Performance of shashlyk calorimeter read out by SiPMs with high pixel density

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The matrix of 3×3 modules of the EM calorimeter ECAL0 (COMPASS II) read out by MPPC S12572-10P SiPM with the pixel density of 10^4 mm^{-2} and an area of 3×3 mm is studied in the range of electron energies 1-30 GeV. It is observed that the MPPC has additional response nonlinearity and a significantly smaller dynamic range of output signals than expected. The mechanism of the effect based on the influence of parasitic capacitance between pixels on the pixel gain is proposed. The energy resolution of the calorimeter is measured to be $\sigma_E/E = 7.1\%/\sqrt{E}(1 + 0.06/E) \oplus 1.4\% E^{0.25}$.

1. Introduction

One of the main tasks objectives of the COMPASS II experiment [1] is the study of generalized parton distributions in the reaction of Deep-Virtual Compton Scattering (DVCS) of muons $\mu p \rightarrow \mu p \gamma$. A new-generation electromagnetic calorimeter ECAL0 was developed at the DLNP, JINR, to detect photons with large angles in the DVCS reaction.

ECAL0 is a shashlyk-type sandwich with high granularity (cell size 4×4 cm) consisting of 194 modules. A calorimeter module (3×3 cells) consists of 109 alternating layers of lead (0.8 mm) and a polystyrene scintillator (1.5 mm) and a nine-channel photodetector unit with MPPC S12572-10P silicon photomultipliers (SiPM) (Hamamatsu) with a record high density of surface pixels 10^4 mm^{-2} and an area of 3×3 mm. The prototype calorimeter module design is described in [2, 3].

2. Response of MPPC S12572-010P SiPM

The matrix of 3×3 modules (81 cells) was studies with test beams at CERN in the range of electron energies 1-30 GeV. Figure. 1 shows the dependence of the calorimeter cell response on the electron beam energy and the energy absorbed in the cell, expressed in term of the average number of electron-hole pairs produced in the MPPC. The response is represented by the number of fired pixels of the MPPC $N_{\text{fired}} = \bar{Q}/Q_1$, where $\bar{Q}$ is the average output charge of the MPPC, $Q_1 = e\, G_{\text{pix0}}$, where e is the electron charge, end G_{pix0} is the pixel gain measured at detection of single photons by MPPC.

The SiPM response function is actually nonlinear due to the finite number of pixels, which leads to saturation of the response at high light levels. Under the assumption that the pixels are independent microcounters of photons at the homogeneous illumination of the SiPM surface, the number of fired pixels is determined by the expression

