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Experimental determination of the intrinsic fluctuations from binding energy losses in Si/Fe and Si/Fe+Pb hadron calorimeters

SICAPO Collaboration

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Abstract

Fluctuations due to binding energy losses were determined experimentally for sampling hadron calorimeters. The active medium of these calorimeters was consisting of layers of silicon mosaics. The absorber was either Fe layers (Si/Fe) or combinations of Pb and Fe layers (Si/Fe+Pb). The calorimeters were exposed to hadrons (π) at incoming energies of 6, 8, 10, and 12 GeV. The contributions (σ_{bind}) of the binding energy losses fluctuations to the energy resolution of these hadron calorimeters were found to be $\sigma_{bind} \approx (16 - 18)\%$ and $(45-49)\%$ for Fe and Pb, respectively. $\sigma_{bind} \sim 24.5\%$ has been found for an almost compensating Si/Fe+Pb calorimeter.

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1. INTRODUCTION

Substantial progress has been achieved during the past few years in the understanding of the phenomenology of hadronic cascading and its application to hadron calorimetry. In particular, sampling hadron calorimeters, where the incoming particle energy is measured in a number of sensitive layers interspersed with absorbing material layers, have attracted considerable attention due to their large use in high energy physics experiments.

The energy resolution of sampling hadron calorimeters is dominated by sampling and intrinsic fluctuations [1] and by their relative response to electromagnetic and hadronic showers. This response is measured by the ratio, e/π , of the electromagnetic (e) to the hadronic (π) calorimeter signals.

The sampling fluctuations originate from the fact that only a small fraction of the incoming energy is deposited in the active layers of the calorimeter and contribute to the calorimeter signal. These fluctuations are mainly generated by the fluctuations in the number and energy of charged particles crossing the active layers [2].

A large amount of the deposited energy goes in breaking nuclei (binding energy) or in low energy neutrons and therefore, is partially not visible. Protons, released in the de-excitation of nuclei, are poorly sampled due to their short range and/or saturation effects in the active material of the calorimeter. In addition, pion and muon decays contribute secondary particles like neutrinos which go largely undetected. The amount of energy, converted into excitation or break-up of the nuclei, of which only a fraction will result in detectable energy, fluctuates from event to event. These intrinsic fluctuations constitute an important contribution to the energy resolution in hadron calorimeters.

The nuclear effects, which dominate pure hadronic shower, have no counterpart in electromagnetic showers and, consequently, the response of the calorimeter to the electromagnetic and non-electromagnetic part of the shower is different, resulting in a e/π signal ratio not equal to 1. The consequences of this non-compensation (unequal response of the calorimeter to electrons and hadrons) have been examined at length in several articles [3,4]. One of these consequences is the existence of a term $\phi(e/\pi)$ contributing to the expected energy resolution, $(\sigma(E)/E)$, of a sampling hadron calorimeter which, thus, can be written as [4]:

$$(\sigma(E)/E) = C_0/\sqrt{E} + \phi(e/\pi) = C/\sqrt{E} \quad (1)$$

where E is the incoming hadron energy, in GeV, and $C = C_0 + \phi(e/\pi)\sqrt{E}$; $C_0 = \sqrt{\sigma_{bind}^2 + \sigma_f^2}$ contains the contributions from the intrinsic fluctuations mostly due to nuclear binding energy losses (σ_{bind}), and from the sampling fluctuations (σ_f). The function $\phi(e/\pi)$ is vanishing for $e/\pi = 1$, i.e., for compensating calorimeters.

The way to equalize the response of a hadron calorimeter to electromagnetic and hadronic showers, i.e., to achieve compensation ($e/\pi = 1$), is largely dictated by the

type of material used as active medium.

In hadron calorimeters employing hydrogeneous materials as active devices, like scintillators, the compensation condition can be achieved by increasing the relative contribution of the pure hadronic signal. This increase is mainly achieved by the detection of neutrons, generated in the last stage of the hadronic shower development, which can be modified by varying the sampling fraction [5].

