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Low energy $e^+e^- \rightarrow e^+e^-\pi^0$ as a probe of chiral perturbation theory

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We analyze the reaction $e^+e^- \rightarrow e^+e^-\pi^0$ at low energies. By selecting the acceptance region for the energies and angles of the two leptons, one obtains a prediction where the relevance of the one loop correction to the tree level result can be modulated. This process is a good candidate to study the region of validity of chiral perturbation theory and the resonance models which have been proposed to merge the perturbative with the resonance dominated behaviour.

The anomalous part of the effective chiral lagrangian is fixed at leading order in the chiral expansion by the Wess–Zumino term. At one loop level the finite part of the counterterms that are needed to regularize the ultra-violet divergences cannot be estimated, contrary to the non anomalous case, from existing experimental data. A hypothesis is used to get an estimate of their value which extends to the anomalous sector a property of the non anomalous one: the dominance of the contribution coming from massive resonance exchange. Indeed, by adding such resonances to the pure pseudoscalar model and by considering their contribution to the effective pseudoscalar lagrangian, one finds that the leading term coming from tree level resonance exchange contributes substantially to the finite part of the one loop counterterms of the pseudoscalar lagrangian, practically saturating its value [1]. Recently, we have shown how the parameters entering the photon–pseudoscalar sector of the one loop effective lagrangian can be fixed completely under the assumption mentioned above in terms of various resonance decay properties like the omega decay width into three pions [2]. Tests of the validity of this hypothesis can be performed at high luminosity e^+e^- machines: in particular the e^+e^- annihilation into three pions [3] and into $\pi^0\mu^+\mu^-$ [4] have been discussed as possible test processes. In both cases, it was rather difficult to approach the kinematical conditions for a perturbative chiral expansion because of the relevant off-shellness of the virtual photon entering the processes.

The purpose of this letter is to consider another process where the photon virtuality can be tuned by varying the experimental cuts and can be made small enough to have observable one loop effects without a large contamination from unknown higher order effects. The process is the e^+e^- annihilation into $e^+e^-\pi^0$. Two diagrams are relevant for the amplitude, the s and the t channel contributions. If one selects the forward region for the leptons and applies a reasonable energy cut, the contribution of the t channel dominates over the one from the s channel, even including the resonance enhancement. This is due to the smallness of the momentum transfer exchanged in the t channel under these conditions. A window exists in the energy–angle plane of one of the two leptons where the prediction up to one loop order of chiral perturbation theory is expected to represent the bulk of the total cross section.

The one loop anomalous effective lagrangian for the photon–pseudoscalar sector has the following form:

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$$L_{\text{eff}}^{\text{odd}}(p^6) = \epsilon_{\mu\nu\alpha\beta} \left\langle \left[\frac{1}{8} i (\mathcal{L}_\lambda, U^\dagger D^\lambda D^\mu U - D^\lambda D^\mu U^\dagger U) - \frac{1}{8} i (\mathcal{L}_\mu, U^\dagger D^2 U - D^2 U^\dagger U) - \frac{1}{2} U^\dagger D^\lambda F_{\lambda\mu} U - \frac{1}{2} D^\lambda F_{\lambda\mu} \right] \right. \\ \left. \times \left(-\frac{h_1}{2M^2} \mathcal{L}_\nu \mathcal{L}_\alpha \mathcal{L}_\beta - i \frac{h_1}{4M^2} [(F_{\nu\alpha} + \tilde{F}_{\nu\alpha}) \mathcal{L}_\beta + \mathcal{L}_\nu (F_{\alpha\beta} + \tilde{F}_{\alpha\beta})] \right) \right\rangle, \quad (1)$$

where

$$\mathcal{L}^\mu = U^\dagger D_\mu U, \quad F_{\mu\nu} = eQ(\partial_\mu A_\nu - \partial_\nu A_\mu), \quad \tilde{F}_{\mu\nu} = U^\dagger F_{\mu\nu} U, \quad (2)$$

and $U = \exp(2i\Phi/f)$, with Φ the usual $N_f \times N_f$ matrix representation of the light pseudoscalar meson fields. $\langle \rangle$ stands for the trace over the $SU(N_f)$ flavour indices. The coefficient h_1 is the only parameter left once the vector mesons are introduced in the model according to a “minimal coupling” scheme which is discussed in ref. [2].

