JOINT INSTITUTE FOR NUCLEAR RESEARCH
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FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Numerical simulation of promt photon production in hadron collisions

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Abstract:

Recent progress in theoretical calculations makes the gluon distributions in pion and kaon especially important. Gluons not only significantly contribute to the internal structure of mesons; they also play a major role in the generation of their mass.In contrast to the rather well mapped gluon distribution in the nucleon, the gluon content of mesons is essentially unknown.In order to measure the gluon PDF (Parton Distribution Function) for the mesons, the prompt-photon production in gluon Compton scattering can be used. Using framework ROOT and high-energy-physics event generator PYTHIA this report will demonstrate the simulation of kaon-proton collisions in order to identify optimization parameters for the future installation of the AMBER experiment.

Introduction:

The structure of hadrons as building blocks of visible matter is still at the core of interest in the quest for understanding nature. The quarks suggested by Gell-Mann and Zweig in 1964 as building blocks of nucleons and mesons were identified with Feynman's partons. This paved the way for the huge success of the Quark-Parton Model (QPM). At the same time, quantum chromodynamics (QCD), which explained the strong interaction in the Standard Model, was actively developing.
The natural energy-scale for strong interactions is characterised by the proton mass mp ≈ 1 GeV ≈ 2000m_e, where m_e is the electron mass. In the Standard Model, m_e is rightly attributed to the Higgs boson; but what is the source of the enormous enhancement to produce m_p? This is the crux: the source of the vast majority of visible mass in the Universe is unknown. In order to solve this conundrum, it is necessary to study the internal structure of hadrons with good accuracy. Thus, the determination of PDF, i.e. the quark-gluon distribution of hadrons is the most essential issue of current high-energy physics.
Mesons, being made by a quark and an anti-quark, are the simplest quark bound system and therefore the ideal benchmark to study the interaction between quarks and understand what the role of gluons is. In contrast to the well-known gluon distribution of the nucleon, our knowledge on the gluon distribution in light mesons is rather limited. It can be considerably improved by studying prompt-photon production in hadronic collisions using a high-energy meson beam.
Prompt photons are photons that are produced by hard scattering of partons. The inclusive cross section for the production of a prompt photon in a collision of hadrons h^A and h^B can be written as follows:

$$d\sigma_{AB\to\gamma X} = d\sigma_{dir} + d\sigma_{frag} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a^A(x_a, Q^2) f_b^B(x_b, \mu^2) d\sigma_{ab\to\gamma x}(x_a, x_b, Q^2) + d\sigma_{frag}.$$

Here,$d\sigma_{dir}$ is the contribution of photons emitted via direct coupling to a quark (direct photons) and $d\sigma_{frag}$ represents the contribution of photons produced from the fragmentation of a final parton (fragmentation photons). The function $f^A{}_a$ ($f^B{}_b$) is the parton density for hadron h^A(h^B), x_a (x_b) is the fraction of the momentum of hadron h^A (h^B) carried by parton a (b), Q^2 is the square of the 4-momentum transferred in the hard scattering process, and $\sigma_{ab\to\gamma x}(x_a,x_b,Q^2)$ represents the cross section for the hard scattering of partons a and b. The measurement of such the differential cross section $Ed^3\sigma_{AB\to\gamma x}/dp^3$ is the clue to determining the gluon distribution in mesons.
As of today, somewhat, these measurements are made for pion-nucleon collisions, but the accuracy in such experiments is not sufficient. Moreover, the data does not exist for the kaon`s PDF. Therefore, the need arises for conducting qualitatively new experiments. [1].

Apparatus for Meson and Baryon Experimental Research

The AMBER experiment is actually the heir to the COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy) experiment aimed at studying the structure and dynamics of hadrons. The installation of the COMPASS shown in Fig.1 experiment is described in Ref. [2].

