At the last DAC meeting a few question were raised to the FHCAL. Here we will consider a part of them devoted to the design and performance of FHCAL.

Below is the list of the questions:

Q1.The DAC considers the present design of the FHCAL not optimal for measuring the hadrons with adequate resolution at these low energies. The design is just taken from sampling calorimeters optimized at much higher energies than at NICA. It recommends a thorough simulation of the energy loss and reaction pattern of protons and neutrons of energies from 100 MeV to 4000 MeV kinetic energy in the proposed scenario, as well as consequences from these studies.

Q2.The DAC emphasizes the crucial importance of dedicated measurements of FHCAL parameters in the energy range of the NICA collider (protons from 1 to 6 GeV/c) and urges the team to present a detailed plan of such beam tests ASAP.

Q3.Can FHCAL longitudinal segmentation improve MPD performance in event centrality selection? In particular, can the energy deposit in the first FHCAL section (maybe modified?) be used in the MPD trigger?

Q4.The DAC recommends the team to look into the possibility of using the signal from the first FHCAL section separately from the total energy deposit in order to get insight into the electromagnetic component in the FHCAL acceptance.

Q5.On slide 7, please plot the energy asymmetry (which is the measured quantity) vs the impact parameter and study the energy asymmetry vs position of the collision vertex along the z-axis

The answers are given in the following pages.

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Initially, the design of the calorimeter prototypes was developed a few years ago for the FAIR beam energies from 1 GeV to 30 GeV. That time, main requirements to the calorimeter were:

1. Modular structure adjustable for the calorimeters with the different geometries;
2. Ability to work in strong magnetic fields;
3. Good energy resolution, close to the best values of existing hadron calorimeters;
4. Detection of the hadrons with low energies;
5. Reliable detection of low energy depositions, comparable to that from the minimum ionizing particles;
6. Longitudinal segmentation to compensate the non-uniformity of the light collection along the modules;
7. Compact and cheap photodetectors with high gain and low noise;
8. Possibility to calibrate with the cosmic muons.

The above requirements were implemented in the current design of the modules. Certainly, the design of the modules implies their use at NICA. It is the reason, why the module prototype was tested at T10 beam line at CERN in 2012 at NICA energies. Unfortunately, that time the performance of the silicon photomultipliers was not perfect. Namely, due to the long recovery time the MAPD photodiodes were very sensitive to the count rate. However, the tests revealed a reliable detection of the low energy hadrons with the expected resolution.

The main tasks of FHCAL at MPD are the measurements of the centrality and the reaction plane. The simulation results presented in FHCAL TDR show the appropriate performance of the calorimeter. Nevertheless, it would be valuable to understand the effect of the FHCAL energy resolution at the measured parameters. Here we will consider it in details.

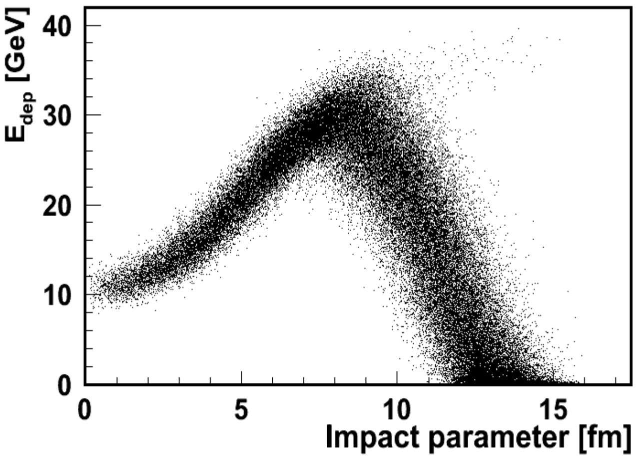
There are three main components in the energy resolution of the calorimeter: stochastic term, noise term and constant term. Noise term is the most critical for the measurements at low energies. However, let us start from the stochastic term, which is mainly determined by two factors: the sampling fraction of the calorimeter (relative energy depositions in the absorbers and scintillators) and by the fluctuations of the photoelectron's statistics.

