Laboratori Nazionali di Frascati

LNF-71/71

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Estratto da : Jnl. de Phys. suppl. 10, C3-93 (1971)

AN EXTENDED VECTOR DOMINANCE MODEL : ITS IMPLICATIONS ON MESON DECAYS AND e$^+$ e$^-$ ANNIHILATION INTO HADRONS

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Résumé. — Les conséquences de l'existence des nouveaux vecteurs mésons sont discutées. On étudie les désintégrations ω, $\varphi \to 3\,\pi$, ω, $\varphi \to \pi_0\,\gamma$, π_0, η, $\eta' \to \gamma\gamma$, η, $\eta' \to \pi^+\,\pi^-\,\gamma$ en tenant compte des contributions des ρ' ($m_{\rho'} \simeq 1{,}5$ GeV, $\Gamma_{\rho'} \simeq 0{,}350$ GeV) et de ses partenaires de SU(3). Cela permet d'estimer le couplage du photon ρ' et des constantes de couplage des différents multiplets SU(3). Les sections efficaces de la production des hadrons dans les collisions e$^+$ e$^-$ sont étudiées et l'on prédit leur grandeur et leur comportement à des énergies totales dans le centre de masse de 1,4 à 2,4 GeV.

Abstract. — The consequences of the existence of new vector mesons are discussed. The decays ω, $\varphi \to 3\,\pi$, ω, $\varphi \to \pi_0\,\gamma$, π_0, η, $\eta' \to \gamma\gamma$, π, $\pi' \to \pi^+\,\pi^-\,\gamma$ are studied taking into account the contributions of the ρ' ($m_{\rho'} \simeq 1.5$ GeV, $\Gamma_{\rho'} \simeq 0.350$ GeV) and its SU(3) partners. This allows an estimate of the ρ'-photon coupling and the coupling constants among the different SU(3) multiplets involved in the model. The cross sections for production of hadrons in e$^+$ e$^+$ collisions are then studied, and their magnitude and behaviour are predicted at total energies of the colliding beams, $2\,E$ ranging from 1.4 to 2.4 GeV.

Recently some experimental effort has been devoted to search for additional vector mesons whose existence has been suggested by many theoretical models [1]. All experiments have looked for a particular decay mode of any vector meson produced. The reaction $\gamma + C \to C + \mu^+ + \mu^-$ has been studied by Hayes et al. [2]. They have found no deviation from QED in the invariant pair mass between 1.3 and 2.1 GeV and give upper limits on the production of a heavy vector boson decaying into muon pairs in this mass region. In particular, by defining em_ρ^2/f_ρ and $em_{\rho'}^2/f_{\rho'}$ as the ρ-photon and ρ'-photon couplings, for any ρ' with mass $m_{\rho'}$, the resulting upper limits on $(f_\rho/f_{\rho'})^2$ are given by 0.064-0.081 in the ρ' mass range 1.4-1.6 GeV. These bounds however depend on the assumed ρ' width, and the above values are obtained by assuming quite arbitrarily $\Gamma_{\rho'} = \frac{1}{2}\,\Gamma_\rho = \simeq 60$ MeV.

Several experiments [3] have been carried out looking at photo-production of high mass pion pairs from nuclei. All these experiments have shown some evidence for a broad enhancement in the mass range 1.4-1.6 GeV, although none of them has unambiguously established its mass and width. The results of the DESY-MIT group (3c) are shown in figure 1, where the mass spectrum for all data is averaged over the spectrometer aperture. The curve is a fit to the resonance shape extrapolated by eye to higher values of $m_{\pi\pi}$. The existence of a broad resonance decaying into $\pi^+\,\pi^-$ pairs could conceibably explain the observed enhancement. Very naively the difference between the experimental data points and the best eye fit

