Muon pair production in proton-nucleon interactions and new parton radiative processes

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An examination of experimental data bearing on the production of muon pairs in nucleon-nucleon interactions demonstrates the existence of a large continuum for pairs with invariant masses less than 1.0 GeV/c^2. The ratio of the pairs to the production of pions, $I(\mu\mu)/I(\pi^0)$, is of the order of 5×10^{-5} in the fragmentation region. The production of the pairs obeys Feynman scaling in the fragmentation region; the cross sections $d^2\sigma/dm\ dx$ are nearly the same for the interactions of 28-GeV protons and 150-GeV protons and the assumption of scaling is consistent with less detailed measurements at 400 GeV over a region of Feynman x such that $0.15 < x < 0.6$ and for values of the invariant mass $m \lesssim 1.0$ GeV/c^2. The invariant-mass spectrum of this continuum varies with x; the mean mass changes from about 450 MeV/c^2 at $x = 0.2$ to about 700 MeV/c^2 for $x \approx 0.6$. The dimuon production varies with the target nucleus as $A^{2/3}$ in an x region where meson production varies as $A^{0.55}$. The production is discussed in terms of parton bremsstrahlung, the annihilation of parton pairs produced by the hadron interaction (the Bjorken-Weisberg process) and line broadening of ρ-meson production.

I. INTRODUCTION

Early measurements[1] of the intensity of single leptons which were produced directly in hadron-nucleon interactions were difficult to understand in terms of conventional or well-understood processes: the intensities seemed to be too great by nearly an order of magnitude. The results of these measurements did indicate that, excepting pairs with small invariant masses, the intensities of muons and electrons were comparable and the charge ratios were near 1. It was not then clear, however, if the leptons were produced in pairs, as one might expect from electromagnetic origins, or if they were produced singly, as from the weak-interaction decays of short-lived heretofore unknown particles.

A series of later measurements then indicated that the muons produced in the fragmentation region certainly were derived largely from the production of muon pairs; measurements of prompt muons produced at values of x_F (the Feynman variable) of the order of 0.5 by the interaction of 400-GeV protons with nuclei gave a value for the proportion of single muons attributable to pair production[2] of 1.0 ± 0.10 and measurements covering a broader kinematic region[3] were interpreted as indicating a ratio of 0.7 ± 0.2.

If the prompt leptons were derived largely from the weak-interaction decays of intermediate particles, the muons would, almost certainly, be polarized along their direction of motion.[4] Measurements[5] of the longitudinal polarization of muons produced in the forward direction at an $x_F = 0.45$ by the interaction of 400-GeV protons gave a value of 0.00 ± 0.10 for the longitudinal polarization of positive prompt muons suggesting that no important part of the flux was derived from parity nonconserving processes. A group at Serpukhov[6] have reported a value of $P_\mu = -0.85 \pm 0.35$ for the polarization of muons produced at large transverse momenta ($\gtrsim 2.0$ GeV/c) by the interaction of 70-GeV protons and recently a value of $P_\mu - 0.41 \pm 0.17$ (for $P_t = 1.9$ GeV/c). These results were not supported by similar measurements of the polarization of muons produced with transverse momenta of about 2.0 GeV/c by 400-GeV protons[7] ($P_\mu = -0.06 \pm 0.16$) or by 28-GeV protons[8] ($P_\mu = -0.10 \pm 0.15$).

In summary, the characteristics of the production of prompt leptons are consistent with the operational hypothesis that they are produced in pairs and they are not polarized. In turn, such a conclusion is consistent with the view that the leptons are produced primarily through electromagnetic processes, and it is most difficult to reconcile our knowledge of the production with any model which demands a substantial production through weak interaction processes. There is, however, one caveat which is pertinent; it is certainly possible that some more exotic process may dominate lepton production in some specific, restricted, kinematic region. There are, however, a variety of electromagnetic processes of greater or lesser importance to us at this time, and the question of the details of the production are still important.

II. CONVENTIONAL SOURCES OF MUON PAIRS

Muon pairs with invariant masses less than or of the order of 1.0 GeV will be produced through the two-body decay of vector mesons: the ρ, ω, and ϕ, and through the three-body decays of the η ($\eta \rightarrow \gamma + \mu^+ + \mu^-$) and the ω ($\omega \rightarrow \pi^0 + \mu^+ + \mu^-$). There are very small contributions from the decays of other mesons and other decay modes which we neglect.[9] Contributions from these sources will be proportional to the product of the production of the parent mesons in nucleon-nucleon interactions and the branching ratios for the decays to two muons.

