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OFF-LINE CORRECTIONS OF THE EFFECT OF RADIATION DAMAGE ON THE EM CALORIMETER ENERGY RESOLUTION

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Introduction

The problem of radiation damage in scintillators and its influence on the energy resolution of EMC is not limited to decreasing detector response. The detector response also becomes non-linear *vs* the insident energy because the shower maximum extends deeper into the calorimeter with the increasing energy moving away from the damaged region. Also the damaged calorimeter is non-uniform in depth. Thus, fluctuation of shower conversion point degrades the energy resolution of the EMC and introduces non-Gaussian tails.

This note presents the results of Monte Carlo simulation study of the radiation damage effect on the EMC energy resolution, and several methods to correct for this effect. The data are obtained using GEANT 3.15. The incident particle was e^-. For each value of energy of 2, 5, 10, 20, 50, 100, and 500 GeV, 500 showers were simulated

The module was assumed to be a set of 7×7 towers, each of $10 \times 10 cm^2$. In depth, there were 7 layers of $0.4cm$ of lead followed by $0.4cm$ of scintillator, then SMD consisting of 2 scintillating tiles, each $0.4cm$, then 93 layers of $0.4cm$ of lead follwed by $0.4cm$ of scintillator. Tiles of SMD are divided into strips of $0.5cm$ or $1.25cm$ wide.

The Radiation Damage Effect

A shower longitutunal profile can be discribed as

$$f_0 = \frac{dE}{dt} \sim t^a e^{-bt}, t = \frac{x}{X_0},$$

$$a = 2.284 + 0.7134 ln(E),$$

$$b = 0.5607 + 0.0093 ln(E).$$

A rather reasonable idea to describe a longitudinal profile of radiation damage is to assume it to be similar to the profile of 2GeV e^-. Actually, the formula given above describes the shape of a shower longitudinal profile but we need to make an assumption about a relative decrease of the detector response, so we normalize f_0 to 1 at maximum.

Thus,

$$E_{vis} = \varepsilon_t E_t,$$

where

$$\varepsilon_t = 1. - \varepsilon_{max} \frac{dE/dt}{dE/dt_{max}},$$

ε_{max} is the measure of the damage, ε_{max}=1 (100%) corresponds to a situation where the detector is dead, at peak of damage.

Fig.1 shows non-linearity of the detector response with respect to the energy scale for different values of ε_{max}. The constant term $\sim 0.5\%$ coinsides $\varepsilon_{max} \sim 5 - 6\%$. Additional contibutions into resolution for different values of ε_{max} are shown at the fig.2

Depth-Segmented EMC

However, if a calorimeter is divided into a few segments in depth, one can estimate the fluctuations, then correct the value of the measured energy on an event-by-event basis. The questions arise : how many segments in depth are necessary and what are the best ratios of their lengths?

If EMC is divided into N segments in depth a measured energy E_{meas} is

$$E_{meas} = \sum_{n=1}^{N} E_{n,\varepsilon_{max}},$$

where

$$E_{n,\varepsilon_{max}} = \sum_{t_{n-1}}^{t_n} \varepsilon_t E_t,$$

is the energy measured in a segment number n with the boundaries t_{n-1}, t_n.

One can calculate a set of coefficients

$$W_{n,\varepsilon_{max}} = \frac{< E_{n,\varepsilon_{max}} >}{< E_{n,\varepsilon_{max}=0} >}, n = 1, N.$$

Thus, a corrected value of a measured energy is

$$E_{corr} = \sum_{n=1}^{N} \frac{E_{n,\varepsilon_{max}}}{W_{n,\varepsilon_{max}}}$$

Then 4 cases of the EMC segmentation were studied :

- 3 compartements in depth, $t_1 \sim 4X_0$, $t_2 \sim 12.5X_0$
- 3 compartements in depth, $t_1 \sim 5X_0$, $t_2 \sim 10.5X_0$
- 2 compartements in depth, $t_1 \sim 7X_0$
- 2 compartements in depth, $t_1 \sim 10X_0$

The results :

- All types of segmentation of EMC allow corrections of the nonlinearity of the response induced by radiation damage. The detector response is corrected (on averrage) to the "ideal", that is, it's absolutely linear (see fig.3)
- There are no non-Gaussian tails in the response curves (see fig.4)
- The segmentation (only these 4 cases are under question) which provides the best minimization of the constant term is of 3 compartements, $t_1 \sim 5X_0, t_2 \sim 10.5X_0$. The case of 2 compartements, division at $\sim 7X_0$, is not that good. The worst case is a segmentation into 3 compartements with $t_1 \sim 4X_0, t_2 \sim 12.5X_0$.

What is the most surprising is that the segmentation of EMC into 2 compartements with the division at $\sim 10X_0$ provides almost the same result as the "best" case of 3 segments, $t_1 \sim 5X_0, t_2 \sim 10.5X_0$.

The conclusion is obvious : 2 compartements in depth are quite enough to correct the effect of radiation damage in EMC on its energy resolution. The question is to make the "best" choice of their lengths.

Two more cases of segmentation of EMC into 2 compartements with the boundary between them at $\sim 9X_0$ and at $\sim 11.5X_0$ were also studied. The dependense of the constant term (corrected) *vs* boundary position has a minimum at $\sim 9 - 10X_0$ for every value of ε_{max} (see fig.5). Such a segmentation allows us to keep a constant term of $\sim 0.5\%$ with the radiation damage of $\sim 30 - 35\%$.

Corrections with the SMD

The longitudinal segmentation of EMC is not the only way to estimate shower fluctuations in depth. These fluctuations are also correlated with energy deposition in SMD and transverse size of shower spot in SMD.

At first, the transverse size of shower spot looks more promising to work with because it's insensitive to the radiation damage.

Actually, a shower transverse profile can be described with 2 Gaussian functions (it becomes visible with increasing energy). But only a "shower core" reflects fluctuations in depth, and the "soft component" was substracted as

$$X' = X - 0.00025E_{e^-},$$

where X is a content of each non-zero channel. The RMS of a shower transverse profile in SMD after a "soft component" substraction is assumed to be the characteristics of a shower.

The dependences $E_{mod,dam}/E_{mod,ideal}$ *vs* RMS were studied (for several values of ε_{max}). Parameters describing the curves depend on energy and ε_{max}.

The results obtained using this idea are not very optimistic.

- The detector response (peak position) is corrected to the "ideal", i.e. "non-damaged". So it's linear *vs* energy.
- No difference in using for corrections E_{e^-} (theoretical) or $E_{meas}/sampl.ratio$ has been seen

- There is no any obvious difference in working with $0.5cm$ or $1.25cm$ strips.

But :

- Non-Gaussian tails remain.
- From the point of view of the const.term one can get slightly better result in comparison with the "non-corrected" case : const.term of $\sim 0.5\%$ for $\varepsilon_{max} \sim 10\%$.

Nevertheless, there is a strong correlation between the fluctuation in the conversion point and energy deposition in SMD (fig.6a-c). The dependences $E_{mod,dam}/E_{mod,ideal}$ *vs* $E_{SM}/E_{mod,dam}$ for several values of ε_{max} were studied. Parameters describing the curves depend on energy and ε_{max}.

The results :

- The detector response is corrected to the "ideal" (i.e. "non-damaged"); it's linear with respect to the energy scale (see fig7a-c).
- There are no non-Gaussian tails in the response curve (see fig.8a,b,c).
- There is no any obvious difference in using the value E_{e^-} or $E_{meas}/sampl.ratio$ for corrections.
- The const. term $\sim 0.5\%$ for $\varepsilon_{max} \sim 25\%$ (5 times better in comparison with non-corrected case but still worse than the case of a longitudinal segmentation of the EMC). Additional contibutions to the resolution for different values of ε_{max} are shown at the fig.9.

The Effect of Photostatistics Variations in the SMD

With increasing radiation damage and decreasing detector response, the effect of photostatistics variations, becomes more important. especially in the SMD. The question arises : taking this fact into account, how well can we correct for the radiation damage effect with the SMD ?

To study the problem a few assumption were made :

- $1 - 2p.e./MIP/tile$
- $N_{p.e.} = (N_{p.e.}/MIP/tile) * (E_{dep}) \ / \ (E/MIP/tile)$
- $E/MIP/tile \approx 0.8MeV$
- $N_{p.e.,real} \longrightarrow$ *Poisson distibution*

The procedure was applied to every strip of SMD.

The result :

- The photostatistics variations induce an additional contribution into a resolution but this effect is not very serious and is visible at low energies only. Anyway, the constant term can be kept on the level of 0.5% with $\varepsilon_{max} \sim 20 - 25\%$

In fig.10, the corrected EMC response, ε_{max}=30%, for the case of no photostatistics variations is compared with that assuming 1p.e./MIP/tile for SMD. Fig.11 shows additional contributions to the resolution with the assumption of 1p.e./MIP/tile.

The Effect of Bulkheads

The effect of photostatistics variations in the SMD can also be important because of the signal drop near gaps (for example, bulkhead areas). Bulkheads were assumed to be of stainless steel, 0.05cm thick, and air gaps, 0.025cm thick each, were on both side of bulkhead. $1.2X_0$ of material was assumed in front of a module to simulate a coil.

Fisrt of all, the simulation shows that the effects of radiation damage and bulkheads on the EMC energy resolution are independant.

Then, the effect of bulkheads is well correctable : scaning across a tower (including bulkheads) and correcting for the energy deposition with respect to the coordinate of the point of incidence, one has the constant term of $\sim$ 0.39% (because of fluctuations of the shower axis which are irreduceable).

To study the effect of photostatistics variations on the corrections for the radiation damage in the bulkhead area, two kinds of simulation were done. For the first one the point of incidence was assumed to be the center of a bulkhead - the "worst" point for the energy deposition in SMD (as well, as in module) and hence the most sensitive for the photostatistics variations. The effect of photostatistics variations (either from radiation damage and bulkhead) is visible at low energies only. Additional contributions to the resolution for the cases of no photostatistics variations assumed and for 1p.e./MIP/tile assumed for the SMD are shown at Fig12a,b, respectivelly.

To study the effect of bulkheads in general, a scan across a tower was made, including the photostatistics variations. The result is that bulkheads are almost "invisible", and the constant term still can be kept to $\sim$ 0.5% with a radiation damage level of $\sim$ 20-25%. Fig.13a,b show additional contribution to the resolution for the cases of no photostatistics variations and 1p.e./MIP/tile for SMD.

The result :

- The effect of photostatistics variations is visible only at low energies, and hence influences on the stochastic term. But for $\varepsilon_{max} \sim$ 20-25% the stochastic term doesn't exceed 13.1% which satisfies the TDR requiremnets.

The Effect the SMD Gain Variations

The SMD gain variations are supposed to be of about 10%. To make sure that this effect does no influence on the procedure of corrections for the radiation damage with the SMD information the SMD gain variations were described by the Gaussian function with mean of 1. and σ_{gain}=0.1.

Fig.14 shows an additional contributions into energy resolution for several values of ε_{max}. They are almost the same as shown at fig.9.

The result :

- This constant term still can be kept of $\sim 0.5\%$ with $\varepsilon_{max} \sim 20-25\%$ if the SMD gain variations are about 10%.

