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A Limit on the Production Cross Section for Massive Leptons*

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ABSTRACT

We have searched for heavy penetrating particles produced in nucleon-nucleon interactions. For the mass range 1 to 5 GeV/c^2 and transverse momenta from 1.0 to 2.25 GeV/c, we conclude that the Lorentz invariant production cross section is less than 6.4×10^{-35} cm^2/GeV^2. Because of the compactness of the detector, this search is especially sensitive for heavy particle lifetimes of a few nanoseconds.

We have recently completed an experiment at the Fermi National Accelerator Laboratory (Fermilab) to study lepton production in high energy nucleon-nucleon collisions. The experiment was sensitive to heavy penetrating particles traversing the detector, as well as to muons which might arise from the decay of shorter lived states. We report here results of a search for heavy penetrating particles.[1] The measurements of prompt muon production will be reported in a subsequent paper.

The motivation for the experiment is similar to that of other particle searches performed at Fermilab and the CERN-ISR.[2-5] It explores the recently expanded range of center of mass energies in an attempt to find newly accessible particle states. Such states might have a significant lifetime if they represented a new conserved quantum number. The apparatus was made compact, 10.5 m long, so that the experiment would be sensitive to penetrating particles with lifetimes of a few nanoseconds. Previous searches are less sensitive at these lifetimes because of the long flight paths used. This experiment explores the relatively low transverse momentum region, 1.0 to 2.25 GeV/c, since all known particle production cross sections fall rapidly with increasing transverse momentum.

The apparatus, shown in Fig. 1, was located downstream from an internal target of the Fermilab accelerator. This target, consisting of 7-micron carbon filaments, was rotated through a portion of the circulating proton beam for proton energies between 30 and 300 GeV. The apparatus was sensitive to penetrating particles emitted near 91 mrad in the laboratory (90° in the cm system at 230 GeV). Particles passed through absorbers totaling

at least 17 absorption lengths for strongly interacting particles, and then traversed a magnetic spectrometer. Six scintillation counters were used for triggering. Four planes of multiwire proportional chambers (MWPC) with 1 mm wire spacing measured the track trajectory on each side of the magnet. For particle identification, gas Čerenkov counters were situated both upstream and downstream of the spectrometer magnet. Two lead-glass Čerenkov counters were located at the end of the detector. Pulse heights from all four Čerenkov counters were recorded with each event. All Čenenkov counters were continuously monitored by their response to muons from hadron decays. The gas counters were calibrated in a special run taken with a lower spectrometer momentum interval which encompassed the muon Čerenkov threshold. Care was taken with the timing of the electronic logic to ensure full detection efficiency over the range of particle velocities which could be encountered. The apparatus subtended a geometrical solid angle at the target of 21 μsr. Because of multiple scattering, its angular acceptance, when folded over the observed muon momentum spectrum, had an RMS width of 8 mrad. This apparatus was sensitive to charged particles of both signs. To guarantee equal detection efficiency, however, the magnetic field polarity was reversed at intervals of a few hours.

Special precautions were taken to ensure reliable detector operation with the highest possible beam-target interaction rates. The timing and pulse height of each of the scintillation counters were recorded with every event. Deadtimeless electronic logic was used. The detector was well shielded from hadrons so that

only a few charged particles passed through the spectrometer during each accelerator cycle. Since the eight MWPC planes overconstrained the particle trajectories, a continuous check of the plane efficiencies was possible. Values of 95% per plane were normal and the probability of extra wires being struck was typically 8%.

The signature for a heavy penetrating particle is taken as no count in either gas Čerenkov and a normal muon-like pulse height from each lead-glass Čerenkov counter. The absence of pulses in the gas Čerenkov counters indicates the high mass of the detected particle, while the traversal of the thick shield and the proper signals from the lead glass counters verify its penetrating nature. The gas counters responded to all particles with $p/m > 14$. Allowing for energy loss in the hadron shield, the requirement of no signal from the gas Cerenkov counters imposes a lower limit on the mass range of 0.4 GeV/c^2 at a P_T of 1 GeV/c and 1.4 GeV/c^2 at 2.25 GeV/c. In the lead glass Čerenkov counters, non-interacting charged particles with $\beta > 0.60$ produce a characteristic line spectrum. For the momentum interval observed, particles of all masses up to the kinematic maximum emit Čerenkov radiation in these counters. Hadrons interacting in the counters (2.3 nuclear absorption lengths) produce a broad pulse height spectrum because of the Čerenkov radiation of charged secondaries. There was no evidence for hadron contamination of the muon data to the level of 2%.

