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A further study of the centrally produced $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ channels in pp interactions at 300 and 450 GeV/c

The WA91 Collaboration

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Abstract

An analysis of the centrally produced $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ mass spectra from the WA76 and WA91 experiments is presented, which shows that in the $\pi^+\pi^-\pi^+\pi^-$ channel there are two new states, the $f_0(1450)$ and $f_2(1900)$. There is another new state in the $\pi^+\pi^-$ channel with $M = 1497 \pm 30$ MeV and $\Gamma = 199 \pm 30$ MeV, which is compatible with the $f_0(1520)$ observed by the Crystal Barrel experiment. Another interpretation is discussed, where the 1450 and 1497 GeV structures are explained as being due to an interference effect between the $f_0(1365)$ and $f_0(1520)$.

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The WA76 collaboration reported the observation of two previously unobserved mesons, which it called the X(1450) and X(1900), decaying to $\pi^+\pi^-\pi^+\pi^-$ in the reaction

$$pp \to p_f(\pi^+\pi^-\pi^+\pi^-)p_s \qquad (1)$$

at 300 GeV/c [1], where the subscripts f and s indicate the fastest and slowest particles in the laboratory respectively. In contrast, no clear evidence was seen for the X(1450) or X(1900) in the 85 GeV/c data of the same experiment [2]. The increase in cross section with increased incident energy [1] is consistent with the formation of these states via a double Pomeron exchange mechanism, which is predicted to be a source of gluonic states [3]. It is interesting to note that the X(1450) state has not been observed in any other production mechanism.

The WA91 experiment [4], which studied reaction (1) at 450 GeV/c, confirmed the existence of these states and, from a spin analysis, showed that the X(1450) has $I^GJ^{PC} = 0^+0^{++}$ and the X(1900) has $I^GJ^{PC} = 0^+2^{++}$; hence they should be called the $f_0(1450)$ and $f_2(1900)$ respectively.

The WA76 collaboration has also published an analysis of the centrally produced $\pi^+\pi^-$ channel [5] in which it showed that, in order to fit the $\pi^+\pi^-$ mass spectrum above the $f_2(1270)$ they needed to introduce a Breit-Wigner with a mass of 1472 ± 12 MeV and a width of 195 ± 30 MeV interfering with the background. This state is similar in mass and width to the $f_0(1520)$ observed by the Crystal Barrel experiment at LEAR [6]. In addition to this state the Crystal Barrel experiment also observed another scalar with a mass of 1365 ± 35 MeV and width 270 ± 70MeV, called the $f_0(1365)$. A recent reanalysis [7] of the $\pi^+\pi^-\pi^+\pi^-$ channel produced in radiative J/ψ decay has shown that the mass spectrum can be described in terms of these resonances and it is possible that the $f_0(1450)$ observed in the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum in central production could also be due to an interference effect between these two states.

This paper presents the combined WA76 and WA91 data on the $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-$ final states and discusses possible interpretations of these final states in the light of the Crystal Barrel results mentioned above.

The data come from experiments WA76 and WA91 which have been performed using the CERN Omega Spectrometer. Details of the layout of the apparatus, the trigger conditions and the data processing have been given in previous publications [8]. The selection of reaction (1) has been given in ref. [1] for the WA76 experiment and ref. [4] for the WA91 experiment.

The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectra from experiments WA76 [1] and WA91 [4] look very similar and the combined spectrum is shown in fig. 1a. In order to describe the $\pi^+\pi^-\pi^+\pi^-$ combined mass spectrum, it has been fitted using three Breit-Wigners representing the $f_1(1285)$, the $f_0(1450)$ and $f_2(1900)$ plus a background of the form $a(m - m_{th})^b exp(-cm - dm^2)$, where m is the $\pi^+\pi^-\pi^+\pi^-$ mass, m_{th} is the $\pi^+\pi^-\pi^+\pi^-$ threshold mass and a, b, c, d are fit parameters. Reflections from the $\eta\pi^+\pi^-$ decay of the η' and $f_1(1285)$ give small enhancements in the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum in the 0.8 and 1.1 GeV regions due to a slow π^0 from the decay of an η falling within the missing momentum cuts. In order to get a correct description of the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum two histograms representing a Monte Carlo simulation of each reflection have been included in the fit. The masses and widths determined from the fit are given in table 1.

A study has been made of the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum in different t intervals where $t = |t_1| + |t_2|$ and t_1 and t_2 are the four momentum transfer squared at the fast and slow vertices respectively. Relative to the $f_1(1285)$ the $f_0(1450)$ and $f_2(1900)$ are both produced predominantly at low $|t|$ and there is no significant variation in mass and width of these states with t. Fig. 1b shows the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum when a cut of $|t| \leq 0.15$ GeV^2 has been placed on the four momentum transfer squared at both the fast and slow vertices. The spectrum is fitted using three Breit-Wigners, with masses and widths fixed to the values given in table 1, and a background as described above.

