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Resonant structure in the $\pi^+\pi^+\pi^-\pi^-$ system between 1.5 and 1.9 GeV

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Resonant structure is studied in the 1.5-to-1.9-GeV mass region of the neutral four-pion system in the reaction $\pi^+n\to p\pi^+\pi^+\pi^-\pi^-$ at 6 GeV/c incident momentum. The ρ^0 and $A_2^\pm$ content are determined as a function of the four-pion mass. The 4π mass spectrum is best fitted by two resonances, both of which decay predominantly into $\rho^0\pi^+\pi^-$, each with evidence for an appreciable $A_2\pi$ component.

The status of the higher radial recurrences of the ρ meson continues to be unclear. Evidence for the $\rho'(1600)$ has come from phase-shift analyses of $\pi\pi$ scattering and from the observation of enhancements in the $\pi^+\pi^+\pi^-\pi^-$ mass spectra produced in e^+e^- annihilation and in both electroproduction and photoproduction.

While the two-pion system is characterized by clear resonant behavior in the D, F, and G partial waves (the f, g, and h mesons), a P-wave resonance (at 1575 MeV with 30% coupling to the $\pi\pi$ channel) appears in only one of the two phase-shift solutions of Martin and Pennington,[1] and no P-wave resonance appears in the four solutions of Hyams *et al.*[2] A later phase-shift analysis, based on an enhanced data sample, shows some preference for a P-wave resonance at $M=1598$ with width $\Gamma=175^{+98}_{-53}$ MeV.[3] In still another phase-shift analysis of $\pi\pi$ scattering, Corden *et al.* report P-wave resonances in two of their *disfavored* solutions.[4] Somewhat more direct evidence is a clear enhancement observed in the $\pi^+\pi^-$ effective-mass spectrum of diffractively produced dipions by high-energy photons (50 to 200 GeV).[5] The reported mass and width are $M=1600\pm10$ and $\Gamma=283\pm14$ MeV.

The four-pion system has been studied since the earliest experiments to detect hadrons in e^+e^- collisions.[6] An Orsay group recently reported fits to the $\pi^+\pi^+\pi^-\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$ mass spectra which tentatively indicate resonances at $M=1533\pm21$, $\Gamma=202\pm70$ MeV and $M=1690\pm14$, $\Gamma=180\pm87$ MeV.[7]

A broad resonance in the $\pi^+\pi^+\pi^-\pi^-$ system was reported in the reaction $\gamma p\to p\pi^+\pi^+\pi^-\pi^-$ at 9.3-GeV photon energy: $M=1430\pm50$, $\Gamma=650\pm100$ MeV.[8] In the high-energy photoproduction experiment mentioned above (in which a dipion enhancement with a width of 283 MeV was observed), the $p\pi^+\pi^+\pi^-\pi^-$ final state was found to have a broad, featureless four-pion enhancement with a width of about 500 MeV, decaying into a ρ^0 and a low-mass (300–500 MeV) pion pair.[5] Coherent photoproduction on deuterons ($I=0$ exchange) of the four-pion system shows an enhancement at $M=1570\pm60$, $\Gamma=340\pm90$ MeV.[9] Most recently, a resonance in the $\pi^+\pi^+\pi^-\pi^-$ system was observed in electroproduction, $ep\to ep\pi^+\pi^+\pi^-\pi^-$ at 11.5-GeV incident energy.[10] The best fit to the four-pion mass spectrum gave $M=1780$, $\Gamma=100$ MeV, with $\rho\pi\pi$ indicated as the dominant decay mode. This is the narrowest structure reported thus far in the four-pion system.

In this paper, we report on structure in the neutral four-pion system observed in the reaction

$$\pi^+d\to\pi^+\pi^+\pi^-\pi^-pp_s\,,$$

where p_s denotes the spectator proton. The data are from an 18-event/μb exposure of the Argonne National Laboratory 30-in. bubble chamber to 6-GeV/c π^+ mesons.[11] We shall restrict our discussion to the 3032 events with $|t'_{4\pi}|<0.5$ (GeV/c)^2, where $t'_{4\pi}=t_{4\pi}-t_{\min}$ and $t_{4\pi}$ is the square of the four-momentum transfer between the incident pion and the outgoing four-pion system.

