Improving HF GFlash Simulations at CMS

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Abstract

We have upgraded HF GFlash, a fast simulation of electromagnetic showers using parameterizations of the profiles in the Hadronic Forward Calorimeter. We set a soft neutron threshold of 1.2 GeV and tuned the parameterization of the electromagnetic shower profiles to achieve a simulation 76% faster than the previous GFlash simulation, reducing error by 55% when tested against Test Beam Data.

Keywords: EM Showers simulation, Geant4, GFlash, Test Beam Data, Shower Library

1. Introduction

1.1. HF Calorimeters

CMS has two Hadron Forward (HF) calorimeters on both sides of the interaction point (IP), at 11.15 m distance, covering the pseudorapidity range $3 < |\eta| < 5$. Such detectors are placed at each end of the CMS detector at beam height. They are sampling calorimeters with plastic clad quartz fibres embedded into the iron absorber. They have an active radius of 1.4 m, each unit is 1.65 m long and composed of 18 slices of 20 degree sections. Long (1.65 m) and short fibres (1.43 m) in the calorimeter sample the energy of the hadronic and electromagnetic showers. These devices can measure hadronic jets up to few TeV energies, detecting Cherenkov light emitted by the shower particles in the quartz fibres, and transported through the same fibres to photomultiplier tubes (PMT), located on the downstream side of the calorimeter modules. On average, 760 GeV per proton-proton interaction is deposited into the two forward calorimeters, compared to only 100 GeV for the rest of the detector.[1]

1.2. Old HF Simulation

GFlash was developed in 2012 as a response to the impossibility of simulating PMT Window Noise with Geant 4 and Shower Library. Previous HF Simulations were also limited in the range of energies they could span, they had discrete energy bins (10, 20, 30, 40, 50 GeV, etc...) that limited their precision significantly. Besides, HF Shower Library has another problem, it immediately deletes particles that enter HF Detector and replace them with Shower Library, that added to the fact that it has very limited statistics, the average computing time per event increases as the Library increases in size. GFlash is a fast simulation of electromagnetic showers using parameterizations of the profiles in Hadronic Forward Calorimeters and it solves almost all the problems previous HF Simulations have.

In 2012, HF GFlash was able to simulate 10000 times faster than Geant4 and had good agreement with Collision Data and Test Beam results. However, due to the future upgrades in the LHC that will allow collisions with a center of mass energy of 14 TeV, more data will be generated and we will need faster and more accurate simulations.

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1.3. Theory [1]

For physics analysis and feasibility studies, large number of Monte Carlo events may have to be produced. Using individual particle tracking, as Geant4 does, the computing time needed for such kind of simulations increases linearly with the energy absorbed in the detector. Using parameterizations for electromagnetic showers speed up the simulations considerably, without sacrificing precision; and the high particle multiplicity in electromagnetic showers, as well as their compactness and the good understanding of the underlying physics makes their parameterization advantageous.

The GFlash package allows the parameterization of electron and positron showers in homogeneous calorimeters and is based on the parameterization described by Grindhammer [2]. The spatial energy distribution of electromagnetic showers is given by three probability density functions (pdf),

$$dE(\overline{r}) = Ef(t)dtf(r)drf(\varphi)d\varphi$$

describing the longitudinal, radial and azimuthal energy distributions. Here t denotes the longitudinal shower depth in units of radiation length, r measures the radial distance form the shower axis in Molière units, and φ is the azimuthal angle. A gamma distribution is used for the parameterization of the longitudinal shower profile $f(t)$. The radial distribution $f(r)$, is described by a two-component ansatz. In φ, it is assumed the energy is distributed uniformly: $f(\varphi) = 1/2\pi$.

$$\begin{aligned} f(t) &= \left\langle \frac{1}{E}\frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1}\beta \exp(-\beta t)}{\Gamma(\alpha)} \\ f(r) &= \frac{1}{dE(t)}\frac{dE(t,r)}{dr} \end{aligned}$$

The center of gravity, $\langle t \rangle$ and the depth of the maximum, T, can be calculated from the shape parameter α and the scaling parameter β according to

$$\begin{aligned} \langle t \rangle &= \frac{\alpha}{\beta} \\ T &= \frac{\alpha - 1}{\beta} \end{aligned}$$

