Fermi National Accelerator Laboratory

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Effects of Radiation Damage on Z Mass Resolution in the Process $H \to ZZ \to eeee$ *

Dan Green
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

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EFFECTS OF RADIATION DAMAGE

ON

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Fermilab

A. INTRODUCTION

The study of radiation damage in scintillation based detectors has received a great impetus with the advent of SSC R&D. One aspect of the subject that has received lesser attention is the creation of a model for the impact of radiation damage to a calorimeter on some ensemble of Physics topics. Clearly, that ensemble is, in itself, somewhat limited. One would not run at elevated luminosities in a study of top; it is likely that high luminosity running would concentrate on rate/statistics limited processes where a 10 fold luminosity increase might yield a two fold increase in mass reach.[1]

Fortunately, these high mass processes are naturally the province of the "central" region. For a state of mass M, the maximum kinematically allowed rapidity is, $y_{max} = \ln [M/\sqrt{s}]$. As an example, a 1 TeV state has a rapidity plateau width, at the SSC, of roughly 2 (y_{max}-2) ~ 3.2. Since the radiation dose is a strong function of rapidity[2], one naturally is in a less severe situation than might initially be feared. Obviously, the impact of radiation damage depends on the physics process that is being considered.

It is also true that a comprehensive understanding of how to translate radiation damage measurements of transmission loss for short time exposures into degradation of detector performance does not exist. A conversion of short term tests into long term exposure needs to be made. Similiarly, a conversion of transmission loss into loss of resolution also needs to be made. Finally, the incorporation of a program of periodic calibration into the radiation damage model must also occur before one can assess the impact of the radiation dose on the physics process in question. An initial attempt has herein been made in modelling the damage and studying its impact on one particular process. Much more needs to be done before one can be comfortable with the conclusions drawn from these Monte Carlo studies. In particular, long term electron exposures of full sized EM prototypes will provide a crucial baseline for the models of radiation damage.

B. H → ZZ AND RESOLUTIONS

The baseline process was chosen to emphasize EM calorimetry, since it is here that the maximum dose occurs. The process is the productaion of a Higgs boson of 0.8 TeV mass which subsequently decays into a pair of Z bosons. The Z bosons then decay into electrons. For a Higgs at y = 0, assuming 90° Z decays, the Z bosons have momenta of 0.4 TeV, and the electrons have 0.2 TeV momenta with a 25° opening angle. The ISAJET events verify this simple estimate; the electron transverse momentum has a mean of 0.166 TeV (Jacobean peak) and an r.m.s. of 0.092 TeV. The Higgs is expected to have a rapidity plateau of ~ 2(y_{max}- 2) or +- 1.9 units of rapidity. The ISAJET distribution of pseudorapidity for the electrons is shown in Fig. 1. Indeed, ignoring the smearing of the 2 sequential decays, one sees that there is a plateau of roughly the expected width.

The natural width against which a particular detector or detector mode of operation should be compared is;

$$\Gamma_Z/M_Z \sim \alpha_W$$
$$\alpha_W = \alpha/\sin^2\theta_W \sim 0.033 \quad (1)$$

This Lorentzian full width implies a standard deviation in Z mass of ~ 1.38%. The contribution to the Z mass resolution due to momentum error in the calorimetric measurement is;

$$dPe/Pe = [0.02/\sqrt{Pe} \oplus 0.01]$$
$$dM_Z/M_Z = 1/\sqrt{2}\ (dPe/Pe) \quad (2)$$

It is assumed that an EM tower has an "intrinsic" error due to transverse and longitudinal nonuniformities in construction, as shown in Eq. 2. Presumably the "stochastic"; term is due to counting statistics, while the "constant" term is due to irreducible nonuniformities. Evaluating the Z mass error due to a calorimetric momentum error as given in Eq. 2, one finds a standard deviation (s.d.) of 1.2%. This term is comparable to the error due to the natural width. The Monte Carlo result, using SSCSIM, a Fermilab product, is shown in Fig.2. The observed s.d. is 1.4%, in good agreement with the simple estimate based on y = 0 production and symmetric decays.

