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Design and Construction of CMS Central Hadron Calorimeter

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Abstract

The hadron calorimeter (HCAL) for the Compact Muon Solenoid Detector (CMS) covers the central pseudorapidity region ($|\eta| < 3.0$). It is a sampling calorimeter with brass absorber plates interspersed with scintillator readout plates. In this note, we discuss test beam results used in the optimization of the final design of the calorimeter and report on the status of the construction of the absorber and scintillator packages of HCAL.

1 The CMS Scintillator Tile-Fiber Hadron Calorimeter

The hadron calorimeter for the Compact Muon Solenoid Detector will be used in the determination of quark, gluon, and neutrino final state momenta by measuring the energies and directions of particle jets and the missing transverse energy flow. The determination of the missing energy flow is crucial in searches for new particles and phenomena, such as possible supersymmetric partners of quarks and gluons. Adequate granularity, resolution, and containment of particle showers are essential in attaining these performance goals and provide one of the benchmarks in the design of the CMS hadron calorimeter. In this communication we report on test beam results [1] used in the optimization of the design of HCAL, including choice of total absorber depth, sampling frequency, and longitudinal readout segmentation. We also present the status of the construction of the absorber and optical readout system of the HCAL.

The central CMS hadron calorimeter [2, 3] is located inside the 4 Tesla coil of the CMS solenoid magnet (inner diameter of 5.9 m). The central pseudorapidity range ($|\eta| < 3.0$) is covered by the barrel (HB) and endcap (HE) calorimeter systems. Segments of the crystal $PbWO_4$ electromagnetic calorimeter with a silicon pre-shower detector (in the endcap region only) are supported by the barrel and endcap hadron calorimeters. The combined response of the $PbWO_4$ crystal electromagnetic calorimeter and the hadron calorimeter is used in the reconstruction of particle jets and missing energy in the central pseudorapidity range.

The calorimeters are constructed using non-magnetic materials. The absorber and structural elements are made out of cartridge brass (70% Cu/ 30% Zn), and stainless steel plates, respectively. Cartridge brass is easy to machine and its hadronic interaction length is approximately 10% shorter than iron. The active sampling elements are 3.7 mm thick plastic scintillator tiles with wavelength-shifting (WLS) fiber readout. The barrel calorimeter inside the solenoid is relatively thin (about 7 interaction lengths at $\eta = 0$). To ensure adequate sampling depth for $|\eta| < 1.4$, a hadron outer calorimeter (HO) is installed outside the solenoid. The outer calorimeter utilizes the solenoid magnet coil and muon absorber plate as an additional absorber equivalent to 2.5/sin(θ) λ_{INT} and is used to identify and quantify the contribution from late starting showers.

In the forward region the radiation doses are expected to exceed 10 Mrads over the 10 year operation of LHC. To extend the hermeticity of the central hadron calorimeter system to pseudorapidity of 5, CMS employs a separate forward calorimeter (HF) located 6 m downstream of HE endcaps. The HF calorimeter covers the region $3.0 < |\eta| < 5.0$. It uses quartz fibers as active elements embedded in steel absorber matrix. Since the quartz fibers are predominantly sensitive to Cerenkov light from showering electrons, HF is mostly sensitive to the neutral pion content of the hadronic shower. Therefore, the HF calorimeter has a very localized response to hadronic showers.

2 Design Requirements

The design of the central hadron calorimeter requires good hermeticity, good transverse granularity, moderate energy resolution, and sufficient depth for hadron shower containment. We have chosen a lateral granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for $|\eta| < 2.0$. This granularity is sufficient to insure good di-jet separation and mass resolution. The calorimeter readout is required to have a dynamic range from 20 MeV to 3 TeV. The sensitivity at the low end allows for the observation of single muons in a calorimeter tower for calibration and trigger redundancy. The scale at the high end is set by the maximum energy expected to be deposited by a jet in a single calorimeter tower.

Initial simulations [4] of the CMS calorimeter indicate that a resolution of $\sigma_E/E = 120\%/\sqrt{E} \oplus$ 5% for single incident hadrons is obtained. In this case, the energy resolution for a jet of particles between 50 GeV and 3 TeV is not degraded by the measurement in the calorimeter, when other fluctuations which are inherent in jets are also considered.

