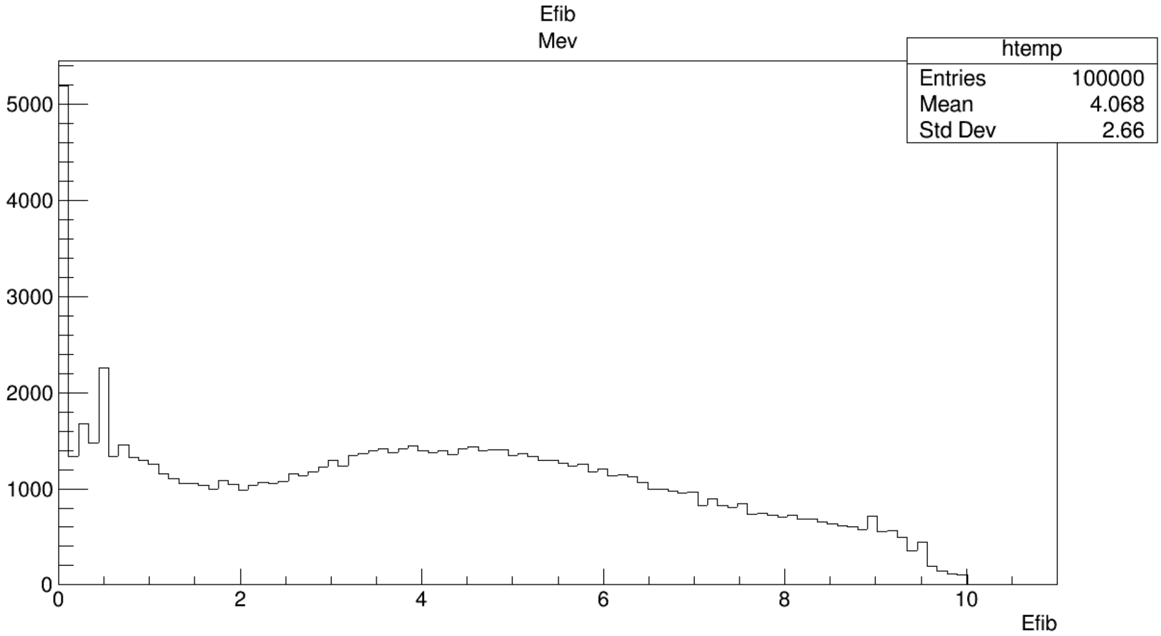


Figure 1. Simulation of electromagnetic shower in GaGG "shashlik" calorimeter (initial particles is 10 MeV photons).



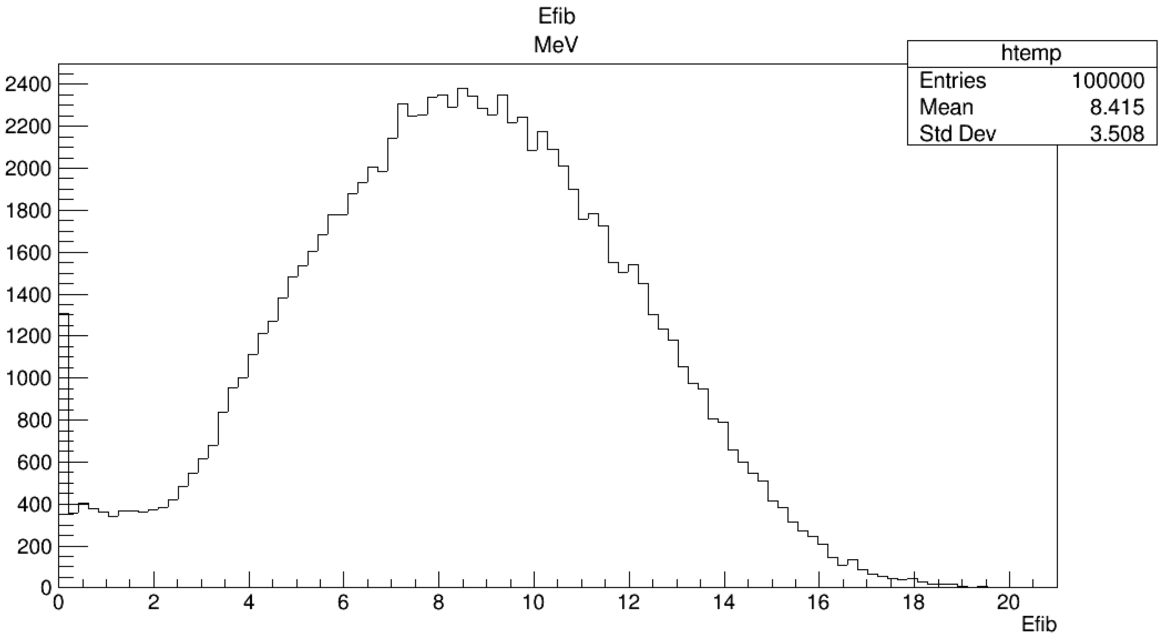


Figure 3. Energy release in GaGG "shashlik" calorimeter for incoming 10 MeV(top) and 20 MeV(bottom) photons.

