**EVIDENCE FOR THE COMPENSATION CONDITION
IN Si/U HADRONIC CALORIMETRY ACHIEVED BY
THE LOCAL HARDENING EFFECT**

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ABSTRACT

In a hadronic calorimeter with silicon readout, a combination of thin plates of low- Z and high- Z materials used as absorbers enables the reduction of the calorimeter response to the electromagnetic component of the incoming hadronic showers (the 'local hardening effect'). As a result, a ratio varying from $e/\pi > 1$ to $e/\pi < 1$ is obtained as a function of the low- Z material thickness, demonstrating the possibility of achieving the compensation condition ($e/\pi = 1$) by exploiting the local hardening effect.

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1. INTRODUCTION

Future experiments at the next generation of colliders [the Large Hadron Collider (LHC) in the LEP tunnel at CERN, the Superconducting Super Collider (SSC) in the USA, and the Accelerating and Storage Complex (UNK) in the USSR] will provide the opportunity to search for new physics: for instance, to search for heavy leptons, supersymmetric particles, the Higgs particle(s), and the additional vector bosons predicted in many possible extensions of the Standard Model.

The possibility of achieving these research programmes will rely on highly performing detection systems. In particular, severe constraints will be imposed on the performances of the hadron calorimeter [1]; this will be the core element of the central detection system that is needed to face the exceptional experimental conditions created by very high luminosity, high multiplicities, and the large variety of physics phenomena to be studied. The performance of hadron calorimeters is determined in fact by their relative response to the electromagnetic (e) and hadronic (π) shower, the e/π signal ratio, defined as:

$$e/\pi = (e/mip)/[(e/mip)f_{em} + (h/mip)(1 - f_{em})].$$

Here, mip is the energy deposited in the sensitive part of the calorimeter by a minimum ionizing particle depositing all its energy in collision losses in similar (with respect to the sampling structure) but indefinitely extended calorimeters; $h(1 - f_{em})$ is the visible hadronic energy (i.e. the energy deposited in the detector readouts by the purely hadronic component of the shower, see ref. [1] and references therein); f_{em} varies with energy and is the average fraction of the converted electromagnetic energy resulting from the photon decays of π^0 and η particles produced during the hadron cascade.

The electromagnetic cascading described by Quantum Electrodynamics (QED) depends essentially on the density of electrons in the absorber medium. In the hadronic interactions of a cascade, a sizeable amount of the available energy is converted into excitation or breakup of the absorber nuclei, of which only a fraction would result in visible energy. As a consequence, the signal per unit of incident energy is different for electromagnetic and hadronic cascades and in general $e/\pi \neq 1$. The signal ratio e/π is energy dependent since f_{em} increases with energy. As a consequence, the energy resolution can then be written as

$$\sigma/E = C/\sqrt{E} + f[(e/\pi) - 1],$$

where $C = (\sigma_{intr}^2 + \sigma_{sampler}^2)^{1/2}$ contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{intr}) and that from the sampling fluctuations ($\sigma_{sampler}$). The equalization between the electromagnetic and the hadronic signals ($e/\pi = 1$, i.e. the compensation condition) is the condition for obtaining a linear response from a calorimeter to hadronic showers and an energy resolution that improves as the incident energy increases [1].

The aim of this letter is to present the results of measurements, recently performed with a hadron Si/U calorimeter, showing an electromagnetic energy smaller than the hadronic energy ($e/\pi < 1$), when sufficiently thick plates (although small when expressed in units of radiation length) of low- Z absorbers (G10) are inserted between the active and passive calorimeter planes. The possibility of obtaining a ratio $e/\pi < 1$, instead of the value $e/\pi > 1$ measured when a small amount of low- Z absorber (G10) is employed, demonstrates that the compensation condition ($e/\pi = 1$) can be achieved via the local hardening effect [2] realized in a hadron Si/U calorimeter through the insertion of G10 plates.