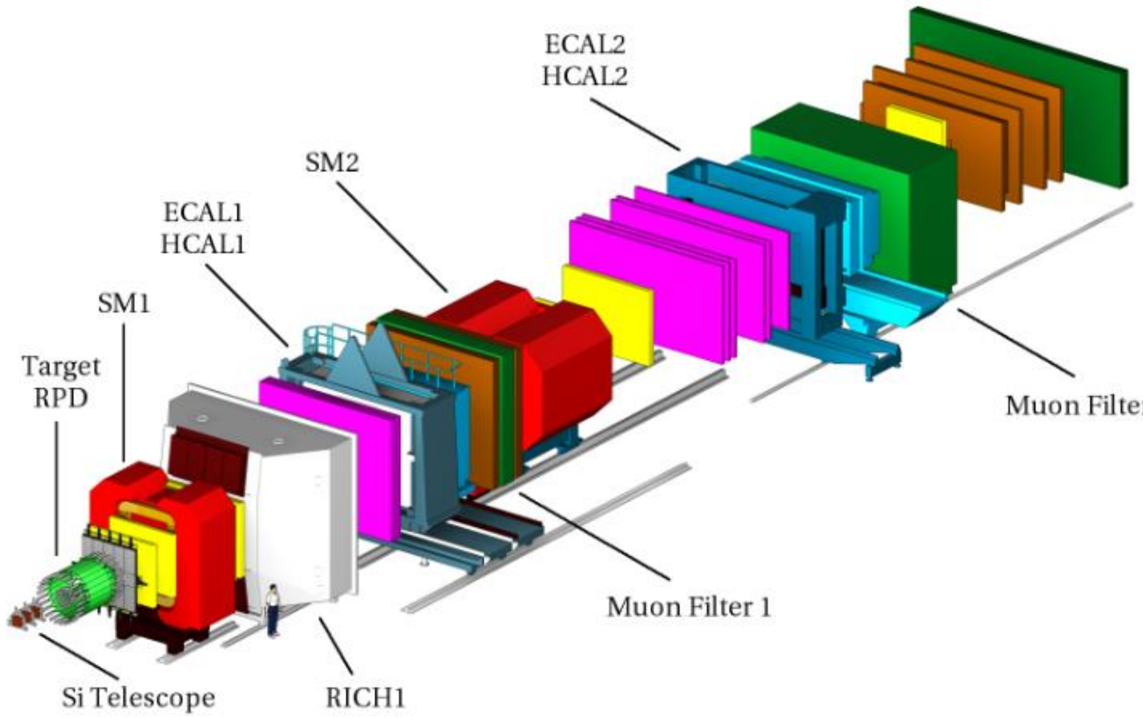

Fig. 1. Three-dimensional view of the COMPASS setup for measurements with hadron beams. The beam comes from the left side. The upstream part of the setup (beam line) is not shown here. The different colours indicate different detector types.

The high-intensity RF-separated kaon beam of the upgraded M2 beam line in AMBER experiment at CERN is an unrivalled site to investigate the gluon content of the kaon . Using a beam of positive kaons with an energy of at least 100 GeV over 1-2 years, the gluon PDF in the charged kaon will be measured using the dominant hard gluon Compton scattering process. A separate data set will have to be taken with a beam of negative kaons in order to allow for a separation of the subdominant quark-antiquark annihilation process. For systematic studies and also to improve the knowledge on the gluon structure of the pion, it is foreseen to also collect data with incoming pions. This can be done either in parallel or separately in a preceding running period. The basic requirements for the proposed measurement are a sufficiently high transparency of the experimental setup for the produced photons, a wide kinematic range of photon detection by the system of electromagnetic calorimeters, efficient beam hadron identification, and a dedicated calorimeter-based trigger on high-p_T photons. [1].

To select a kaon beam, a high-intensity radio frequency field is used. The task itself is not trivial. Therefore, the problem of payback arises: What installation parameters to choose in order to reduce already high costs, but at the same time observe the declared accuracy of the experiment? This question can be answered using simulations of the processes that will occur at the stage of the investigation`s carrying out.