The energy resolution for the GaGG "shashlik" calorimeter is given by,

$$\Delta E_{GaGG} = \frac{\sigma}{E_\gamma}. \tag{9}$$

Following formula (9) we can get: $\Delta E^{10\text{ MeV}}_{GaGG} = 27\%$, $\Delta E^{20\text{ MeV}}_{GaGG} = 17.5\%$.

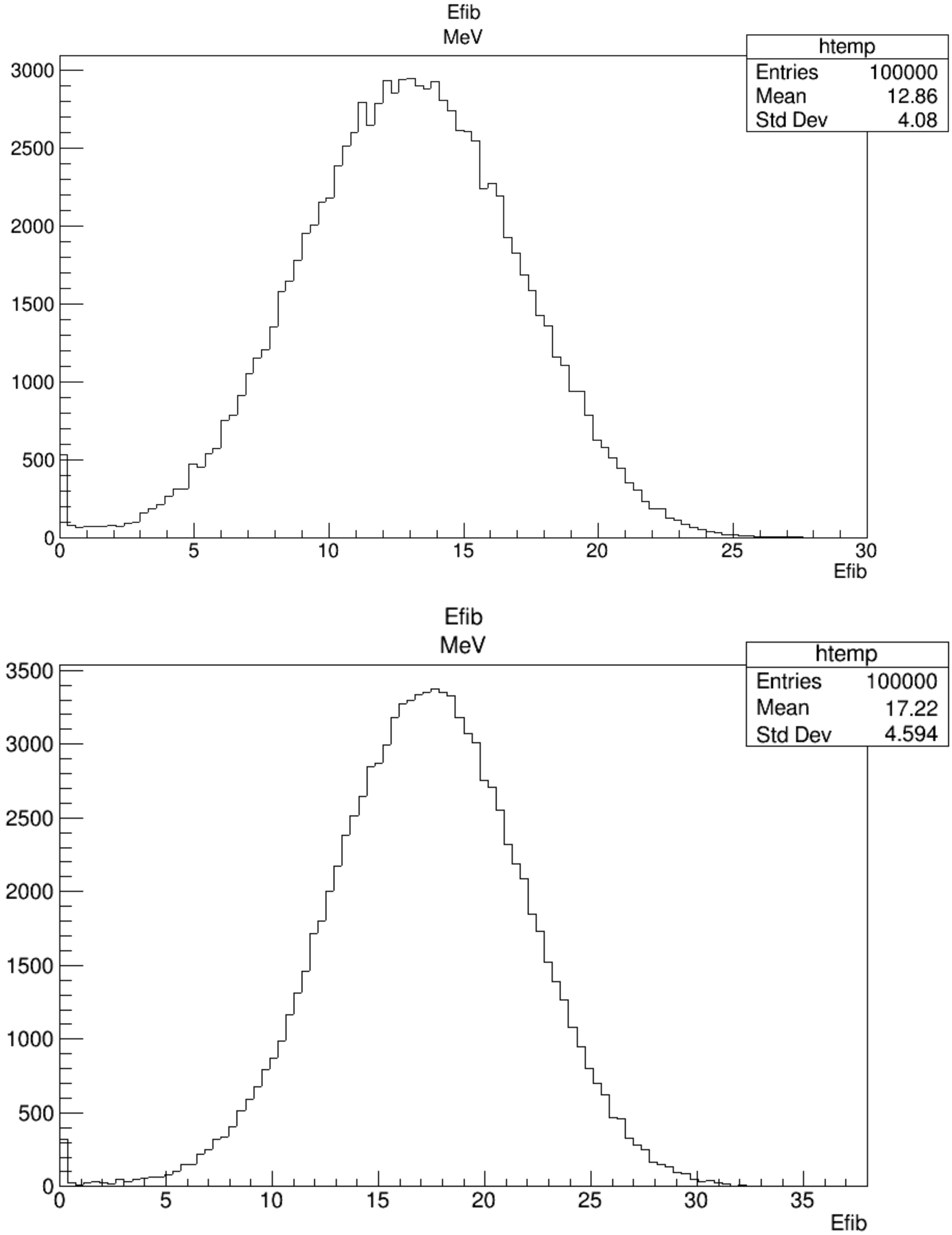


Figure 4. Energy release in GaGG "shashlik" calorimeter for incoming 30 MeV(top) and 40 MeV(bottom) photons.

In Fig.4 case we have: $\Delta E_{GaGG}^{30\ \mathrm{MeV}} = 13.6\%$, $\Delta E_{GaGG}^{40\ \mathrm{MeV}} = 11.5\%$.

