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TILE-TO-TILE NONUNIFORMITY: HOW IT AFFECTS THE CALORIMETER RESPONSE

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1 Introduction

The influence of tile-to-tile nonuniformity on the tile calorimeter response is studied using two different approaches: analytical and Monte-Carlo. Both methods rely on the removing of the stochastic fluctuations by an averaging procedure (in Monte-Carlo approach), or by considering a parametrisation of the mean longitudinal profile of the electromagnetic shower (in the analytical approach). The tiles' nonuniformity was considered as gaussian distributed, the degree of nonuniformity being characterised by the value of the standard deviation σ_{non}. This approach has a justification in the case when the individual tile characteristics are not measured and calorimeter's towers are assembled without any selection of tiles.

2 Tile-to-tile nonuniformity: Monte-Carlo approach

We investigated the systematic error connected to tile-to-tile nonuniformity for the case of a sandwich tile calorimeter. For this purpose we did some simulations of a calorimeter block which consisted of ($N_{tow} = 9$) towers (structure 3x3). The tower dimensions were 10x10x25.6 cm^3 and it consisted of ($N_{tile} = 32$) tiles interleaved with lead layers. The full number of tiles ($N_{full} = N_{tow} \times N_{tile}$) in the calorimeter block was 288. The thickness of the tile and lead layer was 4 mm for each. The characteristics of the calorimeter building elements were chosen according to [1]. We simulated this calorimeter for incident electrons with the energy 5, 20, 50 and 100 GeV by the use of the program GEANT [2]. The centre of the central tower was taken as a point of incidence, because the systematic error is supposed to be the largest there.

For clarity of further explanation we need to define some basic concepts.
Tile signal. The tile signal is defined as follows:

$$S_i = E_i^{sci} C_i \tag{1}$$

where

- E_i^{sci} is the energy released in i^{th} tile;
- C_i is the response coefficient of ith tile characterizing the tile's efficiency for conversion of deposited energy into light signal.

In our case coefficients C_i are defined as:

$$C_i = 1 + \sigma_{non}\, r_i \tag{2}$$

where:

- $i(= 1, .., N_{full})$ is the tile sequence number;
- r_i - a set of random numbers distributed according to a Gaussian distribution of mean value zero and the standard deviation equal to one;
- σ_{non} - the response standard deviation characterizing the size of nonuniformity or the quality of the tile set.

Such a definition of C_i corresponds to the normalization of the full calorimeter signal to the full energy deposition in active medium (tiles).
Calorimeter signal. The calorimeter signal is defined as follows:

$$S^{full} = \sum_{i=1}^{N_{full}} E_i^{sci} C_i \tag{3}$$

Sampling fraction. The sampling fraction (f_{samp}) is defined in an usual way:

$$f_{samp} = \sum_{i=1}^{N_{full}} E_i^{sci} \,/\, E_{inc} \tag{4}$$

where:

- $\sum_{i=1}^{N_{full}} E_i^{sci}$ is full energy deposition in active medium;

- E_{inc} is the energy of incident particle.

In our calculation we have used the fact that the tile signal is a product of two statisticaly independent quantities (E_i^{sci} and C_i). For each simulated event (an electromagnetic shower induced by an incident particle of given energy) the set of the tile energy depositions ($\{E_i^{sci}, i = 1..N_{full}\}$) had been saved and used later for creation of the "real" tile signals corresponding to a concrete arrangement of the tiles in the calorimeter block, characterised by their response coefficients C_i. In the following we will call a "configuration" the set of C_i coefficients ($\{C_i, i = 1..N_{full}\}$) characterising the response of a calorimeter block. Using the same set of events and generating various configurations we can reconstruct the calorimeter response for any event and for any configuration just using the equ.(1). So one simulated event can be "projected" into many configurations and there is no need to simulatea set of events for each configuration. In our case we reconstructed the same set of events in 2500 different configurations. The configurations are divided into 5 groups for 500 ones each. The groups differ each other by the size of nonuniformity (σ_{non}). The calculations were carried out for the following values of σ_{non}: 5%, 10%, 15%, 20% and 30%. The same set of configurations was applied at all energies.

Practically, the different configurations can be interpreted as the different points of beam incidence distributed over the calorimeter surface with a discrete and constant step, with the incidence points of the beam only on the center of the towers. Each configuration group (500 configurations) characterized by a given nonuniformity σ_{non} corresponds to a calorimeter with given quality of tiles.

The nonuniformity and systematic error. Before presenting the results concernig to tile-to-tile nonuniformity we will shortly discuss the nature of the error connected to nonuniformity. As a rule, the resolution (σ_E) of an electromagnetic calorimeter (EC) is expressed as:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \tag{5}$$

where:

- a corresponds to the sampling fluctuations and the fluctuations connected to photoelectron conversion;

- b is the constant term describing the fluctuations connected to energy leakage and light attenuation as well as to the non-stochastic sources of fluctuations such as the non-uniformity of tile response.

- the electronics noise is not taken into account.

The constant term b can be expressed as a quadratic sum of the stochastic part (b_1) and non-stochastic (systematic) one (b_2) (see below). If there are only the stochastic sources of fluctuations ($b_2 = 0$) then the relative error of reconstructed shower energy (E) is:

$$\frac{\sigma_E^{st}}{E} = \sqrt{\frac{a^2}{E} + b_1^2} \tag{6}$$

Taking into account the Poisson-like fluctuations (a, b_1), the error ($\sigma_{E_{av}}^{st}$) for an average energy (E_{av}) over a large sample of N_{event} events :

$$E_{av} = \frac{1}{N_{event}} \sum_{i=1}^{N_{event}} E_i$$

is

$$\sigma_{E_{av}}^{st} = \frac{\sigma_E^{st}}{\sqrt{N_{event}}}$$

It means that $\sigma_{E_{av}}^{st}$ vanishes if N_{event} is getting larger. Now let us suppose that the non-stochastic sources of fluctuations (the tile nonuniformity in our case) are switched on. In this case, if N_{event} is large, we have $\sigma_{E_{av}}^{st} = 0$ but the non-stochastic part of error is non-zero:

$$\frac{\sigma_{E_{av}}^{non}}{E_{av}} = b_2 \tag{7}$$

It is very important to know how to add b_2 term with a and b_1 terms in equ.(5). This addition must be quadratic if the distribution of E_{av} over the calorimeter surface can be approximated by a Gaussian function. Such an approximation is valid at least for a sample of the reconstructed energies (E) uniformly distributed over the calorimeter surface. In this case the energy distribution $G(E_{inc}, \sigma_E; E)$ corresponding to the incident energy E_{inc} can be expressed as follows:

$$G(E_{inc}, \sigma_E; E) = \int g(E_{inc}, \sigma_{E_{av}}^{non}; E_{av})\, g(0, \sigma_E^{st}; E - E_{av})\, dE_{av} \tag{8}$$

where $g(A, \sigma; x)$ is a Gaussian distribution function of x with the mean value A and the standard deviation σ.

