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Dynamic Range of the GEM Calorimetry

November 18, 1992

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A Monte Carlo study has been performed to investigate the required dynamic range for both the electromagnetic and hadronic calorimetry of the GEM experiment. For both systems, the lower end of the range was taken to be the total thermal and pileup noise. In the case of the electromagnetic calorimetry, the upper end of the range has been determined from $Z' \rightarrow e^+e^-$ decays. For the calorimeter, high-p_T two-jet events have been used.

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1 Introduction

Dynamic range requirements for the GEM calorimetry have not yet been adequately studied. It is important that these be determined fairly soon as it will impact on the design of much of the readout. It is generally assumed that the GEM design will incorporate 60 MHz 12-bit or possibly 13-bit ADCs. If the required dynamic range, as defined by

$$\text{range(in bits)} = \log_2\left(\frac{\text{Largest signal of interest}}{\text{Smallest signal of interest}}\right)$$

is larger than this, as it almost certainly will be in GEM, then the effective dynamic range must be increased. There are typically three scenarios envisioned to do this

1. *Nonlinear Response-* Use a nonlinear response function for the amplifier feeding the ADC, such that the gain decreases as the signal increases.

2. *Multiple Range ADCs-* Use two or more ADCs for each signal, operating in different ranges, or equivalently, one ADC with two or more selectable input gains. Which range is used to digitize the signal depends on the size of the signal. Taken to its extreme, this method can effectively provide a floating point representation of the data.

3. *Combination System-* Implement a combination of the above two systems.

The first scheme is in general the simplest to implement; however, it is difficult in practice to design a nonlinear circuit with the required stability which can be calibrated to the desired accuracy. It might also be difficult to deal with nonlinear signals at the trigger level. Therefore in certain energy regions, it is desirable to keep a linear response.

In the second scheme, one has an effective loss of resolution at each "crossover point"; that is, the point where one exceeds one range and crosses into the next. Resolution at this point is determined by the overlap of the two ranges. For example, if one were trying to cover a 16-bit dynamic range with two 12-bit ADCs, the effective resolution would only be 8 bits when one left the range of the lower range ADC and started using the higher range ADC.

Generally, a combination of the two schemes is considered more attractive for GEM. It is the goal of this note to determine the dynamic range which is required for the GEM calorimetry, and to offer suggestions as how this range could be covered with existing and anticipated technology.

2 Event Simulation

Except where otherwise noted, all events were generated using the PYTHIA[1] event generation package. These events were then passed to the "fast 1" GEM detector simulation program [2], which simulates detector response using parameterized showers based on full GEANT[3] simulations.

This parameterized package does not simulate the longitudinal segmentation of the individual calorimeters, so for this study, the "channel" energy is taken to be the total tower energy. This overestimates the upper end of the dynamics range somewhat, but as figure 1 shows, at these high energies the majority of the energy is in the outer layer of the calorimeter and the event to event fluctuations are fairly large, so this conservative approach is justified.

