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Method for calibration of the tile HCAL with silicon photomultiplier as a photodetector (proposal)

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1 Introduction

The physics programme at TESLA mandates a dense calorimeter with a very high granularity in order to separate efficiently the contribution of the different particles in a jet[1].

The silicon photomultiplier (SiPM) found to be a very promising photodetector to meet such requirements and competitive with other types of photodetectors for tile-fiber HCAL [2].

Full calibration of calorimeters requires complicated calibration of about 200 000 cells [3]. Automatic and reliable method is needed to calibrate cells $'in\ situ'$ and also in different stage of calorimeter production and assembling.

2 SiPM transfer performance

The SiPM is a multipixel photodiode with a number of microcells (pixels) with common output load. Each pixel has two states (fired and idle) and operates as a binary counter while entire SiPM works like an analogue device.

Two general and well-defined parameters describe the behavior of SiPM - the total number of pixels and average cross-talk coefficient.

Assume the fraction of cross-talk is proportional to the fraction of fired pixels and proportional to the fraction of idle pixels. For this model the SiPM transfer function is:

$$y = (1 - S(k,x))/(1 + k * S(k,x)), \qquad S(k,x) = e^{-(1+k)x} \tag{1}$$

where: $x = n_{phe}/N$, y=$< n_{fired} > /N$

n_{phe} is the number of initial photoelectrons, which can fire the SiPM pixels ($n_{phe} = n_\gamma * efficiency$, where n_γ is the number of photons coming to SiPM);

N is total number of SiPM pixels;

$< n_{fired} >$ is average number of fired pixels;

k is crosstalk coefficient.

The inverse function is:

$$x = \frac{1}{1+k} * ln\left(\frac{1+k*y}{1-y}\right) \tag{2}$$

It was found that the crosstalk coefficient varies in the range of 0.2 to 0.8 (fig.1). Crosstalk have been measured with low LED flash to see single pixel response. Crosstalk value is defined as enhancement of real mean value of fired pixels over the Poisson mean value obtained from the fraction of events without fired pixels.

Function (1) is in good agreement with experimental measurements [4]. Sensitivity of SiPM response to deviation of total number of SiPM pixels and to deviation of crosstalk value are respectively:

$$\frac{\Delta n_{fired}}{n_{fired}} \Big/ \frac{\Delta N}{N} = 1 - \frac{x*S*(1+k)^2}{(1-S)(1+k*S)}, \qquad \frac{\Delta n_{fired}}{n_{fired}} / \Delta k = \frac{x*S^2}{1+k*S}$$

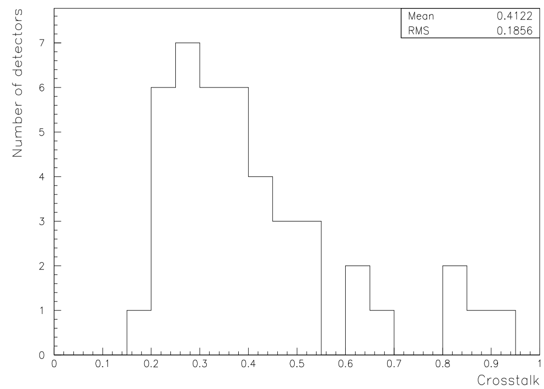

Figure 1: Distribution of SiPM crosstalk value.

Sensitivity of SiPM response to deviation of total number of pixels in SiPM and to deviation of crosstalk value are shown on fig.2 at the left and right plot respectively.