In the parameterization all lengths are measured in units of radiation length (X_o), and energy in units of the critical energy E_c defined as

$$E_c = 2.66\left(X_o \frac{Z}{A}\right)^{1.1}$$

This allows material independence, since the longitudinal shower moments are equal in different materials. The following equations are used for the energy dependence of T_{hom} and α_{hom} with

$$y = \frac{E}{E_c}$$

and

$$t = \frac{x}{X_o}$$

where we define x as the longitudinal shower depth:

$$\begin{aligned} T_{hom} &= \ln y + t_1 \\ \alpha_{hom} &= a_1 + (a_2 + a_3/Z)\ln y \end{aligned}$$

2. Soft Neutron Threshold

To achieve our goal of making our simulation run faster we decided to set a soft neutron threshold, i.e. any neutron with an energy below or equal to threshold is eliminated from the simulation. We chose soft neutrons because of their low interaction rate (they are very low energetic particles), their contribution in the photoelectron counts in our detectors is negligible. We varied the Energy Threshold (ET) from 1.0 to 1.5 GeV and scanned the performance of GFlash. We simulated events for 10000 pions with energies ranging from 100 to 1000 GeV and varying the η of entrance from 3.2 to 4.8. With that information we determined the ratio: photoelectron counts after the cut/ phoelectron counts before the cut (R) and the Relative Error (RE). Then we calculated the Mean Ratio (MR), the Mean Relative Error (MRE), the RE standard deviation and the speed's improvement (equations presented in Appendix A).

ET [GeV]	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
% Faster	30	45	76	81	84	86
MR	1.000	1.003	0.999	0.997	1.002	0.997
MRE	1.15 %	1.04 %	1.24%	1.36%	1.34%	1.32%
RE Std. Dev.	0.59	0.49	0.32	0.42	0.80	0.87

Table 1: Soft neutron threshold results.

Due to the substantial improvement in the simulation's speed between the 1.1 GeV cut and the 1.2 GeV cut, the accurate MR value and the lowest MRE standard deviation we decided to keep the 1.2 GeV soft neutron threshold. We present now the MR vs η plots for the 1.2 GeV cut.

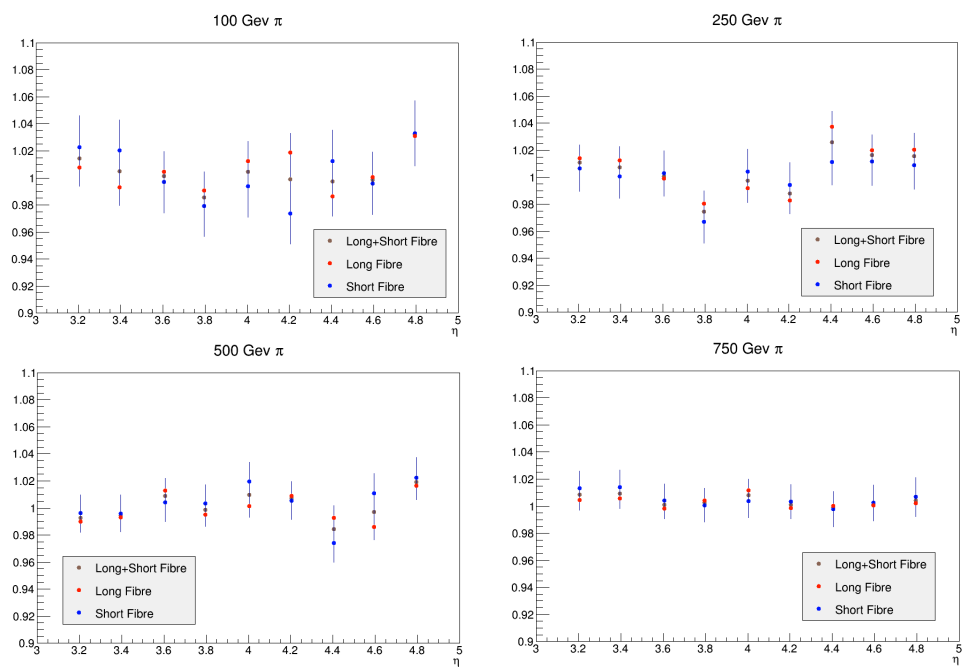

Figure 1: MR vs η plots for 100, 250, 500 and 750 GeV 10000 pions after setting the 1.2 GeV soft neutron threshold.