ROOT and PYTHIA 6.4

ROOT is an object-oriented framework aimed at solving the data analysis challenges of high-energy physics. Together with PYPTHIA , which can be used to generate high-energy-physics ‘events’ (i.e. sets of outgoing particles produced in the interactions between two incoming particles), it is possible to carry out modeling of various kinds of processes. In our case, the production of promt photons from kaon-proton collisions will be investigated.
In order not to be unfounded, one illustrates the compilation of the code, upon completion of which one obtains the energy distribution for promt photons:

```
{
TH1D* h = new TH1D("his", "Energy spectrum for  #gamma",100, 0,20);
h->SetXTitle("E,GeV");
TMCParticle* myParticle=new TMCParticle();
TPythia6* pythia=new TPythia6;
pythia->SetMSEL(0); // Inclusion of subprocesses
pythia->SetMSUB(29,1);
pythia->SetMSUB(14,1);
pythia->Initialize("fix","K+","p",100); // Pythia initialization
for (Int_t i = 0; i <100000; i++)
   {
        pythia->GenerateEvent();
        TObjArray *particles =pythia->GetListOfParticles();
        for(int i=0; i<pythia->GetNumberOfParticles();i++)
        {
                myParticle=(TMCParticle*)particles->At(i);
                Int_t Ks=myParticle->GetKS();
                Double_t E=myParticle->GetEnergy();
                Int_t pid=myParticle->GetKF();
                if (Ks==1 && pid==22)
                        {
                             h->Fill(E); // Histogram filling
                        }
         }
   }
pythia->Pystat(1); // Cross sections of processes
pythia->Pylist(1); // List of particles
h->Draw(); // Histogram plotting
}
```

Fig. 2.: The program which illustrate the energy distribution for promt photons

when compiling, we get:

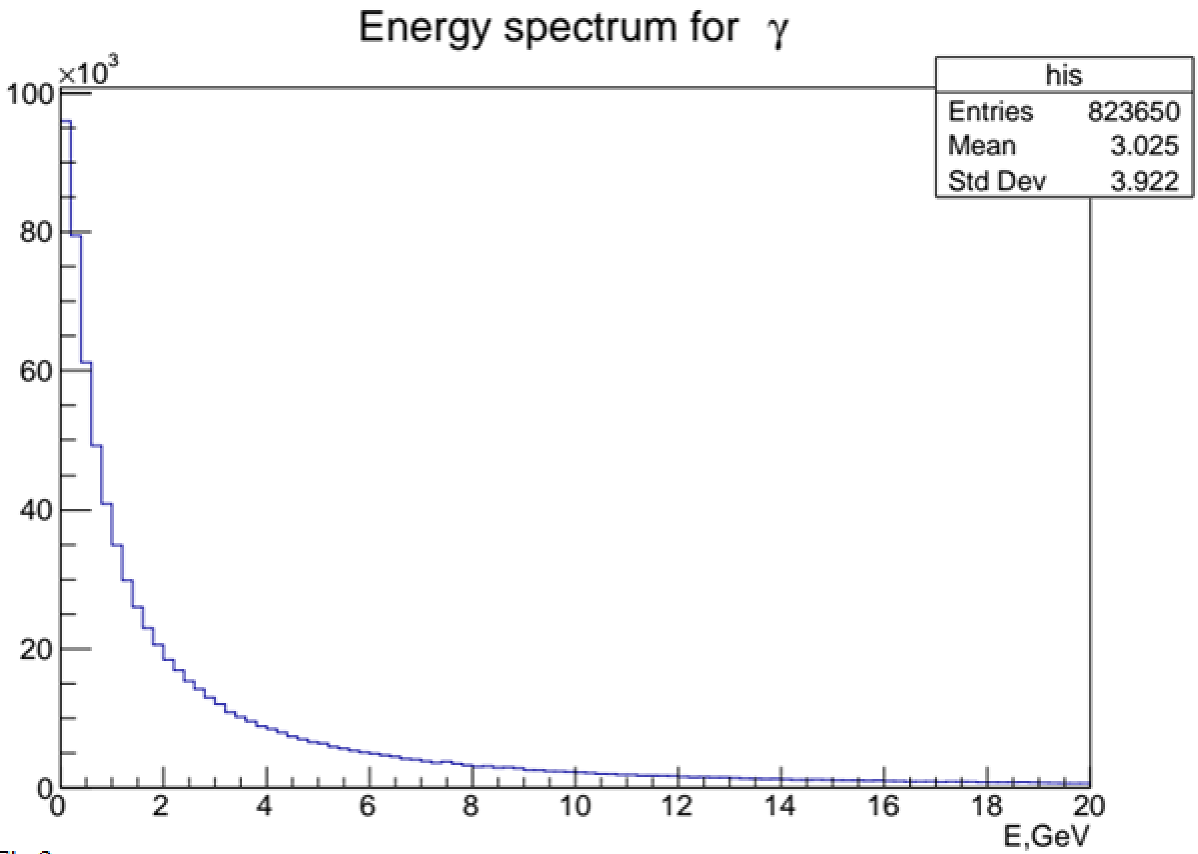

Fig.3.

