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ABSTRACT

A study of the A_2^+ mass spectrum in $\pi^+ p$ interactions at 3.7 GeV/c is presented. For a cut of $t' = 0.1\text{-}2.0$ GeV^2 and on eliminating the Δ^{++} we find that the three pion mass spectrum in the A_2^+ region is fitted by the dipole formula with a confidence level of 53% and a single Breit-Wigner formula with a confidence level of 11%. Our result thus favors A_2^+ splitting although a single Breit-Wigner fit cannot be ruled out. We also report the A_2^+ decay branching fractions measured over all t' values. They are 0.78 ± 0.05, 0.15 ± 0.04, 0.06 ± 0.03, and < 0.02 for $\rho\pi$, $\eta\pi$, $K\bar{K}$, and $\eta'\pi$ respectively, in good agreement with other experiments.

The A_2 meson has been the subject of considerable experimental and theoretical investigation since the observation of the splitting of the A_2^- by the CERN Missing Mass Spectrometer and CERN Boson Spectrometer experiments.[1] Much less was known about the positive A_2 meson. The Bonn-Durham-Nijmegen-Paris(E.P.)-Torino Collaboration reported[2] observing structure in the A_2^+ in 5 GeV/c $\pi^+ p$ interactions, but their statistics were rather limited. More recently Alston-Garnjost et al.[3] have reported on a high-statistics $\pi^+ p$ bubble chamber experiment at 7 GeV/c, where they see no evidence for splitting. Furthermore a neutron missing mass spectrometer experiment[4] has recently

studied the A_2^o in $\pi^- p$ interactions at 3.16 GeV/c incident momentum and observed splitting.

In this Letter we report some evidence favoring the splitting of the A_2^+ produced in $\pi^+ p$ interactions at 3.7 GeV/c with a sample of A_2^+ events intermediate in number between that of the 5 GeV/c and 7 GeV/c experiments. The data comes from a 180,000 picture exposure of the Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber at the Bevatron. The experimental details have already been presented.[5,6] The exposure yielded the following numbers of events in the channels of interest to the A_2^+ study

$\pi^+ p \rightarrow p\pi^+\pi^+\pi^-$	16,445 events	(1)
$\pi^+ p \rightarrow p\pi^+\pi^+\pi^-\pi^o$	16,617 events	(2)
$\pi^+ p \rightarrow p\pi^+\pi^+\pi^-$ MM	7,463 events	(3)
$\pi^+ p \rightarrow pK^+\bar{K}^o$	92 events	(4)

Reaction (3) consists of those events with two or more missing neutral particles for which the proton can be identified by ionization. In channel (4) we require the $K_1^o \rightarrow \pi^+\pi^-$ decay to be observed in the chamber. We have observed the A_2^+ decays to $\pi^+\pi^+\pi^-$, $\eta\pi^+$ and $K^+\bar{K}^o$ in channels (1), (2) and (4) respectively and searched for the $\eta'\pi^+$ decay mode in channel (3). However the statistics are limited for the $\eta\pi^+$, $K^+\bar{K}^o$ and $\eta'\pi^+$ decay modes with the result that we have information on decay branching ratios but can make no statement about structure in these cases.

Reaction (1) is dominated by the production of the $\Delta^{++}\rho^o$ quasi-two-body channel which has been discussed earlier.[6] To eliminate all contamination due to this and other Δ^{++} production channels, events with at least one $p\pi^+$ effective mass less than 1380 MeV were removed. The effect of making this selection can be seen in Fig. 1. The $\pi^+\pi^+\pi^-$ mass spectrum before making any cuts is shown in Fig. 1a. The A_2^+ stands on a very large background. The

shaded histogram in Fig. 1a is the $\pi^+\pi^+\pi^-$ spectrum for the 12,117 events which have at least one $p\pi^+$ mass less than 1380 MeV, i.e., the events which are removed in order to study the A_2^+. It can be seen that there is no evidence for an A_2^+ signal in these events. There is however a shoulder at 1300 MeV. We cannot say whether the absence of an A_2^+ signal in the Δ^{++} region results from the dynamics of the $A_2^+ \to \rho^o\pi^+$ decay being such that there is little overlap with the Δ^{++} band on the $p\pi^+\rho^o$ Dalitz plot, or if some interference effect is occurring with the Δ^{++} amplitude. In Fig. 1b we show the $\pi^+\pi^+\pi^-$ mass spectrum when these Δ^{++} events have been removed. A clear A_2^+ signal is seen. Its mass however is shifted downwards somewhat from its value in the uncut spectrum in Fig. 1a primarily because of the shoulder at 1300 MeV in the Δ^{++} events. A fit of a single Breit-Wigner resonance, with a second-order polynomial in mass as background, made to the data in Fig. 1b (in 20-MeV bins in order to ignore possible structure), gives a resonance mass of 1307±4 MeV. A similar fit to the uncut spectrum in Fig. 1a gives a mass of 1324±6 MeV.

