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A new study of photoproduced $\pi^+\pi^-$ final states at high energy.

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Abstract

Quasi-exclusive $N\pi^+\pi^-$ final states have been studied in the E687 photoproduction experiment at Fermilab. A high precision measurement of the Drell-Söding interference effects and the $\rho(770)$-$\omega(783)$ mixing leads to a new measurement of the branching ratio $\omega(783) \rightarrow \pi^+\pi^-$, equal to $[1.95 \pm 0.02(stat) \pm 0.015(syst)]\%$. Contrary to statistics e^-e^+ experiment, a single ρ' at a mass of $1.66 \pm 0.010(stat)\,^{+200}_{-20}(syst)$ gives a good fit in the high mass region. A two resonance model $[(\rho(1450), \rho(1700))]$ works also, but does not improve the fit to the data, and introduces arbitrary phases. These $\pi^+\pi^-$ fits must be performed over a wide mass range(0.5 to 2.25 GeV), in order to correctly estimate the interfering $\rho(770)$ and its accompanying non-resonant Drell term, still prominent at these high masses. Within the context of this model, it is shown that the parameters of the $\rho(770)$ resonance observed in this experiment are consistent with those measured at e^-e^+ colliders.

1 Introduction

This paper deals with the decay properties of the $\rho(770)$ and ρ' vector mesons decaying to $\pi^+\pi^-$ as observed in photoproduction at high energy ($7.5 < \sqrt{s} < 17.0$). This new analysis is based on approximately 900,000 quasi-exclusive $\pi^+\pi^-$ pairs (the highest statistics sample available at this energy range) recorded with the E687 spectrometer during the 1990/91 fixed target runs [5, 6].

Since about a decade, there seems to be growing evidence that two $\rho-$like resonances are observed in the 1600-MeV region [1, 2]. These states could be required to develop a consistent picture of the electromagnetic form-factors for the di-pion scattering[3]. Ultimately, accurate observations of radial excitations of light hadrons could become a sensitive probe of QCD[4]. Final state re-interactions play a prominent role in these low-Q^2 phenomena, other combinations of states with vector-like quantum numbers will have to be mentioned. Also, the G-parity violating decay $\omega \rightarrow \pi^+\pi^-$ must be included in the global fit. Finally, the non-resonant production of $\pi^+\pi^-$ pairs, in the t-channel, must be taken into account. Despite of this complexity, it should be stressed that the dominant amplitudes reactions can be described very simply in the context of the s-channel helicity conservation (SCHC) model, with a limited number of free parameters.

2 Experimental setup:

The E687 detector is a large aperture multiparticle magnetic spectrometer tuned for studying photoproduced Charmed hadrons . Although the spectrometer is described elsewhere[5], relevant details for this analysis are briefly summarized here. The geometrical acceptance and overall tracking efficiency is well suited for $M \approx 1.5$ GeV states decaying to two pions and carrying about 70 GeV/c momentum in the laboratory system. Tracking and triggering in the forward central cone (≈ 0.5 mrad.) is somewhat compromised due to the very high e^+e^- pair rate. The effective momentum range for this analysis ≈ 50 up to 125 GeV/c for the 2-pion final state. The microstrip detector is used in this context to reject incoherent background originating in multiple hadronic interactions in the 4 cm. long Beryllium target: a single 2-prong vertex with good confidence level is required. The angular and position resolution of the spectrometer allows us to measure a $\pi^+\pi^-$ mass to about 7. MeV at the $\rho(770)$ pole region, allowing us to detect the $\approx$ 13 MeV mass splitting between the $\rho(770)$ and the $\omega(783)$. In order to reject non-negligible $\phi(1020)$ and $K^*(892)K\pi$ production, pions are identified in the momentum range $4.5 - 61$ GeV/c using three multicell Čerenkov counters.

The Fermilab Broad Band laboratory, where this experiment ran, is also equipped with a beam tagging system[6]. However, this system has been tuned for a sensibly higher photon energy range ($\approx$ 225. GeV). It's efficiency and energy resolution at the energy range relevant for this analysis are not good enough to allow us to compute momentum transfers corresponding to $t \approx 0.05\,GeV^2/c^2$. Thus, exclusive final states are selected based on the total number of charged tracks seen in the spectrometer and final states with π^0's are rejected by requiring no visible energy in the electromagnetic calorimeters. Assuming exclusive reactions, t is given[1] by the total measured transverse momentum of the reconstructed final state.

