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Abstract

We have measured the longitudinal particle punchthrough probability from shower cascades produced by hadrons incident on the iron-scintillator calorimeter of the CCFR neutrino detector. Measurements of the dE/dx energy loss in Fe of high energy cosmic ray muons (up to 1 TeV) incident on the same detector are presented and compared against calculations.

The design of muon detectors for the superconducting supercollider (SSC) requires knowledge on two topics: particle punchthrough from the calorimeter in front of the muon detector and the interactions of TeV energy muons with the components of the muon detector. Consider a muon detector that consists of absorber plates interspersed with particle tracking chambers. A large energy loss muon interaction within the absorber produces a shower of secondary particles that can penetrate into the tracking chamber region. How often these interactions occur for TeV muons is an important measurement for the proper design of an SSC muon detector.

Both the measurements on hadronic shower punchthrough and TeV muon dE/dx were taken using the CCFR neutrino detector [1] (the Lab E detector at Fermilab). The detector is a 690 ton iron-scintillator calorimeter followed by a 420 ton toroidal muon spectrometer. Shower punchthrough measurements are extracted from a series of hadron beam energy calibration runs of the calorimeter and measurements of hadron induced muon production rates taken in 1984 and 1987. Measurements of the longitudinal punchthrough probabilities of particles as a function of depth into the iron-scintillator calorimeter from showers produced by 15, 25, 40, 50, 70, 100, 200, and 300 GeV hadrons have been reported [2, 3]. In Reference [3], particle punchthrough rates for 70 GeV tagged pions and kaons are also presented as well as muon production rates from 40, 70, and 100 GeV hadrons. Attempts at reproducing the longitudinal punchthrough rates with shower Monte Carlos [4] have been fairly successful.

The TeV muon dE/dx measurements are from cosmic ray exposures of the CCFR neutrino detector taken in 1987 and 1988. The trigger selected muons that were nearly horizontal. To ensure

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proper reconstruction of the muon momentum by the toroidal spectrometer, only muons that traverse the detector in the direction of the accelerator beam and through the full length of the muon spectrometer are used. The fractional momentum resolution is $\sigma/p \sim 0.11\sqrt{1 + (p/900)^2}$, where p is in GeV. In the final event sample, there are 9443 events, with 236, 95, and 43 events between 500 to 800 GeV, 800 to 1000 GeV, and 1000 to 2000 GeV respectively. Above 2000 GeV, there are 19 events. As resolution errors are expected to be large in this region, they are not used. The differential muon energy spectrum falls approximately as $1/E^2$ and steepens above 400 GeV. Muon energy losses are measured in the CCFR detector's calorimeter, which has 84 scintillation counters, one every 10.3 cm of Fe.

Figure 1 shows the muon dE/dx (average energy loss) as a function of the muon momentum. The measurement in each momentum bin is the total energy deposited by the muons in the bin divided by the total path length in iron traversed by those muons. The solid curve is a theoretical prediction [5], and it is consistent with the measurement. In iron, the energy loss from stochastic processes (bremsstrahlung, e^+e^- pair production, and photonuclear interactions) is predicted to become significant and eventually dominate the dE/dx at muon energies above a hundred GeV. Energy losses from these stochastic processes appear as occasional shower cascades in the calorimeter. These cascades are superimposed above the ionization energy deposited by the muon in the calorimetry counters. Energy losses under a few GeV are difficult to measure because their shower cascades are not readily distinguishable from the ionization background. The stochastic energy loss is obtained from the measured shower cascade energy by subtracting its average ionization energy loss from it.

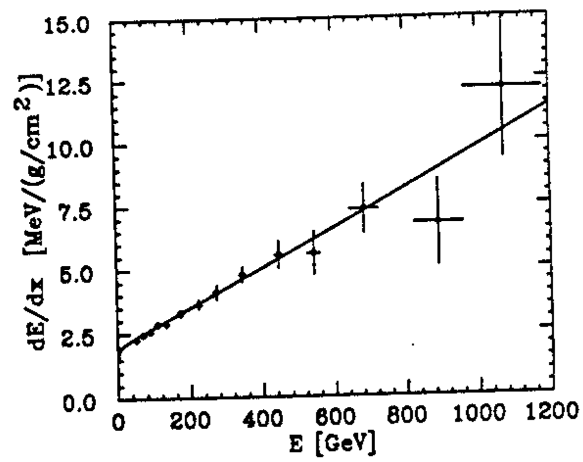

Figure 1: Muon dE/dx. The solid curve is the theoretical prediction.