The number of A_2^+ events above the fitted background in Fig. 1b is 388±64. The error is the combination in quadrature of the statistical error on the total number of events in the fitted region (1100-1500 MeV) and the number of events under the background in this same region. It should be noted that on removing the Δ^{++} events we have a clear A_2^+ signal before applying any t cuts. We have been able to calculate A_2^+ branching ratios without making t selections. This is advantageous since, as has been pointed out,[7] if the A_2 consists of more than one resonance there could be a t dependence of the branching ratios. The branching fractions which we obtain for the $\rho\pi$, $\eta\pi$, $K\bar{K}$, and $\eta'\pi$ decay modes[8-13] are given in Table I. The results are in good agreement with the 5 GeV/c (Ref. 2) and 7 GeV/c (Ref. 7) π^+p values, and with the world averages.[14]

We have searched for evidence of structure by an examination of the 3π spectrum for various t' cuts.($t' = |t - t_{min}|$ where $|t_{min}|$ is the minimum value of $|t|$ kinematically allowed for each event. At a 3π mass of 1300 MeV $|t_{min}| \approx 0.074$ GeV^2.) Figure 2 shows the 3π spectrum in 20-MeV bins for one such set of cuts. As has been observed in other experiments[2,3] the $t' < 0.1$ GeV^2 region (Fig. 2a) is dominated by the broad low mass A_1 enhancement with very little A_2 signal. The A_2 signal is clear in the t' interval 0.1-0.6 (Fig. 2b) and again for $t' > 1.0$ (Fig. 2d,e). There is no compelling evidence for A_2 production in the t' interval 0.6-1.0 (Fig. 2c).

Ideally one would like to study a very narrow t' range both for comparison with the missing mass experiments and for interfering resonance model considerations.[15] In such a model the two resonances can have different production mechanisms so that interference may only be observed over a limited region of t where coherence between the two amplitudes holds. As a compromise, in view of our limited statistics, we show in Fig. 3 the 3π mass distribution in 10-MeV bins for the t' interval 0.1-2.0 GeV^2. This t' interval gives a good A_2-to-background ratio and shows an indication of splitting.

Calibration studies of the mass errors obtained from the kinematic fitting program have been made in connection with the ω-ρ interference effect[5] and the determination of the width of the ω.[16] For the events in Fig. 3, $\Gamma_R/2 = 7$ MeV where Γ_R is the full width at half height of the resolution function. In order to ascertain the statistical significance of the dip centered at 1310 MeV in Fig. 3 we have followed the now "standard" procedure[1] of fitting the data to either a single Breit-Wigner resonance or a dipole shape[17] plus a linear background in each case. The theoretical curves were folded with the experimental resolution function and binned using the program EXTRACT,[18] to make the fit through a χ^2 minimization procedure. The parameters obtained from the fits are given in Table II. It can be seen that the dipole

fit is favored over the single Breit-Wigner resonance, but with a confidence level[19] of 11% the Breit-Wigner cannot be completely ruled out. We also note that the interfering resonance model discussed in the following Letter[15] gives good fits to the mass spectrum.

The number of events in the dipole signal of Fig. 3 for the mass range 1200-1400 MeV is 297, and the background-to-signal ratio in this same region is 1.6/1. The values for the 5 GeV/c experiment are 108 and 1.3 respectively ($t' > 0.1$ GeV^2) and for the 7 GeV/c experiment 833 and 1.4 ($t > 0.2$ GeV^2).

The fitted dipole mass 1311.6±2.6 MeV is rather higher than the CERN value 1298±5 MeV but is more consistent with the value observed in the $\pi^+ p$ experiment[2] at 5 GeV/c 1306±4 MeV and the A_2^o dipole mass[4] 1305.3±1.5 MeV. The errors we quote are those obtained from the fitting program and do not take into account systematic errors. We believe however that systematic mass errors in this channel are small. This is discussed in detail by Coyne et al.[16]

In conclusion we can state that we see some evidence for splitting in the A_2^+ mass spectrum for the t' range 0.1-2.0 GeV^2 when the Δ^{++} signal is removed. The dipole fit is favored over a single Breit-Wigner with confidence levels of 53% and 11% respectively. The single Breit-Wigner hypothesis cannot however be ruled out by our data.

