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Search for narrow $\mu^{\mp}\pi^{\pm}$ mass enhancements in a neutrino bubble-chamber experiment

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In a Fermilab 15-foot bubble-chamber experiment, $\mu^{\mp}\pi^{\pm}$ mass spectra were studied in 8444 neutrino interactions and 1367 antineutrino interactions. No significant narrow mass enhancements were found. A peak near 430 MeV/c^2 was observed, but when resolution is taken into account its significance is only $\approx 1\sigma$ and its angular distributions do not show the characteristics expected for a resonance.

In a recent paper, Ramm[1] has reported evidence for an enhancement near 430 MeV/c^2 in $\mu^{\mp}\pi^{\pm}$ mass spectra in charged-current neutrino and antineutrino interactions. The interactions were observed in two heavy-liquid bubble-chamber experiments at the Proton Synchrotron at CERN. The liquids used were propane and freon, and the maximum neutrino energy was 10 GeV. In 263 events with just one neutral $\mu\pi$ mass combination per event in the first experiment, and $\approx$4000 events with one to three combinations in the second experiment, net signals of about 11 and 20 mass combinations, respectively, were observed near 430 MeV/c^2. The present paper reports on a search for a similar enhancement, or any other $\mu^{\mp}\pi^{\pm}$ enhancements, in a neutrino heavy-liquid bubble-chamber experiment at Fermilab with neutrino energies in the range 10—320 GeV, and antineutrino energies 10—240 GeV.

Any enhancement found could be due to the decay of a short-lived massive neutral lepton. One model in which such leptons occur has recently been studied by Leung and Rosner.[2,3] References to other theoretical discussions of massive neutral leptons, and to searches for such leptons, are given in Ref. 2.

Details of the experiment (E546) have been reported previously.[4] The Fermilab 15-foot bubble chamber filled with a neon-hydrogen mixture (47% atomic neon) was exposed to a quadrupole triplet neutrino beam produced by 400-GeV protons. A two-plane external muon identifier

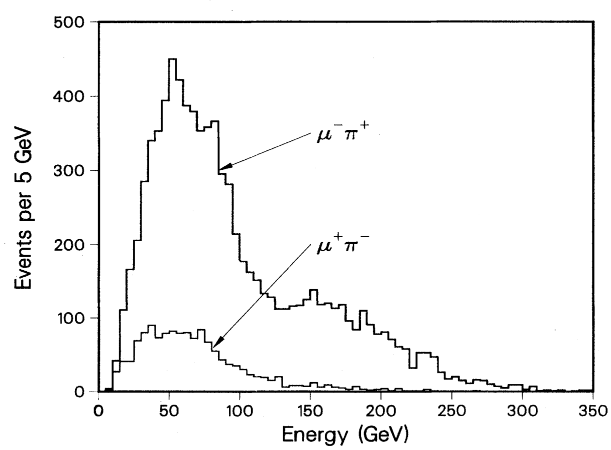

FIG. 1. Distributions of estimated event energy for ν and $\bar{\nu}$ events.

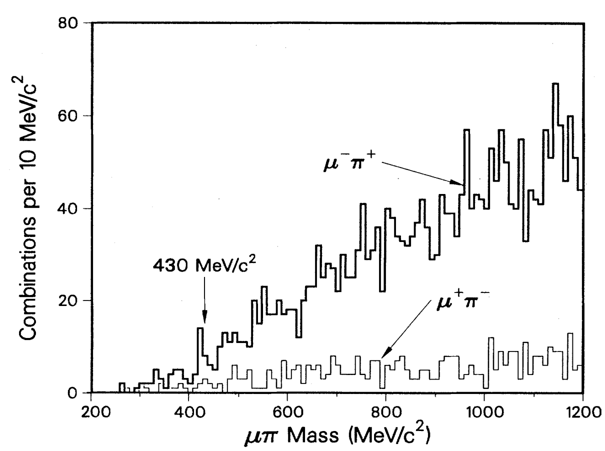

FIG. 2. Invariant-mass spectra for $\mu^-\pi^+$ and $\mu^+\pi^-$ in 10-MeV bins.