Using the ROOT framework in conjunction with PYTHIA package based on Monte-Carlo methods, there will do research aimed at optimizing the future modernized installation of M2 Beam Line.

A brief description of the experiments and the main conclusions are given below.

Experiment 1.

Firstly, The p_T distributions shown in Fig. 4 for photons from gluon Compton scattering and for minimum-bias photons adjusted for interaction cross section are built. The number of events is selected so that the measurement accuracy for the background is no more than 4 %. This is done if we take the initial number of events equal to 10 million.

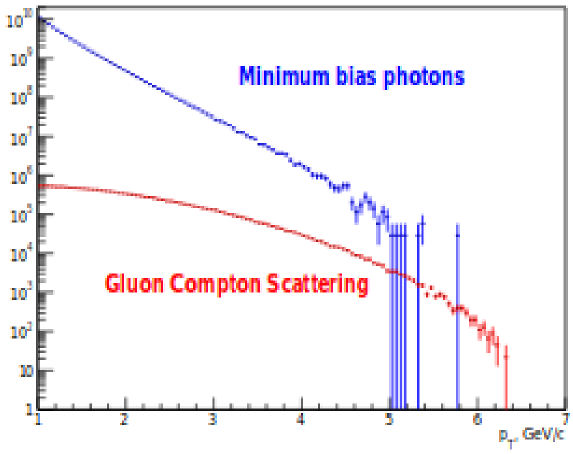

Fig. 4: The p_T distributions for prompt photons from gluon Compton scattering (red) and for minimum-bias photons (blue), produced in the interaction of a 100 GeV K^+ beam and a proton target (according to Pythia6 and assuming that $g_\pi(x,Q^2) = g_K(x,Q^2)$).

The figure shows that this kind of background is especially important at small p_T and gives the lower limit of the accessible p_T range,i.e. with a low transverse momentum of the photon, the signal is practically lost in the background. So it is advisable to consider $p_T > 3$, for example. For practical reasons, it would be interesting to see how the ratio of the background to the signal changes depending on the energy. Since the interaction cross section depends on energy, changing the energy for other constant parameters, the accuracy will also change. Therefore, it would be more correct to consider the interval not $p_T > 3$, but its fraction, i.e. $x_T = 2p_T / \sqrt{s}$, where $\sqrt{s}$ is the energy of two colliding particles in the center mass system. Changing the beam energy from 60 to 120 GeV, we obtain the following data:

Ecms,GeV	E,GeV	Sigmab,mb	Sigmas,mb	Background	Signal	B/S	From P_T
10,664	60	15,95	$2{,}038 \cdot 10^{-4}$	10381x78263,0029	$1{,}58569 \cdot 10^{6}$	521,364±0,982	2,32838
11,095	65	15,89	$2{,}275 \cdot 10^{-4}$	8582x69846,1538	$1{,}42689 \cdot 10^{6}$	420,089±1,079	2,42249
11,510	70	15,83	$2{,}504 \cdot 10^{-4}$	7090x63218,8498	$1{,}29694 \cdot 10^{6}$	345,6±1,188	2,5131
11,911	75	15,78	$2{,}723 \cdot 10^{-4}$	6100x57950,7896	$1{,}16947 \cdot 10^{6}$	302,274±1,280	2,60065
12,298	80	15,74	$2{,}94 \cdot 10^{-4}$	5161x53537,415	$1{,}06981 \cdot 10^{6}$	258,276±1,392	2,68515
12,674	85	15,71	$3{,}151 \cdot 10^{-4}$	4482x49857,1882	978035	228,478±1,494	2,76725