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Table I. A_2^+ decay branching ratios.

Channel	Number of events observed	Number corrected for unseen decays[a]	Cross section μb	Branching fraction
$\rho\pi$	388±64	776±128	166±27	0.78±0.05
$\eta\pi$	34±8	149±34	32±7	0.15±0.04
$K\bar{K}$	17±8	55±25	13±6	0.06±0.03
$\eta'\pi$	2±2	6±6	< 4[b]	< 0.02[b]
A_2^+ total			212±29	

a. See Refs. 8-13.

b. This figure represents an upper limit at the two standard deviation level.

Table II. Fits to the three pion mass spectrum in 10 MeV bins for $t' = 0.1\text{-}2.0$ GeV^2.

	Mass MeV	Γ MeV	χ^2/d.f. 1220-1380 MeV	C.L. 1220-1380 MeV
Dipole	1311.6±2.6	33.5±4.0	9.0/10	53%
Breit-Wigner	1304.0±4.5	111.4±18.0	15.7/10	11%

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2. K. Böckmann et al., Nuclear Physics B16, 221 (1970).
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5. G. Goldhaber et al., Phys. Rev. Letters 23, 1351 (1969).
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8. For $\pi\rho$ decay: As has been found in other experiments[2,3] the Dalitz plot in the A_2^+ region is consistent with the $\pi^+\pi^+\pi^-$ decay of the A_2^+ being entirely $\rho^o\pi^+$. We therefore multiply the observed number of events by two to allow for the unseen $A_2^+ \to \rho^+\pi^o \to \pi^+\pi^o\pi^o$ decays.
9. For $\eta\pi$ decay: To estimate the $\eta\pi^+$ branching ratio we have made the same Δ^{++} antiselection in reaction (2) as was used for reaction (1). We have selected the η events from the remaining events in reaction (2) by a 540-560 MeV cut on $\pi^+\pi^-\pi^o$ effective mass. We estimate that this cut includes as many non-η events as it cuts true η events from the tails of the distribution. A fit to the $\eta\pi^+$ mass spectrum with a phase space curve plus Breit-

Wigner gives an adequate fit and results in the number of events shown in Table I. We have corrected for the unseen η decays using the branching ratios in Ref. 14. For further details see Ref. 13.

10. For $K\bar{K}$ decay: We observe 17±8 events in the $K^{+}\bar{K}^{o}$ decay mode of the A_2^+ where the error includes uncertainty in estimating the background level. This when corrected for unseen $\bar{K}^{o}$ decays gives the total number of events shown in Table I. For further details see Ref. 11.

11. W. R. Butler (Ph.D. Thesis), UCRL-19845 (1970), unpublished.

12. For $\eta'\pi$ decay: We observe a strong η signal in the missing mass distribution for reaction (3) and a clear η' signal in the $\pi^{+}\pi^{-}\eta$ mass distribution for those events in this channel which fit the one constraint hypothesis $\pi^{+}p \rightarrow p\pi^{+}\pi^{+}\pi^{-}\eta$. We do not however see any compelling evidence for the $A_2^+ \rightarrow \eta'\pi^{+}$ decay, and can only set a rough limit at 2±2 events. The corrections for unseen decays allow for the presence of 75% of the $\pi^{o}\pi^{o}\eta$ decay of the η' where η decays to $\pi^{+}\pi^{-}\pi^{o}$, as this fraction of such decays has a $\pi^{o}\pi^{o}\pi^{o}$ mass within our η missing mass limits. For further details see Ref. 13.

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15. K. W. J. Barnham and G. Goldhaber, Phys. Rev. Letters (following Letter, UCRL-20293).

16. D. G. Coyne et al., UCRL-20088, submitted to Nuclear Physics B (1971).

17. $d\sigma/dm \sim (M - M_o)^2/[(M - M_o)^2 + (\Gamma/2)^2]^2$.

18. D. G. Coyne, EXTRACT, Lawrence Radiation Laboratory Trilling-Goldhaber Group Physics Note TG-175 (1969), unpublished.