The first Gaussian function in (8) describes the distribution of the average reconstructed energy E_{av} over the surface of calorimeter from one tower to another. E_{av} depends on the position of the place of incidence. The second one describes the local reconstructed energy (E) distribution around the E_{av}. It means that a and b_1 define the width (σ_E^{st}) of the local energy distribution at fixed place of incidence, while b_2 characterizes the size of variation ($\sigma_{E_{av}}^{non}$) of E_{av} if the place of incidence is changing over the calorimeter surface. The resulting probability function $G(E_{inc}, \sigma_E; E)$ is again Gaussian function with the standard deviation:

$$\sigma_E = \sqrt{(\sigma_{E_{av}}^{non})^2 + (\sigma_E^{st})^2},$$

as can be seen by direct integration of (8) or using the rules for convolution of two Gaussian functions.

Now let us suppose that we have a sample of N_{event} simulated events with the incident energy E_{inc} and a set of N_{conf}(=500) configurations. For each configuration we can reconstruct the energy E coresponding to an event:

$$E = \sum_{j=1}^{N_{tow}} S_j^{tow} K_j \tag{9}$$

where S_j^{tow} defined by:

$$S_j^{tow} = \sum_{i=1}^{N_{tile}} E_i^{sci} C_i \tag{10}$$

represents the signal from the jth tower and $(K_j, j = 1, ..N_{tow})$ is the set of calibration coefficients.

The calibration coefficient (constant) of the jth tower K_j is defined as:

$$K_j = \frac{C_{part} E_{inc}^{cal}}{\overline{S_j^{tow}}} \tag{11}$$

where:

- C_{part} represents the percentage of the energy released in a tower if the incident particle hits on its center;

- $\overline{S_j^{tow}}$ is the jth tower signal averaged over the whole sample of events;
- E_{inc}^{cal} - the energy at which the calibration is done.

The reconstructed energy can be expressed as follows:

$$E = B\, E_{inc} \tag{12}$$

where B is a random variable with the mean value equal to one and the standard deviation

$$\sigma_B = \frac{\sigma_E}{E}$$

. If instead of E (reconstructed energy of one event) we will take E_{av}, then σ_B will represent the systematic error. In each configuration we can construct E_{av} for all incident energies E_{inc} (5, 20, 50 and 100 GeV) and use linear fit ($E_{av} = B\, E_{inc}$) to define B for this configuration. Finding B for all configurations we will finaly obtain the distributions of B for 5 sets (groups) of configurations with different size of nonuniformity (σ_{non}).

3 Tile-to-tile nonuniformity: analytical approach

It is possible to obtain some analytical results concerning the magnitude of the tile-to-tile nonuniformity contribution to the energy resolution.

In equ. (3) is given the expression for the calorimetric signal in the presence of tile-to-tile non-uniformities for a given configuration. Its averaged value over the full set of configurations is:

$$\overline{S^{full}} = \sum_{i=1}^{N_{full}} E_i^{sci} \tag{13}$$

because $\overline{C_i} = 1$.

The variance of the S^{full} is:

$$var(S^{full}) = \sigma_{non}^2 \sum_{i=1}^{N_{full}} (E_i^{sci})^2 \tag{14}$$

One can notice that as the incident energy will increase, more tiles will contribute to the signal and the variance is expected to have a slow increase.

The contribution of tiles nonuniformity to the energy resolution (i. e. the b_2 term) will be:

$$\frac{var(S^{full}))^{1/2}}{\overline{S^{full}}} = \sigma_{non}\frac{(\sum_{i=1}^{N_{full}}(E_i^{sci})^2)^{1/2}}{\sum_{i=1}^{N_{full}}E_i^{sci}} \tag{15}$$

This equation may be used to obtain an upper bound for the magnitude of the b_2 term. It is very easy to observe that the maximum value, which will be denoted by b_2^{max} is attained when all E_i^{sci} are equal ($E_i^{sci} = f_{samp}E_{inc}/n_{eff}$, where n_{eff} is the number of tiles which contribute effectively to the signal):

$$b_2^{max} = \frac{\sigma_{non}}{\sqrt{n_{eff}}} \tag{16}$$

Because both $var(S^{full})$ and $\overline{S^{full}}$ will increase with n_{eff} and n_{eff} is supposed to increase slowly with the incident energy (as $ln(E_{inc})$) one can expect a very weak decrease of this upper bound with the energy (as $(ln(E_{inc}))^{-1/2}$) for a very long calorimeter and for a finite calorimeter, to approach a constant value at higher energies. One can notice the linear dependence of b_2^{max} on σ_{non}, a result obtained also by simulation.

A better estimate for tile nonuniformity contribution to the dispersion of the calorimeter response can be obtained if a more realistic assumption about E_i^{dep} in r.h.s. of equ. (15) is made.