2. EXPERIMENTAL SET-UP AND DATA

The Si sampling hadronic calorimeter consists of 20 U absorber plates, each about 2.5 cm thick, interspaced by Si readout mosaics. The total calorimeter depth is about 4.8 interaction lengths (λ). The readout of this calorimeter consists of mosaic planes (with an active area of $\sim 524 \text{ cm}^2$) each made of 18 trapezoidal Si detectors [3]. The detectors*) are operated at a depleted layer width of 200 μm . The use of serial coupling of five Si detectors along the beam direction [4], although reducing the number of electronic channels and the overall detector capacitance, allows the use of fast electronics (about 200 ns base-time signals) with a wide dynamical range (five decades) and permits the calorimeter to be read out in four longitudinal sections. The electronic readout is described in detail in ref. [5].

The data reported in this letter have been taken at the t_9 beam at the CERN Proton Synchrotron (PS), at incoming energies of 8, 10, and 12 GeV. Two gas Cherenkov counters were used to separate electrons and hadrons. A beam scanner, consisting of a scintillation counter of $0.5 \times 0.5 \text{ cm}^2$ area, ensured that only particles impinging on the middle of the calorimeter triggered [5]. The absolute energy calibration was performed following two independent approaches (as described elsewhere [2]): i) by ^{233}U α sources located on top of the Si detectors; ii) by minimum-ionizing particles (μ). The two methods agree well with each other.

Our measured visible energy, ϵ_{vis} , has to be corrected for the energy losses in the non-active region at the detector edges. The corrections of the hadronic and electromagnetic visible energy losses, of $(3.7 \pm 1.0)\%$ and $(1.5 \pm 0.3)\%$ respectively, have been calculated from previously measured lateral energy distributions [6–9].

The detector mosaic area, transverse to the incoming particle direction, is equivalent to a circle of radius 1.23λ . The hadronic shower energy is laterally contained, at the 95% level, in a cylinder of a radius given by: $r(95\%) \approx 1.00 + 0.06 \log(E)$, in units of λ , where E is the incoming energy in GeV [1]. Thus an energy containment of 95% of the energy in about 1.15λ radially, can be expected at 12 GeV. This prediction is confirmed by the experimental data obtained from measurements of the lateral energy distribution of hadronic showers, generated by $\bar{p}$ of 25 GeV, with a calorimeter having Fe absorber plates 2.5 cm thick interspaced by 1.0 cm thick scintillator readout planes [7]. Experimental data from a scintillator/U calorimeter (3 mm U absorber interspaced by 2.5 mm scintillator) show that a fraction, about 94%, of the energy is contained within about 1.3λ , in hadronic showers generated by π^- of 300 GeV [8]. Furthermore, a special run has been carried out with the Si/U hadronic calorimeter reading the trapezoidal detectors of a mosaic plane individually. The lateral energy distribution has been measured up to about 25 cm (2.4λ) from the centre of the hadronic shower. The data show that the lateral energy loss, for a mosaic configuration with a transverse area of 524 cm^2 , is lower than 5% at an incoming proton energy of 9 GeV and a calorimeter depth of 1.52λ (after the hadronic shower maximum). At this depth, about 65% of the hadron incoming energy has already been deposited in the calorimeter. The estimated value of the overall lateral loss of the hadronic visible energy is $(5.1 \pm 2.2)\%$ for the present Si/U calorimeter, at incoming proton energies of 8, 10, and 12 GeV. The longitudinal hadronic energy deposition in a U calorimeter falls exponentially beyond 2λ for showers generated by hadrons with an energy lower than 20 GeV [8]. By extrapolating the measured values of the visible energy in the longitudinal sections of the calorimeter, it is thus possible to estimate that the longitudinal hadronic visible

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energy losses are $(3.9 \pm 0.3)\%$, $(3.0 \pm 0.3)\%$, and $(1.9 \pm 0.2)\%$ at 8, 10, and 12 GeV respectively, in agreement with the results of ref. [9]. The experimental values of the hadronic visible energy have been corrected in order to take into account the estimated lateral and longitudinal energy losses.

