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We present here evidence showing the existence of a nonstrange meson of mass 959 MeV.

In the current experiment, the 72-in. hydrogen bubble chamber was exposed to a separated beam of 2.45-, 2.63-, and 2.70-BeV/c K^- mesons from the Bevatron. Approximately 370 000 pictures were taken to date; approximately 300 000 have been scanned. The reactions of interest in this paper are

$$K^- + p \rightarrow \Lambda^0 + MM \quad (1)$$

$$\Lambda^0 \ \pi^+\pi^- \quad (2)$$

$$\Lambda^0 \ \pi^+\pi^0\pi^- \quad (3)$$

$$\Lambda^0 \ \pi^+\pi^- + MM \quad (4)$$

$$\Lambda^0 \ \pi^+\pi^+\pi^-\pi^- \quad (5)$$

$$\Lambda^0 \ \pi^+\pi^+\pi^0\pi^-\pi^- \quad (6)$$

$$\Lambda^0 \ \pi^+\pi^+\pi^-\pi^- + MM \quad (7)$$

and

$$\Lambda^0 \ 3\pi^+3\pi^- \quad (8)$$

These reactions are found in the topologies of a V and 0, 2, 4, and 6 prongs. At this time we have measured the V-four-prong and V-six-prong events in 250 000 pictures, the V-two-prongs in 135 000 pictures, and the V-zero-prongs in 100 000 pictures.

Figure 1a shows clearly the existence of the 959-MeV meson as an enhancement in the $\pi^+\pi^+\pi^0\pi^-\pi^-$ spectrum from reaction (6). The mass is 959 ± 2 MeV and the full width is $\Gamma \lesssim 12$ MeV.[1] We observe 35 events in the interval $0.86 \leq M^2(5\pi) \leq 0.98$ BeV^2. The background is estimated to be less than 10% of the peak. These events are produced mainly with a momentum transfer $\Delta^2_{p,\Lambda}$ less than 0.5 BeV^2.[2] We have used the momentum transfer only as a means to separate other decay modes of this meson from the large background in reactions (1 through 5). The distribution of the four $\pi^+\pi^0\pi^-$ combinations for each of the 35 events in the peak (Fig. 1b) clearly shows the presence of the 548-MeV η meson. Each of the 35 events has at least one $\pi^+\pi^0\pi^-$ triplet at the η mass.[3] We conclude that the 959-MeV meson decays into $\pi^+\pi^-\eta$.

We now turn our attention to other possible decay modes of this meson. The neutral MM and the $\pi^+\pi^-$ MM distributions (at 2.45 BeV/c only) from reactions (1) and (4) (Fig. 2, a and b) show enhancements at 959 MeV. In addition, the selection of MM ≈ η in the low-Δ^2 $\Lambda^0\pi^+\pi^-$ MM events gives a practically clean sample for the $\pi^+\pi^-\eta$ where the η decays into all neutrals (Fig. 2b). This last selection gives a sample of 26 events with $0.86 \leq M^2(\pi^+\pi^-\mathrm{MM}) \leq 0.98$ BeV^2 and $0.27 \leq \mathrm{MM}^2 \leq 0.33$ BeV^2 for all the 135 000 pictures in which these events were measured.[4] No appreciable decay into $\pi^+\pi^-$, $\pi^+\pi^0\pi^-$, and $2\pi^+2\pi^-$ is observed (Fig. 2, c and d). In addition, no decay into $2\pi^+2\pi^02\pi^-$ or $3\pi^+3\pi^-$ is observed.[5] We note that the decay rate into all neutrals ($\lesssim 20$ Λ^0 + MM events above background in Fig. 2a) is comparable to the decay rate into $\pi^+\pi^-\eta$ (four of the 35 $\Lambda^05\pi$ events occur in the 2.45-BeV/c part of the sample in addition to the 14 $\Lambda^0\pi^+\pi^-$ MM events in Fig. 2b).

