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Determination of intrinsic fluctuations and energy response of Si/Fe and Si/Fe+Pb calorimeters up to 70 GeV of incoming hadron energy

SICAPO Collaboration

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Abstract

Fluctuations due to binding energy losses were determined experimentally for sampling hadron calorimeters with layers of silicon mosaics as active medium and with either Fe layers (Si/Fe) or combinations of Pb and Fe layers (Si/Fe+Pb) as absorbers. The calorimeters were exposed to hadrons (π) at incoming energies of 10, 15, 20, 30, 40, 50 and 70 GeV at the CERN-SPS. The contributions (σ_{bind}) of the binding energy losses fluctuations to the energy resolution of these hadron calorimeters were found to be $\sigma_{bind} = (19.8 \pm 2.4)\%$ and $(49.9 \pm 14.1)\%$ for Fe and Pb, respectively. $\sigma_{bind} = (25.9 \pm 2.1)\%$ has been found for a compensating Si/Fe+Pb calorimeter. These results are found in good agreement with previous measurements made at lower energies. As expected, an overall non-linearity of about 3.5%, in the 10-70 GeV energy range, has been observed in the Si/Fe non-compensating ($e/\pi \sim 1.11$ at 10 GeV) calorimeter energy response.

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1. INTRODUCTION

The energy resolution, $(\sigma(E)/E)$, of a sampling hadron calorimeters can be expressed as:

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

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). ϕ is a function of e/π , which is the ratio of the electromagnetic (e) (generated by electromagnetically interacting particles such as electrons and photons) to the hadronic (π) (generated by strongly interacting particles such as pions and protons) calorimeter signals [1-4].

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 non-compensation i.e. a e/π signal ratio not equal to 1, reflected by the occurrence of a term $\phi(e/\pi)$ in Eq. (1). The function $\phi(e/\pi)$ is vanishing for $e/\pi = 1$, i.e., for compensating calorimeters, when the equalization of the calorimeter response to electromagnetic and hadronic showers is achieved. This equalization can be achieved via the filtering effect when combinations of Fe and Pb layers are used as passive medium of a silicon sampling calorimeter [5]. 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 [6].

For a non-compensating calorimeter, $\phi(e/\pi)$ varies in the 10-70 GeV energy range [7], which covers the set of data used in the present article. $\phi(e/\pi)$ can be estimated (see Monte-Carlo simulations in Ref. 7) as a function of the e/π ratio at 10 GeV. Experimental data of $\phi(e/\pi)$ are also available. 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 [6,8]), it is possible to determine C_0 , and finally the fluctuations due to the nuclear binding energy losses, once the sampling fluctuations are evaluated [9].

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 calorimeters were exposed to hadron beams at the CERN-SPS facility.

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. $e.f_{em}$ is the hadronic energy deposited by the electromagnetic component of the hadronic shower (see Refs. [6,7] 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 ($f_{em}(E) \sim 0.12 \ln E$, 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). From Eq. (2), the intrinsic e/h ratio can be written as:

$$e/h = \frac{(1 - f_{em})e/\pi}{(1 - f_{em}.e/\pi)} \quad (3)$$

Eqs. (2) and (3) show that if $e/\pi = 1$, then $e/mip = h/mip$, and also $e/h = 1$.

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

$$\epsilon_{vis} = E_s [f_{em}(\frac{e}{mip}) + (\frac{h}{mip})(1 - f_{em})] \quad (4)$$

The energy shared (E_s) by a minimum ionizing particle in the silicon detectors is given by (see Ref. 6 and references therein):

$$E_s = E F(Si) = E G(Si) X_{Si} \quad (5)$$

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. (4) can be rewritten as:

$$\epsilon_{vis} = E.F(Si)[(\frac{h}{mip}) + f_{em}(\frac{e}{mip} - \frac{h}{mip})] \quad (6)$$

or

$$\epsilon_{vis} = E.F(Si)(\frac{h}{mip})[1 + f_{em}(\frac{e}{h} - 1)] \quad (7)$$