As stated earlier, the E687 experiment is focused on Charm physics, where charged multiplicities are typically higher than two. Thus, most of the data was taken with a second level trigger based on a crude charged multiplicity measurement and a minimum hadronic energy recorded in the forward part of the spectrometer. As the multiplicity trigger required at least 3 charged prongs outside the pair region, in principle, virtually no $\rho(770) \to \pi^+\pi^-$ could be recorded. However, due to random noise in the PWC system, this trigger has some, although undetermined, efficiency for the two prong events. Fortunately, the exclusive $\rho(770)$ photoproduction total cross-section has already been well measured at this energy range, yielding $\approx 10\mu b$[7].

The hadron calorimeter (hereafter HC) trigger will also limit our ability to produce an accurate phase shift analysis of the 2-pion final state. The efficiency and energy resolution of the central part of the calorimeter is severely degraded for two independent reasons: for about half the sample, taken during the 1990 run, a compact electromagnetic calorimeter was placed in front of the HC to measure non-interacting photon energies. The output of this calorimeter could not be included in the total HC energy sum at the trigger level. During the 1991 run, this calorimeter was removed and a central hole had to be pierced through the HC to provide beam for an experiment located downstream of E687. A dedicated Monte-Carlo program based on GEANT3 has been written to simulate the HC response. Electronic noise

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[1] in very good approximation, as t_0 can be neglected for a $\approx$ 1. GeV meson at these high energies

in the fast energy sum occurring in this second level trigger has also been included.

Most of the data ($\approx 98\%$) has been taken with a Beryllium target. A small part of the 1991 run was dedicated to A-dependence measurements, with a Lead, Aluminium target segment interleaved with control Beryllium segments. This allows us to prove that our samples are in fact diffractive by relating the highest t-slope to the size of the nucleus.

3 Analysis:

The SCHC production mechanism, characterized by a $sin^2(\theta)$ angular distribution in the Gottfried-Jackson frame[13], has been well established[14, 15].

Our data is entirely consistent with this model and with a photoproduction cross section independent of $\sqrt{s}$ (given by the reconstructed longitudinal momentum P_z of the $\pi^+\pi^-$ pair), as observed by earlier experiments. However, our acceptance estimate is very sensitive to both distributions in θ and P_z. We are therefore unable to *reliably* estimate small deviations (i.e. a few % in the double differential cross section $d^2\sigma/dP_zd\theta$) from this simple model. Indeed, for the 1991 sample, the HC efficiency around the beam hole has been tuned to reproduce this model, so that, under these assumptions, the acceptance correction for the invariant mass $M_{\pi\pi}$ distribution can be determined. It is superimposed, in fig. 1a to our measured mass spactrum displayed in lienar scale. It is almost constant for $M_{\pi\pi} \approx 1.0$ GeV. Its relative derivative at the $\rho(770)$ pole mass has been estimated to be $(0.55 \pm .1)$ GeV^{-1} for the 1990 sample and (1.45 ± 0.15) GeV^{-1} for the 1991 sample.

Fig. 1b shows the $M(2\pi)$ spectra for small t's in logarithmic scale separated for the two E687 running periods.

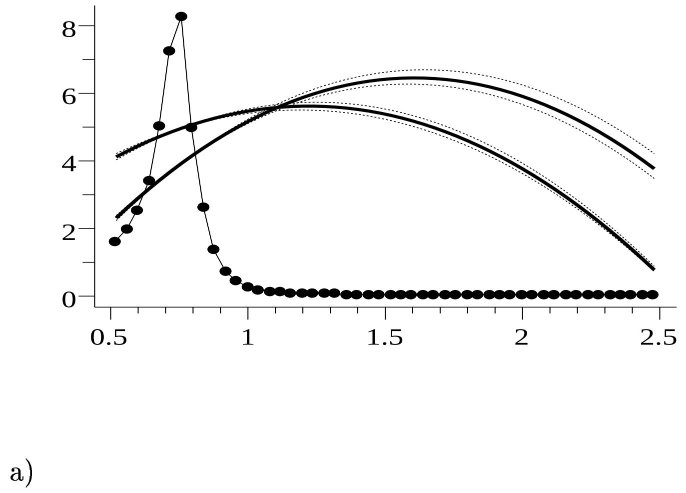
3.1 Formalism of the $\pi^+\pi^-$ channel