We discuss first the two- and three-body mass distributions. The $p\pi^+$ mass distribution, Fig. 1(a), shows a strong signal at ~1200 MeV. The $p\pi^+$ mass plots, for six selections of 4π mass, have been fitted to a Breit-Wigner form and $p\pi$/$p4\pi$ phase space.[12] The numbers of fitted Δ^{++} are shown as a function of the four-pion mass in Fig. 1(b). It is clear that isobar production most strongly affects the high end of the four-pion mass distribution.[13]

The $\pi^+\pi^-$ mass distribution (four combinations per event) is shown in Fig. 1(c) and the fitted intensities of ρ^0 and f^0 production as a function of four-pion mass are indicated in Fig. 1(d). The histogram in Fig. 1(d) is the four-pion mass spectrum and is discussed later. A clear en-

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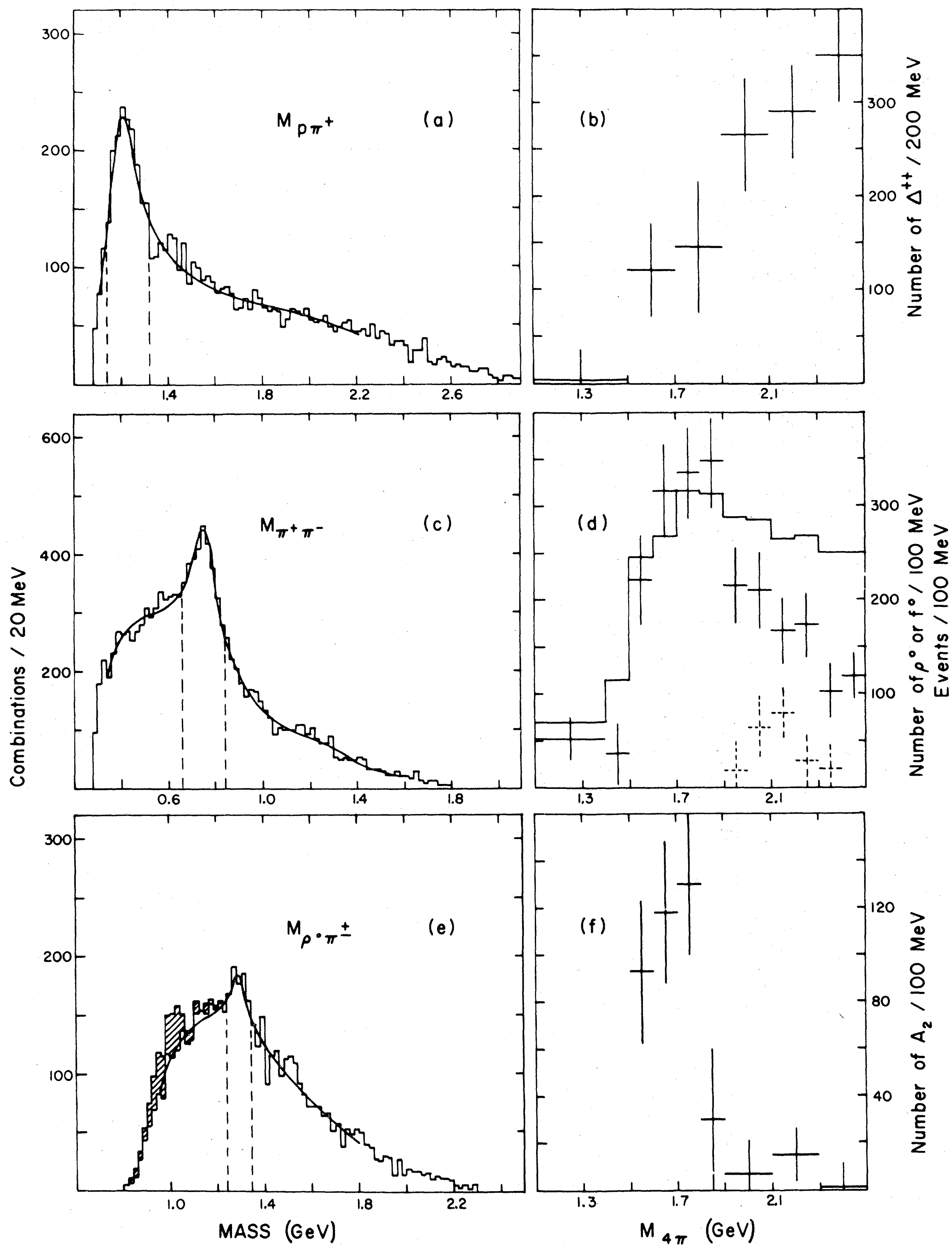