The equalization of the response of a hadron calorimeter, with silicon readout, to electromagnetic and hadronic showers can be achieved by suppressing the electromagnetic response of the calorimeter. Experimental evidence was found for two effects: a local hardening effect [6] obtained by inserting low-Z absorbers (G-10 layers) next to the silicon detectors, and an electromagnetic filtering effect [7] obtained by using a combination of low-Z and high-Z materials as absorbers. The first effect is responsible for the suppression of the electromagnetic response of the calorimeter due to the absorption (in the low-Z material) of soft electrons. It has been experimentally demonstrated that the local hardening effect was leading to the achievement of the compensation condition in silicon calorimeter using U as absorber [8]. The filtering effect is a consequence of the transformation of the electron energy distribution of the incident showers in two media with different critical energies. The filtering effect has the net effect of decreasing the number and energy of electrons of showers. The filtering effect has been shown to allow the achievement of the compensation condition in a calorimeter using silicon as active medium and a combination of Fe and Pb layers as passive medium [9].

It is known [10] that, for a non-compensating calorimeter, $\phi(e/\pi)$ has only moderate variations in the energy range of 5-15 GeV, which covers the set of data used in the present article. Therefore, by combining direct measurements of the energy resolution with computed and/or measured values of $\phi(e/\pi)$ (once the e/π calorimeter ratio is experimentally known [9,11]), it is possible to determine C_0 , and finally the fluctuations due to the nuclear binding energy losses, once the sampling fluctuations are evaluated [12].

The data utilized in the present article, were obtained from calorimeters using silicon as active medium and passive media made either of layers of Fe (Si/Fe), and/or of combinations of Fe and Pb (Si/Fe+Pb).

The article is organized as follows: the various contributions to the energy resolution of the silicon hadron calorimeters are discussed in section 2, including contributions from effects related to the finite dimensions of the calorimeters and to the presence of dead zones between silicon detectors in the active layers. Section 3 is devoted to the presentation of data collected with Si/Fe and Si/Fe+Pb calorimeters. The informations obtained from these data allow the determination of the sampling and nuclear binding energy losses fluctuations. This is presented in section 4. Finally, conclusions are drawn in section 5.

2. SAMPLING HADRON CALORIMETERS AND BINDING ENERGY LOSSES

The e/π signal ratio, appearing in eq. (1), is defined as:

$$e/\pi = \frac{(e/mip)}{(e/mip).f_{em} + (h/mip).(1 - f_{em})} \quad (2)$$

where mip is the energy deposited in the sensitive part of the calorimeter by a minimum ionizing particle depositing all its energy in collisions losses in similar (with respect to the sampling structure), but indefinitely extended calorimeter; $h.(1 - f_{em})$ is the hadronic energy deposited in the detector readouts by the purely hadronic component of the shower. ef_{em} is the hadronic energy deposited by the electromagnetic component of the hadronic shower (see refs. [9,10] and references therein). f_{em} varies with energy and represents the average fraction of the converted electromagnetic energy resulting from the photon decays of π^0 's and η 's particles produced during the hadron cascade. The logarithmic increase of f_{em} with the energy, E ($\sim 0.12 \ln E$, E in GeV [1]), results in a e/π signal ratio which is also energy dependent. The ratio e/mip , in eq. (2), measures the energy deposited in the sensitive part of the calorimeter by electron and photon showers relative to minimum ionizing particles (mip). eq. (2) shows that if $e/\pi = 1$, then $e/mip = h/mip$.

The total visible energy (electromagnetic and hadronic), deposited by hadrons in the calorimeter, can be expressed as:

$$\epsilon_{vis} = E_s [f_{em}(\frac{e}{mip}) + (\frac{h}{mip})(1 - f_{em})] \quad (3)$$

The energy shared (E_s) by a minimum ionizing particle in the silicon detectors is given by (see ref. 9 and references therein):

$$E_s = E F(Si) = E G(Si) X_{Si} \quad (4)$$

with

$$G(Si) = \frac{(dE/dx)_{Si}}{(dE/dx)_{Si}.L_{Si} + \Sigma(dE/dx)_i.L_i}$$

where, X_{Si} , L_{Si} , L_i , $(dE/dx)_i$, E , and $F(Si)$ are the depletion depth, the thickness of the Si detector, the thickness of the absorber i , the average energy loss per unit of length (of a mip) in the absorber i , the incoming particle energy, and the fraction of energy lost in the depleted layers of the silicon detectors, respectively. Furthermore, eq. (3) can be rewritten as:

$$\epsilon_{vis} = E.F(Si)[(\frac{h}{mip}) + f_{em}(\frac{e}{mip} - \frac{h}{mip})] \quad (5)$$

