contaminants were negligible because of the nature of the detection scheme. This point will be discussed more fully in a forthcoming publication.

[4]A more complete discussion of the experimental details is being prepared for publication. For a preliminary presentation of these measuremnts, see P. Slattery, in *Particles and Fields, 1975,* edited by H. Lubatti and P. M. Mockett (Univ. of Washington, Seattle, Wash., 1975).

[5]This correction requires a knowledge of the momentum spectrum of the incident neutrons. This momentum spectrum has been independently determined in our experiment (see Ferbel, Ref. 2), and by M. Longo *et al.*, University of Michigan Report No. UM-HE-74-18 (unpublished), and the two measurements are in very close agreement.

[6]The average value of ν is ~ 0.78 near 30 GeV/c; in excess of 30 GeV/c, ν falls below 0.77 for the data of Ref. 1, and rises to 0.79 for our data. Although small, these differences are statistically significant.

Evidence of Pair Origin of Prompt Muons

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A comparison of measurements of prompt single muons, produced in the forward direction by 400-GeV proton interactions, with the results of measurements of muon pairs produced under the same conditions shows that the pair intensity accounts for the inclusive single-muon flux in a manner which is insensitive to the details of the production and decay of the muon pairs. The mean invariant mass of the pairs is about 900 MeV/c^2.

It has been known for some time that the inclusive production of single leptons in high-energy interactions is anomalously large[1] inasmuch as elementary estimates of the production of leptons from conventional sources, such as the electromagnetic decays of the known short-lived vector mesons, fail to account for the observed intensity by about one order of magnitude. Most conjectures concerning the origins of these leptons consider that the leptons are produced either electromagnetically or through the weak decays[2] of heretofore unknown particles produced in the strong interactions. If the leptons are produced electromagnetically, they will always be produced in pairs; if they are produced through the weak-interaction decay of an intermediate particle, the proportion produced in pairs will be equal to or smaller than the branching ratio for the particle's decay to the lepton and that branching ratio will probably be smaller than one-fourth. In view of the importance of the question of pair production, we have conducted measurements designed to determine the proportion of prompt muons produced in pairs by the nuclear interactions of 400-GeV protons.

Since we had not invented an ideal 4π detector able to identify muons of all energies, we proceeded to design a measurement such that the ratio of measured dimuon intensities to single-muon inclusive intensities in a more limited kinematic region would depend on the proportion of dimuon parentage of the prompt muons in a manner which was insensitive to the largely unknown production and decay characteristics of the dimuons. In general, the production of dimuons will depend upon M, the invariant mass of the pair, and p_T and p_L, the transverse and longitudinal momenta of the center-of-mass of the pair. The decay of the pair will depend upon M and α and φ, where α is the angle of decay with respect to the direction of production of the pair and φ is the azimuthal decay angle. Our experimental design is such that the ratio is nearly independent of the distribution in M and p_T, quite insensitive to the

φ distribution, and not strongly dependent upon the decay distribution in α: We measure the production dependence on p_L.

The basic experimental configuration is described briefly in a previous report.[3] For this measurement, fourteen 2-ft×3-ft counters were arranged in a linear array in the "center" pit of the Fermi National Accelerator Laboratory proton central beam area extending to an angle of 35 mrad on either side of the proton beam line. These counters lie 400 ft from the target and only muons with an initial energy greater than 54 GeV will penetrate the 13 kg/cm^2 of material (mainly steel) in the target area and the 11.6 kg of soil separating these counters and an array of fourteen 9-in.×18-in. counters 200 ft from the target. Each of the smaller counters is aligned with a back counter and operated in coincidence with that counter. Primarily on account of multiple scattering in the earth between the two counter arrays, the acceptance of a channel, consisting of two associated counters, is dependent upon the muon energy: The acceptance is calculated to rise from zero at the threshold of 54 GeV, to 60% at 100 GeV, and to 96% at 300 GeV. The calculations were checked by comparing the measured and calculated scattering into adjacent counters.