19. The confidence levels in Table II were calculated using the same method

as was employed in Refs. 1 and 4. The fits were made over the entire region 1100-1500 MeV. The χ^2 was then calculated for the region 1220-1380 MeV and the total number of parameters (including one for normalization) subtracted from 16, the number of bins in this region, to obtain the number of degrees of freedom. The question of confidence levels is further discussed in Ref. 15.

FIGURE CAPTIONS

Fig. 1. (a) Uncut $\pi^+\pi^+\pi^-$ mass spectrum for the events in reaction (1). The shaded histogram shows the $\pi^+\pi^+\pi^-$ mass spectrum for those events for which at least one π^+p combination has mass < 1380 MeV. (b) The $\pi^+\pi^+\pi^-$ mass spectrum for those events with both π^+p combinations having mass > 1380 MeV (Δ^{++} out). The curve is explained in the text.

Fig. 2. (a-e) The $\pi^+\pi^+\pi^-$ mass spectrum for the events with Δ^{++} out and the cuts on $t' = |t - t_{min}|$ indicated.

Fig. 3. The $\pi^+\pi^+\pi^-$ mass spectrum in 10 MeV bins with Δ^{++} out and $t' = 0.1\text{-}2.0$ GeV^2. The parameters of the dipole fit (full curve) and Breit-Wigner fit (broken curve) are given in Table II. The curves connect the best fit points, the fits having been made by folding the theoretical distributions with the experimental resolution function and binning.