FIG. 1. Two- and three-body mass distributions from $\pi^+ n \to p\pi^+\pi^+\pi^-\pi^-$ at 6 GeV/c. (a) Effective-mass distribution of the $p\pi^+$ combinations; (b) the fitted number of Δ^{++} as a function of 4π mass; (c) the $\pi^+\pi^-$ mass distribution fitted with phase space and ρ^0 and f^0; (d) (solid data points) the fitted number of ρ^0 as a function of $M_{4\pi}$, (dashed data points) the fitted f^0 intensity, (histogram) the 4π mass spectrum; (e) the $\rho^0\pi^\pm$ mass spectrum fitted to phase space and A_2, shaded portion for $M_{4\pi} < 1400$ MeV; (f) fitted A_2 intensity as a function of $M_{4\pi}$.

hancement in the ρ^0 intensity is seen for $1500 < M_{4\pi} < 1900$ MeV. The small signal in the f^0 intensity at $M_{4\pi} = 2100$ MeV indicates that this region should be examined in future experiments for $f^0\pi^+\pi^-$ effects.

In Fig. 1(e) the $\rho^0\pi^\pm$ mass distribution is shown, where ρ^0 indicates all $\pi^+\pi^-$ combinations with $660 < M_{\pi^+\pi^-} < 840$ MeV. The enhancement at ~1 GeV is a reflection of the $f^0 \to 4\pi$ decay and disappears when events with $M_{4\pi} < 1400$ MeV are removed (shaded portion of histogram). The curve is a fit to the unshaded histogram with an A_2 Breit-Wigner and $\rho\pi/\rho\pi\pi p$ phase space. The fitted total number of A_2 events is 355 ± 70. From Fig. 1(f) it can be seen that the A_2 signal comes essentially entirely from the $1500 < M_{4\pi} < 1800$-MeV region. Separate fits to the A_2^- intensity indicate that there are equal numbers of A_2^+ and A_2^-, supportive of the conclusion that all the A_2 come from $A_2\pi$ decay of a neutral boson.

The $\pi^+\pi^+\pi^-\pi^-$ effective-mass distributions are shown in Fig. 2, separately for $|t'_{4\pi}| < 0.5$ and $|t'_{4\pi}| < 0.1$ (GeV/c)^2, both with and without a cut on the $p\pi^+$ mass. In addition to our previously reported [14] f^0 signal, there appear to be two peaks in the 1500–1900 MeV region, especially in Figs. 2(b) and 2(c). Therefore, each distribution has been fitted both with a single broad resonance (dashed curves) and with two Breit-Wigner forms (solid curves). The histograms were fitted to an expression of the form

$$F_{\mathrm{PS}} \times \left[a + bM_{4\pi} + \sum \frac{c_i M_i{}^2 \Gamma_i{}^2}{(M_{4\pi}{}^2 - M_i{}^2)^2 + M_i{}^2 \Gamma_i{}^2} \right],$$

where PS refers to $4\pi/p4\pi$ phase space.[15]

