PUB-76-136-E
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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 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 interaction of 400 GeV protons.

In the absence of an ideal four-pi detector, constructed to identify muons of all energies, we proceeded to design a measurement such that the ratio of measured di-muon intensities to single inclusive intensities in a more limited kinematic region would depend on the proportion of di-muon parentage of the prompt muons in a manner which was insensitive to the largely unknown production and decay characteristics of the di-muons. In general, the production of di-muons 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 distributions 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, 14 2'X3' counters were arranged in a linear array in the "center" pit of the FNAL proton central beam area extending to an angle of 35 mr on either side of the proton beam line. These counters lie 400' from the target and only muons with an initial energy of 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 14 9"X 18" counters 200' 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 $^{o}/_{o}$ at 100 GeV, and to 96 $^{o}/_{o}$ 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 mr acceptance of the array.

While we do not present here the whole results of the (14X13)/2=91 coincidence rates from which we derive the di-muon results, Fig. 2 shows the intensity as a function of angular separation for equal angle pairs suggesting the effective invariant mass resolution and distribution. While the resolution is limited by the large multiple scattering in the target array and from the poor effective energy resolution of the system, it is clear that most of the intensity is derived from pairs with an invariant mass of the order of 900 ± 200 MeV/c^2. A separate measurement, made with magnetic analysis, showed that the 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 di-muon 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 $\mu/10^8$ incident protons) from the measured flux (of 364 $\mu/10^8$p) 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 $\underline{\theta}$ 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 $I(\underline{\theta}_1, \underline{\theta}_2)$. If the di-muon intensity would depend only upon the invariant mass and transverse momentum of the pair, it will be a good approximation to write I as $G(|\underline{\theta}_1 + \underline{\theta}_2|, |\underline{\theta}_1 - \underline{\theta}_2|)$ even as $|\underline{\theta}_1 + \underline{\theta}_2|$ and $|\underline{\theta}_1 - \underline{\theta}_2|$ 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, $\int I \, d\underline{\theta}_1 \, d\underline{\theta}_2$, gives the di-muon intensity at the plane (as 53.5 μ pairs $/10^8$ p) from the measured intensity (of 4.74 μ pairs $/10^8$p). 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 θ 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 $I(\underline{\theta}_1, \underline{\theta}_2)$ 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 di-muon parent defines the sum of the momenta of the two muons, $p_\mu(+) + p_\mu(-) = p_L$. Noting that $E_{lab} \gg M$ and $E_{lab} \gg p_t$, 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 $y = (p_\mu(\pm) - p_{min})/(p_{max} - p_{min})$, where p_{min} is the minimum momentum kinematically accessible and p_{max} is the maximum momenta, is such that $dN/dy = 2\, dN/d\cos\alpha$. Since $p_{min} = \gamma(M/2 - (M^2/4 - M\mu^2)^{1/2}) \to 0$ for $M \gg M_\mu$ and $p_{max} = p_L - p_{min} \to p_L$ 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 di-muon decay angular distribution if the distribution of the di-muon 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 di-muon fit, use as a parameterization for the cross sections for mesons produced by the interaction of protons by 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 π gamma rays[5] and for mesons produced in secondary interactions were made in a straightforward way. The di-muon cross section defined by the curves was described similarly as $d\sigma/dx = 67 \exp(-10.4x)\ \mu b$ for di-muons decaying isotropically in their center-of-mass system.

With this parameterization of the di-muon 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/10^8p 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 $^o/_o$ fewer single muons than predicted by the measured di-muon flux assuming an isotropic di-muon decay. If the di-muon 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 one for muon pairs, a substantial flux of single muon production would be allowed though we believe that the ratio of single to dimuon production $\geq$ 4, expected 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 $\approx$ 900 Mev/c. 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 brehmsstrahlung 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 istropic dimuon decay is not unlikely.

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 ranges from $0.125 < x < 0.70$ 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 di-muon to π^o ratio is then about $1.12 \cdot 10^{-4}$. If the ρ_o production and ω_o production were equal and equal to 10 $^o/_o$ of the π^o cross section, we would deduce a di-muon cross section from ρ and ω decays of about 0.185 μb; about one order of magnitude smaller than that observed.