We now look at the properties of the $\pi^+\pi^-\eta$ decay mode in an attempt to determine the quantum numbers of this meson. When we construct the Dalitz plot of $M^2(\pi^+\eta)$ versus $M^2(\pi^-\eta)$ and their projections (Fig. 3a) for the 61 $\Lambda^0\pi^+\pi^-\eta$ events

($35\ \Lambda^0 5\pi$ and $26\ \Lambda^0\pi^+\pi^-$MM),[6] we observe no particular structure in the $\pi^\pm\eta$ distributions. The distribution of points in the Dalitz plot is consistent with uniformity. The ~20-MeV spread in the observed full width of the meson mass smears out the points appreciably (envelopes labeled 950 and 970 MeV in Fig. 3a). However, the distribution in $M^2(\pi^+\pi^-$ outside the η) (Fig. 3b) is not appreciably affected by the resolution. The $\pi^+\pi^-$ distribution appears to be enhanced around 360 MeV. We now consider the $\pi\pi\eta$ system as a dipion and η, with no final-state interaction between the η and the pions outside it, and denote the angular momentum of the dipion as ℓ and that between the dipion and the eta as L. All J^P states except 0^+ are allowed. For J = 0 or 1, the possible spins and parities are $0^-(\ell = L = 0)$; $1^+(\ell = 0,\ L = 1$, or $\ell = 1,\ L = 0)$; and $1^-(\ell = L = 1)$. For 0^- and 1^+, there can be no correlation between the direction of the η and that of one of the pions as viewed in the dipion rest frame.[7] For 1^-, a $\sin^2\theta_{\pi\eta}$ correlation is required.[8] The distribution in $\cos\theta_{\pi\eta}$ as observed in the dipion rest frame is essentially isotropic, disagreeing with the $\sin^2\theta_{\pi\eta}$ prediction of a 1^- state (Fig. 3c). The ambiguity of the choice of the η in the $\Lambda 5\pi$ events does not alter this conclusion.[9] Thus, we conclude that the 959-MeV meson is probably not a vector particle.

The isospin of the meson is either T = 0 or T = 1 because of its production from an initial K^-p system in association with a Λ^0. Absence of appreciable decay into $\pi^+\pi^-$, $\pi^+\pi^0\pi^-$, $2\pi^+2\pi^-$, $2\pi^+2\pi^0 2\pi^-$ and $3\pi^+3\pi^-$ implies the absence of appreciable decay into $n\pi^0$. If the decay into $\pi^+\pi^-\eta$ occurs strongly, then the neutral mode $\pi^0\pi^0\eta$ determines the isospin to be T = 0. However, a "zero" width for this meson is not excluded ($\Gamma \lesssim 12$ MeV).[10] The predicted branching ratios for a strongly decaying T = 0 $\pi\pi\eta$ system are in fair agreement with the observed ratios.[11] In addition, observation of six e^+e^- conversion pairs and four Compton electrons in association with the ~50 Λ^0 + MM events in the 959-MeV region points to a high multiplicity of gammas in the all-neutral decay, consistent with $\pi^0\pi^0\eta$.[12]

In summary, we have observed a meson of mass 959± 2 MeV,[13] full width $\Gamma \lesssim 12$ MeV, and isospin T = 0 or 1, which decays into $\pi^+\pi^-\eta$. No appreciable decay into two, three, four, or six pions is observed. The angular correlation of the η and the π^+ in the dipion rest system is not $\sin^2\theta_{\pi\eta}$, making unlikely the $J^P = 1^-$ assignment. If we assume a strong decay (nonzero-width), the meson has isospin T = 0 and G parity = + 1, with J^P probably 0^- or 1^+.[14] However, electromagnetic decay cannot be ruled out. The path length at 2.45 BeV/c is approximately 0.6 μb per event. The ~44 $\Lambda\pi\pi\eta$ events at 2.45 BeV/c yield a cross section of about 25 μb. The average polarization of the Λ^0 produced in association with this meson is $\alpha_\Lambda \bar{P} = 0 \pm .2$.

