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Abstract. We report on the performance of the CDF End Plug Hadron Calorimeter in a test beam. The sampling calorimeter is constructed using 2 inch iron absorber plates and scintillator planes with wavelength shifting fibers for readout. The linearity and energy resolution of the calorimeter response to pions, and the transverse uniformity of the response to muons and pions are presented. The parameter e/h , representing the ratio of the electromagnetic to hadronic response, is extracted from the data.

INTRODUCTION

In the next Tevatron collider run (Run II), the time interval between particle bunches will be as short as 132 nanoseconds. The response of the existing (Run I) CDF electromagnetic and hadronic sampling gas calorimeters in the plug region is too slow (≈ 400 nsec) to accommodate this bunch crossing. The detectors are being replaced with new calorimeters using scintillator tiles with wavelength shifting (WLS) fiber readout technology [1–3]. The upgraded Plug Calorimeter consists of an electromagnetic section (EM) with a Shower Maximum Detector and a hadronic section (HAD). The compact design of the new calorimeter and its increased pseudorapidity coverage also allows for increased muon coverage in the upgraded CDF II detector. In this communication we report on the performance of the Plug Upgrade Hadron Calorimeter in a test beam. The performance of the CDF Plug Upgrade EM calorimeter and the wire source calibration procedure are presented elsewhere [4,5].

¹⁾ Members of the following CDF institutions participate in the Plug Upgrade Project: Bologna U., Brandeis U., Fermilab, KEK, MSU, Purdue U., Rochester U., Rockefeller U., Texas Tech U., Tsukuba U., UCLA, Udine U., Waseda U. and Wisconsin U.

HADRON CALORIMETER DESIGN

The angular (θ) coverage of the CDF End Plug Upgrade Calorimeters is from 38° to 3° , corresponding to the pseudorapidity range $1.1 < |\eta| < 3.5$. The upgraded hadronic compartment adds two plates to the 20 existing two inch iron absorber plates. Total thickness of the upgraded hadron calorimeter is approximately $7.1 \lambda_{INT}$. An additional $1 \lambda_{INT}$ is provided by the EM compartment.

Light from scintillator tiles (6 mm thick Kuraray SCSN-38 with typical transverse size of $20 \text{ cm} \times 20 \text{ cm}$) is collected by embedded WLS fibers (Kuraray Y-11 0.83 mm in diameter). Outside the tiles, the WLS fibers are spliced to clear optical fibers. Light is further transported to decoder boxes located outside of the detector via mass terminated connectors and clear optical fiber cables. The decoder boxes re-group the fibers from all layers into towers to be read out by photomultiplier tubes. The East and West Hadron Plugs consist of a total of 864 readout channels.

The performance requirements of the Hadron calorimeter call for a stochastic term in the relative energy resolution function of less than 80% and a constant term less than 5%. The non-linearity in the energy response of the calorimeter to pions in momentum range 10-200 GeV/c is required to be less than 10%. To guarantee good muon identification, the light yield of each tile is required [6] to be above 2 photoelectrons per minimum ionizing particle.

In order to meet the above performance requirements, a strict quality control program was implemented during the production stage of the Hadron calorimeter optical system. The absolute light yield of each batch of scintillator and the light yield and transmission of the WLS and clear fibers were tested. The WLS fibers were spliced to clear fibers glued into optical connectors. These fiber/connector assemblies ("pigtailed") were tested with a UV lamp scanner. The distribution of the relative light yield of over 18,000 individual fibers had an RMS of 3.2%. The light yield of all the tiles after the insertion of WLS fibers into the scintillator was measured using a Cs^{137} γ source. The distribution of the relative light yield of tile/fiber assemblies had an RMS of 6.1%.