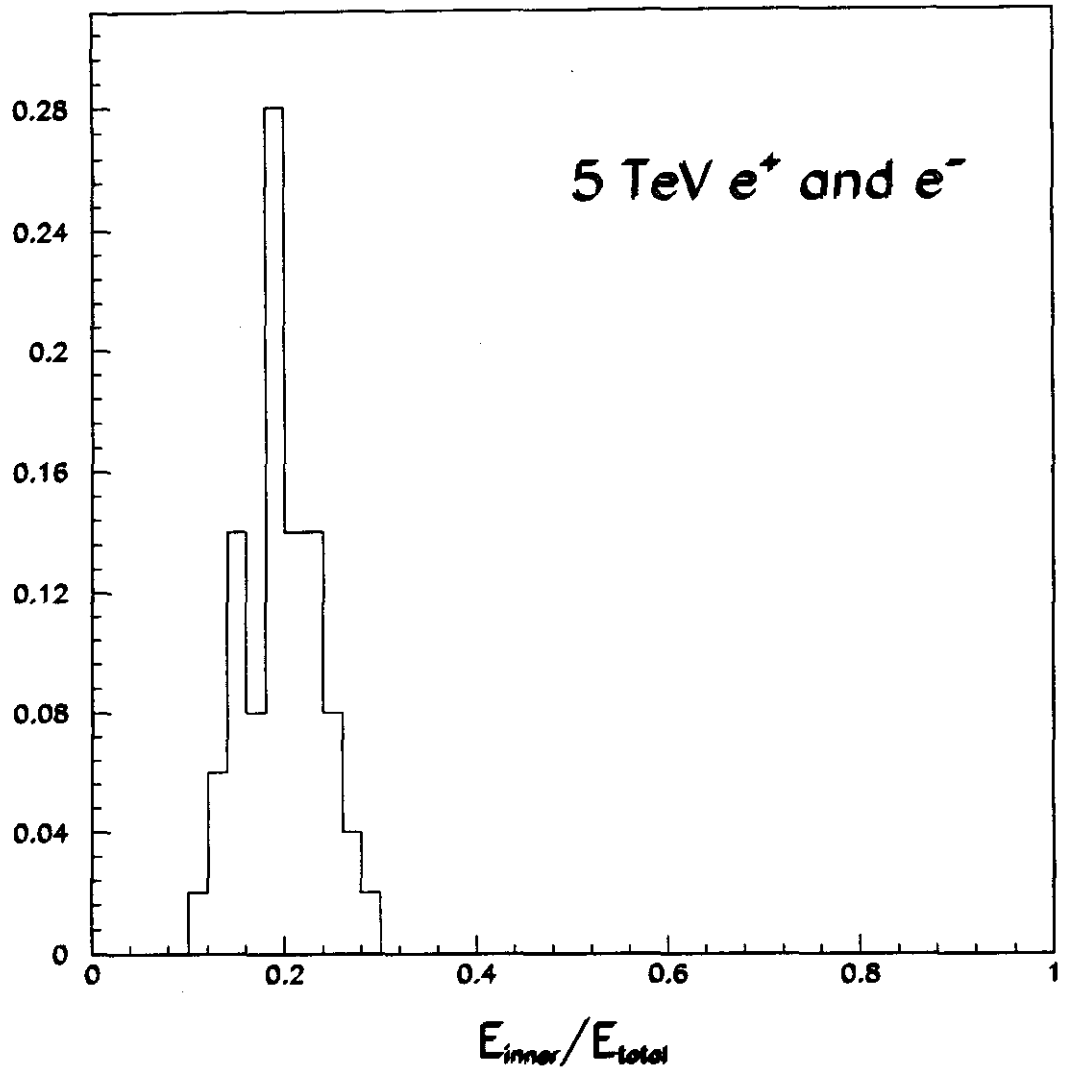

Figure 1: The fraction of energy in the peak tower which is in the inner (front) part of the tower for 5 TeV incident e^+ and e^-.

3 Low End of the Dynamic Range (LSB)

The low end of the dynamic range (least significant bit) is taken to be the total noise (thermal+pileup), as quoted in reference[4] , for the case of 40 ns shaping times. These numbers have been divided by $\sqrt{2}$ because of the inner/outer segmentation of the calorimeters. This is a somewhat approximate treatment, both because the segmentation is not symmetric and because the pileup noise is not expected to scale in this way; However, it should be adequate for this study. Thus, the least significant bit (LSB) values are taken to be 25 MeV for the electromagnetic calorimeter and 140 MeV for the hadronic calorimeter.

4 Response to Minimum Ionizing Particles

It is possible that the low end of the dynamic range could be raised above the noise. In principle, it must be low enough to detect the passage of minimum ionizing particles through the electromagnetic calorimeter, namely muons. These minimum ionizing particles are an important tool for monitoring the calibration of the calorimeter. Also, the calorimeter could conceivably be used in conjunction with the muon system to aid in muon timing.

Figure 2 shows the total energy spectrum from a full GEANT simulation of 2 GeV muons passing through the electromagnetic calorimeter. No noise or pileup has been simulated. The peak is around 300 MeV. Given the definition of LSB above, that is only on the order of 10 ADC counts total. Clearly, one cannot raise the value of the LSB very much and still retain resolution for minimum ionizing particles, particularly if the energy is divided amongst two or more towers. The total noise will therefore remain the definition of the LSB.

5 Electromagnetic Calorimetry

A primary physics interest of the GEM calorimetry is the $H \rightarrow \gamma\gamma$ decay; however, this decay does not push the dynamic limits of the calorimetry. In order to have general purpose discovery potential, one must design calorimetry capable of detecting the highest energy particles of interest.

This is difficult, as new particles are model dependent. However, if a "standard" Z' type gauge boson is assumed, then one can get some idea what mass range should be accessible to GEM. If one requires a minimum of 10 events in one year at $10^{34}s^{-1}cm^{-2}$ luminosity, then PYTHIA predicts that GEM should be capable of seeing a 12 TeV Z', so these decays have been used to define an upper limit to the electromagnetic calorimetry energy scale.

