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Production of $N^*(1518)$ and $N^*(1688)$ isobars in $\bar{p}p$ interactions at 5.7 GeV/c; determination of their widths and decay branching ratios

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Summary

The nucleon isobars $N^*(1518)$ and $N^*(1688)$ are observed in inelastic interactions of 5.7 GeV/c antiprotons in hydrogen. The widths of both of them are found to be - (55 ± 15 MeV and 70 ± 20 MeV respectively), in agreement with recent phase-shift data. The 2-body to 3-body branching ratios are estimated (being $1.25 \begin{smallmatrix} +0.44 \\ -0.71 \end{smallmatrix}$ in the case of the $N^*(1518)$ and less than 1.26 with 95 o/o confidence for the $N^*(1688)$) and show that the inelasticities of both resonances in π^-p scattering are high.

A detailed study of the 3-body $N\pi\pi$ decays provides no evidence in either case for the cascade decay into $N^*(1238)+\pi$. Deviations from uniform population of the Dalitz plots for the 3-body decays are observed and are studied in terms of the 3-body decay matrix elements.

Upper limits for decay of the $N^*(1688)$ into $N\eta$ and ΛK final states are estimated.

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1. Experimental procedure.

Four-prong events produced by a 5.7 GeV/c separated $\bar{p}$ beam in the Saclay 81 cm hydrogen bubble chamber have been measured with the CERN HPD system. 19,100 events without detectable strange particles were accepted for analysis. A study of the HPD measurements has shown that their quality is not inferior to that of conventional IEP measurements(1)(2). It has been checked that 11 o/o of the attempted events, which did not pass successfully through the system, show no special features which could introduce a bias into the accepted sample of 19,100 events(2).

The standard chain of CERN programs was used to reconstruct and analyse the measured events. Ionisation measurements supplied by the HPD for all events were used to help in choosing the right interpretation between different kinematical fits.

The results reported here come from a study of the channels producing 2 or 3 pions :

$\bar{p}p \rightarrow \bar{p}\, p\, \pi^+ \pi^-$	3638 events	(1)
$\bar{p}p \rightarrow \bar{p}\, p\, \pi^+ \pi^- \pi^0$	2312 events	(2)
$\bar{p}p \rightarrow \bar{p}\, n\, \pi^+ \pi^+ \pi^-$	834 events	(3a)
$\bar{p}p \rightarrow p\, \bar{n}\, \pi^- \pi^- \pi^+$	750 events	(3b)

The data on the production of $N^* \bar{N}^*$ pairs in the channel (1) and $\bar{p}p\, \omega^0$, $\bar{p}p\, \eta^0$ and $N^* \bar{N}^* \pi^0$ 3-body final states in the channels (2) are published elsewhere(3)(4).

In the present study we have also used the data of R.K. Böck et al(5) on the channel

$$\bar{p}p \rightarrow \bar{p}\, \Lambda^0 K^+ + \text{c.c.} \qquad (4)$$

to estimate an upper limit on the ΛK decay rate of the $N^*(1688)$. Finally the data on one pion production channels has been communicated to us by the Bonn-Hamburg-Milano collaboration[6] which, as a part of a systematic study of $\bar{p}p$ interactions, has studied 2-prong events in the same film.

Events of the 4-constraint channel (1) have been separated out if the kinematical probability $P(\chi^2_{4C})$ was greater than 1 o/o and if ionisation was compatible with the chosen hypothesis. In 96 events where there was an ambiguity concerning the $\bar{p}$ track the fit with higher probability was accepted.

In separating the channel (2) and (3) we required the probability defined as a normalized product of the kinematical probability and an ionisation probability obtained from the ionisation fit described in the paper by L. Michejda[7] to be larger than 1 o/o. Ambiguous events have been studied separately and then included in the reactions (2) or (3) where they represent 25 o/o and 15 o/o of the cross section for these channels. (see the discussion in Alles-Borelli et al[4] on this point).

For the channels (3a) and 3(b) it has been found that the distribution of kinematical probability $P(\chi^2_{1C})$ for the accepted events had an important excess of events with small $P(\chi^2_{1C})$ values, indicating the presence of a large contamination of events with more than one neutral particle unseen. The events with a small probability value did not show the $N^*(1238)$ peak in the $n\pi^-$, $\bar{p}\pi^-$ + c.c. systems which was strong in the rest of the sample. Therefore it has been decided to use only the events for which $P(\chi^2_{1C})$ was higher than 35 o/o, the numbers for which are given above. In this way part of the statistics has been lost but on the other hand the remaining part is relatively clean and is not biased by the applied cut. We find reasonable agreement in all corresponding distributions made for the charge conjugated channels (3a) and (3b) and in the further study we will discuss them together as channel (3); the total number of considered events being 1584.

The cross-sections and their errors corresponding to 1 event considered for the afore mentioned channels are

(1) $0.910\ \mu b \pm 0.044\ \mu b$

(2) $0.935\ \mu b \pm 0.060\ \mu b$

(3) $1.150\ \mu b \pm 0.120\ \mu b$

(4) $0.264\ \mu b \pm 0.036\ \mu b$.

The data on channel (4) was obtained from a larger sample of film in which strange particle production has been studied[5]. The differences between the channels (1), (2) and (3), which have been studied on the same amount of film, are due to problems concerning their separation from other reactions and contamination by background events which are different for each channel and require different solutions.

2. Observation of the $N^{*+}(1688)$ isobar decaying into $p\,\pi^+\,\pi^-$ system.

In this section we present evidence for the production of a nucleon isobar with a mass of about 1700 MeV which we identify with one of the two known $N^*(1688)$ isobars (see e.g.[8]).

The evidence comes from the channel (1) which is dominated by associated $N^*\,\bar{N}^*$ production accounting for 63 o/o of the cross section[4].

Fig. (1a) shows the $p\,\pi^+\,\pi^-$ and $\bar{p}\,\pi^+\,\pi^-$ mass distribution for 2234 events of channel (1) after exclusion of events where both $M(p\pi^+)$ and $M(\bar{p}\pi^-)$ masses lie between 1.15 and 1.35 GeV. A peak is seen at 1700 MeV which has a statistical significance of about 6 standard deviations. It is not easy to determine the expected form of the mass spectrum below the peak at 1700 and in order to estimate the number of events in the peak we fitted the mass region 1.48 - 1.92 GeV to a sum of a simple Breit-Wigner curve and a straight line. The fit with a least-squares method gave the following result :

Mass	$M = (1695 \pm 9)$ MeV,
Full width	$\Gamma = (70 \pm 20)$ MeV,
Number of events in the peak	$N = 255 \pm 46$.

The fitted curve is shown as a continuous line in Fig. 1(a).

Comparing the mass and the width with those of accepted isobars (see[8] and [9]) we find that there are two possible assignments for the observed peak : both have isospin I = 1/2 and spin J = 5/2, called $N^*(1688)$ but of opposite parities.

In the following we will assume that the peak is due to

$$\bar{p}p \rightarrow \bar{p}\, N^{*+}(1688) + \text{c.c.}\ , \quad (5)$$

followed by the 3-body decay of the isobar

$$N^{*+}(1688) \rightarrow p\, \pi^+ \pi^- \ . \quad (6)$$

Before determining the cross section for this 2-step process it is necessary to estimate the correction due to neglecting events having both $M(p\pi^+)$ and $M(\bar{p}\pi^-)$ masses inside the interval 1.15-1.35 GeV.