Although the steepness of the spectra imposes difficulties on the determinations of absolute cross sections, the ratio of the production cross sections for the different mesons and for dimuons seems to be almost independent of x or of the center-of-mass energy, and direct measurements have been made of the ratio upon production of the mesons of interest to pions as well as measurements of the ratio of pions to dimuons. In particular, the ratio of the inclusive production of ρ^0 and ω^0 in proton-proton interactions has been determined in various bubble-chamber experiments[10] for proton bombarding energies of 12, 24, 69, and 205 GeV and over a variety of center-of-mass energies of the mesons. The measured ratio, $R = I(\rho^0)/(\pi^0)$, is of the order of 0.10 for all conditions. We consider, specifically, the measurements[11] at 205 GeV where the ratios are presented as a function of x. They find $R = 0.10 \pm 0.03$ for $x \lesssim 0.18$, $R = 0.12 \pm 0.03$ for $0.18 \lesssim x \lesssim 0.35$ and for $x \gtrsim 0.35$, they find no ρ^0 signal and their data is consistent with $R = 0.00 \pm 0.10$.

There are no completely comparable measurements of the ω^0 inclusive cross sections inasmuch as the ω^0, which decays primarily to three-body states, is not so easily identified. There are some semi-inclusive measurements of which the most important is the measurement of the cross section for the reaction, $p + p \rightarrow \omega^0 +$ charged particles, measured[12] at 24 GeV. This cross section was found to be almost identical to the similar cross section, $p + p \rightarrow \rho^0 +$ charged particles, over wide ranges of rapidity. We assume then that the whole inclusive cross sections are also nearly the same and the cross sections for ρ^0 and ω^0 are the same at other energies.

The production of the ϕ^0 is inhibited by the Zweig-Iikeda rule and we can then expect that the cross section for ϕ^0 production will be much smaller than the cross sections for the other vector mesons. A value of 0.045 ± 0.012 for the ratio $\sigma(\phi)/\sigma(\rho^0)$ has been reported by Blobel *et al.*[12] for an incident proton energy of 24 GeV. The magnitude of this ratio is confirmed by the dimuon measurements we discuss later; it is only important for our purposes to note that the cross section is small.

Jaeger *et al.*[13] have measured inclusive π^0 production in 12 GeV pp interactions; however, they detect no η^0 signal. This implies the upper limit on η^0 production

$$\frac{\sigma(pp \rightarrow \eta^0 + X)}{\sigma(pp \rightarrow \pi^0 + X)} < 5\% \text{ (95\% confidence level).}$$

Bartke *et al*[14] have measured the ratio of the semi-inclusive cross sections for the η and ρ, and ω production with charged particles for $\pi^+ - p$ interactions at 16 GeV. We should expect that the results of those measurements in the backward direction are not very different from that which might be expected from proton-proton interactions (or proton-nucleon interactions) and this η^0/ρ^0 ratio is determined to be about 0.34 and does not vary much with rapidity. There seems to be no reason for the ratios of inclusive cross sections to be much different.

The values of the ratio of production of these mesons and the production of π^0 mesons is given in Table I together with the branching ratios for the decays of the mesons to dimuons. The branching ratios for the two-body decay of the vector mesons to muon pairs are taken using information from the Tables of Particle Properties[15]; the decay rates for the three-body decays of the η and ω are listed from calculations by Lai and Quigg[9] and by Quigg and Jackson[16] where the form factors were calculated using the ρ-meson pole contribution (vector dominance): The decay rates will be about 30% smaller if this contribution is, in fact, not important.

The last column in Table I, which lists the product of the production cross section and the branching ratio to muon pairs, is an indication of the contributions from each source of muon pairs. However, as a consequence of the steepness of the meson production spectrum, the relative contribution of the two-body and three-body decays will be a function of x, the Feynman variable. The differential cross sections for the production of the ρ and ω in the fragmentation region appear to be the same and appear to be adequately represented[17] by a form such as

$$x\, d\sigma/dx \propto (1-x)^{2.8}.$$

TABLE I. Production and decay parameters for the decay of mesons to muon pairs.