3 The Test Beam Program

A test beam program to investigate some of the design issues of the hadron calorimeter specific to CMS was initiated in 1994 and was continued in 1995 and 1996. A test module of movable brass absorber plates and scintillator tile-fiber sampling was exposed to negative hadrons, electrons, and muons in the CERN test beam over a large energy range. Comprehensive tests of the performance of prototype CMS central hadron calorimeters were done in the H2 and H4 beamlines. Data were taken with both a stand-alone HCAL calorimeter and with a prototype lead tungstate crystal electromagnetic calorimeter (ECAL) placed upstream of the HCAL module. During this period the effects of the following sources on the response of the calorimeter module were investigated:

magnetic field (scintillator “brightening” and geometric effects), presence of crystal electromagnetic calorimeter (e/π effects), and optimization of absorber sampling, thickness, and depth.

3.1 Magnetic Field Effects

One of the primary objectives of the HCAL test beam studies was to investigate the calorimeter performance in the presence of perpendicular and parallel magnetic fields. The intrinsic shower energy development and the containment of hadron showers have been shown not to be affected by the high magnetic field. However, the scintillator itself exhibits an increased response in a magnetic field [5].

A high magnetic field changes the response of the calorimeter in two different ways: (1) the overall light yield of the scintillator is increased in a high magnetic field and (2) the field affects the observed energy deposition of electromagnetic components of showers when it is parallel to the scintillator plates (i.e. perpendicular to the particle direction). For a collider experiment with a solenoid magnet, the magnetic field is parallel to the calorimeter plates in the central part of the detector (barrel configuration) and is perpendicular to calorimeter plates in the large η region (endcap configuration).

When the magnetic field is perpendicular to the scintillator planes (endcap configuration), only an intrinsic increase of the light yield of the scintillator of approximately 5-8% is observed relative to the case with no magnetic field. The increased response of the calorimeter is the same for muons, electrons, pions, and γ rays from a radioactive source. Therefore a calibration source can be used to track and correct for this effect.

An additional geometric effect leads to an increased response of the calorimeter to the electromagnetic component of showers. This effect occurs in the case in which the magnetic field lines are parallel to the scintillator planes (barrel configuration) and originates from an increase in the geometrical path length of low energy electrons in a magnetic field. Since this effect is not present for the calibration source, $in\ situ$ (B field on) calibration is required for the hadron barrel calorimeter.

The size of this effect is approximately proportional to the strength of the B field and depends on the detailed structure and composition of the absorber and scintillator planes. However, the effect is expected to be present in any sampling calorimeter (independent of readout technology) situated in a magnetic field which is parallel to the readout planes (barrel configuration).

In high magnetic field, trajectories of low energy shower particles are curled up and do not strike scintillator. Therefore, in order to minimize the effect of the magnetic field on the response of the CMS calorimeter, one would like to maximize the distance between the scintillator and the upstream absorber. Therefore in the CMS HB calorimeter, the position of scintillator packages relative to the beam direction is the following: 2 mm plastic + 3.7 mm scintillator + 1 mm plastic. In addition, a system of thin brass (Venetian blind type) springs pushes the scintillator tiles radially outwards, such that the scintillator is always positioned closest to the downstream absorber plate. The use of springs ensures that the distance between inner absorber and the scintillator plate will consist of 2 mm $\pm$ 0.5 mm of air and 2 mm of plastic. The placing of 2 mm plastic in front of the scintillator and the introduction of springs should limit the effect of 4 Tesla B field in HB. In particular, the increase of non-linearity of HCAL’s response to pions between 50 GeV/c and 300 GeV/c is expected to be between 2-3%.

3.2 Combined Response of ECAL+HCAL

The test beam data show that the presence of the crystal electromagnetic calorimeter in front of HCAL degrades the linearity and resolution of the combined calorimeter system. However, a large fraction of this degradation can be corrected for by applying constant energy-independent weighting factors to the various longitudinal readout segments of HCAL. The response of the combined calorimeter system using these optimized weights meets the design requirements for resolution and containment of hadron showers.

Due to the highly non-compensating nature of the lead tungstate crystal (ECAL), the linearity and energy resolution of the combined crystal ECAL+HCAL is worse than for HCAL alone. Therefore, improvements in the linearity and resolution using weighting of the two longitudinal readouts (H1 and H2) of HCAL have been investigated.