It consists from the use of the well known parametrisation by a gamma-distribution [3] for the average longitudinal shower profile:

$$\frac{dE}{dt} = E_{inc}\frac{\beta}{\Gamma(\alpha)}(\beta t)^{\alpha-1}e^{-\beta t} \tag{17}$$

with

$$\frac{\beta}{\Gamma(\alpha)}\int(\beta t)^{\alpha-1}e^{-\beta t}dt = 1 \tag{18}$$

The parameters α,β contain energy dependence of shower profile. For instance, for electron induced showers, one takes [3]:

$$\beta \simeq 0.5; \qquad \frac{\alpha-1}{\beta} = ln\frac{E_{inc}}{E_c} - 0.5 \tag{19}$$

where E_c is critical energy for the averaged material of the calorimeter. For E_c the parametrisation given in [3] was used in the subsequent calculations. The depth inside shower is considered relative to the front edge of the calorimeter, and is expressed in radiation lengths X_0 of the averaged material. The use of averaged medium is legitimate for a sufficiently high sampling frequency, of course.

For further calculations a few more assumptions will be made:

- the shower is totally contained in a single tower (i.e. longitudinal and transverse dimensions of tower are sufficient in the considered energy range)
- the tower has a full depth of T radiation lengths, being a stack of N_{tile} identical sections, each consisting of a tile and an absorber plate.

Under these assumptions, in the equ. (18) we can replace the integral by a rectangle-method quadrature over N_{tile} intervals. Multiplying afterwar ds with E_{inc} we get

$$E_{inc} = \sum_{i=1}^{N_{tile}} E_i^{dep} \tag{20}$$

where:

$$E_i^{dep} = E_{inc} \frac{\beta \Delta t}{\Gamma(\alpha)} (\beta t_i)^{fa-1} e^{-\beta t_i} \tag{21}$$

is the total energy deposited in the i-th section of tower and $\Delta t = T/N_{tile}$, $t_i = (i - 0.5)\Delta t$. The energy deposited in the active part of section is $E_i^{sci} = f_{samp} E_i^{dep}$, with f_{samp} as defined in (4). The signal produced in this section is $S_i = C_i E_i^{sci}$, where C_i was defined earlier.

So, according to (9), the reconstructed energy is:

$$E = \frac{1}{f_{samp}} \sum_{i=1}^{N_{tile}} E_i^{sci} C_i \tag{22}$$

In other words, the reconstructed energy is a weighted sum of N_{tile} independent random quantities C_i distributed by the same law. This treatment implies that all tiles are manufactured by using the same technology, so C_i obey to a unique distribution law.

Assuming the distribution (2) for C_i, a straightforward calculation gives

$$\sigma_E^2 = [\frac{E_{inc}}{f_{samp}} \frac{\beta \Delta t}{\Gamma(\alpha)}]^2 \sigma_{non}^2 \sum_{i=1}^{N_{tile}} (\beta t_i)^{2(\alpha-1)} e^{-2\beta t_i} \tag{23}$$

Making use of relation (18) and after some algebra we get:

$$(\frac{\sigma_E}{E})^2 = \frac{\beta \Delta t}{\sqrt{\pi}(2\alpha - 1)} \frac{\Gamma(\alpha + 0.5)}{\Gamma(\alpha)} \sigma_{non}^2 \tag{24}$$

A further simplification can be made, by using the explicit form for α and β (see (19)) and the Stirling asimptotics for $\Gamma(x)$, valid at energies higher than say, 10 GeV. Finally we get

$$\frac{\sigma_E}{E} = 0.45 \sqrt{\frac{\Delta t}{\sqrt{ln(E_{inc}/E_c)}}} . \sigma_{non} \tag{25}$$

that reveals a very slow decrease with energy of σ_E/E, which is proportional with σ_{non} however. For instance at energies of, respectively 10, 100, 1000, 10000 GeV the coefficient multiplying σ_{non} in relation (25) changes as 0.23, 0.22, 0.21, 0.20 respectively. For the range of E_{inc} at which GEANT simulations were performed one can take the value 0.23 . This agrees fairly well with figures from Table 2, obtained with GEANT for several values of σ_{non}.

4 Results

The results of our investigations are summarized in the following tables and figures.

In Table 1 and on Fig.1 are summarized the simulation statistics and the energy resolution for the ideal case ($C_i = 1$):

Table 1: Energy Resolution in Ideal Case				
energy (GeV)	5	20	50	100
Nr. of events	900	500	265	125
E_{sci} (MeV)	401.9	1600.5	3989.1	7956.8
σ_{sci} (MeV)	22.48	47.87	71.28	112.5
Resolution (%)	5.56	2.99	1.79	1.41
Fit $a \oplus b/\sqrt{E}$: $(0.56 \pm 0.25) \oplus (12.6 \pm 0.34)/\sqrt{E}$				

where:

- E_{sci} is the full energy deposition in tiles of calorimeter;
- σ_{sci} is the standard deviation of E_{sci}.

The values of E_{sci} and σ_{sci} are the results of a fitting procedure applied to the corresponding energy deposition distributions.

We suppose that, in the ideal case, the energy leakage is responsible for the presence of a non-zero constant term.

To investigate the manifestation of the tile response nonuniformity we carried out calculations of local energy resolutions (the resolutions for individual towers) for given values of nonuniformity σ_{non} $(= 5\%, 10\%, 15\%, 20\% and 30\%)$. It means that the energy resolution was obtained for various beam incidence places (corresponding to different configurations) of 5 different calorimeters, each being characterized by corresponding value of nonuniformity σ_{non}. In each incident place the energy resolution was obtained for 4 incident energies $(5, 20, 50\, and\, 100\ GeV)$ and fitted to obtain the energy resolution parameters a and b.

In Table 2 is presented the dependence of average values $\overline{a}$ and $\overline{b}$ and standard deviations of the energy resolution parameters a and b on the tile nonuniformity. The distribution of parameters a and b and their standard deviations for various values of nonuniformity are shown on Fig.2 and 3. For illustration on Fig. 4 are shown analoguos distributions (as on Fig. 2 and 3) but for the energy resolution at incident energy 50 GeV. The results presented in Table 2 and Fig. 2-4 can be treated as a general characteristics of calorimeter with a given quality of tiles and correspond to the case when each calorimeter tower is calibrated at 4 energies.