$$N_{\text{fired}} = N_0\left(1 - e^{\frac{-\mu}{N_0}}\right), \quad (1)$$

where N_0 is the total number of pixels, μ is the number of electron-hole pairs produced in the SiPM, $\mu = N_{\text{ph}}\, PDE$, where N_{ph} is the number of incident photons, and PDE is the detection efficiency.
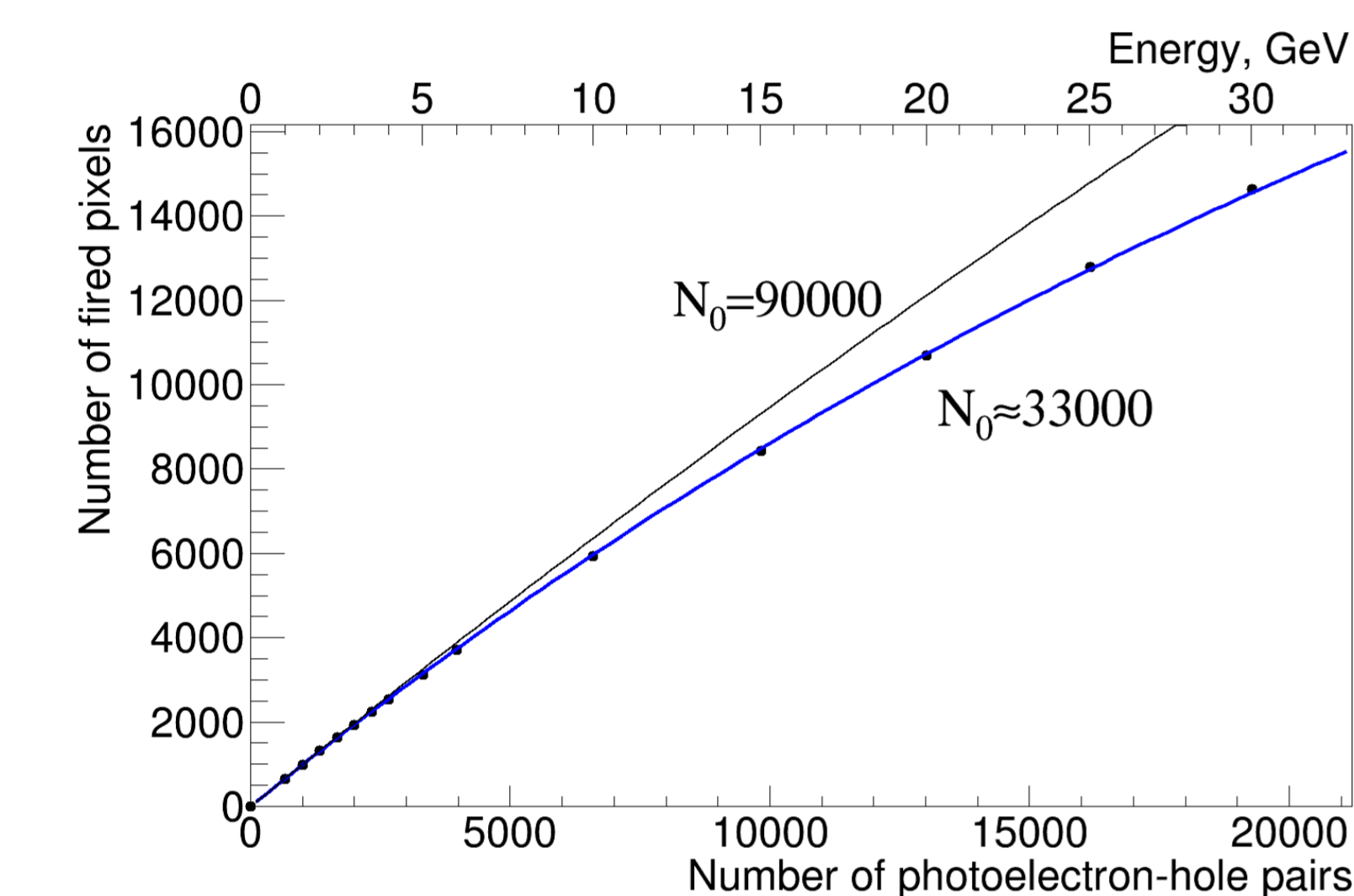

