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COMPARISON OF HADRONIC SHOWER PUNCHTHROUGH AND TeV MUON dE/dx WITH CALCULATION

A. Bodek, et. al.

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Comparison of Hadronic Shower Punchthrough and TeV Muon dE/dx with Calculation *

B.J. KIM, P. de BARBARO, A. BODEK, H.S. BUDD, and W.K. SAKUMOTO
University of Rochester, Rochester, NY 14627

F.S. MERRITT, M.J. OREGLIA, H. SCHELLMAN †, and B.A. SCHUMM ‡
University of Chicago, Chicago, IL 60637

C. ARROYO, K.T. BACHMANN §, R.E. BLAIR ¶, C. FOUDAS ||, B. KING, W.C. LEFMANN, W.C. LEUNG, S.R. MISHRA, E. OLTMAN, P.Z. QUINTAS, S.A. RABINOWITZ, F. SCIULLI, W.G. SELIGMAN, and M.H. SHAEVITZ
Columbia University, New York, NY 10027

R.H. BERNSTEIN, F.O. BORCHERDING, H.E. FISK, M.J. LAMM, W. MARSH, K.W. MERRITT, P.A. RAPIDIS, and D. YOVANOVITCH
Fermi National Accelerator Laboratory, Batavia, IL 60510

P.H. SANDLER and W.H. SMITH
University of Wisconsin, Madison, WI 53706

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 and have compared them to a Monte Carlo simulation. Measurements of the dE/dx energy loss in iron of high energy cosmic ray muons (up to 1 TeV) incident on the same detector are presented and are compared against calculations.

1. INTRODUCTION

Muons are identified by penetration through a hadron absorber. Hence, knowledge of the penetration depth of particles in an hadronic shower is important for the design of future hadronic colliders. Muons are measured in tracking chambers after an absorber. This measurement can be obscured in two ways by the presence of a shower from an interaction created by the muon in the absorber. First, unless the absorber is a calorimeter, the energy lost in the absorber is not measured. Second, the shower could be present in the tracking chambers, making tracking difficult. Accurate information on shower production by muons is necessary for building a reliable muon detector. We present in this paper a measurement of hadronic showers penetration depth and muon energy loss in an apparatus used to detect neutrinos.

2. APPARATUS

The CCFR neutrino detector at Fermilab [1] was used to measure hadronic shower punchthrough and TeV muon dE/dx energy loss. The CCFR neutrino detector consists of a target calorimeter followed by a muon spectrometer. The calorimeter is made of 640 tons of 3 m square steel plates interspersed with drift chambers (every 20.6 cm of steel) and liquid-scintillator counters (every 10.3 cm of steel). The 84 scintillator counters are read out with ADCs and multi-hit TDCs. The 42 drift chambers in the calorimeter are read out with multi-hit

*Presented by H.S. Budd, University of Rochester
†Present address: Fermilab, Batavia, IL 60510.
‡Present address: LBL, Berkeley, CA 94720.
§Present address: Widener Univ.,Chester, PA 19013.
¶Present address: Argonne National Laboratory, Argonne, IL, 60439.
||Present address: University of Wisconsin, Madison, WI 53706.

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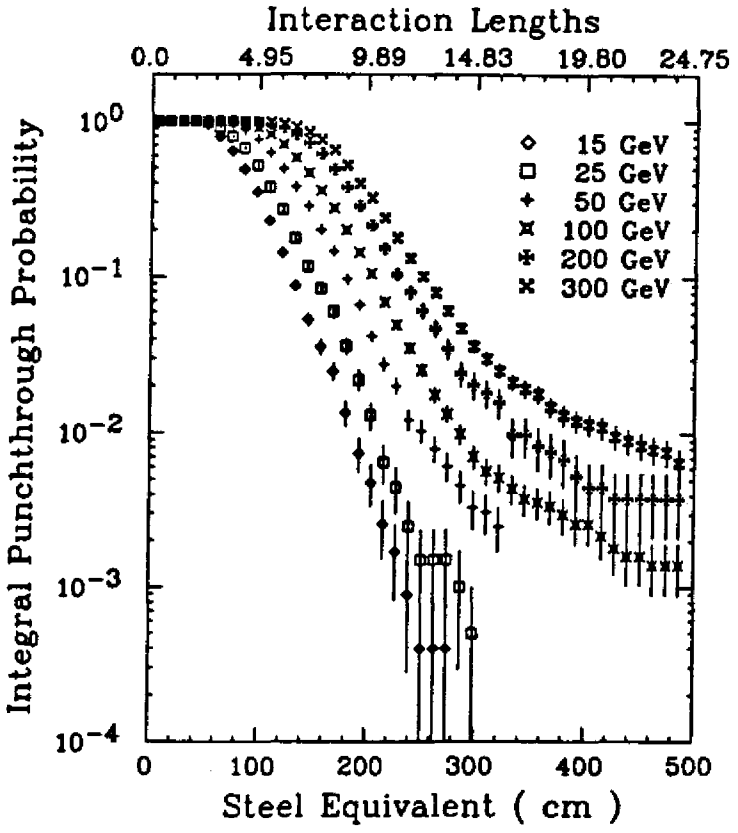