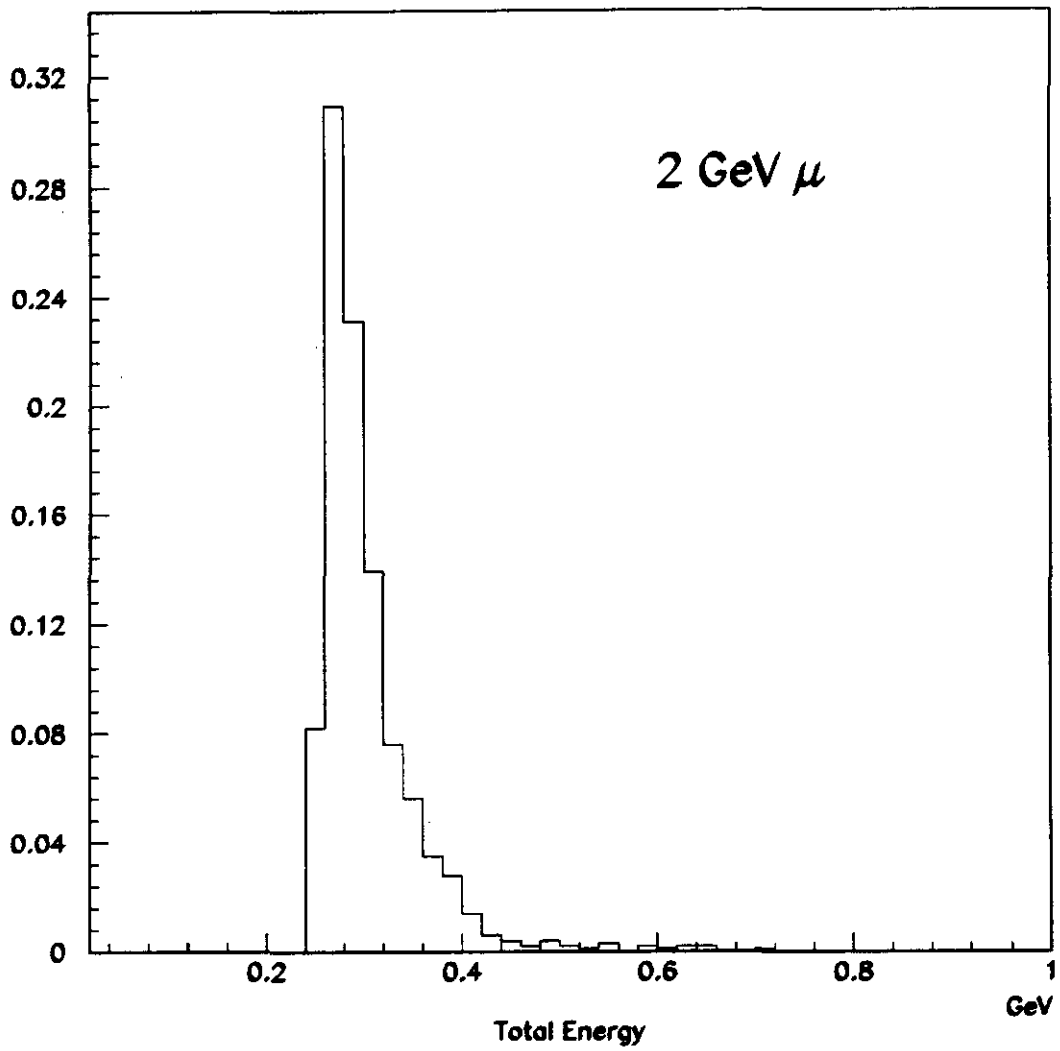

Figure 2: Total energy deposited by muons in the electromagnetic calorimeter.

Figure 3 shows the energy and E_T spectrum for electrons and positrons produced in the decay $Z' \rightarrow e^+e^-$, assuming $M(Z') = 12$ TeV. As expected, the E_T range extends up to about 6 TeV. Ordinarily, the E_T would be more or less invariant over the η region of the calorimeter; however, for such a massive state, kinematic constraints suppress high-η production. The total energy spectrum extends up to about 12 TeV. Luckily, this energy will in general be spread over several towers in the calorimeter. Figure 4 shows the highest energy in a single tower per event for this sample.

It appears that a full scale of about $E = 6$ TeV should be adequate to detect these events. It must be remembered that the calorimeter signal will have about a 20% undershoot, so the actual dynamic range covered must correspond to 6/5 of the largest signal. Taking the lower end of the scale to be the total noise per tower, then a total dynamic range of $(6000/.025) \times 6/5 \approx 288000$, or roughly 18 bits[1], is obtained.

6 Hadronic Calorimetry

In the case of the hadronic calorimetry, it is high-p_T two-jet events which are interesting. A departure from predicted behavior in the high-p_T distribution of jets could be a signature for new physics. One would like at least 10% resolution to detect these deviations, implying the need for at least 100 events. Again using PYTHIA, this translates to two-jet events with roughly $p_T > 8$ TeV, assuming one year of running at $10^{34}s^{-1}cm^{-2}$ luminosity. A sample of two-jet events with a minimum p_T threshold of 8 TeV was therefore generated to determine the upper limit of the dynamic range.

Figure 5 shows the maximum energy in any hadronic channel for each of these events. Coincidentally, the maximum energy is almost identical to that for the electromagnetic calorimeter, namely about 6 TeV. However, the hadronic calorimeter has a slightly higher noise per channel, so the total dynamic range is $(6000/.140) \times 6/5 \approx 51400$ or about 16 bits.

7 Achieving the Dynamic Range

Given that one does not want to add more that .5% to the resolution of the calorimetry, it's necessary to always keep at least 8 bits of overlap between ranges for multiple range ADCs in any range where resolution is important. Since the electromagnetic calorimeter requires an 18 bit dynamic range, it would require three ranges if 12-bit ADCs were used, with 9 bit overlap. On the other hand, 13-bit ADCs could cover

[1] Actually, it is slightly higher than 18 bits, but 18 bits gives a top energy of 5460 GeV, which should be satisfactory.