Eq. (5) shows that it is only in the situation where $e/mip = h/mip$ (i.e. $e/\pi = 1$, the so-called compensation condition) that the calorimeter response is proportional to the incoming energy E , independently of f_{em} which varies with E .

In a sampling calorimeter, the measured energy resolution, $(\sigma(E)/E)_{exp}$, is given by:

$$(\sigma(E)/E)_{exp} = \sigma_{vis}/\epsilon_{vis}(\pi) \quad (6)$$

where σ_{vis} is the standard deviation value of the Gaussian like distribution of the hadronic visible energy, $\epsilon_{vis}(\pi)$, measured in the calorimeter when no correction for energy losses are included. These losses are longitudinal, lateral, and dead area energy losses. The latter have to be considered particularly for calorimeters with high granularity. The effects of energy losses on the energy resolution have been measured experimentally for hadronic and electromagnetic showers. In particular, for hadronic showers, the linear dependence of the hadronic resolution on energy losses has been observed up to energy losses of about 15% [2]. The effect of the fraction of energy lost, on the measured energy resolution, discussed in [2], [13], can be represented (for energy losses up to 15%) according to:

$$(\sigma(E)/E)_{exp} = (\sigma(E)/E)(1 + \Sigma\lambda_P.P) = (C/\sqrt{E})(1 + \Sigma\lambda_P.P) \quad (7)$$

where P is the percentage of lateral (l), longitudinal (L), and dead area (D) energy losses. λ_P is a coefficient depending on the type of energy loss. It has been shown that the lateral energy losses are less effective than the longitudinal energy losses [2], [13], i.e., $\lambda_l < \lambda_L$. Furthermore, it has been also shown [13] that the longitudinal energy losses are as effective as the dead area energy losses, i.e., $\lambda_L \approx \lambda_D$, because both of them are related to event-to-event fluctuations. The experimental data [2] have allowed to determine that, for hadronic showers, the values of λ_l and $\lambda_L \approx \lambda_D$ are 0.027 and 0.077, respectively.

The importance of longitudinal and lateral energy losses, and their effect on the energy resolution of the calorimeter, depends on the calorimeter dimensions. For calorimeter of fixed dimensions, the fraction of energy lost longitudinally increases with energy. As stressed above, fluctuations coming from the transverse leakage are less effective, by a factor 2-3, on the energy resolution compared to those caused by longitudinal leakage [2].

3. EXPERIMENTAL SET-UP AND DATA

The silicon sampling hadron calorimeter was consisting of fifty absorbers of fixed thickness interspaced with silicon readout mosaics. In each sampling, the thickness of Pb and Fe were kept constant as well as the respective positions of the absorbers plates. Each set of absorbers was 15 mm thick. The thickness of Pb and Fe layers was 5 and 10 mm, respectively. Data were taken for the PbFe-Si-PbFe absorber configuration

along the beam direction. Data were also taken with Fe (15 mm thick) as the only absorbers, for comparison.

The total calorimeter depth, in interaction lengths ¹, was about 5.7λ , taking into account the supporting structure of the silicon mosaics. The mosaic supporting structure, mainly made of low-Z (and low-A) magnetized and textilen ribbons located on the front and rear side of the detectors, was equivalent to about $2.6\% \lambda$ per sampling or equivalently to a Fe absorber thickness of about 4.3 mm. This had to be taken into account to determine the overall calorimeter depth.

The readout of this calorimeter consisted of 50 mosaic planes each made of 360 silicon detectors. A detector had an area of about 4 cm^2 , was $400 \mu\text{m}$ thick, and operated at full depletion. On a given mosaic, the detectors were grouped (in parallel) in 36 sets of 10 silicon detectors, each. The corresponding sets (in different mosaics) of 10 detectors were coupled in series in group of 5 along the beam direction. A detailed description of the associated electronics can be found in Ref. [14]. Thus, the overall electronic readout enabled the lateral segmentation given by the sets of 10 detectors (i.e. $\approx 40 \text{ cm}^2$) of a mosaic, to be kept.