Stochastic term (sampling fraction).

In present design the energy resolution of FHCAL is about (55-60)%/√E which is very good number for the hadron calorimeters. For example, the most hadron calorimeters have the energy resolution in the range (50-120)%/√E (excluding some exotic cases with uranium absorbers, where the stochastic term achieves 35%). As seen, FHCAL has the resolution very close to the lowest limit. The stochastic term can be reduced by using more segmented calorimeter. Taking two times finer sampling (lead 8 mm and scintillator 2 mm thicknesses) the resolution could be improved to 47%/√E (see future ILC project, http://www.sciencedirect.com/science/article/pii/S0168900201008919?np=y&npKey=ea5f167b412e7331bcf5766255efcc77a19c86767bfb297e9792193b01b804d6 .)

This improvement in the resolution would cost two times more scintillator plates, WLS-fibers and readout channels. In addition, small thickness of the scintillator plates results in worse light collection efficiency. According to above reference, the light yield of finely segmented calorimeter is 83 photoelectrons/GeV. This is almost two times lower than in present version of FHCAL (see explanation below). Meanwhile, the light yield is the principal parameter for the detection of the low energies, where the contribution of the electronic noise is essential.

The FHCAL energy resolution can be compared with the spread of the spectator energies at some fixed impact parameter, see Fig.1. According to the simulation, these fluctuations of the spectator energies are about 20% for $\sqrt{s_{NN}}$ = 5 GeV and about 10% $\sqrt{s_{NN}}$ = 11 GeV. Note, that the detected in FHCAL energy (Fig.1) is only about 2% from the initial energy at the face of the calorimeter. At these energies the FHCAL resolution itself is a very few percent and is much below of these 10-20% of the intrinsic energy fluctuations. Therefore, FHCAL resolution cannot affect the accuracy of the centrality measurement.



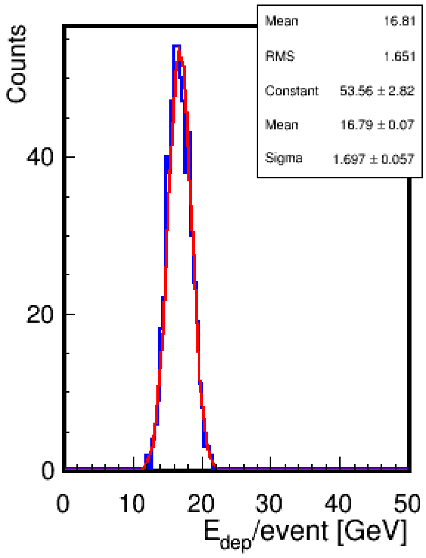


Fig.1 Left - dependence of detected energy on impact parameter for $\sqrt{s_{NN}}$ = 11 GeV and for one arm of FHCAL. The width of the band reflects the intrinsic fluctuation of the spectator energies at some fixed impact parameter. Right – spread of the detected spectator energy at impact parameter b=4.

For the reaction plane measurements, the transverse segmentation of the calorimeter is the most important issue. As shown in FHCAL TDR, the modules with 15x15 cm^2 transverse sizes provide the same angular resolution of the reaction plane as 10x10 cm^2 modules. This is a natural result, because the transverse sizes (as well as the length) of the hadronic cascade are determined by the interaction length, which is 17 cm for the lead. Note, that the most of hadron calorimeters have the module sizes about 20x20 cm^2 to minimize the number of readout channels.

Stochastic term (photoelectron's statistics).