Meson decay	Branching ratio B	$\sigma(\text{mes})/\sigma(\pi^0)$	$B \times (\sigma_m/\sigma_\pi)$
$\rho^0 \rightarrow 2\mu$	4.8×10^{-5}	0.10 ± 0.2	4.8×10^{-6}
$\omega^0 \rightarrow 2\mu$	7.6×10^{-5}	0.10 ± 0.2	7.5×10^{-6}
$\varphi^0 \rightarrow 2\mu$	28×10^{-5}	0.0045 ± 0.0012	1.3×10^{-6}
$\eta^0 \rightarrow 2\mu + \gamma$	29×10^{-5}	0.04 ± 0.01	11.6×10^{-6}
$\omega^0 \rightarrow 2\mu + \pi$	4.8×10^{-5}	0.10 ± 0.02	4.8×10^{-6}

We assume that all of the meson cross sections appear to be adequately represented by this form and, more important, that the ratio of the different meson production cross sections in the fragmentation region, for $0.15 < x < 0.6$, does not change very much. (We have seen that this is the case for the ρ^0, ω^0, and π^0.) With this form for the production spectra we can calculate the x distribution of the muon pairs from the decays. The results of such calculations are seen in the curves of Fig. 1 which show the ratio of muon pairs from the two-muon decays of vector mesons ($B_\mu I_V$) and from all mesons ($B_\mu I_m$) to the production of π^0 as a function of x. At large values of x, the three-body decays contribute, relatively, to a smaller extent than the canonical ratios defined by Table I; at smaller values of x, the three-body-decay pairs are represented to a larger extent.

The invariant-mass distributions are determined by the natural width of the resonance for the ρ for most experimental conditions, by the resolution of the apparatus for the ω and ϕ two-body decays to muon pairs, and by dynamic considerations for the ω and η three-body decays to muons. We assume an instrumental resolution of 30 MeV/c^2 [half-width at half maximum (HWHM)] and use calculated[9,16] invariant-mass distributions for the three-body decays to construct invariant-mass spectra for meson decays. Even as the relative importance of the two-body decays and three-body decays varies with x, the spectrum is a function of x. We show, in the curve of Fig. 2, the invariant-mass distribution for all pairs produced by meson decay such that $x > 0.15$.

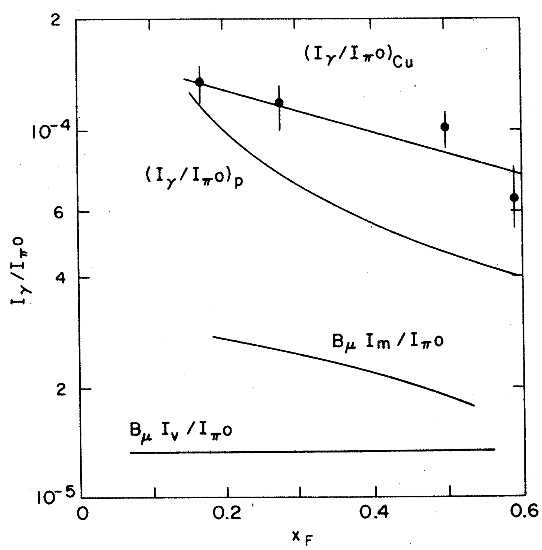

FIG. 1. The ratio of prompt dimuons to π^0 for copper and hydrogen targets. I_γ is the dimuon intensity derived from single-muon measurements. The lower curve labeled $B_\mu I_m/I_{\pi^0}$ shows the dimuon to π^0 ratio expected from the electromagnetic decays of known resonances. $B_\mu I_V$ is the dimuon intensity expected from the two-body electromagnetic decays of ρ, ω, and ϕ.