3. RESULTS

The structure which supports a mosaic of Si detectors consists of two G10 plates 1.0 and 0.2 mm thick. Therefore, G10 is always present in the calorimeter structure. Data were taken in calorimeter configurations where additional G10 plates, 1.0, 3.0, and 5.0 mm thick, were inserted both in front and at the rear of the Si detectors. Data were also taken with no additional G10 plates. The effect of this insertion on the mean energy deposited by electrons and protons in the calorimeter is shown in figs. 1 and 2 respectively, as a function of the incoming energy. In both cases, ϵ_{vis} decreases with the thickness of the inserted G10 plates; it is found to be linear as a function of the incident energy, independently of the G10 thickness. However, the local hardening effect, realized by inserting the low- Z (G10) absorber plates next to the Si mosaics, decreases the electromagnetic visible energy more than the hadronic one, as expected [2]. For instance, for incoming electrons of energy E (in GeV), the measured visible energy varies from $(0.81 \pm 0.02)E$ (no additional G10 plates) to about $(0.48 \pm 0.01)E$ (when 5 mm thick G10 plates are added); for incoming protons, the measured visible energy varies from $(0.63 \pm 0.02)E$ to $(0.56 \pm 0.01)E$, respectively.

The reductions R of the visible energy (from an average of measurements at the three incoming particle energies) for incoming electrons and protons are shown in fig. 3, as a function of the thickness of the additional G10 plates:

$$R = [\epsilon_{\text{vis}}(0) - \epsilon_{\text{vis}}]/\epsilon_{\text{vis}}(0),$$

where $\epsilon_{\text{vis}}(0)$ is the visible energy when no additional G10 plates are inserted. For instance, the effect of 5 mm thick G10 plates, inserted in front and at the rear of the Si readout mosaics, is to reduce the electromagnetic visible energy by about 40% while the hadronic visible energy is only reduced by about 12%. The behaviour of the ratio R for electrons and protons is the essence of the realization of the compensation condition in Si/U hadronic calorimetry. At these incoming proton energies, the average fraction f_{em} of the converted electromagnetic energy in a hadronic shower is about 25–30%. From the electron data of fig. 3, the part of the visible energy that is due to the electromagnetic component of the shower is expected to be reduced by the local hardening effect when low- Z (G10) plates are inserted. However, the reinteractions of the hadronic particles in these plates increase the ionizing hadronic component of the shower, since the A -value of G10 is lower than that of uranium [10]. Thus, when the sampling fraction (defined as the absorber material thickness in units of interaction lengths in between two active planes) is increased by the additional G10 plates, the expected decrease (about 5.5% with 5 mm thick G10 plates at the front and at the rear of the Si mosaics) of the part of the visible energy that is due to the pure hadronic component of the shower is largely attenuated. Consequently, the additional low- Z G10 plates allow the tuning of the e/π ratio, mainly by attenuating the calorimeter response to the electromagnetic component of the hadronic shower.

The e/π ratios, namely the ratio of the visible energy of the electron to that of the proton, $\epsilon_{\text{vis}}(e)/\epsilon_{\text{vis}}(p)$, measured at the same incoming particle energy and calorimeter configuration, are given in table 1. The data show that, at the three incoming particle

energies, the value of e/π is about 1.2–1.3 (when no additional G10 plates are inserted in front and at the rear of the Si mosaics), in agreement with the prediction of ref. [10]. The tuning effect of local hardening, realized by adding G10 plates, allows us to reach e/π ratios lower than 1, at the same energies. In fig. 4, the e/π values (from an average of measurements at incoming particle energies of 8, 10, and 12 GeV) are shown as a function of the thickness of the additional G10 plates. The thickness of the low- Z G10 plates to be located in front and at the rear of the Si mosaics, in order to achieve the compensation condition ($e/\pi = 1$), is estimated to be $t_G = (1.2 \pm 0.2)$ mm. The local hardening effect has allowed the value of the e/π ratio to be modified by about 34%, changing the calorimeter configuration with no additional G10 plates to a configuration where 5 mm thick plates are used.