Photoelectron's statistics is another important factor that has an influence at the energy resolution. This factor is especially important for the detection of the low energies, where the Poisson fluctuations of the signal might be principal. For this reason, the light readout in FHCAL modules was provided in the most sophisticated way by WLS-fibers glued in the groves in each scintillator plate. This approach ensures the highest light yield ever achieved in hadron calorimeters. As shown in Fig.2, the light yield is about 30 photoelectrons for the 5 MeV deposited energy in single longitudinal section. 1 GeV proton deposits in FHCAL module about 25 MeV visible energy that corresponds to the signal of about 150 photoelectrons. According to Poisson distribution, this signal has a fluctuation around 8% that is negligibly small comparing to the stochastic term of 55-60%. The comparable (two times worse) light yield was obtained only in the calorimeter prototypes developed for future ILC projects, where the detection of low energy hadrons is planned.

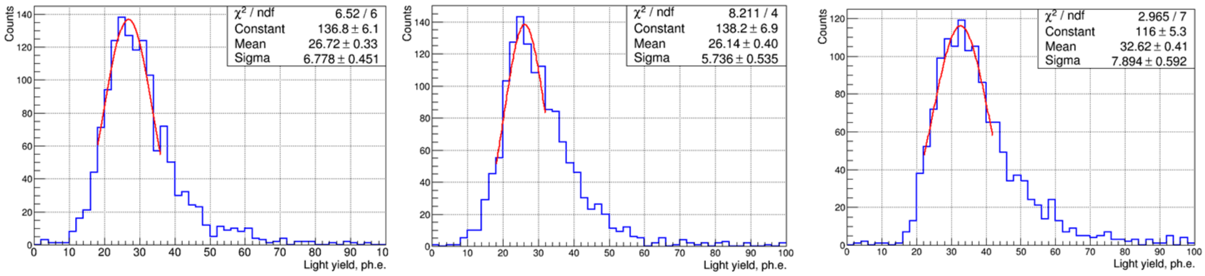


Fig.2 Amplitude spectra in a few longitudinal sections for the cosmic muons crossed the module along axis. Energy deposition in one section corresponds to 5 MeV.

Noise term in energy resolution.

Noise term is especially important for the detection of low energies, where the signal amplitude might be compared with the electronic noise. There are two factors to suppress this noise. First, the use of the photodetectors and electronics with the minimum noise and second, to increase the minimum signal above the electronic noise. In FHCAL both approaches are used. The photodetectors (silicon photomultipliers) have high gain and low intrinsic noise at the level of a very few photoelectrons. From the other side, the minimum signal is about 30 photoelectrons in one longitudinal section for the MIP particle (see Fig.2). Therefore, the minimum signal exceeds the possible electronic noise for a one order. Note, that 300 MeV protons deposit in FHCAL module about 6 MeV visible energy or above 30 photoelectrons signal. This energy might be regarded as a threshold energy for FHCAL module.

Q2.The DAC emphasizes the crucial importance of dedicated measurements of FHCAL parameters in the energy range of the NICA collider (protons from 1 to 6 GeV/c) and urges the team to present a detailed plan of such beam tests ASAP.

We agree with the importance of the beam tests of the FHCAL modules at NICA energies. The only test was done in 2012 with the count-rate dependent silicon photomultipliers. The quality of used SiPMs can affect the obtained parameters of the tested prototype. At the same time, the obtained experimental data show good agreement with the MC simulation. For example, Fig.3.and Fig.4 present the experimental and MC energy spectra in each longitudinal section for proton momenta 2 and 6 GeV/c, respectively. One can see the same behavior of the amplitude spectra and of the longitudinal profiles in experimental and simulation cases. The obtained experimental energy resolutions are rather close to the expected values. The tests confirmed the reliability of the detection of the hadrons with low energies.

Meanwhile, the 2012 tests were done with a single module and the lateral shower leakage might essentially affect the energy resolution. The front-end and readout electronics were quite different from the planned ones in FHCAL. Now the newest photodetectors Hamamatsu MPPCs with high dynamic range are available at the market. The design of the FHCAL modules was essentially improved with the light yield of a factor 3 higher than in the earlier prototype. All these factors require additional tests at NICA energy beam.