Figure 1: Intergral probability distribution for hadronic shower punchthrough as a function of depth in terms of cm of steel for the 1984 Run. Distributions are shown for 15, 25, 50, 100, 200, and 300 GeV/c hadron beam.

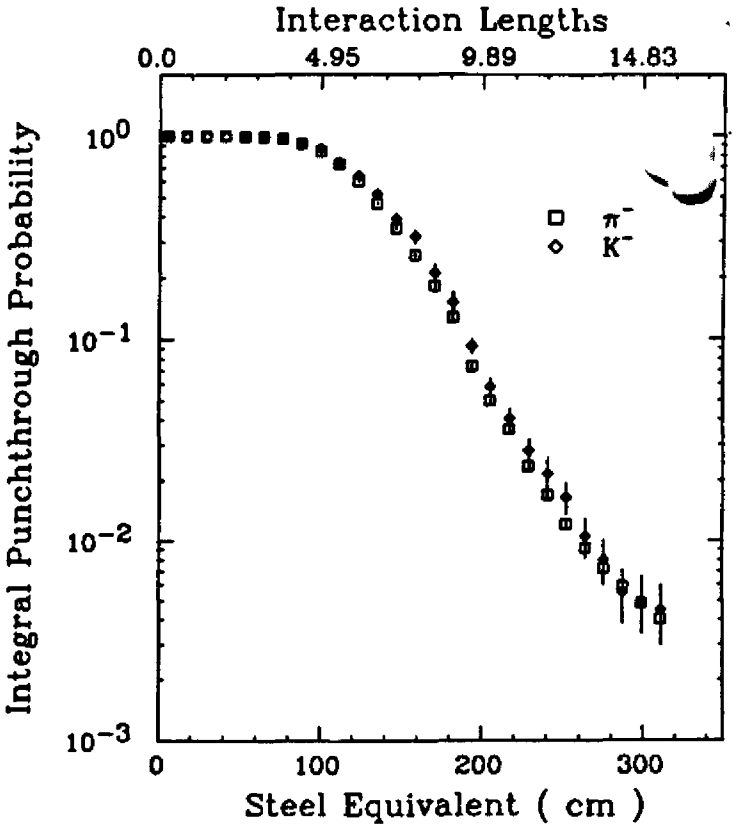

Figure 2: Integral punchthrough probability distributions for 70 GeV/c pions and kaons.

TDCs. In addition, during the 1987 Run the drift chambers were readout with flash ADCs (FADCs). The spectrometer employs 3 toroidal magnets with a total transverse momentum kick of 2.4 GeV/c, 25 drift chambers, and 25 acrylic counters. The 25 drift chambers in the toroid are grouped in 5 clusters, with a chamber cluster downstream of each toroidal magnet and 2 clusters downstream of the spectrometer. The fractional momentum resolution is $\sigma/p \sim 0.11\sqrt{1+(p/900)^2}$, where p is in GeV/c. This indicates our spectrometer can determine the momentum of muons to 2 TeV/c.

3. HADRON SHOWER PUNCHTHROUGH

Shower punchthrough measurements [2, 3] come from data taken for hadron energy calibration and measurements of hadron-induced muon production. These data were taken in 1984 and 1987. During 1984 Run, hadron punchthrough was studied with beams of 15, 25, 50, 100, 200, and 300 GeV/c momentum. During 1987 Run, hadron beams of 40, 70, and 100 GeV/c momentum were used. For the 1987 Run two Čerenkov counters were used to tag pions and kaons for the 70 GeV/c data. For both the 1984 and 1987 Run an upstream spectrometer measured the incoming beam momentum. The spectrometer consisted for four sets of tracking chambers that measured the particle trajectory before and after pair of dipole magnets.

Figure 1 shows [2] the integral probability distribution for hadronic shower punchthrough as a function of depth in terms of cm of steel. The most downstream scintillator counter with a discriminator hit corresponding to a threshold setting of about 25% of minimum ionizing defines the penetration depth. The data is shown for 15, 25, 50, 100, 200, and 300 GeV/c momentum positive hadrons. The punchthrough probability for 100 GeV/c hadrons was measured both in the 1984 Run and 1987 Run, and the two measurements agree.