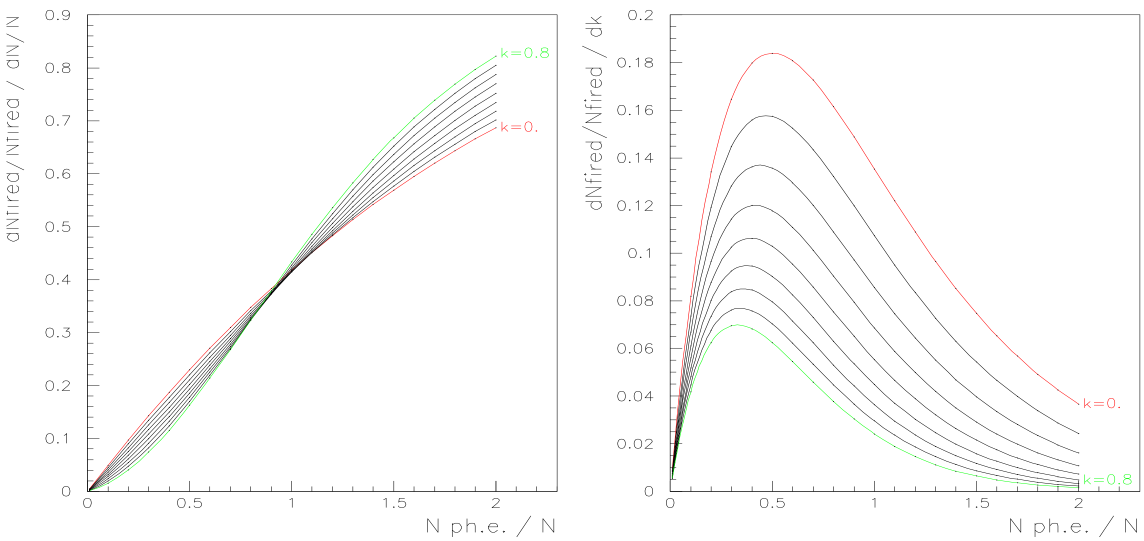

Figure 2: Sensitivity of SiPM response to deviation of total number of SiPM pixels (left plot) and to deviation of crosstalk value (right plot) as a function of $x = n_{phe}/N$

Sensitivity of SiPM response to deviation of total number of pixels is about 0.4 in wide range of crosstalk value, it contributes to deviation of the slope with factor of 0.4 while contribution to nonlinearity is small.

Contribution of the crosstalk deviation to deviation of SiPM response is more complicated, it contributes to nonlinearity rather than to the slope in wide dynamic range. But in dynamic range of half the total number of pixels, it contributes to the slope value rather than to the nonlinearity similar to the contribution of deviation of the total number of pixels.

3 MC simulation

MC simulation was performed in order to study the influence of deviation of two SiPM parameters - total number of pixels and crosstalk value, on reconstruction of electromagnetic shower energy deposited in tiles. In order to see clear influence of deviation of SiPM transfer function, the deviation of all other components supposed to be zero (e.g. equal response of all tiles, no ADC nonlinearity, etc.).

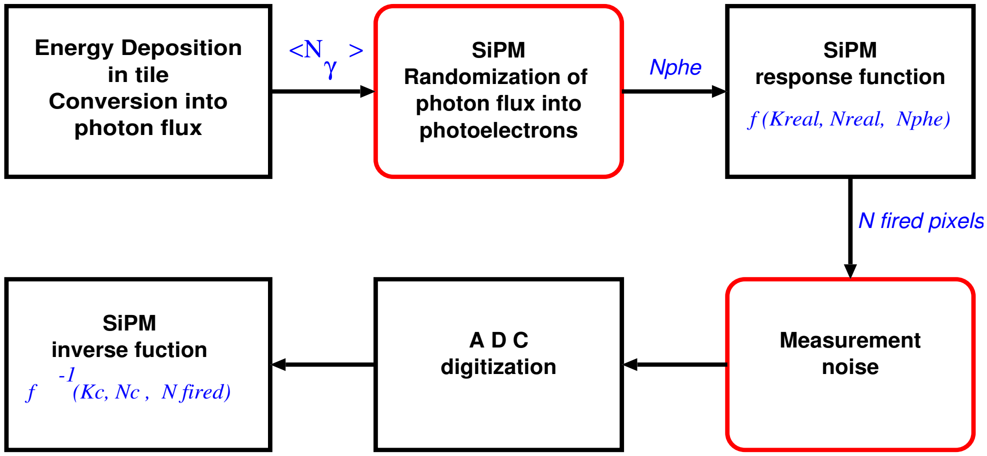

Figure 3: Simulation scheme

The simulation is done with GEANT3, the simulation scheme is shown on fig.3. 17 sandwich layers are included in simulation chain. One layer consists of: 20 mm iron absorber, 1mm + 2mm Aluminium cassette top and bottom covers, 5x5x0.5 cm^3 scintillator tiles. Impact point of initial positrons is smeared uniformly over the tile in the first layer. Simulation is done for 10 values of initial energy of positrons, from 1 Gev to 10 Gev with the step of 1 Gev.