A spin-parity analysis of the $\pi^+\pi^-\pi^+\pi^-$ channel has been performed using an isobar model [4]. Assuming that only angular momenta up to 2 contribute, the intermediate states considered are $\sigma\sigma$, $\sigma(\pi^+\pi^-)_{Swave}$, $\sigma(\pi^+\pi^-)_{Pwave}$, $\sigma(\pi^+\pi^-)_{Dwave}$, $\sigma\rho^0$, $\rho^0\rho^0$, $\rho^0(\pi^+\pi^-)_{Swave}$, $\rho^0(\pi^+\pi^-)_{Pwave}$, $\rho^0(\pi^+\pi^-)_{Dwave}$, $a_1(1260)\pi$, $a_2(1320)\pi$, $f_2(1270)(\pi^+\pi^-)_{Swave}$, $f_2(1270)(\pi^+\pi^-)_{Pwave}$ and $f_2(1270)(\pi^+\pi^-)_{Dwave}$ where σ stands for the low mass $\pi\pi$ S-wave amplitude squared of Au, Morgan and Pennington [9]. The amplitudes have been calculated in the spin-orbit (LS) scheme using spherical harmonics.

In order to perform a spin parity analysis the negative log likelihood function, $\mathcal{L}_j = -\sum_i \log P_j(i)$, is defined by combining the probabilities of all events in 40 MeV $\pi^+\pi^-\pi^+\pi^-$ mass bins from 1.02 to 2.82 GeV. The incoherent sum of various event fractions a_j is calculated so as to include more than one wave in the fit,

$$\mathcal{L} = -\sum_i \log\left(\sum_j a_j P_j(i) + (1 - \sum_j a_j)\right) \tag{2}$$

where the term $(1 - \sum_j a_j)$ represents the phase space background. The function $\mathcal{L}$ is then minimised using MINUIT [10]. Coherence between different J^P states and between different isobar amplitudes of a given J^P have been neglected in the fit. Different combinations of waves and isobars have been tried and insignificant contributions have been removed from the final fit. The results of the best fit are shown in fig. 2 for the combined WA76 and the WA91 data. Superimposed on the figures are the resonance contributions coming from a fit to the mass spectrum in 40 MeV bins. Using Monte Carlo simulations it has been found that the feed through from one spin parity to another is negligible and that the peaks in the spin analysis can not be produced by phase space or acceptance effects. As can be seen, the $J^P = 1^+$ $\rho(\pi\pi)_{Pwave}$ clearly describes the $f_1(1285)$ in size and shape (fig. 2a) and the $J^P = 0^+\rho(\pi\pi)_{Pwave}$ distribution shows the $f_0(1450)$ peak on top of a broad enhancement (fig. 2b). As was already mentioned in the WA91 publication [4], in the analysis of the $f_1(1285)$ and $f_0(1450)$ there is little difference ($\Delta\mathcal{L} = 2$) in the result if the $\rho\rho$ amplitude is used instead of the $\rho(\pi\pi)_{Pwave}$ since one of the $\pi\pi$ pairs is below threshold. The importance of this statement was that it is not the shape describing the $\pi\pi$ pair which is important but the fact that they are in P wave.

In order to test if the $\sigma\sigma$ decay mode of the $f_0(1450)$ can describe the data, the change in log likelihood in the two 40 MeV bins around the $f_0(1450)$ has been calculated by replacing the $J^P = 0^+\rho(\pi\pi)_{Pwave}$ amplitude by the $J^P = 0^+\sigma\sigma$ amplitude. The likelihood decreases by $\Delta\mathcal{L} = 212$ corresponding to $n = \sqrt{2\Delta\mathcal{L}} = 20.6$ standard deviations.

Although, as can be seen from figs. 2c and d, neither the $J^P = 2^+$ $a_2(1320)\pi$ nor the $J^P = 2^+$ $f_2(1270)(\pi\pi)_{Swave}$ alone can describe the $f_2(1900)$, the sum of the two waves (fig. 2e) accounts for most of the $f_2(1900)$ signal. The $a_2(1320)\pi$ distribution and the $f_2(1270)\pi\pi$ distribution peak at different masses which suggests that the $f_2(1900)$ could be composed of two $J^{PC} = 2^{++}$ resonances. If the $a_2(1320)\pi$ contribution is fitted using a Breit-Wigner and polynomial background the resulting mass and width are M = 1880 ± 30 MeV and Γ = 130 ± 40 MeV. A similar fit to the $f_2(1270)\pi\pi$ contribution gives M = 2110 ± 30 MeV and Γ = 240 ± 40 MeV.