In the analysis of the decay (6), discussed in Section 4, we found that 77 out of the 255 decays belonging to the peak of Fig. 1(a) fulfill the condition 1.15 GeV $< M(p\pi^+) <$ 1.35 GeV. We performed a Monte Carlo calculation on the reaction $\bar{p}p \rightarrow \bar{p}\, N^{*+}(1688)$ in which we considered for the $N^*(1688)$ either a 3-body $p\, \pi^+ \pi^-$ decay or a cascade decay

$$N^{*+}(1688) \rightarrow N^{*++}(1238) + \pi^- \ . \quad (7)$$

For the events fulfilling the condition 1.15 GeV $< M(p\pi^+) <$ 1.35 GeV the calculation showed that the number of events having a mass $M(\bar{p}\pi^-)$ in the same interval and therefore simulating $N^*\bar{N}^*$ events represented 14 o/o of the events having a $M(\bar{p}\pi^-)$ outside this interval. We thus conclude that the number of $N^*(1688)$ events should be increased by 0.14 x 77 = 11 events.

In Fig. 1(b) the $p\,\pi^+\,\pi^-$ and $\bar{p}\,\pi^+\,\pi^-$ mass distribution for 1404 events from the $N^*\,\bar{N}^*$ region is shown and an area corresponding to the 11 expected events is shaded. The dashed line is drawn by hand and there is no evidence for a statistical significant excess of events in the neighbourhood of 1.7 GeV. Moreover in these events the $p\,\pi^+$ angular distribution in the $p\,\pi^+\,\pi^-$ rest frame is strongly peaked along the transformed target proton momentum. Any addition of these events to the corresponding distribution of the events in the $N^*(1688)$ region of Fig. 1(a), which is symmetric, would rapidly render the total $p\,\pi^+$ angular distribution asymmetric contrary to what we expect for a decay of a resonance.

As a result of the above considerations we estimate the cross section for the chain of processes (5) + (6) to be

$$\sigma = (242 \pm 42)\ \mu b\ .$$

This may be compared with the proton-proton cross section, viz. $pp \to p\,N^*(1688)$, followed by the decay (6) of $(360 \pm 160)\ \mu b$ reported by G. Alexander et al[10] at 5.5 GeV/c. Further study of the characteristics of the 3-body decay (6) will be based on the 555 events from the peak region of Fig. 1(a), defined as 1.64 to 1.76 GeV, as compared to the 369 events from the adjacent regions 1.58 - 1.64 GeV and 1.76 - 1.82 GeV.

3. The $N\pi$ to $N\pi\pi$ branching ratio for $N^*(1688)$ and upper limits on its $N\eta$ and ΛK decay modes.

In this experiment, as will be discussed in Section 4, it turns out to be impossible to determine the parity of the observed $N^*(1688)$. However, it could be, as indeed we will assume, that the observed peak is due to only one of the two known isobars of this mass. In the present section we will discuss decay branching ratios of the $N^*(1688)$, starting with the problem of the 2-body $N\pi$ to 3-body $N\pi\pi$ branching ratio. From an analysis of two-prong interactions from the same exposure as used in the present experiment, the Bonn-Hamburg-Milano collaboration[6] has estimated that the cross section for the reaction (5) followed by all allowed 2-body $N\pi$ decays of the $N^*(1688)$ is (230 ± 125) μb. In combination with our data one finds the ratio

$$\frac{N^{*+}(1688) \rightarrow \text{all } N\pi}{N^{*+}(1688) \rightarrow p\,\pi^+\pi^-} = 0.95 \pm 0.50 \qquad (8)$$

In order to determine the branching ratio

$$R = \frac{N^*(1688) \rightarrow N\pi}{N^*(1688) \rightarrow N\pi\pi} \qquad (9)$$

we have to estimate the contribution from the two 3-body decay modes which could not be observed in the present experiment :
$N^{*+}(1688) \rightarrow p\,\pi^0\pi^0$ and $N^{*+} \rightarrow n\,\pi^+\pi^0$. The isospin, I, of the $\pi\pi$ pairs in these decays is uniquely defined and equal to I = 0 and I = 1 respectively, whereas in the observed $p\,\pi^+\pi^-$ decay mode the $\pi^+\pi^-$ pair could

'a priori' be in an arbitrary mixture of I = 0 and I = 1 states (an interference term vanishes when integrated over the Dalitz plot). Using Clebsch-Gordan coefficients it may be shown that

$$\frac{3}{2} \leqslant \frac{N^{*+}(I = 1/2) \rightarrow \text{all } N\,\pi\,\pi}{N^{*+}(I = 1/2) \rightarrow p\,\pi^{+}\,\pi^{-}} \leqslant 3 \qquad (10)$$

where 3/2 would correspond to a pure I = 0 amplitude for the decay (6) and 3 to a pure I = 1 amplitude.

Combining (8) with (10) we conclude that the 2-body to 3-body branching ratio R is limited to :

$$0.32 \pm 0.17 \leqslant R \leqslant 0.63 \pm 0.33$$

where both the limiting values have errors of about 50 o/o due mainly to the uncertainty in the 2-body decay rate. This estimate agrees well with the phase-shift analysis data(11) for the negative-parity D-wave resonance but, within 2 standard deviations, is also compatible with the elasticity found for the positive-parity F-wave isobar.

Now we pass to a determination of the upper limits for the decay rates of the $N^{*}(1688)$ into $N\eta$ and ΛK states. In the Fig. 1(c) we present the $p\eta^{o}$ and $\bar{p}\eta^{o}$ mass distribution from the reaction

$$\bar{p}p \rightarrow \bar{p}\,p\,\eta^{o} \qquad (11)$$

which was separated out(3) from the final states (2). In the Fig. 1(d) we finally present the ΛK^{+} and $\bar{\Lambda}K^{-}$ mass distribution for the reaction (4) studied by R.K. Böck et al(5). Neither of them show any excess of events in the 1.7 GeV region. We estimate the possible amount of the $N^{*}(1688)$ in the 1.64 - 1.76 GeV interval of these distributions as equal to 0 + 3 events for the $N\eta$ system and 9 ± 6 for the ΛK system.

Correcting for neutral η^{o} decays and using the lower limit 3/2 in the inequality (10) we obtain the following estimates :

$$\frac{N^{*+}(1688) \rightarrow p\,\eta^{o}}{N^{*+}(1688) \rightarrow \text{all } N\pi \text{ and } N\pi\pi} < 4.2 \text{ o/o}$$

and

$$\frac{N^{*+}(1688) \rightarrow \Lambda^{o}\,K^{+}}{N^{*+}(1688) \rightarrow \text{all } N\pi \text{ and } N\pi\pi} < 1.3 \text{ o/o}$$

Both upper limits correspond to a 95 o/o confidence level.

The non-appearance of the $p\eta$ and ΛK decays in the present experiment supports the conclusions reached in Refs.[12] and [13].

4. Discussion of the Dalitz plot for the $N^{*+}(1688) \rightarrow p\,\pi^{+}\,\pi^{-}$ decay and a search for the cascade decay $N^{*+}(1688) \rightarrow N^{*++}(1238) + \pi^{-}$.

In Fig. 2 Dalitz plots, together with their projections, are presented : the upper one is for 555 peak region events and the lower one for 369 events from the control regions. All plotted mass values have been normalized to the central $M(p\,\pi^{+}\,\pi^{-}) = 1.7$ GeV isobar mass by multiplying the kinetic energies of particles by the ratio of the central to the actual Q-values.

We notice that the Dalitz plot for the control regions is uniformly populated. An excess of events in the $N^{*}(1238)$ region, which exists if all events of the channel (1) are plotted, has disappeared after eliminating the $N^{*}\,\bar{N}^{*}$ events. From the uniform density over the Dalitz plot for the control regions we expect that also in the peak region background events are distributed according to phase space. The estimated background contribution in the $M^{2}(p\pi^{+})$ and $M^{2}(p\pi^{-})$ projections is accordingly shown as a continuous line. The parts of the area which are above these curves should be due therefore only to the $N^{*}(1688)$ decay.

