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Heavy Lepton Cascade Interpretation of the Neutrino Induced Trimuon Events*

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ABSTRACT

The experimental data on neutrino induced trimuon production are compared with the results of a cascade model involving two heavy leptons. The agreement between theory and experiment is excellent.

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The Fermilab-Harvard-Pennsylvania-Rutgers-Wisconsin (FHPRW) group has observed six $\mu^-\mu^-\mu^+$ events produced in neutrino interactions[1]. Two events of this type were seen previously in the Caltech-Fermilab (CALTF) experiment[2]. The FHPRW group has made a careful analysis of these trimuon events[3] and compared them with their previous dimuon events[4]. Almost all $\mu^-\mu^+$ events are compatible with the hypothesis that the prompt μ^- is produced at the neutrino vertex while the μ^+ is a decay product[5] of new charmed hadrons[6]. However an explanation of the $\mu^-\mu^-\mu^+$ events based on charmed particle semileptonic decays[3] gives unsatisfactory fits to the data. After discussing several alternative possibilities, the FHPRW group suggests that the $\mu^-\mu^-\mu^+$ events, together with the $\mu^-\mu^-$ events, and some of the $\mu^+\mu^-$ events, arise from a new phenomenon, namely a heavy lepton cascade decay. In particular, they propose the existence of at least two heavy leptons, called M and L with masses 7^{+3}_{-1} GeV/c^2 and $3{\cdot}5^{+1.5}_{-0.4}$ GeV/c^2 respectively. The trimuons then arise from the decay chain $\nu_\mu + N \rightarrow M + X$, $M \rightarrow \mu + L$ + (neutrino) and finally $L \rightarrow \mu + \mu$ +(neutrino). The precise relationship of M and L to the heavy lepton observed by Perl et al.[7] is unclear. There is no evidence that a charged lepton with mass around 2 GeV/c^2 is produced in neutrino interactions[8].

In this letter we take up the suggestion that the trimuon events can be explained by a heavy lepton cascade hypothesis. We construct a simple model and compare the theoretical predictions for various distributions with the data published in Refs. 1 and 3. We assume the existence of two heavy leptons M^- and L° which have charged current V – A couplings to the known leptons. The production of the M in the reaction $\nu_\mu + N \rightarrow M^- + X$ has been considered previously by several authors[9], who have given cross sections based on the structure functions of the quark parton model. The heavy M^- has decay modes $M^- \to L^0 + \bar{\nu}_\mu + \mu^-$, $L^0 + \bar{\nu}_e + e^-$, $L^0 + X$, $\nu + X$. Then the L^0 can decay via the modes $L^0 \to \mu^- + \nu_\mu + \mu^+$, $\mu^- + \nu_e + e^+$ and $\mu^- + X$. Such decays lead to events with one, two or three muons. We concentrate here on a phenomenological analysis of the $\mu^-\mu^-\mu^+$ final state where one prompt μ^- is produced in the $M^- \to L^0$ transition and the other pair come from the L^0 decay. We note here that this type of model has two obvious consequences. First, because all three muons are produced from the cascade decay of the M^-, where the production and decay are relatively independent (up to small spin-spin corrections), the trimuon and dimuon invariant masses should not show any dependence on the energy of the neutrino beam. Second, all decays involve at least three particles so no invariant mass should peak at a unique value. Also the absence of the neutral current decay $M^- \to \mu^- + \mu^+ + \mu^-$ implies the absence of a peak in the trimuon invariant mass. We assume the $L^0 \to \mu^- + \nu_\mu + \mu^+$ coupling to be small because the L^0 is already ruled out as the main source of the opposite sign dimuon events.[10] We first give a short discussion of our calculation and a presentation of the results. We finish by giving some comments about lepton assignments in gauge-field theory type models, mixing angles at the vertices and branching ratios into different channels. A more detailed paper, which will include a discussion of semileptonic decays involving hadrons and dimuon final states will follow later.