TEST BEAM SETUP

A 60° sector "carbon copy" of the Plug Upgrade Hadron calorimeter modules installed in the CDF hall has been assembled for test beam studies at the MT beamline at FNAL. Data were recorded using electron (5-120 GeV/c), pion (5-220 GeV/c) and muon (10-220 GeV/c) beams. Particle momenta were determined using single wire drift chambers with precision of $\approx 0.2\%$. A $6 X_0$ lead converter instrumented with a scintillation counter was used to reject large positron contamination in hadron tunes, especially at low momenta. For part of the run, a Cerenkov counter was installed to measure both the proton contamination in the hadron tunes and the difference in the calorimeter's response to protons and pions.

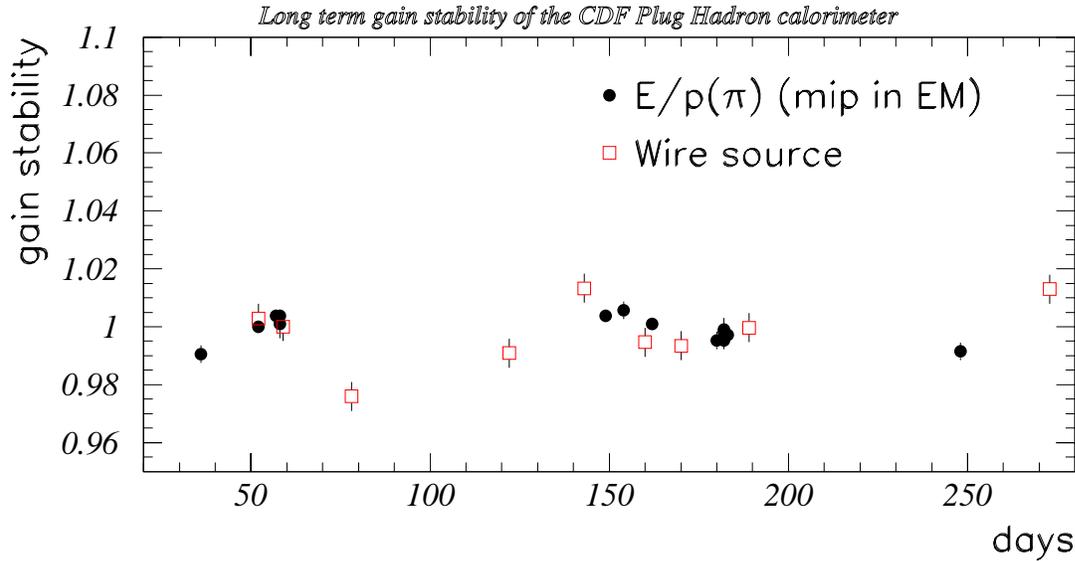


FIGURE 1. Long term stability of the gain of the CDF Plug Upgrade Hadron calorimeter.

The test beam provides the absolute energy calibration of the EM and Hadron calorimeters. A system incorporating removable radioactive γ source which is attached to a wire ("wire source") and can be inserted into tubes mounted on the scintillators is used to illuminate each tile in the calorimeter. The wire source calibration provides a mechanism to transfer the absolute energy scale of the calorimeters from the test beam module to the modules in the CDF hall.

The wire source is also used to equalize the gain (relative calibration) of all calorimeter towers prior to the data taking. The accuracy of the "wire source" calibration is checked by comparing the measured response of individual calorimeter towers to particles (electrons in case of the EM and pions in case of the Hadron calorimeters). The measurement indicates that wire source calibration is accurate within 2%. In addition, the wire source provides an independent tool to monitor the gain stability of individual towers in the Hadron calorimeter. During the test beam study (lasting over 250 days), the stability of the absolute gain of the calorimeter (as determined by the wire source) was constant to within 2%. This is consistent with the measurements based on the energy/momentum ratio, E/p , using test beam pions, as shown on Figure 1.

The CDF Plug Upgrade electronics will use 120 nsec integration time, while the Rabbit based electronics used at the test beam had 2.2 μ sec integration time. A gate length study indicated an increase in the Hadron calorimeter response to pions by approximately 6%, when signals integrated for 120 nsec and 1 μ sec are compared. Therefore the absolute calibration constant of the Hadron calorimeter (short gate) needs to be corrected by 6%, with respect to the calibration constant of the Hadron calorimeter measured in the Test Beam module (long gate).