At present, the available beam lines are restricted by T10 line at CERN and by the beam at BM@N. T10 line has a very tight user's schedule overbooked for full 2017 period. Our group reserved 2 weeks in September 2017 for the test of the calorimeter supermodule of 9 modules. The modules have the same structure and the same front-end and readout electronics as planned at FHCAL. The only difference is the transverse sizes of the modules 20x20 cm^2 that are slightly larger of 15x15 cm^2 in FHCAL case. This difference would not affect the performance of the calorimeter.

Another possibility is the use of 9 FHCAL modules at BM@N experiment in October-November 2017, where the ion beam would be available. As follows from above considerations, new experimental data would be available this fall only.

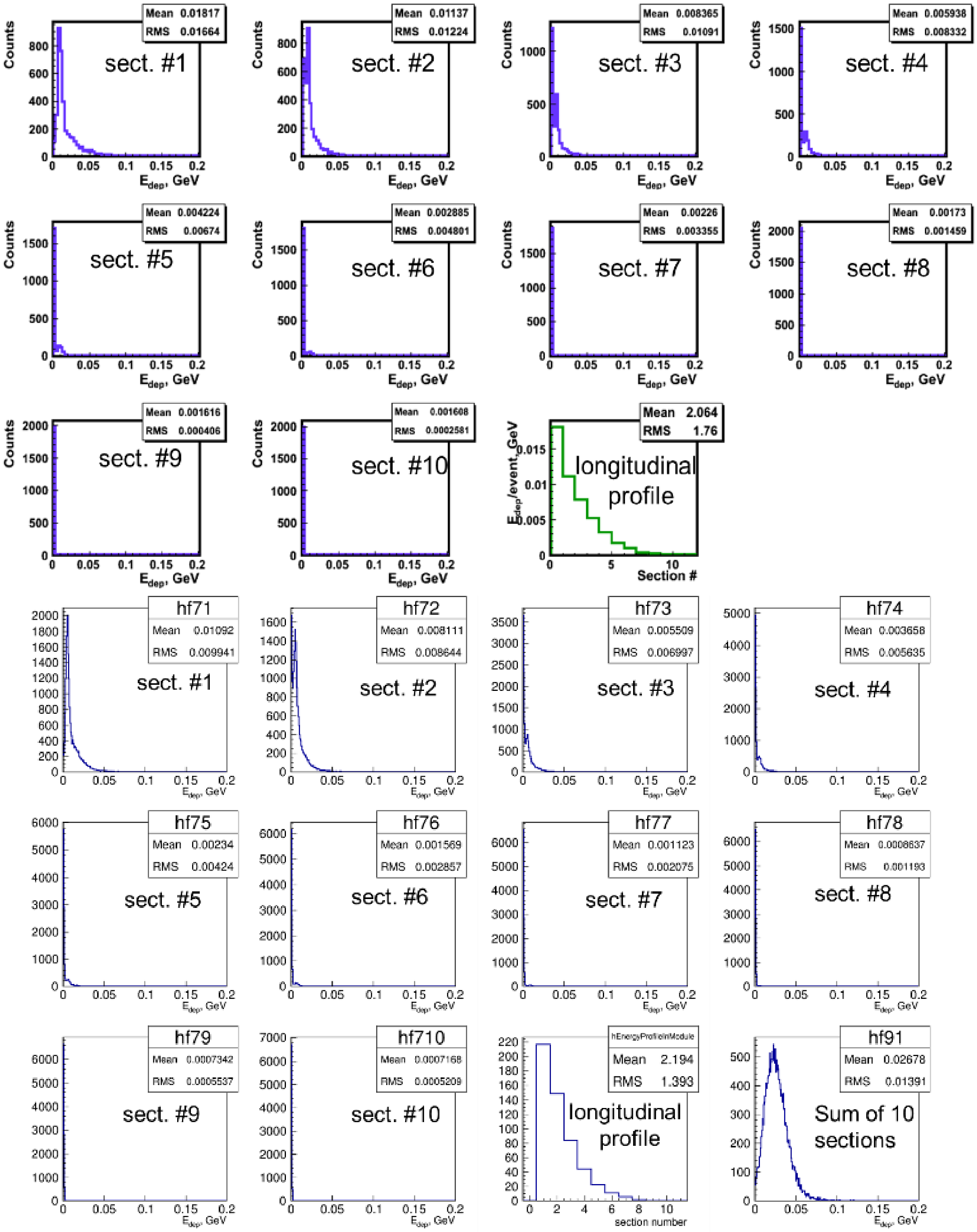


Fig.3. Energy depositions in different sections for protons with p=2 GeV/c. Up panel – experimental data, down panel - MC simulation. The shower profiles are average energy deposition in the corresponding longitudinal sections.