Fig. 1. The dependence of the response of the ECAL0 cell read out by the MPPC S12572-10P on the electron beam energy, and the average number of the electron-hole pairs produced in the MPPC.
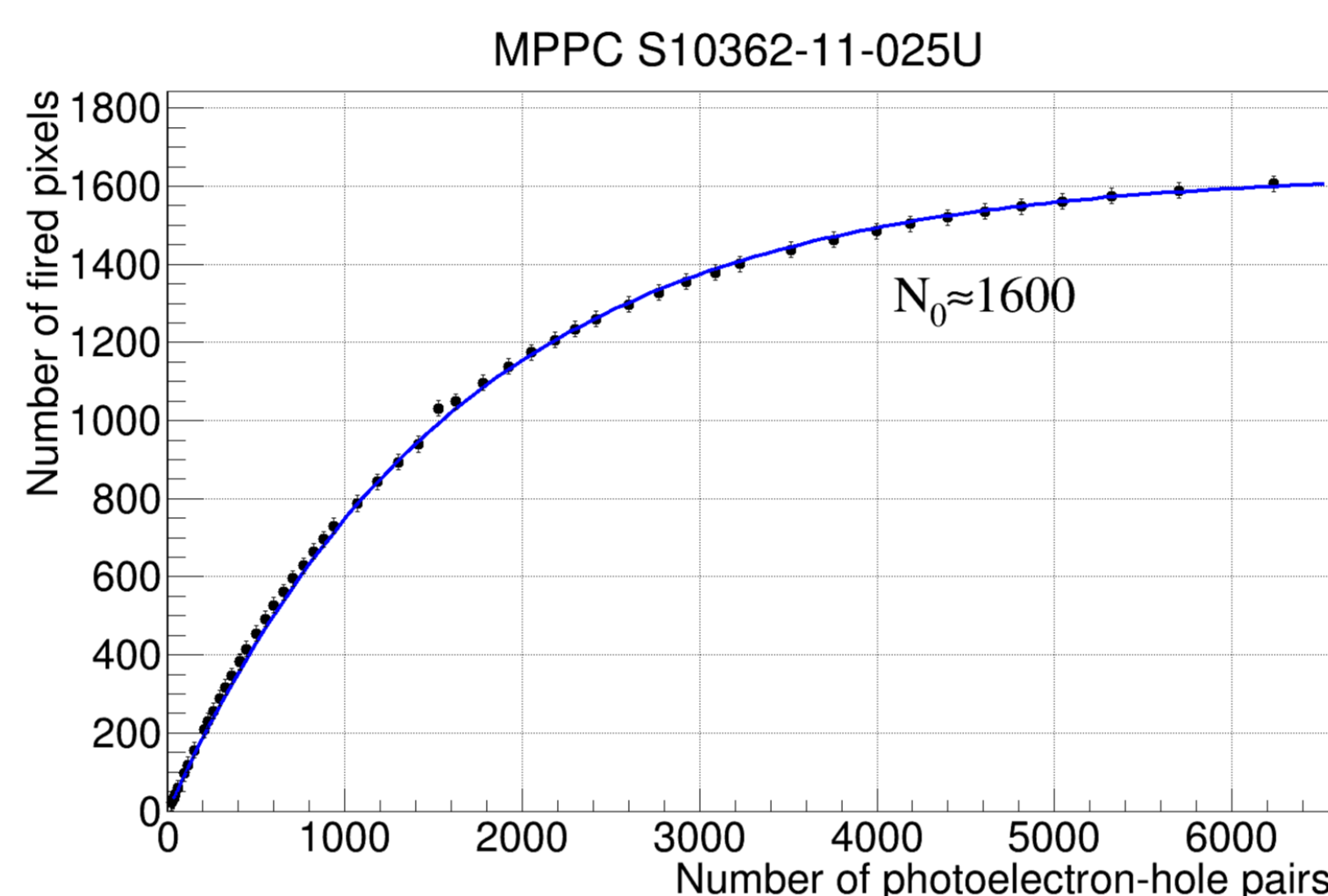