The decay amplitude for a spin 1 relativistic Breit-Wigner can be written as:

$$A_{BW} = A_i \frac{m_r\Gamma_r(m)}{(m_r^2 - m^2) + im_r\Gamma_r(m)}$$

where m_r is the nominal mass of the resonance, m is the di-pion mass and Γ_r is the mass dependent width:

$$\Gamma_r(m) = \Gamma_0 \left[\frac{q_m}{q_{m_r}}\right]^3 \frac{\rho(m)}{\rho(m_r)}$$



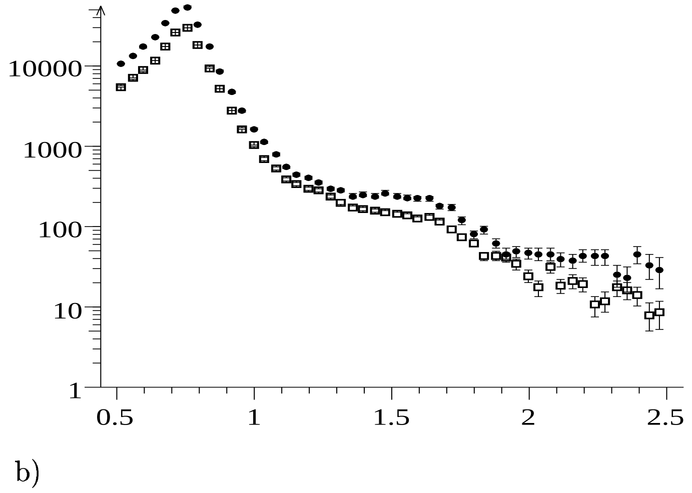


Figure 1: The measured $M_{2\pi}$ distributions for $t < 0.0625\, GeV^2/c^2$: a) Mass spectrum in linear scale (filled circles and solid line), along with the acceptance correction (solid thick lines) for the two running periods, 1990 and 1991. The thin lines around the acceptance curves show the systematic errors. The relative scales between acceptances and distribution are completely arbitrary; b) The same mass spectrum in log scale separated for the 1990 run (back circles) and the 1991 run (open squares).4

$$\rho(m) = \frac{1}{q_m^2 + q_{m_r}^2}$$

where Γ_0 is the nominal width of the resonance and $q(m)$ is the pion momentum transfer in the center of mass of the dipion system. This effective width tends to broaden the resonance at high masses. However, a cursory look at the data tells us that the skewing tends to occur at low mass, in addition, the pole of the resonance seems to be shifted by $\approx -20.$ MeV. This effect, recognized more than 30 years ago[10] is attributed to the interference between a smooth, non-resonant, amplitude, the "Drell" amplitude[11], and the $\rho(770)$ amplitude. This interference is constructive at low mass, destructive above the $\rho(770)$ pole mass. Early analysis of this effect were not very sensitive to the $M_{\pi\pi}$ dependency of this Drell amplitude[16, 14]. We found that a constant form factor gives acceptable fits up to $M_{\pi\pi} \approx 0.9$.

However, at higher mass, $M_{2\pi} \approx> 3 \times \Gamma_0$ above the $\rho(770)$ pole mass, the cross section keeps dropping: this non-resonant amplitude must be dampening as $M_{\pi\pi}$ increases. We have used the following phenomenological expression for this "Drell" amplitude :

$$A_{Drell} \approx F_{nr}\, e^{i\phi_{nr}} \frac{(M_r^2 - M^2)}{(M_r^2 - M^2) + iM_r\Gamma_r(M)}$$

where the phenomenological form factor is hidden in F_{nr}. An exponential-based form factor is used in this analysis:

$$F_{nr} = \frac{q(m)}{M_{\pi\pi}} e^{\frac{-q^2(m)}{2k_0^2}}$$

where q is the 4-momentum transfer estimated in the center of mass of the di-pion pair. Obviously, as we are searching for ρ', other interfering Breit-Wigner amplitudes are added. As described below, one must also add an interfering amplitude for the production and decay of $\omega(783) \rightarrow \pi^+\pi^-$. Finally, a non-interfering $f_2 \rightarrow \pi^+\pi^-$ and exponentially decreasing background at low mass had to be added in to reach an acceptable χ^2. The relative decay fraction Br_i into a given state is estimated by computing the ratio between the integrals of the fitted differential cross section $d\sigma/dM \propto d|A|^2/dM$ for the state of interest over the same cross section with all modes present. These fractions do not sum to one due to the presence of interference between the modes.