Fig. 3a shows the combined WA76 and WA91 $\pi^+\pi^-$ mass spectrum. It has been fitted using the parametrisation described in ref. [5]. In order to fit the region on the high mass side of the $f_2(1270)$ (see fig.3b) a Breit-Wigner interfering with the background has been introduced. The mass and width are found to be

$$\mathrm{M} = 1497 \pm 30 \quad \mathrm{MeV} \qquad \Gamma = 199 \pm 30 \;\; \mathrm{MeV}$$

If the parameters of the $f_0(1450)$ are used instead, then the fit is clearly worse (fig. 3c). Therefore, from the WA76 and WA91 data we conclude that there are two separate resonances, one in the $\pi^+\pi^-\pi^+\pi^-$ channel and a second in the $\pi^+\pi^-$ channel.

After the WA76 and WA91 data were published, the results from the Crystal Barrel experiment have become available. Therefore we now investigate whether the data from WA76 and WA91 can be described using the $f_0(1365)$ and $f_0(1520)$ observed in the Crystal Barrel experiment. It is clear that the mass and width of the state required to fit our $\pi^+\pi^-$ spectrum are close to those of the $f_0(1520)$, but this state on its own can not explain the narrow peak observed in our $\pi^+\pi^-\pi^+\pi^-$ channel.

Since the $f_0(1365)$ and $f_0(1520)$ have the same quantum numbers they can interfere and one possibility is that the effects observed in the $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ channels in central production could be produced by these two states interfering with each other and also with an S-wave background. In order to test this hypothesis an attempt has been made to try to create the narrow peak observed in the $\pi^+\pi^-\pi^+\pi^-$ channel using an expression of the form

$$B_{X(1450)}(m) = |A_{f_0(1365)}BW_{f_0(1360)} + A_{f_0(1520)}BW_{f_0(1520)}e^{i\delta}|^2 \tag{3}$$

where the A_f determine the relative amplitudes of the two Breit-Wigners, BW_f are Breit-Wigner amplitudes and δ is a mass independent phase between the two states. In order to make the shape of this function describe the $f_0(1450)$ the mass and width of each resonance was allowed to change by up to one standard deviation from their published values and their relative amplitudes and phase were varied. The best description was achieved when the masses of the two states tended towards each other. The solid line in fig. 4a shows the Breit-Wigner function used to fit the $\pi^+\pi^-\pi^+\pi^-$ spectrum and the dashed line shows the best curve resulting from interfering the two Crystal Barrel states. The resulting parameters are

$$\begin{array}{lllll} f_0(1365) & \mathrm{M} = 1395 & \mathrm{MeV} & \Gamma = 200 \;\; \mathrm{MeV} & \mathrm{A} = 1.0 \\ f_0(1520) & \mathrm{M} = 1495 & \mathrm{MeV} & \Gamma = 125 \;\; \mathrm{MeV} & \mathrm{A} = 0.8 \\ & & \delta = 180^0 & & \end{array}$$

The agreement is not perfect but the shapes are similar and it must be remembered that in addition to the $J^{PC} = 0^{++}$ resonances there is also a 0^{++} background. As can be seen from fig. 2b there is a background in the $J^P = 0^+\rho(\pi\pi)_{Pwave}$ distribution which could easily interfere with the resonances. However the $J^P = 0^+\rho(\pi\pi)_{Pwave}$ background is not the only 0^+ background possible. Therefore it is not meaningful to try to interfere the two resonances with a background since the shape of that background is arbitrary; hence it will always be possible to choose a background shape that would allow the observed $f_0(1450)$ peak to be fitted. Figs. 4b and c show fits to the total and low t $\pi^+\pi^-\pi^+\pi^-$ mass spectrum using this interference term.

If the same parameterisation is used to fit the $\pi^+\pi^-$ channel, that is, using the two Crystal Barrel states with parameters as given above and allowing interference with the background which is assumed to be S-wave a poor fit results as is shown in fig. 4d. If the amplitude of the two states is allowed to vary but the phase angle is kept constant at 180^0 then the resulting fit is shown in fig. 4e. Although the fit is acceptable the amount of the $f_0(1365)$ required in the fit is very small, only 0.3 % of the $f_0(1520)$. If the phase angle between the $f_0(1365)$ and the $f_0(1520)$ is left free the fit shown in fig. 4f results. This is again an acceptable fit and the ratio of $f_0(1520)$ to $f_0(1365)$ is now two to one. However the phase angle between the $f_0(1365)$ and $f_0(1520)$ is now 90^0.