There is an additional contribution due to the finite size of the EM tower. A rough estimate of the size of this term is;

$$dM_Z/M_Z = \sqrt{2}\ (d\theta e/\theta ee) \quad (3)$$

Assuming a tower size of (0.05) in both pseudorapidity and azimuthal angle, one estimates a Z mass s.d. of 4.1%. This tower size is appropriate for fine grained detectors without "shower maximum" tracking detectors, or for the situation where such tracking detectors fail to function well at elevated luminosities. The Monte Carlo result for this case is given in Table 1, along with tabulated results for all the Monte Carlo conditions herein attempted. The Z mass s.d. of 3.5% agrees well with the simple estimates made above. Clearly, for these boosted Z bosons, it is the angular resolution which dominates and not the calorimetric measurement. It is the mass scale set by the natural width against which the errors in mass due to position and momentum must be evaluated. In addition, this scale is the natural one against which to compare the effects of radiation damage.

Finally, the rest of the event was added. In the previous Figures, only the electrons from the Z decay were counted in the EM calorimeter tower energy. In jet decays of Z bosons, fluctuations in the underlying event and in the jet fragmentation process are very important for the mass resolution.[3] In the leptonic decay case, a smaller cone size of R = 0.1 (~ 16 towers) can be used. As can be seen from Table 1, the effect of the underlying event is very small, given the small size of the cone clustering radius, R = 0.1.

C. MODEL FOR RADIATION DAMAGE, CALIBRATIONS

Any real calorimeter must be calibrated tower to tower and monitored for gain shifts. Irregularities in the production of the absorber thickness, the sampling medium thickness, and/or the sampling signal output will inevitably lead to variations among towers which need to be "calibrated out." The model adopted in this note assigns a point to point random calibration error to this procedure. In what follows a value of 2% (Gaussian s.d.) was assigned. The resulting Z mass error is given in Table 1. There is a degradation in Z mass resolution from 3.5% to 3.9%, which is easily understood using Eq. 2.

The radiation field for the SSC is assumed to be due entirely to beam-beam collisions. The levels may be obtained from simple considerations.[1] The number of neutral pions traversing a detector of area A is given in Eq. 4.

$$\begin{aligned} N(\pi^\circ) &= (\sigma_I \textstyle\int Ldt)\ (1/\sigma_I\ d\sigma/dy)\ (1/2\pi R_t^2)A \\ N(EM) &= N(\pi^\circ)\ N(mip/GeV)\ \langle P_t \rangle/\sin\theta \end{aligned} \tag{4}$$

In Eq. 4. L is the luminosity and σ_I is the inelastic cross section. The first factor in parentheses is then the total number of inelastic interactions. The density of pions in pseudorapidity is the second factor in parentheses. The third factor in parentheses is the solid angle subtended by the detector of area A at a perpendicular distance R_t. The momentum of the pions can be approximated as, $P_t \sim \langle P_t \rangle$ and $P = P_t/\sin(\theta)$. The shower of the neutral pions in the EM calorimeter leads to N(mip/GeV), which allows one to relate $N(\pi^0)$ to the number of mips traversing the calorimeter at shower maximim, N(EM).

The mips deposit an energy E(EM). Since the dose is the energy deposited per unit mass, the radiation dose in the EM calorimeter at shower maximum depends only on fundamental quantities and scales in angle as $1/[R_t^2 \sin(\theta)]$.

$$
\begin{aligned}
\mathrm{E(EM)} &= \mathrm{N(EM)}\ \Delta\mathrm{E}\ \rho l \\
\Delta\mathrm{E} &= 1.8\ \mathrm{MeV/(gm/cm^2)} \\
\mathrm{DOSE\ (EM)} &= \mathrm{E(EM)/V}\rho \\
\mathrm{V} &= \mathrm{A}l
\end{aligned}
\tag{5}
$$

For example, inserting some numbers, one finds that at 90° the dose at a luminosity of $L = 10^{34}/(\mathrm{cm^2sec})$ is 30 Krad for a one year (10^7sec) exposure. Assuming a cylindrical detector, radius 2.3 m, half length 4.5 m, the dose rises to 0.3 Mrad at $\eta = 2$, and 7 Mrad at $\eta = 3$. Assuming a 6% loss of light per Mrad, the light loss is equal to the point to point error of 2% at an η of ~ 2. These estimates serve to give us a ballpark intuition of the angular region over which the radiation damage might be relevant.