Table 2: The resolution coefficients (average values and standard deviations) vs. tile nonuniformity

σ_{non} (%)		5	10	15	20	30
$\overline{a}$ (%)	GEANT	12.63	12.73	12.92	13.18	13.88
σ_a (%)		0.09	0.16	0.31	0.48	0.93
$\overline{b}$ (%)	GEANT	0.85	0.90	0.95	1.05	1.29
σ_b (%)		0.17	0.30	0.42	0.52	0.70

From Table 2 we see that the increasing tile nonuniformity leads to some deterioration of the energy resolution but this dependence is not very strong.

From the increase of the energy resolution parameters ($\overline{a}$, $\overline{b}$) with σ_{non} we infer that tile nonuniformity strengthens stochastic sources of fluctuations (sampling fluctuations).

So far we treated the energy resolution for individual towers of a calorimeter with given tile nonuniformity σ_{non}. This treatment corresponded to the situation where each calorimeter tower was separately irradiated by a beam with 4 different energies. To characterize the dependence of energy resolution on tile nonuniformity we also present the global energy resolution of calorimeter. In our case this resolution responds to the case when the calorimeter surface is uniformly irradiated and the whole calorimeter is characterized by one pair (a^{gl}, b^{gl}) of energy resolution coefficients and not each tower. To obtain the global energy resolution we need to choose a calibration procedure. For this purpose two different calibrations were treated: the global calibration and the "tower-by-tower" one.

4.1 Global Calibration.

In the case of global calibration all calibration coefficients K_j of the individual towers were replaced by a unique average coefficient K, which was defined as:

$$K = \frac{1}{f_{samp}} \tag{26}$$

The dependence of coeficients a^{gl} and b^{gl} on σ_{non} is presented in Table 3 and on Fig.5. In Table 3 there are also the results concerning the non-stochastic part (b_2^{gl}) of the constant term calculated by Monte Carlo [2] as well as analytically (25). As we have already mentioned the constant term b can be expressed as a quadratic sum of the stochastic (b_1) and non-stochastic part (b_2). To investigate the role of b_2^{gl} we used averaging procedure described above (see discusion after eq. 12). Reconstructing the linear dependence $E_{av} = B\ E_{inc}$ for different places of incidence (different configurations) and fitting the distribution of B by a Gaussian function we have obtained the standard deviation of parameter B, which essentialy is equal to b_2^{gl} as the coefficients a^{gl} and b_1^{gl} are turned to zero for E_{av}.

Table 3: The global resolution coefficients vs. tile nonuniformity in global calibration						
σ_{non} (%)		5	10	15	20	30
a^{gl} (%)	GEANT	12.60	12.56	12.78	13.20	14.08
b^{gl} (%)	GEANT	1.46	2.52	3.59	4.66	6.97
b_2^{gl} (%)	GEANT	1.15	2.30	3.44	4.60	6.90
b_2^{gl} (%)	equ.(25)	1.15	2.30	3.45	4.60	6.90

From Table 3 it can be concluded that in the global calibration the dependence of energy resolution on σ_{non} is strong and manifests itself especially by a rapid increase of the constant term (b^{gl}) with σ_{non}. On the other hand comparing b_2 with b_2^{gl} we can conclude that the origin of this increase is in non-stochastic sources of fluctuations. It means that the increase is connected to the fact that various towers have different average responses on the same incident impulse.

4.2 Tower-by-tower Calibration.

A similar procedure was carried out for the case when the calibration coefficients K_j were known for all towers of the calorimeter treated. We assumed that the calibration was done at $E_{inc}^{cal} = 50\ GeV$ and calibration coeficients were calculated according to the equ.(11).

The results for this case of calibration are summarized in Table 4 and in figs. 6 and 7.

Table 4: The global resolution coefficients vs. tile nonuniformity in tower-by-tower calibration						
σ_{non} (%)		5	10	15	20	30
hline a^{gl} (%)	GEANT	12.57	12.78	13.18	13.74	15.12
b^{gl} (%)	GEANT	0.93	0.99	1.06	1.18	1.44
b_2^{gl} (%)	GEANT	0.04	0.09	0.13	0.17	0.26

In the case of tower-by-tower calibration, as is demonstrated by Table 4 and the Fig. 6 and 7, the deterioration of the energy resolution with increasing nonuniformity exibits a similar dependence as in the "ideal" case (Table 2). Confronting b^{gl} with b_2^{gl} as well as with $\overline{b}$ (Table 2) we see that in

this calibration unlike of the global one the non-stochastic sources of fluctuations play minor role here i.e. b_1 component dominates in the constant term b. Practically it means that reconstructed energy spectrum is made slightly wider with increasing σ_{non} but the average value of the reconstructed energy is not displaced when moving from one tower to the another.

5 Conclusions

The influence of the tile-to-tile nonuniformity on the energy resolution of a sandwich tile calorimeter was investigated. The main results of this work are the following:

- The tile nonuniformity leads to a deterioration of energy resolution and manifests itself in both the sampling (coeficient a) and the constant terms (coefficient b). It was proved that this deterioration is not significant if the tile nonuniformity σ_{non} is less than 10% and each calorimeter tower is calibrated (tower-by-tower calibration).

- An original method was proposed to separate the systematic effects (b_2) induced by the tile-to-tile nonuniformity from those of stochastic origin (b_1) in the energy resolution by removing the stochastic term through the use of an averaging procedure.

- It was proved that this systematic error (b_2) due to nonuniformity can be substantialy reduced by the use of the tower-by-tower calibration. *So, it looks that there isn't a severe requirement for a high uniformity of tiles.*

- A very good agreement is observed between the results obtained in Monte-Carlo and analytical approaches of the problem.