PERFORMANCE OF THE HADRON CALORIMETER

Figure 2 shows preliminary results on the linearity of the energy response (E/p), and relative energy resolution (σ_E/E) of the Hadron calorimeter for incident pions. The absolute energy scale of the EM compartment is set using 50 GeV/c electrons. The absolute energy scale of the Hadron calorimeter is established using a subset of 50 GeV/c pion sample (pions which interact in the Hadron calorimeter only). The square symbols indicate that response of the calorimeter to pions which interact in the Hadron calorimeter only. Triangle symbols indicate the response of the combined EM+Hadron calorimeters to pions interacting in either in the EM or in the hadronic compartment. As shown in the figure, the response of the calorimeter to pions which interact in the Hadron calorimeter only is $\approx 3\%$ higher than the response to pions which interact in either the EM or hadronic compartment. The non-linearity of the response of the calorimeter to pions in momentum range 10-220 GeV/c is less than 10%, meeting the CDF Plug Upgrade requirement criteria. The relative energy resolution of pions which only interact in the Hadron calorimeter can be described by the function $\sigma_E/E = (74 \pm 1.0)\% / \sqrt{E} \oplus (3.8 \pm 0.3)\%$. Full pion sample (i.e. pions which interact in either the EM or Hadron calorimeters) have a slightly better energy resolution, $\sigma_E/E = (68 \pm 0.7)\% / \sqrt{E} \oplus (4.1 \pm 0.2)\%$. We attribute this improvement to the fine sampling (4.5 mm Pb) of the EM calorimeter, relative to that of the Hadron calorimeter.

Note however, that linearity of response and good energy resolution for pions for the combined EM+Hadron calorimeters can not be achieved if the ratio of the response to electromagnetic and hadronic components of the pion showers in the EM calorimeter, $e/h(\text{EM})$ is very large. As in the case of the lead tungstate crystal ECAL calorimeter for the CMS [7] or the liquid argon ECAL calorimeter for the ATLAS [8], large e/h of the EM compartments significantly degrades the response of such combined EM+Hadron calorimetric systems to jets.

Comparison of the response to protons and pions

The test beam studies were conducted with positive hadron beam tunes. Protons constitute a significant fraction of the beam, especially at high energies. A correction for the proton contamination must be made in order to extract the response of the calorimeter to pions. During a part of the run, a Cerenkov counter was used to tag (offline) pions and protons. The response of the CDF End Plug Upgrade Calorimeter to protons and pions was measured [9] for incident momentum tunes of 5.6 GeV/c and 13.3 GeV/c.

The difference in the response is primarily due to two effects. The first effect is caused by the difference in the available energy for deposition in the calorimeter. For protons the available energy is the kinetic energy, and for pions it is the total energy; i.e. $\sqrt{P^2 + m_p^2} - m_p$ for protons versus $\sqrt{P^2 + m_\pi^2}$ for pions. The second effect originates from the different fraction of π^0 mesons produced in proton versus