The punchthrough data show two distinct regions [4]. In the region after the flat top most of the puncht' [illegible]h particles are hadrons, and the exponential fall of[illegible]s the absorption of hadrons. In the region where the penetration probability flattens out, punchthrough is due to

shower muons. These muons have longer range at higher energy, hence the number of penetrating muons depends e energy of the shower. Since these muons must be d out, there is a longer attenuation length which depends upon the dE/dx loss of the absorber.

Figure 2 shows [3] the integral punchthrough probability for a tagged beam of π^- and K^-. For thickness up to 3 meter of steel the punchthrough probability for πs and Ks are similar. The K^- induced showers are 3.5% $\pm$ 2.0% (the error is statistical) more likely than π^- to punchthrough at a depth of 5 interaction lengths. Up to 3 meters of iron where most of the punchthrough particles are hadrons, we expect punchthrough probability for π^- and K^- to be similar. As the cross section for π^- is about 15% higher than the cross section of K^- [5], we expect the punchthrough probability for K^- to be slightly larger. However, at a penetration depth of 6 meter of iron and with an 11 GeV/c cut on the muon momentum, the rate of $K^- \rightarrow \mu^-$ is 62% $\pm$ 16% $\pm$ 11% higher than the rate for $\pi^- \rightarrow \mu^-$, while the rate for $K^- \rightarrow \mu^+$ is consistent with the rate for $\pi^- \rightarrow \mu^+$ [3]. The first error is statistical, and the second error is systematic. kaons decay more readily into muons, we expect punchthrough probability to be higher for kaons for very thick absorbers.

A GEANT GHEISHA Monte Carlo simulation [6, 7] of the 15 GeV/c, 40 GeV/c, 100 GeV/c, and 300 GeV/c data has been done for the CCFR detector. For the 40 GeV/c and 100 GeV/c data the simulation uses Version 3.13 of GEANT and Version 8 of GHEISHA. The geometry for GEANT is taken from Table I in Reference 1. A counter is defined as 2.54 cm of mineral oil as the active medium. The mineral oil is surrounded by a total of 3.94 cm of inactive material consisting of lucite, mylar, and water. The distribution of counters, drift chambers, and steel is the same as the CCFR detector. The simulation has cutoffs of 1 MeV for photons, electrons, hadrons, and neutrons. A punchthrough is defined as more than 0.3 MeV of energy loss in the mineral oil of a counter.

For the 15 GeV/c and 300 GeV/c data the GEANT simulation is slightly simpler. This simulation uses Version 3.12 of GEANT. A counter is defined as 6.48 cm neral oil, water, lucite, and mylar mixed together and all of it active. The cell geometry for this simulation is the following: 5.15 cm of steel, a 6.48 cm counter, and 4.44 cm drift chamber. (The CCFR detector actually has twice as many counters as drift chambers.) The above cell has the same density as the CCFR detector. The simulation has cutoffs of 1 MeV for electrons and photon, and 10 MeV for neutrons, hadrons, and muons. A punchthrough is defined by having one of the two following conditions satisfied: 1) Any charged particle with momentum greater than 3 MeV/c reaching a counter. 2) Any neutron with momentum greater than 3 MeV/c which is captured or has a hadronic interaction in a counter. Most of the punchthrough is from charged particles, but some is contributed from interacting neutrons.