We have investigated two possible approaches to correct for the degradation of the performance of the combined crystal ECAL+HCAL calorimeters. Both of these methods make use of the segmented readout of HCAL. The first approach, called passive weighting, increases the weight (α) of the first (H1) HCAL readout segment, where α is an energy independent constant. A value of α =1 corresponds to using the standard ”absorber Simpson’s weighting” used elsewhere in the calorimeter.

$$E_{TOT} = E_{ECAL} + \alpha \times E_{H1} + E_{H2} + E_{HO} \quad (1)$$

The second approach, called dynamic weighting is an event-by-event correction. It also depends on the fraction of the energy deposited in the first readout segment of HCAL immediately downstream of the crystal ECAL. The dynamic weighting effectively allows one to have an energy dependent correction (for single particles) for the low response to pions which interact in ECAL.

$$E_{TOT} = (1 + 2 \times f(H1)) \times E_{ECAL} + E_{H1} + E_{H2} + E_{HO}, \quad (2)$$

$$f(H1) = E(H1)/(E(H1) + E(H2) + E(HO)),\ f(H1) \leq 0.1 \quad (3)$$

As shown on Figures 1 and 2, with either the passive or dynamic weighting, the nonlinearity and resolutions for pions with energies between 30 and 300 GeV/c are improved. With the passive weighing, the fractional energy resolution of the combined ECAL+HCAL calorimetric system can be described by the function σ_E/E = 122%/$\sqrt{E}$ $\oplus$ 5%. Note however, that while the passive weighting can be applied to both single particles and jets, the dynamic weighting may introduce high energy tails in the case of particle jets.

The above described performance of HCAL is achieved by a novel longitudinal segmentation of HCAL with H1 being a single layer immediately behind ECAL. We conclude that for combined ECAL+HCAL calorimeter systems with an ECAL with a large e/h, a very thin first depth segment in HCAL can be used to largely correct for the resultant non-linearity and degradation in energy resolution. Monte Carlo studies of the CMS detector in a collider environment indicate that with the above performance, the energy resolution for jets is not dominated by the energy measurement in the hadron calorimeter, but by other fluctuations which are inherent in jets.

3.3 Optimization of absorber sampling thickness and depth

The conceptual design of the barrel HCAL was a 5.3 λ_{INT} thick calorimeter. The inner half of the calorimeter had 3 cm sampling (first readout segment, H1) while the second readout segment consisted of the outer half of the calorimeter with 6 cm sampling.

Important design choices that were made based on the analysis of the test beam data are:

- the absorber sampling thickness;
- the depth of the HCAL inside and outside of the magnetic coil
- the longitudinal segmentation of the inner HCAL into H1 and H2 readout segments

The fractional energy resolution has been investigated for the following three choices for the inner HCAL absorber samplings: a) 3 cm Cu sampling for the first eight layers followed by 6 cm Cu sampling, b) 6 cm Cu uniform sampling, and c) 12 cm Cu uniform sampling.

The data indicate that the energy resolution is not dominated by the sampling fluctuations in HCAL. A factor of two decrease in the sampling frequency (3 cm/6 cm to 6 cm uniform sampling) for HCAL does not result in a noticeable degradation of the energy resolution of the combined detector system. In the case of 12 cm Cu uniform sampling, the degradation in energy resolution is noticeable, but does not scale with $\sqrt{t}$, where t is the thickness of the absorber plates. For the final design, we chose uniform 5 cm sampling which does not degrade the energy resolution and puts more absorber inside the magnet, relative to the conceptual design.

The average longitudinal hadron shower profiles extend past the inner HCAL located inside the magnetic coil. To collect this leakage energy, the barrel HCAL has been augmented with an additional outer calorimeter (HO) consisting of a single layer of scintillators beyond the solenoid magnet (the solenoid thickness is 1.4 λ_{INT}). For pseudorapidity η less than 0.4, a layer of iron (thickness = 18 cm = 1.1 λ_{INT}) has been instrumented with an additional scintillator layer. The additional scintillators cover the same solid angle as the interior calorimeter and are read out as a single depth segment. The combined solenoid + iron of the HO corresponds to an additional 2.5 λ_{INT}. The addition of HO leads to a total ECAL+HCAL+HO depth of at least 9.5 λ_{INT} for almost the entire η range spanned by the CMS hadron calorimeters.

Thus the final design of the CMS barrel HCAL consists of 17 absorber/scintillator samples with 5 cm absorber thickness. The total thickness of absorber at 90 degrees is 5.9 λ_{INT}. With the ECAL included, the total thickness inside the magnet is 7.0 λ_{INT}. Exterior to the magnet, there is a 2.5 λ_{INT} outer calorimeter. Each projective tower of HB has 3 readouts in depth: the very first scintillator layer (H1); the remaining 16 scintillator layers inside the magnet (H2); and the outer calorimeter (HO).

