SLAC-PUB-11905
hep-ph/0606155
July 2006

Two-photon exchange model for production of neutral vector meson pairs in e^+e^- annihilation

M. Davier[a], M. Peskin[b], and A. Snyder[b1]

[a]*Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud 11, 91898 Orsay, France*
[b]*Stanford Linear Accelerator Center, Stanford, California 94309, USA*

Abstract

A vector-dominance two-photon exchange model is proposed to explain the recently observed production of $\rho^0\rho^0$ and $\rho^0\phi$ pairs in e^+e^- annihilation at 10.58 GeV with the BaBar detector. All the observed features of the data —angular and decay distributions, rates— are in agreement with the model. Predictions are made for yet-unobserved final states.

1 Introduction

So far all observed hadronic processes in e^+e^- annihilation are in agreement with one-photon exchange leading to $C = -1$ final states. However, the BaBar Collaboration has recently presented the first measurement of e^+e^- annihilation into pairs of neutral vector mesons at 10.58 GeV centre-of-mass energy [1]. The final states ρ^0 ρ^0 and ρ^0 ϕ are observed with cross sections

$$\sigma(e^+e^- \to \rho\ \rho) = (20.7 \pm 0.7_{\rm stat} \pm 2.7_{\rm syst})\ \text{fb}, \tag{1}$$
$$\sigma(e^+e^- \to \rho\ \phi) = (5.7 \pm 0.5_{\rm stat} \pm 0.8_{\rm syst})\ \text{fb} \tag{2}$$

in the centre-of-mass angular range $|\cos\theta| < 0.8$. These processes characterized by $C = +1$ final states cannot originate from one-photon exchange followed by quark-antiquark fragmentation.

[1]E-mail: davier@lal.in2p3.fr, mpeskin@slac.stanford.edu, snyder@slac.stanford.edu

Submitted to Physical Review D

Work supported in part by Department of Energy contract DE-AC02-76SF00515

An explanation for these processes is that they arise from e^+e^- annihilation to two virtual photons, with each virtual photon converting to a vector meson. The rates predicted by this mechanism can be computed simply and unambiguously using the effective vector meson-photon couplings determined from the meson leptonic widths. In this note, we present the results for the cross sections and show that they are of the correct size to explain the cross section values obtained by BaBar.

2 The model

We consider the generic process $e^+e^- \to V_1V_2$, where V_1 and V_2 are neutral $C = -1$ vector mesons. It is assumed to proceed with an intermediate $e^+e^- \to \gamma\,\gamma$ process, the two photons converting into V_1 and V_2, with effective couplings e/f_1 and e/f_2.

The cross section in the narrow-width approximation can be simply written in terms of the Mandelstam variables $s = (k+k')^2$, $t = (k-p_1)^2$, and $u = (k-p_2)^2$, where k, k', p_1, and p_2 are the incoming electron, positron, and outgoing vector meson 4-momenta, respectively. In the e^+e^- centre-of-mass, one gets

$$\frac{d\sigma_{V_1V_2}}{d\cos\theta} = \left(\frac{e}{f_1}\right)^2 \left(\frac{e}{f_2}\right)^2 \frac{d\sigma_{\gamma_1^*\gamma_2^*}}{d\cos\theta}\,(m_{V_1}^2, m_{V_2}^2) \tag{3}$$

with

$$\frac{d\sigma_{\gamma_1^*\gamma_2^*}}{d\cos\theta}\,(m_{V_1}^2, m_{V_2}^2) = \frac{\pi\alpha^2}{s}\frac{2|\overrightarrow{p}|}{\sqrt{s}}\;\frac{2(m_{V_1}^2+m_{V_2}^2)sut + (t^2+u^2)(ut - m_{V_1}^2 m_{V_2}^2)}{u^2t^2}, \tag{4}$$

and where θ is the angle between the electron and the V_1 momenta, and $\overrightarrow{p}$ the meson momentum. The last factor reduces to the familiar $t/u + u/t \;=\; 2(1+\cos^2\theta)/\sin^2\theta$ when V_1 and V_2 are made massless. For $m_{V_1} = m_{V_2} = M_Z$, Eq. (3) is consistent with the well-known expression for the vector part of the $e^+e^- \to Z\;Z$ cross section [2].

For masses which are small compared to $\sqrt{s}$, the angular distribution differs little from the massless case. To leading order in m_V^2/s, for the VV case, one obtains:

$$\frac{d\sigma_{VV}}{d\cos\theta} \sim \frac{a+\cos^2\theta}{b-\cos^2\theta}, \tag{5}$$

with

$$a = 1 + \frac{8m_V^2}{s}, \tag{6}$$

$$b = 1 + \frac{4m_V^4}{s^2}. \tag{7}$$

For $m_V = m_\rho$ and $s = (10.58)^2$ GeV^2, $a = 1.043$ and $b = 1.00012$.