A search of the data for events satisfying the Čerenkov requirements described above yielded one heavy particle candidate compared to an expected background of 1.3 ± 0.2 events due to a

simultaneous inefficiency in each counter.

To deduce final cross section limits for heavy particle production, we normalize this result by the number of detected muons. These muons arise primarily from pion and kaon decay in the short gap between the target and first absorber. Since the muons were subject to the same triggering and reconstruction requirements as the heavier particles being sought, the ratio of heavy particles to muons is quite insensitive to systematic effects. In particular, the effects of multiple scattering and energy loss in the thick hadron shield are largely eliminated. We have verified that the observed muons do arise primarily from meson decay. First, the muon event rate is found to vary linearly with the length of decay path between the target and first absorber. Secondly, the observed energy dependence of the muon yield, shown in Fig. 2, agrees well with predictions based on the pion production measurements of Carey et al.[6] and the K to π ratios of Cronin et al.[7] The yield of μ^+ is larger than μ^- because of the copious K^+ production at these transverse momenta.

The cross section limits given below are based on the following factors: (1) the number of observed muons produced in hadron decay, (2) published pion and kaon production cross sections,[6,7] (3) the pion and kaon decay probabilities, (4) the momentum spectrum smearing by the decay process, and (5) the relative detection efficiency for heavy particles compared to the efficiency for muons. This ratio differs from unity only because of the velocity dependence of the energy loss and multiple scattering processes. Over the mass range accessible in this experiment it is unity within 25%. We assumed that the heavy particle production cross

section has the same variation over the detector aperture as pion production, although the sensitivity of the experiment does not depend strongly on this assumption.

The maximum kinematically allowed mass varies slowly with incident proton energy and secondary particle momentum. For example, if heavy particles with baryonic number zero were produced in pairs, then at an incident energy of 50 GeV the maximum mass would vary from 3.4 to 3.6 GeV/c^2 over the momentum range of the search. At 300 GeV the variation would be from 4.3 to 6.0 GeV/c^2. If the particles were produced singly, the mass limit at 300 GeV ranges from 4.5 to 6.5 GeV/c^2. The variation of incident energy and secondary particle momentum does lead to an important feature of this search. Namely, at a given mass the experiment is sensitive to a range of center of mass production angles and momenta.

The cross section limits set by the search are given in Table I and Fig. 3. They apply for particles of either charge and represent 90% confidence limits on the inclusive single particle production cross section. Data are divided into three intervals of secondary particle transverse momentum, spanning the range 1.0 to 2.25 GeV/c. Results are integrated over bombarding energies from 30 to 300 GeV, with roughly an equal number of interacting protons in all energy intervals. The limits of Table I also assume no loss from heavy particle decay. To compensate for the decay of a particle of specific mass and lifetime, the limits should be multiplied by $\exp[35m/(\tau p)]$ where m is the mass in GeV/c^2, τ, the lifetime in nanoseconds,

and p, the momentum in GeV/c. Figure 3 shows the limits in the case of no decays and in the case of a mass 2 GeV/c^2 particle with lifetimes of 3.5 and 0.5 nsec. Results of two other Fermilab experiments are shown for comparison.

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FIGURE CAPTIONS

Fig. 1. Experimental layout.

Fig. 2. Yield of μ^+ and μ^- as a function of bombarding energy for all transverse momenta greater than 1 GeV/c. The smooth curves show predictions based on pion and kaon production cross sections.