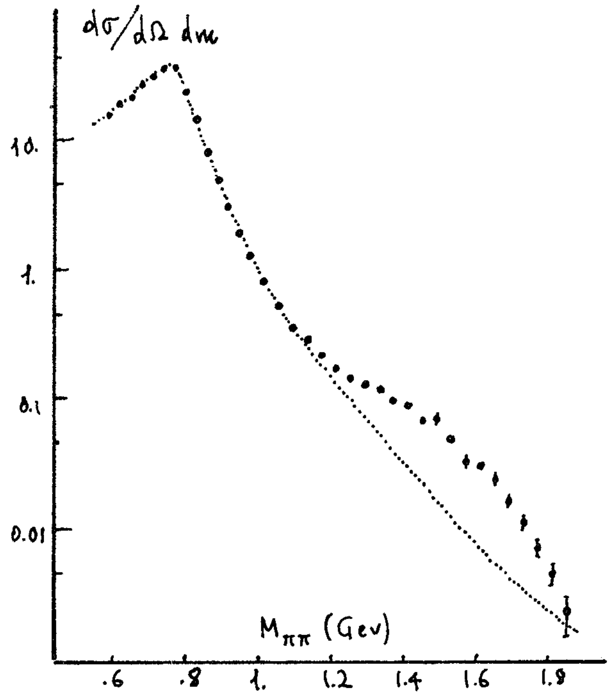

FIG. 1. — Dipion mass spectrum for all data averaged over the spectrometer aperture. The curve is a fit to the ρ resonance shape extrapolated by eye to $m_{\pi\pi} \simeq 1.8$ GeV. The figure is taken from ref. [3c].

shown in figure 1, is in fact well approximated by a Breit-Wigner shape centered at $m_{\rho'} \simeq 1.4$ GeV, with $\Gamma_{\rho'} \simeq 320$ MeV.

A further evidence comes from the SLAC experiment by Davier et al. [4] who have studied the reaction $\gamma p \to \pi^+ \pi^- \pi^+ \pi^- p$. The four pion mass spectrum shows an enhancement near 1.5 GeV which becomes cleaner when the events in Δ^{++} region are removed and a restriction is made that three of the pions are in the A_1 region. This is shown in figure 2. A fit to a resonance shape yields the results :

$$M = 1.55 \pm 0.04 \text{ GeV}$$

and $\Gamma = 0.26 \pm 0.11$ GeV. The same authors have also observed the reaction $\gamma p \to p\pi^+ \pi^-$. In the $\pi^+ \pi^-$ system an enhancement is observed with parameters $M = 1.54 \pm 0.02$ GeV and

$$\Gamma = 0.24 \pm 0.08 \text{ GeV}.$$

This is also shown in figure 2.

Electron-positron storage rings provide the most natural and cleanest way to look for new vector mesons. Should these 1^- states really exist with quite large masses, as the previously discussed evidence seems to indicate, one should expect large inelasticities in $e^+ e^-$ hadronic final states, just by simple statistical