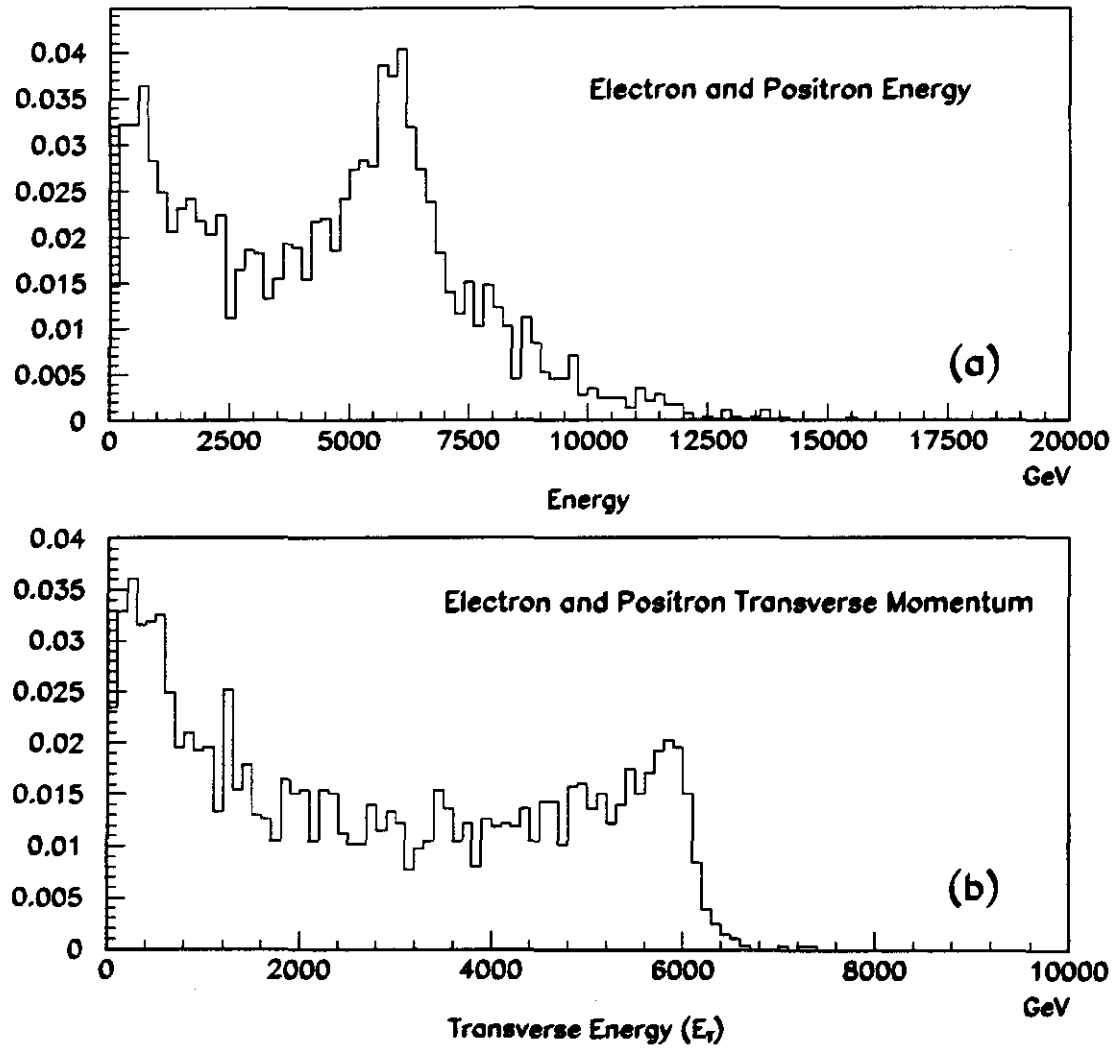

Figure 3: (a) Total energy and (b) transverse momentum of electrons and positrons originating from the decay of a 12 TeV Z'.