Fig. 2. The response function of the MPPC S10362-11-25U with a pixel pitch of 25 μm, size of 1×1 mm, and total number of pixels $N_0 = 1600$ exposed to light from a laser with a pulse width of 40 ps.
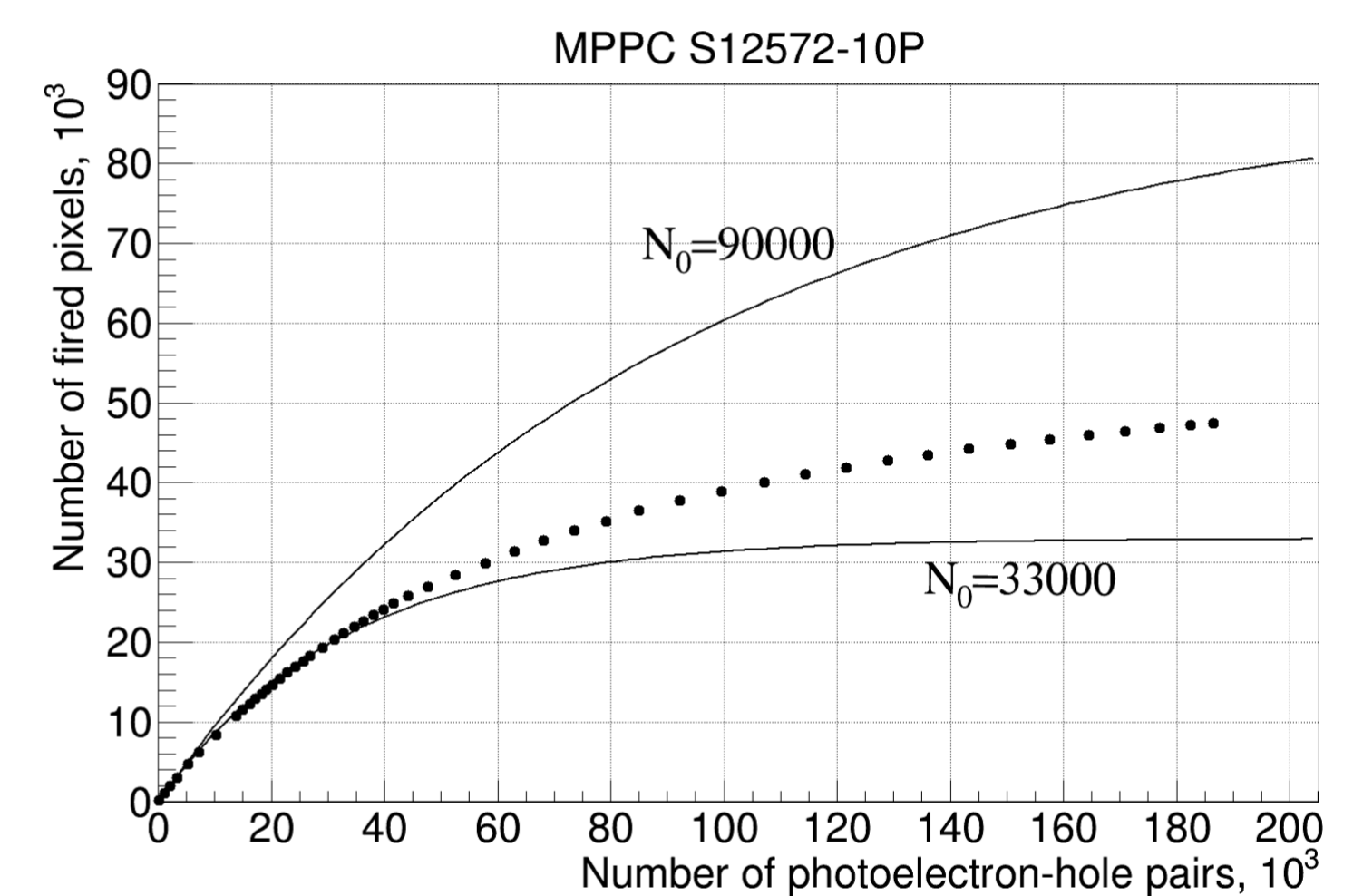

Fig. 3. The response of the MPPC S12572-10P with a total number of pixels $N_0 = 90000$ exposed to light from a laser with a pulse width of 40 ps. For comparison, theoretical functions (1) with $N_0 = 90000$ and $N_0 = 33000$ are shown.