The parameters of the eight fitted curves are listed in Table I. The χ^2 probabilities indicate that although fits can be obtained with a single broad resonance, substantial improvement is obtained when one includes two resonances in the parametrization.[16] On the basis of the two-resonance hypothesis, our best estimate of the resonance parameters are those fitted to the peripheral subset of Fig. 2(b), which are ($M = 1585 \pm 10$, $\Gamma = 119 \pm 37$ MeV) and ($M = 1794 \pm 20$, $\Gamma = 199 \pm 83$ MeV). After correcting for our fit selection criteria, we estimate production cross sections for the two enhancements to be 23 ± 6 and

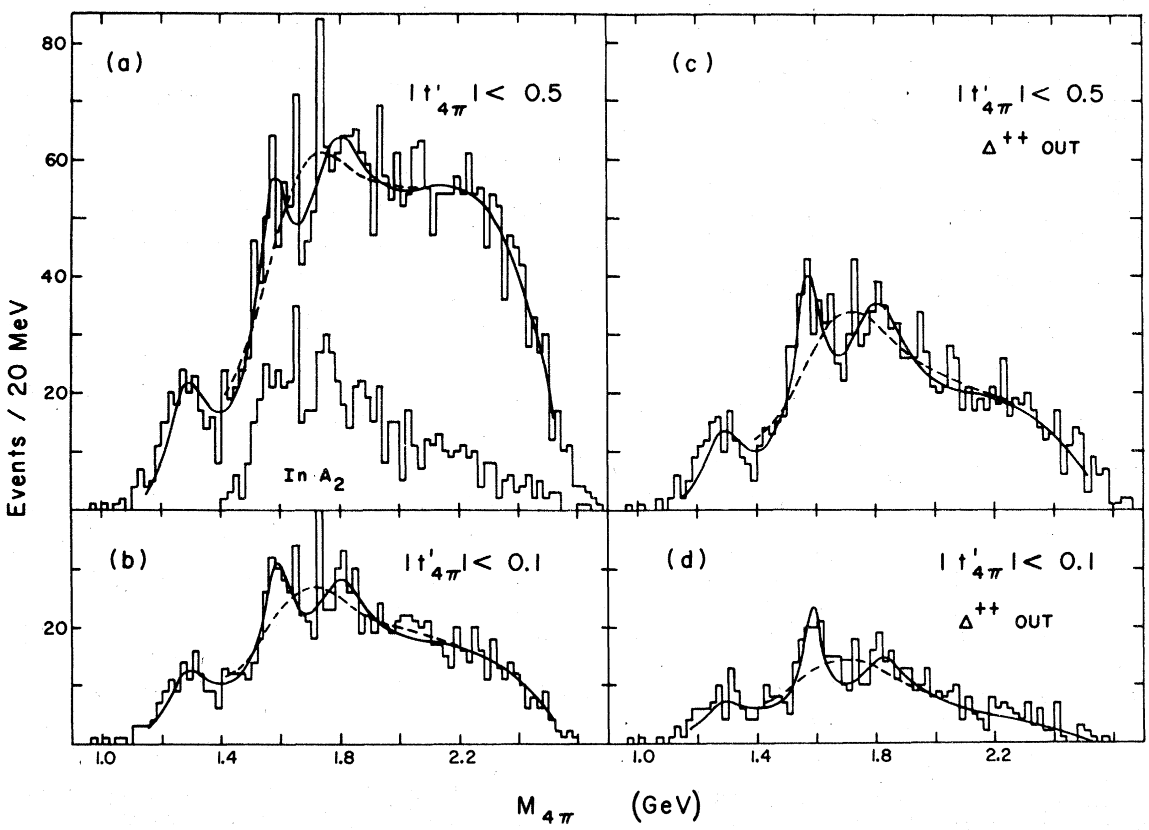

FIG. 2. The four-pion mass spectrum from $\pi^+ n \to p\pi^+\pi^+\pi^-\pi^-$ at 6 GeV/c. (a) (upper) all four-pion combinations with $|t'_{4\pi}| < 0.5$ (GeV/c)^2; (lower) selected in A_2: $1240 < M_{\rho^0\pi} < 1340$ MeV; (b) peripheral subset; (c) Δ^{++} removed: $1140 < M_{\Delta^{++}} < 1320$ MeV; (d) peripheral subset.