The data were taken at the t9 beam at the CERN-PS. The negatively charged hadron incoming energies were 6, 8, 10, and 12 GeV. Two gas Cherenkov counters were used to tag hadrons, mostly pions. A beam scanner consisting of a scintillator counter of $0.5 \times 0.5 \text{ cm}^2$ area ensured that only those hadrons impinging on the middle of the calorimeter triggered. The absolute energy calibration was performed following two independent approaches: i) by $\text{U}^{233} \alpha$ sources (4.8 MeV on average) ii) by minimum ionizing particles (μ) which give a well known energy-loss distribution in the silicon readout detectors. The two methods agreed well with each other and the error on the absolute energy scale was about 2%.

For each group of 5 detector sets, the standard deviation of the Gaussian noise distribution was 195 keV corresponding to a signal of $\approx 0.3 \text{ mip}$. This was measured before and after each data taking run, allowing for the correction of the experimental visible energy distributions for these electronic noise effects.

The measured visible energies have to account for the energy losses in the dead zones between detectors in the mosaics. The dead area energy loss amounted to $(5.1 \pm 1.0)\%$ of ϵ_{vis} [9]. Lateral and longitudinal visible energy losses are generated by the finite transverse and longitudinal calorimeter sizes. The estimate of the lateral energy losses was calculated according to a procedure used in previous articles [8,9] and using data taken during dedicated runs in which mosaic planes (1920 cm^2 of active area) had their detector sets (ten Si detectors, each) readout individually. The value of the overall lateral loss of the hadronic visible energy was estimated to be $(5.4 \pm 0.8)\%$ at the incoming hadron energies of 6, 8, 10, and 12 GeV. Furthermore, the calorimeter

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¹ λ is given by: $A/(N_{av} \sigma) \approx 35A^{1/3}/\rho[\text{cm}]$, where A , N_{av} , ρ , and σ are the mass number, the Avogadro number, the density of the material, and the proton inelastic cross section for the material, respectively. The Pb and Fe absorbers interaction lengths are 17.1 and 16.8 cm, respectively.

was divided into 10 sections along the beam direction, each section being readout independently. This allowed an estimate of the longitudinal loss of visible energy by extrapolating the exponential fall of the longitudinal shower development after the shower maximum. The longitudinal hadronic energy losses were estimated to be $(1.0 \pm 0.2)\%$, $(1.0 \pm 0.3)\%$, $(1.7 \pm 0.7)\%$, and $(2.1 \pm 0.6)\%$ at 6, 8, 10, and 12 GeV, respectively.

The measured visible hadron energy (ϵ_{vis}), for Si/Fe and Si/Fe+Pb calorimeters, is shown in fig. 1 as a function of the incoming hadron energy. The values reported in fig. 1 were corrected for the longitudinal, lateral, and dead area energy losses effects described above. ϵ_{vis} shows a linear behaviour with the incoming hadron energy, E , within the experimental errors. The measured energy resolution $((\sigma(E)/E)_{exp})$ when no correction for dead area, lateral and longitudinal energy losses are taken into account, is shown as a function of $1/\sqrt{E}$ in figs. 2 and 3 for Si/Fe and Si/Fe+Pb calorimeters, respectively. $(\sigma(E)/E)_{exp}$ displays a linear behaviour with $1/\sqrt{E}$, within the experimental errors.

These results allows the determination of the values of C ($C/\sqrt{E} = \sigma(E)/E$) for the energy resolution, corrected for the effects of the visible energy losses (eq. (7)). Table 1 shows the values of C evaluated for the two calorimeter configurations and as a function of the incoming hadron energy. The weighted average value of C over the incoming energies of 6, 8, 10, and 12 GeV is $C = (58.8 \pm 1.9)\%$ and $(59.5 \pm 2.3)\%$ for the Si/Fe and Si/Fe+Pb calorimeters, respectively.