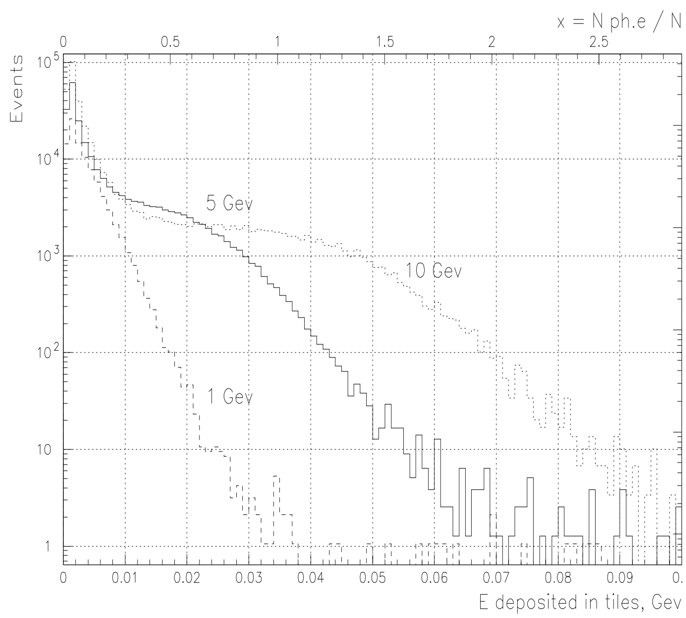

Figure 4: Distribution of energy deposited in tiles and corresponded number of photoelectrons produced in SiPM for initial value of positron energy 1, 5 and 10 Gev. MIP signal corresponds to x = 0.025

SiPM is included as a photodetector. Real values of SiPM parameters - total number of pixels N_{real} and crosstalk coefficient k_{real}, are used for simulation of SiPM response. They are deviated from the nominal values k_c and N_c which supposed to be the nominal ones and which are used for reconstruction of deposited energy. Distribution of energy deposited in tiles and corresponded number of photoelectrons produced in SiPM are shown on fig.5 for different values of positron initial energy. MIP signal corresponds to 25 photoelectrons in SiPM.

The nominal value of parameters are $N_c = 1024$ pixels and $k_c = 0.4$. Deviation of parameters' real values from nominal ones are: down to -30% for total number of pixels and ± 0.4 for crosstalk coefficient.

The results of simulation are shown on fig.5. In energy range of 10 Gev the slope of reconstructed shower energy curve deviates in the range of -0.3 to 0.2 of nominal one while nonlinearity deviates between -2.5 and 7.5%. No valuable influence is observed on resolution curve.