Conclusions

The effect of radiation damage on the EMC energy resolution is a serious problem. But it can be reduced with off-line corrections if there is some information about shower fluctuations in depth.

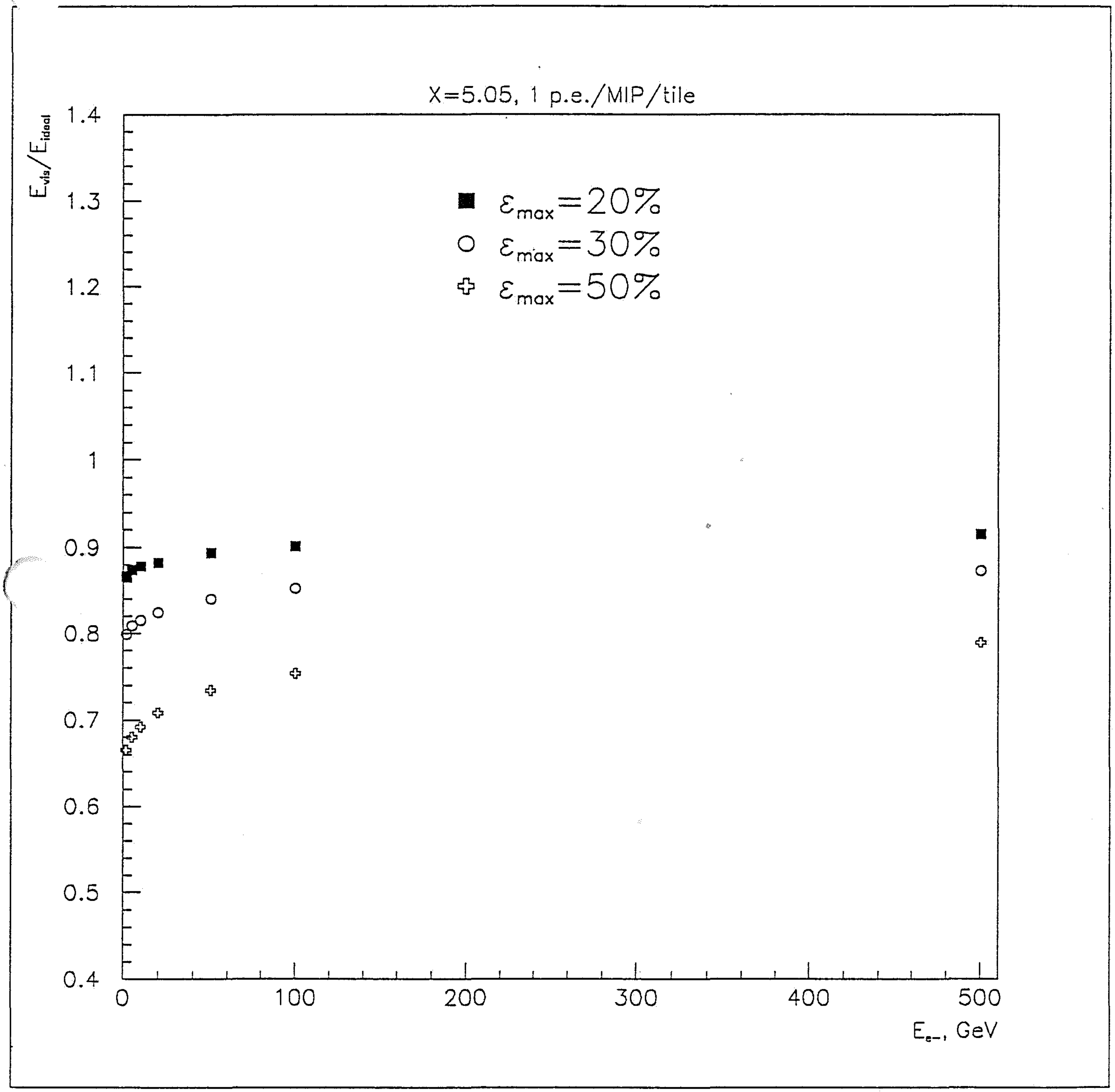
The most promising way is the EMC longitudinal segmentation. Two compartments are enough, and the length of the first one should to be about 9-10X_0. It allows us to reduce the constant contribution to the EMC energy resolution to $\sim 0.5\%$ with the signal drop at peak of damage of 30-35% (see fig.15).

Another way to correct for the radiation damage effect is based on using energy deposition in the SMD. It works slightly worse compared to the case of 2 segments but allows us to reduce the constant contribution to the EMC energy resolution to $\sim 0.5\%$ with the signal drop at peak of damage of 20-25% (see fig.15). This method is usefull if no longitudinal segmentation of the EMC is supposed.

It would be interesting and important to check these ideas in a test beam.

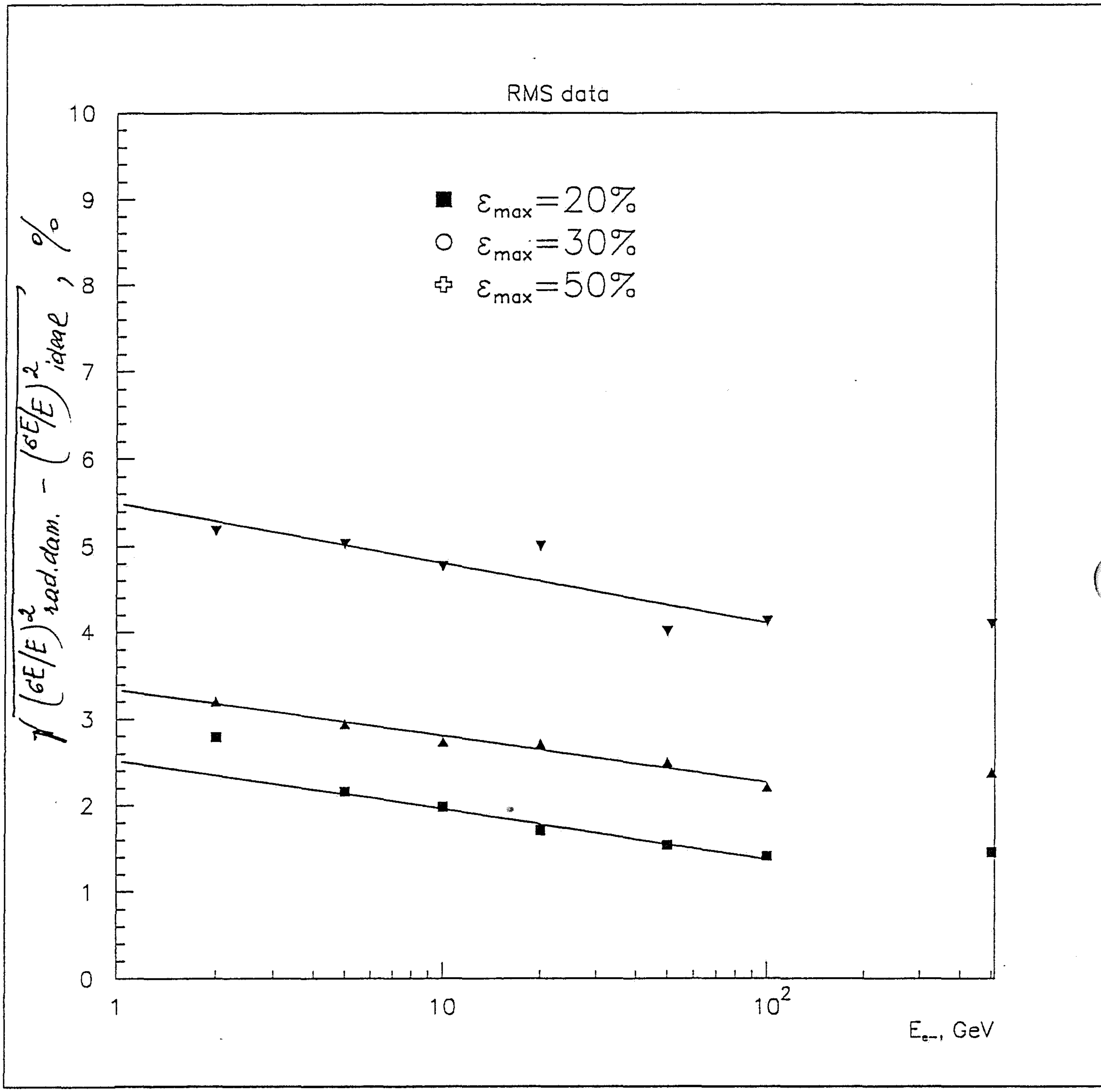
There is a chance to do so while testing a prototype that LBL group is now working on. The prototype consists of 2 compartements in depth, has a completely instumented SMD, and can be supplied with a special longitudinal mask to simulate the radiation damage profile.

Checking experimentally methods to correct for a radiation damage effect on the energy resolution of the EMC is important to optimize the EMC calibration, monitoring, and operation systems from the point of view of performance, as well as of cost.



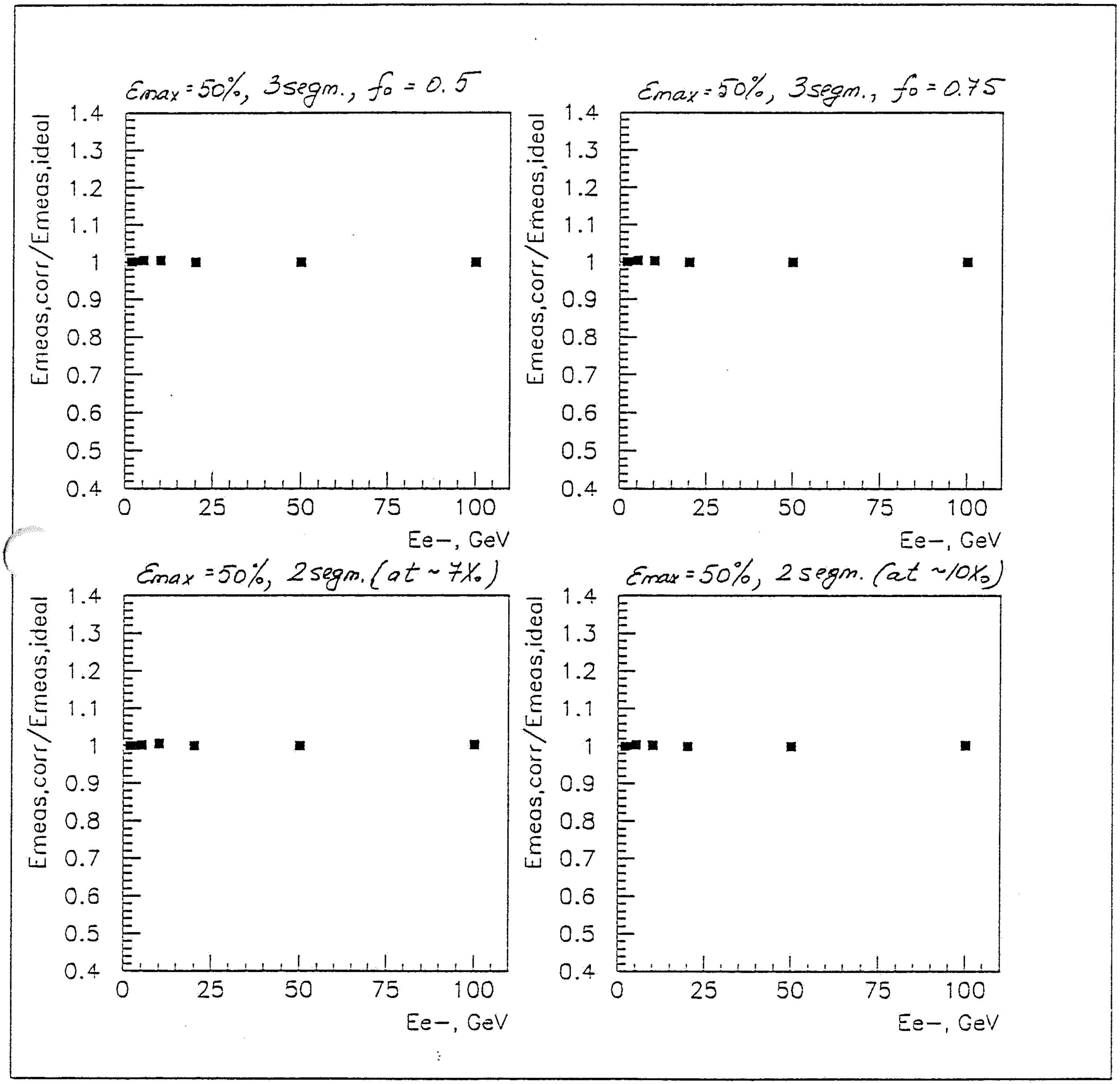
X=5.05, 1 p.e./MIP/tile
E_{vis}/E_{ideal}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
0
100
200
300
400
500
E_{e-}, GeV