We wish to acknowledge helpful discussions with Professors Murray Gell-Mann and Donald H. Miller and Dr. Nicola Cabibbo. We are indebted to the operators of the 72-in. bubble chamber and the Bevatron for their skill and patience. Furthermore, we thank our scanning and measuring staffs for their untiring efforts, without which this experiment would not have been possible.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. The observed full width is ~ 20 MeV, and the resolution is ~ 16 MeV for the fitted $\Lambda^0 \pi^+\pi^+\pi^0\pi^-\pi^-$ reaction.
2. The square of the momentum transfer from the proton to the lambda is defined by $\Delta^2_{p,\Lambda} = -(E_p - E_\Lambda)^2 + (\underset{\sim}{P}_p - \underset{\sim}{P}_\Lambda)^2$.
3. Of the 35 events with $0.86 \leq M^2(5\pi) \leq 0.98$ BeV^2, twelve have one, eighteen have two, three have three, and two have four $\pi^+\pi^0\pi^-$ triplets near the η mass. The η mass is defined by $0.282 \leq M^2(\pi^+\pi^0\pi^-) \leq 0.322$ BeV^2. This distribution is consistent with a random coincidence based on the phase space for the $\pi\pi\eta$ decay (see Fig. 1b) and the resolution.
4. The resolution for the MM and the $\pi^+\pi^-$ MM is ~ 25 MeV, which is essentially due to the 3% momentum spread in the beam. The observed full width in these MM channels of ~ 30 MeV gives a full width for the 959 MeV meson of ≤ 20 MeV.
5. Three Λ^0-six-prong and 28 Λ^0-four-prong events are consistent with $\Lambda^0 6\pi$ or $\Sigma^0 5\pi$ in the total sample (~ 300 000 scanned pictures). All 31 of these eventshave M^2 (6π or $\gamma 5\pi$) ≥ 1.1 BeV^2.
6. In the $\Lambda^0 5\pi$ events we chose as the η that $\pi^+\pi^0\pi^-$ triplet whose mass squared is closest to $M_\eta^2 = 0.300$. This choice does not always pick the correct triplet because of the finite resolution. About half of the ambiguities should be chosen correctly statistically, giving 48 (of which 38 are unambiguous) correctly and 13 incorrectly chosen.[3]

7. The $J^P = 0^-$, 1^+, 1^- states can also be formed from ($\ell = L = 1$ or $\ell = L = 2$), ($\ell = 2$, $L = 1$ or $\ell = 1$, $L = 2$), and ($\ell = 2$, $L = 2$) combinations, respectively. The $0^-(\ell = L = 1)$ state would give a $\cos^2\theta_{\pi^+\eta}$ distribution, in disagreement with the data. The angular correlations would be relatively complicated in the other cases.

8. The odd intrinsic parity of the $\pi\pi\eta$ system requires a 1^+ matrix element (proportional to $\underline{P}_\pi \times \underline{P}_\eta$) for a vector-meson assignment. N. Cabibbo points out that the resulting $\sin^2\theta_{\pi\eta}$ distribution is essentially independent of any $\pi^+\pi^-$ interaction that might be present (such as at 360 MeV, Fig. 3b).

9. The $\Lambda^0 5\pi$ that are unambiguous as to the choice of the eta are shown cross-hatched in Fig. 3c. Replotting the "ambiguous" $\Lambda^0 5\pi$ so that all possible combinations contribute equally to the unit area per event does not appreciably alter the distribution presented in Fig. 3c.