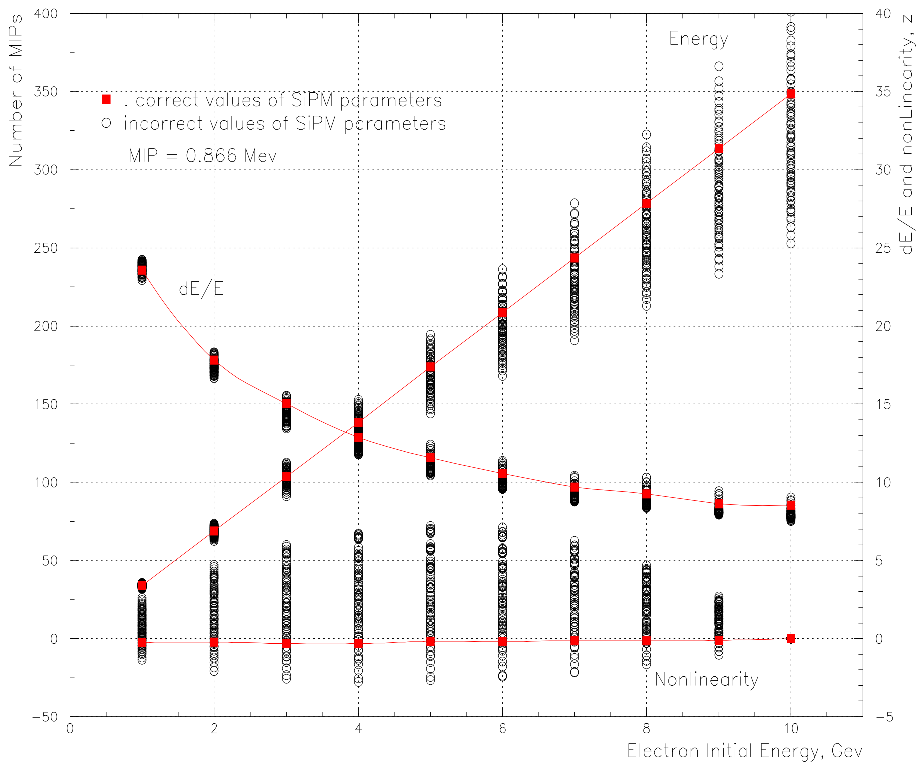

Figure 5: Influence of SiPM parameters deviation on shower visible energy reconstruction. Red curves correspond to the case when the nominal values of SiPM parameters which are used for energy reconstruction are equal to the real ones (i.e. $N_{real} = N_c$ and $k_{real} = k_c$).

Deviation of the slope of reconstructed energy curve of about 50% is too large and periodical online calibration 'in situ' is needed to define (survey) the real values of parameters k_c and N_c of SiPM function which are used for deposited energy reconstruction.

4 Calibration method

The method [5] allows to reconstruct monotonic function and hence applicable for reconstruction of the SiPM function. It is based on producing of 3 test signals. The apriory knowledge of the values of test signals is not required. No strong restrictions are imposed on accuracy and stability of test signals. Only one requirement is imposed - the value of superposition of two test signals have to be the sum of their individual values. The superposition error (but not deviation of the test signals) determines the accuracy of calibration.

In our particular case one should produce 3 light signals - two independent amplitudes x_1 and x_2 and the third signal is superposition (sum) of the two first $x_3 = x_1 + x_2$. The accuracy of fulfilling this equation determines the accuracy of calibration. (No strong requirement on possible nonlinearity of tile-fiber response due to it is included into overall transfer function.) Two possibility are available - one LED with necessary linearity, and two LEDs with any nonlinearity and instability. The second way is easily implemented and much more reliable for long term operation in changeable conditions.

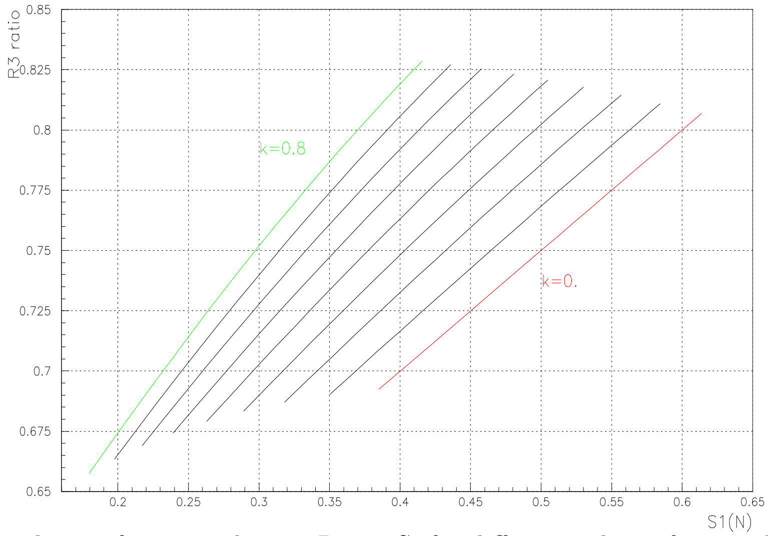

Figure 6: Dependence of measured ratio R_3 on S_1 for different values of crosstalk $0 \leq k \leq 0.8$