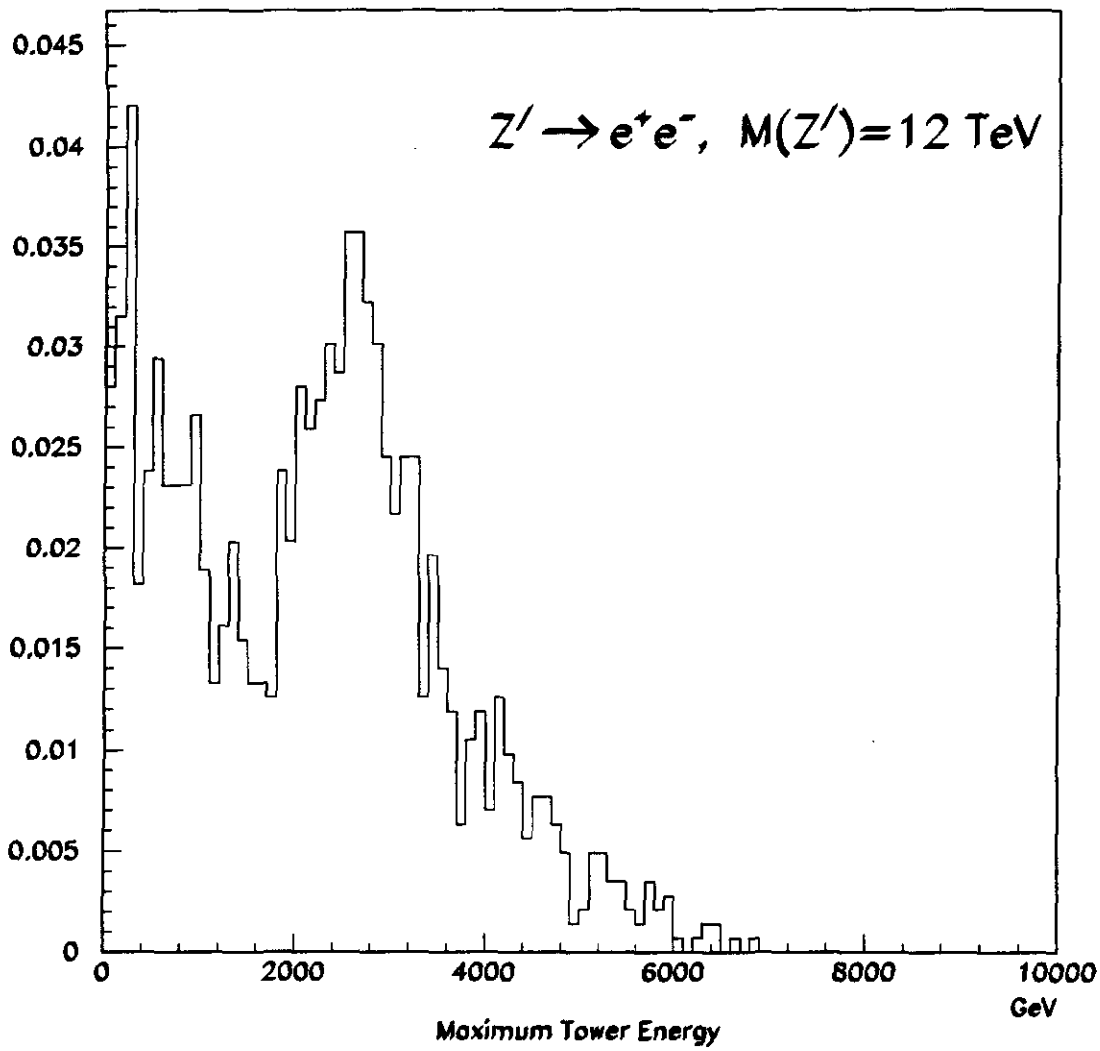

Figure 4: Highest energy in any electromagnetic tower for massive $Z' \rightarrow e^+e^-$ decays.

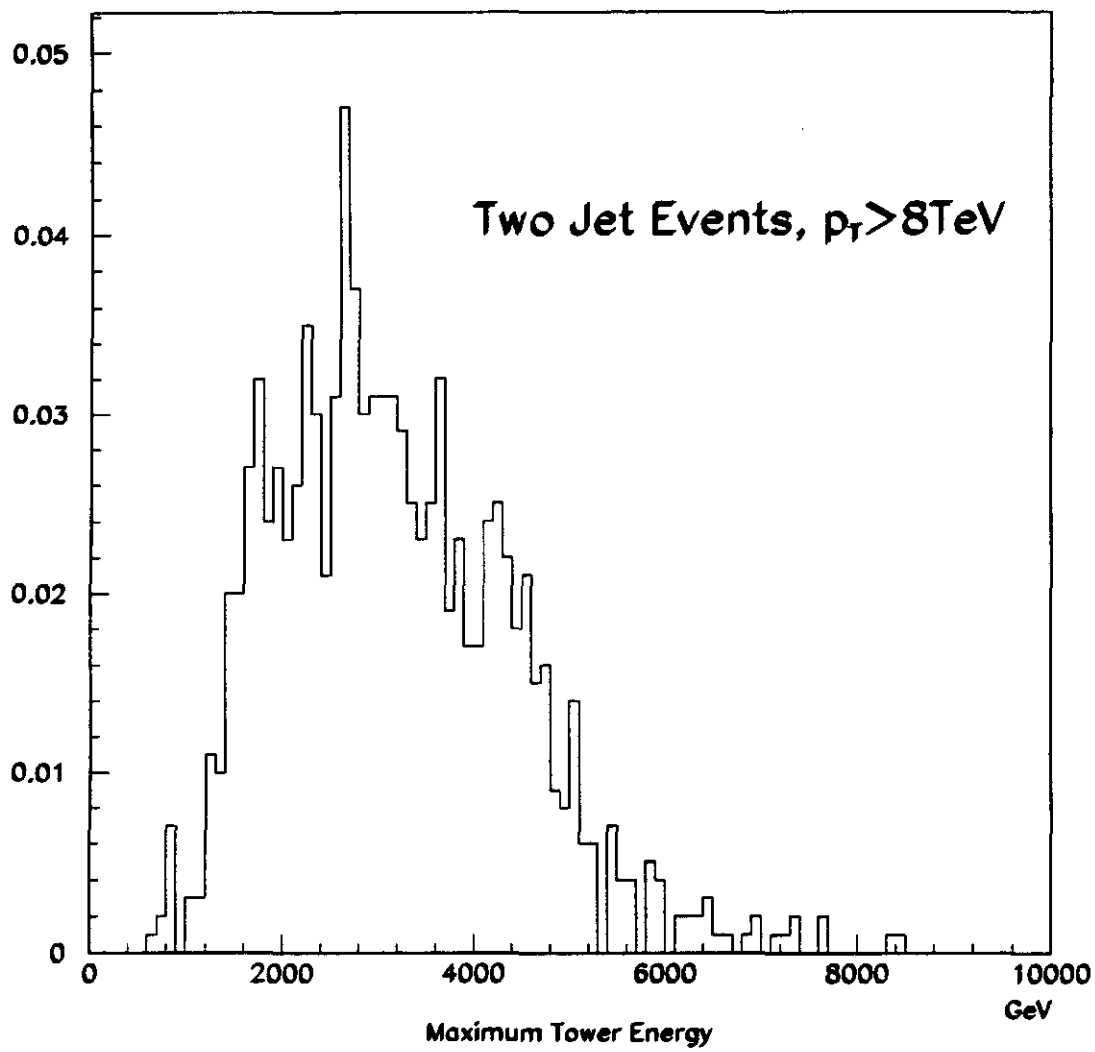

Figure 5: Highest energy in any hadronic tower for high-$p_T$two jet events.

it with two ranges with 8 bit overlap. Either ADC could cover the 16 bit dynamic range of the hadronic calorimeter with acceptable overlap.