13,039	90	15,67	$3{,}417*10^{-4}$	4299x45858,6406	936810	210,444±1,525	2,84694
13,394	95	15,65	$3{,}621*10^{-4}$	3607x43220,1049	854469	182,447±1,665	2,92445
13,74	100	15,62	$3{,}82*10^{-4}$	3068x40890,0524	776721	161,513±1,805	3
14,077	105	15,6	$4{,}017*10^{-4}$	2645x38834,9515	715359	143,59±1,944	3,07358
14,406	110	15,58	$4{,}206*10^{-4}$	2277x37042,3205	656835	128,412±2,096	3,14541
14,728	115	15,56	$4{,}392*10^{-4}$	1931x35428,051	603266	113,402±2,276	3,21572
15,044	120	15,55	$4{,}617*10^{-4}$	1864x33679,8787	636508	98,6308±2,316	3,28471

Based on the data in this table, we construct a graph of the dependence of the ratio of the background to the signal on energy:

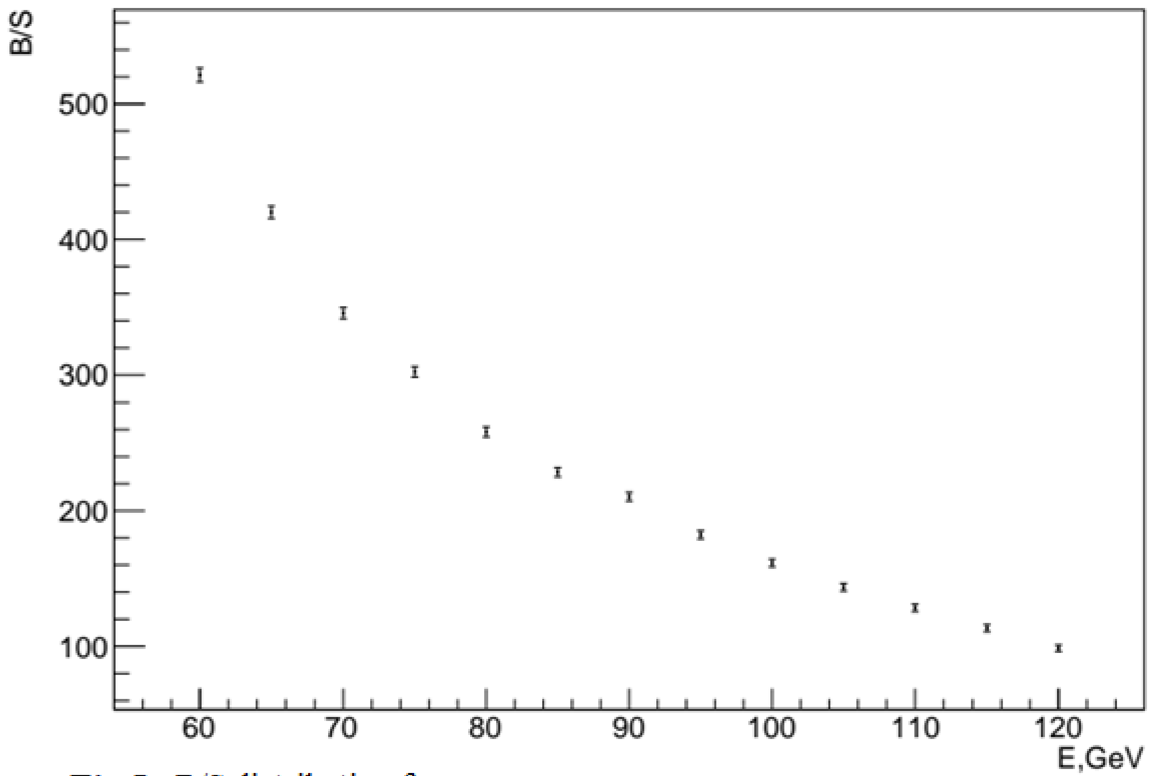

Fig.5.: B/S distribution from energy

It can be seen that with increasing energy, the B/S decreases.

Experiment 2.

Pythia 6 allows you to track the channel of gluon formation, i.e. it is possible to identify only those gluons that were part of the selected parent particles, so it would be interesting to see how promt photons are distributed, which are formed during the hard scattering of gluons of “different sorts” on quarks depending on the angle (or in our case, pseudorapidity).