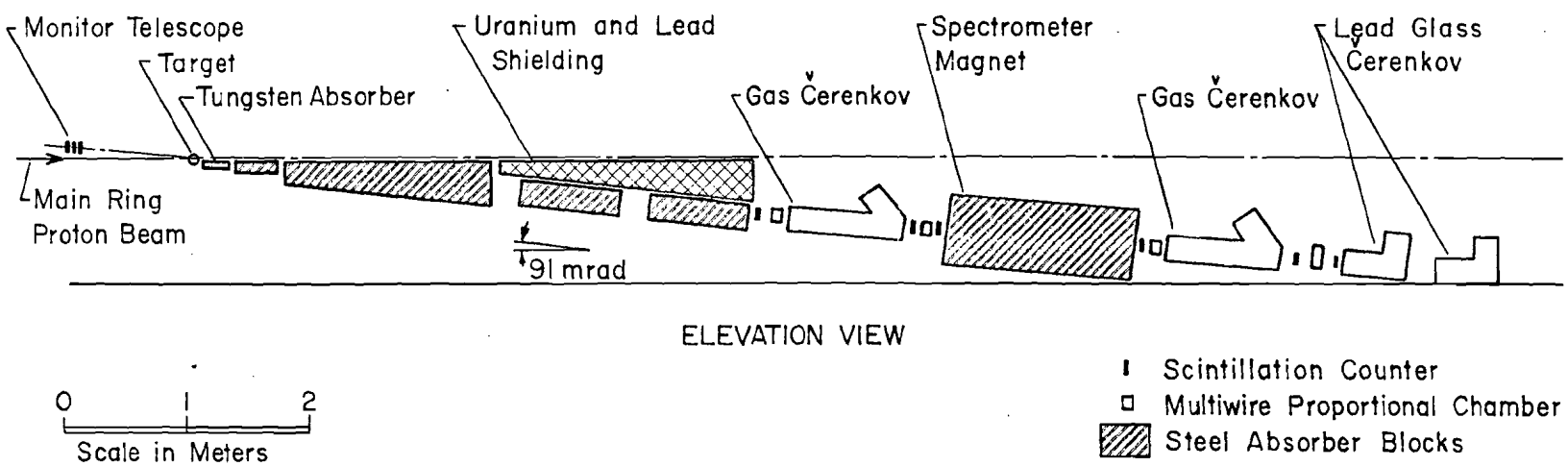
Fig. 3. Upper limits for heavy particle production as a function of transverse momentum and particle lifetime, compared with other searches, (a) results assuming no correction is required to account for particle decay before detection, (b) results for a mass of 2 GeV/c^2 and a lifetime of 3.5 nsec, (c) results for a mass of 2 GeV/c^2 and a lifetime of 0.5 nsec.