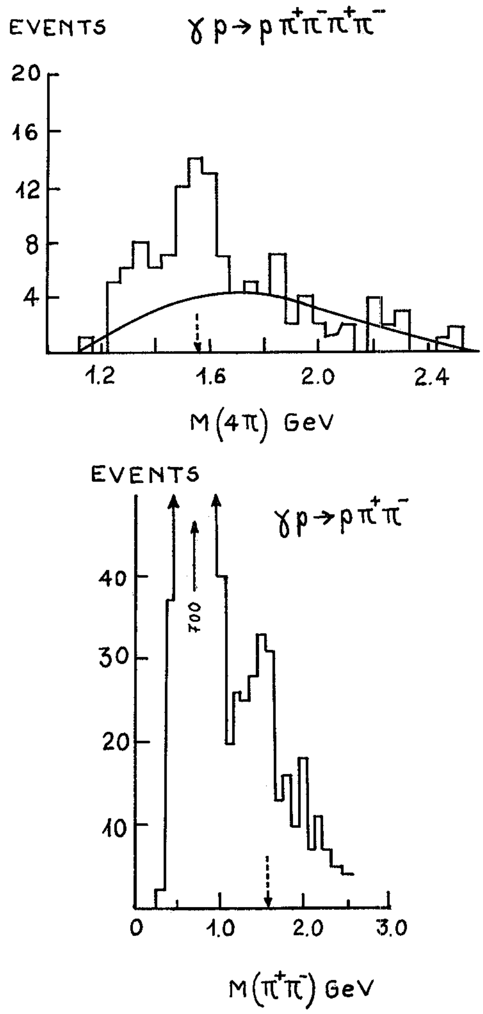

FIG. 2. — *a*) $4\,\pi$ mass distribution in the reaction

$$\gamma p \to \pi^+ \pi^- \pi^+ \pi^- p$$

measured by Davier et al. [4]; *b*) Compilation of data on $\gamma p \to \pi^+ \pi^- p$ for $m_{\pi\pi}$ above 1 GeV. The figure is taken from ref. [4].

arguments. Actually the Frascati results [5] have indicated a large multiple production of hadrons with a cross section of the order of the $\mu^+ \mu^-$ pair production at the same energies.

We have studied the consequences of the existence of new vector mesons concerning the production of hadrons in $e^+ e^-$ collisions in the energy range covered by the Frascati storage ring Adone, namely at total energies of the colliding beams $2\,E$ ranging from 1.4 to 2.4 GeV. It will be shown in the following that an extended vector dominance model is fully adeguate to explain the large multiparticle cross sections observed at Frascati, as well as the rapid decrease of $\pi^+ \pi^-$ cross sections [6].

From the previous analysis of the experimental situation we assume the existence of a meson having the quantum numbers of the ρ, we call it ρ', and we roughly estimate its mass and width as 1.5 GeV and 0.35 GeV respectively. Next we study the decays of the known pseudoscalar and vector mesons at the light of the existence of the ρ' and its SU(3) factores, in addition to the ρ, ω and φ, usual members of the standard vector dominance model. This enables us to have an estimate of the coupling constants among these new vector mesons, the old ones and the photon.

A general analysis of the VMD predictions concerning the electromagnetic and strong decays of the known mesons has been recently made [7] showing that a reasonable agreement with the experimental data can be achieved. We now reconsider the whole situation along the same lines including these new vector mesons. SU(3) is strictly assumed.

The ρ-photon, ρ'-photon couplings and the coupling constants among the different SU(3) multiplets involved in our model are defined as follows :

$$g_{\rho\gamma} = em_\rho^2/f_\rho\,, \quad g_{\rho'\gamma} = em_{\rho'}^2/f_{\rho'} \tag{1}$$

$$g \equiv g_{\rho\rho\eta_8}\,, \quad h \equiv g_{\omega_1\rho\eta_8}\,, \quad f \equiv -\,g_{\rho\rho\eta_1}$$

$$g' \equiv g_{\rho\rho'\eta_8}\,, \quad h' \equiv g_{\omega_1\rho'\eta}\,, \quad f' \equiv -\,g_{\rho\rho'\eta_1}\,. \tag{2}$$

By means of the usual techniques of VMD and SU(3) we obtain the decay rates for processes of the type $V \to 3\,\pi$, $V \to \pi\gamma$ and $P \to \gamma\gamma$ in terms of the products (¹) g/f_ρ, $g'/f_{\rho'}$, h/f_ρ and $h'/f_{\rho'}$. From the experimental values [8]

$$\Gamma(\omega \to 3\,\pi) = 10.7 \text{ MeV},$$

$\Gamma(\varphi \to 3\,\pi) = 0.73$ MeV, $\Gamma(\omega \to \pi^0\,\gamma) = 1.12$ MeV and $\Gamma(\varphi \to \pi^0\,\gamma) \simeq 0\,(< 0.014$ MeV) and taking the $\omega - \varphi$ mixing angle as predicted by the quark model, i. e. $\sin\theta = 1/\sqrt{3}$, we obtain the following values expressed in GeV^{-1} :

$$\frac{eg}{f_\rho} = 0.59\,, \qquad \frac{eh}{f_\rho} = 0.91\,,$$

$$\frac{eg'}{f_{\rho'}} = -\,0.09\,, \quad \frac{eh'}{f_{\rho'}} = -\,0.19\,. \tag{3}$$

(¹) Amplitudes involving the ratio $f_\rho^2/f_{\rho'}^2$, which we find to be small, habe been neglected at this early stage.