Fig. 1



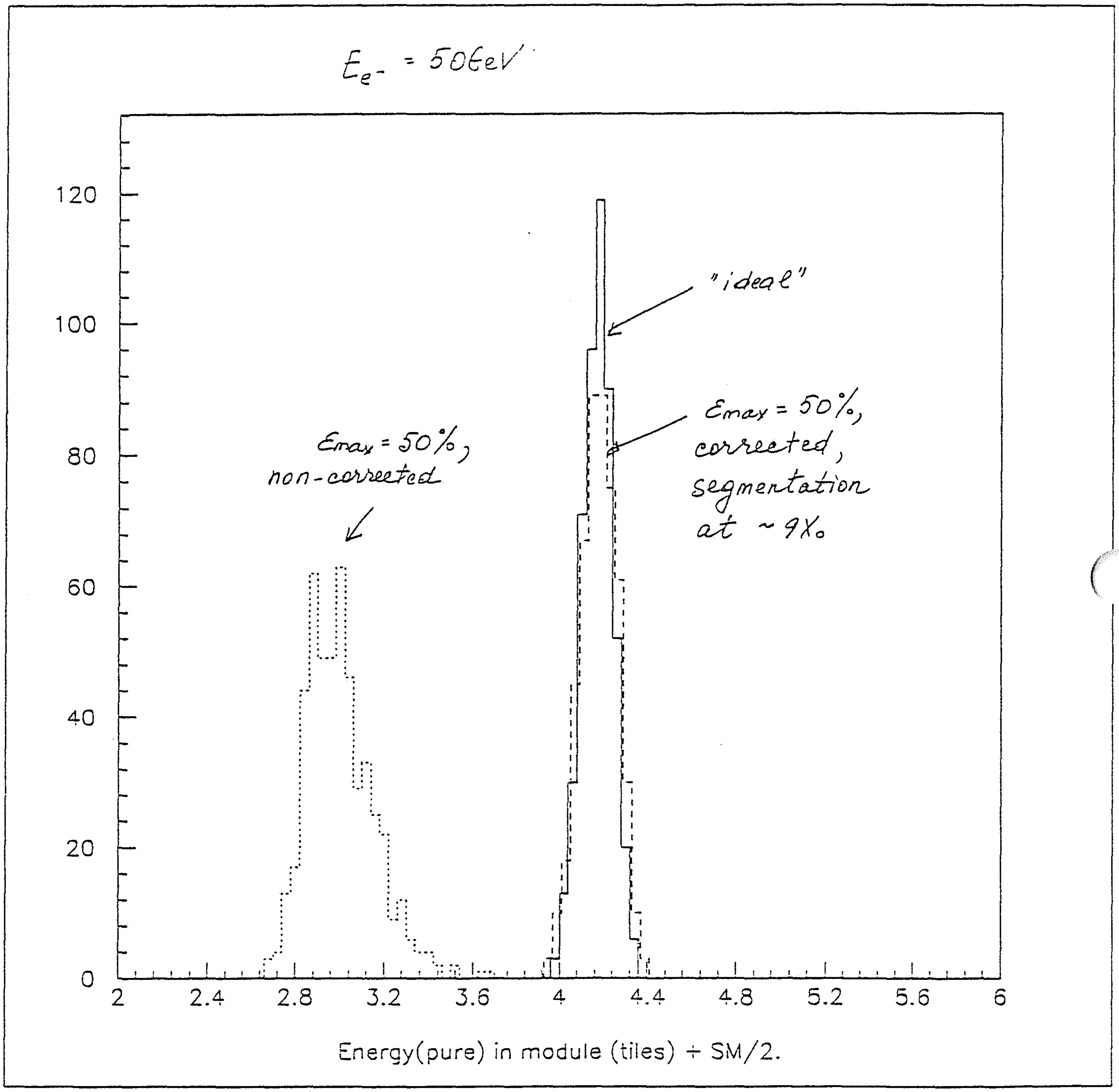
RMS data
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
$\sqrt{(\sigma E/E)^2_{rad.dam.} - (\sigma E/E)^2_{ideal}}$, %
E_{e^-}, GeV
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2

Fig. 2



εmax = 50%, 3segm., f0 = 0.5
εmax = 50%, 3segm., f0 = 0.75
εmax = 50%, 2segm. (at ~7X0)
εmax = 50%, 2segm. (at ~10X0)
Emeas,corr/Emeas,ideal
Ee−, GeV
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
25
50
75
100

Fig. 3



E_{e^-} = 50GeV
120
100
80
60
40
20
0
2
2.4
2.8
3.2
3.6
4
4.4
4.8
5.2
5.6
6
"ideal"
ε_{max} = 50%, corrected, segmentation at ~9X_0
ε_{max} = 50%, non-corrected
Energy(pure) in module (tiles) ÷ SM/2.

Fig. 4

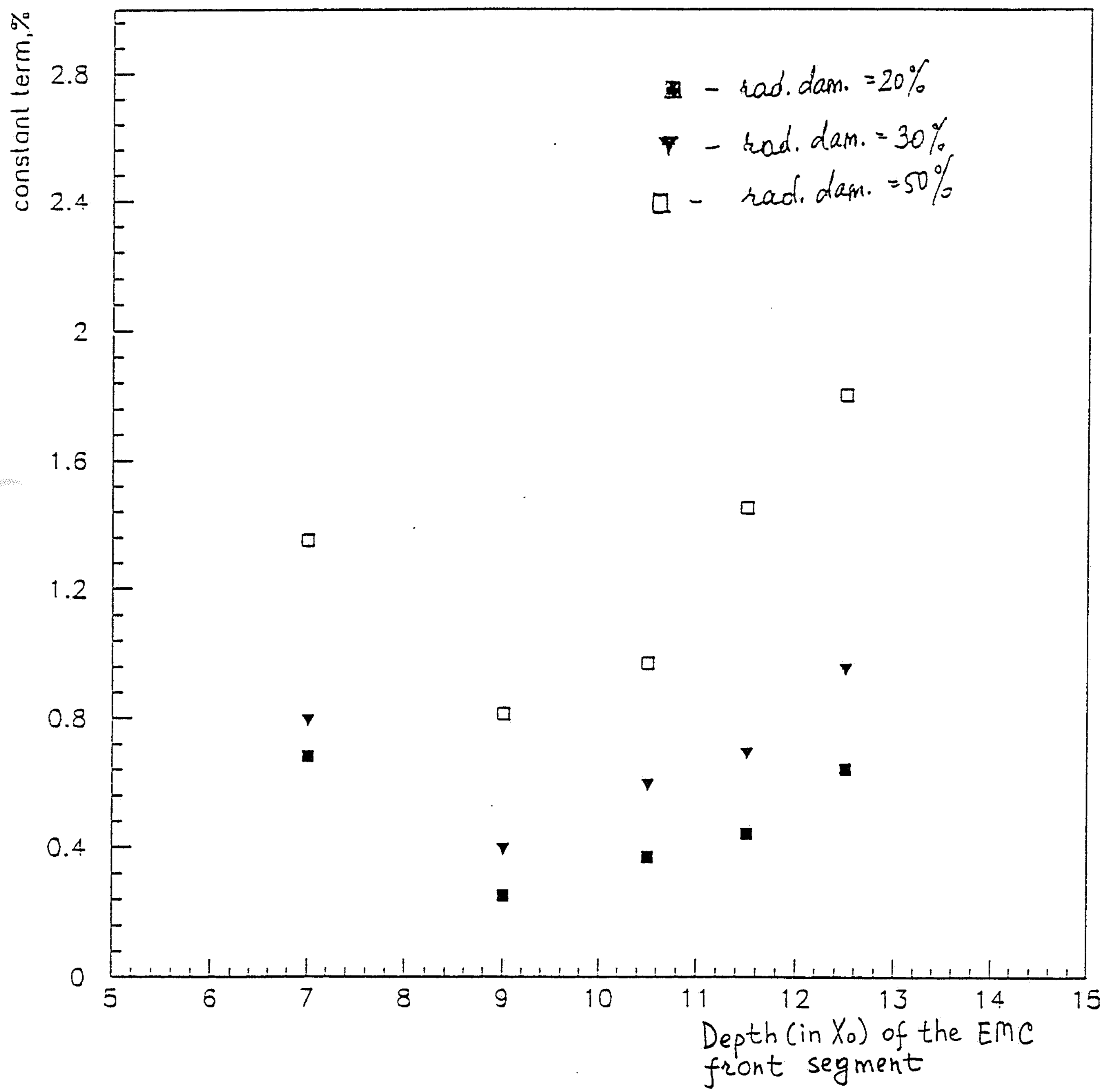

constant term,%
2.8
2.4
2
1.6
1.2
0.8
0.4
0
5
6
7
8
9
10
11
12
13
14
15
- rad. dam. =20%
- rad. dam. =30%
- rad. dam. =50%
Depth (in X_0) of the EMC front segment

Fig. 5

e⁻ (50 GeV)