In summary, in the centrally produced $\pi^+\pi^-\pi^+\pi^-$ mass spectrum two new structures are observed at 1.45 and 1.9 GeV. The peak observed at 1.9 GeV, called the $f_2(1900)$, appears as a broad enhancement in the mass spectrum and decays to $a_2(1320)\pi$ and $f_2(1270)\pi\pi$ with $J^{PC} = 2^{++}$.

There are two interpretations which could explain the 1.45 GeV mass region. Based on centrally produced data alone we would conclude that in the $\pi^+\pi^-\pi^+\pi^-$ channel there is a single resonance, called the $f_0(1450)$, which is a narrow state with $I(J^{PC}) = 0(0^{++})$ and is very interesting since it is only observed in central production, which is believed to be gluon rich. It does not easily fit into the standard ground state $q\overline{q}$ nonet which is already overfull. There is also another state in the $\pi^+\pi^-$ channel with $M = 1497 \pm 30$ MeV and $\Gamma = 199 \pm 30$ MeV, which is compatible with the $f_0(1520)$ observed by the Crystal Barrel experiment.

The second interpretation based on the two states observed in the Crystal Barrel experiment, the $f_0(1365)$ and $f_0(1520)$, is that the peak observed in the $\pi^+\pi^-\pi^+\pi^-$ channel is due to an interference effect between these two states and that a similar effect is observed in the $\pi^+\pi^-$ channel. However, this would require that the phase angle between the two states was different in the two channels. In addition, in order to explain the observed behaviour of the $f_0(1450)$ the $f_0(1365)$ and $f_0(1520)$ must have a similar t dependence and both must be produced at 300 GeV/c and not at 85 GeV/c.

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Tables

Table 1: Parameters of resonances in the fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum

	Mass (MeV)	Width (MeV)	Observed decay mode	$I(J^{PC})$
$f_1(1285)$	1280 $\pm$ 2	36 $\pm$ 5	$\rho\pi\pi$	$0(1^{++})$
$f_0(1450)$	1445 $\pm$ 5	65 $\pm$ 10	$\rho\pi\pi$	$0(0^{++})$
$f_2(1900)$	1918 $\pm$ 12	390 $\pm$ 60	$a_2(1320)\pi$ $f_2(1270)\pi\pi$	$0(2^{++})$