Before going into further details we notice that there is no significant difference between the $M^2(p\pi^+)$ and the $M^2(p\pi^-)$ distributions. A χ^2 test for the hypothesis that they are indeed equal to each other gives a probability of 17 o/o. This fact could be interpreted as a lack of interference between decay amplitudes with the $\pi^+ \pi^-$ pair in the isospin I = 0 and I = 1 states, or possibly the dominance of one of them.

An indication for the existence of the cascade decay mode (7) of the $N^*(1688)$ in the charge symmetric state $n\, \pi^+ \pi^-$ has been recently published by O. Czyżewski et al[14].

However in this experiment the equality of the observed $M^2(p\pi^+)$ and $M^2(p\pi^-)$ distributions in particular in the region around 1230 MeV, shows that there is no indication for this cascade decay since the expected ratio of the number of $N^{*+}(1238)$ isobars to the number of $N^{*0}(1238)$ isobars is equal to 9. Counting the number of combinations in the $N^*(1238)$ bands from 1.15 GeV to 1.35 GeV for both charge states we find that the difference: doubly-charged minus zero-charge combinations, is equal to -7 ± 22. Even after correcting for the 11 neglected $N^*(1688)$ events estimated in Section 2, which are all inside the $N^{*++}(1238)$ band and about 5 inside the $N^{*0}(1238)$ band, there is no indication for an excess of the doubly charged combinations.

The $\pi^+ \pi^-$ distributions both for the peak and the control regions of the $N^*(1688)$ follow phase space.

Due to the lack of any indication for a quasi-two-body decay of the $N^*(1688)$ it seems reasonable to assume a genuine 3-body decay and see what Dalitz plot densities are predicted for a resonance of spin 5/2.

Unfortunately there are a number of different matrix elements which must be considered for each of the 2 possible $J^P = 5/2^+$ and $5/2^-$ assignments. First of all spin 5/2 may be constructed from the proton spin and 2 different total orbital angular momenta of the 3-body system : L = 2 and L = 3. Then for each of these 2 cases there are still various matrix elements which can be built, as one can learn e.g. from the paper of C. Zemach[15]. Following Zemach we construct matrix elements from the vectors $\vec{P}_1$ - momentum of π^-, $\vec{P}_2$ - momentum of π^+ and their vector product $\vec{q} = \vec{P}_1 \times \vec{P}_2$, all momenta being in the rest frame of the decaying $N^*(1688)$.

We will not give here details of the calculations and fitting of the Dalitz plot density distribution since the results are not conclusive. The main feature of the data illustrated by Fig. 2 is the lack of events near the center of the Dalitz plot, where $M^2(p\pi^+) = M^2(p\pi^-)$. When fitted with various matrix elements we find the following fit probabilities (P)

a) $5/2^+$, L = 2, P = 34 o/o, b) $5/2^+$, L = 3, P = 4 o/o,

c) $5/2^-$, L = 2, P = 0.1 o/o, d) $5/2^-$, L = 3, P = 47 o/o.

Thus the basic problem of parity determination cannot be solved due to high background and to the fact that for both parities matrix elements may be constructed capable of predicting an acceptable density distribution. As an example, the fit for the $5/2^+$ assignment is shown in Fig. 2 as a dashed line in the projections of Dalitz plot densities.

5. Observation of the $N^{*0}(1518)$ in the $p \pi^- \pi^0$ systems.

In this section we discuss the evidence for the reaction

$$\bar{p}p \rightarrow \bar{p}\, N^{*0}(1518)\, \pi^+ + c.c. \qquad (13)$$

followed by either the 2-body

$$N^{*o}(1518) \rightarrow p\pi^- \tag{14}$$

or the 3-body

$$N^{*o}(1518) \rightarrow p\,\pi^-\,\pi^o \tag{15}$$

decays of the isobar.

In Fig. 3(a) the $p\,\pi^-$ and $\bar{p}\,\pi^+$ distribution is shown for the channel (1) from which the $N^*(1238)\,\bar{N}^*(1238)$ region discussed in Section 2 has been excluded. One notices a neutral $N^*(1238)$ peak at 1225 MeV and also a peak at about 1510 MeV. Due to difficulties of computing a mass distribution for the background part of the spectrum (a phase space curve does not follow the experimental distribution) we have used a least squares method to fit the experimental distribution in the mass region 1.34 to 1.76 GeV, to a sum of a straight line plus a simple Breit-Wigner curve with the following results :

Mass	$M = (1508 \pm 8)$ MeV,
Full width	$\Gamma = (\ 51 \pm 25)$ MeV,
Number of events in the peak	$N = 160 \pm 44$.

The curve shown in Fig. 3(a) corresponds to the fitted straight line and its extension outside the 1.34 - 1.76 GeV region by hand plus the Breit-Wigner curve.

Fig. 3(b) shows the $p\,\pi^-\,\pi^o$ and $\bar{p}\,\pi^+\,\pi^o$ mass distribution for the 1696 events of channel (2) that remain after removal of events corresponding to the final states : $\bar{p}\,p\,\omega^o$, $\bar{p}\,p\,\eta^o$ and $N^*(1238)\,\bar{N}^*(1238)\,\pi^o$ (see[3]). A bump is apparent around 1510 MeV. For this distribution a phase space curve plus a Breit-Wigner curve fits well (full line curve on Fig. 3(b)) and yields the following values :

$M = (1505 \pm 9)$ MeV

$\Gamma = (57 \pm 18)$ MeV.

Number of events in the peak $N = 108 \pm 24$.

The fitted M and Γ values for the $p\,\pi^-$ and the $p\,\pi^-\,\pi^0$ peaks are in good agreement with each other and thus consistent with the hypothesis that the observed peaks represent two different decay modes of the same isobar. The weighted averages for its mass and width are then

$$M = (1507 \pm 6) \text{ MeV}$$

and $$\Gamma = (55 \pm 15) \text{ MeV} . \qquad (17)$$

It should be noted that although the determination of these parameters from the experimental histograms has been done in an approximate way (e.g. energy dependence of Γ has been neglected), the observed narrow width makes possible corrections unimportant.

If we identify these peaks with the $N^*(1518)$ with $I = 1/2$ and spin parity $3/2^-$, then the above determination of its width gives a value which is in good agreement with the value of 56 MeV determined in phase shift analysis by P. Auvil et al[16] and by Bareyre et al[11].

The cross section for the reaction $\bar{p}p \rightarrow \bar{p}\,N^{*0}(1518)\,\pi^+$ + c.c. followed by the 2-body decay $p\pi^-$ + c.c. is equal to (146 ± 40) μb (a correction for events contained in the $N^*(1238)\bar{N}^*(1238)$ region is small and has been neglected). The cross section for the same production process followed by the 3-body decay $p\,\pi^-\,\pi^0$ + c.c. is estimated to be (117 ± 26) μb after correcting for events which were excluded as background in the $\bar{p}\,p\,\omega^0$, $\bar{p}\,p\,\eta^0$ and $N^*(1238)\,\bar{N}^*(1238)\,\pi^0$ final states.