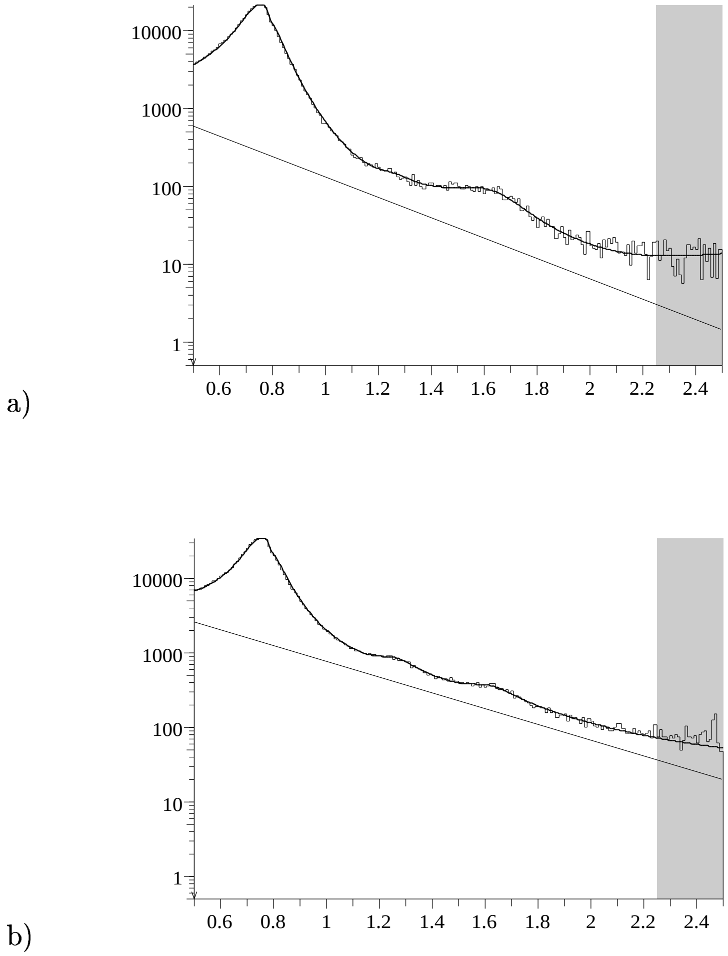


Figure 2: The measured $M_{2\pi}$ distribution in 1 MeV bin, along with a phenomenolgical fit based on multiple Breit-Wigners, the interfering Drell amplitude and an incoherent background (represented independently as straight line on the plots). From top: a) distributionfor small t; b) all events. The χ^2 for the fit on a) is 161, on b) is 147, 162 d.g.f. The grey-shaded area are excluded from the fit.

3.2 Results from a wide mass range fit

The acceptance corrected $M_{2\pi}$ spectra, shown in fig.s 2 for the small t production ($t < 0.0625$ $(GeV/c)2$ (fig. 2a) and for all events (fig. 2b), are fitted with the amplitudes described in the previous section; the fit to fig. 2a is based on the assumption that only one ρ' meson in the high mass region contributes to the signal.

The pole mass value $M = 1656 \pm 10(stat)\,^{+200}_{-20}(syst)$ MeV and the width $\Gamma = [344.0 \pm 36(stat) \pm\ ^{+100}_{-150}(syst)]$ for this single ρ', are in good agreement with previous photoproduction experiments[16].

The systematic errors due to the acceptance correction are small ($\approx 10MeV$ for the width, few MeV for the pole Mass) compared to model uncertainties: the background level at high mass, as well as the interfering Drell amplitude could not be determined independently. In particular, there is a strong correlation between the relative phases among the three amplitudes ($\rho(770)$, $\rho(1650)$ and the Drell process) and the parameters of the $\rho(1650)$ resonance. This is shown in fig. 3.