For the VV final states involving 2 identical particles, the angular distribution must be integrated over only one hemisphere, while for V_1V_2 ($V_1 \neq V_2$), the integration should be done over the full angular distribution. The measurements with BaBar are made from in the $\cos\theta$ range from -0.8 to 0.8.

To take into account the fact that the ρ meson cannot be properly described in the narrow-width approximation and also to generalize to any vector hadronic final state, it is advantageous to rewrite Eq. (3) in a more general form:

$$\frac{d\sigma_{V_1V_2}}{d\cos\theta} = \left(\frac{\alpha}{3\pi}\right)^2 \int \frac{dm_1^2}{m_1^2} \int \frac{dm_2^2}{m_2^2}\ R(m_1^2)\ R(m_2^2)\ \frac{d\sigma_{\gamma_1^*\gamma_2^*}}{d\cos\theta}\ (m_1^2, m_2^2), \tag{8}$$

where $R(m^2) = \sigma(e^+e^- \to \text{hadrons})/\sigma_{pt}$. Eq. (8) is a completely general expression for the 2-virtual-photon cross section, valid as long as the interference between the products of the 2 photons can be neglected. All one has to do is plug in the contribution to R for any final state and integrate. The narrow-width limit is obtained by taking $R(m^2) = 9\pi/\alpha^2\ \Gamma_{ee}^V\ m_V\ \delta(m^2 - m_V^2)$.

3 Results

For the narrow vector mesons the leptonic widths can be directly used to derive the e/f_V values

$$\Gamma_{ee}^V = \frac{\alpha}{3}\left(\frac{e}{f_V}\right)^2 m_V, \tag{9}$$

while for the ρ meson we integrate over the mass distribution, taking as input for $R(m^2)$ the fit to the annihilation data [3, 4].

The angular distribution is given in Fig. 1. It is strongly peaked along the beams, like the $e^+e^- \to \gamma\gamma$ cross section. The behaviour predicted by Eqs. (3,4,5) is in good agreement with the BaBar data [1].

The model also allows one to compute the cross sections for mesons with helicity $\lambda = \pm 1$ and $\lambda = 0$. As expected the former is dominant, *i.e.* the vector mesons are photon-like with transverse polarisation, leading to a $\sin^2\theta_{\pi,K}$ angular distribution in the $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays. This behaviour is also clearly observed in the BaBar data [1].

Integrating numerically Eq. 8 over $\cos\theta$ from -0.8 to $+0.8$ and over the ρ mass distribution, one obtains

$$\sigma_{\rho\,\rho}^{\text{th}} = (21.4 \pm 0.7)\ \text{fb}, \tag{10}$$

$$\sigma_{\rho\,\phi}^{\text{th}} = (6.15 \pm 0.22)\ \text{fb}. \tag{11}$$

The BaBar measurements are given with a cut on the ρ lineshape, retaining only events with a mass between 0.5 and 1.1 GeV. The ϕ window is likewise defined between 1.008 and 1.035 GeV. The cross sections in the BaBar conditions are:

$$\sigma_{\rho\,\rho}^{\text{th, mass cuts}} = (18.7 \pm 0.6)\ \text{fb}, \tag{12}$$

$$\sigma_{\rho\,\phi}^{\text{th, mass cuts}} = (5.3 \pm 0.2)\ \text{fb}. \tag{13}$$

The agreement with the BaBar results is good, thus confirming the vector-dominance two-photon process as the dominant dynamics for $V_1^0 V_2^0$ final states.