Eq. (6) shows that it is only in the situation where $e/mip = h/mip$ (i.e. $e/h = e/\pi = 1$, 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:

$$(\sigma(E)/E)_{exp} = \sigma_{vis}/\epsilon_{vis}(\pi) \quad (8)$$

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 [2,10-12], can be represented (for energy losses up to 15%) according to:

$$(\sigma(E)/E)_{exp} = (\sigma(E)/E)(1 + \Sigma\lambda_P.P) = (C/\sqrt{E})(1 + \Sigma\lambda_P.P) \quad (9)$$

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. The values of $\lambda_l = 0.027$ and $\lambda_L \approx \lambda_D = 0.077$ have been determined experimentally (see Ref. [11] and references therein).

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 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 20 mm thick. The thickness of Pb and Fe layers was 5 and 15 mm, respectively. Data were taken for the PbFe-Si-PbFe absorber configuration along the beam direction. Data were also taken with Fe (20 mm thick) as the only absorbers, for comparison.

The total calorimeter depth, in interaction lengths ¹, was about 7.17λ , taking into account the supporting structure of the silicon mosaics. The mosaic supporting structure, mainly made of low-Z (and low-A) magnetized and texiltex 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. [13]. 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 X1 beam at the CERN-SPS. The negatively charged hadron incoming energies were 10, 15, 20, 30, 40, 50, and 70 GeV. A Cerenkov differential counter with achromatic ring focusing (CEDAR) was used to tag hadrons, mostly negative pions. The CEDAR was capable to separate pions from electrons up to 45 GeV, beyond this energy the beam contained no electrons. 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 290 keV corresponding to a signal of $\approx 0.4 \text{ mip}$. 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.

¹ λ is given by: $A/(N_A \sigma) \approx 35 A^{1/3} / \rho [\text{cm}]$, where A , N_A , 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.

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} [6]. 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 [6,14] 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 lateral loss of the hadronic visible energy was estimated to be $(3.9 \pm 0.5)\%$, $(3.6 \pm 0.7)\%$, $(3.3 \pm 0.6)\%$, $(3.3 \pm 0.6)\%$, $(2.9 \pm 0.5)\%$, $(2.8 \pm 0.3)\%$, and $(2.7 \pm 0.3)\%$ at the incoming hadron energies of 10, 15, 20, 30, 40, 50, and 70 GeV, respectively ² Furthermore, the calorimeter 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 $(0.9 \pm 0.6)\%$, $(1.0 \pm 0.5)\%$, $(1.1 \pm 1.3)\%$, $(1.8 \pm 1.1)\%$, $(2.1 \pm 0.6)\%$, $(3.0 \pm 0.6)\%$, and $(4.0 \pm 0.7)\%$ at the incoming hadron energies of 10, 15, 20, 30, 40, 50, and 70 GeV, respectively.

The measured visible hadron energies $\epsilon_{vis}(Fe)$, $\epsilon_{vis}(Fe+Pb)$ for Si/Fe and Si/Fe+Pb calorimeters, respectively, are 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. For the Si/Fe+Pb calorimeter, the values of ϵ_{vis} measured as a function of the incoming hadron energy, E , can be fitted to

$$\epsilon_{vis}(Fe + Pb, E) = (4.5 \pm 0.1)E(\text{GeV}) + (-3.0 \pm 2.7)[\text{MeV}]$$

and to

$$\epsilon_{vis}(Fe, E) = (5.3 \pm 0.1)E(\text{GeV}) + (-8.8 \pm 2.5)[\text{MeV}]$$

for the Si/Fe calorimeter.