The calculation can be split into two parts, namely the production and the decay. We know that the M^- polarization is important in certain kinematical regions[9], so we calculate the square of the complete matrix element for the reaction $\nu_\mu + N \to M^- + X$ followed by the decay $M^- \to L^0 + \bar{\nu}_\mu + \mu^-$ keeping all spin effects, all terms in the M^- and L^0 masses, and taking the coupling constant at the production vertex to be εG_F, with $\varepsilon=1$. Then, because the L^o polarization will be very small, we complete the decay chain by adding the square of the matrix element for the unpolarized L^o decay $L^o \to \mu^- + \nu_\mu + \mu^+$. The narrow width approximation is used for both the M^- and the L^o particles. Hence our final results need to be multiplied by three factors, ε^2 the square of the suppression factor (mixing angle) at the production vertex, the branching ratio B_1 for the decay $M^- \to L^o + \bar{\nu}_\mu + \mu^-$ and the branching ratio B_2 for the decay $L^o \to \mu^- + \nu_\mu + \mu^+$. We assume the mass of the M^- to be 8 GeV/c^2, and the mass of the L^o to be 4 GeV/c^2.

The total rate is found by folding the production cross section with the normalized neutrino flux for quadrupole triplet focussing and gives the answer 5×10^{-38} cm^2. Actually only the portion of the neutrino spectrum above 80 GeV is effective due to the heavy mass of the M^-. It is remarkable that the effect of the falling spectrum is almost exactly balanced by the rising production cross section over a wide range of neutrino energies. The maximum in the flux times cross section plot is obtained with E =175 GeV and has only decreased by a factor of 8 at E =300 GeV. To get a feeling for this number 5×10^{-38} cm^2, the corresponding number for regular neutrino interactions making single μ^- events is 60×10^{-38} cm^2, for $E_\nu > 50$ GeV. Hence the production of the M particle, if taken at full strength is $\sim 1/12$ of the μ^- cross section in the energy region $E_\nu > 50$ GeV. Folding in the neutrino spectrum does not change the differential distributions in any significant way so we give our results for a fixed beam energy E_ν = 200 GeV. This means that event No. 119, which has a total visible energy of 249 GeV, and is included in our plots, should be given a relatively low weight. We have checked our hadron energy distributions to see that such an event is possible when we take the neutrino spectrum into account. However its probability is exceedingly small.

The primary source of ambiguity in comparing our results with the data is the μ^- identification problem. In order to carefully distinguish between the theoretical results, where we know which vertex the muons come from, and the experimental results, where the like sign muons are indistinguishable, we call the prompt muon at the first decay μ_A^-, and those at the second decay μ_B^-, μ_3^+. In our Monte Carlo calculation of the twelve-dimensional integral for $\sigma \times B_1 \times B_2$ we can simulate the experimental situation by ordering the momentum of the muons according to which μ^- particle has the larger energy. Then we call μ_1 the fast μ^-, μ_2 the slow μ^-, and μ^+ remains μ_3 to conform with the notation in Ref.1.

In Fig.1(a) we give the theoretical opening angle distribution $\sigma^{-1} d\sigma/d\theta$ for $\theta_{AB} = \theta_{12}$ (which is almost identical to the distributions in θ_{B3} and θ_{A3}), and the distributions in θ_{13} and θ_{23}. The angles are given in radians and we also show the experimental values for θ_{12}, θ_{13} and θ_{23} as boxes. The experimental errors are not shown, but they are given in Ref.1. Two dimensional scatter plots in the opening angles θ_{AB} versus θ_{A3}, θ_{A3} versus θ_{B3} and θ_{13} versus θ_{23} are shown in Fig.1(b),1(c), and 1(d) respectively.The first two plots are almost symmetrical about the diagonal. The last diagram shows that the angle between the fast μ^- and the μ^+ is smaller on the average than the angle between the slow μ^- and the μ^+. This effect is clearly present in the data which are marked on Fig.1(d). The opening angles are very small reflecting the jet-like structure of the leptonic cascade.