10. The $T = 0$ component of the vector-meson octet has $TJ^{PG} = 01^{--}$. If the $\pi\pi\eta$ state with $G = +1$ is this 01^{--} meson, it must decay electromagnetically. The 1^- vector assignment is unlikely, because of the $\cos\theta_{\pi\eta}$ distribution (Fig. 3c). An additional argument can be made against this assignment. Charge conjugation invariance in the electromagnetic decay requires a $T = 1$ $\pi^+\pi^-\eta$ system, so that all neutral decay must be due to the modes $\pi^0\gamma$, $2\pi^0\gamma$, and 3γ. However, the decay rate into $\pi^0\gamma$ relative to $\pi^+\pi^-\eta$ is expected to be very large. The $\pi^0\gamma$ rate is proportional to a times a large two-body phase-space factor, whereas the $\pi^+\pi^-\eta$ decay is proportional to a^2 times a smaller three-body phase-space factor. This is in marked disagreement with the observed all-neutral to $\pi^+\pi^-\eta$ rates.

11. We use a branching ratio of ~ 2.5 for (η decay into all neutrals)/(charged decay) and 0.5 for $2\pi^0/\pi^+\pi^-$ (T = 0). For the ~ 44 events at low Δ^2 at 2.45 BeV/c, this predicts an apportionment of 8, 21, 4, and 11 events, respectively, as $\pi^+\pi^-\eta_{chg.}$, $\pi^+\pi^-\eta_{neut.}$, $\pi^0\pi^0\eta_{chg.}$, and all neutral. We observe 4, 14, $\lesssim 6$, $\lesssim 20$, respectively, in fair agreement with the predicted apportionment. In addition, we note that we have not observed any $\pi^{\pm}\pi^0\eta^0$ enhancement in $\Sigma^{\pm}(n\pi)^{\mp}$ states. This constitutes weak evidence against T = 1.

12. None of the 10 detected γ events was consistent with $\Lambda\gamma\gamma$ production. The MM in $K^-p \rightarrow \Lambda + \gamma + MM$ for these events is peaked from 500 to 900 MeV. This suggests an average of approximately 4 to 5 gammas for each of the 50 Λ^0 + MM events. The observed detection efficiency for the gammas is then 10/(4 to 5) $\times$ 50 $\approx$ 4%, a reasonable value for the 72-in. chamber.

13. We note that evidence for an enhancement in the missing mass opposite the Λ in the reaction $K^- + p \rightarrow \Lambda$ + neutrals near this value has been observed by the Brookhaven bubble chamber group. [See M. Goldberg, M. Gundzik, J. Leitner, S. Lichtman, P. L. Connolly, E. L. Hart, K. W. Lai, G. London, G. C. Moneti, R. R. Rau, N. P. Samios, I. O. Skillicorn, and S. S. Yamamoto, Study of $K^-p \rightarrow \Lambda(K^0)$ + neutrals at 2.3 BeV/c, Bull. Am. Phys. Soc. 9, 23 (1964).]

14. The existence of a singlet 00^{-+} meson as well as 1^+ mesons has long been conjectured by M. Gell-Mann. J. Schwinger has also proposed a 0^- δ meson at a mass of ~1500 MeV [Phys. Rev. Letters 12, 237 (1964)].

FIGURE LEGENDS

Fig. 1. (a) Distribution of the effective mass squared of $\pi^+\pi^+\pi^0\pi^-\pi^-$ in the reaction $K^-p \rightarrow \Lambda^0\pi^+\pi^+\pi^0\pi^-$. The shaded area represents events in which the square of the momentum transfer from the proton to the lambda, $\Delta^2_{p\Lambda}$, is less than 0.5 BeV^2. (b) Distribution of the effective mass squared of all four $\pi^+\pi^0\pi^-$ combinations in the 35 $\Lambda^0\pi^+\pi^+\pi^0\pi^-\pi^0$ events in (a) where $0.86 \leq M^2(5\pi) \leq 0.98$ BeV^2. The data are at incident momenta of 2.45, 2.63, and 2.70 BeV/c.