The Si/Fe+Pb calorimeter, using passive samplers such that the probability of interaction on Pb absorbers is about 21%, is almost compensating (i.e. e/h and $e/\pi \approx 1$), as it has been shown experimentally [6]. The Si/Fe calorimeter is non-compensating [6] with a e/π ratio of about 1.11 for 10 GeV incoming hadron energy [6,11]. For the Si/Fe calorimeter, the corresponding intrinsic ratio (which is almost energy independent [1,4,7]) $e/h \approx 1.16$ is obtained from Eq. (3) by using the calculated value of f_{em} at 10 GeV and the e/π ratio (about 1.11) measured at the same energy [6]. The ratio $R = \epsilon_{vis}(Fe)/\epsilon_{vis}(Fe + Pb)$ of the measured visible energy in Si/Fe (non compensating) to Si/Fe+Pb (compensating) is shown in Fig. 2 as a function of the

² The lateral energy losses decrease as the incoming energy increases. They are related to the experimentally determined ratios of the central to peripheral energy distributions (see also Ref. 15). The measurement of the ratios of lateral to peripheral components is possible due to the segmentation of the active layers in the present Si calorimeters.

incoming energy. Using Eq. (7) for $(e/h)_{Fe+Pb} \approx 1$ and $(e/h)_{Fe} \approx 1.16$ respectively for the almost compensating Si/Fe+Pb calorimeter and the non-compensating Si/Fe calorimeter, the calculated R_{cal} ratio is found to be:

$$R_{cal} = K.(1 + 0.16 \times f_{em}(E)) \quad (10)$$

with $K = F_{Fe}(Si)(h/mip)_{Fe} / F_{Fe+Pb}(Si)(h/mip)_{Fe+Pb}$.

K can be determined by imposing that $R_{cal}(at\ 70GeV) = R(70)$, where $R(70)$ is the value of the ratio R measured at 70 GeV ($R(70) \sim 1.155$). The measured R value has the smallest experimental errors at this incoming energy. The following value is found:

$$K = \frac{1.155}{1 + 0.16 \times f_{em}(E = 70GeV)} = 1.068$$

and therefore

$$R_{cal}(E) = 1.068(1 + 0.16 \times f_{em}(E))$$

which is the line shown in Fig. 2. The calculated ratio, R_{cal} , is in good agreement with the measured ratio R , within the experimental errors. Thus, for a non-compensating Si/Fe calorimeter (with a ratio $e/h \approx 1.16$), there is an overall non-linearity in the calorimeter energy response³ of about 3.5%, for incoming hadron energies between 10 and 70 GeV. Because of this small overall non-linearity, the fit to a linear dependence of $\epsilon_{vis}(Fe, E)$ on the incoming energy E will have a negative visible energy intercept non compatible with zero within the errors, as it is indeed found.

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. 3a and 3b 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. (9)). Table 1 shows the values of C evaluated for the two calorimeter configurations and as a function of the incoming hadron energy.

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 [9]:

$$\sigma_f = 11.5\% \sqrt{\Delta E} \quad (11)$$

³The expected overall non-linearity of the Si/Fe calorimeter energy response is reduced to about 1.3% for incoming hadron energies between 6 and 12 GeV [11].

where ΔE is the average energy, in MeV, deposited by a minimum ionizing particle in one passive sampler [9].

From Eq. (11), the sampling fluctuation contributions ⁴ are $\sigma_f[Fe] = (60.2 \pm 0.4)\%$ and $\sigma_f[Fe + Pb] = (60.8 \pm 0.4)\%$ for the Si/Fe and Si/Fe+Pb calorimeters, respectively. Eq. (1) can be rewritten as:

$$\sigma(E)/E = \frac{\sqrt{\sigma_{bind}^2(eff) + \sigma_f^2}}{\sqrt{E}} \quad (12)$$

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:

$$\sigma_{bind}(eff) = \sqrt{\sigma_{bind}^2 + E\phi(e/\pi)^2 + 2\sqrt{E}\phi(e/\pi)\sqrt{\sigma_{bind}^2 + \sigma_f^2}} \quad (13)$$

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

From Eqs. (1) and (12), one has:

$$\sigma_{bind}(eff) = \sqrt{C^2 - \sigma_f^2}. \quad (14)$$

$\sigma_{bind}(eff)(Fe)$ for the Si/Fe calorimeter can be calculated via Eq. (14), using the values of C from Table 1, and σ_f from Eq. (11). The results are shown in Fig. 4 as a function of the incoming hadron energy.