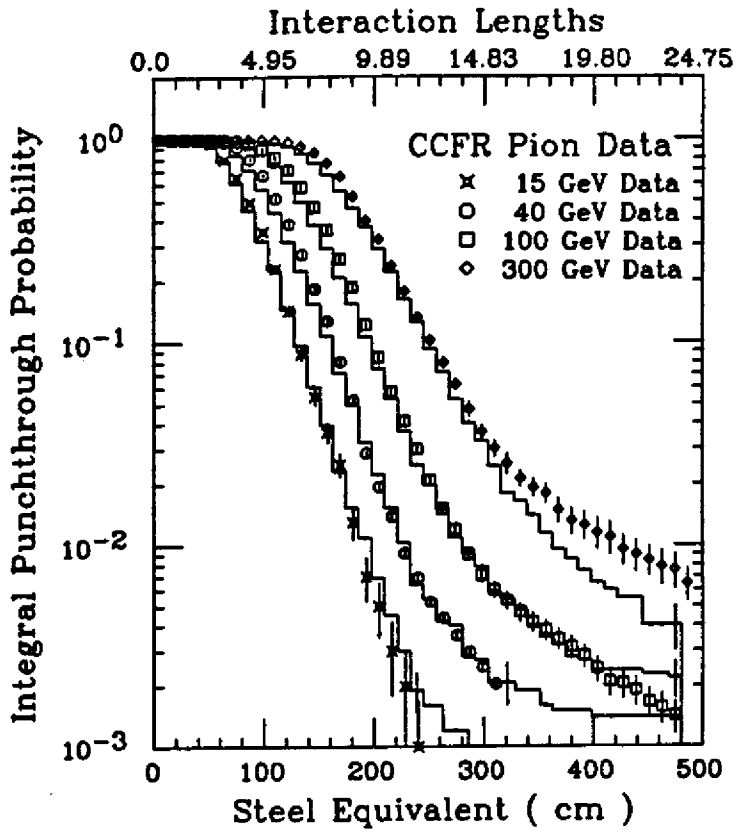

Figure 3: Integral probability distributions for hadronic shower punchthrough for 15 GeV/c, 40 GeV, 100 GeV/c, and 300 GeV/c momentum hadrons compared with a GHEISHA Monte Carlo calculation. The solid histogram is the Monte Carlo calculation with the statistical error bars of each Monte Carlo calculation shown for one point.

The 3.13 GEANT "complete" simulation and the 3.12 GEANT "simpler" simulation were both done at 100 GeV/c. Their results were identical to within the statistics of the Monte Carlo simulations. We conclude a "complete" simulation for 15 GeV/c and 300 GeV/c incident hadrons would be similar to the "simpler" sim-

ulation.

Figure 3 shows a comparison between CCFR data and the GHEISHA simulation. The 15 GeV/c and 300 GeV/c data are taken from the 1984 Run [2], while the 40 GeV/c and 100 GeV/c data are taken from the 1987 Run [3]. At 15 GeV/c, 40 GeV/c, and 100 Gev/c, the Monte Carlo calculation simulates the data very well. However, at 300 GeV/c the Monte Carlo simulation is a little low especially at large absorber thickness where muons are expected to be the dominate source of punchthrough.

We determine the difference in punchthrough measured by ionization in argon-ethane in drift chambers and by scintillator counters. The punchthrough probability for the drift chambers is defined by recording the number of times a drift chamber had a FADC hit above 25% of minimum ionizing. The result is independent of the definition of minimum ionizing. The drift chambers sample every 20 cm of iron while the counters sample every 10 cm of iron. To compare the drift chambers result to the counters, we applied the same algorithm to every other counter. The punchthrough probability at a depth of 169.5 cm for drift chambers is 12% $\pm$ 5% lower than that for scintillator counters at a beam momentum of 40 GeV/c, 16% $\pm$ 9% lower at 70 GeV, and 9% $\pm$ 4% lower at the 100 GeV beam momentum. The error is statistical. Drift chambers are not sensitive to neutrons, hence some of the difference in punchthrough probability between counters and drift chambers may be explained by punchthrough from neutrons.

A muon identifying algorithm is to extrapolate the particle's track through an absorber to a hit in a chamber. If the chamber hit is within a certain distance of the extrapolated track, the algorithm calls the particle a muon. To determine how often the punchthrough particle will be misidentified as a muon under the assumption the incident hadron is a muon, we extrapolate the incoming hadron to drift chambers in the calorimeter. A search is made for the nearest FADC hit to the extrapolated track. Figure 4 shows the result of this study [3]. The radius from 10% to 90% containment of the nearest hit to the extrapolated track is shown as a function of depth in steel. The 1 σ and 2 σ level of multiple scattering for a 10 GeV/c muon are shown. The plot shows that the algorithm finds some fake muons in a hadron shower unless the hadron absorber is thick enough.