(1) F.W. Busser et al., Physics Letters 53B, 212 (1974); J.P. Boymond et al., Phys. Rev. Letters 33, 112 (1974); J.A. Appel et al., Phys. Rev. Letters 33, 722 (1974)

(2) L.M. Lederman and S. White, Phys. Rev. Letters 35, 1543 (1975)

(3) L.B. Leipuner et al., Phys. Rev. Letters 35, 1613 (1975)

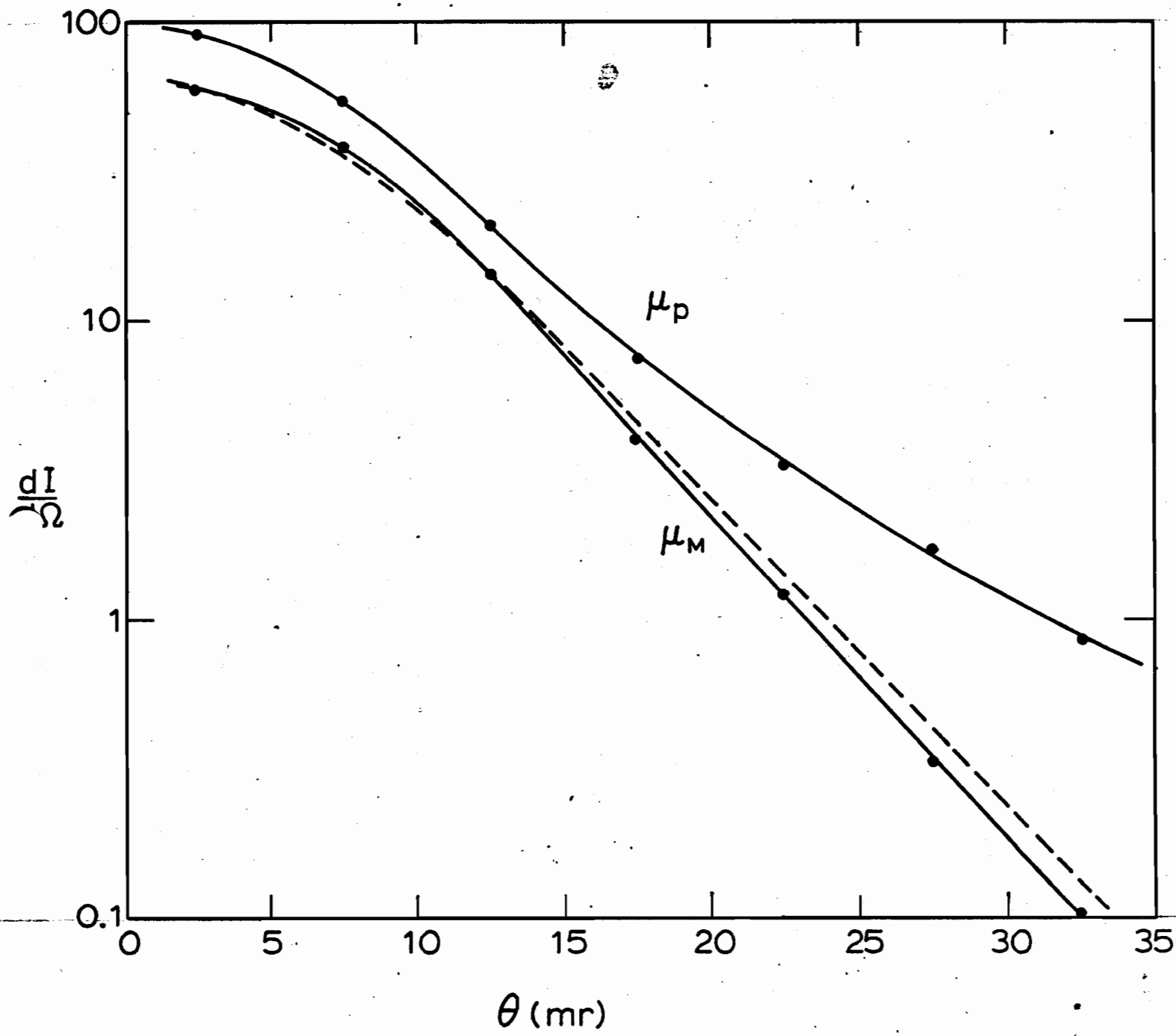
(4) T. Eichten et al., Nucl. Phys. B44, 333 (1972)