The MPPC S12572-010P used in ECAL0 have $N_0 = 90000$ pixels, but approximation of the data by theoretical response function (1) shows that the total number of pixels is $N_0 \approx 33000$. For comparison, Fig. 1 shows the theoretical response function with $N_0 = 90000$. A detailed study of the observed effect was carried out using a laser with a pulse width of 40 ps. The responses of MPPC S12572-010P, S12572-015C, and S10362-11-25U with the pixel pitch of 10, 15, and 25 μm respectively were measured.
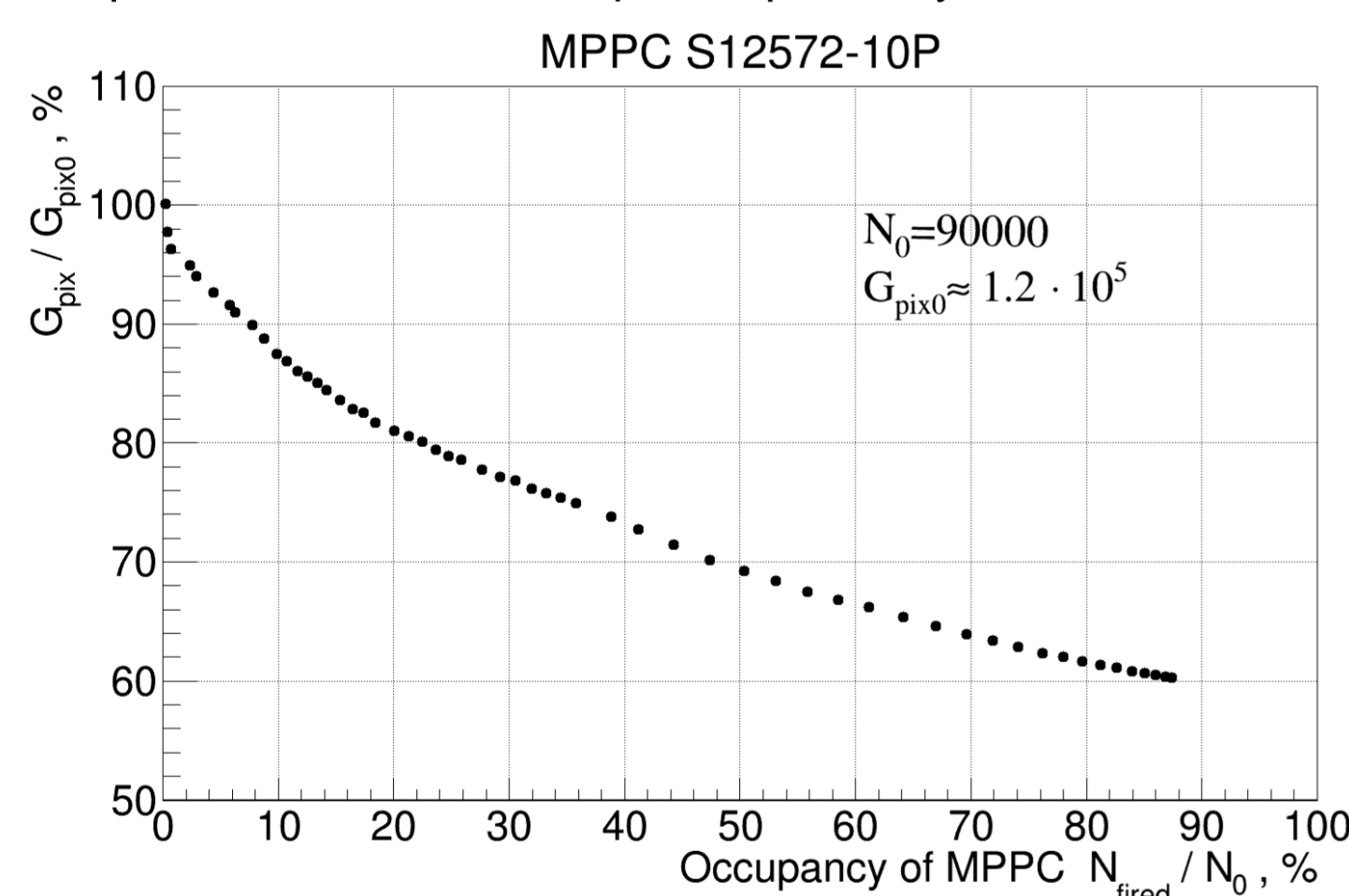