The trimuon invariant mass spectrum in $M_{AB3} \equiv M_{123}$ is shown in Fig. 2(a), and the experimental values are also shown as boxes (without error estimates). Pairing the possible dimuon combinations leads to spectra in $M_{AB} \equiv M_{12}$ (Fig.2(b)), M_{A3} and M_{B3} ,(Fig.2(c)) and M_{13} and

M_{23} (Fig.2(d)). The experimental values for M_{12} ,M_{13} and M_{23} are also given (again without error estimates). Obviously there is good agreement between the predictions of the theory and the experimental results. The M_{123} ,M_{B3} spectra peak around one-half the value of the M^- L^o masses respectively. Theoretically, the average value of M_{13} is slightly larger than the average value of M_{23}. This effect is difficult to see in the data because the errors are so large.

We now discuss several angles between the muon momentum vectors projected on a plane perpendicular to the beam direction. If we form the resultant of the vectors for μ_B^- and μ_3^+, then we define $\Delta\varphi$ to be the angle between that vector and the direction of μ_A^-. The spectrum in $\Delta\varphi$ is shown in Fig.3(a) as curve I. Curve II shows the spectrum in the same opening angle with the exchange of μ_A^- and μ_B^-. If we average these two distributions then we fake the experimental situation. Hence we show the data as boxes for both choices of $\Delta\varphi$. In Fig.3(b) we show a scatter plot of $\Delta\varphi$ versus E_3 . The plot should be compared with Fig. 2(a) in Ref.3 to show the difference between the lepton cascade decay model and the charm decay model. We do not show plots for $\Delta\varphi$ versus E_A or E_B as they are almost identical to Fig.3(b).

We now define another angle φ_{12} as the angle between the projections of the two μ^- vectors. We present a scatter plot of this angle versus E_2 in Fig.3(c). This plot should be compared with Fig.2(b) in Ref.3. The reason for giving these distributions is to try to distinguish between a lepton jet model and a hadron jet model. Another angle which is useful in this regard to this question is φ_{13} the angle between the projections of the fast μ^- and the μ^+. A scatter plot of this angle versus E_3 is shown in Fig.3(d). All these plots show that there is no appreciable peaking in $\Delta\varphi$, φ_{12} or φ_{13}. The reason is that hadrons and undetected neutrinos are taking away some of the momentum transfer and these vectors balance each other. The peaking near $\Delta\varphi = 180^\circ$ in the charmed hadron decay model reflects the balance in the transverse momenta between the prompt μ^- and the hadron jet.[3]

We conclude that there is no problem interpreting the six $\mu^-\mu^-\mu^+$ events as the decay products of heavy leptons. The total event rate can therefore be used to discuss the branching ratios B_1 and B_2 as well as the mixing angle at the production vertex. One problem here is that many of the muons in the lepton cascade decay model are slow and therefore escape detection or are classified as single muon or dimuon events. In fact, if we impose momentum cuts of 5 GeV/c for all three muons the theoretical value of $\sigma \times B_1 \times B_2$ goes down by 30%. Hence any experimental numbers we quote in this paragraph should not be taken too seriously. Our attitude is to take reasonable values for B_1 and B_2 and check the s rength of the production vertex.Previous estimates[11] of leptonic branching ratios for particles with mass 4 GeV/c^2 range between 10% and 20%. The branching ratio for $\Gamma(M^- \to L^0 + \bar{\nu}_\mu + \mu^-)/\Gamma(M^- \to \text{all})$ is probably not as large. If we assume $B_1 = B_2 = 10\%$, then $\sigma \times B_1 \times B_2 \sim 5 \times 10^{-40}$ cm^2,which should be compared with the $\mu^-\mu^-\mu^+$ production cross section estimates of $\sim 5 \times 10^{-4}$ of the regular μ^- production, ie.,3×10^{-40} cm^2. Thus it looks as if the M^- must be produced with the maximum strength (no mixing angle).