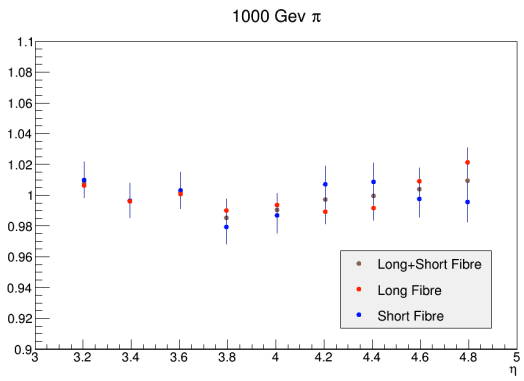

Figure 2: MR vs η plot for 1000 GeV 10000 pions after setting the 1.2 GeV soft neutron threshold. As it can be seen, in figure 1 and figure 2, for all the scanned energies, the MR values accumulate around 1.0, all acceptable within statistical error as it can be appreciated. Also notice that the discrepancy of the simulation after the cut and before it, is below 4%, giving us enough information to consider it as a good option for speeding up the simulation without altering the physics underlying the electromagnetic showers.

3. Tuning and Performance of New HF GFlash

After setting the soft neutron threshold it is mandatory to tune our simulation to achieve the best performance. Using the results of energy response ratio from Test Beam Data as our reference, we can check the performance of energy response ratio of New HF GFlash compared to Old HF GFlash and Shower Library. For completeness, we present in B.2 the ratios of the energies deposited in long and short fibres for electrons and pions, with proper error propagation, of the Test Beam Data experimental results [3].

It is appropriate to introduce now the dictionary of abbreviations that will be further used in plots and tables:

- S_e = Energy deposited in short fibre from electrons.
- L_e = Energy deposited in long fibre from electrons.
- S_p = Energy deposited in short fibre from pions.
- L_p = Energy deposited in long fibre from pions.

Blocking a 3^{10} Factorial Design, we tuned the average and fluctuated longitudinal profiles parameters in the GFlash package. Before the tuning, the mean discrepancy when compared to Test Beam Data Ratios (Table B.2) was 2.57%. After tuning, we reduced this discrepancy by 55% achieving a 1.15% discrepancy. This is a major improvement from the Old GFlash Simulation, because as it can be seen in the GFlash 2012 paper [1] and Table C.3, the four significant figures weren't considered and by rounding two decimals we lose valuable information, ignoring the true accuracy of the simulation.

We simulated 10000 electrons and pions with the next energy bins: 30, 50, 100 and 150 GeV, and compared their energy response ratios vs Test Beam Data (reference), Old GFlash and Shower Library Ratios (Table C.3 and Figure 3).