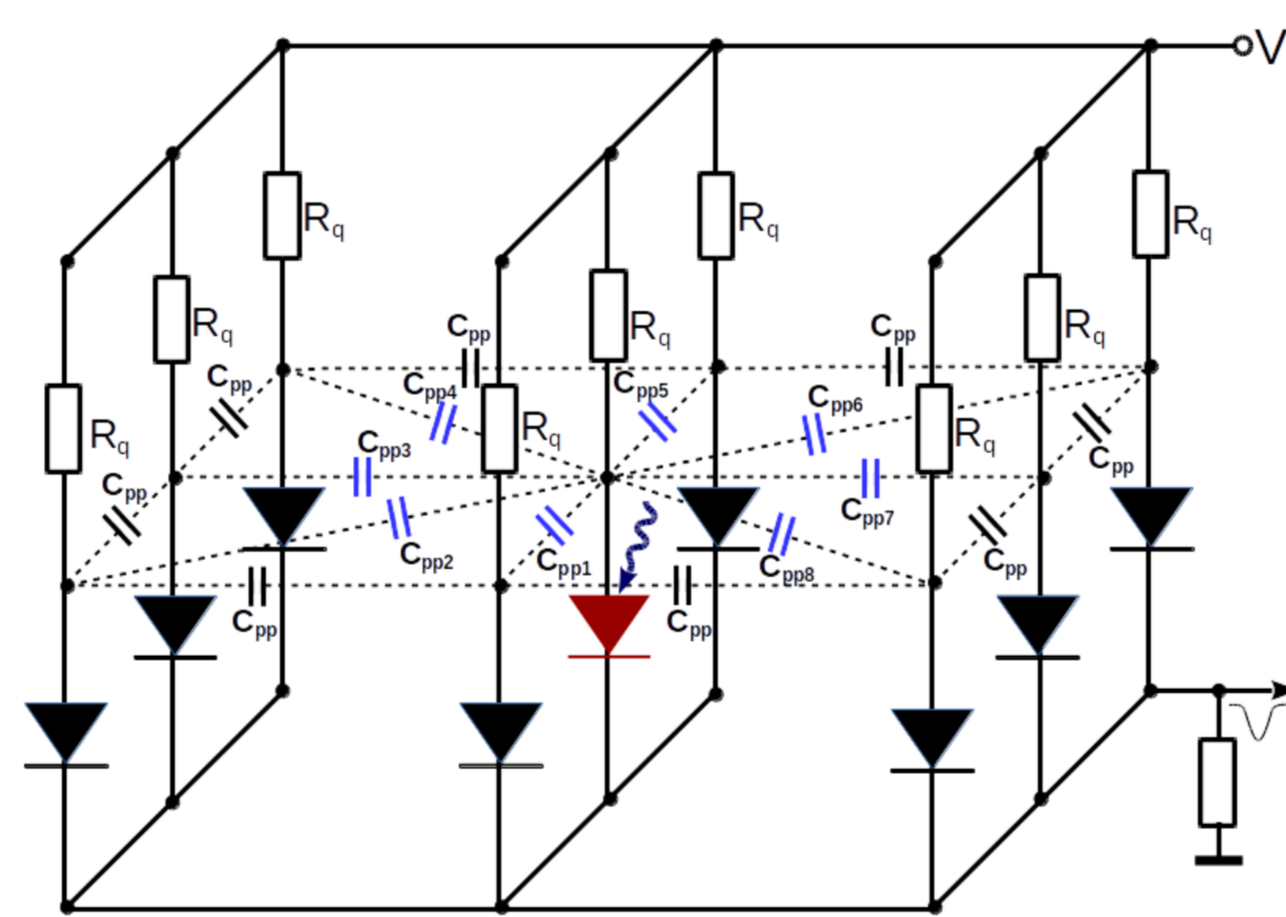Fig. 4. The dependence of the average MPPC S12572-10P gain on the occupancy of pixels.