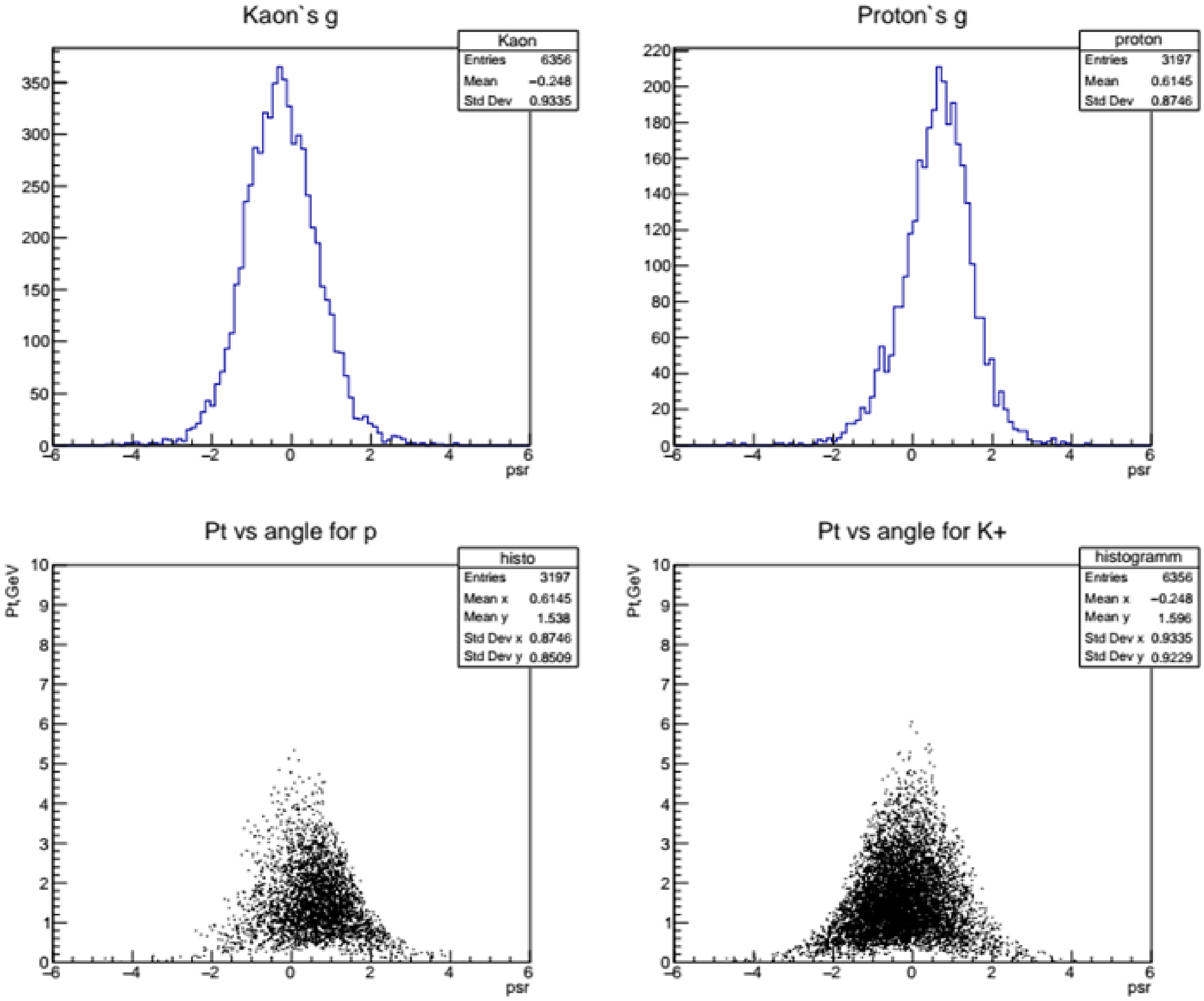

Fig.6.: *bottom*: transverse momentum distribution vs. pseudorapidity for straight photons from protons and kaons, respectively;
top: projections on the OX axis;

As expected, the gluons from kaon are softer than the gluons from the proton, so the promt photons basically fly apart at larger angles, which can be seen from the mean value for pseudorapidity. From the installation of the COMPAS experiment, it can be seen that promt photons register three ECAL0, ECAL1, ECAL2, electromagnetic calorimeters, which are designed for different scattering angles from the interaction vertex. It is important to know how the number of registered photons in these three electromagnetic calorimeters varies with energy.