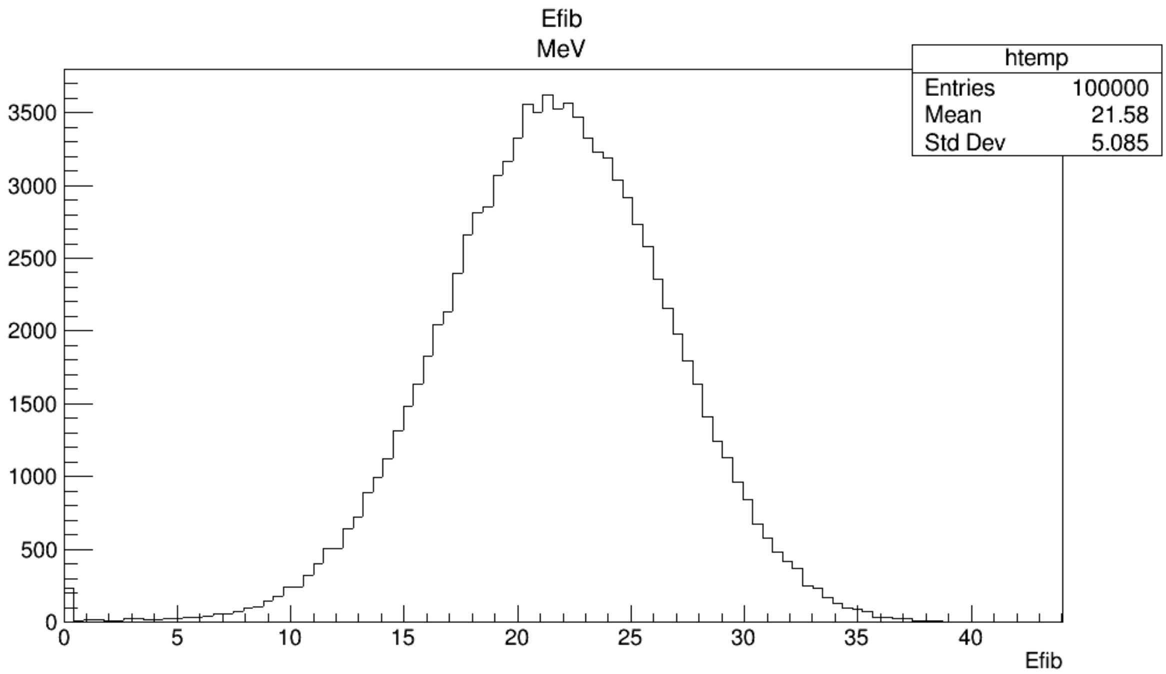


Figure 5. Energy release in GaGG "shashlik" calorimeter for incoming 50 MeV photons.

For 50 MeV energy resolution is: $\Delta E_{GaGG}^{50\text{ MeV}} = 10.2\%$.

Wrapping up previous calculations we get the energy resolution dependence from the initial photons energy (Fig.6). For the sake of completeness, we calculated energy resolution for cases of 100 MeV and 1 GeV photons: $\Delta E_{GaGG}^{100\text{ MeV}} = 7\%$, $\Delta E_{GaGG}^{1\text{ GeV}} = 4\%$.