References

[1] Solenoidal Detector Collaboration, Technical Design Report, Draft SDC-92-201 (1992)

[2] R. Brun et al., GEANT-CERN Program Library W5013

[3] Particle Data Group, Phys. Lett. 239B (1990) pag. III.15

Figure Captions

Fig.1 The energy resolution of a sandwich tile calorimeter in the "ideal" case ($\sigma_{non} = 0\%$);

Fig.2 The distribution of the values of b (the constant coefficient in the energy resolution) over the calorimeter surface for different values of nonuniformity;

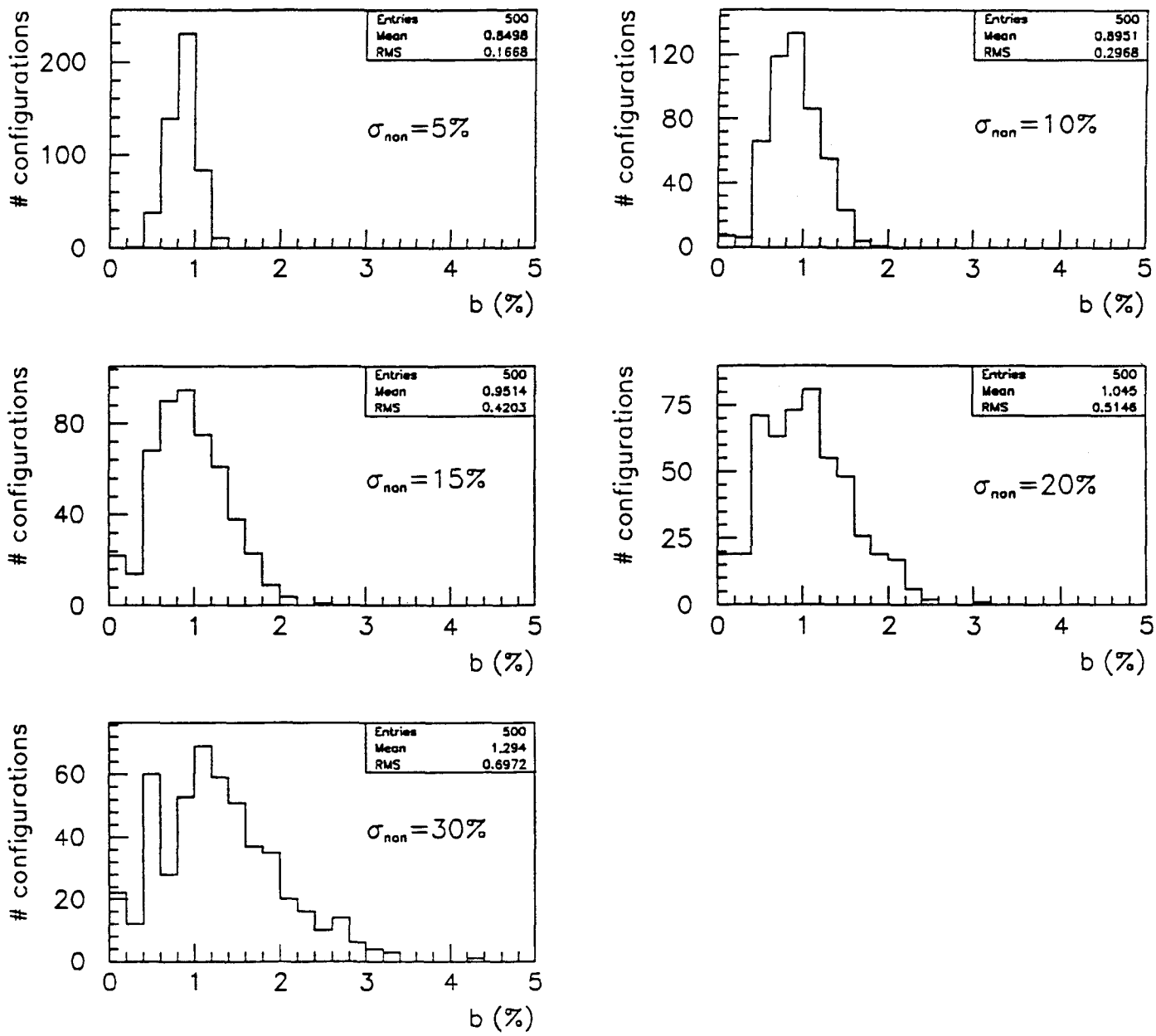
Fig.3 The distribution of the values of a (the scaling coefficient in the energy resolution) over the calorimeter surface for different values of nonuniformity;

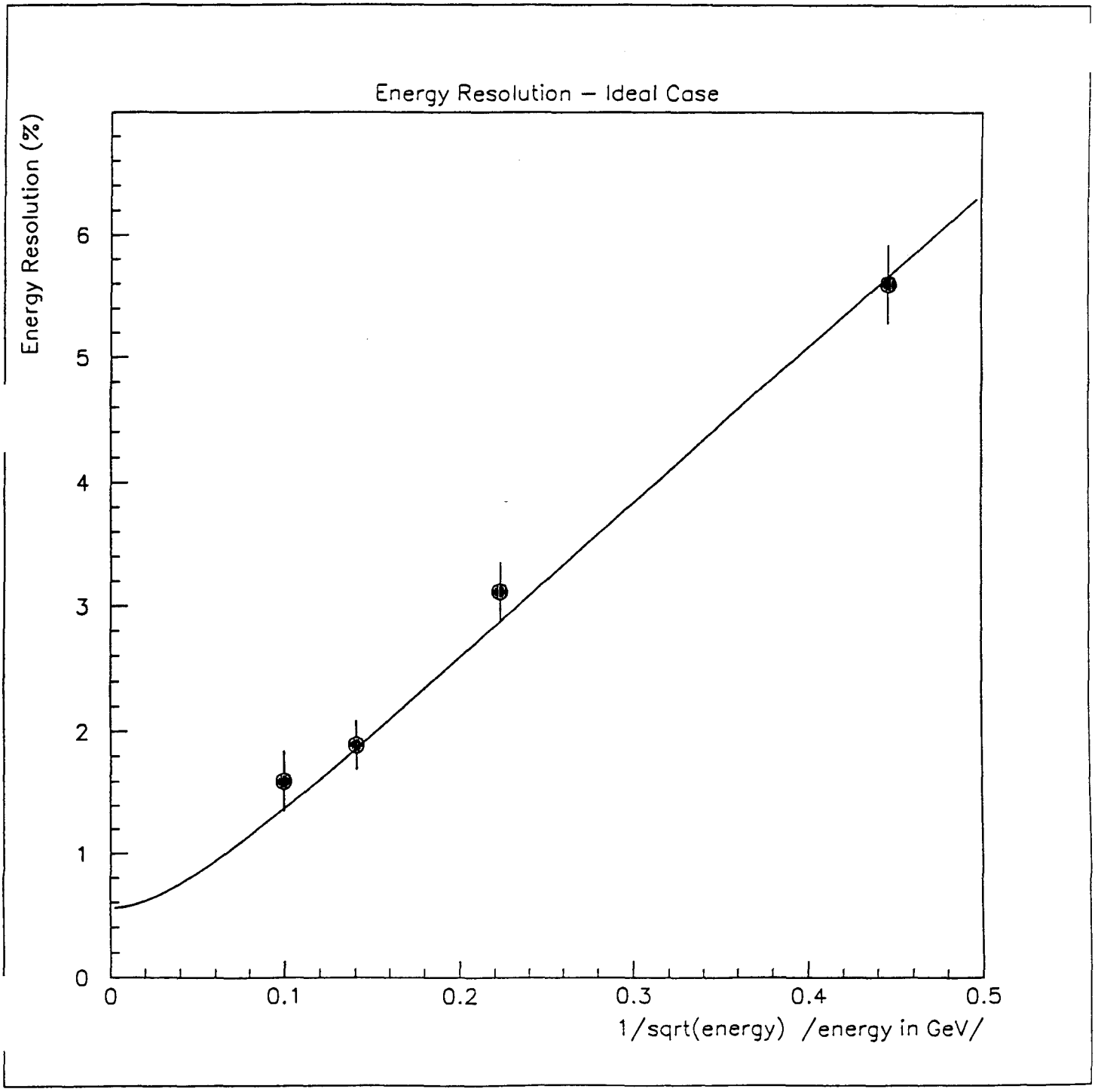
Fig.4 The energy resolution of the sandwich tile calorimeter at $E = 50GeV$ over the calorimeter surface for different values of nonuniformity;