In Fig. 3. is shown the light loss in a variety of commonly used polymers as a function of the dose. The data is taken at 425 nm. The straight line is an approximate value of 6%/Mrad. Clearly, it is a reasonable representation of the data for PVT and polystyrene. It is also true that using longer wavelengths changes the coefficient of damage by significant factors.[4] For example, in polystyrene, for wavelengths > 600 nm, the loss of transmittance is < 10% for doses < 50 Mrad, implying a damage coefficient < 0.2%/Mrad which is 30 times less than the value assumed in this note.[5] Other plastics also hold out the promise of reduced losses. For example, the test beam results for an EM module constructed of 3-HF in FNAL E-774 imply a coefficient of ~ 2%/Mrad.[5]

It should also be pointed out that the dose is localized both in angle and in depth of the EM calorimeter. For $\eta = 3$, the incident momentum is ~ 6 GeV. The shower maximum occurs at a depth of ~ 6 r.l. If the dose were such as to halve the light output at shower maximum, the light output at 2 and 12 r.l. is reduced by only ~ 20%. Therefore, it is pessimistic to take the dose at shower maximum, apply the coefficient shown in Fig. 3, and assume that the signal from the summed depth segments of an EM calorimeter will be reduced by that same amount. Tests of prototypes in electron beams will shed light on just how pessimistic this assumption might be.

Given all these hedges and overestimates, the coefficient used in this note is 6%/Mrad. As discussed above, an individual tower was assigned a stochastic and constant error as in Eq. 2. The ensemble of towers was assumed to be calibrated periodically to 2% random tower-to-tower accuracy. The dose for a luminosity of $10^{34}/(\mathrm{cm^2sec})$ was used, and a period of 1 year between calibrations was chosen. During that period a linear loss in light yield was assumed, (1.-(6%/Mrad)$_*$dose$_*$ranf) but no correction for a knowledge of the time of occurance of the event in the calibration cycle was made. Presumably, this first order correction could trivially be applied, so that the procedure adopted here is, again, pessimistic. Finally, it is assumed that the loss of light output throughout the life of the calorimeter degrades the stochastic term. In this note a linear loss, 0.20$_*$(1. +(6%/Mrad)$_*$dose') was assumed. The dose' in this case was assumed to be due to a 10 year total exposure or, dose' = 10$_*$dose. As discussed above, given the depth localization of the dose, the increase in the stochastic term has probably been overestimated.

Just to set the scale, at 90° these assumptions lead to a 0.2% maximum loss between calibrations and a 1.8% growth of the stochastic term during the 10 year total lifetime of the experiment. At $\eta = 3$ there is a 36% loss between calibrations, and a factor of 4.6 growth in the stochastic error term. Note that, the implied growth in momentum resolution is not as great as it might seem. Using the expression given in Eq. 2, and noting that the momentum is ~ 2.0 TeV at $\eta = 3$ one finds that the factor of 4.6 in light loss translates into only a 2.3% resolution on the individual tower. The reason for this is that the constant term dominates over the stochastic term, even when the stochastic piece is increased by a large factor. Since this intrinsic tower error is still on the scale of the tower to tower calibration error, one can expect that the calorimeter is not degraded in a major way.

These losses appear to be fairly formidable. However, in order to find out how important they really are, one needs to fold in the angular distribution of the process in question (see Fig. 1.). It should also be stressed that the assumptions adopted in this note are perhaps too pessimistic, for the reasons sketched out above.

One note of caution. It has been implicitly assumed that longitudinal calibration has been carried out and that sufficient longitudinal segmentation of the EM calorimetry exists so that longitudinal shower fluctuations do not effect the constant term in Eq. 2. The damage is not constant in depth, and the EM shower fluctuations can lead to fluctuations in the energy measurement. Some experimental input is needed in order to confirm this assumption.

D. RESULTS USING SSCSIM

The model for radiation damage discussed in Section C was installed into SSCSIM. In addition, "minbias" events, *i.e.* dijet events with transverse momentum above 5 GeV, were overlapped as a Poisson distribution of mean = 16. This process assumes that the calorimetry is fast; *i.e.* sensitive only to one bunch crossing, or about 16 nsec. The number of overlap events is appropriate to one bunch live time for the calorimeter at a luminosity of $10^{34}/(\text{cm}^2\text{sec})$ The results are given in Table 1.