4. DISCUSSION AND CONCLUSIONS

The calorimeters in operation in experiments at the next generation of colliders will serve several purposes. One of them is to recognize the signatures of electroweak or supersymmetric processes in a background that is dominated by soft or semi-hard hadronic interactions. Fully contained calorimeters are needed to be able to define the ‘missing momentum vector’ and ‘missing energy’ that will reveal the presence of a neutrino, or of a photino, for instance. The resolution requirements for both, the hadronic and the electromagnetic calorimeters, are becoming more and more determinant as the beam energies increase and as lower energies of the neutrinos are probed. To positively identify a neutrino, the argument of missing energy can be used only if the amount of missing energy is larger than the uncertainty on the visible energy; therefore, the multiparticle energy resolution must be better than $K/\sqrt{E}$, where $K = E_\nu/\sqrt{E_{\text{tot}}}$.

Another condition imposed on the calorimeters for the next generation of colliders is that the multiparticle energy resolution must not be much worse than that for single particles. Cell-to-cell intercalibration errors, cracks, and in-flight decays can make the multiparticle energy resolution worse.

Jets represent a multiparticle situation of interest for physics. However, since an appreciable fraction of the energy of the jet can be carried by a ‘leading particle’ [11], the instrumental resolution for jets approaches that for single particles.

The best possible resolution is also critical for the detection of narrow large-mass resonances decaying into jets. Indeed, the signal/background ratio at the peak is inversely proportional to the calorimeter resolution, and the statistics required to find a resonance is proportional to the square of the resolution. Note that if a resolution of $50\%/\sqrt{E}$ can be maintained for jets, W and Z particles decaying into jets could be distinguished by their mass event by event (whereas with a resolution of $100\%/\sqrt{E}$, the mass peaks of centrally produced W and Z would overlap).

To summarize, the physics goals, and the processes that limit the effective resolution, fix the required calorimeter resolution at $\sim 50\%/\sqrt{E}$, which can be reached, in principle, with a Si hadron calorimeter [1].

However, good energy resolution is a necessary but not sufficient condition: as seen above, the equality of response of the calorimeter to hadrons and electrons has to be satisfied. Experimental evidence has been previously found [2] for a local hardening effect realized by inserting low- Z absorbers (G10 plates) next to the Si readout detectors. In electromagnetic cascade showers, the energy is propagated, both laterally and longitudinally, by an increasing number of electrons and photons of diminishing