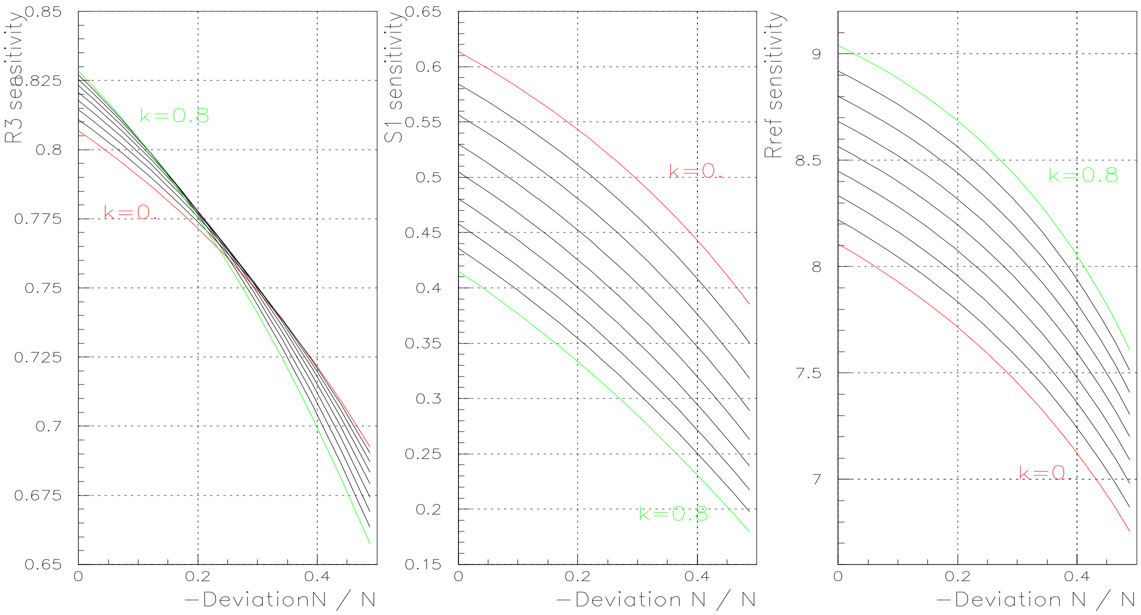

Figure 7: Sensitivity of measured ratios R_3 (left plot) R^{ref} (right plot) and S_1 value (middle) to deviation of the total number of pixels in SiPM for different values of crosstalk $0 \leq k \leq 0.8$

Let us assume at first for the simplicity that there is no nonlinearity in a tile-fiber system and so conversion nonlinearity is determined by SiPM transfer function. Thus one can obtain three equations for measured values of 3 test signals:

$$y^m_{1,2} = C^m * N * (1 - S_{1,2})/(1 + k * S_{1,2}), \qquad S_{1,2} = exp(-(1 + k) * x_{1,2});$$

$$y^m_3 = C^m * N * (1 - S_1 * S_2)/(1 + k * S_1 * S_2), \qquad \text{due to} \qquad S(k, x_1 + x_2) = S_1 * S_2$$

where: C^m is overall conversion coefficient which is equal to the product of all conversion coefficients in entire measuring chain.

We need also the reference signal $x^{ref} = n^{ref}/N$ for absolute calibration in number of fired pixels:

$$y^m_{ref} = C^m * N * (1 - S^{ref})/(1 + k * S^{ref}), \qquad S^{ref} = exp(-(1 + k) * x^{ref})$$

To exclude the value of the product $C^m * N$ one can divide $y^m_{1,2,3}$ and y^m_{ref} to each other: $D = (y^m_2 - y^m_1)/(y^m_2 + y^m_1)$, $R_3 = y^m_3/(y^m_2 + y^m_1)$, $R^{ref} = y^m_1/y^m_{ref}$. Sensitivity of ratios R_3, R^{ref} to deviation of the total number of pixels in SiPM for different values of crosstalk is plotted on fig.7. For simplicity let's at first assume $D = 0$. One can obtain equation for $S_1 = exp(-(1+k)x_1)$ determination: $R_3 = 0.5(1 + (1+k) * S_1/(1 + k * S_1^2))$. This curve is depicted on fig.6 for different values of crosstalk. Then one can calculate the total number of SIPM pixels: $N = \frac{n^{ref}}{1+k} * ln(\frac{A+k}{A-1})$, $A = (1 - S_1)/(1 + k * S_1)$

Calibration error in determination of N is $\frac{\Delta N}{N} = \delta_{ref} + (1 - 0.5 * B)\delta_1 + 0.5 * B\delta_2 + B * \delta_3$, $B = 0.5(1 + k)(1 + S_1)(1 + k * S_1^2)/(1 - S_1)/(1 - k * S_1^2)$, where: $\delta_{1,2,3}$ and δ_{ref} are relative measurement errors of $y^m_{1,2,3}$ and y^m_{ref} respectively. Dependence of these relative errors on value of test signals x_1 and x_2 for different value of crosstalk are shown on fig.8: the overall error (right plot) and contribution factors of δ_1 and δ_3 errors into overall error (left plot), contribution factor of δ_2 is 0.5 of δ_3. Due to δ_1, δ_2, δ_3 are statistical uncertainty of mean values, their magnitudes of 1% can be achieved. The same value of uncertainty can be achieved for δ_{ref} for number of photoelectrons about 50 [2]. The behaviour of calibration error versus values of test signals is shown on fig.8. It is obtained in assumption of $\delta_1 = \delta_2 = \delta_3 = 1\%$ and $\delta_{ref} = 2\%$ (the latter include also the error of association the reference peak with physical signal (e.g. MIP) in order to have absolute energy calibration). According to the error curve on fig.8 in order to achieve calibration accuracy of 6%, the magnitude of test signals have to be in the range of 500-700 photoelectrons.