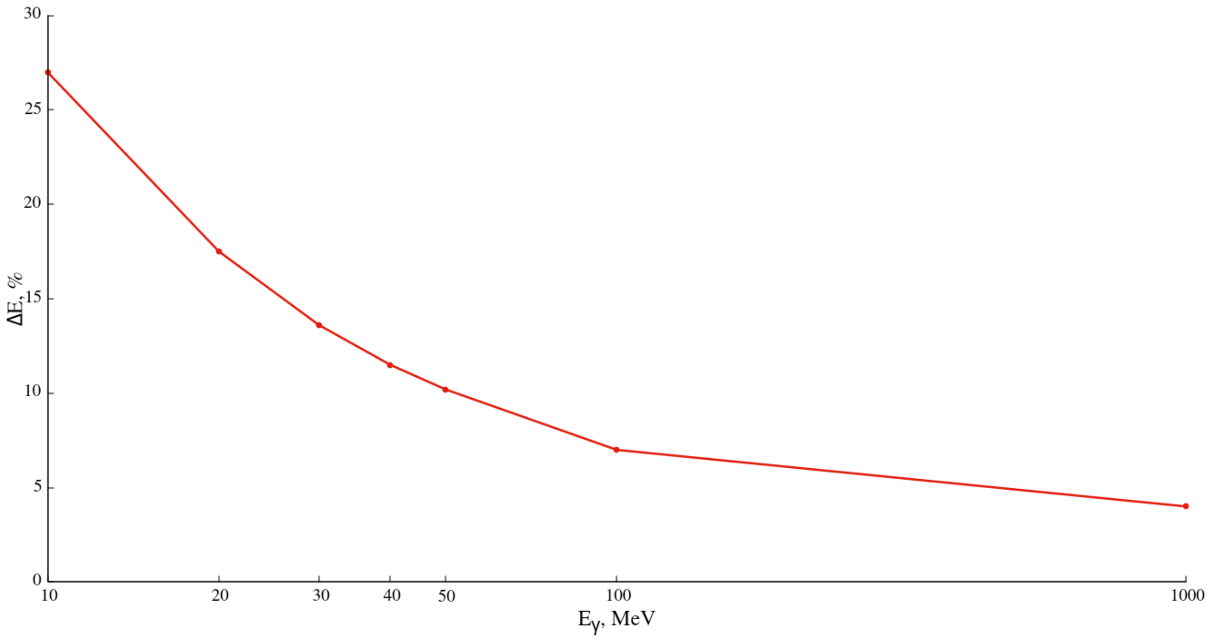


Figure 6. Energy resolution of GaGG "shashlik" calorimeter (x-axis in decimal logarithmic scale).

2.2 YAP scintillator

Yttrium Aluminium Perovskite, $YAlO_3$ – is fast, with a decay time of 28 ns, inorganic scintillator. YAP has a good stopping power with a density of 5.37 g/cm^3.

The model geometry is the same as in subsection 2.1. However, the scintillator plate thickness was increased to 5 mm due to the greater radiation length compared to GaGG, as will be noted below.

Table 2. Component properties of the YAP scintillator

Element	Z	A, g/mole	v_i	ρ_i, g/cm^3	f_i	X_0^i, g/cm^2	X_0^i, cm
Y	39	88.906	1	4.472	0.542482	10.41	2.329
Al	13	26.9816	1	2.7	0.164638	24.26468	8.9869
O	8	16	3	0.00143	0.292884	34.46	24097.9

Having carried out similar calculations as in previous subsection we get:

$$X_0^{YAP} = 3.98 \text{ cm},$$

critical energy:

$$E_c^{YAP} = 21.5 \text{ MeV},$$

and the Molière radius:

$$R_M^{YAP} = 3.89 \text{ cm}.$$

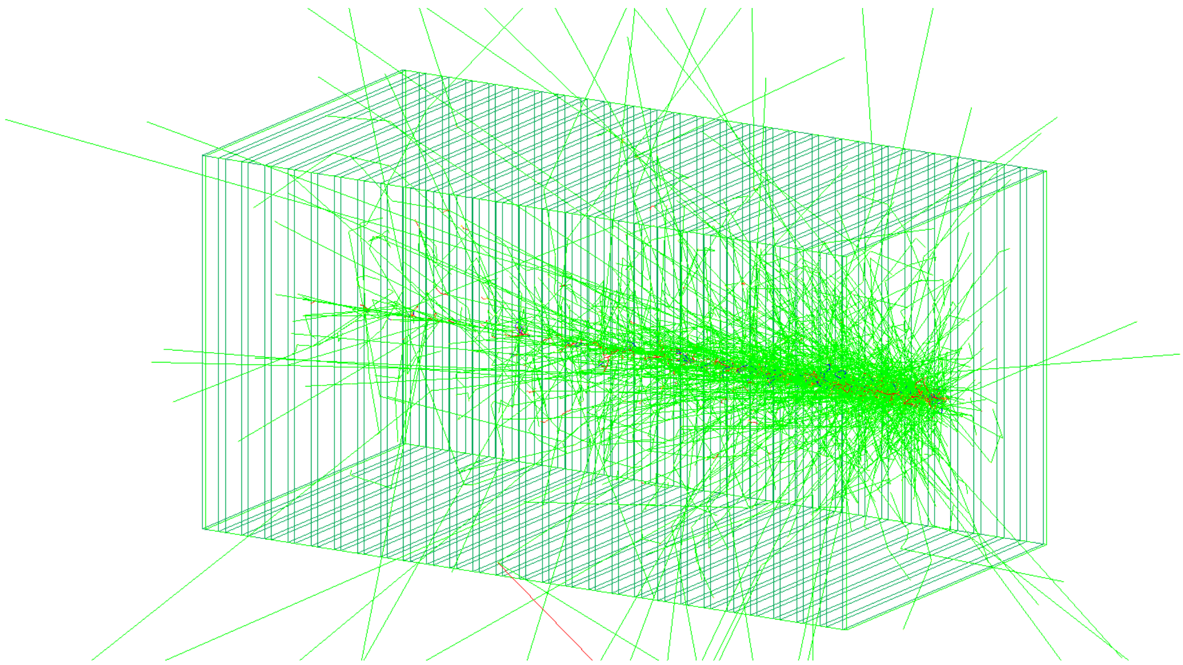


Figure 7. Simulation of electromagnetic shower in YAP "shashlik" calorimeter (initial particles is 10 MeV photons).