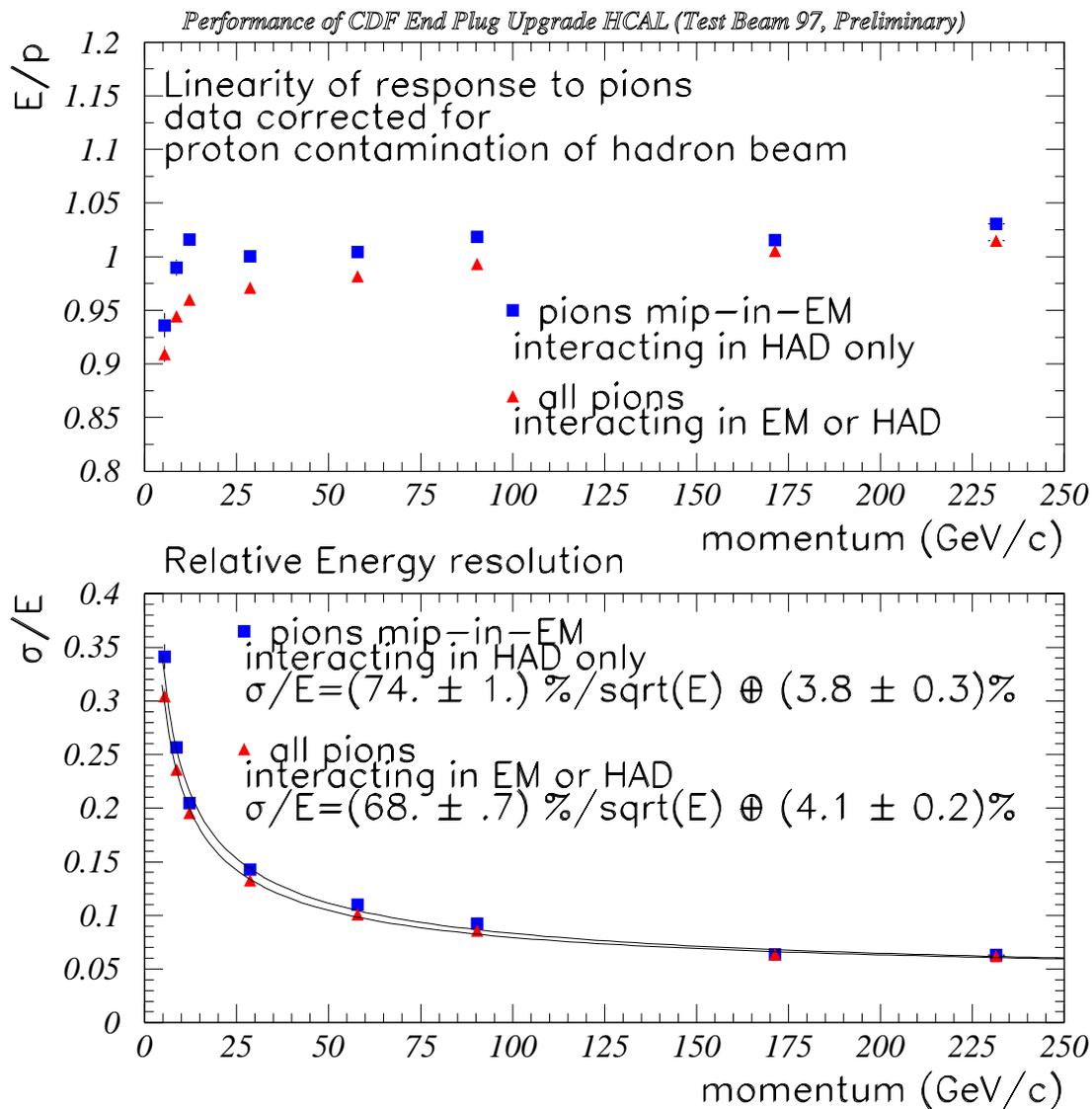


FIGURE 2. Linearity and relative energy resolution of the CDF Plug Upgrade calorimeter to pions (1997 Test Beam, Preliminary results).

pion induced showers. For a non-compensating calorimeter ($e/h \neq 1$), this difference leads to higher response for pion showers. A third effect resulting from the different interaction lengths of pions and protons is negligible. The measured ratio of proton/pion response, $\langle E_\pi \rangle / \langle E_p \rangle$ was 1.227 ± 0.006 at 5.6 GeV/c and 1.104 ± 0.006 at 13.3 GeV/c. The results are consistent with the expectation from the available energy, the fraction of π^0 , and interaction length effects.