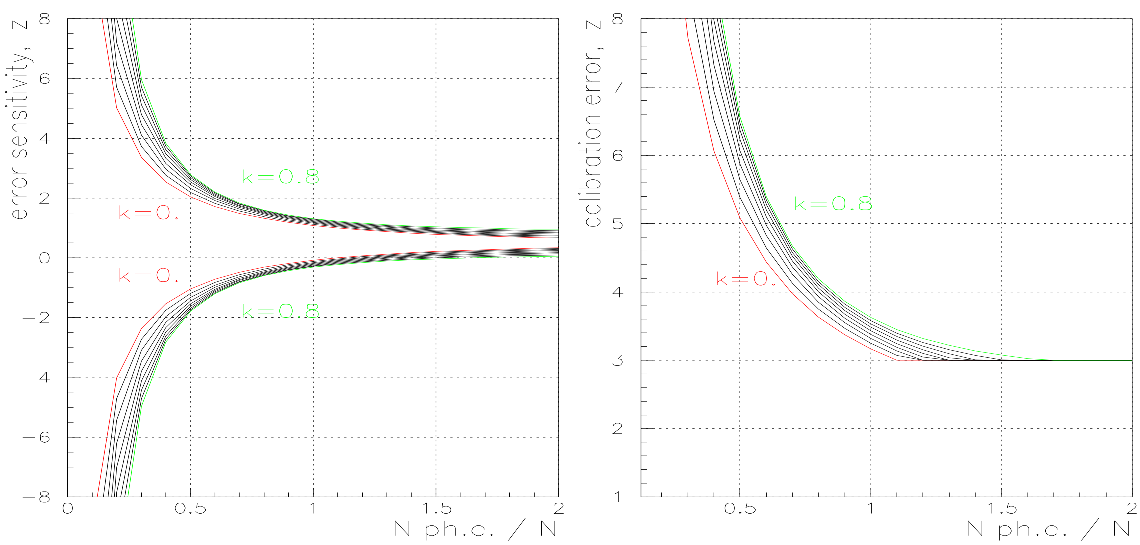

Figure 8: Dependence of errors on value of test signals x_1 and x_2 for different value of crosstalk $0 \leq k \leq 0.8$: the overall calibration error (right plot) and contribution factor of relative errors δ_1 and δ_3 into overall calibration error (the bottom and the top curves of left plot respectively), contribution factor of δ_2 is 0.5 of δ_3

5 Conclusion

SiPM transfer function can be operatively calibrated $'in\ situ'$. No strong restrictions are imposed on accuracy and stability of three test signals. The accuracy of 6% can be achieved.

References

[1] Technical Design Report for a Detector at TESLA. http://www.desy.de/ lcnotes/tdr/

[2] *P.Buzhan* et al. Silicon Photomultiplier and its possible applications. Nucl.Instrum.Meth.A504:48-52,2003

[3] *V.Korbel*, *V.Morgunov*, Calibration and Monitoring of the TESLA Tile Hadron Calorimeter, LC-DET 051-2001, 2001

[4] *V.Morgunov*, Prototype Calorimeter Simulation with Silicon Photomultiplier as Photo–Detector for HCAL, talk given at Fourth ECFA-DESY Workshop, http://www.desy.de/ morgunov/articles.html
B.Dolgoshein, *E.Popova*, Private communication.

[5] *V.Popov*, Real-time calibration methods of experimental equipment. Thesis of dissertation (in Russian). ITEP 1988, Moscow
V.Popov, NIM A274(189)269-274
V.Popov and *A.Semjenov*, Computer Physics Communication 50(1988)257-261

[6] Eur.Phys.J C 15 (2000) PDG Rew.of Part.Phys.