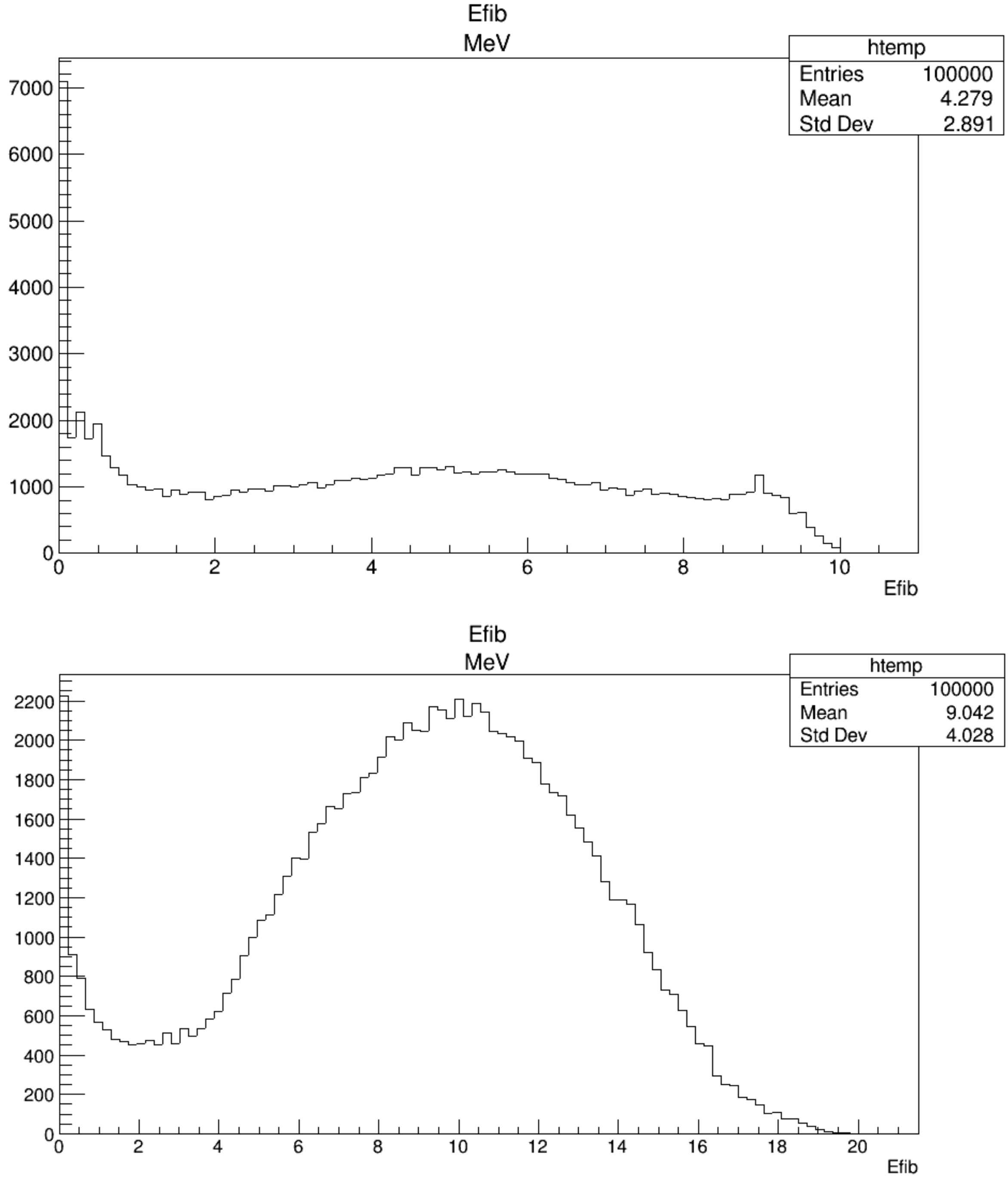
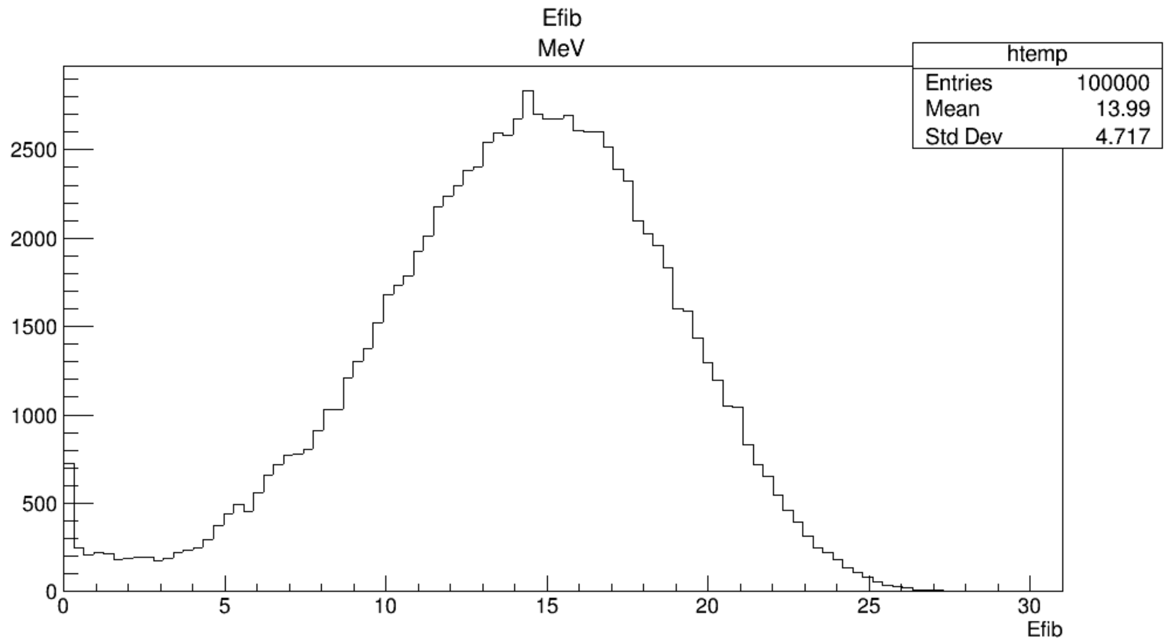