3.4 Radiation Damage Effects

Radiation doses in the central pseudorapidity region ($|\eta| < 3.0$) peak at the front face of the HCAL. The low θ region of the endcap calorimeter gets a maximum dose of 6 Mrads for 10 years of LHC operation. Studies [6] of radiation damage of scintillator (Kuraray SCSN-81) read out by WLS fibers (Bicron BCF91A) show that the reduction in the light yield of the tile/fiber assemblies reaches approximately 20-30% level for a 1 Mrad dose and over 50% (factor of 2 to 4) for a 6 Mrad dose. This implies [7] that above 2 Mrads, the non-uniformity in the light collection would induce a constant term in the energy resolution of the calorimeter which would exceed the intrinsic constant term of the device. In order to reduce the radiation damage contribution to the energy resolution of the endcap calorimeter, we will introduce additional longitudinal segmentation (up to four readout segments) of the calorimeter in the low θ region. The actual radiation damage in each readout segment will be measured using a radioactive γ source. The reduced response of the radiation damaged segment will be compensated by recalibration.

4 Status of the Construction of the CMS HCAL

The Hadron Barrel calorimeter absorber structure has been designed at Fermilab and is being manufactured by the Felguera Constucciones Mecanicas company in Spain. Recently the company has completed machining of the first 18 wedges and successfully assembled them into a half-barrel. The production of the remaining 18 wedges and the assembly of the second half-barrel will be completed by September 2001.

The design of the optical readout system for the Hadron Barrel and Endcap calorimeters has adopted most of the features of the CDF End Plug Hadron Calorimeter [8]. Scintillation light is collected by wavelength shifting (WLS) fibers embedded in the tiles. Each tile is read out by a single fiber, placed in a σ shaped groove. One of the WLS fiber ends is mirrored, the other end is connected (spliced) to clear fiber outside of the tile. Clear optical fiber cables with mass terminated connectors carry light to the outside of the detector. Decoder boxes re-group the fibers from a layer-wise to a tower-wise scheme and house the hybrid photodetectors (HPDs) and readout electronics.

The variation of light yield of fiber-connector assemblies is measured before the fibers are inserted into tiles using a computer controlled scanner and a photoluminescent panel as the light source. Typical spread (RMS) of the fiber-connector assemblies is 3-4%. In addition, we perform sample quality control tests of the fiber mirror reflectivity (average = 83%, RMS= 6.5%) and light transmission across the splice (average = 92%, RMS= 2.1%).

Machined scintillator plates are wrapped using white plastic reflector (Tyvek) and light-tightening material (Tedlar) and placed between the plastic covers. The 2 mm thick top covers house the stainless steel tubes for radioactive source calibration. Following the final assembly of the megatile components (scintillator plates, cover plates, WLS fibers spliced to clear fibers, optical connectors), the megatiles undergo the final quality control checks using a γ radioactive source. Typical spread (RMS) of the light yield of complete tiles is 7-8%. At the present moment (October 2000), we have built and tested over 20,000 individual tiles, corresponding to over 50% of all tiles needed for the Hadron Barrel calorimeter. We expect to complete construction and testing of the HB optical readout system by July-2001. The two remaining critical items for the completion of the Hadron Barrel calorimeter are production of the readout boxes housing the HPDs and the readout electronics.

References

[1] V.V. Abramov *et al*, Studies of the response of the prototype CMS Hadron Calorimeter, including magnetic field effects, to pion, electron and muon beams, submitted to NIM A, hep-ex/0007045

[2] The Compact Muon Solenoid (CMS) Technical Proposal, CERN/LHCC 94-38, December 15, 1994.

[3] CMS Hadron Calorimeter Technical Design Report, CERN/LHCC 97-31, June 20, 1997.

[4] CMS Response Document to LHCC Referees, Appendix A1 to the CMS HCAL TDR, CERN/LHCC 97-31.

[5] D. Blomker *et al*, NIM **A311**, 505-511, 1992.