Triple ADCs might be difficult to design, so for the 12-bit ADCs, one could also implement a scheme using a dual range ADC in conjunction with a nonlinear preamp response to achieve the 18-bit dynamic range required by the EM calorimeter. Current GEM preamp designs allow for a "break" in the response curve where the linearity changes slope, as illustrated in figure 6(a). The penalty that one pays is that in the second region the ADC vs E slope is shallower, thus the lowest ADC bit corresponds to a larger ΔE. The relative magnitude of this effect is largest at energies just above the break point, given by

$$\left.\frac{\Delta E}{E}\right|_{E_{BREAK}} = \left(\frac{1}{E_{BREAK}}\right)\left(\frac{E_{MAX} - E_{BREAK}}{2^{N_{BIT}} - E_{BREAK}/E_{LSB}}\right)$$

where E_{BREAK} is the energy where the break in the slope occurs, E_{MAX} is the maximum energy (in this case 6 TeV), N_{BIT} is the number of bits of the ADC, and E_{LSB} is the energy corresponding to the least significant bit of the higher ADC range (assuming that the break comes after the end of the low range). Figure 6(b) shows $\Delta E/E$ at E_{BREAK} as a function of E_{BREAK} for the case of dual range 12-bit ADCs with 8 bit overlap. The function reaches a minimum of of .3% at about 880 GeV, but the curve is reasonably flat from about 600 to 1200 GeV. Remembering that this will be added in quadrature with about .5% from gain non-uniformity, this is a small contribution to the total noise.

A corresponding plot for the case of dual range 12-bit ADCs with 9-bit overlap is shown in figure 6(c). In this case, the optimum break point is at about 425 GeV, where $\Delta E/E$ would be .7% . This is somewhat larger, but it might be worth it to give the extra resolution provided by the 9-bit overlap at lower energies.

Similarly, one could use the nonlinear preamp in conjunction with the 13-bit ADCs to give 9-bit overlap. In this case, the optimum break point would be at about 2 TeV, where the contribution to $\Delta E/E$ would be negligible at .06% .

The effect of the quantization errors on the effective energy resolution are summarized in figure 7 for various schemes. Based on these plots, the best scheme at all energy ranges appears to be either the triple range 12-bit ADC or the dual range 12-bit ADC with 8-bit overlap and a nonlinear preamp. Using a dual- range 13-bit ADC with a nonlinear response curve (not shown in figure) would give even better performance, assuming 13-bit ADCs will be available in time.

There is also of course the possibility of implementing "floating-point" ADCs of the type being considered by the SDC collaboration, but at present not enough is known about these devices to discuss them in this context.

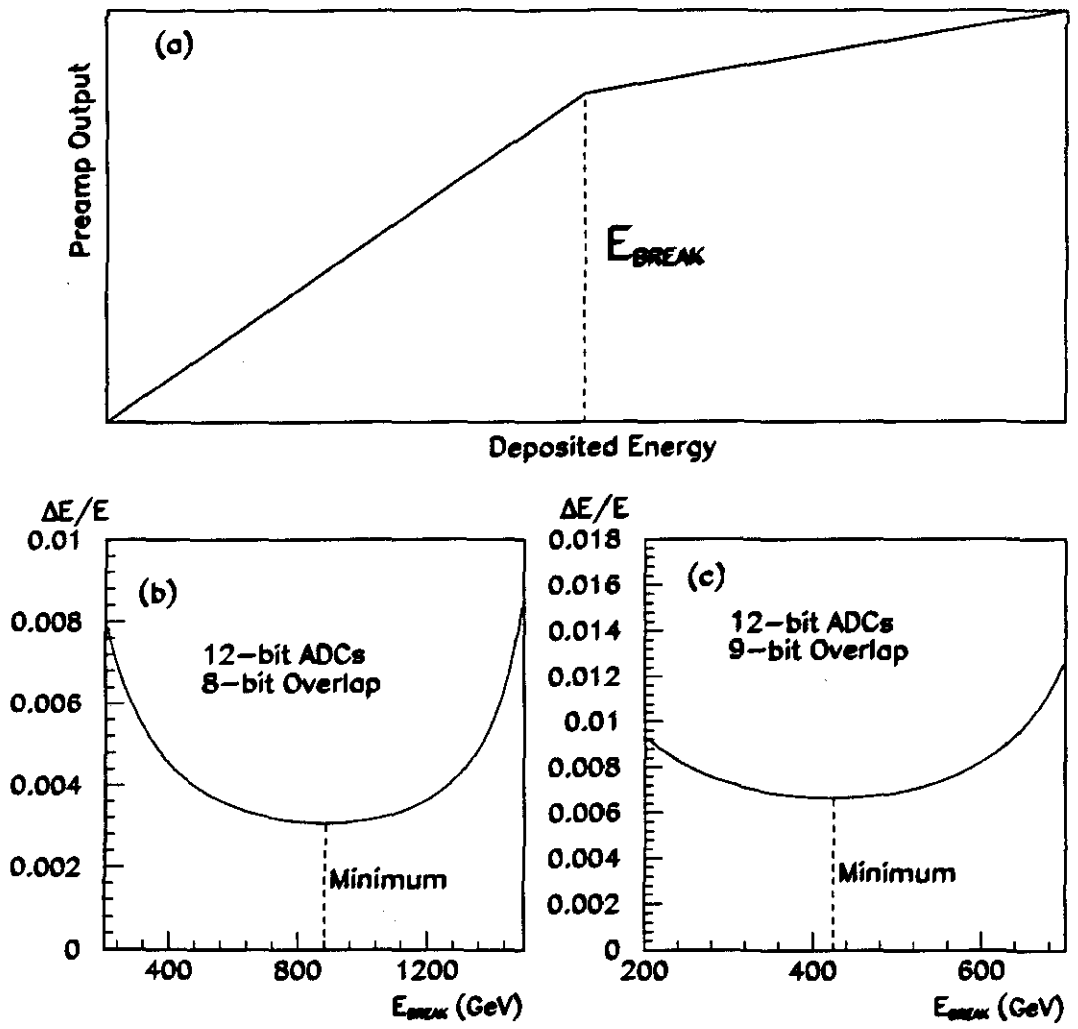

Figure 6: Effect of preamp nonlinearity on quantization error. The nonlinear preamp curve envisioned for GEM is shown in (a). The relative quantization error at the "break" is shown as a function of the break energy for the case of dual range 12-bit ADCs with (a) 8-bit and (b) 9-bit overlap.