REFERENCES

1 A.Benvenuti, et al. FHPRW 77/1 (submitted to Phys.Rev.Letts).

2 B.C.Barish, et al. Phys.Rev.Letts. 38 , 577 (1977).

3 A.Benvenuti, et al. (submitted to Phys.Rev.Letts.).

4 A.Benvenuti, et al. Phys.Rev.Letts. 35 1199,1203,1249 (1975).

See also B.C.Barish, et al. Phys.Rev.Letts. 36 939 (1976).

5 L.M.Sehgal and P.M.Zerwas, Nucl.Phys. B108,483 (1976).

V.Barger,R.J.N.Philips and T.Weiler, Phys.Letts. 62B 227 (1976).

6 S.L.Glashow, J.Iliopoulos and L.Maiani, Phys.Rev. D2 1285 (1970).

7 M.Perl, et al. Phys.Rev.Letts. 35 1489 (1975) , Phys.Letts. 63B 466 (1976).

8 C.H.Albright, Phys.Rev. D13 2508 (1976).

9 A.Soni, Phys.Rev. D9 2092 (1975) , D11 624 (1975).

C.H.Albright and C.Jarlskog, Nucl.Phys. B84 467 (1975).

C.H.Albright, C.Jarlskog and L.Wolfenstein, Nucl.Phys. B84 493 (1975).

10 L-N.Chang,E.Derman and J.N.Ng Phys.Rev.Letts. 35 6 (1975),

Phys.Rev. D12 3539 (1975).

C.H.Albright Phys.Rev. D12 1319 (1975).

A.Pais and S.B.Treiman, Phys.Rev.Letts. 35 1206 (1975).

11 Y-S.Tsai, Phys.Rev. D4 2821 (1971) , D13 771 (E) (1976).

J.D.Bjorken and C.H.Llewellyn Smith, Phys.Rev. D7 887 (1973).

C.H.Albright, C.Jarlskog and M.O.Tjia, Nucl.Phys. B86 535 (1975).

FIGURE CAPTIONS

Fig.1 (a). The trimuon spectra in the opening angles (in radians). The boxes show the distribution of the experimental values according to the different choices for the angles.

(b),(c),(d). Scatter plots of the opening angles (in radians). The first two plots show the theoretical distributions. Our Monte Carlo results, which can be compared with the data points (circles), are shown in Fig.1 (d).

Fig.2 (a). The trimuon invariant mass spectrum. We give the experimental values as boxes. For more see Ref. 1.

(b),(c),(d). Spectra in the invariant masses of the muon pairs. The effect of ordering the momenta is to convert Fig.2(c) into Fig.2(d).