The e/h parameter for the CDF Hadron Calorimeter

The observed non-linearity of the response of the Hadron calorimeter to pions can be explained by the difference in the response of the calorimeter to the electromagnetic and hadronic components of the showers, ($e/h \neq 1$) in combination with the fact that the average fraction of π^0 's in pion induced showers increases as a function of pion momentum. By measuring the ratio of the response of the Hadron calorimeter to pions and electrons as a function of pion momentum, e/h parameter of the calorimeter can be extracted. The measured response of the Hadron calorimeter (using hadrons which do not interact in the EM compartment) is first corrected for proton contamination of the hadron beam. It is also corrected for the longitudinal shower leakage, since the total depth of the Hadron calorimeter is only $7.1 \lambda_{INT}$. The response of the Hadron calorimeter to electrons was measured in dedicated runs for which the electron beam was pointed directly² into the Hadron calorimeter. The response of the Hadron calorimeter to electrons is linear to within 2%, and approximately 20% higher than the response to pions.

Figure 3 shows the pion/electron response ratio of the Hadron calorimeter, after the proton contamination and longitudinal shower leakage corrections have been applied. The extracted value of e/h depends on the functional form assumed for the fraction of π^0 as a function particle momentum. There are two available parameterizations, one by Wigmans [10] which uses $\ln(E)$ form, the other by Groom et al. [11] which uses exponential parameterization. The value of the extracted e/h (using data points between 10 and 230 GeV varies from 1.34 ± 0.01 (Wigmans) to 1.42 ± 0.015 (Groom). Both parameterizations are consistent with the measured pion/electron response ratio at 5 and 8 GeV.

Transverse Uniformity of Response

A fine scan of the response of the Hadron calorimeter with pion and muon beams has been used to measure the transverse uniformity. Figure 4 shows two-dimensional (in ϕ and θ) response maps of the Hadron calorimeter using 150 GeV/c muons (upper left plot), and 50 GeV/c pions (upper right plot). The scanned area fully covers a single calorimeter tower. The four crossing lines on the map indicate

²⁾ The EM module covered only 45° in ϕ of the 60° hadronic module.