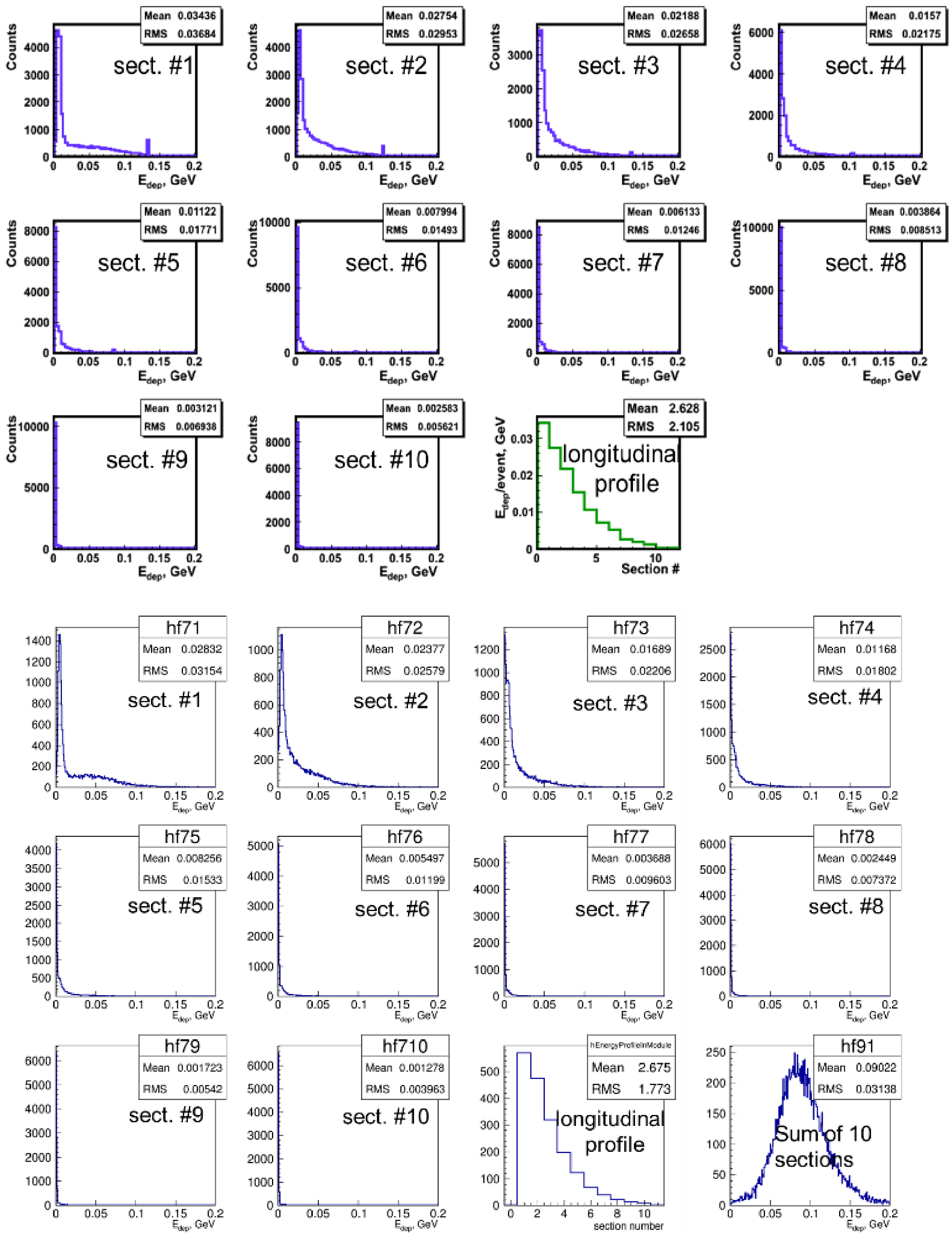


Fig.4 Energy depositions in different sections for protons with p=6 GeV/c. Up panel – experimental data, down panel - MC simulation. The shower profiles are average energy deposition in the longitudinal sections.

The next two questions are tightly connected and will be considered together.

Q3.Can FHCAL longitudinal segmentation improve MPD performance in event centrality selection? In particular, can the energy deposit in the first FHCAL section (maybe modified?) be used in the MPD trigger?

Q4.The DAC recommends the team to look into the possibility of using the signal from the first FHCAL section separately from the total energy deposit in order to get insight into the electromagnetic component in the FHCAL acceptance.

At present, the first section of FHCAL modules has the same segmentation as other ones. This section has 16 radiation lengths and might be regarded as a crude electromagnetic calorimeter with the energy resolution of about 35%/√E(GeV). In principle, the design of FHCAL modules allows the construction of more segmented first section with the 12 layers of the absorber and with the full thickness $12X_0$. To check the performance of such ECAL, the response to e.-m. and hadron components was studied in the simulation. Fig.5 presents the energy depositions in ECAL for to e.-m. and hadron components separately and ratios of these components on event-by-event basis. Left 4 plots are for beam energy $\sqrt{s_{NN}}$ = 5 GeV and right 4 plots - for $\sqrt{s_{NN}}$ = 11 GeV. One can see that e.-m. component alone can be used for the selection of the centrality because of the monotonic dependence on the impact parameter. Unfortunately, this component is only a small (about 20%-30%) fraction of the full energy deposited in first section. This is visible from the ratio of two components. As a result, the dependence of the full energy deposition on the impact parameter practically repeats the behavior of the hadron component. Note, that strong impact of hadron energy is also visible in Fig.3-4, where the longitudinal profile of the hadron shower has a maximum in first section.