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:

$$C(Fe) = \sqrt{\sigma_{bind}[Fe]^2 + \sigma_f[Fe]^2} + \phi(e/\pi)\sqrt{E} \quad (15)$$

and consequently,

$$\sigma_{bind}[Fe] = \sqrt{(C(Fe) - \phi(e/\pi)\sqrt{E})^2 - \sigma_f[Fe]^2} \quad (16)$$

For a Si/Fe hadron calorimeter, the measured e/π ratio is about 1.11 at 10 GeV [6]. The value of $\phi(e/\pi)$ has been estimated by interpolating Monte Carlo simulations of energy resolution dependence on incoming energy (reported in Ref. [7]), for e/π ratios of 1.14, 1.26, and 1.47, at 10 GeV. From these simulations, one can estimate that, for $e/\pi = 1.11$ at 10 GeV, $\phi(e/\pi)$ is about 0.94, 1.01, 1.04, 1.09, 1.15, 1.22 and 1.28 %

⁴The 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.

for the incoming hadron energy of 10, 15, 20, 30, 40, 50 and 70 GeV, respectively. The value of $\phi(e/\pi)$ estimated at 10 GeV is in agreement, within the experimental errors, with the results reported in Ref. [16], 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 $\phi(e/\pi)$, those of C reported in Table 1, and the value of σ_f as given by Eq. (11), it becomes possible to estimate $\sigma_{bind}[Fe]$ (Eq. (16)). The estimated values of $\sigma_{bind}[Fe]$ are reported in Fig. 4 as a function of the hadron energy. The weighted average value $\sigma_{bind}[Fe] = (19.8 \pm 2.4)\%$ is obtained from a weighted average of the values at the incoming energies of 10, 15, 20, 30, 40, 50 and 70 GeV and is shown as a straight line in Fig. 4. The dashed line in the same figure represents $\sigma_{bind}(eff)[Fe]$ as obtained from Eq. (13) with $\sigma_{bind}[Fe] = 19.8\%$. This value is in agreement with the value of $\sigma_{bind}[Fe]$ reported in [11]. It is also in agreement with the values (18-22)% predicted in [7] in the case of negligible neutron absorption.

4.2 Determination of the binding energy losses fluctuations in Pb

The Si/Fe+Pb calorimeter is almost compensating ($e/\pi \sim 1$). Therefore, $\sigma_{bind}(eff)[Fe+Pb] \approx \sigma_{bind}[Fe+Pb]$ (see Eq. 13) and $C \approx C_0$ according to Eq. (1) (because $\phi(e/\pi = 1) = 0$). The weighted average of $C_0[Fe+Pb] \approx C[Fe+Pb]$ (from Table 1) is: $(66.1 \pm 2.1)\%$. Thus, the value of $\sigma_{bind}[Fe+Pb]$ can be evaluated from Eq. (14):

$$\sigma_{bind}(eff)[Fe+Pb] \approx \sigma_{bind}[Fe+Pb] = (25.9 \pm 2.1)\%$$

which is in agreement with the value ⁵ $\sigma_{bind}[Fe+Pb] \approx 24.5\%$ reported in [11] and determined for hadron incoming energies between 6 and 12 GeV.

$\sigma_{bind}[Pb]$ can be obtained from $\sigma_{bind}[Fe+Pb]$. $\sigma_{bind}[Fe+Pb]$ is the sum of $\sigma_{bind}[Pb]$ and $\sigma_{bind}[Fe]$ weighted by the interaction probabilities on Pb and Fe, respectively [11,12]:

$$\sigma_{bind}[Fe+Pb] = (L_{Pb}/L_{tot})\sigma_{bind}[Pb] + (L_{Fe}/L_{tot})\sigma_{bind}[Fe] \quad (17)$$

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. L_{tot} , L_{Pb} and L_{Fe} are 7.17, 1.46 and 5.71 λ , respectively.