energy, and a considerable fraction of the energy deposition in the calorimeter is done through low-energy particles [12]. In the course of the shower development, a large fraction of the energy goes into the production of low-energy photons. The soft photons from the shower interact almost exclusively in the absorber and most of them will transfer their energy partly (Compton effect $\sim Z$ of the absorber material) or totally (photoelectric effect $\sim Z^5$ of the absorber material) to the electrons of the absorber [13]. A fraction of the low-energy photons that convert into electrons in the absorber are sufficiently close to the surface for the electron to escape and contribute normally to the measured signal. Low-energy electrons may be multiply scattered. The number of large-angle electrons is large in high- Z material and small in low- Z material. In high- Z passive material, the multiply-scattered electrons have a path length $d/\langle \cos \alpha \rangle$ where $\langle \cos \alpha \rangle = \cos(21 \text{ MeV}/\epsilon\pi)$; α is the angle with respect to the shower axis and ϵ is the critical energy [14] that is relatively longer than their path length d in the low- Z active material. Multiple scattering can then create a flux of backward-going electrons in the absorber. These soft electrons can be absorbed by the G10 plates inserted between the active and absorber planes; the plates are therefore responsible for the decrease in visible energy as observed from a systematic investigation of the visible energy response for electromagnetic showers in Si/U and Si/W electromagnetic calorimeters [2]. This study, carried out in the past for various incoming electron energies, has shown, for instance, a reduction (29%) of the visible (electromagnetic) energy in the case of the 5.0 mm G10 absorber located at the rear (only) of the detectors, leading to a reduction of about 20% of the ratio of the electromagnetic to the non-electromagnetic shower component [2]. Our present results demonstrate the effectiveness of the local hardening effect in modifying the response to the incoming showers of a hadronic calorimeter, with silicon readout and a combination of low- Z and high- Z materials as absorbers. This local hardening effect increases the reduction of the visible energy beyond the reduction normally expected from energy sharing, as defined in ref. [2]. Furthermore, the reinteractions of the hadronic particles in the G10 plates increase the ionizing hadronic component of the shower. The calorimeter signal for this shower component is primarily the result of the ionization by protons and pions produced in this process, where non-relativistic spallation protons give the dominating contribution of about 70–74% of the total ionization signal [10]. However, the fraction of the initial particle energy that goes into ionization by protons depends on the Z and A values of the absorber medium: in the cascade process, the protons take a fraction of about Z/A of the available energy transferred to the target nuclei during the first and successive generations of interactions. Moreover, the Coulomb barrier for escaping charged particle is proportional to $Z/A^{1/3}$. As a consequence, the difference of about 30% between the Z/A values of G10 and U results in an increase of the effective h/mip value, as the G10 thickness increases. This effect attenuates the expected decrease of the part of the visible energy that is due to the pure hadronic component of the shower, when the sampling fraction is increased by the additional G10 plates. The degree of hardening depends on the thickness of the low- Z absorber. As a consequence, the ratio e/π can be varied by modifying mainly the response to the electromagnetic component of the shower. In the particular U-G10 arrangements used in the measurements reported in the present letter, a ratio $e/\pi < 1$ is obtained instead of the expected value $e/\pi > 1$ resulting from the existence of a fraction of non-visible hadronic energy. This means that we have the possibility of determining a (low- Z)-(high- Z) configuration of absorbers where the compensation condition ($e/\pi = 1$) is achieved.

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Table 1

Ratio e/π of the visible energy
of the electron to that of the proton

	E (GeV)		
	8	10	12
G10 thickness (mm)			
0	1.22 ± 0.09	1.32 ± 0.06	1.27 ± 0.05
1	1.00 ± 0.08	1.07 ± 0.07	1.01 ± 0.05
3	0.96 ± 0.07	0.93 ± 0.06	0.85 ± 0.08
5	0.87 ± 0.06	0.84 ± 0.06	0.88 ± 0.05

* * *

Figure captions

- Fig.1: Mean energy deposited by electrons in the Si/U calorimeter as a function of the incoming energy. The top points correspond to the case of no additional absorber in front of the detectors. The other points correspond to a configuration with additional plates of G10 in front and at the rear of the detectors, at thicknesses (from top to bottom) of 1.0, 3.0, and 5.0 mm.
- Fig.2: Mean energy deposited by protons in the Si/U calorimeter as a function of the incoming energy. The points have the same definitions as in fig. 1.
- Fig.3: Reduction of the visible energy sensed by the calorimeter for incoming electrons ($\diamond$) and protons ($\diamond$) as a function of the thickness of the G10 plates (in addition to the two mosaic supports, 0.2 and 1.0 mm thick respectively) inserted in the front and at the rear of the Si mosaics. The line is to guide the eye.
- Fig.4: Measured values of the e/π ratio (see text) plotted against the thickness of additional G10 plates. The line is to guide the eye.

Fig. 1

Fig. 2

Fig. 3

Fig. 4