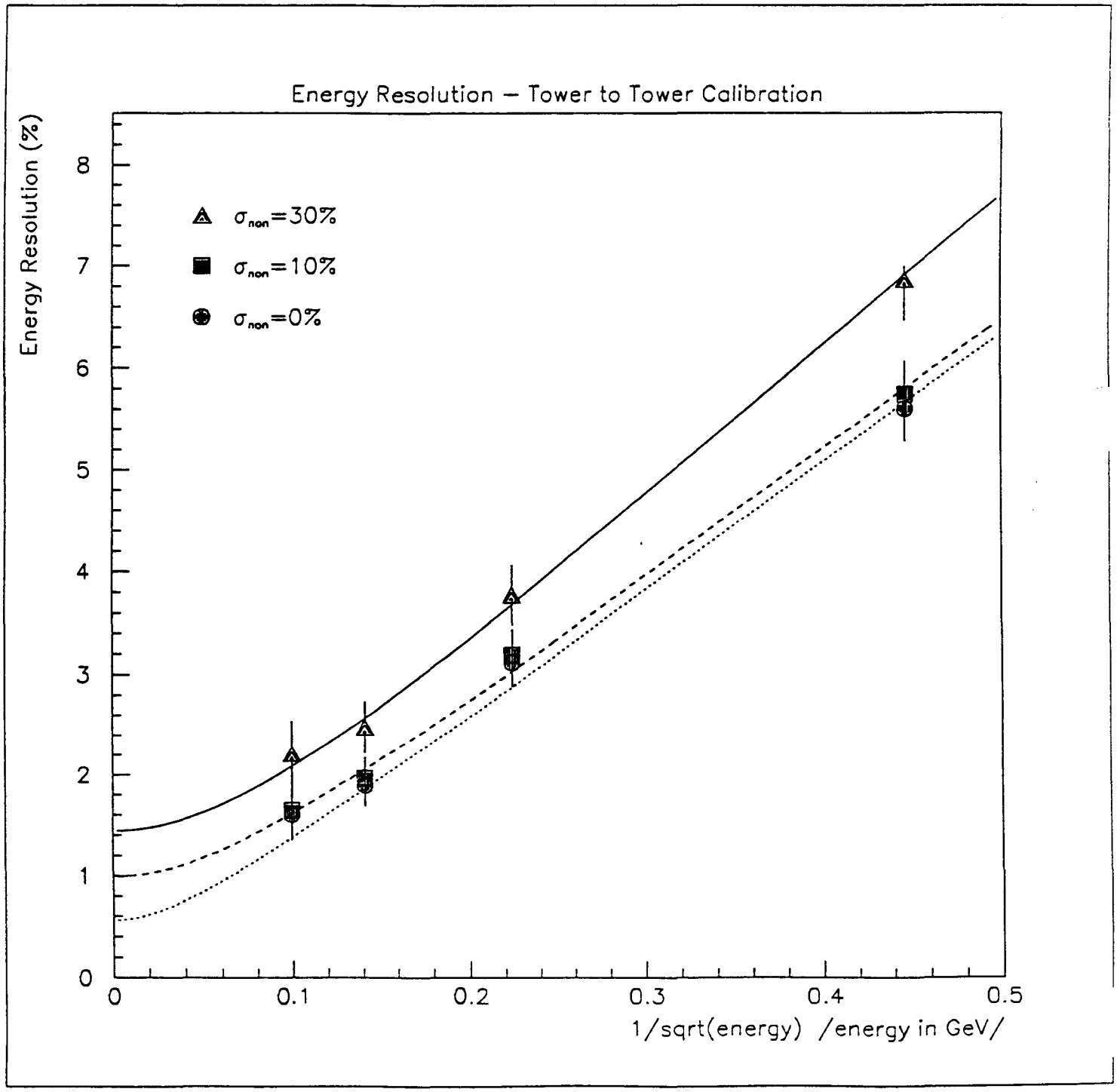
Fig.5 The variation of the energy resolution vs. incident energy in the case of global calibration;