From Eq. (17) and using the determined values of $\sigma_{bind}[Fe+Pb]$ and $\sigma_{bind}[Fe]$, one finds $\sigma_{bind}[Pb] = (49.9 \pm 14.1)\%$. This result is in agreement with the value $\sigma_{bind}[Pb] \approx (42 - 46)\%$ predicted in Refs. [4,7] for the case of negligible or low neutron absorption and with the value $\sigma_{bind}[Pb] = (45 - 49)\%$ found in Ref. [11].

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

⁵In Ref. [11], the Pb fraction was slightly larger than the one of the present calorimeter. However, the experimental errors are larger than the expected slight difference between the $\sigma_{bind}[Fe+Pb]$ values.

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 of the active (scintillator 2.5 mm thick) to passive (Pb thickness of 10.0 mm) medium thicknesses have shown smaller binding energy losses fluctuations [9]: $\sigma_{bind} = (13.4 \pm 4.7)\%$, as previously predicted in Refs. 4 and 7.

5. DISCUSSION AND CONCLUSIONS

Binding energy losses fluctuations contribute to the overall energy resolution of hadron calorimeters. 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 (which give C), 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 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, $\sigma_{bind} = (19.8 \pm 2.4)\%$ and $(49.9 \pm 14.1)\%$ for Fe and Pb, respectively, are found in agreement with earlier predictions made when neutron absorption is negligible [2] and with recent measurements performed at lower incoming hadron energy [11].

For an almost compensating Si/Fe+Pb calorimeter, the contribution to the overall energy resolution of $\sigma_{bind}[Fe + Pb]$ is $(25.9 \pm 2.1)\%$.

Furthermore, in the case of the almost compensating Si/Fe+Pb calorimeter, the visible energy, ϵ_{vis} , has shown a linear dependence on the incoming hadron energy, within the experimental errors. For the Si/Fe non-compensating calorimeter ($e/\pi \approx 1.11$ at 10 GeV), an overall non-linearity of 3.5% is observed in the calorimeter energy response, as expected.

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TABLE CAPTIONS

Table 1: The values 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, o) 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 Si/Fe calorimeter: $\epsilon_{vis}(Fe, E) = (5.3 \pm 0.1)E(GeV) + (-8.8 \pm 2.5)[MeV]$. The bottom line shows a least square fit to the data obtained for the Si/Fe+Pb calorimeter: $\epsilon_{vis}(Fe + Pb, E) = (4.5 \pm 0.1)E(GeV) + (-3.0 \pm 2.7)[MeV]$.

Fig. 2: The ratio (▲) $R = \epsilon_{vis}(Fe)/\epsilon_{vis}(Fe + Pb)$ of the measured visible energy in Si/Fe (non compensating) to Si/Fe+Pb (compensating) is shown as a function of the incoming energy. The line represents $R_{cal}(E) = 1.068(1 + 0.16 \times f_{em}(E))$ (see text).

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

Fig. 4: $\sigma_{bind}(eff)[Fe]$ (top points, o) and $\sigma_{bind}[Fe]$ (bottom points, ●) (in %) are shown as a function of the incoming energy, as obtained from the Si/Fe calorimeter data. The line represents the weighted average value of $\sigma_{bind}[Fe] = 19.8\%$ (from a weighted average of the values at the incoming energies of 10, 15, 20, 30, 40, 50 and 70 GeV) is shown as a straight line. The dashed line represents $\sigma_{bind}(eff)[Fe]$ as calculated from Eq. (13) (see text) with $\sigma_{bind}[Fe] = 19.8\%$.

E(GeV)	C(Fe)[%]	C(Fe+Pb)[%]
10	67.1 ± 7.3	64.4 ± 5.3
15	65.8 ± 7.3	63.8 ± 5.8
20	69.1 ± 7.7	65.2 ± 5.6
30	67.8 ± 5.3	65.2 ± 5.4
40	72.0 ± 6.6	66.3 ± 5.7
50	71.8 ± 6.9	67.3 ± 5.7
70	76.9 ± 8.3	71.7 ± 6.1

Table 1

fig. 1