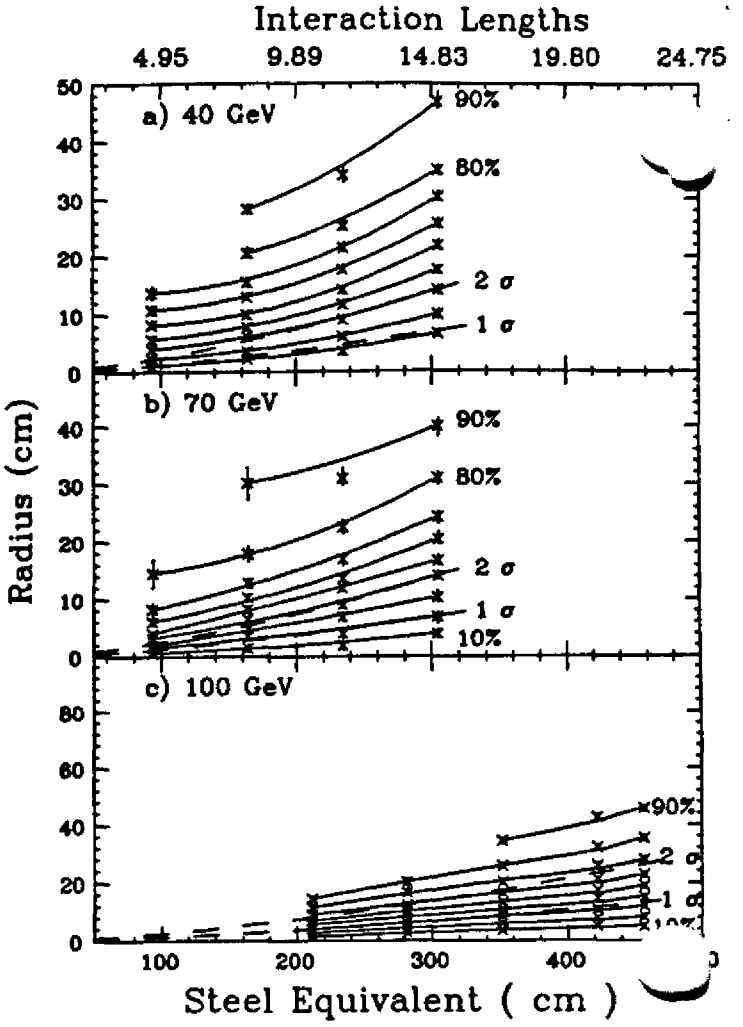

Figure 4: Radius which contains from 10% to 90% of the punchthrough particles as a function of depth in the calorimeter. The dashed curve show the 1σ and 2σ multiple scatter deviation of a 10 GeV/c muon.

4. ENERGY LOSS OF MUONS

The TeV muon dE/dx measurements are from cosmic ray exposures of the CCFR neutrino detector taken during the 1987 CCFR Neutrino Run. The trigger selected muons that were nearly horizontal and went through the entire target calorimeter. To ensure 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 final event sample has 9443 events, with 236, 95, and 43 events between 500 to 800 GeV/c, 800 to 1000 GeV/c, and [illegible] to 2000 GeV/c, respectively. Above 2000 GeV/c, t[illegible]are 19 events. As resolution errors are expected to be large in this region, they are not used. Figure 5 shows the

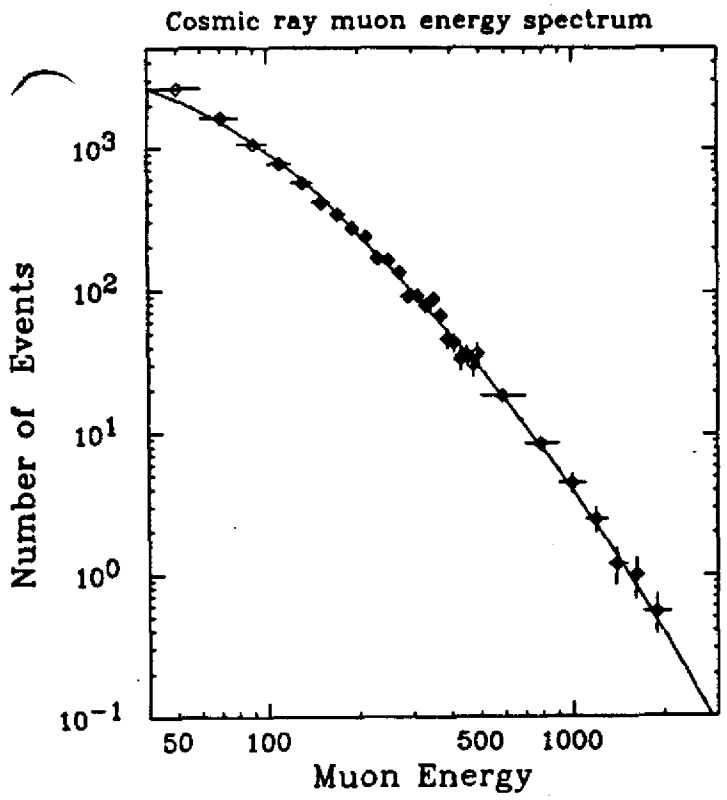

Figure 5: The momentum distribution for cosmic ray muons which traverse the entire CCFR detector. The [illegible] s a fit from data taken by the DEIS spectrometer.