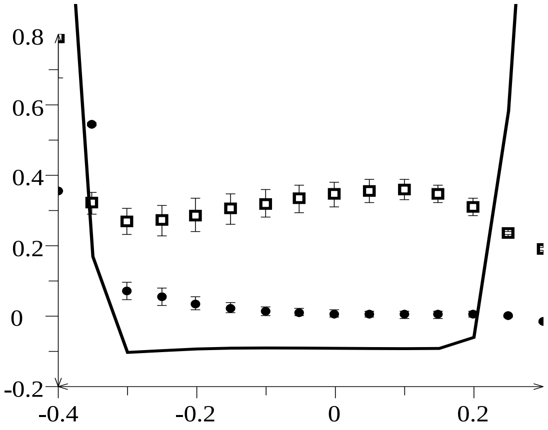


Figure 3: The sensitivity of the $\rho(1650)$ resonance parameters to the assumed relative phase ϕ_{nr} between the $\rho(770)$ and the Drell amplitude (the relative $\rho(770) - \rho'(1650)$ phase is locked at zero). The normalized χ^2 (e.g.,$\chi^2/160$) at the extremum (solid line) is plotted against this phase. Also plotted are $\Delta M = M(\rho'(pole) - 1.650)$ in GeV (black circles) and Γ (open squares) as found by Minuit.

The best estimated values mentioned above corresponds to a fit where these two phases have been fixed to 0. The fit parameters are listed in Table 3.2. The systematic error have been estimated from fig. 3[2].

The sensitivity to the Drell amplitude parameters has been mostly studied for the sample at low momentum transfer ($t < 0.0625 GeV^2/c^2$; fig. 2a), to avoid possible complication coming from the $f_2(1270)$ clearly visible in fig. 2b. However, as we included this state in the global fit, the $\rho'(1650)$ resonance parameters are not sensitive to the t-cut, and no further broadening of the systematic errors are required.

Note that the χ^2 for the fit, at the extremity, is acceptable. Thus, adding free parameters will over-constrain the fit. Despite the success of this single ρ' fit, as suggested by e^+e^- measurement, we fitted the same spectrum with an additional p-wave Breit-Wigner (Table 3.2), fixing the ρ' masses at recommended by the PDG values. However, the quality of the fit does not significantly improve: the data does not requires the introduction of this second ρ'. Also, the relative phases between this ρ' and the $\rho(770)$ take rather unexplainable values, while, for the single ρ' fit, the relative phase is compatible with zero, as naively expected if this ρ' is simply a radially excited $\rho(770)$. It should be noted that the dominant amplitude at $M_{\pi\pi} \approx 1600$ MeV is still the $\rho(770)$ and it's accompanying Drell amplitude, which is by essence very broad. Therefore, fitting over a wide mass range is recommended.

3.3 $\rho - \omega$ mixing

This effect, established first in photoproduction experiments, [18], has been accurately measured in e^+e^-[1]. However, although the E687 spectrometer was not specifically designed for this measurement, this data gives us the most precise measurement of this mixing parameter.

Given the relatively narrow width of the $\omega(783)$, the fit shown in Figure 4 can be safely done between 0.5 and 1.0 GeV. In addition, the t-cut has been removed for the final fit, as the $f_2(1270)$ has a negligible contribution to the total amplitude around $M_{\pi\pi} \approx 0.780 GeV$. The $\rho(770)$ pole mass is a free parameter in the fit, while the pole mass for the $\omega(783)$ has been fixed at the nominal value[1]. However, although we do not have a competitive $\rho - \omega$ mass splitting measurement, it is clear from

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[2] In principle, MINUIT, the CERN minimization program, should be able to estimate the true error taking into account these correlations, however, when the χ^2 is non-parabolic, this MINOS algorithm is not guaranteed to succeed.