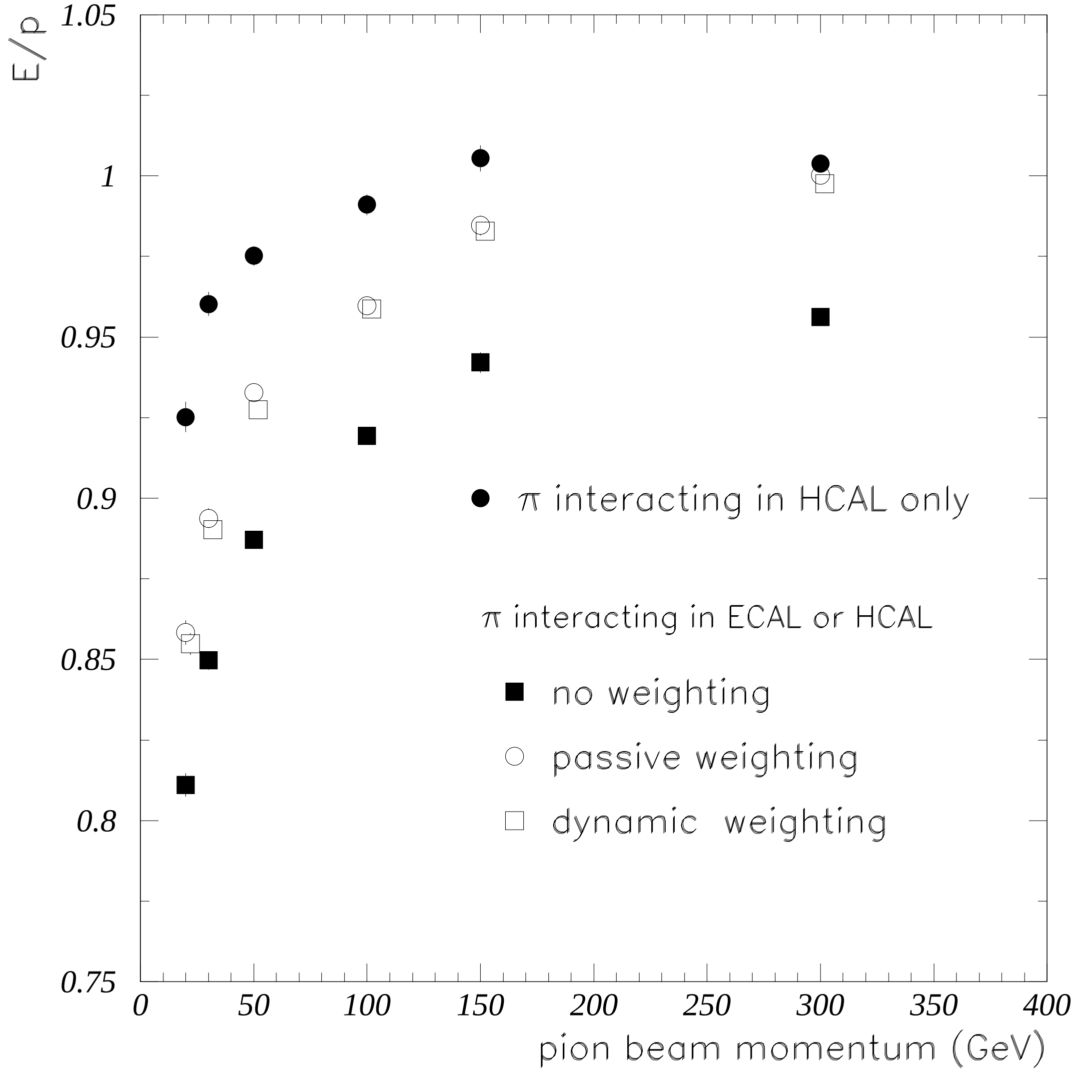

Figure 1: *The linearity of the response of HCAL to pions interacting in HCAL only and of the combined $PbWO_4$ crystal ECAL+HCAL system to all pions with weighting factor α =1.4 and without the weighting of H1. The statistical errors are smaller than the size of the symbols.*

[6] ”Radiation Damage of Fibers”, V. Hagopian and I. Daly, in proceedings of ”SCIFI97 Conference on Scintillating and Fiber Detectors”, ed. A.D. Bross, R.C. Ruchti and M.R. Wayne, p. 53, 1998.
”Radiation hardness tests of scintillating tile/WLS fiber calorimeter modules”, S.W. Han *et al*, NIM **A365**, 337-351, 1995.

[7] P. de Barbaro, A. Bodek, B. Winer, ”Effects of Tile Miscalibrations on the Performance of the Tile/Fiber Based Hadron Calorimeters”, U. of Rochester preprint UR-1301, January 1993.

[8] ”Scintillator Tile-Fiber Calorimeters for High Energy Physics: The CDF End Plug Upgrade, Selected Articles”, edited by P. de Barbaro and A. Bodek, U. of Rochester preprint UR-1309, October 1994.