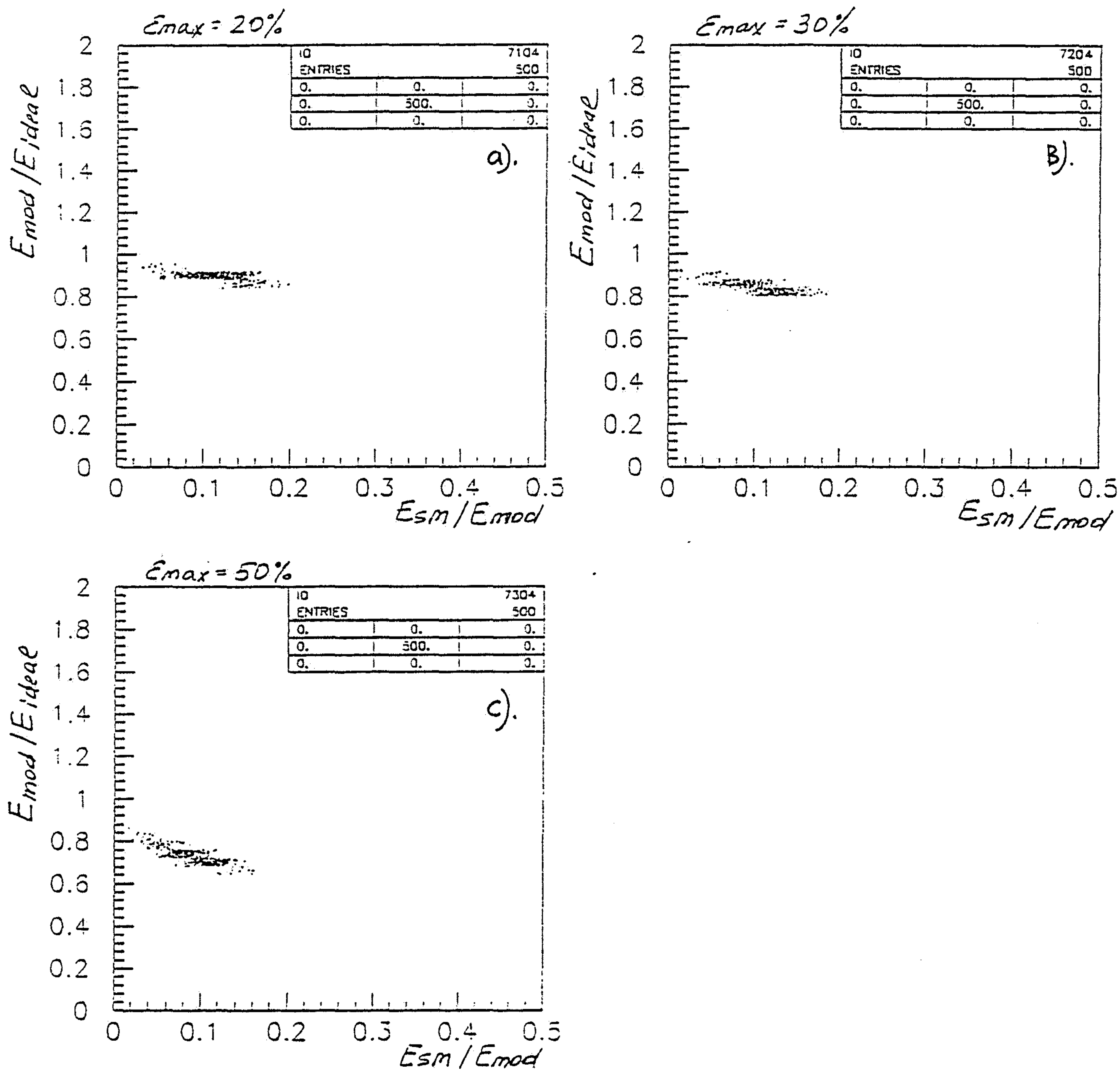
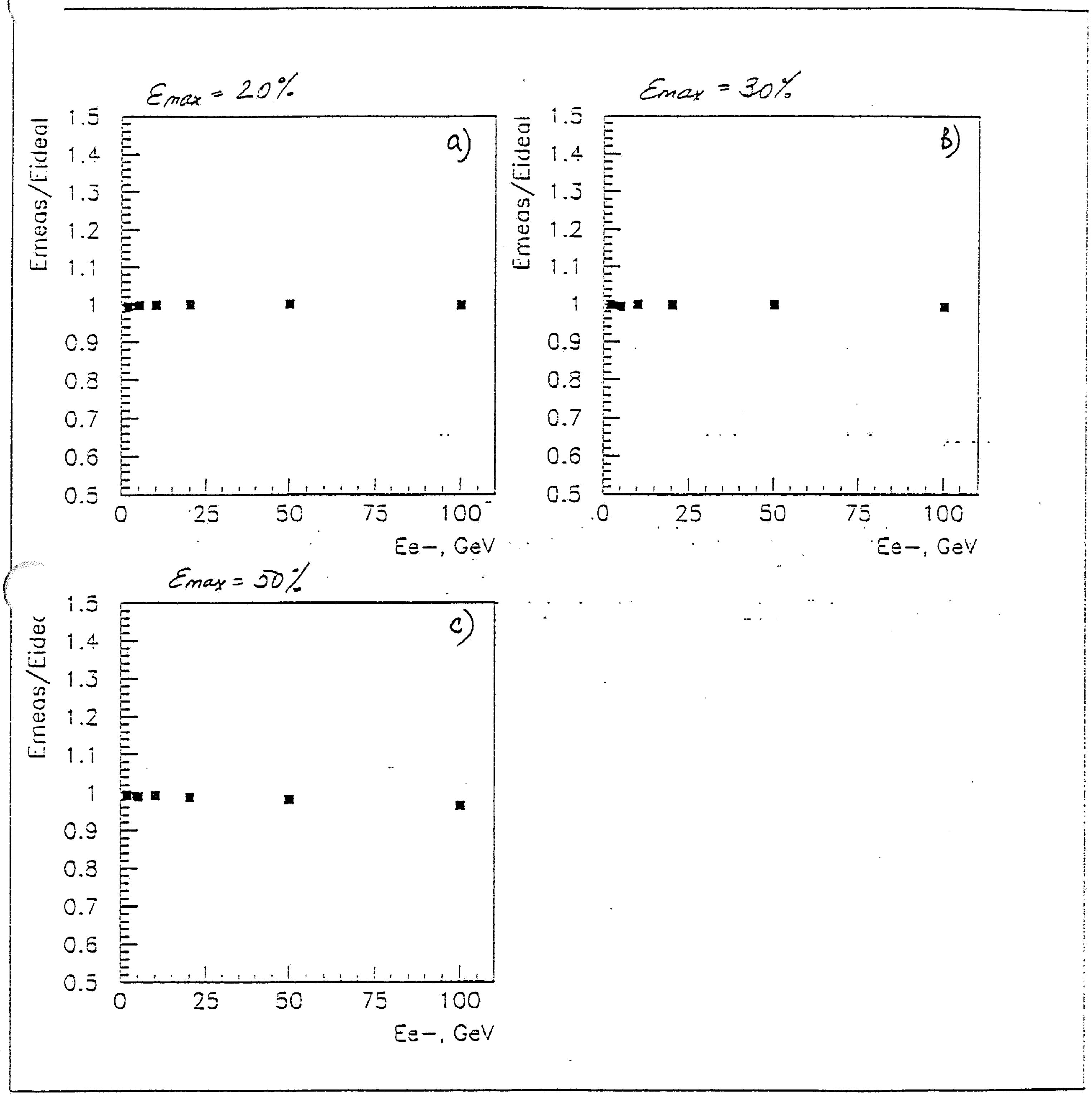

Emax = 20%
ID 7104
ENTRIES 500
a).
Emod / Eideal
Esm / Emod
Emax = 30%
ID 7204
ENTRIES 500
B).
Emax = 50%
ID 7304
ENTRIES 500
c).

Fig. 6



εmax = 20%
a)
Emeas/Eideal
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
25
50
75
100
Ee−, GeV
εmax = 30%
b)
Emeas/Eideal
Ee−, GeV
εmax = 50%
c)
Emeas/Eidea
Ee−, GeV