We check these results by evaluating the decay rate of the neutral pion. We obtain $\Gamma(\pi^0 \to \gamma\gamma) = 8.4$ eV in good agreement with the value

$$\Gamma(\pi^0 \to \gamma\gamma)_{\exp} = 8.5 \pm 1.7 \text{ eV}$$

quoted in ref. [8]. We note that the introduction of the new mesons, their couplings being the 10-20 % of the old ones, may be considered as a rather small correction to the original VMD results.

In order to estimate the coupling constants f/f_ρ and $f'/f_{\rho'}$ we need to consider processes involving the η and η' mesons for which the theoretical and experimental situation is not so clear. Assuming an $\eta - \eta'$ mixing angle $\alpha = 10{,}4^o$ and taking the experimental results [8] $\Gamma(\eta \to \gamma\gamma) = 1.01$ keV and $\Gamma(\eta \to \pi^+ \pi^- \gamma) = 0.127$ keV we deduce :

$$\frac{ef}{f_\rho} \simeq -0.14 \text{ GeV}^{-1}, \quad \frac{ef'}{f_{\rho'}} \simeq 0.84 \text{ GeV}^{-1}. \quad (4)$$

A new check of our values (3) and (4) is again possible by evaluating the radiative decay rates of the η' meson. We find $\Gamma(\eta' \to \gamma\gamma) \simeq 54$ keV and

$$R \equiv \Gamma(\eta' \to \pi^+ \pi^- \gamma)/\Gamma(\eta' \to \gamma\gamma) \simeq 2.4$$

in good agreement with the more recent experimental results [9] from which the values

$$\Gamma(\eta' \to \gamma\gamma)_{\exp} < 400 \text{ KeV}$$

and $R_{\exp} \simeq 2.5$ can be easily deduced. We note from eq. (4) that the ρ' gives now an essential contribution to reduce the value $R \simeq 14$ previously obtained in ref. [5]. We finally emphasize that all the above results do not depend on the exact value of the ρ' mass and width we have used, provided $m\rho' \gtrsim 2\, m_\rho$.

We proceed now to investigate the implications of the ρ' in the production of hadrons in $e^+ e^-$ annihilation. The total cross section for $e^+ e^- \to \rho' \to$ (final state f) at a total energy $2E = \sqrt{s}$ around the mass of the ρ' is given by :

$$\sigma_f(s) = 16\, \pi^2\, \alpha^2 \frac{m_{\rho'}^4}{f_{\rho'}^2} \frac{1}{s^{3/2}} \frac{\Gamma_{\rho' \to f}(s)}{(s - m_{\rho'}^2)^2 + m_{\rho'}^2\, \Gamma_{\rho'}^2} \quad (5)$$

where $f_{\rho'}$ is defined in eq. (1), $\Gamma_{\rho' \to f}$ is the decay rate for $\rho' \to f$ and $\Gamma_{\rho'}$ is the ρ' total width. Let us consider first the final states f which give rise to high multiplicities of produced particles and can be related to the above discussion on meson decays, namely $\omega\pi$, $\varphi\pi$, $\rho\eta$ and $\rho\eta'$. From eq. (5) it follows that the different production cross sections depend only on the ratio $\Gamma_{\rho' \to f}/f_{\rho'}^2$, which, apart from phase-space factors, can be computed using the results of eqs. (3) and (4). We are therefore able to predict the magnitude and the energy behaviour of the total cross sections in the energy region around the mass of the ρ'.