4. Determination of the intrinsic fluctuations

In hadronic sampling calorimeters, sampling fluctuations (σ_f) and intrinsic fluctuations (σ_{bind}) are contributing to the overall energy resolution of the calorimeter, the latter being mostly due to the binding energy losses because of nuclear break-up. The contribution from the sampling fluctuations (σ_f) can be computed from the parametrization [12]:

$$\sigma_f = 11.5\% \sqrt{\Delta E} \quad (8)$$

where ΔE is the average energy, in MeV, deposited by a minimum ionizing particle in one passive sampler [12].

From eq. (8), the sampling fluctuation contributions ² are $\sigma_f[Fe] = (53.4 \pm 0.3)\%$ and $\sigma_f[Fe+Pb] = (54.1 \pm 0.3)\%$ for the Si/Fe and Si/Fe+Pb calorimeters, respectively. Eq. (1) can be rewritten as:

$$\sigma(E)/E = \frac{\sqrt{\sigma_{bind}^2(eff) + \sigma_f^2}}{\sqrt{E}} \quad (9)$$

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² The error on the σ_f values takes into account the uncertainty in the chemical composition of the various materials of the silicon mosaic supporting structure.

where $\sigma_{bind}(eff)$ includes both the effect of intrinsic fluctuations and the effect of non compensation on the calorimeter energy resolution, the latter being accounted by the term $\phi(e/\pi)$. Namely, from eq. 1, we can express $\sigma_{bind}(eff)$ as:

$$\sigma_{bind}(eff) = \sqrt{\sigma_{bind}^2 + E\phi(e/\pi)^2 + 2\sqrt{E}\phi(e/\pi)\sqrt{\sigma_{bind}^2 + \sigma_f^2}} \quad (10)$$

For a compensating calorimeter (i.e. $e/\pi = 1$ and $\phi(e/\pi) = 0$), $\sigma_{bind}(eff) \equiv \sigma_{bind}$.

From eqs. (1) and (9), one has:

$$\sigma_{bind}(eff) = \sqrt{C^2 - \sigma_f^2}. \quad (11)$$

The calculated values of $\sigma_{bind}(eff)$ (using the values of C from Table 1) are shown in figs. 4 and 5, as a function of the incoming hadron energy, for the Si/Fe and Si/Fe+Pb calorimeters, respectively. The weighted average values (obtained from a weighted average of the values at the incoming energies of 6, 8, 10, and 12 GeV) of $\sigma_{bind}(eff)[Fe]$ and $\sigma_{bind}(eff)[Fe + Pb]$ are 24.0 and 24.5%, respectively. The value of $\sigma_{bind}(eff)[Fe]$ is larger than the value $\sigma_{bind}[Fe] \approx (18 - 22)\%$ expected in a situation when neutron capture is negligible (see ref. (4)). This occurs because the Si/Fe calorimeter is non-compensating with a measured e/π ratio of about 1.11 [9], for hadron energies between 6 and 12 GeV. The Si/Fe+Pb calorimeter, using passive samplers such that the probability of interaction on the Pb absorbers is about 25.7%, is almost compensating ($e/\pi \approx 1$), as it has been shown experimentally [9]. Thus, $\sigma_{bind}(eff)[Fe + Pb] \approx \sigma_{bind}[Fe + Pb] \approx 24.5\%$. The value of $\sigma_{bind}[Pb]$ is predicted to be about (42-46)%, when the neutron capture is negligible [4]. As a consequence of the fraction of Pb content of the passive sampler, the $\sigma_{bind}[Fe + Pb]$ overall value is larger than $\sigma_{bind}[Fe]$ but much smaller than $\sigma_{bind}[Pb]$.