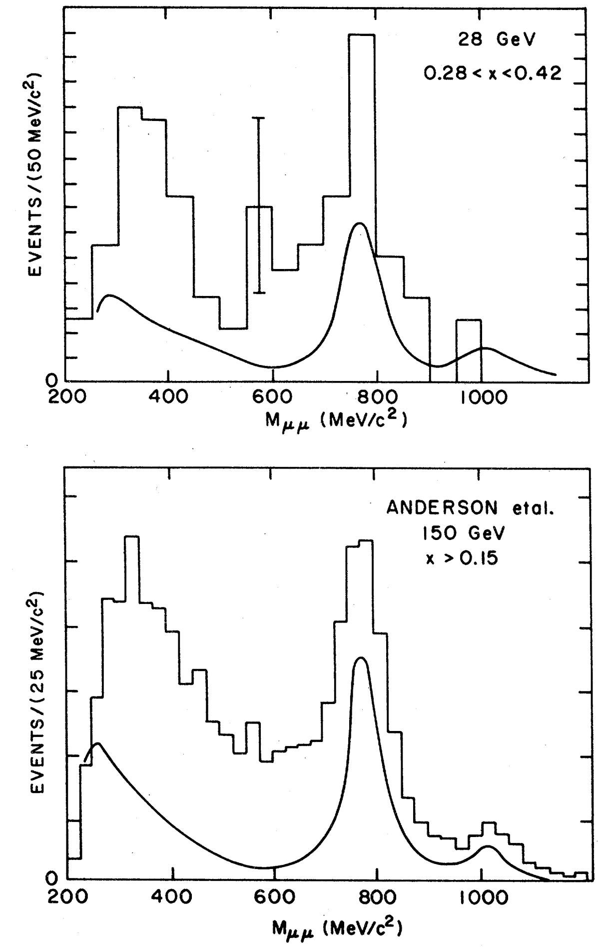

FIG. 2. The dimuon invariant-mass distribution. The curves show the expected contribution from the electromagnetic decays of known resonances.

III. MEASUREMENTS OF SINGLE MUONS

Since the spectra for the mesons produced in nucleon-nucleon interactions falls steeply with the measurement variables, p_t and x (which is essentially proportional to the energy of the meson), there are uncertainties in absolute cross sections which are not reflected in determinations of the ratios of cross sections. It was, of course, for this reason that the production of the heavier, unstable mesons, has been described in terms of the ratio for the production of these mesons with respect to pions; these ratios, unlike the absolute cross sections, are not strongly dependent upon the production kinematics. Measurements of the single-muon spectra are particularly valuable in establishing the total intensity for dimuon production as these measurements constitute, primarily, measurements of the ratios of dimuons to pions and can then be compared to the bubble-chamber measurements of the ratios of vector mesons to pions so as to determine, in a manner especially free from large errors, as to whether the heavy meson decays to dimuons can account for all of the dimuons observed.

The primary measurement, in our determinations of the single-muon spectra which we consider,[18] are measurements of the ratio of prompt muons to muons produced by the decay of π mesons and K mesons in a long dense target. The kinematics of the decays of the pions to a two-body final state of a muon and neutrino are so similar to the kinematics of the decay of virtual photons to final states of two muons, that the relative acceptances of the detection system can be calculated very simply in a manner which would seem to admit no serious error. We discuss these measurements in some detail, from this viewpoint, to establish the reliability of the results.

These single-muon measurements are made by determining the flux of muons of a given energy which are generated in the interaction of a high-energy proton beam interacting in a long, dense, target. Muons of a given energy, defined by the amount of material traversed by the particles, are detected as they stop in, or pass through, a counter assembly placed downstream from the target in line with the incident proton beam. Measurements made with different effective densities serve to differentiate between the prompt-muon flux, where the muons are generated very near the proton point of interaction, and the flux from the decays of the longer lived mesons, the K mesons and pions; the production of prompt muons is independent of the target density while the flux from the meson decays is inversely proportional to density even as the mean free path of the mesons is inversely proportional to the density.

Although the detector subtends only a small solid angle at the target, the multiple scattering of the muons produced in the target region by the considerably shielding near the target acts to ensure that the detector samples the production over a sufficient range in transverse momentum so as to include most of the production. In these experiments, the rms transverse momentum from multiple scattering, p_s, is about 600 MeV/c and the relative detection efficiency for muons with a transverse momentum p_t is about $\exp(-p_t{}^2/p_s{}^2)$. Even if the ratio of prompt muons to muons from meson decay varies sharply with transverse momentum, the measured flux of muons at large transverse momentum is sufficiently small so that no serious error will be induced in the measured ratio by the variance. We can then consider the measurements to adequately represent the ratio of prompt muons to muons from meson decay at a given x for the production integrated over all transverse momentum.

These ratios of prompt muons from meson decay can be related to the ratio for the production of prompt muon pairs to the production of the long-lived mesons in a manner which is largely independent of any likely differences in production spectra because of the deep similarities in the decay spectra of mesons and unpolarized heavy virtual photons as seen in the laboratory system. Consider the "decay" of a virtual γ, with a mass which is appreciably larger than the mass of two muons, traveling with an energy E' in the laboratory system. The product muons, of either charge, will be emitted with equal probability in any energy interval dE between 0 and E' if the virtual photon is unpolarized. Muons from the decay of pions with energy E' will be evenly distributed over a range of energy between 0.58 E' and E' while muons from the decay of K mesons with energy E' will be distributed evenly over the range between 0 and E'. For equal intensities of virtual photons and pions and for any muon energy greater than 0.58 E', the intensity of muons from pion decay will be $(1.0-0.58)^{-1} = 2.4$ greater than from the decays of photons or K mesons. As a consequence of the steepness of the spectrum as a function of E for all particles, the higher-energy muons from any decays are much more heavily weighted than the lower-energy decays and the factor of 2.4 is a good approximation to the exact weight factor except for very small values of x_f or E/E'.