By means of the usual techniques to evaluate the partial decay rates we get the following values for the different peak cross sections :

$$\begin{aligned} \sigma_{e^+e^- \to \omega\pi}(m_{\rho'}^2) &= 3.6 \times 10^{-32} \text{ cm}^2, \\ \sigma_{e^+e^- \to \varphi\pi}(m_{\rho'}^2) &\simeq 0.07 \times 10^{-32} \text{ cm}^2, \\ \sigma_{e^+e^- \to \rho\eta}(m_{\rho'}^2) &= 0.2 \times 10^{-32} \text{ cm}^2, \\ \sigma_{e^+e^- \to \rho\eta'}(m_{\rho'}^2) &= 0.1 \times 10^{-32} \text{ cm}^2. \end{aligned} \quad (6)$$

The energy dependence of the total cross sections for $\omega\pi$ and $\rho\eta'$ production in the range $1.4 \leqslant \sqrt{s} \leqslant 2.4$ is shown in figure 3. It is clear from this figure that the mode $e^+ e^- \to \omega\pi$ dominates all other modes near the $m_{\rho'}$ peak while the channel $\rho' \to \rho\eta'$ opens at 1.7 GeV approximatively and dominates there after. The $\varphi\pi$ and $\rho\eta$ modes are depressed because of the smallness of their coupling constants. The

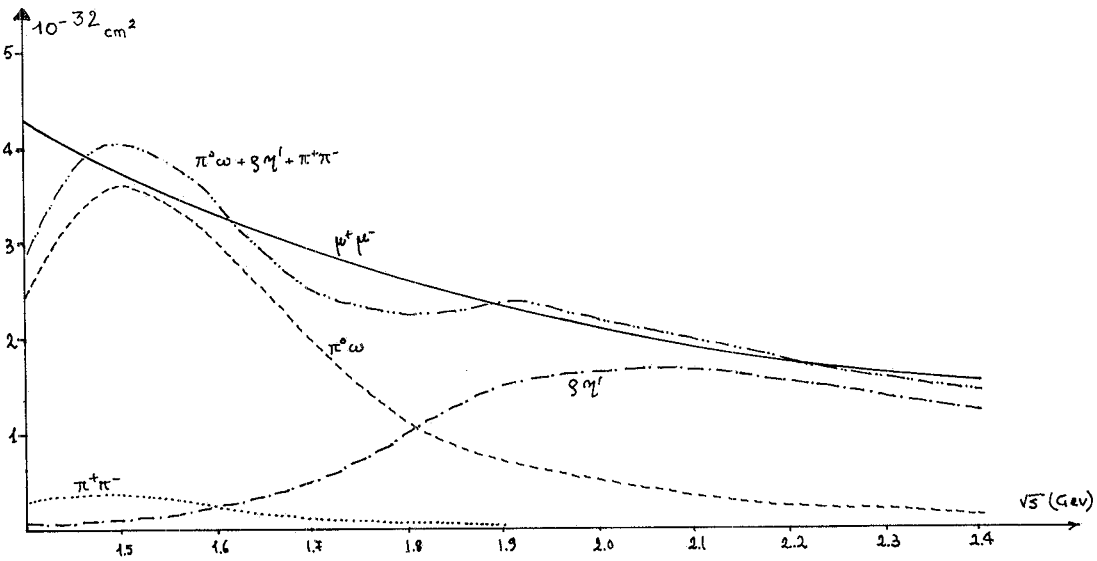

FIG. 3. — $e^+ e^-$ annihilation cross sections in the range $1.4 \lesssim \sqrt{s} \lesssim 2.4$ GeV resulting from eq. (5) for different final states, as explained in the text.

multiplicities produced in the final state are easily found to be

$$\omega\pi^0 \begin{cases} \pi^+ \pi^- \pi^0 \pi^0 & 90\ \% \\ \pi^0 \pi^0 \gamma & 10\ \% \end{cases}$$

$$\rho\eta' \begin{cases} \pi^+ \pi^- + \text{neutrals} & 26\ \% \\ 2(\pi^+ \pi^-) + \text{neutrals} & 62\ \% \\ 3(\pi^+ \pi^-) + \pi^0 \text{ or } \gamma & 12\ \%. \end{cases}$$