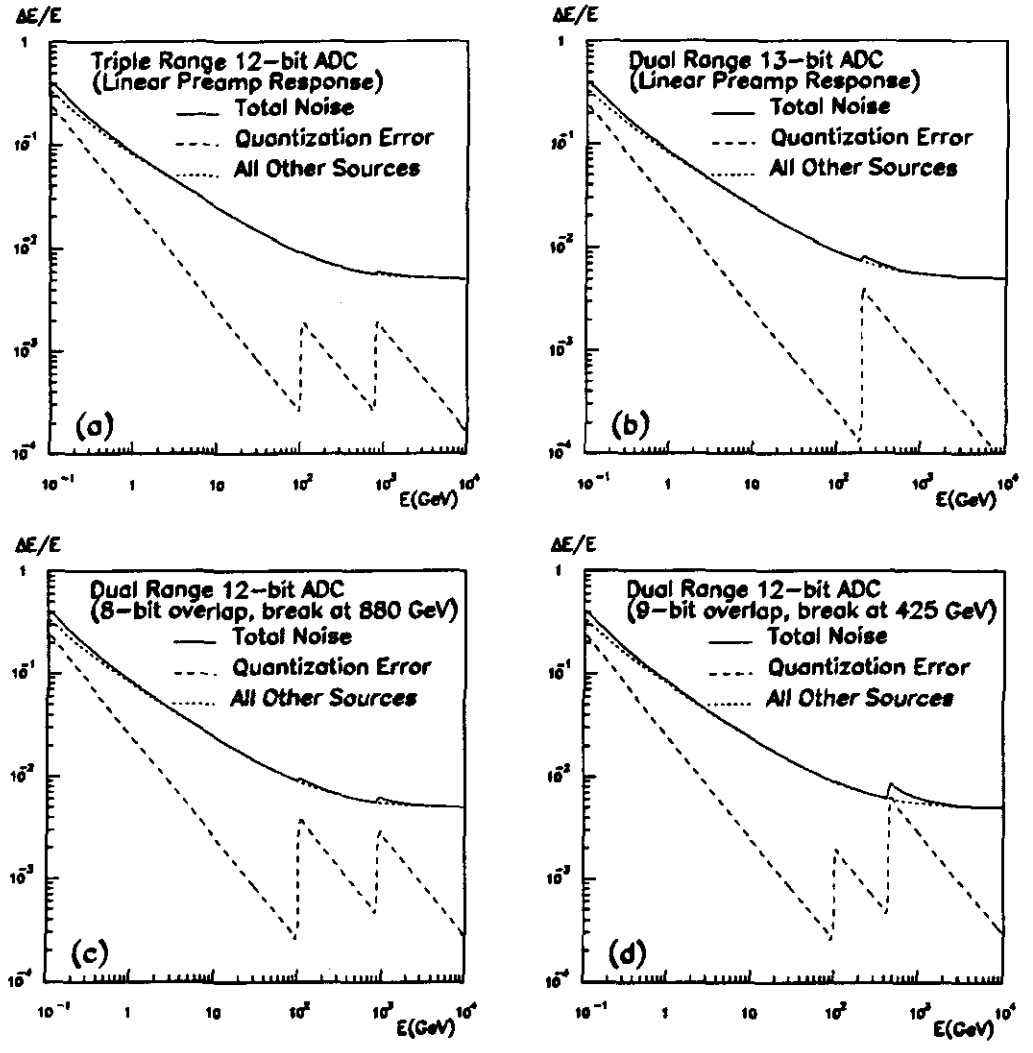

Figure 7: Conribution to the total energy uncertainty from quantization errors for: (a) triple-range 12-bit ADCs with linear preamp response; (b) dual-range 13-bit ADCs with linear preamp response; (c) dual range 12-bit ADCs with 8-bit overlap and a break in the preamp response at 880 GeV; and (d) dual range 12-bit ADCs with 9-bit overlap and a break in the preamp response at 425 GeV.

8 Implications for $H \rightarrow \gamma\gamma$ Decays

It is imperative that the readout digitization system preserves the two-γ mass as it applies to the $H \rightarrow \gamma\gamma$ decay. As mentioned before, in order to keep a .5% energy resolution, one needs at least 8 bits over the range of interest, preferably more. Figure 8 shows the energy of the highest energy channel for a sample of $H \rightarrow \gamma\gamma$ events, with $M(H) = 160$ GeV, probably the highest mass Higgs accessible via the $\gamma\gamma$ decay mode[5]. Also shown are the cutoffs for the low ranges of a 12-bit and a 13-bit ADC. Clearly, if the 13 bit ADC is used, most of the particles fall within the lower range, so the crossover problem is not an issue. In the case of the 12-bit ADC, the crossover falls in the center of the energy distribution. This could present a problem if one uses dual range 12-bit ADCs with only 8-bit overlap. This is an argument for using either triple range 12-bit ADCs or dual range 12-bit ADCs with 9-bit overlap, even though the latter have a somewhat poor energy resolution above 400 GeV.