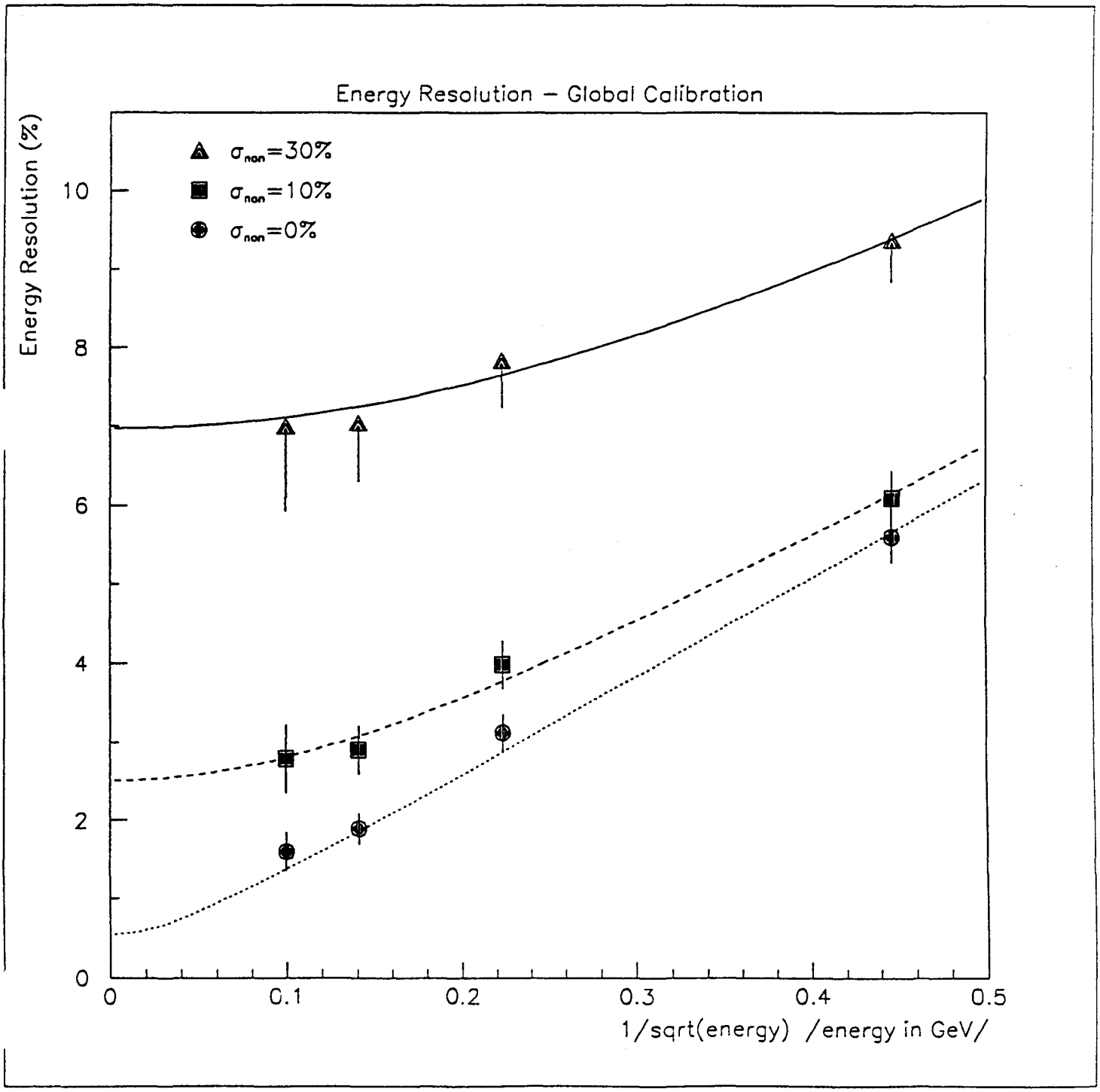
Fig.6 The variation of the energy resolution vs. incident energy in the case of tower-by-tower calibration.