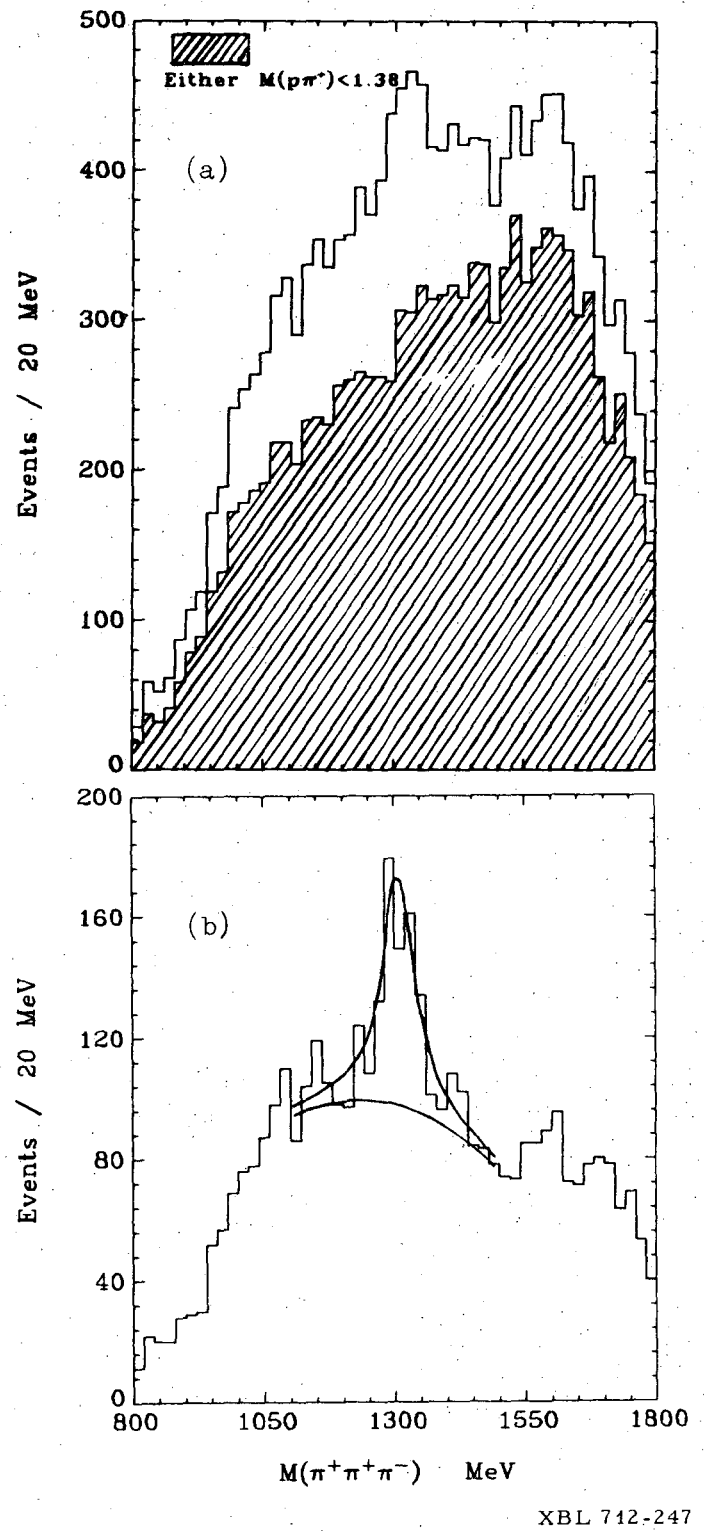

Either M(pπ⁺)<1.38
(a)
Events / 20 MeV
500
400
300
200
100
0
(b)
Events / 20 MeV
200
160
120
80
40
0
800
1050
1300
1550
1800
M(π⁺π⁺π⁻) MeV
XBL 712-247