Although all of the muons from the prompt electromagnetic processes will be accessible to detection, it is a good approximation to consider that only those mesons will contribute to the muon flux through their decays which undergo no collision before they decay. Again, because the meson intensity falls off so rapidly with energy, it is a good approximation to consider that any meson interaction — though it may produce lower-energy mesons — eliminates the interacting meson from the effective flux. The probability of a meson of mass m and energy E decaying to a muon before interacting in the dense target is then just $P = L/(c\tau E/m)$ where L is the mean free path for absorption in the target and τ is the meson mean life.

We can then estimate the ratio of prompt muon pairs to pions of a specific charge, assuming for the moment that we can neglect the contributions from K mesons, as

$$I_\gamma/I_\pi = (I_p/I_m)\times 2.4\times P\,, \qquad (1)$$

where I_γ/I_π is the ratio of the production of muon pairs and pions and I_p/I_m is the ratio of the measured intensities of prompt muons from meson decay. More nearly exact calculations, using numerical techniques, lead to small deviations from the approximation of Eq. (1) and the contributions from K mesons, which contribute about 20% of the muon flux, must be considered also. We note also that the effective energy for the ratio I_γ/I_π will be somewhat greater than the energy at which the ratio I_p/I_m is determined, but the difference will not be large (typically the difference will be of the order of $E_m/10$, where E_m is the kinematic maximum of the muon energy) and since the ratios are found to vary only slowly with muon energy, no important uncertainty is so introduced.

The assumption has been made in these calculations that the virtual photons, considered as parents of the muon pairs, are not polarized. The extreme decay distributions which can follow from complete photon polarization have the form $1+\beta^2\cos^2\theta$ and $(1-\beta^2)+\beta^2\sin^2\theta$ where $\beta\approx 1$ is the velocity of the muon in the rest frame of the heavy virtual photon. Taking the actual distributions as having the form $1+A\cos^2\theta$, where $|A|\lesssim 1$, Eq. (1), is modified by a factor of $(1+A)/(1+A/3)$ which is not likely to be important for any plausible positive values of A and negative values of A, corresponding to a preponderence of photons with zero component of spin in the direction of the beam, seems somewhat unlikely from theoretical considerations. If the pair origin of the single muons is accepted, the measurements of the ratio of single muons to pairs made at 400 GeV set the absolute value of A as very nearly zero.

The values of I_γ/I_π, derived from the measurements of I_p/I_m for the copper target used in the experiment, are shown in Fig. 1. We wish to compare these results with the values of I_m/I_π, the ratio of muon pairs from meson decay to π^0 production, derived in Sec. II. Since the measurements of the prompt muon production concerned production in copper targets and the ratios of the heavy mesons to pions were measured for proton targets in bubble chambers, the A dependences of the relevant production mechanisms must be considered if these two sets of results are to be compared. The A dependence of the low-invariant-mass muon-pair production has been measured as A^α, where $\alpha=0.64\pm0.03$ for pairs produced by 28-GeV protons and α is reported to be $\frac{2}{3}$ at higher proton energies. At large x, the production of mesons per interaction is known to fall off for targets of large A: The curve of Fig. 3 shows the variation of α, the exponent of A, taken from measurements[20] at 24 GeV. Similar A dependences have been demonstrated at much higher energies.[21]

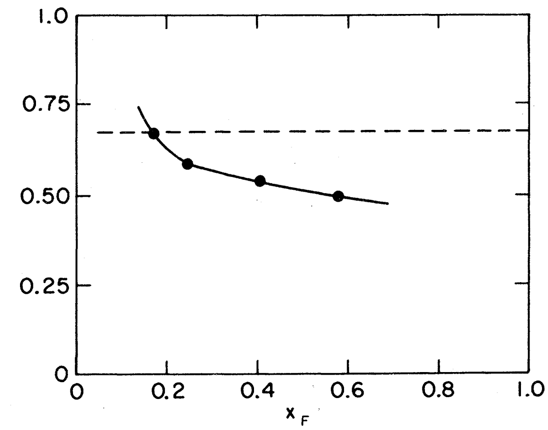

FIG. 3. Atomic-number dependence of pion production as a function of Feynman x from Ref. 20.