TABLE I. Fitted parameters of curves shown in Fig. 2. The f^0 was included in all fits, fixed at $M_0=1267$ and $\Gamma_0=172$ MeV.

Figure curve	Mass (MeV)	Width (MeV)	Mass (MeV)	Width (MeV)	Probability (χ^2)
2(a) solid	1567 ± 8	132 ± 32	1771 ± 17	280 ± 76	35%
2(a) dashed	1632 ± 15	513 ± 88			2%
2(b) solid	1585 ± 10	119 ± 37	1794 ± 20	199 ± 83	99%
2(b) dashed	1654 ± 25	400 ± 146			88%
2(c) solid	1570 ± 8	119 ± 28	1795 ± 16	250 ± 70	67%
2(c) dashed	1641 ± 19	545 ± 105			4%
2(d) solid	1585 ± 12	71 ± 25	1827 ± 23	190 ± 96	75%
2(d) dashed	1656 ± 35	495 ± 200			17%

36 ± 12 μb, respectively. The large errors reflect uncertainties in the fitted widths. We have fitted the number of events in each peak for each of three regions in $|t'_{4\pi}|$ between zero and 0.3 $(\text{GeV}/c)^2$ and then parametrized the results in the form $Ae^{Bt'}$. The fitted slope parameters are $B(1585) = 7.1 \pm 1.8$ and $B(1794) = 4.9 \pm 2.6$ $(\text{GeV}/c)^{-2}$.

We have examined as a function of 4π mass the normalized moments associated with $\cos\theta_{++}$, where θ_{++} is the angle in the 4π rest frame between the $\pi^+\pi^+$ system and the beam. We find no structure which can be associated with the mass enhancements. Between 1400 and 2000 MeV, $\langle P_2(\cos\theta_{++})\rangle \simeq 0.10 \pm 0.02$, $\langle P_4(\cos\theta_{++})\rangle \simeq 0.04 \pm 0.02$, and higher moments are compatible with zero.

It is evident from a comparison between the ρ^0 intensity and the total $M_{4\pi}$ histogram shown together in Fig. 1(d), that both enhancements decay predominantly via $\rho^0\pi^+\pi^-$. Next we examine the role of the $A_2^\pm$. The lower histogram of Fig. 2(a) is for events selected in the A_2 region: we require at least one combination with $1240 < M_{\rho^0\pi^\pm} < 1340$ MeV, with the ρ^0 defined as above. By comparing the two histograms of Fig. 2(a) and assuming that all the A_2 signal is from $A_2\pi$ decays of the two enhancements [cf. Fig. 1(f)], we have determined that the branching ratios for $A_2\pi$ decay relative to the total $\pi^+\pi^+\pi^-\pi^-$ signals are 0.43 ± 0.15 and 0.34 ± 0.12 for the 1585- and 1794-MeV enhancements, respectively.

It is interesting to note, in Fig. 1(f) and the lower histogram of Fig. 2(a), that the A_2 signal is missing from the upper half of the 1794-MeV enhancement. This suggests that the enhancement may encompass two comparatively narrow resonances, one of which may be the state seen in electroproduction.[10]

In conclusion, we have observed in the pion-produced peripheral neutral four-pion system a large excess of events in the $1500 < M_{4\pi} < 1900$-MeV region, which on the basis of the four-pion mass distribution is best parametrized by two resonances with widths of ~120 and ~200 MeV. The size of the fitted ρ^0 signal is sufficient to provide at least one ρ^0 for each 4π combination. The fitted A_2 signal is restricted entirely to the $1500 < M_{4\pi} < 1800$-MeV region, thus indicating both that $A_2\pi$ is a significant decay mode for the four-pion system in this mass range and that the $M = 1794$ enhancement may actually have two components.