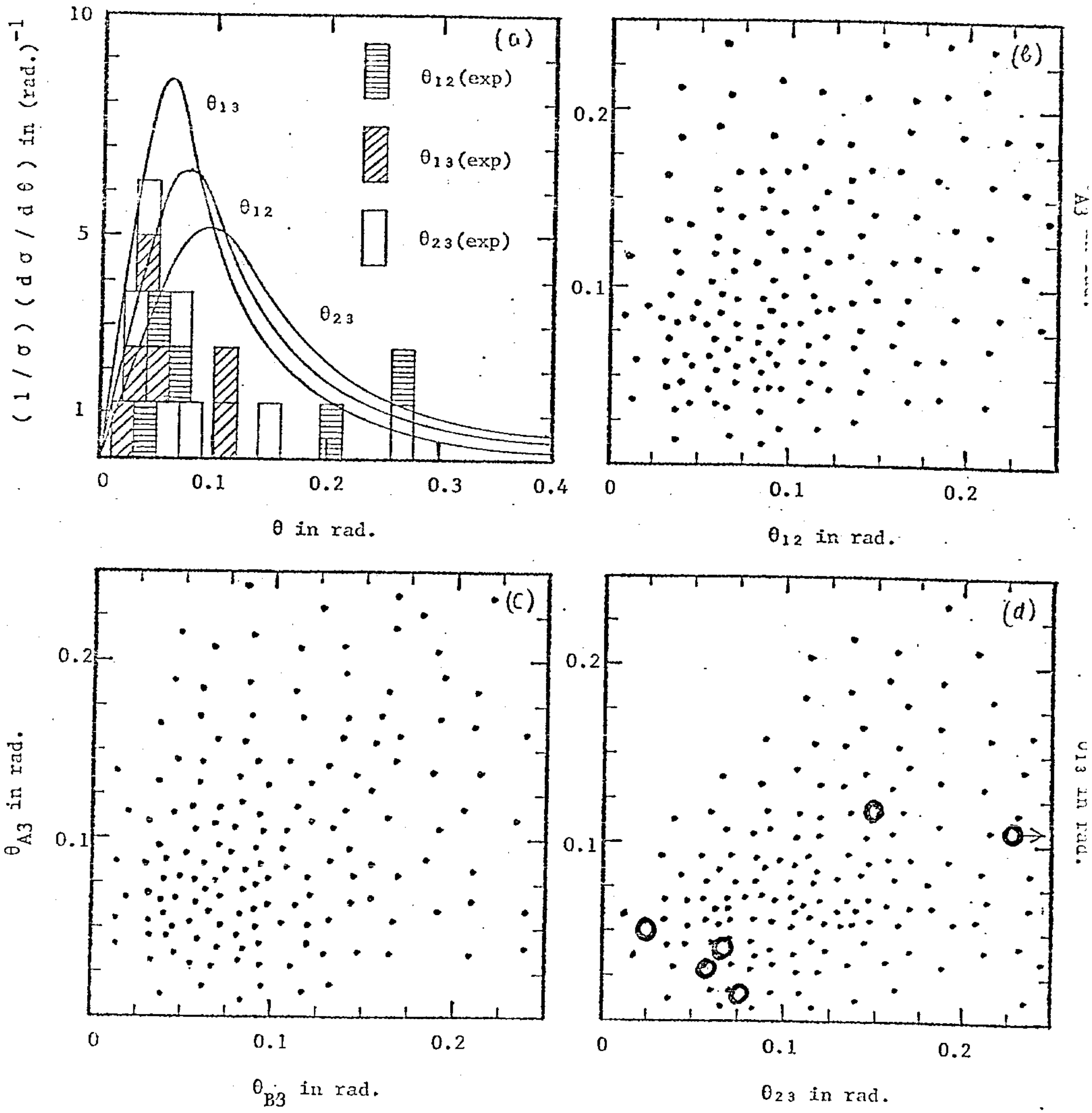
Fig.3 (a). The differential cross section in the angle $\Delta\varphi$ .Curves I and II refer to the ambiguity in choosing the μ^- momentum.

(b). Scatter plot of $\Delta\varphi$ versus E_3 the energy of the μ^+.