Independent experimental data can be used to fix its value: the agreement of such determinations confirms the phenomenological validity of the minimal coupling assumption. Its numerical value will be fixed in the following calculation to -0.036 .

We have performed three estimates of the process: (i) at tree level, (ii) by including the one loop contributions and (iii) by including an estimate of higher order terms which are associated to the full expression for the resonance propagators.

The amplitudes corresponding to these three cases have a general form:

$$A(\pi^0 \rightarrow \gamma^*(q_1) \gamma^*(q_2)) = \frac{\sqrt{2}e^2}{4\pi^2 f} \epsilon_{\mu\nu\alpha\beta} \epsilon_1^\mu \epsilon_2^\nu q_1^\alpha q_2^\beta F(q_1^2, q_2^2), \quad (3)$$

where the form factor F varies in the three cases according to

$$F(\text{tree}) = 1,$$

$$F(\text{one loop}) = 1 + \frac{1}{16\pi^2 f^2} \left[-\frac{1}{3} (q_1^2 + q_2^2) \left(\ln \frac{m_\pi^2}{\bar{M}_V^2} + \ln \frac{m_K^2}{\bar{M}_V^2} \right) + \frac{10}{9} (q_1^2 + q_2^2) \right. \\ \left. + \frac{4}{3} [F(m_\pi^2, q_1^2) + F(m_\pi^2, q_2^2) + F(m_K^2, q_1^2) + F(m_K^2, q_2^2)] \right] \\ - \frac{8}{3} \pi^2 h_1 \frac{q_1^2 + q_2^2}{\bar{M}_V^2},$$

$$F(\text{resonances}) = 1 + \frac{1}{16\pi^2 f^2} \left[-\frac{1}{3} (q_1^2 + q_2^2) \left(\ln \frac{m_\pi^2}{\bar{M}_V^2} + \ln \frac{m_K^2}{\bar{M}_V^2} \right) + \frac{10}{9} (q_1^2 + q_2^2) \right. \\ \left. + \frac{4}{3} [F(m_\pi^2, q_1^2) + F(m_\pi^2, q_2^2) + F(m_K^2, q_1^2) + F(m_K^2, q_2^2)] \right] \\ - \frac{4}{3} \pi^2 h_1 [P_\omega(q_1) + P_\omega(q_2) + P_\rho(q_1) + P_\rho(q_2) + 2P_\omega(q_1)P_\rho(q_2) + 2P_\omega(q_2)P_\rho(q_1)]. \quad (4)$$

The functions $F(m^2, q^2)$ have a logarithmic dependence upon the ratio $x = q^2/m^2$ and are of order q^2 in the chiral expansion. Their full expression is

$$F(m^2, q^2) = m^2 (1 - \frac{1}{4}x) \sqrt{\frac{x-4}{x}} \ln \frac{\sqrt{x} + \sqrt{x-4}}{-\sqrt{x} + \sqrt{x-4}} - 2m^2, \quad x > 4, x < 0, \\ F(m^2, q^2) = 2m^2 (1 - \frac{1}{4}x) \sqrt{\frac{4-x}{x}} \arctan \sqrt{\frac{x}{4-x}} - 2m^2, \quad 0 < x \leq 4. \quad (5)$$

The resonance propagator $P_V(q^2)$ is defined as follows:

$$P_V = \frac{M_V^2}{q^2 - M_V^2 + iM_V\Gamma_V}, \quad V = \rho, \omega. \quad (6)$$

The resonance models formulated so far are based on the hypothesis of degenerate masses for the vector meson octet ($M_\omega = M_\rho$). A reasonable fit with all present experimental data gives $M_V = 768$ MeV. We use such a value in the one loop form factor F , while we introduce a mass splitting in the full propagators present in the expression for F to all orders.