Parameter	Single ρ' fit	Two ρ' fit
$Br_{\rho(771)}$	0.829 ± 0.006	0.835 ± 0.006
$m_\rho(771)$	$773.6 \pm .05\,Mev$	$773.7 \pm .04\,Mev$
$\Gamma_\rho(771)$	$149.5 \pm 0.76\,Mev$	$149.3 \pm 0.76\,Mev$
$\phi_{\rho(771)}$	0. - Defined	0. - Defined
Br_inr	0.223 ± 0.006	0.214 ± 0.006
ϕ_{nr}	0.0 - Fixed	0.0 - Fixed
k_0^2	$0.361 \pm 0.008\,Gev^2$	$0.341 \pm 0.010\,Gev^2$
Br_ω	0.00150 ± 0.00016	0.00151 ± 0.00016
ϕ_ω	1.620 ± 0.052	1.624 ± 0.053
$Br_{f_2(1270)}$	0.00088 ± 0.00022	0.00134 ± 0.00033
$Br_{\rho(1450)}$	0. - Fixed	0.00024 ± 0.00021
$M_{\rho(1450)}$	-	1.45 Gev - Fixed
$\Gamma_{\rho(1450)}$	-	$0.210 \pm 0.077\,Gev$
$\phi_{\rho(1450)}$	-	4.86 ± 0.34
$Br_{\rho(1650)}$	0.0029 ± 0.0004	0.0015 ± 0.0008
$M_{\rho(1650)}$	$1.656 \pm 0.010\,Gev$	1.70 Gev - Fixed
$\Gamma_{\rho(1650)}$	$0.344 \pm 0.036\,Gev$	$0.277 \pm 0.050\,Gev$
$\phi_{\rho(1650)}$	0. - Fixed	0.47 ± 0.24
$R_{bck}(M = 0.5)$	0.197 ± 0.039	0.183 ± 0.023
α_M	$3.07 \pm 0.21\ Gev^{-1}$	$2.864 \pm 0.14\ Gev^{-1}$

Table 1: Result from the fit over the broad $\pi^+\pi^-$ mass range. In the first fit (left column), only one resonance around $M = 1650$ is introduced. The χ^2 is 147.2 for 160 degrees of freedom. One the second fit (right column), a second resonance is introduced, with both ρ' pole mass fixed. The χ^2 is 139.3 for 158 degrees of freedom. The errors are statistical only.

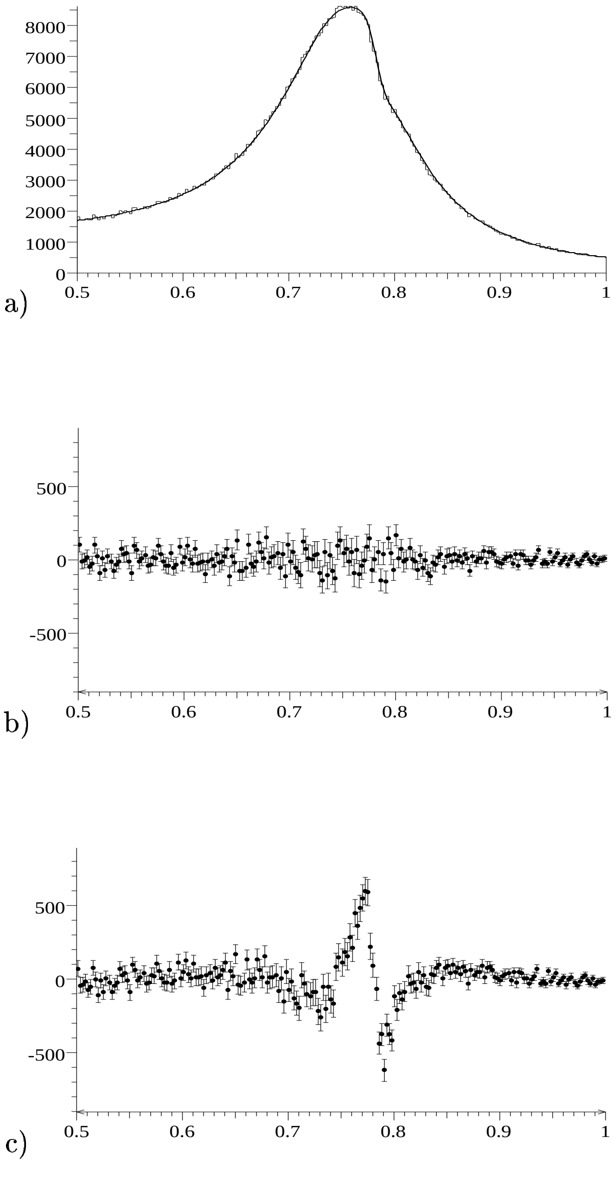

Figure 4: a): the measured $d\sigma/dM_{\pi\pi}$ (arbitrary units), around the $\rho(770)\,,\omega(783)$ pole mass (top); b) residual (fit - data); c) residuals (fit - data) once the mixing amplitude is fixed to 0.