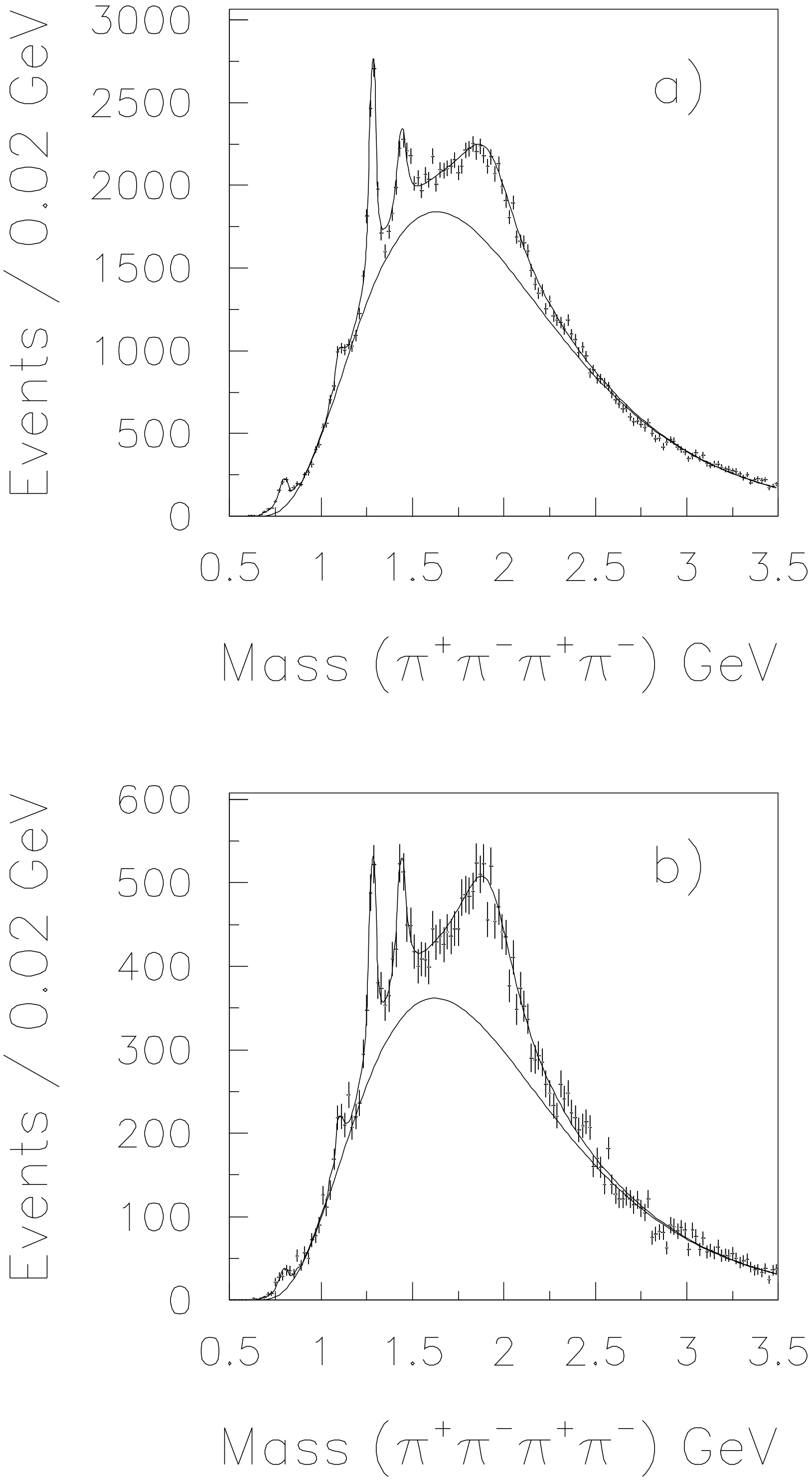
Figures

Figure 1: The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum with fit using 3 Breit-Wigners from the combined WA76 and WA91 data for a) the total spectrum and b) $|t_1| \leq 0.15$ (GeV)^2 and $|t_2| \leq 0.15$ (GeV)^2.

Figure 2: Results of the spin parity analysis for the combined WA76 and WA91 data: a) 1^+ $\rho(\pi\pi)_{Pwave}$, b) 0^+ $\rho(\pi\pi)_{Pwave}$, c) 2^+ $a_2(1320)\pi$, d) 2^+ $f_2(1270)(\pi\pi)_{Swave}$ and e) sum of 2^+ $a_2(1320)\pi$ and 2^+ $f_2(1270)(\pi\pi)_{Swave}$. The superimposed curve is the resonance contribution coming from a fit to the mass spectrum.