Fig. 2. (a) Distribution of the square of the mass of all neutrals (MM) in the reaction $K^-p \rightarrow \Lambda^0$ + neutrals (MM). All events consistent with a fit to $\pi^- + p \rightarrow \Lambda^0 + K^0$ have been subtracted from the plot. (b) Distribution of the effective mass squared of $\pi^+ + \pi^-$ + neutrals (MM) in the reaction $K^-p \rightarrow \Lambda^0\pi^+\pi^-$ + neutrals (MM). The crosshatched events have been selected to be consistent with $\eta^0(0.28 \leq MM^2 \leq 0.32\ BeV^2)$. (c) Distribution of the square of the effective mass of $\pi^+\pi^0\pi^-$ in the reaction $K^-p \rightarrow \Lambda^0\pi^+\pi^0\pi^-$. (d) Distribution of the square of the effective mass of $\pi^+\pi^-$ and $\pi^+\pi^+\pi^-\pi^-$ in the reactions $K^-p \rightarrow \Lambda^0\pi^+\pi^-$ and $\Lambda^0\pi^+\pi^+\pi^-\pi^-$, respectively. Shaded events are those with low momentum transfer from the proton to the lambda ($\Delta^2_{p\Lambda} \leq 0.5\ BeV^2$). All data are at 2.45 BeV/c incident K^- momentum.

Fig. 3. (a) Dalitz plot $[M^2(\pi^+\eta^0)$ versus $M^2(\pi^-\eta^0)]$ and projections for the 61 events in the reactions $K^-p \rightarrow \Lambda^0 5\pi$ and $\Lambda^0\pi^+\pi^-$ + neutrals with $0.86 \leq M^2(5\pi)$ or $M^2(\pi^+\pi^- + MM{=}\eta^0) \leq 0.98$. (b) Distribution of the square of the effective mass of the $\pi^+\pi^-$ outside the η^0 for the 61 events shown in (a). (c) Distribution of the cosine of the angle included between the η^0 and the π^+ as viewed in the dipion $(\pi^+\pi^-)$ rest frame. Shaded events are those from the reaction $K^-p \rightarrow \Lambda^0\pi^+\pi^-$ + neutrals (η^0).