Figure 4 (bottom plot) that the interference is seen at the correct mass. The $\rho - \omega$ mixing amplitude is not strongly correlated to the exact shape of the Drell form factor. However, the relative phase between the ω and ρ, predicted to be $\pi/2$ in photoproduction[17], is more sensitive to this background process. Using a wider mass range and the form factor mentioned above, with $k_0^2 \approx 0.36GeV^-1$, this relative phase is measured to be $1.62 \pm 0.05(stat) \pm 0.05(syst)$. When fitted between 0.5 and 1.0 GeV, a constant form factor gives a relative phase around 1.8 ± 0.06, a significant deviation. Thus, as long as one can trust the naive quark model prediction for this phase, one has a sensitive - albeit indirect - probe for the non-resonant amplitude.

In order to improve the measurement of the G-parity forbidden decay $\omega \rightarrow \pi^+\pi^-$ branching ratio, one needs to measure the $\rho(770)$ to $\omega(783)$ exclusive photoproduction cross section accurately.. This was found to be very difficult due to uncertainties in the π^0 reconstruction efficiency. Assuming that this ratio is 13.6, as predicted by broken SU(3)[12], this branching ratio is $1.95 \pm 0.02(stat) \pm 0.015(syst)\%$. As in previous fits, the mass and width of $\rho(770)$ are in agreement with those measured in e^+ e^-[1].

3.4 Other amplitudes

At large t ($t \approx> 0.01GeV^2/c^2$), the $f_2(1270)$ signal, although small, can not be denied, with a fit fraction of about 0.5%. In the previous section, we have assumed that this state does not interfere with the p-wave, e.g. As this $f_2(1270)$ has clearly a different t-dependence than the $\rho(770)$, this state is probably not diffractively produced. At such low relative yields, some particles (neutrals, most likely) could have been missed by the detector. Hence, this $f_2(1270)$ signal should be considered as a background. However, a small deviation from SCHC can not be ruled out.

While fitting this mass spectrum, we have also allowed for contributions from the scalar state $f_0(980)$ and $f_0(1300)$. As previously stated, the acceptance corrections to the angular distribution are too uncertain to place a meaningful limit on the relative strength of an s-wave. As we have no formal proof that the background estimate is correct at higher mass, our data could accommodate a broad $f_0(1300)$ (i.e. , a pole mass of 1300 MeV and a width of 350 MeV) with a fit fraction of about 1.%. The region around 1.0 GeV is a bit more complicated, as two additional resonances could be expected: the interfering $\phi(1020)$ and the non-interfering[3] $f_0(980)$. The $\phi(1020)$ interference is only seen as a few sigma effect in our data, in quantitative agreement with the accepted branching ratio of $8.\,10^{-5}$[1] and a cross section ratio of (9/1.33). Assuming these accepted values for the $\phi(1020)$ interference, we can deduce an upper limit for the following ratio of cross section × branching ratio:

$$\frac{\sigma_{f_0(980)} \times B.R. \to \pi^+\pi^-}{\sigma_{f_2(1270)} \times B.R. \to \pi^+\pi^-} \leq 0.0023$$

at 95 % confidence level (statistical error only). This fit assumes a width for the $f_0(980)$ of 40. MeV. If this resonance is wider, this stringent upper limit degrades rapidly. However, it is obvious that the exclusive or semi-exclusive photoproduction of a relatively narrow $f_0(980)$ is strongly suppressed.

The Argand diagram for the p-wave, shown on figure 5, summarizes the analysis of the $\pi^+\pi^-$ final state. To first order, the Drell amplitude pushes the entire diagram towards real values for the total amplitude. It should also be noted that, if one asks to find two distinct ρ', with pole masses around 1450 and 1700 MeV, these two resonances add up coherently to simulate a single resonance, with a pole mass around 1660 MeV. Because of it's simplicity, the latter solution is preferred.

To conclude, in the quasi-exclusive, diffractive, reaction $\gamma \to \pi^+\pi^-$ dominated by the t-channel, non-resonant Drell amplitude and the elastic $\rho(770)$ meson, we have observed the $\rho(770) \leftrightarrow \omega(783)$ interference effect, corresponding to a branching ratio for $\omega(783)\pi^+\pi^-$ of $1.95 \pm 0.02(stat) \pm 0.015(syst)\%$. The SCHC model works well at these energies, as demonstrated by the relatively weak amplitude for the $f_2(1270)$. The narrow $f_0(980)$ is not seen in this reaction, suppression beyond small SCHC deviations seems to occur.

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[3] That is, not interfering with the dominant amplitudes from the $\rho(770)$ and the Drell mechanism.