b (=energy res. constant term) for different configurations

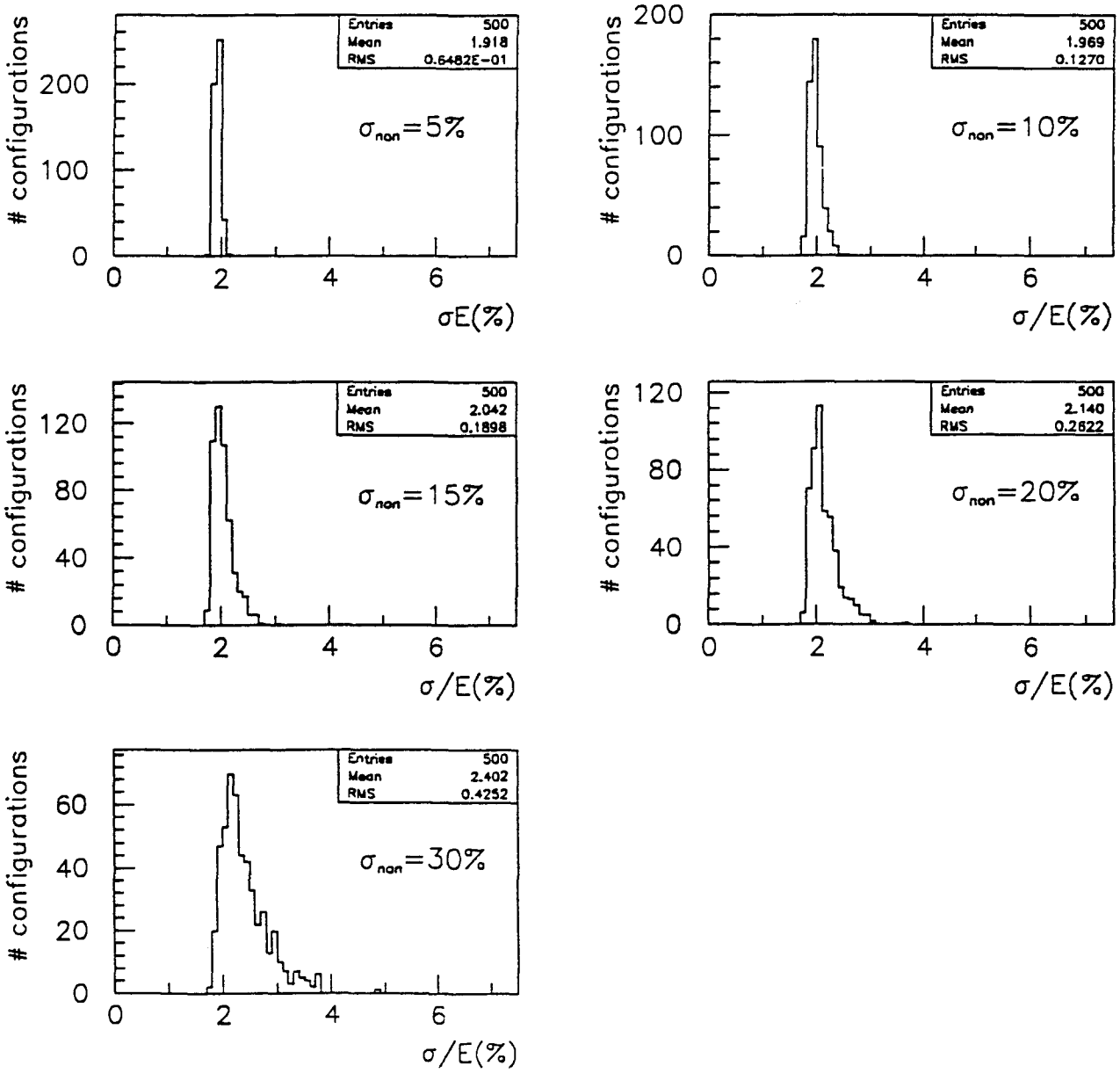
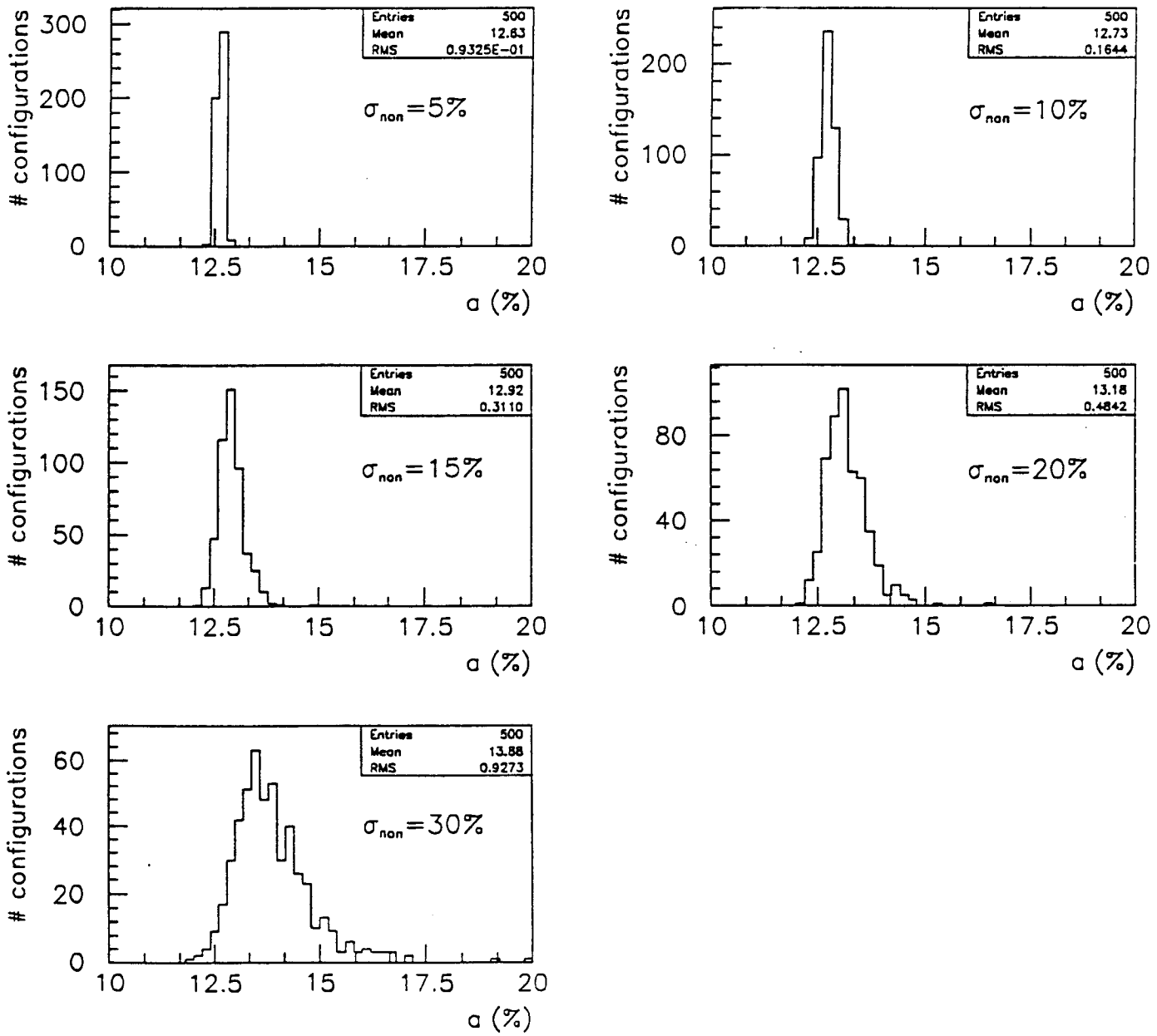



Energy Resolution – Ideal Case
Energy Resolution (%)
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
1/sqrt(energy) /energy in GeV/


Energy Resolution – Tower to Tower Calibration
Energy Resolution (%)
σ_{non}=30%
σ_{non}=10%
σ_{non}=0%
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
1/sqrt(energy) /energy in GeV/


Energy Resolution – Global Calibration
Energy Resolution (%)
σnon=30%
σnon=10%
σnon=0%
0
2
4
6
8
10
0
0.1
0.2
0.3
0.4
0.5
1/sqrt(energy) /energy in GeV/

energy res. at 50 GeV/c for different configurations



a (=energy res. scaling factor) for different configurations