Fig. 5. A simplified equivalent circuit of the MPPC S12572-010 and S12572-015 with high pixel density.

$$\frac{\sigma_E}{E} = \frac{7.1\%}{\sqrt{E}}\left(1 + \frac{0.06}{E}\right) \oplus 1.4\% E^{0.25}$$
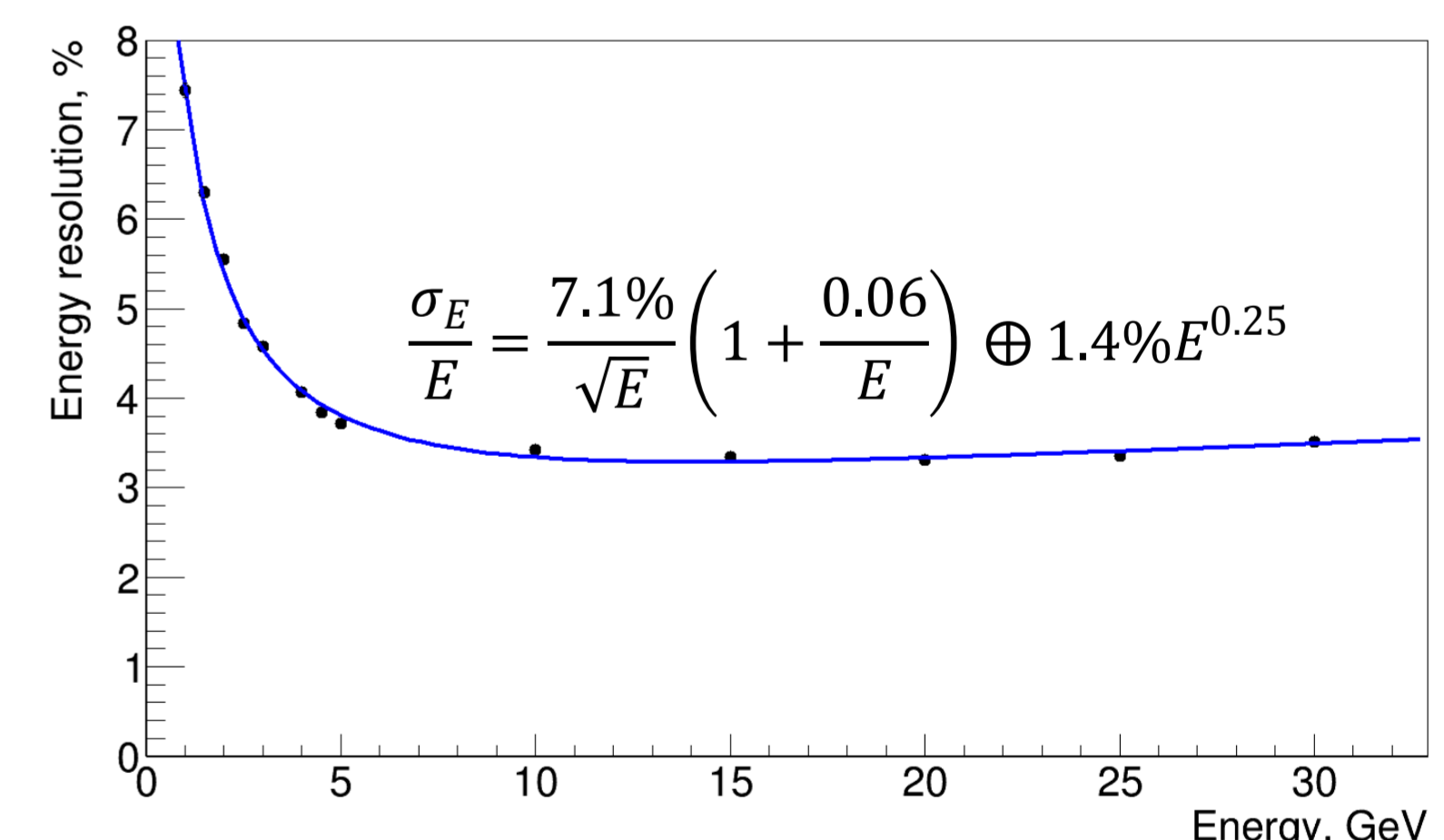
Fig. 6. The dependence of the energy resolution of the ECAL0 3×3 module matrix read out by the MPPC S12572-10P on the electron beam energy.