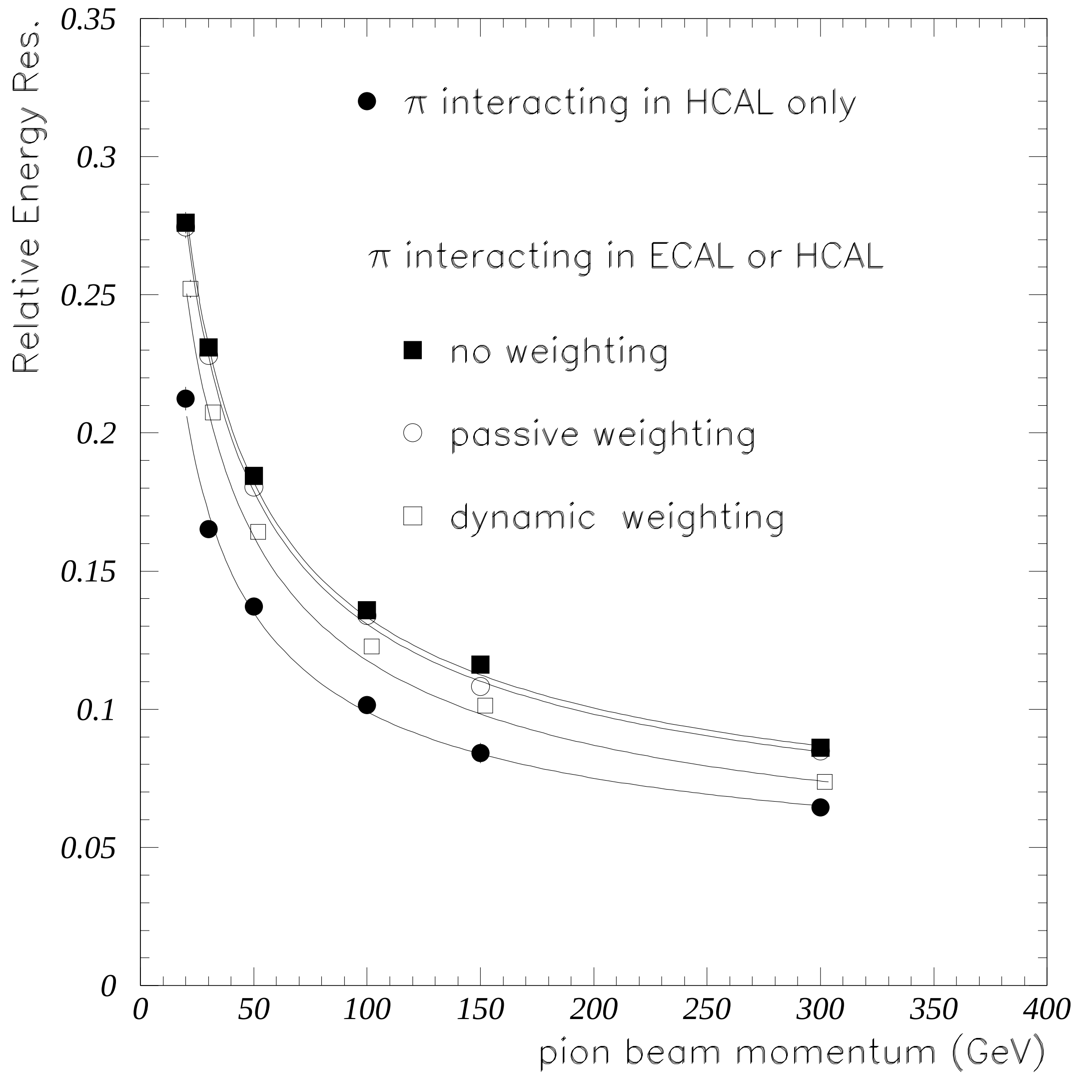

Figure 2: *The fractional pion energy resolution of HCAL to pions interacting in HCAL only and of the combined $PbWO_4$ crystal ECAL+HCAL system to all pions. The statistical errors are smaller than the size of the symbols. For the case of pions interacting in HCAL only, a fit to data for the fractional energy resolution yields the following values for the stochastic term and constant term parameters: σ_E/E=101%/$\sqrt{E} \oplus$ 4%. For the case of all pions, interacting in either ECAL or HCAL, a fit to data for the fractional energy resolution yields the following values for the stochastic term and constant term parameters: σ_E/E=127%/$\sqrt{E} \oplus$ 6.5%.*