The labeled curve $(I_\gamma/I_\pi)_p$ in Fig. 1 then shows the values of I_γ/I_π corrected for the A dependence of the pion intensity I_π so as to represent the results for proton-proton interactions where $A=1$. An inspection of Fig. 1 then indicates that about three times as many muon pairs are produced than can be accounted for by the decays of the heavy, short-lived, mesons.

IV. MEASUREMENTS OF MUON PAIRS

A number of measurements have been made of the production of muon pairs by interactions of different particles, with different particles and at different incident-particle energies. We believe that the measurements of Anderson *et al.*[17] concerning the production of muon pairs as a function of invariant mass, Feynman variable x_F, and transverse momentum from the interaction of 150-GeV protons with nuclei (beryllium) are the most useful for our consideration. They have presented their results in a form, which we can modify slightly, and write

$$d\sigma/dx_F = A(1-x_F)^C(2\pi/b^2x_F)\,, \qquad (2)$$

where the parameters A, b, and C have different values for different ranges of invariant masses. These values are given in Table II.

Measurements made at one specific energy can be used to illustrate general phenomena only if some scaling behavior is established. We consider then the possibility that the production of such pairs follows Feynman scaling in the fragmentation region. If this is the case, the variation of the production as a function of x will be independent of the center-of-mass energy $\sqrt{s}$. In particular,

$$\frac{\partial}{\partial s}(d\sigma/dx)=0\,.$$

TABLE II. Parameters describing the production of muon pairs by 150-GeV protons incident on beryllium according to the formulas of Eqs. (2) (3).

M (GeV/c^2)	A (μb)	b	C	$d\sigma/dx$ (μb) $x=0.2$	$x=0.4$	$x=0.6$
0.21–0.45	26.7	4.63	6.03	10.12	0.893	0.516
0.45–0.65	9.0	4.58	4.34	5.12	0.734	0.0842
0.65–0.93	6.52	3.79	2.79	7.65	1.710	0.369
0.93–1.13	1.61	3.93	4.06	1.32	0.205	0.0263
Total $d\sigma/dx$(Be)				24.28	3.554	0.5315
Total $d\sigma/dx$(nucleon)				5.61	0.821	0.1227
$d\sigma/dx = 67\exp(-10.4x)$ (μb)				8.37	1.045	0.131

We have shown in Fig. 3 of the preceding article[22] the cross sections $d\sigma/dx$ calculated from Table II together with cross sections derived from a relation used to fit much less well-defined data on pairs produced by the interaction of 400 GeV protons with copper:

$$d\sigma/dx = 67\, e^{-10.4x} |\mu\text{b}|, \quad 0.2 \lesssim x \lesssim 0.7 \qquad (3)$$

and the results of measurements of the cross sections for muon pairs produced by the interaction of 28-GeV protons with tungsten. While the data, taken at face value, might seem to indicate a variation from scaling inasmuch as the cross sections are seen to decrease somewhat from 400 to 150 to 28 GeV, the uncertainties in the 400-GeV data and in the 28-GeV data are certainly of the order of 20% and then neither set of data seriously disagrees with the more precise 150-GeV results and the assumption of scaling. A comparison of measurements on single-muon production at 28 GeV with similar data at 400 GeV is completely consistent with the assumption of scaling and this kind of comparison is somewhat less subject to systematic uncertainties than the comparisons of absolute cross sections for the production of pairs.

Of course, it is possible that the cross section for the whole range of invariant masses scales, but that the distribution in invariant mass varies with s. The mean invariant mass of the pairs is shown to increase with x at 150 GeV. The values of the average mass, calculated from Eq. (2) and the values of the parameters listed in Table II, are plotted in Fig. 5 of the preceding article[22] together with the values of the mean mass measured as a function of x at 28 GeV. Again, within small factors of the order of the uncertainties in the experiments, the variation is the same. Still more striking evidence for the detailed scaling of the differential cross sections $d\sigma/dx$ and $d\sigma/dm$ is found in the comparison of the invariant-mass distribution for $x_F > 0.15$ presented at 150 GeV with the high-resolution results at 28 GeV measured for pairs produced with a mean value of $x_F \approx 0.33$. We estimate the mean value of x for the 150-GeV data as about 0.25, not very different from the mean value of x for the 28-GeV data. The similarity of the two distributions, shown by the histograms of Fig. 2 is striking evidence for the detailed scaling of the muon pair production. Altogether, there seems to be no serious deviation from Feynman scaling in the fragmentation region for muon pairs with masses less than 1.0 GeV/c^2 for proton-nucleus interactions where the incident-proton energy ranges from 28 to 400 GeV.