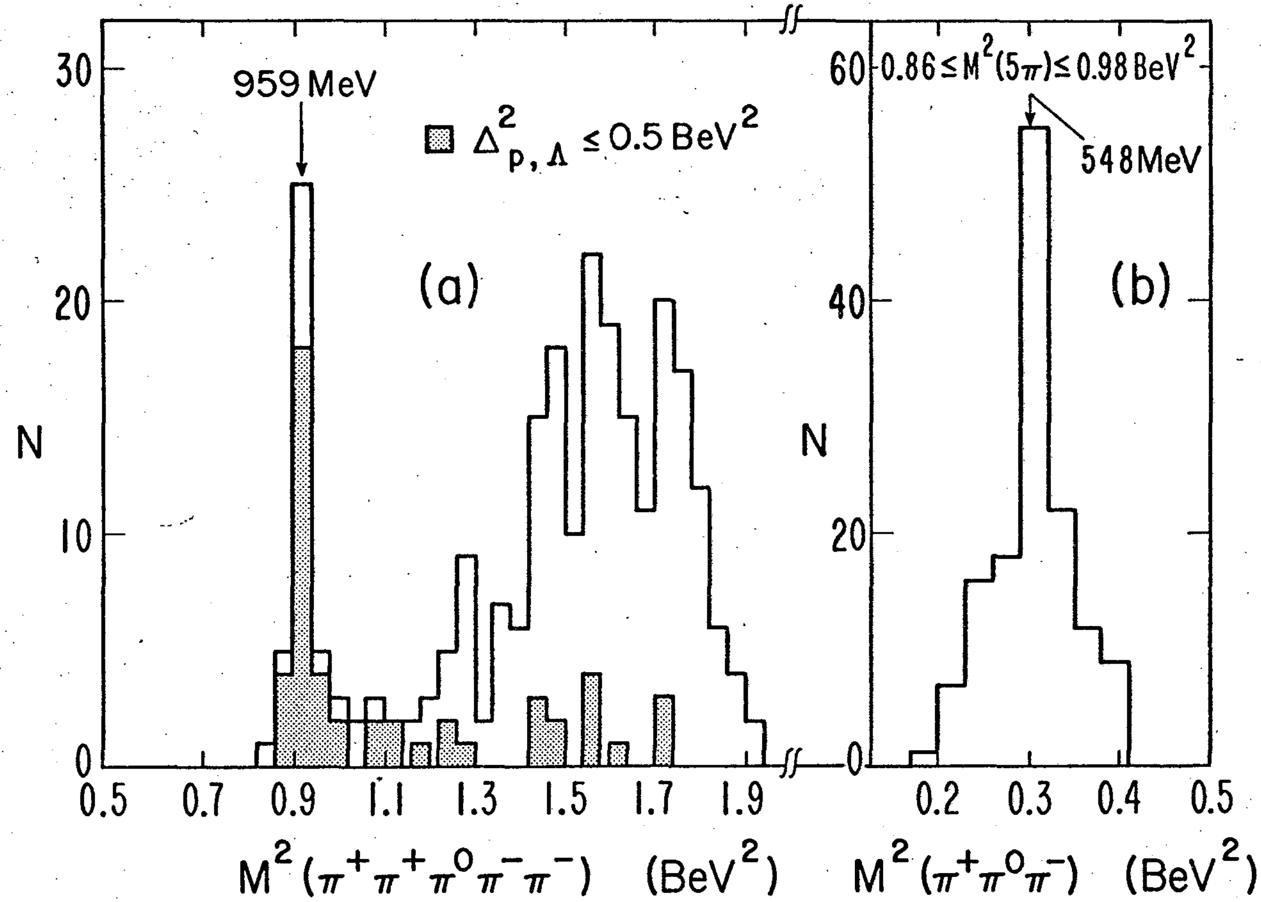

959 MeV
$\Delta^2_{p,\Lambda} \leq 0.5\ BeV^2$
(a)
N
$M^2(\pi^+\pi^+\pi^0\pi^-\pi^-)$ (BeV^2)
$0.86 \leq M^2(5\pi) \leq 0.98\ BeV^2$
548MeV
(b)
N
$M^2(\pi^+\pi^0\pi^-)$ (BeV^2)
MUB-2529