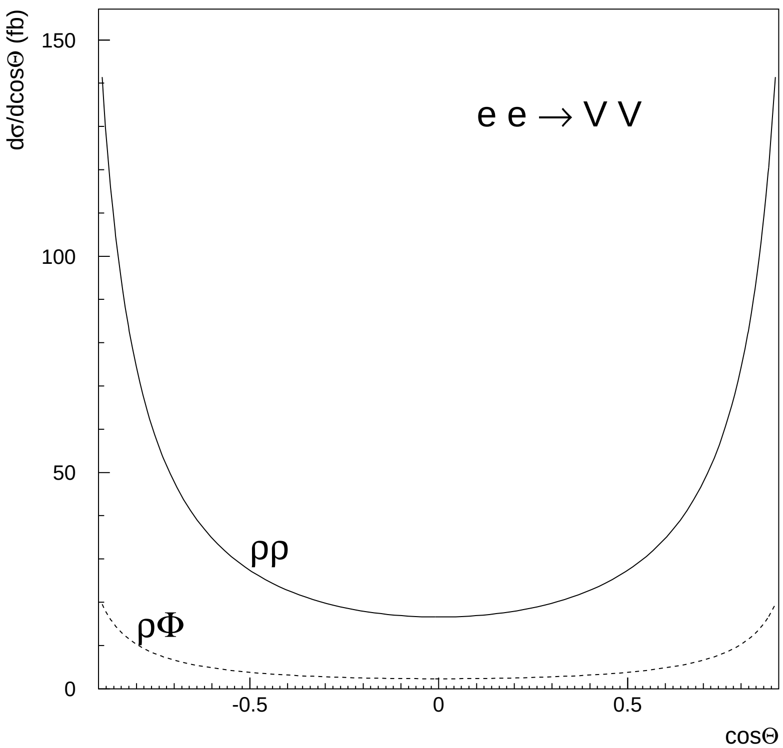

Figure 1: The angular distribution for the processes $e^+e^- \to \rho\,\rho$ and $e^+e^- \to \rho\,\phi$ at 10.58 GeV as predicted by the vector dominance model in the narrow width approximation.

The calculation can be straightforwardly applied to other final states, the corresponding predictions being summarized in Table 1. We emphasize that any interference between the hadronic products originating from the two virtual photons has been neglected —an approximation which is expected to be less valid as the hadronic masses increases on the scale of $\sqrt{s}$.

The value obtained for $e^+e^- \to J/\psi\ J/\psi$ differs somewhat from the estimate given by Bodwin *et al* [6]. That calculation uses the 2-photon exchange model, with splitting of each photon in $c\ \bar{c}$. The authors allow both pairings of the charm and anticharm quarks and account for the interference between these diagrams using a non-relativistic QCD analysis. They find a cross section of (6.6 ± 3.0) fb, integrating the full angular distribution, to be compared with (2.38 ± 0.15) fb for the subset of diagrams that we consider. While the new interference terms could be important for J/ψ production, since $2m_{J/\psi}$ is close to $\sqrt{s}$, they are not significant for the production of pairs of low-mass states such as ρ and ϕ.

The predictions in Table 1 beyond the already measured $\rho\ \rho$ and $\rho\ \phi$ final states can be tested in the future as some of them are within reach of the BaBar and Belle detectors with present and foreseen luminosities.

Table 1: Cross sections for the production of neutral vector meson pairs $V_1\ V_2$ in e^+e^- annihilation at 10.58 GeV. For the final states containing ρ mesons the results are given both with the narrow-width (NW) approximation and the full integration of the mass spectrum. The angular integration is restricted to the $\cos\theta_{V_1}$ range from -0.8 to $+0.8$ for the results in the last column. The values for the leptonic widths are taken from Refs. [3, 4, 5]. The integral over the ρ mass distribution according to Eq. 8 uses a fit to the annihilation data [3, 4].

$V_1\ V_2$	$\Gamma_{V_2\to ee}$ (keV)	σ_{NW} (fb)	σ (fb)	$\sigma_{\lvert\cos\theta\rvert<0.8}$ (fb)
$\rho\ \rho$	7.07 ± 0.11	125.51	115.69	21.39
$\rho\ \omega$	0.60 ± 0.02	21.11	20.27	3.76
$\rho\ \phi$	1.27 ± 0.04	33.70	32.39	6.15
$\rho\ J/\psi$	5.40 ± 0.17	40.66	39.61	10.16
$\rho\ \psi(2S)$	2.10 ± 0.12	13.21	12.89	2.60
$\rho\ \Upsilon(1S)$	1.31 ± 0.03	7.83	7.87	5.45
$\phi\ \phi$	–	2.23	–	0.44
$\omega\ \phi$	–	2.83	–	0.54
$\omega\ \omega$	–	0.89	–	0.16
$\phi\ J/\psi$	–	5.06	–	1.46
$J/\psi\ J/\psi$	–	2.38	–	1.13
$J/\psi\ \psi(2S)$	–	1.49	–	0.78

4 Contributions to R

The computed cross sections can be extrapolated to lower energies in order to estimate the contribution of these $C = +1$ two-photon processes in comparison to the dominant $C = -1$ one-photon annihilation into hadrons. The latter one is the needed input to the calculations of hadronic vacuum polarization at lowest-order.