Fig. 7

e⁻, 50 GeV

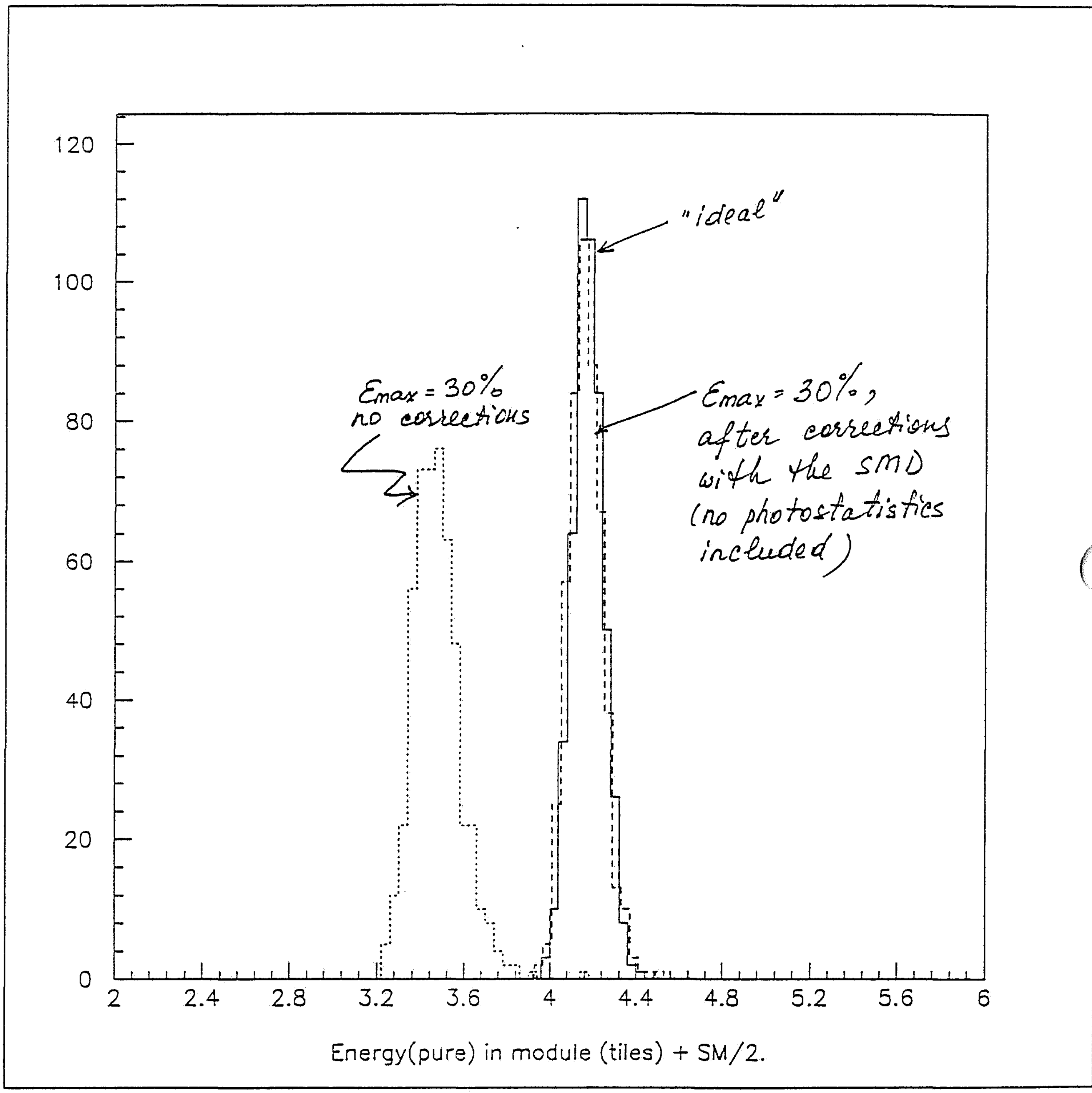


Fig. 8a

e^-, 100 GeV

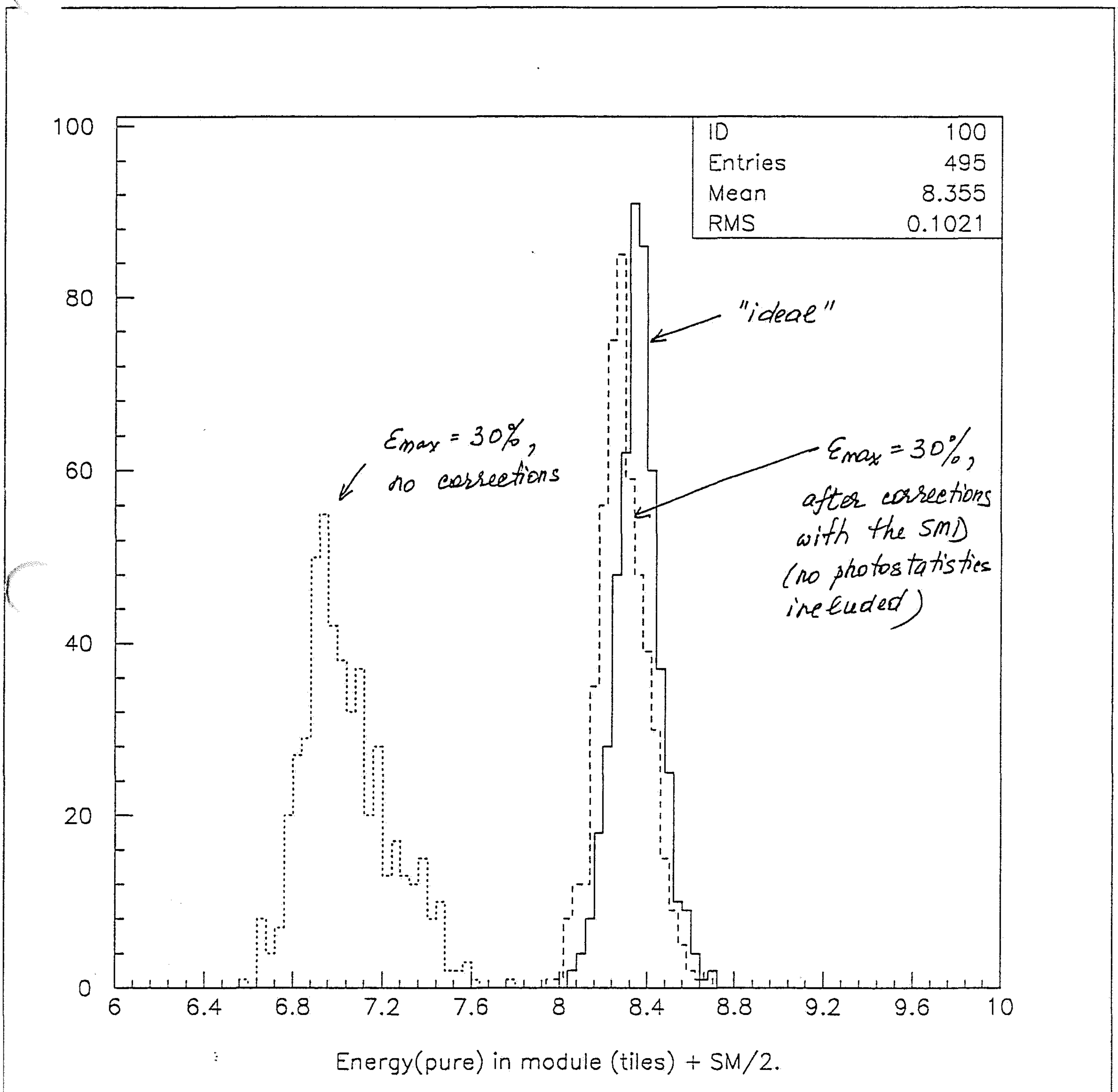


Fig. 8B

e⁻, 500GeV

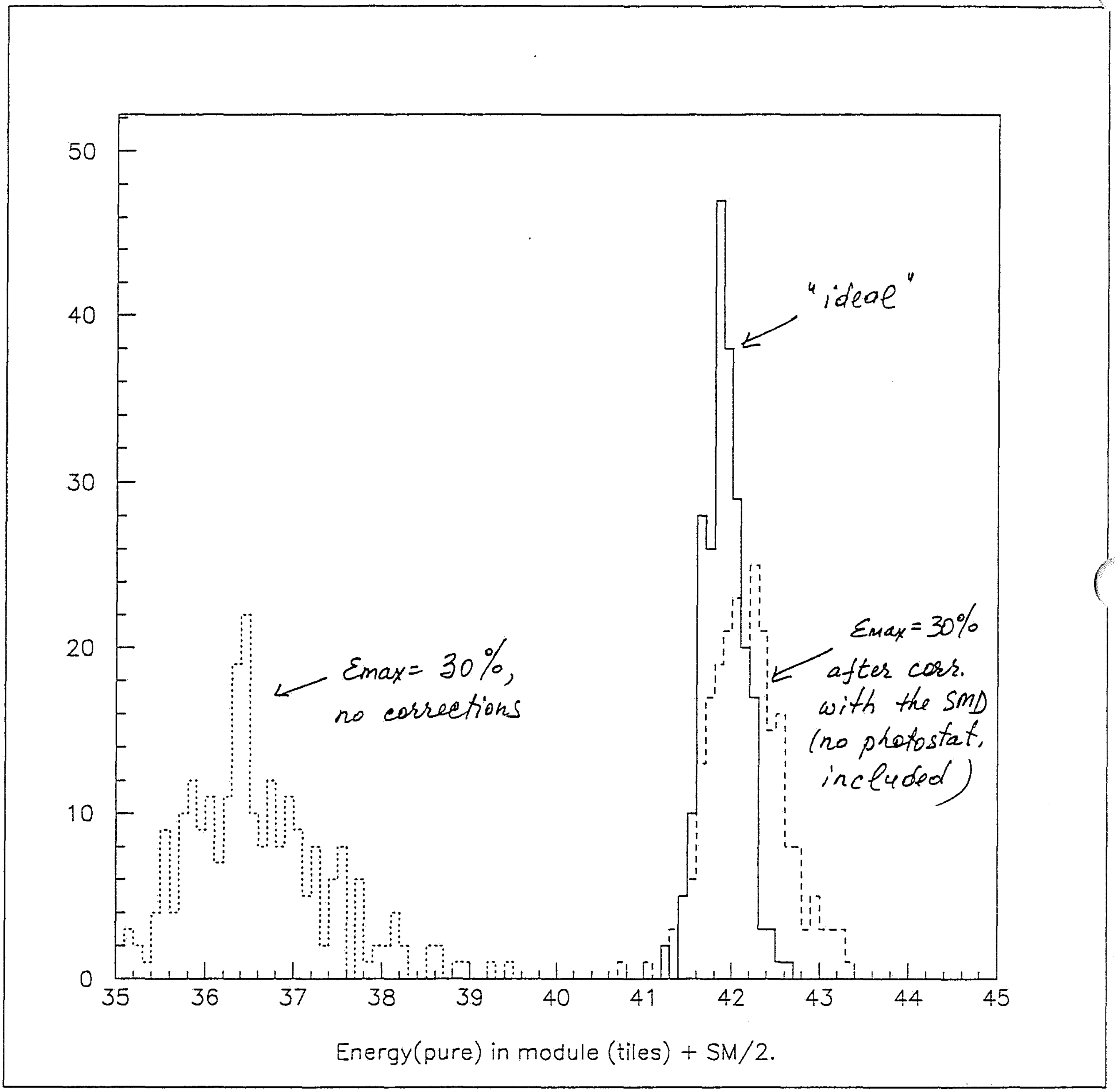


Fig. 8c

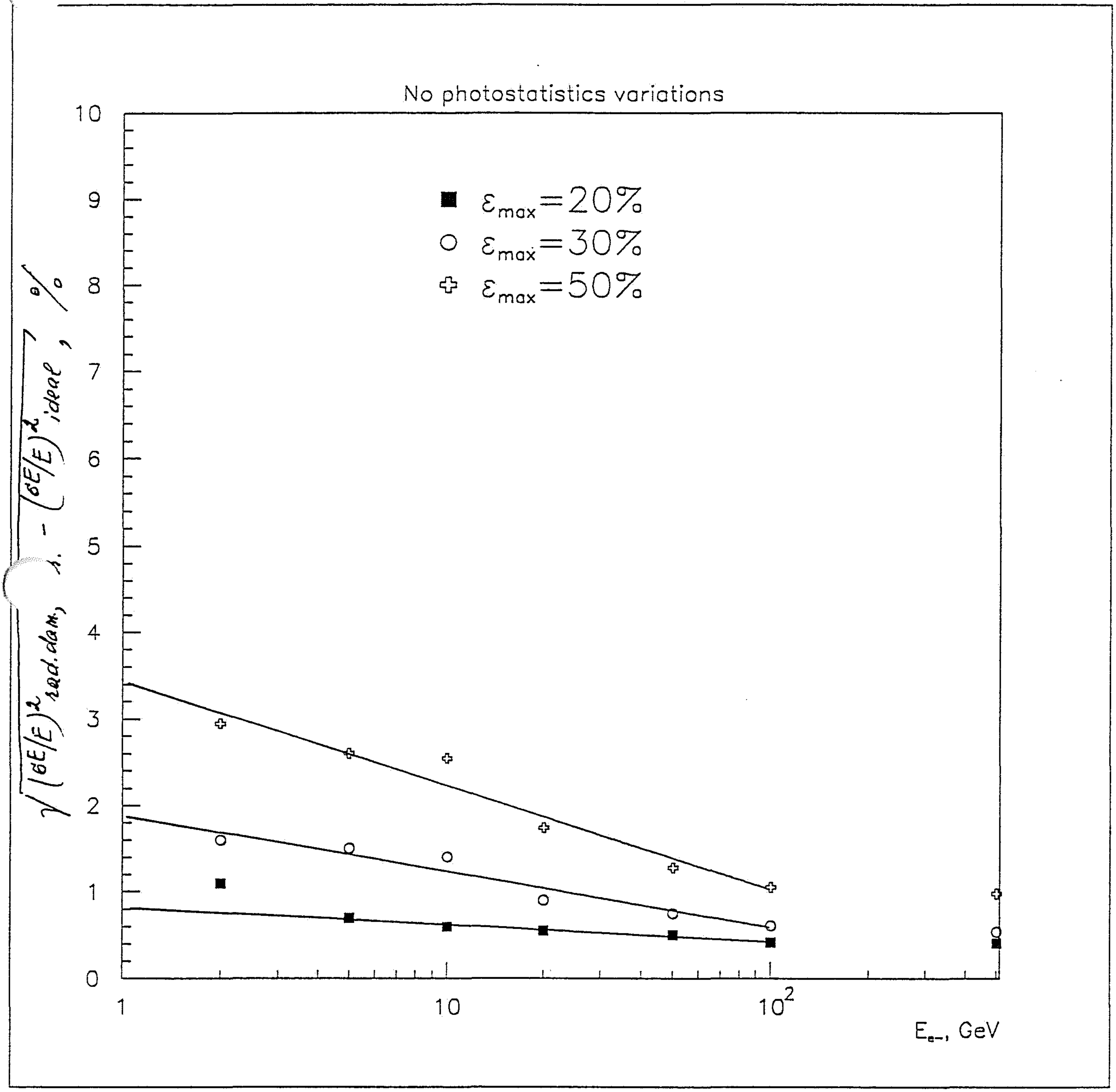

No photostatistics variations
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
$\sqrt{(\sigma E/E)^2_{rad.dam.} - (\sigma E/E)^2_{ideal}}$, %
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2
E_{e^-}, GeV