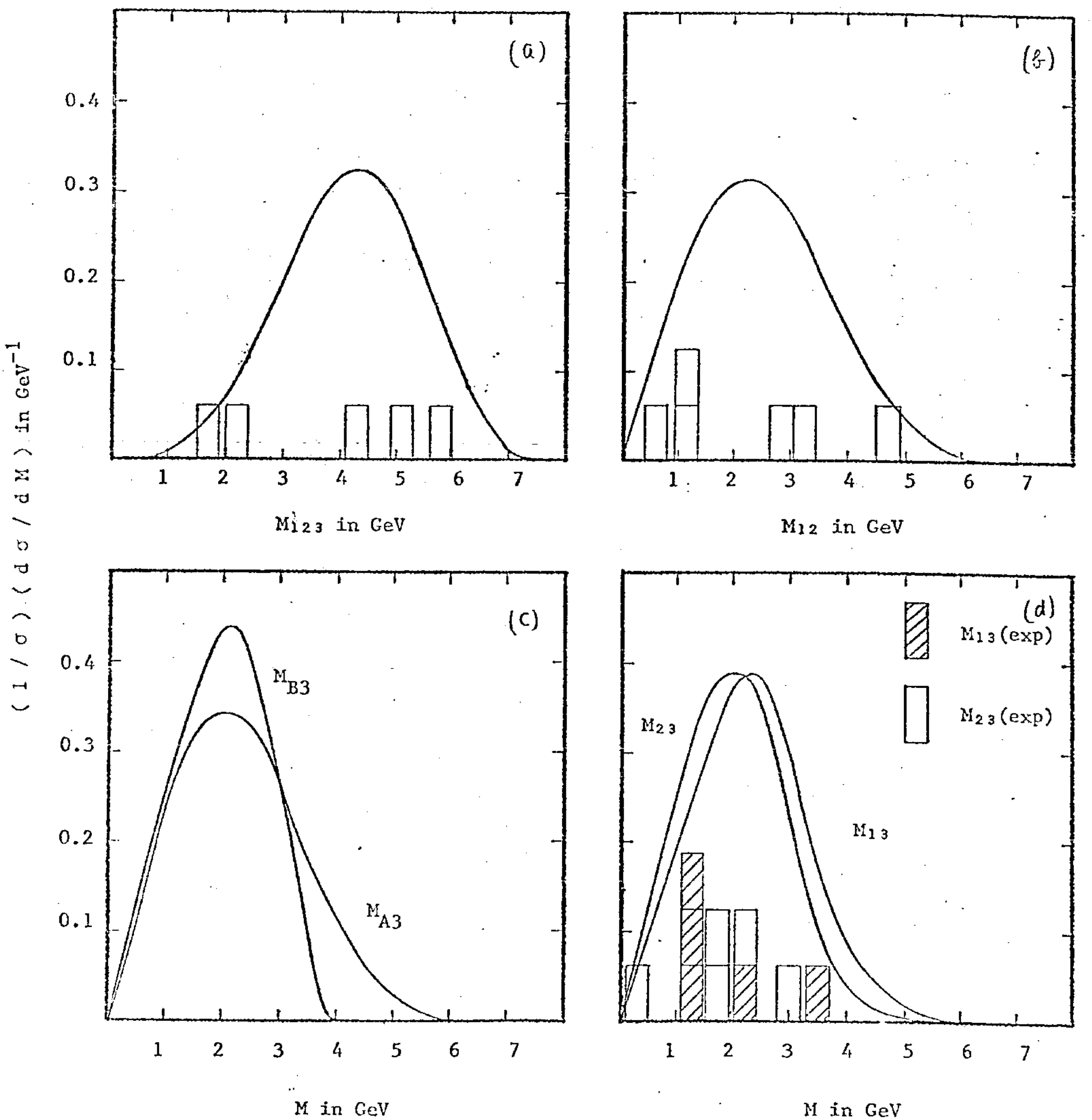
(c). Scatter plot of φ_{12} versus E_2 the energy of the slow μ^-.

(d). Scatter plot of φ_{13} versus E_3 the energy of the μ^+.