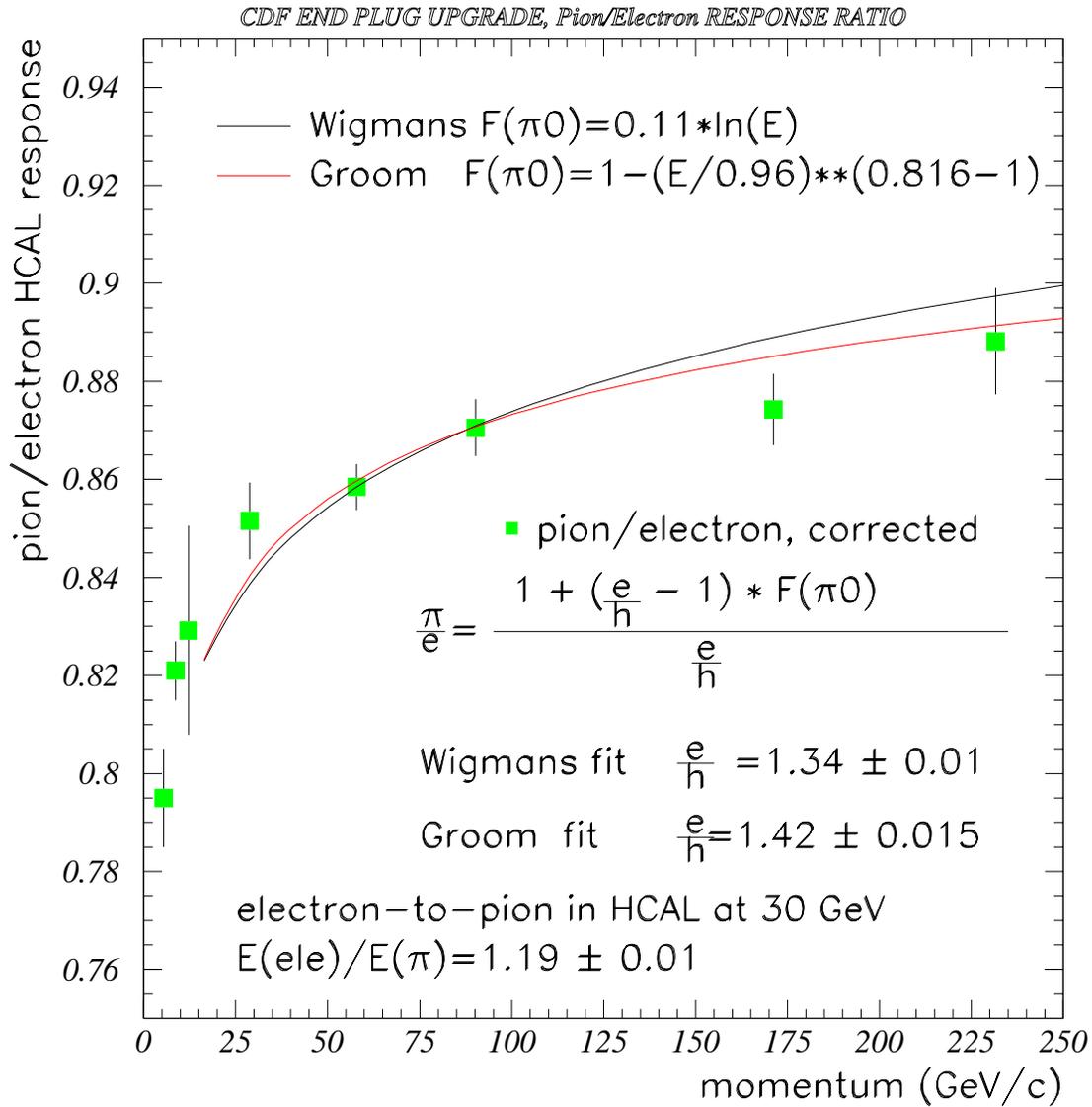


FIGURE 3. Pion/electron response ratio of the CDF Hadron calorimeter. The hadron data has been corrected for the proton contamination of the beam, and for longitudinal shower leakage. The data is used to extract the e/h parameter for the Hadron calorimeter.

the boundary lines between neighboring towers. The lower plot shows the data averaged over the central ϕ bins, as a function of the θ . The muon data (broken line) indicates an increased response of the tiles at $\theta=21.5^\circ$ and $\theta=24.5^\circ$, corresponding to the location of the tile boundaries. The pion data (solid line) indicates a uniform (within 2%) response of the Hadron calorimeter to pions. The drop in response at $\theta=25^\circ$ is caused by transverse leakage out the sides, near the θ edge of the detector.

The plots indicate that the response to muons is uniform within RMS of 5% and response to pion showers is uniform to within $\pm 2\%$. The 8% relative light increase at the tile boundaries observed in the muon scans is consistent with earlier measurements done using a 2 MeV/c electron beam (from a beam line using a β radioactive source) for R&D studies of the optical system.

CONCLUSIONS

The CDF Plug Upgrade sampling calorimeter is based on tile/fiber technology. It has been constructed under a set of strict QC procedures. The calorimeter modularity (megatiles, connectors, optical cables, decoder boxes) greatly simplifies the final assembly at the CDF collision hall. Results from the recently completed Test Beam studies indicate that the detector performance satisfies the design requirements. For the Hadron calorimeter, the linearity of response to pions in the momentum range 5-250 GeV is $\leq 12\%$. The relative energy resolution of the combined EM+Hadron calorimetric system to single pions can be parameterized as $\sigma(E)/E = 74\%/\sqrt{E} \oplus 4\%$. The transverse uniformity of the response to incident pions is constant to within 2%. The installation of the calorimeter is on schedule and we expect to be ready for data-taking in the CDF hall at the end of 1999.