4.1 Determination of the binding energy losses fluctuations in Fe

The intrinsic fluctuations contributions in the case of the Si/Fe calorimeter, $\sigma_{bind}[Fe]$, can be determined once the function $\phi(e/\pi)$ (see eq. (1)) is evaluated. From eq. (1), one has:

$$C(Fe) = \sqrt{\sigma_{bind}[Fe]^2 + \sigma_f[Fe]^2} + \phi(e/\pi)\sqrt{E} \quad (12)$$

and consequently,

$$\sigma_{bind}[Fe] = \sqrt{(C(Fe) - \phi(e/\pi)\sqrt{E})^2 - \sigma_f[Fe]^2} \quad (13)$$

Previous measurements [9] have determined (for the Si/Fe calorimeter) that the e/π ratio is about 1.11 in the 6-12 GeV energy range. Thus, $\phi(e/\pi)$ can be taken as a constant, to a first approximation, in this energy range.

The value of $\phi(e/\pi)$ has been estimated by interpolating Monte Carlo simulations of energy resolution dependence on incoming energy (reported in Ref. [10]), for e/π

ratios of 1.14, 1.26, and 1.47, at 10 GeV. From these simulations, one can estimate that $\phi(e/\pi)$ is about 0.9% (in the 5-15 GeV energy region) for e/π about 1.11. This value is in agreement, within the experimental errors, with the results reported in Ref. [15], where it has been determined that $\phi(e/\pi) = (1.0 \pm 0.1)\%$ for $e/\pi = 1.107 \pm 0.006$ at 9.7 GeV. Using these values of $\phi(e/\pi \sim 1.11)$, those of C reported in Table 1, and the value of σ_f as given by eq. (8), it becomes possible to estimate $\sigma_{bind}[Fe]$ (eq. (12)). The weighted average values of $\sigma_{bind}[Fe]$ (from a weighted average of the values at the incoming energies of 6, 8, 10, and 12 GeV) are about 17.5% and 16.2% for $\phi(e/\pi \sim 1.11) \approx 0.9\%$ and $\phi(e/\pi \sim 1.11) \approx 1.0\%$ (ref. 15), respectively. A slightly lower value of $\sigma_{bind}[Fe]$ is expected compared with the value (18-22)% predicted [10] for negligible neutron absorption, mainly because the supporting mosaic structure materials have lower A-values than iron.

4.2 Determination of the binding energy losses fluctuations in Pb

As discussed above, the Si/Fe+Pb calorimeter has a structure permitting to achieve an almost compensating condition and therefore, $\sigma_{bind}(eff)[Fe + Pb] \approx \sigma_{bind}[Fe + Pb] = 24.5\%$.

$\sigma_{bind}[Pb]$ can be obtained from $\sigma_{bind}[Fe + Pb]$, whose effective value does not need being corrected to take into account the value of $\phi(e/\pi)$ (about zero in this almost compensating condition).

$\sigma_{bind}[Fe + Pb]$ is the sum of $\sigma_{bind}[Pb]$ and $\sigma_{bind}[Fe]$ weighed by the interaction probabilities on Pb and Fe, respectively:

$$\sigma_{bind}[Fe + Pb] \approx 24.5\% = (L_{Pb}/L_{tot})\sigma_{bind}[Pb] + (L_{Fe}/L_{tot})\sigma_{bind}[Fe] \quad (14)$$

with $L_{tot} = L_{Pb} + L_{Fe}$ where L_{Pb} , L_{Fe} are the thicknesses (expressed in hadron interaction length units) of Pb, Fe in the calorimeter, respectively. L_{Fe} includes the contribution of the low-A supporting mosaic structure materials. From eq. (14), one finds:

$$\sigma_{bind}[Fe + Pb] = (1.46/5.68)\sigma_{bind}[Pb] + (4.22/5.68)\sigma_{bind}[Fe] = 24.5\% \quad (15)$$

which gives $\sigma_{bind}[Pb] \approx 48.5\%$ and $\approx 44.7\%$, for $\sigma_{bind}[Fe] \approx 16.2\%$ and $\approx 17.5\%$, respectively. This result is in agreement with the value $\sigma_{bind}[Pb] \approx (42-46)\%$ predicted in refs. [4,10] for the case of negligible or low neutron absorption.

In order to decrease the contribution due to the intrinsic fluctuations, particularly for high-A materials, it is necessary to employ homogeneous materials, in which part of the neutron energy can be detected by the scintillation process induced by the recoiling proton after a proton-neutron scattering. Calorimeters which have scintillator as active medium and a large ratio, R , of the active (scintillator 2.5 mm thick) to passive (Pb thickness of 10.0 mm) medium thicknesses, have shown smaller energy losses fluctuations [12]: $\sigma_{bind} = (13.4 \pm 4.7)\%$, as previously predicted in refs. 4 and 10.