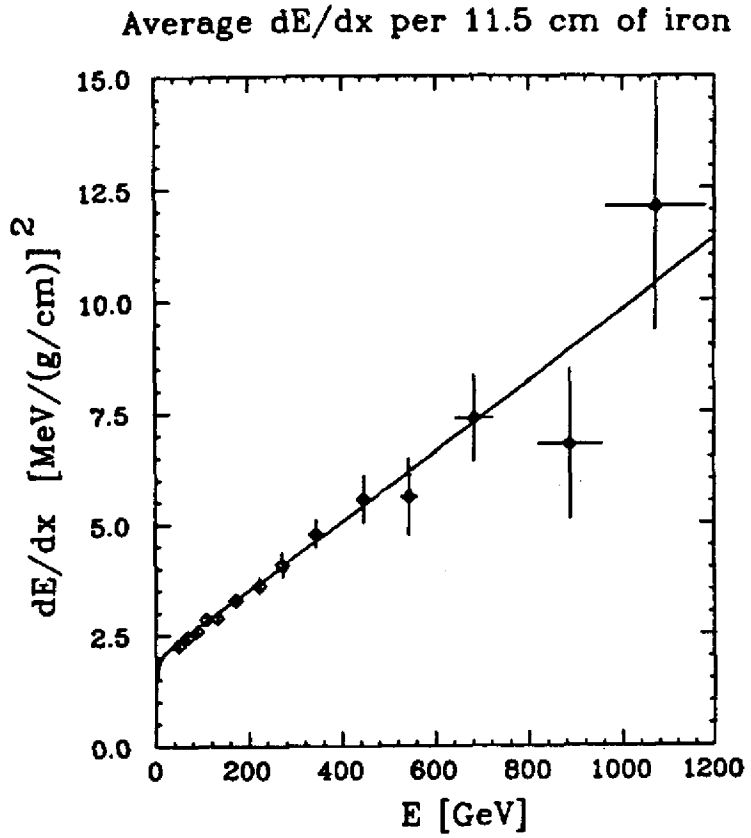

Figure 6: The average muon energy loss <dE/dx> per cm of steel. The solid line is a calculation.

momentum spectrum of the cosmic ray muons. 56% of the cosmic rays are positive, which is in agreement with expectations. For muons with momentum above 800 GeV/c, 60% ± 4% (error statistical) are positive, so that the ratio does not seem to change at high energy. The line is a fit to data taken by the DEIS spectrometer [8].

Figure 6 shows the muon <dE/dx> (average energy loss) as a function of the muon momentum. <dE/dx> measurement in each momentum range equals the total energy deposited by the muons using the calorimetry counters [1, 11] divided by the total path length in iron traversed by those muons. The solid curve is a theoretical prediction [9], and it is consistent with the measurement. In iron the energy loss is due to ionization, bremsstrahlung, e^+e^- pair production, and photonuclear interactions. Ionization is the dominant source o[illegible]gy loss for muon less that about 100 GeV/c. T[illegible] process is seen as an average loss in each scintillator counter. Above 100 GeV/c, stochastic processes dominate the muon energy loss. These process are bremsstrahlung, e^+e^- pair production, and photonuclear interactions. They 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.

In order to measure the cross section for these stochastic processes, we search for showers deposited by cosmic ray muons. One counter with energy greater than 3 times a minimum ionizing particle defines a shower. This requirement puts a 0.4 GeV energy cut on showers. The cosmic ray muons are put into momentum bins of 40-80, 80-180, 180-400, 400-800, and 800-2000 GeV/c. (The mean muon momenta of each bin are: 58, 119, 259, 546, and 1132 GeV/c). Figure 7 shows the differential, stochastic energy loss spectrum for the cosmic ray muons in these bins with energy loss larger than 2 GeV. The solid curve is a prediction [9] for the shape of the