This array was used to measure the single-prompt-muon intensity and the two-muon coincidence intensity. The single-prompt-muon intensity, determined by measuring the intensity as a function of target density and extrapolating the results to infinite density in a manner similar to that described previously,[3] is shown in Fig. 1 together with the intensity of muons derived from meson decays in the solid copper target. The fit of the dashed line, representing the results of a calculation of that intensity from a scaling of meson-production measurements made at lower energy,[4] to the measured points suggests that the technique is well understood. Evidently only a small portion of the muons are produced at angles greater than the 35-mrad acceptance of the array.

While we do not present here the whole results of the $\frac{1}{2}(14\times13)=91$ coincidence rates from which we derive the dimuon results, Fig. 2 shows the intensity as a function of angular separation together with distributions calculated assuming production of specific invariant mass pairs. While the resolution is severely limited by the large multiple scattering in the target array and from the limited energy resolution of the system, it is clear that no substantial flux is derived from invariant masses much greater than 1.0 GeV/c^2

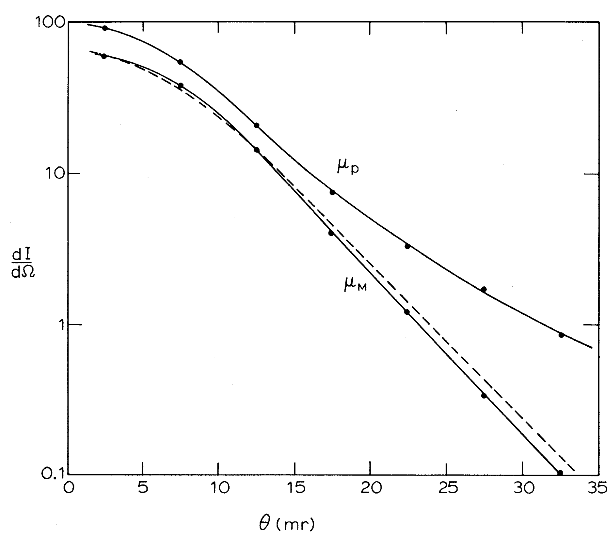

FIG. 1. Angular distributions of prompt muons (μ_p) and muons from meson decay (μ_M). The intensity is defined in arbitrary units. The dashed line shows the intensity calculated from the meson-production data (Ref. 4) normalized to the measured value at 2.5 mrad.

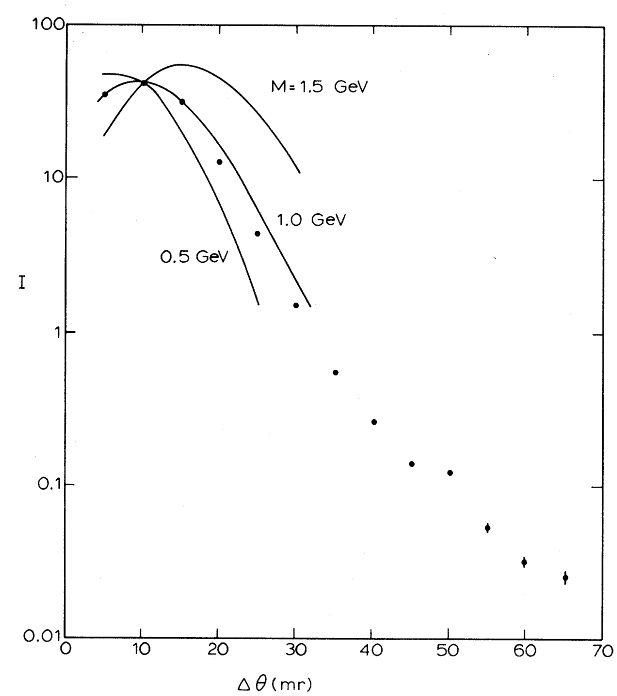

FIG. 2. The distribution of intensity versus opening angle for muon pairs produced in the forward direction. The solid curves show the results of calculations of the distributions to be expected for different pair invariant masses.

nor is the production dominated by invariant masses smaller than 0.6 GeV/c^2. The mean invariant mass appears to be in the neighborhood of 900 ± 200 MeV/c^2. A separate measurement, made with magnetic analysis, showed that pairs produced in the forward direction with small opening angles consisted of muons with opposite charges.