The theoretical response function well approximates the experimental data obtained with MPPC S10362-11-25U (Fig. 2), but absolutely does not describe the data from MPPC S12572-010P and S12572-015C.

The response of the MPPC S12572-10P measured in a large range of light signals and the theoretical functions with $N_0 = 90000$ and $N_0 = 33000$ are shown in Fig. 3. As can be seen in the figure, the response is much smaller than the theoretical function. Such a decrease in the dynamic range is associated with a decrease in the gain factor due to occupancy of MPPC pixels $D = N_{\text{fired}}/N_0$. Dividing the measured response by the theoretical one, we obtain the dependence of the average pixel gain $\overline{G}_{\text{pix}}$ on the pixel occupancy D (Fig. 4). At full illumination of the MPPC, the average pixel gain decreases by more than 40%.

Let us consider the mechanism of the observed effect based on the effect of parasitic capacitance between the pixels C_{pp} on the pixel gain. A simplified equivalent MPPC circuit is shown in Fig. 5. When MPPC detects a single photon and one pixel fires, two processes occur. The first is the capacity discharge of the fired pixel, which creates a potential difference on the parasitic capacitances C_{ppi} with eight adjacent pixels, and the second is the charge C_{ppi} from the external power source. Thus, the effective capacity of the fired pixel and consequently the gain increase.

The pixel gain factor at the detection of single photons by the MPPC is $G_{\text{pix0}} = C_{\text{pix0}} \Delta V/e$, where C_{pix0} is the effective capacitance of the pixel, and ΔV is the overvoltage. The effective capacitance of a pixel is the sum of the real capacitance of a pixel C_{pixr} and eight effective parasitic capacitances $C_{\text{pix0}} = C_{\text{pixr}} + \sum_{i=1}^{8} C_{\text{ppi}}$

With increasing light intensity, when two adjacent pixels are fire, their parasitic capacitance is not charged, because, when the adjacent pixels are simultaneously discharged, no potential difference is created at their parasitic capacitance. Therefore, the effective capacities and the gain of these two pixels are reduced.

The effective capacity of a pixel when one or more adjacent pixels fired can be expressed as $C_{\text{pix}} = C_{\text{pixr}} + \sum_{i=1}^{8} C_{\text{ppi}} - \sum_{i=1}^{n} C_{\text{ppi}}$, where n = 1- 8 is the number of the fired neighboring pixels. Therefore, as the pixel occupancy D increases, the average pixel gain of the MPPC S12572-10P decreases, and at full illumination it becomes minimal $G_{\text{pixm}} = C_{\text{pixr}} \Delta V/e$.

Thus, the high-pixel-density SiPM MPPC S12572-10 (S12572-015) has additional response nonlinearity and a significantly smaller dynamic range of output signals than expected.

3. Energy resolution of the calorimeter ECAL0

The length of the calorimeter ECAL0 module is only 15.2 X_0, which is insufficient for the total absorption of the electron energy in the studied range 1-30 GeV. At energies above 10 GeV, the signal spectra become asymmetric due to leakages of shower energy, and therefore they were approximated by the logarithmic Gaussian distribution [4].

The energy resolution of the calorimeter (Fig. 6) was parametrized by the formula $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}}\left(1 + \frac{m}{E}\right) \oplus cE^d$ where a is a stochastic term, and m is the parameter associated with the ADC registration threshold. The ECAL0 has a high granularity, so the ADC registration threshold degrades the energy resolution, especially at low energies. The last term in the formula determines the contribution of energy leakages, etc.

References
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