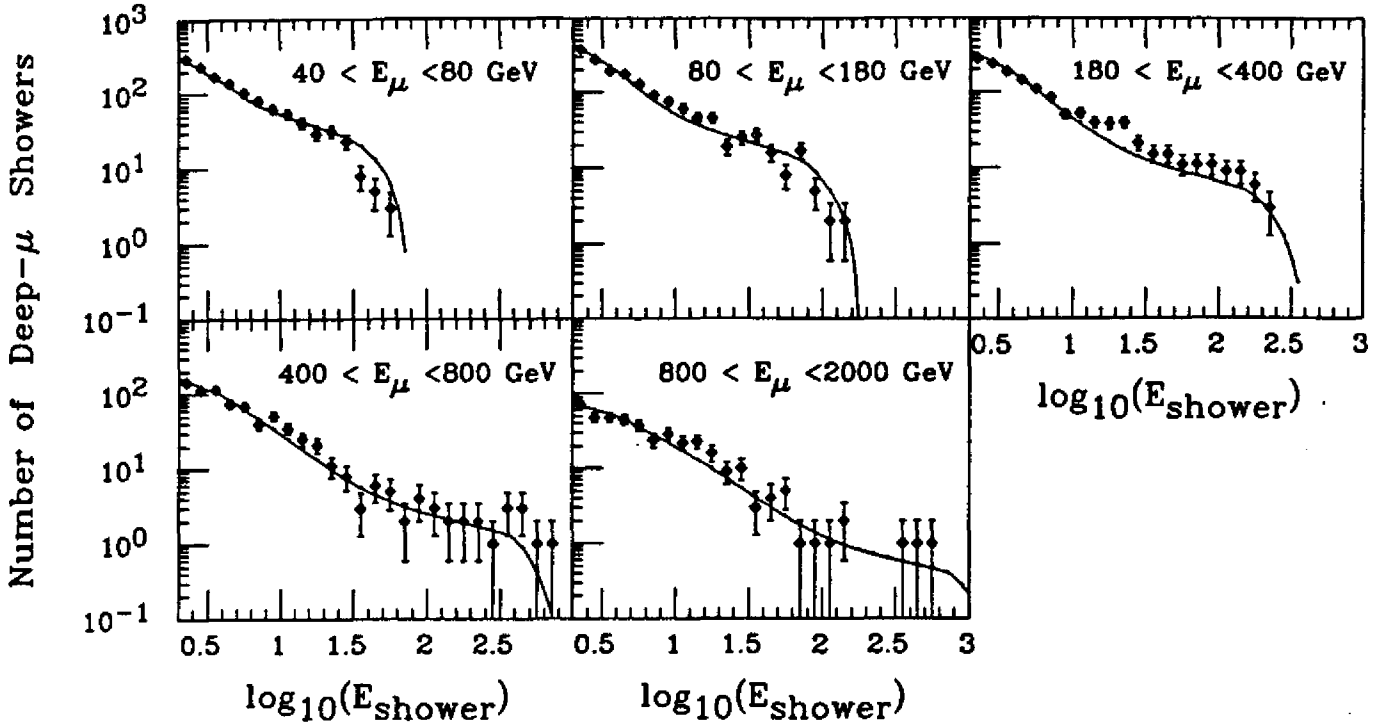

Figure 7: Rate of stochastic energy loss for muons in momentum range from 40-80, 80-180, 180-400, 400-800, and 800-2000 GeV/c. The curves are a theoretical calculation and are normalized to the data.

spectrum. The normalization of the solid curve is to the total number of cosmic ray showers. 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 (the cascades do not penetrate through more than ~30 cm of Fe). Only 5% of the energy loss of high energy muons comes from photonuclear interactions [5]. The calculated [9] interaction lengths for producing energy loss in excess of 2 GeV via stochastic processes for 10, 100, 1000, and 10000 GeV/c muons are 47000, 3900, 280, and 61 cm of Fe respectively. For energy losses under 2 GeV, the corresponding interaction lengths are 330, 78, 34, and 21 cm. The implication is that a muon tracking chamber sandwiched between iron (hadron) absorber sees more activity for increasing muon energies.

We use the FADC electronics of the drift chambers to measure the hit multiplicities as a function of the muon energy. The FADC clock is 48 ns, giving the FADCs a bin resolution of 2.4 mm for counting particles. Figure 8 shows the integral probability vs number of FADC hits per plane for the same previous five energy bins. The fraction of events in each bin where the FADCs are able to detect multiple particles per drift cell are 14, 16, 20, 24, and 28% respectively. In the 40-80 GeV/c momentum bin, the multiplicity drops about two orders of magnitude after four hits, while for the 800-2000 GeV/c momentum bin, the multiplicity drops the same amount after nine hits.

The shower cascades worsen the resolution of the drift chambers. To study their effect, first the muon track is fit. A search for the nearest TDC hit is made in each calorimeter drift chamber. Figure 9 shows the difference between the drift chamber hit and the predicted hit. The difference is shown for drift chambers with one FADC hit (◇) and more than one FADC hit (□). The intrinsic resolution of the drift chambers is 9.8 mils, (250 μm). Hence, the width of Figure 9 is determined by multiple scatter in the calorimeter steel. We see, however, with more than one hit the resolution becomes worse. Reconstructing muons becomes more difficult at higher muon momentum due to the higher rate of stochastic energy loss.