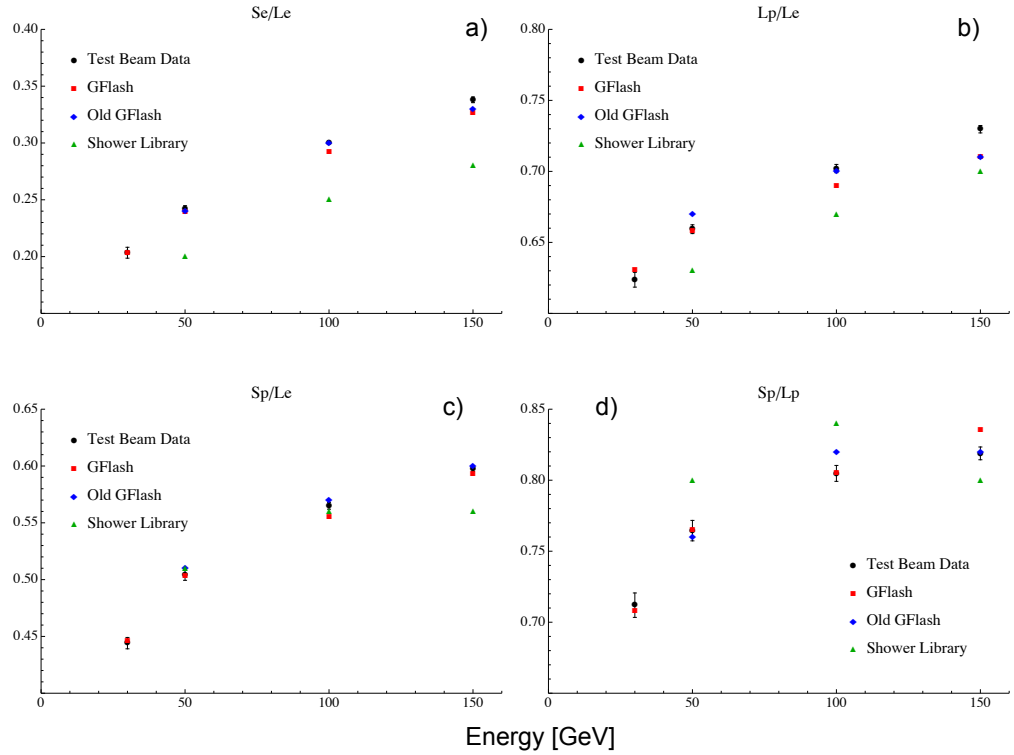

Figure 3: Figure built with data from Table C.3. Comparison of energy response ratio between New HF GFlash, Test Beam (reference), Old HF GFlash and Shower Library as a function of beam energy. a) S_e/L_e plot, b) L_p/Le plot, c)S_p/L_e plot, d) S_p/L_p plot. As it can be seen, New GFlash behaves correctly and has good agreement with Test Beam Data. It is also important to notice that even though some dots of the Old GFlash might seem closer to the Test Beam Data when compared to New GFlash, this maybe misleading information because as it was said before, the last two significant figures were unfairly discarded in Old GFlash energy response ratios.

We also present the normalized responses for both electron and pions, for the long fibres, short fibres and the long+short response provided by GFlash and Test Beam Data. As it can be appreciated in figures 4,5 and 6, New GFlash has great agreement with experimental data, being able to simulate correctly the correlations between electrons and pions responses in the HF Calorimeter. It must be said that New HF GFlash simulates correctly the ratio e/π for long + short response, both at low and high energies.

Electromagnetic energy response of electrons and pions is predicted to be linear and Test Beam Data has shown that it is linear (within statistical error) up to 150 GeV. New HF GFlash preserves the linear energy response achieved with Old HF GFlash. This can be appreciated in figure 7 up to 1000 GeV for both electrons and pions, for long and short fibres.

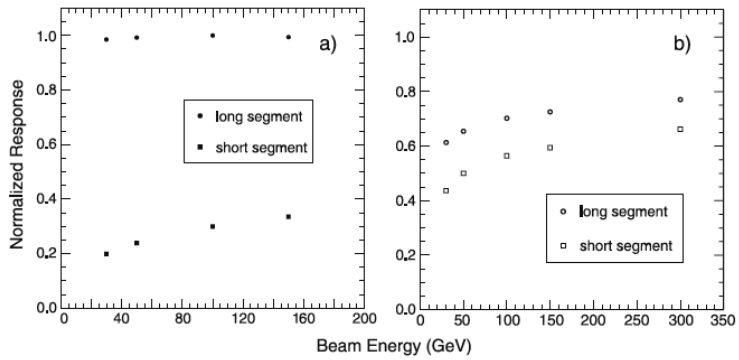

Figure 4: Normalized responses of Test Beam Data as a function of beam energy. a) Normalized response to electrons for long and short fibres. b) Pion response for both long and short fibres is normalized to electrons.

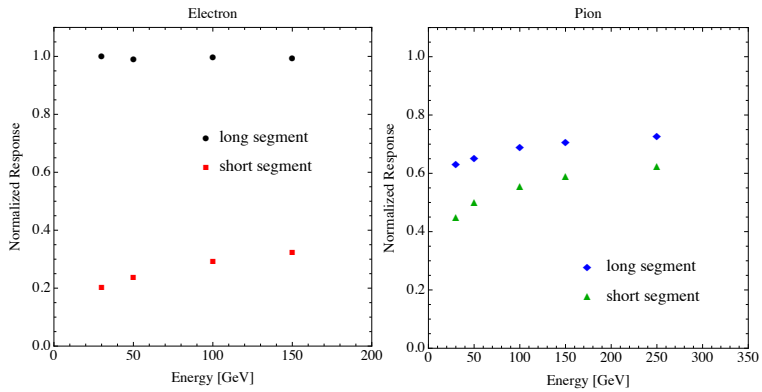

Figure 5: Normalized responses of GFlash simulation as a function of beam energy. a) Normalized response to electrons for long and short fibres. b) Pion response for both long and short fibres is normalized to electrons.