While our data do not resolve the disparate reports on resonance masses and widths in the neutral four-pion system, the shape of the peripheral 4π mass distribution as well as the forms of the $\rho\pi\pi$ and $A_2\pi$ mass spectra cast considerable doubt on the single-broad-resonance interpretation. The association of any particular broad or narrow enhancement with the long-sought ρ' is premature and unjustified. In Fig. 3 we represent the masses and widths of the reported enhancements in this region. The lengths of the lines represent the quoted Breit-Wigner widths (not the mass uncertainties). The chronological trend, as statistics have improved, is toward a multiplicity of resonances with decreasing widths.

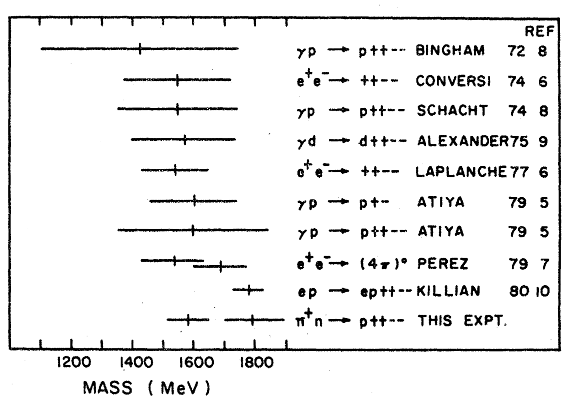

FIG. 3. Representation of the masses and widths of structures reported in the two- and four-pion system. The lengths of the lines indicate the Breit-Wigner widths.

It will take at least an order of magnitude improvement in statistics, whether in photoproduction, electroproduction, pion production, or annihilation, to identify by spin analysis and decay modes all the meson states in this interesting mass region.

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[11]Both invisible- and visible-spectator events are included, with a spectator momentum cutoff, $p_s < 250$ MeV/c. The sample contains 63% unambiguous fits to reaction (1); 13% are internally ambiguous (interchange of π^+ and p), and 24% are ambiguous with $\pi^+ d \to K^+K^-\pi^+\pi^- p p_s$. For the ambiguous events, the fit with highest χ^2 probability was chosen. The ambiguous events do not differ significantly in the 4π spectrum from those which are unambiguous.

[12]The notation $p\pi/p4\pi$ indicates the effective-mass invariant phase-space distribution for the $p\pi$ composite in the final state $p4\pi$, etc.

[13]The low-mass $p\pi^+$ enhancement may not be due entirely to Δ^{++} production, but may arise in part from kinematic reflection of low-energy $\pi^+ n$ scattering as proposed by E. L. Berger and R. A. Morrow, Phys. Rev. Lett. 25, 1136 (1970). The fitted mass of the $p\pi^+$ enhancement rises from 1180 ± 15 to 1230 ± 10 MeV as $M_{4\pi}$ increases from 1700 to 2300 MeV.

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[15]Various forms of the phase-space factor F_{PS} were tried, e.g., $\rho\pi\pi$, $A_2\pi$, etc. Each of these peaks at higher $M_{4\pi}$ than the F_{PS} used, yielding higher numbers of resonant events.

[16]We have fitted the SLAC photoproduction data (Fig. 2 of Park, Ref. 8 above), where the ρ^0-selected 4π mass spectrum was plotted in 40-MeV bins. We find comparable χ^2 probabilities for a fit to a single $M = 1600$-MeV, $\Gamma = 500$-MeV enhancement, and for a fit with the parameters of the first line of our Table I (using $F_{PS} = 1$ and a quadratic multiplier).