We have computed the total cross section for the $e^+(k_1)e^-(p_1) \rightarrow e^+(k_2)e^-(p_2)\pi^0$ process differential in the energies and polar angles of the two outgoing leptons. The expression is

$$\frac{d\sigma}{dE_+ dE_- d\theta_+ d\theta_-} (\text{GeV}^{-2}) = \frac{e^8}{16\pi^4 f^2} \frac{1}{(2\pi)^5} \frac{1}{2s} \times \frac{2\pi E_+ E_- s_+ s_- [4A_t F_t^2 + 4A_s F_s^2 - A_{ts}(F_t F_s^* + F_s F_t^*)]}{\sqrt{(2E_+ E_- s_+ s_-)^2 - [2E_+ E_- (1 + c_+ c_-) - 2\sqrt{s(E_+ + E_-) - m_\pi^2 + s}]^2}}. \quad (7)$$

The form factors F_t and F_s refer to the t and s channel respectively, where F should be one of the expressions in eq. (4). E_+ , E_- are the energies of the two charged leptons and the variables c_+ , c_- (s_+ , s_-) are the cosines (sines) of their polar angles with the beam axis. In the one loop expression for F^2 one neglects the terms which are of order q^4 in the chiral expansion. The tree level squared amplitudes A_t , A_s and the interference amplitude A_{ts} are given by

$$\begin{aligned} A_t &= \frac{1}{8q_1^4 q_2^2} [-2(4p_1 \cdot k_2 p_2 \cdot k_1 - l_1^2 l_2^2)^2 + 4q_1^2 q_2^2 (p_1 \cdot k_2 + p_2 \cdot k_1)^2 + q_1^2 q_2^2 (l_1^2 + l_2^2)^2 - 2q_1^4 q_2^4], \\ A_s &= \frac{1}{8l_1^4 l_2^2} [-2(4p_1 \cdot k_2 p_2 \cdot k_1 - q_1^2 q_2^2)^2 + 4l_1^2 l_2^2 (p_1 \cdot k_2 + p_2 \cdot k_1)^2 + l_1^2 l_2^2 (q_1^2 + q_2^2)^2 - 2l_1^4 l_2^4], \\ A_{ts} &= \frac{1}{2q_1^2 q_2^2 l_1^2 l_2^2} [2(p_1 \cdot k_2 + p_2 \cdot k_1)^2 (l_1^2 l_2^2 + q_1^2 q_2^2) - (l_1^2 l_2^2 - q_1^2 q_2^2)^2 - 8p_1 \cdot k_2 p_2 \cdot k_1 (p_1 \cdot k_2^2 + p_2 \cdot k_1^2)]. \end{aligned} \quad (8)$$

The listed products of four-momenta can be expressed in terms of the cosine of the polar angles and the energies of the outgoing leptons as follows:

$$\begin{aligned} q_1^2 &= -\sqrt{s}E_- (1 - c_-), \quad q_2^2 = -\sqrt{s}E_+ (q - c_+), \\ l_1^2 &= s, \quad l_2^2 = 2\sqrt{s}(E_+ + E_-) - s + m_\pi^2, \\ p_1 \cdot k_2 &= \frac{1}{2}\sqrt{s}E_+ (1 + c_+), \quad p_2 \cdot k_1 = \frac{1}{2}\sqrt{s}E_- (1 + c_-). \end{aligned} \quad (9)$$

The phase space integration has been performed numerically. We have been partially inclusive in one of the two leptons in order to enhance the contribution of the low momentum transfer t channel: the polar angle (referred to the incoming beam axis) has been integrated between 10° and 30° and the energy between 100 MeV and the kinematical upper limit. For the second lepton we have calculated the differential cross section in the same variables.

For the total centre of mass energy we have chosen three values: 600, 800 and 900 MeV.