Figure 8. Energy release in YAP "shashlik" calorimeter for incoming 10 MeV(top) and 20 MeV(bottom) photons.

Following formula (9) we have: $\Delta E_{YAP}^{10\ \mathrm{MeV}} = 28.9\%$, $\Delta E_{YAP}^{20\ \mathrm{MeV}} = 20.1\%$.



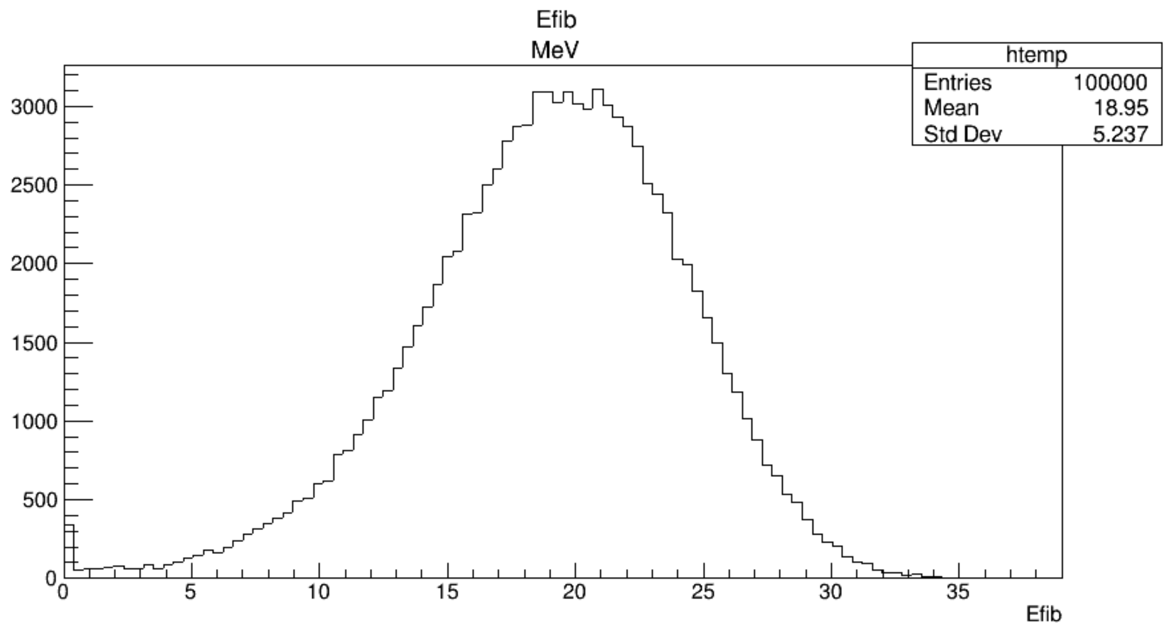


Figure 9. Energy release in GaGG "shashlik" calorimeter for incoming 30 MeV(top) and 40 MeV(bottom) photons.

In case of Fig.9 we get: $\Delta E_{YAP}^{30\ \mathrm{MeV}} = 15.7\%$, $\Delta E_{YAP}^{40\ \mathrm{MeV}} = 13.1\%$.