6. The $N^*(1518)$ $N\pi$ and $N\pi\pi$ decay branching ratios.

The $N^{*o}(1518)$ isobar has two 2-body $N\pi$ decay modes : $p\,\pi^-$ and $n\,\pi^o$. From the known isospin $I = 1/2$ of the isobar one obtains :

$$\sigma\,(N^{*o}(1518) \rightarrow \text{all } N\pi) = \frac{3}{2} \times \sigma\,(N^{*o}(1518) \rightarrow p\,\pi^-) = (219 \pm 60)\mu b \qquad (18)$$

In order to determine the full 3-body $N\pi\pi$ decay rate we note that the N^{*o} may decay into three different $N\pi\pi$ final states viz. : $p\,\pi^-\,\pi^o$ observed in channel (2), $n\,\pi^+\,\pi^-$ which may be observed in channel (3) and $n\,\pi^o\,\pi^o$ which cannot be detected in the present experiment. As in the case of the 3-body decays of the $N^*(1688)$ there is one parameter (the ratio of transition probabilities leading to $N\pi\pi$ systems with a $\pi\pi$ pair in isospin $I = 0$ or $I = 1$ states), which has to be known in order to determine the two ratios among the three decay rates of the aforementioned 3-body final states.

In the case of the $N^{*o}(1518)$ however we are in a more favourable position than for the $N^{*+}(1688)$ since two of the 3-body decays could be observed experimentally and the problem can in principle be solved completely.

The combined $n\,\pi^+\,\pi^-$ and $\bar{n}\,\pi^+\,\pi^-$ mass distribution for the channel (3) is shown in Fig. 3(c). In this channel however, we observe production of the $N^*(1238)$ in four 2-body mass combinations, namely for the case of the channel 3(a), $\bar{p}\,\pi^-$ ($\sim$ 20 o/o), $n\,\pi^-$ ($\sim$ 20 o/o), $n\,\pi^+$ ($\sim$ 16 o/o) and $\bar{p}\,\pi^+$ ($\sim$ 11 o/o). Using these estimates, the $n\,\pi^+\,\pi^-$ + c.c. mass spectrum has been computed as a sum of the five following phase space distributions : 3-body ($N\pi\pi$) out of 5 bodies, 2-body ($N^*\pi$) out of the 4-body reaction ($N^*N\pi\pi$), 3-body ($N\pi\pi$) out of the 4-body reaction ($N^*N\pi\pi$) and an additional two distributions where the neutron or one of the pions is a decay product of the $N^*(1238)$. The result, normalized to all events in the histograms, is shown in Fig. 3(c) as a continuous line.

There is no obvious indication for an excess of events in the $N^{*0}(1518)$ region which could correspond to the peaks observed in the $p\pi^-$ and $p\,\pi^-\,\pi^0$ distributions. The number of the $N^{*0}(1518) \rightarrow n\,\pi^+\,\pi^-$ + c.c. isobar events determined from Fig. 3(c) under the assumption that the background is smooth in the region 1.41 - 1.61 GeV, is found to be $(2\,^{+\,49}_{-\,2})$ events and corresponds to a cross section of $(2\,^{+\,56}_{-\,2})$ μb.

From isospin considerations the branching ratio R_1, defined as

$$R_1 = \frac{N^{*0}(1518) \rightarrow n\,\pi^+\,\pi^-}{N^{*0}(1518) \rightarrow p\,\pi^-\,\pi^0} \tag{19}$$

has a minimum value of 1/2 when the amplitude for $N\pi\pi$ decays with the $\pi\pi$ pair in an isospin state I = 0 is zero. (The amplitude for the I = 1 state, of the $\pi\pi$ pair must be different from zero since this amplitude gives rise to the observed $p\,\pi^-\,\pi^0$ mode). Although the observed value R_1 is $0.0^{+0.5}$ and is one standard deviation below the allowed minimum it is consistent with it, and in the considerations below we will use the minimum value with an upper experimental error, viz. :

$$R_1 = 0.5\,^{+\,0.5}_{-\,0.0} \tag{20}$$

From (20) we deduce that the $n\,\pi^0\,\pi^0$ decay rate of the $N^{*0}(1518)$ is small. Furthermore one can show by I-spin considerations that the ratio

$$\frac{N^{*0}(1518) \rightarrow \text{all } N\,\pi\,\pi}{N^{*0}(1518) \rightarrow p\,\pi^-\,\pi^0} = \frac{3}{2}\left(R_1 + \frac{1}{2}\right) \tag{21}$$

and hence $\sigma\,(N^{*0}(1518) \rightarrow \text{all } N\,\pi\,\pi) = (1.5\,^{+\,.75}_{-\,.0}) \times \sigma\,(N^{*0}(1518) \rightarrow p\,\pi^-\,\pi^0) =$ $(176\,^{+\,88}_{-\,39})$ μb.

The best estimate then of the 2-body $N\pi$ to the 3-body $N\pi\pi$ branching ratio for the $N^*(1518)$ is :

$$\frac{N^*(1518) \rightarrow \text{all } N\pi}{N^*(1518) \rightarrow \text{all } N\pi\pi} = 1.25 \begin{array}{l} + 0.44 \\ - 0.71 \end{array} .$$

This figure is in good agreement with the value of ~1.5 determined from the phase-shift analysis of P. Baryere et al[11] for the $J^P = 3/2^-$, $I = 1/2$, D-wave isobar.

7. Evidence against the importance of the cascade decay of the $N^*(1518)$ into $N^*(1238)$ and π.

In this section we discuss the evidence against the importance of the $N^*(1518)$ decay mode into $N^*(1238) + \pi$ which has been suggested previously by J. Kirz et al[17] and by H.R. Crouch et al[18].

Despite a high background which is present below the $N^{*0}(1518)$ bump in the $p\,\pi^-\,\pi^0$ combinations we now attempt to study the details of this 3-body decay. Firstly we recall that the $\pi^-\,\pi^0$ pair is in a pure $I = 1$ state and therefore due to Bose statistics the wave function of the $p\,\pi^-\,\pi^0$ system must be antisymmetric relative to exchange of pions. So e.g. there should be no difference between the $M\,(p\,\pi^-)$ and the $M\,(p\,\pi^0)$ mass distributions for the isobar decay products.

In Fig. 4 we present the $M(p\,\pi^-)$ and $M(p\,\pi^0)$ distributions in the $M(p\,\pi^-\,\pi^0)$ peak region 1.46 - 1.56 GeV (Fig. 4(b)) and in the 2 control regions 1.36 - 1.46 GeV except those containing an ω^0 or η^0 meson. The plotted masses were normalized to the central $(p\,\pi^-\,\pi^0)$ mass values by multiplying the kinetic energies of the particles in the $p\,\pi^-\pi^0$ rest frame by the ratio of the central to the actual Q value of the $p\,\pi^-\pi^0$ system. The full lines on the figure show the phase space predictions normalized to all 263 background events in the case of the peak region (Fig. 4(b)).

Since the phase space curves fit relatively well the distributions (a) and (c) one might conclude that events above the full line in Fig. 4(b) are genuine $N^{*o}(1518) \rightarrow p\,\pi^-\,\pi^o$ + c.c. decays. There is indeed some accumulation of $M(p\pi)$ masses in the region of the $N^*(1238)$. However the measured low value of the branching ratio R_1 (0.0 + 0.5) is in contradiction, as we show below, with what one expects for the decay via the $N^*(1238)$. Thus consider the cascade decay

$$N^{*o}(1518) \rightarrow N^{*\overset{+}{\underset{-}{o}}}(1238) + \pi^{\overset{-}{\underset{o}{+}}} \begin{cases} \rightarrow p\,\pi^-\,\pi^o \\ \rightarrow n\,\pi^+\,\pi^- \end{cases} \qquad (22)$$

We may express the initial isotopic spin state $N^{*o}(I = 1/2,\ I_3 = -1/2)$ in terms of the final isotopic spin states $p\,\pi^-\,\pi^o$ and $n\,\pi^+\,\pi^-$ as follows

$$N^{*o}(1518) = \sqrt{\frac{1}{9}}(p\pi^o)\pi^- - \sqrt{\frac{1}{9}}(p\pi^-)\pi^o + \sqrt{\frac{1}{2}}(n\pi^-)\pi^+ + \sqrt{\frac{1}{18}}\,(n\pi^+)\pi^- \qquad (23)$$

where the particles in parentheses form the $N^*(1238)$ in the intermediate state and the $n\,\pi^o\,\pi^o$ contribution has been omitted.