Fig. 1

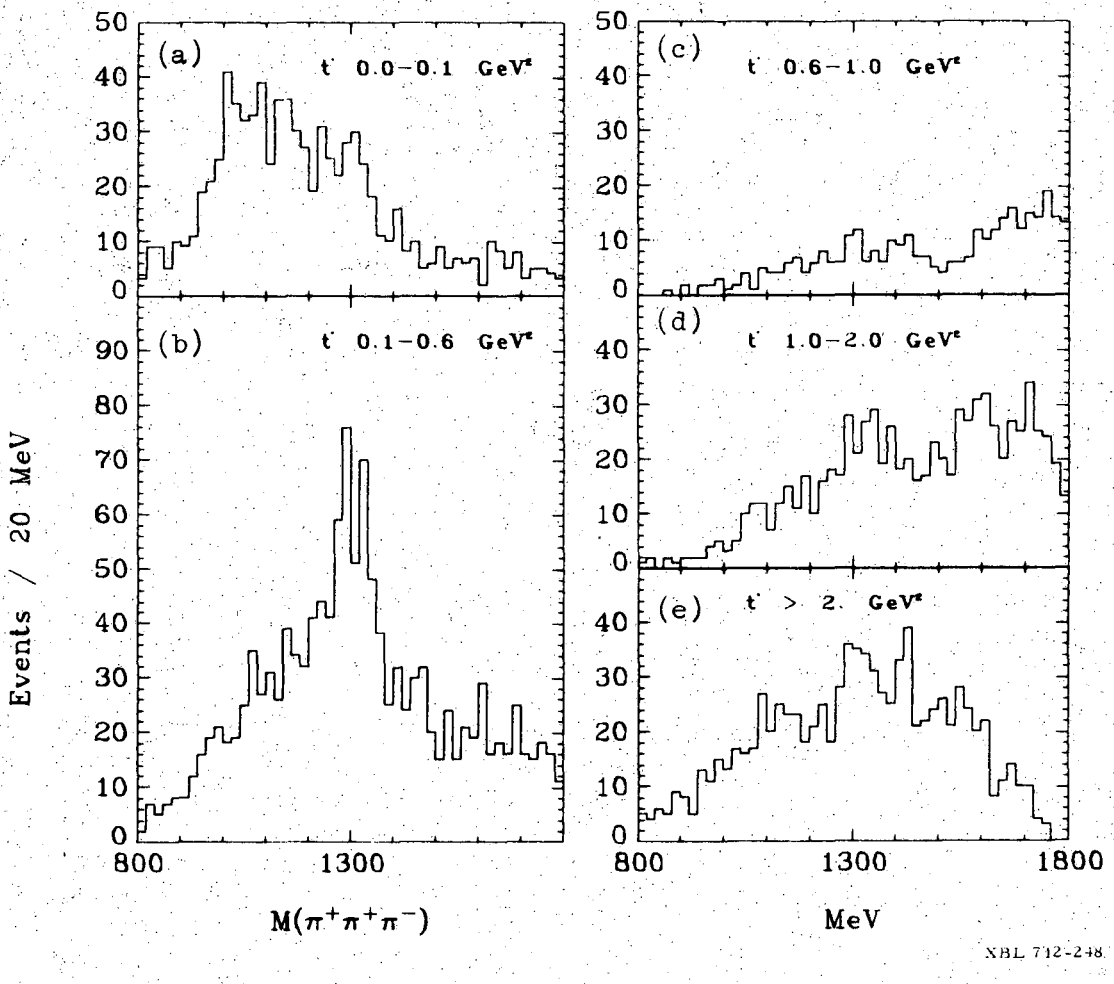
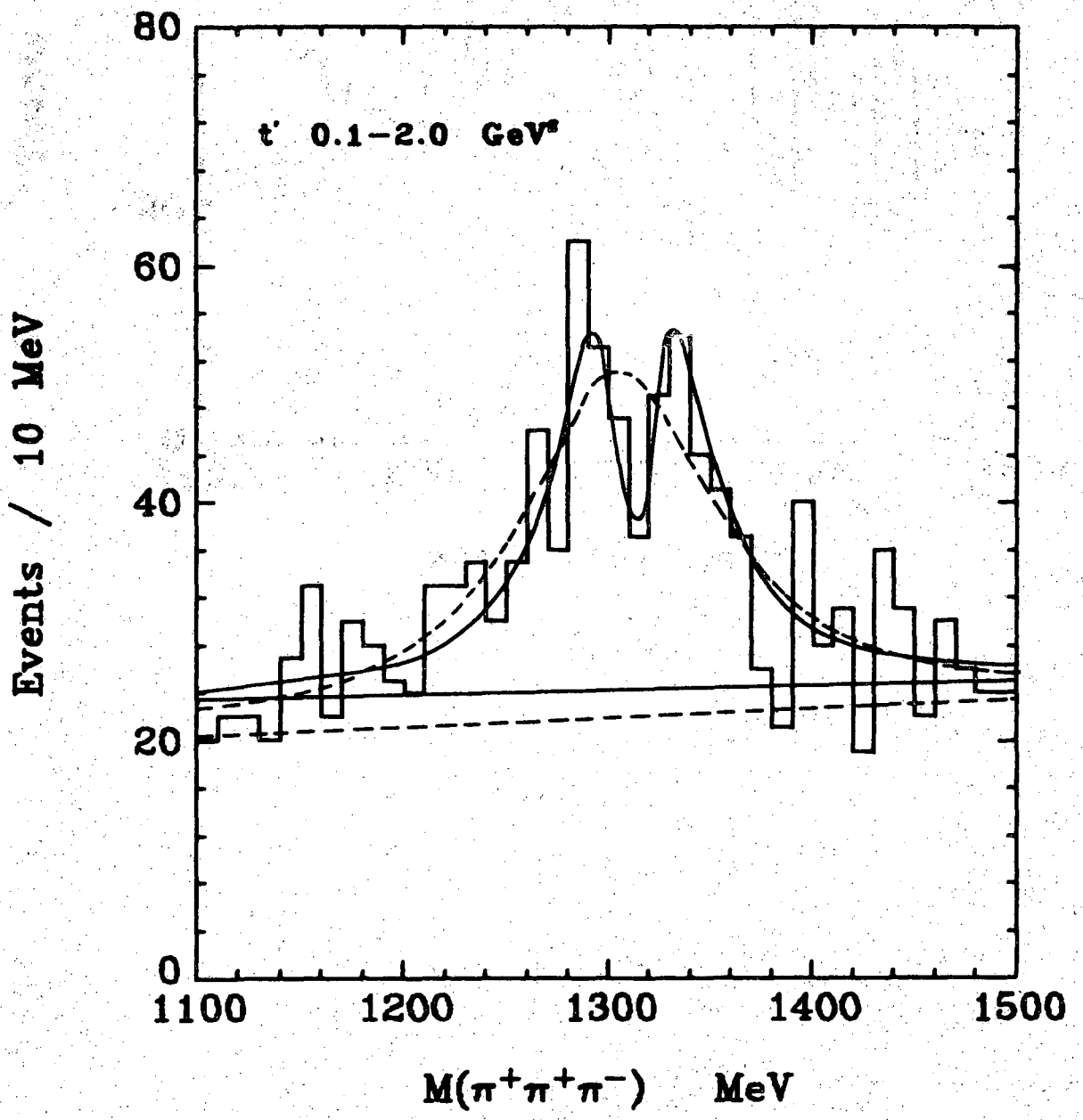

(a) t' 0.0–0.1 GeV²
(b) t' 0.1–0.6 GeV²
(c) t' 0.6–1.0 GeV²
(d) t' 1.0–2.0 GeV²
(e) t' > 2. GeV²
Events / 20 MeV
M(π⁺π⁺π⁻)
MeV
XBL 712-248

Fig. 2



XBL 713-380

Fig. 3

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