It is convenient to consider the geometric correction for the different solid angles subtended by the detector for one and two muons by computing the ratio between the single-muon intensity and dimuon intensity integrated over all production angles in the forward direction. Using the cylindrical symmetry of production from the interaction of nonpolarized protons, this "total" single-prompt-muon production is easily determined as 1365 muons per 10^8 incident protons from the measured flux of 364 muons per 10^8 protons in the counter array. This total flux is the flux which would be detected if the whole plane normal to the beam were filled with detectors of the same characteristics as those making up the array. However, the corresponding muon-pair flux is not defined uniquely by the measurements made by the one-dimensional array but will depend, weakly however, upon the correlation between the projected production directions of the two muons. If we define a vector $\vec{\theta}$ with a magnitude equal to the angle of production and a direction defined by the azimuthal production angle, the intensity at the plane of the detector can be expressed as $I(\vec{\theta}_1, \vec{\theta}_2)$. If the dimuon intensity depends only upon the invariant mass and transverse momentum of the pair, it will be a good approximation to write I as $G(|\vec{\theta}_1+\vec{\theta}_2|, |\vec{\theta}_1-\vec{\theta}_2|)$ since $|\vec{\theta}_1+\vec{\theta}_2|$ and $|\vec{\theta}_1-\vec{\theta}_2|$ are roughly proportional to the mean transverse momentum of the pair and to the invariant mass of the pair. With this form, I is defined completely by the array measurements, and the integration over the plane, $\int I\, d^2\theta_1\, d^2\theta_2$, gives the dimuon intensity at the plane as 53.5 muon pairs per 10^8 protons from the measured intensity of 4.74 muon pairs per 10^8 protons. Other less physically plausible models led to integrals which did not differ by more than 15% from this result. The insensitivity to the model used to extrapolate the array results follows from the large portion of the total area subtended by the array at small angles and the large portion of the intensity found at such small angles.

Since the measurements extend to values of $\vec{\theta}$ which include almost the whole intensity, the ratio of pairs to single muons at the detector plane is independent of the p_T distribution; the insensitivity of the integrated pair intensity to the form of $I(\vec{\theta}_1, \vec{\theta}_2)$ indicates an equal insensitivity of the ratio to the azimuthal decay distribution φ. The ratios will then depend only upon the distribution of the longitudinal momenta, $p(+)$ and $p(-)$, for the two muons. The distribution of the longitudinal momentum p_L of the dimuon parent defines the sum of the momenta of the two muons, $p(+)+p(-)=p_L$. Noting that $E_{\rm lab} \gg M$ and $E_{\rm lab} \gg p_T$, we have that the correlation of the momenta depends upon the invariant mass of the pair, M, and the decay angular distribution $dN/d\cos\alpha$, where α is the angle of decay with respect to the direction of flight of the pair. The distribution in $y=[p(\pm)-p_{\rm min}]/(p_{\rm max}-p_{\rm min})$, where $p_{\rm min}$ is the minimum momentum kinematically accessible and $p_{\rm max}$ is the maximum momentum, is such that $dN/dy = 2\times dN/d\cos\alpha$. Since $p_{\rm min}=\gamma[M/2-(M^2/4-M_\mu{}^2)^{1/2}]\to 0$ for $M \gg M_\mu$ and $p_{\rm max}=p_L-p_{\rm min}\to p_L$, the decay correlations are nearly independent of M for sufficiently large M, i.e., $M > 400$ MeV/c^2.