Neglecting interference terms one obtains for the branching ratio R_1 :

$$R_1 = \frac{1/2 + 1/18}{1/9 + 1/9} = 2.5 \qquad (24)$$

which is 4 standard deviations higher than the minimum possible value of $0.5\,^{+\,0.5}_{-\,0.0}$. However it is necessary to consider the influence of possible interference and to this end Fig. 5 shows the Dalitz plot for the peak region of the $p\,\pi^-\,\pi^o$ mass spectrum excluding ω^o and η^o events. The expected position of the $N^*(1238)$ isobar is indicated. The Dalitz plot is dominated by the overlap region of the two $N^*(1238)$ bands and therefore interference terms in the transition probabilities for the decays (22) could be important and must be taken into account.

Detailed calculations of the ratio R_1 were performed in which s-wave decay of the $N^*(1518)$ into $N^*(1238)$ plus π was assumed (the d-wave amplitude is expected to be unimportant as the Q value of the decay is 150 MeV only). The matrix element for the hypothetical cascade decay is then relatively simple and consists of the $N^*(1238)$ spin function multiplied by a Breit-Wigner resonant factor, which we take as

$$\frac{\Gamma^{1/2}}{(M_{N\pi}^2 - M_o^2) + i\, M_o\, \Gamma}$$

where $M_{N\pi}$ is the effective nucleon-pion mass, M_o, the resonance mass, taken as 1230 MeV, and, Γ the width taken, as 120 MeV with an energy dependence required by the p-wave decay of the $N^*(1238)$.

The two matrix elements for the $p\,\pi^-\,\pi^o$ final state, depending on which of the $p\,\pi^-$ or $p\,\pi^o$ system formed the $N^{*o}(1238)$, were then multiplied by the isospin coefficients given in equation (23), squared and integrated over the Dalitz plot together with appropriate phase space factors. A similar integration has been done for the interference terms.

As can be seen from equation (23) the interference term for $p\,\pi^-\,\pi^o$ decay has a negative sign which follows from the fact that the $\pi^-\,\pi^o$ pair is in an I = 1 state thus yielding completely destructive interference along the line $M^2(p\pi^-) = M^2(p\pi^o)$. Furthermore in the nearby region which covers most of the $N^*(1238)$ area the interference should also be strongly destructive. In contrast the interference in the $n\,\pi^+\,\pi^-$ final state, which is also important, is constructive.

Taking the interference into account the value found, by numerical integration, for the branching ratio R_1 is 6.1, more than 2 times higher than the value found by neglecting interference effects. Thus if the cascade decay rate represents a fraction R_c of the full 3-body decay rate we find that

$$R_c = \frac{N^*(1518) \rightarrow N^*(1238) + \pi}{N^*(1518) \rightarrow N\,\pi\,\pi} = 0.00 + 0.09 \qquad (25)$$

or on a 95 o/o significance level the branching ratio R_c is smaller than 18 o/o.

A few comments remain to be made about the $p\,\pi^-\,\pi^o$ mass spectrum for the peak region which has been shown in Fig. 4(b). Assuming a genuine 3-body decay of the $N^*(1518)$ into $p\,\pi^-\,\pi^o$ we have 2 possible decay matrix elements which correspond to spin-parity $3/2^-$ constructed from the proton spin-parity $1/2^+$ and the total orbital angular momentum and parity of the 3 final bodies of 1^- or 2^-. These matrix elements are

$$p_1^\mu - p_2^\mu \qquad (26a)$$

and

$$(p_1^\mu + p_2^\mu)\;q^\nu + (p_1^\nu + p_2^\nu)\;q^\mu \;, \qquad (26b)$$

where p_1^μ , p_2^μ are the momentum vectors of the π^- and the π^o in the $N^*(1518)$ rest frame, and $\vec{q} = \vec{p}_1 \times \vec{p}_2$. The data in the Dalitz plot are too poor and contain too much background to allow a determination of a ratio of these 2 matrix elements. Both are acceptable, the dashed curve which is shown in Fig. 3(b) corresponds to the square of the one given in (26b) which fits better the data.

8. Conclusions.

Production of the nucleon isobars $N^*(1518)$ and $N^*(1688)$ is observed in $\bar{p}p$ interactions at 5.7 GeV/c.

The cross sections for the reaction

$$\bar{p}p \rightarrow \bar{p}\, N^{*o}(1518)\, \pi^+ + c.c.$$

followed by the 2-body $p\pi^-$ and the 3-body $p\, \pi^-\, \pi^o$ decay of the $N^*(1518)$ are found to be (146 ± 40) μb and (117 ± 26) μb respectively.

The cross section for the reaction

$$\bar{p}p \rightarrow \bar{p}\, N^{*+}(1688) + c.c.$$

followed by the 3-body $p\, \pi^+\, \pi^-$ decay of the $N^*(1688)$ is estimated to be (242 ± 42) μb.

The measured mass (M) and width (Γ) are :

$M = (1507 \pm 6)$ MeV, $\Gamma = (55 \pm 15)$ MeV for the $N^*(1518)$ isobar and $M = (1695 \pm 9)$ MeV, $\Gamma = (70 \pm 20)$ MeV for the $N^*(1688)$ isobar.

The 3-body $N\pi\pi$ decay modes are found to have high rates for both isobars; the 2-body to 3-body branching ratios being equal to $1.25 \begin{smallmatrix} +\ 0.44 \\ -\ 0.71 \end{smallmatrix}$ in the case of the $N^*(1518)$ and less than 1.26 with 95 o/o confidence for the $N^*(1688)$.

Upper limits for the $N\eta$ and ΛK decay modes of the $N^*(1688)$ are estimated to be 4.2 o/o and 1.3 o/o respectively with a 95 o/o confidence level.

A detailed study of the $N\pi\pi$ decays does not provide any evidence for the cascade $N^*(1238) + \pi$ decays. The observed deviations from the uniform population of the Dalitz plots may be explained as due to the 3-body decay matrix elements.

An attempt to determine the parity of the $N^*(1688)$ from its 3-body decay mode failed due to high background and ambiguities concerning various matrix elements which have to be considered.

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FIGURE CAPTIONS

1. (a) Mass distribution of the $p\,\pi^+\,\pi^-$ and $\bar{p}\,\pi^+\,\pi^-$ combinations from channel (1).
Events with $p\pi^+$ and $\bar{p}\pi^-$ mass lying in the $N^*(1238)$ $\bar{N}^*(1238)$ region has been excluded. Continuous lines show the fit to the peak region (1.48 - 1.92 GeV) using a sum of a straight line and a Breit-Wigner curve.

(b) Mass distribution of the $p\,\pi^+\,\pi^-$ and $\bar{p}\,\pi^+\,\pi^-$ combinations from the channel (1). Only events for which both the $(p\pi^+)$ and $(\bar{p}\pi^-)$ mass are inside the interval 1.15 - 1.35 GeV were plotted.