In the first case we obtain a result which is a calculable perturbation of the tree level estimate. In table 1 we report the differential cross section for the all-order estimate from resonance exchange in the minimal coupling scheme, expressed in pb, the ratio of the one loop prediction over the tree level and, for comparison, the ratio of the all-order estimate over the one loop result. The numbers show how the one loop estimate saturates the correction with respect to the tree level due to the dominance of low momentum transfer in the t channel. The

Table 1

The absolute values of the differential total cross section in pb at total centre of mass energy of $\sqrt{s}=600$ MeV are shown in the first column. Data are grouped in blocks. Each of them represents the cross section as a function of the energy starting from 25 MeV in steps of 50 MeV for a fixed range of the polar angle 5° wide. The bins of polar angles are ordered starting from 10° . The other columns show (1) the ratio of the one loop prediction over the tree level, (2) the ratio of the all-order estimate from resonance exchange in the minimal coupling scheme over the one loop result, (3) the t channel contribution to the total cross section in the all-order case. This can be bigger than one due to a negative interference with the s channel. All data are presented with a precision of 1%.

θ (degrees)	σ (pb)	tot loop/tot tree	tot res/tot loop	t res/tot res	E (MeV)
10-15	8.0×10^{-2}	0.96	1.00	1.00	25- 75
	0.105	0.96	1.00	1.00	75-125
	0.148	0.96	1.00	1.00	125-175
	0.232	0.96	1.00	1.00	175-225
	0.376	0.97	1.00	1.00	225-275
15-20	5.6×10^{-2}	0.96	1.00	1.00	25- 75
	7.3×10^{-2}	0.96	1.00	1.00	75-125
	0.101	0.95	1.00	1.00	125-175
	0.155	0.95	1.00	1.00	175-225
	0.236	0.96	1.00	1.00	225-275
20-25	4.31×10^{-2}	0.96	1.00	1.00	25- 75
	5.47×10^{-2}	0.95	1.00	1.00	75-125
	7.5×10^{-2}	0.94	1.00	1.00	125-175
	0.112	0.94	1.00	1.00	175-225
	0.157	0.94	1.00	1.00	225-275
25-30	3.49×10^{-2}	0.95	1.00	1.00	25- 75
	4.32×10^{-2}	0.94	1.00	1.00	75-125
	5.8×10^{-2}	0.93	1.00	1.01	125-175
	8.4×10^{-2}	0.92	1.00	1.01	175-225
	0.106	0.92	1.00	1.01	225-275
30-35	2.87×10^{-2}	0.95	1.00	1.00	25- 75
	3.51×10^{-2}	0.93	1.00	1.00	75-125
	4.60×10^{-2}	0.92	1.00	1.01	125-175
	6.5×10^{-2}	0.90	1.00	1.01	175-225
	7.3×10^{-2}	0.90	1.00	1.01	225-275
35-40	2.43×10^{-2}	0.94	1.00	1.00	25- 75
	2.89×10^{-2}	0.92	1.00	1.01	75-125
	3.69×10^{-2}	0.90	1.00	1.01	125-175
	5.0×10^{-2}	0.88	1.01	1.01	175-225
	4.98×10^{-2}	0.87	1.01	1.01	225-275
40-45	2.07×10^{-2}	0.94	1.01	1.00	25- 75
	2.43×10^{-2}	0.91	1.01	1.01	75-125
	3.01×10^{-2}	0.88	1.01	1.01	125-175
	3.92×10^{-2}	0.86	1.01	1.01	175-225
	3.39×10^{-2}	0.84	1.01	1.01	225-275
45-50	1.79×10^{-2}	0.93	1.01	1.00	25- 75
	2.06×10^{-2}	0.89	1.01	1.01	75-125
	2.46×10^{-2}	0.86	1.01	1.01	125-175
	3.09×10^{-2}	0.83	1.01	1.01	175-225
	2.28×10^{-2}	0.81	1.02	1.01	225-275
50-55	1.58×10^{-2}	0.92	1.01	0.99	25- 75
	1.75×10^{-2}	0.88	1.01	1.01	75-125
	2.02×10^{-2}	0.84	1.01	1.02	125-175
	2.45×10^{-2}	0.80	1.02	1.02	175-225
	1.52×10^{-2}	0.77	1.03	1.02	225-275
55-60	1.39×10^{-2}	0.92	1.01	0.99	25- 75
	1.50×10^{-2}	0.86	1.01	1.01	75-125
	1.67×10^{-2}	0.81	1.02	1.02	125-175
	1.95×10^{-2}	0.77	1.03	1.02	175-225
	1.00×10^{-2}	0.74	1.05	1.02	225-275