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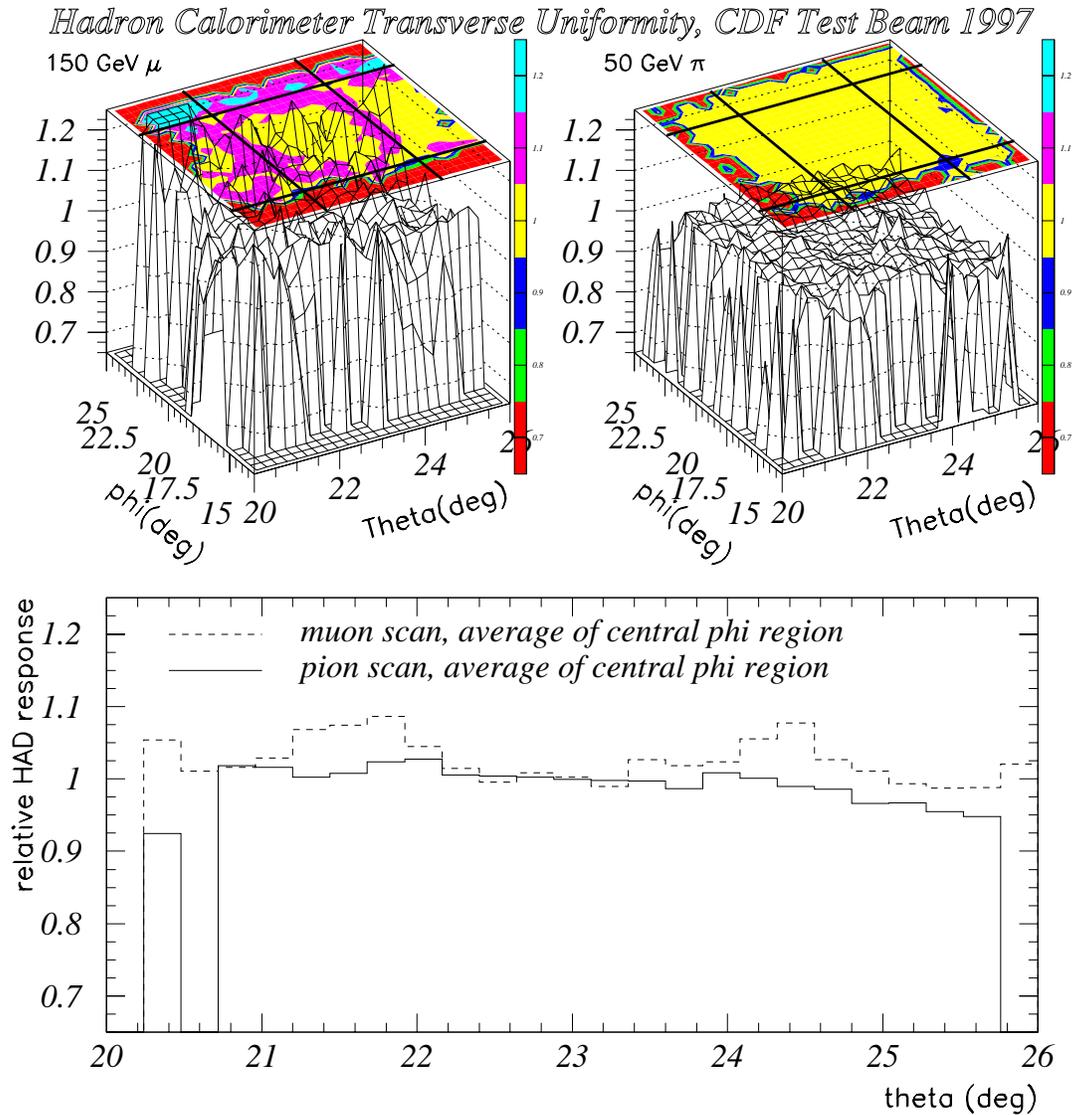


FIGURE 4. Transverse response map of a single CDF Plug Upgrade Hadron calorimeter tower using 150 GeV/c muons (upper left plot) and 50 GeV/c pions (upper right plot). The lower plot shows the data averaged over the central ϕ bins, as a function of the θ . The muons data (broken line) indicates an increased response of the tile at $\theta=21.5^\circ$ and $\theta=24.5^\circ$, corresponding to the location of the tile boundaries. The pion data (solid line) indicates uniform (within 2%) response of the Hadron calorimeter to pions. The drop in response at $\theta=25^\circ$ is caused by transverse leakage (out of the θ edge of the detector).