Since the muon pair production, measured at different energies, concerned production from targets of different nuclei, the results might have been affected by an A dependence of the production mechanism. We have assumed implicitly that the production varied as $A^{2/3}$ and then the number of pairs per interaction was independent of A (even as the total cross section varies approximately as $A^{2/3}$). Though the production of pairs with much higher invariant mass varies as $A^{1.0}$, it is known that at high energies or at 28 GeV, as discussed above, the production of pairs in the mass region below 1.0 GeV, which concerns us, the cross section varies as $A^{2/3}$ and the number of pairs produced per interaction is independent of the target material.

Knowing the invariant-mass spectrum of the low-mass pairs, we can ask if this spectrum can be explained in terms of the production and decay of heavy mesons to muon pairs. Making the same assumptions concerning meson production and decay as presented in Sec. II, we can calculate the invariant-mass spectrum as a function of x. The spectrum for all pairs produced such that x_F is greater than 0.15 is shown as the solid line of the lower graph of Fig. 2. The constraint on x_F corresponds to the cut on the experimental results given in the histogram. The contribution is normalized so that the vector mesons, the ρ and the ω, contribute 20% of the total cross section. The total cross section contributed by all meson decays is then about 40% of the total muon-pair cross section. The ratio of total muon-pair production to the pair contribution from meson decays is then about 2.5/1 in quite good agreement with the ratio of about 3/1 derived from the analysis of the signle-muon production described in the last section. The solid curve in the graph at the top of Fig. 2 shows the calculated spectrum for $x = 0.32$, corresponding to the histogram presented in that graph. Again, the production was normalized so that the contribution of the pairs from the meson decay was 40% of the total production.

V. SUMMARY AND CONCLUSIONS

We have presented analyses, which are largely independent, of the results of the measurements of the production of single muons and of the results of measurements of muon pairs which indicate that about 60% of the pair production is derived from mechanisms other than the decays of the known heavy mesons. Subtracting the calculated spectrum of muon pairs from heavy meson decays, as shown by the solid curves in Fig. 2, from the experimentally determined spectra shown by the histograms, we can gain a rough concept of the continuum spectrum and the results of this subtraction, for the 150-GeV data, are shown in Fig. 4. It is clear from the uncertainties in both the experimental results and the calculations, that the character of the continuum is not defined with any great precision. In particular, the exact shape at the kinematic boundary, where the invariant-mass m is nearly equal to the mass of two muons is affected by assumptions concerning the experimental acceptance and resolution. The exact shape near $m = 775$ MeV/c^2 is also uncertain as the shape here is quite sensitive to the exact magnitude of the subtraction for the contribution of the ρ and ω pair production. However, the general character of the distribution is probably presented correctly.

The distribution shown in Fig. 4 represents the continuum for all pairs produced such that $x > 0.15$. Since the continuum appears to be the larger part of the whole, and the larger part for all values of x (as indicated, particularly in Fig. 1), the variation of the average mass shown in Fig. 4 of the preceding article[22] and the general conclusion that the production of pairs with small invariant masses falls off with x much faster than for large invariant masses, would seem to hold for the continuum alone as well as for the total production.

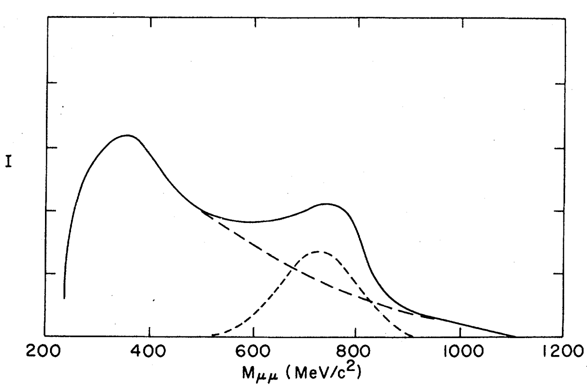

FIG. 4. The dimuon invariant-mass distribution. The spectrum of muon pairs from heavy-meson decays has been subtracted.