The Z mass s.d. for a 2% point to point calibration error, and 16 events, on average, overlapped was 4.1% for no radiation dose, but with towers of size $(0.05)^2$ in pseudorapidity-azimuthal angle space. A "LEGO" tower threshold [3] of 1.0 GeV reduces the s.d. to 3.8%. A dose corresponding to 10 years at $10^{34}/(\text{cm}^2\text{sec})$ with calibrations only every year increases this error to 4.3%. The actual distributions are shown in Fig. 4. Clearly, the effect of radiation damage, as modelled here, is not dramatic. The reasons for this have been indicated previously.

Another set of Monte Carlo runs was made assuming that "shower maximum" detectors were operated successfully at elevated luminosities. The results are given in Table 1 and in Fig. 5. The exposure is the same as that assumed for Fig. 4. A calorimeter without radiation damage has a Z mass s.d. of 2.0%, while the 10 year exposure at 10 times the SSC design luminosity leads to a 2.8% s.d. error. Although noticable, this s.d. is still of the same order as the natural width of the Z.

In summary, it was decided to only study a physics process relevant to high luminosity operation. Since such reactions tend to be high mass, and thus central, the radiation damage problem is somewhat alleviated. The resolution for Z bosons is dominated by angular errors and not by momentum errors unless the angular error is very small; i.e. as supplied by a "shower maximum" detector. Thus, with boosted Z bosons, the shower maximum detector must survive high L running in order that constraints be placed upon the EM calorimetry. In the absence of such a detector, the 0.8 TeV Higgs search is only slightly degraded by a 10 year exposure at 10 times the SSC design luminosity. If such fine resolution position detectors exist and survive, the degradation in Z mass is less than a 50% increase in s.d. error. Such an increase is unlikely to make a major impact on the success of the Higgs search. It would appear then, that existing technologies are sufficient, in that damage coefficients of known scintillators were incorporated into the Monte Carlo model. However, since a complete model has yet to be made, and since extended exposures of real prototype EM calorimeter modules to electron beams of ~ 6 GeV have not yet been carried out, these conclusions are necessarily tentative.

REFERENCES

[1]SDC at High Luminosity, D. Green., Tskuba April 23, 25, 1990, FNAL Conf-90/110

[2]Radiation Levels in SSC Detectors, D. Groom., Snowmass 1988, p. 711

[3]Dijet Spectroscopy at High Luminosity, D. Green., FNAL Conf-90/151

[4]Development of Plastic Scintillation Fibers, Plastic Scintillation Fiber Calorimetry and Its Readout System, F. Takasaki, Snowmass 1988, p. 785

[5]3-HF fiber, private communication, A. Bross, see also, Scintillating Fiber Detectors, Presentation to FNAL SDC group, January 18, 1990

TABLE 1

Z MASS RESOLUTION

Calibration Error (%)	Dose Years @ $10^{34}/(\mathrm{cm}^2\mathrm{sec})$ Between Calibrations	Total Exposure	$\Delta\eta\Delta\phi$	Events Overlapped (Poisson) Mean	LEGO Threshold (GeV)	σ (M_R/M_G) (%)	Comments
0	0	0	0	0	0	1.4	Pure
			$(0.05)^2$	0	0	3.5	Resolution
			$(0.05)^2$	1	0	3.5	Terms
2	0	0	$(0.05)^2$	1	0	3.9	Point To
	1	1		1	0	4.0	Point Errors
	0	0			0	4.1	Fast
2	0	0	$(0.05)^2$	16	1.0	3.8	Calorimetry
	1	10			1.0	4.3	@ 10^{34}; No
							Shower Max
	0	0	0	16	1.0	2.0	Fast
2	1	10				2.8	Calorimetry
							@ 10^{34}; With
							Shower Max