Figure 3: The $\pi^+\pi^-$ mass spectrum with fits described in the text.

Figure 4: Results obtained using the interference term in equation (3). a), b) and c) for the $\pi^+\pi^-\pi^+\pi^-$ channel and d), e) and f) for the $\pi^+\pi^-$ channel with fits described in the text.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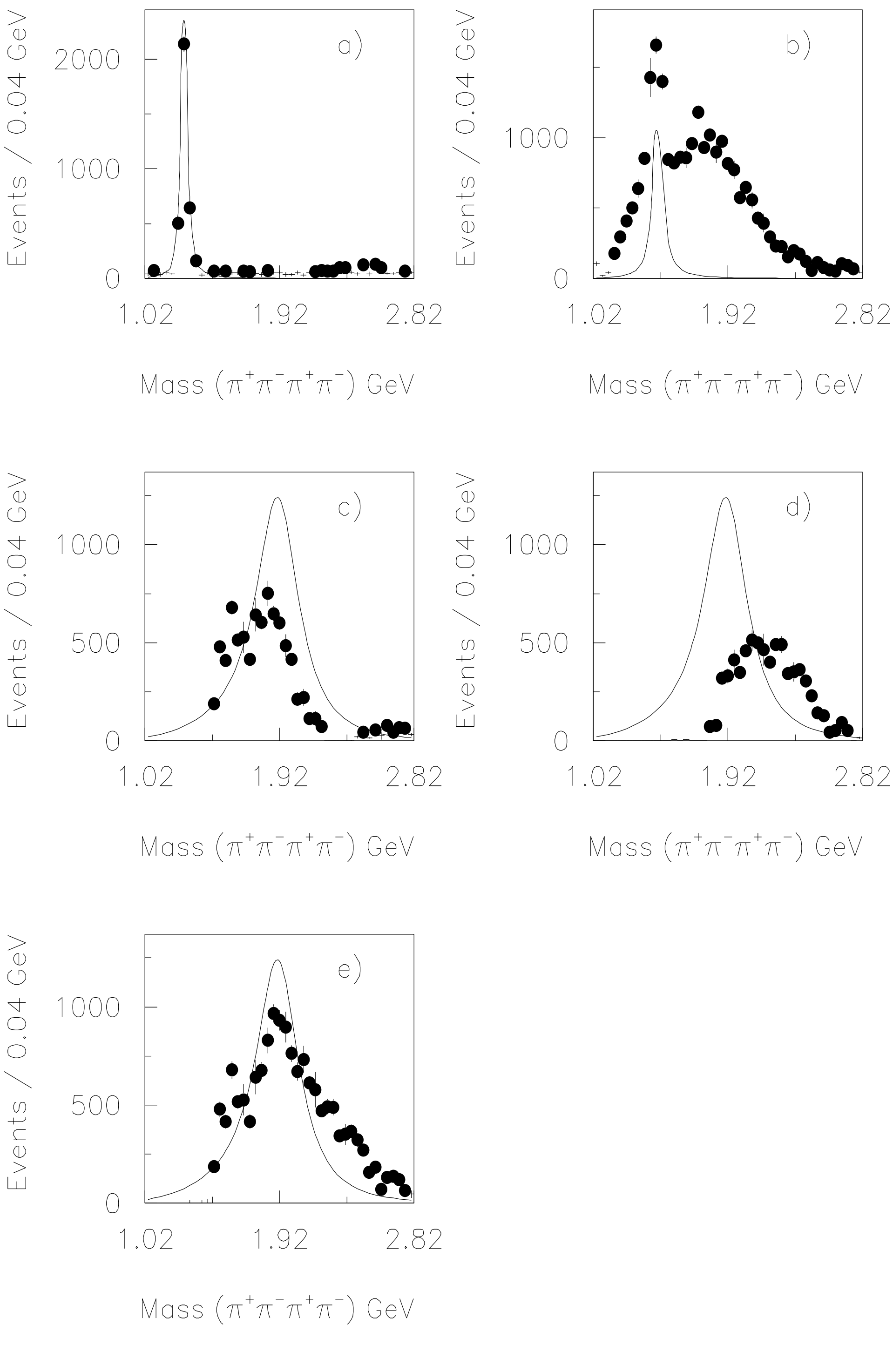
2500
2000
1500
1000
500
0
a)
0.5
1
1.5
2
2.5
3
3.5
Mass ($\pi^+\pi^-\pi^+\pi^-$) GeV
Events / 0.02 GeV
600
500
400
300
200
100
0
b)
0.5
1
1.5
2
2.5
3
3.5
Mass ($\pi^+\pi^-\pi^+\pi^-$) GeV