Figure 2 shows the $\sqrt{s}$ dependence of the cross sections for the dominant processes, computed in the narrow-with approximation and expressed relatively to the pointlike cross section (R). The angular integration is still performed from $\cos\theta_{V_1} = -0.8$ to $+0.8$, values which correspond to a typical experimental acceptance. It is found that the contribution of these 2-photon exchange processes to the measured R is negligible at all energies. In particular, their effect in hadronic vacuum polarization calculations (effect which is presently neglected), such as for the anomalous muon magnetic moment or the running of α is two orders of magnitude smaller than the present experimental accuracy from the R input values.

Interference effects between $C = -1$ and $C = +1$ amplitudes could occur at the $10^{-2}-10^{-3}$ level, but they cancel for charge-symmetric event detection. So their contribution is negligible.

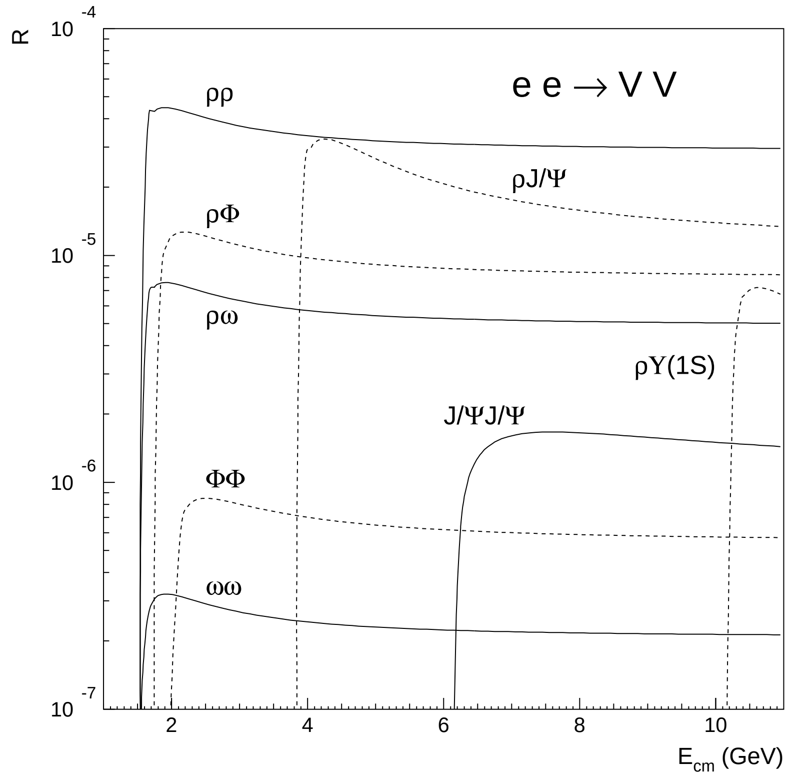

Figure 2: The contributions to R from the dominant processes $e^+e^- \to V_1\ V_2$ as predicted by the vector dominance model in the narrow-width approximation and integrated in the $[-0.8 - 0.8]$ $\cos\theta$ range.

5 Conclusions

The proposed two-photon exchange vector-dominance model for the processes $e^+e^- \to V_1\ V_2$, where V_1 and V_2 are $C = -1$ neutral vector bosons, agrees with all the features of the BaBar data [1] for the $\rho\ \rho$ and $\rho\ \phi$ final states and provides a good description of their rates.

The cross sections for other possible final states, $\rho\ \omega$, $\rho\ J/\psi$, $\rho\ \psi(2S)$, $\rho\ \Upsilon(1S)$, $\phi\ \phi$, $\omega\ \phi$, $\omega\ \omega$, $\phi\ J/\psi$, $J/\psi\ J/\psi$, and $J/\psi\ \psi(2S)$ have been predicted. Most of them are within reach at the B factories with foreseen luminosities.

The contamination of these two-photon exchange processes to the measured R ratio is much smaller than any foreseeable experimental uncertainty on R.

Helpful discussions with S. Brodsky and many BaBar colleagues are warmly acknowledged.

References

[1] P. Patteri, Moriond QCD meeting (March 2006), http://moriond.in2p3.fr/QCD/2006/SundayAfternoon/Patteri.ppt;
K. Yi, Dallas APS DPF meeting (April 2006), http://www.slac.stanford.edu∼yik/tmp/yikaps-mods.pdf.

[2] R. W. Brown and K. D. Mikaelian, *Phys. Rev.***D19** (1979) 922.

[3] R. R. Akhmetshin *et al.*, *Phys. Lett.***B578** (2004) 285.

[4] M. N. Achasov *et al.*, hep-ex/0605013.

[5] Review of Particle Properties, S. Eidelman *et al*, *Phys. Lett.***B592** (2004) 1.

[6] G.T.Bodwin, E.Braaten, and J.Lee, hep-ph/0212181 (v4 October 2005)