5. DISCUSSION AND CONCLUSIONS

Binding energy losses take their origin from the fluctuating large amount of the deposited energy which goes in breaking nuclei during the hadronic cascading. The resulting fluctuations contribute to the overall energy resolution of hadron calorimeters. There is no direct way to measure the fluctuations due to binding energy losses. However, using silicon calorimeters with Fe (Si/Fe) and combinations of Pb and Fe (Si/Fe+Pb) as absorbers, the fluctuations due to binding energy losses, for iron and lead, were determined by combining direct measurements of the energy resolution, estimates of $\phi(e/\pi)$ using previous experimental measurements of the e/π ratio, and calculation of sampling fluctuations.

The binding energy losses depend on the fraction of neutron energy detected by the active sampler. In the present work, the ratio, R , of the active to passive medium thicknesses is very small and little of the neutron energy is seen by the active medium (which does not contain any hydrogenous material), leading to larger intrinsic fluctuations from binding energy losses.

The present results, $\sigma_{bind} \approx (16 - 18)\%$ and $(49-45)\%$ for Fe and Pb, respectively, are found in agreement with earlier predictions made when neutron absorption is negligible [2].

For an almost compensating Si/Fe+Pb calorimeter, the contribution to the overall energy resolution of $\sigma_{bind}[Fe + Pb]$ is about 24.5%.

Furthermore, in both cases of the Si/Fe and Si/Fe+Pb calorimeters, the visible energy, ϵ_{vis} , has shown a linear dependence on the incoming hadron energy, within the experimental errors.

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TABLE CAPTIONS

Table 1: The value of C , as a function of the hadron energy, for the Si/Fe and Si/Fe+Pb calorimeters.

FIGURE CAPTIONS

FIG. 1: The visible energy, ϵ_{vis} , in the Si/Fe (top points) and Si/Fe+Pb (bottom points) calorimeters as a function of the incoming energy. The top line shows a least square fit to the data obtained for the case of pure Fe absorber (Si/Fe calorimeter): $\epsilon_{vis}(Fe) = [(5.8 \pm 0.2)E(GeV) + (-2.7 \pm 1.9)][MeV]$. The bottom line shows a least square fit to the data obtained for the Si/Fe+Pb calorimeter: $\epsilon_{vis}(Fe + Pb) = [(5.2 \pm 0.2)E(GeV) + (-2.8 \pm 1.6)][MeV]$.

FIG. 2: The measured hadron energy resolution, $(\sigma(E)/E)_{exp}$ (in %), as a function of $1/\sqrt{E}$ (E is incoming energy) for the Si/Fe calorimeter.

FIG. 3: The measured hadron energy resolution, $(\sigma(E)/E)_{exp}$ (in %), as a function of $1/\sqrt{E}$ (E is the incoming energy) for the Si/Fe+Pb calorimeter.

FIG. 4: The effective value, $\sigma_{bind}(eff)$, of the fluctuation due to binding energy losses (in %) as a function of the incoming energy, for the Si/Fe calorimeter. The line corresponds to the weighted average value: $\sigma_{bind}(eff)[Fe] = 24.0\%$.

FIG. 5: The effective value, $\sigma_{bind}(eff)$, of the fluctuation due to binding energy losses (in %) as a function of the incoming energy, for the Si/Fe+Pb calorimeter. The line corresponds to the weighted average value: $\sigma_{bind}(eff)[Fe] = 24.5\%$.

E(GeV)	C(Fe)[%]	C(Fe+Pb)[%]
12	58.2 ± 3.6	58.5 ± 3.8
10	58.1 ± 3.8	59.5 ± 5.2
8	58.9 ± 4.1	60.4 ± 5.2
6	59.9 ± 3.7	60.2 ± 4.3
C(weighed value)	58.8 ± 1.9	59.5 ± 2.3

Table 1

fig. 1

fig. 2

fig. 3

fig. 4

fig. 5