Fig. 1. The ratio of the differential cross section at one loop order over the tree level estimate at $\sqrt{s}=600$ MeV as a function of the polar angle and energy of one of the two outgoing leptons. The binning in energy and angles is the one explained for the corresponding table.

Fig. 2. The ratio of the differential cross section with all resonance corrections over the tree level estimate at $\sqrt{s}=800$ MeV.

Table 2

The same quantities as in table 1 are shown for a total centre of mass energy of $\sqrt{s}=800$ MeV.

θ (degrees)	σ (pb)	tot loop/tot tree	tot res/tot loop	t res/tot res	E (MeV)
15	5.8×10^{-2}	0.94	1.03	0.98	25– 75
	7.0×10^{-2}	0.93	1.04	0.97	75–125
	8.8×10^{-2}	0.93	1.04	0.97	125–175
	0.116	0.93	1.04	0.97	175–225
	0.160	0.93	1.03	0.98	225–275
	0.241	0.93	1.02	0.99	275–325
	0.424	0.94	1.02	0.98	325–375
20	4.22×10^{-2}	0.93	1.06	0.95	25– 75
	5.1×10^{-2}	0.93	1.07	0.94	75–125
	6.3×10^{-2}	0.92	1.07	0.94	125–175
	8.1×10^{-2}	0.92	1.07	0.94	175–225
	0.111	0.91	1.06	0.95	225–275
	0.160	0.91	1.04	0.97	275–325
	0.271	0.92	1.05	0.96	325–375
25	3.31×10^{-2}	0.93	1.09	0.92	25– 75
	3.96×10^{-2}	0.92	1.11	0.91	75–125
	4.90×10^{-2}	0.91	1.12	0.90	125–175
	6.2×10^{-2}	0.90	1.12	0.90	175–225
	8.2×10^{-2}	0.89	1.09	0.93	225–275
	0.115	0.89	1.06	0.96	275–325
	0.184	0.89	1.09	0.93	325–375
30	2.75×10^{-2}	0.92	1.13	0.89	25– 75
	3.29×10^{-2}	0.91	1.16	0.87	75–125
	4.00×10^{-2}	0.89	1.18	0.86	125–175
	4.00×10^{-2}	0.88	1.17	0.87	175–225
	6.4×10^{-2}	0.86	1.14	0.89	225–275
	8.5×10^{-2}	0.85	1.09	0.94	275–325
	0.129	0.85	1.14	0.89	325–375

Table 3

The same quantities as in table 1 for a total centre of mass energy of $\sqrt{s}=900$ MeV.