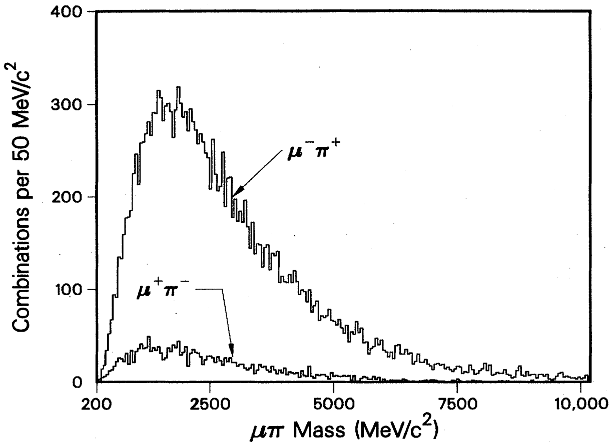

FIG. 3. As Fig. 2, but in 50-MeV bins.

(EMI) was used for muon identification.

For the present study, samples of 8444 fully measured neutrino events and 1367 antineutrino events were used. Each event had a $\mu^{\mp}$ identified by the EMI with an EMI-match confidence level >0.001 and with momentum greater than 4 GeV/c. The contamination of the $\mu^{\mp}$ by like-signed hadrons was estimated to be 0.26% for μ^- and 2.3% for μ^+. Figure 1 shows the estimated-incident-energy distributions of the events; the mean energy was 97 GeV for μ^- events and 68 GeV for μ^+ events.

The $\mu^{\mp}\pi^{\pm}$ invariant-mass distributions are shown in Fig. 2 (10 MeV/c^2 bins, mass <1000 MeV/c^2) and in Fig. 3 (50 MeV/c^2 bins). (There are 121 $\mu^-\pi^+$ and 32 $\mu^+\pi^-$ mass combinations below the K^0 mass.) For these figures a $\pi^{\pm}$ was taken to be any primary track that was not positively identified as a proton, positron or electron. (In less than 1% of the charged-current events is there a second primary muon.[4] Our $\mu\mu$ mass spectra are shown in Ref. 4.) Protons were identified only if they stopped in the bubble chamber without interacting, so that most protons above 500 MeV/c and many below 500 MeV/c are mislabeled pions, as are all charged kaons. Also, for the figures, both muon and pion were required to have fractional momentum errors of less than 10%, in order to remove mass combinations with large errors. The fraction of mass combinations that fail this momentum error cut increases approximately linearly with mass from 0.20 at 400 MeV/c^2 to 0.50 at 6000 MeV/c^2.

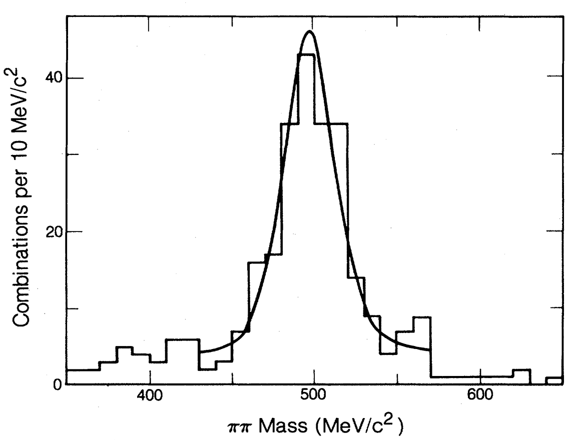

FIG. 4. Histogram of $\pi^+\pi^-$ invariant-mass spectra for vees where each track has $\delta p/p<10\%$ and one or both tracks have $p>4$ GeV/c. The curve is a calculated resolution function plus a flat background. This plot confirms the correctness of our mass scale and calculated mass errors.