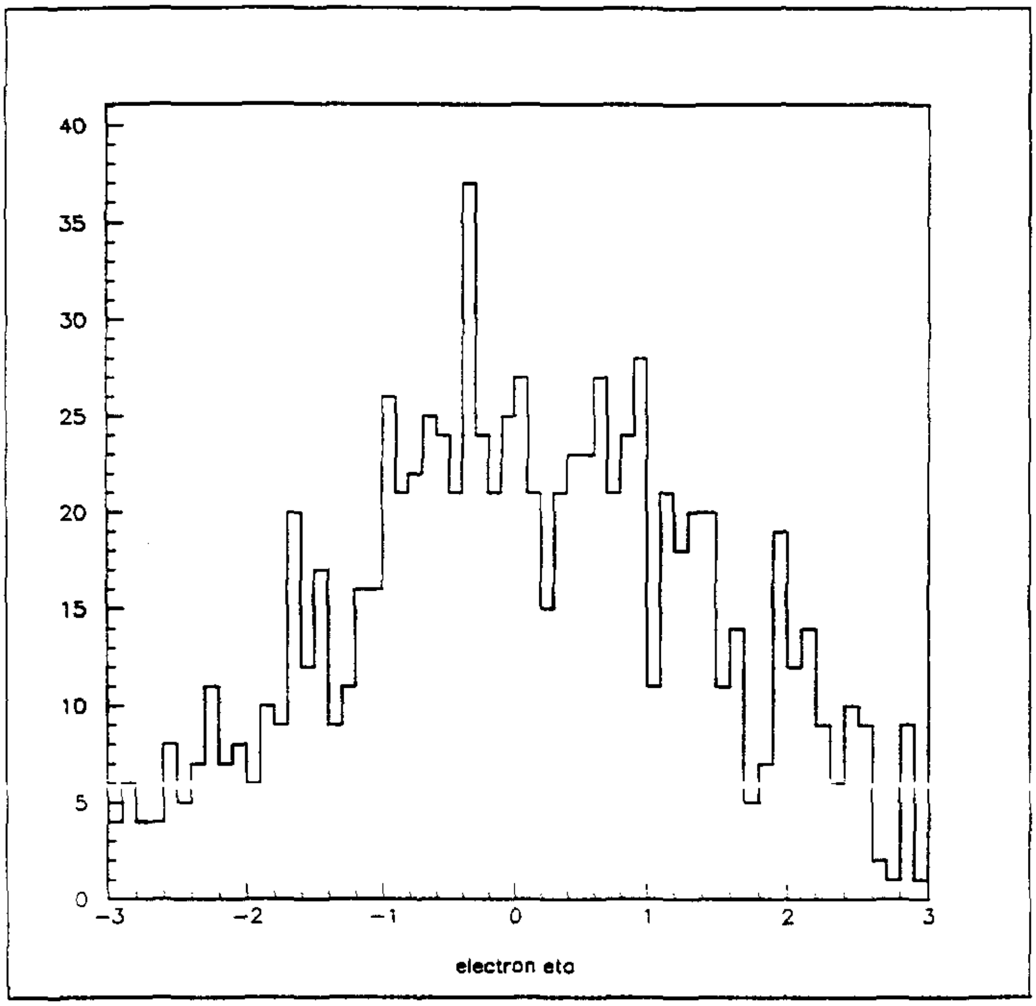

Fig. 1. Pseudorapidity distribution for electrons from the baseline process, H(800) → ZZ → eeee.