(5) Y-S. Tsai, Rev. Mod. Phys. 46, 815 (1974)

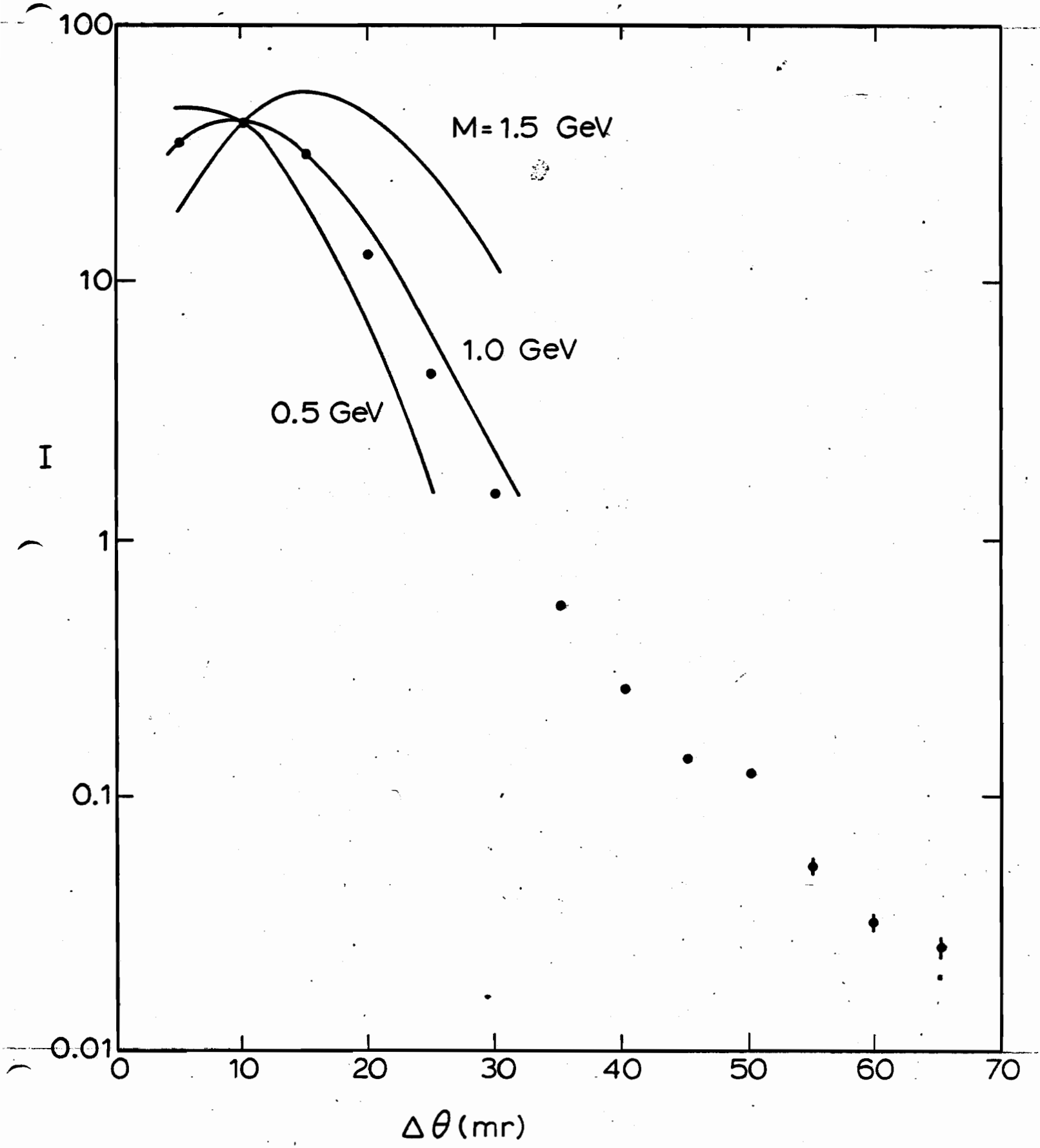
Fig. 1 Angular distributions of prompt muons (μ_p) and muons from meson decay (μ_M). The intensity is defined in arbitrary units. The dashed line shows the intensity calculated from the meson production data[4] normalized to the measured value at 2.5 mr.