Figure 1


a)
b)
c)
d)
e)
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2000
500
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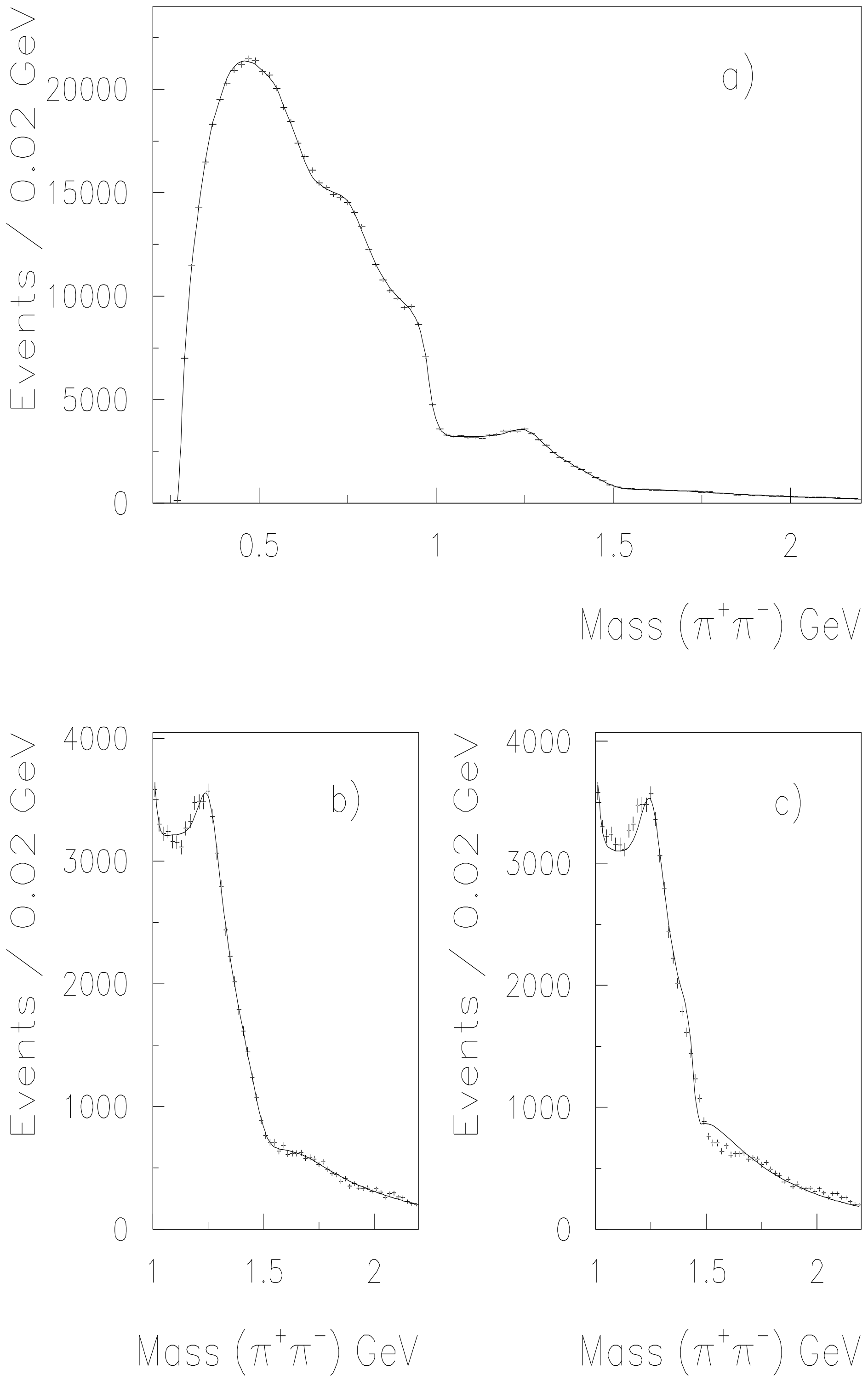
1.92
2.82
Mass $(\pi^+\pi^-\pi^+\pi^-)$ GeV