(c) The $p\,\eta^o$ and $\bar{p}\,\eta^o$ mass spectrum for the 3-body final state $\bar{p}\,p\,\eta^o$ selected from channel (2).

(d) The $\Lambda\,K^+$ and $\bar{\Lambda}\,K^-$ mass spectrum for channel (4).

2. Dalitz plots for the $N^{*+}(1688)$ decay into the $p\,\pi^+\,\pi^-$ system (and c.c.). The upper one is for the peak region and the lower for the adjacent regions as defined in the text. In all projections, both for the peak and the control regions, the full continuous lines show the same phase-space distribution normalized to the 369 non-resonant events. The dashed lines show the best fit for the $5/2^+$ assignment of the $N^{*+}(1688)$ assuming a genuine 3-body decay.

3. (a) Mass distribution of the $p\,\pi^-$ and $\bar{p}\,\pi^+$ combinations from channel (1), events with $p\pi^+$ and $\bar{p}\pi^-$ mass lying in the $N^*(1238)$ $\bar{N}^*(1238)$ region have been excluded. Continuous lines show the fit to the $N^*(1518)$ peak region from 1.34 to 1.76 GeV as a sum of a straight line (extended outside by hand) and a Breit-Wigner curve.

(b) Mass distribution of the $p\,\pi^-\,\pi^0$ and $\bar{p}\,\pi^+\,\pi^0$ combinations from channel (2). The 3-body final states containing ω^0 or η^0 production as well as the $N^*(1238)\ \bar{N}^*(1238)\ \pi^0$ final state have been excluded. The continuous line shows a phase-space curve normalized to all events outisde the $N^*(1518)$ peak plus a fitted Breit-Wigner curve.

(c) Mass distribution of the $n\,\pi^+\,\pi^-$ and $\bar{n}\,\pi^+\,\pi^-$ combinations from channels (3a) and (3b). The smooth line is a phase-space curve which includes reflections of the $N^*(1238)$ production observed in these channels, as explained in the text.

4. Mass distribution of the $p\,\pi^-$, $p\,\pi^0$ and the $\bar{p}\,\pi^+$, $\bar{p}\,\pi^0$ combinations from 3 intervals of the $p\,\pi^-\,\pi^0$ or the $\bar{p}\,\pi^+\,\pi^0$ mass spectrum :

(a) below the $N^*(1518)$ peak : 1.36 - 1.46 GeV,

(b) at the peak region : 1.46 - 1.56 GeV,

(c) above the $N^*(1518)$ peak : 1.56 - 1.66 GeV.

The full, continuous lines in (a) and (c) show phase space distributions normalized to all events and in (b) to the expected number of background events. The dashed line in (b) shows a possible matrix element prediction for the 3-body decay of the $N^*(1518)$.

5. Dalitz plot for the $N^{*0}(1518)$ decay into the $p\pi^-\pi^0$ system (and c.c.). The expected $N^*(1238)$ bands, corresponding to the full width at a half-height, are marked together with the expected positions of the maxima.

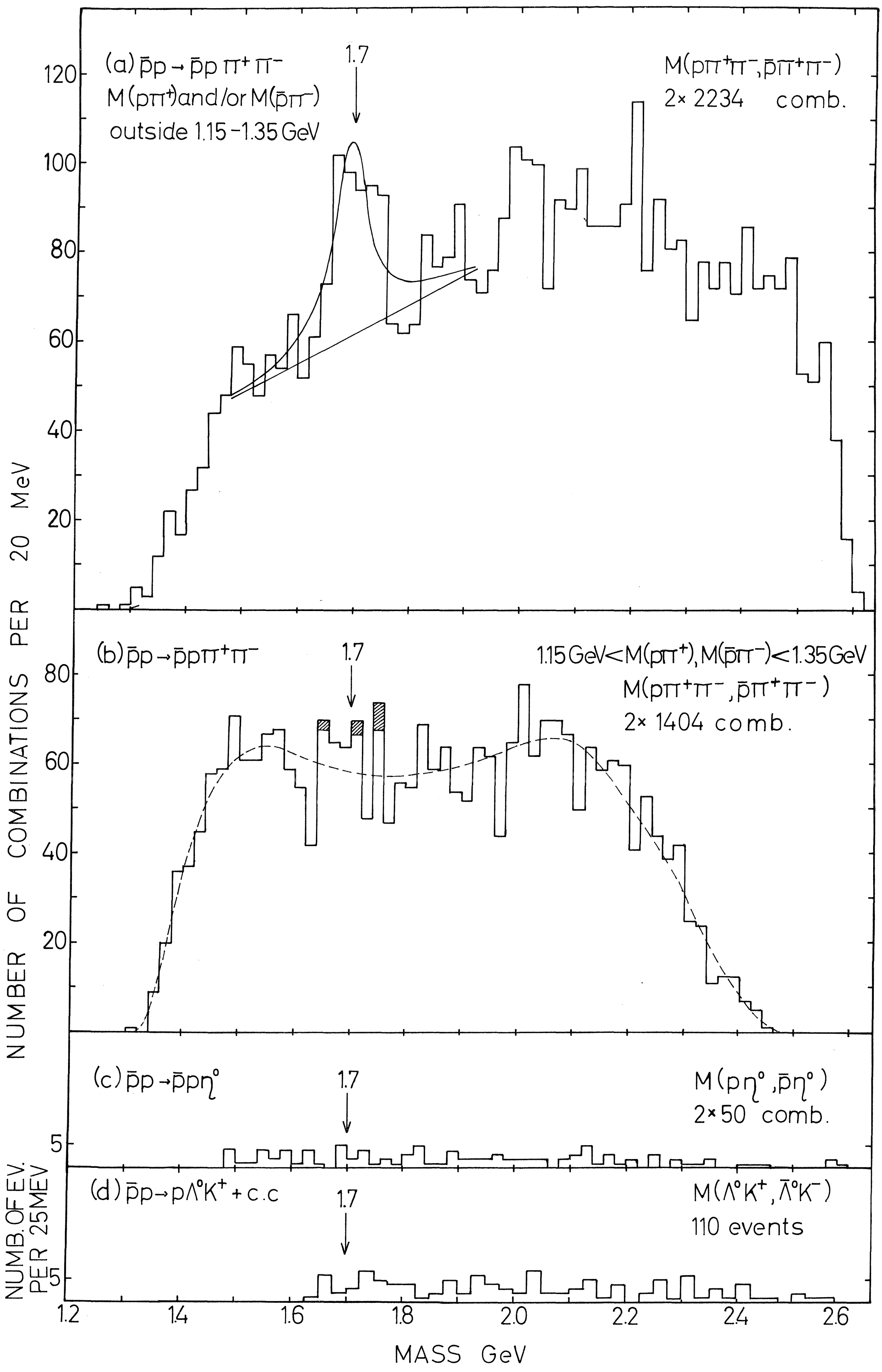
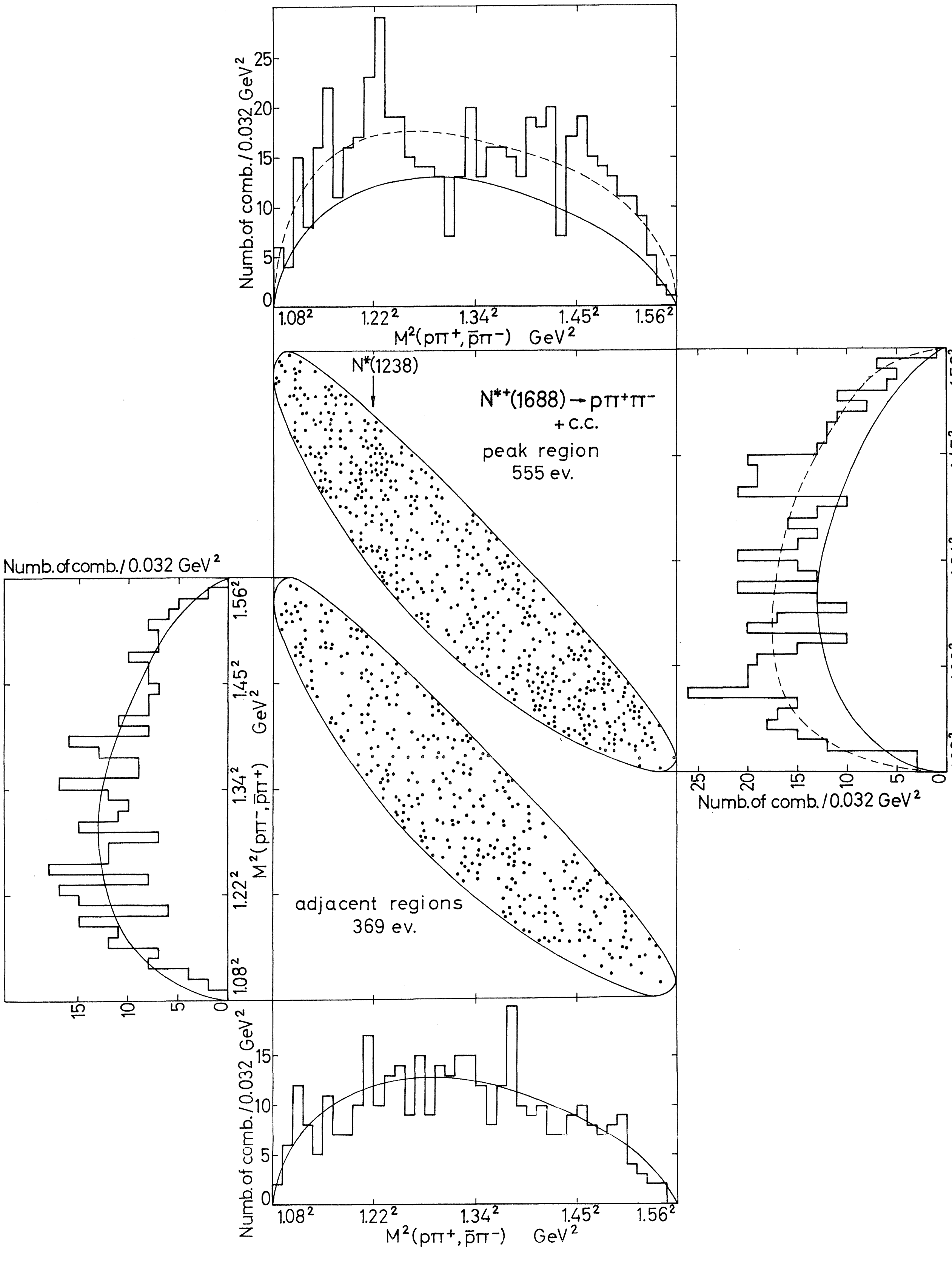