Before detailed conclusions could be drawn from the $\mu\pi$ mass distributions, the mass scale and calculated mass resolution had to be checked.

Vees were used to check the mass scale. Here a vee is a pair of oppositely charged tracks that appear at a point in the bubble chamber; most vees are produced by neutral particle (K_S^0,Λ^0) decays. To be included in the following, both tracks of a vee were required to have fractional momentum errors of less than 10%. A plot (Fig. 4) of the $\pi^+\pi^-$ mass of all such vees shows a strong peak near the K_S^0 mass (497.7 MeV/c^2), and indicates that the absolute mass scale, at least for $\approx$500-MeV/c^2 $\pi^+\pi^-$ pairs, cannot be wrong by >3 MeV/c^2. The preceding statement holds in particular for the subset of vees with one or both pion momenta >4 GeV/c (a relevant subset since accepted muons all have momenta >4 GeV/c).

The geometrical-reconstruction program assigned errors to individual track quantities, so that invariant-mass errors could be calculated. Vees (with a 10% momentum error cut) were used again to check these errors. A plot (not shown) was made of the confidence level (C.L.) for the hypothesis that each vee was a K_S^0 decay. The result was a flat distribution for C.L. >0.10, both for all vees and for the subset with one or both pion momenta >4 GeV/c. (Below C.L. of 0.10, a peak occurs, as expected from Λ^0 decays and from two-prong neutral-particle interactions.) Figure 4 shows our calculated resolution function superposed on the $\pi^+\pi^-$ mass spectrum for vees. The agreement is quite good. Therefore, at least for $\approx$500 Mev/c^2 $\pi^+\pi^-$ pairs, the errors cannot be wrong by $>15\%$.

In addition to the vee checks, the extrapolation of muon tracks measured in the bubble chamber to hits in the EMI indicated that muon track quantities and their errors are estimated correctly.

The mean of the calculated error dm in the $\mu\pi$ mass at a given mass m followed quite closely the relation (units are MeV/c^2):

$$\langle dm\rangle = 0.029m + 3.5 \tag{1}$$

with a standard deviation in dm at a given m of approximately $\langle dm\rangle/3$ (with the 10% momentum error cut). Therefore, the full width at half maximum (FWHM) of a narrow enhancement in the $\mu\pi$ mass is expected to be approximately 38 MeV/c^2 at a mass of 430 MeV/c^2; 76 MeV/c^2 at 1000 MeV/c^2, 145 MeV/c^2 at 2000 MeV/c^2, and so on.

Qualitatively, Figs. 2 and 3 show no strong enhancements. To make a quantitative statement, and to get upper limits, the following procedure was used. For any $\mu\pi$ mass m, the data were rebinned with a bin width approximately equal to the expected FWHM of a narrow enhancement, with bin I centered at m. Then bins I$\pm$1,

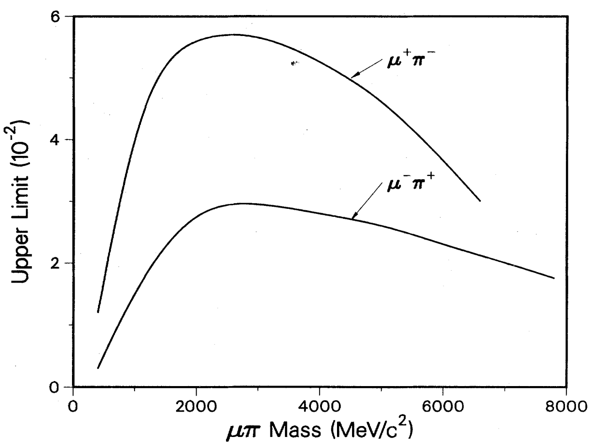

FIG. 5. Upper limits (u's) for narrow $\mu^-\pi^+$ and $\mu^+\pi^-$ mass enhancements as a function of $\mu^-\pi^+$ and $\mu^+\pi^-$ invariant mass. If a resonance at a given mass (with width less than or equal to our mass resolution at that mass) were present in a fraction u of the events, then we would have seen a 3-standard-deviation peak above neighboring bins.