As far as the reaction $e^+ e^- \to \rho' \to \pi^+ \pi^-$ is concerned, for which the previous considerations cannot be applied, it is possible to extract some information from the experimental results on pion pairs photoproduction from nuclei [3]. By assuming that the enhancement observed in ref. [3c] is due to the ρ' and from the fact that the interference between ρ and ρ' at the $m\rho'$ peak is small we obtain

$$\frac{\Gamma_{\rho' \to \pi\pi}}{\Gamma_{\rho'}} \simeq 0.004 \frac{\Gamma_{\rho'}}{\Gamma_\rho} \frac{f_{\rho'}^2}{f_\rho^2} \qquad (7)$$

and therefore $\Gamma_{\rho' \to \pi\pi}/\Gamma_{\rho'} \simeq 3.73 \times 10^{-4} f_{\rho'}^{+2}$. Substituting in eq. (5) we find for the cross section at the peak $\sigma_{e^+e^- \to \pi^+\pi^-}(m_{\rho'}^2) \simeq 0.24 \times 10^{-32}$. The energy dependence of $\sigma_{e^+e^- \to \rho'\pi^+\pi^-}(s)$ is shown in figure 4.

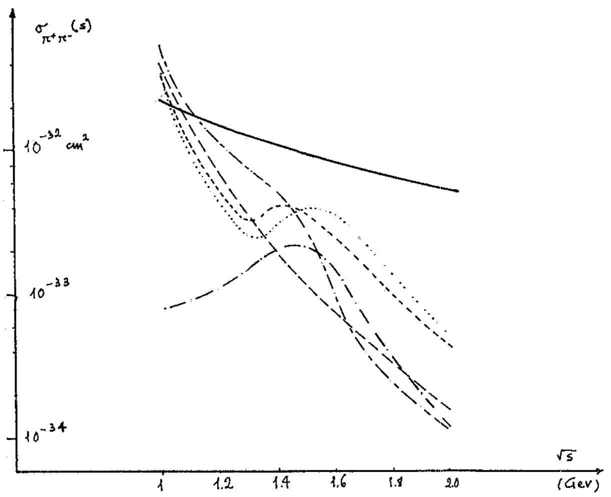

FIG. 4. — Energy dependence of the cross section $\sigma_{\pi^+\pi^-}(s)$, for the reaction $e^+ e^- \to \pi^+ \pi^-$. The curves correspond to different assumptions on the production mechanism.

————	point like
— — — —	ρ only.
· — · — ·	ρ' only $m_{\rho'} = 1.5$ GeV $\Gamma_{\rho'} \simeq .35$ GeV
. . . . .	$\rho + \rho'$ + Inter. ($m_{\rho'} = 1.5$ GeV)
- - - - - -	$\rho + \rho'$ + Inter. ($m_{\rho'} = 1.4$ GeV)
—-.—-.	$\rho + \rho'$ — Inter. ($m_{\rho'} = 1.5$ GeV)

However we have so far neglected the contribution to $\sigma_{\pi^+\pi^-}(s)$ coming from the ρ tail. In the limit that such a procedure makes any sense, we have extrapolated to high energies the fit to the Orsay results [10] based on the Gounaris-Sakurai [11] expression for the pion form factor. This is also shown in figure 4. A relativistic Breit-Wigner description of the ρ shape gives essentially the same result. The overall theoretical predictions for $\sigma_{\pi^+\pi^-}(s)$, which take into account also ρ-ρ' interference effects are shown in the same figure. As one can seee from there, in the case of a positive interference one espects in the energy range $1.4 \leqslant \sqrt{s} \leqslant 2.2$ GeV a total cross section which decreases faster than $1/s$ but which is a factor 2-3 higher than the tail of the ρ. In the same figure is also shown what could be expected if $m_{\rho'} = 1.4$ GeV. The very recent results by Alles-Borelli et al. [6] are in good agreement with this latter result. Due to the fact that the mode $e^+ e^- \to K^+ K^-$ is not distinguished from $e^+ e^- \to \pi^+ \pi^-$ in that experiment, the comparison is done by adding to $\sigma_{\pi^+\pi^-}(s)$ the VMD predictions for $K^+ K^-$ together with the ρ' resonant contribution which is evaluated to be 25% of $\pi^+ \pi^-$, by assuming SU(3) symmetry.