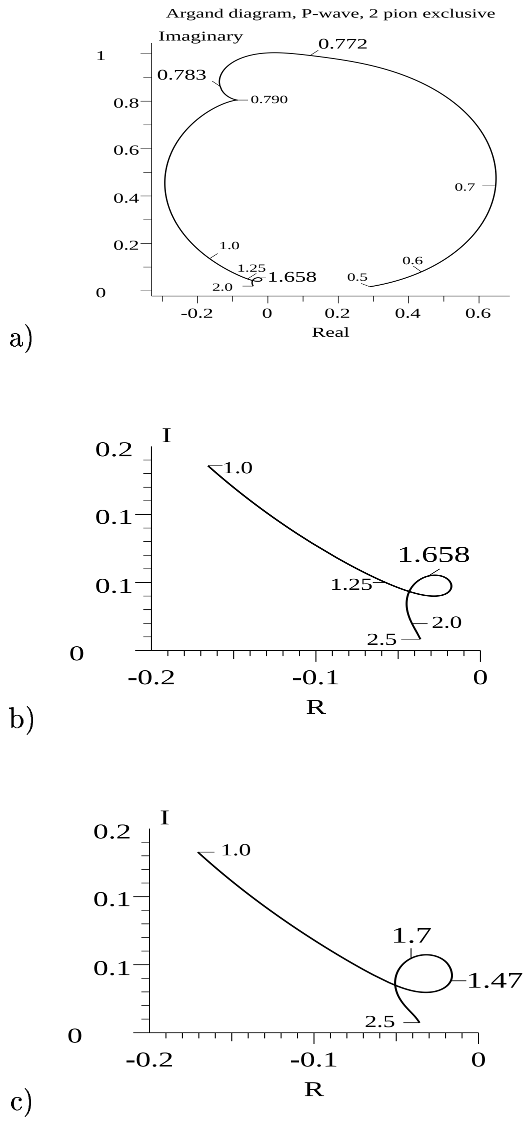

Figure 5: The Argand diagram for the P-Wave amplitude, assuming a single $\rho(1650)$ ((a) and (b)) and two ρ', at 1450 and 1700 MeV (c) respectively.

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[1] Particle Data Group, R. m. Barnett et al. Phys. Rev. **D54**, 1, (1996);

[2] A. Donnachie and A. B. Clegg, Z. Phys. **C51**, 689 (1991)

[3] a- C. Erkal, M.G. Olsson, Z.Phys. **C33**, 445 (1987); b- ibidem **C31**, 615 (1986);

[4] R. Vilela Mendes Phys. Lett. **196B**, 207 (1987);

[5] P.L. Frabetti et al. N. I. M. in Phys. Res. **A320**, 519 (1992);

[6] P.L. Frabetti et al. N. I. M. in Phys. Res. **A329**, 62 (1993);

[7] P.Callahan et al. Fermilab Preprint FERMILAB-PUB-84/36-E;

[8] M. S. Atiya et al. Phys. Rev. Lett. **43**, 1691 (1979);

[9] E. McCrory, *The Reactions* $\gamma P \rightarrow \pi^+\pi^-\pi^+\pi^- P$ *and* $\gamma P \rightarrow K^\pm\pi^\pm K^0 P$ *at 20 GeV*. PhD Thesis, Duke University, 1986;

[10] a- M. Ademollo and C. Chiuderi, Nuovo Cim. **25**, 1113 (1962); b- R. T. Deck, Phys. Rev. Lett. **13**, 169 (1964); c- P. Söding, Phys. Lett. **19**, 702 (1965);

[11] S. D. Drell and J. S. Trefil, Phys. Rev. Lett. **16**, 552 (1966);

[12] R. J. Oakes and J.J. Sakurai, Phys. Rev. Lett. **19**, 1266 (1967);

[13] K. Gottfried and J. D. Jackson, N. Cim. **33**, 309 (1964);

[14] K. Abe et al., Phys. Rev. **D32**, 2288 (1985);

[15] D. Aston et al., Nucl. Phys. **B209**, 56 (1982);

[16] Ballam et al., Phys. Rev. **D5**, 545 (1972);

[17] A. S. Goldhaber, G. C. Fox and C. Quigg, Phys. Lett. **30B**, 249 (1969);

[18] Particle Data Group, J.J. Hernandez et al., Phys. Lett. **239**, 1 (1990).