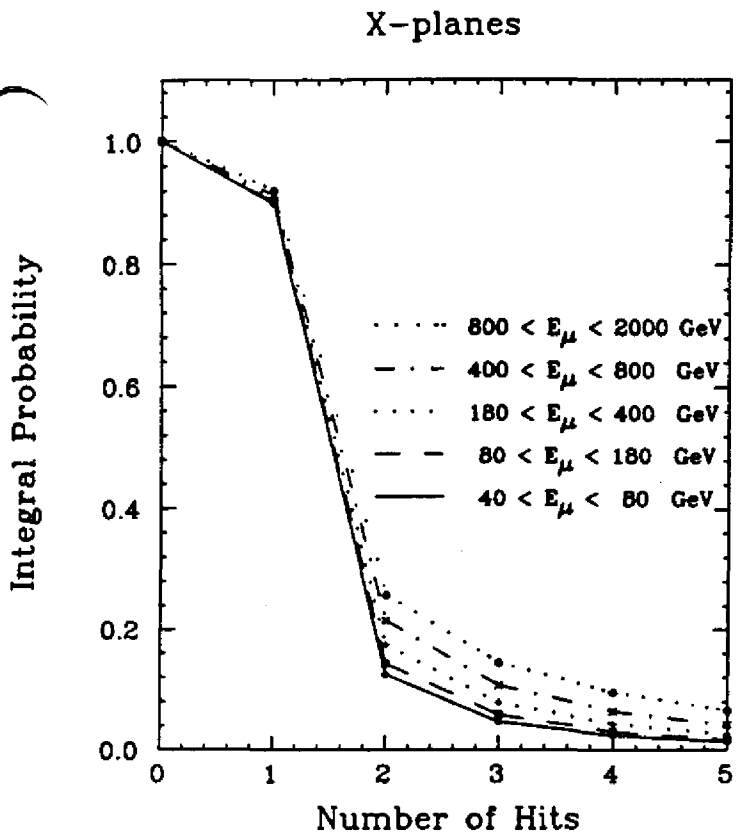

Figure 8: The multiplicity in the drift chambers measured by the FADCs. for muons in momentum range in 40-80, 80-180, 180-400, 400-800, and 800-2000 GeV/c.

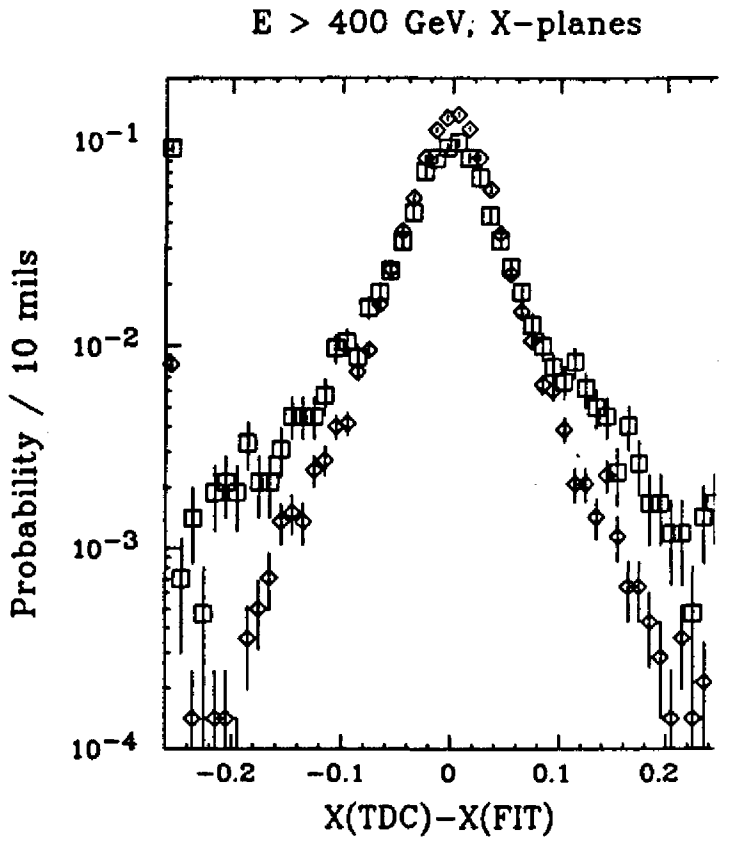

Figure 9: Probability distribution for the distribution between the difference between a drift chamber TDC hit and a predicted hit for events with 1 FADC hit (◇) and more than one FADC hit (□).

5. CONCLUSIONS

In conclusion, Monte Carlo simulation of hadronic punchthrough reproduces the data well for 15 GeV/c through 100 GeV/c hadrons. At 300 GeV/c, especially at thickness where muon production is important, Monte Carlo simulation is a little low. We find that our measurements of average muon energy loss in iron and the differential energy loss spectrum are consistent with the latest theoretical predictions [9]. Thus, the theoretical differential cross sections on bremsstrahlung, e^+e^- pair production, and photonuclear interactions can be used in conjunction with shower Monte Carlo programs to aid in the design of muon detectors that utilize large amounts of hadron absorber [10].

6. ACKNOWLEDGEMENTS

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