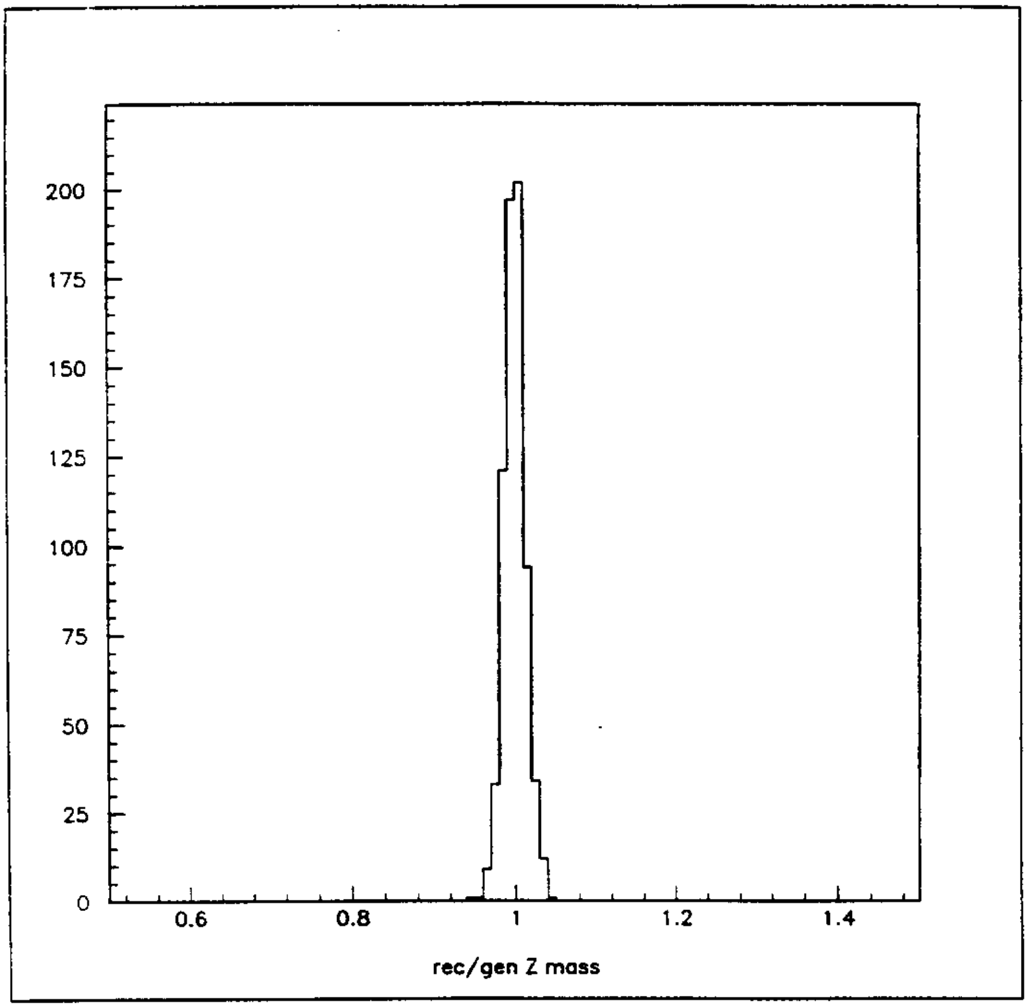

Fig. 2. **Mrec/Mgen distribution for ee in the case of perfect angular resolution and only individual tower resolution in momentum.**

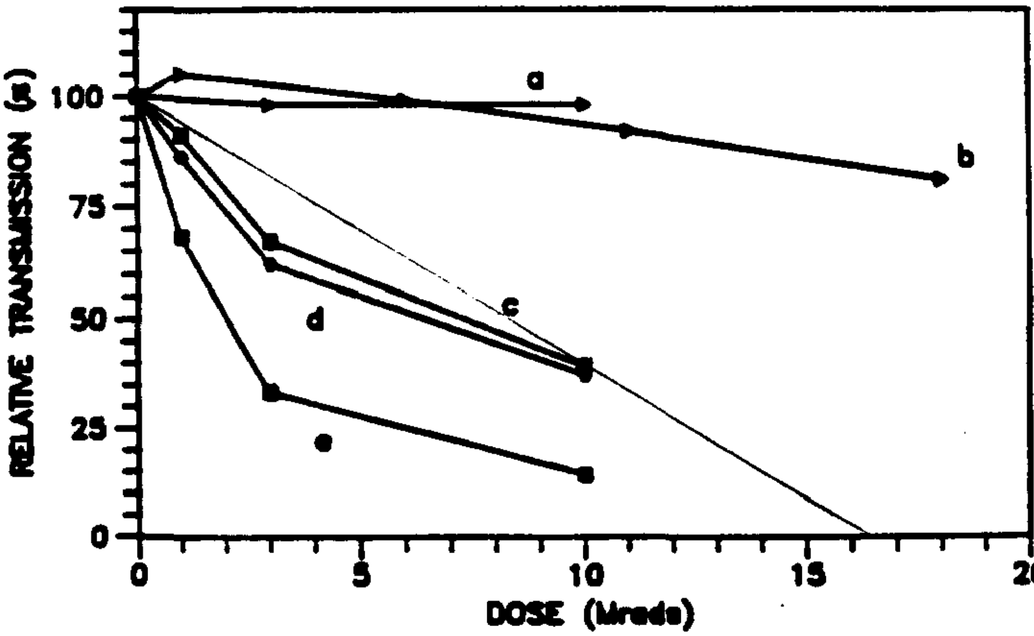

Fig. 3. Transmission at 425 nm for various polymers, normalized to values at no exposure. For example curve c = polystyrene and d = PVT. The linear reduction which is assumed in this note is also indicated.