Fig 1

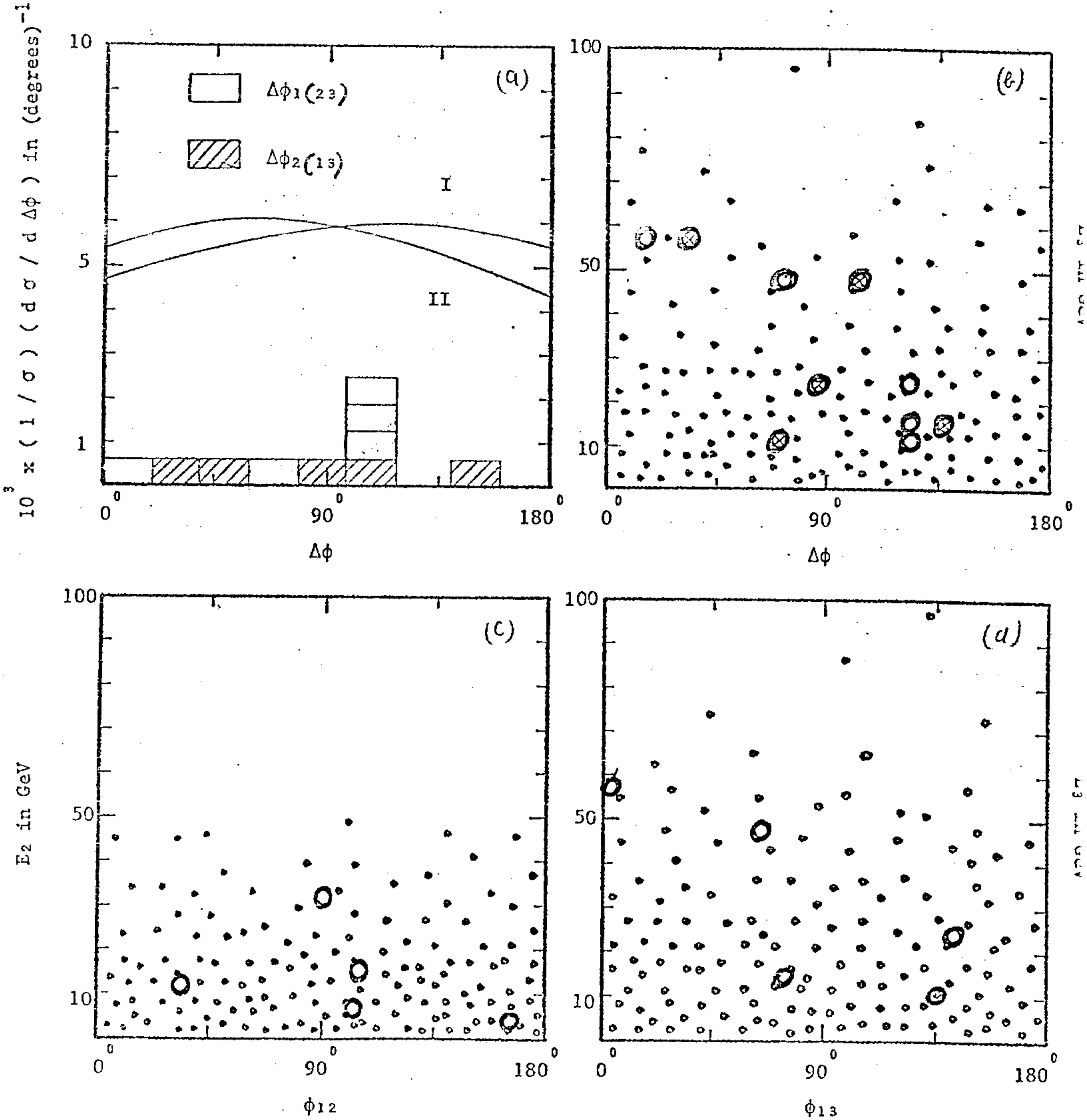


(a)
θ_{12}(exp)
θ_{13}(exp)
θ_{23}(exp)
θ_{13}
θ_{12}
θ_{23}
(1/σ)(dσ/dθ) in (rad.)$^{-1}$
θ in rad.
(b)
θ_{12} in rad.
(c)
θ_{A3} in rad.
θ_{B3} in rad.
(d)
θ_{23} in rad.
θ_{13} in rad.



(1 / σ) (dσ / dM) in GeV^{-1}
(a)
0.4
0.3
0.2
0.1
1 2 3 4 5 6 7
M123 in GeV
(b)
1 2 3 4 5 6 7
M12 in GeV
(c)
0.4
0.3
0.2
0.1
M_{B3}
M_{A3}
1 2 3 4 5 6 7
M in GeV
(d)
M13(exp)
M23(exp)
M23
M13
1 2 3 4 5 6 7
M in GeV

Fig 3



10³ x (1 / σ) (d σ / d Δφ) in (degrees)⁻¹
(a)
Δφ1(23)
Δφ2(13)
I
II
10
5
1
0
90
180
Δφ
(b)
100
50
10
(c)
E2 in GeV
φ12
(d)
φ13