Figure 2


a)
b)
c)
Events / 0.02 GeV
Mass $(\pi^+\pi^-)$ GeV
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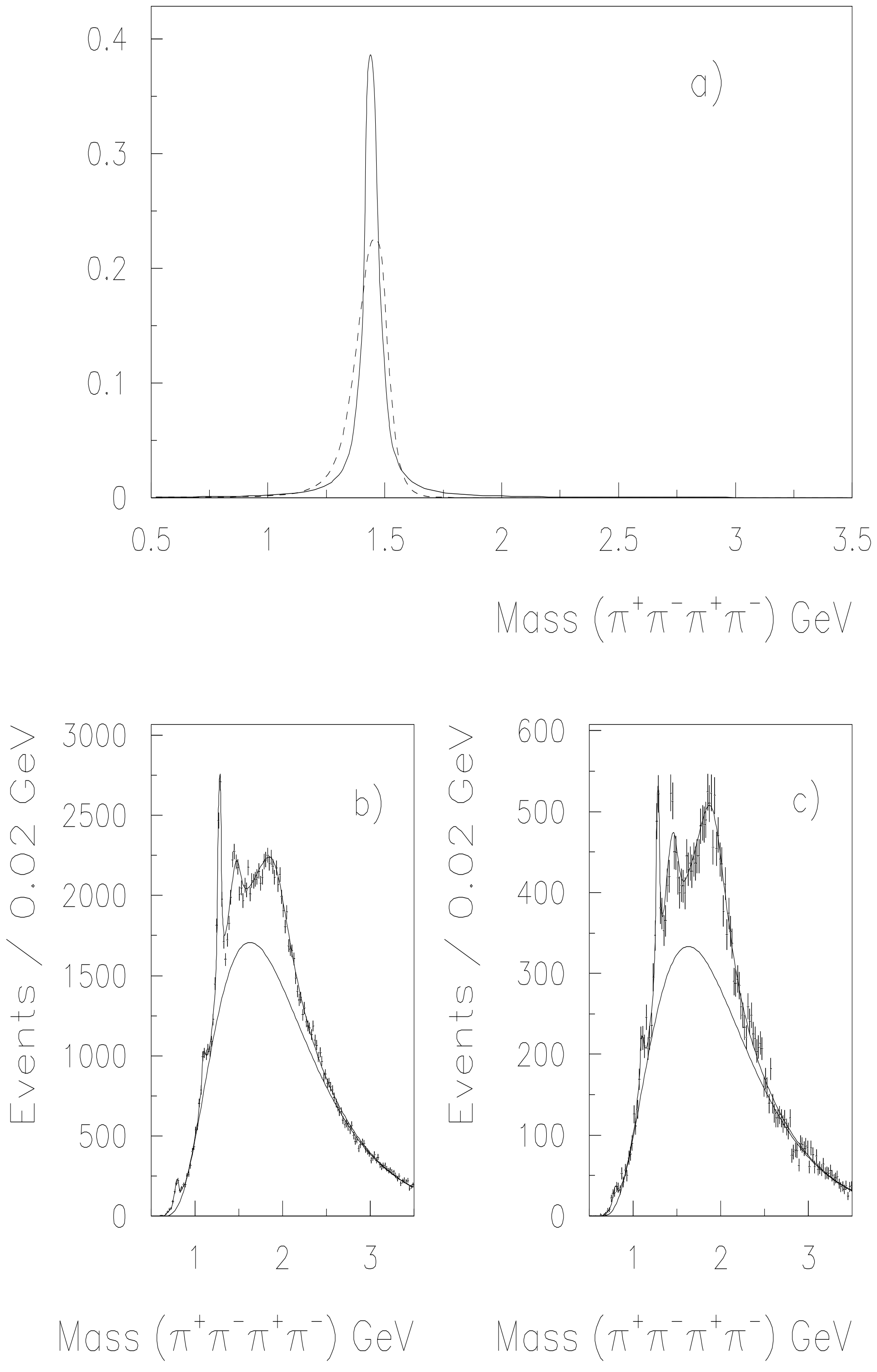
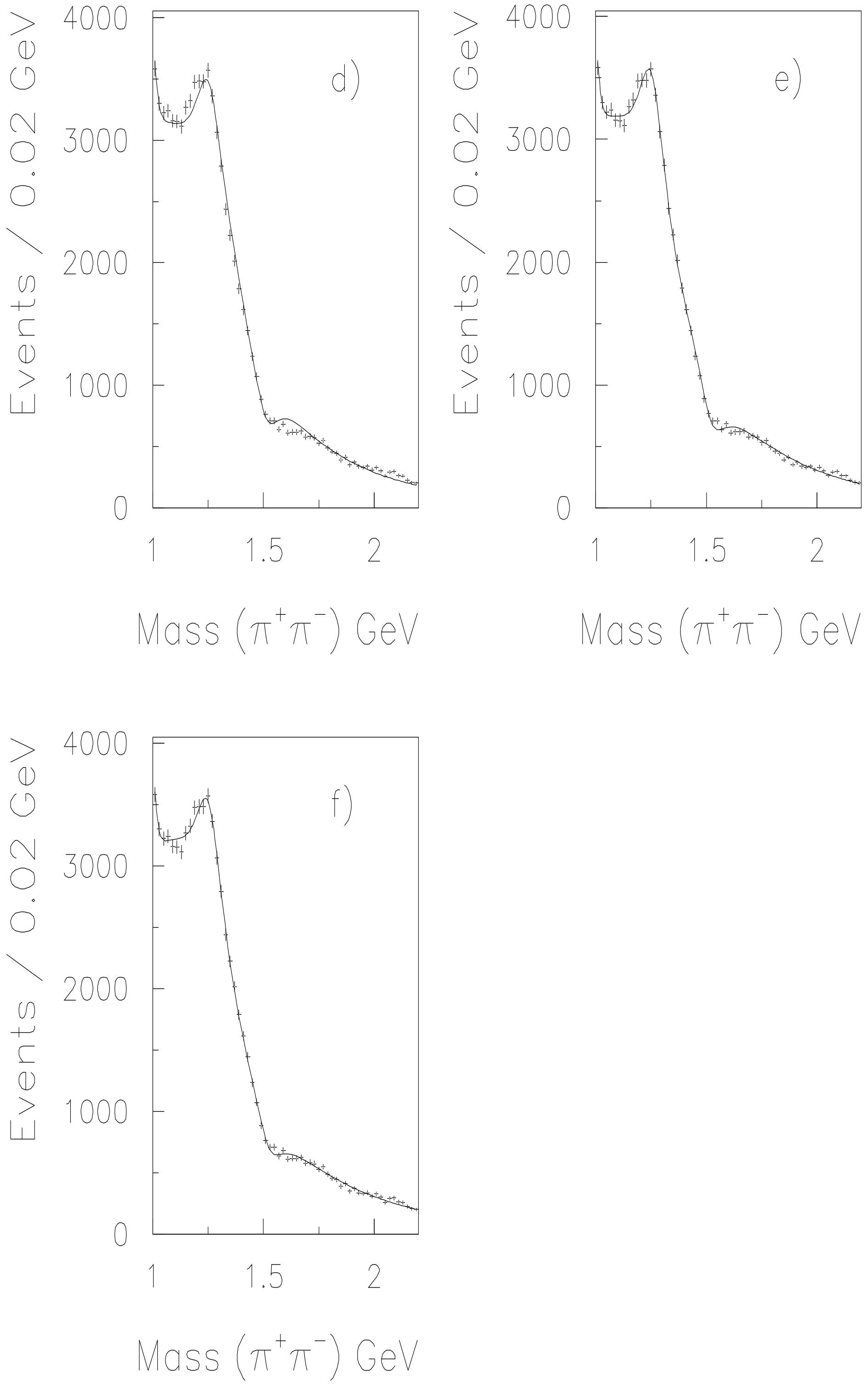
5000
10000
15000
20000
1000
2000
3000
4000
0.5
1
1.5
2

Figure 3



Figures 4a), b) and c)



Figures 4d), e) and f)