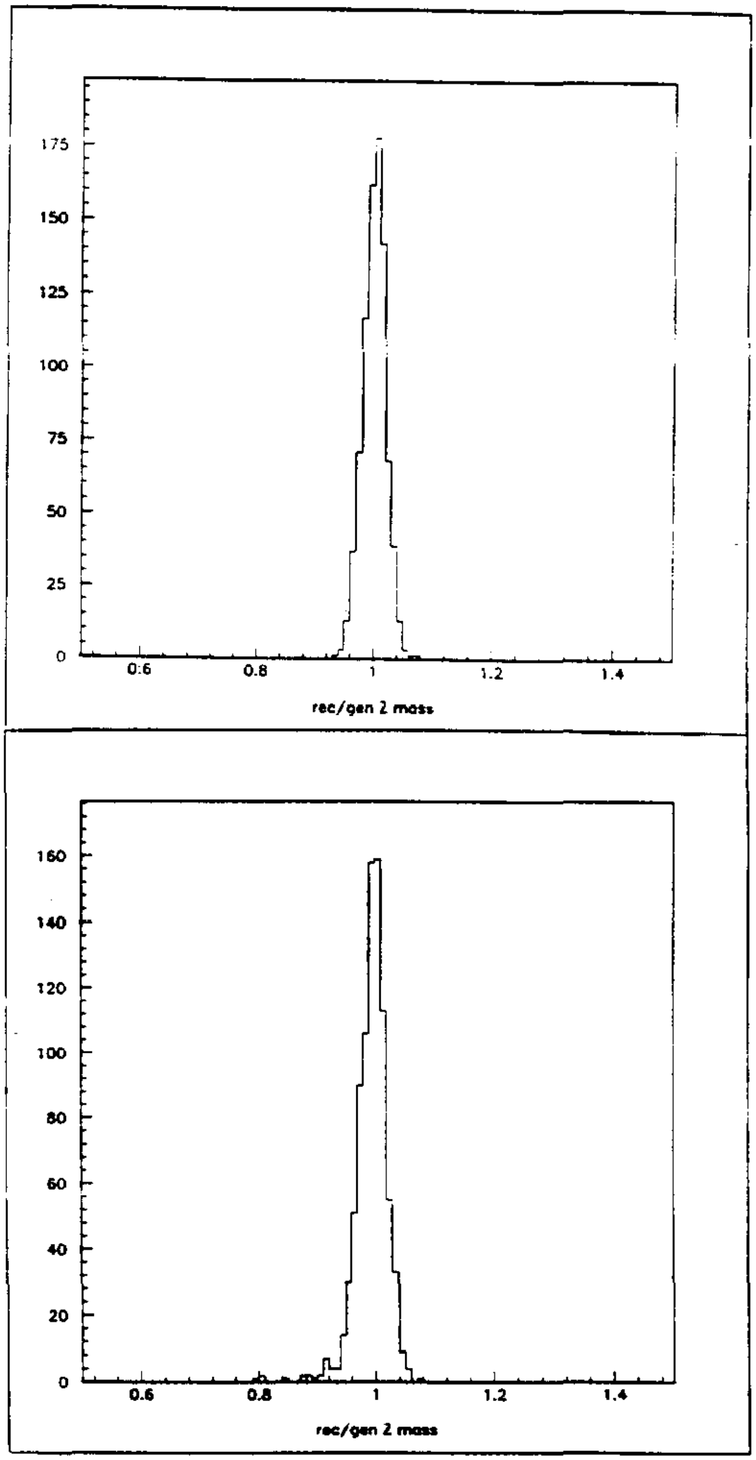

Fig. 4. Distribution of Mrec/Mgen for the case of individual tower resolution and 2% tower to tower resolution in momentum. The finite EM tower size of $(\Delta\phi\Delta\eta) = (0.05)^2$ has been used.

a. Dose of zero

b. Dose due to luminosity of $10^{34}/(\mathrm{cm}^2\mathrm{sec})$ for 10 years, with a recalibration to 2% every year.