I$\pm$2 were used to predict N_i, the expected number of combinations in bin I, assuming a third-order polynomial in m for dN/dm. In no case did the observed contents of bin I exceed N_i by more than 3 standard deviations (1 standard deviation $\approx\sqrt{2N_i}$, where the factor 2 arises from statistical errors in the neighboring bin entries). Upper limits were then calculated as $3\sqrt{2N_i}/(0.8NF)$, and are shown in Fig. 5 as a function of the mass. Here the 0.8 factor arises from the tails of the assumed Gaussian peaks, the factor F takes account of the $\mu\pi$ combinations lost because of the momentum error cut, and N is the number of charged-current events (8444 for μ^- and 1367 for μ^+). The upper limit u at a given mass m has the following meaning: if a narrow $\mu\pi$ enhancement were produced in a fraction u of the events, a three-standard-deviation enhancement over neighboring bins would occur in a bin of width $\approx$FWHM. It is assumed that the resolution of the enhancement would be the same as that of the background. The upper limits are for a $\mu\pi$ system with muon laboratory momentum >4 GeV/c. The exact values of the upper limits depend somewhat on the actual procedure used; for example, use of different bin widths or of different background functional forms will produce small changes in the values.

The statement above about no observed $\mu\pi$ enhancements, and the upper limits, apply in particular to any enhancement near 430 MeV/c^2 as reported by Ramm. However, in the $\mu^-\pi^+$ mass distribution in Fig. 2, the 420—430-MeV/c^2 bin (or the 420—440-MeV/c^2 bins) is higher than nearby bins. A third-order-polynomial fit to the mass range 340—520 MeV/c^2, omitting 420—440 MeV/c^2, predicts 11.3 entries in the 420—440-MeV/c^2 interval, compared to the observed 22 entries. The probability of observing 22 or more entries, when 11.3 are expected, is 0.003. That is, at the 3-standard-deviation level, there is a peak at 430 MeV/c^2 in the $\mu^-\pi^+$ mass distribution. But the significance diminishes when the mass resolution is taken into account. Thus, a third-order-polynomial fit to the mass range 330—530 MeV/c^2, omitting 410—450 MeV/c^2, predicts 26.3 entries in the 410—450-MeV/c^2 interval, compared to the observed 32 entries. The calculated errors on $\mu^-\pi^+$ masses at 420—440 MeV/c^2 were similar to those at nearby mass values, so the peak cannot be attributed to a subset of mass combinations with a considerably improved mass resolution. Hence the simplest explanation for the peak is a statistical fluctuation. Events contributing to the peak were checked and found to have no strong differences from events contributing to nearby masses. Many properties, including multiplicity, close secondary vertices, neutrino energy, muon EMI matching, angular distributions in the $\mu\pi$ rest system, fraction with V^0's, etc., were checked. For example, the mean values of the neutrino, muon, and pion energies for mass combinations in the intervals (a) 420—440 MeV/c^2 and (b) 340—420 or 440—520 MeV/c^2, were 79$\pm$9 GeV and 74$\pm$5 GeV, 19$\pm$4 GeV and 16$\pm$1 GeV, and 6.4$\pm$1.7 GeV and 4.3$\pm$0.5 GeV, respectively. Direct calculation showed that the peak was not caused by a known effect such as K_s^0, Λ^0, or ϕ^0 decays with mass misassignment.