θ (degrees)	σ (pb)	tot loop/tot tree	tot res/tot loop	t res/tot res	E (MeV)
10-15	4.93×10^{-2}	0.92	1.01	1.00	25- 75
	5.7×10^{-2}	0.92	1.01	1.00	75-125
	7.0×10^{-2}	0.91	1.01	0.99	125-175
	8.8×10^{-2}	0.91	1.01	0.99	175-225
	0.115	0.91	1.02	0.99	225-275
	0.159	0.91	1.02	0.99	275-325
	0.237	0.91	1.01	0.99	325-375
	0.410	0.93	1.01	0.99	375-425
15-20	3.50×10^{-2}	0.91	1.01	1.00	25- 75
	4.03×10^{-2}	0.91	1.01	0.99	75-125
	4.83×10^{-2}	0.90	1.02	0.99	125-175
	6.0×10^{-2}	0.89	1.02	0.99	175-225
	7.8×10^{-2}	0.89	1.03	0.98	225-275
	0.106	0.89	1.03	0.98	275-325
	0.155	0.89	1.02	0.99	325-375
	0.255	0.90	1.02	0.99	375-425
20-25	2.66×10^{-2}	0.91	1.01	0.99	25- 75
	3.08×10^{-2}	0.90	1.02	0.99	75-125
	3.64×10^{-2}	0.89	1.03	0.98	125-175
	4.49×10^{-2}	0.87	1.04	0.98	175-225
	5.7×10^{-2}	0.86	1.04	0.98	225-275
	7.6×10^{-2}	0.86	1.04	0.98	275-325
	0.108	0.85	1.03	0.98	325-375
	0.167	0.86	1.03	0.98	375-425
25-30	2.15×10^{-2}	0.90	1.02	0.99	25- 75
	2.45×10^{-2}	0.88	1.03	0.98	75-125
	2.88×10^{-2}	0.87	1.04	0.98	125-175
	3.49×10^{-2}	0.85	1.05	0.97	175-225
	4.38×10^{-2}	0.83	1.06	0.96	225-275
	5.7×10^{-2}	0.82	1.06	0.97	275-325
	7.7×10^{-2}	0.81	1.05	0.98	325-375
	0.112	0.81	1.05	0.97	375-425

Fig. 3. The ratio of the differential cross section with one loop correction over the tree level estimate at $\sqrt{s}=900$ MeV.

contribution of the latter with respect to the total is also shown. Fig. 1 shows the plot of the first ratio presented in table 1. For large angles and for higher energies the t channel contribution becomes less important and makes the result more sensitive to the model dependent estimate of the corrections beyond one loop. By defining a safe region where the uncertainty on the one loop correction does not exceed 15%, we get for the cross section integrated over this region a value of 3.2 pb. Such a region approximately corresponds to the polar angle between 10° and 60° and to the whole sampled energy region between 25 and 275 MeV (283 MeV is the kinematical upper limit). Note that the uncertainty increases with energy at a given angle. A reduction of the lower energy cut from 100 MeV (the value used in the tables) to 50 MeV for the inclusive lepton does not affect the safe region, whereas the integrated cross section increases by about 9%. Throughout the safe region the one loop correction has a truly perturbative behaviour not exceeding 25% of the tree level estimate.

In the case with total centre of mass energy of 800 MeV, the safe region is clearly absent with the uncertainty on the one loop correction bigger than 30% even at small angles, where the overall effect of the correction is small and hard to measure. This is a consequence of the increasing role of the s channel dominated by the ω and ρ resonances exchange. In this case the comparison of the experimental measurements with the resonance model prediction is the only possibility and can give support to the ansatz on the all-order result. The value of the cross section is given in table 2, together with the ratios already discussed for table 1. In fig. 2 we plot the product of the two ratios of the table, corresponding to the correction to the tree level due to the all-order case. The total resonant cross section integrated between 10° and 30° and in the whole energy range is 2.9 picobarn, while becomes 4.7 pb by integrating between 10° and 90° .

In table 3 we give the results of the same analysis performed at total centre of mass energy of 900 MeV. At this energy higher resonance contaminations are negligible. In this case the safe region of 15% of uncertainty corresponds to angles between 10° and 20° , with a total integrated cross section of 2.0 pb. It increases to about 3 pb by relaxing the uncertainty up to 30%, which corresponds to an angular region between 10° and 30° . The ratio of the one loop estimate over the tree level is plotted in fig. 3.

In all interesting cases the cross section is at the level of a few picobarns and the size of the correction to be measured of the order of (10–30)%. A luminosity of $2.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ would lead to about one thousand events in a year and make such a measure feasible.

The reaction $e^+e^- \rightarrow e^+e^-\pi^0$ has been calculated in chiral perturbation theory and compared with an all-order estimate including full resonance propagators. We have shown that, by suitably choosing the experimental conditions to select mainly the contribution of the t channel at low momentum transfer, one can tune the size of one loop corrections with respect to the tree level estimate. This process then appears very useful to study the limits of validity of the chiral expansion.

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