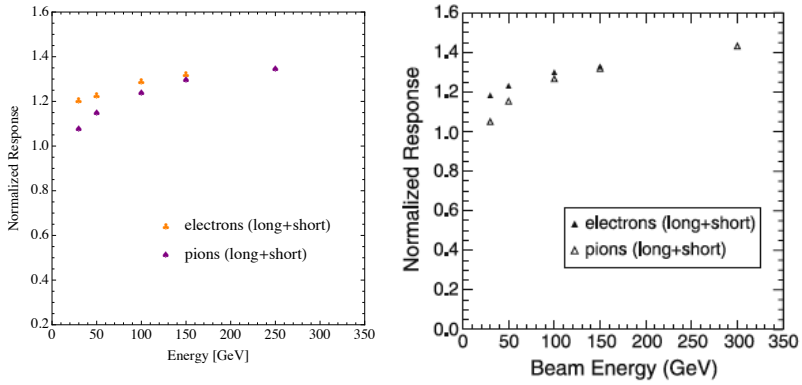

Figure 6: L+S response of the detector for electrons and pions shown as a function of beam energy. Left: GFlash simulation. The e/π ratio varies from 1.12 to 1.01 in the tested range and is flat at high energies. Right: Test Beam Data. The e/π ratio varies form 1.14 to 1.01 in the tested range, and is essentially flat at high energies[3].

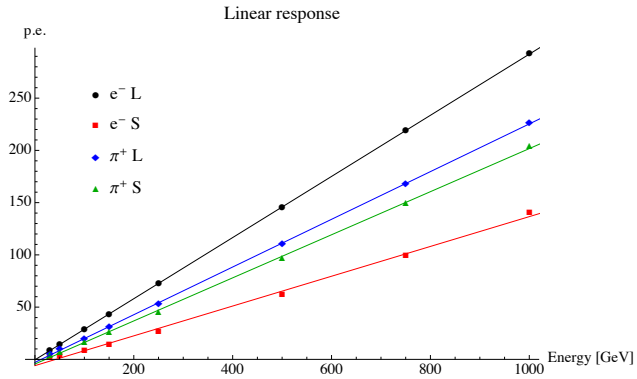

Figure 7: New GFlash has linear response for electron and pions in both long and short fibres, with energy from 50 GeV to 1000 GeV.

And finally we check the longitudinal shower profiles produced using New Flash to assure that its ability to handle very high energy particle simulation is intact, see figure 8.

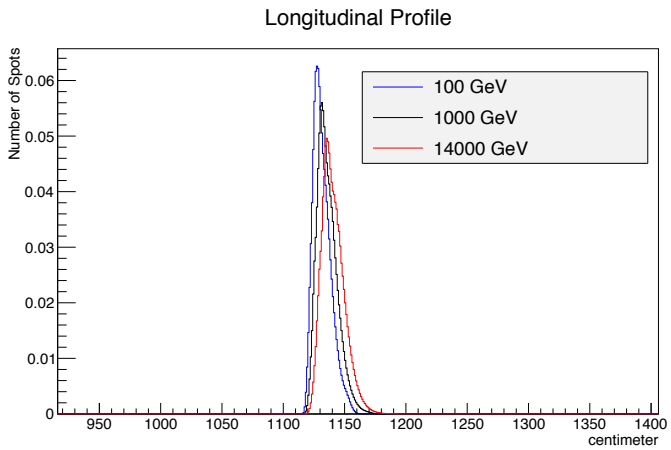

Figure 8: Logitudinal Shower Profiles produced by New HF GFlash for 10000 electrons with 100 GeV (blue), 1 TeV (black) and 14 TeV (red). This plot shows the capability of New HF GFlash to handle very high energy particle simulation.

4. Conclusions

In summary, we have updated and improved GFlash, the fast simulation able to handle very high energetic particles with precision. We have improved it's speed by 76% and reduced the error by 55% when compared with Test Beam Data after setting a 1.2 GeV soft neutron threshold. As for forthcoming research, it can be said that we will get deeper into tuning it and aim to span our simulation to other calorimeters.