The upper limits described above make a minimum of assumptions about the nature of the enhancement. With assumptions about angular distributions in the $\mu^-\pi^+$ center-of-mass system, considerably reduced upper limits can be obtained.[5] For example, requiring the π to be emitted forwards in the $\mu\pi$ center-of-mass system (very nearly equivalent to the π having the greater laboratory momentum) reduces the number of $\mu^-\pi^+$ combinations in the 330—530-MeV/c^2 range from 122 to 4, including one combination at 425 MeV/c^2. An assumption of forward-backward symmetry for the heavy-lepton decay (plus neglect of the 4-GeV muon energy cut) then leads to an upper limit at 430 MeV/c^2 that is a factor 2 or so less than that derived above. However, in general one would not expect such symmetry, and to the extent that the muon "follows" the neutrino, i.e., is forward in the $\mu\pi$ system, any improvement will be less than a factor 2. The distribution of the azimuthal angle of the π about the direction of the $\mu\pi$ system, should be flat for a $\mu\pi$ resonance and peaked on the hadron side for background $\mu\pi$ systems formed with π's from the hadron jet. Requiring that the π be on the "away" side, i.e., the side of the $\mu\pi$ system direction that is opposite the hadron jet side, reduces the 420—440-MeV/c^2 bin from 22 to 9 combinations, while reducing the total background between 330 and 530 MeV/c^2 (excluding this bin) from 122 to 52 combinations. Only two combinations below 530 MeV/c^2 survive the additional requirement that the π have greater laboratory momentum than the μ; neither of these is in or near the 420—440-MeV/c^2 bin.

If one supposes that a narrow heavy lepton does exist near 430 MeV/c^2, then an energy-averaged value can be obtained for the quantity rB, the production rate per charged-current event times the branching ratio into $\mu^\mp\pi^\pm$. The present experiment yields $rB=(10\pm8)/(0.64\times9811)=0.0013\pm0.0011$, after combining the two signs, using 40-MeV/c^2 bins and correcting for Gaussian tails and momentum error cuts. In comparison, the second (higher-statistics) experiment of Ramm yields, approximately, $rB=(20\pm13)/5300=0.0038\pm0.0024$, where 20-MeV/$c^2$ bins have been used (with no correction for Gaussian tails), and an estimated 33% correction has been made to the denominator to include events with 0 or ≥ 4 $\mu^{\mp}\pi^{\pm}$ mass combinations. To the extent that rB may be independent of incident energy, the two experiments do not disagree here. We are unable to extract a value of rB from the first experiment of Ramm, where the requirement that there be only one possible neutral $\mu\pi$ mass combination per event has been imposed.

Conclusion. No significant narrow $\mu\pi$ mass enhancements were found in a neutrino-neon experiment with neutrino energies 10–320 GeV. A peak was observed near 430 MeV/c^2 where Ramm has reported a signal in a lower-energy neutrino experiment. When resolution is taken into account its significance is only $\approx 1\sigma$, however. In addition, the azimuthal and polar angular distributions in the $\mu\pi$ rest system do not show the characteristics expected for a $\mu\pi$ resonance. We believe, therefore, that this enhancement in our data is a statistical fluctuation. It would seem appropriate, nevertheless, for other experimenters to reexamine their $\mu\pi$ spectra.

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[1]C. A. Ramm, Phys. Rev. D 26, 27 (1982). Ramm reports also $\mu\pi$ spectra in K_L^0 decay. We restrict our discussion to our neutrino and antineutrino interactions.

[2]C. N. Leung and J. L. Rosner, Phys. Rev. D 28, 2205 (1983).

[3]Of the massive leptons occurring in the model of Ref. 2, the one (labeled N_1) most likely to be produced in muon-neutrino interactions has an estimated lifetime of about 10^{-8} sec so that the average decay distance may be tens of meters. The analysis reported here is sensitive only to decay distances less than a few centimeters.

[4]H. C. Ballagh *et al.*, Phys. Rev. D 21, 569 (1980).

[5]L. Fluri and E. Wolin, University of Washington (Seattle) Report No. VTL-PHY-69, 1978 (unpublished); M. D. Sokoloff, University of California at Berkeley report, 1978 (unpublished).