For the same reasons, we must conclude that the continuum, as well as the total production, scales according to the Feynman prescriptions and the A dependence of the continuum production is not likely very different than the A dependence of the total pair production and that production is known to vary as $A^{2/3}$.

We summarize the conclusions of the analysis:

(1) There is a large continuum cross section for the production of muon pairs in proton-nucleus interactions. This cross section is of the magnitude of 5×10^{-5} times the cross section for the production of neutral pions and is about 2.5 times larger than the contribution from all meson decays and 5 times greater than the contribution from the decay of vector mesons to a muon pair.

(2) The continuum production cross section varies with Feynman x_F in much the same manner as is observed for meson production. However, the production of the low-mass pairs falls off more quickly with x_F than the high-mass pairs. The mean invariant mass is near 0.5 GeV/c^2 for all pairs produced in the fragmentation region, $x_F > 0.15$.

(3) The production of continuum pairs per interaction appears to be nearly independent of the target material unlike the production of mesons which falls off with increasing A: In the fragmentation region, for $x_F \gtrsim 0.25$, the pair production varies about as $A^{2/3}$ while meson production varies about as $A^{0.53}$.

These properties of the continuum should help to define the character of the electromagnetic processes responsible for the production of the continuum. There are a number of largely separable processes which may contribute.

Drell and Yan[23] have discussed the production of the lepton pairs in hadron-hadron interactions where a valence quark in one hadron is annihilation by an antiquark in the resident sea of the second hadron. For large lepton-pair invariant masses, the production appears to be described rather accurately by considering the interaction as between the quarks of undistrubed hadrons in an impulse approximation where the disturbance of the hadrons by their whole interaction enters only in the disposition of the final-state quarks into final-state hadrons. Other processes might be expected to dominate the production of pairs with smaller invariant masses, i.e., masses $\lesssim 1$ GeV/c^2. In particular, such pairs can be expected to be produced through the internal conversion of photons generated by the acceleration of the partons in the collision (parton bremsstrahlung)[24] and by the annihilation of the quarks and antiquarks which were created in the collision (by the Bjorken-Weisberg mechanism).[25] We must also admit the possibility that there may be a contribution to the pairs from the ρ-meson decays where the ρ is in a region where the pions from the decays are scattered in final-state interaction while the muons escape.

The magnitude of the production cross sections seems to be at least an order of magnitude greater than that to be expected[23] from the simplest descriptions of the Drell-Yan mechanism. The invariant-mass distribution, particularly at large values of x, argues against the possibility that the bremsstrahlung mechanism is the dominant mechanism responsible for the bulk of the cross section. However, the general character of the production is quite similar to that suggested by Bjorken and Weisberg. We suggest that the Bjorken-Weisberg mechanism which attributes the production to the annihilation of quark-antiquark pairs, where the particles are largely *produced* in the interaction of the hadrons, is probably the dominant mechanism. It seems likely that there is an appreciable contribution of pairs from the internal conversion of photons from parton bremsstrahlung. We could then expect to see some flux of single photons of the order of 1% of the neutral pion flux.

There may also be a well-defined contribution from the decay of a portion of the ρ production. While the ρ is characteristically traveling at a very high velocity (or momentum) with respect to the center-of-mass of the interaction, the particle is not necessarily traveling with so large a momentum with respect to the center of mass of the several particles produced in the fragmentation region—the center of mass of that which we might call the fireball or nova descended from the hadron initially moving in the direction of the final-state muon pair. The ρ momentum in this reference frame might reasonably be set as about equal to the mean transverse momentum of the ρ-meson or about 500 MeV/c. From this view, a part of the ρ production of the order of 140/500 will decay within a pion Compton wavelength of the center of a region of space dense with particles. Pions from the ρ decays will likely interact with the hadronic matter in the region, muons will not. We might then expect some production of muons which will not be balanced by an accompanying production of pion pairs which can be recognized as production from the decay of ρ mesons. The muon contribution from the strong-interaction region will probably be centered at the ρ mass (though some line shifts could occur) and we would expect the line width to be broadened even as that part of the production takes place during a very short interval. The dashed lines of Fig. 4 separate the continuum into two parts, one part ostensibly derived from these line-broadened ρ decays, and the other part from other mechanisms such as the Bjorken-Weisberg process. We emphasize, however, the uncertainties in the shape of this continuum and the suggestion in that shape that there is a real ρ-type contribution is certainly not demanded by the treatment of the data we have advanced.

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