References

[1] Rahmat Rahmat. *Performance of HFGFlash at CMS*. *EPJ Web of Conferences*, 49:18805–18817, 2013.

[2] G. Grindhammer and S. Peters. The Parameterized Simulation of Electromagnetic Showers in Homogeneous and Sampling Calorimeters. *ArXiv:hep-ex/0001020v1*, January 2000.

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Appendices

Appendix A. Section 2 Equations

Appendix A.1. Mean Ratio (MR)

We define R_i as the ratio of the photoelectron counts after the cut (p.e.c.) over the photoelectron counts before the cut (p.e.b.) for the ith value.

$$R = \frac{\text{p.e.c}}{\text{p.e.b}} \tag{A.1}$$

We define Mean Ratio (MR) as the average of the R's.

$$MR = \frac{1}{n}\sum_{i=1}^{n} R_i \tag{A.2}$$

Appendix A.2. Mean Relative Error (MRE)

We define the relative error RE_i as a measure of the discrepancy between the value obtained after the cut and the value we had before the cut for the ith value.

$$RE_i = 100\,(r_i - 1) \tag{A.3}$$

We define Mean Relative Error (MRE) as the average of the RE_i's.

$$MRE = \frac{1}{n}\sum_{i=1}^{n} RE_i$$

Which can easily be rewritten as:

$$MRE = 100\,(MR - 1) \tag{A.4}$$

Appendix A.3. RE Standard Deviation (RE Std. Dev.)

$$\text{RE Std. Dev.} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(MRE - RE_i)^2} \tag{A.5}$$

Appendix B. Test Beam Data Ratios

Energy [GeV]	S_e/L_e	L_p/L_e	S_p/L_e	S_p/L_p
30	0.2034 ± 0.0048	0.6237 ± 0.0052	0.4441 ± 0.0050	0.7120 ± 0.0086
50	0.2419 ± 0.0029	0.6593 ± 0.0031	0.5040 ± 0.0046	0.7645 ± 0.0072
100	0.3000 ± 0.0000	0.7020 ± 0.0020	0.5650 ± 0.0030	0.8048 ± 0.0056
150	0.3380 ± 0.0025	0.7297 ± 0.0026	0.5976 ± 0.0025	0.8189 ± 0.0045

Table B.2: Ratios of the energies deposited in long and short fibres for electrons and pions with energies ranging from 30 to 150 GeV for Test Beam Data experimental results.

Appendix C. Comparison Table

30 GeV				
Ratio	**New GFlash**	**Test Beam**	**Old GFlash**	**Shower Library**
S_e/L_e	0.2032	0.2034	- -	- -
L_p/L_e	0.6307	0.6237	- -	- -
S_p/L_e	0.4464	0.4441	- -	- -
S_p/L_p	0.7079	0.7120	- -	- -
50 GeV				
Ratio	**New GFlash**	**Test Beam**	**Old GFlash**	**Shower Library**
S_e/L_e	0.2395	0.2419	0.24	0.20
L_p/L_e	0.6584	0.6593	0.67	0.63
S_p/L_e	0.5063	0.5040	0.51	0.51
S_p/L_p	0.7648	0.7645	0.76	0.80
100 GeV				
Ratio	**New GFlash**	**Test Beam**	**Old GFlash**	**Shower Library**
S_e/L_e	0.2924	0.3000	0.30	0.25
L_p/L_e	0.6898	0.7020	0.70	0.67
S_p/L_e	0.5554	0.5650	0.57	0.56
S_p/L_p	0.8052	0.8048	0.82	0.84
150 GeV				
Ratio	**New GFlash**	**Test Beam**	**Old GFlash**	**Shower Library**
S_e/L_e	0.3264	0.3380	0.33	0.28
L_p/L_e	0.7102	0.7297	0.71	0.70
S_p/L_e	0.5936	0.5976	0.60	0.56
S_p/L_p	0.8358	0.8189	0.82	0.80

Table C.3: Comparison of energy response ratio between New GFlash, Test Beam Data (reference), Old GFlash and Shower Library using electrons and pions at 30,50.100 and 150 GeV.