Fig. 1

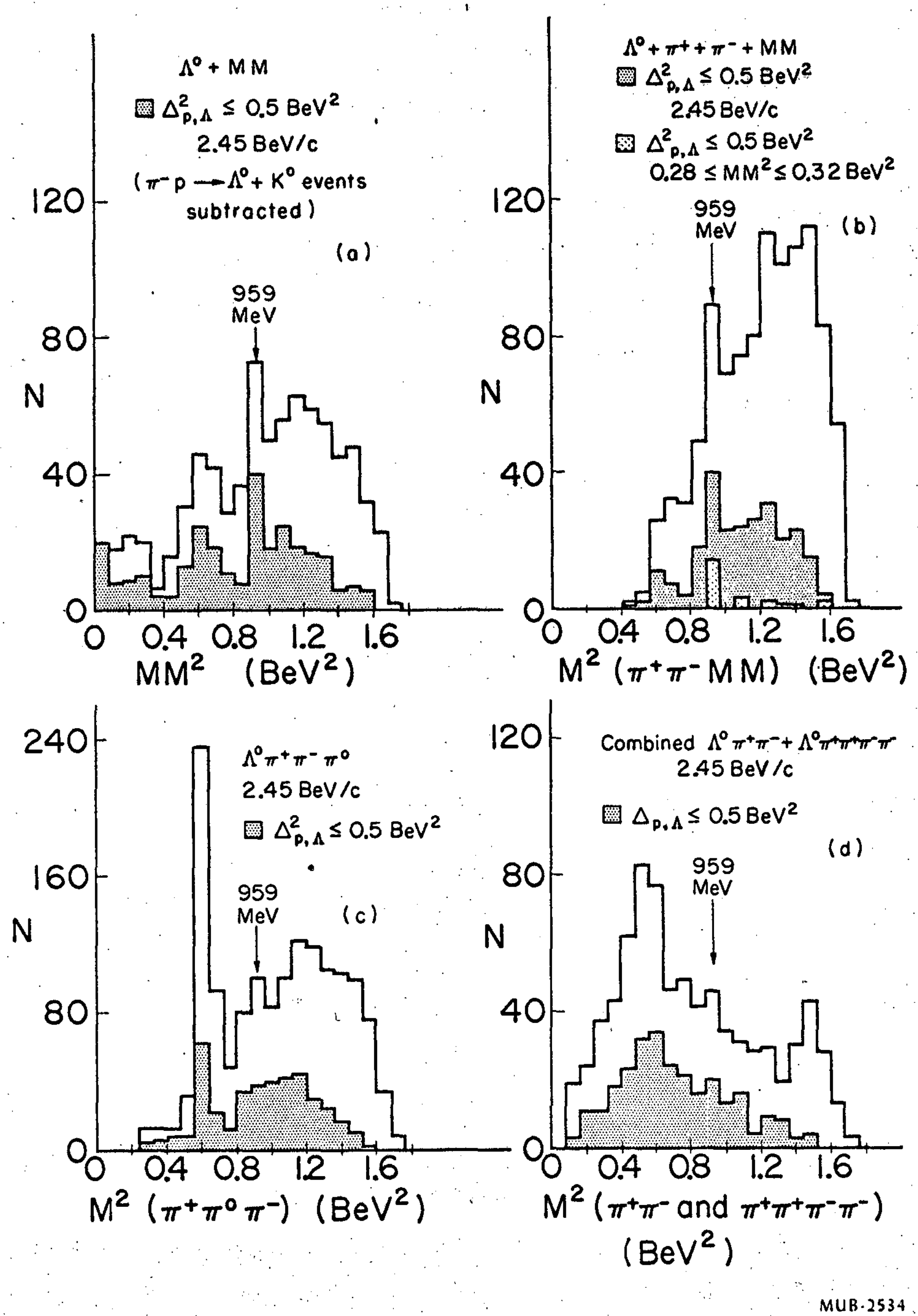
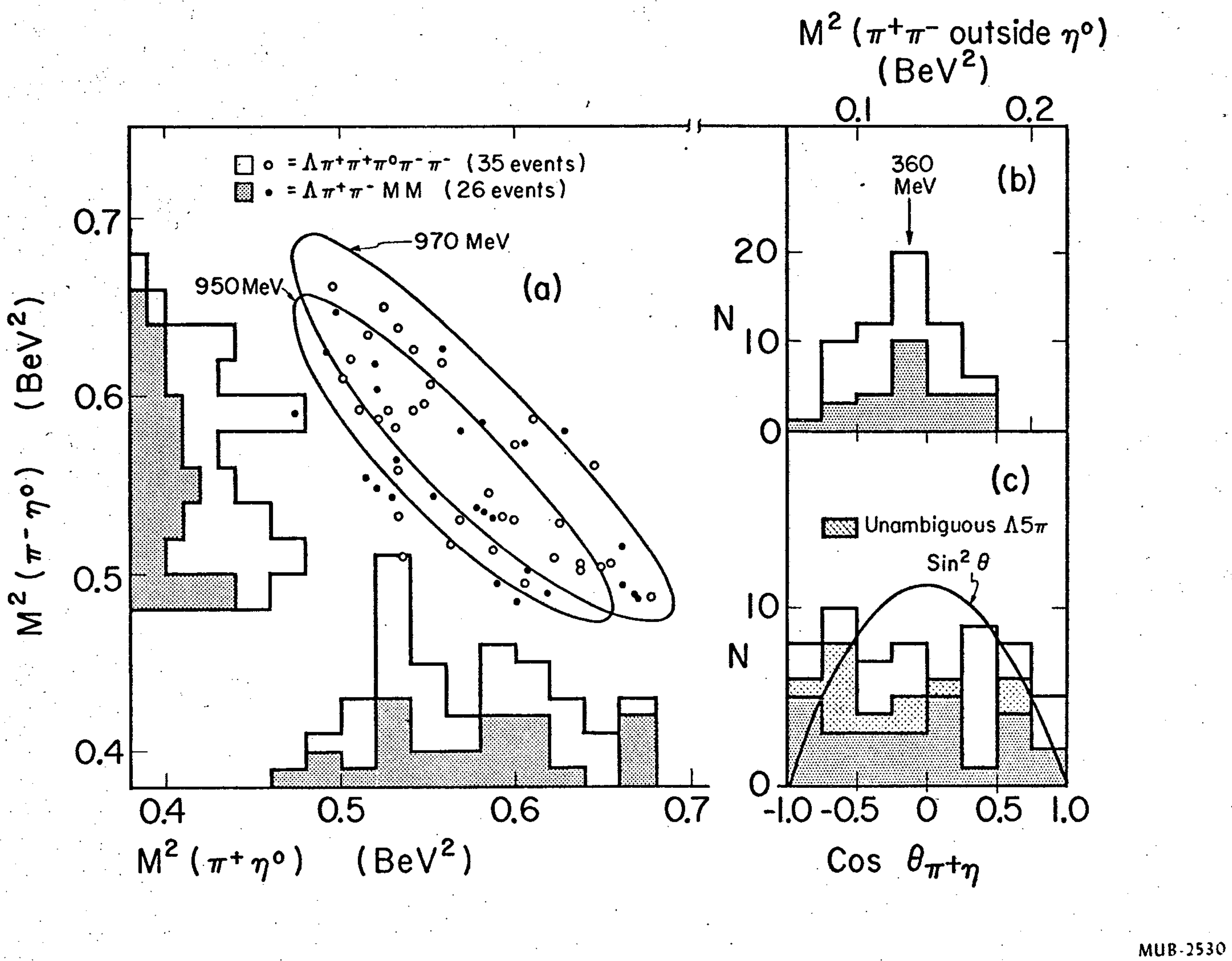