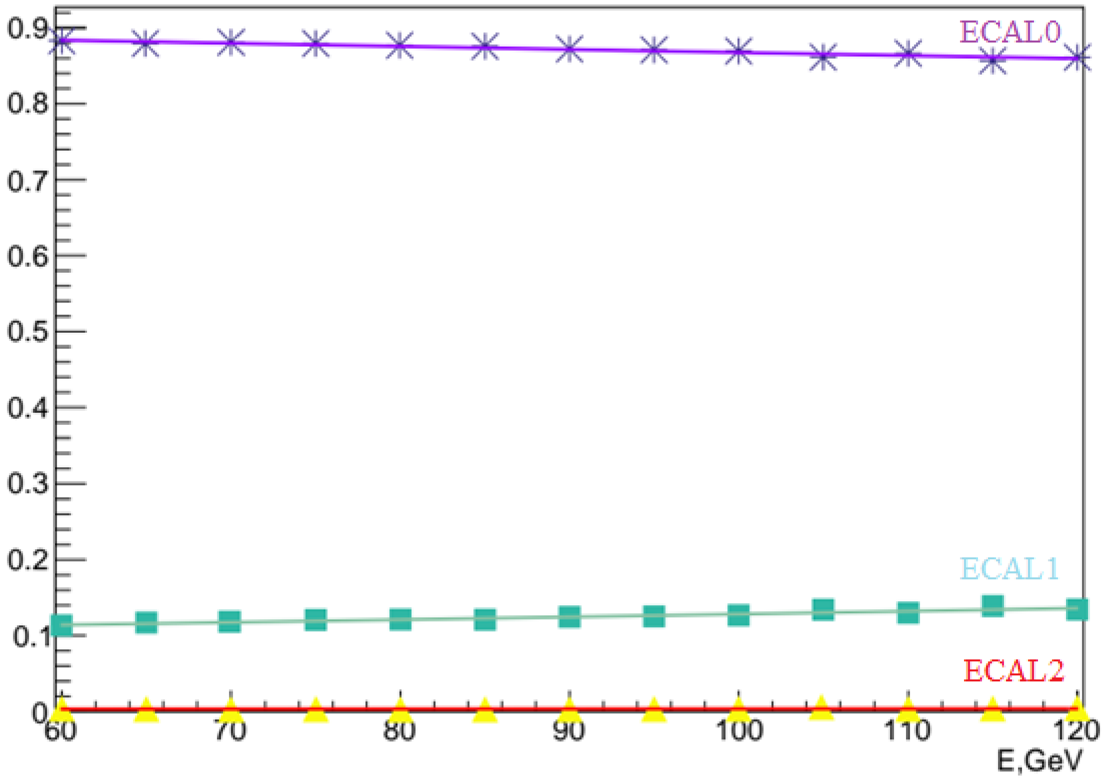

Fig.7.: The dependence of the number of promt photons registered in ECAL0, ECAL1, ECAL2, respectively, of the energy. Each value is normalized to the total number of pront photons.

Obviously, this number does not change much within a large amount of data.

Conclusions

- It can be seen that at low energies of the kaon beam it is difficult to isolate the signal from the background, and because of the design features it is quite expensive to build an installation with high beam energy. It follows that it is necessary to choose the optimal energy, for example: 100 GeV.
- It is quite an interesting result: the number of registered direct photons in the three electromagnetic calorimeters ECAL0, ECAL1, ECAL2 qualitatively not much changes within large amounts of data. Thus, in this case it is possible to use any energy in the range considered in experiment 2.

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References

[1] Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS (COMPASS++/AMBER), arXiv:1808.00848 [hep-ex]

[2] COMPASS Collaboration, The COMPASS Experiment at CERN, CERN – PH – EP/2007-001 (2007), arXiv:0703049 [hep-ex].