Fig. 2 The distribution of intensity vs. 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.

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 x represent measurements made over a broad spectrum of energies where an average energy is plotted. The solid curves represent a fit defining the di-muon spectrum presented in the text.



Kasha Fig 1



Kasha Fig 2

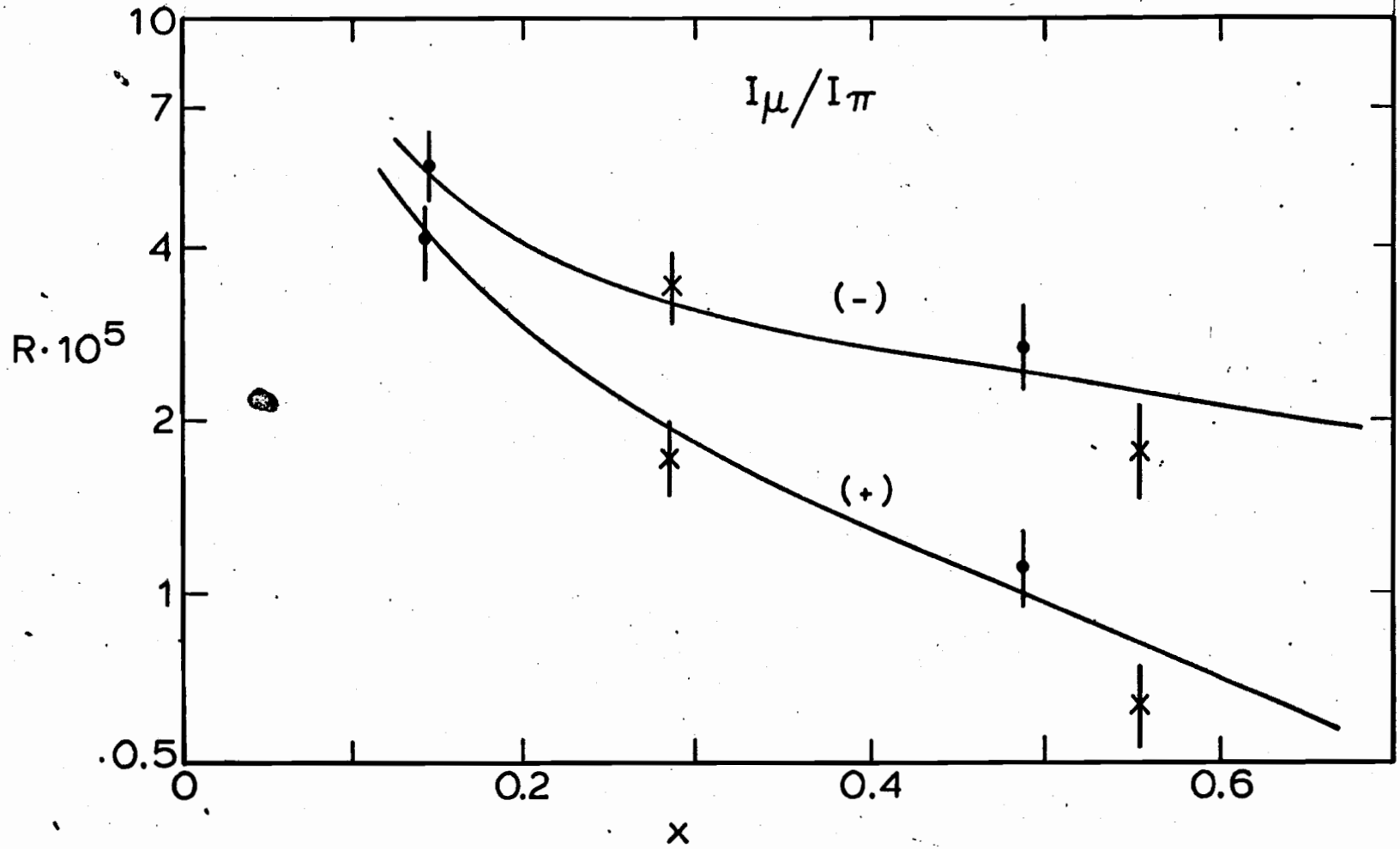


Fig 3