Λ° + MM
Δ²p,Λ ≤ 0.5 BeV²
2.45 BeV/c
(π⁻p → Λ° + K° events subtracted)
(a)
959 MeV
N
MM² (BeV²)
Λ° + π⁺ + π⁻ + MM
Δ²p,Λ ≤ 0.5 BeV²
2.45 BeV/c
Δ²p,Λ ≤ 0.5 BeV²
0.28 ≤ MM² ≤ 0.32 BeV²
959 MeV
(b)
M² (π⁺π⁻ MM) (BeV²)
Λ°π⁺π⁻π°
2.45 BeV/c
Δ²p,Λ ≤ 0.5 BeV²
959 MeV
(c)
M² (π⁺π°π⁻) (BeV²)
Combined Λ°π⁺π⁻ + Λ°π⁺π⁺π⁻π⁻
2.45 BeV/c
Δp,Λ ≤ 0.5 BeV²
(d)
959 MeV
M² (π⁺π⁻ and π⁺π⁺π⁻π⁻) (BeV²)
MUB-2534

Fig. 2



□ ○ = Λπ⁺π⁺π⁰π⁻π⁻ (35 events)
▩ • = Λπ⁺π⁻ MM (26 events)
970 MeV
950 MeV
(a)
M² (π⁻η⁰) (BeV²)
M² (π⁺η⁰) (BeV²)
0.4
0.5
0.6
0.7
M² (π⁺π⁻ outside η⁰)
(BeV²)
0.1
0.2
360
MeV
(b)
N
20
10
0
(c)
Unambiguous Λ5π
Sin² θ
-1.0 -0.5 0 0.5 1.0
Cos θπ+η
MUB-2530

Fig. 3