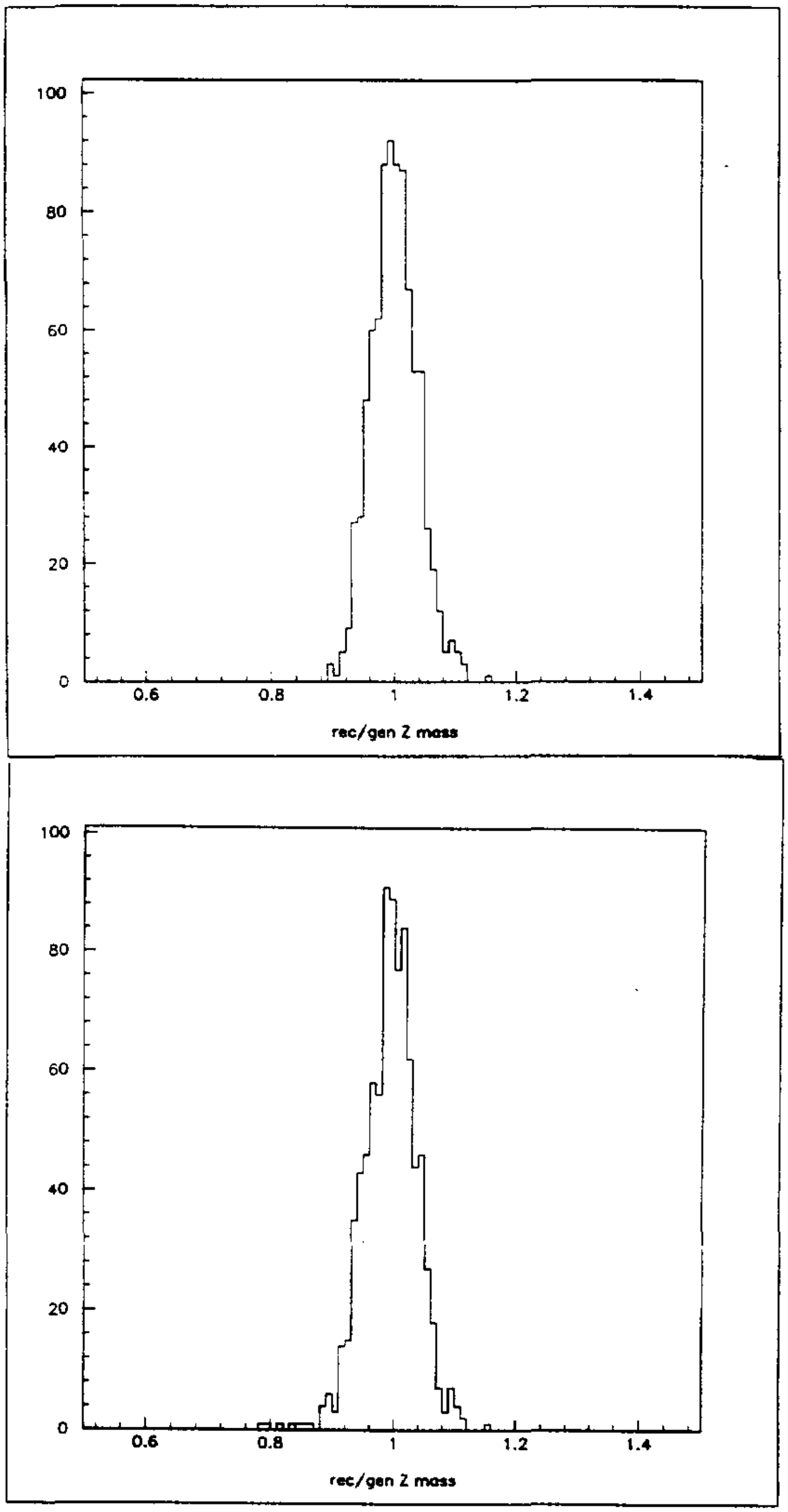

Fig. 5. As in Fig. 4. except that the position resolution is assumed to be perfect.