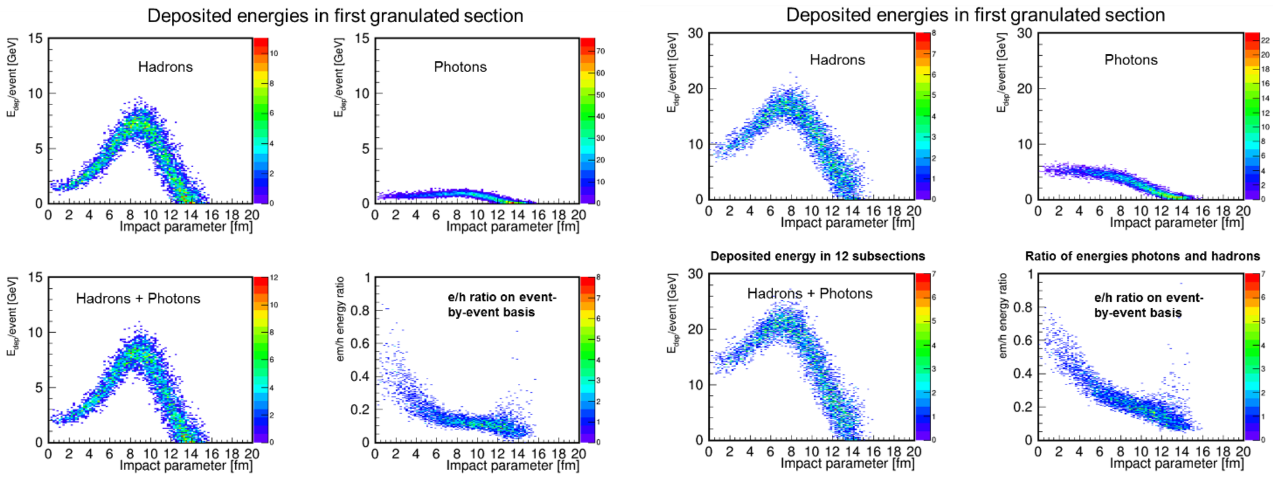


Fig.5 Dependence of energy depositions in first finely segmented sections on the impact parameter for hadrons, e.-m. particles and all particles. Also, the ratios of the electromagnetic and hadron energies on event-by-event basis are shown. Left panel – for for $\sqrt{s_{NN}}$ = 5 GeV and right panel - for $\sqrt{s_{NN}}$ = 11 GeV.

Q5.On slide 7, please plot the energy asymmetry (which is the measured quantity) vs the impact parameter and study the energy asymmetry vs position of the collision vertex along the z-axis

These plots are presented in Fig.6. Here the default distribution of the collision vertex in MPDRoot was used.

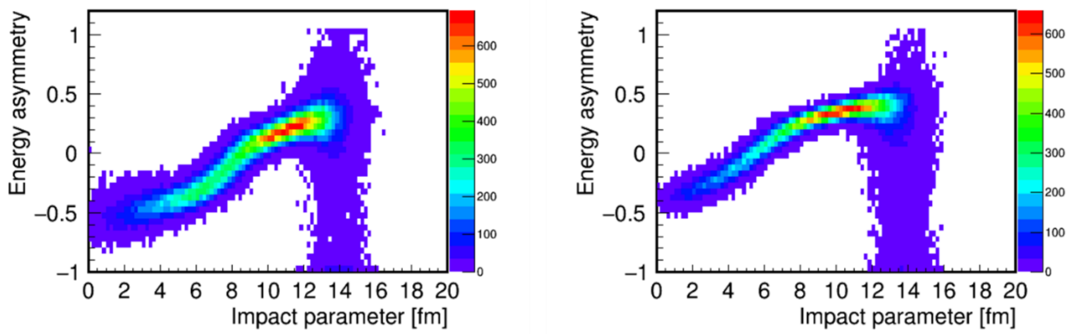


Fig.6 Dependence of the energy asymmetry on the impact parameter for $\sqrt{s_{NN}}$ = 5 GeV (left), and for $\sqrt{s_{NN}}$ = 11 GeV (right).

Conclusion.

In this note, we answered the DAC expert's question on the performance of FHCAL. It was shown that the calorimeter has an energy resolution rather close to the lowest limit for the hadron calorimeters. High light yield of the FHCAL modules ensures the reliable detection of the hadrons with low energy. The threshold of the detected energies can be as low as 300 MeV for the protons that deposit full energy in first section.

The time schedule of the beam tests is discussed. The earliest beam time is the fall 2017, when the tests at T10 line at CERN and at BM@M experiment are scheduled.

The simulation of the first finely segmented section with the length of $12X_0$ was done. As shown, the hadron component dominates here, while the e.-m. component is rather small and is only about 20-30% from the total energy deposition. This feature do not allow the use of the first section for the centrality selection. According to these results, the fine segmentation of first section does not help in the improvement of the FHCAL performance. Moreover, construction of finely segmented first section would spoil the performance of the hadron calorimeter itself because about 20-30% of the hadron showers would deposit energy in the non-compensated part.

We strongly appreciate other question for further understanding of the FHCAL performance.