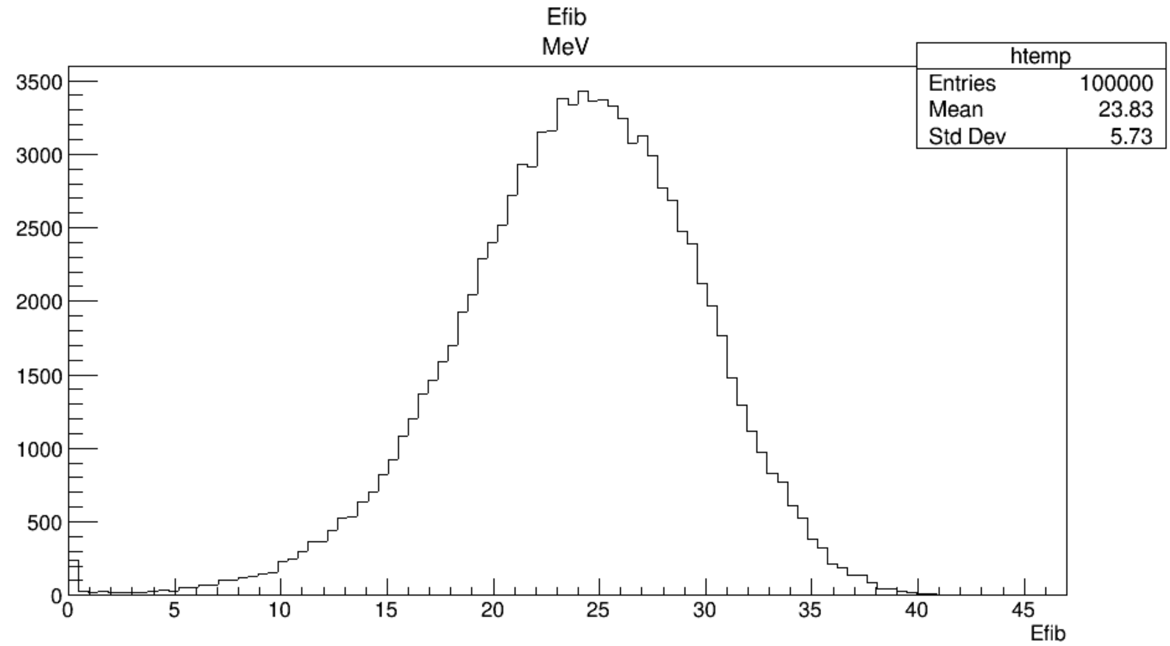


Figure 10. Energy release in YAP "shashlik" calorimeter for incoming 50 MeV photons.

For 50 MeV energy resolution is: $\Delta E_{YAP}^{50\text{ MeV}} = 11.5\%$.

Taking into account previous calculations we get the energy resolution dependence from the initial photons energy (Fig.11). As earlier for GaGG scintillator, we calculated energy resolution for cases of 100 MeV and 1 GeV photons: $\Delta E_{YAP}^{100\text{ MeV}} = 7.9\%$, $\Delta E_{YAP}^{1\text{ GeV}} = 4.3\%$.

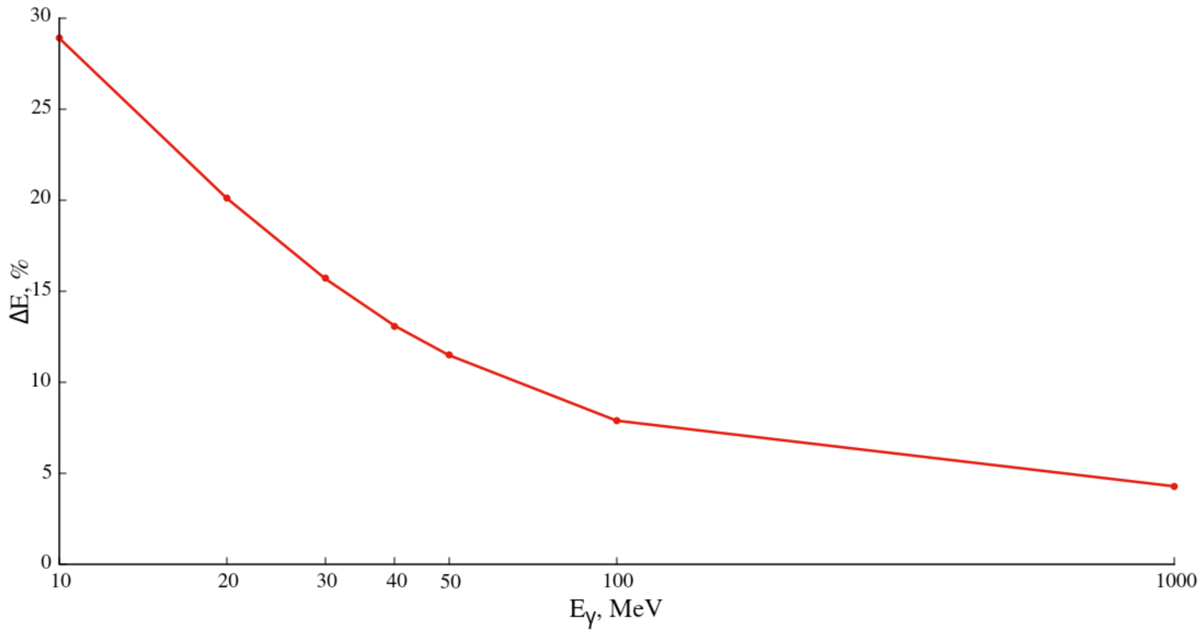


Figure 11. Energy resolution of YAP "shashlik" calorimeter.