Since the distribution of the inclusive flux, $I(\mu) = I(+)+I(-)$, is determined for any dimuon decay angular distribution if the distribution of the dimuon momentum $I(p_L)$ is known, the distribution in p_L is defined by requiring a fit to measurements of the prompt flux. We have augmented our previously reported[3] measurements of prompt muons by another measurement at 185 GeV muon energy. These ratios of prompt muons to pions, shown as a function of the Feynman variable x defined in the lab system, are shown in Fig. 3. The solid curves, representing ratios which define a dimuon fit, use as a parametrization for the cross sections for mesons produced by the interaction of protons with copper[4] the form $d\sigma/dx = A\exp(-bx)$, where A is taken as 550 mb for pions, 70 mb for K^+ mesons, and 55 mb for K^- mesons. The values of b were taken as 9.3 for π^+, 11.2 for π^-, 9.3 for K^+, and 12.2 for K^-. Small corrections for muon pairs produced by pion γ rays[5] and for mesons produced in secondary interactions were made in a straightforward way. The dimuon cross section defined by the curves was described similarly as $d\sigma/dx = 67\exp(-10.4x)$ μb for dimuons decaying isotropically in their center-of-mass system.

With this parametrization of the dimuon production, the ratio of muon pairs to single muons passing through the detector plane (i.e., with the solid-angle correction) can be calculated to be 0.0351; for the 53.5 muon pairs per 10^8 protons

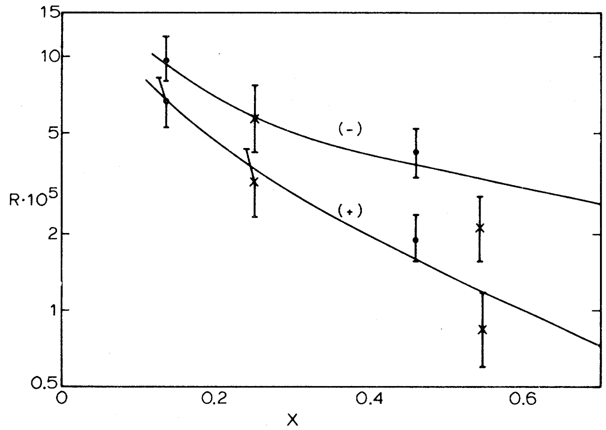

FIG. 3. The ratio of the intensities of prompt muons and pions as a function of the Feynman variable x in the laboratory system. The solid points represent measurements made at discrete muon energies, the × represent measurements made over a broad spectrum of energies where an average energy is plotted. The solid curves represent a fit defining the dimuon spectrum presented in the text. As a consequence of an improved consideration of multiple-scattering effects, the values presented here are larger than those quoted in Ref. 3.

deduced from the pair measurements, 1524 single muons per 10^8 protons should have passed through the detector plane where the measurements indicated that 1365 did so. There were 10% fewer single muons than predicted by the measured dimuon flux assuming an isotropic dimuon decay. If the dimuon decay distribution had the form $dN/d\cos\alpha = 1 + A\cos^2\alpha$, we find $A = -0.15 \mp 0.40$. If the value of A were 1 for muon pairs, a substantial flux of single-muon production would be allowed, although we believe that a ratio of single to dimuon production as large as 4, the value suggested from weak-interaction decay models, is excluded.

In summary, we believe that we have established that the bulk of the anomalous inclusive muon flux is derived from muon-pair production where the mean invariant mass of the pairs is ≈ 900 MeV/c^2. Such a parentage of the muons suggests to us that electromagnetic interactions are responsible for the production and the invariant-mass distributions seem to favor an annihilation process rather than a bremsstrahlung mechanism. For such small values of the dimuon invariant mass which have been noted, the center-of-mass momenta of parton-antiparton parents will not necessarily be closely correlated to the laboratory momentum of the dimuon and an isotropic dimuon decay is plausible.

Since we measure the incoming proton flux, we can also deduce absolute cross sections. Taking the cross section per interacting proton as 30 mb, we find that the cross section for producing muon pairs such that the momentum of the center of mass of the pair is in the range $0.125 < x < 0.70$ is about 1.55 μb. We calculate the charged-pion flux from our measurements of the muon flux from meson decay and find the cross section for charged-pion production in the same kinematic region to be 27.7 mb which is in satisfactory agreement with the value of 30.5 mb derived from an analysis of other measurements.[4]

We note that the dimuon-to-π^0 ratio is then about 1.12×10^{-4}. If the ρ_0 production and ω_0 production were equal and equal to 10% of the π^0 cross section, we would deduce a dimuon cross section from ρ and ω decays of about 0.185 μb; about one order of magnitude smaller than that observed.

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