By adding the cross sections $\sigma_f(s)$ for the states f above considered we give in figure 1 the total cross section which is compared to the theoretical behaviour of $\sigma_{e^+e^- \to \mu^+\mu^-}(s)$. It is striking to note how the different channels add together for $\sqrt{s} \gtrsim 1.5$ GeV to give in good approximation a $1/s$ behaving cross section.

We add some remarks, also in order to clarify the limits of our model. By assuming the existence of a new vector meson having a mass about 1.5 GeV we have shown that the theoretical status of the known meson decays is improved. The cross sections for $e^+ e^- \to$ hadrons in the range $1.4 \leqslant \sqrt{s} \leqslant 2.4$ GeV have been then predicted. However we have so far neglected interference contributions coming mainly from $e^+ e^- \to \rho \to \omega\pi$ [12]. These additional terms, which are negligeable on the ρ' peak, can be present particularly for C. M. energies smaller than $m_{\rho'}$. They can change slightly our results which represent the main contribution to the production cross sections. We have also disregarded final states like $\rho' \to A_1^{\pm} \pi^{\mp}$, $\rho' \to A_2\, \pi$ or more sophisticated ones because of the lack of a clear experimental and theoretical situation avoiding in this way the introduction of unknown free parameters [13]. A precise evaluation of these extra terms should come from a detailed comparison with experiments.

An accurate knowledge of the total peak cross section will lead to a measure of $f_{\rho'}$. Should our results be confirmed without the need of further additional terms, from eq. (5) and $\sigma_{\text{tot}}(m_{\rho'}^2) \approx 4.4 \times 10^{-32}$ cm^2 we would get the ratio $f_{\rho'}^2/f_\rho^2 \simeq 5$. This value has to be compared with the typical limits given in the literature, making however more realistic assumptions on the ρ' width and on the branching ratio to two pions. The results are given in the Table I.

Let us finally note that according to our scheme the SU(3) partners of the ρ', such as ω', could at least in principle contribute to the $e^+ e^-$ annihilation cross sections. Since no experimental information is up to now available we have completely disregarded this kind of contributions.

A more detailed and wide analysis on the argument is actually in progress.

TABLE I

Experiment	Mass range (GeV)	Assumptions	$\left(\frac{f_{\rho'}}{f_\rho}\right)^2$
Mc Clellan et al. [3*a*]	$m_{\pi\pi} \approx 1.45$	$\Gamma_{\rho'} = \Gamma_{\rho'\pi\pi} = 100$ MeV	≈ 240
		$\Gamma_{\rho'} \approx 350$ MeV , $\frac{\Gamma_{\rho'\pi\pi}}{\Gamma_{\rho'}} \simeq 0.1$	≈ 7
Bulos et al. [3*b*]	$m_{\pi\pi} \approx 1.4\text{-}1.6$	$\Gamma_{\rho'} = \Gamma_\rho = \Gamma_{\rho'\pi\pi}$	≈ 100
		$\Gamma_{\rho'} \simeq 350$, $\frac{\Gamma_{\rho'\pi\pi}}{\Gamma_\rho} \simeq 0.1$	≈ 3
Hayes et al. [2]	$m_{\mu\mu} \approx 1.4\text{-}1.6$	$\Gamma_{\rho'} = 60$ MeV	$\approx 12\text{-}15$
		$\Gamma_{\rho'} \simeq 350$ MeV	≈ 3

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