Fig. 9

e^-, 50 GeV

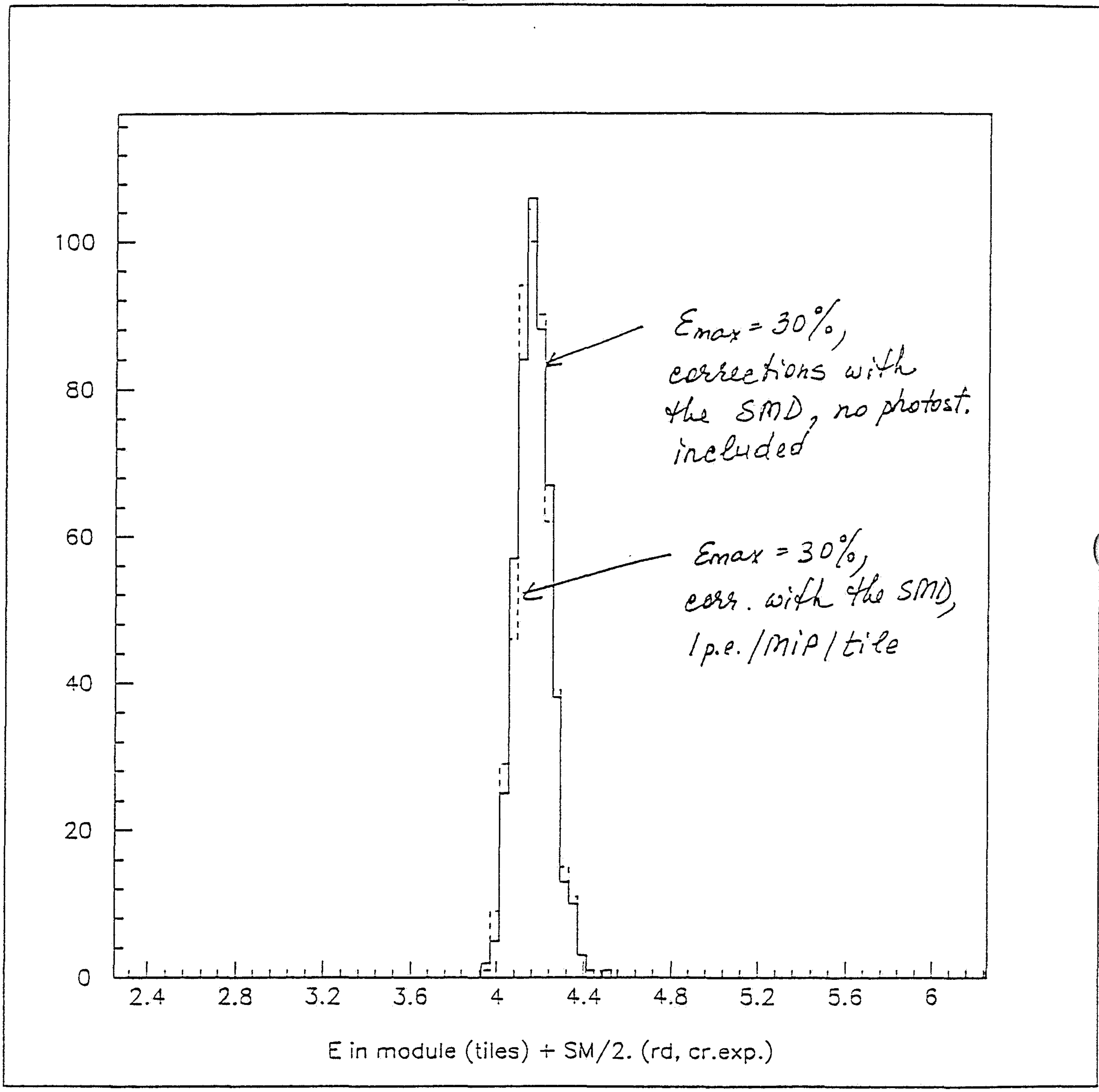
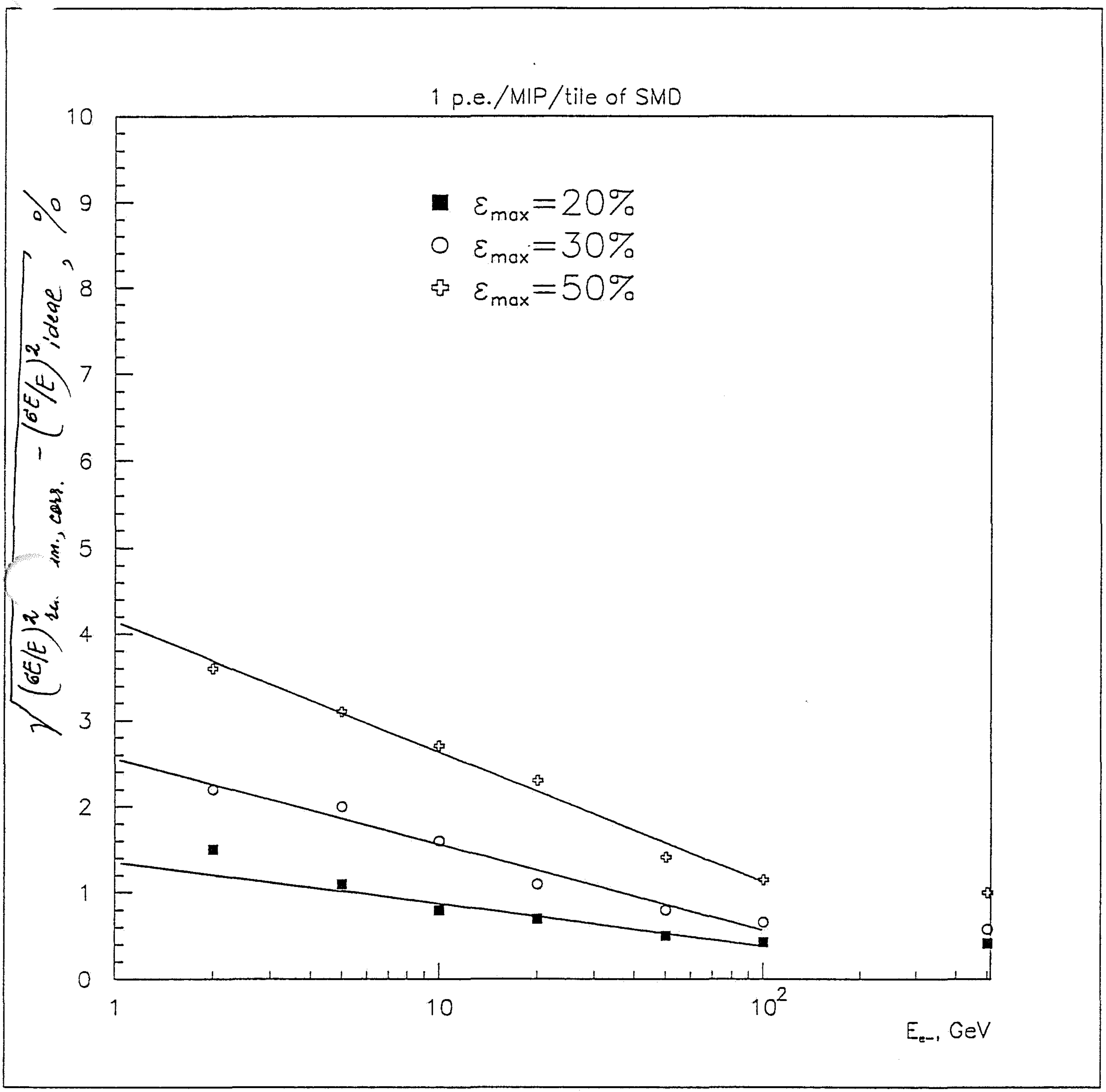


Fig. 10



1 p.e./MIP/tile of SMD
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
E_{e^-}, GeV