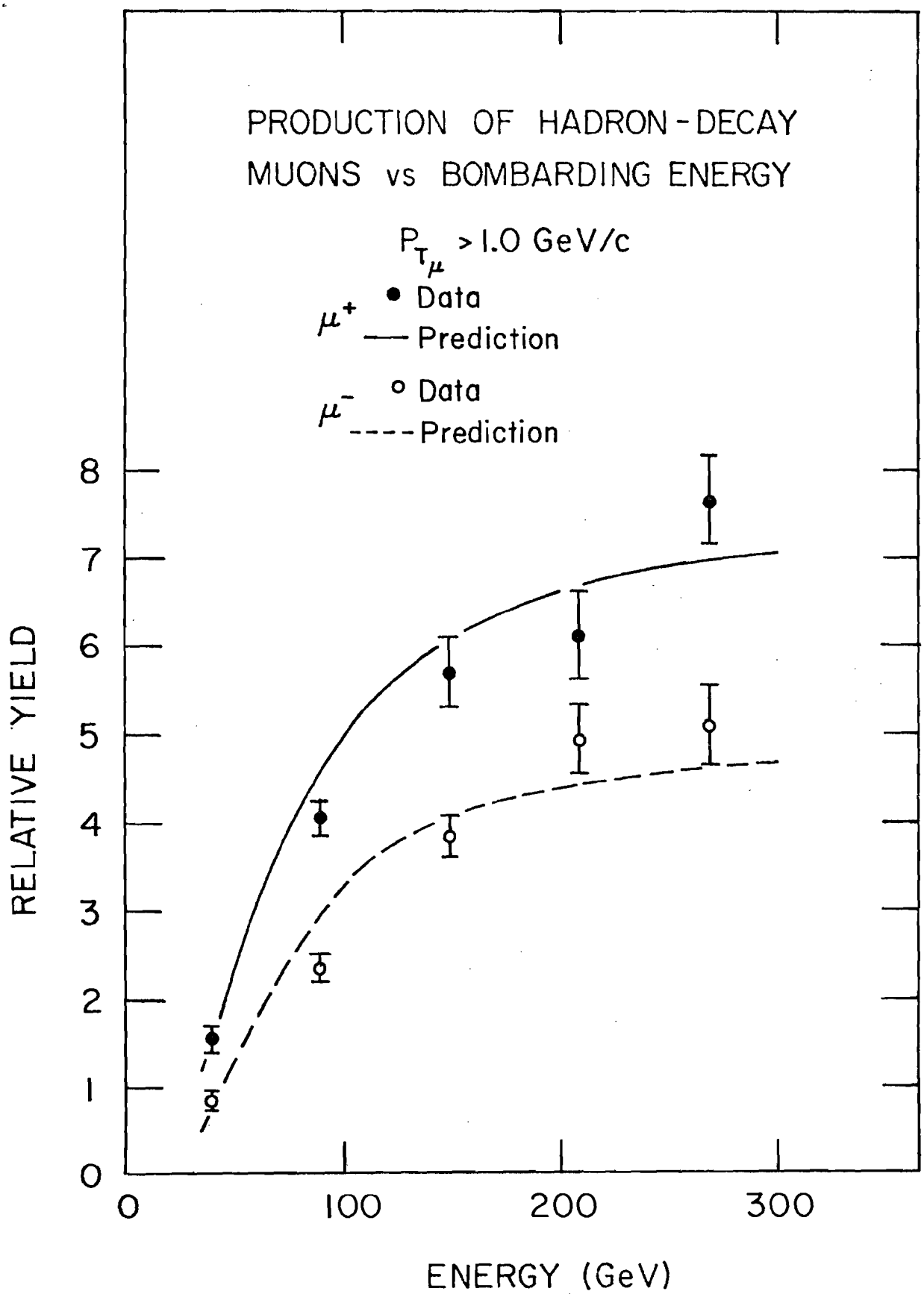
TABLE CAPTION

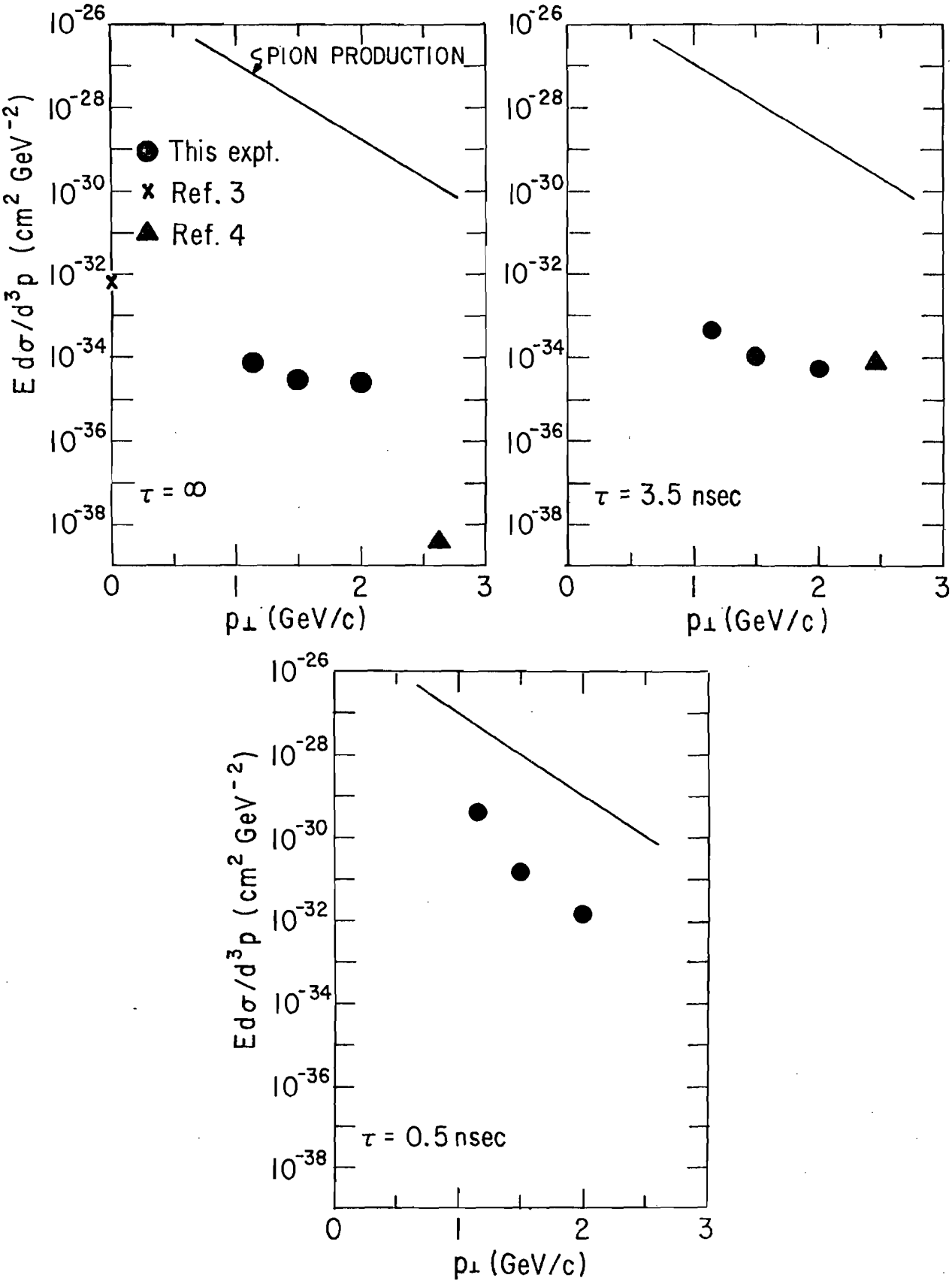
Ninety percent confidence limits for the Lorentz invariant production cross section of heavy penetrating particles of mass 3 GeV/c^2. To apply these limits for higher masses they should be divided by that fraction of the bombarding energy interval for which the mass in question is above threshold (see text). For short lifetime heavy particles the additional factor given in the text must be applied.

$P_\perp$ GeV/c	$E \frac{d^3\sigma}{d^3p}$ cm^2/GeV^2	Lower Limit on Mass Range GeV/c^2
1.0 - 1.25	6.4×10^{-35}	0.6
1.25 - 1.75	2.7×10^{-35}	1.0
1.75 - 2.25	2.4×10^{-35}	1.4

Table I


Monitor Telescope
Target
Tungsten Absorber
Uranium and Lead Shielding
Gas Čerenkov
Spectrometer Magnet
Gas Čerenkov
Lead Glass Čerenkov
Main Ring Proton Beam
91 mrad
ELEVATION VIEW
0
1
2
Scale in Meters
Scintillation Counter
Multiwire Proportional Chamber
Steel Absorber Blocks


PRODUCTION OF HADRON-DECAY
MUONS vs BOMBARDING ENERGY
P_{T_μ} > 1.0 GeV/c
μ^+ ● Data
—— Prediction
μ^- ○ Data
---- Prediction
RELATIVE YIELD
0
1
2
3
4
5
6
7
8
0
100
200
300
ENERGY (GeV)


PION PRODUCTION
This expt.
Ref. 3
Ref. 4
$\tau = \infty$
τ = 3.5 nsec
τ = 0.5 nsec
$E\,d\sigma/d^3p$ (cm^2 GeV^{-2})
$p_\perp$ (GeV/c)
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
0
1
2
3