Fig. 1

SIS/R/13341



Numb.of comb./0.032 GeV^2
M^2(pπ$^+$, p̄π$^-$) GeV^2
N*(1238)
N^{*+}(1688) → pπ$^+$π$^-$ + c.c.
peak region
555 ev.
adjacent regions
369 ev.
M^2(pπ$^-$, p̄π$^+$) GeV^2

Fig. 2

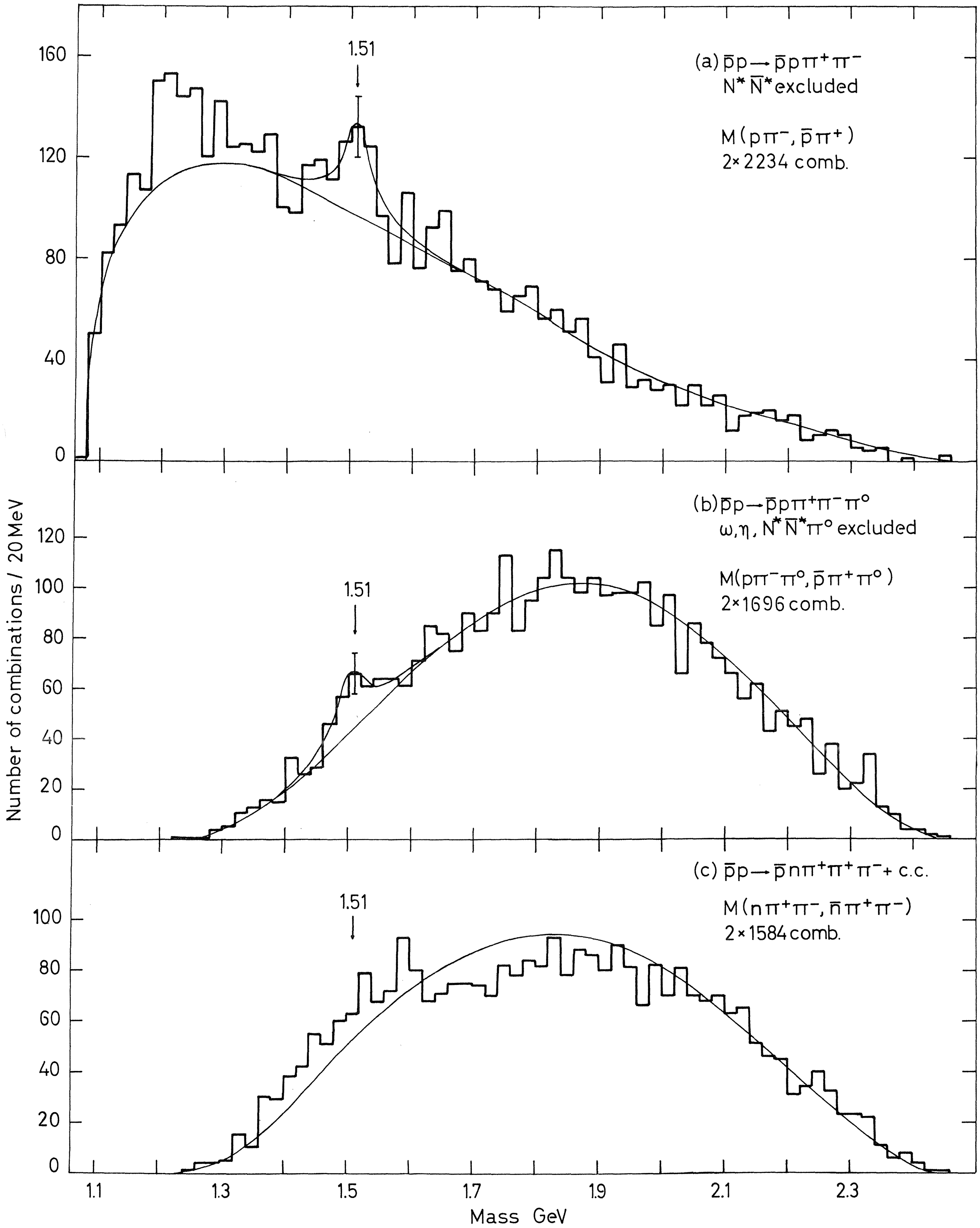


Fig. 3

SIS/R/13345

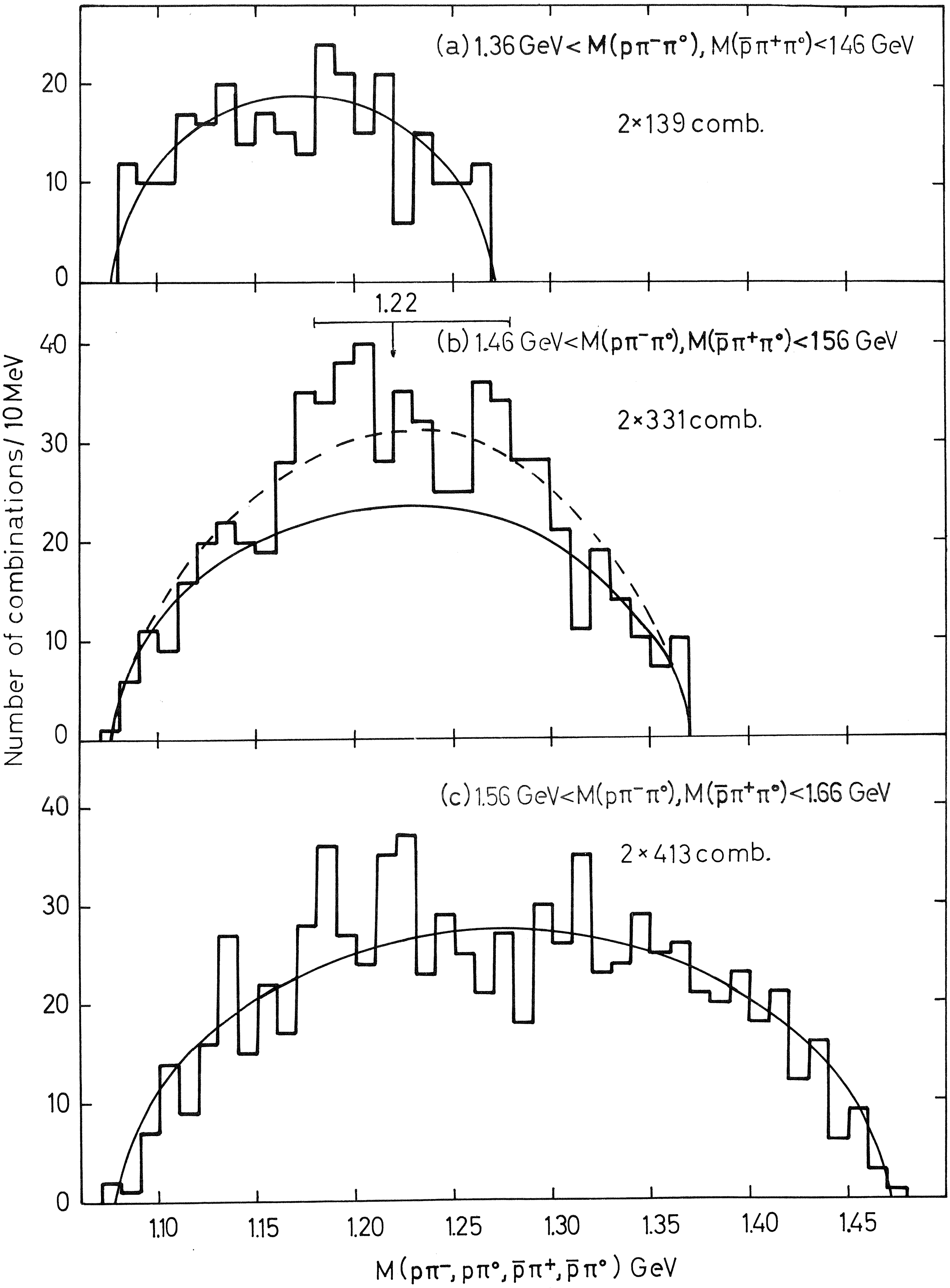


Fig. 4

SIS/R/13342

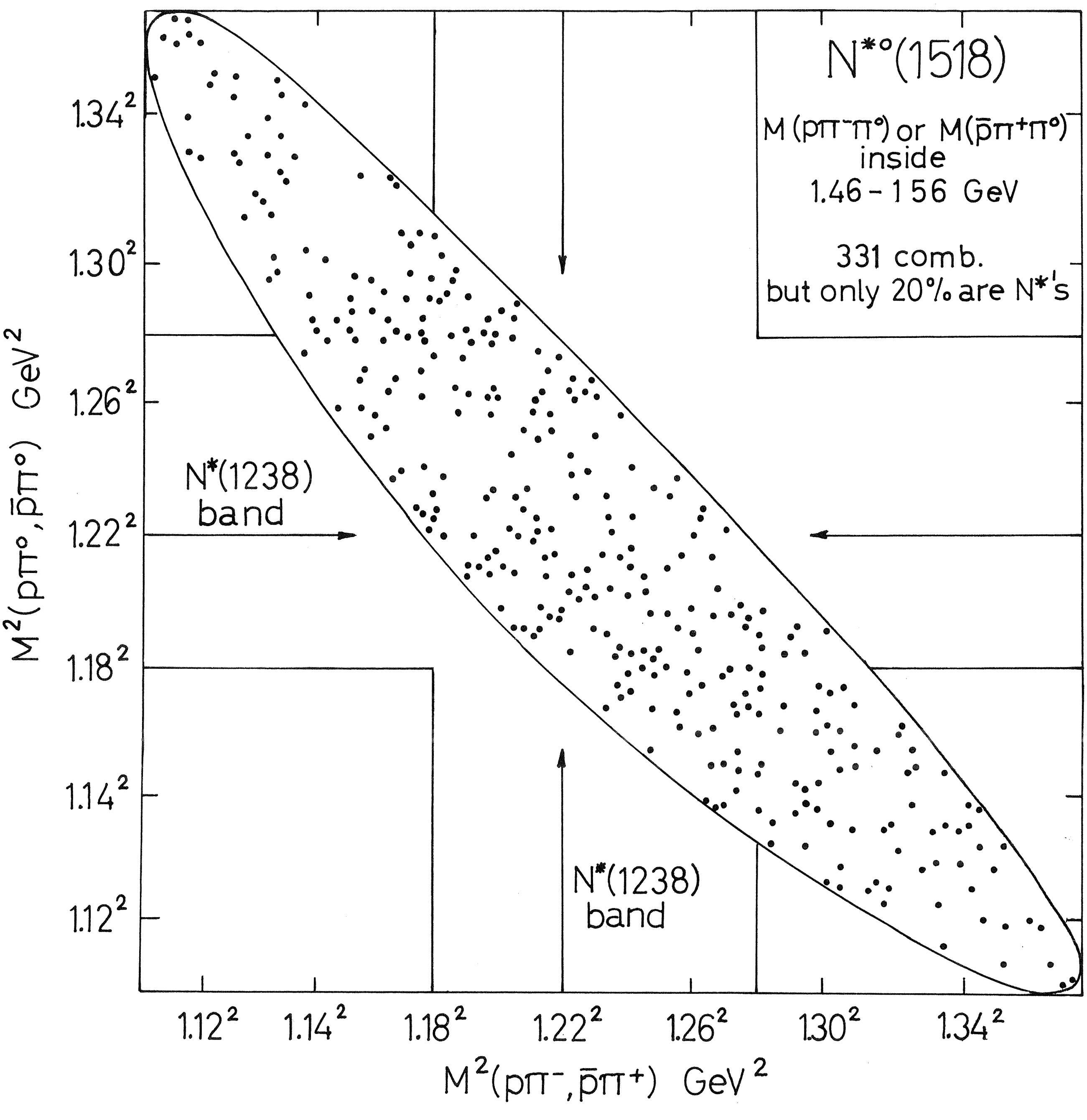


Fig. 5

SIS/R/13344