Fig. 11

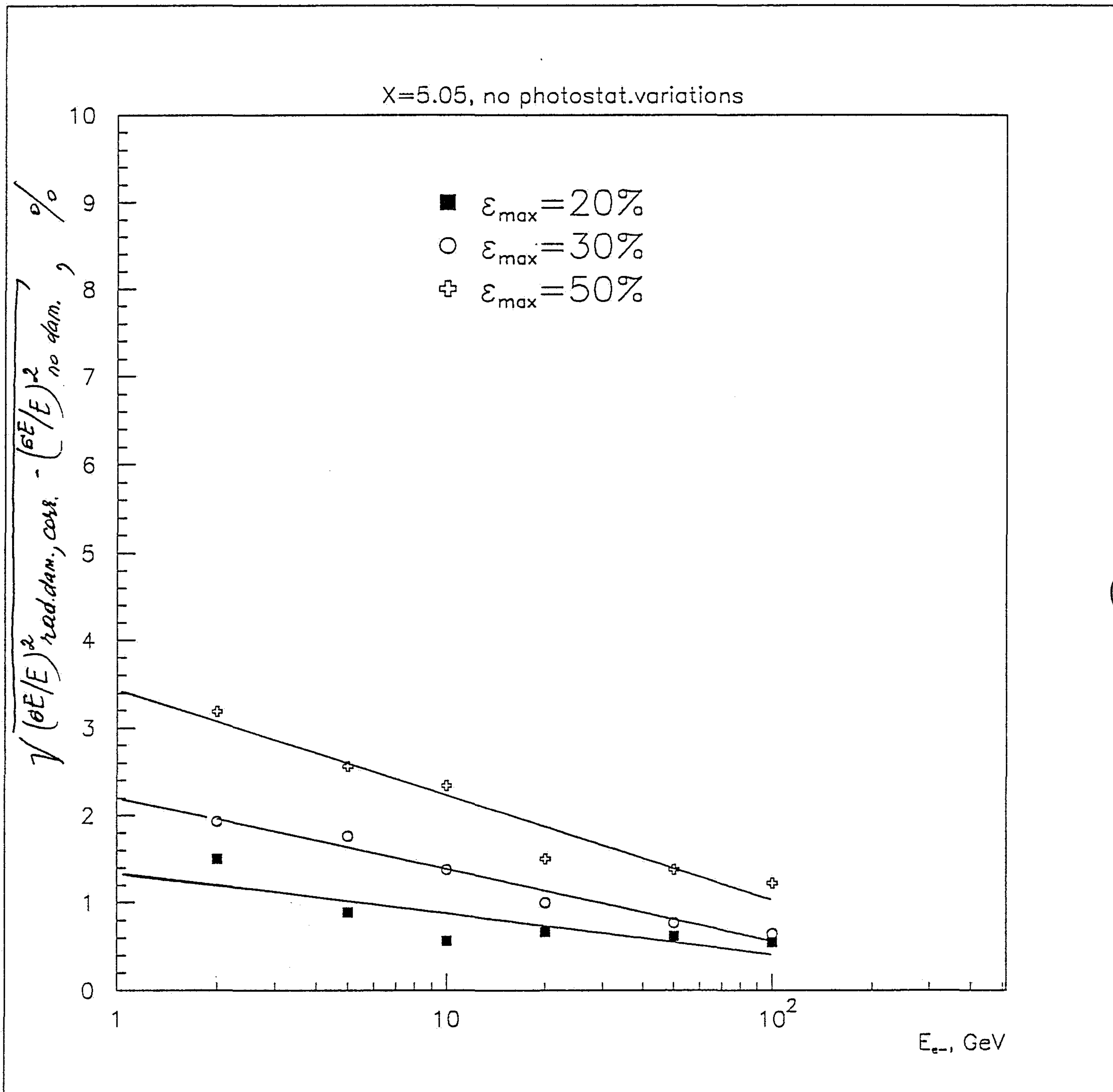
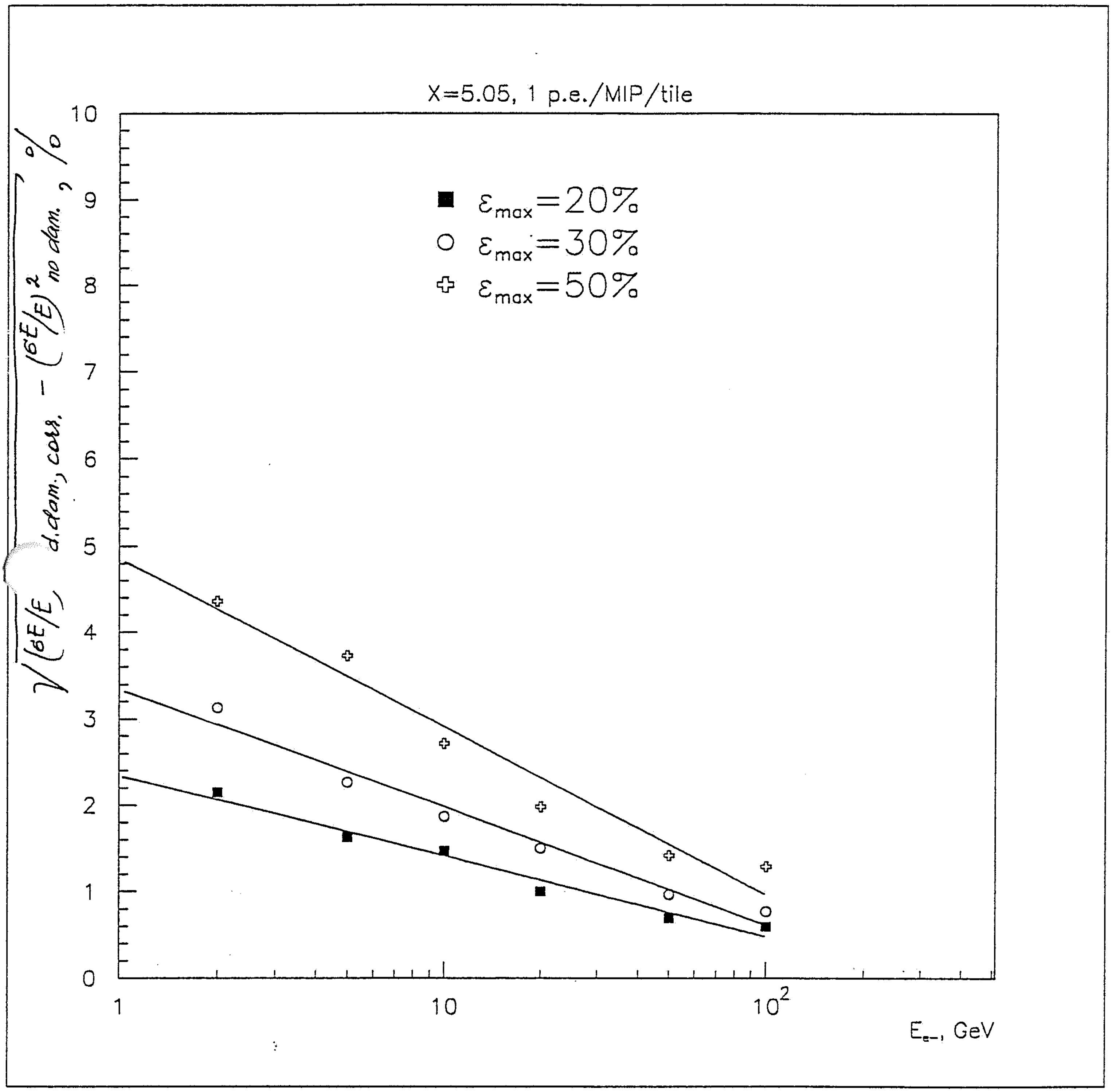
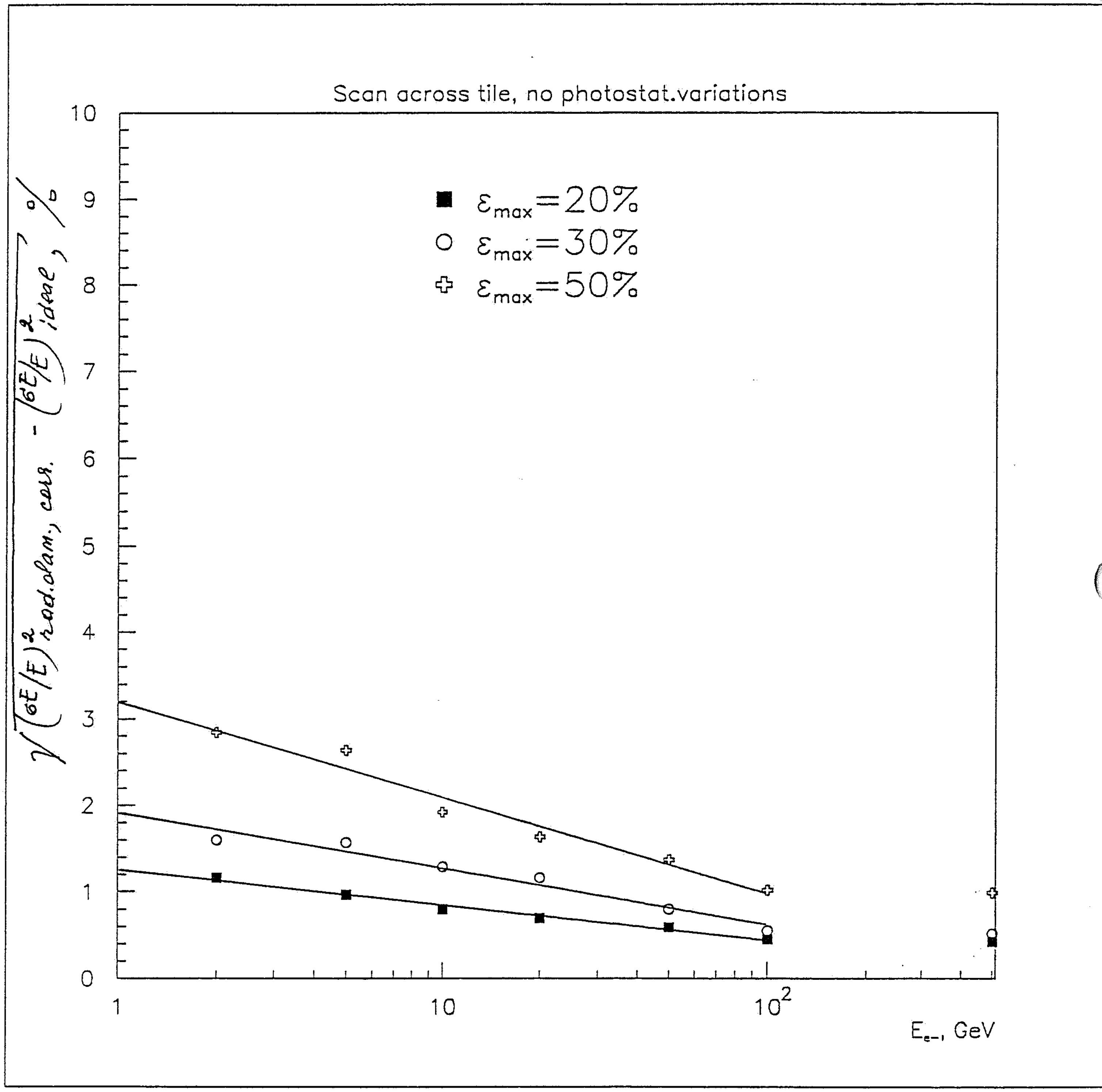

X=5.05, no photostat.variations
ε_{max}=20%
ε_{max}=30%
ε_{max}=50%
$\sqrt{(\sigma E/E)^2_{rad.dam.,corr.} - (\sigma E/E)^2_{no\ dam.}}$, %
E_{e-}, GeV
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2