Figure 2 shows the differential, stochastic energy loss spectrum for very energetic muons and for energy losses larger than 2 GeV. The solid curve is a prediction [5] for the shape of the spectrum. There is reasonable agreement between the measurement and shape predictions for all muon energies. From visual scans of a sample of cosmic ray event pictures, we observe that with increasing muon energies, events contain more visible shower cascades. Nearly all the shower cascades are electromagnetic

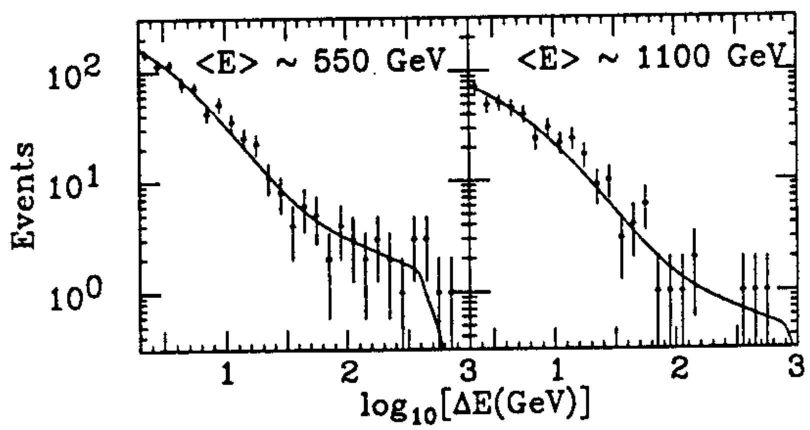

Figure 2: The differential muon energy loss spectrum for muon energies in the range 400 to 800 GeV ($< E >\sim 550$) and 800 to 2000 GeV ($< E >\sim 1100$). The solid curves are the predicted shapes that have been normalized to the data.

(the cascades do not penetrate through more than ~30 cm of Fe). The calculated [5] interaction lengths for producing a muon energy loss in excess of 2 GeV via stochastic processes for 10, 100, 1000, and 10000 GeV muons are 47000, 3900, 280, and 61 cm of Fe respectively. For energy losses under 2 GeV, which are not as readily observable in our calorimeter, the corresponding interaction lengths are 330, 78, 34, and 21 cm. The implication is that a muon tracking chamber sandwiched between iron (hadron) absorbers will see more activity for increasing muon energies.

The CCFR calorimeter has 42 drift chambers, one every 20.6 cm of Fe. They are instrumented with multi-hit TDCs and flash ADCs. For two particles to be resolved by the flash ADCs, they must be separated by at least 2 mm. We use the drift chambers with the flash ADC electronics to measure the hit multiplicities as a function of the muon energy. The cosmic ray muons are put into momentum bins of 40-80, 80-180, 180-400, 400-800, and 800-2000 GeV. (The mean muon momenta of each bin are: 58, 119, 259, 546, and 1132 GeV). The fraction of events in each bin where the flash ADCs are able to detect multiple particles per drift cell are 14, 16, 20, 24, and 28% respectively. In the 40-80 GeV momentum bin, the multiplicity drops about two orders of magnitude after four hits, while for the 800-2000 GeV momentum bin, the multiplicity drops the same amount after nine hits. The resolution of the drift chamber (from the multi-hit TDCs) does degrade with increasing hit multiplicities observed in the flash ADCs.

In conclusion, we find that our measurements on average muon energy loss in iron and on the differential energy loss spectrum are consistent with the latest theoretical predictions [5]. Thus, the theoretical differential cross sections on bremsstrahlung, e^+e^- pair production, and photonuclear interactions can be used in conjunction with shower Monte Carlos to aid in the design of muon detectors that utilize large amounts of hadron absorber [6].

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