9 Summary and Conclusions

The dynamic range required by the readout of the GEM calorimetry has been estimated using the PYTHIA Monte Carlo program and a parameterized representation of the GEM calorimeter.

In the case of the electromagnetic calorimeter, the highest energy physics of interest was taken to be a $Z' \rightarrow e^+e^-$ decay with $M(Z') = 12TeV$. Assuming the lower end of the range to be given by the total noise per channel, this leads to a necessary dynamic range of 18 bits.

Simulated high-p_T two-jet events with $p_T > 8$ TeV were used to study the hadronic calorimeter. These led to energy depositions roughly the same as for the electromagnetic calorimeter; however, because the noise levels in the hadronic calorimeter are higher than in the electromagnetic, it appears that a dynamic range of 16 bits should be sufficient.

If 13-bit ADCs are available, the dynamic range of both calorimeters could be covered with a dual range setup. If only 12-bit ADCs are available, then the electromagnetic calorimeter could be covered either by using a triple range ADC or by using a dual range ADC in conjunction with a nonlinear preamp response.

References

[1] H. U. Bengsson, T. T.Sjöstrand, CERN Program Library W5045 - Long Writeup (1989).

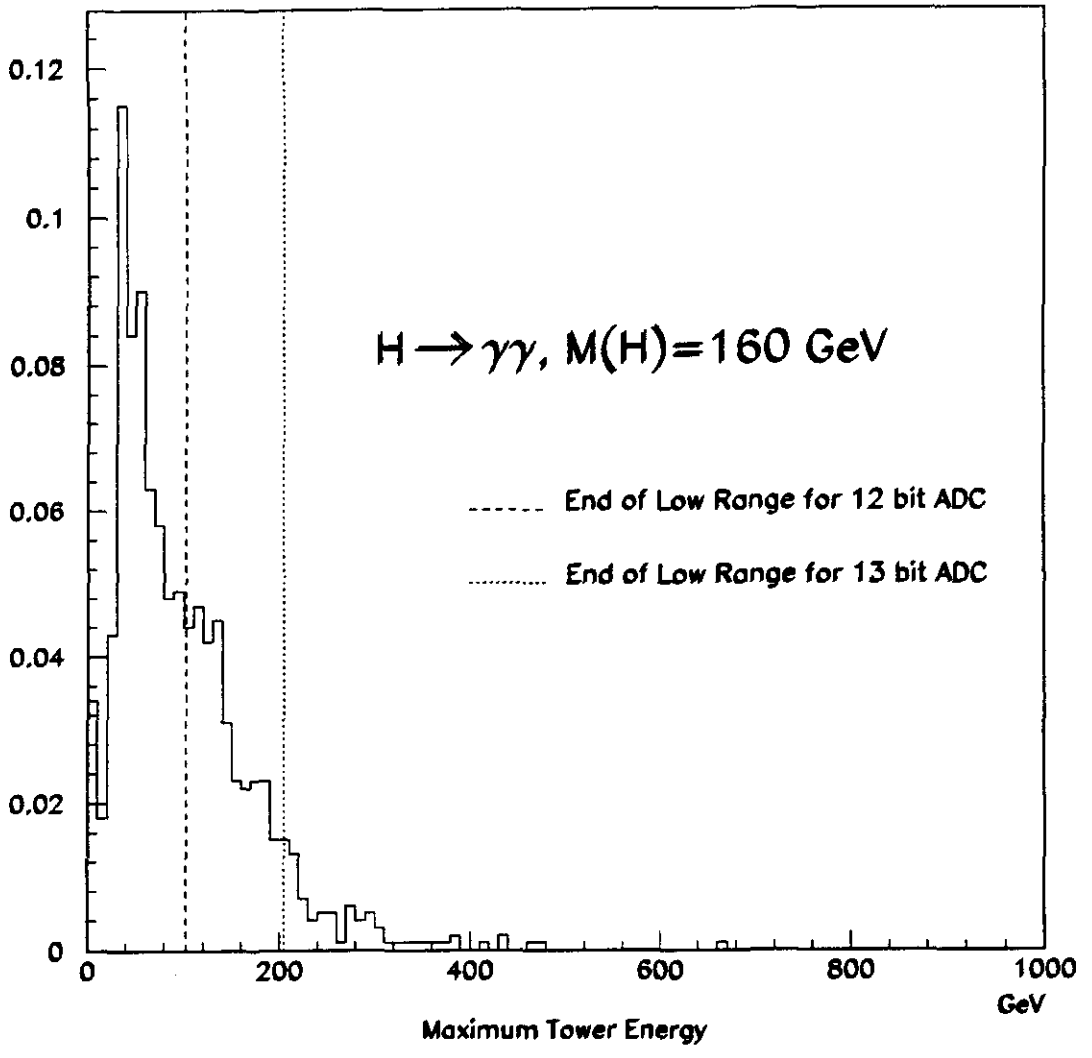

Figure 8: Highest energy in any electromagnetic tower for $H \rightarrow \gamma\gamma$ decays.

[2] T. Skwarnicki, private communication.

[3] R. Brun, F. Bruyant, M.Maire, A.C. McPherson, and P. Zanarini, *GEANT3* CERN DD/EE/84-1 (1987).

[4] The GEM Collaboration, *Occupancy and Pileup in the GEM Detector*, GEM TN-91-41 (1991).

[5] R.-y. Zhu, *Signal and Background of $H \rightarrow \gamma\gamma$ with Proposed GEM Calorimeter Systems*, GEM TN-91-32 (1991).