Fig. 12a



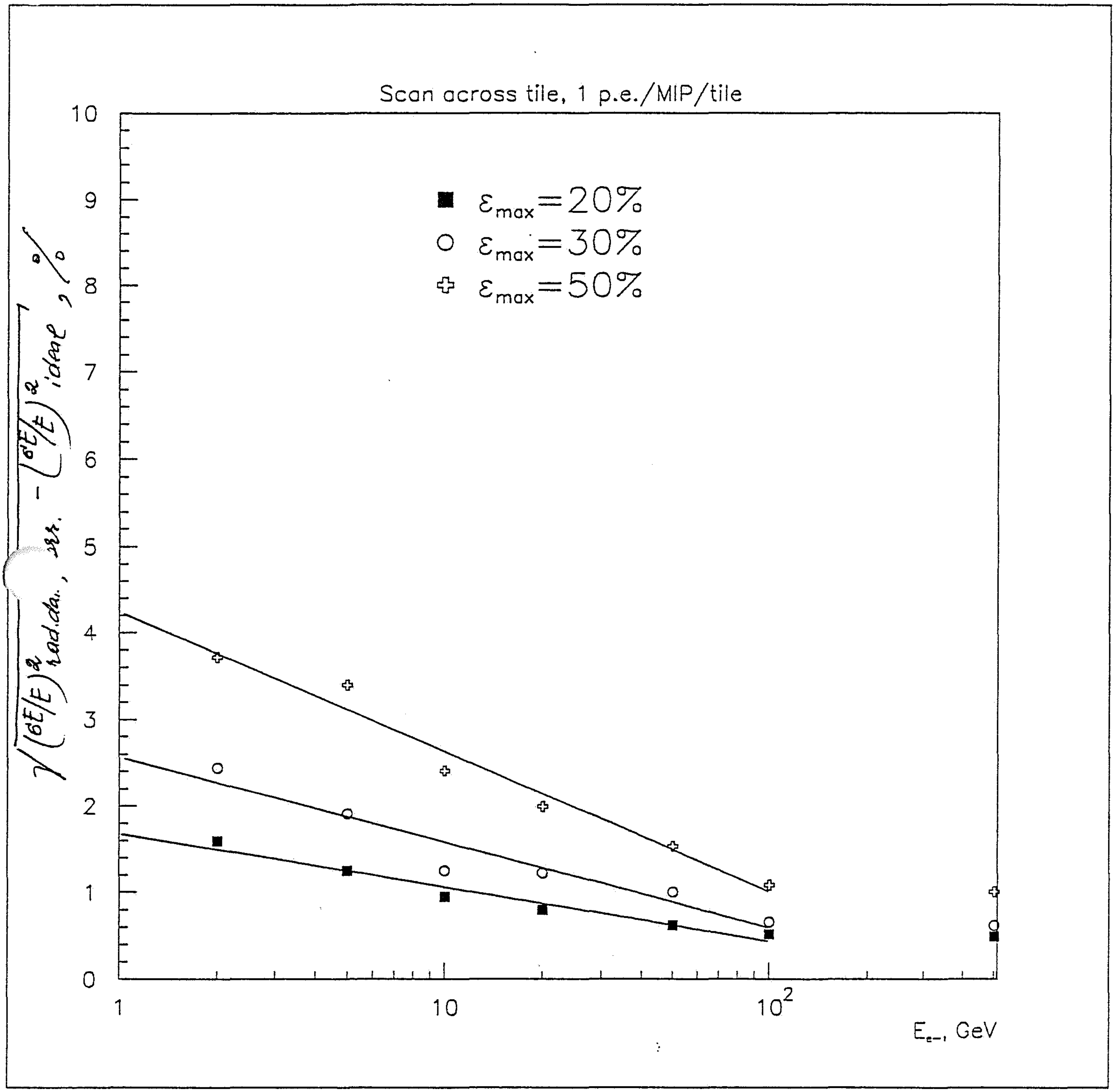
X=5.05, 1 p.e./MIP/tile
$\sqrt{(\sigma E/E)^2_{d.dam., corr.} - (\sigma E/E)^2_{no\ dam.}}$, %
ε_{max}=20%
ε_{max}=30%
ε_{max}=50%
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2
E_{e-}, GeV

Fig. 12b



Scan across tile, no photostat.variations
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
$\sqrt{(\sigma E/E)^2_{rad.dam., corr.} - (\sigma E/E)^2_{ideal}}$, %
E_{e^-}, GeV
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2

Fig. 13a



Scan across tile, 1 p.e./MIP/tile
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
$\sqrt{(\sigma E/E)^2_{rad.dam.,\,corr.} - (\sigma E/E)^2_{ideal}}$, %
E_{e-}, GeV
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2

Fig. 13b

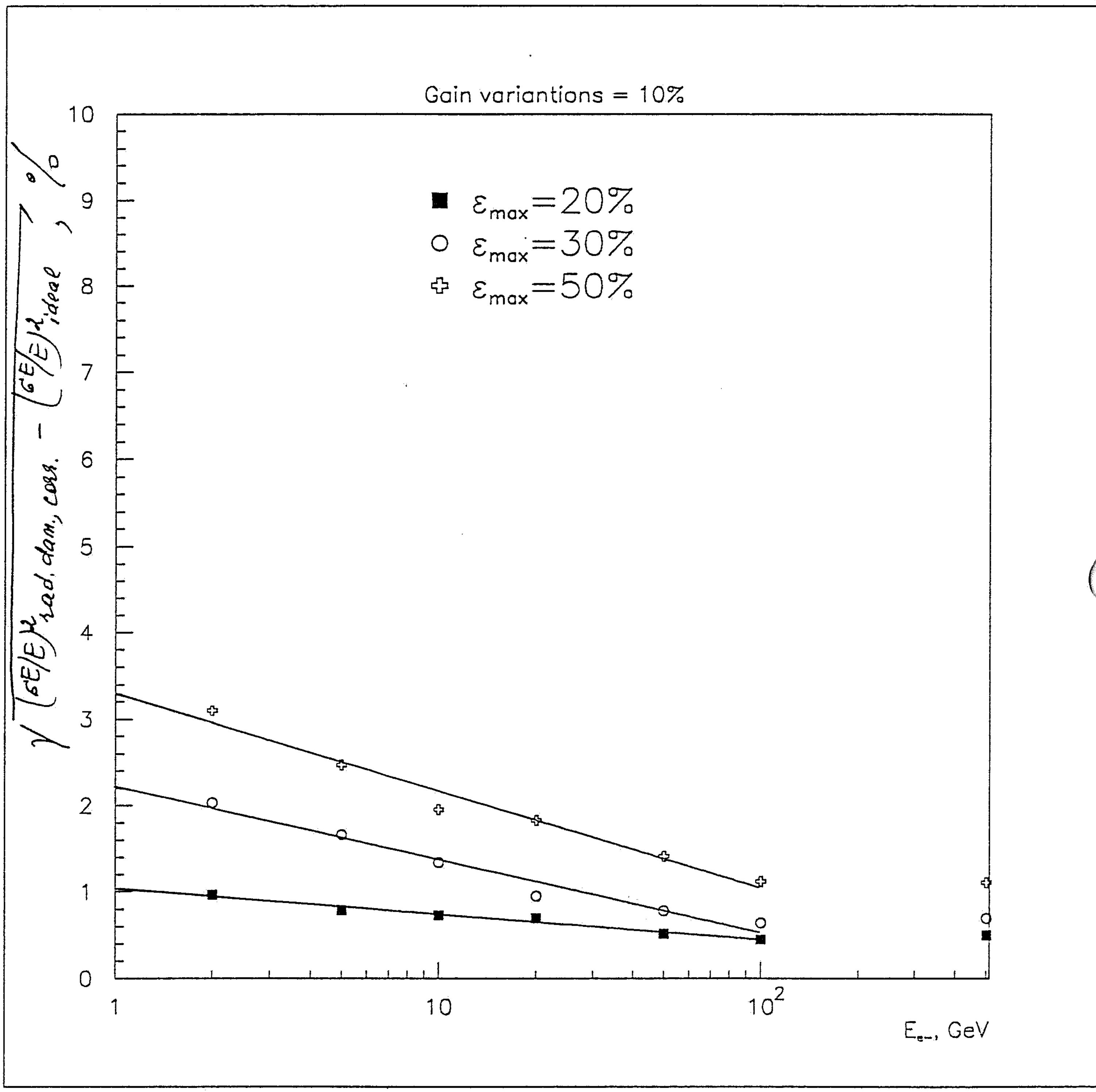
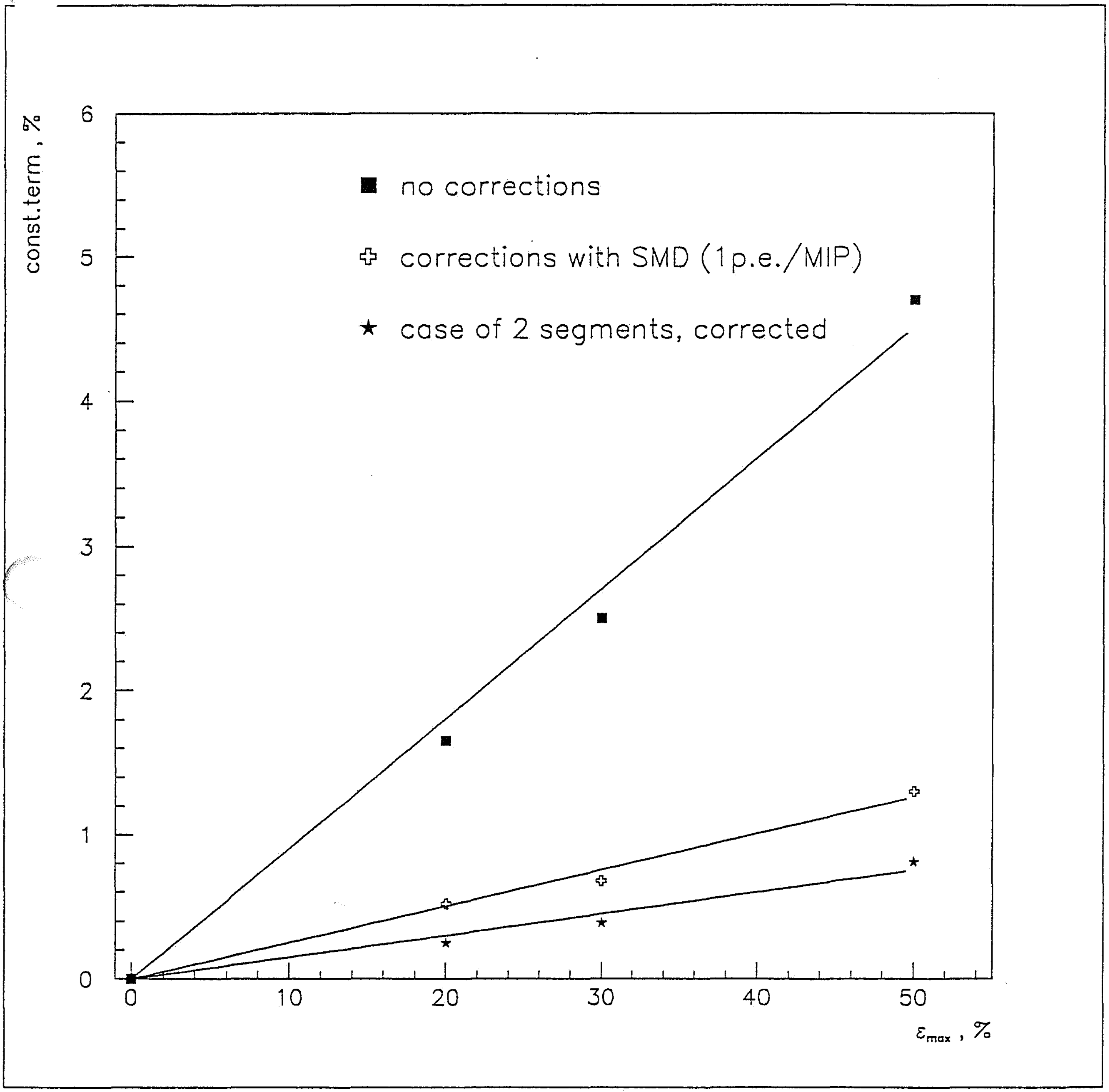

Gain variantions = 10%
$\varepsilon_{max}=20\%$
$\varepsilon_{max}=30\%$
$\varepsilon_{max}=50\%$
$\sqrt{(\sigma E/E)^2_{rad.dam,corr.} - (\sigma E/E)^2_{ideal}}$, %
E_{e-}, GeV
10
9
8
7
6
5
4
3
2
1
0
1
10
10^2

Fig. 14



const.term , %
6
5
4
3
2
1
0
no corrections
corrections with SMD (1p.e./MIP)
case of 2 segments, corrected
0
10
20
30
40
50
ε_{max} , %

Fig. 15