Conclusions

In this work two ”shahlik”-type calorimeters were designed. GaGG and YAP scintillators were used as detecting material and W/Cu as absorber. By calculating different parameters, such as: radiation length, critical energy and Molière radius, we were able to define the optimal calorimeter dimensions to carry off electromagnetic shower energy release in sensitive volume.

After performing various simulations in Geant4, the obtained histograms were analyzed using CERN Root. We calculated for each calorimeter the energy resolution for 10-50 MeV photons coming in the z direction. Monte-Carlo simulations demonstrate the energy resolution of GaGG scintillator at low energy way better than YAP one (Figure 12).

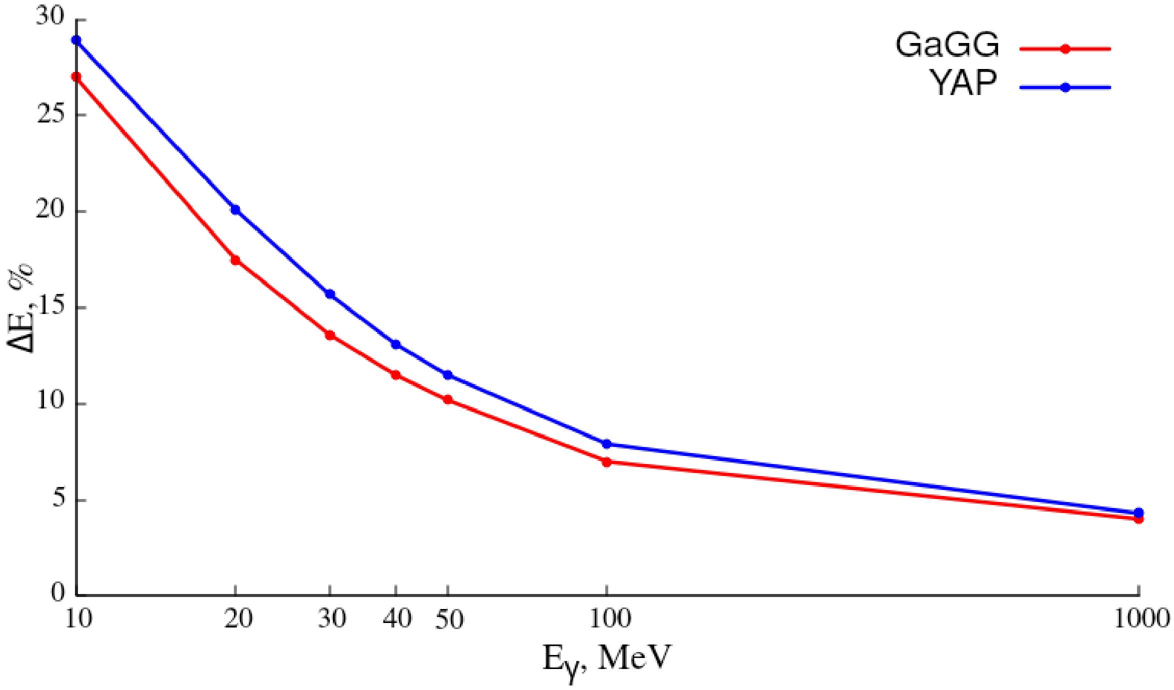


Figure 12. Comparison of energy resolution of GaGG and YAP ”shashlik” calorimeters.

In this way, the ”shashlik” calorimeter with GaGG as a scintillator and W/Cu as an absorber is a good choice in the study of soft photons since it has a good energy resolution compared to a YAP calorimeter.

Bibliography

[1] Advatech. *GAGG(Ce)-Gadolinium Aluminium Gallium Garnet (Ce)*. Last accessed 18 July 2022. URL: https://www.advatech-uk.co.uk/gagg_ce.html.

[2] Advatech. *YAP(Ce)-Yttrium Aluminium Perovskite*. Last accessed 18 July 2022. URL: https://www.advatech-uk.co.uk/yap_ce.html.

[3] Claus Grupen and Boris Shwartz. *Particle Detectors*. 2nd ed. Cambridge University Press, 2008.

[4] Elena Kokoulina et al. "Study of soft photon yield in pp and AA interactions at JINR". In: *XLIX International Symposium on Multiparticle Dynamics (ISMD 2019)*. 2020.